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RESOURCE MANAGEMENT RESEARCH IN ETHERNET PASSIVE
OPTICAL NETWORKS

By

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DE CATALUNYA
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God all is for you.

"The fundamental principle of peace is a belief that each person is important. Do you believe you are important? Do you believe-do we believe-that we can do something to make this world a better place? Why is the gap between the rich and the poor, the powerful and the powerless growing? There can be no peace unless we can become aware of where this growing gap comes from".

—Jean Vanier

To my wonderful family.

ABSTRACT

The last decades, we have witnessed different phenomenology in the telecommunications sector. One of them is the widespread use of the Internet, which has brought a sharp increase in traffic, forcing suppliers to continuously expand the capacity of networks.

In the near future, Internet will be composed of long-range high-speed optical networks; a number of wireless networks at the edge; and, in between, several access technologies. Today one of the main problems of the Internet is the bottleneck in the access segment. To address this issue the Passive Optical Networks (PONs) are very likely to succeed, due to their simplicity, low-cost, and increased bandwidth.

A PON is made up of fiber optic cabling and passive splitters and couplers that distribute an optical signal to connectors that terminate each fiber segment. Among the different PON technologies, the Ethernet-PON (EPON) is a great alternative to satisfy operator and user needs, due to its cost, flexibility and interoperability with other technologies. One of the most interesting challenges in such technologies relates to the scheduling and allocation of resources in the upstream (shared) channel, i.e., the resource management.

The aim of this thesis is to study and evaluate current contributions and propose new efficient solutions to address the resource management issues mainly in EPON. Key issues in this context are future end-user needs, quality of service (QoS) support, energy-saving and optimized service provisioning for real-time and elastic flows.

This thesis also identifies research opportunities, issue recommendations and proposes novel mechanisms associated with access networks based on optical fiber technologies.

RESUMEN

Durante las últimas décadas, hemos sido testigos de diferentes fenómenos en el sector de las telecomunicaciones. Uno de ellos es el uso generalizado de Internet, que ha traído un fuerte aumento en el tráfico, lo que obliga a los proveedores a expandir continuamente la capacidad en las redes.

En el futuro próximo, Internet se compondrá de redes ópticas de alta velocidad y de largo alcance; un número de redes inalámbricas en los bordes, y en el medio varias tecnologías de acceso. Hoy en día uno de los principales problemas de Internet es el cuello de botella en el segmento de acceso. Para solucionar este problema las redes ópticas pasivas (PON) se han presentado con gran éxito, debido a su simplicidad, bajo costo, y el aumento de ancho de banda.

Una red PON se compone de cableado de fibra óptica y divisores pasivos y acopladores que distribuyen una señal óptica a los conectores que terminan cada segmento de fibra. Entre las diferentes tecnologías PON, la PON basada en Ethernet (EPON) es un gran alternativa para satisfacer las necesidades del operador y del usuario, debido a su coste, su flexibilidad e interoperabilidad con otras tecnologías. Uno de los retos más interesantes para dichas tecnologías se refiere a la programación y asignación de recursos en el canal compartido, es decir, la gestión de los recursos.

El objetivo de esta tesis es estudiar y evaluar las contribuciones actuales y proponer nuevas soluciones eficientes para hacer frente a los problemas de asignación de recursos, principalmente en EPON. Factores clave en este aspecto son las necesidades futuras de los usuarios finales, la calidad de servicio (QoS), el soporte para el ahorro de energía y la optimización para la provisión de servicios de tiempo real y los flujos elásticos.

Esta tesis también identifica oportunidades de investigación, recomendaciones y propone nuevos mecanismos asociados con las redes de acceso basados en tecnologías de fibra óptica.

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- **P. Garfias**, M. De Andrade, M. Tornatore, A. Buttaboni, S. Sallent, and L. Gutiérrez, "A Novel traffic-aware mechanism for energy-saving at the OLT in WDM/TDM-PON," in European Conference on Network and Optical Communications (NOC), 2013.

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ACRONYMS

10GEPON	10 Gb/s EPON
AF	Assured Forwarding
ATM	Asynchronous Transfer Mode
AWG	Arrayed Waveguide Grating
APON	ATM-based PON
BE	Best Effort
BPON	Broadband PON
CAPEX	Capital Expenditure
CBR	Constant Bit Rate
CO	Central Office
CDM	Code Division Multiplexing
DBA	Dynamic Bandwidth Allocation
DRA	Distributed Resource Algorithm
DWA	Dynamic Wavelength Allocation
DBWA	Dynamic Bandwidth and Wavelength Allocation
DDSPON	Dynamic Distributed Scheduling for EPON
DiffServ	Differentiated services
DSL	Digital Subscriber Line
DSLAM	Digital Subscriber Line Access Multiplexer
DTE	Data Terminal Equipment
EF	Expedited Forwarding
EFT	Earliest Finish Time
EPON	Ethernet-based PON
EFM	Ethernet in the First Mile
FCFS	First-come, First-served
FTTH	Fiber to the Home

FEC	Forward Error Correction
FSAN	Full Service Access Network
GCD	Greatest Common Divisor
GEM	GPON Encapsulation Method
GPON	Gigabit PON
HFC	Hybrid Fiber Coax
ITU	International Telecommunication Union
IEEE	Institute of Electrical and Electronics Engineers
IPACT	Interleaved Polling with Adaptive Cycle Time
LAN	Local Area Network
LCM	Least Common Multiple
LFT	Latest Finish Time
LRD	Long-Range Dependent
LR-PON	Long-Reach PON
MAN	Metropolitan Area Network
MAC	Media Access Control
MPCP	Multi-Point Control Protocol
ODN	Optical Distribution Network
OFDM	Orthogonal Frequency Division Multiplexing
ONU	Optical Network Unit
OLT	Optical Line Termination
ONT	Optical Network Terminal
OAM	Operation, Administration and Maintenance
OSI	Open System Interconnection
PON	Passive Optical Network
P ₂ MP	Point-to-multi-point
P ₂ P	Point-to-point
PMD	Physical Media Dependent
PMA	Physical Medium Attachment

PCS	Physical Coding Sublayer
QoS	Quality of Service
RTT	Round Trip Time
RS	Reconciliation Sublayer
SLA	Service Level Agreement
SCM	Sub-carrier Division Multiplexing
SIEPON	Service Interoperability in EPON
SRD	Short-Range Dependent
TDM	Time Division Multiplexing
VBR	Variable Bit Rate
VDSL	Very high-speed DSL
WiMAX	Worldwide Interoperability for Microwave Access
WDM	Wavelength Division Multiplexing
WDM-PON	WDM-based PON
WDM/TDM-PON	WDM and TDM based PON
WAN	Wide Area Network

INTRODUCTION

Optical fiber provides the only solution for existing and future Internet requirements because with optical fiber technologies, bandwidth demands are satisfied and a wide range of services and applications can be supplied.

Nowadays one of the problems of the Internet is the performance in the access segment. Although service providers have responded to the demand for broadband services by either moving towards a wireless solution or upgrading their copper infrastructure, both technologies impose a technical trade-off between rate and reach affecting the number and type of services that can be offered. Connecting users directly to fiber optic cable enables enormous improvements in the bandwidth, thereby the delivery of communication signals from service providers all the way to a home or business, regarded as Fiber to the Home (FTTH), is turning out to be the best technology to deliver many broadband services for medicine, education, home-based businesses and entertainment.

There were nearly 75 million FTTH subscribers worldwide at the end of 2012, but only 10.3 million of them are in Europe¹. In the United States of America, one of every five households is within reach of fiber, and more than 8 million households are using FTTH services now. These numbers continue to grow rapidly. China alone expects to have 100 million fiber subscribers by 2015. By then, 90 percent of Australians will be connected².

The most popular solution deployed among operators for FTTH is the Passive Optical Network (PON): it features a Point-to-multi-point (P2MP) architecture to provide broadband access. The great promise of PON is the ability to relieve bottlenecks in the access network. As full services are provisioned by the massive deployment of PON networks worldwide, operators expect more from PONs. This includes service support capabilities, improved bandwidth and enhanced performance of access nodes.

¹ FTTH in Europe: A long way to go - <http://www.lightwaveonline.com/>

² What Fiber Broadband Can Do For Your Community - <http://www.bbpmag.com/>

1.1 THESIS MOTIVATION

The P₂MP architectures are preferred when implementing a PON. However, sharing the same infrastructure among multiple users has introduced challenges at the physical layer, as well as at levels higher than physical layer because it is necessary to implement efficient schemes for dynamic bandwidth and wavelength allocation in the common network segment.

The design of solutions that optimize the resource management in PON, not only based on the type of network but also in hybrid technologies, is an interesting field of research because new solutions are the key to reach the efficiency and the high performance.

This thesis focuses on optical fiber based access networks. The global objective of the thesis is the design and evaluation of an advanced solution for the control and distribution of resources in PONs of high capacity, which optimizes resource management to real time services and elastic flows, fulfilling the end-users requirements.

1.2 THESIS CONTRIBUTIONS

This thesis aims to provide a contribution to the resource management issues particularly in Ethernet-based PON (EPON) but which can easily upgrade to 10 Gb/s EPON (10GEPON) and even to WDM and TDM based PON (WDM/TDM-PON). We provided an extended analysis of the current literature about resource allocation proposals.

During this research we have involved mainly with Dynamic Bandwidth Allocation (DBA) issues in EPON but also in scenarios where EPON and 10GEPON coexist, also we have addressed the energy-saving issues in WDM/TDM-PON. We have reviewed the most relevant proposals in literature. A summary of such proposals can be seen in this thesis as well as in our publications [29]. Figure 1 shows a summary of the thesis contributions.

This thesis is based on a research methodology that comprises simulations, analysis and dissemination of results. Whenever possible, the simulation results were checked against their mathematical analysis.

In order to evaluate the proposed solutions, a simulation network model has been developed. The simulation environment is based on OPNET Modeler tool³. OPNET Modeler provides a comprehensive

³ <http://www.opnet.com/>

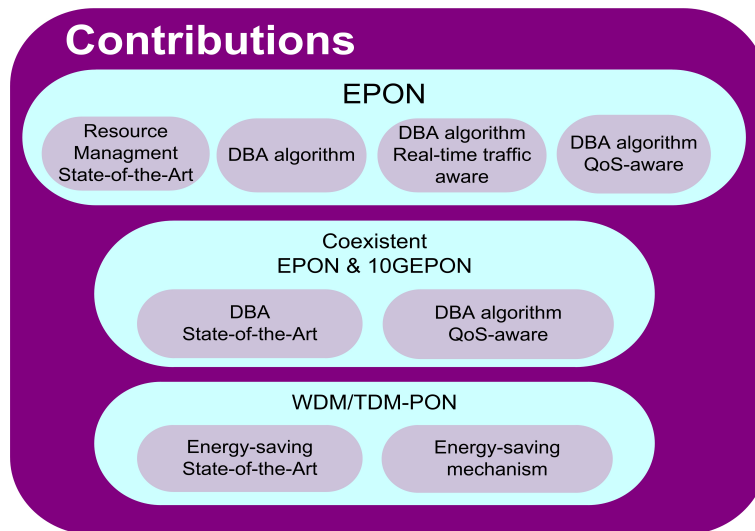


Figure 1: Thesis Contributions.

development environment supporting the modeling of communication networks and distributed systems. We chose OPNET Modeler suite as a tool to model allocation problems in EPON, because both behavior and performance of modeled systems can be analyzed by performing discrete event simulations.

1.3 THESIS ORGANIZATION

The content of this thesis has been divided in three parts. The first part is devoted to present an overview of Access Networks, taking special interest in EPON, also a review of PON evolution and trends is provided. In the second part the resource management issues along with the stat-of-the-art in EPON are presented. Finally, in the last part, the main contributions of this research are detailed. At the end, the conclusions summarizing the contributions, and the bibliography used to elaborate this thesis, are included.

Part I

OPTICAL ACCESS NETWORKS

An access network comprises connections extending from a Central Office (CO), connected to the metro or core network, to the subscribers.

The wired technology deployed varies significantly from one country to another, i.e., Digital Subscriber Line (DSL), based on copper wires; Hybrid Fiber Coax (HFC), and finally, optical fiber.

Optical fiber properties, such as low loss and the extremely wide inherent bandwidth, make them the ideal candidate to meet the capacity challenges for today and for the foreseeable future. They are widely used in core and metropolitan networks, and nowadays their penetration in the access domain is increasing.

This part of the thesis is devoted to presenting the basic knowledge needed to understand the problem this thesis will face. The concepts of Access Networks and its open issues are reviewed here. To obtain a complete understanding of PON, the EPON specifications are presented, finally the application of Wavelength Division Multiplexing (WDM) to PON is addressed.

ACCESS NETWORKS

The access network, also regarded as the "first mile", the "last mile", the subscriber access network, or the local loop, connects the Central Offices (COs) to business and residential subscribers. Since access networks are the bottleneck for providing broadband services, the challenges in access networks have been on developing high capacity networks. Figure 2 shows a Telecommunication Network Overview.

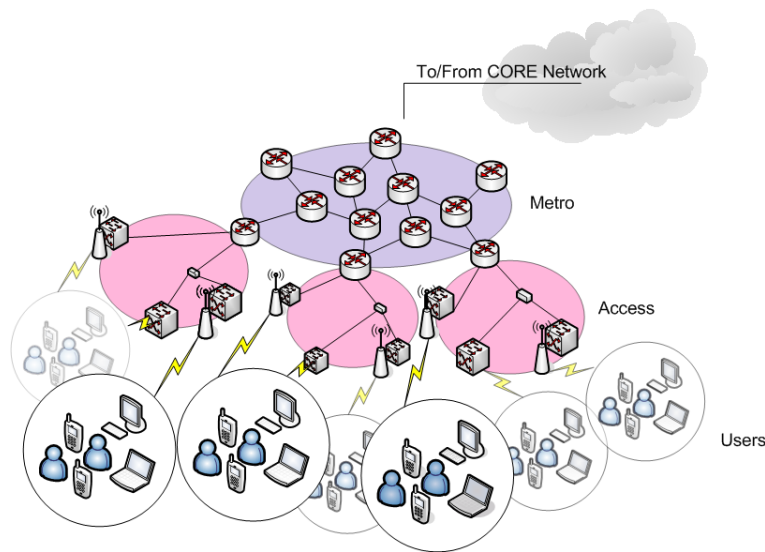


Figure 2: Telecom Network Overview.

Most current access networks are based on copper (mainly Digital Subscriber Line (DSL)) and coaxial cables (Hybrid Fiber Coax (HFC)). The increasing communication service demands are making these networks obsolete and, in most cases, they are being gradually replaced by optical access networks.

The most widely deployed solutions in access segment are DSL networks. DSL uses the same twisted pair as telephone lines and requires a DSL modem at the customer premises and a Digital Subscriber Line Access Multiplexer (DSLAM) in the CO. Several variations of DSL technology have been implemented to meet the needs of different users; however, they are becoming even more challenging as these technologies get closer to their practical capacity limits.

Table 1 shows the results of an analysis conducted in 2009¹ regarding the capacity in access network architectures, such as DSL, HFC and Worldwide Interoperability for Microwave Access (WiMAX). It can be seen that in the next years they will be at the limit of their capabilities.

Table 1: Access Networks per-household capacity expectations.

Access Network	Per-household capacity
DSL	ADSL access networks designed to Carrier Serving Area guidelines will exceed the required capacities projected for year 2015. Very high-speed DSL (VDSL) networks can provide additional capacity above that of ADSL.
HFC	HFC access networks with 250 households per Optical Node and two downstream data channels meet current but not future capacity requirements. Providing an Optical Node per 125 households and increasing the number of downstream channels provides capacity that may become marginal around year 2015.
WiMAX	Range-limited WiMAX such as those expected to serve rural areas are limited by the rate provided out to the cell edge. A range-limited cell with six sectors will support about 30 households at the required capacity for year 2015.

To alleviate bandwidth bottlenecks, optical fibers and thus optical nodes are penetrating deeper into the first mile. This trend is present in both DSL and HFC worlds. In DSL-based access networks, many remote DSLAMs deployed in the field use fiber-optic links to the COs. In HFC networks, optical curbside nodes are deployed close to the subscribers.

The actual phase of access network deployments brings fiber all the way to the office, apartment buildings or individual homes. Optical fiber is capable of delivering integrated voice, data, and video services at distances beyond 20 km in the subscriber's access network. Unlike previous architectures, where fiber is used as a feeder to shorten the lengths of copper and coaxial networks, these new deployments use optical fiber throughout the access network.

While operators prepare their networks for the fiber deployment, new efforts that enable operators to significantly increase the speeds offered over their existing copper infrastructure have been made. Such is the case with a technology known as VDSL2 Vectoring.

¹ Defining Broadband Speeds - <http://www.adtran.com/>

Current DSL networks use cable binders consisting of bundles of twisted copper pairs in order to transmit data to and from various customer premises. The interference between neighboring copper pairs, known as crosstalk, is the main adversary to the achievable data rate in DSL networks. Thus, to improve the achievable data rate, crosstalk must be reduced or, ideally, removed entirely [90].

VDSL2 vectoring, currently the most advanced technology for delivering broadband services over the copper network, is a transmission method that employs the coordination of line signals for reduction of crosstalk levels and improvement of performance [36]. Vectoring is claimed to deliver bandwidths of up to 200Mb/s, but a more realistic expectation is 100Mb/s over 500 meters of copper. This technology is seen as an intermediate step to full FTTH networks.

The extensive research conducted on access networks in the recent past comprises a number of issues arising when service providers have to respond to the growing demand for broadband services, see Figure 3. In fact, many issues appearing in each of such technologies have not yet been solved. Failing to address such issues while each of the technologies matures, may lead to situations where enough bandwidth is available but applications experience poor performance, or where network resources are wasted. To accomplish this, a number of contributions have been made in terms of technologies, services, resources and more.

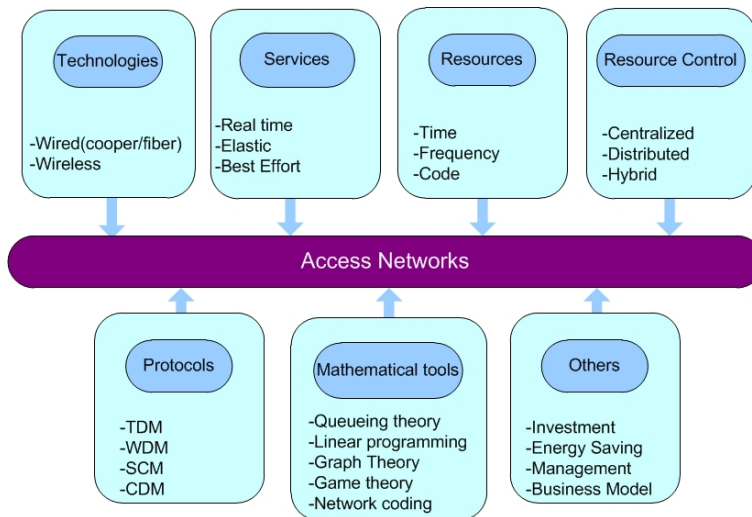


Figure 3: Access Networks Issues.

2.1 PASSIVE OPTICAL NETWORKS

A PON is a P2MP network without active elements in the signal path between source and destination, basically formed by optical fiber and

an optical splitter/combiner. This save on maintenance costs, equipment distribution, power supply and it lead to more optimal and efficient utilization of the fiber optic infrastructure.

A **PON** consists of an Optical Line Termination (**OLT**) at the network provider **CO**, and a number of terminals near the end-user device called Optical Network Unit (**ONU**) or Optical Network Terminal (**ONT**) as shown in Figure 4.

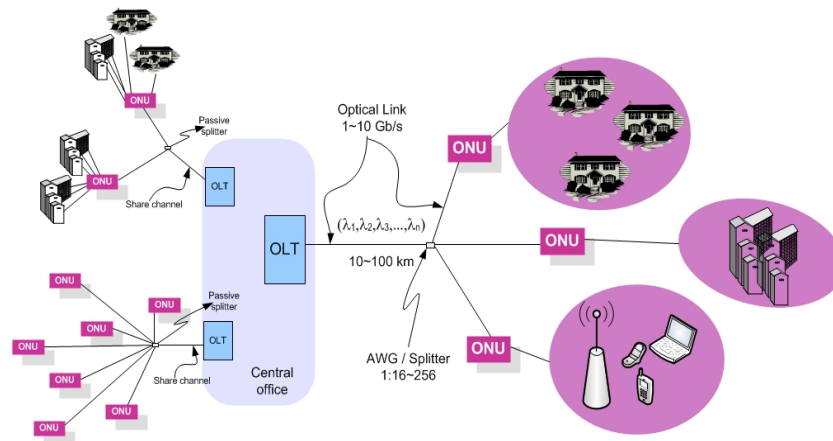


Figure 4: Passive Optical Network.

A **PON** can be represented as a tree (a) or a star topologies, but it can also support topologies such as bus (b), ring (c) and redundant configurations as shown in Fig. 5. The **PON** key element is the splitter that in one direction splits a beam of light into several bundles, distributes it to several optical fibers, and in the other direction it combines light signals from various optical fibers to a single optical fiber output.

Because of its multi-point structure, **PON** offers the service broadcast on downstream while in the upstream end-users need to share the channel. A **PON** can use single or multiple fibers for upstream and downstream traffic, with or without **WDM**, being a single channel tree the most common topology.

The communication of subscribers connected to the **PON** can be performed by several multiple-access techniques such as Time Division Multiplexing (**TDM**), Wavelength Division Multiplexing (**WDM**), Sub-carrier Division Multiplexing (**SCM**) and Code Division Multiplexing (**CDM**) [55]. Table 2 shows the main multiplexing methods in the optical domain.

Different **PON** technologies have been developed: the ATM-based **PON** (**APON**) which uses Asynchronous Transfer Mode (**ATM**) encaps-

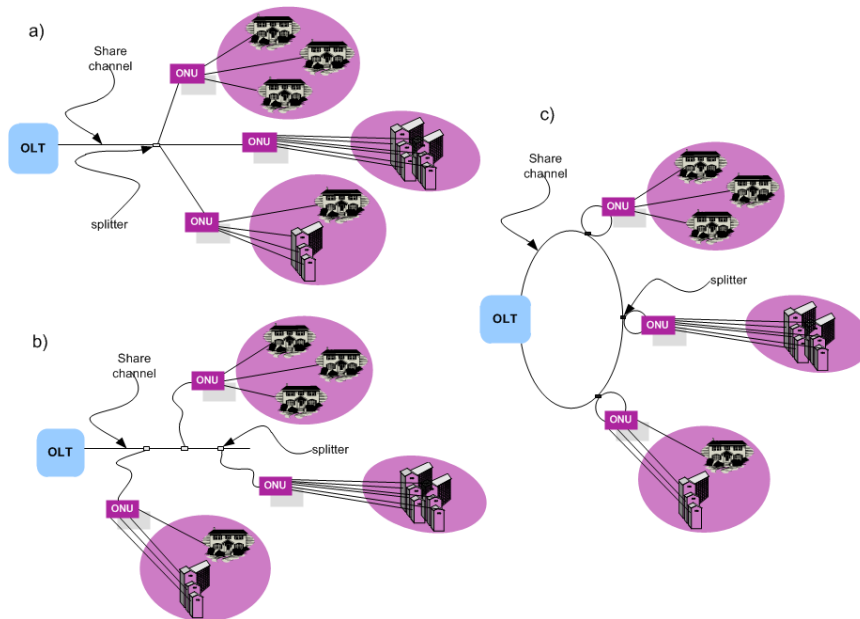


Figure 5: PON Topologies.

sulation of transported data. The Broadband PON (**BPON**) which offers improved and additional features such as **WDM** support, higher upstream bandwidths and upstream bandwidth allocation. The **EPON**, which uses Ethernet rather than **ATM** data encapsulation and is highly suitable for data services. The Gigabit PON (**GPON**), often described as combining the best attributes of **BPON** and **EPON**.

Currently, there are two branches of standardization of **PON**, according to the technology of layer 2 to be used: International Telecommunication Union (**ITU**)² **GPON** (G.984.x) [34] and Institute of Electrical and Electronics Engineers (**IEEE**)³ 802.3ah [2] and 802.3av [3].

2.2 EPON

As **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, **EPON** solution is an interesting, suitable and attractive opportunity to deploy **PON**, mainly because Ethernet technology is making network managers take advantage of their experience i.e., network management, installed equipment and analysis tools. Finally, because Ethernet supports all services and all media types, it represents a cost effective solution.

² <http://www.itu.int>

³ <http://www.ieee.org>

Table 2: Multiplexing Methods in the Optical Domain.

Multiplexing Method	Description
TDM	This technique relies on assigning dedicated time slots to each of the multiple subscribers connected to the PON. To connect the multiple subscribers to a single-feeder fiber, a passive optical-power splitter is used at the remote node.
WDM	In this scheme, each subscriber is assigned a pair of dedicated wavelengths; this contrasts the TDM case where a single pair of wavelengths is shared among all the subscribers connected to the PON. To accomplish this WDM functionality, a WDM multiplexer is used at the remote node instead of a power splitter, and an additional WDM demultiplexer is located at the CO to separate the multiple-wavelength signals at the OLT.
SCM	Subcarrier multiple access enables dedicated point-to-point connectivity over a PON architecture by allocating a different frequency to each subscriber. In this scheme, each subscriber transmits at essentially the same wavelength but is allotted a unique frequency to encode its data. A single receiver at the OLT detects the N different frequencies and demultiplexes them in the electrical-frequency domain.
CDM	Each subscriber is assigned a unique and effectively orthogonal code for transmission at any time regardless of when the others are transmitting. At the OLT/ONU receivers, all the overlapping codes are detected using a single receiver and correlated with sets of matching codes associated with each user-data channel.

The IEEE Std. 802.3ah introduces the concept of EPON in which a P₂MP network topology is implemented with passive optical splitters. EPON is a PON encapsulating data with Ethernet and can offer a nominal bit rate of 1 Gb/s (extensible to 10 Gb/s) for each channel which is defined by two wavelengths: one wavelength for the downstream and the other one for the upstream direction shared among the user devices.

EPON follows the original architecture of a PON, where the Data Terminal Equipment (DTE) connected to the trunk of the tree is called OLT and it typically resides at the service provider; and the DTE connected to the branches of the tree, called 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 study group called Ethernet in the First Mile (EFM) was created in November 2000, having as

its main objectives the study of Ethernet over 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 finished the standardization process with the ratification of the IEEE Std 802.3ah in June 2004.

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. In [50] such standard is deeply explained.

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 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 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 EPON media type(s) as well as to interact with mixed 10/100/-1000/10000 Mb/s Ethernet networks. EPON technologies allow different types of topologies in order to obtain maximum flexibility. 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.

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

The Multi-point MAC Control defines the MAC control operation for optical P2MP networks. The Multi-point MAC Control functionality shall be implemented for subscriber access devices containing P2MP physical layer devices.

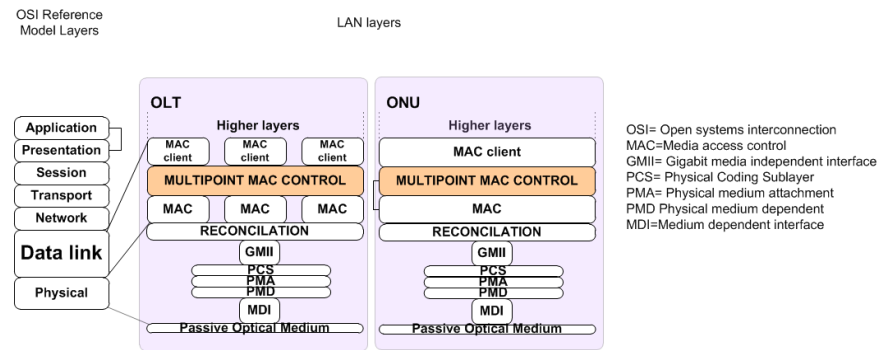


Figure 6: Relationships between EFM elements and OSI. Source [2]

Figure 6, shows the relationships between EPON elements and Open System Interconnection (OSI), a reference model for P2MP topologies. It can also be seen that a Multi-point MAC control is made of one or more MAC instances. The OLT will have several instances, depending on the number of ONUs attached to it, if the OLT has 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.

Commonly, MAC instances offer a P2P emulation service between the OLT and the ONU but an additional instance is included with a communication purpose for all ONUs at once. Through the Multi-point MAC Control it is possible for a MAC client to participate in a P2MP optical network because that is the way to transmit and receive frames as if it was a P2P connection.

2.2.1 Multi-point control Protocol

One of the functional blocks of the Multi-Point MAC Control sublayer is related to the Multi-Point Control Protocol (MPCP) functions, which allows the negotiation of access to the medium 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. MPCP specifies a control mechanism between two units connected to a P2MP network to allow efficient transmission data.

The process of communication from the OLT to the ONU, where data are broadcast using the entire bandwidth and ONU receive frames by matching the address in the Ethernet frames, is regarded as downstream. On the contrary, in the upstream communication, from the ONU to the OLT, multiple ONUs share the common channel which means that in order to avoid data collisions only a single ONU may transmit. Figure 7 shows EPON operation.

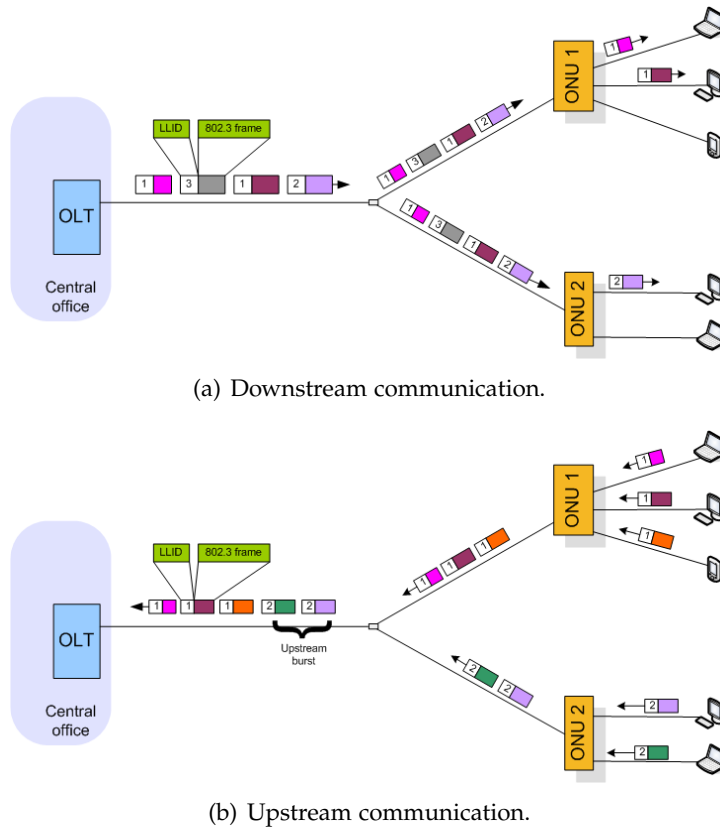


Figure 7: EPON operation.

MPCP introduces 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 request bandwidth to OLT; the OLT in turn generates discovery messages, controls registration process and allocates bandwidth [50]. Table 3 summarizes the function of the control messages in MPCP.

Through a discovery processing function, new ONUs are discovered in the network, and by means of the report processing function it is possible to achieve a feedback mechanism. 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 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 message to the OLT. The off-line ONUs, after receiving the discovery

Table 3: MPCP control messages.

Control message	Description
GATE	Gate messages perform two roles: A discovery GATE message is used to advertise a discovery slot for which all uninitialized ONUs may contend, and a normal GATE message is used to grant transmission opportunity to a single, already discovered ONU.
REPORT	This messages are used by ONUs to report local queue status to the OLT. Report messages have different functionalities other than requesting bandwidth: for example, to submit the time stamp for round trip time calculation and to work as keep-alive to maintain link health.
REGISTER_REQ	Is used by unregistered ONUs to respond to discovery GATEs. When the OLT receives the REGISTER_REQ message from an ONU, it learns two key pieces of information: the roundtrip time to the ONU and the ONUs MAC address. Already registered ONUs may also used the REGISTER_REQ message to request deregistration by the OLT.
REGISTER	The REGISTER message is used by the OLT to assign a unique identity to a newly discovered ONU.
REGISTER_ACK	The REGISTER_ACK message serves as an ONU final registration acknowledgment.

message, will be registered during the previously established 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.

REPORT messages 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 requested.

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 DBA, which is outside the stan-

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 (QoS) parameters, as well as the improvement of the efficiency of the channel and the fairness.

2.2.2 10GEPON

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 and asymmetric line rate operation. The symmetric will operate at 10 Gb/s in both upstream and downstream directions, and the asymmetric option will use 10 Gb/s in the downstream and 1 Gb/s upstream [46]. Thus, advance video service demands in the downstream direction are supported by means of the asymmetric option.

The standardization process to specifying 10GEPON, was formed in September 2006 and finished the standardization work in 2009 (IEEE Std. 802.3av), being the major difference against IEEE 802.3ah, the physical layer resulting in a rather costly upgrade, so EPON equipment must provide a gradual evolution in which a co-existence of 10GEPON and EPON will be implemented.

The standard defines two different single mode fiber data rate channels: symmetric and asymmetric, have a Bit Error Ratio (BER) better than 10^{-12} at the PHY service interface, define up to 3 optical power budgets that support split ratios of 1:16 and 1:32, and distances of at least 20 km and maintain a complete backward compatibility with legacy standards. Table 4 summarizes the differences between EPON and 10GEPON.

The major challenges to symmetrical 10GEPON are the cost of new equipments, the coexistence with current technology, and physical layer technical issues, such as extension of current scrambling coding standards and selection of new Forward Error Correction (FEC) [45].

The MPCP protocol is essentially the same in both 1G and 10GEPON networks. It should also be considered that, for the coexistence of various line rates, the DBA in the OLT will be responsible for scheduling not one but two mutually cross-dependent EPON systems, sharing a single upstream channel with minor changes to the MPCP protocol. As in EPON, the DBA is out of the scope and thus left vendor-dependent.

Table 4: Differences between 1G and 10G EPON.

Item	EPON	10GEPON
Channel Coding	8B/10B	64B/66B
Data rate (DS/US)	1Gb/s/1Gb/s (symmetric)	10Gb/s/10Gb/s (symmetric) 10Gb/s/1Gb/s (asymmetric)
Upstream (λ)	1260-1360 nm	1260-1280 nm
Downstream (λ)	1480-1500 nm	1575-1580 nm
# of Power Budget Classes (PBC)	2 classes	3 classes
Split ratio	1:16	1:16 / 1:32
FEC	Reed-Solomon (RS) code 255,239 (optional)	RS code 255,223 (mandatory)

2.3 GPON

The GPON was developed by the Full Service Access Network (FSAN) group⁴. It is somehow based on the former ATM access networks (APON, BPON), but the encapsulation method is different and more generic, it accepts different network protocols, such as ATM, Ethernet and IP. The GPON network is a P2MP network as well, with two type of active terminals: the OLT and the ONT/ONU. The network path itself is known as Optical Distribution Network (ODN) and it is usually integrated by a passive optical splitter as well.

Regarding the MAC layer, the basic transmission unit is called T-CONT (Transmission Container). The bandwidth is guaranteed by allocating time slots to transport the T-CONT of each communication to the ONU. The bandwidth allocation algorithm is also of the request-permit type and it is performed in the OLT. The ONU requests bandwidth, and the OLT allocates the transmission window guaranteed to each active ONU. Two operations modes are possible: SR (Status Reporting)-DBA, where the ONU requests bandwidth to the OLT, and NSR (Non Status Reporting)-DBA, where the OLT monitors the incoming traffic flows but no information is sent to the OLT from the ONUs.

Table 5 summarizes the ITU-T G.984 GPON recommendation.

The features of GPON and EPON standard are summarized and shown in Table 6. There is a common concern that GPON performs very well when the traffic is of the real time while EPON performs better when the traffic is mostly composed by pure data applications, i.e.,

⁴ <http://www.fsan.org>

Table 5: GPON Recommendations.

Number	Title
G.984.1	GPON General characteristics
G.984.2	GPON Physical Media Dependent (PMD) layer specification
G.984.3	GPON Transmission convergence layer specification
G.984.4	GPON ONT management and control interface specification
G.984.5	GPON Enhancement band
G.984.6	GPON Reach extension
G.984.7	GPON Long reach

the Internet. However, it is not so simple to make a definite statement about the performance, mainly because the data collected depends on many parameters, and more importantly, on its implementation.

Table 6: Comparison between GPON and EPON.

Items		ITU-T G.984 GPON	IEEE 802.3ah EPON
MAC	Service	Full services	Ethernet data
	Frame	GEM frame	Ethernet frame
PHY	Distance	10/20 km	10/20 km
	Split ratio	64	64
	Upstream (bit rate)	155 Mbps, 622 Mbps, 1.25 Gb/s	1 Gb/s
	Downstream (bit rate)	1.25 Gb/s, 2.5 Gb/s	1 Gb/s
	Opt. Loss	15/20/25 dB	15/20 dB
	Wavelength	Down : 1480-1500 nm Up : 1260-1360 nm	Down : 1480-1500 nm Up : 1260-1360 nm

From Table 6, it is important to point out that the power budget limits drastically the range of the network and the split ratio, which is typically 64/32 or less in both standards.

2.4 PON EVOLUTION

Although commercial GPON and EPON systems are still under deployment, upgrades are being studied to increase the bit-rate, link lengths and splitting ratios. This will help to reduce operator costs by concentrating and reducing the quantity of CO equipment and fiber cabling needed in the feeder sections of their networks. The use of WDM in PONs and the reach extension of PON represent such upgrades.

2.4.1 WDM-based PON and Long-Reach PON

WDM-based PON (**WDM-PON**) is an example of new **PON** system based on advanced **WDM** technologies, in which each **ONU** operates on a different wavelength. **ONUs** have light sources at different tuned wavelengths coexisting in the same fiber, increasing the total network bandwidth and the number of users served in the optical access network. Regarding to communications mode, the **WDM-PON** may use **P2P** communications, **P2MP** (like **EPON**/**GPON** trees by each wavelength), or hybrid solutions.

WDM-PON mitigates many of the time-sharing issues in a **TDM** system by providing virtual **P2P** optical connectivity to multiple end users through a dedicated pair of wavelengths. Several key enabling technologies for converged **WDM-PON** systems are demonstrated [41, 59], including the techniques for longer reach, higher data rate, and higher spectral efficiency.

One option to implement **WDM-PON** requires replace the optical power splitter in the distribution node by a wavelength multiplexer, typically an Arrayed Waveguide Grating (**AWG**). **OLT** and **ONUs** will also have to be replaced. **AWGs** work with tunable **ONUs** or reflective amplifiers that simply react to the wavelengths offered to them.

Another option is to keep the optical power splitters in place and filter wavelengths at the **ONUs**, which are each tuned to a single wavelength.

The capacity of a **WDM-PON** system depends on many factors, such as the number and capacities of wavelength channels, the network architecture, the wavelength support of receivers, and the tuning ability of lasers. Different architectures have been proposed for **WDM-PONs**, some of them summarized in [11, 54], the simplest creates a **P2P** link between the **OLT** and each **ONU**, therefore each **ONU** can operate at a different bit rate or even more and different services may be supported by wavelength.

WDM/TDM-PON is another example of new **PON**, in which a number of wavelengths are used in each direction to link the **OLT** to a number of **ONUs**; each wavelength is shared among several **ONUs** rather than being dedicated to a single **ONU**.

WDM technology provides great capabilities, but in a traditional **PON** — where distance is 20 km — the carrier can distribute much more bandwidth than users request, i.e., the capacity is greater than the user needs. The key to make better use of network capabilities pro-

vided by WDM is the network span to cover more users. So, a reach extension of PON called Long-Reach PON (LR-PON) has been studied to extend the coverage span from the traditional 20 km range to 100km and beyond, by exploiting Optical Amplifier and WDM technologies. Several demonstrations of LR-PON have been recently reported. In [75] a complete survey is presented.

2.4.2 Trends in GPON

According to the FSAN group, the PON evolution has been defined in two stages: NG-PON₁ and NG-PON₂. Mid-term upgrades in PON networks are defined as NG-PON₁, while NG-PON₂ is a long-term solution in PON evolution.

As a NG-PON₁ solution, ITU became the G.987 [35] suite of standards in January 2010, building upon the existing G.984 suite. Major requirements of NG-PON₁ are the coexistence with the deployed GPON systems and the reuse of outside plant. Table 7 summarizes the G.987.x recommendations.

NG-PON₁ employs a combination of WDM and TDM techniques to ensure coexistence with legacy GPON systems, it provides 10 Gb/s downstream and is regarded as XG-PON (X stands for 10 in the Roman numeral). The G.987.x recommendation defines two flavours of XG-PONs based on the upstream line rate: XG-PON₁, featuring a 2.5 Gb/s upstream path, and XG-PON₂, featuring a 10 Gbit/s one.

Table 7: XG-PON Recommendations.

Number	Title
G.987.1	XG-PON General requirements
G.987.2	XG-PON Physical media dependent (PMD) layer specification
G.987.3	XG-PON Transmission convergence (TC) layer specification
G.987.4	XG-PON Reach extension
G.988	XG-PON ONU management and control interface (OMCI) specification

After NG-PON₁, FSAN began to work on NG-PON₂, the basic requirements were for a system with no requirement in terms of coexistence with legacy PON, which include 40 Gb/s aggregate rate in downstream or upstream, 40 km reach and 1:64 split ratio and technologies such as WDM and Orthogonal Frequency Division Multiplexing (OFDM). Table 8 summarizes the technologies proposed to support the requirement for 40Gb/s bandwidth [57].

Among all of the aforementioned technologies, WDM/TDM-PON was considered by the FSAN to be the solution for NG-PON₂ which con-

Table 8: FSAN suggested technologies for NG-PON2 .

Technology	Description
XLG-PON	The first proposal was based TDM-PON, which increases the single carrier serial downstream bit rate for XG-PON ₁ from 10 Gb/s to 40 Gb/s, while the upstream supports a 10 Gb/s.
WDM/TDM-PON	The second proposal was based on WDM/TDM-PON. It stacks multiple XG-PON ₁ s using WDM. Four pairs of wavelengths would support aggregated rates of 40 Gb/s in the downstream and 10 Gb/s in the upstream.
WDM-PON	The third direction includes five flavors of WDM-PON. Each provides a dedicated wavelength channel at the rate of 1 Gb/s to each optical ONU. The major differences lie in the employed WDM transmitter or receiver technologies.
OFDM-PON	The last direction employs three types of OFDM-PONs that apply quadrature amplitude modulation (QAM) and the fast Fourier transform (FFT) algorithm to generate digital OFDM signals. Their differences lie in the specific implementation of OFDM technology.

tributes significantly to the advancement in the field of NG-PON2 standardization. It is expected that NG-PON2 increase PON capacity to at least 40Gb/s and deliver services of 1Gb/s or more with platforms that could be deployable in 2015.

2.4.3 Trends in EPON

Million subscribers are currently using EPON but is expected many million more may demand EPON services. While current EPON features fall under IEEE Ethernet umbrella, the setup of subscribers and devices from various corners of the world is a challenge which implies the need for a new standard. Thus, in December 2009 the IEEE P1904.1 Standard for Service Interoperability in EPON (SIEPON) Working Group was formed to take EPON to a global level.

The SIEPON working group is composed of carries, equipment vendors and chip vendors, so rather than focusing on technical solutions, SIEPON focuses on the sharing and reutilization of best practices in networks. Recently the group has released a draft standard [1] that describes the system-level requirements needed to ensure multi-vendor interoperability of EPON.

Furthermore, the IEEE P802.3bk Extended EPON Task Force⁵ was formed in March 2012 to consider the standardization of an increased split ratio, which enables a single line terminal equipment to accommodate more subscribers to reduce Capital Expenditure (CAPEX).

Figure 8, summarizes the standardizations trends of PON system.

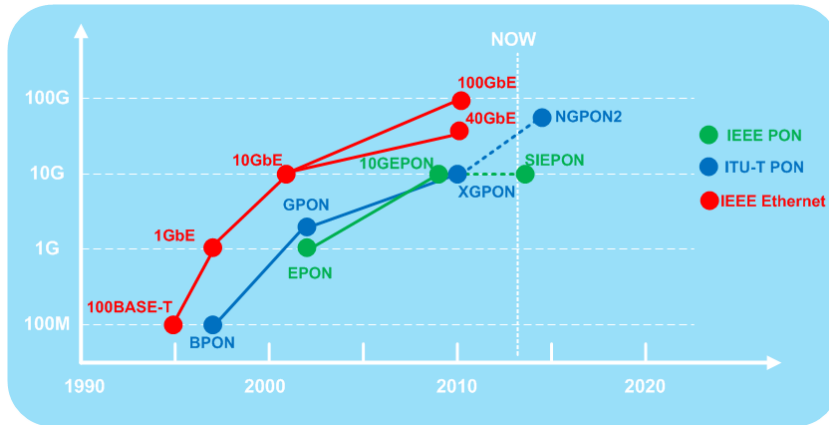


Figure 8: PON Evolution. Source [64]

2.5 SUMMARY

This chapter has presented the fundamentals of PON, and the different types available. EPON is a natural extension of the Local Area Network (LAN) systems, it bridges the gap between the LAN and Ethernet based Metropolitan Area Network (MAN)/Wide Area Network (WAN) structures. We have presented an overview of EPON specifications.

GPON can transport not only Ethernet, but ATM and TDM traffic by using GPON Encapsulation Method (GEM). We have presented a summary of GPON recommendations.

At the end, we briefly discussed the research on WDM-PON and LR-PON to extend the physical reach and increase the splitting ratio in PONs and we also described the evolution stages of PONs.

⁵ <http://www.ieee802.org/3/bk/index.html>

Part II

RESOURCE MANAGEMENT IN PON

Resource management in communication networks is defined as the set of functions that guarantee the allocation, scheduling, control and use of network resources. Goals of a resource management solutions are: efficiency, fairly resource allocation, supporting QoS reducing delay and finally, computational simplicity.

We consider the bandwidth and the wavelength allocation as resource management in PON. Efficient DBA and Dynamic Wavelength Allocation (DWA) algorithms are essential for a successful implementation of PON systems.

This part of the thesis presents the State-of-the-Art of the resource management issues along with the study of the main existing proposals, mainly in EPON.

We categorized the proposals in literature and discussed the major contributions identifying the shortcomings and analyzing them to propose possible improvements.

Since energy efficiency has become an important feature of designing access networks, and due to the relation with medium access control, we also provided here an overview of the energy saving strategies in PON.

RESOURCE ALLOCATION

Dynamic Bandwidth and Wavelength Allocation (DBWA) in EPONs follow a layered approach to scheduling: *the scheduling framework and the scheduling policy*. The scheduling framework is a logistical framework that determines when the OLT makes scheduling decisions, whereas the scheduling policy is a method for the OLT to produce the schedule [63].

The scheduling framework introduced two paradigms for dynamically allocating grants for upstream transmissions on the different upstream wavelengths: *on-line* and *off-line scheduling*.

In an on-line scheduler a given ONU is scheduled for upstream transmission as soon as the OLT receives the REPORT message from the ONU. In other words, the OLT makes scheduling decisions based on individual requests and without global knowledge of the current bandwidth requirements of the other ONUs.

In an off-line scheduler the ONUs are scheduled for transmission once the OLT has received current REPORT messages from all ONUs, allowing the OLT to take into consideration the current bandwidth requirements from all ONUs. Since an off-line scheduler makes scheduling decisions for all ONUs at once, all the REPORTs from the previous cycle must be received [62], which are usually appended to the end of the data stream of a gated transmission window.

Besides the scheduling approach, a *Grant sizing method* is required to determine the size of a grant, i.e., the length of the transmission window assigned to an ONU for a given grant cycle [61]. The cycle is a time period for the transmissions from ONUs, being the cycle length definition an important factor regarding delay issues. In each cycle, every active ONU is polled by the OLT sending the GATE control message which indicates the start time and the amount of bandwidth allocated to it; then the ONU reports the local queue status to the OLT by sending the REPORT control message followed by its data within the allocated window.

3.1 BANDWIDTH ALLOCATION

Bandwidth management in PON has been widely discussed [61, 60, 88, 73], it is an interesting issue that can be solved using different strategies, techniques or mechanisms.

The bandwidth allocation can be categorized under two types of schemes: *fixed* or *dynamic*. The first one allocates the same transmission slots to every ONU in every service cycle regardless of the traffic arrival fluctuations. It is a simple scheme but it does not perform optimally. On the contrary, the dynamic scheme allocates the transmission in the upstream channel based on each ONUs requested bandwidth; consequently, the dynamic scheme provides a more fair, efficient and flexible bandwidth allocation.

DBA algorithms can be performed by OLT (centralized) or by the ONUs (distributed), the centralized DBA algorithms are the most common but many proposals following a distributed scheme. An example of both is shown in section 3.1.2 and 3.1.3 respectively.

3.1.1 DBA Performance Evaluation

The performance evaluation of PON systems using DBA algorithms is based on models which make simplifying assumptions in order to have simple abstractions for reasoning about algorithms. The proper approach of such assumptions leads to a more accurate assessment of the DBA algorithm.

The PON system settings include the definition of parameters such as number of ONUs, number of wavelengths, maximum cycle time, upstream link data rate, guard time interval, distance between OLT and ONU, buffering queue size, timeslot size and traffic model.

The traffic model definition should accurately represent all of the relevant statistical properties of the real traffic. From [48, 79] Table 9 shows different well-known traffic models.

Formulating realistic system models (PON settings) is important, since DBA algorithms are often designed to optimize metrics of interest such as packet delay, queue size, frame loss and channel utilization or throughput.

Effective design of DBA algorithms contributes to the PON efficiency, the main references of the many proposals in literature that address the bandwidth allocation will be commented later in section 3.1.2.

Table 9: PON traffic profiles.

Traffic	Description
CBR	Constant Bit Rate (CBR) traffic is created by aggregating multiple constant packet rate sub-streams. For a long time, classical sources like CBR were used for network analysis, but over the last decade, several research have shown that traditional traffic models are inadequate for modeling real traffic to be carried by advance transport infrastructure.
SRD	Poisson traffic modeling exhibits a Short-Range Dependent (SRD). In this model the packet arrival is modeled by a Poisson process. This model relies on the assumption that the number of packet arrivals has a Poisson distribution with parameter α . Accordingly, the mean number of packets arriving in a duration of T seconds is: αT .
LRD	Studies have reported that LAN, WAN and Variable Bit Rate (VBR) video traffic often display Long-Range Dependent (LRD) and can be better modeled by self-similar processes. LRD traffic, with non-negligible probability, presents extremely large bursts of data and extremely long periods of silence (inter-burst gaps).

3.1.1.1 QoS parameters and metrics

One of the main aspects that SIEPON addresses is the establishment of QoS in EPON. Clause 8 of the SIEPON draft standard provides definitions on mechanisms, parameters, and functions directly related to QoS processes within the EPON system, such as performance metrics. Performance of a EPON can be conveniently characterized by several metrics: bandwidth (throughput), frame delay (latency), delay variation (jitter), and frame-loss ratio.

At the destination, the number of received frames can be counted over a certain time interval, providing a measure of throughput. Additionally, the time between transmission and reception can be determined for each frame, thereby allowing a measure of frame delay (and frame delay variation). Lastly, with the use of timestamps, frame errors and frame loss can be calculated, giving an indication of the robustness of the network [76].

Within the above metrics a set of parameters that describe different services can be defined. Table 10 shows the QoS parameters defined in SIEPON which describe several services in current networks (these services will be discussed later in the chapter 7).

Table 10: QoS parameters.

Metric	Description
Committed Information Rate (CIR)	The CIR defines the average data rate up to which the network guarantees the delivery of data frames.
Committed Burst Size (CBS)	The CBS limits the maximum number of guaranteed octets that are allowed to be sent in a burst (i.e., in data frames transmitted back-to-back at nominal interface rate).
Excess Information Rate (EIR)	The EIR is the allowance of burstable bandwidth above that of the CIR, provided there is adequate bandwidth available.
Excess Burst Size (EBS)	The EBS limits the maximum number of excess octets (octets that are above CIR/CBS allowance) which are allowed to be sent in a burst (i.e., in data frames transmitted back-to-back at nominal interface rate).
Peak Information Rate (PIR)	The PIR is expressed in b/s and is equivalent to the sum of CIR and EIR.
Peak Burst Size (PBS)	The PBS limits the maximum number of octets that are allowed to be sent in a burst (i.e., in data frames transmitted back-to-back at nominal interface rate).
Frame Delay (FD)	The FR consists of several components, such as frame reception delay, internal frame processing delay, queuing delay, frame transmission delay, and propagation delay. These delay components exist on every link or in every device traversed by a given frame.
Frame Delay Variation (FDV)	The FDV defines the maximum allowable jitter in the delay or arrival time of frames at the destination.
Frame Loss Ratio (FLR)	The FLR is defined as a ratio between the number of frames lost between the ingress and egress interface divided by the number of frames which were expected to be transmitted.

3.1.2 IPACT: Centralized scheme

Interleaved Polling with Adaptive Cycle Time (*IPACT*) [48] is one of the early works that became very popular in the literature, its performance has been compared against many latter proposals. *IPACT* uses an interleaved polling scheme to schedule all data *ONU* transmissions so that the other *ONUs* are able to transmit data between two adjacent transmissions of an *ONU* and utilize the channel efficiently.

The most important challenge for a DBA is to define the grant sizing method which can be categorized into: *fixed*, *limited*, *gated*, *constant-credit* and *linear-credit* as seen in Table 11.

Table 11: Grant sizing methods.

Multiplexing Method	Description
Fixed	This method ignores the requested window size and always grants the maximum window. As a result, it has a constant cycle time.
Limited	It grants the requested number of bytes, but no more than the maximum predefined. It is the most conservative scheme and has the shortest cycle of all the methods.
Gated	This method does not impose a maximum limit on the granted window size; i.e., it will always authorize an ONU to send as much data as it has requested. Of course, without any limiting parameter, the cycle time may increase drastically if the offered load exceeds the network capacity.
Constant-credit	It adds a constant credit to the requested window size. The idea behind adding the credit is avoid delay for packets arrived between the time when ONU sent a REPORT and received the grant.
Linear-credit	It uses a similar approach to the constant credit scheme. However, the size of the credit is proportional to the requested window.

Figure 9 shows the criteria in which a bandwidth allocation scheme can be classified.

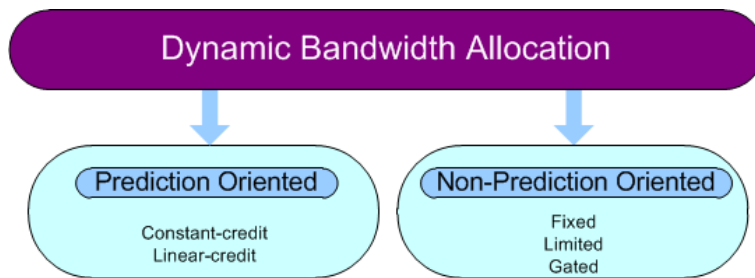


Figure 9: Bandwidth Allocation Criteria

3.1.3 DDSPON: Distributed scheme

In Dynamic Distributed Scheduling for EPON (DDSPON) [6], the bandwidth scheduling algorithm is performed mainly by ONUs, therefore an extra information is introduced in GATE messages; thus, each ONU

calculates the instantaneous transmission window size for itself. Extra information comprises a weight vector that allows **ONU**s 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 **ONU**s.

This **DBA** algorithm requires an **MPCP** extension, because some extra information must be supplied and therefore carried in control messages - mainly the weight vector ϕ .

This data vector, $\vec{\phi} = (\phi_1, \dots, \phi_N)$, allows **ONU**s to compute its transmission window size. Such parameter represents a proportional weight set up according to each **ONU** guaranteed bandwidth agreement. The **ONU** computes the required bandwidth (R_i) and its current weight ϕ_i , then reports such value to the **OLT** in a **REPORT** message.

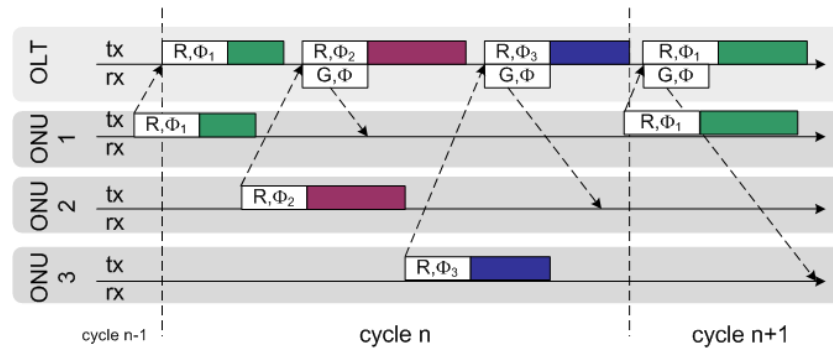


Figure 10: Interleaving Polling Mechanism.

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** [see Figure 10]. A further explanation of **DDSPON** is addressed in chapter 5.

3.1.4 QoS aware DBA algorithms

Several algorithms such as [33, 47, 85, 49, 56] among others, are proposed to address the **QoS** issues in **PON**. Next, we will review some of the main proposals in literature.

In [18], bandwidth is allocated according to traffic priority requests. The algorithm follows a strict priority scheduling approach based on satisfying high-priority flows, because a fixed bandwidth window is assigned for high priority services even if there are no frames to transmit. **OLT** centralizes all the functions of **DBA**, and **ONU**s are responsible of reporting the queue occupancies.

In [47], authors combined **IPACT** and strict priority queuing in order to support **QoS**, they also identifying the *light-load penalty phenomenon*, which is produced when packets arrive during periods when **ONU** is reporting queue states or receiving a grant, causing delay on some lower priority packets in queue if arriving packets have higher priority.

The proposal consists on an inter-ONU and intra-ONU scheduling. 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 incorporates a two-stage queuing system at intra-ONU level. The first stage system classifies and schedules packet transmission based on strict priority. The second queuing stage provides fairness according to the arrival time of packets.

Another solution to light-load penalty problem consists on estimate 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 in [8], it consists on taking the excessive bandwidth, obtained from those **ONUs** which have less traffic to transmit, and fairly distribute it among the highly loaded **ONUs**. This algorithm takes into consideration different traffic classes, so that requested bandwidth consists on 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 arriving 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 is performed, at least for those **ONUs** for which the requested bandwidth is less than the minimum guaranteed, since these do not require waiting to be schedule, grant is sent immediately.

In [33], a different way to address the **QoS** is presented. The algorithm can minimize the delay for high priority traffic through the allocation of constant bandwidth in each frame for it, the solution consists on dividing the cycle into two service classes: one part will be for high priority and the remaining part for low priority, so that 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 bandwidth for one **ONU**. High priority traffic may become variable so

that the ONU needs to redirect the excess 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.

In [85] the division of the frame is also proposed, but in this case the frame is divided into multiple sub-frames 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.

Some algorithm proposals are Service Level Agreement (SLA) aware, i.e., based allocation on its SLA. One of the first contributions of this kind was presented in [58], the method proposed was called Bandwidth Guaranteed Polling (BGP) and is based on the combination of the fixed and the dynamic approaches. In BGP, ONUs are categorized as bandwidth-guaranteed and non-bandwidth-guaranteed – the bandwidth-guaranteed is characterized by the SLA.

Total upstream bandwidth is divided into equivalent bandwidth units which will be distributed among ONUs. The ONUs with bandwidth guaranteed can obtain more than one unit based on the SLA. If one of units 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 bandwidth-guaranteed ONUs and another for non-bandwidth-guaranteed ONUs. 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 traffic and allocate bandwidth.

The algorithm guarantees bandwidth for high-demand users, it can also provides 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 [65] where support of SLA is provided, the allocation process consist on two stages: in the first, a proportional allocation of bandwidth based on classes of traffic is performed; then, a second stage is performed to meet 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 constraints in **SLA** are applied according to different situations, e.g., if the number of assigned bytes exceeds the maximum number of bytes guaranteed, an adjustment is performed, 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 the 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. In order to maintain good traffic parameters for the high priority classes, the time-slots for high priority queues from different **ONUs** are granted at the beginning of the granting cycle and thus it is possible to reduce the jitter to high priority queues.

Similar to the previous algorithm, some proposals are characterized by performing allocation bandwidth directly to a queue e.g., in [49] 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 their weight, making it possible to 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 nodes 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 to the last drawback can be handled through implementation of two groups of nodes, in which those nodes which require a fixed guaranteed bandwidth may belong to one group and 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.

A later proposal *SLA* aware was presented in [10], inspired by the "open access" framework in which users are free to choose what services they need and the corresponding service providers. In open access networks there is a clear demarcation between the network operators, who provide physical connectivity and transport data, and the service providers who deliver content and services – the fairness challenge is not just among users but also for service providers.

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

The algorithm proposed only considers the downstream traffic, from the service provider to the users, in the *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 to the *SLA* requirements.

3.1.5 *DBA algorithms Prediction oriented*

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 try to predict how many bytes an *ONU* will hold from the moment its transmission window begins, in order to decrease packet delay.

In [16] the estimation is performed based on historical values such as queue length and allocated window size. Estimation is performed by the *OLT* according to the information provided by the *ONUs*, i.e., in request message *ONU* includes the difference between the window size allocated by *OLT* and the actual buffered packet size to be transmitted – according to that information *OLT* estimates the allocation size for the next cycle. If the difference between the window size allocated 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 remains as in the previous cycle.

In [56] class-based traffic prediction is taken into consideration in order to reduce packet delay and queue length. OLT serves all ONUs in a fixed round robin order to allow traffic prediction. The estimation is performed not just to the high priority traffic because the request includes all type of classes. To compute estimation the schedule interval is defined as the time between sending report messages, during this interval the 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.

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.

In a proposal presented in [89], the estimation allows to allocate the transmission window size close to the buffer occupancy. The estimation of packets arriving can be predicted 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 ONU initiates a timer each time it receives a grant message. Additionally ONU gets the real time arrival rate during a small interval thus the amount of packets arriving during the next cycle can be estimated, ONUs will report the estimation to the OLT together with the request size that equals to the instant buffer length.

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 accurately as possible. Efficient prediction mechanisms are necessary because overestimating will cause bandwidth to be lost. The ideal mechanism is one which reduces delay packets without underutilized bandwidth.

3.2 WAVELENGTH ALLOCATION

Whereas in PONs the DBA issue is limited to scheduling the upstream transmissions on the single wavelength channel, in WDM-PONs decisions on when and for how long to grant an ONU upstream transmission, as well as which wavelength channel to grant the upstream transmission are required.

Therefore, DBA algorithms initially designated for PON require modifications to exploit the multichannel architecture. The bandwidth

management issue can be split into two problems: grant (bandwidth allocation) and grant scheduling (wavelength selection).

As an evolution of IPACT in WDM, some variants of IPACT were addressed in different proposals, e.g. in [39]. The authors propose an algorithm called WDM IPACT with a single polling table (WDM IPACT-ST). The grant scheduling is of the Next Available Supported Channel (NASC) type and the grant sizing is performed according the IPACT (with fixed, limited or gated approach). This approach requires new devices at both ends of the fiber links to support simultaneous transmissions over multiple wavelengths.

In [19], the authors developed a DBA called Simultaneous and Interleaving Polling with Adaptive Cycle Time (SIPACT). SIPACT allows different architectures to poll ONUs, either intra-wavelength (on the same wavelength) or inter-wavelength (among different wavelengths), simultaneously but depending on the set of wavelengths supported by each individual ONU.

The authors in [21] presented several DBWA variants also based on former EPON DBAs algorithms and compared their performance. The three different approaches compared depend on the weight of the individual ONU, the two more interesting ones consider on-line based mechanisms.

The reference [63] introduces the concept of just-in-time (JIT) which is a hybrid scheduling framework between off-line and on-line. The OLT schedules the grant based on the REPORT messages accumulated since the last channel became available. The ONUs that have not been allocated to a wavelength yet, are scheduled together across all wavelengths as soon as a wavelength becomes available. The on-line JIT scheduling framework gives the OLT more opportunity to make better scheduling decisions.

The simplest grant scheduling policy is to assign the Next Available Supported Channel (NASC) to the ONU, which means that the OLT must know which upstream channel will first turn idle according to its polling table; such policy is not optimal in all cases and it does not consider ONUs which support different wavelengths.

The approach of selecting the wavelength by using the scheduling theory seems a much better policy, e.g. Shortest Path First (SPT), Longest Path First (LPT), and Least Flexible Job First (LFJ) among others [67]. LFJ first schedules transmissions to the ONUs that support the fewest number of wavelength channels at the earliest available supported channel. The LFJ policy is optimal because it minimizes the

length of the schedule under certain conditions. Figure 11 classifies the scheduling framework and the scheduling wavelength policies explained above.

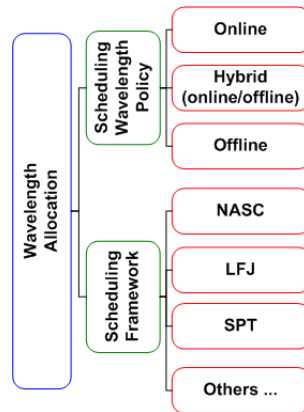


Figure 11: Wavelength Allocation Criteria.

3.3 BANDWIDTH AND WAVELENGTH ALLOCATION FOR LR-PON

The increased reach in LR-PON causes a degradation of DBA performance because of the increased propagation delay of control messages exchanged between different PON elements. The Round Trip Time (RTT) may grow from 200 μ s to 600 μ s (20 and 60 km reach respectively) or 1 ms (100 km reach). With increased RTT, the performance is degraded. Thus, DBA algorithms for LR-PONs have been recently developed to address these issues.

A potential solution to overcome the problem of the increased RTT is the introduction of a multi-threaded DBA [74]. The idea behind a Multi-thread algorithm is to allow an ONU to send its REPORT before the previous GATE message is received. This allocation scheme exploits the benefits of having multiple polling processes running simultaneously, so that ONUs do not have to wait until the end of the data transmission of the previous thread to send a new REPORT message requesting for a new transmission window. Thus, the performance of the LR-PON can be improved.

A number of schemes have been proposed in the literature utilizing the multi-thread scheme to address the DBA performance issue in LR-PONs [31, 43, 38, 72, 5]. In [43], the Multi-thread algorithm has been improved with Gate optimization by means of a periodical Integer Linear Programming (ILP) formulation on the collected requests of the ONUs to calculate appropriate credit ratios for the overloaded ONUs.

In [15], a new DBWA scheme called EFT-partial-VF Multi-threaded is proposed, which effectively combines some of the features of the Earliest Finish Time with Void Filling (EFT-VF) algorithm and the Multi-thread algorithm.

An extensive survey of proposed DBA schemes for LR-PONs is presented in [44].

3.4 SUMMARY

The challenge in designing a DBA algorithm lies in developing an algorithm that is practical, simple, efficient and meets service provider requirements. Throughout our research we have reviewed several proposals on resource management, we have summarized the most relevant in this chapter and we have also provided reference of many others. We also introduced the DDSPON algorithm that has served as the basis for the development of our contributions.

Since the contribution of access networks to the total energy consumption of global networks is large, energy efficiency has become an increasingly important requirement in designing access networks. As a consequence, energy-saving approaches are being investigated to provide high performance which consumes less energy.

The energy-saving of optical networks can be addressed at four levels, as stated in [87]: component, transmission, network and application. Table 12 summarizes the energy-saving approaches at different levels.

Table 12: Energy saving levels.

Level	Description
component	At the component level, highly-integrated all-optical processing components such as optical buffers, switching fabrics, and wavelength converters, are being developed, which will significantly reduce energy consumption.
transmission	At the transmission level, low-attenuation and low-dispersion fibers, energy-efficient optical transmitters and receivers (which improve the energy efficiency of transmission) are also being introduced.
network	Energy-efficient resource allocation mechanisms, green routing, long-reach optical access networks, etc. are being investigated at the network level to reduce energy consumption of optical networks.
application	At the application level, mechanisms for energy-efficient network connectivity such as "Proxying" and green approaches for cloud computing are being proposed to reduce energy consumption.

In this chapter the main energy-saving approaches in PONs at a network level are surveyed. In addition to the management of bandwidth and wavelength resources, there is a new challenge to the previous DBA and DWA algorithms because it is still desirable to cut down energy consumption as much as possible.

Several techniques have been proposed to increase energy efficiency in PONs. Such techniques are regarded as either hardware (or physical), or software (or data-link) approaches [23, 80]. Typically, physical approaches introduce new energy efficient optical device architec-

tures, while data-link proposals require extensions of resource management algorithms to include the energy awareness.

In order to strengthen research on energy-saving besides technical studies, standardization works have been carried out. The ITU Series-G Supplement 45 [37], as will be seen later, describes four basic energy-saving methods to reduce energy in ONUs. The IEEE Std 802.az [4] uses a Low Power Idle mode to reduce the energy consumption of a link when no packets are being sent.

4.1 ENERGY SAVING STRATEGIES

Energy-saving strategies in PON are designed primarily for ONUs and consist on exploiting the variations of upstream/downstream traffic load by enabling the ONUs to switch among different energy-saving modes (shedding, dozing, or sleeping) [37].

With power shedding the ONU turns off non-essential components while a fully operational optical link is maintained. Dozing mode turns off the ONU transmitter function while the receiver function is always on. With sleeping mode both functions, transmitter and receiver, are deactivated. Among the power saving modes, enabling sleep mode in ONU is the most studied approach. The main challenges of this approach are the slow transition from active mode to sleep mode, and the time needed during the wakeup process.

Depending on the traffic load, an ONU sleep mechanism reduces energy consumption by keeping transmitters/receivers inactive if the traffic arrival rate is low according to a defined threshold. The definition of the threshold is a key issue, as an appropriate definition can lead to relevant performance improvements in terms of delay.

In [51] authors propose a Sleep and Periodic Wake-up regime for ONUs to reduce energy consumption. The OLT activates or deactivates the ONU, depending on the presence or absence of downstream traffic. The OLT determines the presence or absence of downstream traffic by monitoring the average frame interval.

In [82], authors experimentally demonstrated a sleep mode ONU architecture that enables ONU to transition from sleep mode to active mode in short time using a fast clock and data recovery (CDR) circuit. In [83], same authors also addressed the ONU wake up time through a novel just-in-time sleep control scheme.

Energy-saving at the OLT has received less attention but due to the increased provisioning data rate in PONs, which implies more energy

consumption, it is desirable to reduce energy consumption in OLT as much as possible. Authors in [71] proposed a sleep control function for energy-saving in PON systems where the configuration of OLT consists on multiple PON-interfaces and two layer-2 switches that provide the multiplexing function to combine upstream and downstream signals and the redundant function to assure redundancy against failures. The sleep control function, based on traffic predictions, allows switch to sleep mode one of the duplicated layer-2 switches in OLT.

Similar proposal is [86], where an OLT comprises multiple OLT line cards, each of which serves a number of ONUs. Authors proposed a new OLT hardware configuration. They placed an optical switch in the OLT to configure the connections between OLT line cards and ONUs, so that in low load traffic conditions the switches can be configured in a way that the same OLT line card provides services to multiple ONUs, and then other OLT line cards can be turning off. Authors discussed the impact of the switch configuration time and the energy consumption added by optical switches.

In WDM/TDM-PON, the WDM components and reach extenders that are required for LR-PONs contribute to the total energy consumption, but at the same time they enable higher capacities and more users per OLT. Therefore, energy-saving has been addressed to effectively control energy consumption of OLT according to downstream traffic. The authors in [77] proposed an energy efficient architecture that reserves a single wavelength and a single low speed transceiver to handle all narrow-band downstream traffic, in order to reduce the energy consumption of the OLT.

In [24] authors proposed inserting a remote channel combine/split module (CCS) in the remote active node of an extended-reach system WDM/TDM-PON to reduce initial investment and achieve good energy efficiency. The key function of CCS is to selectively aggregate optical signals from active subscribers so that a minimal number of OLTs and remote amplifiers are operating. The inclusion of the CCS requires some modification in the MAC layer and setting up a communication channel to the remote node. Thus, DBA modules will decide which OLTs remain active, become active, or inactive. To do so a new mechanism to de-register and reregister ONUs from different OLTs is proposed in [25].

In [69] the energy consumed by the OLT is reduced by using fewer wavelengths and putting idle transmitters to sleep. Authors proposed to use thresholds to determine, based on downstream network traffic, when to use one wavelength less and when to add one more.

The aforementioned works mainly discussed energy efficiency based on the downstream network traffic. As a whole, previous proposals have targeted to energy-saving by sleep mode in **OLT** transceivers or in the **ONUs**. An extensive overview of studies and works to address the energy-saving issue in the optical access network is presented in [70, 40].

4.2 SUMMARY

To save energy in **PON**, an efficient energy management with scheduling for the sleep and wake up period is a challenging task. We provide an overview of existing energy-saving strategies for **PON**. Previous references mainly discussed energy efficiency based on the downstream network traffic. Most proposals have targeted either the sleep modes in **OLT** transceivers or in the **ONUs**.

Part III

CONTRIBUTIONS

Contributions are primarily focused on the [EPON](#), [10GEPON](#) and [WDM/TDM-PON](#). We have studied and proposed a [DBA](#) algorithm QoS aware, then we have addressed the coexistence issue between 1G and 10G [EPON](#) in terms of bandwidth allocation, also we have addressed the real-time services in [EPON](#) and proposed an interesting mechanism to deal with them. In the end, the minimization of energy consumption in [EPON](#), not only based on [WDM](#) but in both [WDM/TDM](#), has been studied and has generated a proposal for energy-saving in the [OLT](#).

The real challenge faced by 10GEPON is to upgrade the channel capacity for both upstream and downstream channels gracefully, while maintaining the logical layer intact ensuring its coexistence with EPON. Minor changes should be performed in the logical level; but the challenge this process faces is to efficiently and fairly allocate bandwidth to ONUs. On that regard, research has been carried out to upgrade existing scheduling algorithms.

In this chapter we present an enhanced distributed DBA algorithm, known as DDSPON, which allows coexistence among both standards in such mixed architecture. In particular, we emphasize that, by using the enhanced DDSPON, the new standardized ONUs will take full advantage of the enhanced rate at 10 Gb/s while the legacy 1 Gb/s ONUs keep a good performance, thus allowing both group of ONUs, legacy and 10 Gb/s, to coexist fairly – even though the individual performance is maximized, regardless of the group being evaluated.

Later, we compare DDSPON with another well-known scheduling algorithm and we show that it performs better specially when the traffic is bursty. Furthermore, the proposed algorithm is scalable, simple to re-configure, and cost-effective, which facilitates a smoother transition from EPON to 10GEPON.

5.1 DDSPON

In section 3.1.3 of chapter 3 we introduced the DDSPON algorithm, which consisted on a distributed scheduling mechanism to allocate bandwidth fairly and efficiently in an EPON; the control channel is performed by OLT, but scheduling process is distributed among ONUs. Here the details of DDSPON will be reviewed.

In DDSPON 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 $\vec{\phi}$, which can be sent through the GATE message in an available header field. This vector is updated by each ONU through the REPORT messages, so an additional parameter in the message is included. At the beginning each ONU has a fixed weight according to its guaranteed bandwidth agreement.

Below we define the notation used hereafter:

US_{rate}	Data rate of the upstream link from an ONU to the OLT in b/s.
N	Total number of ONUs .
US_{1G}	Upstream rate of the 1G ONUs .
N_{1G}	Number of ONUs in group with $US_{1G} = 1$ Gb/s.
US_{10G}	Upstream rate of the 10G ONUs .
N_{10G}	Number of ONUs in group with $US_{10G} = 10$ Gb/s.
n	Current cycle.
$\vec{\phi}$	Weight vector.
ϕ_i^c	Initially configured weight value of the ONU_i .
ϕ_{1G}^c	ϕ_i^c in N_{1G} group.
ϕ_{10G}^c	ϕ_i^c in N_{10G} group.
ϕ_i^n	Weight of ONU_i computed in cycle n .
BW_i^n	Transmission window length of ONU_i in cycle n , in bits.
BW_{max}	Maximum transmission length of all ONUs in bits.
F^{1G}	Maximum allocable window in bits, to ONUs in N_{1G} group.
F^{10G}	Maximum allocable window in bits, to ONUs in N_{10G} group.
T_{max}	Maximum cycle time.
T_g	Interval of time between any two adjacent timeslots.
R_i^n	Requested transmission length of ONU_i in cycle n , in bits.
Q_i	Queue size of ONU_i in bits.

In a **PON** system with N **ONUs**, each ONU_i has a predefined (nominal) weight ϕ_i^c , used to define the guaranteed bandwidth allocable:

$$BW_i^n = \frac{\phi_i^c}{\sum_{j=1}^N \phi_j^n} BW_{max} \quad (1)$$

where the sum of ϕ_j^n should be normalized $\sum_{j=1}^N \phi_j^n = 1$.

BW_{max} is the maximum transmission window size corresponding to the maximum cycle time (T_{max}), i.e. the period during which the **ONUs** transmits its traffic:

$$BW_{max} = US_{rate} \cdot T_{max} \quad (2)$$

Bandwidth allocation in **DDSPON** is as follows: **OLT** receives a **REPORT** message from ONU_i , which contains the requested window size R_i^n and the weight (ϕ_i^n); in turn, **OLT** updates its weight vector $\vec{\phi}$ and send a **GATE** message to ONU_i , in which allocation corresponded to the requested bandwidth.

Gate messages also include the weight vector $\vec{\phi}$, once an **ONU** receives a **GATE** message it transmits data in queue up to the transmission window allocated, then it takes the weight vector $\vec{\phi}$, sets its own

weight to the nominal one (ϕ_i^c), and calculates a maximum window size that such ONU can take on the next cycle $n + 1$:

$$BW_i^{n+1} = \frac{\phi_i^c}{\phi_i^c + \sum_{j=1; j \neq i}^N \phi_j^n} BW_{\max} \quad (3)$$

Also, ONU calculates its required transmission window size:

$$R_i^{n+1} = \min(BW_i^{n+1}, Q_i) \quad (4)$$

where Q_i is the queue size, finally the new weight for the next cycle $n + 1$ is calculated based on previously requested value:

$$\phi_i^{n+1} = \frac{R_i^{n+1} (\phi_i^c + \sum_{j=1; j \neq i}^N \phi_j^n)}{BW_{\max}} \quad (5)$$

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. The scheduling process is executed without needing to wait until all the reports from the ONUs arrive to the OLT (on-line framework). Moreover, by getting the weight vector, each ONU is able to get an overview of all ONU loads, which is characteristic of off-line DBAs.

Comparative results between DDSPON and IPACT were obtained by event-driven simulations using a simulation network model developed with the OPNET Modeler tool (see appendix A). Results in [7, 29] show that the DDSPON remains stable against IPACT with the variation of distances, the most remarkable being that DDSPON presents significant improvements versus the IPACT in all performed simulations, being more relevant in highly loaded scenarios.

5.2 ENHANCED DDSPON

Let us extend the DDSPON algorithm to a mixed plant composed by different groups of ONUs at 1 Gb/s (N_{1G}) and at 10 Gb/s (N_{10G}) ONUs. To allocate the bandwidth that each set of ONUs deserves, we propose to balance the initial weights and the maximum allocable window. Because the 10GEPON rate is ten times higher than the EPON, we balance ϕ according to this ratio. Hence:

$$\phi_{10G}^c = 10 \cdot \phi_{1G}^c \quad (6)$$

With this, the normalization equation is given by:

$$N_{1G} \cdot \phi_{1G}^c + N_{10G} \cdot \phi_{10G}^c = 1 \quad (7)$$

And the maximum cycle time T_{\max} is:

$$T_{\max} = \left(T_g + \frac{F^{1G}}{US_{1G}} \right) N_{1G} + \left(T_g + \frac{F^{10G}}{US_{10G}} \right) N_{10G} \quad (8)$$

where F^{1G} is the maximum transmission length of ONU_i in N_{1G} group and F^{10G} in N_{10G} group. Thus, $N = N_{1G} + N_{10G}$.

In a mixed setting where ONUs with different upstream rates coexist, if we balanced the initial weights, the maximum upstream throughput of ONUs in N_{1G} group will be 60.5 Mb/s and the maximum upstream throughput of ONUs in N_{10G} group will be 605 Mb/s. So the overall value of the upstream channel is about 5.324 Gb/s.

5.2.1 Simulations and Results

Several simulations were carried out to evaluate the performance of the enhanced DDSPON by using our simulation network model based on OPNET Modeler (see appendix A). In this section, we just show the results of the most representative cases. To illustrate equation 8, let us assume the parameters summarized in Table 13.

In the testbed setting some assumptions are made: we consider an infinite buffer in the ONU queues to avoid packet drops, also the OLT buffer is infinite, the inter-frame gap and control messages are according to the EPON standard, packets are extracted from the queue and transmitted according to the First-come, First-served (FCFS) discipline with a single traffic class per ONU.

Table 13: Simulations Parameters.

Parameter	Value
N	16
N_{1G}	8
N_{10G}	8
US_{rate} (single setting)	1 Gb/s
ϕ_i (single setting)	$\phi = 1/16 = 0.0625$
US_{rate} (mixed setting)	1 Gb/s and 10 Gb/s
ϕ_{1G} (mixed setting)	0.01136
ϕ_{10G} (mixed setting)	0.11364
T_g	2 μ s
T_{\max}	1 ms
OLT-ONU distance (d)	$18 < d < 20$ km

Simulations were carried out in two different settings: in the first one we conducted simulations over a single 1G EPON plant with 16 ONUs; the second one was a mixed setting of $N_{1G} = 8$ and $N_{10G} = 8$. The traffic generated is self-similar with a Hurst parameter of 0.7, and finally packet sizes are uniformly distributed from 64 bytes to 1518 bytes (see appendix A).

Figure 12 depicts the average throughput of individual ONUs and Table 14 detailed values.

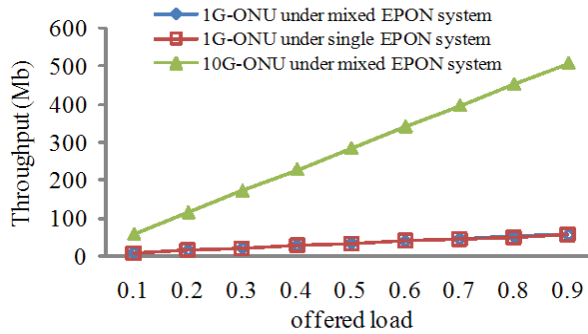


Figure 12: 1G and 10G throughput in single and mixed setting.

Notice that the upstream channel rate is 1 Gb/s when the offered load is $G = 1$ in the single setting, while in the mixed setting the rate of the upstream channel corresponding to $G = 1$ is about 5.324 Gb/s. In conclusion, the maximum throughput allocated matches the aforementioned theoretical result as expected.

Table 14: Average Throughput of individual ONUs.

Offered load	single	mixed	
	1 G	1 G	10 G
0.1	9.07	9.07	58.29
0.2	15.16	15.45	114.81
0.3	21.19	21.71	171.40
0.4	27.49	27.62	227.78
0.5	33.42	34.04	283.55
0.6	39.52	40.14	339.60
0.7	45.66	46.15	395.63
0.8	51.50	52.12	451.23
0.9	57.02	57.59	506.11

Figure 13 depicts the maximum ($G = 1$) aggregated throughput received by the OLT and Table 15 detailed values.

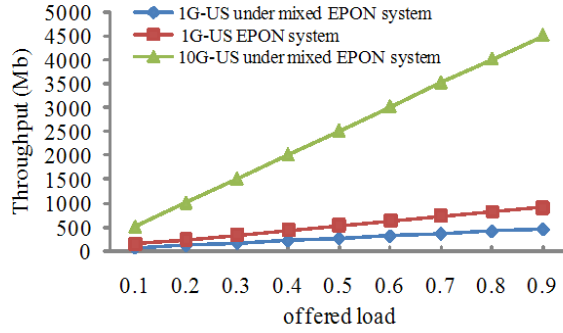


Figure 13: Aggregated throughput in 1G and 10G setting.

Values match what we have computed in previous sections, thus the aggregated throughput of the upstream channel is about 5.324 Gb/s, divided among the 10G [ONUs](#) (4.84 Gb/s) and the 1G [ONUs](#) (0.484 Gb/s).

Table 15: Aggregated Throughput received by the OLT.

Offered load	single	mixed	
	1 G	1G	10 G
0.1	144.91	72.53	515.58
0.2	242.38	123.59	1017.51
0.3	340.20	173.63	1520.04
0.4	440.22	220.95	2023.12
0.5	534.81	272.29	2516.03
0.6	631.92	321.07	3015.37
0.7	729.37	369.15	3515.49
0.8	825.51	416.90	4008.23
0.9	911.15	460.63	4495.28

In Fig. 14 we can observe the average packet delay at the [ONU](#). The 1G [ONUs](#) in a mixed plant show a slight penalty in average packet delay and throughput (mainly in high loads) due to the presence of both rates in the system. However, in low loads the variations are negligible.

The evaluated performance of 1G [ONUs](#) (i.e., throughput and delay), is quite similar no matter which setting they are connected. Figures 13 and 14 show that, as we expected, the throughput of 10G [ONUs](#) is about 10 times that of the 1G [ONUs](#) and delay is quite similar in both group of [ONUs](#); such outcomes shows clearly the fairness and the scalability of the algorithm.

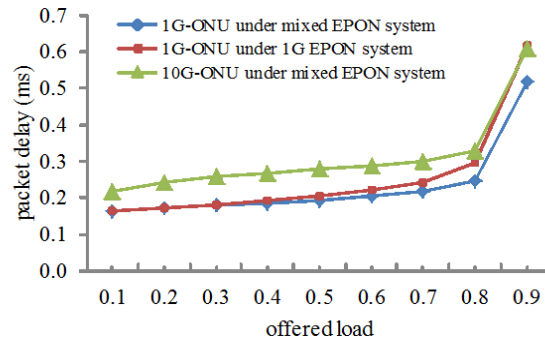


Figure 14: Average Packet Delay.

Previous graphs show average values with a 95% confidence interval (hereinafter for the sake of clarity confidence intervals are not included in the graphs).

5.2.1.1 Comparison among DDSPON and IPACT

Simulations usually compare the performance of different DBAs in the steady-state but they scarcely present comparison in a transitory state. This section is devoted to show the performance of the DDSPON compared to the IPACT in a transitory period of one second. In this test the overall throughput received at the OLT is about 4 Gb/s (80%), but traffic is generated in a way that only one target ONU transmits a heavy burst of traffic as depicted in the next figures while the rest of the ONUs transmit self-similar traffic as usual.

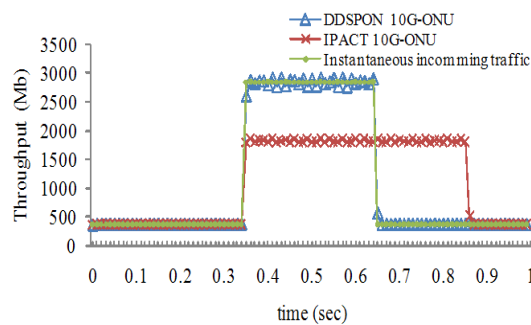


Figure 15: DDSPON vs. IPACT throughput in a bursty traffic.

Figure 15 shows the incoming traffic pattern and the throughput of the 10G targeted ONU. It shows that the throughput of the target ONU closely follows the input traffic when the DDSPON is used, but the throughput of the ONU when IPACT is used last much more time before the burst is completely transmitted.

Simulations illustrate how the transitory impacts over the performance values, which somehow is what affects the level of QoS that users can experience in access networks. Figure 16 depicts the instantaneous packet delay in the same setting, where our proposal improves the jitter over IPACT.

The conclusion of the comparison performed in this section, is that although in the steady-state setting the performance is quite similar among different DBAs, when we consider bursty traffic the throughput allocated to the targeted ONU is closer to the input traffic while the IPACT last more time to recover, and furthermore, the instantaneous delay of the IPACT is much higher than expected.

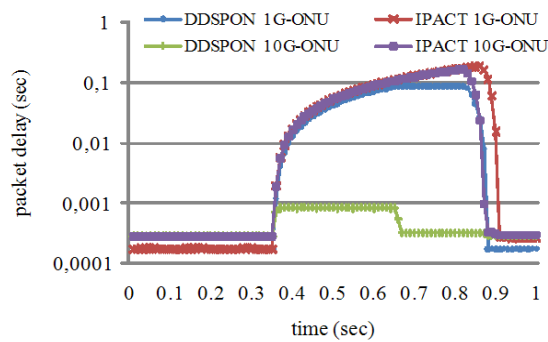


Figure 16: DDSPON vs. IPACT packet delay in a bursty traffic.

5.3 SUMMARY

We have presented a variation of DDSPON DBA for EPON in a 1G and 10G mixed network. Such DBA schedules the allocation of bandwidth according to the guaranteed bandwidth agreed with each user; it is a distributed algorithm, so the bandwidth computation is performed at the ONU, the window allocated is proportional to the ONUs needs and the previous requirements of the rest of the ONUs – which improves the performance of the overall network.

The simulations results showed a good performance in terms of delay, and the throughput is fairly balance among both ONUs either 1G or 10G. We have also illustrated that such algorithm is easily scalable to be used in legacy EPON, new 10GEPON or mixed settings. And what is also important – the migration is simple without disrupting/interrupting the network. The transition from 1G to 10G is quite smooth. The DDSPON performance is especially relevant when we consider bursty traffic instead of uniform traffic.

The provision of QoS in EPONs is addressed through the DBWA algorithms; most proposals in literature follow a Differentiated services (DiffServ) approach where high priority traffic is served regardless of the penalization introduced in low priority traffic. In order to support the coexistence of new real-time emerging applications and the traditional applications, an appropriate mechanism to manage the bandwidth allocation in an efficient way remains an open issue.

Real-time traffic consists of streams that are continuously delivered through the network from source to destination. In EPONs real-time and Best Effort (BE) traffic can both be served. Real-time traffic is given higher priority in order to satisfy its delay requirements, and its performance should not be affected by the transmissions of the non-real-time traffic or BE.

The cycle time in EPON can have a fixed or variable length, in a cycle each ONU should receive a GATE message, transmit the allowed window and send a REPORT message. To accomplish time-based restrictions that some applications demand, a fixed cycle length should be the most appropriate. However, the coexistence of real-time and BE applications suggests a variable cycle length. Thus, the available service time in every cycle for the BE traffic depends on how much time is reserved for real-time traffic.

In this chapter we study the influence of high priority at real-time traffic on the low priority (non-real-time) traffic. We aim guaranteeing the requirements of real-time traffic while reducing the delay penalty of the BE traffic. A novel mechanism for the real-time traffic management is presented, merging two scheduler approaches for bandwidth allocation in EPON. First, we will use the Distributed Resource Algorithm (DRA) to manage real-time flows to guarantee delay and delay jitter. And then, we use the DDSPON algorithm to allocate the bandwidth that non real-time traffic deserves in the intervals left free by the real-time flows.

Previous proposals [17, 22] addressed the problem of delay and delay jitter, but concentrating the high priority flows at the beginning of each cycle, unlike our proposal that spreads as much as possible the real-time flows along the cycle.

6.1 REAL-TIME TRAFFIC SCHEDULE

We have introduced the [DRA](#) algorithm in the context of [EPON](#). Although the [DRA](#) was defined in the context of wireless networks, it might be used in any context where scheduling of periodic flows is required. The [DRA](#) is devoted mainly to determine the service start time of each real-time flow in order to distribute in time as uniformly as possible the allocation of resources for the different real-time flows. Figure 17 provides an example of allocation distribution according to the concentrate (a) and spread (b) distribution approaches.

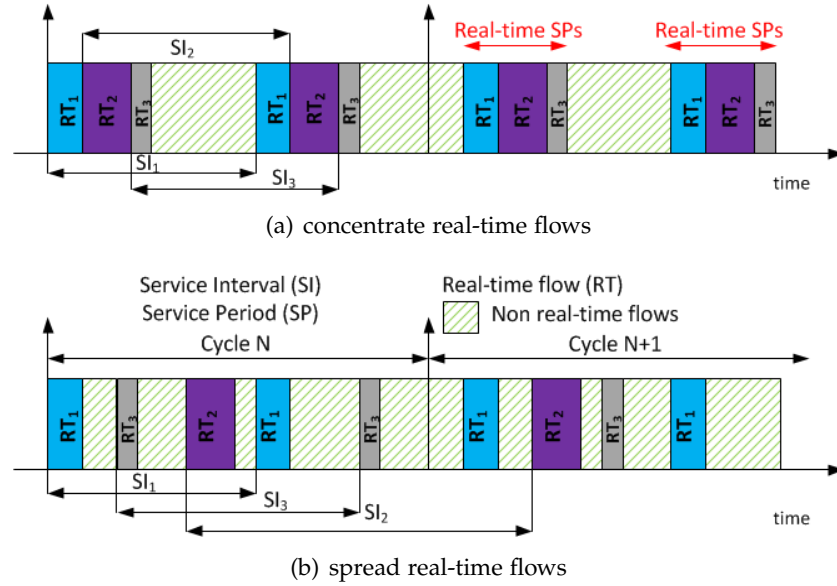


Figure 17: Example of flows allocation.

The real-time flows are spread because the [DRA](#) algorithm schedules the start time of a new real-time flow requested by any [ONU](#), by maximizing the minimum distance between the real-time service periods of this new flow and the real-time service periods of the already scheduled flows, and thus minimize the overlapping probability.

We argue that an algorithm which distributes the real-time service periods as much as possible is better than a scheduler which concentrates them, because the concentrated service periods capture the channel for a long time, increasing the average delay of non-real-time flows.

6.1.1 Distributed Resource Allocation Algorithm

In this section we show how we have achieved our desired separation or distribution of real-time flows by means of the [DRA](#) algorithm, which maximizes the minimum distance between allocated real-time

flows. The complete reference of [DRA](#) algorithm is in [20].

Below we define the notation used hereafter:

N	Number of real-time flows.
SST_i	Service Start Time of flow i .
SI_i	Service Interval of flow i .
$d_{i,j}(k)$	Sequence of distances of flows i and j .
$d_{\min_{i,j}}$	Minimum distance of flows i and j .

[DRA](#) algorithm schedules the real-time flows following a spread approach, thus a better understanding on the concept of distance between periodic flows is needed. [Figure 18](#) represents the occurrences in the channel of two periodic flows with service intervals SI_1 and SI_2 , which have service starting times SST_1 and SST_2 . The figure also depicts the distance between consecutive allocations of the two flows $d_{2,1}(k)$.

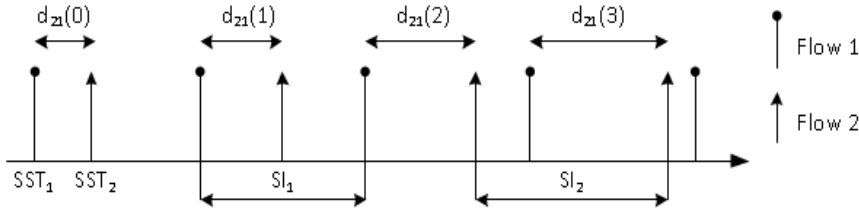


Figure 18: Distance between resource allocations.

The distance between an occurrence of flow 2 and the previous occurrence of flow 1 can be expressed as:

$$d_{2,1}(k) = (d_{2,1}(0) + k \cdot SI_2) \bmod SI_1 \quad (9)$$

where $d_{2,1}(0)$ is a reference distance between two resource allocations, $d_{2,1}(0) = SST_2 - SST_1$ as shown in [Fig. 18](#).

The previous sequence $d_{2,1}(k)$ is indeed periodic and its elements can be expressed as:

$$d_{2,1}(j) = d_{\min_{2,1}} + j \cdot \gcd(SI_1, SI_2); \quad j \geq 0 \quad (10)$$

where $d_{\min_{2,1}} = d_{2,1}(0) \bmod \gcd(SI_1, SI_2)$ and \gcd stands for Greatest Common Divisor ([GCD](#)). Therefore, how to increase the separation between the service times of flows 1 and 2 is by increasing $d_{\min_{2,1}}$ and/or $\gcd(SI_1, SI_2)$.

A simple algorithm that computes the new SST of the $N + 1$ flow ($SST_{(N+1)}$), and maximizes the distance to the rest of the N flows can be implemented by performing the process in [Algorithm 1](#).

Algorithm 1. Distributed resource allocation algorithm (DRA)

- Compute $\gcd(SI_i, SI_{(N+1)})$ for all the N already scheduled flows:
 $0 < i = N$.
 - 1. Compute the period of the absolute minimum distance:
 $T' = \text{lcm}(\gcd(SI_i, SI_{(N+1)}), \dots, \gcd(SI_N, SI_{(N+1)}))$.
 - 2. For each scheduled flow generate all critical points:
 $\phi_{N+1,i} + k * \gcd(SI_i, SI_{N+1})$, contained in T' .
 - 3. Define a sorted list L containing all critical points.
 - 4. Define a function F that operating on list L obtains the SST that maximizes the minimum effective distance.
 - The function F iterates over the list L containing the critical points of the absolute minimum distance function in order to find where the maximum of this function is.
-

The [DRA](#), in principle, would require to check all possible overlappings of scheduled flows in the future, depending on the considered service starting time. Obviously, this would lead to an infinite number of operations to determine the desired service start time, thus making it impossible to implement the method in practice.

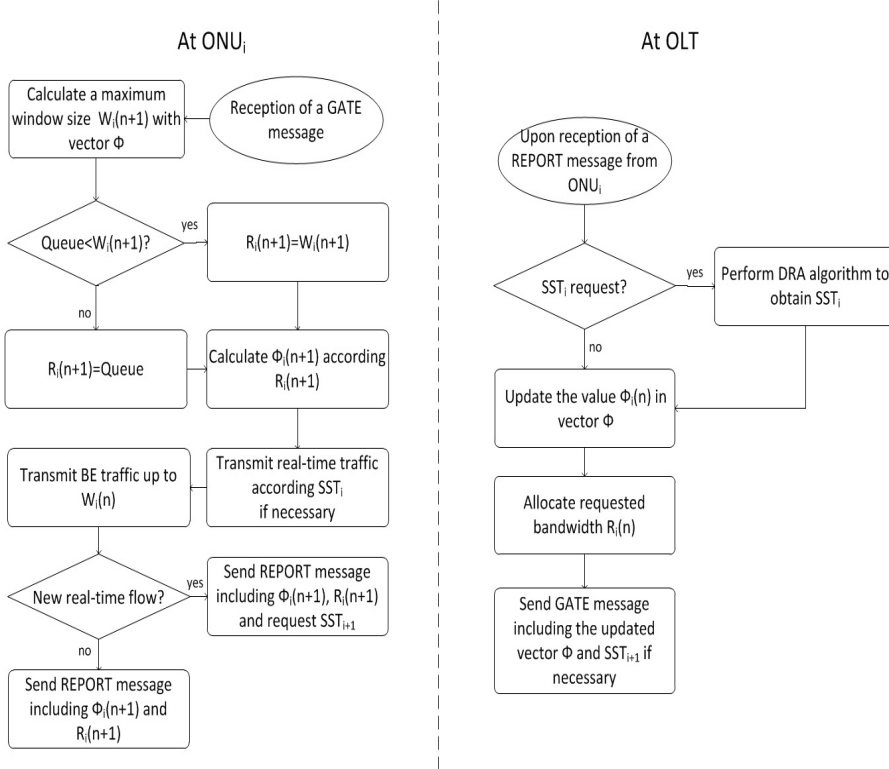
Fortunately, when a limited number of scheduled events is considered, defined by their service start time and service interval, it can be realized that a repetition pattern occurs with a period corresponding to the Least Common Multiple ([LCM](#)) of the different service intervals. As a result, the period of time to be considered by the algorithm to find the service start time which minimizes the overlapping is not infinite limited to the [LCM](#) of the service intervals.

6.2 NON-REAL-TIME TRAFFIC SCHEDULE

As it has been mentioned above, the non-real-time traffic uses the [DDSPON](#) algorithm, detailed in section [5.1](#) of chapter [5](#), to optimize the upstream bandwidth, while the real-time traffic schedule is performed by [DRA](#) in the [OLT](#). Figure [19](#) shows the process of bandwidth management – the interaction of both algorithms – performed in the [OLT](#) and [ONU](#)s.

6.3 RESULTS AND DISCUSSION

In this section, we presented the simulations carried out to evaluate the performance of the proposal by using the OPNET Modeler package. Our goal is to show that our scheme can guarantee the [QoS](#) requirements of the real-time services while reducing the delay of the rest of services as well.

Figure 19: Flow diagrams of bandwidth management in OLT and ONU_i .

In the testbed setting some assumptions have been made: we have considered an infinite buffer in the ONU to avoid packet drops, and the interframe gap and control messages are according to the standard. The initial values of the parameters of the simulation have been set as follows: the number of ONU s is set up to 16; the channel data rate is set up to 1 Gb/s; the maximum cycle length is set to 2 ms.

Table 16: Simulations Parameters.

Parameter	Value
Number of ONU s (N)	16
Weight value (ϕ)	$1/N = 0.0625$
Upstream data rate	1 Gb/s
Guard time	2 μ s
Maximun cycle time	2 ms
OLT- ONU distance	$18 < d < 20$ km
Hurst Parameter	0.7
Packet size	64-1500 bytes
Service interval of real-time flows (SI)	10, 20, 30 ms

The input traffic simulating non-real time services is of the self-similar type with a pareto parameter set to 0.7. The packet length is

uniformly distributed between 64 bytes to 1500 bytes (see appendix A). We have assumed that each ONU has three different real-time flows with a service interval of 10, 20 and 30 ms respectively. The real-time flows were initialized during first the 5% of the simulation time to make sure that the impact of initial conditions on the final outcome could be neglected. The simulation parameters are summarized in Table 16.

We have compared the performance of our scheme with a strict priority scheduling mechanism (defined in P802.1D, clause 7.7.4). It schedules packets from the head of a given queue only if all higher priority queues are empty. This situation will penalize traffic with lower priority at the expense of uncontrolled scheduling of higher priority traffic, thus increasing the level of unfairness.

Figure 20 shows the service start times of real-time flows in both scenarios (DRA and strict-priority), where the allocation according to the spread and concentrate distribution approaches is easily depicted such as in figure 17.

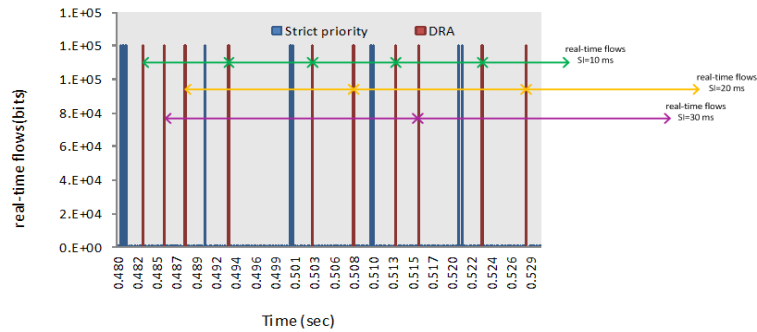


Figure 20: SST of real-time flows.

Figure 21 shows the advantage in delay that our scheme provides to non-real time services even when real-time services have already fulfilled with the QoS requirements. Notice that even when it shows the results of delay only for non-real time traffic, both flows (real-time and non-real time) coexist. So the throughput of real-time flows is guaranteed and the delay of non-real time flows is improved.

6.4 SUMMARY

Based on the previous arguments we have designed a new solution to resource allocation in EPON; it has mainly focused in the guaranteed QoS requirements of real-time traffic, but it has also reduced the impact that the other kind of traffic can experiment.

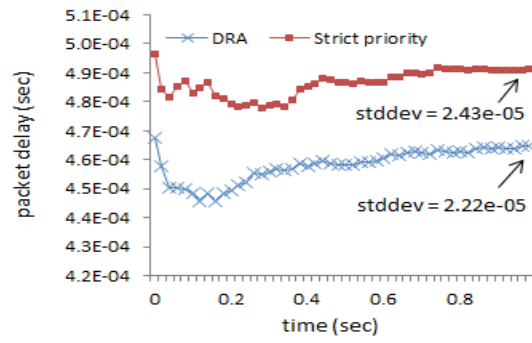


Figure 21: Delay of non-real time flows.

Unlike most of the proposals existent in the literature, our proposal is the one which distributes in the channel as much as possible the resource allocations of the different admitted real-time flows improving not only the overall performance of the real-time traffic but also of the non-real time yielding an overall better channel usage efficiency.

QOS AWARE DBA IN COEXISTENT EPON AND 10GEPON NETWORKS

The EPON standard, as part of the IEEE 802 family of standards, must be compliant with definitions in P802.1D/Q regarding a strict priority scheduling. In such scheduling approach, a lower-priority queue is scheduled only if all queues with higher priority are empty. It is well known that such strict behavior promotes an increasing level of unfairness among queues, because the service to the traffic with lowest priority is highly penalized with respect to the highest priority traffic. Thus, among others it suffers from uncontrolled packet delay and loss [8].

Several DBA algorithms based on inter-ONU and intra-ONU scheduling approaches have been proposed to enable EPON to provide differentiation of traffic (like those mentioned in chapter 3 section 3.1.4) and thus meet the QoS requirements of the various services that EPON networks transport. Table 17 shows the different traffic types and services defined in SIEPON.

Table 17: Traffic types and services.

Traffic type	Description
Real-time flows with periodic fixed-size data frames	Are characterized by a CBR (or quasi-CBR) profile. Example: Circuit emulation services or mobile backhaul.
Real-time flows with variable-sized data frames or with periodic inactivity	Are characterized by VBR. Example: IPTV and VoIP.
Non-real-time flows that require throughput/frame loss guarantees	Require variable-sized data grants on a regular basis. Example: Various tiered data services.
Non-real-time, non-guaranteed flows	Are equivalent to the BE Service Example: Peer-to-peer, e-mail services and text messaging.

SIEPON addresses QoS issues in EPON. However the specific implementation of the scheduler operation to provide QoS is outside the scope of the SIEPON standard. Such scheduler implementation and performance depend on an extensive knowledge of queuing theory, packet drop techniques, and thorough provisioning of the devices [76].

In this chapter we address the issue of QoS support in DBA. We upgrade the proposed DDSPON algorithm in a coexistent 1G/10G network (the one explained previously in chapter 5). We present a solution to fulfill the QoS based on the DiffServ architecture [14]. The well-known DiffServ is the architecture that makes possible to segregate network traffic into several different categories or classes. In DiffServ, traffic is classified in three classes – from high to low priority: Expedited Forwarding (EF), Assured Forwarding (AF) and BE.

The highest priority traffic is the EF class, whose characteristics are low delay, low loss and low jitter. AF is intended for services which are not delay sensitive; the delivery of the AF class traffic is assured as long as it is under a certain subscribed rate. Finally, the unused bandwidth is left to be used by the BE lowest priority class.

We also present an analytical model to evaluate the performance of the DDSPON in the proposed coexistent network. The aim is to evaluate the time cycle and the delay of ONUs either at 1G or 10G in the steady-state.

7.1 ENHANCED QOS DDSPON (EQ_DDSPON)

In this section we present the enhancement of the DDSPON that allows the provisioning of QoS to different services under the DiffServ architecture.

Below we define the notation used hereafter:

N	Total number of ONUs.
n	Current cycle.
ϕ_i^c	Set up weight value of the ONU _i .
ϕ_i^n	Weight value of the ONU _i computed in cycle n .
$\phi_i^{EF,c}$	ϕ_i^c for EF traffic class.
$\phi_i^{EF,n}$	ϕ_i^n for EF traffic class.
BW_i^n	Maximum bandwidth allocable of ONU _i in cycle n , in bits.
$BW_i^{EF,n}$	BW_i^n for the EF traffic class.
BW_{max}^{EF}	Set up maximum bandwidth allocable for EF traffic, in bits.
R_i^n	Requested transmission length of ONU _i in cycle n , in bits.
$R_i^{EF,n}$	R_i^n for the EF class.
$R_i^{AF,n}$	R_i^n for the AF class.
$R_i^{BE,n}$	R_i^n for the BE class.
Q_i	Queue size of ONU _i , in bits.
Q_i^{EF}	Q_i for the EF class.
Q_i^{AF}	Q_i for the AF class.
Q_i^{BE}	Q_i for the BE class.

Our first statement is that such enhancement profits from the DDSPON approach, using weights (Φ_i) to balance the traffic among ONUs. Hereafter we use the definitions of DDSPON in Chapter 5 section 5.1.

7.1.1 The computations in cycle n

Upon reception of the GATE, first BW_i^{n+1} is computed as in Eq. 3 in chapter 5 and $BW_i^{EF,n+1}$ as:

$$BW_i^{EF,n+1} = \frac{\Phi_i^{EF,c}}{\Phi_i^{EF,c} + \sum_{j=1; j \neq i}^N \Phi_j^{EF,n}} BW_{max}^{EF} \quad (11)$$

Second, we compute the required bandwidth values for each traffic class and R_i^{n+1} as Eq. 4 in chapter 5.

$$R_i^{EF,n+1} = \min(Q_i^{EF}, BW_i^{EF,n}) \quad (12)$$

$$R_i^{AF,n+1} = \min(Q_i^{AF}, (BW_i^n - R_i^{EF,n+1})) \quad (13)$$

$$R_i^{BE,n+1} = \min(Q_i^{BE}, BW_i^n - (R_i^{EF,n+1} + R_i^{AF,n+1})) \quad (14)$$

$$R_i^{n+1} = R_i^{EF,n+1} + R_i^{AF,n+1} + R_i^{BE,n+1} \quad (15)$$

And finally, we compute next weights values Φ_i^{n+1} :

$$\Phi_i^{n+1} = \frac{R_i^{n+1} (\Phi_i^c + \sum_{j=1; j \neq i}^N \Phi_j^n)}{BW_{max}} \quad (16)$$

$$\Phi_i^{EF,n+1} = \frac{R_i^{EF,n+1} (\Phi_i^{EF,c} + \sum_{j=1; j \neq i}^N \Phi_j^{EF,n})}{BW_{max}^{EF}} \quad (17)$$

7.1.2 The EQ_DDSPON in a coexistent 1G/10G EPON

The EQ_DDSPON may be easily extended to be used in a coexistent 1G/10G-EPON network just by setting the appropriate values to the weights as we did before. Thus we must just balance the configuration values of the weight of the 1G ($\Phi_{1G}^{EF,c}$) and 10G ($\Phi_{10G}^{EF,c}$) ONUs respectively.

If we assume that the **ONUs** in each group have the same weight, configuration values should satisfy

$$\Phi_{10G}^{EF,c} = 10 \cdot \Phi_{1G}^{EF,c} \quad (18)$$

The rest of the variables and computations remain unchanged.

7.2 RESULTS AND DISCUSSION

The present section analyzes deeply the performance of the proposed algorithm in two different settings: uniform and bursty traffic load. To evaluate the EQ_DDSPON in both settings we run extensive simulations using our developed Simulation Network Model with OPNET Modeler (see appendix A). In the following sections we show the most relevant results among the several simulations performed.

7.2.1 Evaluation of steady-state with QoS

We present and compare the simulation results for four algorithms: the proposed EQ_DDSPON, **DDSPON** P802.1D compliant with strict discipline, **IPACT** P802.1 compliant (strict) and **IPACT** without priorities. Table 18 summarizes the parameters used.

Table 18: Simulation Parameters.

Parameter	Description	Default Value
N	Full ONU s set	16
N ^{1G}	# 1G ONU s	8
N ^{10G}	# 10G ONU s	8
R ^{1G}	Upstream data rate	1 Gb/s
R ^{10G}	Upstream data rate	10 Gb/s
Λ_{1G}	ONU arrival rate	from 10 to 60 Mb/s
Λ_{10G}	ONU arrival rate	from 100 to 600 Mb/s
T _g	Guard Time	2 μ s
P	Packet size	64 - 1500 (bytes)
d	Distance (Km)	10 Km
CM	Control message size	73 bytes
Φ_{1G}	1G ONU weight	0.01136
Φ_{10G}	10G ONU weight	0.11364
ratio	$\Phi_{10G}:\Phi_{1G}$	10:1
T _{cycle}	Time cycle max	1 ms
EF traffic	CBR type	20% of the total traffic
AF traffic	Self-similar type (H=0.7)	40% of the total traffic
BE traffic	Self-similar type (H=0.7)	40% of the total traffic

In our test-bed setting each **ONU**, either 1G or 10G, has three different sources that generate packets according to some pattern. The **EF** traffic amounts to 20% of the total traffic generated and it belongs to

CBR type, while the AF and BE traffic load is about 80% (40%+40%) of self-similar traffic with Hurst parameter equal to 0.7. The maximum load of 1G ONUs is about 60 Mb/s. The 10G ONUs generated traffic follows the same strategy but at a rate 10 times higher, and therefore, the aggregated traffic rate generated is about 600 Mb/s.

Compared to the rest of scheduling mechanisms tested, the enhanced EQ_DDSPON shows better performance in almost all measured parameters: throughput, cycle time and delay.

Figure 22 and Fig. 23 show the average delay for 1G and 10G ONUs. In such figures we observe that the EQ_DDSPON global delay and even AF and BE classes are serviced much better, and thus the delay is lower with respect to the rest – despite EF delay, which is better when using the strict policy mechanism as we might have expected.

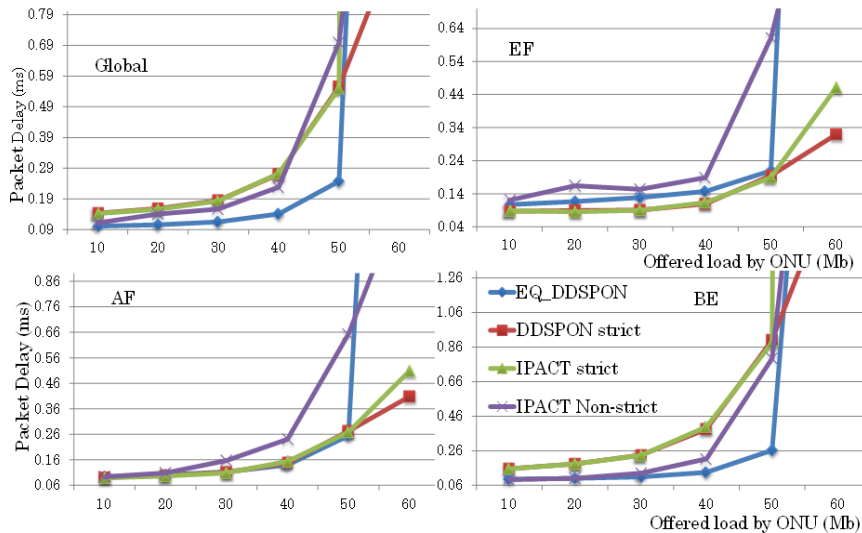


Figure 22: Average packet delay in 1G ONU. Global and DiffServ classes (EF, AF and BE) results.

We also observe that for heavy loads approaching the maximum utilization $\rho = 1$, the slope of the delay of EQ_DDSPON increases much more rapidly than strict EF and AF class average, again due to a strict algorithms approach. So we can say that our proposal for offered load higher than 86% mainly benefits the BE traffic, but for low and medium offered loads we improved the global delay.

Anyway, at such high loads end users will not probably get the QoS (delay, packet loss) they expect from the operator no matter the algorithm being used. In Table 19 we summarize the results of the simulations where the values corresponds to the offered load about 86%, so the OLT throughput refers to the total upstream traffic received by the OLT from all ONUs.

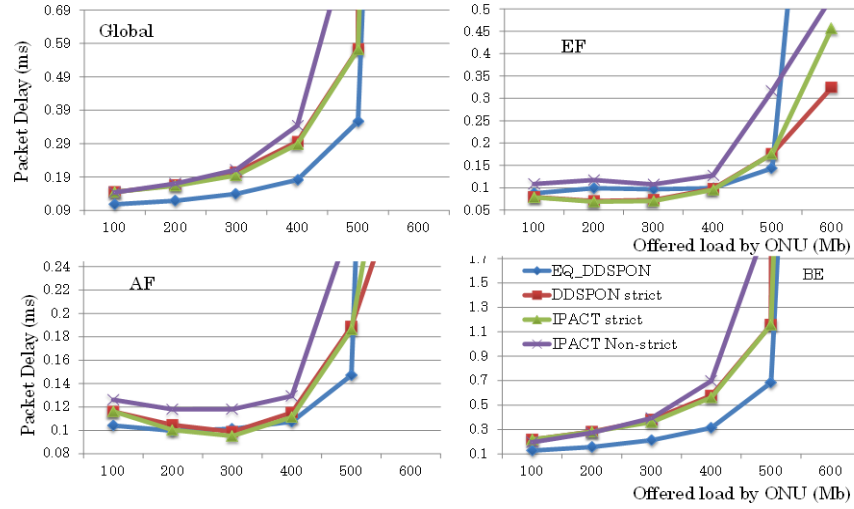


Figure 23: Average packet delay in 10G ONU. Global and DiffServ classes (EF, AF and BE) results.

Table 19: Average results of the Steady-State 1G and 10G analysis.

	EQ_DDSPON	IPACT Strict	DDSPON Strict	IPACT Non-strict
Average T_{cycle} (ms)	0.25	0.38	0.38	0.55
ONU 1G				
OLT throughput Mb/s	420.69	413.31	414.52	409.13
Average packet Delay (ms)				
Global	0.25	0.55	0.56	0.70
EF	0.21	0.19	0.19	0.61
AF	0.25	0.27	0.27	0.65
BE	0.26	0.89	0.90	0.79
ONU 10G				
OLT throughput Mb/s	4060.01	4055.62	4050.04	4049.80
Average packet Delay (ms)				
Global	0.356	0.572	0.574	0.996
EF	0.14	0.18	0.18	0.32
AF	0.15	0.19	0.19	0.28
BE	0.68	1.16	1.16	2.07

7.2.2 Evaluation of the transient with QoS

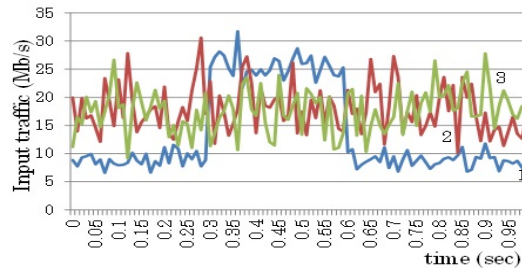
The initial simulation values and the input traffic pattern used in the simulations are summarized in Table 20.

The goal is not only to evaluate the network in the steady-state but also in a setting where the traffic load is not uniform, but changes abruptly over time. That is why in the simulations presented in this

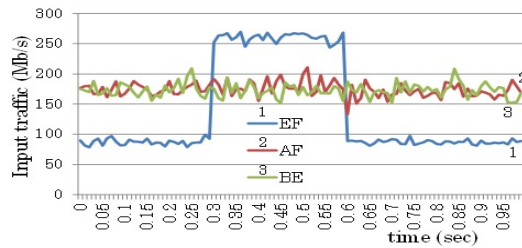
Table 20: Initial simulations parameters of the transient setting.

Description	Value
ratio	$\Phi_{10G}:\Phi_{1G}$
$\Phi_{10G}:\Phi_{1G}$	10:1
T_{cycle}	Time cycle max
Φ_{1G}	1G ONU weight
Φ_{10G}	10G ONU weight
ONU 1G	
EF traffic	CBR type
AF traffic	Self-similar type (H=0.7)
BE traffic	Self-similar type (H=0.7)
ONU 10G	
EF traffic	CBR type
AF traffic	Self-similar type (H=0.7)
BE traffic	Self-similar type (H=0.7)

section not all ONUs have the same input traffic pattern – on the contrary, in each group, either 1G or 10G there is a target ONU that supports a burst of traffic for a small period of time as it is depicted in Fig. 24.



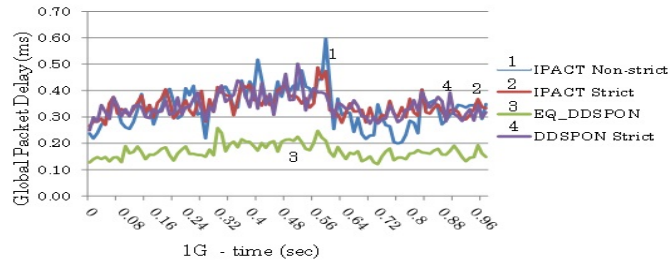
(a) 1G ONUs



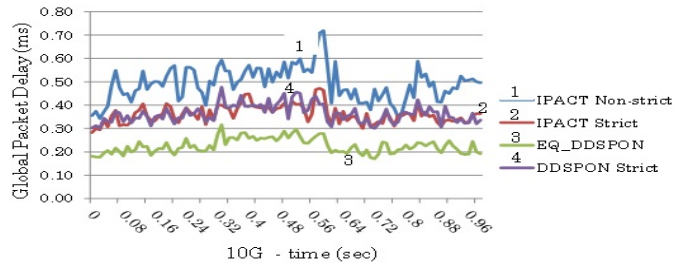
(b) 10G ONUs

Figure 24: Input (transient) traffic pattern. EF (CBR 20%), AF (self-similar 40%) and BE (self-similar 40%).

Figure 25 depicts the instantaneous global packet delay in the bursty setting. Note that the EQ_DDSPON delay is half of the rest of the algorithms simulated. In the same figure we also observe the impact of the input burst of traffic load which is highly smoothed when using EQ_DDSPON.



(a) 1G ONUs



(b) 10G ONUs

Figure 25: Global average packet delay.

Tables 21 and 22 summarize the results of simulations where the values corresponds to the offered load about 86%. So the values in tables corresponding to the OLT throughput refers to the total upstream traffic received by the OLT from all ONUs.

Table 21: Target ONU Average Results of the Transitory 1G and 10G.

	EQ_DDSPON	IPACT Strict	DDSPON Strict	IPACT Non-strict
Average T_{cycle} (ms)	0.175	0.25	0.25	0.28
ONU 1G				
OLT throughput Mb/s	385	375	375	372
Average packet Delay (ms)				
Global	0.17	0.35	0.35	0.36
EF	0.19	0.14	0.14	0.37
AF	0.16	0.18	0.18	0.32
BE	0.16	0.6	0.6	0.35
ONU 10G				
OLT throughput Mb/s	3610	3600	3600	3590
Average packet Delay (ms)				
Global	0.24	0.37	0.37	0.52
EF	0.11	0.118	0.118	0.165
AF	0.12	0.13	0.13	0.16
BE	0.5	0.9	0.9	1.22

Table 21 presents the performance of the target 1G and 10G ONUs while Table 22 presents the results for the the rest of ONUs. Again, the performance of EQ_DDSPON is much better than that of the rest of algorithms. The cycle time, throughput and delay in 1G and 10G ONUs are better, with the exception of the EF class that suffers a slightly higher delay compared to the strict policies.

Table 22: Any ONU average results of the transient 1G and 10G.

	EQ_DDSPON	IPACT Strict	DDSPON Strict	IPACT Non-strict
Average T_{cycle} (ms)	0.175	0.25	0.25	0.28
ONU 1G				
OLT throughput Mb/s	385	375	375	372
Average packet Delay (ms)				
Global	0.16	0.34	0.34	0.34
EF	0.155	0.145	0.145	0.31
AF	0.165	0.19	0.19	0.34
BE	0.158	0.5	0.5	0.335
ONU 10G				
OLT throughput Mb/s	3610	3600	3600	3590
Average packet Delay (ms)				
Global	0.225	0.35	0.35	0.5
EF	0.108	0.124	0.124	0.126
AF	0.115	0.118	0.118	0.16
BE	0.4	0.71	0.71	1

The results show that the performance of the EQ_DDSPON is much better than the others, specially when we consider non uniform loads. This is because the weights facilitate the balancing of the allocated bandwidth among ONUs.

7.3 STEADY-STATE ANALYTICAL MODEL OF A 1G/10G-EPON

Previous works were based mainly on Queuing Theory [66, 13, 78, 53, 52, 12, 32, 81]. On the contrary, in [68] the modeling was done using Stochastic Colored Petri Networks (SCP_N), from where the average queue size is obtained and used to analytically obtain the total delay.

Finally, in [9] the capacity is evaluated, i.e., maximum mean packet throughput and packet delay of a wide range of PON through probabilistic analysis. More specifically, it analyzes the capacity and delay of various subnetworks, interconnected through metro networks, from which PON can be formed.

Our aim is to present the analytical model to evaluate the performance of **DDSPON** in a 1G/10G network in a steady-state. We present a Markov chain model that allows the evaluation of expected values of the cycle time, and the queuing delay that packet experiments in a coexistent 1G/10G plant. To the best of our knowledge, our analysis is the first to consider mixed networks.

The distribution function and thus our expected values of the random variables of the performance parameters evaluated are: cycle time, queue size, throughput, delay and stability. In our opinion, modeling a protocol is worthwhile work and although the proposed model assumes that the network runs under ideal conditions and simplifies it by imposing some constraints, the results provide insight to understand the mechanisms that play part in it.

The model assumes that there is a single error-free slotted broadcast channel. For the sake of clarity and unlike the values used in previous simulations, **ONUs** generate traffic of fixed packet size (P bytes), according to a Poisson process of rate λ , where all **ONU**s are homogeneous and at the same distance from the **OLT**. We first concentrate our efforts in solving a system with N **ONU**s.

7.3.1 The distribution of departures

This paragraph illustrates how to compute the throughput distribution in equilibrium by applying formal Multiqueue Theory [84], and Equilibrium Point analysis [39]. We denote such distribution as, \vec{S} . $\vec{S} = (d^0, d^1, \dots, d^D)$; where d^k is the probability that the cycle contains k packets, independent of the cycle and the **ONU** itself; and where D is the maximum number of departures per cycle.

The queue size of the cycle $n + 1$ depends only on the past through the present and is also independent from the cycle n itself and the **ONU**; therefore it can be modeled as a Closed Jackson Network where **ONUs** are routed from one node to another in each cycle (Fig. 26). Each node is populated by **ONU**s that have some packets backlogged in the queue. Thus in node j , there are u^j **ONU**s with j packets backlogged at the beginning of the cycle.

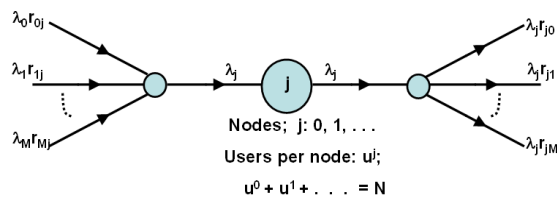


Figure 26: Closed Jackson Network.

The transition probabilities are based on the Poisson probability of having a certain number of packet arrivals in a fixed timespan, that is equal to the mean value of the cycle time, $\overline{T_{\text{cycle}}}$.

The number of packet departures in a cycle is limited to a constant value (IPACT with limited discipline), which we always refer to by the maximum allocatable window (F). The maximum number of departures in a cycle is therefore $D = N \cdot F$.

We denote by r_{jk} the probability of an ONU staying at node j to be routed to a node k after having been serviced completely. The set of values r_{jk} compose the so-called routing probability matrix [R]. The balance equations to solve the system are:

$$\lambda_j = \sum_{k=0}^M \lambda_k r_{kj} \quad (j : 0, 1, \dots, M) \quad (19)$$

where λ_j is the vector of the mean number of arrivals to a node of the chain, $\vec{\lambda}, \vec{\lambda} \equiv \{\lambda_0, \lambda_1, \dots, \lambda_{M;M \rightarrow \infty}\}$. And because the ONU at node j should be routed to any other node of the chain; any element r_{jk} holds that $\sum_{j=0}^M r_{jk} = 1$ being $0 \leq r_{jk}$ for each k . The linear system of equations in Eq. 19 is limited to M for computation reasons although the discrete-time Markov Chain is theoretically composed by an infinite number of nodes.

Let X be the set of all possible combinations of the N ONUs spread out among the M nodes of the chain. We first need to compute the probability of each combination, which is a product form of a Closed Jackson Network type, $P_{r_0, r_1, \dots, r_M} = \frac{1}{G_M} r_0 \cdot r_1 \dots r_M$. The service time of each packet is $\mu_j = 1$ because the packet length is always the same (P bytes) as stated. Hence the values of r_j are given by $r_j(u^j) = \frac{\lambda_j}{u^j!}$. Finally, G_M is known as the normalization constant. The number of packet departures for each combination and its probability are:

$$k = \sum_{j=0}^M u^j \cdot \min(j, F); \quad (20)$$

$$p(k) = P_{r_0, r_1, \dots, r_M};$$

Let X^k be the subset of X such that the packet departures are equal to k . Each element d^k of \vec{S} is given by:

$$d^k = \sum_{X^k} p(k); \quad (0 \leq k \leq D) \quad (21)$$

Which finishes the process of computing the distribution of the packet departures, i.e., the throughput distribution, \vec{S} .

7.3.2 The distribution of the cycle time

The cycle time, T_{cycle} , is a random variable defined as the time between two successive transmissions of an ONU. We now show how to compute its distribution, which then permits to calculate its mean value at the discrete points in time. In a cycle where there are k packet departures, the cycle time is given by:

$$T_{\text{cycle}}^k = \frac{k \cdot P \cdot 8}{R_u} + T_{\text{ov}} \quad (22)$$

where T_{ov} stands for the time overhead generated first due to the guard time (T_g), and due to the transmission time of the REPORT control message whose length is CM (bytes) in Eq. 23. The time overhead in each cycle is therefore:

$$T_{\text{ov}} = N \cdot \left(\frac{\text{CM} \cdot 8}{R_u} + T_g \right) \quad (23)$$

We must take care because the lower bound of the cycle time $T_{\text{cycle}}^{\text{min}}$, is limited by the RTT of the network. In other words, a cycle will last at least $T_{\text{cycle}}^{\text{min}}$ even for small values of k such that T_{cycle}^k is less than $T_{\text{cycle}}^{\text{min}}$.

And since we know the throughput distribution from previous paragraph, we now can compute the cycle time distribution in equilibrium, T_{cycle} . The mean value is given by:

$$\overline{T_{\text{cycle}}} = \sum_{k=0}^D d^k \cdot \max(T_{\text{cycle}}^{\text{min}}, T_{\text{cycle}}^k) \quad (24)$$

Notice that we face a system of the type $x = f(x)$, because we need first the mean value of the cycle time, $\overline{T_{\text{cycle}}}$ to compute the arrivals in a cycle and then the packet departures distribution \vec{S} ; however $\overline{T_{\text{cycle}}}$ in turn comes from \vec{S} . We apply numerical methods to solve such system; for instance by iteration as depicted in Fig. 27.

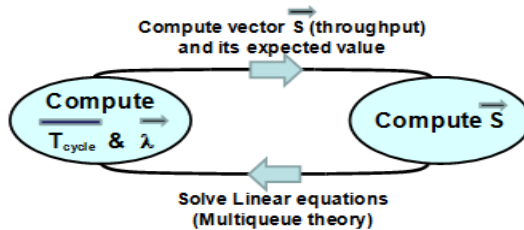


Figure 27: Steady-state iteration process.

7.3.3 Extension to a coexistent 1G/10G network

Next we extended our analysis to consider a coexistent 1G/10G network. The network is composed by N^{1G} and N^{10G} ONUs ($N^{1G} + N^{10G} = N$); and then, the above process is carried out separately for each group. We assume that both groups of ONUs are served independently, which means that we might compute \vec{S}^{1G} and \vec{S}^{10G} separately, that are the equilibrium distribution of packet departures of 1G and 10G ONUs respectively. The joint equilibrium distribution of packet departures is given by the convolution:

$$\vec{S} = \vec{S}^{1G} \otimes \vec{S}^{10G} \quad (25)$$

The rest of equations should be modified accordingly. The cycle time where the set of 1G ONUs transmit k packets and the set of 10G ONUs transmit m packets is given by:

$$T_{cycle}^{k,m} = \frac{k \cdot P \cdot 8}{R^{1G}} + T_{ov}^{1G} + \frac{m \cdot P \cdot 8}{R^{10G}} + T_{ov}^{10G} \quad (26)$$

where T_{ov}^{1G} and T_{ov}^{10G} stand for the overheads of 1G ONU and 10G ONU respectively, calculated as :

$$T_{ov}^{1G} = N^{1G} \cdot \left(\frac{CM \cdot 8}{R^{1G}} + T_g^{1G} \right) \quad (27)$$

$$T_{ov}^{10G} = N^{10G} \cdot \left(\frac{CM \cdot 8}{R^{10G}} + T_g^{10G} \right) \quad (28)$$

$\overline{T_{cycle}}$ is calculated applying the above overhead and constraints as:

$$\overline{T_{cycle}} = \sum_{k=0}^{D^{1G}} d_k^{1G} \sum_{m=0}^{D^{10G}} d_m^{10G} \cdot \max(T_{cycle}^{\min}, T_{cycle}^{k,m}) \quad (29)$$

In Eq. 29, D^{1G} ($D^{1G} = N^{1G} \cdot F^{1G}$), and D^{10G} ($D^{10G} = N^{10G} \cdot F^{10G}$) are the maximum number of departures of the 1G and 10G ONUs respectively and d_k^{1G} and d_k^{10G} are the elements of vectors \vec{S}^{1G} and \vec{S}^{10G} .

7.3.4 DDSPON upper and lower bounds

The allocated bandwidth computed by the DDSPON (Eq. 3 and 4) varies each cycle depending on the weights received from the OLT. Equation 30 holds:

$$\Phi_i^c \cdot BW_{max} \leq BW_i^{n+1} \leq BW_{max} \quad (30)$$

In previous analysis the routing probabilities (r_{jk}) and the departures (Eq. 20) analysis are based on a maximum fix constant value of the window F , which also holds $\Phi_i^c \cdot BW_{max} \leq F \leq BW_{max}$. Therefore, the process explained so far does not compute the right **DDSPON** steady-state values, but it might be rather used to compute the upper and lower bounds of the performance of the **DDSPON**. We define:

- $F_{low}^{1G}, F_{low}^{10G}$: lower value of the bandwidth allocable to 1G and 10G **ONUs**, i.e., the minimum window to use in computations.
- $F_{up}^{1G}, F_{up}^{10G}$: upper value of the bandwidth allocable to 1G and 10G **ONUs**, i.e., the maximum window to use in computations.

We compute both lower and upper values easily from (Eq. 4) where $F_{low}^{1G} = \frac{BW_{max}^{1G}}{N^{1G}}$ and $F_{up}^{1G} = BW_{max}^{1G}$; and we also compute F_{low}^{10G} and F_{up}^{10G} , which are the respective values for the 10G **ONUs** computed likewise replacing 1G by 10G in both equations.

Results to be obtained with this approach are:

- $S_{low}^{1G}, S_{up}^{1G}$: lower and upper equilibrium distribution of 1G **ONU**.
- $S_{low}^{10G}, S_{up}^{10G}$: lower and upper equilibrium distribution of 10G **ONU**.
- $\vec{S}_{low}, \vec{S}_{up}$: joint equilibrium distribution of packet departures, i.e., lower and upper throughput distribution.
- $\overline{T_{low}^{cycle}}, \overline{T_{up}^{cycle}}$: lower and upper mean value of the cycle.

The lower values $S_{low}^{10G}, S_{low}^{1G}$ and $\overline{T_{low}^{cycle}}$ will be the results obtained if we use the aforementioned algorithm **IPACT** using the limited discipline, which limits the maximum amount of packet departures to a constant window, instead of using **DDSPON**. In fact, the upper values $S_{up}^{10G}, S_{up}^{1G}$, and $\overline{T_{up}^{cycle}}$ will correspond to those of the gated **IPACT**, where there is not allocable window limit. The **DDSPON** expected lower and upper bound values can be computed using the methodology proposed.

7.4 ANALYTICAL AND SIMULATED PERFORMANCE EVALUATION

In this section we present the analytical and simulation results computed for the coexistent 1G/10G **EPON** network. They are presented jointly to show the accuracy of the model. Furthermore, such results are compared to the **IPACT**.

The values of the variables used in the analysis and simulations are the same used in Table 18. Set up values of the **DDSPON** are:

$$\begin{aligned} F_{\text{low}}^{1\text{G}} &= 5 \text{ and } F_{\text{up}}^{1\text{G}} = 40 \text{ (packets)} \\ F_{\text{low}}^{10\text{G}} &= 50 \text{ and } F_{\text{up}}^{10\text{G}} = 400 \text{ (packets)} \end{aligned}$$

For simplicity we also set up the guard time to a constant value, thus $T_g = T_g^{1\text{G}} = T_g^{10\text{G}} = 2\mu\text{s}$.

Next sections illustrate the average values of the performance, i.e., cycle, throughput and delay. The figures 28, 29 and 30 depict the analytical lower bound (F_{low}), upper bound (F_{up}) and the simulation results of the DDSPON and the IPACT.

7.4.1 The mean value of the cycle

We first show in Fig. 28 the mean value of the cycle, $\overline{T_{\text{cycle}}}$. We see that $\overline{T_{\text{cycle}}}$ is almost constant for low and medium rates, independently of the initial maximum cycle time setup; its value is very close to RTT no matter the ONUs input rate. It is also very surprising that the values of the upper and lower bounds computed are almost the same, which suggests that in the steady-state the lower window is big enough to allocate the packets arrived along the cycle, and no extra bandwidth is needed by any ONU.

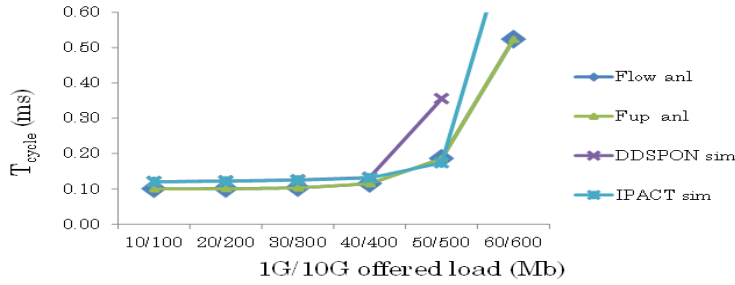


Figure 28: Mean value of the cycle. Steady-state setting.

7.4.2 The mean value of the throughput

Figure 29 shows the bounds for the mean value of the throughput for 1G ($\overline{S_{1\text{G}}}$) and 10G ($\overline{S_{10\text{G}}}$) ONUs. The maximum throughput reached by 1G ONUs is 60.5 Mb/s, while 10G ONUs is as much as 605 Mb/s and the overall throughput of the upstream channel is about 5.324 Gb/s; transmission times are the same $T_{1\text{G}} = T_{10\text{G}} = 0.484$ ms and the mean value of the throughput is $\overline{S_{10\text{G}}} = 10 \cdot \overline{S_{1\text{G}}}$, as expected.

7.4.3 The mean value of the Delay

The packet delay is defined as the time elapsed since the packet is generated until it is finally transmitted to the OLT. The packet delay is

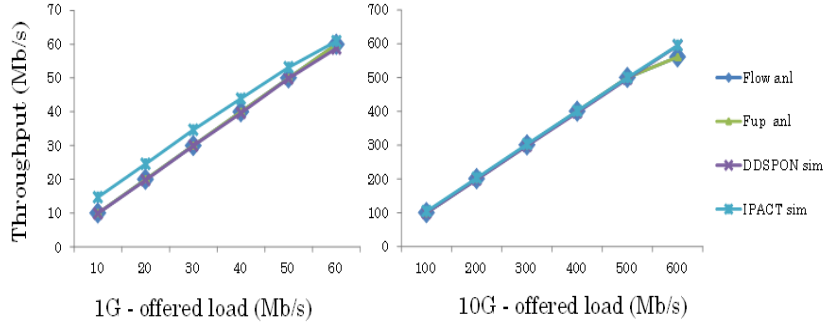


Figure 29: Analytical and simulated mean value of the throughput $\overline{S_{1G}}$ and $\overline{S_{10G}}$. Steady-state setting.

decomposed in three random variables: W_{poll} , W_{grant} and W_{queue} as described in [50]. Thus, the average value of the access delay $\overline{W_{acc}}$, is given by:

$$\overline{W_{acc}} = \overline{W_{poll}} + \overline{W_{grant}} + \overline{W_{queue}} \quad (31)$$

where:

- W_{poll} : Queue time. The time elapsed since the arrival of the packet until the beginning of the next cycle. The mean value is approximately $\overline{W_{poll}} = \frac{T_{cycle}}{2}$.
- W_{grant} : time elapsed since the REPORT transmission until the start of the transmission of backlogged packets. Notice that this delay may span more than just one cycle if the queue length is higher than the maximum allocable window.
- W_{queue} : delay interval from the arrival of the GATE message till the beginning of the packet transmission. The Service Time is usually negligible compared to previous components specially in low traffic load typically $\overline{W_{queue}} = \frac{slot_time}{2}$.

$\overline{W_{acc}}$ is quite difficult to compute, but a good approximation of such average is: $\overline{W_{acc}} \approx \frac{3 \cdot T_{cycle}}{2}$. And because we know from previous paragraphs that $T_{cycle}^{min} = RTT$ in the steady-state; the low value is approximately $\overline{W_{acc}} \approx \frac{3 \cdot RTT}{2}$; as Fig. 30 depicts. We observe that the delay $\overline{W_{acc}}$ is almost constant for low and medium traffic values, and increases dramatically when the load approaches $G=1$.

This results suggest that analytical and simulated results are very close for light loads, and what is more surprising is that analytical upper and lower bounds are similar because the the cycle time is independent of the initial conditions of the maximum allocable window (F).

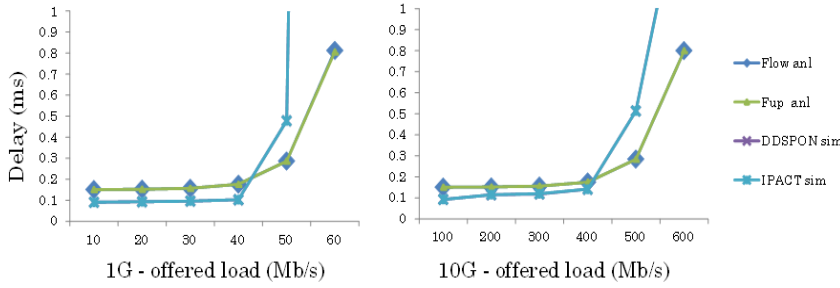


Figure 30: Analytical and simulated average value of the delay in 1G ONU and 10G ONU. Steady-state setting.

7.5 SUMMARY

In this chapter, we have presented the EQ_DDSPON scheme, the enhancement to the former DDSPON that offers service differentiation according to a non-strict policy. We have first described the DDSPON in a coexistent 1G/10G EPON network and then analytically evaluated its performance in the steady-state applying the Equilibrium Point theory. Such analysis proves to be very useful to capture the relation between configuration parameters, i.e., packet size, data rate and guard time.

Simulation results highlight the advantages of the proposed algorithm in a coexistent plant including QoS. Results also show a good performance in terms of delay, with a fairly balanced throughput amongst ONUs both 1G and 10G. The DDSPON performance is specially relevant when we consider bursty traffic instead of uniform.

In a bursty setting the overall delay and throughput of the target ONU is also much better when using the EQ_DDSPON. Only the EF class suffers a slight higher delay compared with strict policy applied by the IPACT or DDSPON. In spite of the global, AF and BE delay are much better than with IPACT (Fig. 22, 23, 25 and Tables 21 and 22).

In steady-state we observe that the mean cycle time $\overline{T_{\text{cycle}}}$ and the global delay are much better when using EQ_DDSPON instead of strict algorithms: IPACT and DDSPON. In steady-state analysis the performance of EQ_DDSPON in terms of delay is better even at high loads because of the distributed property of DDSPON that allows taking advantage of the unused bandwidth (Fig. 28, 29, 30 and Table 19).

Even if PONs have proven to be more energy-efficient than other access solutions, energy consumption minimization is becoming an important research target also in PON. In particular, to sustain the increased bandwidth demand of emerging applications in the access section of the network, new hybrid PON solutions employing WDM/TDM are being investigated. Compared with classical PON, the architecture of WDM/TDM-PONs requires more transceivers/receivers, hence they are expected to be more energy hungry than classical PONs.

In this chapter, we focus on the energy consumption minimization in WDM/TDM-PONs and we propose an energy-efficient mechanism based on Dynamic Bandwidth and Wavelength Allocation whose objective is to switch off, whenever possible, the unnecessary receivers for upstream traffic at the OLT.

Our proposed energy saving mechanism is able to decrease energy consumption at the OLT of about 30%, while maintaining the penalty introduced in terms of channel utilization and packet delay within an acceptable range. Detailed implementation of the proposed algorithm is presented in the following sections, and simulation results are reported to quantify energy savings and effects on network performance on different network scenarios.

8.1 MINIMIZING ENERGY CONSUMPTION IN OLT

This section presents our energy-saving mechanism. To implement our mechanism, we take advantage of the MPCP in EPON (standard IEEE 802.3ah) that the ONUs employ to report their upstream queue lengths and to transmit their traffic to the OLT. The information exchanged in the control messages between OLT and ONUs, is exploited to disclose the use of resources and based on that information to decide how much energy can be saved by turning OLT receivers off.

8.1.1 Energy-aware wavelength assignment (EWA)

Let us define as *energy-aware wavelength assignment (EWA)* the energy-saving mechanism performed by the OLT to decide whether receivers can be put to sleep mode. Fig. 31 illustrates the methodology of our proposal.

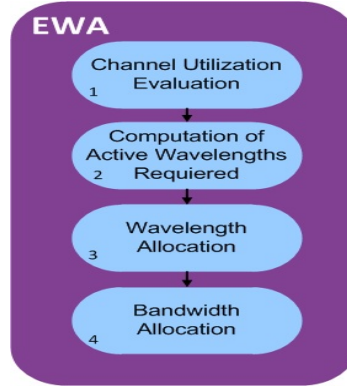


Figure 31: Energy-aware Wavelength Assignment.

Our proposal requires to collect the channel utilization measurements which describe the current use of wavelengths. Based on those measurements, the OLT can decide whether to switch to sleep mode one or more receivers and finally performed the bandwidth and wavelength allocation.

Below we define the notation used hereafter::

T_D	Time needed for the transmission of a set of timeslots.
T_{cycle}	Time needed for the transmission of a set of timeslots together with their associated guard intervals.
T_g	Interval of time between any two adjacent timeslots.
N	Number of active ONUs.
R	Data rate of the upstream link from an ONU to the OLT.
BW_i	Requested transmission length of ONU_i expressed in bits.
$BW_{all_{i,j}}$	Allowed transmission length of ONU_i wavelength j expressed in bits.
BW_{max}	Maximum transmission length in bits of all ONUs in the same wavelength.
$BW_{max_{i,j}}$	Maximum allowed transmission length of ONU_i in wavelength j .
W	Number of supported wavelengths.
W_c	Number of current utilized wavelengths.
W_a	Theoretical minimum number of wavelengths needed.
W_{off}	Number of receivers in OLT to be switched to sleep mode.
W_{on}	Number of receivers in OLT to be switched to active mode.
T_c	Current Time.
U_{high}	Observation period for high channel utilization.
U_{low}	Observation period for low channel utilization.

Once low channel utilization is detected the observation period U_{low} begins to count. If during that period the level of utilization

does not change then one or more receivers in **OLT** can be put in sleep mode. On the contrary, when high utilization is detected the observation period U_{high} begins to count and only if during that period the level of utilization does not change then one or more receivers in **OLT** can be put in active mode. Fig. 32 illustrates the operation of the energy saving mechanism.

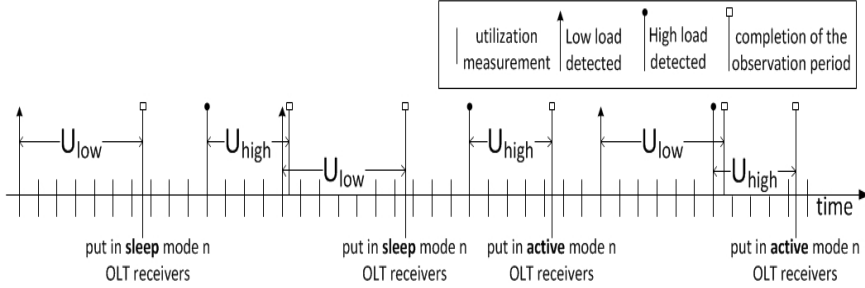


Figure 32: Energy saving mechanism.

8.1.2 Channel Utilization Evaluation

Our algorithm decides to switch off receiver only if during a pre-defined observation period U_{low} , the **OLT** detects low-load channel utilization.

The **OLT** evaluates the channel utilization by summing of the current timeslots requested, i.e., checking if:

$$\sum_{i=1}^N BW_i/R < (W_c - 1)T_D \quad (32)$$

where T_D is the data cycle duration, i.e., the time needed for the transmission of a set of timeslots in the same wavelength of different **ONU**s, computed as:

$$T_D = BW_{\text{max}}/R \quad (33)$$

where BW_{max} is the sum of the maximum transmission length of all **ONU**s in the same wavelength $\sum_{i=1}^N BW_{\text{max},i}$. The cycle size with guard intervals is:

$$T_{\text{cycle}} = T_D + N(T_g) \quad (34)$$

If $\sum_{i=1}^N BW_i/R < (W_c - 1)T_D$, then all reported **ONU** requests can be accommodated in a cycle, and this is regarded as a low-load channel utilization. If $\sum_{i=1}^N BW_i/R > (W_c)T_D$, then not all the requests can be served by the current number of active wavelengths and this is regarded as high-load channel utilization.

8.1.3 Number of Active Wavelengths Required

If the OLT detects low-load channel utilization during U_{low} then W_{off} is calculated as:

$$W_{\text{off}} = W_c - W_a \quad (35)$$

where $W_a = \lceil BW/T_D \rceil$ is the theoretical minimum wavelengths needed in the current time T_c and where BW is the total ONU's request $\sum_{i=1}^N BW_i/R$.

If on the contrary, the OLT detects high-load channel utilization during U_{high} then W_{on} is calculated as:

$$W_{\text{on}} = W_a - W_c \quad (36)$$

8.1.4 Wavelength Allocation

As mentioned before, our resource management scheme can work with any DWA, but in order to illustrate it by example in the following we use two well known algorithms, called Earliest Finish Time (Earliest Finish Time (EFT)) and Latest Finish Time (Latest Finish Time (LFT)) [42], to perform wavelength allocation. Also, we use EFT and LFT to select the OLT receivers to be put in sleep or active mode after the computation of the active wavelengths required.

In EFT the wavelength with the earliest-finish time is assigned for the next transmission, while in LFT the wavelength with the latest-finish time is assigned, as long as this time is not later than a threshold T_{lft} (Fig. 33a). If no channel has a finish time lower than T_{lft} , then the LFT algorithm switches to EFT for this cycle (Fig. 33b).

8.1.5 Bandwidth Allocation

We assume that each ONU can only be scheduled on one wavelength j in a cycle, so the OLT updates the value of $BW_{\text{max}_{i,j}}$ for the next cycle according to the new value of W_c . If all the ONUs have the same traffic load then:

$$BW_{\text{max}_{i,j}} = T_D/(N/W_c) \quad (37)$$

The scheduling in time, i.e., the bandwidth allocation is:

$$BW_{\text{all}_{i,j}} = \min(BW_i, BW_{\text{max}_{i,j}}) \quad (38)$$

where BW_i is the ONU queue size in bits.

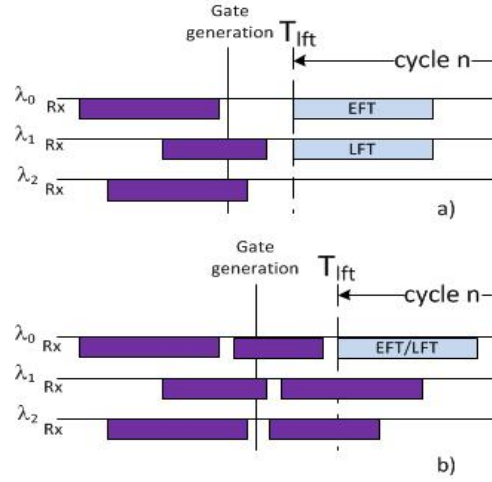


Figure 33: LFT and EFT operation.

8.1.6 EWA Algorithm

To know the number of **OLT** receivers we need in active or sleep mode we propose an algorithm. It can be implemented in the **OLT** by performing the process in Algorithm 1.

Algorithm 1. Energy-aware wavelength assignment (EWA)

1: Channel utilization evaluation

$$\sum_{i=1}^N BW_i/R < W_c - 1(T_D)$$

2: Computation of active wavelengths required

IF low-load during U_{low} THEN

$$W_a = \lceil BW/T_D \rceil$$

$$W_{off} = W_c - W_a$$

$$W_c = W_a$$

Switch OFF W_{off} OLT receivers.

IF high-load during U_{high} THEN

$$W_a = \lceil BW/T_D \rceil$$

$$W_{on} = W_a - W_c$$

$$W_c = W_a$$

Switch ON W_{on} OLT receivers.

3: Wavelength Allocation

EFT or LFT

4: Bandwidth Allocation

$$BW_{max_{i,j}} = T_D/(N/W_c) \text{ according the new value of } W_c$$

$$BW_{all_{i,j}} = \min(BW_i, BW_{max_{i,j}})$$

8.2 RESULTS AND DISCUSSION

In this section, we evaluate the performance of our proposal in terms of energy saving and effect on packet delay. We developed a simulation network model using the OPNET Modeler tool (see appendix A). The objective is to observe the tradeoffs among channel utilization, packet delay, and energy consumption in two representative scenarios. We refer to them as balanced/unbalanced input traffic and residential and business user input traffic.

We use a single (tunable) transmitter and receiver at the ONU side and multiple receivers/transmitters at the OLT. We assume that each ONU can support all wavelengths (tunable ONU), but it can only be scheduled on one wavelength in a cycle.

We implemented EWA with EFT and LFT, as wavelength allocation, based on two approaches where the way to switch to sleep/active mode the OLT receivers can follow a one-by-one or n-by-n approach. In the one-by-one approach, if OLT decides to save energy, switch to sleep mode only one OLT receiver no matter if the number of unused channels is greater than one. Thus saving energy is gradual unlike the n-by-n approach which is exponential.

Bandwidth allocation is performed according to limited service as described in [48], where $BW/\max_i \leq T_D/N$. The power consumption of each receiver in the OLT was set to 0.5 Watt (W) based on the power consumption of commercial transceivers/receivers modules [77]. Therefore, the total power consumption by OLT receivers in our simulation setting is set to 4 W.

The input traffic is of the self-similar type and packet length is uniformly distributed based on Ethernet frame size. We assume a wake-up time for OLT receivers lower than the RTT in the order of 0.2 ms. Thus the operation of our proposed mechanism is not affected as long as the wake-up time is less than 0.2 ms. Table 23 summarizes the simulation parameters of the set of simulations.

8.2.1 *Balanced/Unbalanced input traffic*

The first set of simulations evaluates the performance of EFT and LFT algorithms in terms of power consumption and average packet delay.

Fig. 34 shows the average number of wavelength used in function of the offered network load, which also indicates the number of receivers in OLT that can be put into sleep mode, i.e., the power consumption is directly related to the number of wavelengths used for

Table 23: Simulations Parameters.

Number of ONUs (N)	64
Number of upstream channels (W)	8
Maximum cycle time (T_{cycle})	2ms
PON upstream channel data rate (R)	1Gb/s
Guard time (T_g)	2 μ s
OLT-ONU distance (d)	18 < d < 20 Km
Hurst parameter (H)	0.7
Packet size (uniform distribution)	64 - 1518 bytes

the upstream transmissions because in our simulation setting each wavelength represents one OLT receiver.

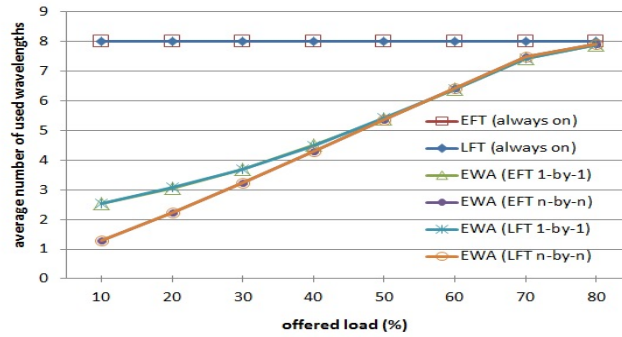


Figure 34: Wavelengths used - EWA with LFT and EFT wavelength allocation.

We can observe that both algorithms yield similar results. This confirms that our approach can be used with different DWA approaches and suggest that significant energy reduction can be achieved independently of the DWA approach. Also the fact that LFT and EFT yield very similar results demonstrates that LFT most of times reaches the T_{lft} and it switches to EFT.

Choosing an appropriate value of T_{lft} (higher than the one used in our simulations), LFT will allow a better performance of the energy mechanism proposed in terms of energy consumption. Nevertheless, with a higher T_{lft} the average packet delay should be degraded. The T_{lft} in these simulations was set up as $T_{lft} = RTT + T_{cm}$ where RTT is the round trip time and T_{cm} is the time required for the transmission of control messages.

Fig. 35 shows the effect of EWA on the average packet delay: we can see that the average packet delay increases for the cases where we apply the energy-saving mechanism. But its absolute value is still

acceptable (below 2 ms, i.e., the duration of a data cycle).

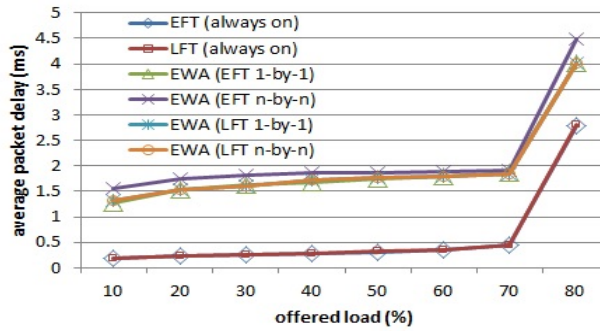
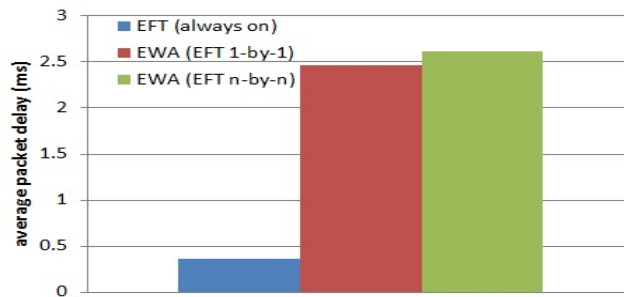
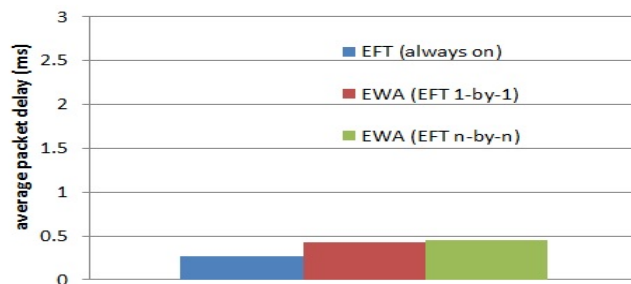


Figure 35: Average packet delay - EWA with LFT and EFT wavelength allocation.

In the same set of simulations, we evaluated the performance of LFT and EFT, but in a scenario where the upstream network traffic is unbalanced among ONUs, i.e., ONUs are divided in two groups with different input traffic pattern (32 ONUs high-load and 32 ONUs low-load). Since the results of LFT and EFT are similar also in this case, we will focus hereafter only in EWA with EFT as wavelength allocation method.



(a) high-load ONUs



(b) low-load ONUs

Figure 36: Average packet delay of ONUs of each group.

Fig. 36 shows the average packet delay. In this case we can see relevant variations in the delay between the different approaches, mainly high-load ONUs are affected because the maximum bandwidth guaranteed is the same for all ONUs. Higher delay is a consequence of energy-saving, and this may affect some applications or services that are delay sensitive.

8.2.2 Traffic variation during the day

We performed a different set of simulations with different configurations settings. In this case we model a network traffic with varying intensity with two classes of users representing residential and business usage behaviors as shown in Fig. 37. The upstream traffic behavior that we evaluated represent the different network usage along the day.

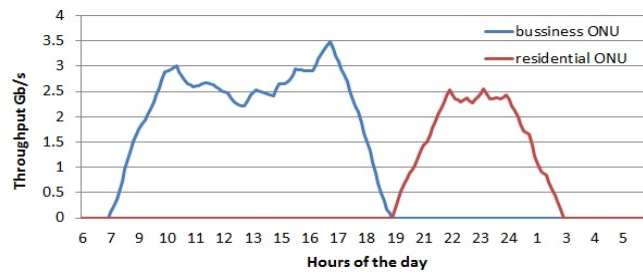


Figure 37: Input traffic of each ONU.

In this study we tested different values of U_{low} , also we introduced a threshold to define high load observation period U_{high} . In this manner, based on the utilization measurements, the OLT switches the receivers to sleep/active mode after U_{low} and U_{high} thresholds are reached.

Figure 38 shows the number of wavelengths used along the simulation time. The use of wavelengths corresponds to the traffic pattern. The scenario based on EFT n-by-n slightly outperforms the energy consumption.

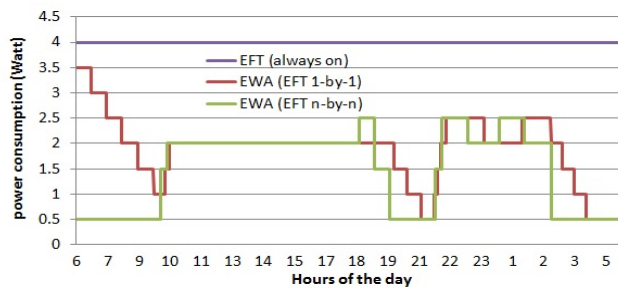


Figure 38: Energy consumption.

Differences are seen mainly in the absence of traffic, because even though the number of receivers that can be shut down is the same, how they are turned off is different. Following approach one-by-one at the beginning of the simulation, when no traffic, saving energy is gradual because our proposed EWA starts with all the available wavelengths switched on. We show the power consumption in terms of number of wavelengths used. Thus, the fewer wavelengths are used less OLT receivers are required.

Figure 39 shows the average packet delay of business and residential users, respectively. The energy-saving mechanism based on EFT n-by-n slightly outperforms the EFT 1-by-1 mechanism. The average packet delay represents instantaneous measurements of packet waiting times in the queue.

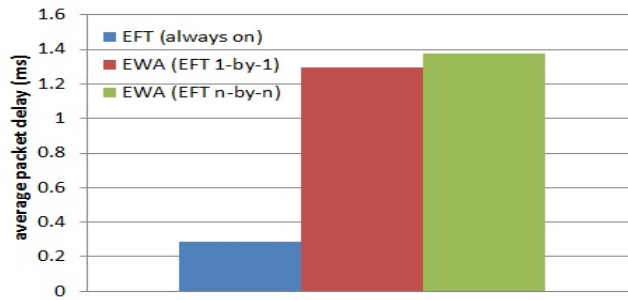


Figure 39: Business and Residential users.

8.3 SUMMARY

In this chapter we have presented a novel energy-aware wavelength assignment mechanism to save energy at the OLT in a WDM/TDM-PON based on upstream network traffic. Simulations results show that our proposal is able to save energy in the OLT, based on a periodic evaluation of channel utilization.

In our study we have assumed some specific values of the duration of OLT receivers in sleep or active modes as well as the length of the observation periods U_{low} and U_{high} . Such values are crucial parameters that impact directly the delay performance. Regarding the wake-up time for elements in OLT, we found that our proposal does not introduce any penalty whenever the wake-up time in OLT receivers is less than the RTT equal to 0.2ms.

The study of the most effective values under different scenarios as well as a generic and suitable definition of T_{lft} for the LFT algorithm, will provide energy-saving and efficient resource management. Also,

the combination of both EFT and LFT could yield to interesting results in terms of energy-saving.

CONCLUSIONS

The design of solutions that optimize the resource management in [PON](#), not only based on the type of network such as [WDM-PON](#) or [LR-PON](#), are the key to reach the efficiency and the high performance that demand the emerging services and applications.

This thesis makes four important contributions to the operation of [PONs](#). The mechanisms and algorithms developed in this thesis can be used to help design and implementation of [PONs](#). This chapter summarizes the main results and contributions of this thesis.

During this study, a detailed understanding of current optical access networks as well as their evolution and trends has been gained. Moreover, this research has surveyed and identified relevant contributions in literature regarding the resource management in [PON](#), mainly [EPON](#), [LR-PON](#) and [WDM-PON](#). Furthermore, novel mechanisms and algorithms have been proposed and demonstrated through several simulations to verify the feasibility towards practical implementation.

Since energy efficiency has become an increasingly important aspect of designing access networks, this thesis presents an overview of energy management in [PON](#) where relevant proposals have been identified. A novel energy-efficient resource management mechanism for [WDM/TDM-PON](#) has been proposed, which can be applied in combination with any [DBA](#) or [DWA](#) algorithm.

9.1 CONTRIBUTIONS

The main contributions of this thesis are in terms of resource management. We have studied and performed a widespread analysis of the current literature about resource allocation proposals, especially we studied the [DDSPON](#) algorithm. The state of the art in [DBA](#) solutions, as well as the study of [PON](#) was presented in a chapter book published in [29]. The study of [DDSPON](#) was reflected in publication [7].

Adaptations of [DDSPON](#) for new scenarios, such as [EPON/10GEPON](#) coexistence for elastic and real-time services, have been done. Important results have been obtained, such results have been published in [30, 27].

By using the [DDSPON](#), enhanced [ONUs](#) will take full advantage of the 10 Gb/s rate while legacy 1G [ONUs](#) maintain their [SLA](#); as a result, the individual performance is maximized for both [ONUs](#). We performed an analytical model to evaluate the algorithm performance in a coexistent 1G/10G network. Results were published in [26].

Resource management can also address the energy-saving issue since access networks consume a big part of the overall energy of the communications networks. How to perform effective bandwidth and wavelengths utilization in terms of energy consumption have been addressed in the end phase of this thesis. Results of this research have been published in [28].

Extensive simulation experiments have been carried out on [EPON](#) simulator. A robust network simulation model has been developed to verify the feasibility of the contributions. This simulator has been validated through comparison with specifications in [EPON](#) standards.

9.2 FUTURE WORK

Although there are several contributions in the literature and many research projects related to the topics covered in this thesis, the field of resource management research is not closed at all. There remain several future research directions that may provide additional benefits:

- The study of the contributions presented in this thesis using more complex traffic models.
- Extend the study of contributions related to both the energy savings and the provision of [QoS](#) in new generation [PONs](#) combining new types of modulations like [WDM](#) with [CDM](#), [TDM](#) and spatial modulations.
- Regarding [QoS](#) in order to support and provide guarantees to real-time traffic, in addition to bandwidth allocation and service differentiation, an admission control algorithm is required.
- Upgrade the simulator network model used to allow the validation of new scenarios such as [LR-PON](#) networks and rates of the order of 40-100 Gb/s.
- Analytical study of a network model to optimize energy savings and [QoS](#) in next generation [PONs](#).

Part IV

APPENDIX

In this thesis, the performance of the proposed resource management mechanisms has been extensively evaluated by simulations that show the channel utilization, throughput, delay and the effect of channel losses.

According to the simulations results the shortcomings have been identified and enhancements have been incorporated. So we built a test framework based on simulations. In appendix [A](#) the architecture of this framework is explained. The framework simulator designed has meant an in-depth study and definition of the main tools to model [PON](#) issues as well as [EPON](#) standard and finally, since the simulation of high speed networks is not a trivial problem, a long period for the framework simulator development has been necessary.

Throughout this appendix an overview of the Integrated Framework Simulator is explained.

SIMULATOR

In this thesis the performance of EPON is based on simulations techniques. We build a simulation network model with the OPNET Modeler tool, as there are no available PON modules at time a substantial amount of time was required to developed an integrated framework simulator. An in-depth knowledge of the OPNET Modeler tool and the IEEE 802.3ah standard, which was based on the simulation network model, has been required.

A.1 OPNET MODELER OVERVIEW

OPNET Modeler, is a communications-oriented simulator. Because it has been developed with such guidance, the OPNET Modeler contains a large number of options for monitoring the performance of communication links, whether wired, satellite or wireless. Behavior and performance of modeled systems can be analyzed by performing discrete event simulations.

OPNET Modeler consists of a number of tools, each one focusing on particular aspects of the modeling task. These tools fall into three major categories that correspond to the three phases of modeling and simulation projects: model specification, data collection and simulation, and analysis. These phases are necessarily performed in sequence. They generally form a cycle, with a return to Specification following Analysis. Specification is actually divided into two parts: initial specification and re-specification, with only the latter belonging to the cycle, as illustrated the following Fig. 40.

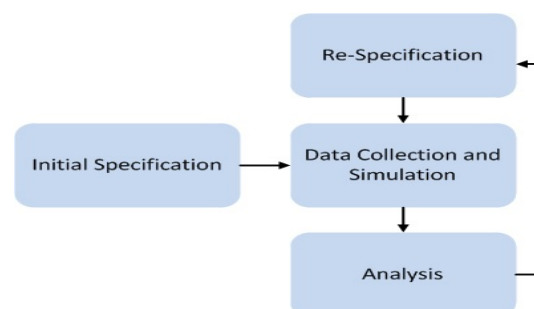


Figure 40: Simulation Project Cycle.

A key feature in OPNET Modeler is the model library, which incorporates significant modeling capabilities packaged into easy-to-use objects.

OPNET Modeler uses distinct modeling paradigms to represent the fundamentally different components of a network. Each paradigm has an associated modeling domain (see Table 24¹). This allows the structure of models to closely resemble that of real-world systems and to be more intuitive.

Table 24: Modeling Domains.

Network Domain	concerned with the specification of a system in terms of high-level devices called nodes, and communication links between them.
Node Domain	concerned with the specification of node capability in terms of applications, processing, queueing, and communications interfaces.
Process Domain	concerned with the specification of behavior for the processes that operate within the nodes of the system. Fully general decision making processes and algorithms may be specified.

Although OPNET Modeler does not have a paradigm dedicated to resource modeling, the power and generality of the node and process domains make it an excellent environment for modeling complex resource-based systems. Thus, we decided that OPNET Modeler simulator is a suitable tool to build a custom PON simulator to model the issues regarding resource management in PON.

A.2 SIMULATION NETWORK MODEL

In order to adhere the Network Model developed to the EPON standard specifications the PON elements were structured such that the simulator flow of events coincide with state diagrams presented in the standard. Fig. 41 shows the Network Model.

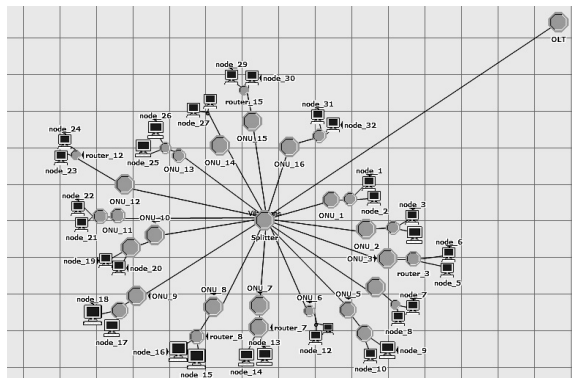


Figure 41: Simulation Network Model.

¹ OPNET Modeler Documentation

Following the modeling paradigms that OPNET Modeler implements, we defined the *network model* as the **PON** where the **ONUs**, the **OLT** and the splitter/combiner represent the *nodes model* and by the definition of the *process model*, the standard specifications are declared. Figure 42 shows the integrated framework simulator.

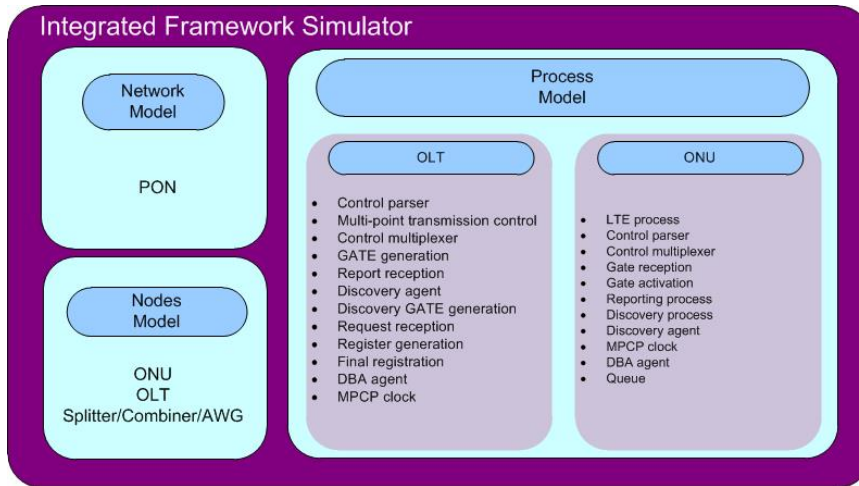


Figure 42: Definition of modeling domains.

OPNET Modeler allows creating a high level model from various processors models. At the same time, each processor contains a state machine model where each state contains the code that defines the program behavior on event successions. The following sections detail the process model of the Integrated Framework Simulator which is based on the standard specifications specifically in the **MPCP**. An overview of the standard can be found in [50].

To demonstrate the reliability of the built simulator several tests were performed. Throughout all of our research have added new features that allow the assessment of the contributions presented in previous sections, so that up to date an integrated model has been achieved considering the coexistence between 1G and 10G **EPON**, the **WDM** technology and the energy issues in **EPON**. Also, the model provides the most networks traffic flows.

A.2.1 OLT Node Model

Throughout this section it is described the processes that comprise the **OLT** Node Model, shown in Fig. 43. Hereafter we referred to modules and process indistinctly.

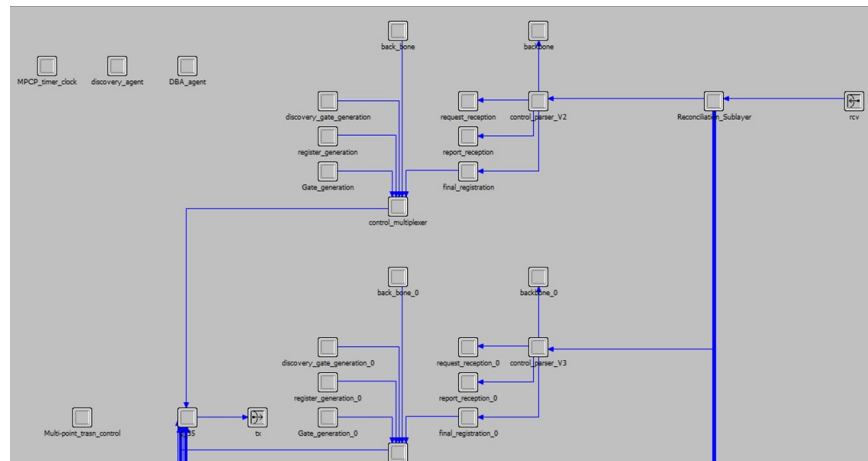


Figure 43: OLT Node Model.

A.2.1.1 Control Parser

This process is responsible for analyzing the received packets, distinguishing control messages and data messages. Moreover, this module is the responsible for calculating the **RTT** of each **ONU**. With the arrival of each message the **RTT** control is re-calculated and compared with the previous **RTT**, whether the absolute difference between these exceeds the predefined threshold an error condition which causes the invocation of the Discovery Agent module requesting the deregistration of the **ONU**.

A.2.1.2 Multi-point Transmission Control

The **OLT** is the only device transmitting in the downstream channel, however it contains as many **MPCP** instances as **ONUs** has the network. Each of these instances acts independently generating control messages and data as a result of the dynamic communication. Therefore, there must be a mechanism to regulate the transmitting each instance, with the objective of avoiding collisions and loss of packets. This process has a global view of all the **MPCP** instances and is responsible for allowing only one **MPCP** instance to transmit at any given time.

A.2.1.3 Control Multiplexer

This process has functions similar to the **ONU** control multiplexer, is responsible for prioritizing and serialize packets received, to be sent by the transmission channel once authorized by the arbitration module Multi-point Transmission Control. If the message to transmitting is a control message, this module is responsible for stamping the current time of **OLT** in the corresponding field.

A.2.1.4 *Gate Generation*

A separate instance of the gate generation process exists for each logical port at the OLT (or for each registered ONU). The gate generation process is driven by the DBA agent, which determines the start time and length for each grant issued to an ONU. Upon receiving a request from the DBA agent, the gate generation process forms a GATE message and transmits it to the ONU.

The GATE messages are also used as a keep-alive mechanism, informing the ONUs that the corresponding logical port at the OLT is functioning properly.

A.2.1.5 *Report Reception*

This module exists independently for each MPCP instance of the OLT and is responsible for receiving REPORT control messages and send the information received to the DBA agent, to plan the next transmission windows. This process has an associated timer that activated by receiving the control message, if this timer expires, causes ONU deregistration associated such instance.

A.2.1.6 *Discovery Gate Generation*

This process is responsible for generating Discovery Gate control messages indicating start time and duration of the window discovery. The Discovery Agent is responsible for invoking this module. The Discovery Gate Generation must also inform to the Register Reception process the start time and end of the discovery window, in order to receive only registration request messages arriving at the OLT within reserved time.

A.2.1.7 *Request Reception*

This module exists independently for each MPCP instance of the OLT and is responsible for receiving the REGISTER control message within the window of discovery. Once received the message invokes the Discovery Agent.

A.2.1.8 *Register Generation*

This module is responsible for generating a REGISTER control message after Agent Discovery request. Depending on the configuration of one of the bits of the control message indicates the condition of registration or deregistration, this information is provided by the Discovery agent.

A.2.1.9 *Final Registration*

This module is responsible for generating a GATE control message to one specific ONU, to grant transmission time for sending a registration confirmation message. On the other hand, is responsible for receiving the confirmation of registration issued by the ONU, and complete the registration of the same to the network.

A.2.1.10 *Discovery Agent*

The Discovery Agent is responsible for initiating rounds of discovery. Indicates when to start a window discovery, thus the ONUs not connected to the network can register. When the agent detects time of onset of a period of discovery invokes the Discovery Gate Generation to begin the process. This module is responsible for assigning logic unique identification tags to each ONU in the system.

A.2.1.11 *DBA Agent*

In this module resides the algorithm for bandwidth allocation. Upon receiving a REPORT message from an ONU, the DBA agent calculates the new GATE parameters, such as the grant start time and grant length.

A.2.1.12 *MPCP Clock*

To allow decoupling of GATE transmission time from the timeslot start time, the OLT and each ONU should maintain a local clock, called the MPCP clock. The MPCP clock is a 32-bit counter which counts time in units of time quanta (TQ). The TQ is defined to be a 16-ns interval, or the time required to transmit 2 bytes of data at 1 Gbps line rate. Correspondingly, the timeslot start times and lengths in GATE messages, as well as queue lengths in REPORT messages, are expressed in TQ.

A.2.2 *ONU Nodel Model*

Throughout this section it is described the processes that comprise the ONU Nodel Model, shown in Fig. 44.

A.2.2.1 *LTE Process*

Operation of this function relies on tagging of Ethernet frames with tags unique for each ONU. These tags are called logical link identifiers (LLIDs) and are placed in the preamble at the beginning of each frame. To guarantee uniqueness of LLIDs, each ONU is assigned one or more tags by the OLT during the initial registration (autodiscovery) phase.

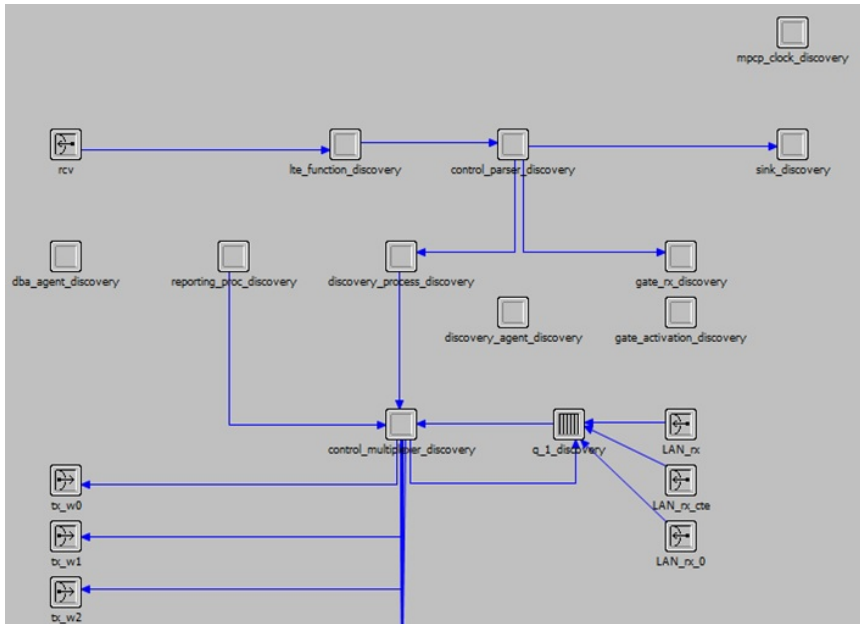


Figure 44: ONU Node Model.

A.2.2.2 Control Parser

The control parser is responsible for parsing the received frames and demultiplexing them to opcode-specific control functions, such as gating, reporting, or discovery processes. The operations of the control parsers in the **OLT** and an **ONU** are very similar, the only difference being the PARSE TIMESTAMP state.

A.2.2.3 Control Multiplexer

The control multiplexer is responsible for gating the transmission data path, i.e., for allowing the data to pass only inside the transmission window specified by a previously received grant.

A.2.2.4 Gating Process

In the **IEEE 802.3ah** standard, the gating process at the **ONU** is divided into two separate processes: the gate reception process responsible for parsing and verifying the received GATE frames and the gate activation process, which controls the **ONU** transmission timing.

A.2.2.5 Reporting Process

The reporting process is responsible for passing queue status information from an **ONU** to the **OLT**. Reports are generated by the **DBA** agent at the **ONU** and are sunk by the **DBA** agent in the **OLT**.

A.2.2.6 *Discovery Process*

The discovery process in the ONU is responsible for generating REGISTER_REQ control messages, processing the received REGISTER control message, and issuing acknowledgments in the form of REGISTER_ACK control messages.

A.2.2.7 *Discovery Agent*

This module is responsible for maintaining the status of the connection and registry. Also, is responsible for informing to the Discovery Process module the ONU request to register the system and finally notifies the end node registration to the network. Any condition of deregistration is notified to the Discovery Agent.

A.2.2.8 *MPCP Clock*

This process is responsible to increase and update the localTime variable. The localTime account in TQ units, one (1) unit equivalent to 16 nanoseconds of the "timer" simulator.

A.2.2.9 *DBA Agent*

This module is responsible for requesting the generation of REPORT control messages to the Reporting Process, at the beginning of a transmission window, for sending the ONU queues status. For decentralized DBAs, this module is responsible of perform the DBA algorithm. 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.

A.2.3 *Traffic Sources*

OPNET Modeler allows create traffic manually by setting attributes on various network objects or by importing traffic from external files or programs.

In order to obtain a realistic performance analysis, the traffic model considered in most of our simulations was self-similar. Many studies show that through self-similar traffic model, 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 Internet applications. Whenever necessary, the traffic sources have been configured differently to self-similar taking advantage of the objects attributes provided by OPNET Modeler .

To generate self-similar traffic, OPNET Modeler 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.

A.3 SIMULATION EXPERIMENTS PARAMETERS.

During the simulation experiments, the network is connected in a tree topology. The link capacity was 1 Gb/s or 10Gb/s. The experiments were performed for a network of 16 ONUs but the framework can support up to 64.

Every ONU had three separate queues with independent buffering space assigned to different classes of traffic, each with an independent buffering space. The queue length can be configured to any size, we set infinite size. We were only interested in measuring the performance of the ONUs queues as we only evaluate the upstream traffic.

The guarding interval between time slots allocated to different ONUs was equal to 2μ . Interframe Gap (IFG) between Ethernet frames was used to model the flow of frames as closely as possible to the reality. The standard value of IFG for different architectures of Ethernet networks is equal to 96 bits. A summary of experimental setup is shown in Table 25.

Table 25: Simulations Parameters

Parameters	Supported Values
Number of ONUs	8-64
Link speed	1 Gb/s, 10 Gb/s, mixed 1/10 Gb/s
Network topology	Tree
Cycle time	1-2 ms
Number queues per ONUs	1-3
Queuing Scheme	Weighted round-robin, Round-robin, Priority queuing (FCFS)
IFG	96 bits
Guard time	2 μ
Traffic source	Self-similar, CBR, VBR, Poisson
Packets size	Random, Fixed
OLT-ONU distance (d)	$18 < d < 20$ km

To set the size of the packets we use a OPNET function that provides a mechanism for obtaining a uniformly-distributed random number. The function generates a random value that is uniformly distributed in a bounded range starting at 0.0 and extending to (but not including) the specified limit. So the packet size follows a uniform distribution for random size of packets with an lower limit of 512 bits

and an upper limit of 12144 bits corresponding to the Ethernet frame.

Regarding the simulation time, due to the complexity of the simulated system and the speed at which the link was operating the duration of simulations was fairly limited. In most of the experiments the maximum simulated period of time was equal to 1 second.

The simulations have been run with several random number seeds to obtain several samples, thus determine the mean value that approximates the true mean. The confidence in simulations results is based on the T-distribution. The T-distribution resembles the normal distribution in its characteristic "bell curve" shape. However, this distribution is based on the use of the sample variance rather than the assumed or known variance. It is therefore useful for simulation studies where fewer than 30 samples are used. As the number of samples become large, the T-distribution begins to approximate the normal distribution ².

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