DESIGN AND ANALYSIS OF NEXT GENERATION ETHERNET-BASED PASSIVE OPTICAL ACCESS NETWORKS

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Abstract

Design and Analysis of Next Generation Ethernet-based Passive Optical Access Networks

Ahmad R. Dhaini

Ethernet Passive Optical Network (EPON) has emerged as an optimized optical next-generation access network that is capable of providing high speed Internet to the ever increasing end-users carrying applications such as, voice communications (VoIP), standard and high-definition video,video conferencing (interactive video) and data traffic, at the minimum cost. However, although standardized, EPON presents network designers with several challenges.

In this thesis, we address many of these issues and we propose appropriate solutions that we believe can be adopted by EPON designers. First, we introduce the technologies currently deployed and we motivate our work. Next, we overview the EPON technology along with its related work, and highlights the challenges it carries. Our main contributions start when we investigate the fairness issue in EPON. Here, a new intra-ONU scheduler is presented in order to provide every class of service (CoS) of every ONU with a fair access to the bandwidth allocated by the OLT. We then present the first admission control (AC) framework with all its rules and functionalities along with a new dynamic bandwidth allocation (DBA) designed especially for the application of AC. This framework will resolve the *bandwidth guaranteed* matter that stems from the lack of QoS flows protection.

In our next main contribution, we discuss a possible upgrade of the current time division

multiple access (TDMA) PON to a wavelength division multiplexing (WDM) PON. This upgrade is evident with the continuous growth of Internet users, that makes traditional EPONs not capable of coping with this increase. Here, we present novel dynamic wavelength and bandwidth allocation schemes (DWBAs) to arbitrate the transmission of ONUs over multiple wavelengths. We then present three new DWBAs to support quality of service (QoS) in the new WDM-PON. We validate all the proposed models and schemes by conducting comprehensive experiments and extensive simulations, where performance is evaluated.

Finally, we conclude our work and presents suggested future work.

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- **Ahmad R. Dhaini**, Chadi M. Assi, Abdallah Shami, "Dynamic Bandwidth Allocation Schemes in Hybrid TDM/WDM Passive Optical Networks", in *IEEE Consumer Communications and Networking Conference (CCNC'06)*, Las Vegas, USA, January 2006.
- **Ahmad R. Dhaini**, Chadi M. Assi, Martin Maier, Abdallah Shami, "Dynamic Wavelength and Bandwidth Allocation in Hybrid TDM/WDM Ethernet Passive Optical Networks (EPONs)", *IEEE Journal of Lightwave Technology (JLT)*, Under Review.
- **Ahmad R. Dhaini**, Chadi M. Assi, Abdallah Shami, and Nasir Ghani, "Adaptive Fairness through intra-ONU Scheduling for Ethernet Passive Optical Networks", *IEEE International Communications Conference (ICC'06)*, Istanbul, June 2006.
- **Ahmad R. Dhaini**, Chadi M. Assi, and Abdallah Shami, "Quality of Service in WDM Ethernet Passive Optical Networks (EPONs)", *IEEE Symposium on Computers and Communications (ISCC'06)*, Sardinia, Italy, June 2006.
- **Ahmad R. Dhaini**, Chadi M. Assi, Martin Maier, Abdallah Shami, "Per-Stream QoS and Admission Control in Ethernet Passive Optical Networks (EPONs)" , *IEEE Journal of Lightwave Technology (JLT)*, submitted.
- **Ahmad R. Dhaini**, Chadi M. Assi, Martin Maier, Abdallah Shami, "Admission Control in Ethernet Passive Optical Networks (EPONs)", *IEEE International Communications Conference (ICC'07)*, to be submitted.

Abbreviations

AC - Admission Control
AC-DBA - Admission Control Dynamic Bandwidth Allocation
ACU - Admission Control Unit
AF - Assured Forwarding
APON - ATM Passive Optical Network
ATM - Asynchronous Transfer Mode
BE - Best Effort
CBR - Constant Bit Rate
CM - Cable Modem
CO - Central Office
CoS - Class of Service
DBA - Dynamic Bandwidth Allocation
DSL - Digital Subscriber Loop
DWBA - Dynamic Bandwidth and Wavelength Allocation
DWDT - Dynamic Wavelength Dynamic Time
DWRR - Deficit Weighted Round Robin
EF - Expedited Forwarding
EPON - Ethernet Passive Optical Network
FTTB - Fiber To The Building
FTTC - Fiber To The Curb
FTTH - Fiber To The Home
GPON - Gigabit Passive Optical Network
HL - Highly Loaded
IEEE - Institute of Electrical and Electronics Engineers
ISDN - Integrated Services Digital Network
LAC - Local Admission Control
LAN - Local Area Network

LL - Lightly Loaded
MAC - Medium Access Control
MAN - Metropolitan Area Network
M-DWRR - Modified Deficit Weighted Round Robin
MPCP - Multi-Point Control Protocol
OLT - Optical Line Terminal
ONU - Optical Network Unit
P2MP - Point-to-Multipoint
PCU - Policy Control Unit
PON - Passive Optical Network
PtP - Point to Point
PQ - Priority Queue
QoS - Quality of Service
RAC - Remote Admission Control
ROF - Radio Over Fiber
RR - Round Robin
RTT - Round Trip Time
SLA - Service Level Agreement
SP - Strict Priority
SWDT - Static Wavelength Dynamic Time
TDM - Time Division Multiplexing
TDMA - Time Division Multiple Access
TW - Transmission Window
VBR - Variable Bit Rate
VoD - Video on Demand
VoIP - Voice over IP
WAN - Wide Area Networks
WDM - Wavelength Division Multiplexing
WLAN - Wireless Local Area Network
WiMAX - Worldwide Interoperability for Microwave Access

Chapter 1

Introduction

Over the past decade, major research work has been done in the area of Optical Networking; more specifically, *dense wavelength division multiplexing* (DWDM), optical amplification, wavelength add-drop multiplexer (WADM) and many others have significantly improved the telecommunications backbone capacity and reliability.

Concurrently, access networks have been exposed under substantial challenges with the exponentially increasing per-user bandwidth demand and ever increasing backbone capacity. Moreover, the tremendous growth of Internet traffic has drawn a deep attention to the aggravating lag of access network capacity.

The "first mile" [1](or "last mile" as called by some telecommunications operators), also referred to as the *subscriber access network* or the *local loop*, has never received the proper attention to satisfy the subscriber's demand for new services. To date, the most widely deployed technologies to provide services in the last mile, are Digital Subscriber Loop (DSL) and Cable Modem (CM). However, although these technologies provide much more bandwidth than 56 Kbps dial-up lines, they cannot offer enough bandwidth for the emerging

[1] *First Mile*: Mile or Km that connects the service provider central offices to businesses and residential subscribers.

bandwidth-intensive services such as Video-On-Demand (VoD) and two-way video conferencing.

1.1 Traffic Growth

The Internet has become phenomenally popular and the number of users requiring "broadband" [2] access and willing to pay for it, has been increasing steadily despite the drops in the global economy [1,27].

A growth in the number of people requiring broadband access is forecasted. Much of the current development of broadband networks based on the optical technology has been achieved as a result of an active and stimulating role of governmental agencies. These agencies are responsible for implementing policies that encourage the development of broadband access networks as a way to increase computer literacy rates amongst citizens [1].

According to most analysis, data traffic is increasing at an exponential rate and has already surpassed voice traffic [2,4,29]. Furthermore, Market research shows that after upgrading the broadband connection, a significant increase in the amount of users ($\approx 35 \sim 40\%$) that are online, have been witnessed. Not only that, but also the voice traffic, which used to be requested in small amounts, have been witnessing an increase of $\approx 8 \sim 9\%$ per annum [2,4]. This trend is expected to continue in the future, especially with the new emerging bandwidth-intensive and real-time services that the users are subscribing to.

[2] Broadband refers to a transmission speed of 1.54 million bits per second or more using a single medium, such as a wire, that has two or more channels carrying information at once.

1.2 The "Bottleneck" Problem & First Mile Evolution

The last mile, still remains a major bottleneck between high-capacity Local Area Networks (LANs) and the subscriber home network. The huge amount of bandwidth that the backbone carries, has to reach the users premises through the access network. This lag of "bandwidth balance" generates a problem, known as the bandwidth *bottleneck problem.* The current broadband technologies, that are widely deployed to provide services in the last mile, are DSL and CM.

DSL is built on the traditional twisted lines for telephone service. It delivers two data services utilizing the so-called Digital Modulation technology via a DSL modem at the subscribers 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 128Kbps to 1.5Mbps.

CM is another expedient of *community antenna television or cable television* (CATV) companies to respond the explosion of Internet service demand. This technology realizes data service delivery 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 with the way in 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 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 [4]. 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. Given that DSL 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 18000 ft. In general, network operators do not provide DSL services to subscribers located more than 12000 ft from the CO because of the potentially increased cost. Although other variants of DSL that provide higher data rate are also being considered (VDSL, ADSL2, G.SHDSL), these technologies are more riche and pose even more distance limitations. Also, CM is incapable of offering broadband services over large distances with high reliability. To alleviate these bandwidth bottlenecks, optical fibers are penetrating deeper into the first mile with a great promise to offer fiber to the home (FTTH) and fiber to the building (FTTB). Consequently, most companies (e.g., NT&T, Verizon) are switching to fiber technology [9]. This, as a result, raises the need for inexpensive, simple and scalable technology, capable of delivering bundled *"triple-play"* to end-users (i.e.voice, data and video).

1.2.1 Passive Optical Network (PON)

Passive Optical Network (PON) is basically a point-to-multipoint (PtMP) optical network with no active elements from the source to destination. The only interior elements used in PON are passive, such as optical fiber, splices and splitters. It is a topology viewed by many as an attractive solution to the bottleneck problem. This is due to the fact that

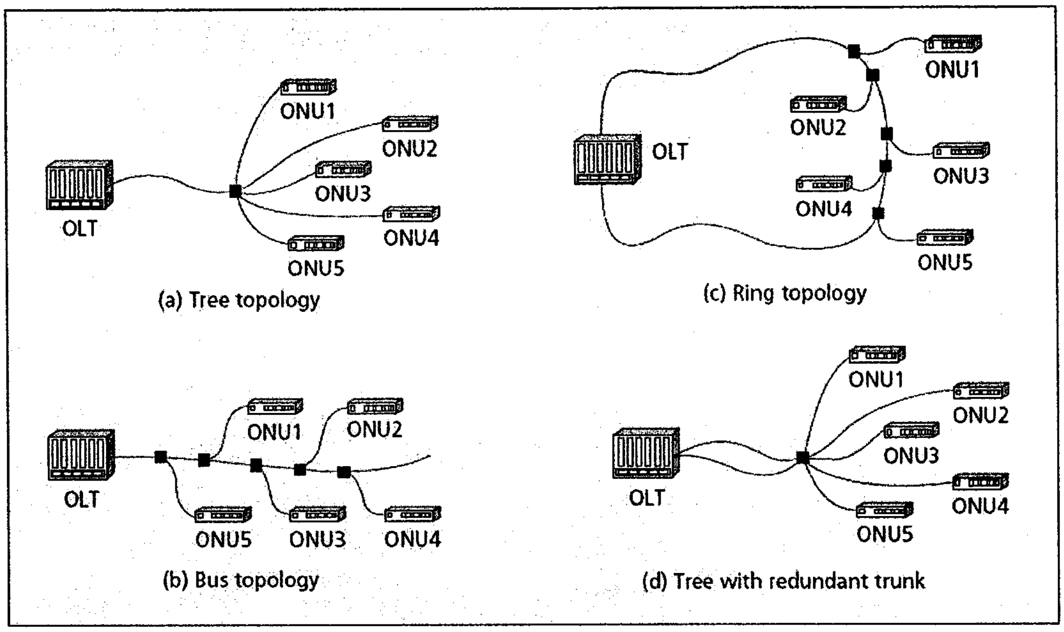


Figure 1.1: PON Topologies [30]

PON (1) allows for long reach between central offices and customer premises, operating at distances over 20 km, (2) minimizes the amount of optical transceivers, central office terminations, and fiber deployment, (3) provides higher bandwidth due to deeper fiber penetration, offering gigabit per second solutions, (4) allows for video broadcasting as either IP video or analog video using a separate wavelength overlay, (5) eliminates the necessity to install active multiplexers at splitting locations, thus relieving network operators of the dreadful task of maintaining active curbside units and providing power to them, and (6) is optically scalable since it allows for upgrades to higher bit rates (i.e., GPON) or additional wavelengths (i.e., WDM-PON).

A cost analysis presented in [3] shows that, in many situations, deploying fiber is now less costly than deploying copper. On the other hand, because an access network aggregates traffic from a relatively small number of subscribers (compared to metro or regional networks), it is very cost sensitive. Therefore, a PON design should not require over-provisioning and should allow for incremental deployment.

PON basically comprises one Optical Line Terminal (OLT) and multiple Optical Network Units (ONUs). The OLT resides in the Central Office (CO) and connects the access network to the MAN (metropolitan area network) or WAN (wide area network) [29]. Logically, the first mile is P2MP, with a central office typically servicing thousands of subscribers. There are several multipoint topologies suitable for the access network, including tree, tree-and-branch, ring, and bus (Fig. 1.1). Using 1:2 optical tap couplers and 1:N optical splitters, PONs can be flexibly deployed in any of these topologies. In addition, PONs can be deployed in redundant configurations such as double rings or double trees; or redundancy may be added only to a part of the PON, say the trunk of the tree (Fig. 1.1(d)).

Broadband PON (BPON)

The Broadband Passive Optical Network (BPON) [5] standard was introduced first; in 1999, it was accepted by the International Telecommunications Union (ITU). The standard was endorsed by a number of network providers and equipment vendors which cooperated together in the Full Service Network Access (FSAN) [3] group. The FSAN group proposed that the ATM protocol should be used to carry user data, hence sometimes access networks based on this standard are referred to as APONs [6]. The architecture of the BPON is very flexible and adapts well to different scenarios. The underlying ATM protocol provides support for different types of service by means of adaptation layers. The small size of ATM cells and the use of virtual channels and links allow the allocation of available bandwidth

[3] http://www.fsanweb.org

to end users with a fine granularity.

Yet, the advantages of ATM proved to be the main obstacle in deployment of BPON and despite many field trails [5] BPON did not gain much popularity. The complexity of the ATM protocol made it difficult to implement and in many cases superfluous. The much simpler, data only oriented Ethernet protocol found a widespread use in local area networks and started to replace ATM in many metropolitan area and backbone networks.

Ethernet PON (EPON)

In November 2000, a group of Ethernet vendors (e.g., Passave Networks, PMC-Sierra Inc. and Dasan Networks) kicked off their own standardization effort to develop Ethernet Optical Network (EPON) under IEEE 802.3. The new study group comprised of sixty-nine companies aims to develop a standard that will apply the proven and widely used Ethernet networking protocol to the access market. The key difference between EPONs and APONs is that in EPONs, data is transmitted in variable-length packets of up to 1,518 bytes according to the IEEE 802.3 protocol for Ethernet, whereas in APONs, data is transmitted in fixed-length 53-byte cells (with 48-byte payload and five-byte overhead), as specified by the ATM protocol. This EPON advantage allows carriers to eliminate complex and expensive ATM and SONET elements and to simplify the networks dramatically. EPON vendors and network operators are focusing initially on developing a solution for delivering data, video, and voice over a single platform. While EPONs offer higher bandwidth at lower costs, and broader service capabilities than APON, the architecture is broadly similar and adheres to many ITU-G.983 recommendations.

Gigabit PON (GPON)

BPONs and EPONs deliver between 600 Mbits/sec and 1.2 Gbits/sec of capacity with up to 1:32 split ratios in the distribution network. But now there is a new kid on the block that offers network architects significant cost savings while doubling deliverable capacity and enabling higher split ratios.

Using recent innovations in optical transceiver products, Gigabit PON (GPON) [7] was released and adopted by the ITU in 2003. GPON delivers twice the bandwidth of EPON at its full speed of 2.5 Gbits/sec. At the same time, GPON-capable transceivers provide an adequate loss budget to enable higher split ratios up to 1:64 splits and the ability to achieve the necessary optical loop length distances. Thus, the attributes of GPON make it a logical choice for all FTTx deployments. Like EPON, GPON uses Ethernet as the Layer 2 technology, but it goes much further. However, the deployment of GPON requires an upgrade in all the optical units of PON. One simple example of these changes, each ONU will be altered to enable transmission on a higher rate channel. In that context, EPON is currently considered the most cost-effective solution for the bottleneck access.

1.2.2 What's Next?

The penetration of wireless technology in the telecommunications field and the tremendous success that is gaining, in addition to the huge efforts to ameliorate its reliability and efficiency, have made the idea of a broadband wireless, as a next-generation access network, become viable. Two conspicuous technologies, that are considered as strong candidates that operate at high speed rates, are (1) Worldwide Interoperability for Microwave Access

(WiMAX) [4] and (2) Radio Over Fiber (ROF) [8].

Nevertheless, these two technologies are currently being standardized and under intensive research and development.

1.3 Thesis Motivation & Contributions

In this thesis, we study most of the EPON problems that are currently of high interest to most researchers in the telecommunications area [4]. These problems include:

- Enabling the support of fair and efficient Quality of Service (QoS) in EPON.
- The application of Admission Control to provide guaranteed bandwidth in EPON.
- Spatial EPON upgrade (e.g., from TDM-PON to WDM-PON).

Supporting differentiated services in EPON has been, for the past five years, under intensive research in both the academia and industry. In this thesis, we begin by studying the QoS support in EPON and the related work done in this field, including both dynamic bandwidth allocation schemes and intra-ONU scheduling perviously proposed to efficiently allocate bandwidth for all types of services. To date, various DBAs have been designed [31] for the QoS support in EPON; each seeking to improve the overall QoS performance. For that reason, we shift our attention to the intra-ONU scheduling in EPON.

Current intra-ONU schedulers aim at providing an efficient prioritized packet selection, but do not take into account the fairness among all classes of services (CoS) aggregated in each ONU. For that reason, we propose and validate a new decentralized (i.e. at the ONU)

[4]http://www.wimaxforum.org/home/

intra-ONU scheduler that ensures a *fair* access to the allocated bandwidth for every CoS. We then undertake a topic that has not been addressed before, namely the Admission Control (AC) issue in EPON. The purpose of AC is (1) to protect the already admitted flows and (2) to ensure their *bandwidth guaranteed.* For that reason, we propose the first EPON framework that enables the application of a two-stage admission control (i.e., at the ONU and at the OLT) along with a new AC-enabled DBA, and we set the basis for what can be an open research subject in the future, i.e. AC in EPON.

Finally, We study the performance of EPON under heavy traffic loads and we show that the need for an upgrade from a single wavelength channel to multiple wavelength channels (i.e. WDM-PON) is becoming absolutely crucial; especially with the continuous Internet growth and demand for bandwidth [27]. In that context, we suggest two hybrid TDM/WDM-PON architectures that will mitigate the latter problem. Moreover, we propose several dynamic bandwidth and wavelength allocation schemes (DWBAs) for the TDM/WDM-enabled upgraded Medium Access Control (MAC). Furthermore, we integrate these DWBAs with new intra-ONU schedulers to enable QoS support in the new hybrid TDM/WDM-PON architectures.

1.4 Organization of The Thesis

The rest of the thesis is organized as follows. In chapter 2, we present an overview of the EPON technology and the relevant to-date related work. In chapter 3, we discuss the QoS support in EPON and we present our proposed intra-ONU scheduler. Moreover, we explain the "QoS protection" problem to motivate the application of admission control in

EPON. We then propose the first AC framework in EPON along with an AC-enabled DBA to mitigate the QoS problem. In chapter 4, we discuss a simple upgrade from TDM-PON to hybrid TDM/WDM-PON. We also present various dynamic bandwidth and wavelength allocation schemes in the new TDM/WDM-PON architecture(s). Furthermore, we present new intra-ONU schedulers to integrate the proposed DWBAs for the QoS support in the new TDM/WDM-PON. Finally, we conclude our thesis in chapter 5.

Chapter 2

EPON Technology : An Overview

2.1 EPON Architecture

Ethernet Passive Optical Networks (EPONs), which represent the convergence of inexpensive and ubiquitous Ethernet equipment and low-cost fiber infrastructure, appear to be a natural candidate and this technology has been under intense research activities recently [29, 36]. EPON is a point-to-multipoint (P2MP) optical access network with no active element in the signal's path from source to destination; the only interior elements used in this architecture as passive components such as optical splitters and optical fibers. EPON has been standardized by the IEEE 802.3ah working group [37] and it comprises one Optical Line Terminal (OLT) and multiple Optical Network Units (ONUs). The OLT resides in the Central Office (CO) and connects the access network to the MAN or WAN [29]. The ONUs are located at the subscribers premise and provide bandwidth either to the home resulting in Fiber To The Home (*FTTH*) architecture, or to the business resulting in Fiber To

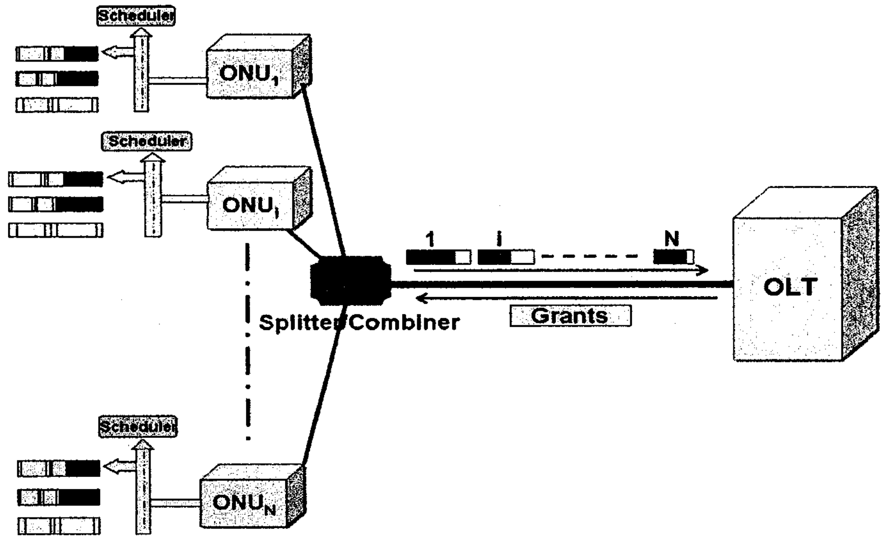


Figure 2.2: EPON Architecture

The Business (*FTTB*) architecture or to the curb resulting in Fiber To The Curb (*FTTC*) architecture. As shown in Fig.2.2, a single fiber extends from an OLT to a $1 : N$ passive optical splitter. The splitter fans out to multiple single fiber drops, which are connected to different ONUs. Traffic from the OLT to an ONU is called "downstream" (point-to-multipoint), and traffic from an ONU to the OLT is called "upstream" (multipoint-to-point) [29].

2.2 EPON Operation

Currently, EPON systems deploy two wavelengths: typically 1310 nm for the upstream transmission and 1550 nm for the downstream transmission. In the downstream direction (Fig. 2.3), Ethernet frames are broadcast by the OLT and are selectively received by each ONU. Alternatively, in the upstream direction (Fig. 2.4), multiple ONUs share the same transmission channel to transmit data and control packets to the OLT. Since ONUs are unable to detect collision occurring at the OLT and due to the difficulty to implement a

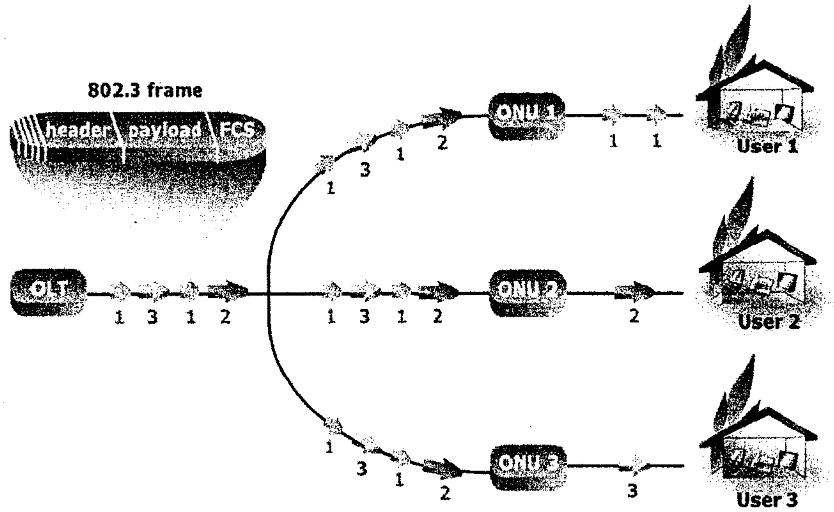


Figure 2.3: Downstream EPON Operation [10]

carrier sense multiple access with collision detection (CSMA/CD), it is necessary to design a mechanism that arbitrates the access of ONUs to the shared medium. This is achieved by designing Medium Access Control (MAC) [52] protocols to prevent collision between Ethernet frames of different ONUs transmitting simultaneously. Current MAC supports Time Division Multiplexing (TDM), where each ONU is allocated a fixed or dynamic time slot (transmission window) to transmit data to the OLT. Each ONU buffers data packets received from different subscribers until they are transmitted in the assigned time window.

2.3 Multi-Point Control Protocol (MPCP)

Transmission of different ONUs over the shared upstream channel is typically arbitrated by the OLT through the use of MPCP (multi-point control protocol). MPCP is a signaling access protocol which is being developed and standardized by the IEEE 802.3ah Task

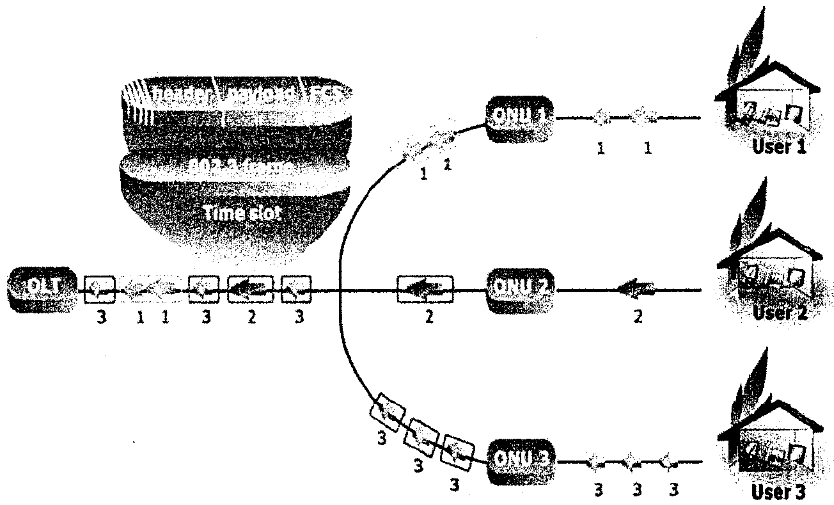


Figure 2.4: EPON Upstream Control [10]

Force [37]. MPCP resides at the MAC control layer and relies on two Ethernet control messages (GATE and REPORT) in its regular operation and three other message frames (REGISTER_REQUEST, REGISTER, REGISTER_ACK) in the auto-discovery mode. Auto-discovery mode is used to detect a newly connected ONU and to learn the round-trip delay and MAC address of that ONU. In our thesis, we are only concerned about the regular (non-discovery) operation of MPCP.

In its normal operation, MPCP gets a request from the higher MAC control client layer to transmit a GATE message to a particular ONU with the following information: time when the ONU should start transmission (T_{start}) and the length of the transmission T_{length}. Upon passing a message to the MAC layer, MPCP (in OLT and each ONU) time-stamps the message with its local time. Upon receiving a GATE message matching its MAC address, each ONU will program its local registers with T_{start} and T_{length}. Also, the ONU will update its local clock to that of the time-stamp in the received control message, hence avoiding any potential clock drift and maintaining in SYNC with the OLT. When the transmission "start timer" expires, the ONU will start its contention-free transmission. The transmission may include multiple Ethernet frames, depending on the size of the allocated transmission window and the number of backlogged packets at the ONU. Note that in MPCP, no packet fragmentation is allowed within the same transmission window (TW), and the "unfit" Ethernet frame will be deferred to the next TW ("time slot" or "cycle"). Within each cycle, to inform the OLT about its bandwidth requirements, ONUs use REPORT messages to report its bandwidth requirements (e.g. buffer occupancy) to the OLT. Note that the ONU should also account for additional overhead when requesting the next time slot; this includes 64-bit frame preamble and 96-bit inter-frame gap (IFG) associated with each frame. Upon receiving the REPORT message from the ONU, the OLT passes the received message to a DBA module and performs the appropriate bandwidth allocation computation. At the end, the OLT broadcasts a GATE message to that ONU, containing the appropriate transmission grants. When supporting differentiated services (DiffServ), each ONU has to report the status of its individual priority queues (PQ) and the OLT can choose to send one or multiple priority grants within the same GATE message depending on the bandwidth allocation algorithm implemented. Moreover, MPCP does not specify any particular bandwidth allocation algorithm. Instead, it is designed to facilitate the implementation of dynamic bandwidth algorithm (DBA).

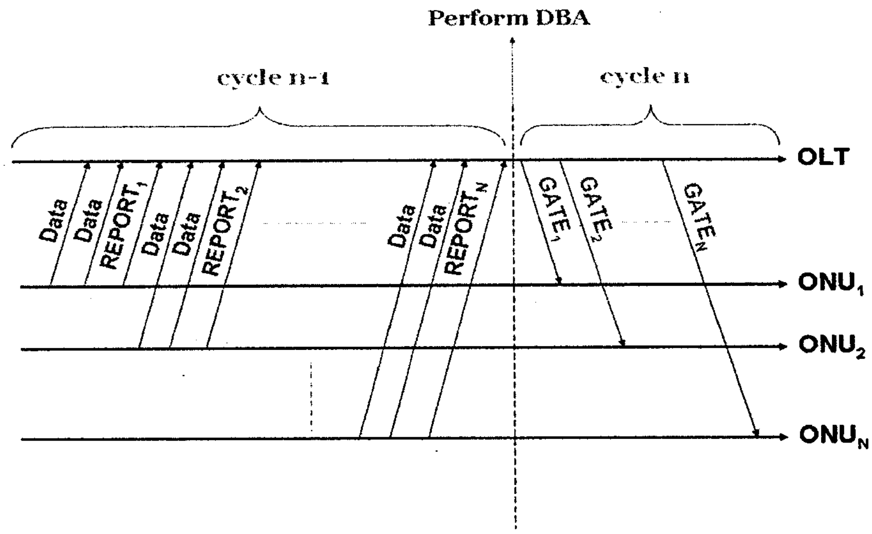


Figure 2.5: Conventional DBA Operation

2.4 Dynamic Bandwidth Allocation Algorithms(DBAs)

Dynamic Bandwidth Allocation (DBA) is deployed at the OLT to assign transmission bandwidths for the different ONUs sharing the EPON network. DBA uses the services offered by the MPCP protocol to communicate assigned transmission windows to their appropriate ONUs. In the conventional DBA operation, as shown in Fig. 2.5, the OLT waits until all REPORTs from all ONUs are received[1] in cycle $n-1$ to perform the appropriate computation. Consequently, the OLT broadcasts MPCP's GATE messages to grant transmission windows for cycle n. Mainly, DBAs can be categorized into algorithms with statistical multiplexing and algorithms with quality of service (QoS) support [31].

In algorithms with statistical multiplexing, the authors of [47] provided a considerable

[1]REPORT messages can be either sent at the end of the data transmission or at the beginning. However, if the latter is applied, the OLT might be receiving an *out-of-date* information from the ONUs. For that reason, we consider the first case in our work.

improvement to the EPON performance by presenting a novel dynamic bandwidth allocation algorithm, named *interleaved polling with adaptive cycle time(IPACT)*. Each ONU is served by the OLT once per round-robin polling cycle. Here, the OLT keeps track of the round trip time (RTT) of all ONUs to send a grant to the next ONU in order to decrease the un-utilized waiting time between consecutive upstream transmissions. Hence, the cycle is not static (e.g. 2ms [29]). Instead, it adapts to the instantaneous bandwidth requirements of the ONUs. At the same time, a maximum transmission window size W_{MAX} is set for each ONU in order to prevent highly loaded ONUs from monopolizing the bandwidth. Here notable examples including fixed, limited, constant credit, linear credit, and elastic service schemes were also tabled. However, IPACT does not allocate bandwidth for the incoming traffic at the ONU between two successive requests. To overcome this problem, the authors of [17] presented a theoretic extension to IPACT. Here, the amount of traffic arriving between two successive requests is estimated using a control gain factor "α" that is then incorporated with the next grant. The advantage of such a scheme is that the grant size is typically closer to the size of the backlog at the instant of receiving the grant at the ONU. However, this controlling scheme might not be optimal if the incoming traffic is highly variable. IPACT does not also consider the excessive bandwidth resulting from "lightly loaded" *(LL)* ONUs in each cycle. *LL* ONUs are the nodes requesting below their minimum guarantee and the "highly loaded" *(HL)* ONUs are those requesting greater than or equal their minimum guarantee.

Furthermore, EPON is expected to support diverse applications with various QoS requirements, where various traffic sessions are aggregated into different classes which will be serviced with differentiated services. These services are classified as follows: *Best Effort*

(BE) "data" traffic, *Assured Forwarding (AF)* traffic such as variable-bit-rate (VBR) video stream and *Expedited Forwarding (EF)* traffic used to emulate point-to-point connections or real time services, such as Voice over IP (VoIP). The high-priority class is *EF*, which is delay-sensitive and requires bandwidth guarantees. The medium-priority class is *AF*, which is not delay-sensitive but requires bandwidth guarantees. The low priority class is *BE*, which is neither delay-sensitive nor bandwidth guaranteed.

Many schemes have been explored in the area to fairly allocate bandwidth for different classes of services. The authors in [36] presented a new method to "evenly" distribute the remaining excessive bandwidth over *HL* ONUs. This scheme results in a remarkable improvement to the network performance for different classes of services and also allows for statistical multiplexing traffic into unused bandwidth units. The authors also consider the option of reporting queue size using an estimator for the occupancy of the high priority queue. Nevertheless, due to the unpredictable behavior of *HL* ONUs that varies from one cycle to another where a *HL* ONU tends to be a "slightly" *HL* one; and thus the allocated bandwidth is not being fully utilized, this uniform distribution of excessive bandwidth might not be the best possible solution.

On the other hand, the authors of [13] proposed a new concept of DBA, where ONUs are divided into two sets, namely *bandwidth guaranteed* (BG) ONUs (premium subscribers according to the SLAs) and *non-bandwidth guaranteed* (non-BG) ONUs (subscribers with best-effort service). Here, the bandwidth guaranteed polling scheme (BGP) provides guaranteed bandwidth to BG ONUs while providing best-effort services to non-BG ONUs. However, the proposed BGP can not be standardized with the MPCP arbitration mechanism proposed by the IEEE 803.2ah Task Force for the reason that in the future emerging

PON technologies, each ONU must be capable of provisioning differentiated services for different users requirements.

Alternatively, the authors of [58] proposed a new DBA to support multimedia services in EPON. Here, incoming traffic to each ONU is buffered into one of the three priority queues (High, Medium and Low). The sizes of these queues are reported to the OLT using an "upgraded" REPORT message. An inter-scheduler (i.e. at the OLT) is considered where the OLT, based on the priority queues sizes, issues grants separately. In particular, the DBA satisfies requests of flows by priority preference (High first, Medium second and Low last). Then, if all flows are satisfied and additional bandwidth is still available, the remaining resources are distributed among all priority flows in the same manner. However, strict priority scheduling based on the traffic classes at the PON level may result in starvation of ONUs that have only low priority traffic.

To overcome this problem, the authors of [14] present a new DBA for multiservice access, namely DBAM. DBAM applies priority queuing to enqueue the EF, AF, and BE frames, and gives preference to higher-priority traffic. Priority-based scheduling is exploited to schedule the buffered frames, and the schedule interval is the time between sending REPORT messages. DBAM also employs class-based traffic prediction to take the frames arriving during the waiting time into account with dynamic and diverse bandwidth requests. In particular, an *estimator credit* α, which is the ratio of the waiting time of the ONU over the interval length, is estimated and then incorporated in the request for bandwidth of all BF, EF and AF traffic. Multiservice access for different end users is realized by means of class-based traffic estimation and SLA-limited bandwidth allocation.

Furthermore, the authors of [15] presented a two-layer DBA where the total available bandwidth is allocated on two phases. Here, the OLT allocates bandwidth among different classes of services first, then among ONUs. This scheme provides a higher priority to the class-level Quality of Service over the ONU-level bandwidth guarantee. However, since subscribers are practically considered non-cooperative entities, ONU-level bandwidth guarantee should be considered first.

In addition, the authors of [18] proposed a new GRANT "pre-allocation" mode for *EF* traffic named Grant-Before-Report (GBR) and the traditional Grant-After-Report (GAR) mode for both *AF* and *BE* traffics. Here, the OLT divides the ONU transmission cycle into two sub-cycles; namely DBA sub-cycle (DBA-CL) reserved for EF traffic, and MPCP sub-cycle (MPCP-CL) reserved for AF and EF traffic.

A new GATE scheduling mechanism is also presented in [16]. This mechanism allocates GRANTs based on the traffic priority rather than the ONU classification (e.g. Round Robin). Here, all high priority traffic (from all ONUs) are granted first (in order to minimize its sensitive delay), and then low priority traffic second. This algorithm can be also applied with any DBA.

2.5 Intra-ONU Scheduling

As shown in Fig.2.6, upon receiving traffic "flows" from the registered subscribers, the ONU performs three main operations before transmission in the upstream channel. First, it classifies every newly arriving packet using a "packet-based" classifier. Next, and before placing packets in the corresponding priority queues, the ONU decides whether a packet

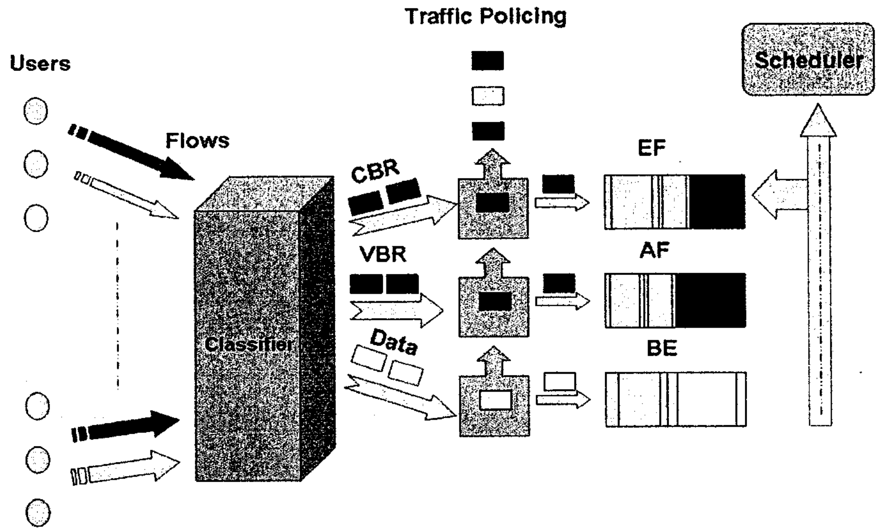


Figure 2.6: Intra-ONU Scheduling

should be admitted depending on the adopted traffic policing (admission control) mechanism (e.g., Leaky Bucket). Finally, it selects packets from its queues, depending on the intra-/inter-ONU scheduling algorithm [47,55], and sends them to the OLT as "flows" in the assigned transmission window (TW). Moreover, there are two types of intra-ONU scheduling: strict and non-strict priority scheduling algorithms. In strict priority scheduling, a lower-priority queue is scheduled only if all queues with higher priority are empty. However, this may result in a starvation for low-priority traffic or as dubbed in [57], "light-load penalty".

Non-strict priority scheduling addresses this problem by allowing reported packets (regardless of their priority) to be transmitted first as long as they are transmitted in the allocated TW. In other words, here, the transmission order of different priority queues is based on their priorities. As a result, all traffic classes have access to the upstream channel while maintaining their priorities; which enables fairness in scheduling. Note that inter-ONU control messages for allocating bandwidth to different ONUs are transmitted via the MPCP (multi-point control protocol) access protocol. To cope with the light-load penalty caused by applying strict priority scheduling technique, the authors of [57] proposed two methods. The first method involves a two-stage queueing process. Here, the incoming packets after sending the REPORT message are placed in the second-stage queue. Consequently, when a new GATE is received, the second-stage queue is emptied first. This however results in an increased average delay for all types of traffic. In the second method, the "after-report" incoming traffic is estimated, and thus the grant window will be large enough to accommodate the newly arriving high priority packets.

Alternatively, in [36], the intra-ONU scheduler employs priority scheduling only on the packets that arrive before sending the REPORT message. This scheme eliminates the "light-load penalty" and allows all services to access the shared medium.

On the other hand, the authors of [55] proposed a new intra-ONU scheduling scheme named "*Modified Start-Time fair queueing*" (M-SFQ) that muses the performance of VBR traffic. Here, the scheduler selects for transmission the queue with the minimal *start time*, derived from the head-of-line (HOL) packet in each queue, and synchronized with a *Global Virtual Time*.

Chapter 3

Quality of Service and Admission Control in EPON

3.1 Introduction

Currently, broadband access providers view QoS and multimedia-capable networks as an essential ingredient to offer residential customers video-on-demand, audio-on-demand, voice over IP (VoIP) and high speed Internet access. Furthermore broadband access networks, and EPON in particular, are especially appropriate for peer to peer applications (P2P) (which permit files to be interchanged through the Internet). The authors of [27] have shown that P2P applications represent a high fraction of the upstream traffic in hybrid fiber-coax cable access network. Unlike early file sharing applications (such as Napster and Gnutella), many recent P2P applications include live media broadcasting, high bandwidth content distribution and real time audio conferencing and require high performance access networks in order to deliver satisfying QoS to the users [22].

Hence, in order to provide QoS in the access network, bandwidth management on the upstream channel is essential for successful implementations of EPONs. Various inter-ONU and intra-ONU scheduling approaches have been recently proposed in order to enable the support of QoS. However, in order to support and "protect" the QoS of real time traffic streams in the access network, one needs, in addition to bandwidth allocation and service differentiation, an admission control algorithm which makes decision on whether or not to admit a new real-time flow based on its requirements and the upstream channel usage condition. We note that the problem of QoS protection is significant in EPON networks because the bandwidth allocated by the OLT to one ONU can only be guaranteed for a significantly short time (e.g., one cycle, as will be explained later). For example, when an ONU is highly loaded, it may be allocated more than the minimum bandwidth guaranteed (e.g., using surplus or excess bandwidth allocation [30]). However in subsequent cycles this excess bandwidth may not be available and hence some real-time streams that were admitted according to this bandwidth availability may have their QoS requirements no longer satisfied. Furthermore, appropriately controlling the admission of real time traffic streams will prevent malicious users from manipulating the upstream channel by sending traffic into the network more than their service level agreement (SLA). Accordingly, in this chapter we will present a suitable admission control scheme that may be deployed for EPON networks in order to support QoS and protect it and enable the transmission of emerging real-time traffic with guaranteed performance.

The rest of the chapter is organized as follows. A solution for intra-ONU scheduling based on the Deficient Weighted Round Robin (DWRR) [56] is presented in Section 3.2. This scheme ensures that every class of traffic gets a fair share of the assigned bandwidth at the

ONU by forcing the scheduler to visit every priority queue for a specific period of time that is determined by the weight allocated to the corresponding queue. Section 3.3 presents our Admission Control scheme with detailed analysis. Section 3.4 presents the performance evaluation and finally we conclude in Section 3.5.

3.2 A Decentralized Intra-ONU Scheduling

To date, a wide range of scheduling schemes have been studied, (e.g. weighted fair queuing (WFQ), self-clocked fair queuing (SCFQ), start-time fair queuing (SFQ), Weighted Round Robin (WRR) and Stratified Round Robin (SRR)). One distinguished scheme for achieving fairness with low complexity is the Deficient Weighted Round Robin (*DWRR*) [56]. In this chapter we propose a modified algorithm (M-DWRR) to enforce fairness among the various classes of service.

3.2.1 DWRR scheduling discipline

DWRR as proposed, defines the following three main parameters for each CoS or priority queue (PQ)*i*:

1. A "weight" α_i that defines the percentage of the output port bandwidth allocated to the queue.

2. A "Deficit Counter" *DC(i)* that specifies the total number of bytes that the queue is permitted to transmit in each scheduler's visit. The DC saves "*credits*" remaining from previous scheduling visit and adds them to the DC of the next visit until the

queue is empty and hence $DC(i) = 0$.

3. A "quantum" $Q(i)$ that is proportional to α_i and is expressed in bytes.

First, a Round Robin (*RR*) scheduler initializes the deficient counters, $DC(i) = 0_{,i=0...x}$ (where x is the number of PQs) , then visits each non-empty queue and determines the size (in bytes) of the *Head Of Line* (HOL) packet. Q(i) is computed from the available port bandwidth as follows:

$$Q(i) = \lceil \alpha_i \times B_{port} \rceil \tag{1}$$

Where B_{port} is the bandwidth available on the transmission port (in bytes). Next, the scheduler computes:

$$DC(i) = DC(i) + Q(i) \tag{2}$$

At this time, it checks if the HOL packet is greater than $DC(i)$; if yes, it moves to the next queue and "saves" the remaining *credits* in $DC(i)$, otherwise will select the packet for transmission and updates its deficient counter:

$$DC(i) = DC(i) - S_i^{HOL} \tag{3}$$

Where S_i^{HOL} is the size of the HOL packet in queue i. When queue i is empty, $DC(i)$ is reset to 0, and the pointer of the RR scheduler moves to the lower priority queue.

Fig. 3.7 shows a DWRR numerical example with three queues [56]. Here, the first queue is considered with the highest priority with $\alpha_1 = 50\%$; the other two, medium and low priority, queues are allocated an equal weight rate $\alpha_2 = \alpha_3 = 25\%$; $B_{port} = 2000$ Bytes. Consequently, $Q(1) = 1000$ bytes and $Q(2) = Q(3) = 500$ bytes. As Fig. 3.7 shows, when the scheduler starts, it looks at the HOL packet in the high priority (HP) queue and sets $DC(1) = Q(1) = 1000$ bytes. Here, $S_1^{HOL} < DC(1)$ and thus will be selected for transmission. Hence, DC(1) is updated and is now equal to 400 bytes. The HOL packet is now of size 300 and is going to be selected for transmission (following equation (2) in DWRR rules). DC(1) becomes equal to 100 bytes. Next, the HOL is of size 400 bytes which is greater than DC(1). For that reason 100 bytes are then saved as *credits* for the next scheduling round on queue 1, and the scheduler moves to next non-empty queue. In other words, when the scheduler re-visits queue 1, DC(1) will be equal 1100 bytes instead of 1000 bytes. The advantages of DWRR over other schemes are listed below:

- DWRR accurately supports weighted fair bandwidth distribution for CoS queues of variable-length packets.
- DWRR combines both the class-based queueing approach along with the Weighted round robin scheduling scheme.
- DWRR has lower complexity than WFQ and can be implemented in hardware.

3.2.2 Integrating DWRR with EPON

In EPON, every ONU maintains a number of priority queues where incoming packets are classified and queued based on their priorities. Unlike the system discussed in Section 3.2.1, in EPON, the ONU accesses the channel during the assigned TW that is specified by T_{start} and T_{length}. Hence, ONU j will compute the quantum for each queue i based on the weight assigned to the queue and the transmission window allocated by the OLT. Therefore, DWRR will have to set its three defined parameters (i.e., $\alpha_{i,j}$, $DC(i,j)$ and $Q(i,j)$)

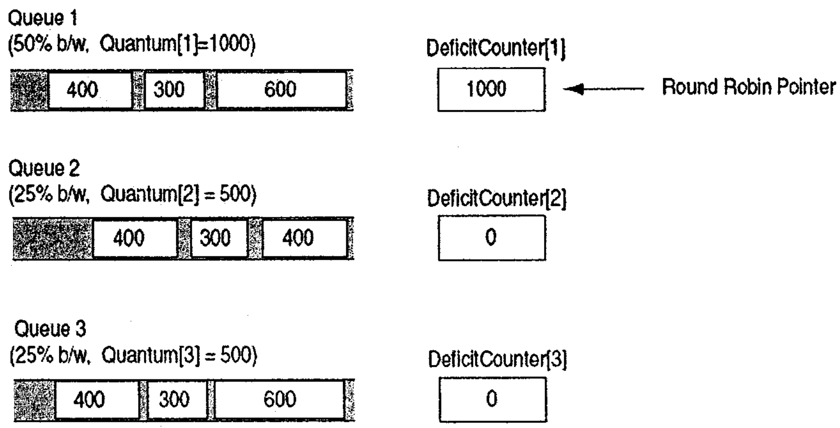


Figure 3.7: DWRR Example - Round 1 with Round Robin Pointer = 1 [56]

for each queue i. Suppose that the allocated TW is of size S_j (bytes) and is computed as follows :

$$S_j = \min(B_{min} + B^j_{excess}, \sum_{i=1}^{x} R_{i,j}) \tag{4}$$

Where $R_{i,j}, i = 1...x$ is defined as the requested size of each queue i, B^j_{excess} is the excess bandwidth allocated to ONU j and B_{min} is the minimum bandwidth guaranteed [29, 36]. Then the quantum is computed:

$$Q(i, j) = \lceil \alpha_{i,j} \times S_j \rceil \tag{5}$$

The update of the deficient counter is computed as in (2). Note that $Q(i, j)$ can be set by the OLT and incorporated in the GRANT message.

3.2.3 Modified DWRR (M-DWRR)

As mentioned before, DWRR scheduling discipline visits each PQ in a round robin fashion. Moreover, after each visit made by the scheduler to all PQs, the deficient counter is updated according to the rules explained in Section A. On the other hand, in M-DWRR, once the scheduler has finished visiting all the queues, the remaining bandwidth from the assigned TW of the current cycle is distributed to all the PQs based on the corresponding weights:

$$DC(i,j) = DC(i,j) + \lceil \alpha_{i,j} \times B^{j}_{remain} \rceil \quad (6)$$

Where B^{j}_{remain} is the remaining bandwidth (in bytes) from the assigned TW of the same cycle. This remaining bandwidth is found from the unutilized bandwidth after the first scheduling visit to all PQs. In other words, since the TW is divided among priority queues depending on their weights (and not their needs), some queues might not utilize all their corresponding assigned bandwidth. Thus, in order to eliminate the waste of bandwidth, we re-allocate this portion to the PQs based on the same weight assignment.Alternatively, the ONU might follow a different "update scheme" and hence re-validates the deficient counters based on a different weight assignment scheme, that might be derived/concluded from the different traffic requirements and queues occupancies rather than the original weight agreement.

Furthermore, another "update discipline" might be implemented, where $DC(i,j)$ is computed as in (6), but yet if the allocated bandwidth of higher-priority is not needed (i.e., queue is empty), it will be distributed to the lower priority queues. However, since high priority traffic (e.g., Expedited Forwarding, EF) are delay-sensitive and since incoming packets might arrive after the described distribution, the scheduler *must* permit transmission of these packets by setting a *flag* that triggers its pointer, upon the arrival of these packets, to the appropriate queue. In this way, high priority traffic delay is preserved and its jitter is protected. On the other hand, the scheduler might allocate the remaining bandwidth in a traditional round robin fashion while assigning bandwidth for each non-empty queue such that this allocated bandwidth is "*just*" equal to the HOL packet of each queue. Algorithm 1 illustrates this scheme (where $R_{i,j}$ is the *variable* remaining bandwidth after each allocation done by the scheduler for each PQ i).

The advantage of such a scheme and of DWRR in particular, is that each ONU can *adaptively* set (depending on the traffic demand and the Service Level Agreement (SLA)) its own weights in both phases (i.e., initially and/or after computing B^j_{remain}). Hence, every class of service (CoS) is guaranteed to receive locally at the ONU a fair share or a fair access to the bandwidth allocated by the OLT. Moreover, if the traffic of one priority queue is light, then the allocated resources can be utilized by other traffic classes. However, the drawback of this scheme and of other schemes proposed so far is that there is no guaranteed that each ONU will get the bandwidth required to service its admitted streams while satisfying their QoS requirements. A bandwidth guaranteed polling (BGP) scheme was proposed in [13] to provide guaranteed QoS; here the ONUs are divided into bandwidth guaranteed (e.g., premium subscribers) and best effort ONUs. However, BGP does not consider the case of multi-services ONUs where both bandwidth and QoS guaranteed and best effort users co-exist. Further, BGP does not provide any QoS protection for existing streams in a more dynamic environment.

Algorithm 1 M-DWRR Deficient Counter Update

```
R_{i,j} = B^j_{remain}
while R_{i,j} > 0 do
    for all i ∈ ONU j do
        if queue i !empty() && S^{HOL}_{i,j} ≤ R_{i,j} then
            DC(i, j) ← S^{HOL}_{i,j}
            R_{i,j} ← R_{i,j} − S^{HOL}_{i,j}
        end if
    end for
end while
```

3.3 Admission Control in EPON

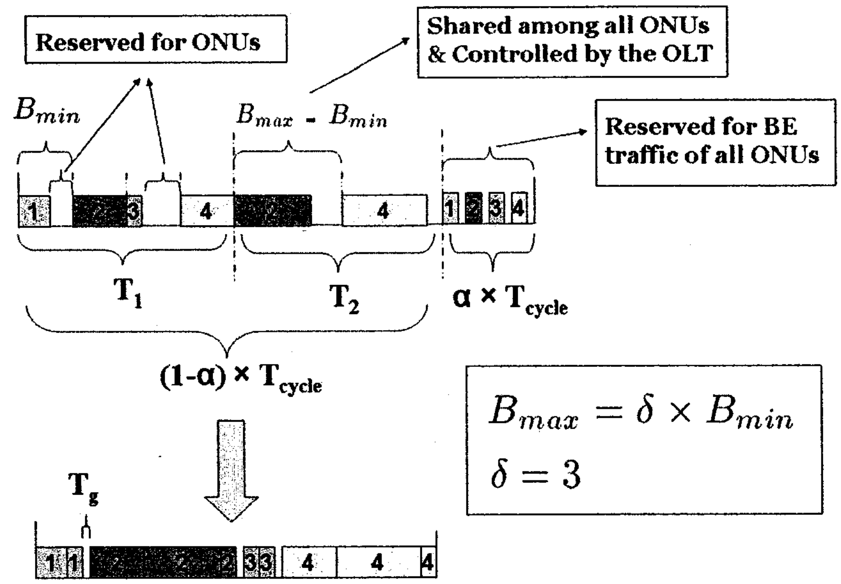
3.3.1 Preliminaries

In order to provide sustainable QoS in the access network, bandwidth management on the upstream channel is essential. In order to support and protect the QoS of real time traffic streams, one needs, in addition to bandwidth allocation and service differentiation, an admission control algorithm which makes decision on whether or not to admit a real-time traffic stream based on its requirements and the upstream channel usage condition. As we mentioned earlier, the problem of QoS protection is significant because the bandwidth allocated by the OLT to one ONU can only be guaranteed for one cycle. Furthermore, appropriately controlling the admission of real time traffic will prevent malicious users from manipulating the upstream channel by sending traffic into or requesting bandwidth from the network more than their service level agreement (SLA). Accordingly, admission control helps in protecting the QoS of existing traffic and admit new flows only if their QoS requirements can be guaranteed.

In current EPON networks, the bandwidth of the upstream channel is shared among different ONUs using a time division multiple access (TDMA) scheme; the OLT allocates a transmission bandwidth for every ONU either equals to its bandwidth request from the previous cycle, or equals to the minimum bandwidth guaranteed (B_{min}), or equals to the minimum bandwidth guaranteed plus a surplus bandwidth that may remain unused in the cycle. Clearly, the bandwidth of one ONU cannot be guaranteed and may vary from one cycle to another according to the load at other ONUs.

Bandwidth reservation resolves the uncertainty in allocating enough bandwidth resulting from the load variations at different ONUs. Hence, each ONU is required to reserve bandwidth for its real time streams in order to satisfy their QoS requirements. Once this bandwidth is reserved, the OLT can no longer allocate it to other ONUs. Every ONU is guaranteed a new minimum bandwidth (B_{min}) and could be allocated up to a maximum bandwidth (B_{max}) in order to allow other ONUs to receive their share of the channel. Best effort (BE) traffic shares a fraction of the total cycle (T_{cycle}, $T_{cycle} \leq 2ms$ in EPON networks [29]), e.g., $\alpha \times T_{cycle}$ where $\alpha < 1$. When $\alpha = 0$, all the bandwidth of the upstream channel is used to transmit bandwidth guaranteed traffic.

The new cycle ($(1-\alpha) \times T_{cycle}$) is used to provide services for bandwidth guaranteed traffic. This new cycle in turn is divided into two sub-cycles (T_1, T_2); the OLT computes the minimum bandwidth guaranteed (B_{min}) for each ONU using T_1 ($B_{min} = \frac{(T_{cycle} - N \times T_g) \times \xi}{8 \times N}$, where ξ is the transmission speed of the PON in Mb/s, N is the number of ONUs and T_g is the guard time that separates the TW for every ONU_n and ONU_{n+1}) and the ONU has total control over this bandwidth, while the bandwidth of the second sub-cycle is under the control of the OLT (please refer to Fig. 3.8 for a graphical elaboration, with $N = 4$). This new system



Cycle after performing Bandwidth Allocation/Reservation & Admission Control

Figure 3.8: Proposed Cycle Framework

enables us to implement a two-step admission control (AC); the first is a local AC at the ONU and the second is a global AC at the OLT (as explained later). Note that, although the minimum guaranteed bandwidth is under the control of the ONU, the scheduling of various ONUs is still done centrally at the OLT in order to achieve a collision free access to the upstream channel. The two sub-cycles are selected of equal length; however, if $T_1 < T_2$, then the OLT will have more control over the bandwidth with less bandwidth guaranteed per ONU. Conversely, the ONU is guaranteed more bandwidth, which may be un-utilized if the load at a particular ONU is not high. Under our assumption of equal lengths for the sub-cycles, we set the maximum bandwidth that a highly loaded ONU can be allocated, $B_{max} = \delta \times B_{min}$. For example, when $\delta = 3$, a highly loaded ONU may or could be assigned a maximum of $2\times B_{min}$ from the second half cycle and hence a total of $3\times B_{min}$ per cycle. For real-time applications, QoS metrics can be predefined in a policy control unit (PCU)

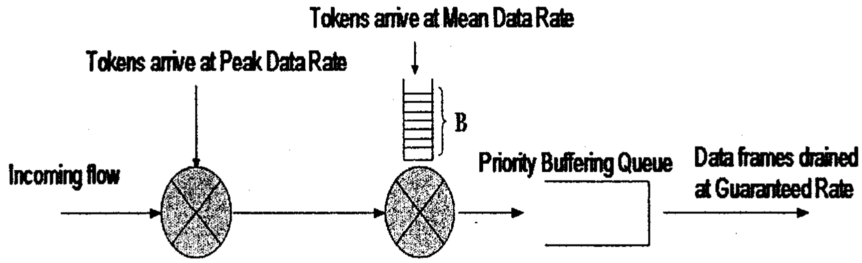


Figure 3.9: Dual Token Bucket Filter Framework

and various thresholds could be specified/defined. For example, if the expected drop rate or the delay requirement for a certain flow/application cannot be be respected, the flow should not be admitted. Admitting such a stream will not only experience a degraded level of service, but it will also degrade the QoS of existing streams. Alternatively, best-effort traffic is never rejected. and is always guaranteed a minimal bandwidth (B_{BE}^{min}). Hence, to achieve these goals, the following two rules should not be violated before and after admitting a new real-time flow:

1. The QoS of each real-time stream (existing or new) should be guaranteed.

2. The BE traffic throughput ($BE_{Throughput}$) $\geq B_{BE}^{min}$

In every cycle, the ONU reports (using the MPCP protocol) to the OLT the BE buffer occupancy for bandwidth allocation in the next cycle; for real-time streams that the ONU has already admitted, the OLT will schedule only their transmission since the bandwidth of each stream has already been pre-determined and reserved and it is guaranteed per cycle for the rest of the lifetime of each stream.

3.3.2 Traffic Characteristics and QoS Requirements

Clearly, an admission decision for a new flow arrival should be made according to both admission policies and QoS requirements supplied often by the application layer at the end users. The set of parameters that characterize the traffic stream vary from one traffic class to another. For example, CBR traffic is non bursty and characterized by its mean data rate (μ), which makes it quite predictable. With respect to QoS, CBR traffic requires stringent packet delays and delay variations (jitter). Alternatively, VBR traffic is quite bursty and may be characterized by the following parameters [23]:

- Mean Data Rate (μ) in bits per second (bps).
- Peak Arrival Data Rate (σ) in bits per second (bps).
- Maximum Burst Size (ρ) in bits.
- Delay Bound (θ) which is the maximum amount of time in units of microseconds allowed to transport a traffic stream (flow) measured between the arrival of the flow to the MAC layer and the start of transmission in the network.

Finally, BE traffic is bursty and requires neither delay requirements nor bandwidth guaranteed (note that network operators may set a certain minimum bandwidth that should be guaranteed for BE traffic; e.g., by appropriately adjusting the value of α).

When these parameters are specified by the end-user, the problem left for the admission control unit (ACU, which is either at the ONU or OLT) is simply to determine whether a new stream should be admitted and whether its QoS requirements can be guaranteed while the QoS requirements for already admitted streams can be protected. For CBR traffic, the admission decision is straight forward; if the mean data rate can be supported, then the stream is admitted. Hence, enough bandwidth per cycle should be reserved to guarantee the stream data rate. Here, the average delay of CBR traffic is guaranteed to be bounded by the length of cycle. For VBR traffic, the ACU may decide to admit a stream only if its peak rate can be supported (for the best QoS) or may admit the stream as long as the mean data rate is available [23]. The former approach ends up admitting few streams and the latter approach barely supports QoS for bursty streams. Therefore, a guaranteed bandwidth based on the traffic parameters could be derived and we use a dual-token bucket for traffic regulation; this dual-token bucket is situated at the entrance of the MAC buffer and is associated with each stream. Fig. 3.9 shows the dual token bucket where the bucket size is calculated:

$$B = \rho \times (1 - \mu/\sigma) \tag{7}$$

Accordingly, one can easily determine the arrival process of the stream passing through the filter [23]:

$$A(t, t+\tau) = \min(\sigma\tau, B + \mu\tau) \tag{8}$$

Where $A(t, t+\tau)$ is the cumulative number of arrivals during $(t, t+\tau)$. The arrival rate curve could be constructed from the above equation and is shown in Fig. 3.10. Therefore, the guaranteed rate for every real-time flow i can be easily derived from Fig. 3.10 using the distance formula [23]:

$$g_i = \frac{\rho_i}{\theta_i + \frac{\rho_i}{\sigma_i}} \tag{9}$$

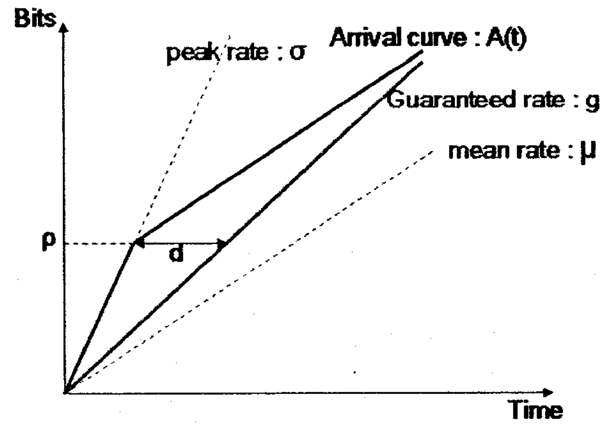


Figure 3.10: Guarantee Bandwidth Derivation Graph [23]

Since CBR traffic is deterministic and its peak rate is equivalent to its mean rate, therefore its bandwidth guaranteed will be:

$$g_i = \mu_i \tag{10}$$

Consequently, a conventional rate based admission control [24] can be used to determine whether a new stream can be admitted or not. For example, if S_j^{TW} is the bandwidth (bps) allocated and reserved for ONU j, then a new flow $i+1$ could be admitted if:

$$g_{i+1}^j + \sum_{i=1}^{h_j} g_i^j \leq S_j^{TW} \tag{11}$$

Where h_j is the number of real time streams (CBR or VBR) at ONU j. Now, the difficulty stems from the fact that in EPON the bandwidth assigned per ONU is not guaranteed, as mentioned earlier. Hence, we next propose a two step admission control scheme that will provide bandwidth guaranteed for each CoS stream.

3.3.3 Local Admission Control (LAC)

As we discussed earlier, each ONU is guaranteed a minimum bandwidth per cycle, B_{min}. Hence, the ONU can locally perform rate-based admission control according to the bandwidth requirement of the new arriving flow and the bandwidth availability. For example, if g_f^j is the guaranteed rate for the new flow, f, arriving at ONU j, then the bandwidth requirement (in bytes) per cycle for the new flow is: $R_f^j = g_f^j \times T_{cycle}$. Therefore, this new flow will be admitted according to the following condition:

$$R_f^j + \sum_{i=1}^{h_j} R_{f_i}^j \leq B_{min} \tag{12}$$

Where h_j is the total number of flows already admitted by the ONU; $R_{f_i}^j$ is the bandwidth requirement for a flow f_i, $R_{f_i}^j = g_{f_i}^j \times T_{cycle}$, and $g_{f_i}^j$ is the guaranteed rate (bps) for the flow computed according to either equation (9) or (10).

Fig. 3.11 shows the local admission control at the ONU. The scheme classifies the arriving flow into BE traffic or real-time traffic. If it is BE, then the traffic is admitted. Otherwise, the ONU will derive the guaranteed rate and check equation (12). If (12) holds, then the ONU will conditionally admit the flow and monitor its QoS for a predefined number of cycles (e.g., for 20 ms). If the QoS requirements of the newly admitted flow are satisfied and the QoS of existing flows remain intact, then the flow is admitted. Otherwise, the flow is dropped.

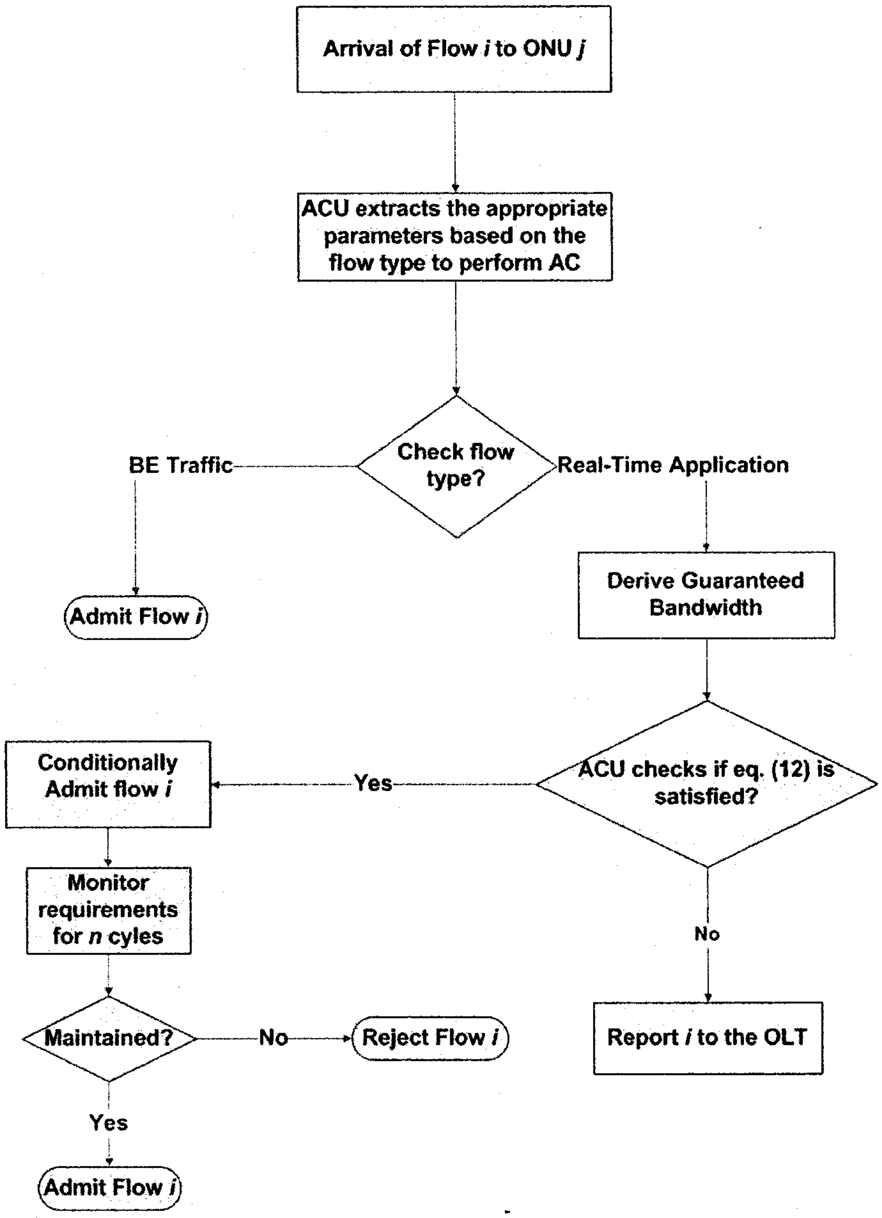


Figure 3.11: Local Admission Control

3.3.4 Global Admission Control (GAC)

When a flow f cannot be admitted locally at the ONU (due to bandwidth insufficiency), the ONU reports the arrival of a new flow to the OLT. The OLT may admit this new flow only if there is bandwidth available in the second sub-cycle (T_2) and if the ONU sending the request has not been allocated more than B_{max}. Hence, the OLT maintains a variable for every ONU designating the bandwidth allocated so far to this ONU, $B^j_{alloc} = \sum_{i=1}^{h_j} R^j_i$, where R^j_i denotes the bandwidth guaranteed for already admitted h_j flows for ONU j. The OLT maintains as well another variable that indicates the bandwidth that is still available, B_{avail}, (i.e., not committed yet) in T_2. The new flow may be admitted if the following two conditions (13a, 13b) hold simultaneously:

$$R^j_f + \sum_{i=1}^{h_j} R^j_i \leq B_{max} \tag{13a}$$

$$R^j_f \leq B_{avail} \tag{13b}$$

Upon admitting a new flow, the OLT will reserve additional bandwidth for ONU j and update accordingly the total available bandwidth: $B_{avail} = B_{avail} - R^j_f$.

Similarly, the OLT performs the above algorithm for every admission request of a new flow at any ONU. A flow will be rejected if at least one of the above two conditions is not satisfied. If both conditions are satisfied, then the OLT will conditionally admit the new flow and monitor its QoS parameters for the subsequent n cycles in order to determine whether it finally should admit the flow, as shown in Fig. 3.12. When a flow leaves the network, the ONU reports to the OLT and the latter will update the available bandwidth

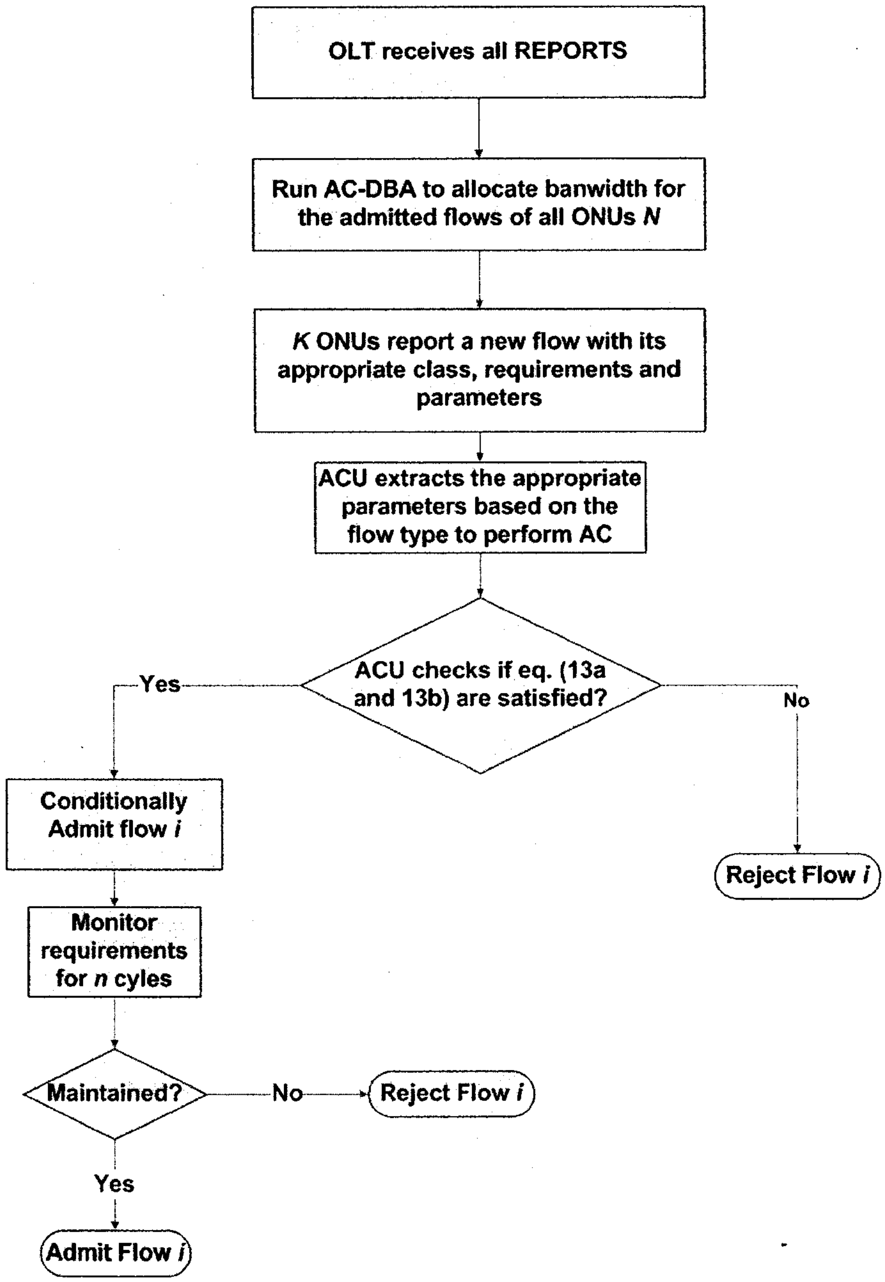


Figure 3.12: Global Admission Control

accordingly: $B_{avail} = B_{avail} + R_f^j$.

3.3.5 Issues and Solutions

In the proposed AC scheme, every real time stream is provided a guaranteed bandwidth that is computed based on the guaranteed rate of the flow and is reserved and fixed per cycle. The OLT then allocates a transmission window that encompasses all the guaranteed bandwidth for every ONU per cycle. A subtle issue which may arise is due to the statistical nature of real-time traffic and hence guaranteeing bandwidth per flow per cycle may ultimately waste the bandwidth. In other words, if one ONU is being reserved bandwidth for a particular flow per cycle and has no traffic from this flow to transmit, then this bandwidth is not utilized and wasted. This issue arises because the allocation became static (i.e., reservation) and not dynamic as in traditional EPON systems, where the bandwidth is allocated on demand. Moreover, if a flow had more bytes to be sent than the reserved ones (i.e., guaranteed), then our purpose on providing *bandwidth guaranteed* in every cycle will be unsuccessful. This is because estimating the bandwidth requirement for a flow based on its guaranteed rate does not accurately reflect the real nature of the traffic, especially with respect to the arrival of its packets in a short period of time (i.e., the short length of the cycle) and hence the inefficiency of the bandwidth prediction and reservation.

To resolve the above problems, we propose a two-branch solution. In the first branch, the OLT selects a super-cycle ($T_{sc} = \lambda \times T_{cycle}$, where λ is a constant) instead, and every admitted real-time flow is now guaranteed a bandwidth per T_{sc}. The purpose of this proposal is to mitigate the inefficiency of the bandwidth reservation caused by the short-time prediction, and thus a more accurate bandwidth estimation will take place. Here as before, the period $(1-\alpha) \times T_{sc}$ is divided into two periods, T_1 and T_2. Each ONU is now guaranteed a bandwidth of B^{new}_{min} which is computed based on T_1. The OLT controls the remaining bandwidth of the super-cycle. Upon the arrival of a new flow f at ONU j with bandwidth guaranteed B^f_g, the flow is either admitted/rejected locally at the ONU or globally by the OLT, as described earlier.

In the second branch, we ensure that the reservation does not waste any bandwidth. Here, we apply a *crediting system* where each flow's estimated bandwidth is saved as credits at the OLT. In other words, every time a flow is admitted, the OLT will be informed and it will compute/estimate a total credit (number of bytes available per T_{sc} for this flow) $C^j_{f_i} = B^{f_i}_g \times T^r_{sc}$, where T^r_{sc} is the period between the arrival of the flow and the end of the current super-cycle. The OLT maintains as well a total credit per type of traffic (C^j_{CBR} for CBR and C^j_{VBR} for VBR) per ONU; for example, $C^j_{CBR} = \sum_{i=1}^{N_j} C^j_{f_i}$ where N_j is the number of CBR flows at ONU j. Now, in every cycle, the OLT deducts the requested/allocated bandwidth of this flow from its reserved credits until the time of a new super-cycle. At this point, the credits are reset to the estimated ones. Next, we will explain how this solution will help in designing a DBA with effective reservation scheme.

3.3.6 Admission Control-enabled Dynamic Bandwidth Allocation Scheme (AC-DBA)

To apply the solutions proposed in the pervious Section, we propose a new hybrid DBA that will perform both bandwidth allocation and reservation at the same time. As any conventional DBA, the ONU reports to the OLT, in every cycle, its buffer occupancy ($Q_{CBR}(n-1)$, $Q_{VBR}(n-1)$, and $Q_{BE}(n-1)$, where n is the cycle number) and requests transmission bandwidth accordingly. However here, the OLT will allocate bandwidth to each CoS at each ONU according to its available credit in the current super-cycle, as well as based on the requests received from other ONUs. Let $A^j_{CBR}(n)$, $A^j_{VBR}(n)$, $A^j_{BE}(n)$ be the bandwidth allocated for ONU j; then we have:

$$\sum_{j=1}^{N}(A^j_{CBR}(n)+A^j_{VBR}(n)) \leq B_{cycle} - T^t_{gt} - (N \times B^{min}_{BE}) \tag{14}$$

$$\sum_{j=1}^{N} A^j_{BE}(n) \leq N \times B^{min}_{BE} \tag{15}$$

where B_{cycle} is the total bandwidth available in a T_{cycle} and T^t_{gt} is the total guard time (in bytes) between ONUs transmissions and B^{min}_{BE} is the minimum bandwidth guaranteed (in bytes) for Best Effort traffic computed as follows:

$$B^{min}_{BE} = \frac{T_{cycle} \times \frac{\alpha \times T_{sc}}{N}}{8 \times T_{sc}} \times \xi = \frac{T_{cycle} \times \alpha}{8 \times N} \times \xi \tag{16}$$

where ξ is the PON speed (1Gbps).

Every time the OLT allocates bandwidth to one ONU, it will adjust the available credit for every CoS accordingly: $C^j_{CBR}(n) = C^j_{CBR}(n-1) - A^j_{CBR}(n)$. The credit for VBR traffic is updated similarly. If the ONU has run out of credits, then the OLT does not allocate any bandwidth for this CoS at this ONU during this super cycle.

As for the computation of the available bandwidth for each CoS, the OLT waits until all requests $(R(Q^j_{CBR}(n-1) + Q^j_{VBR}(n-1) + Q^j_{BE}(n-1))$ are received from all ONUs. If $\sum_{j=1}^{N}(Q^j_{CBR}(n-1) + Q^j_{VBR}(n-1)) \le B_{cycle} - T^t_{gt} - N \times B^{min}_{BE}$, then $A^j_{CBR}(n) = min(Q^j_{CBR}(n-1), C^j_{CBR}(n-1))$; similarly for VBR traffic, $A^j_{VBR}(n) = min(Q^j_{VBR}(n-1), C^j_{VBR}(n-1))$ and their credits (for both CBR and VBR) are updated accordingly. Otherwise, the OLT will compute the total guaranteed bandwidth, B_j, for each ONU j as follows:

$$B_j(n-1) = \frac{R_j(n-1) \times (B_{cycle} - T^t_{gt} - (N \times B^{min}_{BE}))}{\sum_{j=1}^{N} Rj(n-1)} \tag{17}$$

where $R_j(n-1) = Q^j_{CBR}(n-1) + Q^j_{VBR}(n-1)$. Then the OLT allocates bandwidth as follows:

$$A^j_{CBR}(n) = min(Q^j_{CBR}(n-1), C^j_{CBR}(n-1)) \tag{18a}$$

$$A^j_{VBR}(n) = min(B_j(n-1) - Q^j_{CBR}(n-1), C^j_{VBR}(n-1)) \tag{18b}$$

Next, the OLT will allocate bandwidth to BE traffic based on the requests received from the ONUs. The total BE bandwidth per cycle is $B_{BE} = N \times B^{min}_{BE}$, which is shared by all ONUs. Note, however, if $\sum_{j=1}^{N}(A^j_{CBR}(n) + A^j_{VBR}(n)) \le B_{cycle} - T^t_{gt} - N \times B^{min}_{BE}$, then the total bandwidth available for BE traffic becomes:

$$B_{BE} = N \times B^{min}_{BE} + (B_{cycle} - T^t_{gt} - \sum_{j=1}^{N}(A^j_{CBR}(n) + A^j_{VBR}(n))) \tag{19}$$

If $Q^j_{BE}(n-1) \leq B^{min}_{BE}$, then $A^j_{BE}(n) = Q^j_{BE}(n-1)$. Otherwise, the OLT will allocate to the ONU requesting less than B^{min}_{BE} and will compute the excess bandwidth from these ONUs to distribute them to other ONUs requesting more BE traffic. Accordingly, if $Q^j_{BE}(n-1) > B^{min}_{BE}$, then $A^j_{BE}(n) = B^{min}_{BE} + \chi_j$, where χ_j is the excess bandwidth allocated for ONU j:

$$\chi_j = \frac{\alpha_j \times B^{rem}_{BE}(n)}{\alpha_t} \tag{20}$$

where $\alpha_j = Q^j_{BE}(n-1) - B^{min}_{BE}$, $\alpha_t = \sum_{j=1}^{N} \alpha_j$, and $B^{rem}_{BE}(n)$ is the remaining bandwidth in the cycle n after allocating all ONUs bandwidth for their BE traffic such that :

$$B^{rem}_{BE} = B_{BE} - (N-L) \times B^{min}_{BE} - \sum_{j=1}^{L} Q^j_{BE}(n-1) \tag{21}$$

Now, in order to prevent the waste of bandwidth and control the allocation of surplus to various ONUs, the excess bandwidth allocated for the BE traffic at a highly loaded ONU (χ_j) is computed as follows:

$$\chi_j = \min(\chi_j, \alpha_j) \tag{22}$$

3.4 Performance Evaluation

In this Section we will study the performance of both the proposed intra-ONU scheduler (M-DWRR) and admission control schemes for their QoS support and protection via simulations. Here, the performance is measured with respect to maintaining satisfiable QoS

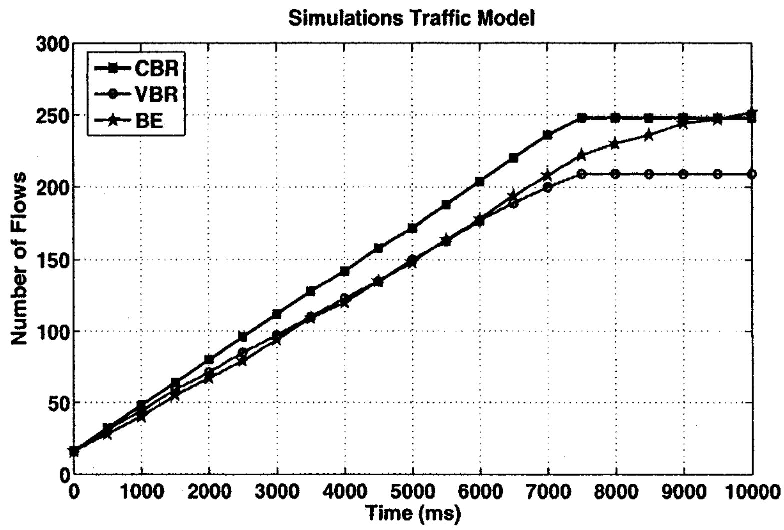
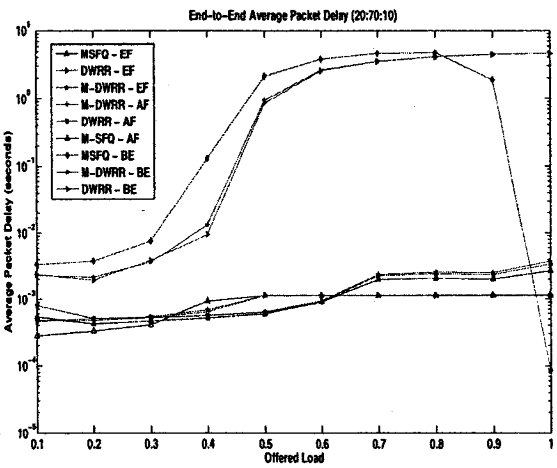


Figure 3.13: Traffic Model Used for the AC framework

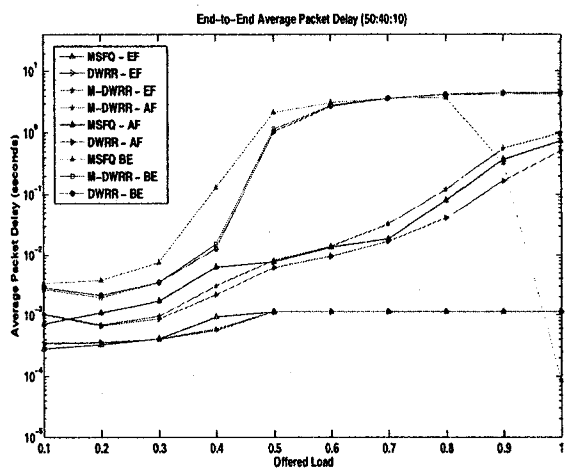
requirements for real-time streams while guaranteeing minimum required service for best effort traffic. An event-driven packet-based simulator using C++ is developed for performing the various simulations and collecting the measurements. The total number of ONUs $N = 16$, and the PON speed = $1Gbps$. The guard time between different transmission windows is equal to $1\mu s$, the cycle time $T_{cycle} = 2ms$ and the ONU buffering queue size to $10Mbytes$.

In our study, we consider two simulation models. The first model is used to evaluate the performance of M-DWRR and compare its performance with M-SFQ intra-ONU scheduling. An extensive study shows that most network traffic (i.e., http, ftp, variable bit rate (VBR) video applications, etc.) can be characterized by self-similarity and long-range dependence (LRD) [53]. Hence, our traffic model is used to generate highly bursty BE and Assured Forwarding (AF) traffic classes, and packet sizes are uniformly distributed between 64 and 1518 bytes. On the other hand, high-priority (Constant Bit Rate CBR) traffic (e.g., voice applications), is modeled using a Poisson distribution and packet size is fixed to 70 bytes. The traffic profile of the first model is as follows: the high priority traffic load is fixed at 4.48 Mbps, and the remaining load is equally distributed among low- and medium-priority traffic.

For the second simulation model, we consider a more realistic traffic profile where real-time bandwidth guaranteed streams (CBR and VBR) and BE traffic arrive dynamically at the ONUs that are randomly selected for hosting these flows. This scenario is appropriate to study the performance of the AC scheme presented. To apply AC rule (1) described in Section IV, each CBR flow is generated at a mean rate of 64 Kbps with a delay bound $\theta_{CBR} = 2 \sim 4\ ms$ as QoS requirement [62], each VBR flow at a *guaranteed rate* (based on eq. (9)) of 4 Mbps with a delay bound $\theta_{VBR} = 25 \sim 30\ ms$ as QoS requirement [62], and each BE flow at a mean rate of 5 Mbps. Here, the load increases incrementally as more flows are admitted in the network. Fig. 3.13 depicts the chronological arrival of flows sorted by class of service, and injected in the network. As shown, we stop generating real-time flows (i.e., CBR and VBR) at time 7500 ms, whereas BE flows continue to arrive until the end of the simulation. As for AC rule (2), we choose $B_{BE}^{min} = 4100$ bytes (in each cycle); which means that each ONU is guaranteed a BE throughput of 15 Mbps (i.e., $BE_{throughput} >\simeq 20Mbps$, if available) if $T_{cycle} = 2\ ms$ or more if $T_{cycle} < 2\ ms$. Consequently, 16 ONUs will equally share a maximum of 20~24 % of PON's available bandwidth. Finally, for the setting of T_{sc}, we found that the smaller T_{sc} is chosen, the less accuracy is achieved when predicting the *credits* saved for the VBR traffic; and the larger it is chosen, the less up-to-date flows requirements information will be available at the OLT. Thus, T_{sc} should be chosen such that a balance, between an accurate crediting system and



(a) $\alpha_1 = 20\ \%, \alpha_2 = 70\ \%$ and $\alpha_3 = 10\ \%$



(b) $\alpha_1 = 50\ \%, \alpha_2 = 40\ \%$ and $\alpha_3 = 10\ \%$

Figure 3.14: Comparison of Average Packet Delay

an up-to-date information at the OLT, is achieved. For that reason, after many experiments we found that by setting T_{sc} = 500 ms, we can more or less achieve the described balance. The metrics of comparisons are: average packet delays for CBR and VBR real time streams, the CBR, VBR and BE flows throughput, the flow rejection rate, and the total system utilization. Note that, in our work, we do not consider the flow QoS monitoring described earlier.

3.4.1 M-DWRR Performance

To evaluate the performance of M-DWRR, we use the first simulation model described earlier. Here, we consider two sets for weight assignment for priority queues: Set 1 : ($\alpha_1 = 20\%$, $\alpha_2 = 70\%$ and $\alpha_3 = 10\%$) and Set 2 : ($\alpha_1 = 50\%$, $\alpha_2 = 40\%$ and $\alpha_3 = 10\%$). Our objective is to show how the selection of the weights can affect the overall network performance. Moreover, this selection will show that our proposed scheme can adaptively ensure fairness among all traffic classes even if the weights selection was not fair to lower priority queues.

Fig. 3.14 compares the average packet delay of EF, AF, and BE services for M-SFQ and both our proposed DWRR and M-DWRR scheduling schemes under both sets of weights. Note that the traffic load of a high loaded ONU is varied between 0.1 and 1 (i.e., 10Mbps and 100Mbps).

As shown, all schemes behaved similarly under light and heavy loads for EF traffic. On the other hand, the impact of the weight selection appears on both AF and BE traffic behaviors. Here, DWRR and M-DWRR schemes exhibit better results under set 2 (best suiting the AF traffic) than M-SFQ, given that M-SFQ is designed to satisfy the high and medium priority (HP and MP) traffic and especially VBR traffic; (e.g., $\approx$ 90 ms difference at load 0.8). Meanwhile, our schemes demonstrate better performance for BE traffic. For example in Fig. 3.14(a), at load 0.8, BE traffic, in both DWRR and M-DWRR, shows better performance of almost 75% improvement (i.e., 1 s and 4 s) over M-SFQ where a dramatic delay degradation starts, because almost all BE packets are dropped. Moreover, as discussed, the weight selection does affect the delay performance for both DWRR and M-DWRR. Accordingly, with Set 1, the behavior of all traffic classes in all schemes (in terms of delay) is similar, while with Set 2, the performance varies. This shows the advantage of our schemes, that is the capability of assigning weights in a way to poise the performance of each traffic aside. At the same time, by enforcing the weight policy, our schedulers make sure to provide each PQ a share of the assigned bandwidth. In this way, fairness is ensured among different classes of traffic, and the traffic priority (delay sensitivity) is respected. For further comparisons, we measured the packet loss rate for a new set of weights where

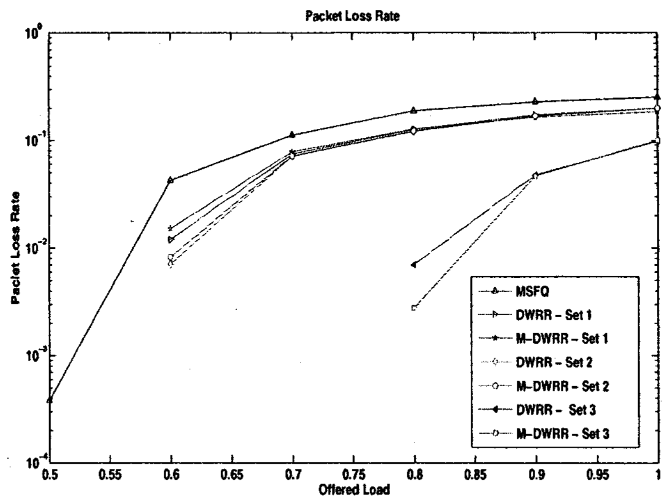


Figure 3.15: Packet Loss Rate

$\alpha_1 = 20\ \%, \alpha_2 = 40\ \%$ and $\alpha_3 = 40\ \%$ (Fig. 3.15). Here, regardless of the weight combination, DWRR and M-DWRR improve the buffer occupancy of all PQs, and thus significantly reduce the packet drop rate (e.g., 50% better than M-SFQ at load 0.8). On the other hand, the packet loss rate in M-DWRR with Set 3 is $\approx$ 80% improved over M-SFQ and DWRR. These noticeable results are achieved because the weight profile selection meets the preselected traffic profile. This minimized packet loss rate eventually maximizes the overall network throughput. Fig. 3.16 shows that DWRR and M-DWRR schedulers offer the same level of throughput as the M-SFQ scheduler if the offered load is less than 0.4. However, for higher load, Fig. 3.16 shows that the proposed schedulers offers 70.5% throughput, compared with 60% in M-SFQ. Thus our schemes not only ensures fairness but also improves the network throughput. This is achieved by eliminating the BE traffic starvation status.

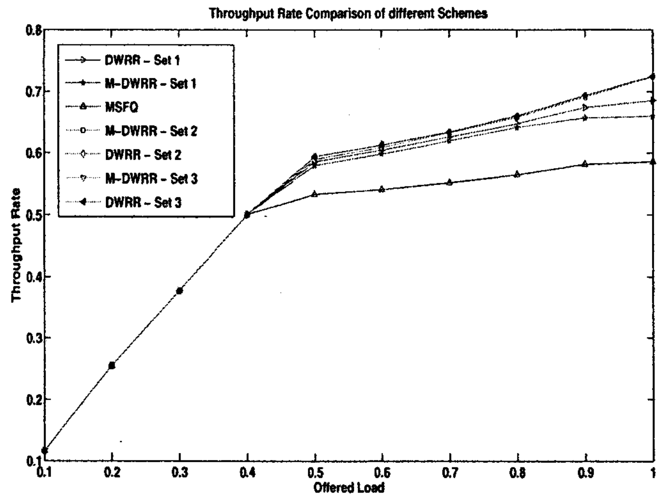


Figure 3.16: Comparison of Network Throughput

3.4.2 Performance of AC

The evaluation of the AC framework is based on the second simulation model that is, to the best of our knowledge, the first EPON simulation model that truly models the real Internet traffic (that arrives to the ONUs as flows or streams); and that enables the support of AC in EPON.

We begin by testing the behavior of our admission control by showing in Fig. 3.17 the number of admitted real-time traffic streams. As shown, our system reaches saturation (i.e., no more real-time flows can be admitted in the network) at time 7000 ms. As we continue generating real-time flows until 7500 ms, all the real-time flows arriving afterwards are rejected. However, this does not mean that no flows were rejected earlier since conditions (12) or (13a) and (13b) need to be respected to admit a new arriving real-time flow otherwise a flow is rejected. The figure shows that starting 450 ms as they arrive are rejected.

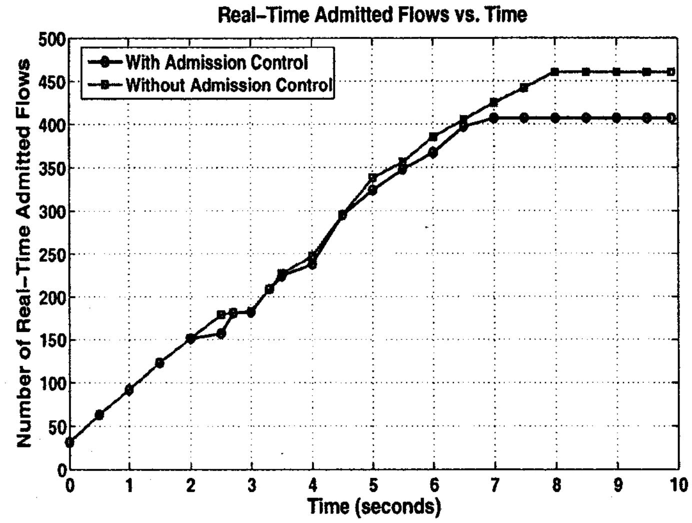


Figure 3.17: Admission Control Behavior

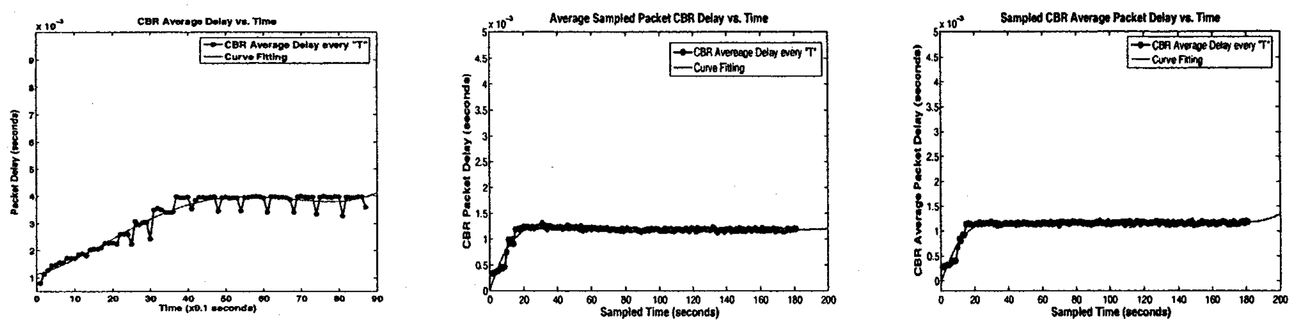
Next, we study the performance of real-time traffic by measuring the instantaneous average packet delays. To reduce the measurements complexity, we choose the sampling period $T = T_{sc} = 500$ ms. Figs. 3.18 and 3.19 show these measurements, with admission control (i.e., AC-DBA) and without admission control (using M-DWRR (set 1) and Strict Priority (SP) schedulers). Clearly, using M-DWRR and SP schedulers, CBR traffic shows the optimal performance where its average packet delay remains under 2 ms even when the load continuously increases (i.e., as the simulation time continues to increase). This shows the advantage of M-DWRR; that is, although it divides the cycle among the CoS queues based on their assigned weights, it also provides an optimal performance for CBR traffic. This is due to the fact that the assigned weights are adaptively set based on the QoS requirements. On the other hand, using the Strict Priority scheduler that always selects packets from higher priority queue until satisfied (i.e., until it is empty), CBR traffic will accordingly exhibit the best performance. As for AC-DBA, it makes sure to satisfy the QoS requirements defined previously (in terms of delay and throughput) by *crediting* every real-time traffic the appropriate bandwidth and reserving it in every super-cycle/cycle, since a CBR flow is admitted only if its guaranteed bandwidth is assured in every cycle. Hence, AC-DBA maintains a CBR average packet delay of 2$\sim$4 ms with a noticeable slight decrease pattern that repeats every super-cycle. This is due to the fact that the credits assigned in one super-cycle n were consumed just before the "credit refilling" for super-cycle $n+1$, which is due to the statistical multiplexing nature of CBR traffic; and thus, the delay decreases after the latter operation.

As for the VBR traffic, as shown in Fig. 3.19, AC-DBA maintains its delay performance to meet the specified QoS requirements of the stream (i.e., 25$\sim$30 ms) while the delay witnesses an exponential increase under both adopted schedulers (Figs. 3.19(b) and 3.19(c)), i.e., a system that does not deploy any admission control. This behavior highlights the need for the application of admission control in EPON, because when the system reaches saturation (as described earlier) and all the arriving streams are admitted, the performance is no more maintained; more specifically, no bandwidth is guaranteed for all types of traffic and the QoS requirements are no longer met (not only for new application but for existing applications as well). On the other hand, the deployment of AC in EPON allows for a bandwidth guaranteed service with guaranteed protected QoS.

We further investigate our AC framework by measuring/monitoring the throughput of one flow from each CoS (i.e., CBR, VBR) with AC (i.e., AC-DBA) and with no AC (i.e. M-DWRR and SP) in Fig. 3.20. As shown and expected, the selected CBR flow exhibits the same performance with and without AC, while the selected VBR flow shows a different behavior. Here, the VBR flow with AC, maintains its derived 4 Mbps throughput through out the simulation, even after the system reaches saturation. On the other hand, when no AC is applied, the VBR flow does not show a stable throughput behavior. Moreover, when the system reaches saturation, the throughput of the VBR flow starts decreasing. This is due to the fact that when more real-time flows are admitted and no AC is applied, the bandwidth that was guaranteed for the already admitted flows (before saturation) is now shared by more flows. Hence, the *guaranteed bandwidth* is no longer guaranteed for the already admitted flows and for the newly admitted ones. This again shows the need for admission control in EPON to stabilize and guarantee the throughput for all admitted flows and reject the flows that will break this theme. This, in real and practical settings, will deny all malicious users from monopolizing the bandwidth provided; and at the same time, it will allow for *bandwidth protection* to the bandwidth assigned for other well-behaved users.

As for the BE traffic, our concern is to guarantee a minimum total throughput that meets rule (2) in the AC scheme. For that reason, we measure its total throughput rather than the per-flow throughput as we did for CBR and VBR traffic. Here, the BE throughput increases to reach a total of ≈ 400 Mbps under all schemes (i.e., with AC and with no AC) when the load is low and decreases when more flows are admitted into the network. However, when the system reaches saturation, AC-DBA makes sure to preserve the minimum pre-defined throughput; while with M-DWRR and Strict Priority schedulers, the throughput is not guaranteed and hence the pre-defined throughput is no longer respected. Nevertheless, M-DWRR still provides a minimum throughput (which is one of the advantages of M-DWRR) by forcing the weight policy, while it reaches a very low one ($\approx 0\ Mbps$) with SP; a phenomenon known as BE traffic starvation.

Finally, Table 3.1 shows some interesting statistics collected from our simulations. These

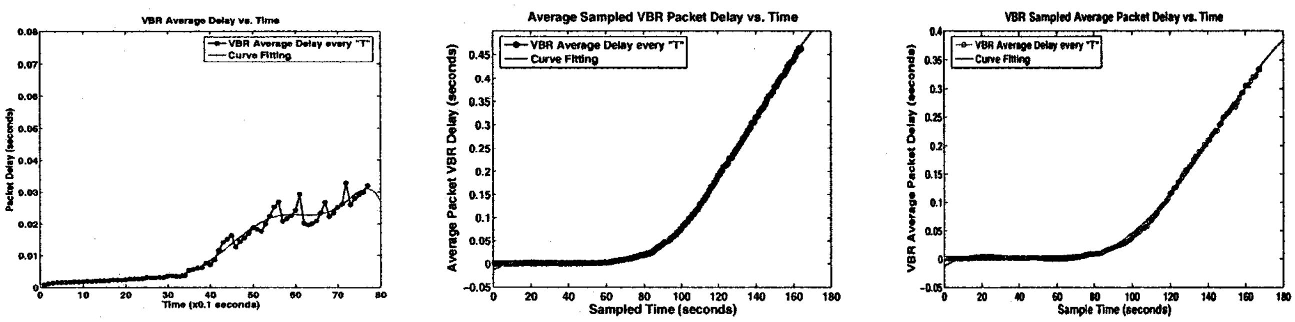


(a) AC-DBA

(b) NO-AC using M-DWRR

(c) NO-AC using Strict Priority

Figure 3.18: CBR Packet Delay



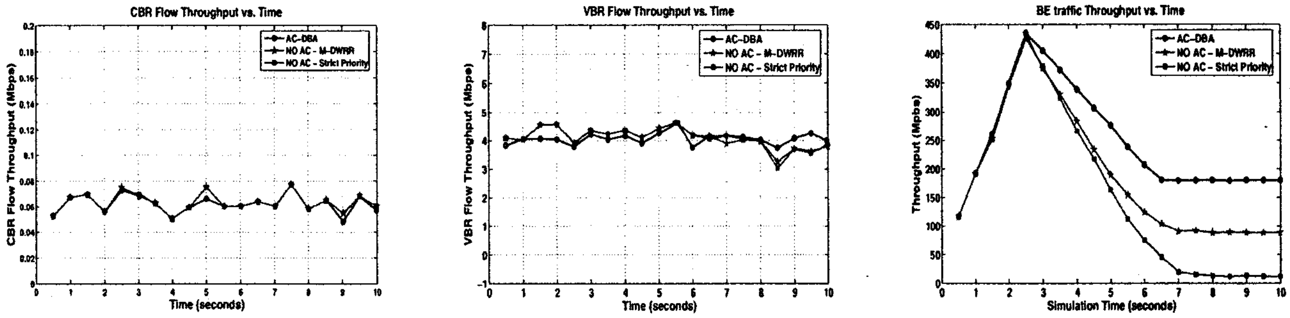
(a) AC-DBA

(b) NO-AC using M-DWRR

(c) NO-AC using Strict Priority

Figure 3.19: VBR Packet Delay

results show that $\approx 92\%$ of the generated CBR traffic are admitted into the network while their overall QoS and bandwidth requirements are guaranteed; $\approx 83\%$ of VBR flows are admitted as well and finally all BE arriving are admitted. Note that under M-DWRR and SP scheduling, all traffic is admitted; however their QoS requirements are not guaranteed (except for CBR traffic). Note also that these collected results are traffic-model dependent. In other words, more flows can be admitted or rejected depending on all of the required guaranteed throughput for real-time traffic and for BE traffic, the generated flows mean rates, and the number of flows generated. Hence, various scenarios can be applied for future studies.



(a) CBR Flow Throughput (b) VBR Flow Throughput (c) BE Total Throughput

Figure 3.20: CoS Traffic Throughput

Table 3.1: Traffic Control Stats

Number of Generated CBR Flows	252
Number of Admitted CBR Flows	234
Number of Rejected CBR Flows	18
CBR Admission Rate	$\approx 92\%$
Number of Generated VBR Flows	209
Number of Admitted VBR Flows	173
Number of Rejected VBR Flows	36
VBR Admission Rate	$\approx 83\%$
Number of Generated BE Flows	247
Number of Admitted BE Flows	247
Number of Rejected BE Flows	0
BE Admission Rate	100%

3.5 Summary

Providing bandwidth guaranteed service in EPON is a challenging subject that has not been addressed in the literature. In this chapter, we have presented a novel decentralized bandwidth intra-ONU scheduler, based on DWRR scheduling scheme. The scheme features low implementation complexity, hardware implementation ability, fairness assurance and possible inter-operation with any inter-ONU (DBA) scheme. Moreover, the adaptive weight policy allows a unique ONU-gripping to QoS traffic. We have also presented the first complete EPON framework that supports the application of admission control (AC) in EPON. This framework implements a two-stage admission control (i.e., at the ONU and at the OLT) with all its rules and functionalities, along with a new hybrid AC-enabled DBA that performs both bandwidth allocation and reservation simultaneously. We have also presented a new simulation model that is designed to test this framework. Extensive simulation results show the effectiveness of our proposed intra-ONU scheduler and its influence on the QoS performance. We showed that although some of the scheduling mechanism can provide QoS for various types of traffic in the network, none of these schedulers could protect these QoS requirements. Our AC system has shown a good performance in terms of maintaining the QoS level for already existing traffic while providing an overall acceptable minimal throughput for BE traffic even under network saturation.

Chapter 4

EPON Upgrade : TDM/WDM Passive Optical Network

4.1 Introduction

The increased demand for more bandwidth and bandwidth services [9] in the access network has been growing rapidly over the past several year [27] and there have been great efforts to develop economical subscriber networks based on optical technology [26, 28, 29, 32–34]. Passive Optical Networks (PONs) are viewed by many as an attractive and promising solution for the broadband access network bottleneck. Ethernet Passive Optical Networks (EPONs), which represent the convergence of inexpensive and ubiquitous Ethernet equipment and low-cost fiber infrastructure, appear to be a natural candidate and this technology has been under intense research activities recently [29, 36].

Given the steadily increasing number of users and emerging bandwidth intensive applications, current single channel TDM EPONs are likely to be upgraded in order to satisfy the growing traffic demands in the future. We performed a simulation study on the existing TDM EPON architecture to examine its scalability as more ONUs are connected to the network. We varied the number of ONUs ($16 \leq N \leq 64$) and as shown in Fig. 4.21, when more users are connected, the load on the single EPON channel becomes excessive and therefore there will be a considerable increase in the packet drop rates and the overall average packet delays. One approach for upgrading EPON systems is to increase the current line rate from 1Gbps to 10Gbps [26,35]. However, this implies that all EPON nodes need to be upgraded by installing new higher speed transceivers, resulting in a rather costly upgrade. Alternatively, another approach is to deploy multiple wavelengths in the upstream/downstream directions of the installed fiber, resulting in a WDM-based topology. WDM provide a cautious upgrade wherein wavelengths can be added as needed and one at a time. Further, only EPON nodes with higher traffic may be WDM upgraded by either deploying fixed-tuned and/or tunable transceivers [35].

We introduce a WDM-PON architecture and we present a possible incremental migration from TDM-PON to TDM/WDM-PON. We also present new bandwidth allocation schemes for the hybrid WDM/TDM PON and we show their differences. These schemes enable different ONUs to efficiently share (both in time and wavelength space) the access network bandwidth based on their traffic load to achieve better utilization. Furthermore, we enable our WDM-PON to deliver differentiated services (quality of service) to the end-users by providing an integration of our proposed DBAs with an intra-ONU scheduler proposed [50]. The rest of the chapter is organized as follows. In section 4.2, we overview the related literature. Section 4.3 presents the proposed WDM-PON architecture with the upgrade of MAC protocol, and MPCP control messages and in section 4.4 we present our

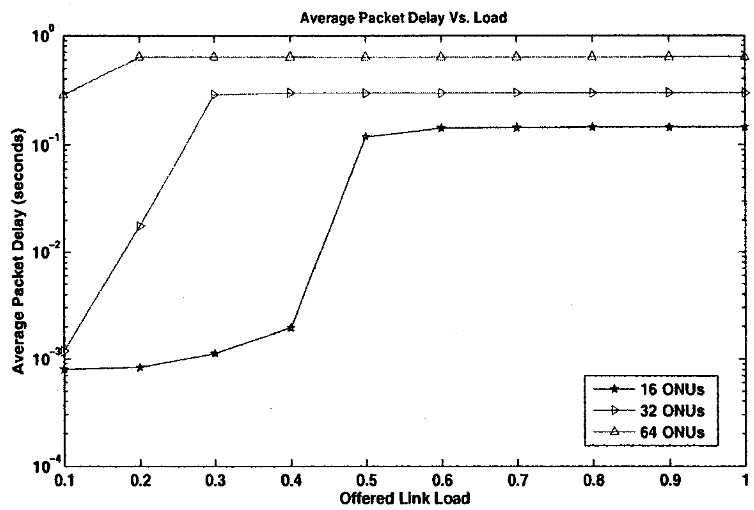


Figure 4.21: Average Packet Delay in E-PON

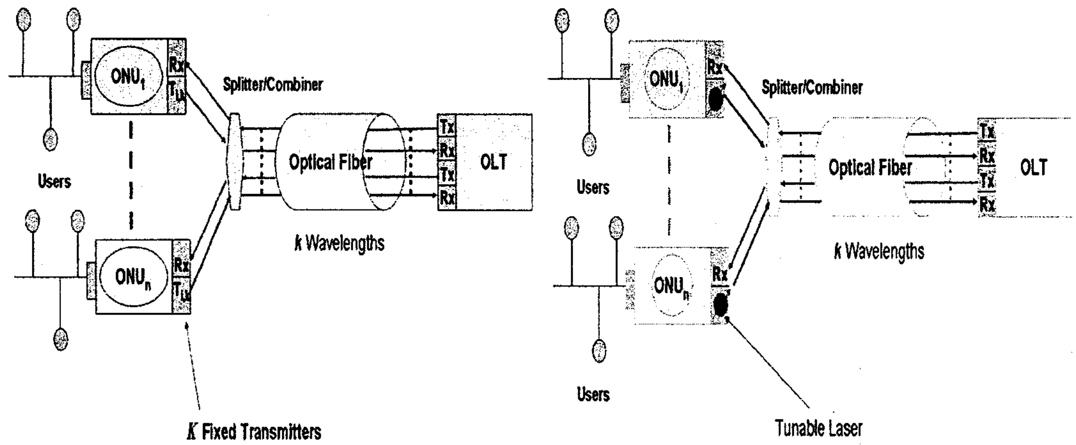
bandwidth allocation schemes. Section 4.5 presents a comparison between the proposed schemes and in section 4.6 we present a dynamic bandwidth allocation with QoS support in the hybrid WDM/TDM PON. In section 4.7, we present our simulation results and we study the performance of these schemes along with their advantages and disadvantages, and finally section 4.8 concludes our work.

4.2 Related Work

Various early work has considered the deployment of WDM technology in the access network and some WDM-PON architectures have been proposed; namely, the composite PON based on the AWG concept and which uses WDM in the downstream and one channel in the upstream [38], the local access router network [39], the remote integration of terminal network [40], the multistage AWG-Based WDM-PON [41], and more recently the WDM-Super PON [42,43].

One straight forward approach to build a "high performance" WDM-PON is to employ a separate wavelength channel from the OLT to each ONU, for each of the upstream and downstream directions [44]. This approach effectively creates a point to point link between the CO (central office) and each ONU; this architecture results however in a poor resource utilization and high deployment cost. Alternatively, the authors of [32], [33] proposed a new hybrid architecture (referred to as SUCCESS) which provides a practical migration from current TDM PONs to future WDM access networks while maintaining backward compatibility for users on existing TDM PONs. The SUCCESS architecture is based on a collector ring and several distribution stars connecting the central office (CO) and the users. Each star is defined as either a TDM-PON or WDM-PON (where each ONU is assigned one wavelength channel for both upstream and downstream transmission) depending on the bandwidth need and the incoming traffic load. The authors proposed a particular WDM-PON MAC protocol for this architecture but however did not present any WDM-DBA algorithms. Further, the architecture does not allow for any inter-channel statistical multiplexing to better harness the available bandwidth on different PONs. More recently, the authors of [34] proposed a SUCCESS-DWA PON that employs dynamic wavelength allocation (DWA) to further provide bandwidth sharing across multiple physical PONs and hence achieve both cost effective and high performance architecture. Under SUCCESS-DWA PON, existing field deployed PON infrastructures remain intact making the architecture an ideal candidate for upgrading existing PONs. The authors presented the upstream and downstream system upgrade; tunable lasers,arrayed waveguide grating, and coarse/fine filtering are combined to create a flexible access in the downstream. Alternatively, several distributed and centralized access schemes are proposed for the upstream upgrade. The authors of [28] have similarly proposed a new WDM-PON in which each upstream wavelength channel can be shared among multiple ONUs by means of TDM. Here, the ONUs can use their *wavelength-selection-free* (i.e., without wavelength tuning) transmitters to operate on any wavelength. No WDM-DBAs algorithms were discussed, however.

With respect to bandwidth and resource management, access control and quality of service (QoS) support in WDM-PON, some work only recently started to appear and remains very limited. The authors of [35] have presented extensions to the MPCP protocol for WDM-PON, where wavelength channels in addition to time windows can be assigned; they presented both online and offline scheduling. Additionally, they discussed an evolutionary architecture for WDM-PON where the OLT maintains an array of fixed-tuned transceivers and one or more tunable transceivers at the ONU allowing for incremental upgrade depending on the traffic demand. The authors of [45] proposed WDM IPACT-ST scheme based on the interleaved polling with adaptive cycle time (IPACT) proposed for EPON access network [47]. Here, IPACT protocol was adopted and applied on a multi-channel WDM-PON, where the ONUs are equipped with fixed transceivers. Furthermore, they applied strict priority scheduling to support quality of service in WDM-PON. A byte size clock (BSC) protocol with QoS support that allocates wavelengths on a user-basis rather than ONU-basis is proposed in [46]. The approach is scalable in terms of bandwidth assignment and achieves reduction in packet delays; however, in BSC all nodes need to be synchronized and as result the TDM frame does not comply with IEEE 802.3ah. For a comprehensive overview of WDM-PON technologies, including devices, architectures and protocols that have been so far proposed, we refer the reader to [26].



(a) A1 (Fixed Transceivers) (b) A2 (Tunable Lasers)

Figure 4.22: WDM-PON Architectures

4.3 WDM-PON Architecture

The protocols and algorithms for WDM-PON are currently at their initial stage of study because of their strong dependance on the network architecture to be deployed; while various types of architectures have been proposed, as we discussed in the previous section, no specific one is dominant [26] yet. Because we emphasize on the performance study of various DBAs for WDM-PON, we assume two different architectures for our study. The first architecture (scheme A_1) is shown in Fig. 4.22(a) and assumes a fixed grouping of ONUs (as in scheme A in [34]). Here, the ONUs are divided into multiple subsets each allocated a fixed wavelength channel for upstream transmission. Hence, every ONU maintains a fixed transceiver, whereas the OLT maintains a bank of fixed transceivers. Within each subset, the transmission of different ONUs is arbitrated by the OLT through either a fixed or dynamic time division slot assignment scheme. Clearly, this architecture limits the shareability of different wavelengths among ONUs since a single wavelength is statically allocated to each subset of ONUs and hence no inter-channel statistical multiplexing.

This, therefore limits the overall utilization of the WDM-PON available resources. This architecture can be viewed as a straightforward upgrade from conventional TDM-PON and provides a baseline for comparison with the proposed WDM-DBAs. Fig. 4.22(b) shows the second architecture (scheme A_2) which is more flexible and allows for simultaneous time-sharing and wavelength-sharing of WDM-PON resources among all ONUs. This architecture is similar to scheme C presented in [34]. For upstream scheduling, every ONU can be equipped with one or more fixed transmitters, allowing for an incremental upgrade depending on the traffic demand at the ONU. In this case, the ONU will inform, during the registration process, the OLT of the wavelength(s) it can support for appropriate resource allocation and management. The OLT upon receiving bandwidth requests from the ONUs, it will allocate transmission windows for the various ONUs taking into account the wavelengths they support. Alternatively, the ONU could optionally maintain a fast tunable laser to allow for more flexibility. To develop our dynamic wavelength and bandwidth allocation (DWBA) algorithms, we assume in this work the latter approach; we assume a tuning speed in the range of microseconds, which is conservatively small enough to moderate the transmission on multiple channels and a tuning range of more than $60nm$ [32]to cover a large number of wavelength channels. This architecture enables the ONU to tune its upstream transmission from one wavelength to another at different times depending on the DWBA algorithm deployed at the OLT. Hence, here the WDM-PON resources act as a pool and all ONUs share these resources. This resource sharing is arbitrated by the OLT using DWBA. This architecture seems to be more favorable than the previous (scheme A_1), since it increases the efficiency of the network in terms of bandwidth utilization and packet delays. Nevertheless, such architecture makes the implementation of the DWBA more challenging and requires an upgrade in the MAC as well. In our architecture, we upgrade the MAC to support both time and wavelength assignment where each ONU will be allocated both a transmission window and a wavelength for data transmission to the OLT. The OLT may have a bank of fixed transceivers to be able to simultaneously receive data from the various ONUs on different wavelengths and transmit data and control messages to the ONUs.

4.4 WDM/TDM Dynamic Bandwidth Allocation

To develop our dynamic wavelength and bandwidth allocation algorithms, we assume MPCP extensions for WDM-PON as proposed in [35]. The MPCP GATE message proposed in the standard [37] is modified by adding an additional field (one byte) indicating the channel number assigned by the OLT to the ONU. Thus the OLT will provide each ONU with its appropriate transmission start time T_{start}, transmission length T_{length} and corresponding wavelength channel identifier to enable transmission in the upstream direction. We present two different WDM-DBA schemes (MAC protocols) for wavelength and bandwidth allocation in this hybrid WDM/TDM PON.

4.4.1 Static Wavelength Dynamic Time (SWDT):

This simple scheme relies on the simple architecture A_1; the OLT allocates wavelengths statically and time slots dynamically depending on the bandwidth request of each ONU. Here, the ONUs will be divided into as many classes as the number of wavelengths, and each class of ONUs will share a predefined wavelength. Since the number of ONUs on each wavelength is identified, SWDT is run on each channel separately (the OLT waits until all reports from one subset is received and runs the SWDT allocation algorithm). This scheme is easy to implement; however it under-utilizes the available bandwidth of the offered resources since it does not exploit the inter-channel statistical multiplexing. We refer to this scheme as the worst case (i.e., SWDT-WC) scheme. Alternatively, and to provide a fair comparison, a best case (SWDT-BC) may be obtained when the set of all ONUs are evenly distributed with respect to their loads on the available channels. That is, each wavelength channel will equally have both highly loaded and lightly loaded ONUs (i.e., almost the same load on every channel). Note that the SWDT-BC normally should achieve better performance than SWDT-WC; however, in a real deployment of an access network, the traffic is more dynamic and random [27] and it would not be feasible to pre-classify ONUs as highly and lightly loaded ONUs; accordingly, this best case scheme is only an artificial scheme that is presented here for our comparison in section 4.5. This shows that SWDT schemes cannot fully exploit the available bandwidth resources on the various channels and hence more dynamic schemes are required.

4.4.2 Dynamic Wavelength Dynamic Time (DWDT):

Unlike the previous approach where the channel is predetermined and fixed for every ONU and the OLT arbitrates only the transmission of ONUs on the same fixed channel, the second approach relies on the second architecture A_2 and enables the dynamic allocation of bandwidth for different ONUs in both wavelength and time domains. DWDT reliefs the network manager from performing the "ONU-classification" required when using SWDT, by allowing the set of ONUs N to share all the available wavelengths simultaneously.

Here, the OLT maintains a variable for every channel that designates the time T^k_{free} for wavelength k when the next transmission is possible on that particular channel. For every REPORT message received from any ONU, the OLT allocates a channel with the least T^k_{free} to this ONU and further it also determines the length (e.g., in bytes) of the transmission window allocated to this ONU on the assigned channel. We refer to this procedure as dynamic wavelength and bandwidth allocation (DWBA) and we present three variants namely DWBA-1, DWBA-2 and DWBA-3. In these variants, the minimum bandwidth guaranteed B_{MIN} defined in [36], is dependant on the weight assigned to each ONU based on the Service Level Agreement (SLA) between the service provider (SP) and users. We consider a PON access network with N ONUs. The transmission speed of the PON is R_N Mb/s (same for both upstream link and downstream link). We denote T_{cycle} as the granting cycle which is the time during which all ONUs can transmit data or/and send REPORT messages to the OLT. We also denote T_g as the guard time that separates the transmission window for every ONU_n and ONU_{n+1} and w_i as the weight assigned to each ONU based on its SLA such that $\sum_{i=1}^{N} w_i = 1$.

$$B_i^{MIN} = \frac{(T_{cycle} - N \times T_g) \times R_N \times w_i}{8} \tag{23}$$

In case of no SLA classification per ONU, $w_i = w = 1/N, \forall i$ and $\sum_{i=1}^{N} w_i = 1$ then :

$$B_i^{MIN} = B_{MIN} = \frac{(T_{cycle} - N \times T_g) \times R_N}{8 \times N} \tag{24}$$

The three variants are now introduced:

DWBA-1

The OLT waits until all the REPORTs are received from all ONUs (on all channels). Upon that, the OLT runs a bandwidth allocation algorithm to determine the bandwidth and channel for every ONU. Here, if $B^i_{req} \leq B_{MIN}$ where B^i_{req} is the requested bandwidth by ONU_i and B_{MIN} is the minimum bandwidth guaranteed [29,36], then $B^i_{assign} = B^i_{req}$ and a GATE message is sent to ONU_i. Alternatively, if $B^i_{req} > B_{MIN}$ then the OLT computes the excessive bandwidth resulting from the lightly loaded ONUs and assigns to ONU_i a bandwidth B^i_{assign} depending on the excess bandwidth allocation type, and sends a GATE message accordingly. There are two ways to assign transmission windows using the excess bandwidth, namely Controlled Excess (CE) and Un-Controlled Excess (UE) allocation schemes.

In UE scheme, the OLT collects from the received REPORTs all the excessive bandwidth available for the next cycle and assigns this total excess uniformly to all highly loaded ONUs regardless of their requested bandwidth. The total excess bandwidth is:

$$B^{total}_{excess} = \sum_{i=1}^{N} (B_{MIN} - B^i_{req}) \mid B^i_{req} <= B_{MIN} \tag{25}$$

Then :

$$B_{excess} = B^{total}_{excess}/M \tag{26}$$

Where "M" to be the number of overloaded ONUs.

The advantage of this uncontrolled scheme is that highly loaded ONUs are assigned enough bandwidth to satisfy their high demands (assuming the excess is enough); however, if some ONUs are only "slightly" highly loaded, they are being assigned an unfair share of the excess bandwidth that could ultimately be not utilized. Hence, the assignment of the excess bandwidth must be controlled (i.e., CE) by the OLT in order to guarantee a fair bandwidth allocation for all highly loaded ONUs. Another way to perform bandwidth assignment using the CE scheme is as follows:

$$B^i_{assign} = \begin{cases} B^i_{req} & \text{if } B^i_{req} \leq B_{MIN} \\ B^i_{req} & \text{if } B_{MIN} < B^i_{req} \leq B_{MIN} + B^i_{excess} \\ B_{MIN} + B^i_{excess} & \text{if } B_{MIN} < B_{MIN} + B^i_{excess} < B^i_{req} \end{cases} \quad (27)$$

Where, the assignment of the excess bandwidth is controlled in the following way. Let $\chi = \{ONU_i\}_{i=0,\ldots,M-1}$ be the set of highly loaded ONUs. Then, B^i_{excess} is computed as follows:

$$B^i_{excess} = \begin{cases} B^{total}_{excess}/(M-i) & \text{if } B_{MIN} + (B^{total}_{excess}/(M-i)) < B^i_{req} \\ B^i_{req} - B_{MIN} & \text{otherwise} \end{cases} \quad (28a)$$

Where the total excess B^{total}_{excess} is updated as follows every time B^i_{excess} is assigned:

$$B^{excess}_{total} = B^{excess}_{total} - B^i_{excess} \quad (28b)$$

However, the CE allocation scheme allocates the excessive bandwidth in a round robin fashion. Thus, some highly loaded ONUs might not have the chance to receive any share of this bandwidth due to the fact that B^{excess}_{total} will be ≈ 0 before visiting all ONUs; or in a very common case, these "last" ONUs might get a less share than the "first" ones. For that reason, we propose a fair excess allocation scheme, namely FE, that assigns portions to highly loaded ONUs with respect to their bandwidth demand.

Let $B_{req}^{excess,i} = B_{req}^{i} - B_{MIN}$ be the excess bandwidth requested from a highly loaded ONU_i and $B_{excess}^{req} = \sum_{i=0}^{N} B_{req}^{excess,i}$ the total excess requested bandwidth from all ONUs, then:

$$B_{excess}^{portion,i} = \frac{B_{req}^{excess,i} \times B_{total}^{excess}}{B_{excess}^{req}} \tag{29a}$$

where $B_{excess}^{portion,i}$ is the computed portion of excess bandwidth for each highly loaded ONU_i. Hence, and to prevent the waste of bandwidth, B_{excess}^{i} is computed as follows:

$$B_{excess}^{i} = \min(B_{req}^{excess,i}, B_{excess}^{portion,i}) \tag{29b}$$

As a result, FE will ensure fair excess bandwidth allocation among all highly loaded ONUs. Note that unlike CE, FE ensures a fair bandwidth allocation but might not satisfy any highly loaded ONU; on the hand, CE makes sure to satisfy the demand of a highly loaded ONU if enough excess bandwidth is available, but not all ONUs in case all the total excess bandwidth is fully exploited.

Now for the wavelength selection criteria, as mentioned before, the OLT maintains for every wavelength k the time it becomes available for next transmission $T_{free}^{k}, k = 1 \ldots K$ where K is the total number of wavelengths in the WDM PON. The channel with smallest T_{free}^{k} is selected for next transmission.

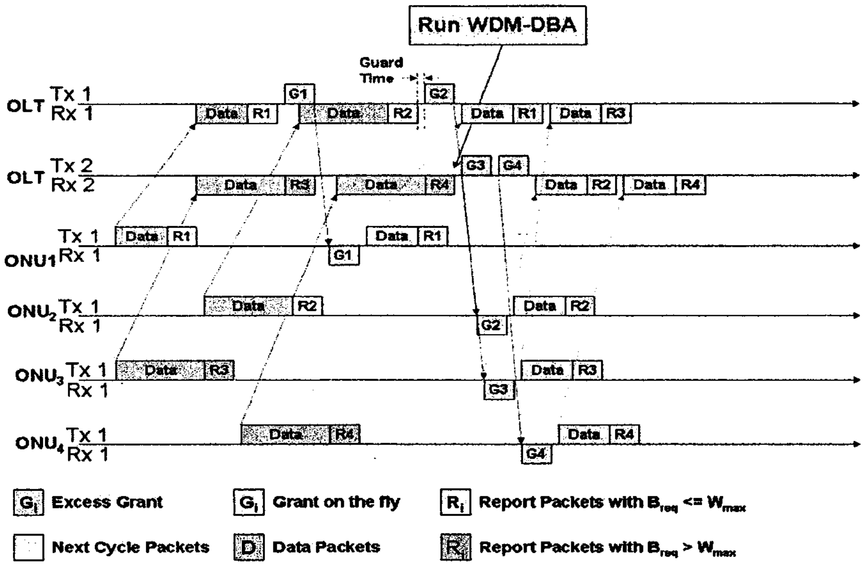


Figure 4.23: DWBA-2 Protocol

DWBA-2(fig. 4.23)

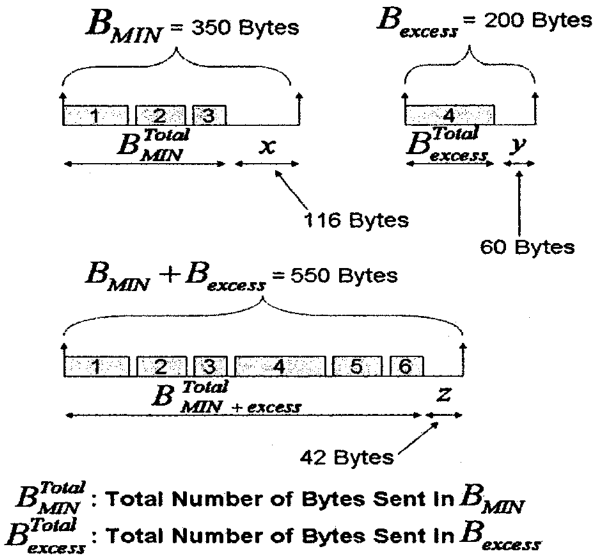
In this variant, upon receiving a REPORT from ONU_i, the OLT checks whether $B^i_{req} \leq B_{MIN}$; in this case, the OLT assigns "on the fly" a GATE to that ONU with bandwidth $B^i_{assign} = B^i_{req}$. Otherwise, the OLT waits until all the REPORTs from the other ONUs are received and then assigns a bandwidth of B^i_{assign} computed using UE, CE or FE. The difference here is that ONUs that are lightly loaded can be scheduled immediately on the particular channel without waiting for the rest of the ONUs to send REPORTs. This early allocation will result in improved delay performance.

However, such a scheme increases the complexity of the design and implementation of the DWBA due to the fact that the OLT will have to keep track of each REPORT message received from each ONU on all channels (e.g., sometimes one ONU can send two or more REPORTs before the OLT receives all the other REPORTs because of the *grant-on-the-fly* manner). Hence, the OLT will have to store *excess information* (i.e., excess table) that holds the status of each ONU (Highly Loaded or Low Loaded), to be able to assign the appropriate transmission window.

DWBA-3

This variant is similar to DWBA-2. Here the OLT will always assign "on the fly' a GATE to the ONU regardless of its requested bandwidth. However the size of the transmission window is dependant on the requested bandwidth. Upon receiving a REPORT from ONU_i, the OLT checks if $B^i_{req} \leq B_{MIN}$; in this case, as in DWBA-2, the OLT will assign "on the fly" a GATE with $B^i_{assign} = B^i_{req}$; otherwise, it will assign "on the fly" a GATE with $B^i_{assign} = B_{MIN}$. Subsequently, the OLT waits until it receives all the REPORTs from all ONUs, and collects the information about the excess bandwidth from each channel as well as the number of "highly loaded" ONUs "M". Each highly loaded ONU_i is allocated its share of the excess bandwidth in either an uncontrolled manner (B^i_{excess} as in (4)), in a controlled manner as in (6.a), or in a fair manner as in (7.b). Note, here the REPORT message is always transmitted *once* by the ONU in the first assigned transmission window (i.e., not in the excess window) regardless of whether an excess bandwidth is assigned or not. This is because (1) the allocation of the excess window cannot be guaranteed for a particular ONU and (2) since the OLT sends a GATE upon the receipt of a REPORT (i.e., on the fly) to allocate bandwidth, the ONU should not send a second REPORT (i.e., in the excess window) in the same cycle. That is because the OLT may already have done the scheduling of transmission of other ONUs over the same channel and this second REPORT cannot "void" the first received one.

This scheme is considered complex as well, since the OLT will have to use its *excess table*,



ONU Data Buffer

Packet	Bytes
1	100
2	64
3	70
4	140
5	64
6	70
7	64
. . .	. . .

Figure 4.24: Excess Bandwidth Allocation

and at the same time will have to keep track of the two *to-be-sent* (if applicable) GATE messages to each ONU.

4.5 Comparison & Analysis

SWDT clearly enables efficient bandwidth utilization of individual channels by providing effective time-sharing of the bandwidth among all the ONUs of the same group. However, the algorithm does not offer any inter-channel statistical multiplexing between all the ONUs connected to the network, and therefore yields a lower network utilization and higher packet delays. The advantage here, however, is its reliance on the simple architecture ($A1$) to enable the upgrade from TDM to WDM PON. Moreover, in case the BC scenario is applied, SWDT has the advantage of performing bandwidth allocation for each channel separately, which will reduce the idle wasted time caused by waiting for all REPORTs to be received from all channels. Furthermore, BC balances the load on the shared channels, which will give SWDT the "feels-like" dynamic behavior. On the other hand, if WC or any random case are applied, the lack of inter-channel statistical multiplexing will evidently and significantly affect the network performance. Alternatively, DWDT enables ONUs to share the network resources both in time domain and wavelength domain *and resolves the "ONU-classification" issue*. First, DWBA-1 is straight-forward; the OLT allocates GRANT messages only after receiving all the REPORTs from all the ONUs (N) in the network. Evidently, this simple algorithm has deficiencies; namely, consider two channels PON network where t_1 and t_2 are the times where each of the channels is available (assume $t_1 \geq t_2$) for next transmissions. Therefore, we can compute the period during which channel 1 is not being utilized:

$$T_1^{idle} = (t_2 - t_1) + K \tag{30a}$$

where:

$$K = \tau + T_{transmission} + T_{DWBA} \tag{30b}$$

Here, τ and $T_{transmission}$ are the RTT and the transmission time of a GATE message from the OLT to the ONU consecutively. T_{DWBA} = DWBA computation time. Clearly, the upper bound of T_1^{idle} corresponds to the maximum of $(t_2 - t_1)$. This maximum, in turn, corresponds to the case where the last ONU in this cycle starts its transmission (on channel 2) at time $t_{start} \geq t_1$. Accordingly, the upper bound of $(t_2 - t_1)$ is T_{assign}^N (the time window in seconds assigned to the last ONU). Therefore:

$$T_1^{idle} \leq T_{assign}^{N} + K \tag{31}$$

Moreover, if $t_2 - t_1$ is large (e.g., when the majority of ONUs on channel 1 are lightly loaded and the majority of ONUs on channel 2 are highly loaded), then the period of time where channel 1 is idle is much larger than that of (8). Overall, this idle time experienced by a channel results in poor bandwidth utilization and thus increased overall packet delays. DWBA-2 and DWBA-3, on the other hand, solve this problem of efficiency by sending GATE messages "on the fly" to all ONUs requesting bandwidth less than the minimum guaranteed (B_{MIN}). This "on the fly" bandwidth assignment mitigates the effects of the channel idle time experienced by DWBA-1 and results in a better throughput and delay performance for DWBA-2 and DWBA-3. However, these two schemes (DWBA-2 and DWBA-3) exhibit different behaviors. Namely, under DWBA-2, the OLT defers ONUs with $B_{req} > B_{MIN}$ until all REPORTs are received and then performs its assignment as explained in the previous section. DWBA-3 rather assigns "on the fly" all ONUs including those with $B_{req} > B_{MIN}$ (see section 4.3). In other words, the bandwidth allocated to a highly loaded ONU in DWBA-2 is a complete entity (i.e., minimum guaranteed plus the excess bandwidth (controlled or uncontrolled)) whereas DWBA-3 segregates the excess bandwidth from B_{MIN}. This results in two transmission windows being allocated at different times to a highly loaded ONU in the same cycle. The immediate implication of this transmission segregation is that a large packet may not fit in the first granted window and gets deferred to the second granted window (or perhaps to a subsequent cycle), blocking other packets from being transmitted and wasting a fraction of the allocated bandwidths. This implication increases the packet delays by holding unnecessarily these packets and ultimately resulting in increased buffer occupancy. On the other hand, in DWBA-2 every ONU is allocated only one transmission window in the same cycle; this window (combining both B_{MIN} and B_{excess}) is large enough and thus mitigates the impact of the previous problem. We demonstrate this through an example shown in Fig. 4.24.

First, let B_{MIN}^{Total} be the total number of bytes of transmitted data packets in the window allocated for B_{MIN}; let B_{excess}^{Total} be the total number of bytes of transmitted data packets in the window assigned for the excess bandwidth B_{excess}. Let $B_{MIN+excess}^{Total}$ be the total number of bytes of transmitted data packets in the window assigned for B_{MIN} combined with B_{excess}. Let x be the remaining bandwidth from B_{MIN}, y from B_{excess} (when DWBA-3 is used) and z from $B_{MIN+excess}$ (when DWBA-2 is used).

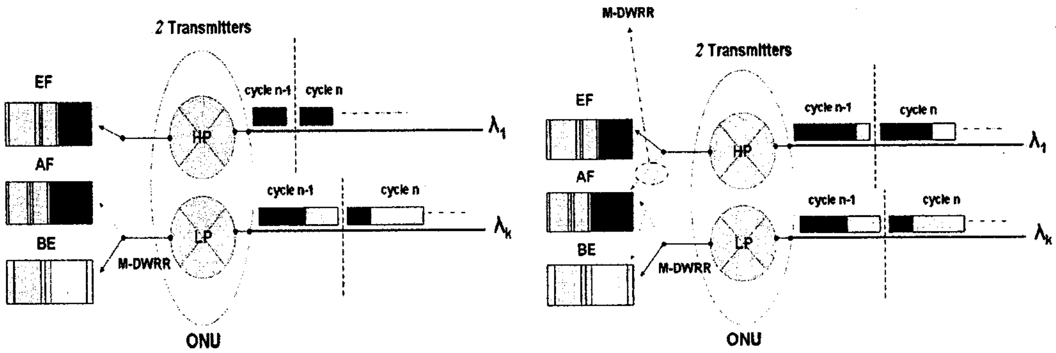
In DWBA-3, since the allocated bandwidth in one cycle is split into two windows (B_{MIN}, B_{excess}), one packet P of large size "p" may not fit in x and hence gets deferred to next the transmission window. This will effectively block other packets from being transmitted and result in inefficient use of the allocated bandwidth as well as increased delays. A total bandwidth of $(x+y)$ is hence not being utilized by the ONU under DWBA-3. On the other hand, in DWBA-2 combining B_{MIN} and B_{excess} in one transmission window, enables the transmission of P (here, the concept of x does not apply) and unblocks the rest of the buffered packets. This ultimately allows the transmission of larger number of packets, therefore reduced packet delays and increased bandwidth efficiency (wasted allocated bandwidth is only z, $z \leq x+y$).

Another implication of allocating two windows in the same cycle for a high loaded ONU stems from the fact that the ONU reports its buffer occupancy in the first window of cycle $n-1$ and subsequently after some time, some already reported packets for the next cycle will be transmitted during the excess window. The OLT will allocate bandwidth for cycle n based on the reported traffic from the previous cycle. This will result in granting bandwidth more than needed since the buffer occupancy has decreased. Let $t_{end}^{1,n-1}$ be the time where the REPORT message is transmitted by the ONU in cycle $n-1$ and $Q(t_{end}^{1,n-1})$ be the buffer occupancy (in bytes) at time $t_{end}^{1,n-1}$. Similarly, let $t_{end}^{2,n-1}$ be the time where the same ONU finishes sending traffic in the excess window of cycle $n-1$ and $Q(t_{end}^{2,n-1})$ be the buffer occupancy (in bytes) at time $t_{end}^{2,n-1}$. Here, the requested bandwidth for cycle n is $B_{req}^{n} = Q(t_{end}^{1,n-1})$. Now, we can write :

$$\tilde{B}_{req}^{n} = B_{req}^{n} - (Q(t_{end}^{1,n-1}) - Q(t_{end}^{2,n-1})) \tag{32}$$

where $\tilde{B}_{req}^{n}$ is the amended value of B_{req}^{n} before the OLT performs DBA in cycle n, and $Q(t_{end}^{1,n-1}) - Q(t_{end}^{2,n-1})$ is the size of the excess window of cycle n-1 which is known by the OLT. Hence, the OLT will allocate more bandwidth than the ONU requires at time $t_{end}^{2,n-1}$. This will result in increasing the cycle time, and hence inefficient use of the allocated bandwidth, and ultimately increased overall packet delays.

To overcome this deficiency, we propose a modified version of DWBA-3, namely DWBA-3a, that mitigates the "out-of-date" request information at the OLT and subsequently eliminates the in-efficient bandwidth allocation for highly loaded ONUs. Here, the OLT keeps track of the allocated excess bandwidth $B_{excess}^{i,n-1}$ in cycle $n-1$ and then extracts this excess out of the allocated bandwidth in cycle n. Consequently, the allocated bandwidth, in cycle



(a) First Approach

(b) Second Approach

Figure 4.25: Proposed Intra-ONU Schedulers

n, $B^{i,n}_{alloc}$ is computed as follows:

$$B^{i,n}_{alloc} = B^{n}_{req} - B^{i,n-1}_{excess} \tag{33}$$

As a result, DWBA-3a will improve the overall network performance as well as reduce the wasted bandwidth caused by DWBA-3.

4.6 Quality Of Service Support

Quality of service is a critical concern in current EPONs [31, 36]. Furthermore, providing *fair* QoS is considered an issue by itself, and is currently under intensive investigation. We propose and investigate three dynamic bandwidth allocation schemes for QoS in WDM-PON, namely QoS-DBA-1, QoS-DBA-2, and QoS-DBA-3.

4.6.1 QoS-DBA-1

This scheme can be implemented/installed in both A1 and A2 WDM-PON architectures. Moreover, we use the dynamic wavelength and bandwidth allocation scheme *DWBA-2* proposed in [49] to perform both wavelength and bandwidth allocation.

To integrate QoS with DWBA-2, we additionally use the intra-ONU scheduler proposed in [50] (namely M-DWRR) that proved to ensure *adaptive fairness* among different classes of services by forcing the weight policy.

In other words, the OLT will now allocate transmission windows to the ONUs using DWBA-2, and then each ONU will use its intra-ONU scheduler to *fill* its allocated window with packets from different priority queues.

4.6.2 QoS-DBA-2

In this scheme, we present a hybrid inter/intra-ONU scheduling mechanism where both the OLT and ONU are responsible of performing the bandwidth allocation.

This scheme relies on the second WDM-PON architecture A2, but yet we propose that each ONU is equipped with only *two* fixed transmitters, taking into account the ONU's installation and equipments cost. This is different from the architectures previously proposed [35] where each ONU, when equipped with fixed transceivers, should have *K* transceivers in case of having *K* wavelengths.

The idea here is to allow each ONU to use two wavelength channels simultaneously; one dedicated for high priority (HP) traffic (i.e., Constant Bit Rate *CBR* traffic) transmission, and the other for medium (MP) and low (LP) priority traffic (i.e., Variable Bit Rate *VBR* and Best Effort *BE* respectively) transmission. Thus in case of having more than two channels (for simplicity and without loss of generality, we assume that the number of available wavelengths is a multiple of 2), each *pair* of wavelengths will be allocated to multiple ONUs to transmit accordingly.

Moreover, each ONU will follow a *request-per-channel* trend to report its bandwidth requirements of each traffic class separately. Hence, it will send two REPORT messages, one to request bandwidth for HP traffic (i.e., channel one) and the other to request bandwidth for MP and LP traffic (i.e., channel two). Thus, the requested bandwidth of ONU_i is computed as follows:

$$B^i_{req} = \begin{cases} S_1 & \text{if } \lambda_m = 1 \\ \sum_{j=2}^{3} S_{j,i} & \text{if } \lambda_m = 2 \end{cases} \tag{34}$$

where, λ_m is the wavelength number of a chosen pair m. Correspondingly, the OLT is unaware of the quality of service requirements of the ONU. It waits until all REPORTs from all ONUs are received on one channel, and allocates the appropriate bandwidth based on the requested bandwidth of each ONU_i for each channel disjointedly. In other words, if ONU_i is requesting less than the minimum bandwidth guaranteed B_{MIN}, a bandwidth equivalent to the requested one is allocated. In contrast, if the requested bandwidth is larger than B_{MIN}, the OLT allocates B_{MIN} plus a share of excess bandwidth (if available).

Accordingly, each ONU will end up with two transmission windows (TW), one on each channel (i.e., T^1_{start}, T^1_{end}, T^2_{start} and T^2_{end}). Furthermore, since each ONU is being assigned on the second channel a transmission window that will be used to transmit both VBR and BE traffic, an intra-ONU scheduler is required to arbitrate the packet selection from both queues. Fig. 4.25(a) shows the proposed intra-ONU scheduler integrated with QoS-DBA-2. Here, each ONU uses its first transmitter to select and send packets from HP queue while the transmission window is available on the first CBR dedicated channel. It also applies M-DWRR to perform intra-ONU scheduling among MP and LP queues, and consequently uses its second transmitter to send the selected packet(s) while the transmission window is still available on the second channel.

This scheme provides a protection to the jitter performance of the HP traffic while conserving the fairness to MP and LP traffic. However, this scheme raises up many concerns listed as follows:

- Wasted Bandwidth: CBR (HP) traffic conventionally carries out a low transmission rate (e.g., 4.8 Mbps). Hence, the dedicated HP channel cycle size is very small, which in turn will cause a highly wasted bandwidth caused by the continuous polling overhead (REPORTs and GATEs).

- Channel Utilization: Since HP traffic is rarely loaded, thus the available bandwidth of the channel of speed $1Gbps$ dedicated for this traffic is misused/wasted.

Thus, this scheme can be adopted in WDM-PON if an optimal jitter performance is of high interest, and the cost of deploying an additional wavelength without fully utilizing its bandwidth is highly affordable.

4.6.3 QoS-DBA-3

To overcome these quandaries, we propose an inter-channel multiplexing bandwidth allocation scheme that will minimize the polling overhead as well as increase the channel utilization of the HP dedicated channel. Like the pervious scheme, this scheme restricts the use of fixed transmitters in each ONU, since it gives each ONU the ability to transmit packets on both wavelengths of the same pair simultaneously.

In this scheme, the ONU will enable its first transmitter, that had access to the HP queue only in the previous scheme, to have access to both MP and LP queues as well. This, as a result, permits each ONU to transmit MP and LP traffic on the HP dedicated channel as long as the QoS requirement for HP traffic is not affected.

To identify the amount of bandwidth to be selected from MP and LP queues, we supply the ONU with a parameter "α" that keeps track of both requested and granted bandwidths for MP and LP traffic in cycle $n-1$. The computation of α is done as follows:

$$\alpha = \sum_{j=2}^{3} B_{req}^{n-1}(j) - \sum_{j=2}^{3} B_{assign}^{n-1}(j) \qquad (35)$$

where $\sum_{j=2}^{3} B_{req}^{n-1}(j)$ is the requested bandwidth of MP and LP traffic in cycle $n-1$, and $\sum_{j=2}^{3} B_{assign}^{n-1}(j)$ is the granted bandwidth to MP and LP traffic in cycle $n-1$. Subsequently, the ONU will then incorporate α (for $\alpha > 0$) in the requested bandwidth for the HP traffic on the first channel. Thus the ONU essentially requests *additional credit* to its actual requested one:

$$B_{req}^{n}(1) = S_1 + \alpha \qquad (36)$$

where $B_{req}^{n}(1)$ is the requested bandwidth of HP traffic in cycle n, S_1 is the requested bandwidth of the backlogged queued HP traffic (buffer size) in cycle n.

This selection gives the backlogged MP and LP traffic the chance to be transmitted on the first channel in case they were not satisfied in their respective allocated transmission window on the second channel. However, to preserve the jitter performance of the HP traffic, we propose a new intra-ONU scheduler (Fig. 4.25(b)) that enables the first transmitter to access all priority queues while maintaining the access restriction on the second transmitter to MP and LP queues only. Here, the ONU transmits on the second channel MP and LP traffic using the M-DWRR scheduler. On the other hand, to preserve the jitter performance of HP traffic, it will transmit HP traffic on the first channel until fully satisfied (i.e., until HP queue is empty). Then, if the TW is still available and has enough bandwidth (Note that the TW on the first channel is now increased by α than the requested), it will use M-DWRR to schedule MP and LP traffic in the remaining TW.

4.7 Performance Evaluation

In this section we study the performance of the different wavelength and bandwidth allocation algorithms presented in the previous sections. For that reason, we developed a WDM-PON event driven simulator in C++. Table 4.2 shows the parameters used in our simulations. A subset of 32 ONUS out (of the 64 ONUs) is lightly loaded whereas the remaining ONUs are highly loaded. A lightly loaded ONU generates traffic at rate of $10Mbps$ ($load = 0.1$). For the traffic model considered here, an extensive study shows that most network traffic (i.e., http, ftp, variable bit rate (VBR) video applications, etc.) can be characterized by self-similarity and long-range dependence (LRD) [53]. To model the bursty nature of Internet traffic, we generated self similar traffic based on pareto distribution with a hurst $H = 0.8$; the source code was provided by [54], where packet sizes are

Table 4.2: Simulation Parameters

Number of ONUs N	64
Number of Wavelengths channels K	2,4
Maximum Cycle Time	$2ms$
B_{MIN}	$7688Bytes$
PON Channel Speed	$1Gbps$
End-users/ONU Link Speed	$100Mbps$
Guard time	$1\mu s$
Distance between OLT and ONU	$20Km$
Distance between ONU and End-Users	$5Km$
Buffering Queue Size	$1Mbytes$

uniformly distributed between 64 and 1518 bytes.

4.7.1 WDM-DBAs Performance Evaluation

Fig. 4.26 presents the average delay for SWDT with both scenarios (i.e., SWDT-WC and SWDT-BC), DWBA-1, DWBA-2 and DWBA-3 all under uncontrolled excess (UE). The traffic load of a high loaded ONU is varied between 0.1 and 1 (i.e., $10Mbps$ and $100Mbps$). Clearly, the results show a better performance for DWBA-2/3 over SWDT-BC/WC, while SWDT-BC exhibits better performance than DWBA-1 and naturally better than SWDT-WC. The first observation is mainly because, as explained previously, SWDT does not exploit the inter-channel statistical multiplexing between the various wavelengths. The second observation is because ONUs of different class (highly loaded and lightly loaded)

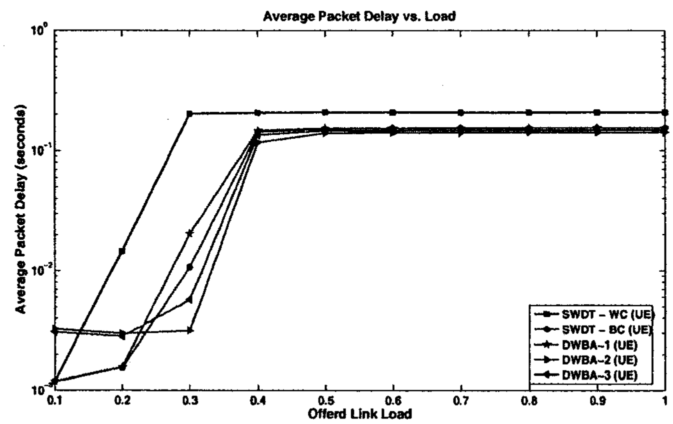


Figure 4.26: Average Packet Delay Comparison (k=2)

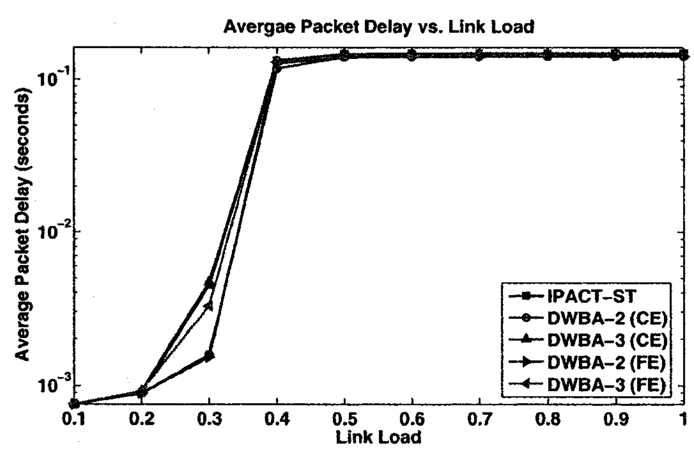


Figure 4.27: Delay Measurements with CE and FE (K=2)

are evenly distributed over the channels, in contrast to SWDT-WC where the available resources capacities are under-utilized on one channel and over-utilized on another. In addition, SWDT is run over each channel separately, which as explained previously, eliminates the idle wasted time found when using DWBA-1 where the OLT waits until receiving all REPORTs from all ONUS on all channels before allocating bandwidth for the next cycle. Alternatively, DWBA achieves good performance; in particular, DWBA-2 and DWBA-3 exhibit better performance than DWBA-1 due to the channel idle time explained in the previous section. For example, at a load of 0.3, the average packet delay under DWBA-2 (DWBA-3) is $17ms$ ($14ms$) better than that under DWBA-1. Now, as we mentioned in section 4.5, there are some critical differences between DWBA-2 and DWBA-3. Our simulation results show a better performance of DWBA-2 over DWBA-3. The main reason is due to the fact that in DWBA-3, the OLT allocates the excess bandwidth to a high loaded ONU in a separate window in the same cycle. This, as explained before, results in under-utilizing the allocated bandwidth especially for the two reasons mentioned in the previous section. The average packet delay of DWBA-2 is slightly better than that of DWBA-3; for example, at $load = 0.4$, a difference of $18ms$ is shown. Note, when the assignment of the excess is controlled by the OLT (as discussed in section 4.5), better results are obtained in terms of overall average packet delays; however, the relative difference between the different algorithms is the same.

Fig. 4.27 shows the delay performance of DWBA-2 and DWBA-3 using both Controlled and Fair Excess allocation schemes in comparison with the algorithm proposed in [45], namely IPACT-ST. Clearly, DWBA-2 and DWBA-3 exhibit better performance than IPACT-ST. For example, at load = 0.4, there is $\approx 16ms$ improvement of DWBA-2 (CE) over IPACT-ST. The reason behind this improvement is due to the statistical multiplexing implemented in our schemes and the judicious use of the excess bandwidth found in each transmission cycle. Hence, the available bandwidth in each cycle is efficiently utilized, and as result the overall network performance is ameliorated.

Moreover, FE improves the performance of DWBA-3 over CE, while it shows a similar performance for DWBA-2 using the CE allocation. This is due to the fact, that FE as named, fairly allocated the excess bandwidth among highly loaded ONUs, in contrast to CE, that concentrates on satisfying highly loaded ONUs until the available bandwidth is fully consumed.

In addition, we examine the network performance when the number of upstream channel wavelengths increases (e.g., $K = 4$). Fig. 4.28 shows the average packet delay under both IPACT-ST and DWBA-2. As expected and observed, increasing the number of wavelengths leads to a significant decrease in the packet delay. Moreover, as observed at load 0.8, IPACT-ST exhibits better performance than DWBA-2; this is due to the following. When the number of wavelengths increases, DWBA-2 will have to wait until all REPORTs from all ONUs on all wavelengths are received to calculate the excess bandwidth and consequently schedule the ONUs for the next cycle; which will cause a "waiting-for-all-reports" delay as well as buffering delay more than IPACT-ST that always schedules GRANTs on-the-fly for the next cycle. Nevertheless, DWBA-2 increases the channel utilization by fully exploiting the bandwidth available in each cycle. However, augmenting the number of wavelengths may become costly, and inefficient, if the wavelengths capacities are not fully utilized. Note that, we believe an incremental upgrade, in which multiple wavelength channels are added as needed, achieves a cost effective solution for the access network. Note also, once the upgrade from a TDM to a WDM-based PON takes place, one needs to rethink the MAC protocol, as discussed throughout this chapter. Moreover, as the simulation run-time becomes prohibitive at higher loads and especially with higher number of wavelengths, we consider here-to-after two wavelengths to simulate the WDM-PON.

Figs. 4.29 and 4.30 show a comparison of the overall packet drop rate for all the allocation algorithms. As expected, DWBA-2 exhibits a better drop rate whereas SWDT-WC shows the highest.

We now focus our attention on DWBA-2 and DWBA-3 (since they have shown better performance than the other proposed two) to further study their dissimilarities. As mentioned before, the main difference between DWBA-2 and DWBA-3 is the efficient use of the total allocated bandwidth for high loaded ONUs. Clearly, if the allocated bandwidth is not fully utilized (as in DWBA-3), the buffer occupancy of the high loaded ONU will increase substantially and therefore more bandwidth will be requested for the subsequent cycle(s). Since in our experimental setup about half of the ONUs are highly loaded, more high bandwidth requests will arrive at the OLT and each ONU will be rewarded "*excess*" from whatever is available. This inefficiency of utilizing the allocated bandwidth may occur more often, and thus may accumulate throughout the duration of the burst and after. Alternatively, under DWBA-2, the behavior is conversed. Namely, the allocated bandwidth is used more efficiently, and hence fewer ONUs will be requesting additional bandwidth. To validate our reasoning, we measure the probability density function (pdf) of the number of ONUs with $B_{req} \geq B_{min}$ for both algorithms and under the two allocation schemes of excess bandwidth (UE and CE). Clearly, as Fig. 4.33 shows, more ONUs will be requesting bandwidth more than B_{min} under DWBA-3 (both under UE and CE). However, under DWBA-2, always fewer ONUs are requesting more than B_{min}. This clearly indicates that (1) the inefficient use of allocated bandwidth and (2) the misguided allocation of bandwidth in DWBA-3 results in more increased queuing of ONU's traffic (higher occupancy) and hence more ONUs requesting bandwidth larger than the minimum guaranteed from the OLT.

To further compare the performance of the two algorithms with respect to their efficient use of the allocated bandwidths, we measure the number of bytes wasted in each cycle for a highly loaded ONU under controlled excess scheme: $B_{wasted} = B_{alloc} - B_{sent}$, where B_{alloc} and B_{sent} are the amount of bandwidth allocated to the ONU and effectively used by the ONU respectively. Fig. 4.31 shows the results of this experiment where we plot B_{wasted} collected in each cycle throughout the simulation at a particular high loaded ONU. Clearly, the figure shows that, under DWBA-2, there exists no cycle where $B_{wasted} \geq 1518 bytes$ (maximum packet size). By conclusion, DWBA-2 will defer at most one packet from one transmission cycle to the following one; however, there is an excessive waste of allocated bandwidth under DWBA-3. This is largely due to the over-allocation of unnecessary bandwidth by the OLT. Overall, this allocation results in increased average cycle times, inefficient bandwidth utilization, and therefore increased overall packet delays.

We mitigate this problem by proposing a modified version of DWBA-3, namely DWBA-3a (see section 4.5). To test the validity of this new scheme, we also plot in fig. 4.32 B_{wasted} collected in each cycle throughout the simulation at the same high loaded ONU previously selected. As shown, DWBA-3a significantly decreases the waste of bandwidth

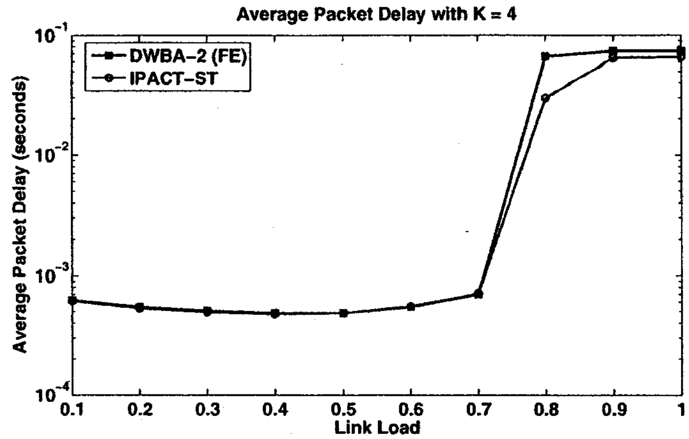


Figure 4.28: Delay Measurements with K=4

founded in DWBA-3; and shows a similar behavior to the one observed using DWBA-2 (i.e. $B_{wasted} \leq 1518 bytes$).

Finally, to compare the fairness of both CE and FE allocation schemes, we simulate the network at load = 0.5 and we measure the performance of two particular highly loaded ONUs. We choose the first ONU as the first highly loaded ONU (namely ONU_1) among the 64 since it expected to be always satisfied when applying the CE scheme (see section 4.4); while the second ONU (namely ONU_2) is chosen to be the last one among the 64. As expected and observed, the average packet delay for ONU_1 with FE is equal to 0.176690 seconds, and for ONU_2 it is equal to 0.176705 seconds; while with CE, it is 0.175538 seconds for ONU_1 and 0.176988 seconds for ONU_2. Which shows the advantage of FE that fairly allocates the excess bandwidth and thus provide almost the same performance for all highly loaded ONUs, whereas CE satisfies one highly loaded ONU over the other and mainly depends on the availability of the excess bandwidth.

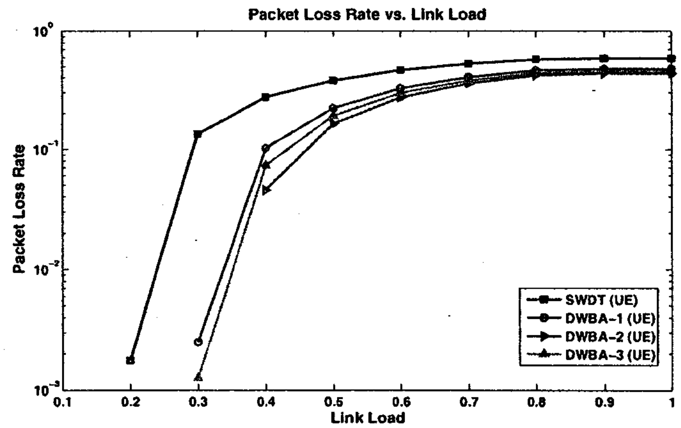


Figure 4.29: Packet Loss Rate (k=2)

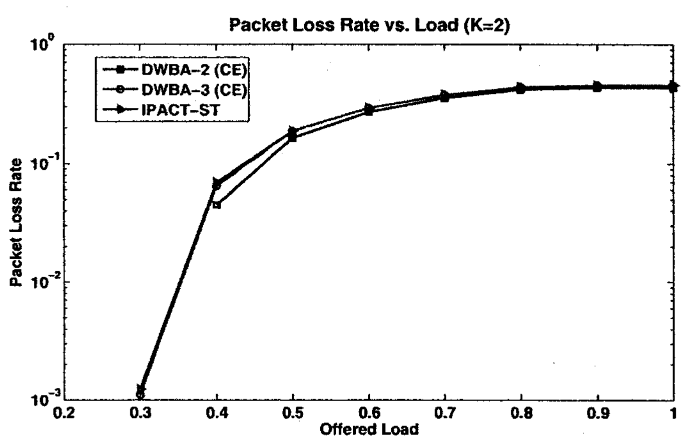
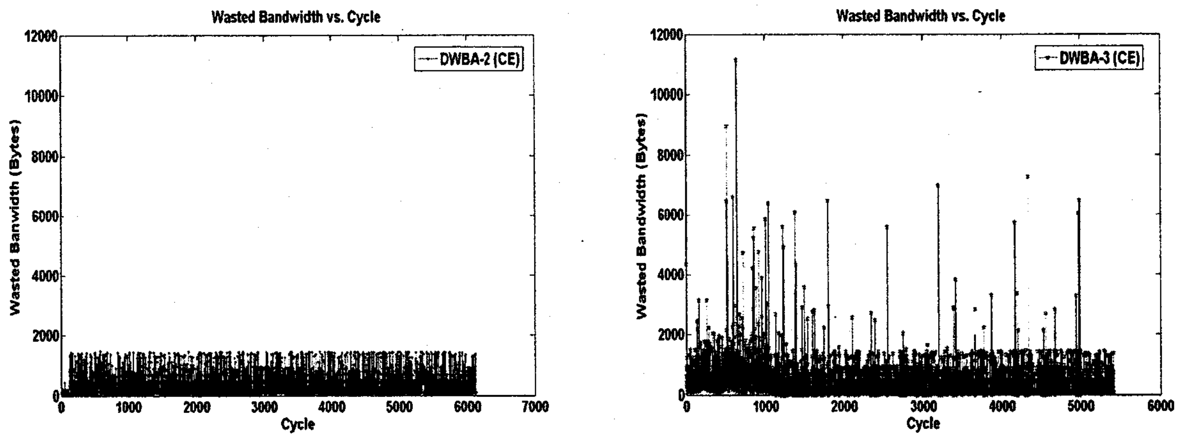


Figure 4.30: Packet Loss Rate Comparison (k=2)



(a) DWBA-2(CE)

(b) DWBA-3(CE)

Figure 4.31: Wasted Bandwidth Comparison

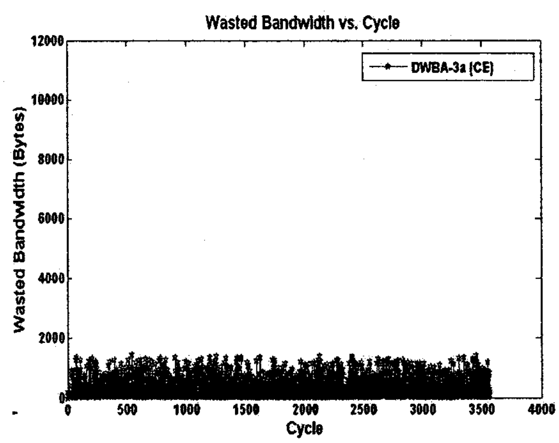


Figure 4.32: DWBA-3a(CE) Wasted Bandwidth (k=2)

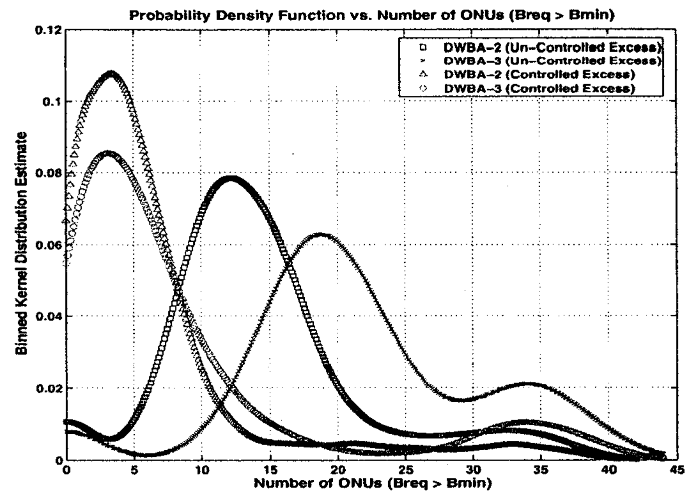


Figure 4.33: *"PDF"* of Number of ONUs (with $B_{req} > B_{MIN}$) (k=2)

4.7.2 QoS WDM-DBA Performance Evaluation

In this section we study the performance of the different WDM-DBA algorithms presented in the previous sections. For that reason, we developed a WDM-PON event driven simulator in C++. The total number of ONUs $N = 32$, the number of wavelength channels $K = 2$, and the wavelength speed (W_s) = $1Gbps$. The guard time is equal to $1\mu s$, the maximum cycle time to $2ms$ and the ONU buffering queue size to $10MBytes$.

For the traffic model considered here, an extensive study shows that most network traffic (i.e., http, ftp, variable bit rate (VBR) video applications, etc.) can be characterized by self-similarity and long-range dependence (LRD) [53]. This model is used to generate highly bursty BE and AF traffic classes, and packet sizes are uniformly distributed between 64 and 1518 bytes. On the other hand, high-priority (EF) traffic (e.g., voice applications (CBR)), is modeled using a Poisson distribution and packet size is fixed to 70 bytes. The traffic profile is as follows: the high priority traffic load is fixed at 4.48 Mbps, and the remaining load is equally distributed among low-and medium-priority traffic.

A subset of 16 ONUS out (of the 32 ONUs) is lightly loaded whereas the remaining ONUs are highly loaded. A lightly loaded ONU generates traffic at rate of $10Mbps$ ($link\_load = 0.1$). Our simulator takes into account the queuing delay, transmission delay and the packet processing delay. The metrics of comparison are: average packet delay, network throughput, packet drop rate and the jitter performance of CBR traffic. Note that the offered load is proportional to $(K \times W_s)$.

We first start by investigating the performance of QoS-DBA-1 that represents the enhacement of DWBA-2 of [49] with M-DWRR scheduling discipline of [50]. Moreover, we test QoS-DBA-1 with the intra-ONU scheduler proposed by [55] (so-called M-SFQ) to show the effect of our proposed intra-ONU scheduler on the overall network performance. In that context we consider the following sets of priority queues weights :

- Set 1 : $W_{CBR} = 20\%$, $W_{VBR} = 70\%$ and $W_{BE} = 10\%$
- Set 2 : $W_{CBR} = 50\%$, $W_{VBR} = 40\%$ and $W_{BE} = 10\%$
- Set 3 : $W_{CBR} = 20\%$, $W_{VBR} = 40\%$ and $W_{BE} = 40\%$
- Set 4 : $W_{VBR} = 60\%$, $W_{BE} = 40\%$
- Set 5 : $W_{VBR} = 70\%$, $W_{BE} = 30\%$

Where sets 1, 2 and 3 are employed in QoS-DBA-1 M-DWRR; while sets 4 and 5 are employed in both QoS-DBA-2 and QoS-DBA-3 M-DWRR since the scheduling is done from MP and LP queues only.

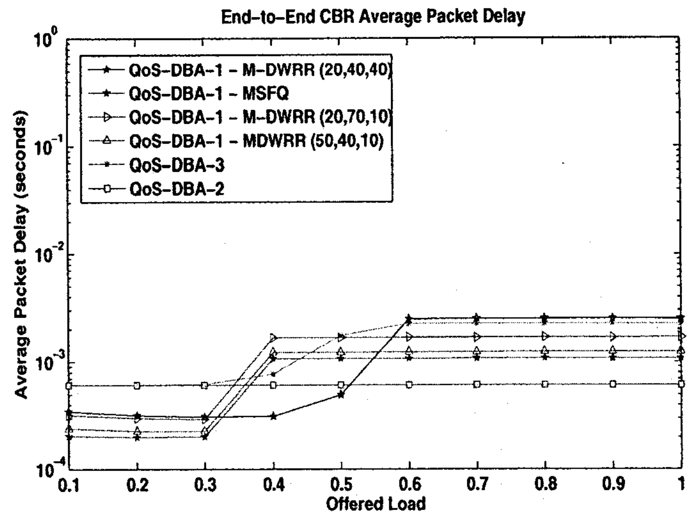


Figure 4.34: CBR Average Packet Delay

Average Packet Delay

Figs. 4.34, 4.35 and 4.36 compare the end-to-end average packet delay of all CBR, VBR and BE traffic respectively in our three proposed WDM-DBA schemes.

Moreover, given that M-SFQ is designed to satisfy high- and medium-priority traffic and especially VBR traffic, we can explicitly identify the behavior of our proposed schemes in the graphs. In Fig. 4.34 for instance, the weight selection clearly affects the performance of CBR traffic in QoS-DBA-1. Thus with *Set 2*, where CBR traffic is allocated higher weight (50%), its delay shows an improvement over the other sets. However, QoS-DBA-2 shows the optimal performance by offering a *static* CBR delay ($\approx 0.6ms$) on all loads. The reason behind this excellent behavior, as mentioned, is that each ONU is being dedicated one wavelength for HP traffic transmission, which keeps this traffic protected from the bursty nature of MP and LP traffic. Furthermore, QoS-DBA-3, as promised, maintains a low CBR packet delay, even though higher than other schemes, and ensures fairness among

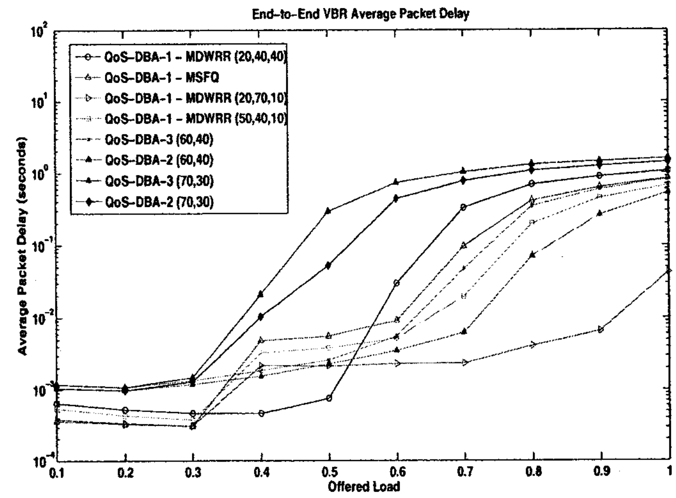


Figure 4.35: VBR Average Packet Delay

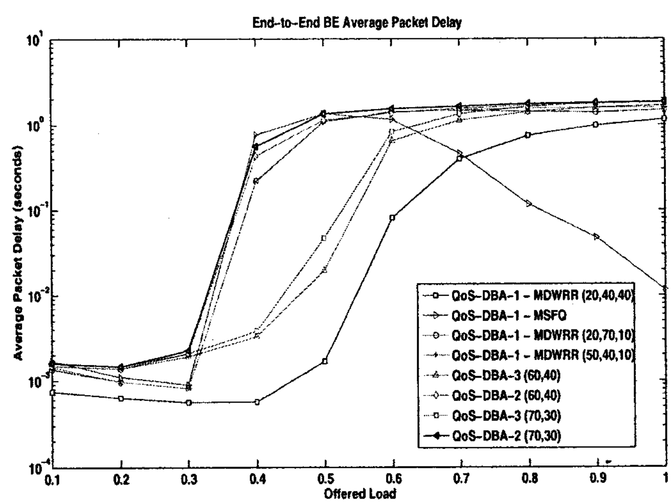


Figure 4.36: BE Average Packet Delay

other types of traffic.

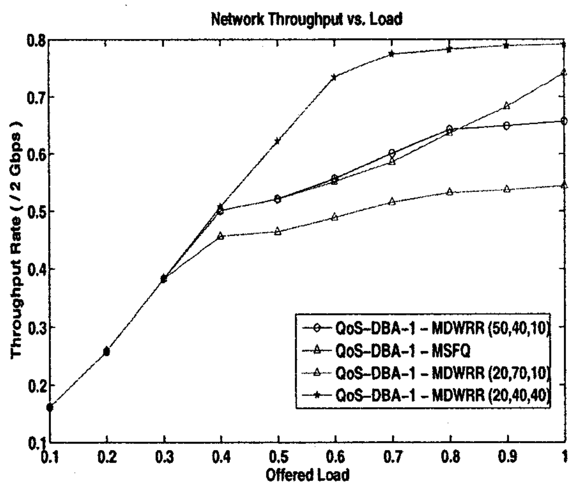
This fairness is evidently revealed in Figs. 4.35 and 4.36. Here, QoS-DBA-3 tremendously improves the delay performance of VBR and BE traffic over QoS-DBA-2 in both sets 4 and 5 (e.g., on load 0.5 QoS-DBA-3 shows $\approx 80\%$ improvement in both VBR and BE traffic over QoS-DBA-2). On the other hand, QoS-DBA-1 shows the best VBR and BE performances when applying the *Set 3* weight profile. This due to the fact that our traffic model outlines an equal increase of VBR and BE traffic, while fixing the load on CBR traffic (i.e., $4.8Mbps$). Moreover, the design of DWBA-1 which is the adopted DBA in QoS-DBA-1, applies the *grant-on-the-fly* technique, which compensates for the DBA idle time by allocating the lightly loaded ONUs earlier than the *wait-for-all* fashion.

Note that the *grant-on-the-fly* mechanism could have been applied in QoS-DBA-2(3). However, this will result in a wasted bandwidth caused by the polling overhead in a small cycle time where the OLT sends two GATEs and waits for two REPORTs from each ONU (especially when the load is small).

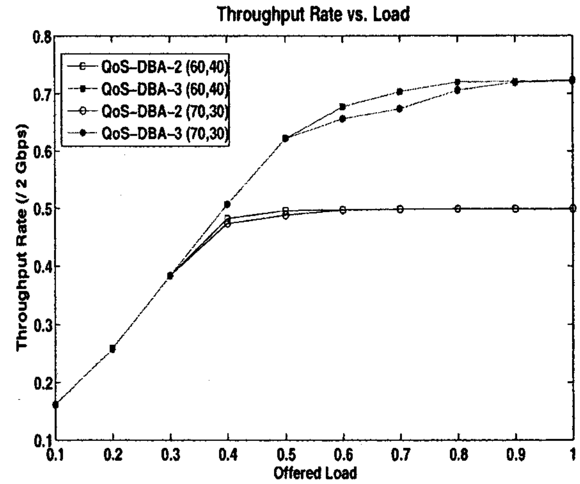
One key observation is the unexpected behavior of BE traffic on high load when applying the M-SFQ intra-ONU scheduler with QoS-DBA-1. Fig 4.36 shows that BE's delay improves; but in fact, the M-SFQ scheduler penalizes low-priority traffic and actually drops almost all its packets. Hence, this improvement arises from very few packets that were only transmitted before the bursts of other traffic arrived. This is more illustrated when the packet loss rate is investigated next.

Network Throughput & Packet Loss Rate

As discussed earlier, QoS-DBA-1 integrates DWBA-1 with M-DWRR and robustly relies on the weight profile selected. Fig. 4.37(a) shows the throughput rate performance with QoS-DBA-1. Here, as proved, the *Set 3* weight profile provides the perfect balance between the expected traffic load (here, simulation traffic profile) and the weight assignment of the intra-ONU scheduler. Hence, it provides a high throughput rate of 80% at full loading scenario while the use of M-SFQ scheduler shows a low throughput rate of 50% in the same scenario. On the other hand, QoS-DBA-2 is more concerned of providing an optimal delay variation for HP traffic rather than an efficient bandwidth utilization. Meanwhile, QoS-DBA-3 stabilizes this hitch by judiciously utilizing the bandwidth available on all WDM-PON channels, by allowing transmission of MP and LP traffic on the HP dedicated channel. Consequently, as shown in Fig. 4.37(b), QoS-DBA-3 improves the overall throughput rate while QoS-DBA-2 shows a poor one (e.g., at full loading, QoS-DBA-3's throughput rate is $\approx 75\%$ and QoS-DBA-2's throughput rate is $\approx 50\%$). The same behavior applies on the packet loss rate performance in all schemes. As shown in Fig.4.38, QoS-DBA-1 with M-DWRR and the *Set 3* weight profile demonstrate no packet loss at low loading and small loss rate at high loading. However, the use of M-SFQ dramatically affects the network performance, where almost all BE packets are dropped; which explains the degradation of the BE traffic delay observed previously. Alternatively, QoS-DBA-2 demonstrates higher packet loss rate than QoS-DBA-3 on all loads. This is due to the fact that one channel only dedicated for MP and LP only is not enough to satisfy their demands (i.e., QoS-DBA-2),



(a) QoS-DBA-1



(b) QoS-DBA-2 and QoS-DBA-3

Figure 4.37: Network Throughput

while the *permission* to use more than one channel improves their performances (QoS-DBA-1 in A1, and QoS-DBA-3 in A2).

Jitter

Another positive contribution of our proposed schemes is the ability to preserve the packet delay variation for EF services discussed in details in [59]. The jitter is represented by the packet delay variation of two consecutively departed EF packets from the same ONU in the same transmission window.

Fig. 4.39 shows the probability density function (pdf) of EF service packet delay at full loading scenario (i.e., load = 1.0). It is shown that the EF delay sequence presents a dispersion with enough number of data points in a tail until 6 ms for QoS-DBA-1 with *Set 1* profile (proved to provide the best CBR delay performance), reduced to 5.5 ms in QoS-DBA-3 and a centralization with all data points condensed before 0.6 ms for QoS-DBA-2.

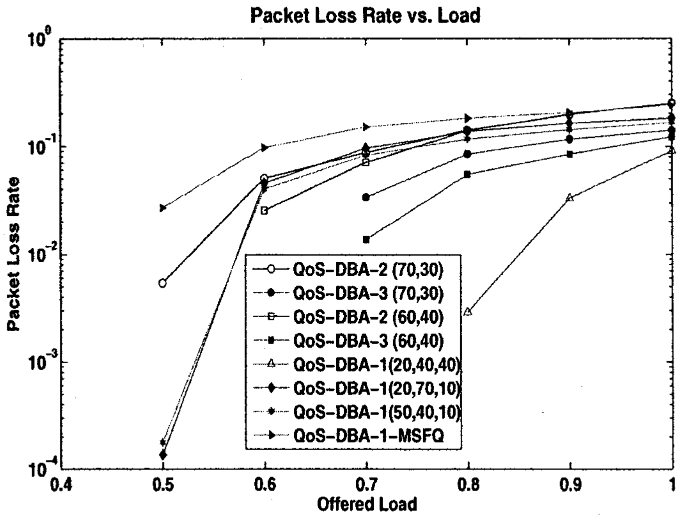


Figure 4.38: Packet Loss Rate

Thus QoS-DBA-2 presents the optimal EF "delay variation" over QoS-DBA-1 and QoS-DBA-2. However, these last two schemes maintain a good EF jitter performance while providing fairness to other types of traffic and improving the bandwidth utilization.

4.8 Summary

We have proposed a new WDM-PON architecture to tolerate high bandwidth utilization among multiple wavelengths. We then presented novel bandwidth allocation schemes over WDM-PON, provided a thorough comparison between them and studied their performances advantages and disadvantages and proved the increase of efficiency in the Network. We showed that static wavelength allocation will penalize ONUs with high load and will under-utilize the PON resources. We also proved that dynamic wavelength allocation increases the network scalability and efficiency by providing simulation results and experiments analysis. Moreover, we presented three ways to efficiently allocate excess bandwidth

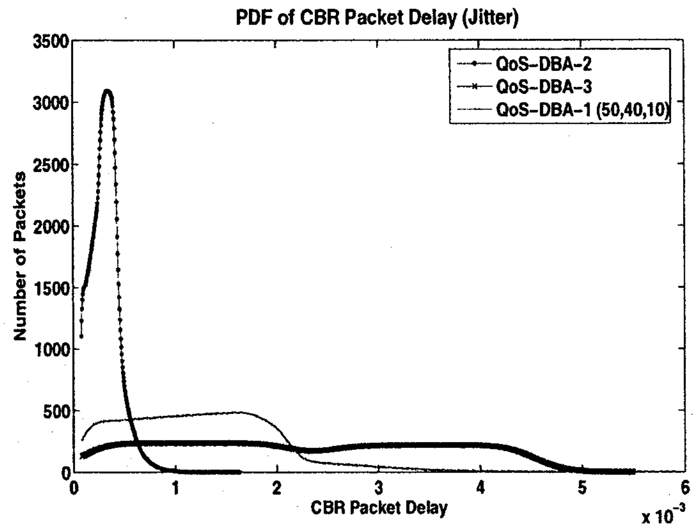


Figure 4.39: CBR Jitter Performance

among highly loaded ONUs, namely controlled, fair and uncontrolled. We showed that by using controlled excess bandwidth allocation, we increase the bandwidth utilization and as a result we improve the overall network performance; and by using fair excess bandwidth allocation we balance the overall performance. We then augmented three hybrid WDM/TDM bandwidth allocation algorithms to support QoS in a differentiated services framework. The first scheme showed its dependency on the adopted intra-ONU scheduler weight profile and its impact on the overall performance of the first proposed WDM-PON architecture. On the other hand, we showed that the other two schemes, which are designed to handle the bandwidth allocation in the second proposed WDM-PON architecture that allows transmission of each ONU on two channels simultaneously, demonstrate different *preference* in the network performance. The second scheme provides optimal HP traffic jitter performance but with low bandwidth utilization and MP/LP traffic increased delay. Alternatively, the third scheme provides a performance balance between these parameters.

We used simulation experiments to validate the effectiveness of the proposed algorithms.

Chapter 5

Conclusion & Future Work

Ethernet Passive Optical Networks (EPONs) have emerged as the best solution for the *last mile* bottleneck. EPONs not only provide high speed bandwidth for the emerging QoS applications, but also offer high reliability, maintenance, low cost and most importantly an easy spatial upgrade that can meet the continuous Internet growth in terms of users and bandwidth demand.

Although standardized, EPON carries many "yet-to-be-solved" problems such as, efficient bandwidth allocation (inter- and intra-ONU schedulers), fairness, WDM upgrade, QoS protection and many more. From this point, EPON stands as an interesting to-be-investigated technology and is still exposed to intensive research from both the industry and academia. In this thesis, we addressed these problems and we proposed various solutions to improve the overall performance in the access network.

5.1 Conclusion

After the first two chapters where we introduced our work and motivate it, we started in chapter 3 by addressing the fairness issue in EPON and we presented a novel decentralized bandwidth intra-ONU scheduler. This scheduler allows for a unique ONU-gripping to QoS traffic by adaptively setting weights for the different CoS. Extensive simulation results show the effectiveness of our proposed intra-ONU scheduler, that enables a *fair* access to the bandwidth for all CoS queues, and its influence on the QoS performance.

Another major contribution in this chapter, is the proposal of the first and complete EPON framework that supports the application of admission control (AC). This framework resolves the *guaranteed bandwidth* issue for the QoS applications and protects the performance of on-going admitted traffic. The AC framework implements a two-stage admission control, namely locally at the ONU and globally at the OLT, with all its rules. Moreover, we have supported this framework with the first hybrid AC-enabled DBA that performs both bandwidth allocation and reservation. We have also presented the first simulation model that is designed to test this framework. Our AC framework showed that the application of admission control in EPON is becoming crucial for providing *bandwidth guaranteed* for the emerging QoS applications, and their protection against the malicious users that aim on monopolizing the bandwidth provided.

In chapter 4 we discussed a smooth and simple upgrade from TDM-PON to WDM-PON. Here, we proposed two hybrid TDM/WDM-PON architectures where multiple upstream channels are additionally deployed with various ONU/OLT architectures (i.e., fixed transceivers or tunable lasers). We then presented three dynamic bandwidth and wavelength allocation schemes for these WDM-PON architectures. We showed that static wavelength allocation will penalize ONUs with high load and will under-utilize the PON resources. We then augmented three novel bandwidth allocation schemes to support QoS in a differentiated services WDM-PON framework. These schemes demonstrate different *preference* in the network performance and in the adopted WDM-PON architecture. We used simulation experiments to validate the effectiveness of the proposed algorithms.

5.2 Future Work

Our proposed work leaves some interesting and potential issues that need further research and investigation. Hence, future work can include the following:

- Extension to the work proposed in chapter 3; especially that our AC framework has set the basis for the application of Admission Control in EPON. This can include the investigation of a more efficient DBA to allocate and protect bandwidth in our proposed AC framework. It can also include the discussion of more/less conservative rules than the ones presented in the proposed framework and their effect on the overall network performance.

- WDM-PON, as presented in chapter 4, has not been standardized yet, and thus requires further investigation; especially with the high cost that results from the upgrade from TDM-PON to WDM-PON. Currently, this effort is being viewed from two main perspectives. The first one implies that the upgrade can lead to a pure WDM-PON where TDM is no more utilized, and the second one involves the use of the TDM technology, resulting in a hybrid TDM/WDM-PON. Thus, an interesting comparison can be done on both the cost benefit and the performance benefit between both visions.

- With the rapid expanding of mobile users and IP traffic in local access network, there has been an increasing urgent need to provide IP micro-mobility in EPON-based access network. Hence, a hybrid wireless/wired access network is an interesting research topic for future invesitgation.

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