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1.- Dades bàsiques i resums
2.- Memòria del treball (informe científic)

Tots els camps són obligatoris

1.- Dades bàsiques i resums

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Resource Management research in Passive Optical Networks (PON)

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Resum en la llengua del projecte (màxim 300 paraules)

Las redes de acceso de próxima generación (NGAN) son la nueva forma de ofrecer servicios de banda ancha y facilitan la integración de diferentes tecnologías. Es plausible suponer que, desde un punto de vista tecnológico, la Internet del Futuro se compone de redes ópticas de largo alcance y alta velocidad, redes inalámbricas y varias tecnologías de acceso, entre las cuales, el redes ópticas pasivas (xPON) son las que prometen mayor éxito, debido a su simplicidad, bajo costo y mayor ancho de banda.

Entre las diferentes tecnologías PON, Ethernet PON (EPON) es la alternativa más prometedora para satisfacer las necesidades del operador y el usuario, debido a su costo, flexibilidad e interoperabilidad con otras tecnologías. Uno de los retos más interesantes de estas tecnologías se refiere a la programación y asignación de recursos en el canal compartido de subida.

El objetivo de este proyecto de investigación ha sido estudiar y evaluar las contribuciones actuales y proponer nuevas soluciones eficaces para resolver los problemas de asignación de recursos en las redes EPON de próxima generación (NG-EPON). Temas claves en este contexto son las futuras necesidades del usuario final, el soporte de la calidad integral del servicio (QoS) y la provisión de servicios para la optimización de flujos de tiempo real y elásticos. Este proyecto identifico oportunidades de investigación, recomendaciones y propone nuevos mecanismos asociados a la convergencia de las redes de acceso heterogéneas y por lo tanto servirá de base para proyectos de investigación a largo plazo en este sentido.

El proyecto ha servido de plataforma para la generación de nuevos conceptos y soluciones que fueron publicados en conferencias nacionales e internacionales, en revistas científicas y también en un capitulo de libro. Para los próximos meses esperamos nuevas publicaciones además de las antes mencionadas.

Resum en anglès(màxim 300 paraules)

Next Generation Access Networks (NGAN) are the new step forward to deliver broadband services and to facilitate the integration of different technologies. It is plausible to assume that, from a technological standpoint, the 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, among which, the Passive Optical Networks (xPON) are very likely to succeed, due to their simplicity, low-cost, and increased bandwidth.

Among the different PON technologies, the Ethernet-PON (EPON) is the most promising 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.

The aim of this research project is to study and evaluate current contributions and propose new efficient solutions to address the resource allocation issues in Next Generation EPON (NG-EPON). Key issues in this context are future end-user needs, integrated quality of service (QoS) support and optimized service provisioning for real time and elastic flows. This project will unveil research opportunities, issue recommendations and propose novel mechanisms associated with the convergence within heterogeneous access networks and will thus serve as a basis for long-term research projects in this direction.

The project has served as a platform for the generation of new concepts and solutions that were published in national and international conferences, scientific journals and also in book chapter. We expect some more research publications in addition to the ones mentioned to be generated in a few months.

2.- Memòria del treball (informe científic sense limitació de paraules). Pot incloure altres fitxers de qualsevol mena, no més grans de 10 MB cadascun d'ells.

Resource Management research in Passive Optical Networks (PON)

By
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Advisor: Sebastiá Sallent Ribes

A Report submitted to the
Agencià de Gestió d'Ajuts Universitaris i de Recerca

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Abstract

Next Generation Access Networks (NGAN) are the new step forward to deliver broadband services and to facilitate the integration of different technologies. It is plausible to assume that, from a technological standpoint, the 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, among which, the Passive Optical Networks (xPON) are very likely to succeed, due to their simplicity, low-cost, and increased bandwidth.

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Chapter 1

Introduction

The improvement of transmission systems and networking equipment during the last decade and the development of wireless technologies have made the Internet a worldwide network capable of providing ubiquitous, near-instantaneous broadband communications. Nowadays one of the problems of Internet is the performance bottleneck in the access segment. To address this issue a promising alternative of access networks is certainly the Passive Optical Network (PON) because of their cost-effective and high-performance benefits.

This research project was initiated as part of the Euro-NF project "Anticipating the Network of the Future - From Theory to Design" aimed at building an access and metropolitan network architecture that integrates upcoming optical and broadband wireless technologies, thereby enjoying the complementary characteristics of these technologies, so that the user will be able to access diverse communication services in a transparent manner and with a high degree of ubiquity, being able to move among different networks, while maintaining a high resource utilization efficiency.

The sustained improvement of link speeds in optical technologies (both access and transport) and the reduction of optical fiber costs have contributed to make the Internet a huge high-speed multiservice network able to seamlessly support a number of applications, from bulk data transfers and e-mail to rich real-time multimedia content or P2P. At the same time, the proliferation of wireless networks and their connection to the Internet have greatly widened its reach and added an extra degree of freedom, providing mobility and connectivity without the need for a permanent fixed infrastructure. Such an increase of bandwidth and flexibility have led to the emergence of new services and communication paradigms.

This project discoursed on optical fiber based access networks. The main goal is to design a suitable solution to control the resources in PON of high capacity. The project proposes also, the development of new tools for network dimensioning and simulation environment for the verification of the solution proposed.

This document describes the project outlook of the Ph.D student Paola Garfias, carried out inside the Telematics Engineering doctoral program offered by the Technical University of Catalonia (UPC). The research for the thesis is undertaken by the direction of Professor Dr. Sebastiá Sallent Ribes inside the research group BAMPLA, and it is supported by the Comissionat per a Universitats i Recerca del Departament de Innovació, Universitats i Empresa de la Generalitat de Catalunya and the Social European Budget.

1.1 Content Organization

The content of this document has been divided in four parts. The objectives of the project are presented in Chapter 2. Chapter 3 is devoted to present the main concepts needed to understand the problem, later in Chapter 4 the proposals that have been made to current date are summarized. Finally, Chapter 5 is devoted to present the contributions performed during this research project. At the end conclusions summarized the whole contributions and the bibliography used to elaborate this document is included.

Chapter 2

Objectives

In this Chapter the objectives of this research project are introduced giving a more detailed description of their contents. It presents the reasons of the research and the initial hypothesis which support its objectives.

2.1 Global Objective

For 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. The study of resource management in passive optical networks of high capacity represents an interesting field of research, especially regarding the Ethernet PON. At the same time, mobile communications and wireless technologies have become everyday tools, providing highly flexible communication scenarios such as heterogeneous networks that integrate optical and wireless technologies.

Considering the above, the global objective of the project is **the design and evaluation of an advanced solution for the control and distribution of resources in passive optical networks of high capacity, that optimizes the resource management to real time services and elastic flows, fulfilling the end-users requirements.**

The objective falls under the future research issues the research community is giving special attention and priority too. It is quite general and requires too many issues to be addressed. The following section 2.2 introduces the specific objectives which overall research copes with.

2.2 Specific Objectives

The global objective is divided into four research activities.

1. Next Generation Optical Access Networks.
2. Design of a resource management mechanism for NGAN.
3. Develop and deploy a simulation-emulation environment for the assessment of the proposed solution.
4. The analysis, evaluation and comparison proposals.

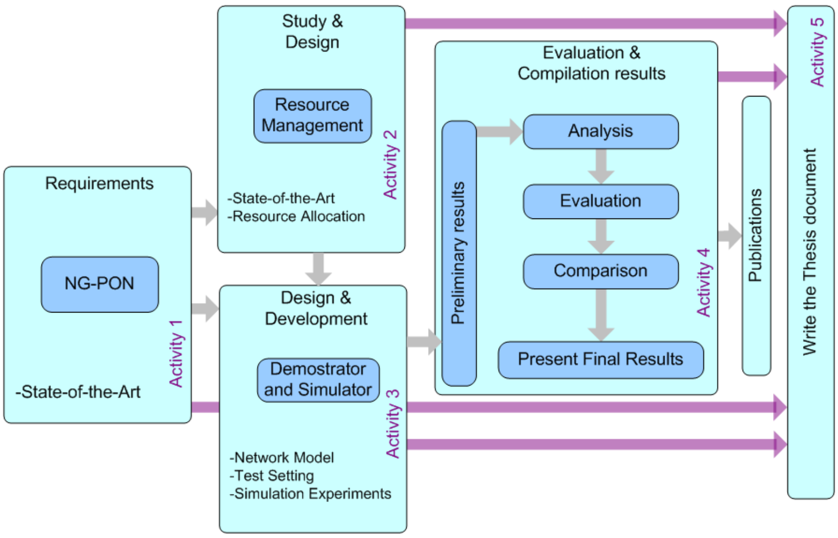

Figure 1: Activities of the project. Activities have been defined in order to accomplish the objectives

The following subsections explain details of the above activities emphasizing the specific objectives of the project.

2.2.1 Next Generation Optical Access Networks

This activity comprises different objectives such as:

- Study and definition of the requirements and scenarios where NGAN will be applied.
- Identification and design of the necessary functional entities and protocol architecture, and an analysis of its feasibility.

- Design of new access network architecture that integrate upcoming optical and broadband wireless technologies capable of offering reliable point-to-point communications in heterogeneous environments.
- Study and definition of a set of tools for network planning and dimensioning, which will be applied to design the proposed architecture network.

2.2.2 Design of resource management mechanism for NGAN

In this stage a new scheduling algorithm, which copes with the challenge of supporting NGAN functionalities for real-time and elastic flows, will be design. The objectives related to this activity are:

- Study of resource management in PON.
- Analysis, enhanced and evaluation of DDSPON algorithm.
- Design an efficient solution to resource allocation in NGAN.

2.2.3 Develop and deploy a simulation-emulation environment for the assessment of the proposed solution

In this project, the performance of the proposed resource management mechanisms will be evaluated by simulations that will include the effect of channel losses and will draw recommendations accordingly, so we build a test framework based on simulations of the proposed solution. This activity include the use of innovative tools for the network dimensioning, as well as virtualization and simulation environments to validate the proposed solutions. The objectives related to this activity are:

- Study and definition of the main tools to model EPON problems.
- Design a general EPON simulation network model.
- Incorporate new requirements and constrains to the EPON model.

The results of the above specific objectives should be tested extensively by means of an integrated framework simulator. The framework designed in this activity should complement the overall simulator of the project and aid the construction of the demonstrator of the project.

2.2.4 Analysis, evaluation and comparison

The results of the above activities should be analyzed, evaluated and validated by simulation models developed specifically for these tasks. This activity establishes the following objectives:

- Analysis and evaluation of DDSPON variations.

- Identify shortcomings of DDSPON variations and analyzed them to propose possible improvements.
- Analysis and evaluation of resource allocation proposals in NGAN.
- Carry out comparisons of the most important proposals in literature based on the above results.

Chapter 3

Background

In this Chapter the basic knowledge required to develop this research project is presented. An overview of Access Networks will be presented and the problematic will be contextualized, taking special interest in Passive Optical Access Networks.

3.1 Access Networks

To meet the application demands, service providers were moving toward wireless solutions or upgrading their existing copper infrastructure with digital subscriber line (xDSL) technologies. But, due to rate limitations of wireless and the transmission limitations of copper lines, the number and type of services offered were limited. Optical fiber technologies provide the solution for application demands, through fiber technologies the communications infrastructure becomes powerful, providing very high speeds to transfer a high capacity of data.

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 Telecom Network Overview.

Most current access networks are based on copper (mainly digital subscriber lines (DSL)) and coaxial cables. The increasing communication service demands is making these networks obsolete and, in most cases, they are being gradually replaced by optical access networks.

The most widely deployed solution in access segment today 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.

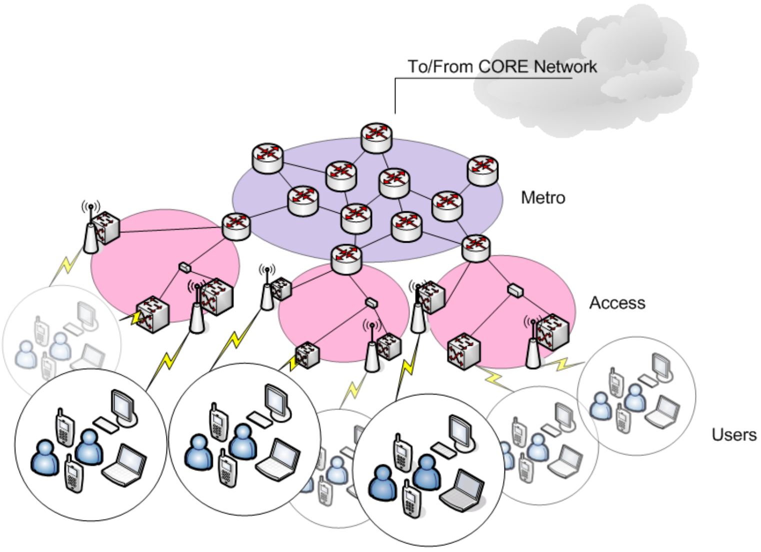

Figure 2: Telecom Network Overview.

The variations of DSL technology have been implemented to meet the needs of different users. See Table 1 for a comparison of main DSL variations.

Table 1: DSL variants [Source [1]].

Variant	Features
`The high-speed digital subscriber line (HDSL).`	It is made compatible with T1 rate of 1.544 Mbps and E1 rate of 2.048Mbps. HDSL is a better way of transmitting T1 or E1 over twisted pair copper lines. HDSL splits a 1.544Mbps signal into two twisted wire pairs which run at 784Kbps, allowing the service to run on longer loops without repeaters. HDSL uses more advanced modulation techniques than T1 and E1. HDSL does not allow standard telephone service over the same line.
`The asymmetric digital subscriber line (ADSL).`	It is the most widely deployed flavor of DSL. It uses one Plain Old Telephone Service (POTS) line and has an asymmetric line speed. The actual rate is chosen by the ADSL modem based on line conditions and anomalies. ADSL is the transmission of integrated voice and data services with higher data rates downstream (to the user) than upstream. ADSL can reach speeds of up to 10Mbps downstream and 1Mbps upstream.
`The very high-speed digital subscriber line (VDSL).`	It can have a symmetric or an asymmetric line speed. It achieves much higher speed than HDSL or ADSL, but operates over much shorter loops. VDSL provides the highest data rates of the DSL technologies, supporting asymmetric transmission speeds of up to 52Mbps over short distances. VDSL can also be configured for symmetric transmissions to provide 10Mbps full duplex Ethernet services for distances up to 1.3km.

Community Antenna Television (CATV) networks are also deployed today; they were originally designed to deliver analog broadcast TV signals to subscriber TV sets. Following this objective, the CATV networks adopted a tree topology and allocated most of its spectrum to downstream analog channels. Typically, CATV is built as a hybrid fiber coax (HFC) network with fiber running between a video head end or a hub to a curbside optical node, and the final drop to the subscriber being coaxial cable. Faced with competition from telecom operators in providing Internet services, cable television companies responded by integrating data services on top of their HFC cable networks. The major limitation of CATV architecture for carrying modern data services is a consequence of the fact that this architecture was originally designed only to broadcast analog services [1].

Single-mode (SM) fiber properties, such as low loss and extremely wide inherent bandwidth, make them the ideal candidate to meet the capacity challenges today and in the foreseeable future. This kind of fiber is often used in core and metropolitan networks, and nowadays their penetration in the access domain is increasing as well [2].

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 cable TV worlds. In DSL-based access networks, many remote DSLAMs deployed in the field use fiber-optic links to the COs. In cable TV 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. Emerging optical fiber network architectures are capable of supporting gigabit per second (Gbps) speeds, at costs comparable to those of DSL and HFC networks.

Optical fiber is capable of delivering bandwidth-intensive, integrated voice, data, and video services at distances beyond 20 km in the subscriber 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.

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 alone 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 so on. In this project, access networks are studied, focusing specially in resource allocation field.

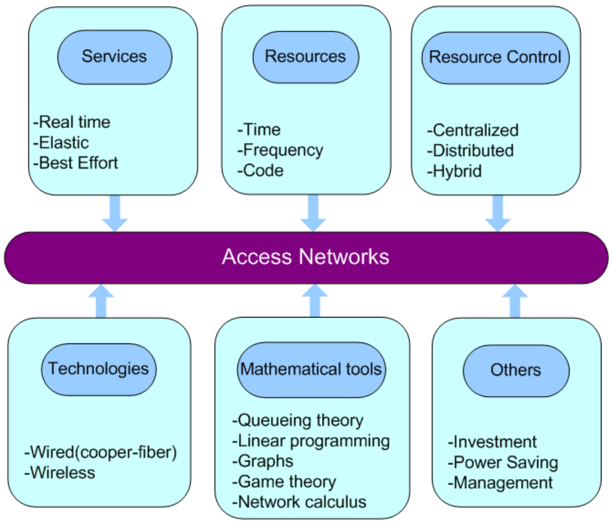

Figure 3: Access Networks Issues.

3.2 Passive Optical Access Networks

In recent years, the increase in the capacity of transport networks, together with the exponential increase in applications and services that reach residential users and small businesses, has created a bottleneck problem in the access network. Without a doubt, optical networks are presented as a necessary solution given the higher capabilities they can provide. In particular, PONs are being considered as the most promising access networks, thanks to its low cost of deployment.

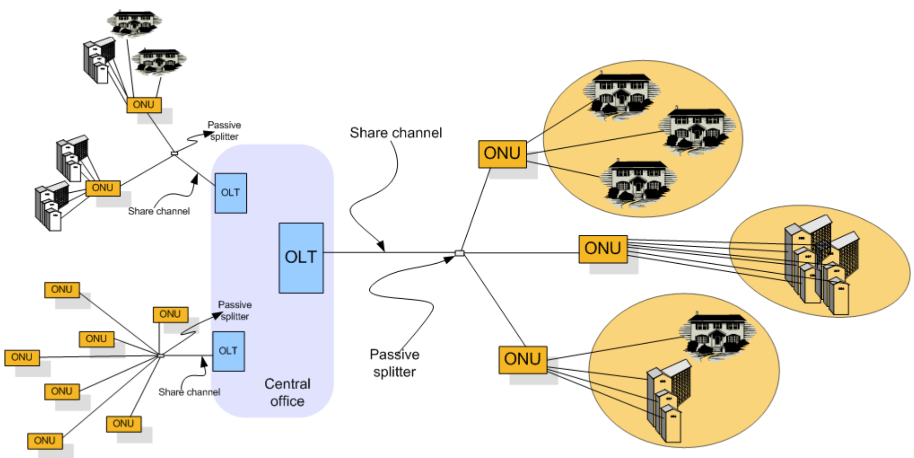

Figure 4: Passive Optical Network.

A PON is a point-to-multipoint network without active elements in the signal path between source and destination, basically formed by optical fiber and an optical splitter/combiner. This will save on maintenance costs, equipment distribution, power supply and more optimal and efficient utilization of the fiber optic infrastructure.The usage of PON technology to provide broadband connectivity to subscribers in the access network is called fiber-to-the-x (FTTx). Depending on how deep the fiber penetrates into the first mile, FTTx can be classified as show in Table 2.

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

Table 2: Optical Fiber Architectures.

FTTx	Description
`Fiber to the Premises (FTTP)`	The goal is to provide an optical fiber to each costumer premise; this type of network is commonly used in several contexts such as term for both FTTH and FTTB, or where the fiber network includes both homes and businesses. In general, the term FTTP does not restrict the type of fiber architecture used.
`Fiber to the Business (FTTB)`	In a FTTB architecture, an optical fiber is deployed all the way to the business premises. It describes a PON where the fiber arrives directly from the CO to the building (or business premises) and the signal is converted and carried to the user dependencies by using copper or coaxial cables.
`Fiber to the Node (FTTN)`	In FTTN configurations, an optical link is deployed to the cabinet located near a residential community, subdivision or business setting where the optical signal will become to an electrical signal where the services are easily transferred to existing copper facilities.
`Fiber to the Home (FTTH)`	FTTH refers to the reach of the fiber wire until the subscriber premises.
`Fiber to the Curb (FTTC)`	FTTC refers to the reach of the fiber wire until the subscriber premises, is very similar to FTTN, but the cabinet is closer to the user's premises.

A PON can be represented as tree (a) or a star topologies, but it can also support topologies such as bus (b), ring (c) and redundant configurations. Figure 5 shows the most common PON network topologies.

The key element for passive optical networks is the splitter that in one direction split a beam of light into several bundles, distributed to several optical fibers, and in the other direction it combines light signals from various optical fibers to a single optical fiber output. Another advantage of PONs, is their ability to provide high bandwidth (of the order of 1 Gbps) due to the use of fiber optic operating at a distance of around 20km. Because of its multi-point structure, it is possible to offer 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 Wavelength-division multiplexing (WDM), being a single channel tree the most common topology. The downstream channel is a broadcast channel, and the upstream channel is often shared among user devices, so their access must be arbitrated in order to avoid collisions. Each ONU transmits a burst of data that cannot be interfered by any other burst sent from another ONU.

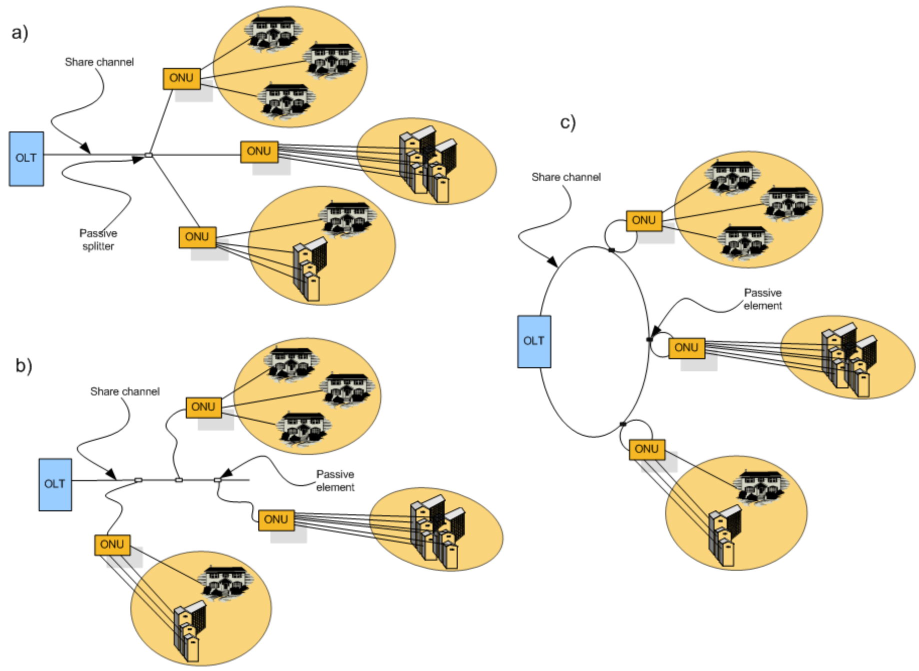

Figure 5: PON Topologies.

The communications of subscribers connected to the PON can be performed by several multiple-access techniques such as time-division multiple access (TDMA), wavelength-division multiple access (WDMA), subcarrier multiple access (SCMA) and code-division multiple access (CDMA). The Table 3 shows the main multiplexing methods in the optical domain.

There are several different PON technologies, such as the Asynchronous Transfer Mode (ATM) PON (APON) which uses ATM encapsulation of transported data. APON was followed by the Broadband PON (BPON), which offers improved and additional features such as Wavelength Division Multiplexing (WDM) support, higher upstream bandwidths and upstream bandwidth allocation; the Ethernet PON (EPON), which uses Ethernet rather than ATM data encapsulation and is highly suitable for data services; and the Gigabit PON (GPON), it is an IP-based protocol designed for IP traffic often described as combining the best attributes of BPON and EPON at gigabit rates.

Table 3: Multiplexing Methods in the Optical Domain.[Source [3]]

Multiplexing Method	Description
`Time Division Multiple Access (TDMA)`	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.
`Wavelength Division Multiple Access (WDMA)`	In this scheme, each subscriber is assigned a pair of dedicated wavelengths; this contrasts the TDMA case where a single pair of wavelengths is shared among all the subscribers connected to the PON. To accomplish this WDMA 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.
`Subcarrier Multiple Access (SCMA)`	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. The frequencies are the subcarriers, while the transmitted upstream optical wavelength is the main carrier.
`Code Division Multiple Access (CDMA)`	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.

Currently, there are two branches of standardization of PON according to the technology of layer 2 to be used: ITU-T and IEEE. The first one incorporates ATM-based such as APON and BPON (G.983.x) and is based on GFP (Generic Framing Protocol) known as GPON (G.984.x). However, the standards of the IEEE 802.3ah [4] and IEEE 802.3av [5], are those emerging as the most promising candidates for networks of broadband access for the next generation.

The features of both standards are summarized and shown in Table 4. There is a common concern that the ATM-oriented technology, BPON and GPON, performs very well when the traffic is of the real time and emulation service, i.e. T1/E1 type; while Ethernet-oriented networks perform better when the traffic is mostly composed by pure data applications, i.e. 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.

From Table 4, 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. EPON is a natural extension of the LAN systems, it bridges the gap between the LAN and Ethernet based MAN/WAN structures.

Table 4: Comparison between legacy GPON and EPON.

Items		ITU G.984	IEEE 802.3ah
MAC Layer	Service	Full services (Ethernet, TDM, POTS)	Ethernet data
	Frame	GEM frame	Ethernet frame
PHY Layer	Distance	10/20 km (logical: 60 km)	10/20 km
	Split ratio	64 (logical: 128)	64 max
	Upstream (bit rate)	155 Mbps, 622 Mbps, 1.25 Gbps	1.25 Gbps
	Downstream (bit rate)	1.25 Gbps, 2.5 Gbps	1.25 Gbps
	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
	Efficiency	95%	89%

GPON, on the other hand, has an improved capability compared to APON and BPON and is backward compatible. GPON can transport not only Ethernet, but ATM and TDM (including PSTN, ISDN, E1 and E3) traffic by using GPON encapsulating method (GEM). GPON supports several line rates in both the upstream and downstream directions. It also supports legacy ATM and packet-based transport, and it is planned to support legacy efficiently, as well as current and future services through the GEM encapsulation method, which can be enhanced to support future technologies.

3.3 IEEE Std. 802.3ah

As the PONs are considered the best choice to meet the demand for broadband requirements, and the Ethernet protocol is presented with a giant impact because of its technological advantages, Ethernet-based PON solution is an interesting, suitable and attractive opportunity to deploy PON among other kind of PONs solutions, mainly because Ethernet technology is making network managers 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.

The IEEE Std. 802.3ah introduces the concept of EPON in which a point-to-multipoint (P2MP) network topology is implemented with passive optical splitters.Ethernet Passive Optical Network (EPON) is a PON encapsulating data with Ethernet and can offer a nominal bit rate of 1 Gbps (extensible to 10 Gbps) for each channel which are defined by two wavelengths: one wavelength for the downstream and the other one for the upstream direction shared among the user devices; EPON follows the original architecture of a PON, where the DTE connected to the trunk of the tree is called OLT and it typically resides at the service provider; and the Data Terminal Equipment (DTE) connected to the branches of the tree, are 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 [4] 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.

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).

EFM covers a family of technologies that differ in media type and signaling speed, it is designed to be deployed in networks of one or multiple EFM media type(s) as well as to interact with mixed 10/100/1000/10000 Mbps Ethernet networks. EFM 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. Figure 6, shows the relationships between EFM elements and Open system Interconnection (OSI), a reference model for P2MP topologies. In [1] the author explains such standard deeply.

The Multipoint MAC Control defines the MAC control operation for optical P2MP

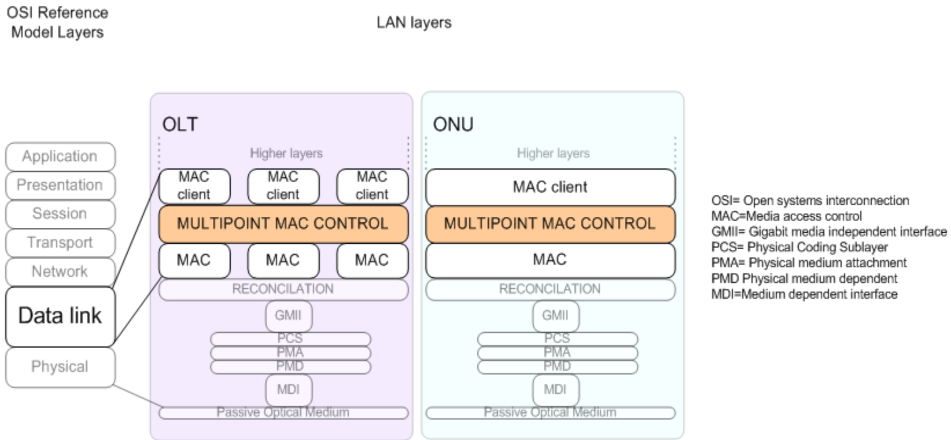

Figure 6: Relationships between EFM elements and OSI.

networks. The Multipoint MAC Control functionality shall be implemented for subscriber access devices containing P2MP physical layer devices. 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.

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

Through the Multipoint MAC Control is possible for a MAC client to participate in a P2MP optical network because that is the way to transmit and receive frames as it was a connection P2P, i.e. MAC client through the Multi-point MAC Control sublayer, which decides when a frame will be transmitted, transmits and receives frames.

3.3.1 Multi-Point Control Protocol

One of the functional blocks of the Multi-Point MAC Control sublayer, includes those related to the MPCP functions, which allow the negotiation of access to the environment through the exchange of control messages. On the one hand, the ONU may request their immediate requirements of bandwidth; and on the other, the OLT allocates the start and duration of ONU transmission. 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 ONUs is regarded as downstream; in downstream, data are broadcast using the entire bandwidth and ONUs receive frames by matching the address in the Ethernet frames, and on the contrary, the upstream communication, from the ONUs to the OLT, multiple ONUs share the common channel which means that in order to avoid data collisions only a single ONU may transmit. Figure 7 and 8 show EPON operation.

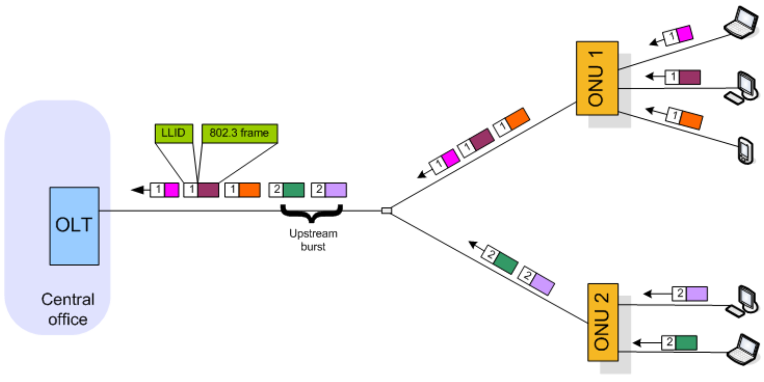

Figure 7: Downstream communication PON.

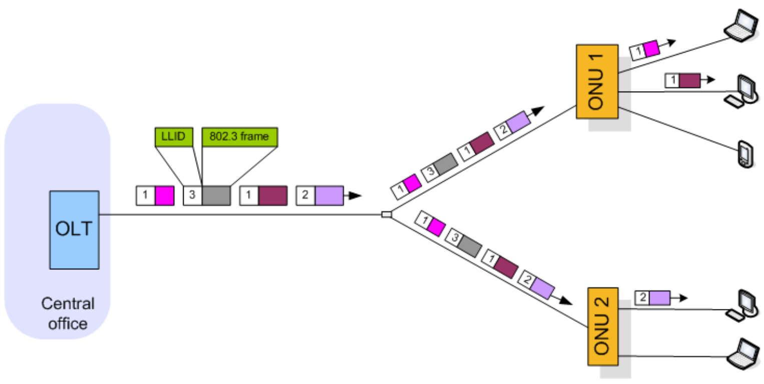

Figure 8: Upstream communication PON.

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 requested bandwidth to OLT, the OLT in turn generates discovery messages, controls registration process and allocates bandwidth. Table 5 summarizes 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,

Table 5: MPCP control messages [Source [1]].

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.

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 message, will be registered during the previously establish window, this window is unique because this is the only time when the ONUs without specific grant window are able to communicate with the OLT.

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

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

The way the OLT distributes the bandwidth depends on a medium access mechanism implemented by a dynamic bandwidth allocation algorithm (DBA), which is outside the standard and is left free to the implementation of the manufacturer, the provision of quality service is also free. For this reason, mechanisms to distribute the bandwidth are of great interest in DBA design currently, taking into consideration the quality of service parameters, as well as the improvement of the efficiency of the channel and the fairness. Chapter 4 is devoted to present a brief survey on such proposals.

3.4 IEEE Std. 802.3av

EPON and GPON represent the current state-of-the-art of commercially available optical access networks. The standardization process to specifying 10 Gbps EPON (10GEPON), was formed in September 2006 and finished the standardization work in 2009, being the major difference against IEEE 802.3ah, the physical layer resulting in a rather costly upgrade, so EPON equipment must be provide a gradual evolution in which a co-existence of 10GEPON and EPON will be implemented.

The IEEE Std. 802.3av [5] extends EPONs operation to 10 Gbps providing both symmetric, 10 Gbps downstream and upstream, and asymmetric, 10 Gbps downstream and 1 Gbps upstream, data rates. It specifies the 10 Gbps EPON Rs, PCSs, PMAs and PMDs that support both symmetric and asymmetric data rates while maintaining complete backward compatibility with already deployed 1 Gbps EPON equipment. An additional MAC Control opcode is also defined to provide organization specific extension operation.

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 Gbps in both upstream and downstream directions, and the asymmetric option will use 10 Gbps in the downstream and 1G bps upstream [6]. Thus, advance video service demands in the downstream direction is supported by means of the asymmetric option.

Transition in operation mode is a combination of 1 Gbps downstream/1Gbps upstream, 10 Gbps downstream/1 Gbps upstream, 10 Gbps downstream/10 Gbps upstream over a single fiber [7]. 10GEPON increase channel capacity for both upstream and downstream channels maintaining the logical layer such as 1 Gbps EPON, taking advantage of the already existing MPCP and DBA agent specifications.Coexistence must be mandatory to assure smooth transition that should be conducted in such a way that only small parts must be replaced [8]. Table 6 summarizes the differences between EPON and 10GEPON.

The standard pursues the objectives listed below:

- To support subscriber access networks using P2MP topologies.
- To standardize two different SM fiber data rate channels: symmetric (10 Gbps both down and up) and asymmetric (10 Gbps in the downstream channel and 1 Gbps in the upstream channel).
- To have a Bit Error Ratio (BER) better than 10^{-12} at the PHY service interface.

- To define up to 3 optical power budgets that support split ratios of 1:16 and 1:32, and distances of at least 20 km.
- To maintain a complete backward compatibility with legacy standards.

Table 6: Differences between 1G and 10G EPON.

Item	EPON	10EPON
Channel Coding	8B10B	64B66B
Data rate (DS/US)	1 Gbps/1 Gbps (symmetric)	10 Gbps/10 Gbps (symmetric) 10 Gbps/1 Gbps (asymmetric)
Upstream (λ)	1260-1360 nm	1260-1280 nm
Downstream (λ)	1480-1500 nm	1575-1580 nm
# of Power Budget Classes (PBC)	2	3
Split ratio	1:16	1:16 / 1:32
FEC	Reed-Solomon (RS) code 255,239,8 (optional)	RS code 255,223 (mandatory)

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) [9]. In terms of overhead [6] mentions that compared to 1 Gbps EPON only line-coding, control messages and frame-delineation overhead would change to 10GEPON.

The goal of 10GEPON is to upgrade the channel capacity for both upstream and downstream channels gracefully, while maintaining the logical layer intact, taking advantage of the already existing MPCP and DBA agent specifications. Furthermore, 10GEPON keeps on utilizing the analog video delivery systems before such delivery shifts gradually to an IP-based distribution system.

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 legacy EPON, the DBA is out of the scope of the IEEE802.3av standard, and thus left vendor-dependent.

Chapter 4

State-of-the-Art

In this Chapter an overview of the resource management issues along with the stat-of-the-art in EPON will be provided, taking special interest in Bandwidth Allocation. The DBA proposals in literature based on their features will be categorized, then the major contributions will be discussed.

4.1 Research in Bandwidth Allocation

To guarantee the efficiency and scalability of EPON in terms of Bandwidth Allocation, numerous contributions have been presented. There are two main strategies: the fixed bandwidth allocation (FBA), and the DBA. The first one allocates the same transmission slots to every ONU in every service cycle. It is a simple scheme but it does not perform optimally. On the contrary, the dynamic policy 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.

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

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

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

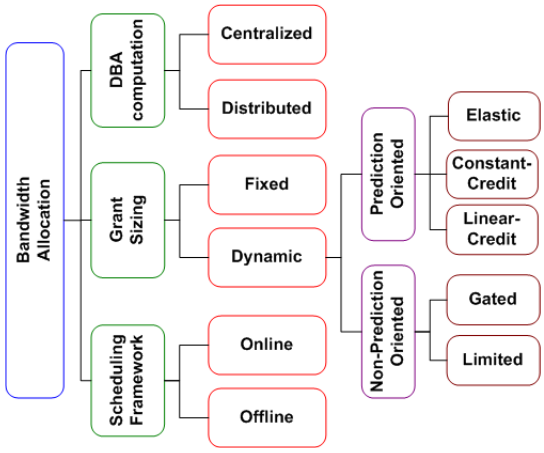

Figure 9: Badwidth Allocation Criteria. DBA algorithms proposed so far for EPONs deal with different criteria and can be categorized as shown in this Figure.

DBA algorithms proposed so far for EPONs can also be categorized based on the criteria it deals with, as shown in Figure 9. DBA algorithms may be either centralized or distributed. Besides, might be based on a prediction oriented or non-prediction oriented approaches. Prediction oriented algorithms implement some prediction of arrival packets in order to base the allocation on that estimation, thus avoiding packet delay, meeting the QoS requirements and avoiding the degradation of the network performance. Some examples of algorithms prediction-oriented are: [10–13].

The scheduling framework, determines the way scheduling decisions are made. There are two main frameworks to consider: online and offline scheduling. With online scheduling, the OLT makes scheduling decisions "on-the-fly" based on individual requests and without global knowledge of the network. On the other hand, offline scheduling requires a full knowledge of the network status, thus its scheduling decisions are computed after having received the requests from the entire ONUs [14]. In many settings, the online scheme performs better than the offline scheduling, but with less control of channel transmission times.

The IPACT [14] is one of the early works that became very popular in the literature. The cycle period adjusts to the bandwidth requirements of the ONUs, and the definition of a maximum transmission window does not allow ONUs with high traffic level to monopolize the bandwidth resource. What is more interesting in this proposal is that IPACT uses an interleaved polling approach, in which the next ONU is polled before the transmission of the previous one is finished in order to utilize the channel efficiently.

The IPACT grant sizing is performed using five different alternatives: fixed, limited, gated, constant credit, linear credit and elastic. Summarizing, the prediction-oriented DBAs are: constant credit, linear credit and elastic. The credit approach - constant or linear - grants the ONU's requested bandwidth plus an extra amount of bandwidth; while the elastic approach basically limits the maximum cycle time. The rest of the options - fixed, limited and gated- are non prediction-oriented DBAs. The limited approach allocates no more than a predefined amount of bandwidth to an ONU, the gated one grants the requested bandwidth without any limitation. Finally, the authors demonstrate that the limited discipline is more efficient than the gated one and it has been the most preferred one to compare with in the literature.

The bandwidth allocated to each ONU is guaranteed by the DBA (inter-ONU scheduling), but the QoS is guaranteed internally by the ONU the so-called intra-ONU scheduling process. The EPON follows the IEEE QoS policy defined in the standards IEEE 802.1P/Q. There are up to eight sub-queues in each ONU depending on the traffic type; the intra-ONU scheduling is of the strict type; hence, queues are served in order of priority. Such procedure does not perform optimally in light load networks, so many algorithms, such as [11,15–18] among others, propose to maximize intra-ONU scheduling.

According to the QoS policy, [19] classifies DBA algorithms into two categories: algorithms with statistical multiplexing (no QoS guaranteed), and algorithms with quality of service. The latter is further separated into algorithms with absolute QoS assurances, i.e. those that follow the integrated services paradigm; and algorithms with relative QoS assurances, which provide different QoS levels according to the traffic classes, i.e. differentiated services.

DBA algorithms introducing the support of differentiated services use strict priority scheduling. Some of the examples developed in the past can be listed: (i) in [20], where bandwidth is allocated according to traffic priority requests; (ii) in [16], which combines IPACT and strict priority queuing in order to support QoS; (iii) [21] introduced an approach that consists of distributing the fairly excessive bandwidth amongst the highly loaded ONUs. It takes also into consideration different traffic classes, so that requested bandwidth consists of high, medium and low priority; and (iv) in [17], the authors propose the division of the frame, but in this case the frame is divided into multiple subframes according to the different traffic classes, in order to reduce the delay of high priority and medium priority classes; the size is variable depending on the request, and through the definition of weights for each class, it is possible to avoid bandwidth monopolization. The aforementioned algorithms are the main contributions regarding DBA with differentiated QoS support; more references can be found in [22].

4.2 Next Generation Optical Access Networks

While the current backbone networks support high capacities, the last mile for the access network remains a bottleneck. New standards allowing the upstream/downstream channel line rate to 10 Gbps. But the more important step toward NGA is the implementation of the WDM technology.

There are huge research efforts worldwide in order to develop metro and access networks based on WDM, using either DWDM or CWDM. Nowadays, the research is focused on improving the optical devices as well as in developing new architectures to handle the multi-wavelength channel efficiently. Such solutions are not only based on the type of network -such as WDM-PON or 10G PON- but also on hybrid technologies. Furthermore, the new goals are directed to support scalable networks and to help the coexistence between legacy and NGA.

Moreover, incumbent operators are interested in the so-called Long Reach-PON (LR-PON) that will help the growing process of PON deployment. LR-PON is a very cost-effective solution because the CAPEX and the OPEX of the network are lower mainly due to the fact that the number of equipment interfaces, network elements, and intermediate nodes are reduced.

The new Internet media services, such as symmetrical real time applications, video-conferencing and broadcast, among others, followed by the new type of communications, like P2P or multipoint-to-point, increase drastically the end-user bandwidth demand. This bandwidth has an exponential growth that should cope with deployments of NGAN. The evolution of legacy PON technologies (GPON/EPON) should provide huge network resources and cost-effective solutions to fulfill the new user applications and network provider demands. Requirements of Long-Reach NGA are listed below:

- To extend the geographical reach to a minimum of 100 Km.
- To increase the split ratio up to 128 or more, reducing the cost per subscriber.
- To increase the downlink and uplink throughput (evolution to 10 Gbps).
- To be transparent or compatible as much as possible with current legacy PONs.
- To reduce the CAPEX and OPEX (operation, deployment, and maintenance).

Finally, it is also desirable for NGAs to be deployed in a reasonable temporal horizon, 2010 to 2015, using available technologies (lasers, APD, amplifiers, new modulation schemes). Several proposals are being launched by the standardization bodies (mainly ITU and IEEE), as well as research projects and position research papers. However, few approaches cover the previous requirements in their totality. The Long Reach Optical Access Network (LROAN) objective is to increase the reach of Optical Access Network under a common umbrella. It was proposed as an extension of the PLANET ACTS project, developed in the late 90s with a split ratio of 2048 users over 100 Km at 2.5 Gbps downstream rate, and 311 Mbps upstream rate [23].

The next generation PON concerns two ways of updating PON: The first approach refers to employ multiple wavelengths between OLT and each ONU, and the second approach suggest an enhancement of EPON to run at higher speed.

4.2.1 Hybrid Optical and Wireless Access Networks

The attractiveness of ubiquitous access and the rapid progress in wireless technologies is making radio based communications more attractive for access networks. For broadband access, the most interesting options available nowadays are IEEE 802.16 (WiMAX) and IEEE 802.11 (Wi-Fi), which offer maximum transmission rates of several tenths of Mbps at present. WiMAX has a maximum range of 15 Km and the typical range of Wi-Fi is around 100 m. The IEEE 802.11n have maximum user data rates above 100 Mbps (several hundred Mbps are expected).

There exist few contributions in literature about the integration of present optical networks and wireless technologies in the metropolitan and access segments. Four architectures for the integration of WiMAX and EPONs can be found in [24], where the optical network functions as backhaul to connect multiple WiMAX base stations. The common characteristic of these architectures is that the ONU and the WiMAX base station are integrated in a single piece of equipment that matches the QoS support mechanisms in both technologies. There are also proposals for Metro and Access Rings Integrated Network, with QoS-aware scheduling schemes employing priority queue for both metro and access traffic for effective differentiation of classes of services and avoiding contention in the metro segment [25].

Another work introduces a hybrid network architecture named WOBAN, composed of optical backend and IEEE 802.11-based front end [26]. The optical network can be supported by PON and the wireless portion may employ technologies such as WiFi (IEEE 802.11a/b/g) or WiMAX. The authors highlight the challenges in the deployment of such hybrid architecture and discuss station placement and routing issues in hybrid PON-wireless access networks. Progress in the design of future (beyond TDM-PONs) optical access networks is closely related to its integration with wireless technologies, as discussed in [9]. In fact, research directions point at architectures that contemplate WDM-PONs functioning as backhaul for WiMAX and IEEE 802.11n, where WiMAX links could form multihop wireless networks (mesh networks) and the IEEE 802.11n technology could provide connectivity at hot spots.

The future evolution of access architectures is also tightly related to the changing user needs. It is becoming usual to find mass-consumer devices with multiple network interfaces. Also, radio coverage is becoming dense and ubiquitous, not only due to the amount of accumulated investment so far but also due to the ease of access to technologies. These scenarios pave the way to everywhere connectivity and high mobility. Such pervasive connectivity will increase the expectations of the regular user that, beyond simple connectivity, will want high Quality-of-Experience (e.g., minor service disruptions or smooth video calls).

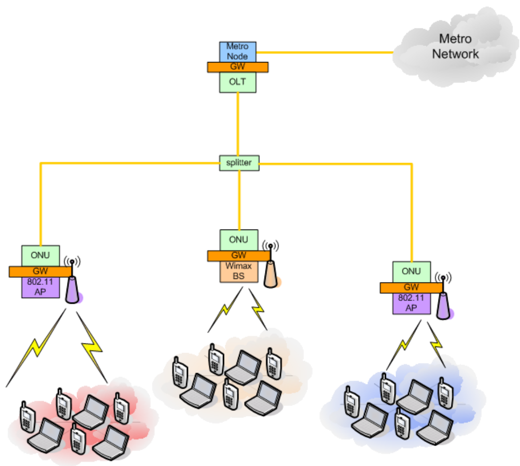

Figure 10: Hybrid Network Architecture

Integration of PON and wireless technologies are presented as a promising architecture for NGAN. Figure 10 shows a hybrid optical wireless network. In EPON an OLT communicates with multiple connected ONUs via a passive optical splitter, in wireless domain a Base Station (BS) manages channel allocation to Subscriber Stations (SSs) using a poll/request/grant scheme. In the hybrid optical wireless network, ONU functions and BS functions are integrated into a single device, namely an Gateway (GW), which handles connections within the wireless network or cross both EPON and wireless network.

The control planes of EPON and wireless network can be merged into an integrated control plane, which offers optimal control solutions in admission control, scheduling, signaling, according to the overall network information.In terms of DBA mechanisms, it continues being relevant because of the integration of PON with other technologies introduces new challenges to DBA definitions. Both EPON and wireless technologies are based on a similar request and grant mechanism which facilitates the integration of bandwidth allocation. In terms of QoS support, since each of one allows traffic classification, EPON also allows different priority queues in each ONU, while wireless such as WiMAX, classifies traffic into different QoS levels that can be strategically combined to provide an efficient QoS support.

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

4.2.2 WDM-PON

WDM-PON is the application of WDMA that uses individual wavelength for each PON network. 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.

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

Different architectures have been proposed for WDM-PONs. A simple one creates a P2P link between the OLT and each ONU, therefore each ONU can operate at a different bit rate or even more, different services may be supported by wavelength.

In the P2P, no dynamic bandwidth allocation mechanisms are needed. The P2MP uses a WDM/TDM, achieving high resource utilization efficiency. To provide higher bandwidth in PONs, a WDM technique can be performed incorporating multiple wavelengths in either the upstream or downstream direction, so a WDM-PON has many advantages such as increasing network capacity in terms of bandwidth or user scalability.

Using WDMA many of the time-sharing issues can be eliminated in a TDMA system. WDM-PON provides an optical P2P connection by allocating a pair of bidirectional wavelengths to each user connected to the PON. The only difference in the outside-fiber plant is the optical-power splitter in a TDM-PON has been replaced with an AWG to demultiplex the downstream wavelengths and multiplex the upstream wavelengths [3].

At the same time, the ONU/ONT in a WDM-PONs are classified as colorless or colored. In the former one, the optical user terminal is wavelength-seeded from the remote OLT located in the central office, using the same wavelength path for downstream and upstream channels. In this case, the upstream optical flow is modulated using FSK, inverse return-to-zero (IRZ), or intensity modulation (IM) [27], [28].

Such device is the preferred one because network management is gracefully reduced. The splitter is replaced by a wavelength selective filter, implemented with an arrayed waveguide grating (AWG) when the ONU is color-sensitive and the communication mode is of the P2MP type. Long reach WDM-PON is feasible using low-loss AWG - in this case, the link budget is 28 dB, the splitting ratio is up to 64, and the reach increases to up to 80 km. The reference [29] explains largely the current WDM technology.

A proposal for a long-range architecture was implemented by the ACTS (Advanced Communications and Technologies and Services) project, called Photonic Local Access NETwork (PLANET) [23]. The splitting factor was 2048 with a span of 100 km in the PLANET project. The span comprehends a maximum feeder length of 90 km and a drop section of 10 km.

The transport system supported on this SuperPON architecture was based on an asynchronous transfer mode (ATM) cell. A bit rate of 2.5 Gbps was distributed to the optical network units (ONU) by time-division multiplexing (TDM) in the downstream direction, whereas a time-division multiple access (TDMA) protocol was used to share the 311 Mbps upstream bit rate. In order to compensate the fiber and splitting ratio losses, some optical amplifiers were housed in optical repeater units (ORUs), located at the feeder section and between the feeder and the drop sections.

Another related proposal on LR-PON is the SuperPON architecture based on GPON by British Telecom. This was GPON over 135 km compliant with the standards of ITU-T. The channels are 2488 Gbps downstream and 1244 Gbps upstream, using 1490 nm and 1552.924 nm wavelengths.

Advanced dense-wavelength-division-multiplexing (DWDM) equipment is used to extend the physical reach and to provide fiber gain. Each wavelength can support a split of 64 (1 x 8 followed by 1 x 8), so that a fully populated system could support 2560 ONUs. The combined loss of the splitters and the last 10 km of the fiber is 23 dB.

The Hybrid DWDM-PON [27] by University College presents the extension in the reach toward 100 km and an upstream bit rate of 10 Gbps. It can potentially support 17 TDM PONs operating at different wavelengths - each with up to 256 customers, giving an aggregate number of 4352 customers in total. It uses 100-GHz channel spacing, and divides the C-band into two, with one half (1529-1541 nm) carrying downstream channels and the other (1547.2 - 1560.1 nm) carrying upstream channels.

Further implementations using DWDM in the backhaul to increase the fiber efficiency are demonstrated in the EU project PIEMAN [30]. In this architecture, the network has a 100-km reach with a 32 wavelength DWDM backhaul. Each 10 Gbps wavelength is uniquely allocated to a PON with a 512-way split, enabling the network to support (32 x 512) up to 16,384 users with an average bandwidth of $\sim$20 Mbps. By using dynamic bandwidth allocation and 10 Gbps - components in the ONU, it is possible for each user to burst at 10 Gbps.

One promising WDM-PON network, is the so-called SUCCESS network [31]. The SUCCESS-HPON architecture is based on a topology formed by a collector ring and several distribution stars connecting a central office (CO) and several optical networking units (ONUs). It uses Coarse WDM (CWDM) and dense WDM (DWDM) technologies. Each ONU has its own dedicated wavelength for both upstream and downstream transmissions on a DWDM grid to communicate with the OLT. The communication is a half-duplex communication - the tunable transmitters at the OLT are used for both downstream and upstream modulated frames by ONU.

Furthermore, a scheduling algorithm has been developed to keep track of the status of all shared resources and arrange them properly in both time and wavelength domains, including the control for both tunable transmitters and tunable receivers. The research is also focused on the evaluation performance of two scheduling algorithms: 1) batching earliest departure first (BEDF); and 2) sequential scheduling with schedule time framing (S3F). Lastly, there are also important investments in optical technologies in Europe.

The current FP7 framework of the CE launched in 2007 funds several projects related to optical technologies. Amongst others, is interesting to consider the project called Single-fiber Advanced Ring Dense Access Network Architecture (SARDANA) - its goals are quite ambitious: up to 1024 users per PON, 10 Gbps data rate, remote passive amplification and wavelength-agnostic customer equipment. Finally, it also aims to score well in traffic balancing, as well as being highly scalable and allowing cascading [32].Table 7 shows a summary of Long Reach-PON projects.

Table 7: Long Reach-PON projects.[Source [33]]

Project	Reach(km)	#λ	Dw/Up (Gpbs)	#ONTs
`PLANET`	100	1	2.5/0.311	2048
`Super-PON`	100	17	10/10	17*256=4352
`PIEMAN`	100	32	10/10	32*512=16384
`SUCCESS`	25	4*16	1.25/1.25	4*16
`SARDANA`	100	1	10/10	1000

The new challenge for WDM-EPON is to allocate bandwidth to ONUs in both time and wavelength domains, maximizing the whole network efficiently. Therefore, DBA algorithms initially designated for EPON require modifications to exploit the multichannel architecture. The bandwidth management problem can be split into two sub-problems: grant (bandwidth allocation) and grant scheduling (wavelength selection). Such algorithms hereinafter are known as Dynamic-Wavelength and Bandwidth Allocation (DWBA).

Grant sizing is not analyzed anymore because none of the aforementioned DBAs may be used. Instead, two main approaches cope with grant scheduling by improving a former DBAs, e.g. SIPACT [34], or developing new mechanisms for instance, applying a well-known scheduling theory [35]. The backward compatibility of the MPCP is mandatory, but some extensions to the MPCP must be considered to deal with the wavelength discovery and scheduling.

The reference [36] introduces the concept of just-in-time (JIT) which is a hybrid scheduling framework between offline and online. 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 online 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 that support different wavelengths.

The approach of selecting the wavelength by using the scheduling theory seems a much better policy [36], e.g. Shortest Path First (SPT), Longest Path First (LPT), and Least Flexible Job First (LFJ) amongst others [35]. 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.

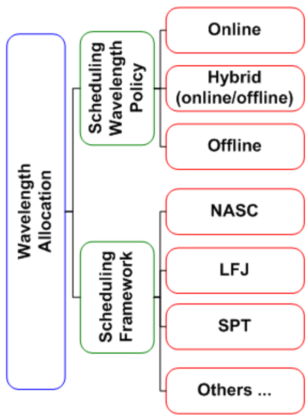

Figure 11: Wavelength Allocation Criteria.

As an evolution of IPACT in WDM, some variants of IPACT are addressed in different proposals, e.g. in [37]. The authors propose an algorithm called WDM IPACT with a single polling table (WDM IPACT-ST). The grant scheduling is of the 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 [34], 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 (amongst different wavelengths), simultaneously but depending on the set of wavelengths supported by each individual ONU.

The authors in [38] presented several DWBA 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 the fly" (online) mechanisms. Simulations performed showed that such approach presents a better throughput and delay performance.

Finally, the recent proposal [36] addressed the queuing delay and channel utilization through the scheduling theory, which is concerned to scheduling a set of jobs with specific processing times to be executed on a set of machines. In this case, the ONUs represent the jobs, the grant size is represented by the processing time, and the channels are represented by machines.

4.2.3 CDMA-PON

Optical code division multiple access (OCDMA) PONs have been considered an alternative solution for residential access. In OCDMA, an optical code represents a unique source node and signs each transmitted bit. The destination node decodes the transmitted bit by applying the same optical code. The performance of OCDMA systems is severely limited by two major issues: (i) optical and electrical (photodetector) noise such as beat noise and shot noise, and (ii) multiple access interference (MAI) [39]. Some relevant aspects of OCDMA following the point of view of [40] are presented in Table 8.

An interesting research avenue for next-generation WDM-PONs is the use of Optical Code (OC) techniques to enable advanced management and control functionalities. Beside fault detection and localization, OC techniques enable enhanced real-time DBA algorithms in PONs.

The PON in which the passive components potentially reduce the operation and maintenance expenses is a P2MP transport network. It is very similar to the concept of optical code-division multiple-access (OCDMA) technique. In OCDMA-PON each subscriber channel is allocated with a unique address code for data encoding-decoding. This scheme is an excellent approach to cost-effective, simple and noise reducing network architecture due to the spread spectrum properties [41].

OCDM is a multiplexing procedure through which each communication channel is distinguished by a specific optical code rather than a wavelength or time-slot. An encoding operation optically transforms each data bit before transmission. At the

Table 8: OCDMA Strengths and Challenges.

	OCDMA
Strengths	-Network operation and management are greatly simplified. Ideally, no channel control mechanism (such as a Medium Access Control protocol) is required to avoid collisions or allocate bandwidth. -No synchronization scheme or scheduling algorithm is required, eliminating an important source of processing and overhead in TDMA-based systems. -OCDMA supports a larger number of users than TDMA or WDMA, especially 2D-OCDMA systems where codes exploit both time and wavelength dimensions. -OCDMA access systems may accommodate additional users with less cost and complexity. A new TDMA or WDMA user reduces free bandwidth irreversibly, thus requiring changes to bandwidth allocation. -In OCDMA, adding a user does not reduce the bandwidth of other users. By virtue of its inherent bandwidth and quality fairness, OCDMA avoids the complexity of measures such as admission control.
Challenges	-The main drawbacks to OCDMA deployment reside in the physical layer. OCDMA implementations span a large array of disparate optical and optoelectronic component technologies. -In OCDMA, MAI exacerbates two major types of noise: beat noise and shot noise. WDMA and TDMA do not suffer as much from those physical impairments. -Component cost and complexity are key issues in OCDMA system design. For instance, the tunability of encoders and decoders represents a significant challenge compared to tunability of WDMA transceivers

receiver, the reverse decoding operation is required to recover the original data. The encoding and decoding operations alone constitute optical coding. OCDMA is the use of OCDM technology to arbitrate channel access among multiple network nodes in a distributed fashion [40].

There are few contibutions of PON based on CDMA and most of them try to meet the problems at the physical level, in order to suppress the beat noise coming from the interference generated in the detection of OLT optical receiver, when the diode-laser of different ONUs transmit at a wavelength that is not perfectly centered in the corresponding wavelength, which is degraded further when the light intensity increases.

OCDMA has considerable potential on the networking level. A well-designed OCDMA access network eliminates channel contention. In other words, provided interference is controlled, an upstream or downstream connection can be established asynchronously with no collisions or blocking.

Chapter 5

Resource Management in EPON (proposals)

Resource management in communication networks is defined as the set of functions that guarantee the allocation, scheduling, control and use of networks resources.This means, that a connexion specifies a certain level of QoS based on the amount of request resources and submits a request for the resources to the network manager. The negotiation process in EPON was specified in the MPCP control protocol, reviewed in Chapter 3. Figure 12 shows the resource management issues in EPON.

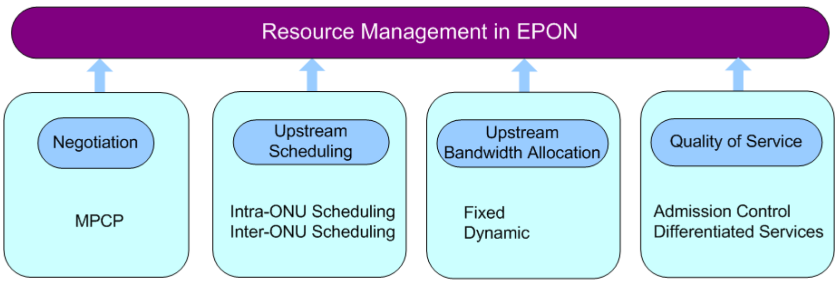

Figure 12: Resource Management Issues

One of the main challenges of a TDM-PON is to schedule the transmissions and the bandwidth allocation in the upstream shared channel efficiently. The issue of developing appropriate scheduling algorithms is an important topic of research. Goals of a resource management solutions are: be efficient; support the QoS of each traffic flow requirements; allocate fair bandwidth to users reducing delay and jitter; and finally, it must be computationally simple.

In addition to bandwidth allocation and service differentiation an admission control to support and protect the QoS of real time traffic is required. There exist few contributions in literature about the admission control in the access segment. An admission control algorithm makes decision on whether or not to admit a real-time traffic, thus an appropriate admission control will prevent malicious users from manipulating the upstream channel by sending traffic more than their service level agreements (SLAs).

5.1 FI-WI: Future Integrated Access Architecture Based on Optical and Broadband Wireless Technologies

Within the Euro-NF project "Anticipating the Network of the Future - From Theory to Design" the FI-WI research envisioned a future metro-access architecture that comprises Optical Burst Switching networks that feed Ethernet Passive Optical Networks (PON) or upcoming Wavelength-Division Multiplexing PON, which in turn feed IEEE 802.16 and IEEE 802.11 nodes.

To maintain cost and resource efficiency, we proposed the introduction of Quality of Service (QoS) proxies at the border between different link technologies. These entities handle QoS requirements and aid to the support of mobility. The architecture requires no modification of the Medium Access Control mechanisms of the different technologies.

This is a highly scalable solution, since adjacent QoS proxies exchange signaling information, thereby allowing fine admission control and providing useful information to the data schedulers in the different network nodes for handling heterogeneous services.

Within the issue of end-to-end QoS support, we have considered two separate scenarios: 1. An EPON that feeds WiMAX base stations. 2. An EPON that feeds WiMAX base stations and is fed by an OBS network.

In Scenario 1, we have came up with a novel MAC mechanism in the EPON that uses the anticipated knowledge that the WiMAX base station has on the resource needs for real-time periodic data flows in order to improve resource allocation amongst different ONUs. We incorporated the novel mechanism to the already implemented model of EPON in order to predict the performance improvement.

In Scenario 2, we have designed a novel MAC mechanism in the EPON that uses padding bits of the MAC control frames in order to make upstream frames that are intended for the same OBS burst (i.e. same traffic class and OBS destination node) arrive consecutively at the OLT-OBS interface. We obtained results that show that the OBS burst sizes are significantly increased with negligible increase of average access times. At present, we are implementing the model with OPNET in order to assess the performance of the model with different traffic load, traffic classes and burst assembly criteria (time/size).

The FI-WI project perfectly fits the scope of EuroNF, since the main target of the project is to propose and evaluate convergent network access technologies to support seamless and effective communication in the future Internet. FI-WI has served as catalyser for the research activities, in particular having introduced the concept of QoS proxy and developed novel MAC mechanisms in the QoS support scenarios mentioned above.

5.2 DDSPON

The Distributed Dynamic Scheduling for EPON (DDSPON) [42] is a DBA algorithm developed by some of the members of the BAMPLA research group. DDSPON proposed that active ONUs were responsible of managing transmission times for the upstream channel, while reporting to OLT about such allocation. OLT continues having control of the channel because centralized allocations through the gate message complies with MPCP protocol. 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 allows ONUs to compute its transmission window size. Such parameter represents a proportional weight set up according to each ONU's guaranteed bandwidth agreement. The ONU computes the required bandwidth (Ri) and its current weight ϕ_i, then reports such value to the OLT in a report message. The interleaving polling mechanism is applied here as well as IPACT [14] does [see Figure 13].

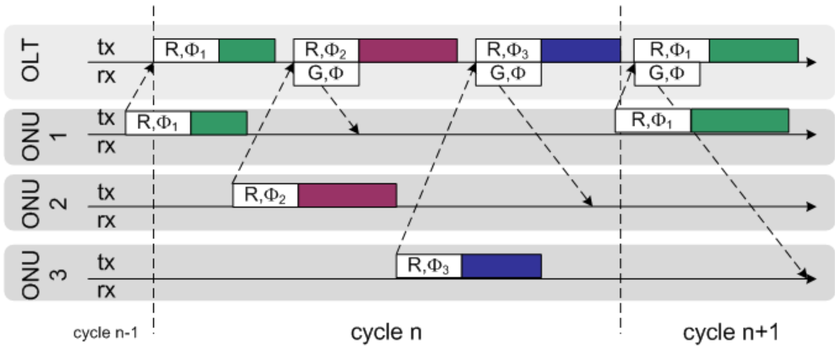

Figure 13: Interleaving Polling Mechanism. In DDSPON the interleaving polling mechanism is also applied (as well as IPACT), but the size of the transmission window for the ONU is calculated by each respective ONU. This figure illustrates the interleaved polling mechanism perform by DDSPON.

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 ϕ,which can be sent through the gate message in an available header field.

Weight vector facilitated by OLT to each ONUs represents a portion time in the transmission window, this vector is updated by each ONU through the report messages, so an additional parameter in the message is included. Each ONU has a fixed weight according to its guaranteed bandwidth agreement.

In a PON system,N is the total number of active ONUs, each ONU$_i$ have a predefined (nominal) weight ϕ_i, it is used to define ONUs transmission window size as the equation below.

$$W_i = \frac{\phi_i}{\sum_{j=1}^{N} \phi_j} W_{MAX} \tag{1}$$

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

Bandwidth allocation in DDSPON is as follows: OLT receives a report messages from ONU$_i$, it contains the requested window size ($R_i(n)$) and the weight (ϕ_i) for cycle , thus OLT updates its weight vector for cycle and send a gate message to ONU$_i$ in which allocation corresponded to the requested bandwidth.

Gate messages also include the weight vector (ϕ), once an ONU receives gate message transmit data in queue up to the transmission window allocated, then takes the weight vector (ϕ), sets its own weight to the nominal one (ϕ_i), and calculates a maximum window size that such ONU can take on next cycle $n + 1$:

$$W_i(n+1) = \frac{\phi_i}{\sum_{j=1}^{N} \phi_j(n)} W_{MAX} \tag{2}$$

Also, ONU calculates its require transmission window size:

$$R_i(n+1) = min(W_i(n+1), Q_i) \tag{3}$$

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

$$\phi_i(n+1) = \frac{R_i(n+1) \sum_{j=1}^{N} \phi_{j(n)}}{W_{MAX}} \tag{4}$$

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

Notice that each ONU schedules the size of its transmission window dynamically. DDSPON is executed in an online framework because the scheduling process is executed without the need of waiting for the reports from the rest of the ONUs. Moreover, by getting the weight vector, each ONU is able to get an idea of the rest of the ONUs' loads, which is characteristic in offline DBAs.

Preliminary comparative results between DDSPON and IPACT were obtained by event-driven simulations using the OPNET Modeler simulator [43], [33]. Results show that the DDSPON remains stable against IPACT with the variation of distances, and the most remarkable is that DDSPON presents significant improvements versus the IPACT in all simulations performed, being more relevant in highly loaded scenarios.

Moreover, a very interesting feature of the DDSPON is that the transmission window (R_i^{n+1}) is adjusted to an exact number of Ethernet frames rather than wasting upstream bandwidth because the last Ethernet packet does not fit in the window allocated to such ONU. Such adjusted value $R_i^{ADJ,n+1}$ is given by:

$$R_i^{ADJ,n+1} =_m^{upper} \left(\sum_{k=1}^{m} Q_k \right) \leq R_i^{n+1} \tag{5}$$

It is remarkable that such adjustment would only be possible in a distributed algorithm such as the DDSPON but not in centralized ones. Simulations shows that such feature is not negligible at all and more than 3% of the overall upstream bandwidth might be saved in heavy loads.

These simulations considered an ideal channel and identical network parameters. To be more accurated, the distance parameter was modified through the different scenarios of simulations from long (20 km) to short distances (5 km), and the traffic model considered was self-similar in order to obtain more realistic results. The performance was evaluated by computing packet delay, average queue size and throughput for different setting scenarios from low to high offered loads.

5.3 DBA coexistence in 1G and 10G EPON

The Next Generation Access Networks (NGAN) are the new step forward to deliver broadband services and to facilitate the integration of different technologies.

The real challenge faced by 10GEPON new standard IEEE 803.3av is to upgrade the channel capacity for both upstream and downstream channels gracefully, while maintaining the logical layer intact ensuring the coexistence with legacy 1 Gb/s (IEEE 802.3ah).

The DBA for the upstream shared channel is a key issue. We propose in this work [44] an improvement of DDSPON- that allows the coexistence among both standards in such mixed architecture. In particular, we remark that, by using the enhanced DDSPON, the new standardized optical network units (ONUs) will take full advantage of the enhanced rate at 10 Gb/s while the legacy 1 Gb/s ONUs keep a good performance, and thus allowing a fair coexistence of both group of ONUs -legacy and 10 Gb/s-, and even though the individual performance is maximized, no matter the group being evaluated.

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 1G to 10G EPON.

Let us extend the DDSPON algorithm to a mixed plant composed by different group of ONUs at 1G (N_{1G}) and at 10 G (N_{10G}) ONUs. The value of BW_{max} is computed:

$$T_{max} = \left(T_g + \frac{BW_{1G} * 8}{1 * 10^9} \right) * N_{1G} + \left(T_g + \frac{BW_{10G} * 8}{1 * 10^9} \right) * N_{10G} \qquad (6)$$

To illustrate this equation, let us consider the following initial values of $N_{1G} = N_{10G}$ $= 8$, ($N = 16$); $T_{max} = 1$ msec and $T_{guard} = 2\mu$sec; and equal initial weights.

The maximum throughput is $BW_{1G} = BW_{10G} = 110$ Mb/s to any ONU no matter if we consider 1G ONUs or 10G ONUs. Therefore, such setting is not fair at all because although 1G ONUs have better throughput they would have in a single 1G EPON which is usually about 60 Mb/s , the throughput of the 10G ONUs is heavily penalized because in a single 10G plant should be about 605 Mb/s instead of 110 Mb/s.The overall throughput in such mixed setting is enhanced to a rate only about 1.76 Gb/s, and the transmission times are T_{1G} = 10*T_{10G}.

To allocate the bandwidth to each set of ONUs deserve we simply proposed balancing the initial weights. Let us define ϕ^c_{1G} and ϕ^c_{10G} the weights of 1G ONUs and 10G ONUs respectively, its balanced weights should be computed as follows:

$$\phi^c_{10G} = 10\phi^c_{1G} \tag{7}$$

$$N_{1G} * \phi^c_{1G} + N_{10G} * \phi^c_{10G} = 1 \tag{8}$$

Equations 7 and 8 yields the values of $\phi^c_{1G} = 0.01136$ and $\phi^c_{10G} = 0.11364$. Simple computations yields to a throughput of $BW_{1G} = 60.5Mb/s$, while $BW_{10G} = 605Mb/s$ and the overall throughput of the upstream channel is about 5.324 Mb/s.

Therefore, in such mixed plant the single upstream TDM channel is shared among both groups of ONUs fairly, each ONU is allocated with exactly the bandwidth they will be allocated in a single plant without any penalization because being in a mixed plant.

In such setting the transmission time are the same $T_{1G} = T_{10G} = 0.484$, and the throughput $BW_{1G} = BW_{10G} = 10 * BW_{1G}$ as expected. Of course, we might balance the values of ϕ^c_{1G} and ϕ^c_{10G} to any other combination and the throughput allocated to each group of ONUs varies accordingly.

The delay is also an important parameter to evaluate the performance of a DBA. We define the delay in multi-access channels as the time elapsed since the packet arrival until it is transmitted to the upstream channel. We consider the steady-state average values and we decompose the overall delay (D) in three components:

$$D = W_{poll} + W_{grant} + W_{queue} \tag{9}$$

Where

- W_{poll}: Time between the packet arrival and the REPORT, on average $W_{poll} = T_{max}/2$.
- W_{grant}: Time between the REPORT and the beginning of the transmission window, this delay may span 1 to several cycles depending on the queue size.
- W_{queue}: Delay since the beginning of the transmission window till the packet is finally transmitted, on average is $W_{queue} = T_{slot}/2$, which is a negligible value compared to the other components.

The most important delay in heavy loads, when queue size is quite big, is W_{grant}, because new packets should wait one or more cycles before they are transmitted. On the contrary W_{poll} is the one to be considered at low loads.

Finally, the upper limit of the delay in a heavy load setting is similar in any DBA being evaluated because the bandwidth allocated to any ONU is its guaranteed bandwidth and the US delay is similar to that of a TDM channel. Therefore, we conclude by saying that the upper limit delay of DDSPON should be similar or less than other DBAs such as the IPACT because starving ONUs profit from those with lower traffic reducing the overall delay. Simulations performed show the performance evaluation, i.e. throughput and delay, in our mixed 1G and 10G EPON setting.

5.3.1 Performance Evaluation

In this section, we present the simulations carried out to evaluate the performance of the DDSPON by using the OPNET Modeler. In the testbed setting some assumptions are made: we consider an infinite buffer in the ONU to avoid packet drops, an interframe gap and control messages are according to the standard and packets are extracted from the queue and transmitted according to the first-in first-out discipline with a single traffic class per ONU. QoS and inter-ONU scheduling is out of the scope of this paper. Table 9 summarizes the testbed setting described.

Table 9: Simulations Parameters.

`Number of ONUs`	16
`Bit rate (single setting)`	16 ONUs at 1G $\phi = 1/16 = 0.0625$
`Bit rate (mixed setting)`	8 ONUs at 1G, $\phi = 0.01136$ 8 ONUs at 10G, $\phi = 0.11364$
`Guard time` (T_g)	$2\mu s$
`Maximum cycle time` (T_{max})	1msec
`OLT-ONU distance (d)`	$18 < d < 20$(Kms.)

Simulation were carried out in two different settings: 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 and uniform with a Hurst parameter of 0.7, and finally packets sizes are uniformly distributed from 64 bytes to 1518 bytes.

The next figures depict the simulated outcomes in the setting aforementioned using the proposed algorithm DDSPON. Notice that in the single scenario the ONUs are uniformly weighted, $\phi^c = \phi_i^c = 1/N; (i : 1...N)$, while in the mixed scenario weights are balanced 1:10 ($\phi_{1G} = 0.01136$ and ϕ_{10G}=0.11364).

Figure 14 depicts the throughput of individual ONUs. 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 that corresponds to $G = 1$ is about 5.5 Gb/s. As a conclusion, in such setting the maximum throughput allocated to an individual 1G-ONUs is up to 60.5 Mb/s while a 10G-ONUs gets about 605 Mb/s.

Figure 15 depicts the maximum ($G = 1$) aggregated throughput received at the OLT. Values match what we have computed in previous section, thus the aggregated throughput of the US channel is about 5.5 Gb/s, divided among the 10G ONUs (5

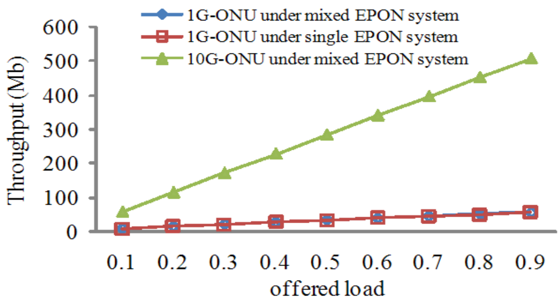

Figure 14: 1G and 10G throughput in single and mixed setting.

Gb/s) and the 1G ONUs (0.5 Gb/s). Finally, figure 16 depicts the average packet delay at the ONU.

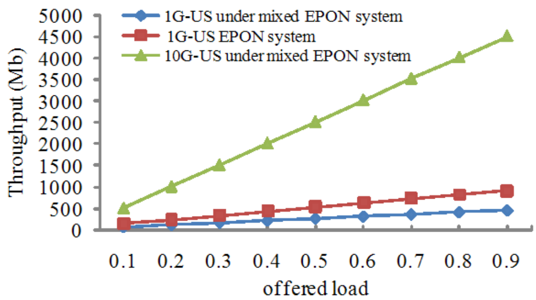

Figure 15: Aggregated throughput in 1G and 10G setting.

The evaluated performance of 1G ONUs, i.e. throughput and delay, is quite similar no matter which setting they are connected to. To conclude figures depicted show that the throughput of 10G ONUs is about 10 times that of the 1G ONUs as we expected and delay is quite similar in both group of ONUs; such outcomes shows clearly the fairness and the scalability of the algorithm.

5.3.2 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 1 sec. 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 next figures while the rest of ONUs transmit self-similar uniform constant as usual.

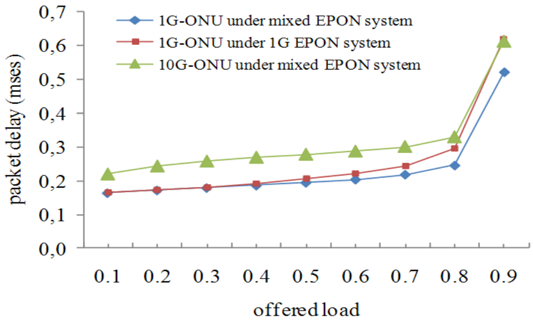

Figure 16: Average Packet Delay.

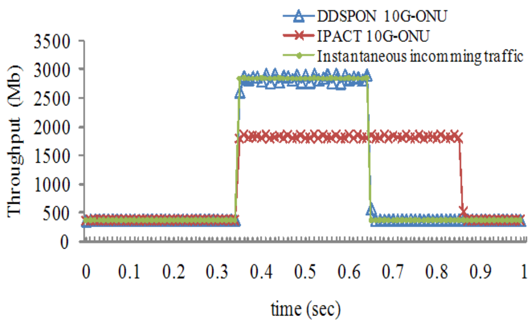

Figure 17: DDSPON vs. IPACT throughput in a bursty traffic.

Figure 17 shows the incoming traffic pattern and the throughput of the 10G targeted ONU. It shows that the throughput of the target ONU follows closely 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. In other words, the bandwidth the targeted ONU request in a bursty traffic is rapidly provided to it by the DDSPON discipline despite the rest of ONUs are lowering its request, although it is not depicted the rest of ONUs are not penalized so much because of such burst. Figure 18 depicts the instantaneous packet delay in the same setting.

The conclusion of the comparison performed in this section, is that although in a 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 even more, the instantaneous delay of the IPACT is much higher as expected.

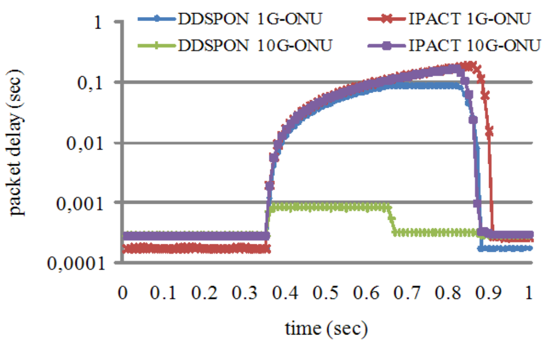

Figure 18: DDSPON vs. IPACT packet delay in a bursty traffic .

5.3.3 Conclusions and Future Work

We have presented a new dynamic bandwidth allocation algorithm for Ethernet-based Passive Optical Networks in a 1G and 10 G mixed network. Such DBA schedules the allocation of bandwidth according to the guaranteed bandwidth agreed with each user, it is distributed and computation is performed at the ONU, the window allocated is proportional to the ONUs needs and the previous requirements of the rest of the ONU which improves the performance of the overall network.

The simulations results showed a good performance in terms of delay and t, and the throughput is fairly balance amongst ONUs either 1G or 10G. We have also illustrated that such algorithm is easily scalable to be used in legacy TDM-EPON, new 10G-EPON or mixed settings. And what is also important the migration is simple without disrupting/interrupting the network; and the transition from 1G to 10G is quite smooth. The DDSPON performance is especially relevant when we consider bursty traffic instead of uniform. Finally, the outcomes presented do not include QoS, it is an ongoing work which will be presented in the future.

5.4 Real-time Services in EPON

In this proposal [45], we merge two scheduler approaches. First, we will use the Distributed Resource Algorithm (DRA) [46] to manage the real-time flows to guarantee delay and delay jitter. And, then, we propose an algorithm based on our previous proposals, the DDSPON [42] to allocate the bandwidth that non real-time traffic deserves in the intervals left free by the real-time flows. The proposals [47, 48] address the problem of delay and delay jitter but concentrating the high priority flows at the beginning of each cycle unlike our proposal that spread as much as possible the real-time flows during the cycle.

An algorithm that distributes the real-time service periods as much as possible is better than a scheduler that concentrates them, because the concentrated service

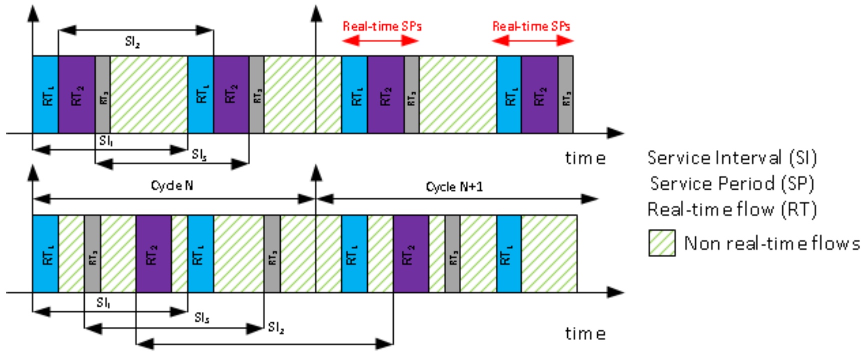

Figure 19: Example of flows allocation with a concentrate and spread distribution approach.

periods capture the channel for long time increasing the average delay of non-real time flows. 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 flow in order to distribute in time as uniformly as possible the allocation of resources for the different flows. The Figure 19 provides an example of allocation distribution according to the spread and concentrates distribution approaches.

The flows are spread because the DRA algorithm allocates the start time of a new flow requested by any ONU by maximizing the minimum distance between the service periods of this new flow and the service periods of the already scheduled flows and thus minimize the overlapping probability. The Figure 20 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 flows $d_{21}(k)$; to better understand of the distance concept between periodic flows and its distance in a channel.

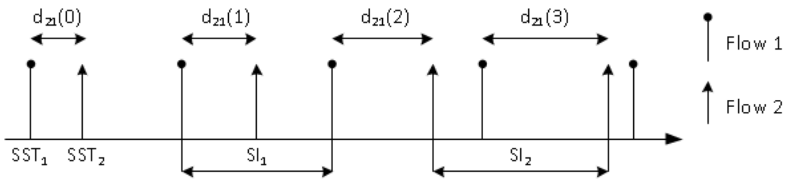

Figure 20: Sample figure with preferred style for labeling parts.

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

$$d_{2,1}(k) = (d_{min2,1}(0) + k * SI_2) mod SI_1 \tag{10}$$

The elements of the previous sequence, $d_{2,1}(0)$, can be expressed as:

Algorithm 1. Distributed resource allocation algorithm (DRA)

− Compute $gcd(SI_(i, SI_{(N+1)})$ for all the already N already scheduled flows, $0 < iN$.
1. Compute the period of the absolute minimum distance,
$T' = lcm(gcd(SI_i, SI_{(N+1)}), ..., gcd(SI_N, SI_{(N+1)})$.
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.

$$d_{2,1}(j) = d_{min2,1} + j * gcd(SI_1, SI_2)j >= 0 \tag{11}$$

Where $d_{min2,1} = d_{2,1}(0)modgcd(SI_1, SI_2)$ and gcd stands for greatest common divisor. Thus an objective way of increasing the separation between the service times of flows 1 and 2 is to increase $d_{min2,1}$ and/or $gcd(SI_1, SI_2)$.

The DRA algorithm requires checking all possible overlapping of scheduled flows along the time depending on the considered service start time; unfortunately, this would lead to an infinite number of operations impossible to implement in a polynomial time, but when we consider a EPON with a limited number of scheduled flows, defined by their service start time and the service interval, what happens in fact is that a repetition pattern occurs with a period corresponding to least common multiple (LCM) of the different service interval flows.

A simple algorithm that computes the new service start time 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.

The non-real time flows uses the DDSPON algorithm to optimize the upstream bandwidth. In DDSPON active ONUs are charged of managing the transmission times, while reporting to the OLT about such allocation. Notice that each ONU schedules the size of its transmission window dynamically and that the DDSPON is executed in an online framework because the scheduling process is executed without the need of waiting for the reports from the rest of the ONUs.

5.4.1 Experiments and results

In the testbed setting some assumptions are made: we consider 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 are: the number of ONUs is set up to 16; the channel data rate is set up to $1Gb/s$; the maximum cycle length is set to 2ms.

The input traffic that simulates 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. We assume that each ONU has three different real-time flows with a service interval of 10, 20 and 30ms respectively and with a payload of

15000bytes.

We show the performance of our scheme compared 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, resulting in increasing the level of unfairness.

The Figure 21 shows the service start times of real-time flows in both scenarios (DRA and strict-priority), as in figure 1 we can show the allocation according to the spread and concentrate distribution approaches, the last to the case of strict-priority. The DRA distribute the real-time flows so that the rest of the traffic could be placed between these flows.

The figure 22 shows the advantage in delay that our scheme provides to the non-real time services even when the real-time services already fulfilling with the QoS requirements.

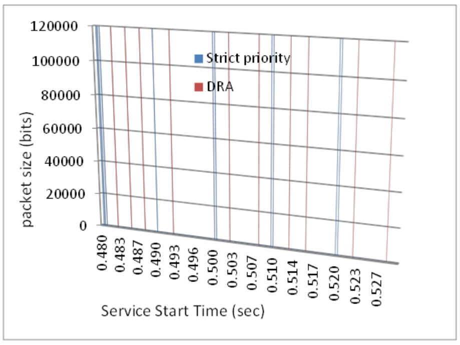

Figure 21: SST of real-time flows

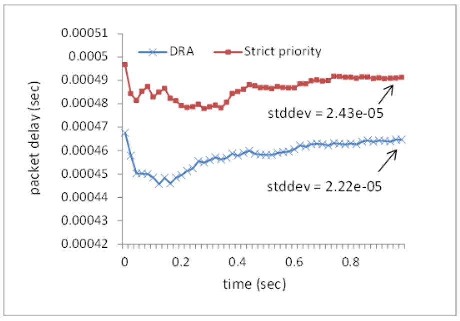

Figure 22: Delay of non-real time flows

5.4.2 Conclusions

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

Unlike most of the proposals existent in the literature, our proposal is the one that 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.

5.5 QoS aware DBA in EPON

In this proposal [49] we present a distributed algorithm to dynamically allocate the bandwidth requested by the user equipment with QoS constrains. The proposed algorithm is scalable and simple to re-configure, which facilitates a smoother transition from legacy 1G to 10G networks.

We also present an analytical model to evaluate the algorithm performance in a coexistent 1G/10G network.

5.5.1 Steady-state analytical model of a coexistent1G/10G-EPON

Like any other algorithm, the DBAs performance evaluation needs formal mathematical analysis for a deeper understanding. The most analyzed DBA in the past is the Interleaved Polling with Adaptive Cycle Time (IPACT). It defines different disciplines for the OLT to determine the granted window size for the ONU, i.e., fixed, gated, limited, linear credit, constant credit and elastic services [50]; however, most of the analysis in the literature focus on the fixed and gated discipline.

Such analysis are usually based on Queuing Theory [51–59]. On the contrary, in [60] the modeling was done using Stochastic Colored Petri Networks (SCPN), from where the average queue size is obtained and used to analytically obtain the total delay.

Finally, in [61] the capacity is evaluated, i.e., maximum mean packet throughput and packet delay of a wide range of NGAN - GPON and EPON - through probabilistic analysis. More specifically, it analyzes the capacity and delay of various subnetworks, interconnected through metro networks, from which NGAN-PONs can be formed.

5.5.2 The steady-state Analysis

Our aim is to present the analytical model to evaluate the performance of DDSPON in a 1G/10G network in 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 experiment 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 a part in it. For a better understanding, a wider explanation of the analysis of this section can be read in [62] for 1G EPON.

The model assumes that there is a single error-free slotted broadcast channel, with ONUs generating traffic of fixed size Ethernet frames (P bytes), according to a Poisson process of rate λ, traffic is symmetric and all ONUs are at the same distance from the OLT. We first concentrate our efforts in solving a system with N ONUs.

The distribution of departures

This paragraph illustrates how to compute the throughput distribution in equilibrium by applying formal Multiqueue Theory [63], and Equilibrium Point analysis [37]. We denote such distribution as, $\vec{S}$. $\vec{S} = (d^0, d^1, ..., d^D)$; where d^k 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. 23). Each node is populated by ONUs that have some packets backlogged in the queue. Thus in node j, there are u^j ONUs with j packets backlogged at the beginning of the cycle.

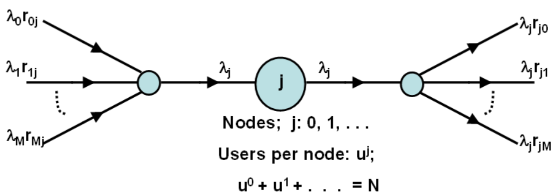

Figure 23: Closed Jackson Network.

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, $\overline{T_{cycle}}$.

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:

$$\lambda_j = \sum_{k=0}^{M} \lambda_k r_{kj} \quad (j : 0, 1, ..., M) \tag{12}$$

where λ_j is the vector of the mean number of arrivals to a node of the chain, $\vec{\lambda}$, $\vec{\lambda} \equiv \{\lambda_0, \lambda_1, ..., \lambda_{M;M\to\infty}\}$. And because the ONU at node j should be routed to any other node of the chain; any element r_{jk} holds that $\sum_{j=o}^{M} r_{jk} = 1$ being $0 \leq r_{jk}$ for each k. The linear system of equations in Eq. 12 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, $P_{r_0,r_1,...,r_M} = \frac{1}{G_M} r_0 \cdot r_1 .... r_M$. 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:

$$k = \sum_{j=0}^{M} u^j \cdot min(j, F); \qquad (13)$$
$$p(k) = P_{r_0, r_1, \ldots, r_M};$$

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:

$$d^k = \sum_{X^k} p(k); \quad (0 \leq k \leq D) \qquad (14)$$

Which finishes the process of computing the distribution of the packet departures, i.e., the throughput distribution, $\vec{S}$. Readers are encouraged to consult [62] for further details.

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:

$$T^k_{cycle} = \frac{k \cdot P \cdot 8}{R_u} + T_{ov} \qquad (15)$$

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. 16. The time overhead in each cycle is therefore:

$$T_{ov} = N \cdot \left(\frac{CM \cdot 8}{R_u} + T_g \right) \qquad (16)$$

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

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:

$$\overline{T_{cycle}} = \sum_{k=0}^{D} d^k \cdot max(T^{min}_{cycle}, T^k_{cycle}) \qquad (17)$$

Notice that we face a system of the type $x = f(x)$, because we need first the mean value of the cycle time, $\overline{T_{cycle}}$ to compute the arrivals in a cycle and then the packet departures distribution $\vec{S}$; however $\overline{T_{cycle}}$ in turn comes from $\vec{S}$. We apply numerical methods to solve such system; for instance by iteration as depicted in Fig. 24.

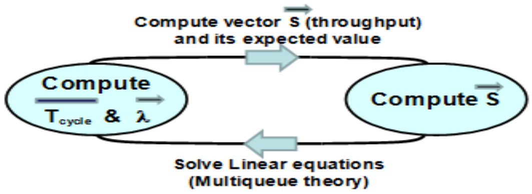

Figure 24: Steady-state iteration process.

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:

$$\vec{S} = \vec{S}^{1G} \otimes \vec{S}^{10G} \tag{18}$$

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:

$$T^{k,m}_{cycle} = \frac{k \cdot P \cdot 8}{R^{1G}} + T^{1G}_{ov} + \frac{m \cdot P \cdot 8}{R^{10G}} + T^{10G}_{ov} \tag{19}$$

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

$$T^{1G}_{ov} = N^{1G} \cdot \left(\frac{CM \cdot 8}{R^{1G}} + T^{1G}_{g} \right) \tag{20}$$

$$T^{10G}_{ov} = N^{10G} \cdot \left(\frac{CM \cdot 8}{R^{10G}} + T^{10G}_{g} \right) \tag{21}$$

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

$$\overline{T_{cycle}} = \sum_{k=0}^{D^{1G}} d^{1G}_{k} \sum_{m=0}^{D^{10G}} d^{10G}_{m} \cdot max(T^{min}_{cycle}, T^{k,m}_{cycle}) \tag{22}$$

In Eq. 22, 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 $\vec{S}^{10G}$.

DDSPON upper and lower bounds

The allocated bandwidth computed by the DDSPON (Eq. 2 and 3) varies each cycle depending on the weights received from the OLT. Equation 23 holds:

$$\Phi_i^c \cdot BW_{max} \leq BW_i^{n+1} \leq BW_{max} \tag{23}$$

In previous analysis the routing probabilities (r_{jk}) and the departures (Eq. 13) 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:

- $BW_{low}^{1G}, BW_{low}^{10G}$: lower value of the bandwidth allocable to 1G and 10G ONUs, i.e., the minimum window to use in computations.
- $BW_{up}^{1G}, BW_{up}^{10G}$: 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. 3): $BW_{low}^{1G} = \frac{BW_{max}^{1G}}{N^{1G}}$ and $BW_{up}^{1G} = BW_{max}^{1G}$; and we also compute BW_{low}^{10G} and BW_{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.

5.5.3 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, as we believe it is a reference algorithm in many papers. The OPNET Modeler is the package used to run the simulations presented.

Set up values of the setting

The values of the variables used in the analysis and simulations are summarized in Table 10.

Table 10: Initial Values of the Steady-State Anaylisis

	Explanation	Default Value
N	Full ONUs set	16
N^{1G}	# 1G ONUs	8
N^{10G}	# 10G ONUs	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	$2\mu s$
P	Packet size	1.500 (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
$ratio$	Φ_{10G}:Φ_{1G}	10:1
T_{cycle}	Time cycle max	1 ms

Set up values of the DDSPON that come from the above values are:

$F_{low}^{1G} = 5$ and $F_{up}^{1G} = 40$ (packets)

$F_{low}^{10G} = 50$ and $F_{up}^{10G} = 400$ (packets)

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

We expect the throughput allocated to 10G ONUs to be 10 times (ratio) higher than the throughput of 1G ONUs. In other words, 1G ONUs maintains the same performance of a legacy 1G EPON network, while 10G ONUs are allocated with the bandwidth they deserve.

Next sections illustrate the average values of the performance, i.e., cycle, throughput and delay. The figures 25,26 and 27 depict the analytical lower (F_{low}), upper (F_{up}) and the simulation results of the DDSPON and the IPACT.

Mean value of the cycle

We first show in Fig. 25 the mean value of the cycle, $\overline{T_{cycle}}$. We see that $\overline{T_{cycle}}$ 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.

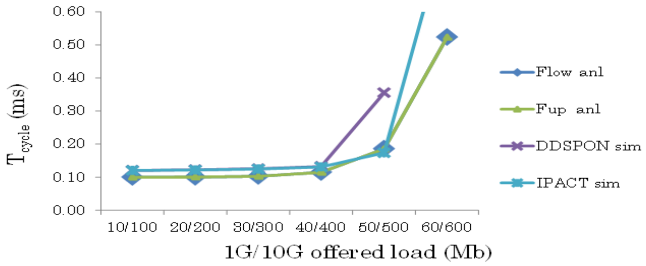

Figure 25: Mean value of the cycle. Steady-state setting

We conclude that the results remain very close to the performance of the IPACT algorithm, but it falls short when evaluating the $\overline{T_{cycle}}$ of the DDSPON for high loaded network (50 Mb/s in our model) which approximately corresponds to G=0.9.

The mean value of the throughput

Figure 26 shows the bounds for the mean value of the throughput for 1G ($\overline{S_{1G}}$) and 10G ($\overline{S_{10G}}$) 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 $\overline{T_{1G}} = \overline{T_{10G}} = 0.484$ ms and the mean value of the throughput is $\overline{S_{10G}} = 10 \cdot \overline{S_{1G}}$, as expected. Therefore, in such mixed plant the single upstream TDM channel is shared among both groups of ONUs fairly, and each ONU is allocated with exactly the bandwidth it will be allocated in a single homogeneous plant.

The average 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 decomposed in three random variables: W_{poll}, W_{grant} and W_{queue} as described in [53]. Thus, the average value of the access delay $\overline{W_{acc}}$, is given by:

$$\overline{W_{acc}} = \overline{W_{poll}} + \overline{W_{grant}} + \overline{W_{queue}} \tag{24}$$

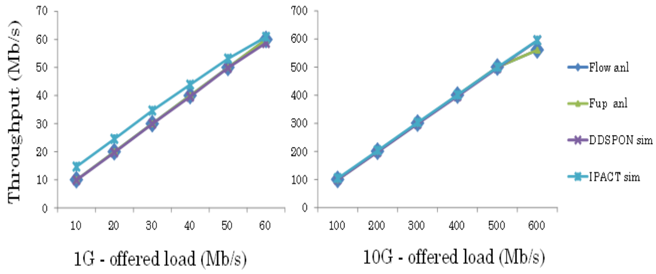

Figure 26: Analytical and simulated mean value of the throughput $\overline{S_{1G}}$ and $\overline{S_{10G}}$. Steady-state setting

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: $\overline{W_{acc}} \approx \frac{3 \cdot \overline{T_{cycle}}}{2}$. 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. 27 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.

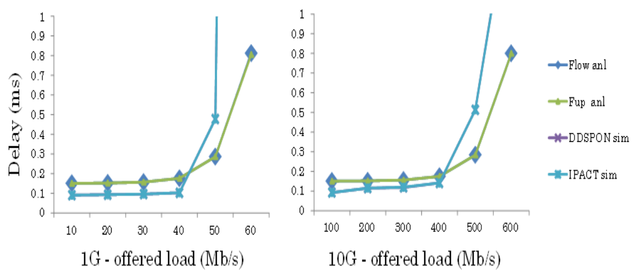

Figure 27: Analytical and simulated average value of the delay in 1G ONUs and 10G ONUs. Steady-state setting

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.

5.5.4 SLA aware DBA scheme for QoS

EPON is expected to offer service differentiation to provide diverse QoS to applications depending on their requirements. The well-known DiffServ approach [34] is the architecture that provides QoS in IP networks, and thus it is the model used in access networks like the EPON. In DiffServ, traffic is classified in three classes from high to low priority: Expedited forwarding (EF), Assured forwarding (AF) and Best effort (BE). The highest priority traffics is the EF class, whose characteristics of low delay, low loss and low jitter. AF is intended for services that 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.

The most common strategy to provide DiffServ in EPONs is to perform the inter-ONU scheduling either by a centralized or distributed DBA, and then leave the intra-ONU scheduling task to the ONU. In other words, the ONU decides which packets from each service have to be served first (intra-ONU scheduling) once it knows the bandwidth allocated (inter-ONU scheduling) in the next cycle. The effort should be employed in avoiding the monopoly on bandwidth by higher classes, while keeping the QoS to each class deserves. Two main approaches can be used to perform the intra-ONU scheduling task: either the ONU places packets in a single queue, and re-order packets according its priority or each ONU is equipped with a number of queues and the transmission order depends on a strict and non-strict priority scheduling.

The EPON standard is compliant with the strict priority mechanism, defined in P802.1D, clause 7.7.4, as well as the rest of IEEE 802 standards. Such mechanism forces the ONU to schedule first the packets of the higher priority queue to empty it before proceeding to the next lower priority queue. 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. Reference [53] describe the light load penalty problem because of the strict policy, in which delay for low-priority classes increases even when network load decreases.

To mitigate such problems non-strict priority-aware scheduling algorithms were proposed in [22, 50, 64]. The packets transmitted when using the non-strict scheduling should be reported first, as long as they can be transmitted within the allocated time slot. Thus, the transmission of the packets arrived along the cycle but not yet reported is deferred unless there is enough bandwidth allocated in the current cycle. The transmission order of different queues is based on their priorities.

5.5.5 Enhanced QoS DSSPON (EQ_DDSPON)

In this section we present the enhancement of the DDSPON that allows the provisioning of QoS to different services under the DiffServ. Our first statement is that such enhancement profits from the DDSPON approach of using weights (Φ_i) to balance the traffic among ONUs. In what follows, we use the definitions of DDSPON in section III and add the following ones:

- BW_{MAX}^{EF}: is the set up maximum bandwidth allocable for EF traffic. Such value satisfies that $BW_{MAX}^{EF} \leq BW_{MAX}$. Such inequality allows us to save some bandwidth left for the rest of the traffic classes; set up values depends upon the specific implementation.

- $\Phi_i^{EF,c}$: is the set up weight value of ONU_i for Expedited Forwarding traffic class. The partial weight values $\Phi_i^{EF,c}$ might not be the same as the global weight, $\Phi_i^{EF,c} \approx \Phi_i^c$.
- $\Phi_i^{EF,n+1}$: is the value of ONU_i for Expedited Forwarding class in cycle $n+1$.
- $BW_i^{EF,n+1}$: is the maximum bandwidth allocable of ONU_i for the Expedited Forwarding traffic class.
- $R_i^{EF,n+1}$: is the required bandwidth of ONU_i for the Expedited Forwarding class.
- $R_i^{AF,n+1}$: is the required bandwidth of ONU_i for the Assured Forwarding class.
- $R_i^{BE,n+1}$: is the required bandwidth of ONU_i for the Best effort class.

The computations in cycle n

Upon reception of the GATE and as explained in previous section III the DDSPON computes the required bandwidth values $R_i^{EF,n+1}$, $R_i^{AF,n+1}$ and $R_i^{BE,n+1}$ as well as the weight $\Phi_i^{EF,n+1}$, jointly with the global values R_i^{n+1} and Φ_i^{n+1}. Detailed computation steps are as follows:

First BW_i^{n+1} is computed as in Eq. 3 and $BW_i^{EF,n+1}$ as:

$$BW_i^{EF,n+1} = \frac{\Phi_i^{EF,c}}{\Phi_i^{EF,c} + \sum_{j=1;j\neq i}^{N} \Phi_j^{EF,n}} BW_{max}^{EF} \tag{25}$$

Second, we compute the required bandwidth values R_i^{n+1} (Eq. **??**) and $R_i^{EF,n+1}$, $R_i^{AF,n+1}$ and $R_i^{BE,n+1}$

$$R_i^{EF,n+1} = min(Q_i^{EF}, BW_i^{EF,n}) \tag{26}$$

$$R_i^{AF,n+1} = min(Q_i^{AF}, (BW_i^n - R_i^{EF,n+1})) \tag{27}$$

$$R_i^{BE,n+1} = min(Q_i^{BE}, BW_i^n - (R_i^{EF,n+1} + R_i^{AF,n+1})) \tag{28}$$

And finally we compute the next weights values Φ_i^{n+1}, $\Phi_i^{EF,n+1}$ and the overall requested bandwidth R_i^{n+1}

$$R_i^{n+1} = R_i^{EF,n+1} + R_i^{AF,n+1} + R_i^{BE,n+1} \tag{29}$$

$$\Phi_i^{n+1} = \frac{R_i^{n+1}(\Phi_i^c + \sum_{j=1;j\neq i}^{N} \Phi_j^n)}{BW_{max}} \tag{30}$$

$$\Phi_i^{EF,n+1} = \frac{R_i^{EF,n+1}(\Phi_i^{EF,c} + \sum_{j=1;j\neq i}^{N} \Phi_j^{EF,n})}{BW_{max}^{EF}} \tag{31}$$

In the end, we report the new values computed: Φ_i^{n+1}, $\Phi_i^{EF,n+1}$ and the overall requested bandwidth R_i^{n+1} to the OLT.

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 just must 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 ONUs in each group have the same weight, configuration values should satisfy

$$\Phi_{10G}^{EF,c} = 10 \cdot \Phi_{1G}^{EF,c} \tag{32}$$

The rest of the variables and computations remain unchanged.

5.5.6 Performance Evaluation

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 OPNET Modeler and the setting presented in previous paragraphs but upgraded to evaluate the EQ_DDSPON in DiffServ.

Evaluation of steady-state with QoS

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 is 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 Mbps.

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.

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

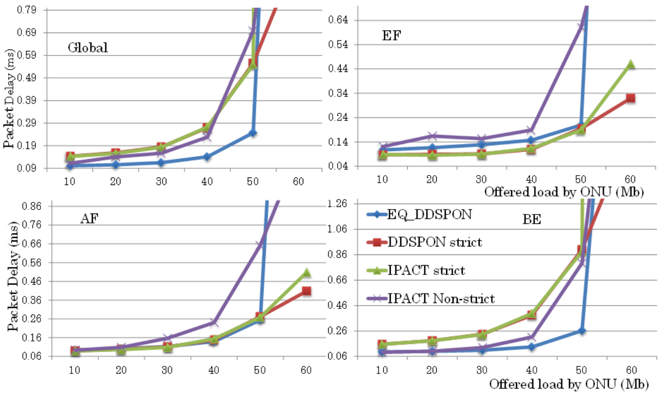

Figure 28: Average packet delay in 1G ONU. Global and DiffServ classes (EF, AF and BE) results.

and delay. Fig. 28 and Fig. 29 show the average delay for 1G and 10G ONUs. We observe in such figures 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 expect.

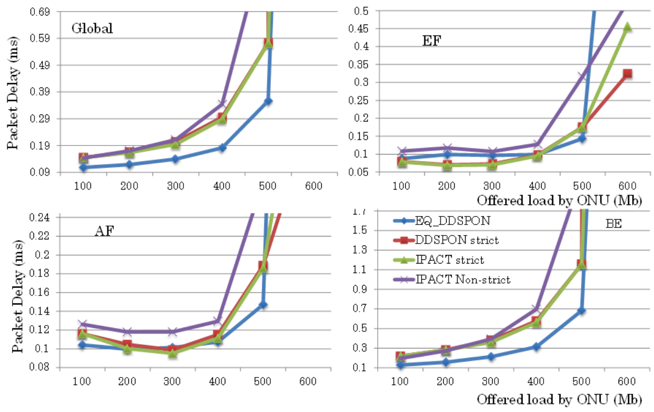

Figure 29: Average packet delay in 10G ONU. Global and DiffServ classes (EF, AF and BE) results.

We also observe that for such heavy loads approaching the maximum utilization $\rho = 1$, the slope of the delay of EQ_DDSPON increases much more rapid than strict EF and AF class average, again due to strict algorithms prioritization; more precise simulation should be carried out for loads beyond 0.9, as in [50]. Anyway, at such high loads end users will not probably get the SLA (delay, packet loss) they expect from the operator no matter the algorithm being used.

Evaluation of the transitory with QoS

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 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. 30.

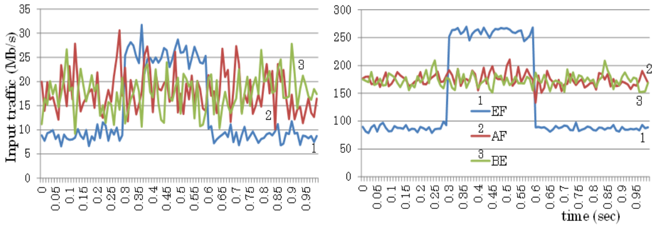

Figure 30: Input (transitory) traffic pattern ONU 1G and 10G. EF (CBR 20%), AF (self-similar 40%) and BE (self-similar 40%).

The initial simulation values and the input traffic pattern used in the simulations are summarized in Table 11. Fig. 31 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 Fig. 31 we also observe the impact of the input burst of traffic load which is highly smoothed when using EQ_DDSPON.

Table 11: Initial simulations parameters of the transitory setting

	Description	Value
`1G ONU`	weight	0.01136
`10G ONU`	weight	0.11364
`F 10G:1G`	ratio	10:1
`T cycle max`	ms	1
	ONU 1G	
`EF`	CBR	9 Mb/s
`AF`	self similar (H:0.7)	18 Mb/s
`BE`	self similar (H:0.7)	18 Mb/s
	ONU 10G	
`EF`	CBR	90 Mb/s
`AF`	self similar (H:0.7)	180 Mb/s
`BE`	self similar (H:0.7)	180 Mb/s

The results show that the performance of the EQ_DDSPON is much better than the rest, specially when we consider not uniform loads, this is because the weights facilitate the balancing of the allocated bandwidth among ONUs.

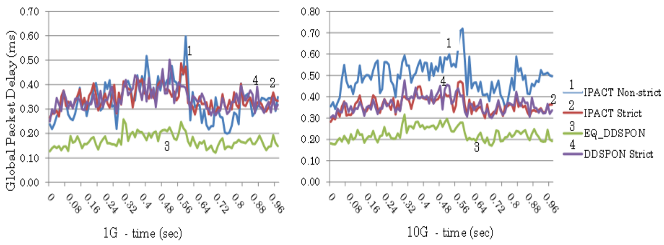

Figure 31: Global packet delay of 1G and 10G target ONU.

5.5.7 Conclusions

In this proposal, we have analyzed the DDSPON algorithm to be used either in an homogeneous EPON network or in a coexistent 1G/10G plant with QoS support. 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.

Finally, we have enhanced the DDSPON to support QoS. 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.

5.6 Energy-aware DBWA in WDM/TDM-PON

The next-generation PONs are expected to adopt the wavelength division/time division multiplexing (WDM/TDM) technique to improve its operation. However, the minimization of energy consumption is also becoming a main target in the operation of WDM/TDM-PONs due to the architecture of optical devices that require more transceivers/receivers. To reduce such consume, in this study we argue that an efficient mechanism based on Dynamic Bandwidth and Wavelength Allocation (DWBA) allows an optimal operation of optical devices such as the Optical Line Terminal (OLT) regarding energy consumption.

There are many reported contributions on energy efficiency in PONs but less on WDM/TDM-PONs. Such techniques are regarded as either hardware or physical, and software or data-link approaches [65, 66]. Physical approaches introduced new optical device architectures and data-link proposals are extensions of the Dynamic Bandwidth and Wavelength Allocation (DBWA) algorithms. In WDM/TDM-PON if we run the network with fewer wavelengths while serving all the bandwidths demands the power consumption is minimized by shutting down idle receivers in the OLT.

This contribution [67] presents an energy-efficient WDM/TDM-PON proposal, which takes advantage of the upstream scheduling and wavelength assignment algorithms presented in [68], to improve the power consumption in OLT. Results show that energy consumption in OLT receivers can be reduced in at least 30%.

5.6.1 Minimizing the power consumption in OLT

In this proposal we show a novel energy-aware wavelength assignment mechanism to save energy in OLT based on upstream network traffic. In the proposed mechanism bandwidth allocation can be performed using any of the existing DBWA methods. Here we focus on two well know algorithms called Earliest Finish Time (EFT) and Latest Finish Time (LFT), see [68].

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}. If no channel has a finish time lower than T_{lft}, then the algorithm switches to EFT.

Our objective of such energy saving mechanism is to decrease the power consumption while channel utilization and packet delay are not significantly affected. 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.

If the OLT detects low-load channel utilization during a predefined period U_{low}, it performs the energy-aware wavelength assignment to evaluate the number of receivers to be switched to sleep mode. When channel utilization has a high-load, then the OLT has a chance to switch to active mode. The duration of the sleep mode for OLT receivers is L_{sleep}, which is at least the length of a cycle, while the duration of an active mode of a receiver is L_{active}, which is at least the length of the predefined period U_{low}.

5.6.2 Performance Evaluation

We carried out some simulations to evaluate the performance of our proposal by using the OPNET Modeler tool. The objective is to observe channel utilization, delay and power consumption in two particular scenarios. The first case considers a balanced input traffic and the second an unbalanced input traffic.

We assumed that each ONU can support all wavelengths (tunable ONU), but it can only be scheduled by one wavelength in a cycle. The power consumption of each receiver in the OLT was set to 0.5 W based on the power consumption of commercial transceivers modules. Bandwidth allocation is performed according to limited service described in [14], where $BW_{max} < TD/N$. The following are the parameters used in our simulations: the number of ONUs N=16; the number of upstream channels W=4; maximum cycle time TD= 1ms; PON upstream data rate R=1Gb/s; distance between OLT and ONU is 20km; the guard time = 2 μs; packet size is uniformly distributed by 64 and 1518 bytes. In the simulations, each ONU carries self-similar traffic with a Hurst parameter H=0.7.

In the scenario where the input traffic is balanced, ONUs upstream traffic is similar, we compare the performance of EFT and LFT. In Fig. 32 (a) and (b) EFT has better performance during low offered loads while LFT it has during high offered loads, however as we can see in Fig. 32 (c) the average packet delay increases. In medium loads EFT and LFT has a similar behavior which means that LFT most of times reaches the T_{lft} and switches to EFT. T_{lft} in this 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. In LFT the optimal value of T_{lft} will allow a better performance of the energy mechanism proposed.

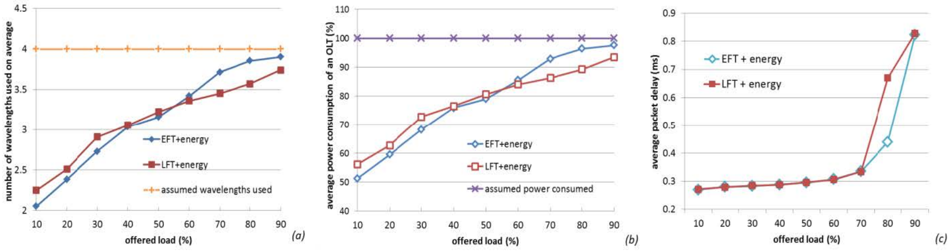

Figure 32: Performance Evaluation(a) number of wavelengths used, (b) OLT power consumption, (c) average packet delay.

Fig. 33 shows the number of wavelengths used in function of the input network traffic as well as the average power consumption in an scenario where ONUs input traffic is unbalanced. EFT shows a better performance over LFT, but of if we set up the $T_{lft} > RTT + T_{cm}$ in LFT then it presents better results in such scenario.

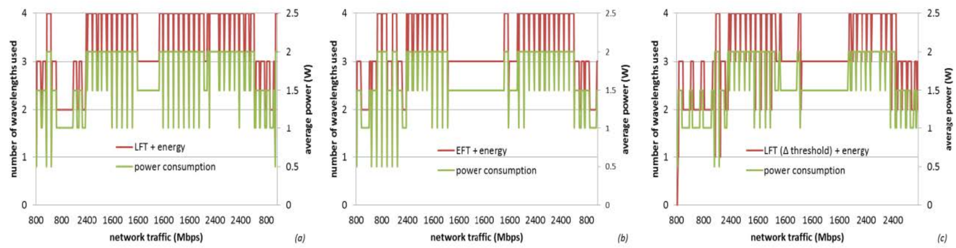

Figure 33: Number of wavelengths used and average power consumption, (a) LFT, (b) EFT and (c) LFT with $T_{lft} > RTT + T_{cm}$.

5.6.3 Conclusions

Simulations results show that our proposal is able to save energy in OLT with a periodic evaluation of channels utilization, also show the relation between power consumption and delay. In our study we assumed particular values of the duration of OLT receivers in sleep or active modes (L_{sleep}, L_{active}) as well as the length of low-load channel utilization (U_{low}). Such values are crucial parameters that impact directly the delay performance, so that, we are working in the formulation of new values under different scenarios. We are also working with the evaluation of LFT because the suitable definition of T_{lft} provides energy-saving by itself, also the combination of both

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

Chapter 6

Conclusions

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

This project started with a review of literature on expected users demands. Since the project is intended as a basis for long-term research, we studied those works that focus on future rather than imminent user needs. In parallel, the initial stage included the study of research contributions to the resource management.

In order to gain a deep understanding of the issues that can have an impact on the design of our solution, this project will not only consider contributions with general scenarios but integrated architectures or technologies, as well as proposals of specific mechanisms in similar heterogeneous scenarios. The state of the art in Dynamic Bandwidth Allocation (DBA) solutions, as well as the study of NGAN was presented in a chapter book published in [33].

The project also considered the design of the integrated optical-wireless access architecture. The architecture will include the most adequate set of relatively broad range of upcoming technologies in optical and broadband wireless access/metropolitan networks. Some of the technologies considered were WDM, Optical Burst Switching (OBS) optical networks, IEEE 802.16 (WiMAX) or IEEE 802.11e/n. The research performed has been developed in the framework of the European Networks of Excellence Euro-NF under the FIbre-WIreless Access: Future Integrated Access Architecture Based on Optical and Broadband Wireless Technologies (Fi-Wi) project.

The main contributions of this project are in terms of resource management, we provided an extended analysis of the current literature about resource allocation proposals, especially we studied the DDSPON algorithm. The study of DDSPON was reflected in publication [43].

Adaptations of DDSPON to new scenarios, such as EPON and 10GEPON coexistence and LR-PON, have been done and important results have been obtained, these results have been published in [44, 45].

By using the DDSPON, enhanced ONUs will take full advantage of the 10Gb/s rate while legacy 1G ONUs maintain their SLA; as a result, the individual performance is maximized for both groups of ONUs. We performed an analytical model to evaluate the algorithm performance in a coexistent 1G/10G network. Results were published in [49].

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 project. Results of this research were published in [67].

During the project, in order to evaluate the algorithm proposals, a simulation network model was developed. Simulation environment is based on OPNET Modeler tool. OPNET Modeler provides a comprehensive development environment supporting the modeling of communication networks and distributed systems. We choose OPNET Modeler suite as a tool to model allocation problems in NGAN, because both behavior and performance of modeled systems can be analyzed by performing discrete event simulations.

An important step towards NGAN is the implementation of the WDM technology. There are huge research efforts worldwide in developing metro and access networks based on WDM. The research is focused on improving the optical devices as well as in developing new architectures to handle the multi-wavelength channel efficiently. Such solutions are not only based on the type of network -such as WDM-PON or 10G PON- but also on hybrid technologies.

Moreover, incumbent operators are interested in the so-called Long Reach-PON (LR-PON) that will help the growing process of PON deployment. LR-PON is a very cost-effective solution because the CAPEX and the OPEX of the network are lower mainly due to the fact that the number of equipment interfaces, network elements, and nodes are reduced, and moreover, the network management complexity is also simplified.

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