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On the fairness of dynamic bandwidth allocation schemes in Ethernet passive optical networks ☆

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Abstract

Ethernet passive optical networks (EPONs) technology has emerged as a promising candidate for next-generation broadband access networks. As this technology evolves, the development of efficient dynamic bandwidth allocation (DBA) algorithms has become a key concern. This paper devises and presents the principle and implementation issues of a new robust DBA scheme. This proposed scheme consistently maintains a robust fairness mechanism in the DBA operation. With the better maintained fairness mechanism, network performance is improved; specifically average packet delay and upstream link utilization, as well as inter-ONU statistical bandwidth multiplexing. Detailed simulation experiments are presented to study the performance and to validate the effectiveness of the proposed algorithm.

Keywords: Ethernet passive optical network; Dynamic bandwidth allocation; Weighted max–min fairness; Statistical bandwidth multiplexing; Network performance

1. Introduction

Recently, the access networks have been exposed under substantial challenges with the exponentially increasing per-user bandwidth demand and ever-increasing backbone capacity [2]. Although access technologies such as *digital subscriber line* (xDSL) and *cable modem* (CM) offer affordable solutions for residential data users, they pose fundamental distance and bandwidth limitations [3]. It is expected that the next-generation access network will be able to support various emerging broadband applications as well as emulating many kinds of legacy services over the same infrastructure, with minimal engineering investment.

Since the cost for broadband access technology is usually prohibitive for household implementations, there is not a prevalent and dedicated infrastructure deployed that promises to carry broadband and data-dominated services with different *quality of service* (QoS) requirements and revenue-generating value. As a matter of fact, the most widely deployed "broadband" solutions today are *Digital Subscriber Line* (DSL) and *Cable Modem* (CM) networks. DSL is built on the traditional twisted lines for telephone service. It deliveries data services utilizing the so-called Digital Modulation technology via a DSL modem at the subscriber's premise and *Digital Subscriber Line Access Multiplexer* (DSLAM) in the *central office* (CO) of the provider. The data rate provided by DSL is typically offered in a range from 128 Kbps to 1.5 Mbps. While it is capable of offering general web browsing and email services, it is not able to support the ever-emerging media-rich broadband services. Moreover, due to signal distortion, the physical area that one central office can cover with DSL is limited to distances less than 18,000 ft. In general, network operators do not provide DSL services to subscribers located more than 12,000 ft from the CO because of the potentially

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☆ A partial version of this work was presented in [1].

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increased cost. Although other variants of DSL that provide higher data rate are also being considered (VDSL, ADSL2, G.SHDSL), these technologies are more user-specific and pose even more distance limitations.

CM is another expedient of *Community Antenna Television* (CATV) companies to respond the explosion of Internet service demand. This technology delivers data service through some pre-allocated analog video channels and offers a higher theoretical data rate than DSL. Nevertheless, unlike DSL where there is a dedicated bandwidth for every subscriber, CM performs bandwidth sharing amongst multiple subscribers, which is similar to the case of *Local Area Networks* (LANs). Therefore, it is hard to assert a constant higher data rate provision for CM over DSL, especially in peak hours. Most modern CM networks are *Hybrid Fiber Coax* (HFC) networks, where a fiber runs between a video head-end and a curbside optical node, with the final drop to the subscriber being coaxial cable, repeaters, and tap couplers. In this setup each shared optical node typically has less than 36 Mbps effective data throughput, which typically supports 2000 house connections. Frustrating speed degradation during peak hours is the primary report of dissatisfied subscribers. Moreover, the most widely deployed CM standard today is data over cable service interface specifications, i.e., DOCSIS 1.0. It functions on a "best effort" basis and treats all modems with the same class of *quality of service* (QoS). DOCSIS 1.1 addresses this deficiency by supporting multiple classes of service with different QoS guarantees. However, DOCSIS 1.1 is yet to be extensively deployed in the future.

Ethernet Passive Optical Network (EPON) is viewed by many as a promising solution that is capable of delivering bundled data, voice, and video over the same high-speed connection. These architectures combine the latest in electronic and optical advances. A *passive optical network* (PON) is basically an *optical line terminal* (OLT) residing in the *central office* (CO) connected to multiple *optical network units* (ONUs) near subscribers' premise. All ONUs share a single landline running between the CO and a passive optical splitter/coupler located near the service neighborhood. Fig. 1 briefs the skeleton of an EPON architecture. By eliminating regenerators and active equipments normally used in fiber runs, PONs reduce the deployment and maintenance costs of fiber. In addition, sharing the network equipments among the maximum number of customers reduces considerably the per-subscriber cost. Various ONU deployments exist, as per different architectures, such as *fiber-to-the-home* (FTTH), *fiber-to-the-building* (FTTB), and *fiber-to-the-curb* (FTTC). Here it is important to state that the number of FTTx users, e.g., FTTH, has rapidly increased worldwide in the last few years [4].

Two standard organizations, i.e., ITU-T and IEEE, have led discussion of PON specifications. Specifically, the International Telecommunication Union – Telecommunication Standardization Sector (ITU-T) has developed

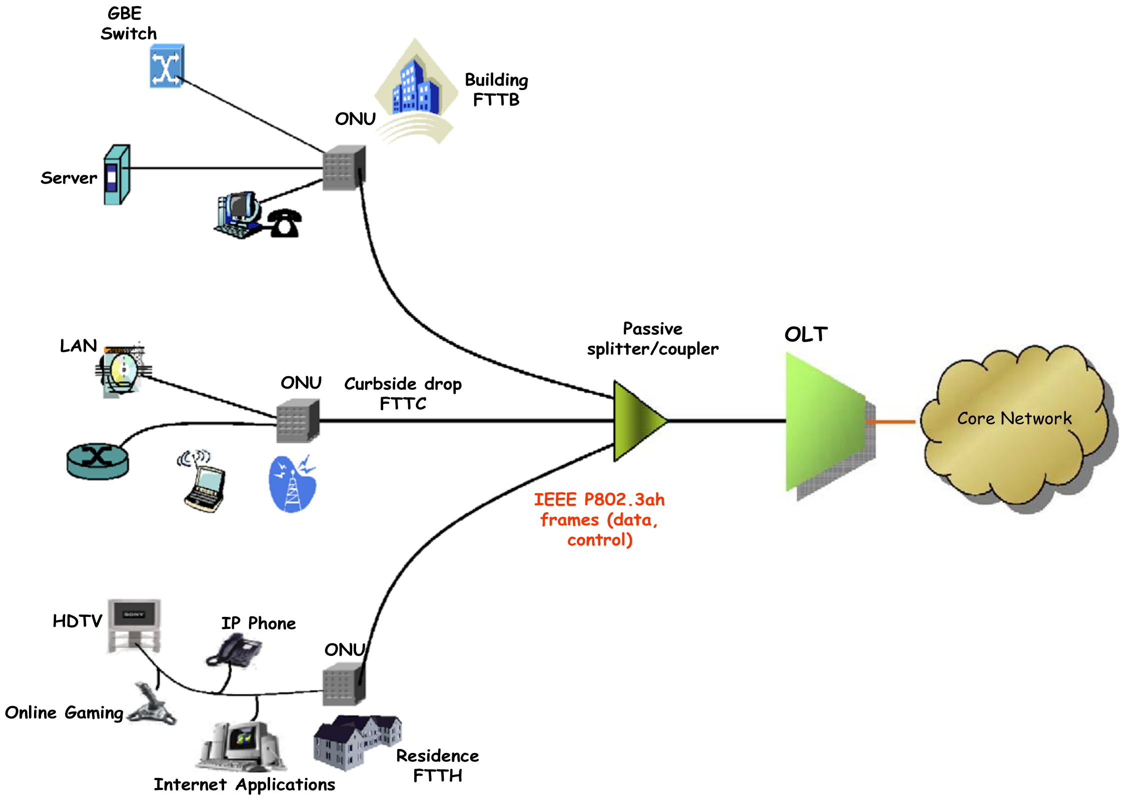

Fig. 1. EPON model.

a series of ATM-based Broadband PON (BPON) recommendations, e.g., ITU-T G.983, and ITU-T Q.834. Gigabit PON (GPON) has also been standardized recently in ITU-T G.984 to support up to 2.4 Gbps full optical access [5]. The Full Service Access Network (FSAN) group [6] substantially supports all the ITU-T PON recommendations. This group is organized by many worldwide major service operators and corporate vendors. Another PON standardization effort was contributed by IEEE Ethernet in the First Mile (EFM) Task Force, which has been engaged in IEEE 802.3ah [7]. The Ethernet in the First Mile Alliance (EFMA) is an industrial organization that solidly supports IEEE 802.3ah; it includes currently twenty-five industrial members [8]. Now considering that nearly 90% of today's IP traffic originates and terminates with Ethernet frame, *Ethernet PON* (EPON) is well suited to provide the most cost-effective solution for the next-generation access network.

In general, in the downstream direction of an EPON network packets are broadcast by the OLT and received by all the ONUs. Each ONU extracts those packets that contain the ONU's unique media access address. While in the upstream direction, multiple ONUs share the same transmission channel. Thus, an appropriate access protocol is required to avoid collision. This sharing can be realized by *wavelength division multiple access* (WDMA). However, this entails an individual type of transceiver at each ONU and a tunable transceiver for the OLT. Currently, the expense of WDMA equipment prohibits its wide implementation. On the other hand, many researchers have tabled *time division multiple access* (TDMA) schemes to achieve reliable and robust channel sharing in optical access networks [9–13]. This latter approach allows the ONUs to share a single upstream wavelength in which the OLT allocates time slots to each ONU.

To implement TDMA scheme, upstream data transmission can be scheduled using *static bandwidth allocation* (SBA), where each ONU is pre-assigned a fixed timeslot to send its backlogged packets at the full capacity of the link. SBA schemes have shown satisfactory performance in *metropolitan area networks* (MANs) and *wide area networks* (WANs), where the bandwidth requirement is nearly time-invariant. However, owing to end-user service diversity, next-generation access networks are expected to provide each subscriber bundled support for a wider range of services, including *video-on-demand* (VoD) and various data applications, e.g., ftp, email, etc. It is well-known that such aggregated traffic profiles can exhibit very non-uniform behaviors, thereby presenting highly oscillated bandwidth demand at each moment. Therefore more advanced bandwidth allocation schemes are desirable to provide efficient statistical bandwidth multiplexing among multiple ONUs.

In order to achieve efficient statistical bandwidth multiplexing in EPON architectures, the IEEE 802.3ah has devised the *multipoint control protocol* (MPCP) [7]. MPCP defines a message-based mechanism to facilitate real-time information exchange between the OLT and each ONU. The control messages defined in MPCP are *REPORT*, *GATE*, *REGISTER_REQ*, *REGISTER* and *REGISTER_ACK*. Instead of specifying a particular scheduling approach, MPCP only provides a basic framework for developing a wide range of bandwidth allocation schemes. The exact choice of such scheme is left to vendor discretion. Due to large message propagation distance between the OLT and ONUs, i.e., typically 20 km, many DBA approaches adopt interleaved polling scheme, where the next ONU is polled before the current ONU's transmission ends. In particular, at the beginning of every scheduling frame the OLT sends each ONU a *GATE* message to inform its scheduled transmission start time and granted transmission duration (window size); while in the granted transmission window, besides its payload, the ONU sends the OLT a *REPORT* message to report its buffer occupancy and to request transmission time for the next frame. Since distances between the OLT and ONUs may vary, the downstream *GATE* messages can be scheduled properly such that the transmissions are eventually lined up without gaps. In addition, technical recommendation also defines a mechanism to measure round trip propagation time between the OLT and ONUs. This is called "ranging". In order to appropriately delimit transmissions by neighborly scheduled ONUs with different distances from the passive splitter, a *guard time* (guard band) is scheduled before the start of each transmission window. This guard time permits an instant break, thereby the transmitters of ONUs can completely turned on/off, and the OLT can adjust its receiving power to counteract the above near-far effect. The other three messages are designed for activating newly joined ONUs and for network initialization. Detailed introduction and discussion on these topics can be found in [7] and [14]. By using MPCP an OLT is capable of scheduling transmission using various DBA strategies amongst ONUs [11]. Essentially, DBA improves upon SBA by allowing the OLT to support multiple different *Quality of Service* (QoS) requirements over a single platform.

EPON architectures have recently been given more and more attention from both the research community and the telecommunication industry. Recently many DBA algorithms have been presented in the literature. In most of these proposed DBA schemes sharing the network resources is dependent mainly on the instant request of every ONU. This work addresses the fairness issues in EPON networks. Specifically, this paper proposes a robust DBA scheme that well maintains fairness mechanism of the DBA operation and guarantees efficient statistical bandwidth multiplexing at the global level, as well as improving the upstream link utilization. We conduct detailed simulation experiments to study the performance of the proposed algorithm and validate its effectiveness.

The rest of this paper is organized as follows. Section 2 overviews some related literature and provides background for further discussion. Section 3 introduces our new DBA scheme with theoretical explanations as well as involved implementation issues. Quantitative performance evaluation and detailed analyses are presented in Section 4. Section 5 concludes this study.

2. Literature review and related background

2.1. Literature review

To date, various DBA algorithms have been proposed for EPON networks. Most notably, the *interleaved polling scheme with adaptive cycle time* (IPACT) [13] requires the OLT to poll ONUs in a round-robin fashion and dynamically assign them bandwidth before transmission. The bandwidth is allocated according to the buffer occupancy status of every ONU delivered by its last *REPORT* message. Any un-requested bandwidth will not be granted and the scheduling frame size is therefore not fixed. Here notable examples including *fixed*, *limited*, *constant credit*, *linear credit*, and *elastic* service schemes were also tabled. In order to better utilize the leftover bandwidth from ONUs with smaller traffic backlogs, the authors in [12] proposed DBA1 scheme in which ONU nodes were partitioned into two groups – *underloaded* and *overloaded* – according to their minimum guaranteed transmission window sizes. Here, total bandwidth saved from *underloaded* group is proportionally re-allocated to *overloaded* ONUs. This approach provides statistical bandwidth multiplexing among the ONUs and achieves higher link utilization. In [15], the authors introduced the *Hybrid Slot-Size/Rate* (HSSR) protocol to support QoS in EPONs. This is achieved by separating the transmission of high priority and low priority packets into steady part and dynamic part respectively within one scheduling frame. Here the high priority class is guaranteed a fixed bandwidth in each scheduling frame. The fairness of sharing the dynamic part in HSSR is provided by a counter weighted by the amount of backlogged low priority data at each ONU. However, this mechanism does not yet explicitly guarantee a minimum bandwidth for low priority streams, especially when one or more ONUs pump a large amount of low priority data into the network. In [16], the authors presented a new perspective of DBA, i.e., two-layer DBA, where the total available bandwidth is allocated among different classes first, then among ONUs. This approach prioritized the class-level QoS consideration over ONU-level bandwidth guarantee. Nevertheless, the per-ONU bandwidth guarantee should be practically considered first on the operator's stand, as the subscribers are usually not cooperative individuals. The per-queue based *logical link identifier* (LLID) proposed in [17] concentrated more intelligence at the OLT by assigning it a handle for each queue in the ONUs. This mechanism enables the OLT to perform more sophisticated DBA schemes at an even deeper level. Other literatures also contributed valuable points from different considerations. For example, in [9] the authors employed priority queuing and intra-ONU queue scheduling to provide differentiated service for each service class and to eliminate the light load penalty [18]. Meanwhile, [19] decouples the generation of grant window sizes from the decision of transmission start times. Namely, grants for different purposes (e.g., SBA, DBA, auto-discovery, etc) are generated independently and then scheduled and converged into the downstream flow by the OLT. Finally, as an architectural enhancement [20] proposes an extended version of EPON and corresponding new DBA schemes to increase the viability and coverage of PON technology over a broader range of subscriber access scenarios.

Jitter performance is another important concern in the MAC protocol design of EPON, especially for the high priority service, which is typically used to emulate T1 lines over packet switching networks. However, comparatively minor contributions could be found on this topic. Some primary research framework about jitter performance in EPON is given in [21]. Here one transmission cycle consists of two sub-cycles, i.e., EF sub-cycle and AF sub-cycle. Though the scheduling frame size is not fixed, by protecting EF service in a separate sub-cycle, its delay jitter is considerably improved. Since in every sub-cycle each ONU is served in a round-robin fashion, the per-ONU bandwidth guarantee still exists. Additionally, because the size of Ethernet packets varies from 64 to 1518 bytes and ONUs do not report detailed packet segmentation, there may be some potentially wasted bandwidth when the granted transmission window is less than requested amount and does not exactly match a packet boundary. Few papers deal specifically with this issue. As a part of [18], the author proposed a two stage queue at the ONU, where Ethernet packets are firstly classified into multiple priority queues (stage one) then advanced into a *first-come-first-serve* (FCFS) queue (stage two). Here the size of stage-two queue is limited by the maximum transmission window and only packets in this stage are reported. By this approach, the requested bandwidth will always be fully granted and there is no bandwidth wasted. The proposed scheme in [22] permits the ONU to report multiple packet boundaries below a threshold. Furthermore, the D-CRED algorithm proposed in [23] employs two reporting before transmitting the reported packets. Here the first reporting requests bandwidth and the second informs the OLT corresponding packet boundary within the granted amount. The cost of this scheme is that packets have to wait for at least two scheduling frames before departure. Instead of specifying packet boundaries at each ONU, our proposed DBA scheme mitigates this issue by maximizing the number of ONUs whose bandwidth requests are fully satisfied.

Most of the previous DBA schemes enforced the fairness of sharing the resource dependent on the instant request of every ONU. However, from the perspective of the network operators, the fairness policy should be a pre-defined mechanism by the *Service Level Agreement* (SLA) between the OLT and the ONUs (subscribers). Namely, an ONU has the right to share any available resources according to its pre-assigned weight (related with SLA) before its bandwidth request is fully satisfied. This later point ensures that any ONU cannot affect others by overloading the network.

We will distinguish this advantage by comparing our new approach with other request-dependent fairness algorithms.

2.2. About DBA1

In [12], the authors defined a maximum transmission cycle time $T_{\max}$ as the upper-bound of the transmission cycle time. In every transmission cycle, each ONU will be able to transmit and/or report once to the OLT. This $T_{\max}$ guarantees the ONU opportunities to access the link within a bounded time interval. According to individual weight defined by corresponding SLA, each ONU is guaranteed a minimum transmission window in every transmission cycle.

$$B_i^{\min} = C \times (T_{\max} - N \times t_g) \times w_i \quad \left(\sum_{i=1}^{N} w_i = 1\right), \tag{1}$$

where $B_i^{\min}$ is the minimum guaranteed window for ONU i, t_g is the guard time that separates the transmissions of neighborly scheduled ONUs, w_i is the weight of ONU i, C and N are the upstream link capacity and the number of ONU nodes respectively. ONUs requesting less bandwidth than corresponding guaranteed window, termed as *underloaded*, will be granted bandwidth as they requested. While ONUs requesting more bandwidth than corresponding guaranteed window, termed as *overloaded*, will be granted their guaranteed window plus a share of the total excessive bandwidth saved by *underloaded* ONUs. It is helpful to clarify that the transmission cycle [in Eq. (1)] is understood as the time interval between the moment when the foremost *GATE* message is completely received and the moment when the lattermost *REPORT* message is completely transmitted. The basic principle of DBA1 scheme can be formularized as follows:

$$G_i = \begin{cases} r_i & r_i \leqslant B_i^{\min} \\ r_i + b_i^{\text{excess}} & r_i > B_i^{\min} \end{cases} \tag{2}$$

$$b_i^{\text{excess}} = \frac{r_i}{\sum_{k\in K} r_k} b_{\text{total}}^{\text{excess}}, \tag{3}$$

$$b_{\text{total}}^{\text{excess}} = \sum\nolimits_{l\in M} \left(B_l^{\min} - r_l\right) \quad \left(b_{\text{total}}^{\text{excess}} > 0\right), \tag{4}$$

where G_i is the bandwidth allocated to ONU i, r_i is the requested bandwidth of ONU i. $b_{\text{total}}^{\text{excess}}$ is the total excessive bandwidth saved by *underloaded* ONU nodes (i.e., $r_i < B_i^{\min}$). b_i^{excess} is the corresponding share of the total excessive bandwidth allocated to *overloaded* ONU i (i.e., $r_i > B_i^{\min}$). K and M are the set of *overloaded* and *underloaded* ONU nodes respectively. DBA1 provides statistical bandwidth multiplexing by having the *overloaded* ONUs proportionally share the total excessive bandwidth according to their requested amount.

Nevertheless, DBA1 assumes that the total excessive bandwidth always can be efficiently occupied by the *overloaded* ONUs, which is not a consistent presumption for non-uniform traffic. For example, instantly there is only one slightly *overloaded* ONU while other ONUs do not request any bandwidth from the OLT. In this situation DBA1 will mistakenly leave most of the available bandwidth idle. In order to combat this deficiency and based on DBA1, in [24] the authors proposed an improved dynamic bandwidth allocation algorithm and introduced a measurement for the total extra demanded bandwidth of the *overloaded* ONUs. The modified DBA1 scheme in [24], referred to as M-DBA1, can be described as follows:

$$b_{\text{total}}^{\text{demand}} = \sum_{k\in K} \left(r_k - B_k^{\min}\right) \quad \left(b_{\text{total}}^{\text{demand}} > 0\right), \tag{5}$$

$$G_i = \begin{cases} r_i & r_i \leqslant B_i^{\min} \text{ or } b_{\text{total}}^{\text{excess}} \geqslant b_{\text{total}}^{\text{demand}}, \\ r_i + b_i^{\text{excess}} & \text{otherwise}, \end{cases} \tag{6}$$

where $b_{\text{total}}^{\text{demand}}$ denotes the total extra demanded bandwidth of the *overloaded* ONUs. M-DBA1 essentially ensures that no grant exceeds corresponding request.

2.3. Fairness analysis

M-DBA1 seems now an efficient DBA scheme. It guarantees a minimum bandwidth for each ONU in every transmission cycle, as well as offering statistical bandwidth multiplexing among ONUs to accommodate non-uniform traffic. Nevertheless, M-DBA1 and most of other earlier scheduling algorithms, i.e., tabled in [9,12,15,23], allow the instant bandwidth request of each ONU to affect the fairness policy of the OLT's DBA decision. This request-dependency may leave the fairness mechanism of these schemes vulnerable to any irregular end user behavior. In order to quantitatively analyze this point, we first introduce the fairness index f initially defined by Raj Jain in [25]. The fairness index f, in the context of DBA in EPON, is defined as:

$$f = \frac{\left(\sum_{i=1}^{N} G_i\right)^2}{N \sum_{i=1}^{N} G_i^2}. \tag{7}$$

It can be proved (in the appendix) that $0 < f \leqslant 1$ and $f = 1$ only when all $G_i (i = 1, 2, \ldots, N)$ have the same value. Here a smaller value of f implies more unfairness in the resource allocation. However, this definition is based on the assumption of equal-weight scenario among ONUs. When the weights are different, i.e., diff-weight scenario, the direct application of Eq. (7) is inappropriate to numerically evaluate the fairness property. In this case, we define a more generalized form of f to adapt it for diff-weight scenario. Let us consider the minimum pre-assigned weight among the ONUs as a unit weight w_u, every other weight w_i can be divided by w_u to obtain corresponding normalized weight w_i^{nor}. Here w_i^{nor} is not necessary an integer. Every G_i, divided by w_i^{nor}, is the amount of bandwidth allocated to ONU i with respect to the unit weight w_u. We term this normalized bandwidth allocated to ONU i as *stripped granting*, G_i^{str}. Now every G_i^{str} can be viewed as equally weighted and Eq. (7) is applicable. More formally, we have

$$f = \frac{\left(\sum_{i=1}^{N} G_i^{str}\right)^2}{N\sum_{i=1}^{N} G_i^{str^2}} = \frac{\left(\sum_{i=1}^{N} \frac{G_i w_u}{w_i}\right)^2}{N\sum_{i=1}^{N}\left(\frac{G_i w_u}{w_i}\right)^2} = \frac{\left(\sum_{i=1}^{N} \frac{G_i}{w_i}\right)^2}{N\sum_{i=1}^{N}\left(\frac{G_i}{w_i}\right)^2}. \tag{8}$$

We can see that when all w_i have the same value, Eq. (8) degrades to Eq. (7).

It is reasonable to assume that the fairness concern is present only among contending ONUs, i.e., ONU whose bandwidth demand is yet to be fully satisfied. Therefore, in M-DBA1 the fairness issue only involves the sharing of $b_{\text{total}}^{\text{excess}}$ amongst *overloaded* ONUs when $b_{\text{total}}^{\text{excess}} < b_{\text{total}}^{\text{demand}}$. For DBA schemes, however, this is not a marginal concern. When $b_{\text{total}}^{\text{excess}} < b_{\text{total}}^{\text{demand}}$ in M-DBA1, the bandwidth allocated to an *overloaded* ONU i consists of two parts – its $B_i^{\min}$ and a share of the $b_{\text{total}}^{\text{excess}}$, i.e., b_i^{excess}. The first part is defined by Eq. (1), the fairness index according to Eq. (8) is then

$$f_1 = \frac{\left(\sum_{k=1}^{n} \frac{B_k^{\min}}{w_k}\right)^2}{n\sum_{k=1}^{n}\left(\frac{B_k^{\min}}{w_k}\right)^2} = \frac{\left(\sum_{k=1}^{n} \frac{C\times(T_{\max}-N\times t_g)\times w_k}{w_k}\right)^2}{n\sum_{k=1}^{n}\left(\frac{C\times(T_{\max}-N\times t_g)\times w_k}{w_k}\right)^2} = 1. \tag{9}$$

Here, n is the number of *overloaded* ONUs in K, i.e., $n \leqslant N$.

Regarding the second part $b_k^{\text{excess}} = \frac{r_k}{\sum_{k\in K} r_k} b_{\text{total}}^{\text{excess}}$, the fairness index defined by Eq. (8) is then

$$f_2 = \frac{\left(\sum_{k=1}^{n} \frac{b_k^{\text{excess}}}{w_k}\right)^2}{n\sum_{k=1}^{n}\left(\frac{b_k^{\text{excess}}}{w_k}\right)^2} = \frac{\left(\sum_{k=1}^{n} \frac{r_k}{w_k} \frac{b_{\text{total}}^{\text{excess}}}{r}\right)^2}{n\sum_{k=1}^{n}\left(\frac{r_k}{w_k} \frac{b_{\text{total}}^{\text{excess}}}{r}\right)^2}$$

$$= \frac{\left(\sum_{k=1}^{n} \frac{r_k}{w_k}\right)^2}{n\sum_{k=1}^{n}\left(\frac{r_k}{w_k}\right)^2}, \tag{10}$$

where $r = \sum_{k\in K} r_k$. Comparing Eqs. (8) and (10), it is obvious that the fairness index of f_2 depends on the requested bandwidth by ONUs instead of granted amount by the OLT. According to the explanation of Eq. (7), $f_2 = 1$ only when $\frac{r_k}{w_k}$ of every *overloaded* ONU coincides with the same value. This is a very critical requirement for the non-uniform traffic behavior in EPON. In fact, due to the random bandwidth requests of ONUs, the value of f_2 is oscillating between 0 and 1. The exact value of f_2 is decided by the bandwidth request of every *overloaded* ONU and the population of this group. Particularly, when one ONU is maliciously overloaded by its users or is temporarily experiencing very long bursts, the value of f_2 will seriously decrease. It is necessary to note that even in light loading scenario, f_2 may still be occasionally drawn back by the highly fluctuating traffic generated in LANs.

3. Weight-based dynamic bandwidth allocation

3.1. Weight-based DBA scheme

The vulnerability of fairness introduced by M-DBA1 is a result of its inappropriate target orientation when b_{total}^{excess} is shared. Namely, it gives higher priority to satisfying ONU's bandwidth request over maintaining better fairness, because it is shown in Eq. (10) the value of f_2 is decided by factors the OLT cannot adjust. Nevertheless, from the stand of network operators, global fairness deserves the first consideration. In order to remove the fairness vulnerability in M-DBA1, the value of f_2 must be constantly maintained at 1 by proper assigning b_k^{excess} on the basis of Eq. (8). According to Eq. (10) and previous discussion, here $f_2 = 1$ only when $\frac{b_k^{\text{excess}}}{w_k}$ of every *overloaded* ONU is given the same value. Clearly, if b_k^{excess} is assigned as $\alpha \times w_k$ the condition of $f_2 = 1$ will be constantly maintained. Consider the fact that

$$\sum_{k=1}^{n} b_k^{\text{excess}} = \sum_{k=1}^{n} (\alpha \times w_k) = \alpha \sum_{k=1}^{n} w_k = b_{\text{total}}^{\text{excess}}, \tag{11.a}$$

$$\alpha = \frac{b_{\text{total}}^{\text{excess}}}{\sum_{k=1}^{n} w_k}, \tag{11.b}$$

the value of b_k^{excess} is then determined as

$$b_k^{\text{excess}} = \alpha \times w_k = \frac{w_k}{\sum_{k=1}^{n} w_k} b_{\text{total}}^{\text{excess}}. \tag{12}$$

The above discussion quantitatively justified an intuitive fact, i.e., in order to keep complete fairness, the excessive bandwidth should be shared among *overloaded* ONUs according to the proportion of corresponding weight within the overloaded group.

In fact, if $n = N$ and $b_{\text{total}}^{\text{excess}} = C \times (T_{\max} - N \times t_g)$, Eq. (12) becomes Eq. (1) and the value of b_k^{excess} represents the minimum guaranteed bandwidth for ONU i, i.e., $B_k^{\min}$. In other words, if no ONU is over-granted and any sharable bandwidth is allocated according to Eq. (12), the fairness index will be well maintained at 1 without discriminating *underloaded* and *overloaded* ONUs. We refer to this strictly weight-based scheme as W-DBA. The reason we use "any sharable bandwidth" here is because when any ONU is requesting less bandwidth than its "earned" amount, some bandwidth may be continuously resumed as sharable to favor other starved ONUs. Therefore, the final solution of W-DBA is reached by multiple iterations until every ONU is granted. Specifically, when every ONU is given the same weight, W-DBA becomes the Max-Min fairness principle that is originally designed for multi-hop flow control [26,27]. Since the initial value of b_k^{excess} in Eq. (12) is the $B_k^{\min}$ in Eq. (1), the minimum guaranteed bandwidth for every ONU is still ensured. Bearing the same merits of M-DBA1, W-DBA offers more advantages as we will show later.

3.2. Implementation issue

As we just mentioned, in equal-weight scenario, W-DBA is equivalent to a Max-Min fairness scheme. Hence, in diff-weight scenario, W-DBA can be viewed as a weighted Max–Min fairness scheme, where any resource is allocated in a weighted manner. Having theoretical feasibility of weighted Max–Min fairness for DBA in EPON, one purpose of this work is to specify an operational procedure for the implementation of W-DBA. Based on previous discussion, the OLT can perform W-DBA scheme as follows:

> ***Step 1***: According to the total available bandwidth, set a bandwidth threshold for each ONU based on weighted Max–Min fairness principle, i.e., Eq. (12).
> ***Step 2:*** Iterate the bandwidth request of each ONU and grant as much as requested bandwidth to ONUs that are requesting no more resource than their corresponding threshold. These ONUs are termed as satisfiable ONUs.
> ***Step 3***: If one or more satisfiable ONUs were found in step 2, repeat step 1. Otherwise grant each remaining ONU its corresponding threshold and end the DBA process.

We can see that when a *satisfiable* ONU is granted bandwidth, the thresholds of other remaining ONUs may increase. Therefore, we denote $Thr_i(n)$, non-decreasing real-time variable, as the current threshold for an un-processed ONU_i after *n satisfiable* ONUs have been granted bandwidth. The pseudo-code in Fig. 2 illustrates the above steps with more details.

As mentioned earlier, in order to reach final solution the OLT has to repeatedly compare the bandwidth requests of the remaining ONUs with the continuously updated $Thr_i(n)$. This may prohibit the implementation of W-DBA scheme when the number of active ONU becomes large. To realize this algorithm, we start with an equal-weight scenario, i.e., based on Max-Min fairness, where every ONU shares the same $Thr(n)$. Our idea is to have the OLT sort the bandwidth requests from ONUs into ascending order while it is receiving the *REPORT* messages. When the DBA process starts, the OLT grants *satisfiable* ONUs their requested bandwidth and keeps updating $Thr(n)$, until the first ONU with bandwidth request more than $Thr(n)$ is found. This ONU is termed as an *un-satisfiable* ONU. At this moment, every remaining ONU will be granted the current threshold $Thr(n)$ and the DBA process is completed ($Thr(n)$ will not increase any more). With this analysis, the OLT can follow the steps below for the equal-weight case:

```
TotalBand = value defined by $T_{\max}$ ; TotalWeits=1;
GrantedNbr=0;  N=Total number of active ONUs;
while GrantedNbr<N
{
    iterate the bandwidth request $R_i$ of each un-processed ONU
    {  // i is the ID number of ONU;
        $thr_i(GrantedNbr)$ =TotalBand* $\frac{weit_i}{TotalWeits}$ ;
        If ( $R_i <= thr_i(GrantedNbr)$ )
        {
            $G_i = R_i$ ;  GrantedNbr= GrantedNbr+1;
            TotalBand= TotalBand- $G_i$ ;  TotalWeits= TotalWeits- $weit_i$
        }
    }
    if no satisfiable ONU was found in this iteration
    {  // i is the ID number of ONU;
        for every un-processed ONU set $G_i$ = TotalBand* $\frac{weit_i}{TotalWeits}$ ;
        GrantedNbr=N;
    }
}
```

Fig. 2. Pseudo-code for W-DBA.

> ***Step 1***: Sort the ONUs' bandwidth requests in ascending order.
> ***Step 2***: Compute the initial value of $Thr(n)$, i.e., $Thr(0)$, by dividing the total available bandwidth by N.
> ***Step 3***: Compare the ascended bandwidth requests with $Thr(n)$. If the next request is less than $Thr(n)$, issue grant as requested and update $Thr(n)$. If the next request is greater than $Thr(n)$, grant each of the remaining un-processed ONU the current $Thr(n)$ and end the DBA process.

These steps are illustrated in Fig. 3.

In the equal-weight scenario the DBA process ends when the first *un-satisfiable* ONU is found. However, if the weights are different (diff-weight), the OLT can not finalize its DBA decision when the first *un-satisfiable* ONU is found, even though the bandwidth requests are ascended. Here, every ONU has its own threshold $Thr_i(n)$. In this case, we employ a *stripped reporting* approach similar to the one of *stripped granting* mentioned in the last section. We still normalize the minimum weight among ONUs as 1 and all the other weights will be greater than 1. For example, if the minimum weight 0.1 is normalized to 1, another weight of 0.25 is then normalized as 2.5. With these normalized weights, the OLT samples a stripped report of every ONU by dividing its bandwidth request by the corresponding normalized weight. The stripped reports can be viewed now as equally weighted and the above steps can apply. When the OLT computes $Thr(0)$ or updates $Thr(n)$, it evenly divides the currently available bandwidth into S sections, where S denotes the sum of normalized weights of all un-processed ONUs. Every *satisfiable* ONU, on the other hand, will be granted bandwidth of its stripped report timed by its normalized weight, i.e., as requested. While when the OLT finds the first *un-satisfiable* ONU, it grants every remaining *un-satisfiable* ONU with the current $Thr(n)$ timed by the corresponding normalized weight of the ONU. The background basis of this stripped reporting approach is as follows: based on the currently available bandwidth, the OLT computes the amount of bandwidth it can offer in each minimum unit, i.e., a strip, while keeping full fairness. Then it estimates the desired amount in one strip for

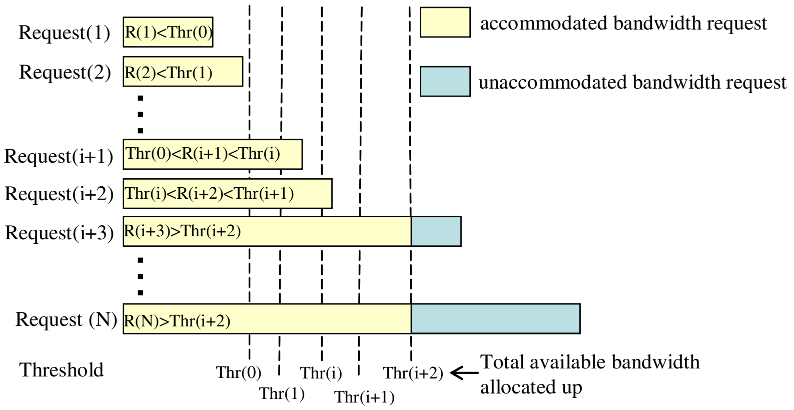

Fig. 3. Illustration of W-DBA operation steps (equal-weight).

each ONU to be granted, and compares it with the former for granting.

3.3. More advantages

The successful application of weighted Max–Min fairness principle in EPON DBA protocol design introduces multiple new advantages. Another purpose of this study is to address some of these favorable findings.

3.3.1. Idled fragment effect

In Section 2, we mentioned the issue of potentially wasted bandwidth at the end of a transmission window. We refer to this phenomenon as *idled fragment* effect. It can be deduced that every *overloaded* ONU in M-DBA1 and every *un-satisfiable* ONU in W-DBA may experience idled fragment effect, when the total available bandwidth cannot accommodate every ONU's request. Nevertheless, we have analyzed that in W-DBA the initial threshold $Thr(0)$, computed in Step 2 of equal-weight case (or diff-weight case with stripped reporting applied), is essentially the minimum guaranteed window $B_i^{\min}$ in M-DBA1 for equal-weight case (or the minimum guaranteed strip for diff-weight case). Furthermore, the threshold $Thr(n)$ is a non-decreasing variable as well. This implies that the number of *satisfiable* ONUs in W-DBA is equal of or greater than the number of *underloaded* ONUs in M-DBA1. Therefore, by maximizing the number of fully satisfied ONUs, W-DBA mitigates the idled fragment effect, as shown in Figs. 4a and b.

The mitigation of idled fragment effect in W-DBA in turn leads to improved upstream link utilization, as less bandwidth is idled. This improvement is further discussed in the next section along with our simulation results.

3.3.2. T-SBM and A-SBM

We categorize the *statistical bandwidth multiplexing* (SBM) provided by DBA into two classes. One is achieved by favoring heavily loaded ONUs with the bandwidth saved by lightly loaded ONUs. We refer to this class as *inter-ONU SBM* (T-SBM). On the other hand, if an ONU is guaranteed a minimum bandwidth, it also can achieve SBM with the assistance of its buffer, which permits the ONU to hold some packets arriving in bursts and transmit them in later gaps. We refer to this class as *intra-ONU SBM* (A-SBM). T-SBM enables the OLT to timely extricate heavily loaded ONUs by appropriately allocating resource from the global perspective. A-SBM, however, has to relieve heavily loaded ONUs with the expense of increased packet queuing delay. A good example of A-SBM may be the *leaky bucket* model [28], where the network node receives

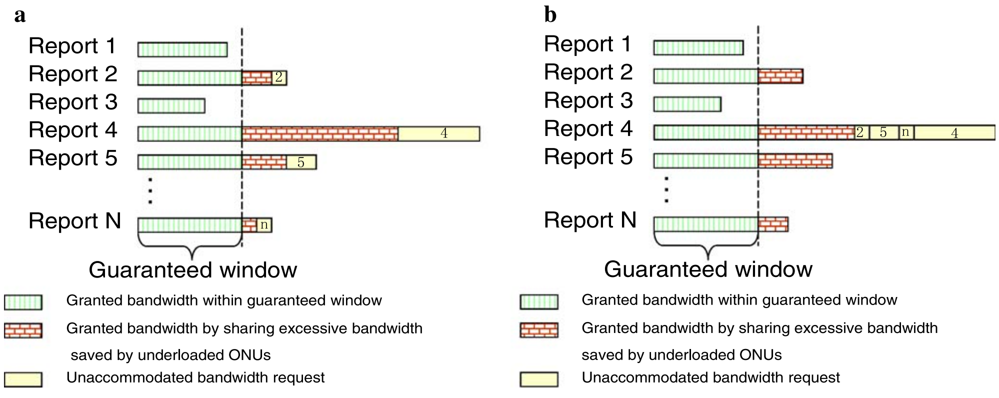

Fig. 4. Illustration of idled fragment in (a) M-DBA1 and (b) W-DBA.

non-uniform ingression while suffering from uniform output capacity.

Recalling the analysis of fairness index, it can be concluded that full fairness ($f = 1$) guarantees the best T-SBM mechanism, where every starved ONU can be serviced as timely as possible with the bandwidth saved by lightly loaded ONUs. Therefore, the constantly well maintained f in W-DBA leads to a persistent T-SBM among the ONUs. Due to the unstable value of f in M-DBA1, however, the T-SBM also appears erratic. When the T-SBM fades off in M-DBA1, the A-SBM still prevents the unfairly treated ONUs from constant bandwidth starvation. In this case, as discussed above, the expense is the unnecessarily increased packet queuing delay at the unfairly treated ONUs. This robustness improvement of W-DBA in terms of average packet delay is firmly verified by our simulations.

A quantitative measurement for the strength of T-SBM can be provided by the correlation coefficient between the packet arrival and departure processes of the ONUs. Here, the correlation coefficient between two random processes is defined as:

$$\gamma = \frac{\mathrm{E}[(\zeta_1 - m_1)(\zeta_2 - m_2)]}{\sigma_1\sigma_2}, \tag{13}$$

where m_i and σ_i denote the mean and standard deviation of random process ζ_i; while $\mathrm{E}(\cdot)$ is the expectation of the operand. The value of γ is between -1 and 1, where 1 indicates two completely homo-directionally varying processes and -1 implies completely anti-directionally varying processes. Therefore, a larger γ implies a stronger T-SBM, which is confirmed by the simulation for W-DBA.

3.3.3. Computational complexity

In M-DBA1, the OLT needs to iterate every *REPORT* message one time after they are partitioned into *underloaded* and *overloaded* groups, in order to decide the bandwidth allocation solution.

In W-DBA, for equal-weight case or diff-weight case with stripped reporting applied, the OLT ends its DBA process whenever the first *un-satisfiable* ONU is found. The complexity is hence reduced. This reduction can be attributed to the request-independency property of W-DBA and the ascended request table. It should be noted that the request/stripped report ascending work is performed when each *REPORT* message is received. When the OLT receives the last *REPORT* message in a scheduling frame, all the requests/stripped reports are ascended. Thus step 1 in the equal-weight case does not entail extra DBA time, which begins after all the *REPORT* messages have been received. Therefore, we can conclude that for both equal-weight and diff-weight cases, the complexity of W-DBA is no greater than M-DBA1. Moreover, when the network is becoming heavily loaded, i.e., less *satisfiable* ONUs could be detected, the complexity of W-DBA desirably decreases.

4. Performance evaluation

4.1. Simulation model

We conduct detailed simulations to quantitatively evaluate the performance of different DBA schemes. Our simulator is written in C++ using discrete event simulation technique. We set up an EPON model with one OLT and 32 ONUs. The upstream link capacity is set at 1.0 Gbps and OLT-ONU distance is uniformly 20 km. The guard time is 1 μs and the maximum transmission cycle time is 2 ms.

The simulation is conducted in the context of DiffServ [18,29], where expedited forwarding (EF), assured forwarding (AF), and best effort (BE) services are employed to simulate three service classes with high, medium, and low priorities, respectively. To eliminate light load penalty, we apply non-strict priority inner-ONU scheduling policy at each ONU [12], where only packets that have been reported by the last *REPORT* message of the parent ONU are eligible for transmission in the current transmission cycle. The inner-ONU scheduling process is illustrated in Fig. 5.

We apply Poisson trace for EF traffic to simulate highly prioritized voice service, and self-similar traces [30] for AF and BE traffic to capture the bursty nature of video and data streams generated in LANs. At each entry point of the network, 20% load is offered by EF service and the other 80% are evenly split by AF and BE services, i.e., 40% for each. The size of Ethernet packet is uniformly distributed between 64 and 1518 bytes for AF and BE classes, whereas constantly 70 bytes for EF class [18]. Since diff-weight case can be transferred to equal-weight case by applying stripped reporting, we simulated equal-weight scenario for simplicity. The simulation is initialized at a regularly operated scenario where the network is loaded with 60% of its upstream capacity, and each ONU offers 18.75 Mbps (on average) traffic intensity. Then the network performance by different DBA schemes are tracked, while the users of one ONU keep increasing traffic injection until the network is fully and even over loaded; meanwhile other regularly behaved ONUs keep 18.75 Mbps offerings. In the simulation we take into consideration packet propagation, transmission, and queuing delays as well as the 12 bytes

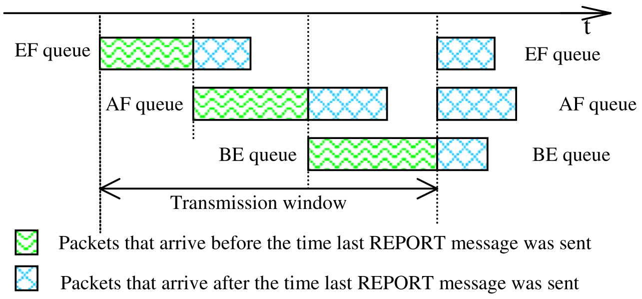

Fig. 5. Inner-ONU transmission scheduling.

inter-packet gap (IPG) and 8 bytes preamble ahead of each Ethernet packet [31].

4.2. Average packet delay

Fig. 6 shows the average packet delay of each class at every regularly behaved ONU versus the offered bit rate by the ill-behaved ONU. We can clearly recognize the out-performance of W-DBA over M-DBA1 in terms of average packet delay, especially for BE traffic whose bandwidth provision is the most vulnerable to bandwidth starvation, i.e., about 70% reduction after the ill-behaved ONU fully loaded the network. Furthermore, converse to M-DBA1, when the network becomes fully loaded (about 260 Mbps injection from the ill-behaved ONU), the average packet delays (EF, AF, and BE) of regularly behaved ONUs in W-DBA do not increase any more. This substantially verifies the enhanced robustness of W-DBA contributed by its well maintained fairness index, which completely screens out the destructive effect of the ill-behaved ONU on the other ONUs. Specifically, for EF traffic, M-DBA1 offers the same level of average delay as W-DBA after the network is fully loaded. This is because EF traffic is generated by non-bursty narrow bandwidth services and is given the highest inner-ONU scheduling priority. Therefore, its bandwidth demand can be timely satisfied by the minimum guaranteed window in M-DBA1 without incurring extra delay.

4.3. Upstream link utilization

Fig. 7 shows the upstream link utilization and average transmission cycle time for M-DBA1 and W-DBA. The simulation reveals that before the network is fully loaded, after which the average transmission cycle time tends to be constantly fixed at 2 ms, W-DBA leads to a shrunk transmission cycle in comparison with M-DBA1. This is because of the mitigation in W-DBA on the idled fragment effect we mentioned before. Since W-DBA more efficiently utilizes the network resources, the transmission cycle time in W-DBA climbs up to $T_{\max}$ slower than the one in M-DBA1. The shrunk transmission cycle also explains the reduced EF packet delay in Fig. 6 before the network is fully loaded. Fig. 8 records the simulation estimated probability whereby the bandwidth requests of all the regularly behaved ONUs are fully granted. The much higher full granting probability exhibited by W-DBA over M-DBA1 again substantiatizes the mitigated idled fragment effect. As a result, the upstream link utilization in Fig. 7 reveals that W-DBA achieves 91% maximum utilization compared with 88% for M-DBA1.

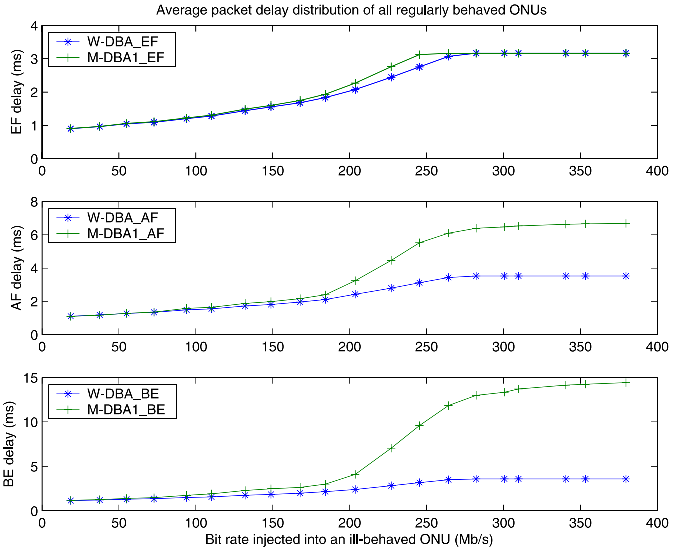

Fig. 6. Average packet delay comparison.

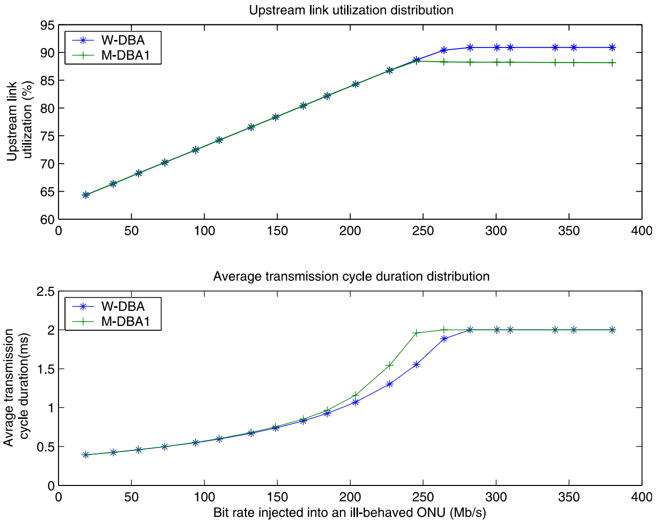

Fig. 7. Upstream link utilization and average transmission cycle time.

4.4. Correlation coefficient

In order to verify the different effects of T-SBM and A-SBM, we tracked the behavior of arrival and departure

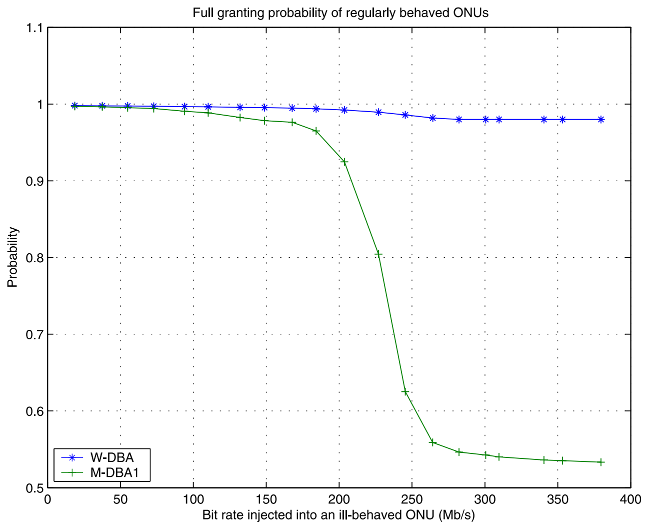

Fig. 8. Full granting probability of regularly behaved ONUs.

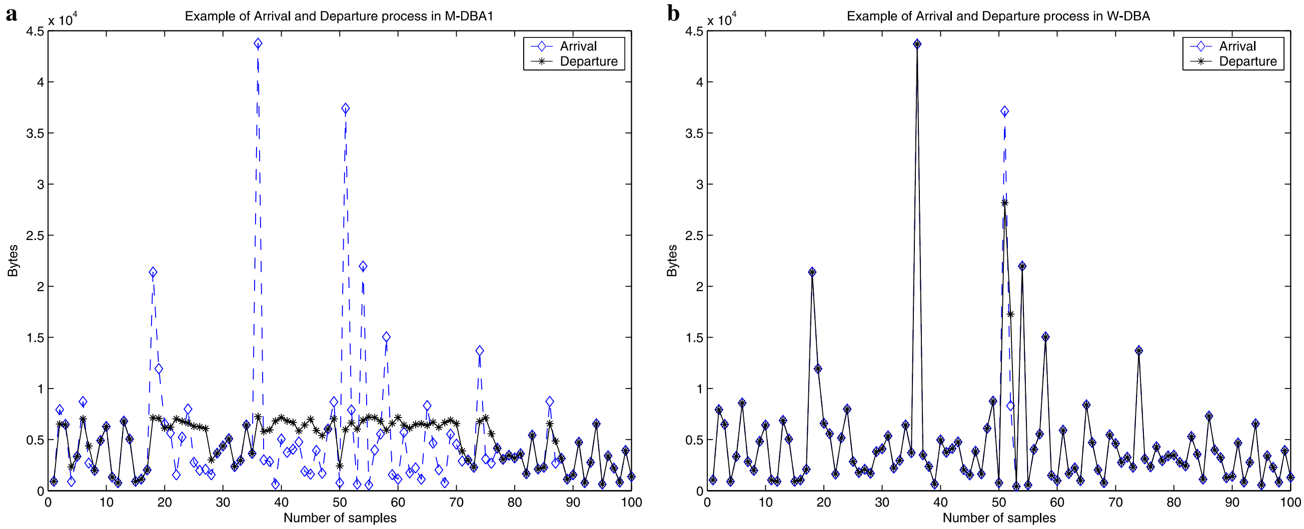

Fig. 9. Illustration of arrival and departure processes in (a) M-DBA1 and (b) W-DBA.

processes at all regularly behaved ONUs. Specifically, at each reporting moment (ONU sends *REPORT* message), the arrived and departed traffic amount (since the last reporting moment of the same ONU) are recorded. We compare the arrived amount recorded in transmission cycle i with the departed amount recorded in transmission cycle $i+1$ to examine how well the departure process responds to the arrival process, in different schemes. Figs. 9a and b explore the difference between M-DBA1 and W-DBA. Here a fraction of the sampled sequences at a randomly selected regularly behaved ONU (after the network is fully loaded by the ill-behaved ONU) is expanded for clarity. It can be concluded from the figures that T-SBM outperforms A-SBM essentially in terms of promptness, from the perspective of ONU's bandwidth availability, other than the overall amount.

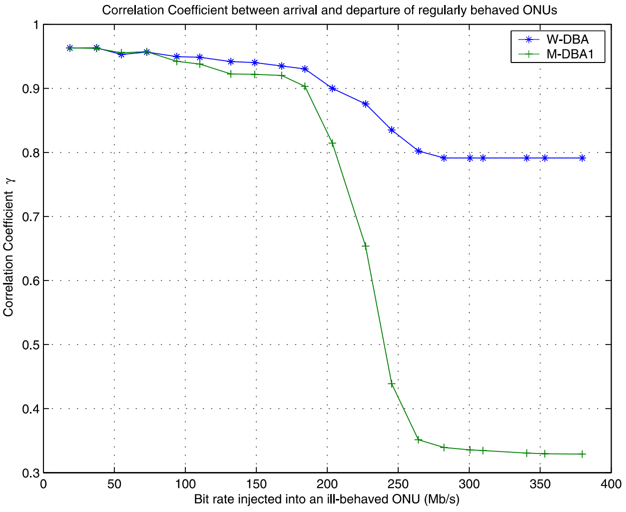

Fig. 10. Correlation coefficient between arrival and departure processes in different schemes.

The correlation coefficient γ in Fig. 10 is computed by averaging the correlation coefficient obtained from every regularly behaved ONU in the network. The figure shows that when the network becomes heavily loaded, it becomes more difficult for the departure process in both schemes to keep up with the fluctuation of the arrival process. This is because when the transmission cycle time is running larger, the reporting interval of the ONUs increases, permitting more traffic to arrive at the ONUs before their next reporting. Clearly, more arrived traffic is less possible to be fully conveyed by the next departure. However, Fig. 10 also shows that the γ in W-DBA decreases much slower than the one in M-DBA1 and tends to be constant, after the network is fully loaded (maximum transmission cycle time is met). This higher γ is maintained by the better sustained T-SBM in W-DBA.

5. Conclusion

Dynamic bandwidth allocation (DBA) is a key issue in EPON. In this paper, a robust DBA scheme, termed as W-DBA, is presented. This scheme constantly maintains a maximum fairness index throughout the DBA operation. Multiple performance improvements introduced by the well maintained fairness index are also analyzed with details. Besides theoretical analysis, an operational procedure for the implementation of W-DBA is also explained. Finally, simulation results firmly verified the improvements introduced by the new DBA scheme.

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Appendix A

In order to prove

$$f = \frac{\left(\sum_{i=1}^{N} G_i\right)^2}{N \sum_{i=1}^{N} G_i^2} \tag{A.1}$$

achieves its maximum value when every $G_i (i = 1, 2, \ldots, N)$ is given the same value, let the total amount of shared resource be

$$A = \sum_{i=1}^{N} G_i. \tag{A.2}$$

Consider any G_i, and if there is any $G_j (j \neq \text{ i})$ such that $G_j - G_i = \delta$, The value of f is computed as

$$\begin{aligned} f &= \frac{A^2}{N\left(\sum_{\substack{m=1 \\ m \neq i,j}}^{N} G_m^2 + G_i^2 + G_j^2\right)} \\ &= \frac{A^2}{N\left[\sum_{\substack{m=1 \\ m \neq i,j}}^{N} G_m^2 + \left(\frac{G_i + G_j - \delta}{2}\right)^2 + \left(\frac{G_i + G_j + \delta}{2}\right)^2\right]} \\ &= \frac{A^2}{N\left\{\sum_{\substack{m=1 \\ m \neq i,j}}^{N} G_m^2 + \frac{1}{2}\left[(G_i + G_j)^2 + \delta^2\right]\right\}} \\ &= \frac{A^2}{N\left\{\sum_{\substack{m=1 \\ m \neq i,j}}^{N} G_m^2 + \frac{1}{2}\left[\left(A - \sum_{\substack{m=1 \\ m \neq i,j}}^{N} G_m\right)^2 + \delta^2\right]\right\}} \end{aligned} \tag{A.3}$$

Clearly, when f achieves its maximum value, there must be $\delta = 0$, i.e., $G_j = G_i$. In other words, f achieves its maximum value when every $G_j = G_i$ for $j \neq \text{i}$, i.e., when $G_i (i = 1, 2, \ldots, N)$ are given the same value. In this case

$$G_i = \frac{A}{N} (i = 1, 2, \ldots, N) \tag{A.4}$$

and

$$f_{\max} = \frac{(A)^2}{N \times N\left(\frac{A}{N}\right)^2} = 1. \tag{A.5}$$

Also since $A > 0$, we have

$$0 < f \leqslant 1. \tag{A.6}$$

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