Chapter 35
Efficient Bandwidth Allocation Methods in Upstream EPON

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Abstract The Internet has become the world's leading universal global communication infrastructure. Optical solutions are sought after at the access network to support the ever increasing demand in bandwidth. Passive Optical Networks (PONs) are seen to provide a cost effective solution for this. PON Dynamic Bandwidth Allocation (DBA) scheme provides the means for upstream traffic allocation. In this paper, the operation of several bandwidth allocation algorithms in upstream Ethernet PON (EPON) is presented. An Efficient Distributed DBA (EDDBA) that supports Quality of Service (QoS) for both inter and intra ONU allocation is proposed. The proposed scheme introduces an identical DBA algorithm running simultaneously in each ONU. The simulation performance for the proposed DBA was conducted using Prolog and shows flexibility, reliability in handling data, voice, and video traffic.

Keywords DBA · Decentralized allocation · EPON · PROLOG · Qos · SBA

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H. K. Kim et al. (eds.), *Transactions on Engineering Technologies*,
DOI: 10.1007/978-94-017-9115-1_35,

1 Introduction

The notable success of the Internet has created new challenges. There has been a recorded exceptional increase in data traffic since the last decade [1]. Though the internet was originally designed for data transfer to cater for specific needs of daily life, many of the current applications such as Internet protocol (IP) telephony, video conferencing and video broadcasting need to be supported with additional requirements [2].

The first Passive Optical Network (PON) standard from the International Telecommunication Union (ITU) is based on the asynchronous transfer mode (ATM), i.e. ITU-T G.983 known as APON (ATM PON) [3]. It is used largely for business applications, and earmarked for PON devoted to deliver voice and data services. Further improvements to the original APON standard led to the emergence of broadband PON (BPON).

BPON is as an extended version of the APON network with better transmission capabilities and extra services. BPON is able to support wavelength-division multiplexing (WDM), dynamic and advanced up-stream bandwidth allocation, as well as larger sustainability than APON. BPON is defined under the ITU-T G.983.2 and G.983.3 standards [4, 5]. Although the structures of both these PONs were flexible and adaptable to different scenarios, they did not gain much popularity due to the complexity of the ATM protocol. The advent of technology saw the introduction of gigabit PON (GPON) which was introduced in 2003 by the Full Service Access Network (FSAN) group. GPON provides ATM interconnections. GPON is a PON version that is able of distributing data traffic with a capability of gigabit-per-second bit-range. It is defined in ITU-T G.984. It supports higher rates, enhances security, and has a choice of Layer 2 protocols. The GPON transportation mechanism is referred to as GPON Encapsulation Method (GEM) [6, 7].

Ethernet technology was introduced in the 70s as a local area network (LAN) technology for interconnecting desktop computers [8]. It catered for high bandwidth, low operation cost, and simplicity of installation and usage. The media access control (MAC) protocol used by Ethernet is the carriers sense multiple accesses with collision detection (CSMA/CD) for local area networking [9]. Ethernet PON was established by the Institute of Electrical and Electronics Engineers, Inc. (IEEE) 802.3ah task force [10].

GPON and EPON standards have already been established and deployments are seen worldwide. The existing and next generation PON should be flexible in supporting multiple existing and emerging services across multiple market segments, such as consumer, business, and mobile backhaul and therefore requires appropriate traffic management mechanisms. Dynamic Bandwidth Allocation (DBA) can play an effective part in improving the network performance and optimising capacity in the Fiber-to-the-x (FTTx) networks. A PON DBA scheme provides the means for upstream traffic control by the OLT of the ONUs.

In EPON, the available bandwidth is broadcasted to each ONU from the OLT through a splitter or network of splitters during downstream transmission. In the case of the upstream direction, the available bandwidth is shared amongst all ONUs at the optical splitter using the same fibre. To prevent congestion and collisions between frames from different ONUs, an OLT assigns a non-specific and non-repeated time-slot to each ONU using time division multiplexing (TDMA) technology. This facilitates transmission without overlapping difficulties. There is a need to effectively assign time slots for ONUs [11].

This paper focuses on several efficient bandwidth allocation algorithms for upstream EPON. Section 2 explains the static and dynamic bandwidth allocation schemes. Section 3 elaborates on DBA examples of efficient dynamic bandwidth allocation scheme including a new decentralised scheme. Section 4 provides the conclusion.

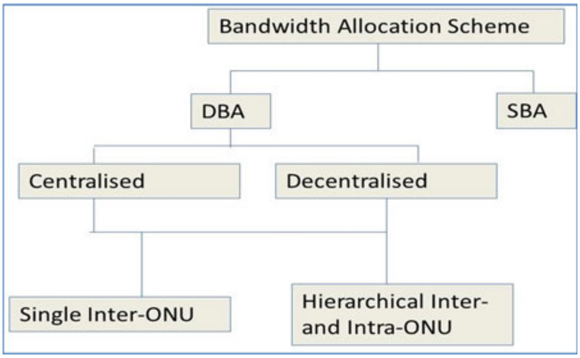
2 Static and Dynamic Bandwidth Allocation

The support of Quality of Service (QoS) within an EPON domain is currently one of the main areas of research [11] as they are less structured than in GPON. The assignment of bandwidth to each ONU could be either fixed or variable. Fixed timeslot allocation, also known as Static Bandwidth Allocation (SBA) [12], is straight forward to implement. In the case of SBA, once the bandwidth is allocated to a network user, it becomes unavailable to other users on that network [13]. Given the unpredictable nature of the network traffic, there will be situations where some timeslots overflow even under a very light load and causes delay for some packets. On the other hand, other timeslots may not be totally used even during heavy traffic, resulting in underutilized usage of the upstream bandwidth. For this reason, these shortfalls in SBA are addressed by allocating the bandwidth dynamically.

In order to optimize bandwidth utilization, it is desirable that the OLT allocates a varying timeslot in a dynamic manner to each ONU based on the actual demand of the ONUs. The DBA can be strategized to provide the necessary QoS as demanded by applications. Various DBA algorithms have been established to report this aspect [14–17]. Figure 1 depicts the DBA research areas. The DBA schemes are divided into two categories: centralized and decentralized where both may comprise of single level inter-ONU allocation or hierarchical with inter- and intra-ONU allocations. Though DBA algorithms have been reported in previous years [18–23], these algorithms have difficulty in estimating the proper allocation of the bandwidth to each ONU, especially for the discontinuous data traffic such as IP traffic [18]. In addition, the QoS and the satisfaction of subscribers are still open issues.

The first and largest category of bandwidth allocation scheme is the centralized bandwidth allocation approach. In this scheme the reports travel to the OLT from the ONUs to inform about their bandwidth needs for upstream bandwidth admission. The decision controller is located at the OLT. This means that a bandwidth decision controller located in the OLT would receive information from the ONUs and dynamically and individually schedules each queue located in the multiple ONUs.

Fig. 1 Bandwidth assignment research categorization



However, any software failure in the OLT will halt the ONU upstream transmission [23] adding additional delay if the bandwidth allocations failed in one cycle and the ONUs have to wait several more cycles to get grants. Centralized scheme could be either single-level or hierarchical. The classical and first example of centralized allocation with single-level algorithm is Interleaved Polling with Adaptive Cycle Time (IPACT) scheme by Kramer et al. [24] and it was the pioneering algorithm produced for DBA. In this algorithm, the OLT polls each of the ONUs individually in a round-robin fashion to dynamically allocate the bandwidth in accordance with the requested bandwidth of each ONU.

The hierarchical scheme involved algorithms at the OLT for inter and intra ONU bandwidth allocation. The hierarchical allocation allows expansion and efficient manage of bandwidth's resources besides resolving the need of separating GATE and REPORT messages, so they can be sent together to each queue over an EPON system [25]. Numerous hierarchical DBA algorithms are illustrated in the references [26, 27]. Assi et al. [28] upgraded the initial interleaved polling with adaptive cycle time (IPACT) algorithm by making more efficient usage of the under loaded unwanted excessive bandwidth. The excess bandwidth is effectively utilized by evenly assigning it amongst the highly loaded ONUs. However, this DBA may cause wasted bandwidth since the highly loaded ONUs can receive more bandwidth than requested. Hence, Bai et al. [29] improved the algorithm by adding a weight-based DBA scheme that is called weighted-DBA. The excess bandwidth from classes that need less than their maximums in lightly loaded ONUs is distributed among the classes that need more than their maximums in highly loaded ONUs.

Lately, a few researches dealt with the decentralized bandwidth allocation approaches for the EPON, as EPON's bandwidth allocation schemes were relying on centralized architecture. OLT is regarded as the only intelligent device that could arbitrate time-division access to the shared channel. However, any failure in the OLT bandwidth allocation would halt the allotment for ONUs. Nevertheless, most of the solutions for decentralised bandwidth allocation included additional expenses and complexity to the original architecture proposed by IEEE 802.3ah. The original EPON architecture had to be modified, such that each ONU's upstream transmission is echoed at the splitter to all ONUs. Each ONU is equipped with an additional receiver to obtain the copied transmission. As such, the entire ONUs is able to monitor the transmission of each ONU and determine the upstream channel access.in a dispersed manner [30].

Sherif et al. [31], proposed an Ethernet over a star coupler-based PON architecture that uses a distributed TDMA arbitration scheme. The paper anticipated several QoS-based DBA algorithms in which the OLT is excluded from the implementation of the time slot assignment. Wong [32], simulated a network frame in a Local Area Network (LAN) and all the ONUs were connected with one star coupler by two fibres. The ONUs was able to accept the frames transmitted by the other ONUs.

Delowar et al. [33] conducts a study of a distributed DBA scheme over a decentralized architecture and explored the control plane feasibility of such architecture. However, the proposed decentralized architecture saw increased complexity and cost of the ONUs. Also, Feng et al. [34] published an article analysing a distributed DBA by using simulation. The proposed algorithm does not alter the existing EPON architecture, but only transferred the requested bandwidth information transmitted to all ONUs by using the broadcasting capability of the OLT. It was completely in congruence with the Multi Point Control Protocol (MPCP), as regulated by the IEEE 802.3ah standard and only needed to add some new fields in the REPORT and GATE frames. However, this algorithm did not support traffic classes, e.g. Differentiated Services (Diffserv), and could lead to an inefficient QoS.

A new decentralised scheme for the emerging long reach (LR)-PON was proposed by Helmy et al. [35], where the PON network range is extended to over than 100 km where the propagation delays will increase and severely affect the performance of the algorithms as they are based on the bandwidth. However, this technique requires additional ONU transceivers.

3 DBA for Upstream EPON Examples

Several bandwidth allocation scheme proposed previously by researchers have been reviewed in the introduction. A discussion of efficient bandwidth allocation works by the authors is elaborated in this section.

3.1 Centralized Allocation: Single Level

The global priority DBA is a centralized DBA solution proposed by the authors in [36] as shown in Fig. 2. In global priority DBA, three queues are inside the ONU, OLT and the user's side, consistent with the needs of supporting QoS based on DiffServ. The three types of services are voice-DiffServ Expedited Forwarding (EF), video-DiffServ Assured Forwarding (AF), and data—DiffServ Best Effort (BE) respectively. The ultimate highest priority traffic is the voice bandwidth

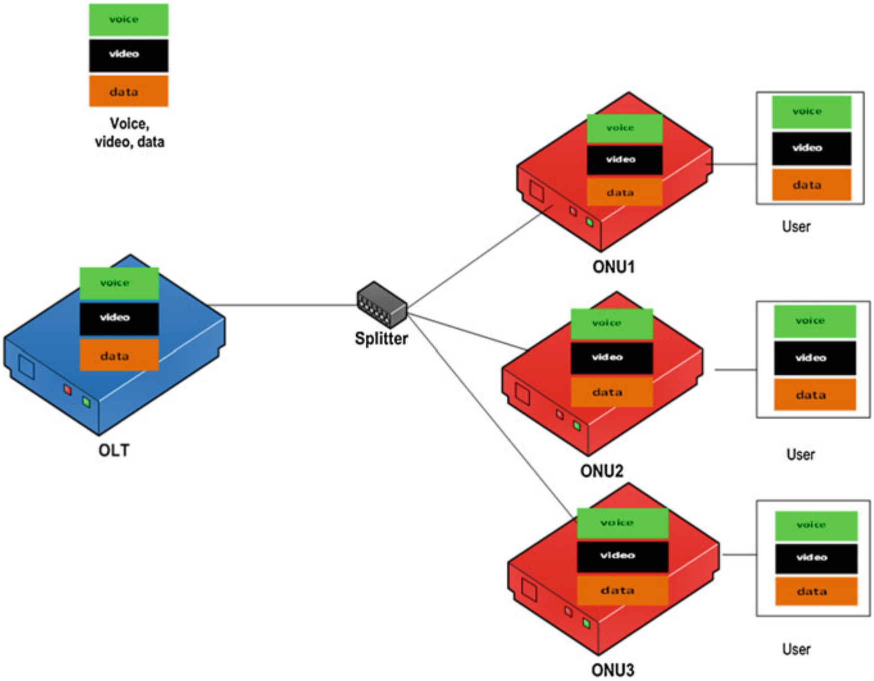


Fig. 2 DBA with global priority

because it requires strict delay and jitter guarantee. The medium priority traffic is the video bandwidth that requires bandwidth assurances. Finally, the lowest priority traffic is the data bandwidth that is more concerned with throughput.

The amount of excess bandwidth for lightly loaded queues is calculated and then allocated to the highly loaded queues according to their priority. Universally the needs of higher priority traffic would be met first, followed by the medium and low priority traffic. Thus, this method ensures the QoS support in the EPON system.

3.2 Hierarchical Allocation

3.2.1 Russian Doll Model (RDM) Algorithm

The DiffServ Aware Traffic Engineering (DS-TE) architecture provides the recommendation for the establishments of how the bandwidth could be allocated to different traffic classes in order for network suppliers to adopt the wide range of services, such as voice-over-IP (VoIP), IPTV, and video on demand (VoD) [37]. The bandwidth constraints (BC) model considers one of the most essential aspects

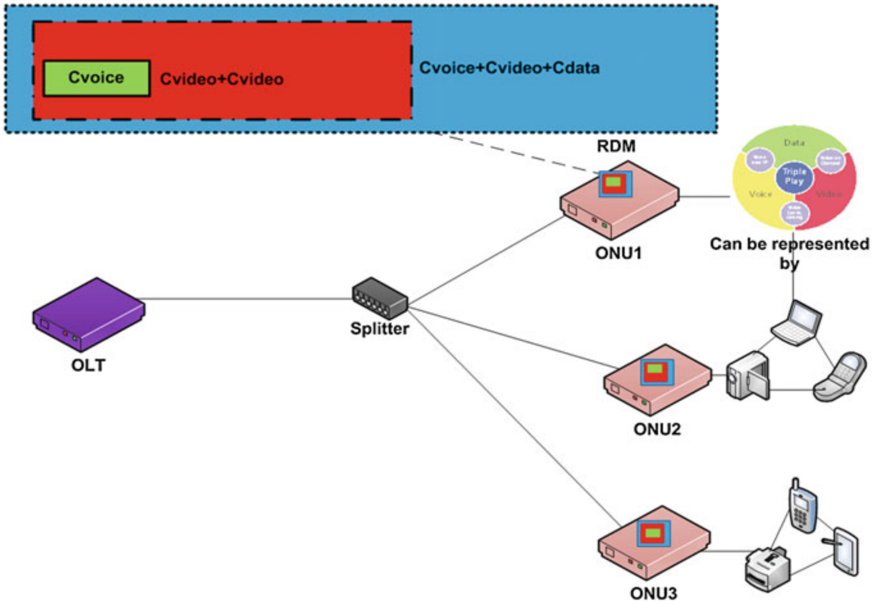


Fig. 3 DBA with RDM

of the DiffServ. The RDM [12, 13] is a technique that could be used to guarantee bandwidth efficiency and QoS of many types of services. It could also be used to simultaneously achieve isolation across the three types of traffic classes, so that each class type is guaranteed its share of bandwidth and bandwidth efficiency, with prevention of QoS degradation for all traffic types. The RDM improves bandwidth efficiency by allowing the triple play services to share the bandwidth, whereby the lower priority class are able to use the available excess bandwidth from a higher priority class of up to the summation of their bandwidth constraint values.

The hierarchical RDM architecture is shown in Fig. 3, C_{voice} is the traffic class with the highest strictest QoS requirements, C_{video} is the medium priority, while C_{data} is the best effort traffic class. The algorithm provides the allocation of bandwidth between the optical ONUs and within the ONUs based on RDM rules. The RDM bandwidth constraints are as expressed in Table 1.

The hierarchical dynamic bandwidth allocation algorithm based on RDM which is referred as the Russian Doll Dynamic Bandwidth Allocation (RDDBA) was able to distribute the bandwidth in an effective way for inter- and intra-ONU in an EPON. The allocation of bandwidth is strategized according to the ordering and prioritization of triple play services. The simulation results indicated that the proposed algorithm addresses the perfect differentiated services by balancing priority and fairness by supporting the triple-play services rather well, i.e. video, voice, and data, as well as makes effective adjustment in balancing bandwidth sharing between the ONUs.

Table 1 RDM rules

Symbol	Description	Amount	RDM rules
$C_{voice}(I)$	Aggregated bandwidth for voice	20 % of total bandwidth	$BC2 = C_{voice}(I)$
$C_{video}(I)$	Aggregated bandwidth for video	50 % of total bandwidth	$BC1 = C_{voice}(I) + C_{video}(I)$
$C_{data}(I)$	Aggregated bandwidth for data	30 %of total bandwidth	$BC0 = C_{voice}(I) + C_{video}(I) + C_{data}(I)$

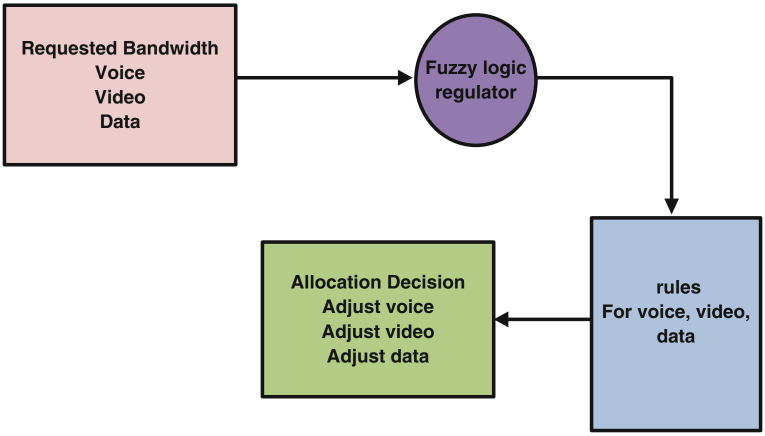


Fig. 4 DBA based fuzzy logic

3.2.2 Fuzzy Logic Algorithm

A hierarchical fuzzy logic was also incorporated in the intra-ONU allocation as shown in Fig. 4. The bandwidth allotment for each ONU in this algorithm is done accordingly by using fuzzy logic. The service discipline bandwidth that is assigned first is voice traffic. Then, the remaining bandwidth is allocated to video and finally to the data bandwidth.

The fuzzy logic regulator mechanism involves three input parameters implied by requested bandwidth for voice, video and data, and one output parameter. The output decision used to allocate bandwidth in each ONU is triggered when there is conflict for bandwidth between the classes [37, 38].

The hierarchical fuzzy logic scheme for EPON is called intelligent fuzzy logic-based dynamic bandwidth allocation algorithm (IFLDBA) [37]. The algorithm offers an intelligent decision making scheme for the allotment of bandwidth between the ONUs and within the ONUs. Fuzzy logic is used to improve the bandwidth allocation for inter and intra ONU scheduling. The results obtained showed that the IFLDBA has a better bandwidth utilization of up to 21 % and lower delay than the earlier introduced classical algorithm called the broadcast polling algorithm.

Table 2 The fuzzy logic rules

Rule	rvoice	rvideo	rdata	Decision
1	Low	Low	High	Adjust data
2	Low	High	Low	Adjust video
3	Low	High	High	Adjust video
4	High	Low	Low	Adjust voice
5	High	Low	High	Adjust EF
6	High	High	Low	Adjust EF
7	High	High	High	Adjust EF

The fuzzy decision rules for bandwidth allocation decision are shown in Table 2. There are seven rules that are related to the three inputs with the fuzzy output.

The fuzzy output range and the resultant allocation decision are based on the Sugeno inference method. It is noted that the delay for the IFLDBA increased linearly as the offered load increases to 1 Gbps with bandwidth limitation is set to avoid voice monopoly for the EF traffic class. The AF traffic class delay is seen be reduced as the offered load increases to 1 Gbps [37].

3.3 Decentralized Allocation

The flow chart of the proposed Efficient Distributed DBA (EDDBA) is depicted on Fig. 5. EDDBA is based on the existing EPON structure with no modification [39, 40] and only transfer the information window transmitted by one ONU to the other ONUs by broadcasting, similar to the OLT functionality. In the downstream direction, the OLT will insert a "broadcast" link ID which will be accepted by every ONU which complies with the MPCP requirements as outlined in the IEEE 802.3ah standard. The OLT will then add some fields in the REPORT frame and the GATE frame. To avoid frame duplication when an ONU receives its own frame, the ONU accepts a frame only if the frame's link ID is different from the link ID assigned to that ONU. All information will be kept in a look- up table to be used later in bandwidth allocation decision making.

The decentralized algorithm will run simultaneously at each ONU, and the requested bandwidth for each ONU is then calculated.

If the requested bandwidth is less than the allowed bandwidth then the bandwidth given is the requested bandwidth based on defined criteria where the voice will get up to 20 % of the available bandwidth with the highest priority, the video's portion is 40 % with medium priority and the data's share is 40 % with lowest priority.

If the total demanded bandwidth is higher than the available bandwidth then excessive bandwidth from other ONUs will be considered as in equations below in the same manner as the algorithm in [28]. Then the extra bandwidth will be distributed between the ONUs.

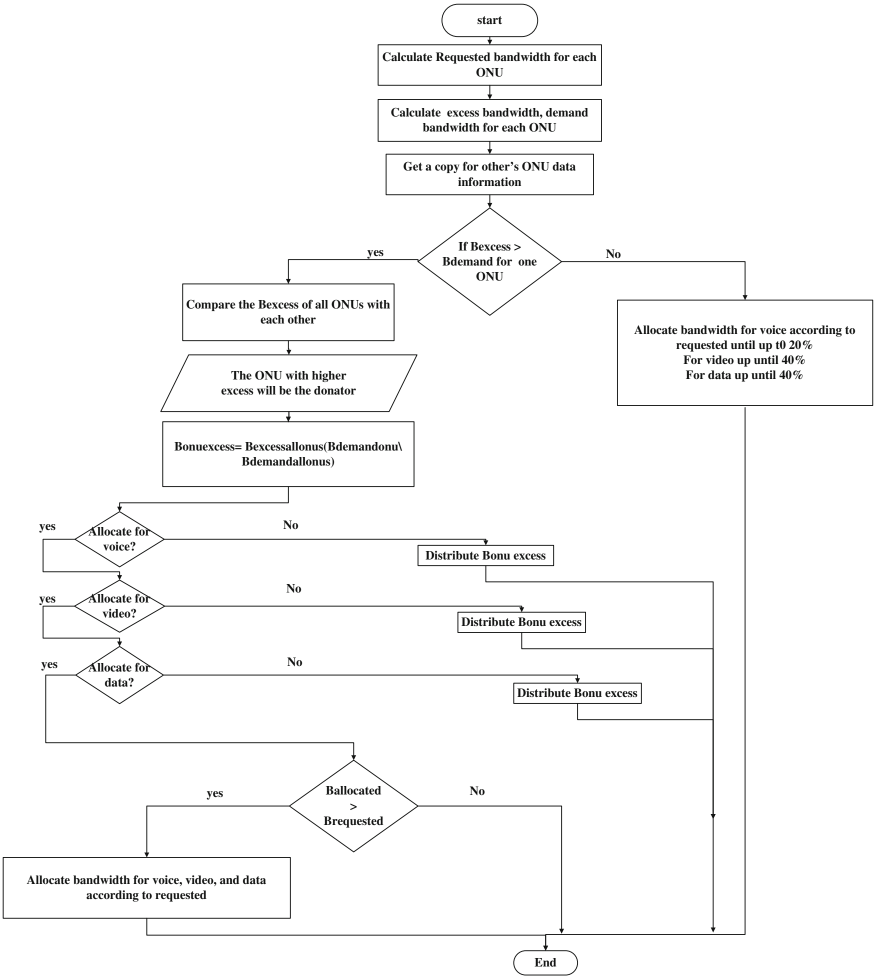


Fig. 5 Flow chart of the efficient distributed DBA

To ensure the efficient utilization of excess bandwidth, the excessive bandwidth should be shared according to the requested bandwidth within the overloaded group. The performance model comprise of ONUs that maintain three separate priority queues which share the same buffering space to allow straight forward mapping of DiffServ's expedited forwarding (EF), assured forwarding (AF), and best effort (BE) classes [31].

A simulation study for EDDBA was performed as in [41] with the traffic scenarios of considering three priority classes P0, P1, and P2, with P0 being the highest priority constant-bit-rate (CBR) used for delivering voice, and P1 for variable-bit-rate or (VBR) traffic, which represents the video stream, and P2 the best-effort data. The simulation study was conducted using the PROLOG simulation [42].

The starting point for our comparative study is to look at how the offered load affects the bandwidth utilization of the IPACT [24] and EDDBA. An efficient decentralized DBA algorithm strives to achieve as high bandwidth utilization as possible. The improvement of the bandwidth utilization for EDDBA shows a useful performance via PROLOG simulation in comparison to the IPACT algorithm due to the efficient reuse of unclaimed access bandwidth.

4 Conclusion

This paper provides the background on DBA methods in upstream EPON systems. The operation of several bandwidth allocation algorithms in upstream EPON has been highlighted for centralised (single level and hierarchical) and decentralised DBA schemes. A new decentralised DBA for EPON, i.e. EDDBA has been proposed and deliberated in this paper.

Acknowledgment We would like to acknowledge and thank the Ministry of Science, Technology and Innovation Malaysia for funding this project under the Escience Fund 01-02-03-SF0247.

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