A Novel Fault-Tolerant Multi-EPON System with Sharing Protection through Bridge ONUs

I-Shyan Hwang, Zen-Der Shyu and Liang-Yu Ke

***Abstract*—In the EPON, many previous studies proposed dedicated protection architectures to protect the critical components which results in high cost for deployment. To achieve high reliability and low-cost for deployment, this article proposes a novel fault-tolerant Multi-EPON system with cost-effective shared protection through Bridge ONUs. Under the failures, the Bridge ONU controls the faulty EPON, plays the role of OLT and the transmission of faulty EPONs is restored by relaying to other interconnected adjacent EPONs. The minimum hop count relay algorithm and the relay window mechanism are also proposed in this article to help the data for relaying efficiently. Furthermore, the One-Wait DBA enables the controller of affected PONs to obtain more up-to-date buffer information from each ONU in order to enhance overall system performance. The simulation results show that the proposed Multi-EPON system can provide high system performance for different failed situations in terms of average delay, MAX delay and EF jitter, especially in high traffic loads.**

***Index Terms*—Bridge ONU, DBA, EPON, fault-tolerant, protection.**

I. Introduction

In the EPON, all ONUs are served by the OLT using a discovery handshake in *Multi-Point Control Protocol* and share a common transmission channel towards the OLT by time-division multiple access schemes. Only a single ONU may transmit data in one timeslot to avoid signal collisions. After the ONU is registered by discovery process, the OLT controls PON and coordinates the transmission window of ONUs with granted GATE messages, which contain the transmission start time and transmission length of the corresponding ONU. To avoid signals collisions and allocate bandwidth fairly in the upstream direction, schedule algorithms which have been extensively researched. There are two categories of bandwidth allocation schemes on EPONs: *fixed bandwidth allocation* (FBA) and *dynamic bandwidth allocation* (DBA). In the FBA scheme, each ONU is assigned fixed timeslots in data transmission from the ONUs to the OLT at full link capacity. In contrast to the FBA, the DBA further improves the system in a more efficient way; the OLT allocates a variable timeslot to each ONU dynamically based on the bandwidth request and ensures the Quality-of-Service (QoS) by guaranteed service level agreement (SLA). Furthermore, fault tolerance is also an important issue in PONs. There are two categories of network failures in EPON, one is link failure and the other is node failure. In link failure, the failure of feeder fiber will halt the whole PON system, but the failure of a branch will halt just one ONU. In the node failure, the failures of OLT or splitter will cause the whole PON system to fault. Therefore, the OLT, feeder fiber and splitter are the most critical components in the PON system. In order to protect PONs against these serious failures, many researchers proposed dedicated protection architectures, however, they are not cost-effective, as they require many redundant components. Sharing bandwidth to protect the neighboring PONs is an efficient way to reduce the cost of protection. To achieve high reliability and low-cost for deployment, a novel *fault-tolerant Multi-EPON* system with shared protection is proposed in this article to provide protection against OLT failure and feeder fiber failure.

The rest of this paper is organized as follows. Section 2 decries the related work. Section 3 proposes a novel *Fault-Tolerant Multi-EPON* System which is provided a robust fault-tolerant mechanism based on the concept of shared protection. Section 4 shows the simulation results in terms of the average packet delay, MAX packet delay and jitter performance. Finally, Section 5 draws conclusions and offers further suggestions.

II. Literature Review

A. Fault-Tolerant Architectures

Four protection architectures are discussed on PON in the ITU-T Recommendation G.983.1 [1]. However, those architectures have a lot of redundancy, and they are not economical solutions. Moreover, the protection scheme with one cold standby OLT is proposed in [2] and the standby OLT utilized to protect multiple PONs. The scheme still needs cold standby equipment and supports only one OLT failure. A resilient fast protection switching scheme [3], when a feeder fiber break or equipment failure occurs in central office (CO), and the switching is performed at the CO. Because of the switch, it is more complex and the scheme still needs a redundant feeder fiber to protect the feeder fiber. In [4], an automatic-protection-switching mechanism is proposed in the ONU to fight against distribution fiber breaks. The transmission of affected ONU is restored by other interconnected ONUs when branches are down. However, it cannot provide any protection for OLT and feeder fiber which are the most critical components of PON. In the ring topologies, the protection scheme in [5] has a large

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conventional ring and a cold backup transceiver and receiver to protect one point failure. The drawbacks of the ring topologies are more fiber usage, higher signal attenuation and serious near-far problems. To address those problems, the double feeder fibers with a hybrid small ring are introduced in [6]. The scheme minimizes the fiber usage and assures no packet loss by using hot standby components. However, the ONU is more complex in the scheme and 1+1 protection schemes have a low market penetration due to its high cost. Therefore, this paper proposed a shared protection scheme with interconnected adjacent PONs by Bridge ONUs to avoid redundancy in the EPON.

B. ONU Priority Scheduling

To support differentiated service classes, a priority queuing scheme, such as DiffServ, and the queue management tasks are carried out by each ONU. The transmission of queued packets is decided by a specific scheduling scheme. The *strict priority scheduling* serves the buffered higher-priority packets first as defined in IEEE 802.1D. Lower-priority packets can only be transmitted when the higher-priority queues are empty. Therefore, the lower-priority packets suffer excessive delays and unfair increased packet loss. However, a scheduling scheme is also necessary to control the high-priority traffic if it exceeds the contract of service level agreement (SLA). In [7], priority-based scheduling is proposed to deal with the problems by employing *strict priority scheduling* within a specific time interval. This scheme provides a bounded delay for low-priority packets and ensures fairness by transmitting packets of all traffic classes.

C. Dynamic Bandwidth Allocation

The dynamic bandwidth allocation (DBA), such as limited bandwidth allocation (LBA), has been studied in [8]. In the LBA, the timeslots length of each ONU is upper bounded by the maximum timeslots length, $B_{\max}$, which could be specified by SLA. The drawback of LBA is the poor utilization for the upstream bandwidth and it restricts aggressive competition for the upstream bandwidth, especially under non-uniform traffic. In order to better utilize the leftover bandwidth from ONUs with some traffic backlogs, the authors in [7] proposed a DBA scheme called Excessive Bandwidth Reallocation (EBR) in which ONUs were divided into two categories, lightly-loaded and heavily-loaded, according to their guaranteed bandwidth $B_{\max}$. Total excessive bandwidth, B_{excess} , saved from lightly-loaded group is redistributed to heavily-loaded ONUs to improve efficiency. Unfortunately, the drawbacks of EBR are unfairness, *idle period problem* and allocating more than the requested bandwidth to ONUs [9], which was redefined as *redundant bandwidth problem* in our previous research [10]. To improve bandwidth utilization, an early allocation mechanism was proposed in [7], which grants the bandwidth of lightly-loaded ONUs immediately without any delay when it receives the REPORT message. Moreover, the efficient bandwidth allocation algorithm (EAA) with a time tracker is proposed to address the *idle period problem* [11]. It forces the OLT to grant the bandwidth to a heavily-loaded ONU without waiting reallocation when the upstream channel is going to idle. However, the drawback of [7], [11] is that the service order of ONUs changes in each service cycle, therefore, the estimation of the incoming high priority traffic is severely impaired because the waiting time in each ONU may change drastically. In [12], Xiaofeng *et al*. proposed another DBA scheme that maintains fairness mechanism of the excessive bandwidth reallocation operation well for heavily-loaded ONUs, but ignores the fairness of lightly-loaded ONUs. The reason is that the request by the lightly-loaded ONU does not consider the possible packets arriving during the waiting time. Jitter performance studied in [13] is another important concern in EPON, especially for the high priority service which is delay-variation sensitive traffic (e.g. voice transmissions). In this scheme, high priority service is protected in a separate sub-cycle, therefore, the jitter performance is considerably improved.

III. The Proposed Novel Fault-Tolerant Multi-EPON System

A novel *fault-tolerant Multi-EPON* system is presented in this section. In section 3.1, we propose a fault-tolerant architecture in Multi-EPON, which provides protection by sharing the bandwidth with the neighboring PONs. In section 3.2, the minimum hop count relay path main algorithm is proposed to address the shortest path to relay data and calculates the available bandwidth to each PON under failure. In section 3.3, the Relay Window Mechanism is proposed to relay data between PONs and cooperates with two DBA schemes that are proposed to help the data relay and improve the system performance.

A. Fault-Tolerant Architecture

To achieve high reliability and low-cost for deployment, each EPON system is connected the nearest EPON by a Bridge ONU in order to minimize fiber usage, shown in Fig. 1. When the feeder fiber is cut or OLT is down, the Bridge ONU controls the PON, plays the role of OLT and receives the data coming from the ONUs. Then, the Bridge ONU relays the data to the OLT of the adjacent PON. In normal situations, the Bridge ONU ignores the upstream signal of ONUs and monitors the signal of downstream channel to detect the failures. In [14], the passive optical splitter/combiner (PSC) broadcasting the upstream signal to all ONUs may cause potential security problems and higher signal power attenuation. To alleviate those problems, the PSC, constructed by a $2 \times N$ PSC and a 2×2 PSC, is considered in the proposed architecture, shown in Fig. 2. In the PSC, the upstream optical signal power is only transmitted to OLT and Bridge ONUs and the downstream optical signal transmitted by the Bridge ONU is broadcasted to all ONUs as the downstream signal of OLT. In the Bridge ONU, both interfaces connect with two adjacent EPON. Note that in addition to the conventional transceiver (a 1310nm transmitter and a 1490nm receiver) of normal ONU maintained at the Bridge ONU, the Bridge ONU requires an extra 1310nm receiver, an extra 1490nm transmitter and a switch. The advantages of the proposed architecture are that no backup feeder fibers and backup OLT modules are needed and the fiber usage is close to standard EPON which is without any protection mechanism.

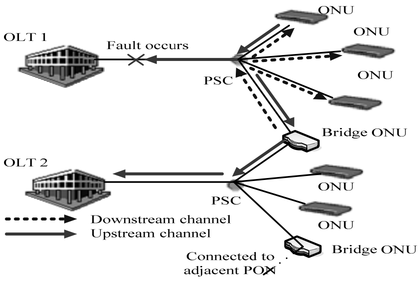


Fig. 1 The Bridge ONU connects two adjacent PONs

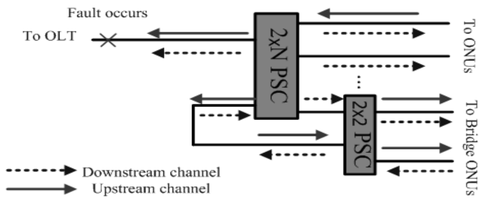


Fig. 2 Architecture of the PSC

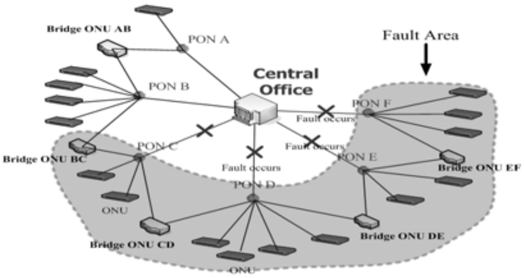


Fig. 3 Cost-effective Shared Protection System

B. Minimum Hop Count Relay Path Main Algorithm

When faults occur, in order to let the affected PONs determine the system situation and decide the relay path with minimum hop count, the Bridge ONUs will execute four phases in the *Minimum Hop Count Relay Path Main Algorithm*, and they are described in the following subsection. Note that there are two definitions of the Bridge ONU in the boundary of fault area, one is that the Bridge ONU has a failed PON on only one side (i.e. Bridge ONU BC in Fig. 3), the other one is the Bridge ONU has two failed PONs on both sides and a failed PON of the two has only one Bridge ONU (i.e. Bridge ONU EF in Fig. 3).

1) **Information Sending Phase**

When the fault occurs, the Bridge ONUs in the boundary of fault area send the *Fault Information Message*, shown in Fig. 4, to the Bridge ONU inside the fault area in order to let other Bridge ONUs and affected OLTs get the Multi-EPON system situation, such as the number of hop count and guaranteed timeslots in the left and right paths, to decide the relay path with minimum hop count. After sending the *Fault Information Message*, the sender waits for the *ACK Message* reply by the receiver. If the waiting reaches timeout, the *Fault Information Message* will be resent after random delay.

2) **Waiting Information Phase**

When the Bridge ONU received the *Fault Information Message*, it replied an *ACK Message* to the sender. Then, it adds one to the *Number of hop count* field and records the information of the current PON, such as the hop count and guaranteed timeslots fields in the *Fault Information Message*, and sends it to the next Bridge ONU or OLT.

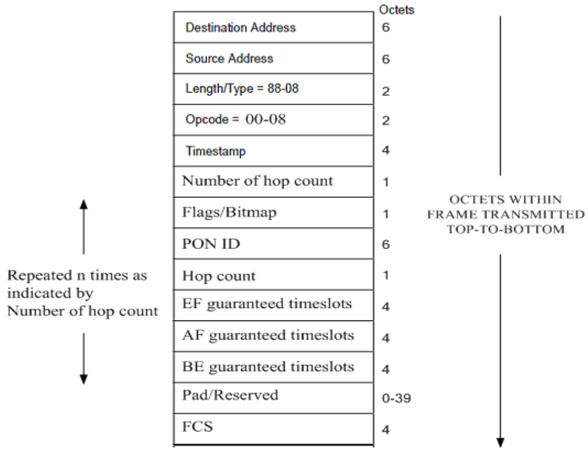


Fig. 4 The *Fault Information Message*

3) **Deciding Relay Path Phase**

After getting all information of the affected PONs, the Bridge ONU decides the relay paths. In order to reduce the packet delay during the failure time, each PON chooses the relay path with minimal hop count.

4) **Calculating Available Bandwidth Phase**

The controller of affected PONs calculates the available bandwidth of each PON as follows:

$$PON\_BW_i = (T_{cycle}^{MAX} - Ng) \times \left(\sum_{k \in PON_i} S_k / \sum_{j \in ALL\_PON} S_j \right)$$

, where $\sum_{k \in PON_i} S_k / \sum_{j \in ALL\_PON} S_j$ is the proportion of PON$_i$ can get minimum guaranteed bandwidth from the available bandwidth, T_{cycle}^{MAX} is the maximum cycle time, g is the guard time, N is the number of ONUs in the PON providing the bandwidth to Faulty PON, S_k is the sum of S_k^c, the minimum guaranteed timeslots for the *EF*, *AF* and *BE* traffic determined by SLA of ONU$_k$ which is in the PON$_i$. And S_j is the sum of S_j^c, the minimum guaranteed timeslots for the *EF*, *AF* and *BE* traffic determined by SLA of ONU$_j$ which is in the relay path that including PON$_i$. The S_j and S_k can be expressed as $S_k = \sum_c S_k^c$ and $S_j = \sum_c S_j^c$, $c \in \{EF, AF, BE\}$.

C. Relay Mechanism and Local DBA

The PON with fault is referred to as *Faulty PON* and the PON, which provides protection by sharing bandwidth to the Faulty PONs, is referred to as *Protection PON*. After calculating the available timeslots of the PONs, the Bridge ONUs start to control the adjacent PON of the downstream relay path. The Bridge ONUs, in the Faulty PON, execute the One-Wait DBA for local ONUs and the OLT in the Protection PON executes the Protection DBA for local ONUs. Then both DBA schemes cooperate with the Relay Window Mechanism to help relay the data hop-by-hop in the Faulty PONs. For example, the Bridge ONU EF controls the PON F and the Bridge ONU DE controls the PON E, shown in Fig. 3. The Bridge ONU EF relays the data queuing in its buffer to the Bridge ONU DE. Then, the Bridge ONU DE has two kinds of data in its buffer; one is PON E coming from local ONU; the other is PON F coming from Bridge ONU EF. The Bridge ONU DE relays the data queuing in its buffer to the controller of PON D that is the Bridge ONU CD and the Bridge ONU CD relays queuing data to the Bridge ONU BC. Finally, the Bridge ONU BC relays all queuing data to the controller of PON B. The proposed Relay Window Mechanism and two DBA schemes are described in the following subsection.

1) **Relay Window Mechanism**

There are two transmission windows in each PON of the relay path. One is the local DBA window transmitted by local ONUs and the other one is the relay window transmitted by the adjacent Bridge ONU in the downstream relay path, shown in Fig. 5. The OLT or the Bridge ONU specifies the start time of the relay window in the GATE message and transmits it to the adjacent Bridge ONU in the downstream relay path. When the relay window begins, the Bridge ONU specifies transmission length in a REPORT message and sends it to the controller of upstream PON. After the controller gets the REPORT message, it can know when the end of relay window is and then start to execute the local DBA. When a Bridge ONU transmits an upstream packet in the relay window, the packets from local ONUs or the adjacent Bridge ONU in the downstream relay path are still arriving. The EF traffic class with the highest priority for strictly delay sensitive services is typically a constant bit rate (CBR). To further reduce the EF packet delay time, the Bridge ONU predicts the EF bandwidth requirement during the relay window by the EF traffic rate with the rate-based prediction scheme presented in [15]. Then, the Bridge ONU reports the total length transmitting timeslots of this relay cycle with upper bounded by guaranteed bandwidth in the downside relay path, and it can be expressed as

$$G^{Total}_{i,n+1} = \min(R^{Total}_{i,n}, \sum_{k \in downstreamPONintherelaypath} PON\_BW_k) \quad (1)$$

, where $R^{Total}_{i,n}$ is the sum of request timeslots for differentiated traffics in the queues of the Bridge ONU$_i$ in the n*th* cycle, i.e. $R^{Total}_{i,n} = R^{EF}_{i,n} + R^{AF}_{i,n} + R^{BE}_{i,n} + P^{EF}_{i,n}$, the $P^{EF}_{i,n}$ is the predicted timeslots of EF traffic coming during the relay window, and $\sum_{k \in downstreamPONintherelaypath} PON\_BW_k$ is the sum of available bandwidth of Faulty PONs in the downside of the relay path.

2) **Two DBA Schemes for Local ONUs**

In the Faulty PONs, the link utilization is impossible to use fully. The reason is that the available bandwidth is provided by the OLT in Protection PON and is shared with the affected PONs. The packet delay is more important than link utilization in the Faulty PONs. However, the link utilization and the packet delay are of the same importance in Protection PON. Therefore, the two DBA are proposed to deal with the different network characteristics for improving the whole Multi-EPON system performance. First, the One-Wait DBA is proposed to reduce the packet delay in the Faulty PON. Second, the Protection DBA is proposed to improve the channel utilization and reduce the packet delay in the Protection PON.

- *One-Wait DBA Scheme in the Faulty PON*

The operation of traditional DBA schemes are that the REPORT messages piggyback in data timeslots and report

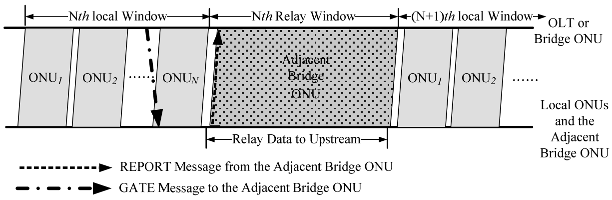


Fig. 5 The Relay Window

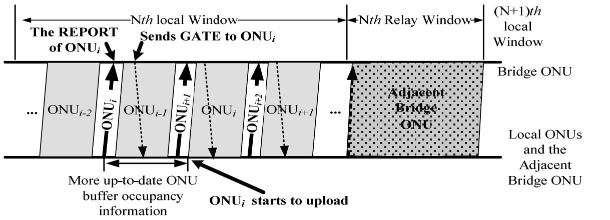


Fig. 6 One-Wait DBA

the queue length of the ONU, but without considering the packet arriving during the waiting time. It is observed that the packet delay in those DBA schemes is close to 1.5 transmission cycle time. Therefore, the packets arriving in the waiting time cannot be transmitted in the current cycle even if the ONU is lightly-loaded. This will result in longer packet relayed delay and is unfair to the lightly-loaded ONU. To improve the drawbacks and offer better QoS in the Multi-EPON system, the proposed One-Wait DBA shifts the report time of ONUs purposely in order to enable the Bridge ONU to obtain more up-to-date buffer occupancy information from each ONU. This point is further illustrated in Fig. 6. The ONU$_i$ uploads its REPORT message between the (i-2)*th* and (i-1)*th* ONU. When the Bridge ONU receives the REPORT message of ONU$_i$, it starts to calculate available bandwidth of ONU$_i$ and grant the available bandwidth in the GATE message to ONU$_i$ immediately. After the end of transmission window of ONU$_{i-1}$, the REPORT message is uploaded by (i+1)*th* ONU, and then, the ONU$_i$ starts to upload the queuing data in granted timeslots. Although the amount of cost guard time in the One-Wait DBA is twice as much as the number of the DBA schemes piggybacking their REPORT messages in data timeslots. However, the average packets delay is smaller than one cycle time and close to half of a cycle time. Therefore, the One-Wait DBA can reduce to almost one cycle time in the average packet delay.

When it receives a REPORT message from a local ONU, the One-Wait DBA assigns the timeslots to the ONU based on the guaranteed timeslots immediately and can be expressed as $G^{Total}_i = \min(R^{Total}_i, PON\_BW_i \times (S_i / \sum_{k \in PON_i} S_k))$, where R^{Total}_i is the sum of requested BW for differentiated traffics of ONU$_i$, and $S_i / \sum_{k \in PON_i} S_k$ is the proportion of ONU$_i$ can get granted bandwidth from the available bandwidth of this PON denoted as PON_BW_i. After finishing granting bandwidth to the ONU$_i$ by sending GATE message, the One-Wait DBA specifies the REPORT sending time of ONU$_{i+2}$ at the end of uploaded timeslots in ONU$_i$. Moreover, after granting the last ONU in local cycle, the controller of the PON invokes the *Relay Mechanism.* When the controller received the REPORT message of the adjacent Bridge ONU of the PON, it executes the One-Wait DBA again.

- *Protection DBA Scheme in the Protection PON*

The Protection PON is the final hop in the relay path, the performance of packet delay in relay data and link utilization are the key factors on the system performance. To further improve bandwidth utilization and packet delay of relay data, there are two transmission windows in the *Protection DBA*. One is the relay window for Bridge ONUs to relay data; the other is local transmission window for local ONUs, shown in Fig. 7. Furthermore, to address the jitter performance of EF traffic, the proposed Protection DBA fixed the service order of all local ONUs and the Bridge ONU in the PON.

Firstly, at the beginning of N*th* Relay Window to transmit the data, the Bridge ONU limited the transmitting timeslots by equation (1) and broadcasts the REPORT message to the OLT in order to specify its transmission length. Then, the Bridge ONU starts to relay the data queue in its buffer to OLT, shown in Fig. 7. Secondly, after receiving the REPORT message of the Bridge ONU, the OLT executes the Protection DBA scheme to allocate bandwidth to local ONUs for (N+1)*th* transmission cycle and sends all GATE messages to local ONUs. Thirdly, the OLT specifies the beginning timeslots of (N+1)*th* Relay Window by sending a GATE message to the Bridge ONU. Note that the transmissions of different nodes are separated by a guard time.

The detail of allocating timeslots for local ONUs in the proposed Protection DBA is described as follows. First, calculate $R_{i,n}^{Total}$ of all ONUs and initialize the available bandwidth, $B_{available}$, which is expressed as $B_{available} = PON\_BW_i$. Then, the proposed Protection DBA will select the ONU$_i$ with the maximal residue bandwidth, i.e. $\max\left(S_i - R_{i,n}^{Total}\right)$, from unassigned ONUs. The granted bandwidth for ONU$_i$, $G_{i,n+1}^{Total}$, in the next cycle is given as follows

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

, where R_i^{Total} is the sum of requested BW for differentiated traffics of ONU$_i$ in the n*th* cycle, i.e. $R_{i,n}^{Total} = R_{i,n}^{EF} + R_{i,n}^{AF} + R_{i,n}^{BE} + P_{i,n}^{EF}$, where $P_{i,n}^{EF}$ is the predicted timeslots of *EF* traffic with the rate-based prediction scheme presented in [15] and $S_i / \sum_{k \in unassigned} S_k$ is the proportion of ONU$_i$ can get granted bandwidth from the available bandwidth, $B_{available}$. Furthermore, the granted bandwidth for *EF*, *A*F and *BE* classes are as follows:

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

In the final, the available bandwidth becomes $B_{available} = B_{available} - G_{i,n+1}^{Total}$. The whole process continues until all local ONUs have been assigned, and the Protection DBA fixes the transmission order of ONUs to improve the jitter performance. Then, the OLT sends the GATE message to all local ONUs and specifies the start time of (N+1)*th* Relay Window by sending a GATE message to the Bridge ONU.

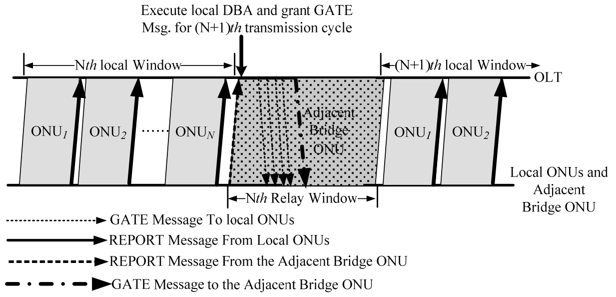
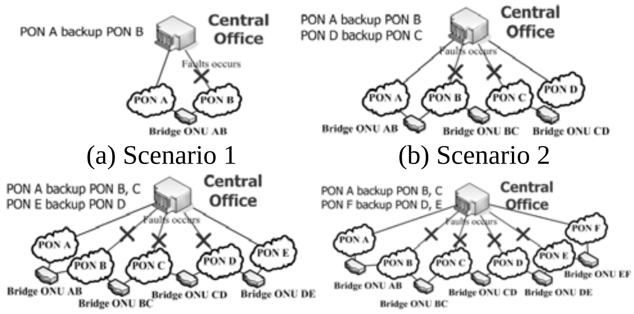


Fig. 7 The operation of Protection DBA with a Relay Window



(a) Scenario 1 (b) Scenario 2
(c) Scenario 3 (d) Scenario 4
Fig. 8 Four Significant Scenarios

IV. PERFORMANCE EVALUATION

The system performance is analyzed by simulating the four significant scenarios, shown in Fig. 8, and compared with EAA [11] in terms of average packet delay, MAX packet delay and jitter. The performance evaluation is studied using the OPNET simulator with one OLT and 32 ONUs in a PON. The downstream and upstream capacities are both 1 Gb/s. The distance from an ONU to the OLT is assumed 20 km and the distance between each PON is assumed 1 km. Each ONU has infinite buffer and the service policy is in first-in first-out discipline. The traffic model is characterized by self-similarity and long-range dependence (LRD) [16]. This model is used to generate highly bursty AF and BE traffic classes with a Hurst parameter of 0.7, and packet sizes are uniformly distributed between 64 and 1518 bytes. Furthermore, high-priority traffic is modeled using a Poisson distribution and packet size is fixed to 70 bytes. The traffic profile is as follows: 20% of the total generated traffic is considered high priority, and the remaining 80% equally distributed between low- and medium-priority traffic [7]. For simplicity, the total network load is evenly distributed amongst all ONUs in the same relay path and the ONUs are equally guaranteed bandwidth weighted [7], [8].

A. *Average End-to-End Delay*

Fig. 9 compares the average packet delay from ONUs to central office among the four scenarios and EAA for EF, AF, BE, and total traffic, respectively. Fig. 9(a) shows the proposed Multi-EPON system under failures has better performance than EAA when the traffic load is greater than 40%. The EF delay time of Multi-EPON reaches 1 *ms* when the traffic load is heavy, but still is less than 1.5 *ms*, which is specified by ITU-T Recommendation G.114. Fig. 9(b) shows the delay time of Multi-EPON scenarios for AF traffic are still shorter than the EAA when traffic load exceeds 70%. Fig. 9(c) shows that Multi-EPON yields notable improvements of EF and AF services without degrading the BE services.

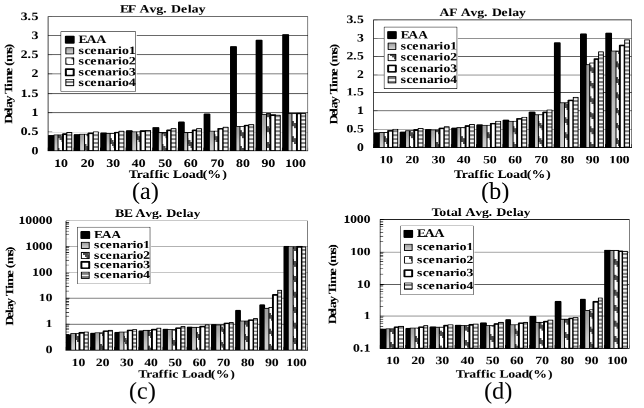


Fig. 9 Average End-to-End Delay

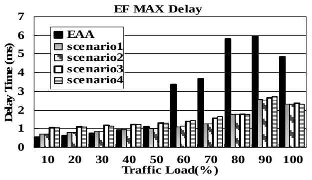


Fig. 10(a) EF MAX Delay

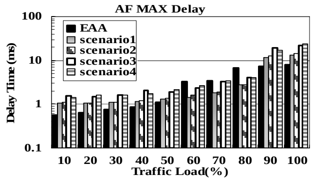


Fig. 10(b) AF MAX Delay

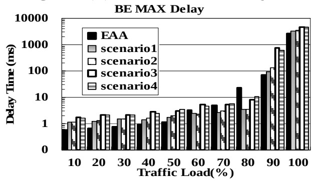


Fig. 10(c) BE MAX Delay

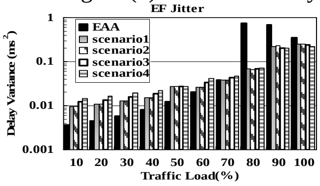


Fig. 11 Jitter for EF traffic

B. MAX End-to-End Delay

Fig. 10 compares the maximum packet delay among the four scenarios and EAA for all traffic classes. Fig. 10(a) shows the proposed Multi-EPON system has better performance than the EAA when traffic load exceeds 60% in the EF traffic. In Multi-EPON scenarios, the MAX delay for EF traffic increases smoothly with traffic loads and implies the control ability in the Multi-EPON. The MAX delay for EF traffic at full traffic load is less than 90%. The reason is that the transmission cycle reaches T_{cycle}^{MAX} results in the rate-based prediction of EF traffic more accurately. In Fig. 10(b), the MAX delay performance of EAA for AF traffic is better than the Multi-EPON scenarios, because the AF packet encounters long relay time in the relay path. However, while the traffic is between 60%-80%, the EAA has the longest MAX delay because of the transmission order of ONUs changing drastically. In Fig. 10(c), the MAX delay for BE traffic increases rapidly when the traffic load exceeds 90% because the system is in full load.

C. EF Jitter Performance

The delay variance is calculated as $\sigma^2 = \left(\sum_{i=1}^{N}(d_i^{EF} - \bar{d})^2\right) \cdot N^{-1}$, where the d_i^{EF} is the delay time of EF packet i and N is the total number of received EF packets. As Fig. 11 shows, the delay variances of Multi-EPON are higher than the EAA when traffic load is below 70%. The reason is that the EF packets coming from PONs with failures may be relayed by other Bridge ONUs. However, the delay variance of EAA scheme increases drastically when traffic load exceeds 80%. The reason is that the service cycle order in every cycle of the EAA is changed drastically and the order of Multi-EPON is always fixed.

V. Conclusion

In this article, a novel *fault-tolerant Multi-EPON* system is proposed to protect the critical PON element failure, such as OLT failure or feeder fiber cut. Because of no limited number of interconnected EPONs and without any redundant components, the proposed system is very flexible, cost-effective and uses simple shared protection architecture on EPON. Overall, the simulation results confirm that the *fault-tolerant Multi-EPON* system yields notable improvements in average packet delay, MAX packet delay and delay variation for EF traffic under different failures.

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