Departament d'Enginyeria Telemàtica
UNIVERSITAT POLITÈCNICA DE CATALUNYA

MASTER PROJECT

NEW DYNAMIC BANDWIDTH ALLOCATION ALGORITHM ANALYSIS: DDSPON FOR ETHERNET PASSIVE OPTICAL NETWORKS

AUTHOR: PAOLA GARFIAS HERNÁNDEZ
DIRECTOR: SEBASTIÀ SALLENT RIBES

TABLE OF CONTENTS

INDEX OF FIGURES

INDEX OF TABLES

1 INTRODUCTION

Optical fiber technologies could provide the solution for current and future applications demands – through fiber technologies the communications infrastructure becomes powerful, providing very high speeds to transfer a high capacity of data. Some of the advantages that an optical fiber system can provide are: a higher bandwidth capacity, longer reach, longer life, lower maintenance cost, a resistance to outside interference and the better reliability.

Nowadays one of the main problems of Internet is the performance bottleneck in the access segment. To address this issue a promising alternative of access networks is certainly the Passive Optical Network (PON), since it relieves bottlenecks in the access network. A PON is made up of fiber optic cabling and passive splitters and couplers that distribute an optical signal, commonly through a tree topology, to connectors that terminate each fiber segment. There are several different PON technologies, such as the Asynchronous Transfer Mode PON (APON) which uses ATM encapsulation of transported data. APON was followed by the Broadband PON (BPON), which offers improved and additional features such as Wavelength Division Multiplexing (WDM) support, higher upstream bandwidths and upstream bandwidth allocation; the Ethernet PON (EPON), which uses Ethernet rather than ATM data encapsulation and is highly suitable for data services; and the Gigabit PON (GPON), it is an IP-based protocol designed for IP traffic often described as combining the best attributes of BPON and EPON at gigabit rates.

Among the PON technologies, EPON is considered the best alternative as the broadband access network for the networks of the next generation. EPON is a point-to-multipoint network in which the upstream channel has to be shared among users, thus a suitable access mechanism is required to avoid collisions, but also to meet the requirements of quality of service. Standard specifications on EPON left an open issue in terms of bandwidth allocation and several up to date studies have been carried out to improve EPON efficiency through the proposals of different bandwidth allocation mechanisms.

The capacity of EPON can be drastically increased by means of the WDM, so that multiple wavelengths may be supported in either or both upstream and downstream directions. Bandwidth allocation becomes an important issue of study in WDM-EPON, but so does wavelength allocation, therefore recent research in this area has produced solutions to support multiple wavelengths and efficient management of the bandwidth among users. WDM-PON is referred to as one solution for the next generation of access networks as well as the upcoming standard IEEE 802.3av about 10GEPON. Both of them are technologies that can meet the growing demands of future applications.

This project aims to present the state of the art in Dynamic Bandwidth Allocation (DBA) solutions, as well as the study and evaluation of one proposal of DBA algorithm: the Distributed Dynamic Scheduling for EPON (DDSPON), which is the UPC contribution to the research in scheduling algorithms for EPON.

This paper is organized in five sections; Section II provides a background of PON technologies with a special emphasis in the GPON technology. Section III presents an overview of EPON technology, starting with a review of the standard specifications – the same section continues with a summary of the research in DBA, and finishes with a discussion about the issues regarding the next generation of EPON. Section IV presents the DDSPON algorithm as an alternative solution of bandwidth management in EPON.

Section V presents the evaluation results of DDSPON simulation. Towards the end, Section VI comments upon the future work in the Passive Optical Networks.

2 BACKGROUND

In the future, networks are expected to be capable of supporting high capacity, as well as its granularity to offer services in an adaptive and optimal way. Currently, the ability of PON access networks fluctuates between 622Mbps for networks APON, 1Gpbs to 2.5Gbps for EPON and GPON networks respectively. While EPON networks are prepared to increase their rate from 1Gbps to 10Gbps, this will not be sufficient in the future, given the growing demand for bandwidth that the new media services and applications require. To meet these requirements, PON networks should use the physical environment with high efficiency so that access protocols can handle the combination of resources in time, frequency and code. This requires new algorithms that dynamically allocate resources in an optimal temporal, frequency and code domains in response to requests from users and according their SLA (Service Level Agreement).

Other important aspects consider necessary in the PON of the future are related to the independence of the topology, network transparency and versatility, to support the policy of centralized and distributed allocating resources. The high-capacity PON networks should make optimum use of their resources regardless of the topology and raise in the policy followed by the control of resources, either concentrated in a single device (usually in the OLT) or distributed.

There are several general techniques for communicating to multiple subscribers sharing a single PON architecture such as Time Division Multiplexing (TDM), Wavelength Division Multiplexing (WDM), Subcarrier Multiplexing (SCM), and Code Division Multiplexing (CDM). Of these multiple techniques, the authors expect that TDM and WDM to be the most promising candidates for practical future systems. While a TDM appears to be a satisfactory solution for current bandwidth demand, the combination of future data-rate projections coupled with recent advances in WDM technology may result in WDM becoming the preferred solution for a future PON.

2.1 PASSIVE OPTICAL NETWORKS (PON)

In recent years, the increase in the capacity of transport networks, together with the exponential increase in applications and services that reach residential users and small businesses, has created a bottleneck problem in the access network. Without a doubt, optical networks are presented as a necessary solution given the high capabilities that it can provide. In particular, passive optical networks (PON) are being considered as the most promising access networks, thanks to its low cost of deployment. A PON is a point-to-multipoint network without active elements in the signal path between source and destination, basically formed by optical fiber and an optical splitter/combiner (Figure 1). This will save on maintenance costs, equipment distribution, power supply and more optimal and efficient utilization of the fiber optic infrastructure.

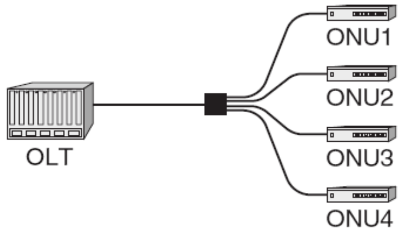


Figure 1.Passive Optical Network (Tree Topology)

Currently, there are two branches of standardization of PON according to the technology of layer 2 to be used: ITU-T and IEEE. The first one incorporates PON-based ATM such as APON and BPON (G.983.x) and based on GFP (Generic Framing Protocol) known as GPON (G.984.x). However, it is the standard of the IEEE 802.3ah which emerges as the most promising candidate for networks of broadband access for the next generation. The PON proposal is based on Ethernet (EPON), which is a widely used and known technology, adapted to IP traffic.

PON can be represented such as tree or star topologies, but it can also support topologies such as bus, ring and redundant configurations. The key element for passive optical networks is the splitter that in one direction split a beam of light into several bundles, distributed to several optical fibers, and in the other direction it combine light signals from various optical fibers to a single optical fiber output.

Another advantage of PON networks is their ability to provide a high bandwidth (of the order of 1Gbps) due to the use of fiber optic operating at a maximum distance of 20km. Because of its multi-point structure, it is possible to offer the service broadcast on download while in the upload end-users need to share the channel.

The first PON was based on the Asynchronous Transfer Mode (ATM) communication protocol; it used a shared transmission data rate of 54Mbps and was mainly designed to be compatible with existing voice and phone services – subsequently, to reflect the increase of bandwidth, APON was replaced by broadband PON (BPON). The ATM-based PON was developed towards the 90s by FSAN; it was anticipated that ATM technology was prevalent in LANs, MANs and in the backbone but ATM has failed to comply with the premise of being a low-cost technology. Both the cost and complexity were the reasons why it was quickly replaced. Moreover, it does not look like it could be the technology used in the future, due to overloading by dividing the IP packets of variable length in cells. Additionally, even if a damage ATM cell invalidates an entire IP packet, the rest of cells transmitting use resources unnecessarily.

2.2 GIGABIT-capable PASSIVE OPTICAL NETOWRK (GPON)

The GPON is specified by International Telecommunication Union – Telecommunication Standardization Sector (ITU-T) G.984 series [1]-[4]. G.984.1 recommendation describes the GPON general characteristics; G.984.2 refers to the Physical Media Dependent (PMD) layer specification; G.984.3 describes the Transmission Convergence (GTC) layer specification and finally G.984.4 provides the Optical Network Termination (ONT); Management and Control Interface (OMCI) specification.

GPON definition began in the Full Service Access Network (FSAN) consortium in 2001 with the aim of standardizing PON networks operating at rates above 1Gbs so FSAN started the generation of G.GPON.GSR – Gigabit Service Requirements, G.GPON.GPM – Gigabit Physical Media and G.GPON.GTC – Gigabit Transmission Convergence. In

September 2002 GPON Encapsulated Method (GEM) was choose as the frame transport for GPON. In January 2003 the main documents were approved, on February 2004 the rest of specification was ratified.

GPON has an improved capability compared to APON and BPON and is backward compatible. GPON can transport not only Ethernet, but ATM and TDM (including PSTN, ISDN, E1 and E3) traffic by using GPON encapsulating method (GEM).

GPON supports several line rates in both the upstream and downstream directions. It also supports legacy ATM and packet-based transport, and it is planned to support legacy efficiently, as well as current and future services through the GEM encapsulation method, which can be enhanced to support future technologies.

2.2.1 Architecture of GPON Networks

The optical access network is common to all architectures. The optical section of a local access network system can be either active or passive and its architecture can be either point-to-point or point-to-multipoint – it is possible identify some architectures whose differences are mainly due to the different services supported.

GPON identifies 7 transmission speed combinations; 155 Mbps up, 1.2 Gbps down; 622 Mbps up, 1.2 Gbps down; 1.2 Gbps up, 1.2 Gbps down; 155 Mbps up, 2.4 Gbps down; 622 Mbps up, 2.4 Gbps down; 1.2 Gbps up, 2.4 Gbps down; 2.4 Gbps up, 2.4 Gbps down. Figure 2, represents the main elements and interfaces (Service Node Interface and User Network Interface, SNI and UNI respectively) that define the general network architecture.

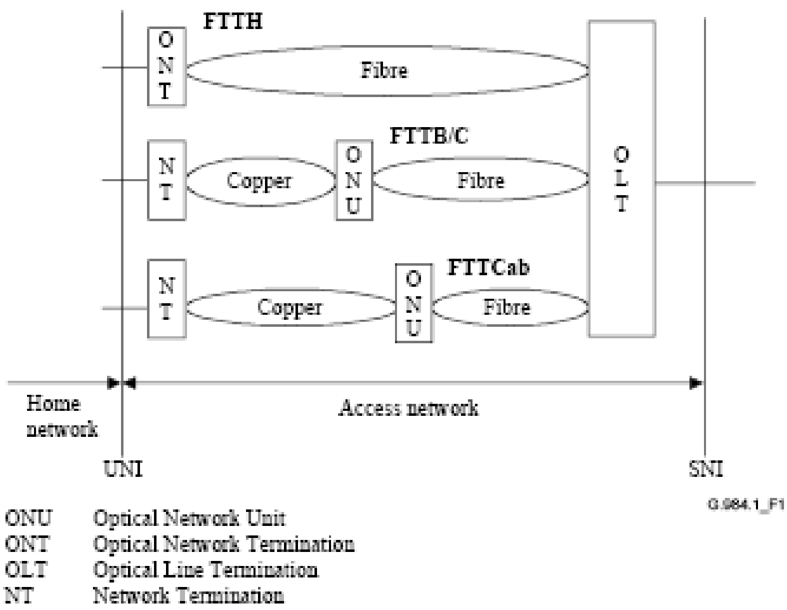


Figure 2. G.984.1 Network Architecture

GPON network architecture supports two wavelength WDM scheme for downstream and upstream digital services, but it additionally allocates another downstream wavelength for distribution of analog video service. GPON supports up to 60km reach, with 20km differential reach between ONUs, the split ratio supported by the standard is up to 128. In practice, the deployments typically would have lower reach and a split ratio limited by the optical budget.

Summarizing, GPON supports several line rates for both the upstream and downstream directions and supports legacy ATM and packet-based transport, but also has an efficient Ethernet transport capability. GPON supports packet fragmentation, enabling efficient utilization of transport media; it also provides adequate bandwidth and QoS for the residential customers and small businesses, and some of the large enterprise services can also be supported.

2.2.2 Physical Media Dependent (PMD)

The physical layer requirements and specifications for GPON are defined in the G.984.2 recommendation covering the range on GPON upstream and downstream bit rates and the optical parameters for the different rate combinations.

The nominal bit rate of the OLT-to-ONU signal is 1244.16, or 2488.32 Mbps, and the nominal bit rate of the ONU-to-OLT signal is 155.52, 622.08, 1244.16, or 2488.32 Mbps.

The operating wavelength range for the downstream direction on single fiber systems shall be 1480-1500 nm and the operating wavelength range for the downstream direction on two fiber systems shall be 1260-1360 nm. The operating wavelength range for the upstream direction shall be 1260-1360 nm.

The following Figure 3, summarizes the main aspects of the PMD layer.

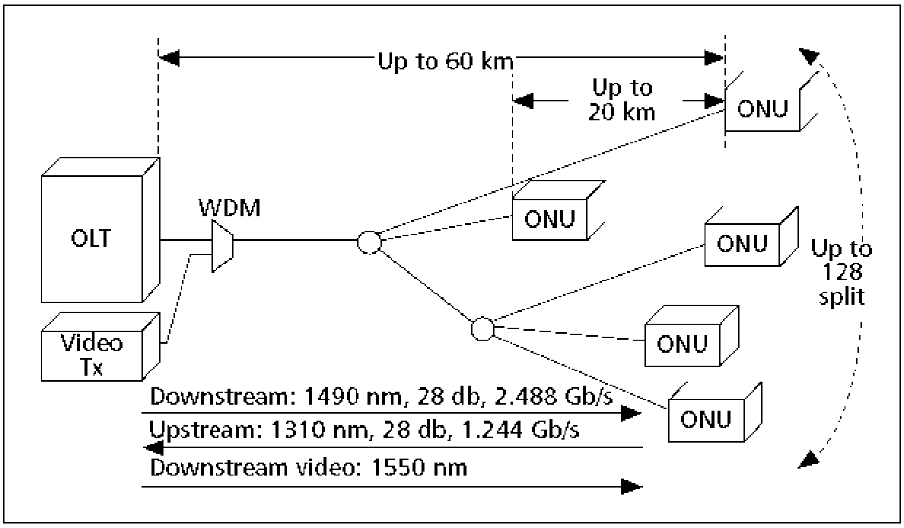


Figure 3. GPON physical network architecture

2.2.3 GPON Transmission Convergence (GTC)

GTC performs the adaptation of user data onto the PMD layer and additionally provides basic management of the GPON. The G.984.3 recommendation describes GTC functionality and deals with specifications for frame format, media access control method, ranging method, the Operations, Administration and Maintenance (OAM) functionality and finally, the issues related to the security. GTC defines two adaptation methods for data transport: on the one hand ATM, an on the other a GPON Encapsulation Method (GEM) – this method allows low overhead adaptation of various protocols, including Ethernet and Time Division Multiplexing (TDM). OLT and ONU are categorized into several types, such as ATM, GEM, and Dual mode. The G.984.3 recommendation allows all types of equipment.

The GTC layer is comprised of two sub-layers: the GTC Framing sub-layer and the TC adaptation sub-layer. From another perspective, GTC consists of a Control and Management (C/M) plane, which manages user traffic flows, security, and OAM features, and a User (U) plane which carries user traffic. In the GTC system, OLT and ONU do not always have two modes. Recognition of which modes are supported is defined at the time of system installation; the ONU reports its basic support of ATM or GEM modes through a message. If the OLT is capable of interfacing to at least one of the offered modes, it proceeds to establish the ONU Management and Control Interface (OMCI) channel in order to discover ONU capabilities, and the ONU equipment is discovered. If there is a mismatch, the ONU is ranged, but declared to be incompatible to the operations support system.

Through the following Figure 4, it is possible to identify the functional relationships and layering of GPON.

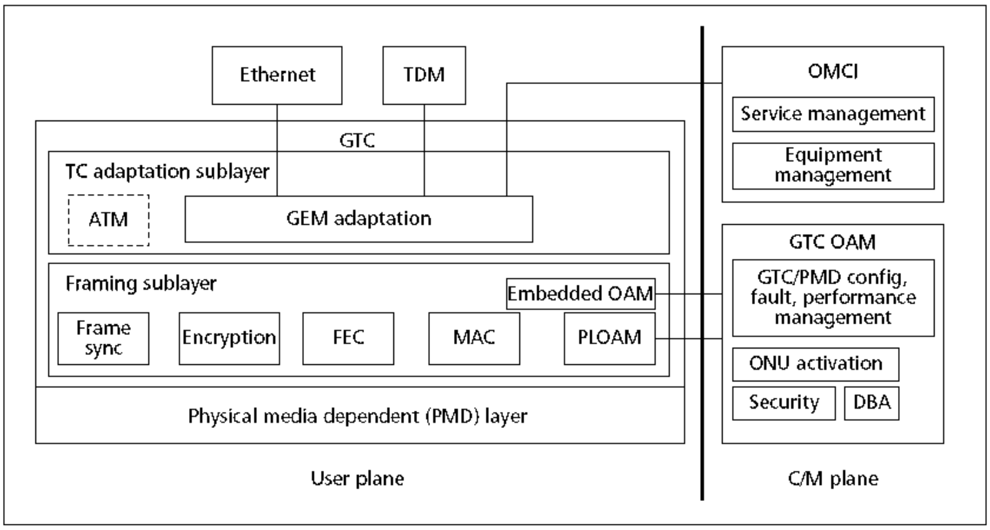


Figure 4. GPON functional relationships and layering

The control and management planes in the GTC system consist of three parts: the OAM, the Physical Layer Operations, Administration and Maintenance (PLOAM) and the OMCI. The OAM and the PLOAM manage the functions of the PMD and the GTC layers and the OMCI provides a uniform system of managing higher layers.

Traffic flows in the U Plane are identified by their traffic type and their Port-ID or Virtual Path Identifier (VPI). Traffic type can be ATM or GEM, in the downstream for ATM traffic the cells are carried in the ATM partition arriving to all ONUs. The ONU framing sub-layer extracts the cells, and the ATM TC adapter filters the cells based on their VPI, so only cells with the appropriate VPIs are allowed through to the ATM client function; for the upstream, the ATM traffic is carried over one or more T-CONTs (transmission containers) – then each one is associated with either ATM or GEM traffic, the OLT receives the transmission associated with the T-CONT identified by Allocation Identifier (Alloc-ID), and the cells are forwarded to the ATM TC adapter, and then to the ATM client. The GEM traffic flows is similar in downstream, the GEM frames are carried in the GEM partition, and arrive at all the ONUs. The ONU framing sub-layer extracts the frames, and the GEM TC adapter filters the cells based on their 12-bit Port-ID. Only frames with the appropriate Port-IDs are allowed through to the GEM client function. In the upstream, the GEM traffic is carried over one or more T-CONTs. Each T-CONT is associated with either ATM or GEM traffic. The OLT receives the transmission associated with the T-CONT, and the frames are forwarded to the GEM TC adapter, and then to the GEM client.

2.2.4 Media Access Control (MAC) flow

GTC system provides media access control for upstream traffic. This is achieved through the downstream frames that indicate the permitted locations for upstream traffic in upstream frames synchronized with downstream frames. Thus, only one ONU can access the medium at the time, and there is no contention in normal operation. The pointers are given in units of bytes, allowing the OLT to control the medium at an effective static bandwidth granularity of 64 kbps. However, some implementations of the OLT may choose to set the values of the pointers at a larger granularity, and achieve fine bandwidth control via dynamic scheduling.

Resources are assigned to every logical link, dynamically or statically. In case of dynamic resource allocation, an OLT investigates congestion status by examining the Dynamic Bandwidth Assignment (DBA) reports from ONU and/or by self-monitoring the incoming traffic. It can then allocate adequate resources.

DBA functionalities are performed in every T-CONT and are categorized into the detection of congestion status by OLT and/or ONU; report of congestion status to OLT; update of assigned bandwidth by OLT according to provisioned parameters; issues of grants by OLT according to updated bandwidth and T-CONT types; and finally the management issues for DBA operations.

There are two modes in DBA operations: SR (Status Reporting)-DBA, and NSR (Non Status Reporting)-DBA. All OLTs must support both status reporting and non-status reporting systems, so that all ONUs can provide some level of DBA functionality. To operate DBA, some parameters should be provisioned or negotiated by management functionalities i.e., the OLT and ONU agree on the DBA mode of operation, and respond accordingly to requests from each other.

The downstream GTC TC frame structure comprises the physical control block (PCBd), the ATM partition and the GEM partition. It provides the common time reference for the PON and provides the common control signaling for the upstream.

The PCBd includes framing related fields and the PLOAM field. The PLOAM carries a message-based protocol for PMD and GTC layer management. Finally, the PCBd includes the bandwidth map field specifying the ONUs' upstream transmission allocation. On the GTC upstream, each ONU transmission is headed by a physical layer overhead field (PLOu), including a preamble and delimiter, which are configurable by the OLT. To assist with dynamic bandwidth allocation (DBA), the PLOu may include the dynamic bandwidth report field (DBRu), which carries traffic queuing reports from ONUs. The PLOu may also include a PLOAM field of identical format to the downstream PLOAM. The PLOAM and DBRu are optional and present in a frame only upon OLT request.

2.2.5 GEM (G-PON Encapsulation method)

GEM is a method which encapsulates data over GPON. Although any type of data can be encapsulated, actual types depend on service situation. GEM provides connection-oriented communication as well as ATM. GEM traffic is carried over the GTC protocol in a transparent fashion. In the downstream, frames are transmitted from the OLT to the ONUs using the GEM payload partition. The OLT may allocate as much duration as it needs in the downstream, up to and including nearly all the downstream frame. The ONU framing sub-layer filters the incoming frames based on Port-ID, and delivers the appropriate frames to the ONU GEM client. In the upstream, frames are transmitted from the ONU to the OLT using the configured GEM allocation time. The ONU buffers GEM frames as they arrive, and then send them in bursts in the allocated time indicated by the OLT. The OLT receives the frames, and multiplexes them with bursts from other ONUs, passing them all to the OLT GEM client.

Figure 5, shows the protocol stack for U Plane where both the ATM and the GEM services and its respective TC and GTC sublayer can be identified.

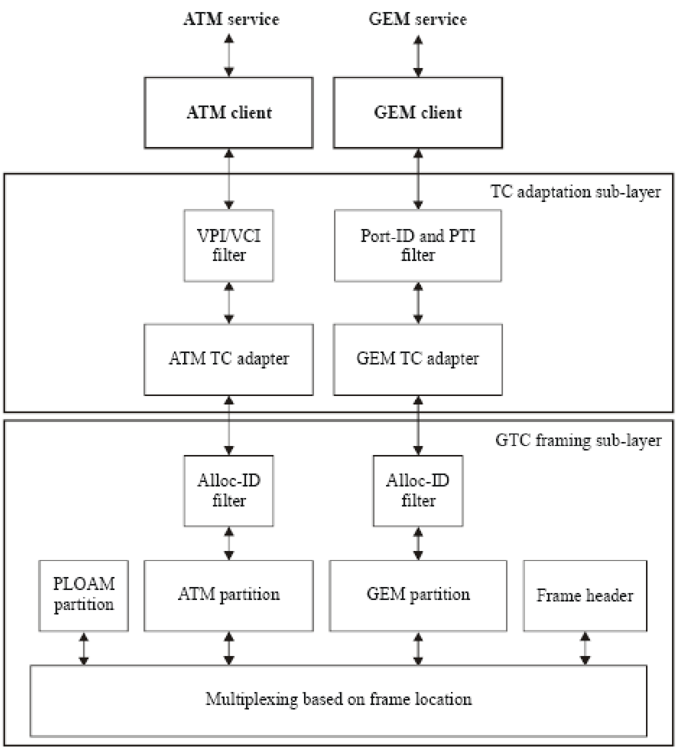


Figure 5. G.984.3 – Protocol stack for U-Plane and identification by partition and Port-ID or VPI

Until this point, the main characteristics associated to the GPON specifications have been reviewed i.e., physical and transmission layers. Also, the more significant details about the encapsulation method were presented. It is important mention the GPON management that is specified through the recommendation G.984.4 – this recommendation specifies the OMCI for the GPON system, to enable multi-vendor interoperability between the OLT and the ONT. The OMCI specification addresses the ONT configuration management, fault management and performance management for GPON system operation and for several services including ATM adaptation layers 1, 2, and 5; GEM adaptation layers; circuit emulation service; Ethernet services, including MAC Bridged LAN; voice services and wavelength division multiplexing.

OMCI comprises a full ONU management information base (MIB), and the ONT management control channel protocol (OMCC) that conveys MIB information between the OLT and ONUs. The MIB comprises a set of managed entities, each containing a set of attributes. Creation of managed entities and their attributes is designated to either the OLT or ONU. Since GPON ONUs may support a broad variety of interfaces and services, OMCI modeling is very rich in content. However, each MIB instance, representing a specific ONU, contains a small subset of objects. OMCI models physical aspects of the ONUs, such as their equipment configuration, power, and various port types, such as plain old telephone service (POTS), Ethernet, xDSL, T1/E1, radio frequency (RF) video, among others. At the service layer, OMCI covers high-speed Internet access using various flow classifications and quality of service (QoS) schemes, TDM-voice, voice over IP (VoIP), IPTV, and more. For each of those objects OMCI supports configuration, fault, and performance management.

3 STATE OF THE ART

As the Passive Optical Networks (PONs) are considered the best choice to meet the demand for broadband requirements, and the Ethernet protocol is presented with a giant impact because of its technological advantages, Ethernet-based PON solution is an interesting, suitable and attractive opportunity to deploy PON among other kind of PONs solutions, – mainly because Ethernet technology is making network managers to take advantage of their experience i.e. network management, installed equipment and analysis tools, finally because Ethernet supports all services and all media types, this represents a cost effective solution.

This section introduces an overview of the IEEE Std 802.3ah, followed by a review of DBA algorithms, and concludes with a summary of reference about proposals in literature, finally commenting on technologies of the next generation of PON that are being introduced, as well as the new contributions in terms of hybrid wireless and optical networks are presented.

3.1 EPON

Ethernet Passive Optical Network (EPON) is a PON encapsulating data with Ethernet and can offer from 1Gbps to 10Gbps of capacity; EPON follows the original architecture of a PON, where the DTE connected to the trunk of the tree is called *optical line terminal* (OLT) and it typically resides at the service provider, and the DTE connected at the branches of the tree are called *optical network unit* (ONU), located at the subscriber premises. The signals transmitted by the OLT pass through a passive splitter in order to reach the ONU and vice versa.

The standardization process started when a new study group called Ethernet in the First Mile (EFM) was created in November 2000, having as its main objectives the study of Ethernet over point-to-multipoint (P2MP) fiber along with Ethernet over copper, Ethernet over point-to-point (P2P) fiber and in addition a mechanism for network Operation, Administration and Maintenance (OAM), in order to facilitate network operation and troubleshooting. The EFM task force finishes the standardization process with the ratification of the IEEE Std 802.3ah [5] in June 2004.

IEEE standard 802.3ah specified access network Ethernet and it is also called *Ethernet in the First Mile.* Section five of the documents that make up the IEEE Std 802.3

corresponds to the definition of the services and protocol elements that permit the exchange of IEEE Std 802.3 format frames between stations in a subscriber access network. EFM introduces the concept of EPON in which a point-to-multipoint (P2MP) network topology is implemented with passive optical splitters, while Ethernet over point-to-point optical fiber offers the highest bandwidth at reasonable cost, Ethernet over point-to-multipoint optical fiber offers relatively high bandwidth at a lower cost. The purpose of the IEEE Std 802.3ah was to expand the application of Ethernet to include subscriber access networks in order to provide a significant increase in performance while minimizing equipment, operation, and maintenance costs. IEEE Std 802.3ah-2004 adds clause 54 through clause 67 and annex 58A through annex 67A.

The conclusion of the IEEE 802.3ah EFM standard significantly expands the range and reach of Ethernet transport for use in the Access and Metro networks. This standard gives service providers a diversity of flexible and cost-effective solutions for delivering broadband Ethernet services in Access and Metro networks.

EFM covers a family of technologies that differ in media type and signaling speed – it is designed to be deployed in networks of one or multiple EFM media type(s) as well as interact with mixed 10/100/1000/10000 Mb/s Ethernet networks. Any network topology defined in IEEE Std 802.3 can be used within the subscriber premises and then connected to an Ethernet subscriber access network. EFM technologies allow different types of topologies in order to obtain maximum flexibility.

3.1.1 IEEE Std 802.3ah

Section five of the IEEE Std 802.3ah includes the specifications related to the Ethernet for subscriber access networks and according to IEEE Std 802.3ah an EPON supports a nominal bit rate of 1Gb/s (extensible to 10Gb/s) for each channel which are defined by two wavelengths: one wavelength for the downstream and the other one for the upstream direction shared among the user devices. EFM supports only full duplex links so a simplified full duplex Media Access Control (MAC) was defined. Ethernet architecture divides the Physical Layer into a Physical Media Dependent (PMD), Physical Medium Attachment (PMA) and a Physical Coding Sublayer (PCS).

EPON implements a P2MP network topology along with the appropriate extensions to the MAC Control sublayer and Reconciliation sublayer, as well as optical fiber Physical Medium Dependant sublayers (PMDs) to support this topology.

Figure 6, shows the relationships between EFM elements and Open system Interconnection (OSI) – a reference model for P2MP topologies.

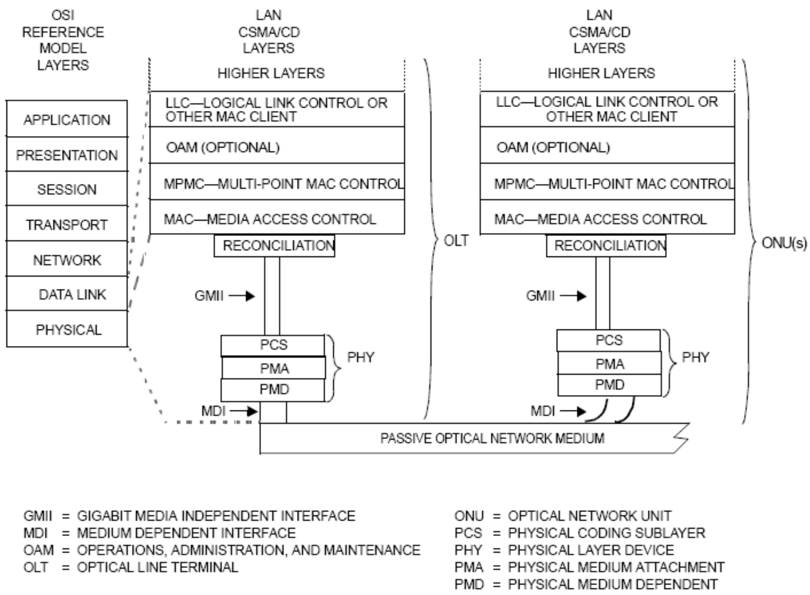


Figure 6. IEEE 802.3ah Architectural positioning of EFM: P2MP Topologies

3.1.2 PHYSICAL LAYER

For P2MP topologies, EFM introduces a family of Physical Layer signaling systems which are derived from 1000BASE-X, but which include extensions to the RS, PCS and PMA, along with an optional forward error correction (FEC) capability. 1000BASE-X PCS and PMA sublayers map the interface characteristics of the PMD sublayer (including MDI) to the services expected by the Reconciliation sublayer. 1000BASE-X can be extended to support any other full duplex medium – requiring only that the medium be compliant at the PMD level.

Medium Dependant Interface (MDI) is the interface between the PMD and the physical media; it specifies the signals and the physical media and the mechanical and electric interfaces.

Physical Medium Dependent (PMD) is in charge of the interface with the transmission medium. PMD generates electrical or optical signals depending on the nature of the physical medium connected. 1000BASE-X connections over PONs up to at least 10km and 20km (1000BASE-PX10 and 1000BASE-PX20 PMD sublayers) provide P2MP. In an Ethernet PON, the suffixes D and U indicate the PMDs at each end of a link, which transmit in these directions and receive in the opposite direction i.e., a single downstream PMD is identified as 1000BASE-PX10-D and upstream as 1000BASE-PX10-U PMD. The same fibers are used simultaneously in both directions. A 1000BASE-PX-U PMD or a 1000BASE-PX-D PMD is connected to the appropriate 1000BASE-X PMA and to the medium through the MDI. A PMD is optionally combined with the management functions that may be accessible through the management interface. In order to allow upgrade possibilities in the case of 10km or 20km PONs, both 1000BASE-PX20-D PMD and 1000BASE-PX10-U PMD are interoperable with each other.

The *Physical Medium Attachment* (PMA) includes the transmission, reception, clock recovering and align functions. The PMA provides a medium-independent means for the PCS to support the use of a range of serial-bit-oriented physical media.

The *Physical Coding Sublayer* (PCS) includes the codifications bits functions. The PCS interface is the Gigabit Media Independent Interface (GMII) that provides a uniform interface to the Reconciliation sublayer for all 1000 Mb/s PHY implementations.

The *Gigabit Media Independent Interface* (GMII) refers to the interface between the MAC gigabit layer and the physical gigabit layer. It allows that multiples DTE mixes with a variety of implementations from the physical layer gigabit speed. The PCS Service Interface allows the 1000BASE-X PCS to transfer information to and from a PCS client. PCS clients include the MAC (via the Reconciliation sublayer) and repeater. The PCS Interface is accurately defined as the Gigabit Media Independent Interface (GMII).

The *Reconciliation Sublayer* (RS) provides the mapping of the GMII signals to the definition of the service access control medium. The Reconciliation sublayer maps the signal set provided by the GMII to the Physical signaling service primitives provided by the MAC. GMII and RS interface are used to provide media independence so that an identical media access controller may be used with any of the copper and optical PHY types.

3.1.3 DATA LINK LAYER. Multipoint MAC Control

The MAC Control protocol was specified so that, in such a way that it can support new functions to be implemented and added to the standard in some time – such is the case of the Multi-point control Protocol (MPCP). The management protocol for P2MP is one of these functions, so Multi-point MAC Control defines the MAC control operation for optical point-to-multipoint networks. The Multipoint MAC Control functionality shall be implemented for subscriber access devices containing point-to-multipoint physical layer devices. Commonly, MAC instances offer a point-to-point emulation service between the OLT and the ONU but an additional instance now is included with a communication purpose for all ONUs at once.

The functions that comprise Multi-point MAC Control are grouped in different blocks that are identified such as: the Multi-point Transmission Control that synchronizes the instances associated with the Multi-point MAC Control, and also controls its multiplexing functions, the Multi-point MAC Control Instance *n* holds the variables associated with operating MAC control protocols for a particular instance, the Control Parser is where MAC control frames are analyzed and where the interface to the MAC client is, the Control Multiplexer is in charge to forwarding the frames i.e., selecting the source of the forwarded frames and finally, those functions that are involve in the MPCP and will discussed later.

A Multi-point MAC control instance is made up of one instance but the OLT will have several instances, depended on the number of the ONUs attached to it – if OLT have associated multiple instances, the Multi-point MAC Control block will be employed at the OLT to synchronize the instances. On the contrary, on the ONU side there would only be one Multi-Point MAC Control instance.

3.1.4 MPCP

One of the functional blocks of the Multi-Point MAC Control includes those related to the MPCP functions, which allow the negotiation of access to the environment through the exchange of control messages. On the one hand, the ONU may request their immediate requirements of bandwidth; and on the other, the OLT allocates the start and duration of ONU transmission. The method to be followed to coordinate the different time slotted for each ONU transmission and manage the available resources in accordance with certain requirements of quality of service, is left open for its implementation. MPCP specifies a control mechanism between two units connected to a P2MP network to allow efficient transmission data.

Through the Multi-point MAC Control is possible for a MAC client to participate in a point-to-multi-point optical network because that is the way to transmit and receive frames as it was a connection point-to-point i.e. MAC client through the Multi-point MAC Control sublayer –which decides when a frame will be transmitted – transmits and receives frames. The medium is shared by multiple MACs – a single MAC is allowed to transmit upstream at any given time using time division multiple access method, and this is achieved through the Gate processing function.

Through the discovery processing function new ONUs are discovered in the network and by means of the report processing function it is possible achieved a feedback mechanism.

MPCP introduces new control messages; GATE and REPORT messages are used to assign and request bandwidth respectively; REGISTER is used to control the process of self-discovery; taking into consideration that the main functions of the ONUs are to perform the process of self-discovery and requested bandwidth to OLT – the OLT in turn, generates discovery messages, controls registration process and allocates bandwidth.

The discovery process aims to provide access to the PON to those newly connected or to the off-line ONUs. The OLT performs a periodical discovery time window in order to offer the opportunity to those unregistered ONUs to be active, so that the OLT broadcasts a discovery gate message, which includes the starting time and length of the discovery window. ONUs, upon receiving this message, wait for the period to begin and then transmit a REGISTER_REQ message to the OLT. The offline ONUs, after receiving the gate message, will be registered during the previously establish window – this window is unique because this is the only time when the ONUs without specific grant window are able to communicate with the OLT.

Figure 7 shows the discovery handshake message exchange that is performed during the discovery process. To reduce the probability of overlapping, each ONU shall wait a random time, shorter than the discovery time window before transmitting. The REGISTER_REQ message contained an ONU MAC address and a number of maximum pending grants; the OLT registers the ONU assigning a new port identity (LLID) and sends a standard GATE message allowing the ONU to transmit a REGISTER ACK message – from this point, OLT can schedule the ONU for access to the PON.

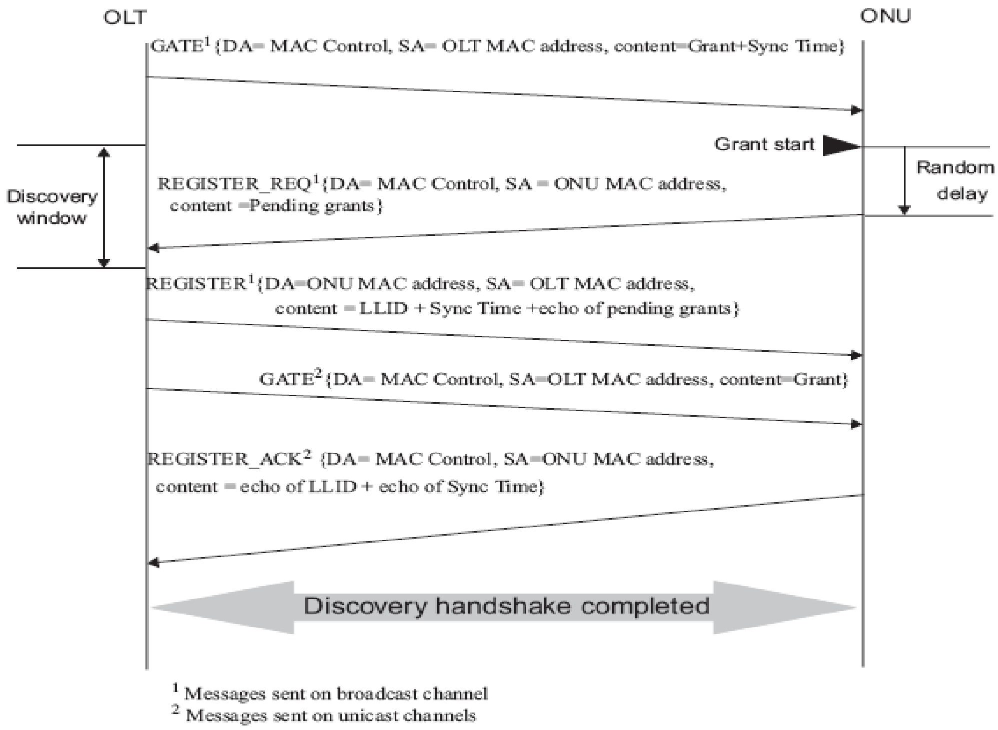


Figure 7. IEEE 802.3ah Discovery Handshake Message Exchange

Reports have to be generated periodically even when no request for bandwidth is being made – OLT shall grant the ONU periodically, so as to keep a watchdog timer in the OLT that prevents it from expiring and deregistering the ONU. Report process is responsible for taking bandwidth requests generated by higher layers and sending them to the OLT – it will then decide whether to grant the bandwidth request.

Report messages have several functionalities other than requesting bandwidth – for example, the time stamp for round trip time calculation, also used as keep-alive to maintain link health.

The transmission window of an ONU is indicated through the gate message, it includes the start time and the length of the transmission granted, the gate process is performed by the OLT, not just to assign a transmission window but also to maintain the watchdog timer at the ONU – if this is the case, grant messages are generated periodically.

The way the OLT distributes the bandwidth depends on a medium access mechanism implemented by a dynamic bandwidth allocation algorithm (DBA), which is outside the standard and is left free to the implementation of the manufacturer, the provision of quality service is also free. For this reason, mechanisms to distribute the bandwidth are of great interest in DBA design currently, taking into consideration the quality of service parameters, as well as the improvement of the efficiency of the channel and the justice.

3.1.5 OPERATION, ADMINISTRATION AND MANTAINANCE (OAM)

The OAM provides data link layer mechanisms that complement applications that may reside in higher layers. OAM sublayer provides useful mechanisms for monitoring the link operation; it also provides network operators with the ability to monitor the health of the network and quickly determine the location of failures. OAM does not include functions such as station management, bandwidth allocation or provisioning functions, which are considered outside the scope of the IEEE Std 802.3ah. Implementation and activation of OAM is optional, so a mechanism is provided to perform OAM capability discovery, and an extension mechanism is provided and made available for higher layer management applications. Some physical layer devices have specific remote failure signalling mechanisms in the physical layer. OAM includes vendor extension mechanisms to provide a convenient and lightweight method to manage the additional functionality; this can lead to differing OAM variants as carriers customize their products.

Subscriber access physical layer devices in P2MP networks support unidirectional operation in the direction from the OLT to ONU that allows OAM remote failure from OLT during fault conditions but not all physical layers devices support unidirectional operation allowing OAM remote failure indication during fault conditions some of them have specific remote failure signaling mechanisms in the physical layer.

Figure 8 shows where the OAM sublayer is located – it is also represented as an optional sublayer between MAC Control sublayer and MAC Client.

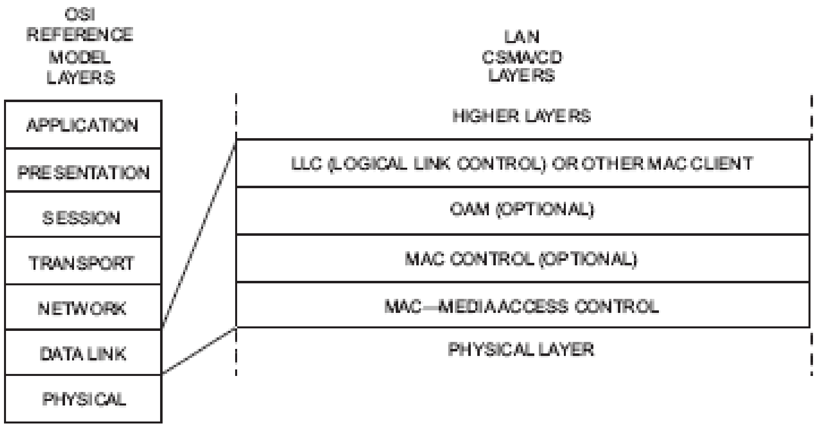


Figure 8. IEEE 802.3ah OAM sublayer relationship to the ISO/IEC Open Systems Interconnection (OSI) reference model and the IEEE 802.3 CSMA/CD LAN model

3.2 DBA EPON

IEEE Std 802.3ah specify the so-called multipoint control protocol which arbitrates the channel access among central office and subscribers (OLT and ONU) but is essential to specify a particular resource allocation mechanism to manage and distributed fairly the resources, not just bandwidth but also channels in the case of multichannel architecture.

The process of communication from the OLT to the ONUs is regarded as downstream; in downstream data are broadcast using the entire bandwidth and ONUs receive frames by matching the address in the Ethernet frames, and on the contrary, the upstream communication from the ONUs to the OLT, multiple ONUs share the common channel which means that in order to avoid data collisions only a single ONU may transmit. Effective bandwidth allocation schemes are required to assign resources equally but also to ensure the QoS. To guarantee the efficiency and scalability of EPON in terms of resource management numerous contributions has been presented to solve the different challenges that bandwidth allocation suppose.

"An algorithm implemented in the OLT, which uses Report and Gate messages to construct a transmission schedule and convey it to the ONUs is know as a Dynamic Bandwidth Allocation (DBA) algorithm" [6].

There are two main strategies of bandwidth allocation, the fixed bandwidth allocation (FBA) and dynamic bandwidth allocation (DBA) the first one assign the same time slot to every ONU in every service cycle, i.e., ONU will absorb the upstream channel for its assigned time slot even if there is no frame to transmit, is a simple scheme but time delay in other ONUs increase causing throughput decrease. Contrast to the FBA, the DBA assign the bandwidth based on the requested bandwidth by each ONU, hence the DBA scheme provide more efficient bandwidth allocation.

This section is intended to show a kind of survey about the proposals of DBA algorithms, first, the different classifications in which we can locate the algorithms but also the characteristics that a DBA should follow will be presented, then the major contributions will be discussed and finally a comparative table can be generated in order to summarize the proposals. One proposal generated in the BAMPLA research group of UPC is explained, emphasizing the novel ideas against other algorithms and performing and showing the results of simulations.

3.2.1 DBA Characteristics.

An important feature that EPON is expected to provide is the capacity to deliver different services such as multimedia traffic with special QoS requirements, different DBA algorithms to effectively and fairly allocate bandwidth should have characteristics as business transparent to meet the demands of current and future applications and the high bandwidth utilization. EPONs require accommodate various kinds of traffic and due to differences in subscribers service level agreements, ONUs may have different bandwidth requirements.

In [7] an overview of different DBA algorithms is presented and as conclusion two key challenges that a DBA development should deal are presented, the first is refer to accommodating traffic fluctuations and second one to providing QoS to the different kinds of traffic. On the other hand in [8] characteristics such as avoid frame collisions, maximize available bandwidth for each subscriber, manage real-time traffic through an efficient QoS policy and decrease delay of low priority traffic are the main characteristics that any DBA algorithm should have. As each ONU provide multiple services to its different end users the combination of different techniques like queuing, scheduling and QoS based bandwidth allocation should be considered to developed an efficient DBA.

In order to facilitate the implementation of a DBA algorithm the MPCP does not specify any particular DBA, thus bandwidth management for fair bandwidth allocation among different ONUs will be a key requirement for MAC protocols. QoS support is an imperative requirement that EPON expected provide to deliver the emerging IP-based services. The basic concept of DBA relies on the possibility to allocate dynamically upstream bandwidth based on customer activities, it makes possible for operators not just share between users a common channel but also a common transmission capacity that involves an imperative requirement for MAC protocols for EPON.

"The challenge in designing a DBA algorithm lies in developing an algorithm that is practical, simple, efficient and meets service provider requirements" [6].

3.2.2 DBA Classification.

Bandwidth allocation can be categorized under two types of schemes: DBA and FSA, it is not possible to deal with the demands that some applications require with the second one; therefore, all contributions in bandwidth allocation to EPON are under a DBA scheme. There are at least a hundred up-to-date papers related; many of them are proposals of DBA algorithms, others are discussions or comparisons about them.

The most basic categorization that can be identified according to the different proposals is a centralized or a distributed approach. The centralized approach involves just one of the elements in an EPON, for those operations related with the computation of bandwidth allocation, usually OLT. This way, it is easy to adapt changes in the scheduling process, according to the requirements of certain networks, and in the ONU side new settings or parameters are not required to synchronize. On the other hand, the functions of the algorithm involve the participation of both OLT and ONU. Most contributions are based on a centralized approach, and although the participation of both sides is required in those cases where QoS is supported, OLT can perform the entire DBA role.

Within this basic classification it is possible to locate any algorithm, and once categorized, to highlight other ways of classification, e.g. some algorithms take into account the service level agreement (SLA) as a way to guaranteeing a minimum degree of service; other algorithms are categorized according to whether they implement some prediction of arrival packets in order to base the allocation on that estimation, thus avoiding packet delay, meeting the QoS requirements and avoiding the degradation of the network performance. Algorithms that base the scheduling techniques in well-known strategies or proposed novel techniques can also be found.

In terms of scheduling, another classification can be identified: the inter-ONU or intra-ONU, which refers to the location where the scheduling technique is performed, as shown in figure 9 [9], i.e. OLT or ONU respectively, but some proposals perform even both. When a proposal deals with QoS, it can be located under this classification. A centralized DBA in OLT also can be called inter-ONU because the computation of allocation is performed in the OLT in order to assign the bandwidth among ONUs. When an ONU hosts many users that demand different classes of services, or when a SLA is established, the ONU defines queues with different priorities, so that an intra-ONU scheduler can be used, therefore making possible the development of a centralized DBA algorithm with intra-ONU scheduler. An EPON scheduler should consider any case when a user presents wrong behaviors that can produce an impact among others users.

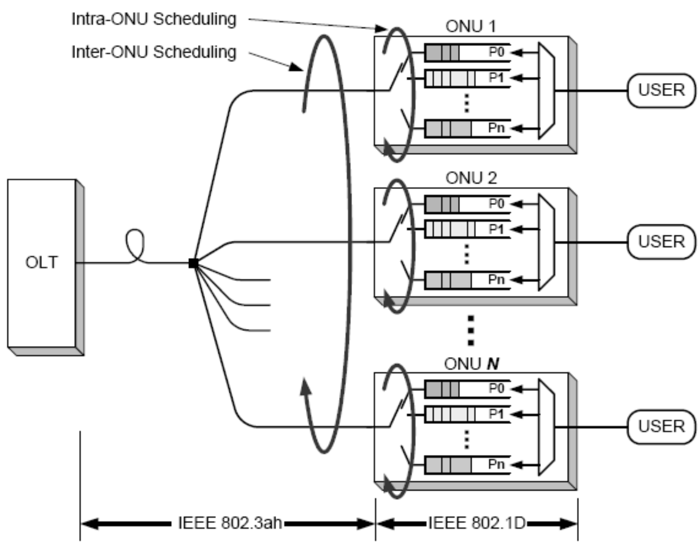


Figure 9. Intra-ONU and inter-ONU scheduling

The classification above is based on what the proposals show. This document takes into consideration the study, in a categorized way, of the most representative algorithms found in literature up to now, so that the following section summarizes those proposals of DBA algorithms that can be found under some of the classification described before. Prior to proceeding summarizing proposals, it is important to mention that [7] was presented as a taxonomy of DBA algorithms, and it has been cited in various proposals for placing the algorithm within a certain taxonomy, or simply as a reference.

In [7], DBA algorithms for EPON are categorized into algorithms with statistical multiplexing and with QoS assurances – the latter is also categorized into algorithms with absolute or algorithms with relative QoS. Statistical multiplexing methods are simply to implement but do not support priority scheduling. OLT allocates bandwidth according to the ONU request but without distinguishing between traffic priorities, i.e. it does not perform inter-ONU scheduling. In contrast, algorithms with QoS assurances can prioritize bandwidth according to traffic classes, e.g. the absolute QoS assurance is characterized by their SLA, this being the way to specify the bandwidth guarantee to some node. In [7], the most representative examples up until then were presented according to that categorization.

McGarry et al. recently review and classify the existing architectures and DBA for EPON [10], they use a different taxonomy to classify their research. The taxonomy consists of three major branches: the grant sizing, which determines the length of the transmission windows assigned to an ONU for a given grant cycle, the grant scheduling, it determines the order of ONU grants for a given cycle, namely, inter-ONU scheduling; and the queue scheduling, which is concerned with scheduling the individual queues at an ONU.

In [11], the authors review the studies conducted in EPON and classify it according to the main issues addressed in the different proposals. Figure 10 shows the criteria in which a bandwidth allocation scheme can be classified. Classification includes characteristics that will be discussed in the next section.

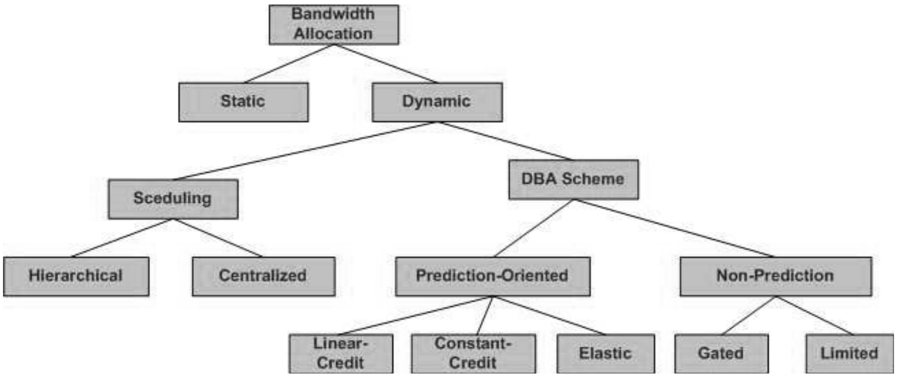


Figure 10. Classification of DBA schemes

As it already has been mentioned, is mandatory to consider QoS in DBA algorithms development. The most representative categorization of it is based on the distinction between those proposals were QoS is implemented, but also where the QoS is managed (OLT or ONU), so that the following summary of DBA algorithms is presented in such a way that the proposals with similar characteristics are grouped.

3.2.3 DBA Algorithms

In recent years, several proposals of DBA in EPONs have been studied. Some relevant findings will be explained here. As an introduction for this section it is important to present an overview of the scheme regarded as one of the early works to dynamically allocate bandwidth in EPON. Its performance has been compared against many latter proposals – it was presented in [12] by Kramer et al. in 2002 and is called Interleaved Polling with Adaptive Cycle Time (IPACT).

The IPACT scheme can be categorized as a centralized approach where the entire scheduling and bandwidth allocation algorithm are located in the OLT [12]; here, the OLT polls ONUs to assign bandwidth according to its needs, ONU distributes its bandwidth among all traffic classes without notifying OLT. The ONU request is granted by the OLT, based on the previous polling cycle – that is why the packets arriving after the request will be delayed at least to the next polling cycle, even when arriving in the same polling cycle. The cycle period adjusts to the bandwidth requirements of the ONUs, and the definition of a maximum transmission window allows that ONUs with high traffic degree do not monopolize the bandwidth resource.

The scenario where an algorithm takes part is as follows: at the beginning, OLT knows how many packets are waiting in the ONUs buffers and the corresponding round-trip time (RTT), so OLT broadcasts a grant message. ONUs start their transmission accordingly with granted window and continue receiving and keeping the new packets, so that at the end of their transmission they will generate their new request based on the packets received so far. OLT knows when each packet of any ONU will arrive, so it can schedule a grant to the next ONU but with a small guard interval in between. The information received from the ONUs and its RTT is stored in the polling table. Each ONU performs the same procedure, characterized by the Grant message, while the scheduling and the DBA algorithm are located and performed in the OLT.

In [12] some methods to determine the transmission window size, according to the ONUs request, have been proposed e.g. limited service, this algorithm allocates the bandwidth to an ONU but no more than a predefined value, i.e. the maximum transmission window; the gated algorithm grants the request without any limitation;

credit algorithm grants the request plus a constant credit (previously agreed or proportional to the request); and finally, an elastic algorithm where the only limitation is the maximum cycle time.

The most efficient is the limited service where the transmission window is obtained from the minimum between the predefined maximum transmission window or the transmission window requested. IPACT does not support service level agreements (SLA) and cannot support QoS for services that are sensitive to time delay; therefore, IPACT is not a suitable algorithm for several services.

To address QoS in DBA algorithms, some other algorithm proposals were published, e.g. in [13], bandwidth is allocated but according to traffic priority requests. The algorithm follows a strict priority scheduling approach based on satisfying mainly all the requests of high-priority flows, because a fixed bandwidth window is assigned for high priority services even if there are not frames to transmit. OLT centralize all the functions of DBA, and ONUs are responsible of reporting the queue occupancies.

Kramer et al. in [9] combined IPACT and strict priority queuing in order to support QoS, also identifying the light-load penalty phenomenon, it is produced when packets arrive during periods when ONU is reporting queues states or receiving a grant, causing delay on some lower priority packets in queue if arriving packets have higher priority. The proposal consists of an inter-ONU and intra-ONU scheduling, but is a centralized approach, while the allocation bandwidth is performed in OLT. Through the intra-ONU scheduling, is possible to arbitrate the transmission from the different flows in such a way that it avoids the light-load penalty. The proposal raises two ways to overcome the problem: the first consists on two-stage scheduling – one stage for multiple priority queues and a second stage just for on FCFS queue – thus ONU request a window transmission equivalent to the FCFS queue. During transmission the packets in first stage change to the next stage, i.e. FCFS queue, it represents the following transmission window request. There is a problem with this solution, mainly because high priority packets experience further delay. The second option to overcome the light-load penalty can be throughout estimation of the high priority arrivals, it requires having some knowledge about traffic behavior; in essence, OLT assign the requested transmission window plus an additional window based on that estimation.

A similar approach to the previous one was proposed by Assi et al. in [14], in which the first contribution under the limited bandwidth allocation approach, introduced in IPACT, consists of taking the excessive bandwidth, obtained from those ONUs that have less traffic to transmit of the minimum guaranteed bandwidth, and fairly distribute it among the highly loaded ONUs. This algorithm takes into consideration different traffic classes, so that requested bandwidth consists of high, medium and low priority. On the other hand, to prevent the light load penalty, estimation is also performed, but in this case the ONU is responsible of estimating the bandwidth that its high priority traffic can require. The estimation is based on traffic arrived in previous cycles. Finally, the algorithm also incorporates a special characteristic in order to reduce the time in which bandwidth allocation and computation of grant messages are performed, at least for those ONUs for which the requested bandwidth is less than the minimum guaranteed, since these does not require wait to be schedule – grant is sent immediately.

In [15], a different way to address the QoS is presented. The algorithm can minimize the delay for high priority traffic through the allocation of a constant bandwidth in each frame for it, the solution consists on dividing the cycle in two service classes: one part will be for high priority and the remaining part for low priority, so the cycle is divided into fixed and dynamic, when network load is low more than one ONU can transmit their low priority traffic in the dynamic part – otherwise, if network load is very high OLT just assigns for one ONU. High priority traffic may become variable so that ONU needs to redirect the excess of it into the dynamic part of the low priority. This proposal considers a fixed cycle size, hence the bandwidth reserved for an ONU is shared only by its subscribers and the remaining cannot be used by other ONUs.

Xie, et al. in [16] also proposes the division of the frame, but in this case the frame is divided into multiple subframes according to the different traffic classes in order to reduce the delay of high priority and medium priority classes; the size is variable depending on the request, and through the definition of weights for each class is possible to avoid bandwidth monopolization.

The algorithm considers three service classes; therefore the frame is divided into three subframes. Because the bandwidth demand is variable in every cycle, the subframes sizes are variable too, but the cycle size is fixed. Weights determine the proportion of bandwidth among service classes; it can be dynamically adjusted by the OLT if it wants to increase the throughput of some class. The frame or cycle format is shown in figure 11 [16]. Within a service class, the bandwidth distributed is based on the max-min fairness policy. The problems presented in this proposal are related to guard times that suppose an underutilization of bandwidth and also the time that OLT have to wait while all requests from different ONUs arrive.

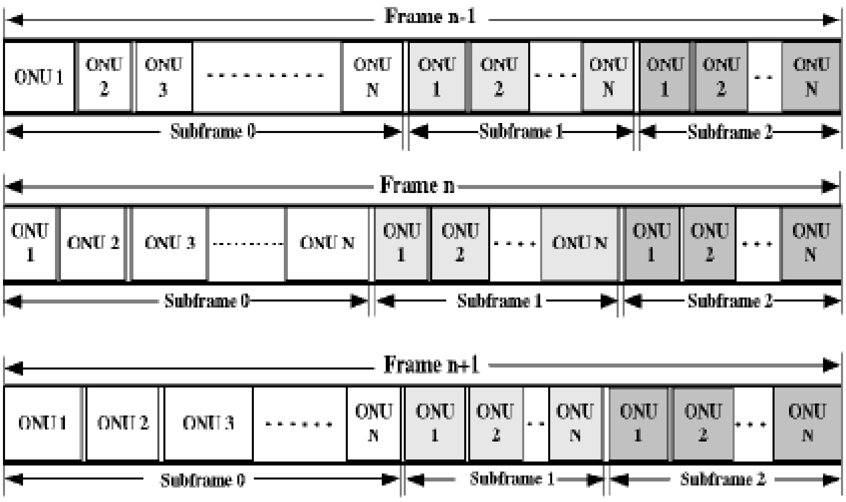


Figure 11. Frame Format

Some algorithm proposals are service level agreement aware, i.e. based allocation on its SLA. One of the first contributions of this kind was presented in [17], the method proposed was called Bandwidth Guaranteed Polling (BGP) and is based on the combination of fixed and dynamic approach. In BGP, ONUs are categorized such as bandwidth-guaranteed ONUs and non-bandwidth-guaranteed, the bandwidth guaranteed is characterized by the SLA. The total upstream bandwidth is divided into equivalent bandwidth units; it also indicates a fixed cycle length that will be distributed among ONUs – but in case of bandwidth-guaranteed ONUs, according to the SLA, can obtain more than one unit. If one of them is not occupied it can be assigned to the best effort traffic. OLT performs the allocation bandwidth functions so that the approach is considered centralized; OLT maintains two table entries, one for guaranteed and another for non-guaranteed. OLT polls ONUs according to the sequence in the entry table; when one entry is not allocated to a guaranteed-bandwidth ONU it can be used to poll other entry table corresponding to best effort and allocate bandwidth. The algorithm guarantees bandwidth for high-demand users and also can provide QoS according to its SLA. The clearest disadvantage is that, due to the fixed bandwidth units that represent the use of more guard times, throughput reduction can be caused.

In [18] through the cyclic polling, i.e. every ONU is polling periodically, is possible support SLA such as minimum and maximum bandwidth. Polling process looks like in Figure 12. As was addressed in [13] traffic is categorized in high, medium and low priority, the bandwidth of high priority classes is constant and the rest is proportionally distributed. Simulations results shown a constant delay for high priority classes for different loads and does not show a light-load penalty.

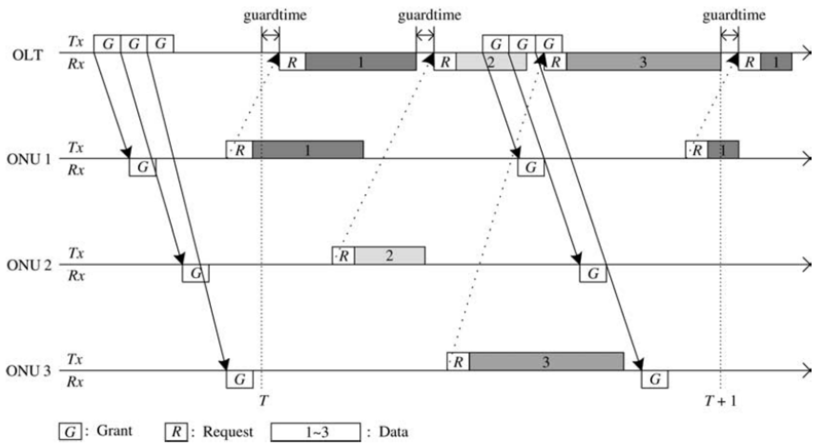


Figure 12. Cyclic polling algorithm

Nowak et al. proposed in [19] a new approach where support of SLA is addressed. This is a strict centralized approach where the resources are allocated by OLT to a particular queue rather than to an ONU, thus ONU remain as simple as possible. The allocation process consist of two stages: in the first, a proportional allocation of bandwidth based on classes of traffic is performed, and then to met the SLA a second stage is performed to ensure the demand of bandwidth of certain classes, i.e., a minimum and maximum bandwidth guaranteed is demand for certain queues according to its SLA. Firstly, OLT assigns a number of bytes proportionally to the reported queue length, then the constrains in SLA are applied according to different situations, e.g. if number of assigned bytes exceeds the maximum number of bytes guaranteed, an adjustment is perform, thus the number of bytes allocated will be the maximum guaranteed. On the other hand, when the bandwidth allocated in the first stages is smaller than the minimum and queue length is greater than the bandwidth allocated, it will be adjusted to be equal to the queue length. Another contribution of this approach is the grant multiplexing mechanism showed on Figure 13. In order to maintain good traffic parameters for the high priority classes time-slots for high priority queues from different ONUs are granting at the beginning of the granting cycle and thus is possible to reduce the jitter to high priority queues.

Similar to algorithm [19] some proposals are characterized by performed allocation bandwidth directly to a queue e.g. in [20] an algorithm called Fair Queuing with Service Envelopes (FQSE) expects to provide fairness among each queue independently of its parent node (ONU). FQSE algorithm guaranteed a minimum bandwidth and shares the excess of bandwidth fairly. Allocation is performed based on demands of all the queues and proportionally to its weights, therefore should be possible provide different levels of QoS. The proposal introduces a concept named service envelope and also a satisfiability parameter, the service envelope represents the amount of service given to a node as a function of some nonnegative value which is the satisfiability parameter. Each node has associated its service envelope function, so each intermediate node collects service envelopes from its nodes, i.e. nodes that depend on it, and based on that, they generate their own service envelope and then send them to their parent. Once the OLT receives service envelopes from its children's it is capable to calculate its own service envelope. This in turn will allow the definition of the size of the cycle, as well as knowing the start time cycle and the satisfiability parameter for each node. A drawback of this scheme is the message processing delay at each level in the hierarchy and the delay experienced by some packets, because allocation is performed in every queue at the end of each cycle. The solution of the last drawback can be handled through implementation of two groups of nodes, in which those nodes which required a fixed guaranteed bandwidth may belong to one group an the rest can be grouped in the other one. This solution will also allow a SLA aware behavior since groups can be defined according to SLA demands.

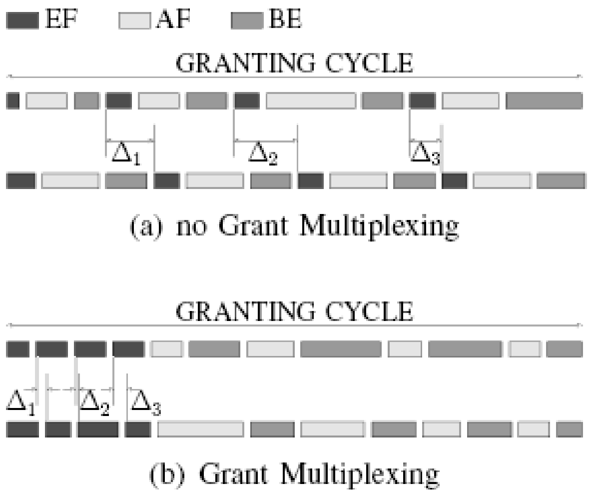


Figure 13. Bandwidth assignment with and without Grant Multiplexing

A later proposal SLA aware was presented by Kramer et. al. in [21], inspired by the "open access" framework [22] in which users are free to choose what services they need and the corresponding service providers, the service providers are able to solicit subscribers and deliver services to same or different sets of users which leads to the requirement of fair allocation of network resources among both service providers and users. In open access networks there are a clear demarcation between the network operators, who provide physical connectivity and transport data, and the service providers who deliver content and services thus the fairness challenge is not just among users but also for service providers.

In [21] a dual SLA method for achieving fairness in an open access for EPON was investigate, but as its framework involves the upstream and the downstream fairness the implementation of dual SLAs become a challenge. Dual SLA incorporates both user and service provider SLAs, but as the sum of both of them may exceed the channel capacity it could be not possible to meet both – therefore, a primary and secondary SLA in which those who specified minimum guarantees must be give the highest priority.

The algorithm proposed only consider the downstream traffic for the service provider to users, at OLT there is a queue for traffic corresponding from each service provider to each user - thus the objective is to schedule from each of the queues by granting a window into the fixed cycle according the SLA requirements. The Dual SLA scheduling algorithm is shown in the following figure 14.

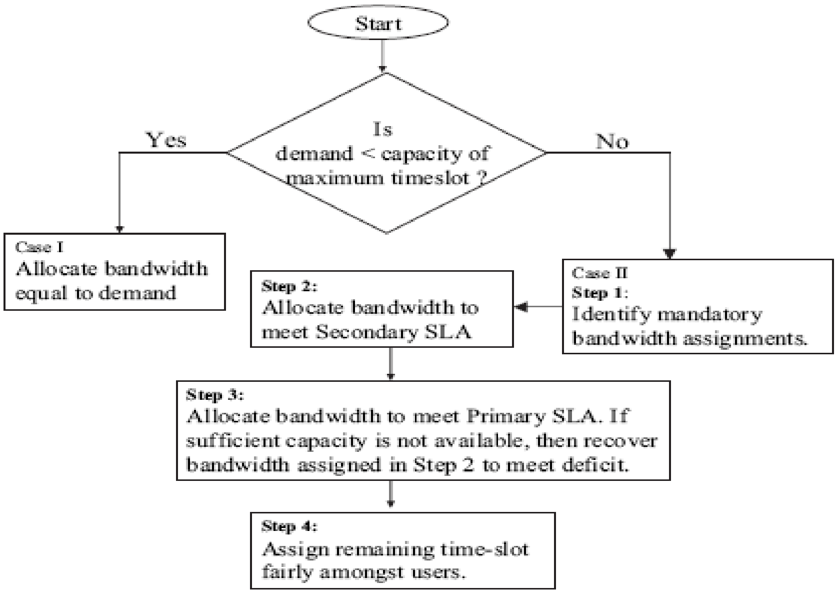


Figure 14. Flowchart for Dual-SLA Scheduling Algorithm

When demand is greater than available capacity, the objective should be first meet the primary SLA; then try to meet the secondary SLA - but if is not possible, the deficit in meeting the SLAs for each SP should be fair; and finally remaining capacity is fairly distribute.

Different approaches are combined to strengthen a DBA algorithm: the classes of services, SLA parameters, the request or assignment based on estimation, among others. The following algorithm descriptions are focused on the estimation of bandwidth as main characteristic; these proposals consist of trying to predict how many bytes an ONU will hold at the moment its transmission window begins, in order to decrease packet delay. An illustrative example where the packets arrive in waiting time causing packet delay is shown in figure 15 [14]; the ONU sends a report message based on its current buffer occupancy, OLT allocates a window transmission indicating the time to start transmission, during waiting time more packets may be arriving so its transmission is deferred to the next cycle causing additional delays that some traffic delay-sensitive can not tolerate.

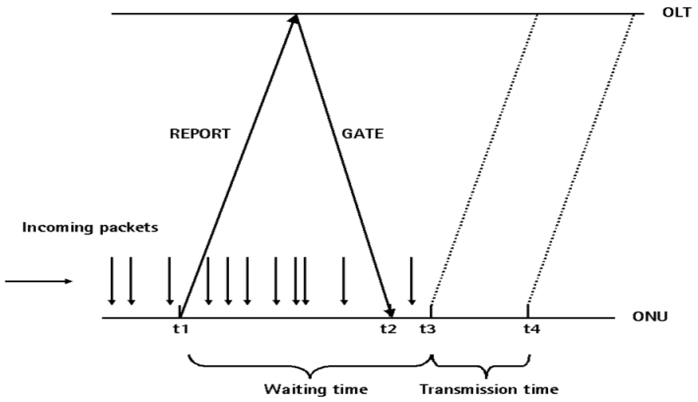


Figure 15. Waiting time example

In a couple of above-mentioned algorithms this characteristic already was mentioned, e.g. in [9] one option to overcome the light-load penalty is through the estimation of high priority arrivals. In this proposal the estimation is perform by OLT in order to predict the amount of high priority traffic, packets are expected to arrive and based on this the allocation is adjusted; the prediction is about a predefined constant bit rate (CBR) so light-load penalty remains over other kind of traffic. As the prediction is based on the knowledge of a CBR flow, it just can be applied for services with a CBR arrival process.

In [14] ONU estimates bandwidth for high priority traffic based on the traffic arriving in the previous waiting time period but no more details were presented, the proposal was compared with previous algorithms where average and maximum packet delay presented a better performance.

As IPACT continues to have great importance in the design of EPON, some proposals were develop with the aim of improving it performance, so the characteristic of estimate bandwidth was introduced in algorithms to cover weakness of IPACT, such as packet delay. Among the first proposals that addressed that issue is [24], in which estimation is performed based on historical values such as queue length and allocated window size. Estimation is performed by OLT according with information provided by ONUs, i.e. in request message ONU include the difference between the allocated window size by OLT and its actual buffered packet size to be transmitted; according that information OLT estimates the allocation size for the next cycle; if the difference between the allocated window size and the actual buffered packet size becomes positive, the allocation window size to the next cycle decreases; on the contrary if it becomes negative, allocation window size to the next cycle increases; and finally if is equal to zero the allocation window size to the next cycle remain as in the previous cycle.

In subsequent proposals also the estimation issue was addressed, e.g. in [25] class-based traffic prediction is taken into consideration in order to reduce packet delay and queue length. A key issue is that OLT serves all ONUs in a fixed round robin order to avail traffic prediction. The estimation is perform not just to the high priority traffic, because request includes all type of classes, to compute estimation the schedule interval is define as the time between sending report messages, during this interval ONU transmits buffered frames and send the request at the end of time slot, so the waiting time in an interval is the time during which ONU is idle and more frames are buffered. In the Figure 16, interval of ONU1 ranges from t1 to t6 and waiting time from t2 to t6. Bandwidth request for a given class of traffic includes the amount of traffic already buffered and an estimation credit, which is the ratio of the waiting time in a given interval against its length. Bandwidth allocation is based on limited approach according to the maximum bandwidth parameter of a specific class of traffic determined by the SLA.

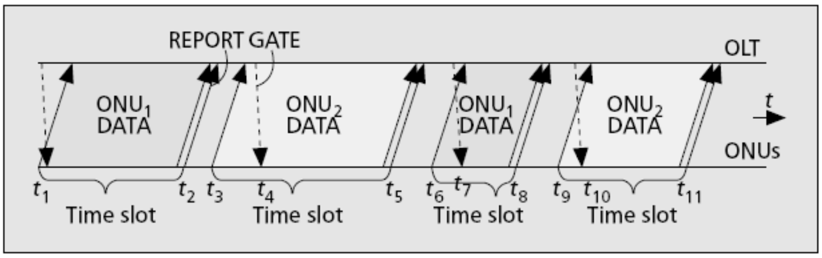


Figure 16. Upstream transmission

A later proposal focused on the same issue was presented in [26]: the estimation allows allocate the transmission window size close to the buffer occupancy. The estimation of packets arriving can be estimated according to the packet arrival rate at the ONU and the length of the time interval. ONUs will be responsible for computing that information in each cycle so that ONUs initiates a timer each time it receives a grant message; additionally get the real time arrival rate during a small interval thus the amount of packets arriving during the next cycle can be estimated, ONU will report the estimation to the OLT together with the request size that equals to the instant buffer length. Following figures, 17 and 18 [26], show the operation of both OLT and ONU respectively.

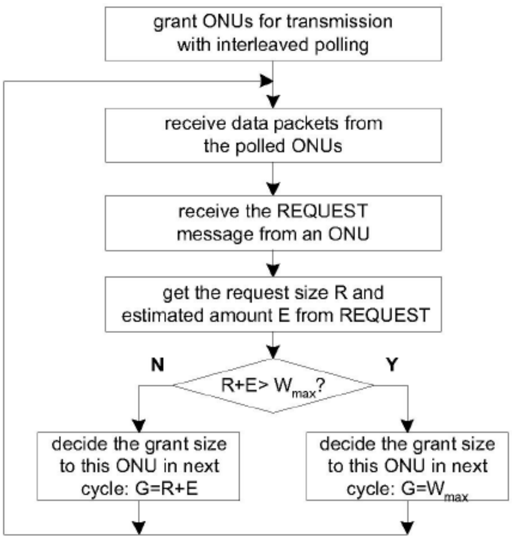


Figure 17. OLT operation

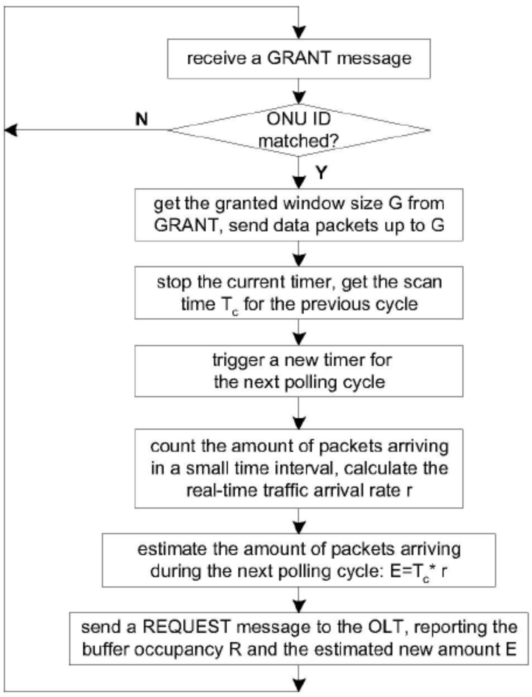


Figure 18. ONU operation

There are different mechanisms based on estimation but the proper implementation should be able to predict the number of packet arrivals during the waiting time period as precisely as possible. In [23], Lanoo et al. presents an extensive research about IPACT and consider that the simplest approaches based on estimation, add a constant credit to the requested window or multiply the requested window size by a constant, but much more efficient prediction mechanisms are necessary because overestimating will cause bandwidth to be lost. The ideal mechanism is one that reduces delay packets without underutilized bandwidth.

Revising DBA-related literature, it was found that some of the proposals include new EPON architecture; in fact, the new architecture is the main contribution, but the modification in architecture implies a new DBA. In [27] a two-stage EPON architecture that allows more users to share the OLT link and enables longer distances was proposed; additionally, a DBA algorithm is introduced. The architecture adds another level of ONU nodes to the network in which more users share the upstream channel and at the same time allows longer distances because of the use of intermediate sub-OLT; it also reduces the OLT hardware complexity significantly. This modification in EPON architecture facilitates migration for future 10Gbps PON networks. To address the issue of DBA two sections are identified: first, from OLT to the sub-OLT; and second, from the sub-OLT to the attached nodes. Each one could perform an independent DBA algorithm.

The algorithm for a sub-OLT has been designed to estimate its future incoming traffic within a time reference, thus OLT will try to satisfy first the bandwidth request for its actual buffer occupancy and then the predicted bandwidth request. The estimation is performing based on a reference time and also depends on the link capacities from OLT to sub-OLT and sub-OLT to ONUs. Sub-OLT incorporates extra queues to distinguish priority classes offered by ONUs and the ones offered by local users. The ONU section support different classes of service, therefore packets are classified into their queue correspondently. Simulations results were compared with algorithm presented in [14] and shown better performance in terms of average packet delay.

In [28], a novel architecture is projected; this is a novel ring-based EPON architecture with its corresponding DBA algorithm. The architecture replaces the common tree architecture because the area after the splitter becomes a ring, upstream traffic travels in the ring to reach OLT and downstream traffic enters the ring after the trunk fiber. Figure 19 shows and overview of novel ring [28]. DBA algorithm incorporates a global knowledge, i.e. allocation is based on the demands of all ONUs because the computation of allocation is performed at the end of the cycle - at least for those ONUs requiring more than an establish maximum bandwidth transmission, as opposite to IPACT algorithm in which allotment is base on a single ONU report. This allows efficient cycle bandwidth utilization.

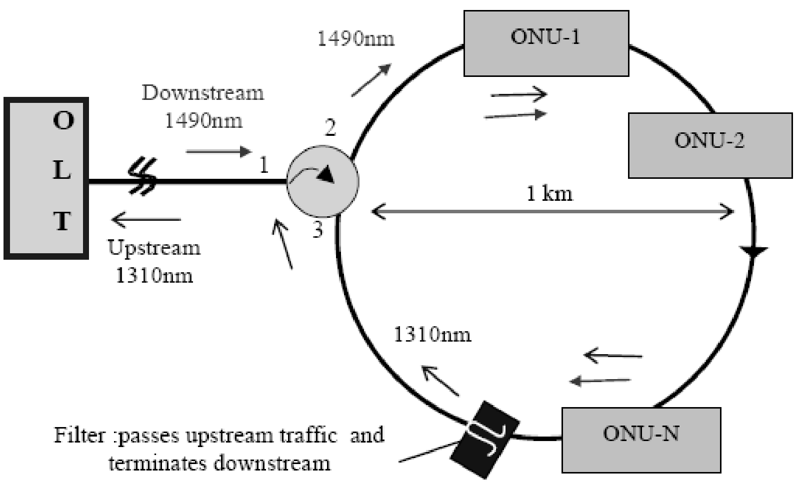


Figure 19. Ring-based EPON architecture

Process of bandwidth allocation starts with ONUs report messages in which request is transmitted before data frames; therefore, demands up to the maximum transmission window will be grant without waiting to the computation of bandwidth allocation thus they can start their transmission at the beginning of the next cycle. ONUs which requirements of bandwidths are higher than maximum established require waiting for OLT receive all request and, based on that, calculate excess bandwidth and distribute fairly. DBA approach is similar than [14] because ONUs with lower bandwidth demands receive allocation immediately. Results and conclusions of the proposal show that ring architecture is a cost effective alternative of EPON architecture that also can adapted ring protection to provide redundancy, and in the other hand, DBA algorithm outperforms IPACT algorithm in terms of packet delay.

The proposals presented so far have been in a way centralized approach, although there are very important functions that are performed on both sides (OLT and ONU). In a distributed approach, bandwidth allocation is calculated by ONU although it may be authorized by OLT. There are not too many proposals that handle the management of resources in this manner; the most of them are centralized approaches.

Following, some proposals based on a distributed approach will be explained. In a distributed scheme changes in architecture need to be perform, as ONUs will require know the other transmissions in the channel.

In [29] a DBA algorithm based on upstream broadcast is presented, the architecture enables LAN emulation, frames transmitted from ONUs are redirected back to all ONUs including the transmitting ONU; this enables each ONU can measure its round trip time during every transmission. Architecture connects an OLT to *N* ONUs via a passive star coupler, each ONU are connected to the passive star coupler via two distribution fibers as show the Figure 20.

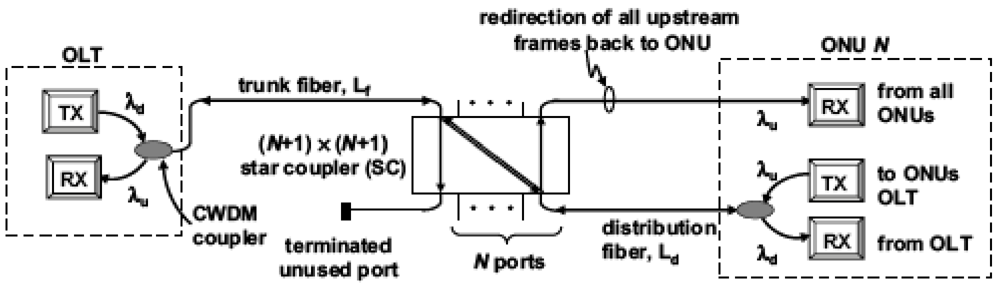


Figure 20. Physical Architecture of EPON

The proposed algorithm in [29] is named Upstream Broadcast DBA (UB-DBA); it considers two types of upstream traffic: the high priority and the best effort. The transmission cycle is divided into fixed and variable periods to control messages and data traffic correspondingly. High priority traffic have a fixed bandwidth allocated, previously agreed, so report messages only are sent to request bandwidth to low priority traffic and includes MAC address and the ONU priority number assigned by OLT during registration process. During the fixed period of the cycle each ONU listen the channel to re-measure its round trip time for ranging purposes, after receive the final report message, the ONU with largest priority number broadcasts the grant message in which the order of transmission and low priority bandwidth allocation is designated to each ONU. During the variable cycle period the high priority traffic is transmitted first, followed by low priority traffic according to the order indicated in grant message. This way, each ONU transmits without colliding because it knows the transmission order, granted bandwidths and its own RTT – it also knows the size of the cycle that can be implemented in such a way that real-time services does not experiment delay. Bandwidth allocation is calculated on the basis of a maximum transmission cycle time, in which the time period reserved to high priority, the fixed period to control messages and the guard times represent some time in the cycle; the excess bandwidth from light load ONUs will then fairly distributed among ONUs with heavy load. Simulations compare channel utilization against typical proposals as IPACT; results showed a high channel utilization and QoS management achievement.

The proposal in [30] suggested a distributed EPON architecture; similar to the previous one, this architecture also replace the passive splitter by a star coupler, therefore a portion of the optical signal power transmitted from ONUs to OLT will be redirected back and broadcasted to all ONUs. The proposed architecture is shown in figure 21.

The cycle is divided into three periods: the first is a control period used by ONUs to communicate their status and exchange signaling information in a fixed time slot; the second is waiting period used for allowing ONUs to process the information and the last is a data period for data transmission.

Some of the advantages mentioned in the proposal indicate that bandwidth allocation is performed in such a way that a global optimization is achieved; priority and demands are accomplished because of the flexibility of varying the order of ONUs transmission. DBA algorithm is similar to the previous proposals but incorporates some more characteristics to handle QoS demands.

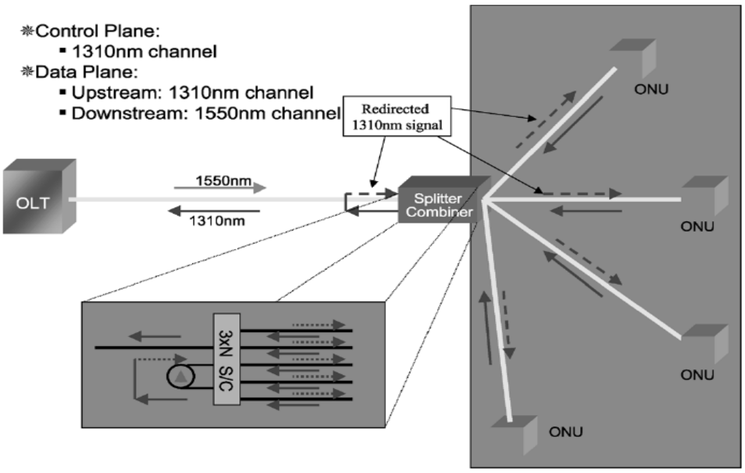


Figure 21. Proposed distributed EPON architecture

Figure 22 shows the operation of the scheduler, where ONU i is requesting transmission based on its buffer occupancy, report message reach the star coupler where is then combined with all other ONU report messages, the update message is then broadcasted to all ONUs. Upon receiving the multiplexed updated message, the ONU passes the message to the DBA module in order to allocate a transmission time slot.

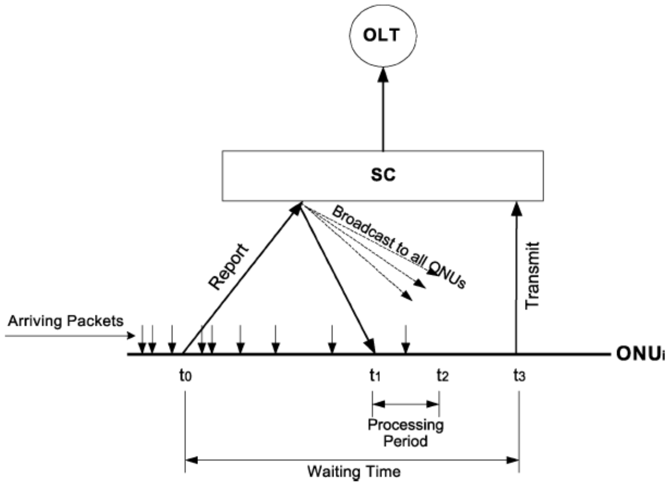


Figure 22. Scheduler Operation

Some other proposals based on decentralized approach introduce a modification in the architecture of the network but not address the DBA proposal as a main purpose. Most of decentralized proposals include a change either in the architecture or in the standard control messages; this modifications affect performance in DBA algorithms that under a centralized approach present an efficient operation handling demands of QoS or SLA parameters.

Recently an interesting algorithm developed by the research group in the Telematics Engineering Department of UPC was proposed such as a contribution of DBA algorithm for EPON in which a distributed approach is addressed. The proposal consisted of a distributed scheduling mechanism in order to allocate bandwidth fairly and efficiently in an EPON; this mechanism is centralized because control channel is performed by OLT, but scheduling process is distributed among ONUs. The mechanism is called Dynamic Distributed Scheduler for EPON (DDSPON) [31]. In it, the bandwidth scheduling algorithm is perform mainly by ONUs, therefore an extra information is introduce in gate messages; thus, each ONU calculates the instantaneous transmission window size for itself. Extra information comprises a weight vector that allows ONUs to calculate its transmission window size. A different aspect of this algorithm with respect to further implementation of algorithms is a distributed calculation of the bandwidth performed by ONUs. Section IV introduces the performance of DDSPON.

The following table shows a comparison among various DBA algorithms for EPON, it highlights the most common characteristics addressed by several proposals. The table is a reference that considers several of the most representative proposals of DBA algorithms so far.

Table I. Comparison of DBA algorithms.

Reference	DBA algorithm	Features								
		MPCP compatible	centralized / distributed	intra-ONU scheduler	inter-ONU scheduler	light-load penalty aware	QoS aware	SLA aware	prediction based	new architecture
12	IPACT	✔	centrilized		✔					
13	DBA for multimedia services	✔	centrilized		✔		✔			
9	Intra-ONU and Inter-ONU scheduling	✔	centrilized	✔	✔	✔	✔		✔	
14	DBA with QoS support	✔	centrilized		✔	✔	✔	✔	✔	
15	SUCCEES-HSSR DBA	✔	centrilized	✔	✔		✔	✔		
16	DWPS	✔	centrilized	✔	✔		✔	✔		
17	BGP	✔	centrilized		✔		✔	✔		
18	Cyclic polling-based DBA algorithm	✔	centrilized		✔	✔	✔	✔		
19	SLA-DBA	✔	centrilized		✔		✔	✔		
20	FQSE	✔	distributed	✔	✔		✔	✔		
21	DUAL-SLA scheduling		centrilized		✔		✔	✔		
24	new-DBA	✔	centrilized		✔	✔			✔	
25	DBAM	✔	centrilized	✔	✔	✔	✔	✔	✔	
26	IPACT-GE	✔	centrilized		✔	✔			✔	
27	DBA for P-EPONS	✔	distributed		✔		✔		✔	✔
28	DBA for Novel Ring architecture	✔	centrilized		✔	✔	✔	✔	✔	✔
29	UB-DBA	✔	distributed		✔	✔	✔			✔
30	Decentralized DBA	✔	distributed		✔	✔	✔			✔
31	DDSPON	✔	distributed	✔		✔	✔	✔		

3.3 NEXT GENERATION PON

The next generation PON concerns two ways of updating PON, the first approach refers to employ multiple wavelengths between OLT and each ONU, and the second approach suggest an enhancement of EPON to run at higher speed. Then each approach is review and in the case of WDM PON the DBA algorithms in literature are presented.

3.3.1 WDM PON

Commonly, EPONs are TDM single-channel systems, where the fiber infrastructure carries a single upstream wavelength channel and a single downstream wavelength channel [32]. To provide higher bandwidth in PONs, a WDM technique can be performed incorporating multiple wavelengths in either, the upstream or downstream direction so a WDM-PON has many advantages such as increasing network capacity, in terms of bandwidth or user scalability.

Different architectures have been proposed for WDM-PONs, a simple one creates a point-to-point link between the OLT and each ONU, therefore each ONU can operate at a different bit rate or even different services may be supported by wavelength.

A PON is overtaken by a WDM-PON since PONs, in which a different wavelength is employed to downstream or upstream traffic (1490nm or 1310nm respectively, in EPONs scenarios), the bandwidth is share amongst all the end-users. As basic idea of WDM-PON is increase bandwidth, DBA algorithms initially designated for EPON require modifications to exploit the multichannel architecture.

EPONs are single-channel systems, i.e. fiber infrastructure carries a single downstream wavelength channel and a single upstream wavelength channel, in upstream, the channel bandwidth is shared by the EPON nodes by means of TDM but in order to satisfy the growing traffic demands in future EPONs should be upgrade. TDM-EPONs may be upgrade by deploying multiple wavelength channels in the installed fiber infrastructure resulting in WDM-EPONs [33].

WDM-PONs would require special hardware which would result in higher cost, an interesting review of device technologies and network architectures that may be deployed on a WDM-PON was addressed in [34], also there are in literature various proposals of scenarios for upgrading EPONs to WDM-PONs.

Proposals of bandwidth allocation in WDM-EPON the most of times include an architecture proposal; since DBA algorithms designed for EPON require appropriate modifications to handle the multichannel architecture, this document will focus mainly in the review of DBA proposals over WDM (WDM-DBA).

As an evolution of IPACT [10] in WDM, some variants of IPACT are addressed in proposals, e.g. in [35] the authors proposed an algorithm called WDM IPACT-ST (WDM IPACT with a single polling table) in which transmission windows are assigned to ONUs allowing them to transmit in the first available upstream channel so OLT has to know which upstream channel will first turn idle according to its polling table, as IPACT transmission windows size is based on some algorithm, e.g. fixed, limited or gated. In terms of differentiated services support ONU handles queues to store a particular class of traffic. This approach requires new devices at both ends of the fiber links to support simultaneous transmissions over a multiple wavelengths. Simulation results shown that IPACT-ST outperforms IPACT in terms of delay, due to the fact that in TDM EPONs the polling cyclic time increases linearly according to the attached ONUs and WDM EPONs maintain a short polling cycle time.

Clarke et al. studied a DBA called Simultaneous and Interleaving Polling with Adaptive Cycle Time (SIPACT) [36], in this proposal OLT could poll intra-wavelength (on the same wavelength) and inter-wavelength (among different wavelengths) simultaneously. SIPACT allows different architectures since ONUs can support a different set of wavelengths so through a discovery process information about ONU architecture is established thus ONUs can be polled simultaneously on separate wavelengths otherwise interleaving polling is performed.

Some proposals focus its contributions taking into account migration issues to upgrade from TDM to WDM, e.g. in [37], an interesting architecture of hybrid WDM/TDM called Stanford University Access (SUCCESS) was presented, it is based on a collector ring and distribution star networks. Collector ring, with stars attached to it, formulates the basic topology, the collector ring strings up remote nodes (RNs), which are the centers of the stars. This proposal did not present any DBA; it just proposed a particular MAC protocol. The following Figure 23 [38] shows an overview of SUCCESS architecture.

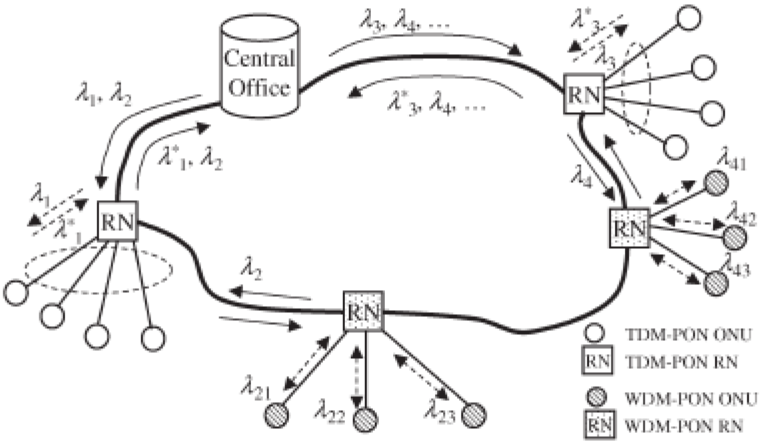


Figure 23. Overview of SUCCESS-HPON

In [39], an upstream and downstream system upgrade is presented, in which various devices such as tunable lasers and arrayed-waveguide granting (AWG) are combining to create flexibility in the upgrade process, thus interconnection of multiple PONs can be performed. This proposal did not include a specific WDM-DBA it just discuss and examined ONU structures for deploying a WDM-DBA.

McGarry et al. in [34] discussed a comparison of two paradigms for dynamically allocating WDM upstream bandwidth: online and offline scheduling. In the first one OLT makes scheduling decisions based on individuals requests and without global knowledge thus OLT schedule the upstream transmission on the earliest supported wavelength channel available. The offline scheduling on the contrary, make scheduling decisions based on global knowledge, .i.e. scheduling algorithm should be execute after the OLT receives requests. In both schemes, the amount of bandwidth allocated to an ONU can be determined according to any of the existing DBA mechanisms based on a MPCP protocol. Comparison results shows that at medium and high traffic load, online scheduling experiments lower packet delays.

Also McGarry et al. in [40] discussed bandwidth management issues in order to find a best scheduler for WDM EPONs, several simulations studies and interesting conclusions were presented. Bandwidth management is addressed according the grant sizing and grant scheduling methods, grant sizing determines the size of a grant and the grant scheduling considers when and on which wavelength channel to schedule the grant, both issues are necessary to fully utilize the network resources.

Dhaini et al. in [41] presented several dynamic-wavelength and bandwidth allocation schemes (DWBA) and compared its performance. DWBAs are based on two different architectures, the first assume a fixed group of ONUs where ONUs are divided into multiple subsets, each allocating a fixed wavelength channel for upstream transmission, the second architecture allows simultaneous time-sharing and wavelength sharing. Under the first architecture a Static Wavelength Dynamic Time (SWDT) is performed, under this scheme allocation of wavelengths is static, i.e. OLT allocates wavelength statically among ONUs and upstream bandwidth is assigned dynamically, each channel performs its SWDT algorithm. Under the second architecture a Dynamic Wavelength Dynamic Time (DWDT) approach is reviewed, it enables the dynamic allocation of bandwidth for different ONUs in both wavelength and time domains.

Three variants of previous scheme are presented in which the minimum bandwidth guaranteed is dependent on weight of each ONUs. In the first variation OLT collected all report messages form ONUs and upon that perform a bandwidth allocation algorithm to determine the bandwidth and channel. The later variation consider the “on the fly” (such as online scheduling [34]), i.e. assign a gate immediately without wait for the arrival of the other report messages, allocation for cases in which bandwidth request is less than minimum guaranteed. Final variation introduces a strict “on the fly” allocation in which OLT will always assign a gate messages regardless of its requested bandwidth. The last two schemes outperform the first one because mitigates the effects of the channel idle time experienced and present a better throughput and delay performance.

A recent proposal [42], addressed the queuing delay and channel utilization through the scheduling theory, which is concern with scheduling a set of jobs with specific processing times to be execute on a set of machines, and thus ONUs represents the jobs, the processing times are represented by grants size and channels represents machines. The proposal introduces a layered approach to scheduling: scheduling framework determines when the OLT makes scheduling decisions and scheduling policy is a method for the OLT to produce the schedule. Scheduling framework can be online or offline such as [34] as well as online just-in-time (JIT) in which scheduling process is handle by channel availability, i.e. OLT makes an access decision based on report messages accumulated since the last channel became available. Through online JIT scheduling is possible provide lower average queuing delays.

3.3.2 10G EPON

EPON and GPON represent the current state of the art of commercially available optical access networks, but standardization efforts have already been initiated in the IEEE 802.3av Task Force to specifying 10Gbs EPON (10GEPON) [32]. 10GEPON was formed in September 2006 and is expected that standardization work will be finished in 2009 being the major difference against IEEE 802.3ah, the physical layer.

To increase the current line rate from 1 to 10 Gbs, the update of EPON is needed; nevertheless it could implies upgraded EPON nodes resulting in a rather costly upgrade, so EPON equipment must be provide a gradual evolution in which a co-existence of 10GEPON and EPON will be implemented.

The 10GEPON represents the EPON next generation in which channel capacity is increased for both upstream and downstream channels through specifying both symmetric line rate operation as well as asymmetric line rate operation, the symmetric will operate at 10 Gbps in both upstream and downstream directions and the asymmetric option will use 10Gbps in the downstream and 1Gbps upstream [43]. Thus, advance video services demand in the downstream direction is supported by means of the asymmetric option.

Transition in operation mode is a combination of 1Gbps downstream/1Gbps upstream, 10Gbps downstream/1Gbps upstream, 10Gbps downstream/10Gbps upstream over a single fiber [44]. 10GEPON increase channel capacity for both upstream and downstream channels maintaining the logical layer such as 1Gbps EPON, taking advantage of the already existing MPCP and DBA agent specifications, thus coexistence must be mandatory to assure smooth transition that should be conducted in such a way that only small parts must be replace [45].

In [46] next generation PON systems were investigated, in terms of rate enhancement 10G technologies were presented, the major challenges to symmetrical 10GEPON are the cost of new equipments such as transceiver and the coexistence with current technology, as the major difference is the physical layer technical issues were mentioned such as extension of current scrambling coding standards and selection of new forward error correction (FEC). In terms of overhead [43] mentions that compared to 1Gbps EPON only line-coding, control messages and frame-delineation overhead would change to 10GEPON.

Lin in [44] summarize the four respects to be considered in physical layer modifications, the wavelength plan in which downstream channels for two data rates will be WDM multiplexed due to incompatible data rates, on the other side as the fiber plant architecture will not be change during transition different power budgets have been defined, also to comply with IEEE 802.3ae a new line code is adopted and finally in PCS sub-layer of new IEEE 802.3av FEC is used to provide, after scrambling the line, a coding gain. Details of physical layers are out of scope of this research project for further information refers to draft standard.

In terms of MAC layer Lin mentioned the need in MPCP sub-layer of an auto-recovery process to distinguish 1G or 10G registration and also a new flag to identify the bit rate in the control messages. Since DBA mechanism was considered out of scope of IEEE 802.3ah it is very unlikely that DBA agent operation and functionality will find its way into future releases of IEEE 802.3, leaving its specifications to be implementation-dependant. As DBA implementation still rely on the underlying MPCP layer the upstream channel, which in case of coexisting will be sharing, become problematic for a number of issues such as the various line coding with incompatible clock rates, MPCP layer must be aware of the data rate to ensure proper scheduling [47].

3.4 HYBRID WIRELESS-OPTICAL ACCESS NETWORKS

Recently some contributions in terms of integration of PON and wireless technologies are presented as a promising architecture for future access networks. It is an interesting research area where different technologies are addressed and in which Passive Optical Networks are an important reference since it are the most attractive optical access networks. In terms of DBA mechanisms, it continue taking relevance in one side because of the next generation of PON require new approaches of this mechanisms and in the other side because of the integration of PON with other technologies that introduce new challenges of DBA definitions.

In literature there are few contributions to the integration of optical networks and wireless technologies, in [48] four architectures for the integration of WiMAX (IEEE 802.16) and EPONs are presented, where the optical network functions as backhaul to connect multiple WiMAX base stations. The common characteristic of these architectures is that the ONU and the WiMAX base station are integrated in a single piece of equipment that matches the QoS support mechanisms in both technologies. About Bandwidth Allocation, as both EPON and WiMAX are based on a similar request and grant mechanism it facilitates the integration of bandwidth allocation, also in terms of QoS support since each of one allows traffic classification, EPON allow different priority queues in each ONU while WiMAX classifies traffic into different QoS levels that can be strategically combined to provide an efficient QoS support.

In [49], a novel hybrid network architecture is introduced named WOBAN, it is composed of optical network at the backend and wireless network at front end. The optical network can be supported by PON and the wireless portion may employ technologies such as WiFi (IEEE 802.11a/b/g) or WiMAX. The authors highlight the challenges in the deployment of such hybrid architecture and discuss station placement and routing issues in hybrid PON-wireless access networks.

The future perspectives contemplate WDM-PONs functioning as backhaul for WiMAX, therefore integration of technologies suppose efficient mechanisms for scheduling and bandwidth allocation that achieve the utilization and the support of QoS.

4 DDSPON: A DISTRIBUTED DYNAMIC SCHEDULING FOR EPON

DDSPON [31] proposed that active ONUs were responsible of manage transmission times for the upstream channel, while reporting to OLT about such allocation. OLT continues having control of channel because centralized allocations windows and through the gate message complies with MPCP protocol.

Additional information must be sent to the ONUs from the OLT in order to calculate their instantaneous transmission window size, that information is the weight vector (Φ), it can be sent through the gate message in an available header field. Weight vector facilitated by OLT to each ONUs represents a portion time in the transmission window; this vector is updated by each ONU through the report messages, so an additional parameter in the message is included. Each ONU has a fixed weight according to its guaranteed bandwidth agreement.

In DDSPON the interleaving polling mechanism is also applied (as well as IPACT), but the size of the transmission window for the ONU is calculated by each respective ONU. Figure 24 illustrates the interleaved polling mechanism perform by DDSPON.

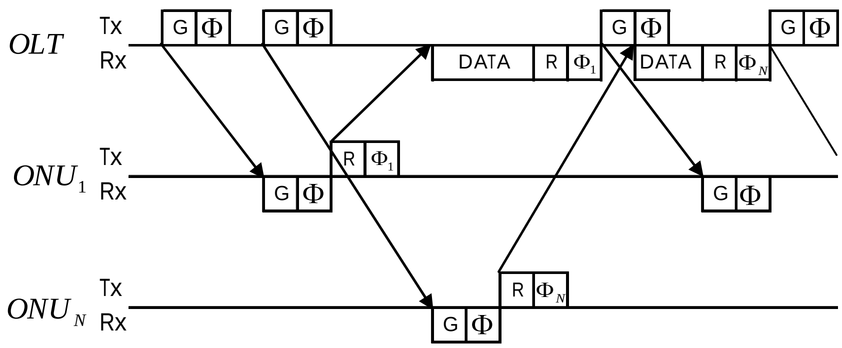


Figure 24. Illustration of the Interleaved Polling Mechanism

4.1 Bandwidth Distribution and Scheduling in EPON

In a PON system, N is the total number of active ONUs, each ONU i have a predefined (nominal) weight (Φ_i), it is used to define ONUs transmission window size as follows:

$$W_i = \frac{\Phi_i}{\sum_{j=1}^{N} \Phi_j} W_{MAX}$$

Where W_{MAX} is the maximum transmission window size that corresponds to the maximum cycle time (T_{MAX}), i.e. the period during ONUs transmits its traffic.

$$W_{MAX} = \frac{T_{MAX}}{N}$$

The OLT guarantees the instantaneous window size $\Phi_i W_{MAX}$ if $\sum_{j=1}^{N} \Phi_j = 1$

Bandwidth allocation in DDSPON is as follows:

1) OLT receives a report messages from ONU i, it contains the requested window size ($R_i(n)$) and the weight (Φ_i) for cycle n, thus OLT updates its weight vector for cycle n and send a gate message to ONU i in which allocation corresponded to the requested bandwidth.
2) Gate messages also include the weight vector (Φ), once an ONU i receives gate message transmit data in queue up to the transmission window allocated, then takes the weight vector (Φ) sets its own weight to the nominal one (Φ_i) and calculates a maximum window size that such ONU can take on next cycle $n+1$:

$$W_i(n+1) = \frac{\Phi_i}{\sum_{j=1}^{N} \Phi_j(n)} W_{MAX}$$

Also, ONU calculates its require transmission window size:

$$R_i(n+1) = \min(W_i(n+1), Q_i)$$

Where Q_i is the queue size, finally new weight for next cycle $n+1$ is calculated based on previous request value:

$$\Phi_i(n+1) = \frac{R_i(n+1) \sum_{j=1}^{N} \Phi_j(n)}{W_{MAX}}$$

The same process is performed by each ONU. Thus ONU is the one who schedules dynamically the size of its transmission window fixing it to real number of bytes in each Ethernet frame. Scheduling process is executed without need to wait until all the reports from ONUs arrive to the OLT.

5 DDSPON EVALUATION RESULTS

In order to evaluate the DDSPON algorithm, several simulations based on OPNET were conducted to study its performance and validate its effectiveness. Different scenarios were analyzed in which parameters were varied. Figure 25 shows the general OPNET network model in which the system is a tree topology with 16 ONUs, each of them separated from the OLT over the interval from 10km to 20 km.

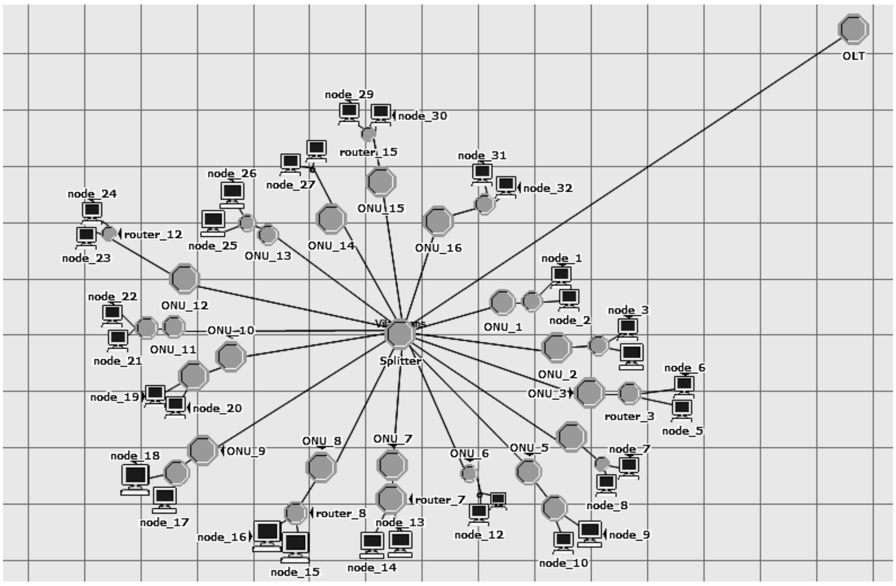


Figure 25. Network Model

The simulations compare the performance of DDSPON and IPACT algorithms, the IPACT according to the limited service method to determine the transmission window size, i.e. OLT grants the requested number of bytes, but no more than a predefined maximum transmission window.

In order to obtain a realistic performance analysis, the traffic model considered was self-similar. Many studies show that through self-similar traffic model, the most networks traffic flows can be characterized – thus self-similar traffic is characterized by the same fractal properties that are present in the traffic generated by many of today’s Internet applications.

To generate self-similar traffic, OPNET simulator provides a traffic source model called the Raw Packet Generator (RPG), in which the attributes of the self-similar traffic are specified – attributes such as the packet size, the average arrival rate and Hurst parameter. The Hurst parameter was varied from H=0,7 to H=0,8 among scenario 1 and scenario 2 respectively. The packet size follows a uniform distribution for random size of packets with an under limit of 512 bits and an upper limit of 12144 bits corresponding to the Ethernet frame.

To obtain simulations with variations to the ONU offered load, where the total offered load is 1Gbps and is equally distributed among all active ONUs, the average arrival rate varies depending on the values of the following table (Table II). The model simulation considers a tree topology with 16 ONUs, thus the first column shows the traffic arrival rate by each active ONU and the corresponding offered load.

Table II. Traffic Arrival Rate

Traffic arrival rate (packets/sec)	Offered load (%)
494	5
988	10
1482	15
1975	20
2470	25
2963	30
3457	35
3951	40
4445	45
4938	50
5432	55
5926	60
6420	65
6914	70
7407	75
7901	80
8395	85
8889	90
9383	95
9877	100

The simulations have been run with a different number of seeds to obtain different samples, thus determine the mean value that approximates the true mean.

The collected statistics were the average queue size and average packet delay. The queue size represents the current number of bits in the queue. The packet delay represents three components [12]: the polling delay, i.e. the time between packet arrival and the next request, the grant delay, i.e. the time interval from ONUs request till the grant from OLT received and the queue delay which is the instantaneous measurement of packet waiting times in the transmitter channel's queue; measurements are taken from the time a packet enters the transmitter channel queue to the time the last bit of the packet is transmitted. Figure 26 represent the components of packet delay.

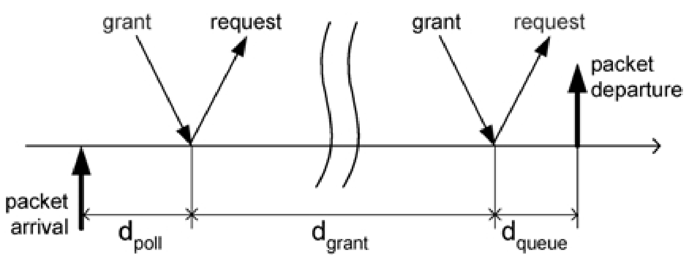


Figure 26. Components of packet delay

The simulations were performed without the discovery window process in such a way that only the issues involved with the algorithm were taken into consideration.

The simulations were performed during 0,3 seconds in order to obtained valid results that allow analyzed the behaviour of DBA algorithms. Issues such as real-time duration and consume resources (memory and processing) were considered to determine the time modeled in the simulation. So that after several tests the simulation time was defined.

5.1 Simulation Parameters

Five scenarios of simulations were analyzed in which parameters such as distance and traffic were modified. Table III summarizes the simulations parameters used in the simulations experiments.

The statistics were evaluated to the different offered loads; therefore the mean values obtained by each scenario were graphed in order to study them as a function of the offered load.

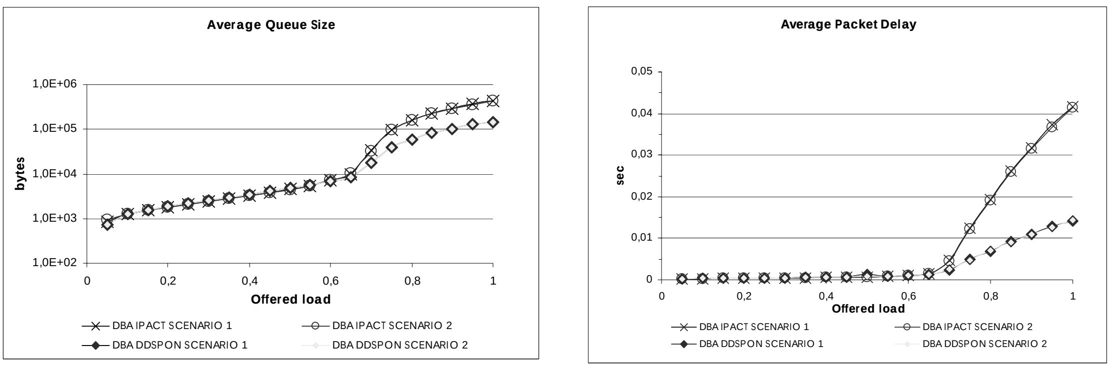
Table III. Simulation Parameters

PARAMETERS	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Number of ONUs	16	16	16	16	16
Line rate of user to ONU link	100Mbps	100Mbps	100Mbps	100Mbps	100Mbps
EPON line rate	1Gbps	1Gbps	1Gbps	1Gbps	1Gbps
Number of queues per ONU	1	1	1	1	1
Buffer size for each queue	Infinity	Infinity	Infinity	Infinity	Infinity
Guard interval between timeslots	.008ms	.008ms	.008ms	.008ms	.008ms
Maximum cycle time	1ms	1ms	1ms	1ms	1ms
Distance between OLT and ONU (d) in km	18<d<20	18<d<20	10<d<20	10<d<11	4<d<5
Hurts traffic parameter	H=0,7	H=0,8	H=0,8	H=0,8	H=0,8

The simulations for simplicity of analysis just consider one queue per ONU, but it can be easily extended to several queues per ONU (up to eight).

5.2 Simulation Results

The results of comparing simulations of scenario 1 and scenario 2, in which the Hurst traffic parameter is different, are shown in figure 27.



(a) (b)

Figure 27. Average queue size and Average packet delay as function of offered load

The Figure 27 shows the average queue size in scenario 1 and scenario 2 for both algorithms with various offered network loads; the behavior of algorithms in each scenario is very similar so the Hurst traffic parameter did not affect the expected results.

In Figure 27a, both algorithms experience a similar behavior for low loads; however, when the network load is bigger than 0,6, the IPACT starts to experience an increase in the queue size bigger than DDSPON's. When the network load reaches its maximum capacity, IPACT presents an average value (which is the maximum in both scenarios) of 427966 bytes, whereas DDSPON reaches 148205. These results have implications in the queue buffer size since, in the case of IPACT, it will require to be larger to avoid the packet loss.

In terms of average packet delay the Figure 27b shows the increase of delay as a result of the queue size, i.e. when the network load is bigger than 0,6 and the queue size starts to increase the delay also increases. DDSPON shows lower delays for higher networks loads compared with IPACT, where delay reaches, for the maximum network capacity, a value of 0,041sec – as opposed the 0,014sec reached by DDSPON.

The confidence in simulations results is based on the T-distribution since the number of samples are lower than 30, therefore we can be 95% confident that true average queue size and packet delay lie between the values that are shown in Table IV.

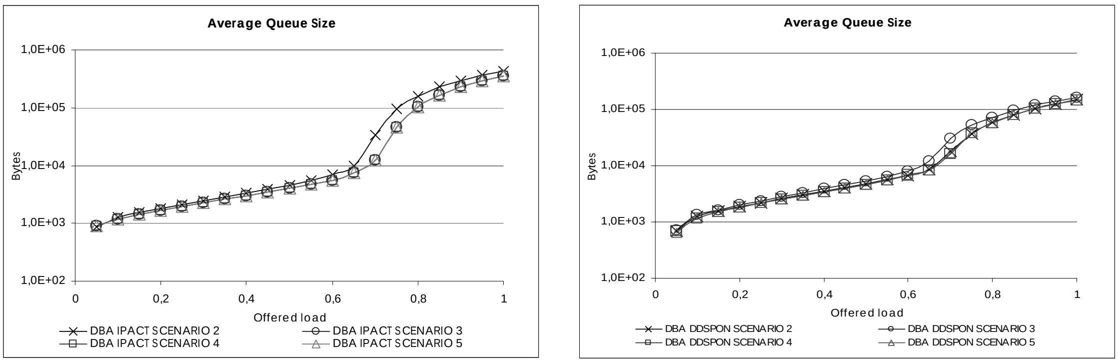
Table IV. Confidence intervals (Scenario 1 and 2)
(a) Average queue size (bytes)

Offered Load	CONFIDENCE INTERVAL			
	IPACT scenario 1	IPACT scenario 2	DDSPON scenario 1	DDSPON scenario 2
0,05	859 ± 53	942 ± 52	726 ± 99	694 ± 59
0,2	1818 ± 16	1809 ± 14	1849 ± 17	1890 ± 16
0,4	3302 ± 16	3292 ± 13	3512 ± 29	3497 ± 31
0,6	7058 ± 35	7078 ± 38	6852 ± 70	6766 ± 90
0,8	158655 ± 4223	157538 ± 5268	57266 ± 3080	59307 ± 3134
1	427966 ± 4807	425367 ± 4952	146609 ± 3804	148205 ± 4004

(b) Average packet delay (seconds)

Offered Load	CONFIDENCE INTERVAL			
	IPACT scenario 1	IPACT scenario 2	DDSPON scenario 1	DDSPON scenario 2
0,05	0,000283 ± 2,262E-06	0,0002857 ± 2,47E-06	0,0002895 ± 5,6856E-06	0,000290251 ± 4,96606E-06
0,2	0,000374 ± 1,206E-06	0,0003728 ± 8,29E-07	0,0004063 ± 5,4909E-06	0,000411083 ± 4,27911E-06
0,4	0,000568 ± 1,349E-06	0,0005673 ± 1,18E-06	0,0006221 ± 3,0743E-06	0,000622161 ± 4,45099E-06
0,6	0,001049 ± 2,908E-06	0,0010503 ± 3,45E-06	0,0010151 ± 9,0265E-06	0,001000875 ± 9,62725E-06
0,8	0,019284 ± 0,0004955	0,0190945 ± 0,000571	0,0068649 ± 0,00035637	0,007091637 ± 0,000353267
1	0,04162 ± 0,0004001	0,0413375 ± 0,000378	0,0141784 ± 0,00029868	0,014310852 ± 0,000366334

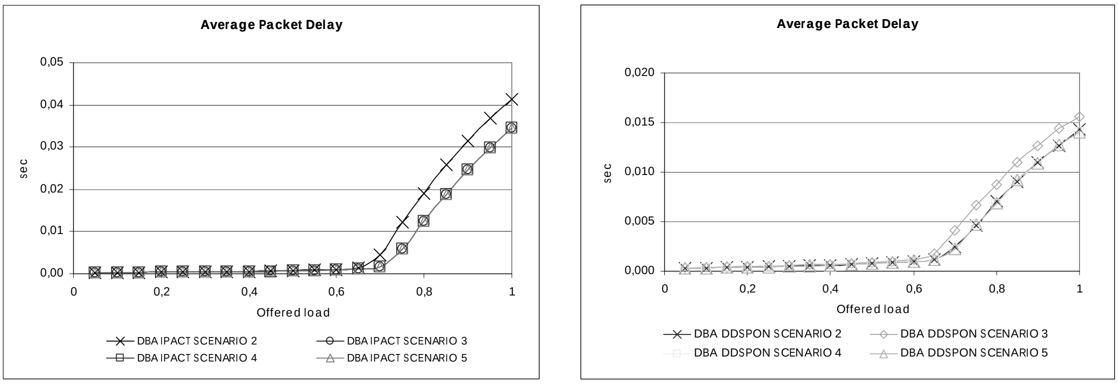
The following simulation results considered the same Hurst parameter traffic but different distances. Figure 28a shows the behavior only for IPACT algorithm in scenario 2, 3, 4 and 5. IPACT in scenario 2, in which all ONUs have a distance over the interval from 18km to 20km, shows a higher average queue size for elevated network loads since IPACT in the other scenarios have a similar average queue size.



(a) (b)

Figure 28. Average queue size as function of offered load

Figure 28b, shows the relationship between the queue size of the different ONUs and the offered network load for DDSPON in 4 scenarios, DDSPON in scenario 3 in which ONUs are over the interval from 10km to 20km and an offered load between 0,65 and 0,75 presents a smooth increase but in most offered loads the behavior is similar.
The maximum value for IPACT is located in scenario 2, in which the average queue size for the maximum offered load has a value of 425367 bytes while the maximum value for DDSPON is located in scenario 3 with 161325 bytes. IPACT decreases their efficiency for long distance but also for high loads while DDSPON maintains its efficiency for short or long distances. The smooth increase comes in scenario 3, in which ONUs are located over the interval from 10km to 20km.



(a) (b)

Figure 29. Average packet delay as function of offered load

Figure 29, represents the Average packet delay for both algorithms in scenarios 2, 3, 4 and 5. The Figure 29a shows the delay as a consequence of the queue size; as it can be observed, IPACT shows a different behavior in scenario 2 compared to other scenarios, reaching for a maximum capacity to the offered load – a value of 0,041 sec – whereas, as shown in Figure 29b, DDSPON's value for the maximum offered load is 0,015 sec.

Table V shows the 95% confidence intervals for the average queue size and packet delay respectively for the most representative offered loads.

Table V. Confidence intervals (Scenario 3, 4 and 5)

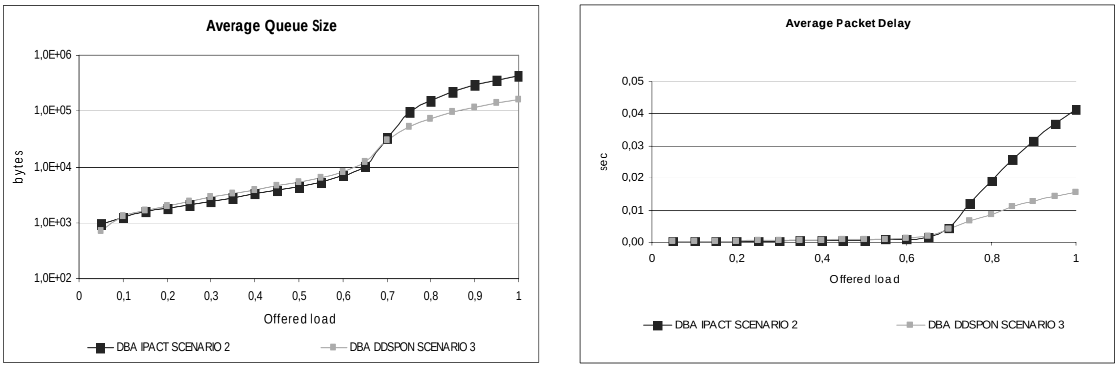
(a) Average queue size (bytes)

Offered Load	CONFIDENCE INTERVAL					
	IPACT scenario 3	IPACT scenario 4	IPACT scenario 5	DDSPON scenario 3	DDSPON scenario 4	DDSPON scenario 5
0,05	898 ± 115	814 ± 114	827 ± 111	722 ± 76	699 ± 56	639 ± 74
0,2	1680 ± 218	1683 ± 214	1685 ± 233	2032 ± 78	1840 ± 22	1833 ± 35
0,4	2946 ± 387	2954 ± 398	2948 ± 390	3914 ± 96	3386 ± 28	3396 ± 37
0,6	5513 ± 752	5629 ± 758	5614 ± 748	7955 ± 171	6816 ± 74	6647 ± 67
0,8	103050 ± 15140	102879 ± 15116	102992 ± 15130	72506 ± 6929	56616 ± 3369	56890 ± 3437
1	354008 ± 50343	353821 ± 50330	353418 ± 50285	161325 ± 8730	144941 ± 4307	145151 ± 4387

(b) Average packet delay (seconds)

Offered Load	CONFIDENCE INTERVAL					
	IPACT scenario 3	IPACT scenario 4	IPACT scenario 5	DDSPON scenario 3	DDSPON scenario 4	DDSPON scenario 5
0,05	0,00028189 ± 2,7101E-06	0,00027 ± 4,29565E-06	0,000266 ± 4,22846E-06	0,000334 ± 2,46063E-05	0,0002713 ± 3,13787E-06	0,0002675 ± 4,27156E-06
0,2	0,00036028 ± 3,13444E-06	0,00036 ± 1,69056E-06	0,000362 ± 4,69176E-06	0,0004744 ± 3,04895E-05	0,0003868 ± 1,58567E-06	0,0003858 ± 1,87386E-06
0,4	0,00052688 ± 2,67898E-06	0,00053 ± 2,4047E-06	0,000528 ± 2,87499E-06	0,0007252 ± 2,76556E-05	0,0005889 ± 2,5129E-06	0,0005904 ± 3,60742E-06
0,6	0,00084181 ± 4,56266E-06	0,00086 ± 3,54181E-06	0,000856 ± 5,00712E-06	0,0012142 ± 3,14266E-05	0,0010064 ± 8,51185E-06	0,0009798 ± 8,00483E-06
0,8	0,01253803 ± 0,001644225	0,01252 ± 0,001638312	0,01253 ± 0,001646676	0,0087012 ± 0,000788819	0,006787 ± 0,000372766	0,0068168 ± 0,000384658
1	0,03444678 ± 0,004711822	0,03443 ± 0,004699723	0,034395 ± 0,004691306	0,0155929 ± 0,000797015	0,0140298 ± 0,000396848	0,0140594 ± 0,000403095

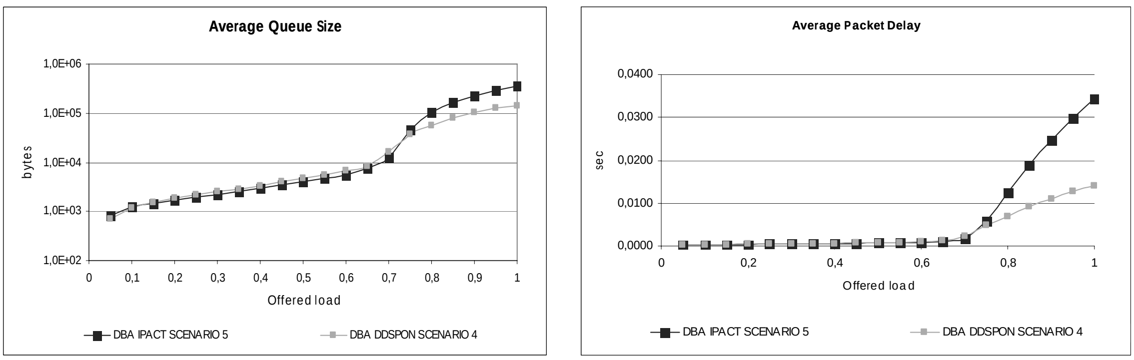
Figure 30 shows the average queue size and average packet delay for both algorithms. As it can be seen, IPACT scenario 2 and DDSPON scenario 3 show the worst behavior for high loads to each algorithm. The comparisons demonstrate that DDSPON improves the performance at high loads in terms of both the average queue size and the average packet delay.



(a) (b)

Figure 30. Average queue size and packet delay as function of offered load. Worst Scenarios

On the contrary, Figure 31 shows the comparison between the best scenarios for each algorithm, IPACT scenario 5 and DDSPON scenario 4, in which the behavior is better for high loads.



(a) (b)

Figure 31. Average queue size and packet delay as function of offered load. Best Scenarios

To IPACT in scenario 5, in which the distances are short, the average queue size for the maximum traffic load is 353418 bytes with an average packet delay of 0,034 seconds, while DDSPON reaches the best performance in scenario 4 in which ONUs are at half distance showing values such as 144940 bytes for average queue size and 0,0140 seconds for average packet delay.

It is important to mention that the values presented as the best and worst scenarios from the same algorithm vary little in relation to the other scenarios, i.e. the value to the average queue size in the worst scenario for the maximum load capacity for DDSPON is 162325 bytes while the value for the best scenario is 144940 bytes; in terms of average packet delay the worst scenario shows a value of 0,0155 seconds and the best is of 0,0140 seconds. In the case of IPACT the difference is bigger between the worst and best scenario, i.e. the average queue size in the worst is 427966 bytes and in the best is 353418 bytes; the average packet delay in the worst is 0,041 seconds while in the best is 0,034 seconds.

Through the simulation results is possible to confirm the better performance of DDSPON, especially for high traffic network loads, regardless of ONUs distance in terms of average queue size and average packet delay.

6 FUTURE WORK

WDM-EPON and 10G EPON bandwidth allocation are an important research area in scenarios such as hybrid WDM/TDM-PON or EPON/10G EPON even WDM/10G EPON in which new techniques are required to efficiently share the same wavelength or in which not only time-slots but also wavelengths are required to be assigned.

The design of solutions that optimize the resources utilization in the PON, not only based on the type of network such as WDM-EPON or 10G EPON but also in hybrid technologies, such as those presented in previous sections, are a recent and interesting field of research because new solutions are the key to reach the efficiency and the high performance that demand the emerging services and applications.

Future work are not only oriented to DBA contributions but also in terms of standardization of PON such as 10G EPON as well as in terms of optical devices that can achieve the physical features.

REFERENCES

[1] ITU-T G.984.1, SG 15, "Gigabit-Capable Passive Optical Networks (G-PON): General Characteristics," March. 2003.

[2] ITU-T G.984.2, SG 15, "Gigabit-Capable Passive Optical Networks (G-PON): Physical Media Dependent (PMD) Layer Specification," March. 2003.

[3] ITU-T G.984.3, SG 15, "Gigabit-Capable Passive Optical Networks (G-PON): Transmission Convergence Layer Specification," July 2005.

[4] ITU-T G.984.4, SG 15, "Gigabit-Capable Passive Optical Networks (G-PON): ONT Management and Control Interface Specification," June 2005.

[5] IEEE 802.3ah, "Ethernet in the First Mile," June 2004.

[6] S. Bhatia and R. Bartos, "IPACT with smallest available report first: A new DBA algorithm for EPON," IEEE International Conference on Communications, 2007. June 2007, pp. 2168-2173.

[7] M. McGarry, M. Maier, and M. Reisslein, "Ethernet PONs: A survey of dynamic bandwidth allocation (DBA) algorithms," IEEE Communications Magazine, vol. 42, August 2004, pp. S8-15.

[8] R. Mastrodonato and G. Paltenghi, "Analysis of a bandwidth allocation protocol for Ethernet passive optical networks (EPONs)," Proceedings of IEEE International Conference on Transparent Optical Networks, vol. 1, July 2005, pp. 241-244.

[9] G. Kramer, B. Mukherjee, S. Dixit, Y. Ye, and R. Hirth, "Supporting differentiated classes of service in Ethernet passive optical networks," Journal of Optical Networking, vol. 1, August 2002, pp. 280-298.

[10] M. McGarry, M. Reisslein and M. Maier, "Ethernet passive optical network architectures and dynamic bandwidth allocation algorithms", IEEE Communications Surveys & Tutorials, vol. 10, Third Quarter 2008, pp. 46 – 60.

[11] S.Hussain and X. Fernando, "EPON: An extensive review for up-to-date dynamic bandwidth allocation schemes", Canadian Conference on Electrical and Computer Engineering, 2008. pp. 000511 - 000516.

[12] G. Kramer, B. Mukherjee, and G. Pesavento, "Interleaved polling with adaptive cycle time (IPACT): A dynamic bandwidth distribution scheme in an optical access network," Photonic Network Communications, vol. 4, January 2002, pp. 89-107.

[13] S. Choi and J. Huh, "Dynamic bandwidth allocation algorithm for multimedia services over Ethernet PONs," ETRI Journal 24, June 2002, pp. 465-468.

[14] C. Assi, Y. Ye, S. Dixit and M. Ali, "Dynamic bandwidth allocation for quality-of-service over Ethernet PONs," IEEE Journal on Selected Areas in Communications, vol. 21, November 2003, pp. 1467-1477.

[15] Y. Hsueh, F. An, K. Kim and L. Kazovsky, "A new media access control protocol with quality of service and fairness guarantee in Ethernet-based passive optical networks," in Proc. IASTED Wireless Optical Communications Conf., July 2003, pp. 165–169.

[16] J. Xie, S. Jiang and Y. Jiang, "A class-based dynamic bandwidth allocation scheme for EPONs," International Conference on Communications Systems, September 2004. pp. 356-360.

[17] M. Ma, Y. Zhu, and T. Cheng, "A bandwidth guaranteed polling MAC protocol for Ethernet passive optical networks," INFOCOM 2003. Twenty-Second Annual Joint Conference of the IEEE Computer and Communications Societies 2003, vol. 1, pp. 22-31.

[18] S. Choi, "Cyclic polling-based dynamic bandwidth allocation for differentiated classes of service in Ethernet passive optical networks," Photonic Network Communications 2004, vol. 7, pp. 87-96.

[19] D. Nowak, P. Perry and J. Murphy, "Bandwidth allocation for service level agreement aware ethernet passive optical networks," Global Telecommunications Conference, 2004. GLOBECOM '04. vol. 3, pp. 1953-1957.

[20] G. Kramer, A. Banerjee, N. Singhal, B. Mukherjee, S. Dixit and Y. Ye, "Fair queuing with service envelopes (FQSE): A cousin-fair hierarchical scheduler for subscriber access networks," IEEE Journal on Selected Areas in Communications, vol. 22, October 2004, pp 1497-1513.

[21] A. Banerjee, G. Kramer and B. Mukherjee, "Fair sharing using service-level agreements (SLAs) for open access in EPON," IEEE International Conference on Communications, 2005, vol. 3, pp. 1858-1862.

[22] A. Banerjee, B. Mukherjee and G. Kramer, "Achieving open access in Ethernet PON (EPON)," Optical Fiber Communication Conference, 2005.

[23] L. Bart, L. Verslegers, D. Colle, M. Pickavet, P. Demeester and M. Gagnaire, "Thorough analysis of the IPACT dynamic bandwidth allocation algorithm for EPONs," Broadband Communications, Networks and Systems, 2007. pp 486-494.

[24] H. Byun, J. Nho and J. Lim, "Dynamic bandwidth allocation algorithm in Ethernet passive optical networks," Electronics Letters, vol. 39, June 2003, pp. 1001-1002.

[25] L. Yuanqiu and N. Ansari, "Bandwidth allocation for multiservice access on EPONs," Communications Magazine, vol. 43, February 2005, pp. S16-S21.

[26] Z. Yongqing, M. Ma, and T. Cheng, "IPACT with grant estimation for EPON," IEEE Singapore International Conference on Communication Systems, 2006. pp. 1-5.

[27] A. Shami, X. Bai, C. Assi, and N. Ghani, "A new dynamic bandwidth allocation scheme in ethernet passive optical access networks," International Conference on Parallel Processing Workshops, 2004. pp. 371-378.

[28] D. Hossain, H. Erkan, R. Dorsinville, M. Ali, and A. Shami, "A novel ring-based EPON architecture," 2nd International Conference on Broadband Networks, 2005, vol. 2, pp.1535-1540.

[29] E. Wong, and C. Chang-Joon , "Efficient dynamic bandwidth allocation based on upstream broadcast in Ethernet passive optical networks," Optical Fiber Communication Conference, 2005, vol. 6, pp. 3.

[30] SR. Sherif, A. Hadjiantonis, G. Ellinas, C. Assi, and MA Ali, "A novel decentralized Ethernet-based PON access architecture for provisioning differentiated QoS," Journal of Lightwave Technology 2004, vol. 22, pp 2483-2497.

[31] De Andrade, M., L. Gutiérrez, and S. Sallent, "A Distributed Scheduling Approach for Ethernet-based Passive Optical Networks," IEEE Conference on Local Computer Networks, October 2007, pp. 205-206.

[32] M. Maier, "WDM EPON: Future applications and services," Second International Conference on Access Networks & Workshops 2007, pp. 1-8.

[33] M. McGarry, M. Reisslein and M. Maier, "WDM Ethernet passive optical networks," Communications Magazine, vol. 44, February 2006, pp. 15-22.

[34] A. Banerjee, Y. Park, F. Clarke, H. Song, S. Yang, G. Kramer, K. Kim, and B. Mukherjee, "Wavelength-division-multiplexed passive optical network (WDM-PON) technologies for broadband access: A review [invited]," Journal of Optical Networking, vol. 4, 2005, pp. 737-758.

[35] H. Kae, D. Harle and I. Andonovic, "Dynamic bandwidth allocation algorithm for differentiated services over WDM EPONs," International Conference on Communications Systems, 2004, pp. 116-120.

[36] F. Clarke, S. Sarkar, and B. Mukherjee, "Simultaneous and interleaved polling: An upstream protocol for WDM-PON," Optical Fiber Communication Conference, 2006 and the 2006 National Fiber Optic Engineers Conference, pp. 3.

[37] A. Fu-Tai, K. Kyeong Soo, D. Gutierrez, S. Yam, E. Hu, K. Shrikhande, and L. G. Kazovsky, "SUCCESS: A next-generation hybrid WDM/TDM optical access network architecture," Journal of Lightwave Technology, vol. 22, 2004, pp. 2557-2569.

[38] K. Kyeong Soo, D. Gutierrez, A. Fu-Tai and L. G. Kazovsky, "Design and performance analysis of scheduling algorithms for WDM-PON under SUCCESS-HPON architecture," Journal of Lightwave Technology, vol. 23, 2005, pp. 3716-3731.

[39] H. Yu-Li, M. Rogge, S. Yamamoto, and L. G. Kazovsky, "A highly flexible and efficient passive optical network employing dynamic wavelength allocation," Journal of Lightwave Technology, vol. 23, 2005, pp. 277-286.

[40] M. McGarry, M. Reisslein, M. Maier, and A. Keha, "Bandwidth management for WDM EPONs," Journal of Optical Networking, vol. 5, 2006, pp. 637-654.

[41] A. Dhaini, C. M. Assi, M. Maier and A. Shami, "Dynamic wavelength and bandwidth allocation in hybrid TDM/WDM EPON networks," Journal of Lightwave Technology, vol. 25, 2007, pp. 277-286.

[42] M. McGarry, M. Reisslein, C. J. Colbourn, M. Maier, F. Aurzada, and M. Scheutzow, "Just-in-time scheduling for multichannel EPONs," Journal of Lightwave Technology, vol. 26, 2008, pp. 1204-1216.

[43] G. Kramer, "What is next for Ethernet PON?," Joint International Conference on Optical Internet and Next Generation Network, 2006. pp. 49-54.

[44] L. Rujian, "Next generation PON in emerging networks," Conference on Optical Fiber communication/National Fiber Optic Engineers Conference, 2008. pp. 1-3.

[45] M. Hajduczenia, H. Da Silva, and P. Monteiro, "10G EPON development process," International Conference on Transparent Optical Networks, 2007, vol. 1, pp. 276-282.

[46] L. Kazovsky, S. Wei-Tao, D. Gutierrez, N. Cheng and S. Wong, "Next-generation optical access networks," Journal of Lightwave Technology, vol. 25, 2007, pp. 3428-3442.

[47] M. Hajduczenia, H. Da Silva and P. Monteiro, "Development of 10 Gb/s EPON in IEEE 802.3av," Communications Magazine, vol. 46, 2008, pp. 40-47.

[48] S. Gangxiang, R. Tucker and C. Chae, "Fixed mobile convergence architectures for broadband access: Integration of EPON and WiMAX [topics in optical communications]," Communications Magazine, vol. 45, 2007, pp. 44-50.

[49] S. Sarkar, S. Dixit and B. Mukherjee, "Hybrid wireless-optical broadband-access network (WOBAN): A review of relevant challenges," Journal of Lightwave Technology, vol. 25, 2007, pp. 3329-3340.