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BACHELOR DEGREE THESIS

TITLE: **Dynamic bandwidth allocation algorithms with non-zero laser tuning time in TDWM passive optical networks**

DEGREE: Degree on Telecommunications System Engineering

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Resum

El present document té l'objectiu d'analitzar el funcionament de les xarxes d'accés Passive Optical Networks (PONs). El focus d'analitzar aquest tipus de xarxes és degut la seva alta eficiència en termes de ample de banda, velocitat, consum d'energia i cost. Les xarxes PONs estan compostes per l'Optical Network Unit (ONU), l'Optical Line Terminal (OLT) i elements passius com divisors, combinadors i fibres. Concretament, en aquest document s'analitzaren les xarxes Ethernet Passive Optical Networks (EPONs) definides per l'Institut d'Enginyers Elèctrics i Electrònics (IEEE) en l'estàndard IEEE 802.3ah. La característica principal d'aquest estàndard és el seu format de trama essent les xarxes EPONs compatibles amb les trames Ethernet.

Inicialment, les xarxes PONs es basaven en una única portadora òptica. Això implica que en la direcció de pujada el canal és un recurs compartit i ha d'existir una coordinació per evitar col·lisions en les transmissions dels usuaris. Els primers protocols anomenats Time-Division Multiple Access (TDMA) eren basats en divisió per temps. En les xarxes PON la OLT juga un paper important ja que s'encarrega de l'assignació de ample de banda dinàmica. El Dynamic Bandwidth Allocation agent (DBA agent) té un algoritme encarregat de programar les diferents transmissions dels usuaris. Amb el pas del temps i el creixement de la necessitat d'ample de banda i velocitat per part dels usuaris s'esdevé una nova generació de xarxes òptiques passives anomenada Next-Generation Passive Optical Networks (NG-PONs). Aquestes xarxes de nova generació son multiportadores. És a dir, el canal de pujada que és un recurs compartit ara necessita un protocol d'accés al medi (MAC) basat en la longitud d'ona i temps anomenat Wavelength-Time-Division Multiple Access (WTDMA). L'algoritme de programació de les transmissions situat al DBA agent de la OLT incrementa la seva complexitat, ja que ha de ser capaç de programar les transmissions basades en temps i en la longitud d'ona.

En la nova generació de PON, per a canviar de longitud d'ona, les ONUs han de sintonitzar els seu làsers. Aquest canvi de longitud d'ona afegeix un retard (tuning time delay). L'objectiu d'aquest projecte és dissenyar, implementar i analitzar un algoritme DBA basat en WTDMA capaç de tenir en compte el tuning time delay per minimitzar el retard global del sistema. A més a més,

aquest algoritme haurà d’aplicar la tècnica coneguda com Just In Time (JIT) per augmentar la seva eficiència.

Totes les simulacions i implementacions s’han realitzat sobre el simulador OPNET sobre un projecte base d’una xarxa EPON multiportadora realitzat per un altre estudiant. Per a poder implementar l’algoritme s’ha realitzat un treball previ per posar en marxa i adaptar el model a les noves condicions.

S’ha aconseguit simular una xarxa EPON de 4 portadores a 1 Gbps per portadora. Finalment, s’ha implementat amb èxit l’algoritme dissenyat, que pren decisions de forma eficient considerant el retard de sintonització dels làsers.

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Overview

The goal of this document is to analyse the functionality of Passive Optical Networks (PONs). The reason for focusing on these technique networks is due to their high efficiency in terms of high bandwidth, high rate, low energy consumption and low cost. PONs are composed of Optical Network Unit (ONU), Optical Line Terminal (OLT) and passive elements (splitters/combiners, optical fibres…). Specifically, this document analyses Ethernet Passive Optical Networks (EPONs) defined by Institute of Electrical and Electronics Engineers (IEEE) in the IEEE 802.3ah standard although there is another standard. The main difference between them is the framing protocol, being the EPONs compliance with Ethernet frames.

The first PONs used a single optical carrier. That means that upstream channel is a shared resource and a scheduling is needed to avoid collisions between users' transmissions, by using Time-Division Multiple Access (TDMA). In PONs the OLT plays an important paper, since it is the responsible of the dynamic bandwidth allocation (DBA). The DBA agent in the OLT has an algorithm that schedules the users' transmissions. Since the deployment of the first PONs, the requirements of the users have increased, and users need high bandwidth and high rate. Thus, a new generation of PONs (NG-PON) have been designed. These next generation of PONs are multicarrier. That means that upstream channel that is a shared resource needs a Medium Access Protocol (MAC) based on wavelength/time-sharing known as Wavelength-Time Division Multiple Access (WTDMA). The algorithm placed on the DBA agent in the OLT increases its complexity. The algorithm should be able to schedule the transmissions based on time and wavelength.

In the new generation of PON, in order to change the transmission wavelength, the ONUs have to retune their lasers. This wavelength change causes a tuning time delay. The target of this project is to design, implement and analyse an algorithm based on WTDMA and able to consider the tuning time delay and to minimize the global average delay of the system. Besides, the algorithm should apply the Just-In-Time (JIT) technique for increasing the system efficiency.

All the simulations and implementations have been performed in the OPNET simulator, over a base code based on multicarrier EPON created by another

student. In order to implement our algorithm a previous upgrading work has been realized for running the model and adapting it for the new requirements.

We have succeeded in simulating an EPON with 4 channels where every channel has a 1 Gbps of bandwidth in OPNET simulator. In EPON we have introduced a laser tuning time control. Finally, we have implemented the designed algorithm. The algorithm schedules efficiently the network transmissions considering the laser tuning time delay.

We have successfully simulated an EPON with 4 carriers, with 1 Gbps per carrier. Finally, we have implemented an algorithm able to schedule efficiently the network transmissions considering the laser tuning time delay.

I would like to dedicate this project to the
people who have helped me to finish it.

To my family for helping me to believe in
myself when I didn’t and to my pi friends’ group
who have supported me all the time and
motivated me to be better,

To my lovely battle sidekick Alba who has
believed in me and kept me focused in the
important things.

Finally, to my advisor, David Rincón
for helping me to manage this project.

INDEX

CHAPTER 1. INTRODUCTION

1.1. The future of telecommunications and optical technologies

The bandwidth requirement of Internet applications is increasing continuously [1]. This is because the new trend between the users is to share media like videos, audios, music, photos… Multiple applications share live video and audio. Extrapolating this trend, it is clear that bandwidth requirements are going to increase in the next years. Besides, 5G will require very strict parameters in terms of rate, bandwidth and delay [2]. Networks are structured in three parts, backbone, metro and access network. The last one is the responsible for connecting the end-users to the networks and it is the most restrictive in terms of bandwidth and delay. One of the best solutions to cover these requirements are Passive Optical Networks (PONs).

Telecommunications companies are investing on optical fibre since many years ago. Practically, in all the cities of Europe, Asia and part of North-America there are Internet connection through optical fibre until to office or home.

PONs are very good in terms of cost-efficiency. PON is a Point-Multi-Point (P2MP) network. PONs are composed by the Optical Line Terminal (OLT), the Optical Network User (ONU) and a passive distributors network with fibres, splitters and combiners. There are two main standards for PONs, one of them is defined by the Institute of Electrical and Electronics Engineers (IEEE), and the project started in March of 2001 as 802.3ah Ethernet First Mile (EFM) project. The standard is called Ethernet Passive Optical Network (EPON) [3]. In parallel, the International Telecommunication Union (ITU) defined a new protocol in the recommendation G.984 ITU-T called Gigabit Passive Optical Network (GPON) [4]. The main difference between both standards is the framing mode. While GPON is using a GPON encapsulation mode (GEM), EPON uses the Ethernet as frame format.

As PON is P2MP, in the downstream the transmission is configured as broadcast. In the upstream, the users have to share the channel. Therefore, in the upstream there must be a Medium Access Protocol (MAC) in order to avoid the collisions between the different users. The first PONs used a single optical carrier. As the channel is shared, a MAC protocol based on Time-Division Multiple Access (TDMA) is used. Also, it there should be an algorithm to manage the resources called Dynamic Bandwidth Algorithm (DBA). The standards do not define any bandwidth allocation solution, thus the researchers, companies and universities started to study new purposes of defining an algorithm to schedule the channel transmissions.

During last years, due to the increasing bandwidth requirements a new generation of PONs have been defined. These new networks are called Next-Generation Passive Optical Networks (NG-PONs). NG-PONs use several optical carriers, that means that there are more than one (four per standard definition) wavelengths and the new MAC protocol is now based on time and wavelength.

The MAC protocol for the NG-PONs is called Wavelength-Time-Division Multiple Access (WTDMA). Thus, the complexity of the algorithm increases. In order to use different carriers, the laser in the ONU has to be able to change its transmission wavelength. This change depends directly on the hardware and implies a tuning time delay. This delay appears each time that ONU has to change its transmission wavelength. For solving this problem and at the same time reducing the consumption of energy the scheduling resources have to be managed. DBAs have to be able to manage the bandwidth on-demand. Some of them are centralized in the OLT and the others are decentralized (OLT and ONU cooperates).

The goal of this project is to design, implement and analyse a DBA for multiwavelength EPON. Specifically, ONUs have 4 wavelengths available for transmissions. The algorithm should comply some requirements. It should work with WDTMA, in an online fashion, it should consider the tuning time delay for its scheduling decisions and also it should use the just in time technique. All the simulations will be carried out in the OPNET simulator. An EPON base model designed in a previous thesis [5] has been used. The first step is to have the base model running. For achieving this it is necessary to analyse the base model and do some modifications. Secondly, we apply some changes in the base model to control the tuning time delay in the project. We have also reviewed several algorithms before implementing and analysing the new technique, and we have earnt about some dynamic of the system. The algorithm implementation and the simulations have been performed successfully. For instance, a middle tuning delay on laser could provoke more average queue delay in the system than a small tuning delay on laser.

This document is organized as follows, Chapter 1 introduces the topic of PONs. The main goals of this project are also defined. Chapter 2 presents the Ethernet Passive Optical Networks (EPONs), focusing in its main functionality, structure, the Multi-Point Control Protocol (MPCP) and finally the evolution of PONs. Chapter 3 presents the Bandwidth Allocation algorithms in PON. One of them, the Interleaved Polling with Adaptative Cycle Time (IPACT) is described in detail because is the protocol used as base in this project. Besides, the main characteristics of the algorithms and the laser tuning time delay concept are introduced. Chapter 4 describes the statement of the problem and objectives. In Chapter 5, the software used in this project to implement and analyse the algorithms implemented is presented. Also, a previous thesis that has been used as a base and its main changes to adapt the new environment are described. Chapter 6 presents a review of the DBAs proposed in the scientific literature. Some of these algorithms are online and others are offline. One of the algorithms analysed with offline configuration considers the tuning time. This algorithm has been taken as reference to define a new algorithm with online configuration that considers the tuning time to decide the scheduling. Its implementation and the logic of the algorithm are described. This chapter presents the algorithm simulations and its analysis. This document finishes with the conclusions and future works.

Additionally, Annex 1 and Annex 2 show the base model validation for the EPON model working with bit rates of 1 and 10 Gbps respectively. Data collected for the validation is presented as well. Annex 3 demonstrates that the data collected from one ONU could be taken as reference for the system behaviour. A comparison of the results obtained with one ONU and all the ONUs in the system is shown. Annex 4 presents the validation of the DBA algorithm Next Available Supported channel (NASC) JIT. For validating it, the algorithm has been implemented, and the simulation results are compared with the results published. Annex 5 shows simulations results and analysis of different simulation times in order to find the optimum parameter for our simulations. Annex 6 presents all the results obtained after simulating the algorithm implemented. These results are commented in the main body of this document (Chapter 6). Annex 7 concludes the document with a brief description of OPNET simulator and its basic principles, together with the simulation logic.

CHAPTER 2. Passive Optical Networks (PONs)

This chapter presents what PONs are and how they work. Besides, it presents the evolution of PONs during the last years. Finally, it presents the two mains standards in the market and describe their main differences.

2.1. Introduction to PONs

A passive optical network has following elements: optical network unit (ONU), optical line terminal (OLT), physical medium (optical fibre) and splitters/combiners. PON networks are called passive because the distribution network does not have any active element, for instance signal amplifiers. Also, these networks are defined as point-to-multipoint network, since in a PON there are one OLT for several ONUs. PONs use a tree topology, as illustrated in Fig. 2.1.

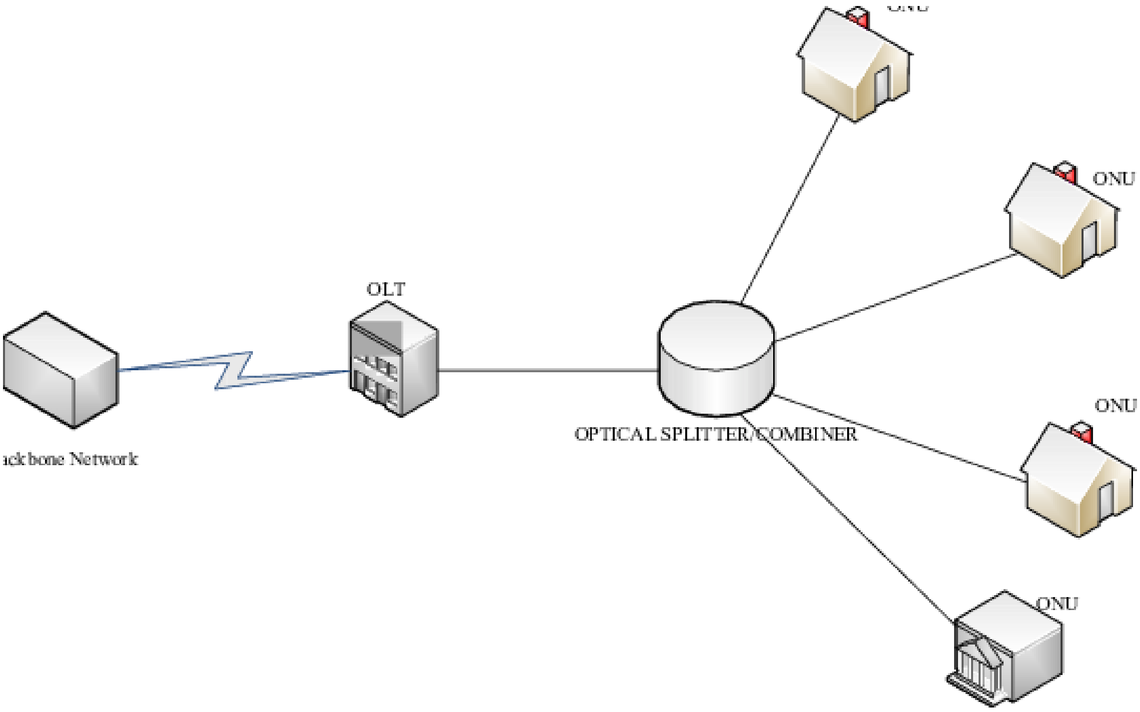

Fig. 2.1 Tree-based PON topology [6]

2.2. EPON vs GPON

The two main PON standards are the GPON defined by the ITU G.984 [4] and the EPON defined by the IEEE 802.3 ah [3]. These standards are very similar from the hardware point of view but the main difference is in the encapsulation of the information carried in the packets. GPON carries the information using the

GPON encapsulation mode (GEM) while EPON carries the information using Ethernet frames.

It is not easy to say which standard is better but given the wide domain of Internet and residential networks, from the point of view of end-to-end performance EPON is better suited than GPON [7]. A comparison between EPON and GPON since DBA is presented in Table 2.1.

Table 2.1 Basic features of GPON and EPON standards [8]

Feature	GPON	EPON
Standard	ITU G.984	IEEE 802.3 ah
Capacity Downstream	1244 / 2488 Mbps	1000 Mbps
Capacity Upstream	155 / 622 / 1244 / 2488 Mbps	1000 Mbps
Typical Split Ratios[1]	1:32 / 1:64	1:16 / 1:32
Distance Range	10 – 20 Km	10 – 20 Km
Maximum Data Rate	2.5 Gbps	1 Gbps
MAC (Framing)	GEM	Ethernet

2.2. EPON

EPON has defined new Ethernet MAC protocol by adding a Multiple Access Control (MAC) through Multiple-Point-Control-Protocol (MPCP) [9].

2.2.1. Multi-Point Control Protocol (MPCP)

MPCP is a mechanism for allowing efficient transmission of data in the upstream direction. MPCP is defined within the MAC control layer. MPCP can operate in two modes, one of them is called ‘auto discovery mode’ and is used during registration of new ONUs in the network, and the other one is called ‘bandwidth assignment mode’ and is performed continuously.

The main functionalities of this protocol are to provide a timing reference to synchronise ONUs, control the auto discovery process and perform bandwidth assignment to ONUs.

1 Split Ratio is defined as the number of ONUs serviced by an OLT.

2.2.1.1.MAC Control messages in MPCP

MCPC defines five MAC control messages:

- GATE: It is used to assign the bandwidth (timeslot and length to transmit) to the ONUs. GATEs contain two important values, the start time and the length window.
- REPORT: It is used by the ONUs to request the required bandwidth.
- REGISTER_REQ: Control message to request a registration in the network.
- REGISTER: Control message that contains the registration information.
- REGISTER_ACK: Control message to confirm that the registration has been done successfully.

GATE and REPORT messages are used in the bandwidth assignment mode operation. GATE, REGISTER_REQ, REGISTER and REGISTER_ACK are used in the auto discovery mode operation.

2.2.1.2.Bandwidth assignment operation mode

In the bandwidth assignment mode operation, the OLT manages the scheduling of the different transmissions of the ONUs. Fig. 2.2 illustrates how it works.

Firstly, the OLT sends a GATE to the ONU with the information of the timeslot assigned to the ONU and the window length. When the ONU receives a GATE, it has to wait until the start time to transmit. Then, the ONU transmits the data followed by a REPORT control message. This REPORT message contains the information regarding the queue status and the bandwidth requirement for the next transmission. Secondly, when the OLT finishes the cycle, it schedules the next transmissions considering the information received in the REPORT from the ONUs. Finally, the OLT sends the GATEs to the ONUs. The scheduling of GATEs is done by the dynamic bandwidth allocation algorithm which will be explained in the next sections.

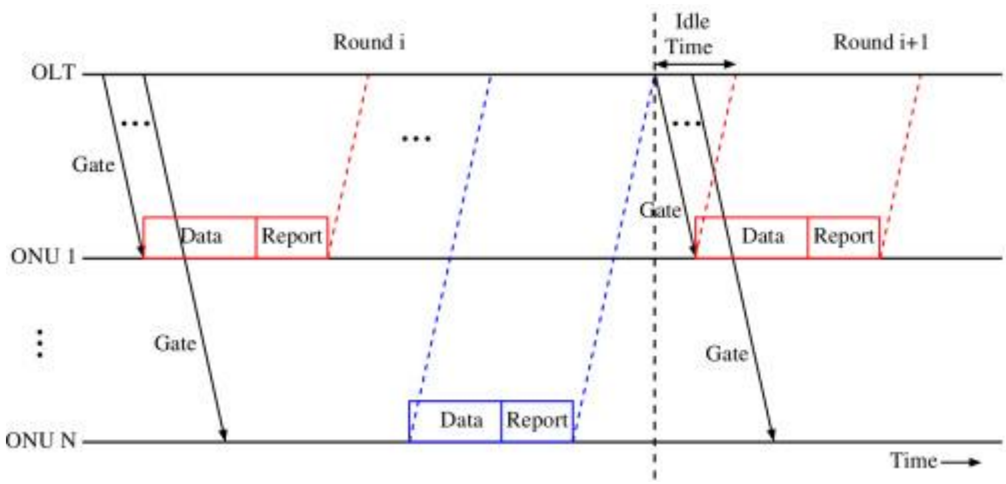

Fig. 2.2 Bandwidth assignment mode [10]

2.2.1.3.Auto Discovery operation mode

The auto discovery mode operation is used to discover the newly connected ONUs in the network.

The Discovery Agent at the OLT periodically starts an auto discovery window. In this interval of time, the ONUs that already have established a channel are not allowed to transmit. The OLT sends a discovery GATE informing to the ONUs the start time and the duration of the discovery window. Also, the discovery GATE contains the local OLT time timestamped by the MPCP. When an unregistered ONU receives the discovery GATE, ONU defines its local time as the local time received in the GATE. Secondly, the unregistered ONU will wait until the start time informed in the GATE, and then it will apply a random delay to avoid collisions with another unregistered ONUs. Thirdly, the unregistered ONU sends a REGISTER_REQ control message. This control message contains the ONU source address and the timestamp of REGISTER_REQ. In the fourth place, the OLT receives the REGISTER_REQ from the unregistered ONU. Then, the OLT saves the source address from the ONU and calculates the round-trip time (RTT) of the ONU (see section 2.2.2.1). In addition, the OLT sends a REGISTER control message to the ONU. This REGISTER message contains a unique identifier called Logical Link ID (LLID). This identifier is unique for each ONU and it is saved in the OLT side. Next, the OLT sends a GATE message to the unregistered ONU. Finally, when the ONU receives the REGISTER and GATE messages, the ONU sends a REGISTER_ACK message to the OLT. Therefore, OLT has registered the ONU in the network and it will be scheduled in the next pool transmission time.

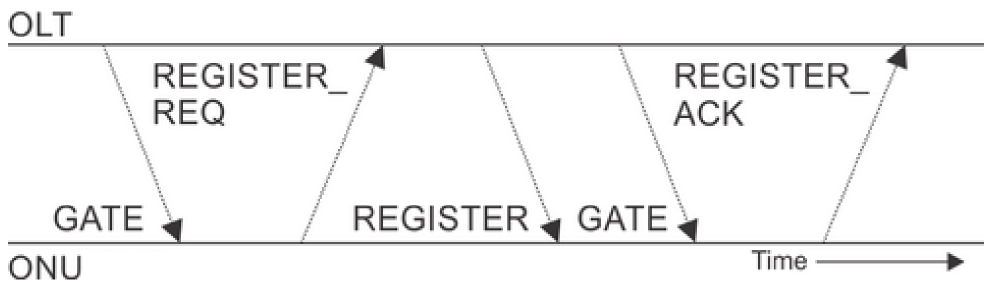

Fig. 2.3 Auto Discovery mode

2.2.1.4.Ranging process – RTT measurement

The ranging process is a method to synchronise the clocks of ONUs and OLT and compensate the propagation delay caused by the distance between the OLT and the ONU. This aspect is critical, because the upstream transmissions are scheduled based on the OLT local time. Therefore, in order to avoid the collisions in the channel the OLT has to know the round-trip time delays of each ONUs connected in the network, and compensate them. More details about ranging process can be found in [11].

As it has been described in the previous sections, the OLT sends GATE control messages to indicate the scheduling of each ONUs and also register new ONUs. This GATE is additionally used to timestamp the local time of the OLT. Every time an ONU receives a GATE, it updates its local time with the local time timestamped in the GATE message. Then, the ONU sends a DATA + REPORT message or a REGISTER_REQ with local time timestamped. Then, when the OLT receives the REPORT or REGISTER_REQ messages it calculates the RTT of each ONU (see Fig. 2.4).

$$RTT = OLT\ localtime - ONUi\ timestamp, \\ where\ i\ is\ the\ ONU\ number \tag{2.1}$$

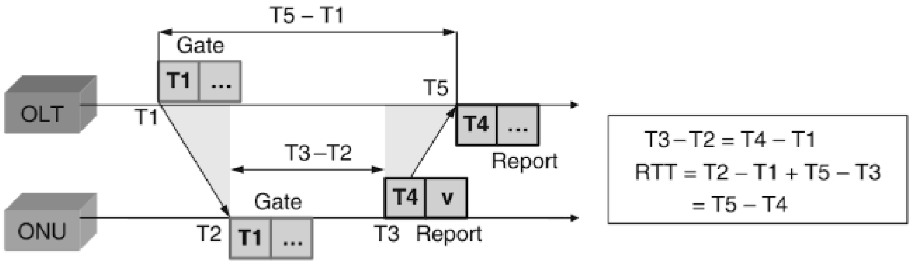

Fig. 2.4 Ranging Process [11]

2.3. Evolution of PONs

Passive Optical Networks are a good option of access networks in terms of cost-effectiveness. As these networks do not have active elements except the OLT and ONUs their deployment and maintenance are cheaper than other technologies.

Due to the high bandwidth demand in the last years, operators need to migrate to the so called Next-Generation Access (NGA). Besides, these new NGA PONs are going to play an important role in 5G backhaul and fronthaul [2].

Legacy PON standards are based on a single channel shared in the upstream and scheduled by TDMA. NG-PONs introduce Wavelength-Division Techniques (WDM). Therefore, the current TDM-PON networks are being or will be migrated to WDM-PON or hybrid TWDM-PON. The content of this section has been referenced in [8] and [12].

2.3.1.10G-PON

10G-PON is the update of the GPON standard defined by the ITU-T. This update increases the bandwidth from 2.5 to 10 Gbps. This standard is defined in the recommendations ITU-T G.987 and G.988.

The update increases the data rate in the downstream to 10 Gbps, and in the upstream can be 2.5, 5 or 10 Gbps and they have different name depending on the bandwidth.

- Asymmetric 10G-PON specified as XG-PON1 should have 10 Gbps in downstream and 2.5 or 5 Gbps in the upstream.
- Symmetric 10G-PON specified as XG-PON2 should have symmetric rate having 10 Gbps in downstream and 10 Gbps in upstream.

Besides, the 10G-PON also includes the using of WDM techniques, meaning that the migration can be done at the same time or in parallel.

2.3.2.10G-EPON

10G-EPON standard is defined by the IEEE in the publication IEEE 802.3av [13] and it can be compared with the 10G-PON standard but using Ethernet frames instead of GEM.

This standard supports two kinds of configuration and they are similar to 10G-PON differentiating between asymmetric and symmetric configurations.

- Asymmetric 10G-EPON with 10 Gbps in downstream and 1 Gbps in upstream.
- Symmetric 10G-EPON with symmetric rate having 10 Gbps in the downstream and upstream.

The IEEE 802.3av standard also describes ‘the rules’ for compatibility of 10G-EPON and the 1G-EPON networks. That means that an OLT can transmit 1 Gbps and 10 Gbps wavelengths simultaneously. These rates are separated in the wavelength domain, with 1 Gbps is limited to 1480-1500 nm band and 10 Gbps is limited to 1575-1580 nm band. The OLT can transmit in different rates in downstream and downstream, as shown in Table 2.2.

Table 2.2 OLT/ONU types of implementation

OLT Implementation	Supported ONU types
Downstream: 2 wavelengths Upstream: single rate	1G-EPON ONU 10G/1G-EPON ONU
Downstream: single wavelength Upstream: dual rate	10/10G-EPON ONU 10/1G-EPON ONU
Downstream: 2 wavelengths Upstream: dual rate	1G-EPON ONU 10/1G-EPON ONU 10/10G-EPON ONU

2.3.3. WDM-PON

One of the most attractive techniques to increase the bandwidth available is to increase the number of wavelength channels and thus multiply the PON capacity.

WDM-PON has a special architecture in order to achieve the wavelength division. Optical splitters have an array for guiding the different transmissions incoming from the ONUs. This array is called Arrayed Wavelength Grating (AWG). In the base model presented in Chapter 4 the AWG is used in the splitter [5]. This device works as follows: in downstream it splits the optical signal to broadcast the optical signal and in upstream it multiplexes the optical signal from the different ONUs. It is just a passive optical device, and it introduces some losses.

2.3.4. Hybrid WDM/TDM-PON

Current PON technologies use a single channel shared following TDM. An attractive solution is presented in NG-PON1 [14] standards. NG-PON increases the bandwidth and also achieves a cost-effectiveness improvement through combining WDM and TDM techniques.

In the hybrid TWDM-PON the users can transmit through different carriers and also, these carries are shared with TDM. Thus, the system bandwidth is increased directly with the number of carriers and these carriers are shared between all network users. The hybrid configuration can be used in GPON, EPON, 10G-PON and 10G-EPON, but only with asymmetric bandwidth. The baseline for TWDM in NG-PON1 uses 4 carriers per ONU. This configuration increases the complexity of the scheduling algorithms.

NG-PON2 standards define an architecture capable of a total network bandwidth throughput of 40 Gbps. Also, each end-subscriber must have 10 Gbps symmetric upstream/downstream speeds available and they can transmit on the 4 available wavelengths, by using multicarrier configuration. NG-PON2 networks must have the following characteristics: channel shared with TWDM, ONUs can be served by different wavelengths.

CHAPTER 3. Bandwidth Allocation in PONs

Chapter 3 presents the bandwidth allocation in PON describing the crucial role of DBAs. Besides, it presents in detail IPACT, an algorithm based in TDMA, and finally presents the concept of laser tuning delay.

3.1. Introduction to Bandwidth Allocation in PONs

Bandwidth Allocation is a technique to manage the shared bandwidth in PONs. Specifically, it is a method to manage the bandwidth efficiently and dynamically on the upstream channel. For this purpose, there are different techniques and they consider different resources as round-trip time, length of packets, ONU’s loads… By analysing these resources an algorithm decides how the channel resources will be used. PONs must be compliant with some standard like EPON or GPON. But, these standards do not consider the bandwidth allocation. Therefore, DBAs are open for vendors to innovate.

There are some reasons for choosing a good bandwidth allocation algorithm:

- The resources will be managed depending on ONU’s demands.
- Networks can add more subscribers if resources utilization is more efficient.
- The end subscribers will enjoy of better quality of service because the bandwidth allocation will be managed depending on users’ requirements.
- Streams can have Service Level Agreement (SLA)/priority assigned depending on the service. For instance, an IP Telephony service may require less latency than an IP TV service.

There are two kinds of bandwidth allocation algorithm, static or dynamic:

- Static: A static algorithm fixes the amount of bandwidth to each ONU. Normally, it is fixed by timeslot. This timeslot just depends of the contract that the user has with the internet provider company.
- Dynamic: A dynamic algorithm does not have a fix bandwidth assigned. Also, bandwidth allocation is based on demand of each ONU.

By definition, a dynamic algorithm is more efficient that a static algorithm because the allocation is based on the demand. The algorithms considered in this thesis have been dynamic.

3.2. Classification of Dynamic Bandwidth Algorithms

DBAs can be classified depending on the DBA computation, cycle size and scheduling framework, as illustrated in Fig. 3.1. DBAs can be centralized or distributed. In a centralized algorithm the scheduling decision is taken solely by the OLT. ONUs just transmit the information about their queues to OLT, who decides on the bandwidth assigned. On the other hand, in a distributed algorithm the decision is taken by the OLT too but, the ONUs also play a role. For example, they may be calculating constantly the traffic load of network. Then, this information is transmitted to the OLT who decides.

Another classification of DBAs might be in terms of the cycle size. In a variable case the cycle size is determined by the ONUs requirements. Finally, the scheduling framework can be online, offline or hybrid. An offline algorithm waits for all the report messages before scheduling the transmissions. An online algorithm schedules the transmissions as soon as report messages are received. Finally, a hybrid algorithm is a combination between online and offline algorithm. This algorithm waits to schedule the transmission until the cycle time is finished, then the algorithm schedules its transmission considering the different report messages available.

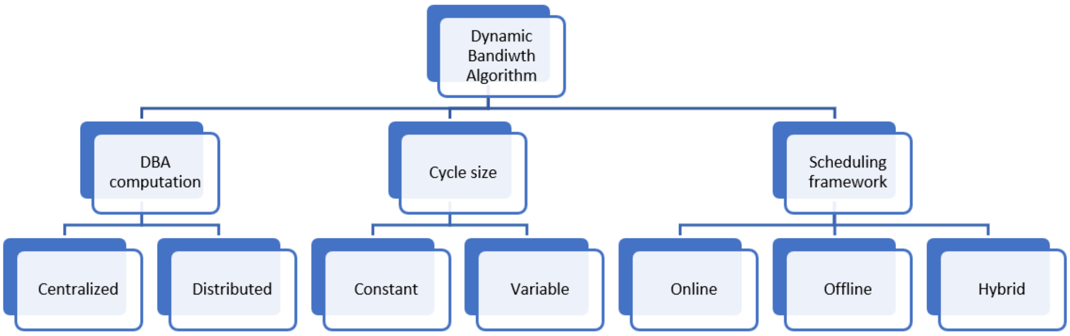

Fig. 3.1 Categorization of DBA algorithms [8]

On one hand, in a centralized scheme algorithm, the allocation decision power is centralized in the OLT. For example, the Interleaved Polling with Adaptative Cycle Time (IPACT) algorithm explained in section 3.3. On the other hand, in a distributed scheme algorithm, the allocation decision is shared among all the ONUs and the OLT of the system. ONUs have the capacity to estimate the global free capacity and proportionally perform requests based on the state of their queues. An example of distributed scheme algorithm is the Distributed Dynamic Scheduling for PON (DDSPON) [15]. This technique uses a weight vector who calculates the load of the system. This vector is saved in the OLT and it is sent to each ONUs in the GATE message. Then, ONUs calculates their weigh based on the global weigh vector and send the information to the OLT into the REPORT message.

3.3. IPACT

IPACT (Interleaved Polling with Adaptative Cycle Time) [16] is the reference mechanism for EPON DBAs since its creation.

In IPACT, the cycle period adjusts to the bandwidth requirements of the ONUs. It also defines a maximum transmission length in order to avoid ONUs with high traffic monopolizing the bandwidth. In IPACT, every ONU analyses their queues before requesting a transmission length. Then, the OLT analyses all the ONUs reports before scheduling their transmission.

Fig. 3.2 illustrates how IPACT works.

1) In the first step (a), the polling table contains the REPORT of ONUs 1, 2 and 3, as well as, the round-trip time (RTT) value which is used to calculate the start time. The OLT sends a GATE assigning 6000 bytes to ONU 1. Then, ONU 1 begins to transmit the window length assigned. Followed by the data there is a REPORT message which contains the next transmission data requirement of ONU 1.

2) In the second (b) step, while ONU 1 is transmitting its data, the OLT transmits a GATE message to ONU 2 with an assignment of 3200 bytes of window length. The OLT can send the GATE message before receiving the ONU 1 packets because it knows the RTT values and start time assigned to ONU 1. Therefore, there will not be any collision.

3) In the third step (c), the OLT updates its polling table because it has received a REPORT message from ONU 1. Also, the GATE message for ONU 3 is transmitted too. That means that all the transmissions of this cycle have been scheduled.

4) Finally, in the last step (d) the OLT updates the polling table with the REPORT message received from ONU 2. At the same time, the ONU 3 is transmitting its data message followed by a REPORT with the new length transmission requirement.

In summary, the OLT assigns timeslots in a cyclic order to the ONUs. In this timeslot, each ONU transmit ‘DATA + REPORT message’. Then, the OLT updates its polling table and schedules the next transmission for the next cycle. Before scheduling the next transmission based on the ONU requirement, the OLT compares if the length required is less the than maximum window allowed. If it is not, the length assigned will be the maximum one.

$$BW_i \leq BW_{max} + REPORT\ message \qquad \textbf{(3.1)}$$

This algorithm provides advantages such as good channel utilization and efficiency, but it incurs in high delays and jitter because of the variable polling cycle times. As shown in Fig. 3.1, IPACT is centralized and has a variable cycle time.

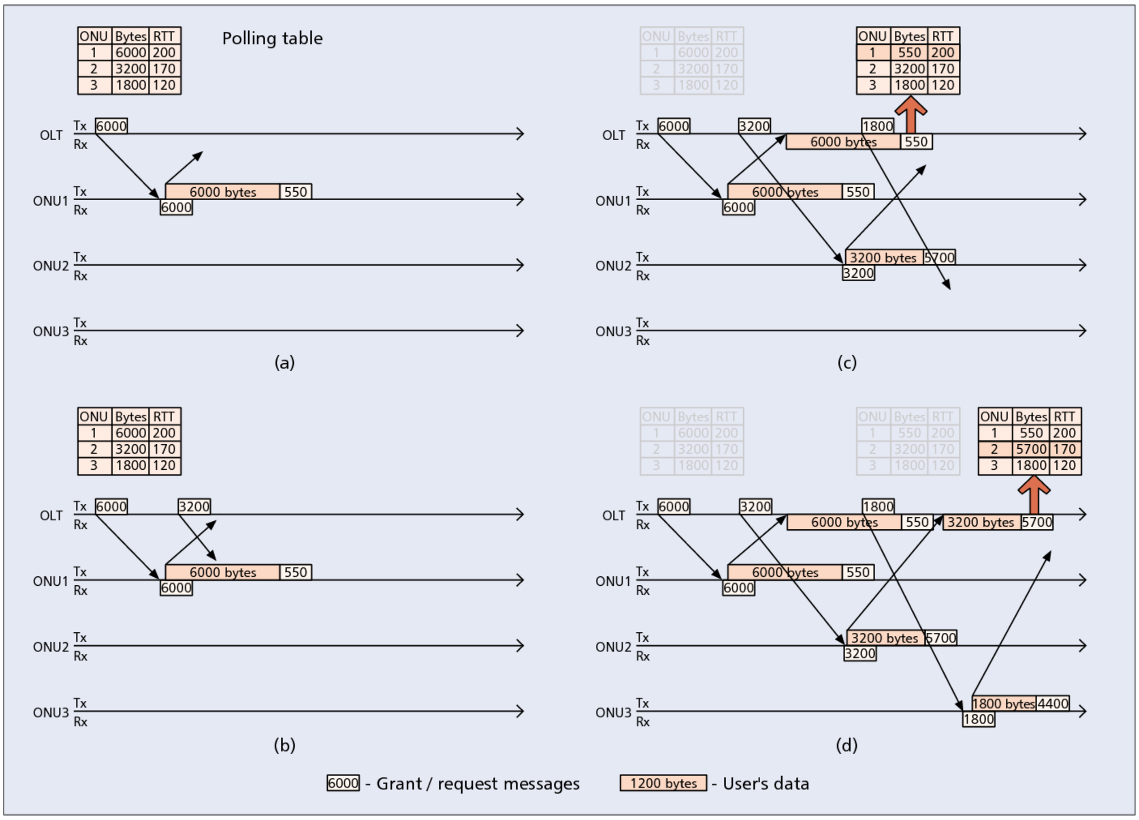

Fig. 3.2 Example of IPACT operation [16]

3.4. Dynamic Bandwidth allocation with multicarrier

With the Next-Generation PON (presented in Section 2.3) in order to increase the system bandwidth a new technique is implemented by using multiple optical carriers. The dynamic bandwidth allocation algorithms have to consider that in one channel more than one ONU can transmit and the ONUs can transmit on different carriers. For scheduling the channel transmissions two algorithms have to coexist: a TDM algorithm (such as IPACT) schedules the channel assigning timeslots to ONUs and another WDM algorithm should decide which carrier is going to use a specific ONU for the next transmission. In order to keep compatible with legacy equipment, the messages exchanged between OLT and ONUs must be kept unchanged or at most extended with extra information.

3.4.1. Laser Tuning Time Delay

In WDM algorithms the DBA in the OLT decides which wavelength is going to use each ONU for its transmissions. When the algorithm decides for one ONU its wavelength it might happen that this wavelength is different from the wavelength used in the last transmission. In this case, the laser of the ONU has to tune the new wavelength, causing a delay called ‘Tuning Time Delay’. In this document each ONU will have a multicarrier fiber able to transmit through four wavelengths.

According to the ITU-T G.9802 recommendation [17], the tuning time delays can be categorized in three classes:

- Slow: 25 ms to 1 s
- Middle: 10 μs to 25 ms
- Fast: < 10 μs

CHAPTER 4. Statement of the problem and objectives

Chapter 4 presents a statement of the problem and objectives. It explains all the challenges faced regarding the base code and the implementation our own algorithm.

4.1. Statement of the problem and objectives

This project has the main goal to design, implement and test our algorithm. The implementation will be done with the OPNET simulator. An introduction to OPNET and its main functionalities can be found in Annex 7.

We had access to the OPNET code used in an EETAC Master Thesis [5] that we used as base for our simulations. But the base model had some issues to be fixed. In order to fix these problems, it was necessary first an effort to acquire the knowledge about 1/10G-EPON defined in the standard IEEE 802.3ah and IEEE 802.3av, and to understand how OPNET software works. The first goal was to fix some errors in the current state of the code (since it passed through different students) and adapt the code to newest version of OPNET. These problems are explained in section 4.2.

In the first chapters of this project we have presented concepts such as DBA for single carrier and multicarrier systems. The configuration selected to carry on our work was a centralized configuration based on TDM and WDM with multicarrier. These new algorithms have to be able to assign the timeslots for the ONUs transmissions, avoiding collisions. On the other hand, DBA should decide which wavelength will be used for the different transmissions. In this document the DBA agent placed on the OLT uses IPACT.

Regarding multicarrier configuration, the DBA agent has to decide which wavelength is the best option to transmit in each time that OLT receives a REPORT message. As was presented in Chapter 3, by using multicarrier configuration the ONUs have to tune a laser for transmitting in different wavelengths. Each time that any ONU has to change its laser configuration it needs a Tuning Time Delay. Therefore, our Multicarrier DBA must consider the tuning time delay. In fact, it should be able to schedule the timeslots intelligently to minimize the system delay. For achieving the objectives proposed we first studied the scientific literature analysing different kinds of algorithms. We focused on online DBAs with multicarrier capabilities or tuning time laser. The knowledge acquired after analysing the different papers was used to design the new algorithm.

Finally, a new algorithm that complies the requirements of this project will be presented. We describe its pseudocode, its implementation over the base model and finally, the tests and obtained results.

4.2. Base Model

The base code for multicarrier PONs was created by Marc Carné, who implemented WDM adding 8 wavelengths available for each ONU [5]. Then, the project was continued in Paola Garfias PhD thesis [12] by adding an intelligence algorithm to sleep or wake up the lasers wavelengths depends on the network load, this introducing energy-saving capabilities.

Considerable effort has been performed in order to understand how the code works and how was implemented.

The EPON model is composed by sixteen ONUs distributed by a splitter which is connected to the OLT. In principle, this code worked with eight wavelengths. Four of them worked at 1 Gbps and the other four wavelengths worked at 10 Gbps. The EPON model is compliant with the IEEE 802.3ah standard. This model was a TDM-PON using the centralized IPACT algorithm.

First of all, the code was analysed and compared against [5] in order to ensure that the EPON was working successfully. In this analysis step we find some issues with the functionality of the models. Some stopped working, because of the upgrade to a newer OPNET version.

Furthermore, the 10 Gbps code was analysed against [5] obtaining successful results. However, after analysing the results we found some incongruences in the behaviour and we abandoned the 10 Gbps case. That is why we implemented the algorithms and analysed them in 1 Gbps code. Annex 1 and 2 include a more extensive explanation and show the validations.

CHAPTER 5. Description and Validation of the base model

Chapter 5 presents the base code over we built our simulations. We also describe some modifications needed in order to get the model running on OPNET simulator. Finally, it describes the functions we added to implement our algorithm.

5.1. EPON model

The model contains sixteen ONUs. These ONUs are connected to a splitter/combiner device through eight upstream channels of 1 Gbps. The splitter/combiner is connected through eight upstream channels of 1 Gbps. These eight channels represent the different wavelengths available in each ONU. The downstream uses an unique channel of 1 Gbps of bandwidth, because in the downstream direction there are no restrictions of changing wavelength. The OLT has all the lasers always available and also the ONUs have a receiver for all the available wavelengths in the system. Therefore, the restriction is in the upstream where the OLT has to manage the different wavelengths of each ONU and change the transmission wavelength when it is necessary. By having only one downstream channel the model is easier to manage and it is not necessary to study its behaviour because it does not have very restrictions in terms of bandwidth and delay.

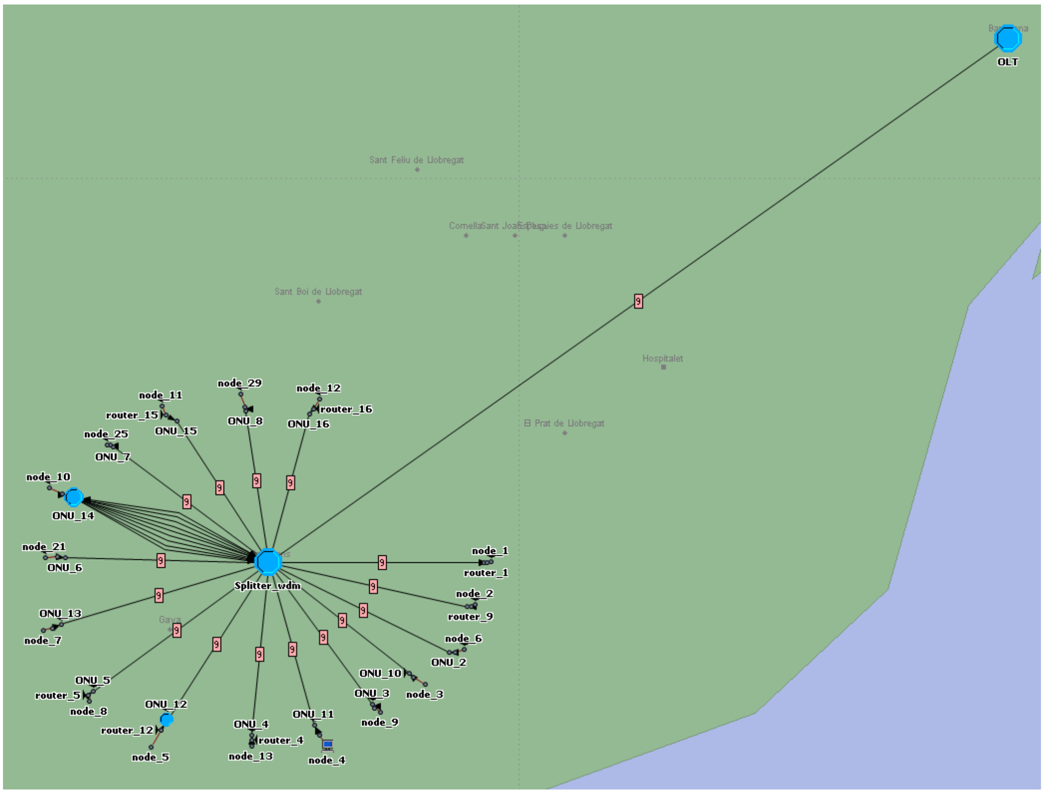

Fig. 5.1 EPON model in OPNET

5.2. ONU model

The ONU is modelled by a node that contains several process models which define the ONU behaviour.

First of all, it has been considered that the ONU model is composed of several node models to do simplify the explanation: workstation, router and ONU.

Workstation defines some traffic source parameters: the data rate, the data distribution function, packet length or Hurst parameter, among others. In our simulations we used a self-similar source [18] and this source can be changed in this node model just changing some parameters in the edit attributes options (see Fig. 5.2). The interarrival packet time should be defined in the simulation sequence editor as input attribute value.

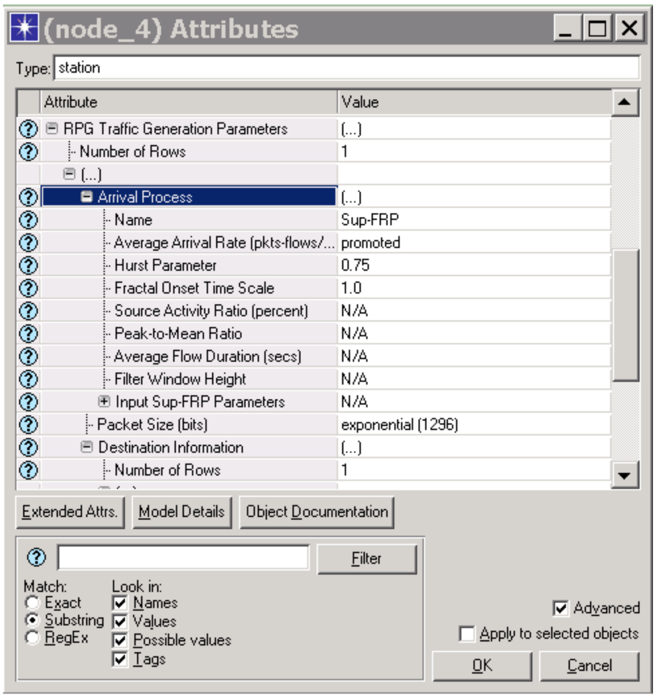

Fig. 5.2 Workstation attributes in OPNET

The workstation is connected to a router node. The router node is the responsible for generation of the traffic in OPNET to the ONU with the packet format defined.

Finally, the ONU model has two inputs and eight outputs. One input is for receiving the traffic from the router and the other one is for receiving the traffic from the GATE messages from the OLT. The eight outputs represent the different wavelengths.

The ONU has an internal clock of 16 bits according to the standard [3], meaning that in a 1 Gbps link system the clock tick should be defined as 16 ns. For 10

Gbps link this clock must be defined as 1.6 ns. Equations 5.1 and 5.2 show the calculation of the clocks.

$$Clok\ tick\ time\ (1Gbps) = \frac{clock\ length}{bit\ rate} = \frac{16\ bits}{1\frac{Gbits}{s}} = 16\ ns \tag{5.1}$$

$$Clok\ tick\ time\ (10Gbps) = \frac{clock\ length}{bit\ rate} = \frac{16\ bits}{10\frac{Gbits}{s}} = 1.6\ ns \tag{5.2}$$

In consequence, there are some variables into the processes models that should be modified, for instance, the ‘control_multiplexer_discovery’ and ‘gate_rx_discovery’.

The ONU model has to consider that the throughput data can be sent via different outputs, but only though one at the same time. To achieve this behaviour, when a GATE is coming the ‘control_parser_discovery’ model is called to parse the packet and read which wavelength has been assigned by the OLT DBA algorithm. Then, the model called ‘control_multiplexer_discovery’ is called and it adds a new variable for the multiplexing process. This variable was defined in [5].

Finally, before transmitting the packets to the OLT, the ONU model reads the wavelength assigned by the OLT in the GATE message.

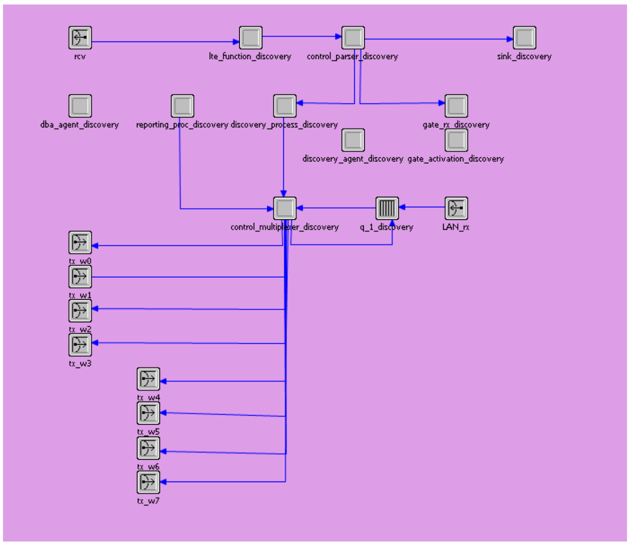

Fig. 5.3 ONU model

5.3. OLT model

We describe in this section the OLT model functionality, but more details about the DBA Agent process model (responsible of executing the scheduling algorithm implemented in the project) can be found in Chapter 6.

The OLT model has one output. Through this output it sends the GATE messages to the ONUs in the network.

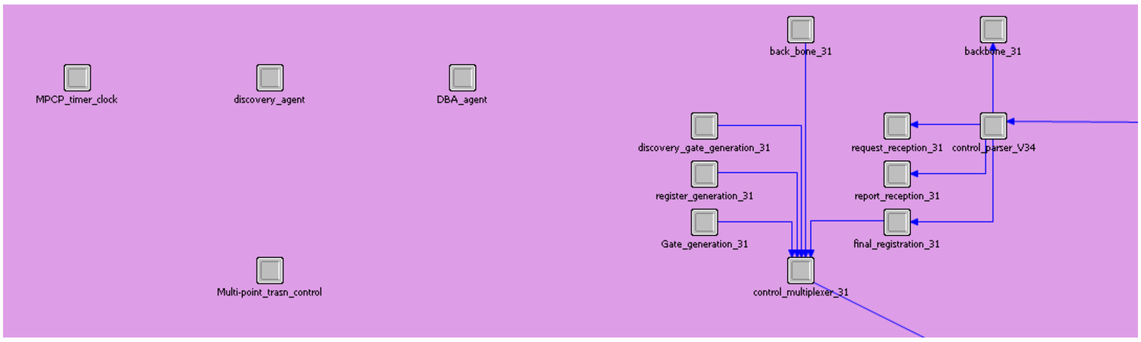

Fig. 5.4 OLT model

The OLT also includes the DBA_Agent. The DBA_Agent is the process modeler which computes the DBA algorithm in the project. The DBA algorithm used in this project has been the Next Available Supported Channel (NASC) algorithm, and it was implemented in [5]. The NASC algorithm can be found into the function block of the DBA_Agent process model. This algorithm iterates all the available wavelengths of each ONU and selects the earliest wavelength that is going to be free.

The tuning delay was not considered in [5]. Thus, some modifications have been done in order to apply this tuning delay every time an ONU changes its transmission wavelength. We considered that the tuning time delay will be transparent for the ONU side. Since the OLT has all the information regarding which wavelength is being used by each ONU, the tuning time delay will be applied directly to the scheduling of each ONU transmission. This tuning time delay control has been added into the DBA process model.

We present the Pseudocode of the tuning time controller:

1) **If** wavelength **of** current ONU **is equal** last wavelength **then:**
2) **Do not** apply tuning time delay
3) **Else**
4) **Apply** tuning time delay

The tuning time delay parameter has been added by modifying the internal code of the project. The parameter has been added in the OLT attributes as a new field. We want to maintain the project as understandable as it possible. Thus, the delay can be modified for anyone without knowing the functionality of code. The delay is expressed in seconds (see Fig. 5.5).

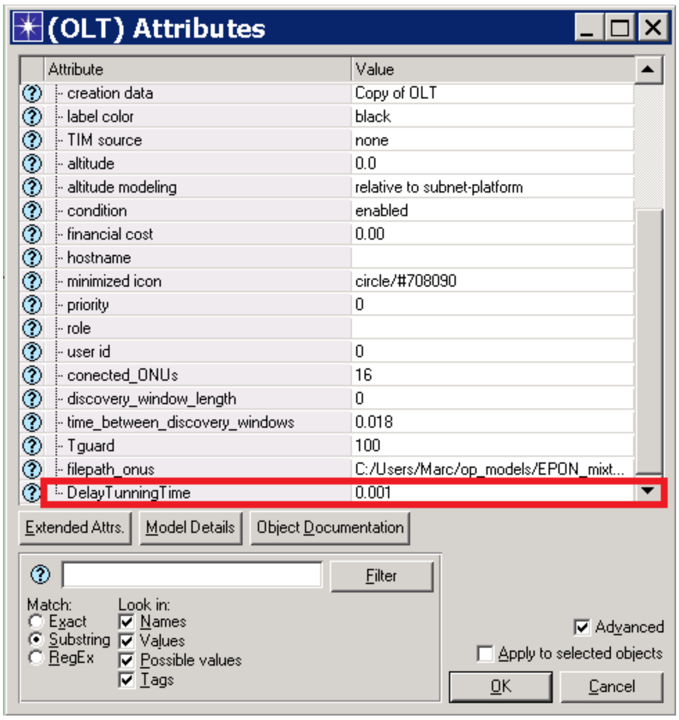

Fig. 5.5 Delay Tuning Time in seconds

After adding a tuning time delay controller, the algorithm has been modified to introduce intelligence at the time to decide if the wavelength will be changed. The new algorithm implementation will be explained in Chapter 6.

When the DBA algorithm has decided which wavelength will be used for a next ONU transmission, the OLT has to inform the ONU about it by writing the wavelength in the GATE packet (see Fig. 5.6) before sending it to the ONUs. The packet format was modified as described in [5].

5.1. Splitter/Combiner model

Splitter and combiner are passive modules, meaning that there should not be any packet processing (not even a delay).

The Splitter is the responsible of dividing the channel from the OLT to the ONUs. Theoretically, this process should introduce power loss because the signal is divided between N outputs without amplifying it, since the physical layer parameters are outside the scope of this work, we did not modify that.

On the other hand, the combiner is the responsible of adding all the signals from the ONUs. Again, this module is completely passive.

In our work there are sixteen ONUs and each ONU, supporting eight wavelengths. The connections have the following names:

- OLT-Splitter-ONU: RX_OLT_AWG to TX_AWG_ONUi where i is the ONU index (only one channel for each ONU because it is the downstream direction).
- ONU-Combiner-OLT: RX_ONU_AWGi_wj to TX_OLT_AWG_j where i is the ONU index and j is the wavelength index.
-

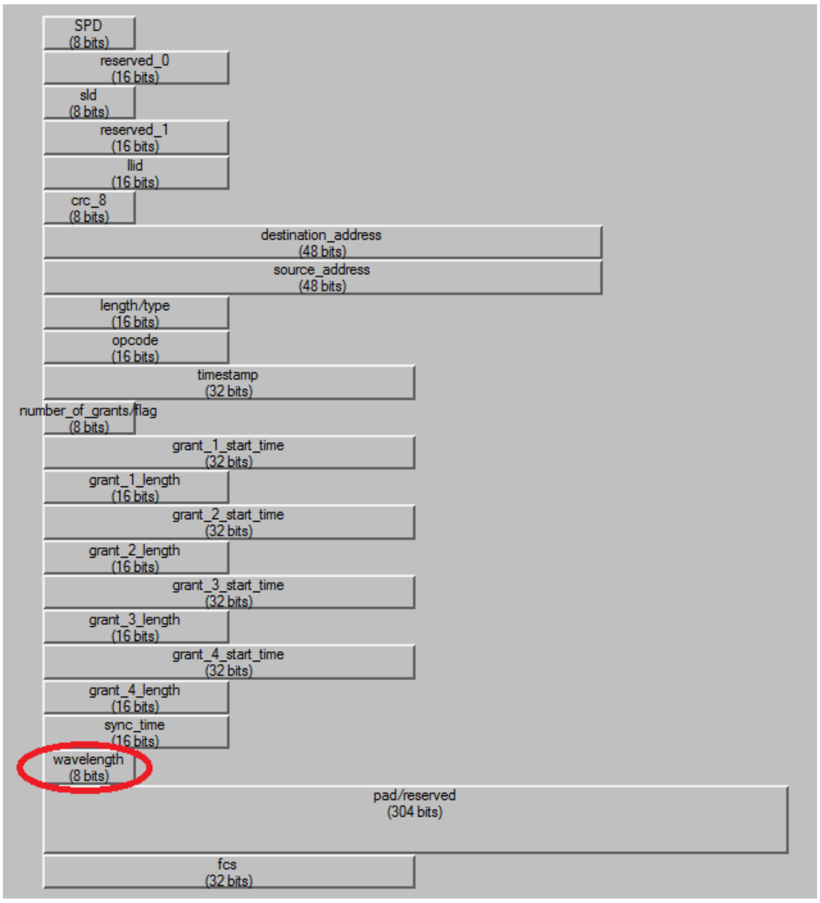

Fig. 5.6 GATE packet format with the wavelength extension

5.4. Support of multiple wavelength in the code

Normally, for the simulations carried out in this project the most restrictive configuration has been selected in order to test the algorithms in the worst conditions. But the network model offers possibility to select the different available wavelengths for each ONU. Thus, different combinations can be simulated in order to analyse the behaviour of the network.

In the attribute options of the OLT there is a field called 'filepath_onus' (see Fig. 5.7). This field has to be filled with a path to a CSV file with the format explained below.

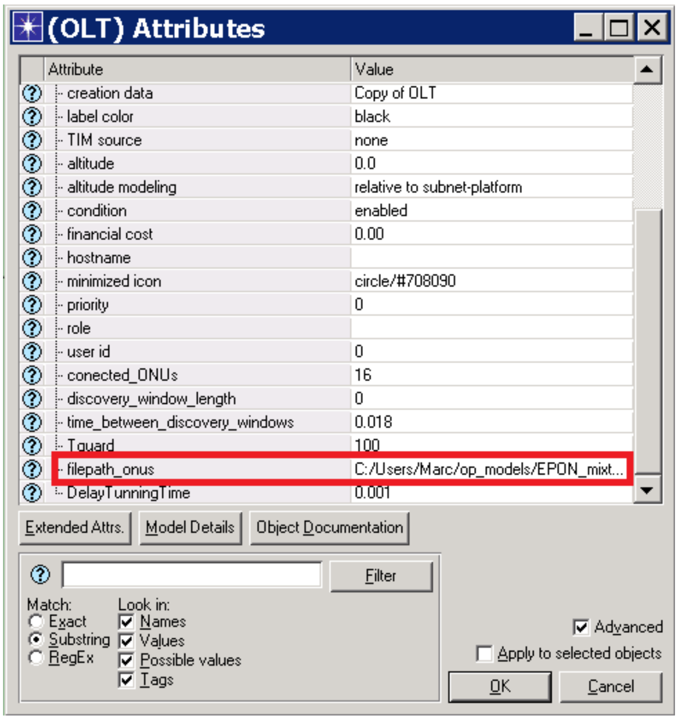

Fig. 5.7 File path for the assignment of wavelengths

The CSV file has to follow the format shown in Fig. 5.8. The file is organized by lines, and each line has part of the configuration. The first line has 'ONU;1;1'. This column is informing about the distribution of the next lines. Let's see the parsing of these line:

- 'ONU': number of ONU
- ';': separator
- '1': bandwidth (1 Gbps) the first group of four wavelengths (w3, w2, w1, w0)
- ';': separator
- '1': bandwidth (1 Gbps) the second group of four wavelengths (w7, w6, w5, w4)

The next following contain the information of the wavelengths supported for each ONU following the above format. For example:

Line: '06;1111;0000'
Parsing: '#ONU;w3w2w1w0;w7w6w5w4'

The wavelengths are divided in groups of four because the standard says that the maximum wavelengths available in one ONU are 4. In the previous version of the code [5] the first four wavelengths were for 1 Gbps bandwidth and the other four for 10 Gbps bandwidth. But, as a problem with the 10 Gbps was found in our project we modified it to use only the 1 Gbps links (more information can be found in Annex 1 and 2).

Table 5.1 Parsing of supported wavelengths

	Is the wavelength supported?							
ONU	W0	W1	W2	W3	W4	W5	W6	W7
06	Yes	Yes	Yes	Yes	No	No	No	No

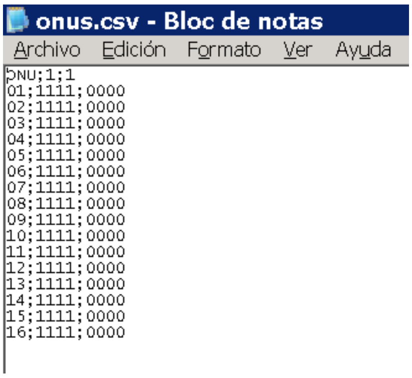

Fig. 5.8 Example of the CSV file format for supporting wavelength configuration

5.5. Solving ONUs' transmission issues

The first step in our project was to validate that the simulation code was working correctly. After doing some simulations it was discovered that ONUs 1 and 16 were not working. ONU 1 always transmitted on wavelength 1 without caring which wavelengths were assigned, while ONU 16 did not work under any condition.

The ONUs have some variables to identify which ONU is working at a specific moment and which wavelength has been assigned. These variables have been defined as can be seen in Table 5.1.

Table 5.1 Variables ONUs

VARIABLE																
NUMBER_ONU	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	0
WL_ONU	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
MAC_ONU	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16

The variables are called as ‘NUMBER_ONU’,’WL_ONU’ and ‘MAC_ONU’. These variables are for identifying which ONU we refer to and its wavelength assigned.

The flow of packets was analysed step by step, and we discovered that the problem was that the source address MAC address in the packets was wrong. After analysing the possible issues, the problem was fixed by modifying some variables (they were not defined as integer and they should). Probably, this error was due to an update of last version of OPNET. Currently, ONUs one and sixteen are working correctly.

CHAPTER 6. Analysis and Simulations of DBA algorithms

Chapter 6 describes and analyses some DBA algorithms proposed in scientific literature. These algorithms have particular characteristics needed for implementing the new algorithm proposed for solving the goals presented in Chapter 1. Finally, the chapter describes the implementation of our algorithm.

6.1. Analysis of DBA Algorithms

This section presents different characteristics of bandwidth allocation algorithms. These characteristics are taken as reference from different researchers' papers and they are going to be considered during the design of our algorithm.

6.1.1. Offline vs online algorithms

As explained in Section 3.1 Dynamic Bandwidth Allocation algorithms can be online or offline. The first difference between them is that offline algorithms have to wait for all the reports from the ONUs to arrive before scheduling the next transmission cycle. From a channel optimization point of view, offline algorithms perform better because the DBA agent of the OLT has all the information about the bandwidth requests to do the scheduling and therefore, the decisions are made with more information. But they have a big disadvantage in front of online algorithms from a time efficiency point of view: the channel might be empty while the OLT is waiting to have all the reports. This is bad, because nowadays there are a lot of applications that need to have low delays.

Online algorithms, unlike offline algorithms, as soon as they receive a report from any ONU, schedule its transmission. The advantage of using online algorithms is that the waiting time for the ONUs to transmit is usually lower than offline algorithms. On the other hand, the online algorithms cannot optimize the channel as an online algorithm does because the DBA agent does not have all the information to schedule the channel.

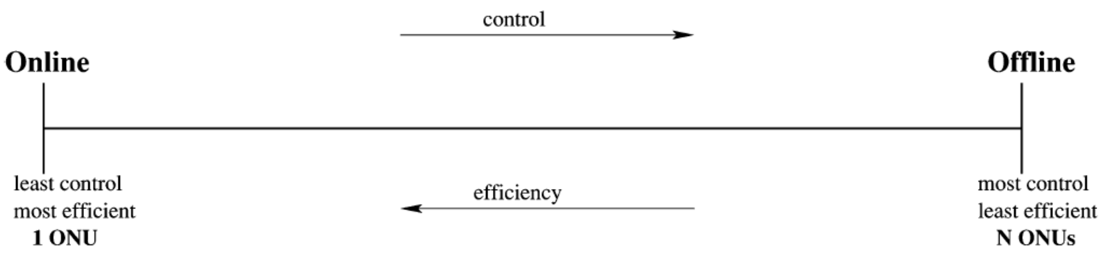

Fig. 6.1 Online vs Offline algorithms

A hybrid algorithm is a combination between offline and online algorithms. These algorithms decide to schedule the transmissions depending on the reports that they have and the scheduling status. Some transmissions will be scheduled as online other ones will be scheduled for the next cycle time. An example can be found here [14].

In this project we have focused in online algorithms.

6.1.2. Hybrid WDM/TDM scheduling algorithm

Paper 'Scheduling Hybrid WDM/TDM Passive Optical Networks With Nonzero Laser Tuning Time' referenced in [14] has been studied in order to understand and implement the idea of considering the tuning time delay in our algorithms. The paper claims to be the first one to take into account the tuning delay time of ONUs at the time that they have to change their wavelengths.

There are four kind of algorithms in the paper. The one we selected for understanding was he fourth called 'Heuristic Non-pre-emptive Scheduling'. We considered to study the fourth algorithm in the literature scientific because is the last version, while the other three algorithms are previous designs before having the final algorithm.

This algorithm operates offline. As our algorithm works in an online fashion, this paper has been taken only as reference. In summary, the algorithm iterates all the jobs (reports from ONUs) and sort them by processing time. The next step is to schedule the jobs in the wavelength assigned in the previous cycle if its processing time does not overcome the tuning delay. If the tuning time delay is bigger than the waiting time for the new wavelength it will be scheduled in the preassigned wavelength obtained by the MULTIFIT algorithm. The MULTIFIT algorithm basically sorts in descending order by tasks lengths, defining a lower and upper threshold. Then it schedules the task by starting with the lowest one without exceeding schedule length. More information about MULTIFIT algorithm can be found in [19].

6.1.3. Just-In-Time Scheduling for Multichannel EPONs

We focus on TDM and WDM algorithms. In this project, the TDM is provided by the use of IPACT (see Section 3.3). The algorithm described in this section is focused on the analysis of the WDM part of our ONUs.

The concepts presented here come from [20]. Just-In-Time (JIT) is a concept that means that the resources have to be delivered in the moment that are necessary. In WDM scheduling it means that the OLT has to schedule the start time transmission of the ONU just in the moment that channel is going to be free. It can be achieved because the OLT knows the round-trip time (RTT) value of each ONU. Thus, when an ONU transmission is scheduled, the start time has to be configured at least a time equivalent to a RTT before. By using this technique, the channel is used more efficiently because it will not be free waiting for ONU transmissions. Equation 6.1 shows the calculation of the next start time for an ONU.

$$T_{scheduled} = T_{free} - RTT + T_{GATE} \tag{6.1}$$

where,
$T_{scheduled}$ is the start time of the scheduled transmission.
T_{free} is the time when the wavelength is free.
RTT is the time from OLT to the ONU and return.
T_{GATE} is the processing time of the GATE message.

Besides, the algorithm has to follow a scheduling policy such as one of the following options (more information can be found in [20]):

- NASC: Next Available Supported Channel, where a job will be scheduled in the wavelength that will be available earlier.
- LFJ: Least Flexible Job, where the ONUs are sorted in ascending order on the basis of the number of channels supported by each ONU. ONUs with minimum number of supported cannels should at the top of the list and ONU with maximum number of supported channels should be at the bottom of the list.
- SPT: Shortest Processing Time, where the first jobs scheduled will be which ones have the smaller process time. There is a threshold to avoid that ONUs with long processing time do not starve.

6.2. Definition of the Algorithm

We now provide more details of the algorithm.

6.2.1. NASC JIT algorithm

The algorithm implemented in this project has been the Just-In-Time online algorithm described in [20], [21] and [22].

In [20] there are a lot of scheduling frameworks and policies for the JIT algorithm. In order to ensure that the network model is working fine, the Just-In-Time algorithm configured with online scheduling framework and NASC technique as scheduling policy has been implemented. The scenario ‘WDM-1’ described in [20] has been simulated and compared in order to validate our implementation.

The Pseudocode of the JIT NASC algorithm implemented in the project is:

1) **If** REPORT is received **then**
2) **Apply** NASC algorithm
3) **Assign** wavelength

4) **Add** waiting time **to** time scheduled **of** current ONU
5) Start time **is** (Tfree – RTT) **of** current ONU

6.2.1.1. Scenario

The source used in the simulations of the scenario WDM-1 is self-similar[1]. All the ONUs transmit the average packet length calculated in Equation 6.2. 60 % of packets have 64 bytes, 4 % of packets have 300 bytes, 11 % of packets have 580 bytes and the 25 % of packets have 1518 bytes, as used in [20].

$$\begin{aligned} &Average\ packet\ length = (0.6 * 64) + (04 * 300) + \\ &+ (0.11 * 580) + (0.25 * 1518) = 601.7\ bytes \rightarrow\ 4813.6 \frac{bits}{packet} \end{aligned} \quad \textbf{(6.2)}$$

The Hurst parameter[2] is H = 0.75 and the distance of the ONUs from the OLT follows a uniform distribution between 2 and 15 Km. The RTT value in the paper [13 µs, 100 µs] has been calculated assuming that the propagation velocity is the power light, as Equation 6.3. shown. But, in an optical fibre is $2{\cdot}10^8$ m/s, and we have used the correct value.

$$Propagation\ speed = \frac{Distance_{min}}{\frac{RTT_{min}}{2}} = \frac{2 * 10^3\ m}{\frac{13 * 10^{-6}\ s}{2}} = 3 * 10^8 \frac{m}{s} \quad \textbf{(6.3)}$$

In the paper there are 32 ONUs: 16 of these ONUs support 8 lambdas, 8 support 4 lambdas and the last 8 ones support the other 4 lambdas. However, in our work there are 16 ONUs and they support 4 wavelengths each one to be compliant with IEEE standard. The channel bandwidth in both networks is 1 Gbps. The distribution of wavelengths in this simulation is different but, in terms of total capacity is similar, as can be seen in Table 6.1. Table 6.2 summarises the configuration parameters of both simulations.

Table 6.1 Wavelength distribution (where λ = λ' + λ'')

Wavelength distribution	
WDM-1 paper	Our simulation
16 ONUs / 8 λ	8 ONUs / 4 λ
8 ONUs / 4 λ’	4 ONUs / 2 λ’
8 ONUS / 4 λ”	4 ONUs / 2 λ”

1 A self-similar object is exactly or approximately similar to a part of itself (i.e. the whole has the same shape as one or more of the parts). It is a feature of a fractal. From a statistical point of view, Internet traffic can be modelled as self-similar.
2 The Hurst parameter is an exponent used as a measure of long-term memory of time series. It relates to the autocorrelations of the time series, and the rate at which these decrease as the lag between pairs of values increases. For self-similar time series, H is directly related the to fractal dimension, i.e., the “intensity” of self-similar larity (0.5 → no self-similar, H → 1 maximum self-similar).

Table 6.2 Scenario configuration

Configuration		
Scenarios	WDM-1 paper	Our simulation
ONUs	32	16
Line rate of user to ONU link	-	1 Gbps
EPON line rate	1 Gbps	1 Gbps
Media Packet Length (bits/packet)	4813.6	4813.6
Guard interval between timeslots	-	0,008 ms
Distance between OLT and ONU (d) in Km.	2 < d < 15	18 < d < 20
Maximum cycle time	-	1 ms
Hurst traffic parameter	H = 0,75	H = 0,75
System Bandwidth	8 Gbps	4 Gbps
Number of wavelengths per ONU	8	4
Propagation speed	$3{\cdot}10^8$ m/s	$2{\cdot}10^8$ m/s

The offered load in the paper simulation is over 8 Gbps as system bandwidth, but in this project the system capacity is 4 Gbps. Therefore, the offered load has been re-escalated. The offered load values can be seen in Table 6.3.

Table 6.3 Offered load distribution

WDM-1 (load in Gbps)	load (offered load/system bandwitdth)	Our simulation (load in Gbps)	Packet Arrival Rate (packets/second)
0,5	0,0625	0,25	3246
1	0,125	0,5	6492
1,5	0,1875	0,75	9738
2	0,25	1	12984
2,5	0,3125	1,25	16230
3	0,375	1,5	19476
3,5	0,4375	1,75	22722
4	0,5	2	25968
4,5	0,5625	2,25	29214
5	0,625	2,5	32460
5,5	0,6875	2,75	35706
6	0,75	3	38952
6,5	0,8125	3,25	42198
7	0,875	3,5	45444

6.2.1.2. Simulation Results

All the values obtained in the simulations and the values reported in the paper are in Annex 4. We now summarise the results and discuss the conclusions.

Fig. 6.2 and Fig. 6.3 shown the results reported by the WDM-1 paper and the scenario simulated in this project, respectively. These graphics show the average queue delay with low offered load (meaning that we are not saturating the channel). Fig. 6.4 and Fig. 6.5 extend the load image.

The figures show that the results values of the scenario simulated in this project have a little offset compared to those reported in the WDM-1 paper. This offset can be due to the distance between the ONUs and OLT, which is higher than the WDM-1 case, and the discrepancy of propagation delay. Also, the system bandwidth in the scenario simulated is lower than the WDM-1.

Nonetheless, the shape of the graphics is similar, and we consider that the algorithm is working fine. Therefore, this algorithm will be used as the base to implement the algorithm with tuning time delay.

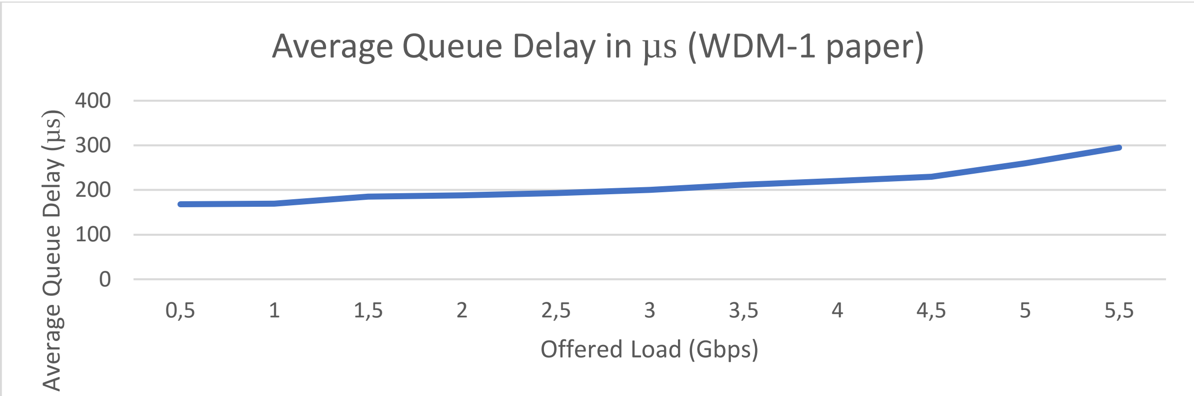

Fig. 6.2 Average Queue Delay versus offered load (WDM-1 paper)

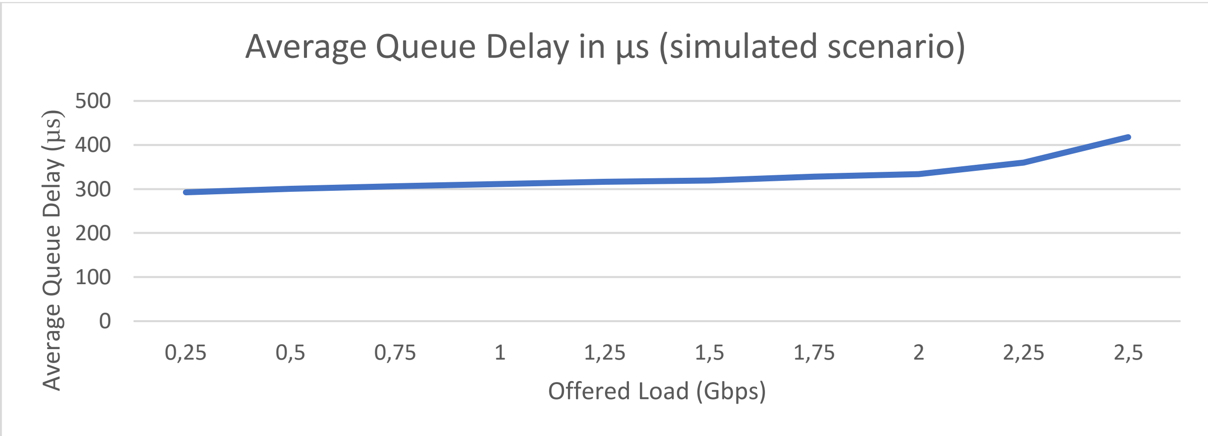

Fig. 6.3 Average Queue Delay versus offered load (simulated scenario)

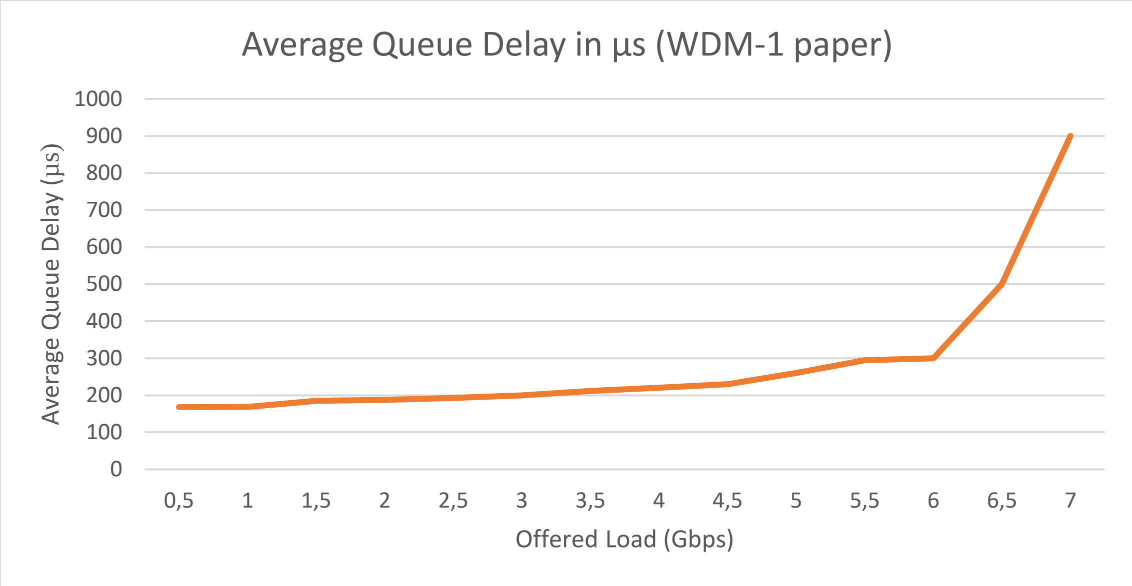

Fig. 6.4 Average Queue Delay versus offered load (WDM-1 paper)

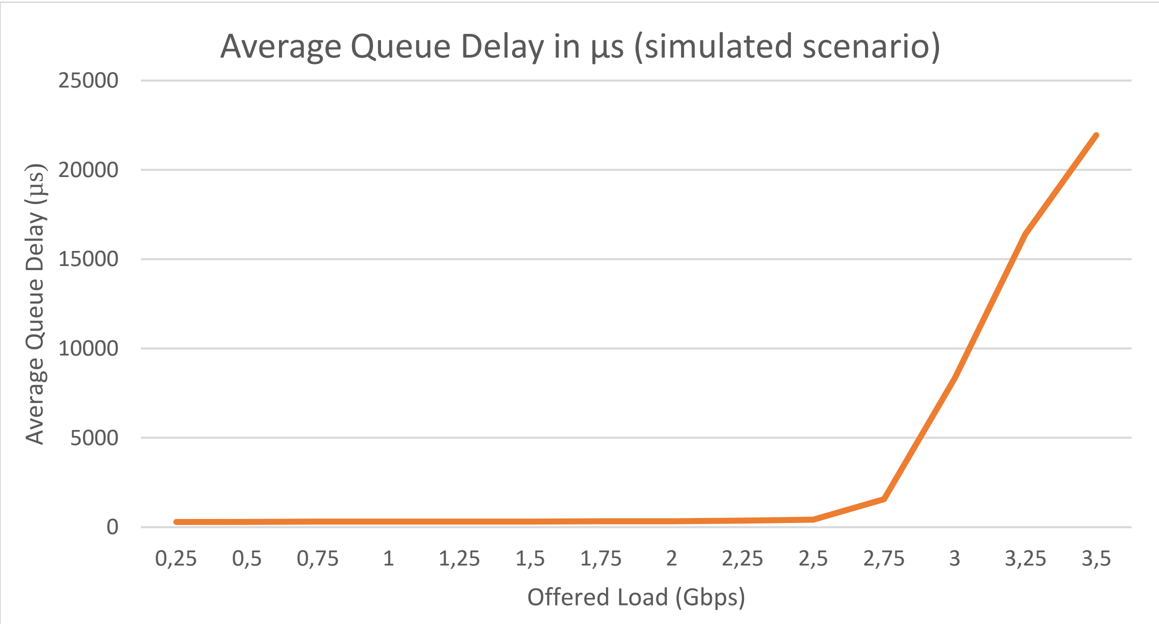

Fig. 6.5 Average Queue Delay versus offered load (simulated scenario)

6.2.2.NASC JIT non-zero tuning time algorithm

The previous section described the NASC algorithm with the JIT technique and its validation. This algorithm has been taken as base to implement the non-zero tuning time delay in the ONUs. Being the upstream channel a multimode fibre with 4 available wavelengths the lasers can change its wavelength in order to minimize the average queue delay. But, every time that ONU changes its wavelength is applying a delay to tune the new one.

Our algorithm will consider the tuning delay of the ONUs laser in order to schedule the transmission as efficiently as possible. Our algorithm should consider the tuning time delay. This consideration could avoid to increase of the average delay of the system. The idea of the algorithm intelligence was taken from [14].

6.2.2.1. Influence of the wavelength change rate

If the ONUs do not change its wavelength transmission frequently during the transmissions the performance is better. That is because few time is wasted in the laser tuning and the total average queue delay is low. On the other hand, if the ONUs change their wavelengths many times the total average queue delay increases.

6.2.2.2. Description of the Algorithm

Firstly, the OLT receives a REPORT with a request (we call it job). This job is sent to the DBA Agent who is the responsible to schedule the next transmission for the REPORT owner. Then, the NASC technique is applied to preassign a wavelength for the transmission. The next step is to compare if the preassigned wavelength is the same that the wavelength used in the last transmission. If they are equal, the transmission can be scheduled immediately because the tuning time will be 0. If they are not equal, the DBA will compare the tuning time against the time when the last wavelength used will be free. If the tuning time is higher than this time the last wavelength used will be assigned. Else, the DBA will decide to use the preassigned wavelength. Finally, when the wavelength has been assigned the DBA will apply the JIT technique and it will send the GATE to the respective ONU. The DBA in OLT will add the tuning delay in the variable that controls the time when each wavelength will become free. Fig. 6.6. summarizes the description of the algorithm.

The pseudocode of the algorithm is:

1) **If** REPORT is received **then**
2) **Apply** NASC algorithm
3) **Preassign** wavelength
4) **If** preassigned wavelength **is equal** last wavelength **then**
5) Wavelength = preassigned wavelength
6) **Else if** Tfree(preassigned wavelength)

7) **Add** waiting time **to** tschceduled **of** current ONU
8) Start time **is** Tfree – RTT **of** current ONU

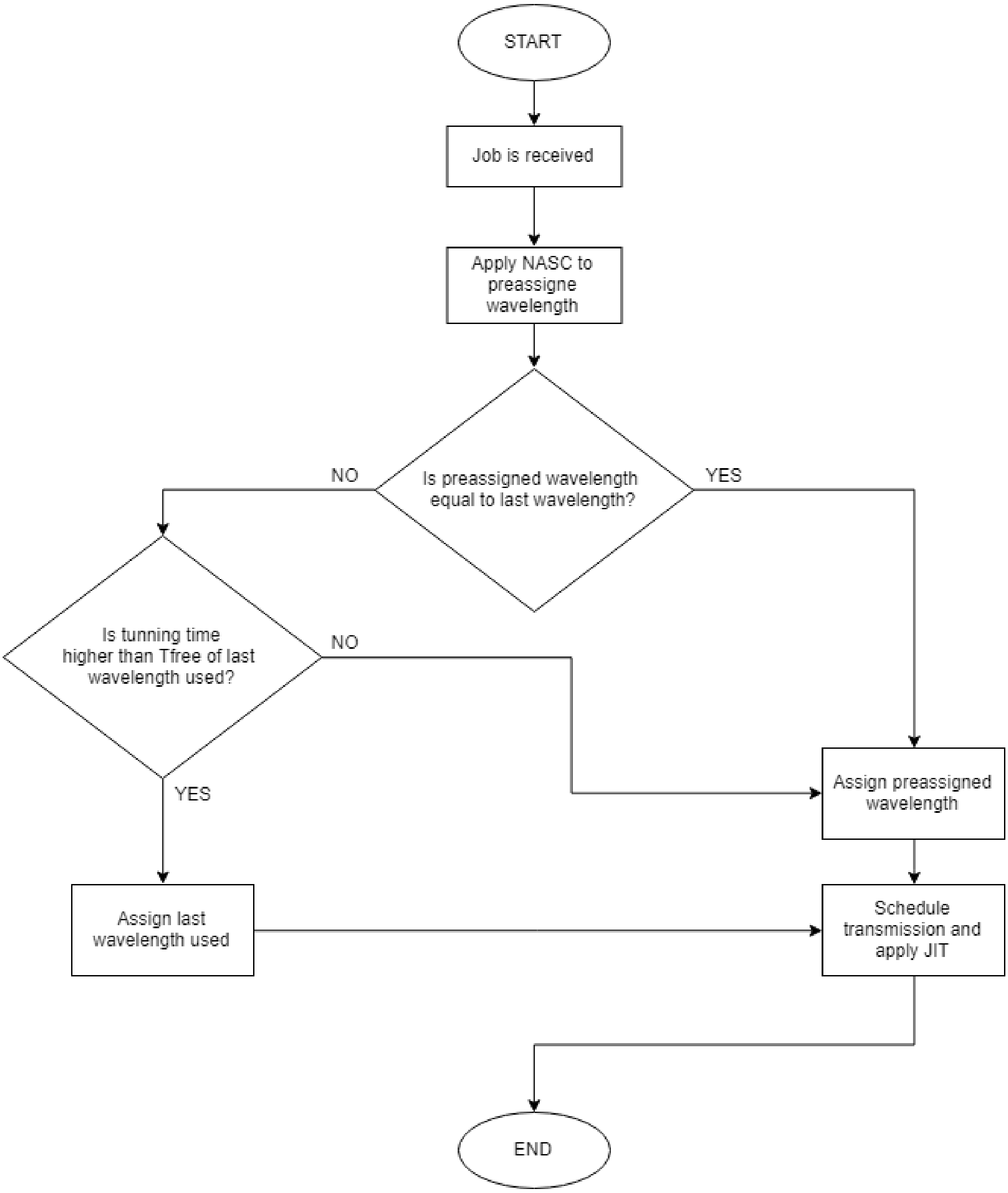

Fig. 6.6 Process flow of the JIT NASC non-zero tuning delay algorithm

The first version of our algorithm assigned the wavelengths randomly in the first loop. But after analyzing the results, when the ONUs have been configured with short tuning delay, the system does not change frequently the wavelengths and some channels are overloaded while others are under-utilized. In order to get better performance, we implement a second version of the algorithm. The second version of the algorithm assigned the wavelengths uniformly in the first loop.

We called the first version of algorithm ‘unforced algorithm’ (randomly) and the second version ‘forced algorithm’.

6.3. Simulations and Analysis of results

6.3.1. Description of the scenario

The scenario for the new algorithm implemented in this project has been configured as show in Table 6.4.

All the simulations have been done during 20 seconds. This duration has been selected after analysing and verifying that this length does not alter the results. To validate it has been compared against longer simulations, as shown in Annex 5.

Our EPON model supports up to eight wavelengths for each ONU. However, to be compliant with the standard definition, we have used four wavelengths per ONU.

In section 3.4.1. we presented the categorization of the tuning time delay in lasers described in [17]. For the simulations we have selected some different values in order to analyse the algorithm behaviour. The values selected are 0 s, 1 µs, 10 µs and 0,5 ms. We selected these values for testing the different kinds of lasers: non-delay (ideal), fast and middle. The slow configuration of laser tuning time has not been presented in the simulation because the delay is so small that it has no influence.

All the ONUs generate the same traffic and its distance to the OLT is distributed between 18 and 20 km uniformly. The interarrival packet time and packet rate can be seen in the Table 6.5.

The bandwidth of the system is 4 Gbps and the offered load is normalized between 0 and 1. The equivalence is presented in Table 6.6.

Table 6.4 Configuration parameters of the scenario

Configuration	
Parameters	Values
ONUs	16
Line rate of user to ONU link	1 Gbps
EPON line rate	1 Gbps
AveragePacket Length (bits/packet)	4813.6
Guard interval between timeslots	0,008 ms
Distance between OLT and ONU (d) in Km.	18 < d < 20
Maximum cycle time	1 ms
Hurst traffic parameter	H = 0,75
System Bandwidth	4 Gbps
Tuning Time	0 s, 1 μs, 10 μs and 0,5 ms
Number of wavelengths per ONU	4

Table 6.5 Interarrival packet time and packet rate

Offered Load	Interarrival packet time in sec	Packet rate in packets/sec
0,0625	3,08E-04	3246
0,125	1,54E-04	6492
0,1875	1,03E-04	9738
0,25	7,70E-05	12984
0,3125	6,16E-05	16230
0,375	5,13E-05	19476
0,4375	4,40E-05	22722
0,5	3,85E-05	25968
0,5625	3,42E-05	29214
0,625	3,08E-05	32460
0,6875	2,80E-05	35706
0,75	2,57E-05	38952
0,8125	2,37E-05	42198
0,875	2,20E-05	45444

Table 6.6 Equivalence in Gbps of the offered load.

Offered Load	Load in Gbps
0,0625	0,25
0,125	0,5
0,1875	0,75
0,25	1
0,3125	1,25
0,375	1,5
0,4375	1,75
0,5	2
0,5625	2,25
0,625	2,5
0,6875	2,75
0,75	3
0,8125	3,25
0,875	3,5

6.3.2. Results and discussion

All the results presented has been obtained from one ONU of the system. The values from one ONU are very similar to the average values, as can be seen in Annex 3.

The data collected to analyse the behaviour or the system has been the average queue delay, the average queue size and throughput.

All the values used for the following figures can be found in Annex 6.

6.3.2.1. Unforced Algorithm

The unforced algorithm is the algorithm that was called ‘NASC JIT non-zero tuning time’. The only difference is that in the first loop the wavelength assignment is done randomly. That means that the channel can be differently loaded depending on the distribution of the initial jobs. A uniform distribution has been used but as there are short jobs the distribution cannot be perfectly uniform.

Fig. 6.7 shows the average queue delay. This graphic includes all the load that can be offered to the system. The vertical axis has been cut at 3000 µs, because it is considered that with this delay the system is overloaded and representing bigger values does not add useful information. We can see the that algorithm where tuning delay of the ONUs is 0 is the last one in being overloaded. The algorithm where tuning delay of the ONUs of 10 µs is over-loaded earlier than algorithm where the tuning time delay of the ONU of 500 µs. This is because when the algorithm has a tuning delay of 10 µs, the algorithm becomes very unstable inducing ONUs to change their wavelength very frequently, and this behavior increases the average delay. When the delay is bigger (500 µs), the system becomes more stable.

In the simulation with a tuning delay of 1 µs there is almost no delay and is the closest to the simulation without tuning delay. This is because the tuning delay is too short for increasing the average queue delay.

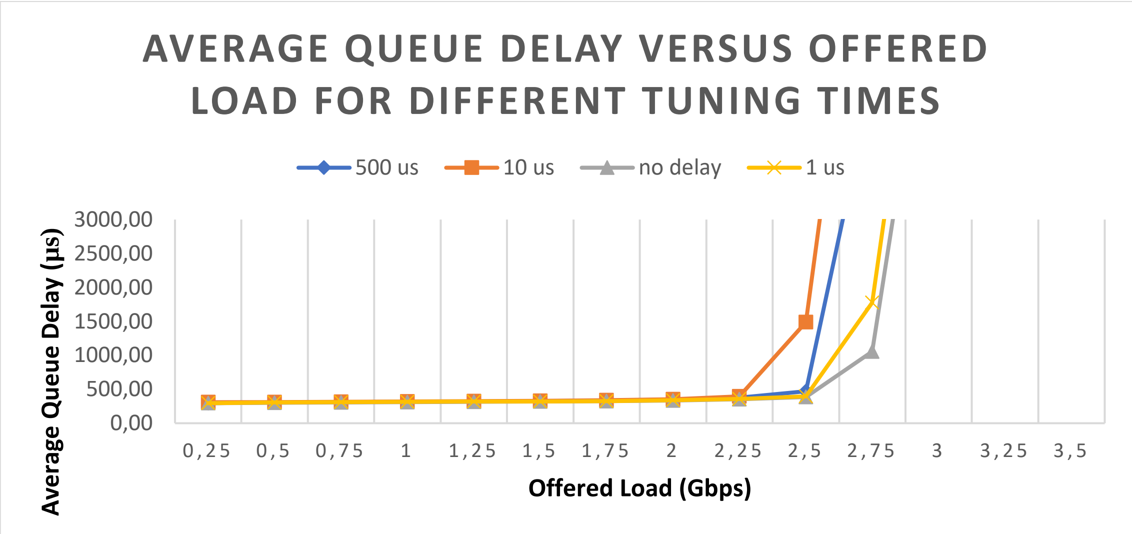

Fig. 6.7 Average Queue Delay versus offered load, for different values of the tuning time

Fig. 6.8 and Fig. 6.9 show the average queue delay with light and medium offered load respectively. In Fig. 6.8 the line of 1 µs tuning delay starts with low delay. It is close to the 500 µs curve. This phenomenon happens because on one hand, the fast tuning time delay configuration is provoking many changes of wavelength but the delay is too small for increasing the average queue delay. On the other hand, with a tuning time delay of 500 µs the algorithm does not change too much the wavelength. This is because the algorithm calculates that the cost of changing the channel in terms of time is bigger. In summary, when the tuning delay is fast the algorithm change frequently the assigned wavelength and when the delay is middle or slow, the algorithm does not often change the assigned wavelength. The algorithm is making the decisions comparing the cost of changing the channel and the laser tuning time.

Fig. 6.10 and Fig. 6.11 show the average queue size. The shape of graphics is very similar to the average queue delay presented previously, because there is a directly connection between the packets in the queue and the delay.

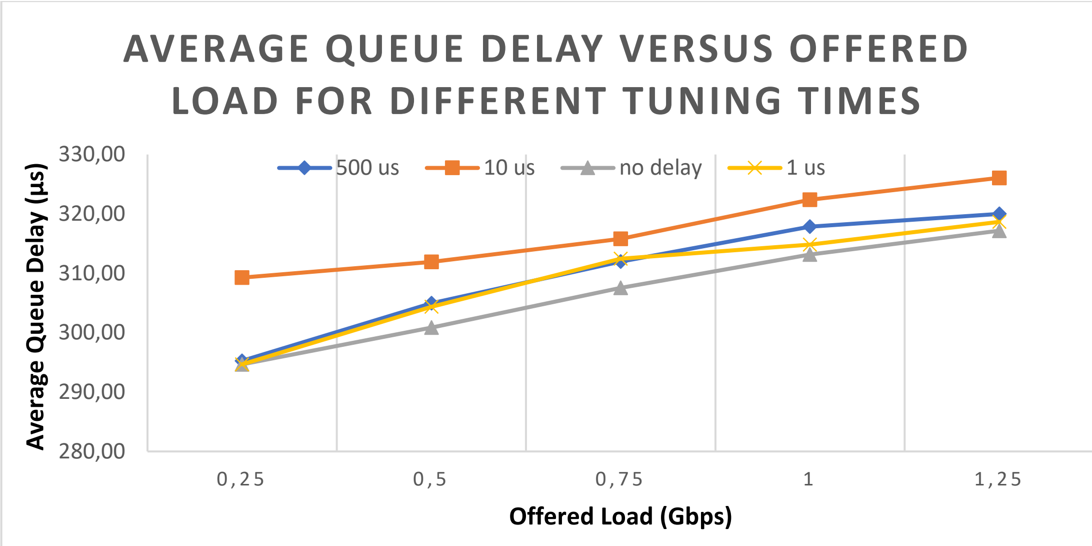

Fig. 6.8 Average Queue Delay versus offered load, for different values of the tuning time

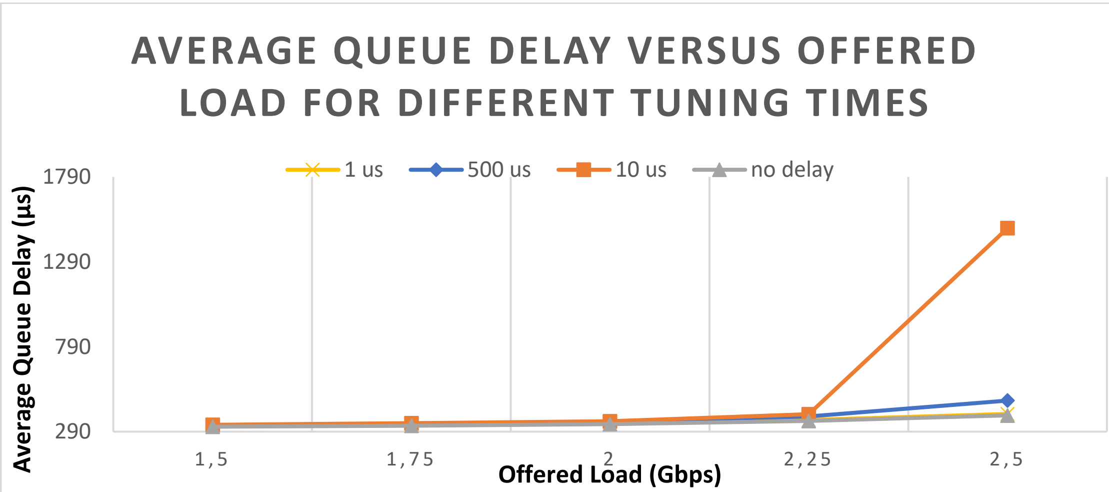

Fig. 6.9 Average Queue Delay versus offered load, for different values of the tuning time

Finally, the throughput of the 4 wavelengths is representing in Fig. 6.12, Fig. 6.13 and Fig. 6.14. As can be seen in Fig. 6.12 when the tuning delay is big, ONUs do not change often wavelengths. In consequence, if the initial distribution the jobs in the channel is not uniform the throughput is lower. After analysing the throughput of the channels, we have implemented a new algorithm called forced algorithm. The attribute forced and unforced refers to the initial distribution of the jobs in channel, as explained previously in Section 6.2.2.2.

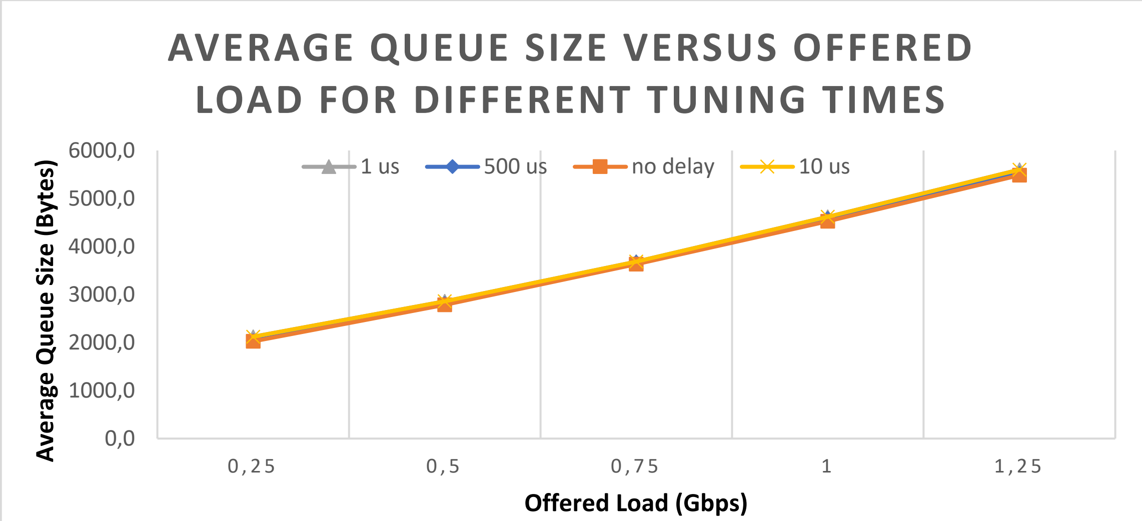

Fig. 6.10 Average Queue Size versus offered load, for different values of the tuning time

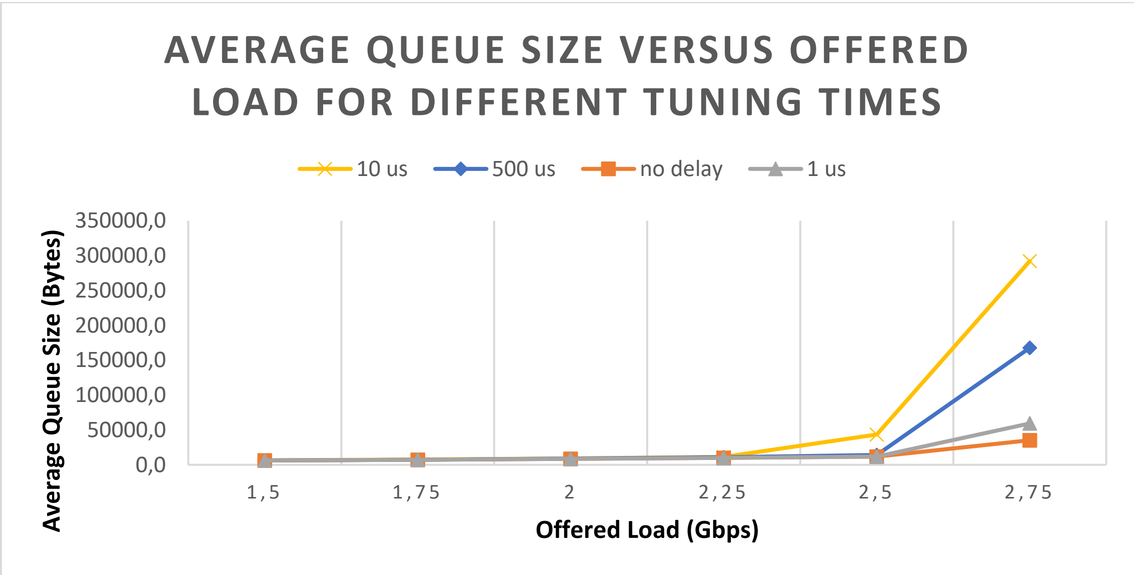

Fig. 6.11 Average Queue Size versus offered load, for different values of the tuning time

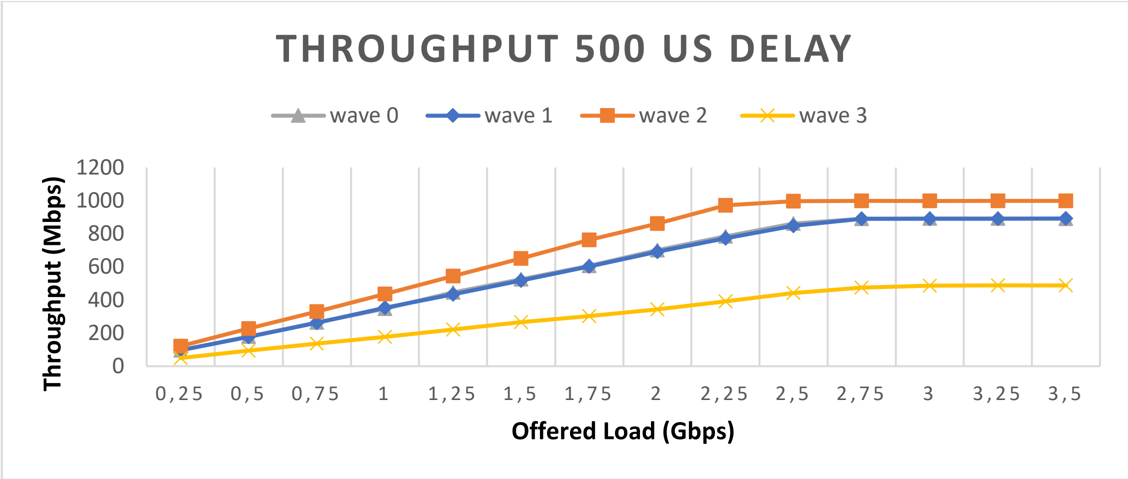

Fig. 6.12 Throughput in Mbps with 500 µs tuning delay versus offered load, for each one of the 4 wavelengths

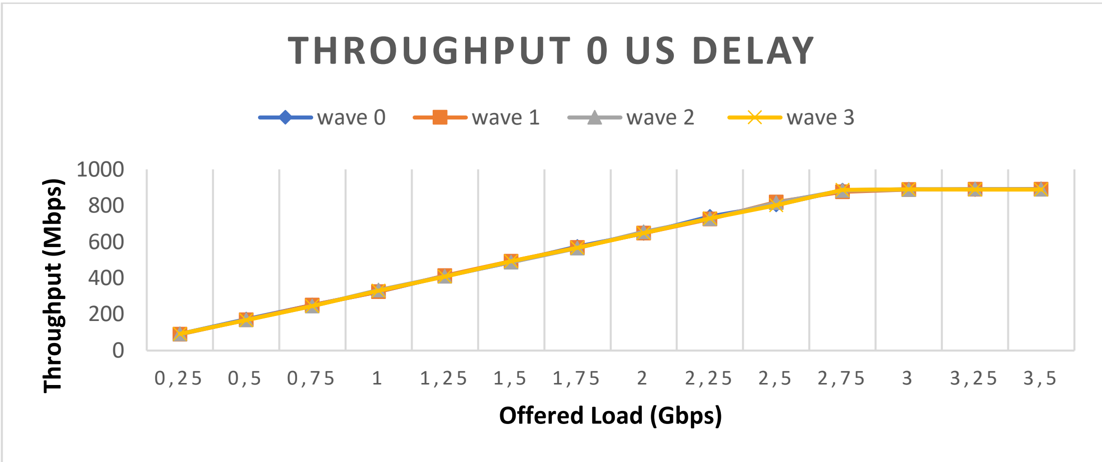

Fig. 6.13 Throughput in Mbps with 0 us tuning delay versus offered load, for each one of the 4 wavelengths

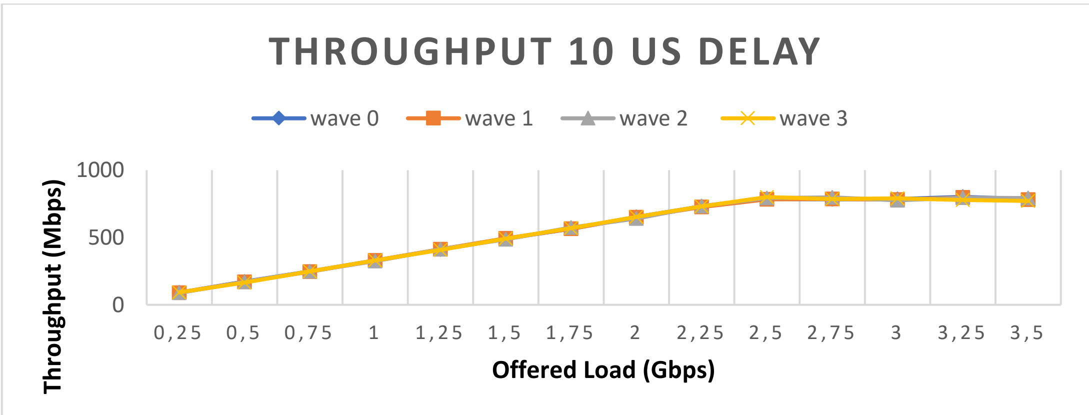

Fig. 6.14 Throughput in Mbps with 10 us tuning delay versus offered load, for each one of the 4 wavelengths

6.3.2.2. Forced Algorithm

The forced one is the same algorithm called 'NASC JIT non-zero tuning time', but in the first loop, the wavelengths assignment is forced. That means that the channel is always scheduled with the same distribution, 4 ONUs' transmissions per channel.

Fig. 6.15 shows the average queue delay versus the offered load. The system is overloaded with a small or higher offered load depending on the tuning delay of the ONUs. The tuning time delay of zero is a non-realistic that is taken as reference for understanding the behavior of our algorithm. When the laser tuning time is 1 µs the ONUs change usually their wavelengths, but how the tuning delay is small the changes do not increase the average queue delay. The behavior when the tuning delay is 10 µs and 500 µs is similar to the unforced algorithm. When the tuning time delay is not so big but too little the system becomes unstable provoking bigger average delay than when the ONUs have bigger delay as 500 µs or upper.

The difference between the unforced and forced algorithm is the efficient use of the channel. This can be observed comparing the Fig. 6.12 and Fig. 6.16. In the forced algorithm, the initial distribution of the jobs is uniform comparing with the unforced algorithm. In consequence, the throughput is better given that when the algorithm does not often change the wavelength, the channel is more efficient in terms of channel capacity.

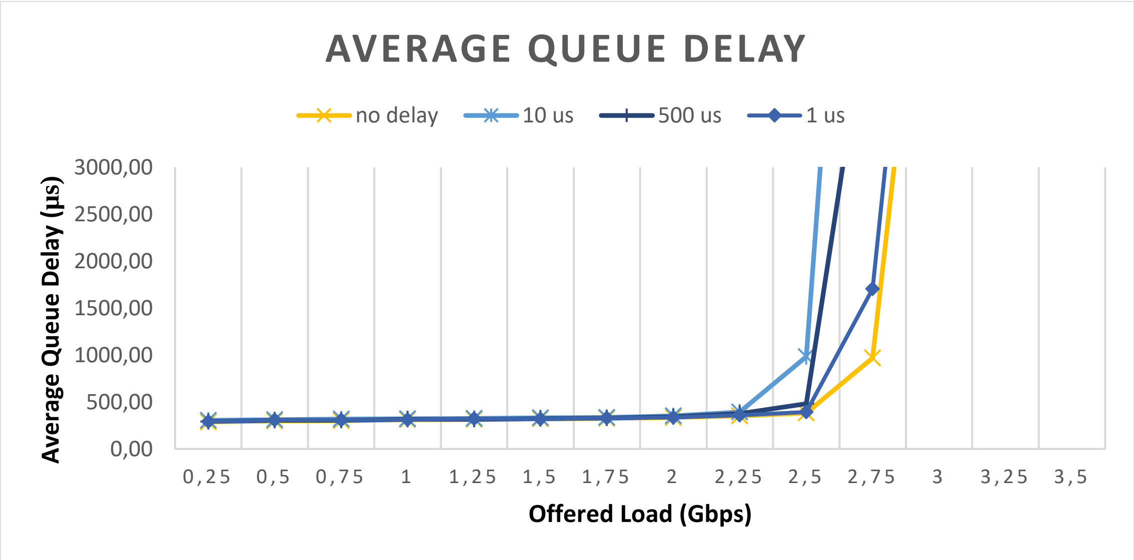

Fig. 6.15 Average queue delay in us versus offered load, for different values of the tuning time.

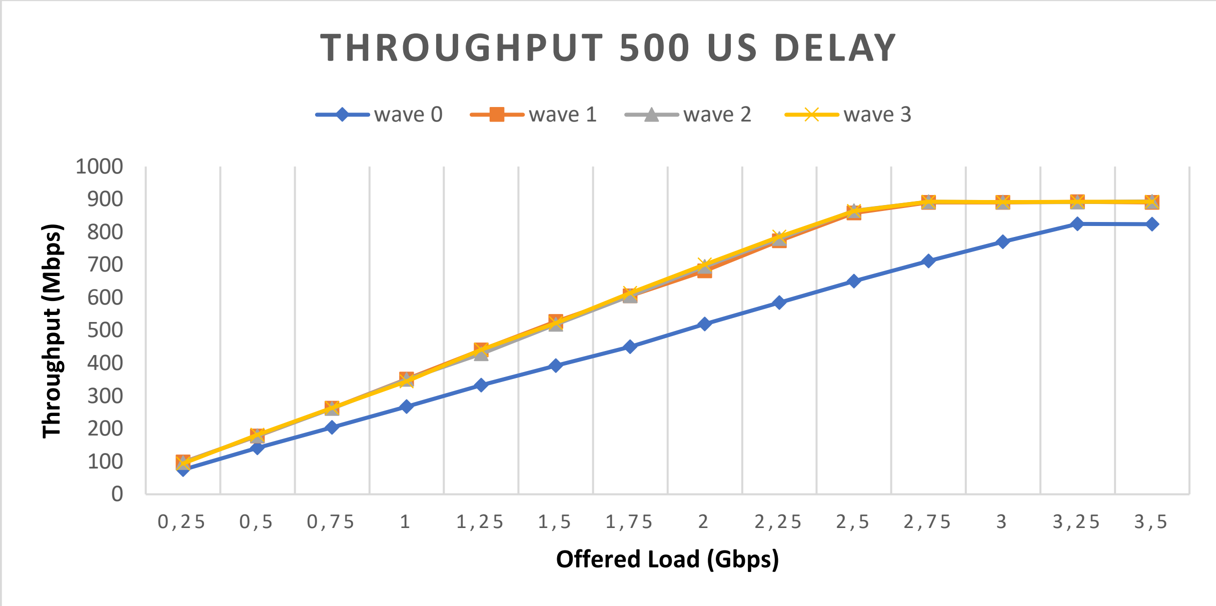

Fig. 6.16 Throughput in Mbps with 500 μs tuning delay, tuning delay versus offered load, for each one of the 4 wavelengths

CHAPTER 7. Conclusions and Future work

Conclusions

The main goal of this project has been the development of an algorithm able to schedule the bandwidth using the TWDM technique and consider the Tuning Time Delay to decide the most efficient scheduling. For achieving the goals some issues in the base model from [5] had to be fixed and a Tuning Time Delay control was applied.

To reach this goal, several steps were successfully completed:

Firstly, we had to learn about EPON and OPNET in order to fix some bugs, For example, some ONUs that were not working appropriately. Also, the clocks of the base model did not synchronize correctly, meaning that packets were lost and the average queue delay trended to infinity. After analysing the code and testing the solutions both problems were fixed, but it was decided to implement the algorithms using only four wavelengths and 1G-EPON configuration because the 10G-EPON configuration did not work correctly. After fixing the issues the base model was simulated in order to validate it, with success.

Secondly, the tuning time delay was studied and the base code was modified in order to apply the delay in the ONUs every time that they change their wavelength. Besides, a new attribute option was added in the model configuration form in order to do easier the future analysis.

Thirdly, we analysed several literatures scientific in order to get ideas for the design of our algorithm. These literatures have some of the following requirements: use of WDM techniques, online fashion or considering the laser tuning time. Before implementing the algorithm designed in the system we validated the base model against [20] with success.

Finally, we implemented our algorithm and after analysing the simulation results, we modified the algorithm in order to improve the throughput.

After analysing the algorithm considering the tuning time delay we could say that some algorithms in literature scientific could not be such efficient as they present. This is because considering the tuning time delay, sometimes it is not good to change the transmission wavelength. If the tuning delay is big having many changes could increase the average queue delay of the system.

From a personal point of view, this project needed many hours, a lot of knowledge regarding this theme is necessary to understand and analysis the new purposes. I have acquired new skills during its development like self-learning and information selection.

Future Work

The current work has implemented a Tuning Time Delay control and is complianct with 1G-EPON standard with multicarrier. Also, the Dynamic Bandwidth Allocation algorithm implemented is working in an online configuration applying the NASC, Just-In-Time techniques and considering the tuning time delay for the scheduling. From this base scenario, it would be interesting to investigate different scheduling policies such as LFJ (Least Flexible Job) and SPT (Shortest Processing Time) presented in [20] and [22] in combination with the Tuning Time Delay in order to analyze which scheduling framework is the most efficient. Another future line is to extend the current algorithm to be compatible with the energy saving mode studied in [23] and [24], that in combination with our basic algorithm could achieve a joint optimization of scheduling delay and energy consumption. Finally, the last line we think that would be interesting to study is to add a packet priority. With this final as studied in [25]. This priority could assure more quality of service to the more restrictive services.

Environmental Impact

PONs are a good option for access networks because they are efficient from a cost-effective point of view. Also, they provide high transmission rate. But, from another point of view and not less important, PONs are efficient from the environmental point of view. That is because ONUs does not have few active elements and low energy consumption. [26] compares between DSL, VDSL and GPON technologies from an energy consumption point of view (see Fig. 7.1).

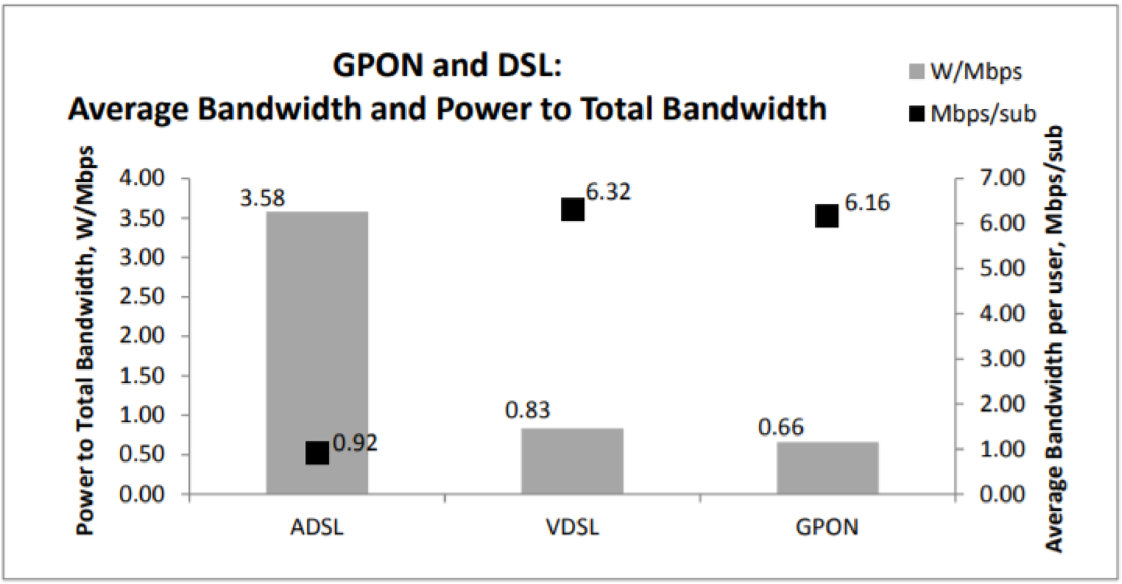

Fig. 7.1 GPON and DSL Technoloy - Average bandwidth and Powe consumption per bandwidth [26]

The solutions presented in this document have a positive impact to the environment. The efficient managing of bandwidth improves the throughput of the system by considering the laser tuning delay. That is because manging the bandwidth optimally the networks need less energetic resources for connecting the users.

In conclusion, PONs are a great candidate for a greener access network.

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ACRONYMS

10G-EPON	10 Gigabit/s Ethernet Passive Optical Network
10G-PON	10 Gigabit/s Passive Optical Network
AWG	Arrayed Wavelength Grating
DBA	Dynamic Bandwidth Allocation
DDSPON	Distributed Dynamic Scheduling for PON
EFM	Ethernet in the First Mile
EPON	Ethernet Passive Optical Network
GEM	GPON Encapsulation Mode
GFP	Generic Framing Protocol
GPON	Gigabit Passive Optical Network
IEEE	Institute of Electrical and Electronics Engineers
IPACT	Interleaved Polling with Adaptative Cycle Time
ITU	International Telecommunications Union
JIT	Just in Time
LFJ	Least Flexible Job
LLID	Link-Logical ID
MAC	Medium Access Control
MPCP	Multi-Point Control Protocol
NASC	Next Available Supported Channel
NGA	Next Generation Access
NG-PON	Next Generation Passive Optical Network
OLT	Optical Line Terminal
ONU	Optical Network User
P2MP	Point-To-Multi-Point
PON	Passive Optical Network
RTT	Round-Trip Time
SLA	Service Level Agreement
SPT	Shortest Processing Time
TDMA	Time-Division Multiple Access
WDMA	Wavelength-Division Multiple Access
WDM-PON	Wavelength-Division Multiple Passive Optical Network
WTDMA	Wavelength-Time-Division Multiple Access

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ANNEXES

TITLE: Dynamic bandwidth allocation algorithms with non-zero laser tuning time in TDWM passive optical networks

DEGREE: Degree on Telecommunications System Engineering

AUTHOR: Kilian Cañizares Mata

DIRECTOR: David Rincón Rivera

DATE: September 7th 2018

INDEX

ANNEX 1. Validation 1 Gbps

Annex 1 presents the validation of the base code with 1 Gbps.

1.1. Scenario configuration

In order to validate the model network working with 1 Gbps the same simulation scenario parameters from Marc Carné's Master Thesis [1] has been used.

Table 1.1 shows the traffic arrival rate and the interarrival packet time used.

Table 1.1 Interarrival packet time and packet rate

Offered Load	Traffic Arrival Rate (packets/s)		Interarrival packet time (s)	
	Bit Rate per channel		Bit Rate per channel	
	1 Gbps	10 Gbps	1 Gbps	10 Gbps
0,1	987,67383	9876,73831	1,01E-03	1,01E-04
0,2	1975,34766	19753,47661	5,06E-04	5,06E-05
0,3	2963,02149	29630,21492	3,37E-04	3,37E-05
0,4	3950,69532	39506,95322	2,53E-04	2,53E-05
0,5	4938,36915	49383,69153	2,02E-04	2,02E-05
0,6	5926,04298	59260,42984	1,69E-04	1,69E-05
0,7	6913,71681	69137,16814	1,45E-04	1,45E-05
0,8	7901,39064	79013,90645	1,27E-04	1,27E-05
0,9	8889,06448	88890,64475	1,12E-04	1,12E-05
1	9876,73831	98767,38306	1,01E-04	1,01E-05

Table 1.2 shows the scenario configuration. The scenario configuration of [1] can be seen in Table 1.3.

Table 1.2 Scenario Configuration in our simulations

Scenario configuration			
ONUs	16	16	16
Line rate of user to ONU link	100 Mbps	100 Mbps	100 Mbps
EPON line rate	1 Gbps	1 Gbps	1 Gbps
Number of queues per ONU	1	1	1
Buffer size per queue (pcks)	1000	1000	1000
Guard interval between timeslots	0,008 ms	0,008 ms	0,008 ms
Distance between OLT and ONU (d) in Km.	18 < d < 20	18 < d < 20	18 < d < 20
Maximum cycle time	1 ms	1 ms	1 ms
Hurst traffic parameter	H = 0,7	H = 0,7	H = 0,7
Number of wavelengths	1	2	4

Table 1.3 Scenario Configuration in [1]

PARAMETERS	Scenario 1	Scenario 2	Scenario 3
Number of ONUs	16	16	16
Line rate of user to ONU link	100Mbps	100Mbps	100Mbps
EPON line rate	1Gbps	1Gbps	1Gbps
Number of queues per ONU	1	1	1
Buffer size per queue (pcks)	1000	1000	1000
Guard interval between timeslots	0.008ms	0.008ms	0.008ms
Distance between OLT and ONU (d) in Km.	18<d<20	18<d<20	18<d<20
Maximum cycle time	1ms	1ms	1ms
Hurst traffic parameter	H=0,7	H=0,7	H=0,7
Number of wavelengths	1	2	4

1.2. Simulations Results

The source was a self-similar traffic generation and the packets have a length between 512 bits and 12144 bits. In order to calculate the traffic arrival rate, the average of bits per packets used has been 6328 bits per packet.

Fig. 1.1 shows the average queue delay for 1 Gbps of [1]

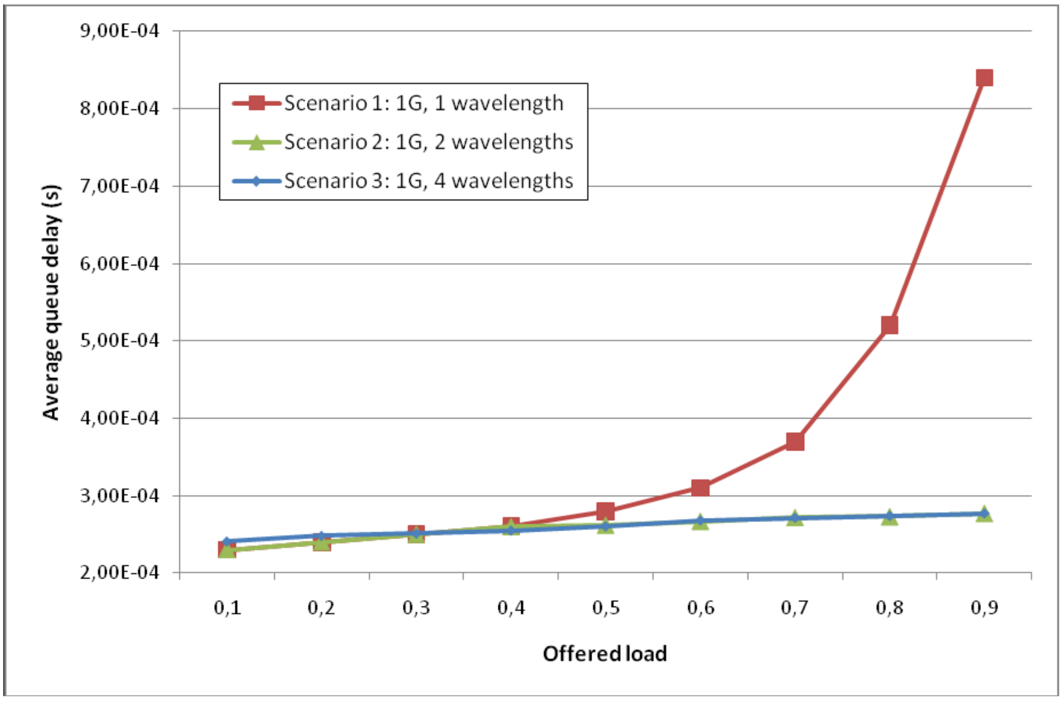

Fig. 1.1 Average Queue Delay versus offered load for different available wavelengths configuration. The link rate is 1 Gbps. [1]

Fig. 1.1 shows that when the system works with 1 available wavelength and the offered load is too high the average queue delay is tending to infinity as expected. Otherwise, when the system works with 2 or 4 wavelengths configuration the system supports more offered load. By increasing wavelengths, the bandwidth of system grows proportionality to the wavelengths used (in this case, each wavelength added increases 1 Gbps the system bandwidth). This behaviour demonstrates the correct working of the network.

Fig. 1.2 shows the simulation results after simulating the same scenario presented in Fig. 1.1. The behaviour of the system is very similar. Besides, in Fig. 1.3 can be read that average queue delay is between 0.2 and 0.3 ms as was shown in Fig. 1.1. The difference of the average queue delay with 1 wavelength available might be because the duration of the simulations. After analysing this simulation results, we validated the base code, with successful.

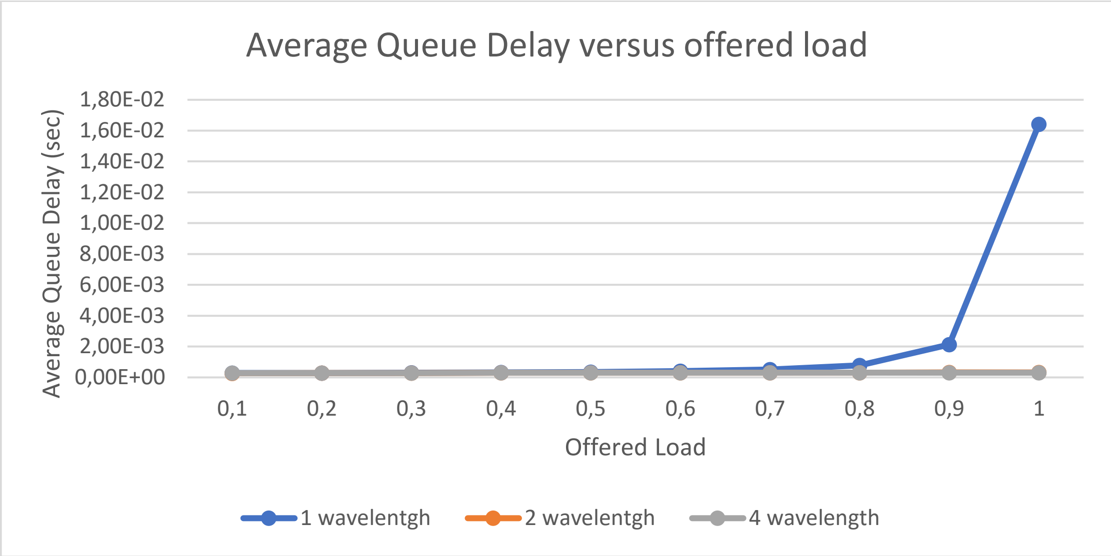

Fig. 1.2 Average Queue Delay versus offered load for different available wavelengths configuration. The link rate is 1 Gbps.

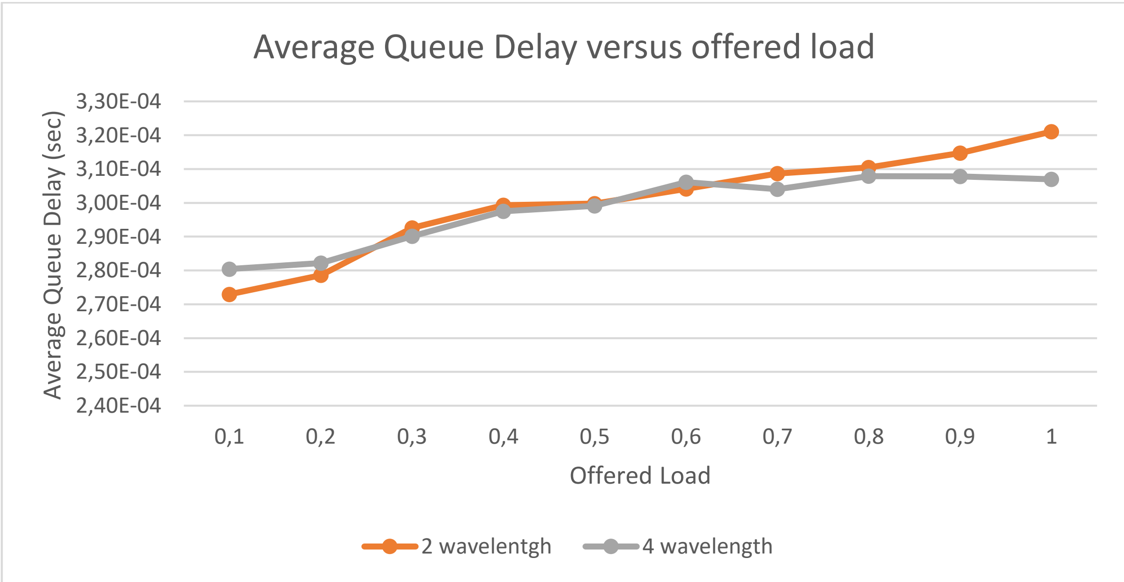

Fig. 1.3 Average Queue Delay versus offered load for different available wavelengths configuration. The link rate is 1 Gbps.

1.3. Data obtained

The data obtained doing the simulations and used for representing the graphics have been the

Table 1.4, Table 1.5 and Table 1.6. present the data obtained from the simulations.

Table 1.4 Average queue delay versus offered load for different values of wavelengths

Offered Load	Average queue delay (s)	Average queue delay (s)	Average queue delay(s)
	1 wavelength	2 wavelengths	4 wavelengths
0,1	2,89E-04	2,73E-04	2,80E-04
0,2	2,90E-04	2,79E-04	2,82E-04
0,3	3,03E-04	2,93E-04	2,90E-04
0,4	3,23E-04	2,99E-04	2,98E-04
0,5	3,46E-04	3,00E-04	2,99E-04
0,6	4,02E-04	3,04E-04	3,06E-04
0,7	5,18E-04	3,09E-04	3,04E-04
0,8	7,81E-04	3,10E-04	3,08E-04
0,9	2,14E-03	3,15E-04	3,08E-04
1	1,64E-02	3,21E-04	3,07E-04

Table 1.5 Average queue size versus offered load for different values of wavelengths

Offered Load	Average queue size (bits)	Average queue size (bits)	Average queue size (bits)
	1 wavelength	2 wavelengths	4 wavelengths
0,1	1,15E+04	1,08E+04	1,12E+04
0,2	1,34E+04	1,31E+04	1,33E+04
0,3	1,57E+04	1,54E+04	1,54E+04
0,4	1,81E+04	1,75E+04	1,74E+04
0,5	2,10E+04	1,93E+04	1,96E+04
0,6	2,56E+04	2,17E+04	2,19E+04
0,7	3,47E+04	2,45E+04	2,43E+04
0,8	5,11E+04	2,63E+04	2,62E+04
0,9	1,42E+05	2,80E+04	2,78E+04
1	1,17E+06	3,09E+04	3,00E+04

Table 1.6 Throughput of system versus offered load for different values of wavelengths

Offered Load	output (bps)	output (bps)	output (bps)
	1 wavelength	2 wavelengths	4 wavelengths
0,1	1,43E+08	1,49E+08	1,52E+08
0,2	2,38E+08	2,40E+08	2,40E+08
0,3	3,38E+08	3,40E+08	3,41E+08
0,4	4,33E+08	4,37E+08	4,37E+08
0,5	5,27E+08	5,33E+08	5,34E+08
0,6	6,19E+08	6,30E+08	6,30E+08
0,7	7,12E+08	7,30E+08	7,31E+08
0,8	8,04E+08	8,31E+08	8,32E+08
0,9	8,89E+08	9,28E+08	9,30E+08
1	9,01E+08	9,80E+08	9,80E+08

ANNEX 2. Validation 10 Gbps

Annex 2 describes the validation of the base code with 10 Gbps.

2.1. Scenario configuration

In order to validate the base code working with 10 Gbps, we validate the data in [1] against our simulations.

Table 2.1 shows the traffic arrival rate and the interarrival packet time that Marc Carné used in [1]. We used the same values.

Table 2.1 Interarrival packet time and packet rate in [1]

Offered Load	Traffic Arrival Rate (packets/s)		Interarrival packet time (s)	
	Bit Rate per channel		Bit Rate per channel	
	1 Gbps	10 Gbps	1 Gbps	10 Gbps
0,1	987,67383	9876,73831	1,01E-03	1,01E-04
0,2	1975,34766	19753,47661	5,06E-04	5,06E-05
0,3	2963,02149	29630,21492	3,37E-04	3,37E-05
0,4	3950,69532	39506,95322	2,53E-04	2,53E-05
0,5	4938,36915	49383,69153	2,02E-04	2,02E-05
0,6	5926,04298	59260,42984	1,69E-04	1,69E-05
0,7	6913,71681	69137,16814	1,45E-04	1,45E-05
0,8	7901,39064	79013,90645	1,27E-04	1,27E-05
0,9	8889,06448	88890,64475	1,12E-04	1,12E-05
1	9876,73831	98767,38306	1,01E-04	1,01E-05

Table 2.2 describes the scenario configuration. The scenario configuration of [1] can be seen in Table 2.3.

Table 2.2 Scenario Configuration in our simulations

Scenario configuration			
ONUs	16	16	16
Line rate of user to ONU link	100 Mbps	100 Mbps	100 Mbps
EPON line rate	10 Gbps	10 Gbps	10 Gbps
Number of queues per ONU	1	1	1
Buffer size per queue (pcks)	infinity	infinity	infinity
Guard interval between timeslots	0,008 ms	0,008 ms	0,008 ms
Distance between OLT and ONU (d) in Km.	18 < d < 20	18 < d < 20	18 < d < 20
Maximum cycle time	1 ms	1 ms	1 ms
Hurst traffic parameter	H = 0,7	H = 0,7	H = 0,7
Number of wavelengths	1	2	4

Table 2.3 Scenario Configuration in [1]

PARAMETERS	Scenario 4	Scenario 5	Scenario 6
Number of ONUs	16	16	16
Line rate of user to ONU link	100Mbps	100Mbps	100Mbps
EPON line rate	10Gbps	10Gbps	10Gbps
Number of queues per ONU	1	1	1
Buffer size per queue (pcks)	1000	1000	1000
Guard interval between timeslots	0.008ms	0.008ms	0.008ms
Distance between OLT and ONU (d) in Km.	18<d<20	18<d<20	18<d<20
Maximum cycle time	1ms	1ms	1ms
Hurst traffic parameter	H=0,7	H=0,7	H=0,7
Number of wavelengths	1	2	4

2.2. Simulations Results

The source was a self-similar traffic generation and the packets have a length between 512 bits and 12144 bits. In order to calculate the traffic arrival rate, the average of bits per packets used has been 6328 bits per packet.

Fig. 2.1 shows the average queue delay for 1 Gbps of [1].

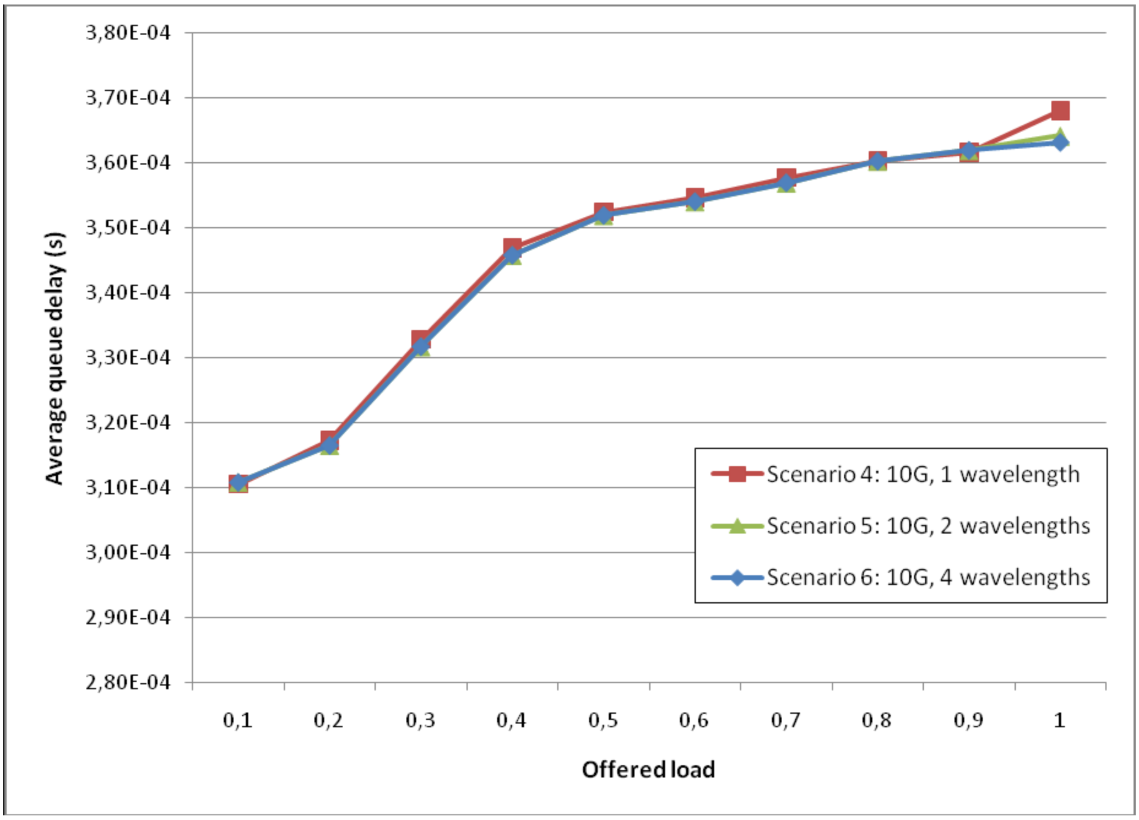

Fig. 2.1 Average Queue Delay versus offered load for different available wavelengths configuration. The link rate is 10 Gbps. [1]

Fig. 2.1 shows the average queue delay for the system with link rate of 10 Gbps. The PONs, when they are working close to the maximum offered load supported they should tend to infinity. After analysing these simulations, we considered that base code with link rate of 10 Gbps did not work. Nevertheless, in Fig. 2.2 shows our simulations reproducing the same scenario used in [1]. Therefore, we decided to implement the algorithm using the base code with 1 Gbps of bandwidth.

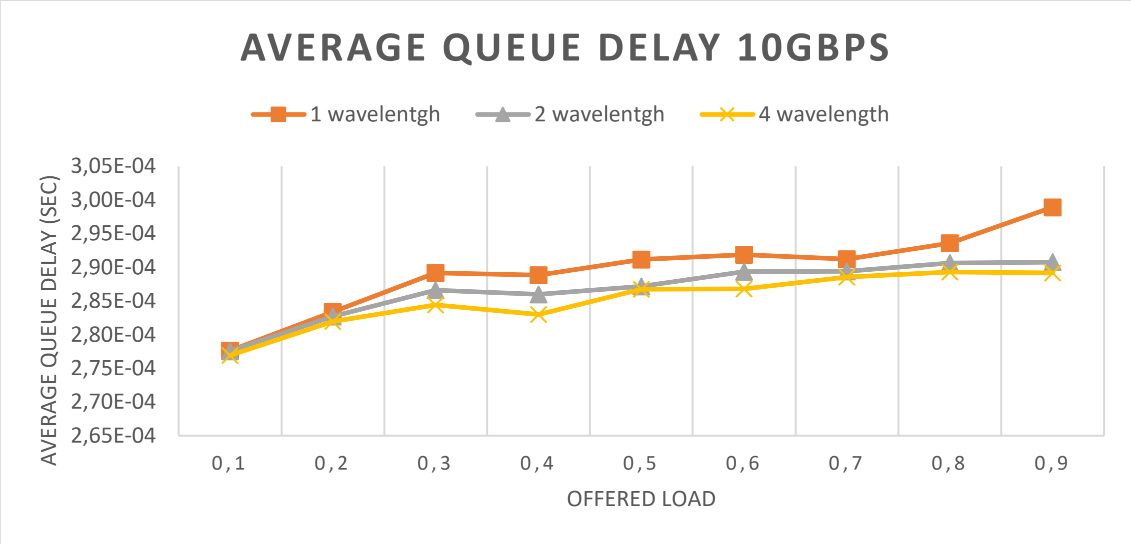

Fig. 2.2 Average Queue Delay versus offered load for different available wavelengths configuration. The link rate is 10 Gbps.

2.3. Data obtained

Table 2.4, Table 2.5 and Table 2.6 collect the data used for our simulations.

Table 2.4 Average queue delay versus offered load for different wavelengths available

Load	Average queue delay (s) 1 wavelength	Average queue delay (s) 2 wavelengths	Average queue delay (s) 4 wavelengths
0,1	2,78E-04	2,78E-04	2,77E-04
0,2	2,83E-04	2,83E-04	2,82E-04
0,3	2,89E-04	2,87E-04	2,84E-04
0,4	2,89E-04	2,86E-04	2,86E-04
0,5	2,91E-04	2,87E-04	2,87E-04
0,6	2,92E-04	2,89E-04	2,87E-04
0,7	2,91E-04	2,89E-04	2,89E-04
0,8	2,94E-04	2,91E-04	2,89E-04
0,9	2,99E-04	2,91E-04	2,89E-04

Table 2.5 Average queue size versus offered load for different wavelengths available

Offered Load	Average queue size (bits)	Average queue size (bits)	Average queue size (bits)
	1 wavelength	2 wavelengths	4 wavelengths
0,1	2,69E+04	2,70E+04	2,69E+04
0,2	4,80E+04	4,80E+04	4,79E+04
0,3	6,46E+04	6,40E+04	6,37E+04
0,4	8,50E+04	8,42E+04	8,46E+04
0,5	1,05E+05	1,04E+05	1,04E+05
0,6	1,25E+05	1,24E+05	1,23E+05
0,7	1,41E+05	1,40E+05	1,40E+05
0,8	1,64E+05	1,62E+05	1,62E+05
0,9	1,84E+05	1,80E+05	1,79E+05

Table 2.6 Total throughput for different wavelengths available

Offered Load	output (bps)	output (bps)	output (bps)
	1 wavelength	2 wavelengths	4 wavelengths
0,1	1,02E+09	1,06E+09	1,08E+09
0,2	2,01E+09	2,01E+09	2,01E+09
0,3	2,99E+09	2,99E+09	2,99E+09
0,4	3,97E+09	3,97E+09	3,97E+09
0,5	4,94E+09	4,94E+09	4,94E+09
0,6	5,94E+09	5,94E+09	5,94E+09
0,7	6,93E+09	6,93E+09	6,93E+09
0,8	7,90E+09	7,90E+09	7,90E+09
0,9	8,87E+09	8,88E+09	8,88E+09

ANNEX 3. 1 ONU vs ALL ONUs

All the data collected for the analysis were from an ONU. Annex 3 validates that the data collected from an ONU is similar of the media of all the ONUs in the system.

3.1. Data comparison

Fig. 3.1 shows the average queue delay versus offered load. The difference between one ONU and all the system is little. Therefore, we considered that data collected from one ONU represents the system behaviour.

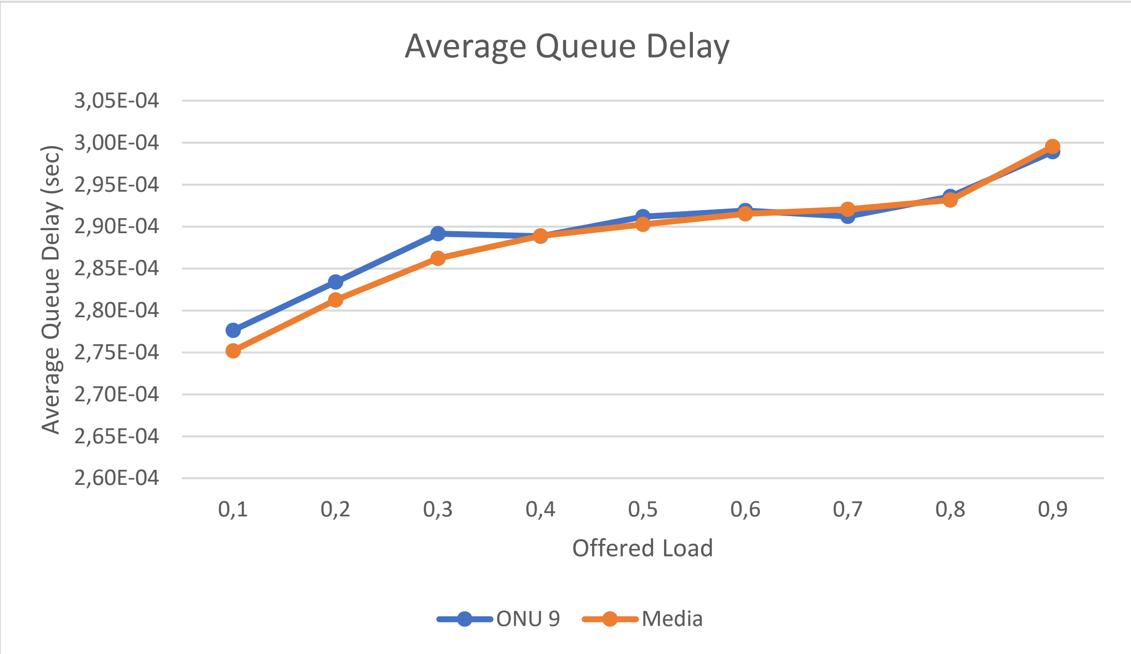

Fig. 3.1 Average Queue Delay versus offered load of the ONU and the average of all ONUs

3.2. Data obtained

Table 3.1, Table 3.2, Table 3.3 and Table 3.4 describe the data collected for this demonstration. We used the scenario presented in section 2.1.

Table 3.1 Average queue delay versus offered load for different ONUs

Offered Load	Average queue delay (s)			
	ONU 1	ONU 2	ONU 3	ONU 5
0,1	2,85E-04	2,80E-04	2,74E-04	2,82E-04
0,2	2,88E-04	2,83E-04	2,78E-04	2,87E-04
0,3	2,89E-04	2,89E-04	2,83E-04	2,89E-04
0,4	2,90E-04	2,90E-04	2,89E-04	2,90E-04
0,5	2,90E-04	2,89E-04	2,89E-04	2,90E-04
0,6	2,92E-04	2,90E-04	2,91E-04	2,92E-04
0,7	2,92E-04	2,92E-04	2,92E-04	2,92E-04
0,8	2,93E-04	2,93E-04	2,94E-04	2,94E-04
0,9	3,00E-04	2,99E-04	2,99E-04	2,99E-04

Table 3.2 Average queue delay versus offered load for different ONUs

Offered Load	Average queue delay (s)			
	ONU 6	ONU 7	ONU 8	ONU 9
0,1	2,80E-04	2,74E-04	2,64E-04	2,78E-04
0,2	2,85E-04	2,82E-04	2,70E-04	2,83E-04
0,3	2,89E-04	2,89E-04	2,78E-04	2,89E-04
0,4	2,90E-04	2,89E-04	2,86E-04	2,89E-04
0,5	2,90E-04	2,90E-04	2,91E-04	2,91E-04
0,6	2,93E-04	2,92E-04	2,91E-04	2,92E-04
0,7	2,92E-04	2,93E-04	2,92E-04	2,91E-04
0,8	2,94E-04	2,94E-04	2,92E-04	2,94E-04
0,9	3,00E-04	2,99E-04	3,01E-04	2,99E-04

Table 3.3 Average queue delay versus offered load for different ONUs

Offered load	Average queue delay (s)			
	ONU 10	ONU 11	ONU 12	ONU 13
0,1	2,73E-04	2,72E-04	2,72E-04	2,80E-04
0,2	2,82E-04	2,76E-04	2,80E-04	2,89E-04
0,3	2,85E-04	2,84E-04	2,88E-04	2,87E-04
0,4	2,88E-04	2,89E-04	2,90E-04	2,89E-04
0,5	2,90E-04	2,90E-04	2,91E-04	2,91E-04
0,6	2,90E-04	2,92E-04	2,91E-04	2,92E-04
0,7	2,92E-04	2,92E-04	2,92E-04	2,92E-04
0,8	2,94E-04	2,92E-04	2,93E-04	2,93E-04
0,9	3,00E-04	3,00E-04	3,00E-04	2,99E-04

Table 3.4 Average queue delay versus offered load for different ONUs

Offered load	Average queue delay (s)			
	ONU 14	ONU 15	ONU 16	Average
0,1	2,82E-04	2,67E-04	2,65E-04	2,75E-04
0,2	2,86E-04	2,78E-04	2,72E-04	2,81E-04
0,3	2,89E-04	2,84E-04	2,81E-04	2,86E-04
0,4	2,91E-04	2,89E-04	2,85E-04	2,89E-04
0,5	2,91E-04	2,90E-04	2,90E-04	2,90E-04
0,6	2,92E-04	2,91E-04	2,91E-04	2,91E-04
0,7	2,92E-04	2,93E-04	2,92E-04	2,92E-04
0,8	2,94E-04	2,93E-04	2,92E-04	2,93E-04
0,9	3,00E-04	3,00E-04	2,99E-04	3,00E-04

ANNEX 4. NASC JIT algorithm results

Annex 4 presents the results of the simulations for validating the NASC JIT algorithm in Chapter 5.

4.1. Data obtained

Table 4.1 Average queue delay versus offered load in [2] and our scenario

Offered Load in [2] (Gbps)	Average Queue Delay in [2] (µs)	Offered Load	Offered Load (Gbps)	Average Queue Delay (s)	Average Queue Delay (µs)
0,5	168	0,0625	0,25	2,93E-04	292,566708
1	169	0,125	0,5	3,00E-04	300,4988281
1,5	185	0,1875	0,75	3,06E-04	306,4298332
2	188	0,25	1	3,11E-04	311,4849408
2,5	193	0,3125	1,25	3,16E-04	316,3823263
3	200	0,375	1,5	3,19E-04	319,0570584
3,5	212	0,4375	1,75	3,28E-04	328,3464885
4	220	0,5	2	3,34E-04	334,1989642
4,5	230	0,5625	2,25	3,60E-04	360,3174133
5	260	0,625	2,5	4,18E-04	417,8158607
5,5	295	0,6875	2,75	1,57E-03	1568,57508
6	300	0,75	3	8,33E-03	8331,797526
6,5	500	0,8125	3,25	1,64E-02	16427,99825
7	900	0,875	3,5	2,19E-02	21948,26798

ANNEX 5. Simulation time analysis

Annex 5 compares the duration of the simulations of 20 secs and 1 sec.

5.1. Simulations Results

For these simulations we used the same scenario presented in section 2.1.

Table 5.1 Average queue delay with 1 wavelength available during 1 min and 20 secs of simulation versus offered load

Offered Load	Average queue delay (s)
0,1	2,78E-04
0,2	2,83E-04
0,3	2,89E-04
0,4	2,89E-04
0,5	2,91E-04
0,6	2,92E-04
0,7	2,91E-04
0,8	2,94E-04
0,9	2,99E-04

Table 5.2 Average queue delay with 1 wavelength available during 20 secs versus offered load

Offered load	Average queue delay (s)
0,1	2,75E-04
0,2	2,81E-04
0,3	2,86E-04
0,4	2,89E-04
0,5	2,90E-04
0,6	2,91E-04
0,7	2,92E-04
0,8	2,93E-04
0,9	3,00E-04

Table 5.1 and Table 5.2 present the difference between short and long simulation. Such as that difference is insignificant. We consider to use a simulation time of 20 secs for our simulations.

ANNEX 6. NASC JIT non-zero tuning time algorithm

Annex 6 presents the data collected for the figures presented in Chapter 6.

6.1. Simulations results of the unforced algorithm

Table 6.1 and Table 6.2 present the average queue delay and the average queue size versus offered load for different values of tuning time respectively. These values were obtained simulation the unforced algorithm explain in Chapter 6.

Table 6.1 Average queue delay versus offered load for different values of tuning time

Offered Load (Gbps)	Average Queue delay (µs)						
	Tuning delay						
	1 ms	1,5 ms	2 ms	no delay	10 µs	1 µs	500 µs
0,25	295,27	295,27	295,27	294,67	309,27	294,67	295,27
0,5	304,94	304,94	304,94	300,84	311,90	304,347204	304,94
0,75	311,98	311,98	311,98	307,54	315,79	312,435549	311,98
1	317,87	317,87	317,87	313,15	322,37	314,828408	317,87
1,25	320,00	320,00	320,00	317,17	326,07	318,659764	320,00
1,5	327,36	327,36	327,36	319,06	330,19	320,165919	327,36
1,75	335,59	335,59	335,59	325,47	339,40	326,890009	335,59
2	349,44	349,44	349,44	335,14	351,44	336,967482	349,44
2,25	378,63	378,63	378,63	353,64	393,64	358,156019	378,63
2,5	472,98	472,98	472,98	386,04	1488,23	394,296345	472,98
2,75	5021,79	5021,79	5021,79	1055,93	8733,24	1776,17181	5021,79
3	12182,09	12182,09	12182,09	7331,72	17110,78	8660,12268	12182,09
3,25	19697,04	19697,04	19697,04	15268,63	23279,67	16493,1134	19697,04
3,5	24103,45	24103,45	24103,45	19997,90	27716,15	20943,9322	24103,45

Table 6.2 Average queue size versus offered load for different values of tuning time

Offered Load (Gbps)	Average Queue Size (bytes)						
	Tuning delay						
	1 ms	1,5 ms	2 ms	no delay	10 µs	1 µs	500 µs
0,25	2036,0	2036,0	2036,0	2024,6	2121,8	1982,5	2036,0
0,5	2812,6	2812,6	2812,6	2783,6	2861,8	2803,9	2812,6
0,75	3673,1	3673,1	3673,1	3633,2	3686,2	3685,8	3673,1
1	4587,7	4587,7	4587,7	4524,8	4617,8	4540,3	4587,7
1,25	5517,4	5517,4	5517,4	5484,7	5600,7	5528,5	5517,4
1,5	6333,6	6333,6	6333,6	6191,6	6362,5	6201,8	6333,6
1,75	7426,2	7426,2	7426,2	7237,6	7488,3	7264,6	7426,2
2	8826,8	8826,8	8826,8	8476,2	8848,7	8519,5	8826,8
2,25	10700,7	10700,7	10700,7	10036,7	11134,0	10182,4	10700,7
2,5	14190,4	14190,4	14190,4	11620,2	43656,3	11850,2	14190,4
2,75	167725,0	167725,0	167725,0	35253,7	292130,3	59327,3	167725,0
3	440319,0	440319,0	440319,0	265903,6	616551,8	313658,9	440319,0
3,25	779003,2	779003,2	779003,2	604877,5	920840,9	653072,8	779003,2
3,5	1010524,5	1010524,5	1010524,5	838020,7	1163179,7	877662,8	1010524,5

Table 6.3 Throughput versus offered load of the different channels for tuning time value of 500 µs

Throughput (Mbps)				
Offered Load (Gbps)	Channel 0	Channel 1	Channel 2	Channel 3
0,25	96,44866	97,017685	121,68	49,620675
0,5	180,116225	177,146505	227,74	95,0635
0,75	264,99106	262,573625	330,07	136,07487
1	346,47349	353,578005	435,79	178,07542
1,25	446,022995	433,76378	543,60	220,838715
1,5	525,97515	517,8391	650,74	266,801795
1,75	606,062835	602,96071	762,84	302,27851
2	700,132075	691,04788	861,82	343,91297
2,25	783,65189	772,674265	972,06	391,82536
2,5	861,01852	847,880245	997,55	442,854665
2,75	890,95276	891,43147	997,90	474,891765
3	892,63244	891,373085	998,02	486,92589
3,25	892,635495	891,20003	997,95	487,63112
3,5	890,86254	892,472715	998,02	487,7226

Table 6.4 Throughput versus offered load of the different channels for tuning time value of 10 µs

Throughput (Mbps)				
Offered Load (Gbps)	Channel 0	Channel 1	Channel 2	Channel 3
0,25	91,27579	90,519305	89,22	92,885205
0,5	172,998155	170,611655	170,18	165,308695
0,75	249,312185	246,425565	248,88	248,1442
1	329,845555	329,41514	325,13	328,485685
1,25	410,108625	412,37794	412,21	408,37141
1,5	490,694415	492,76235	486,17	491,411815
1,75	565,19604	564,07255	573,99	569,945135
2	652,78656	650,00315	641,14	652,15878
2,25	731,76757	726,90649	732,37	730,019685
2,5	785,56898	782,107045	791,95	800,11874
2,75	782,862725	785,669195	797,77	786,19962
3	786,72838	779,712695	776,93	789,72864
3,25	801,784425	796,45702	796,06	779,056065
3,5	784,809385	781,20186	791,76	771,50723

Table 6.5 Throughput versus offered load of the different channels without tuning delay

Throughput (Mbps)				
Offered Load (Gbps)	Channel 0	Channel 1	Channel 2	Channel 3
0,25	91,78643	89,80313	91,41	92,0611
0,5	172,675725	169,83787	170,31	167,623855
0,75	250,48278	251,725905	245,54	246,222955
1	325,11433	325,306745	333,92	329,849245
1,25	411,884585	413,51326	410,22	408,95922
1,5	487,666445	492,874555	488,40	493,684395
1,75	574,82315	568,154615	564,46	567,46518
2	645,624855	648,116935	655,33	649,14108
2,25	740,651875	726,791065	728,27	728,869665
2,5	803,539785	820,455355	815,56	802,551485
2,75	884,57842	876,87468	882,70	885,84436
3	889,63583	889,298185	888,91	889,575495
3,25	888,316495	890,22214	891,46	889,24818
3,5	891,670015	889,90951	889,40	888,026935

Table 6.6 Throughput versus offered load of the different channels for tuning time value of 1 µs

Throughput (Mbps)				
Offered Load (Gbps)	Channel 0	Channel 1	Channel 2	Channel 3
0,25	89,72724	92,768635	90,38	92,098095
0,5	171,220925	173,243175	166,94	168,890665
0,75	246,434635	247,94548	253,31	246,12747
1	327,406425	324,547695	331,32	330,598185
1,25	411,37812	409,40598	417,19	406,63769
1,5	489,419295	492,217985	491,45	489,29263
1,75	571,198415	573,725485	559,92	570,06574
2	646,92393	646,429805	655,70	649,141705
2,25	732,78966	722,37358	735,40	733,77499
2,5	815,14799	808,640645	815,36	802,22628
2,75	875,646015	874,983525	870,47	877,29796
3	874,537785	874,40594	874,39	875,851665
3,25	875,26182	874,80471	874,77	877,08716
3,5	874,478155	874,229035	879,35	872,69417

6.2. Simulations Results Forced algorithm

Table 6.7 and Table 6.8 present the average queue delay and the average queue size versus offered load for different values of tuning time respectively. These values were obtained simulation the forced algorithm explain in Chapter 6.

Table 6.7 Average queue delay versus offered load for different values of tuning time

Offered Load (Gbps)	Average Queue Delay (µs)						
	Tuning delay						
	1 ms	1,5 ms	2 ms	no delay	10 µs	1 µs	500 µs
0,25	292,46	292,46	292,46	289,18	304,86	290,47	292,46
0,5	303,37	303,37	303,37	297,83	311,35	307,39	303,37
0,75	303,61	303,61	303,61	302,81	317,03	309,58	303,61
1	313,52	313,52	313,52	312,78	323,00	313,12	313,52
1,25	315,03	315,03	315,03	314,81	326,70	321,68	315,03
1,5	321,81	321,81	321,81	320,89	332,48	318,31	321,81
1,75	327,42	327,42	327,42	325,57	336,84	328,08	327,42
2	342,85	342,85	342,85	335,58	351,65	333,74	342,85
2,25	377,76	377,76	377,76	353,27	394,73	359,94	377,76
2,5	481,07	481,07	481,07	382,90	981,11	392,30	481,07
2,75	5070,19	5070,19	5070,19	969,71	10533,90	1706,16	5070,19
3	12040,13	12040,13	12040,13	7258,45	17864,24	8512,35	12040,13
3,25	19768,04	19768,04	19768,04	15651,67	23595,16	16515,90	19768,04
3,5	24008,29	24008,29	24008,29	19919,93	27137,76	21148,33	24008,29

Table 6.8 Average queue size versus offered load for different values of tuning time

Offered Load (Gbps)	Average queue size (bytes)						
	Tuning delay						
	1 ms	1,5 ms	2 ms	no delay	10 µs	1 µs	500 µs
0,25	2007,3	2007,3	2007,3	1989,4	2071,9	1967,5	2007,3
0,5	2795,8	2795,8	2795,8	2751,0	2851,6	2843,5	2795,8
0,75	3592,7	3592,7	3592,7	3519,3	3710,1	3658,7	3592,7
1	4537,2	4537,2	4537,2	4522,8	4635,1	4495,3	4537,2
1,25	5455,6	5455,6	5455,6	5449,0	5631,7	5558,0	5455,6
1,5	6233,7	6233,7	6233,7	6230,3	6442,6	6172,9	6233,7
1,75	7274,9	7274,9	7274,9	7225,8	7445,9	7290,1	7274,9
2	8685,3	8685,3	8685,3	8490,5	8855,1	8445,8	8685,3
2,25	10767,1	10767,1	10767,1	10036,8	11164,6	10221,6	10767,1
2,5	14485,4	14485,4	14485,4	11542,9	28964,7	11826,5	14485,4
2,75	169351,9	169351,9	169351,9	32425,4	352342,9	57022,5	169351,9
3	435341,6	435341,6	435341,6	263263,3	643347,9	308524,1	435341,6
3,25	781893,7	781893,7	781893,7	619886,6	932744,0	653922,6	781893,7
3,5	1006987,5	1006987,5	1006987,5	835007,8	1138804,6	886452,0	1006987,5

Table 6.9 Throughput versus offered load of the different channels for tuning time value of 500 μs

Throughput (Mbps)				
Offered Load (Gbps)	Channel 0	Channel 1	Channel 2	Channel 3
0,25	75,07	98,19	97,08	93,87
0,5	141,79	177,41	178,96	181,30
0,75	204,40	263,15	261,84	263,73
1	267,31	351,54	350,53	344,29
1,25	333,40	440,86	428,66	441,17
1,5	392,59	527,40	518,94	522,88
1,75	450,23	605,00	604,97	614,01
2	519,68	681,32	694,81	701,54
2,25	584,43	772,91	780,45	785,82
2,5	650,70	858,77	864,75	864,63
2,75	711,64	890,66	892,06	892,81
3	770,30	890,89	891,19	891,59
3,25	824,91	892,28	891,76	892,10
3,5	824,26	890,94	893,73	892,13

Table 6.10 Throughput versus offered load of the different channels without tuning time

Throughput (Mbps)				
Offered Load (Gbps)	Channel 0	Channel 1	Channel 2	Channel 3
0,25	90,63	90,45	93,13	90,88
0,5	170,65	169,30	170,43	169,86
0,75	247,57	247,58	248,22	250,56
1	329,96	331,37	328,92	323,90
1,25	410,91	411,95	414,28	407,53
1,5	493,45	492,98	489,84	486,10
1,75	569,94	566,73	571,84	566,60
2	642,35	650,87	652,41	652,77
2,25	729,37	727,35	737,03	731,05
2,5	807,14	810,39	809,28	814,92
2,75	873,97	887,08	883,49	887,45
3	891,93	890,13	887,04	887,16
3,25	890,09	891,69	889,51	887,72
3,5	889,83	889,43	888,72	891,09

Table 6.11 Throughput versus offered load of the different channels for tuning time value of 10 µs

Throughput (Mbps)				
Offered Load (Gbps)	Channel 0	Channel 1	Channel 2	Channel 3
0,25	91,77	89,97	90,30	91,93
0,5	170,72	171,57	167,00	170,02
0,75	253,39	246,85	246,61	245,93
1	324,49	327,81	327,29	333,32
1,25	412,40	409,43	409,53	411,98
1,5	488,36	488,94	493,63	490,10
1,75	571,05	566,98	573,85	561,62
2	651,61	655,22	642,10	647,29
2,25	725,56	735,70	724,12	735,87
2,5	785,14	798,04	790,98	804,21
2,75	769,40	764,37	771,11	771,08
3	772,58	774,45	779,40	785,10
3,25	787,36	781,35	781,69	778,03
3,5	797,08	789,08	801,03	794,66

Table 6.12 Throughput versus offered load of the different available wavelengths for tuning time value of 1 µs

Throughput (Mbps)				
Offered Load (Gbps)	Channel 0	Channel 1	Channel 2	Channel 3
0,25	91,97	92,87	91,98	88,12
0,5	167,78	171,07	168,31	173,03
0,75	248,97	246,47	248,16	250,35
1	335,88	326,95	322,32	328,92
1,25	413,77	409,11	408,15	413,49
1,5	491,48	488,87	491,78	490,27
1,75	570,73	574,65	561,03	568,31
2	648,83	653,43	649,30	646,56
2,25	725,30	728,18	731,74	739,33
2,5	813,58	809,71	809,44	808,77
2,75	877,00	874,79	868,45	878,99
3	872,51	874,06	878,07	874,97
3,25	879,06	876,06	872,51	874,68
3,5	875,21	875,15	873,87	877,39

ANNEX 7. Introduction to ONET simulator

Annex 7 explains briefly the OPNET simulator how it works.

7.1. OPNET

OPNET is a very potential software for designing and analysing networks. The simulator uses devices from different suppliers. Besides, OPNET permits to design your own networks by programming in C language. More information regarding OPNET can be found in [2].

7.2. Structure of OPNET

ONET has hierarchical structure for designing the modules, as shown in Fig. 7.1. The modules represent a more complex network. There are several models such as: node model, process model, packet format model.

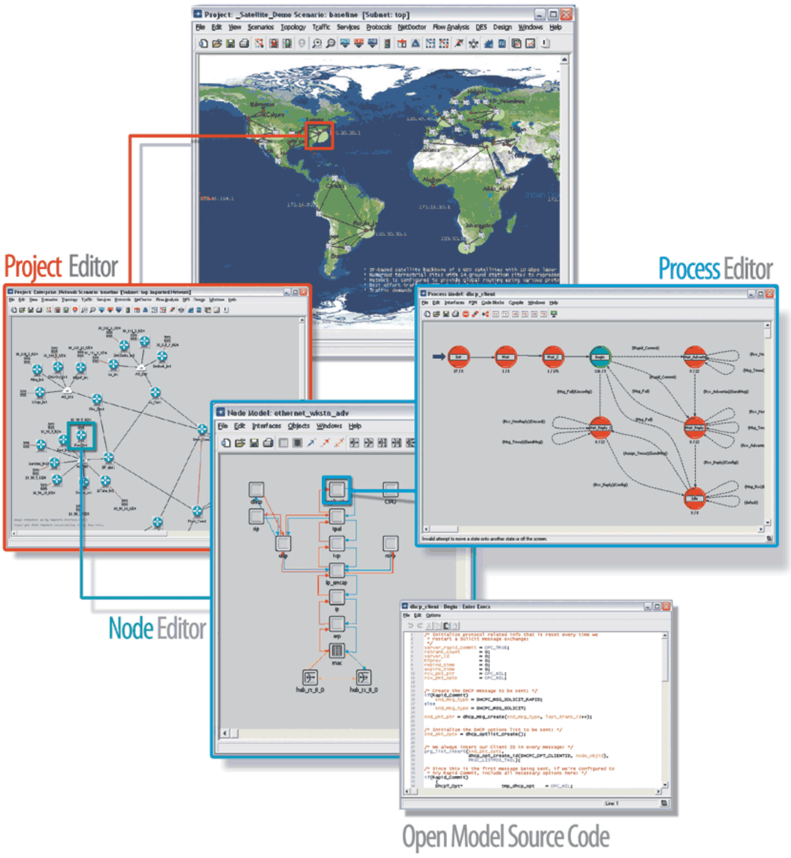

Fig. 7.1 Hierarchical structure of OPNET

7.3. Network model

The network model contains all the components of the network. This model connects the network nodes. Network model defines the distances between the components.

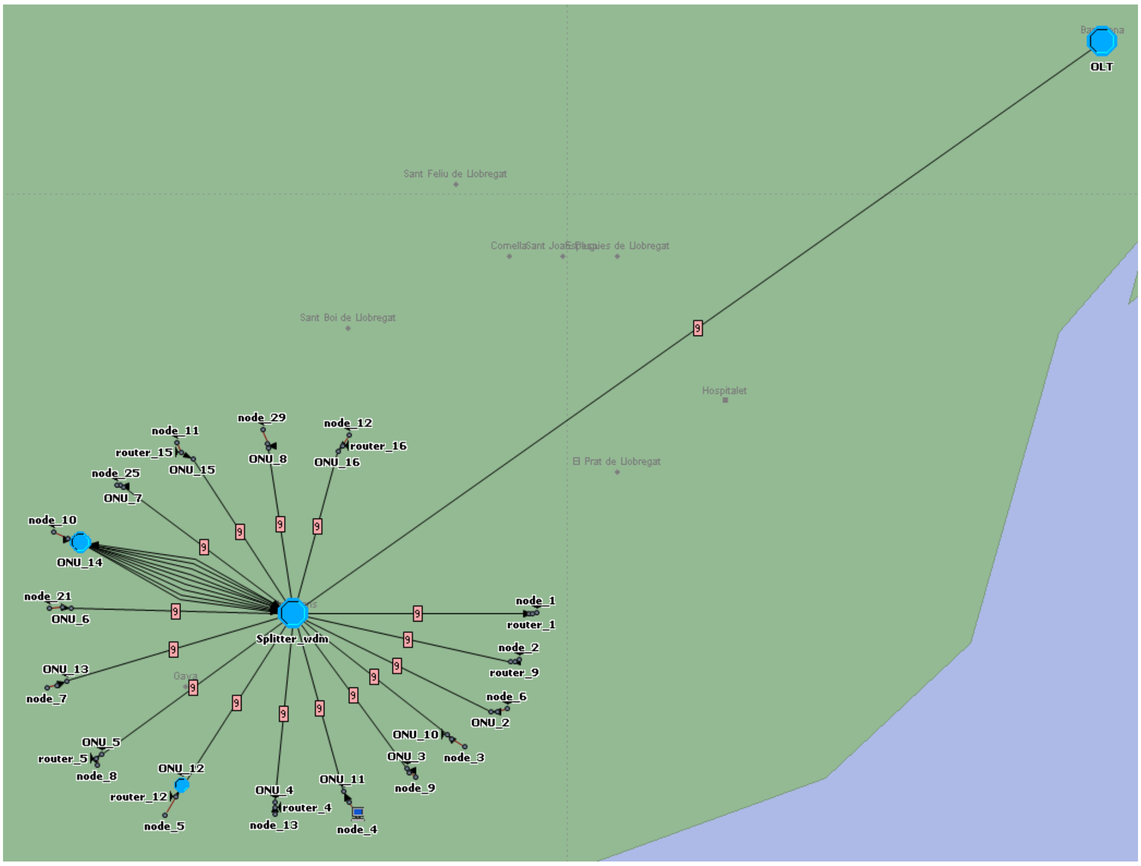

Fig. 7.2 Network Modeler. EPON

7.4. Node model

The node model defines the workflow of the nodes and its composed by process models. The packets are defined in this model as well. The workflow is defined by logical connections between process models.

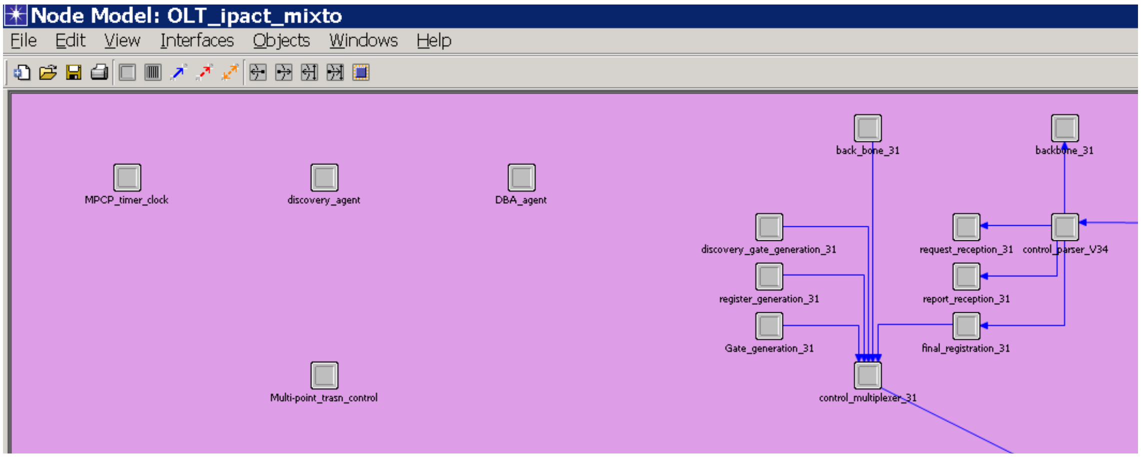

Fig. 7.3 Node Model

7.5. Process Model

Process model defines some functions need for the node workflow. In process model are implemented algorithms and protocols.

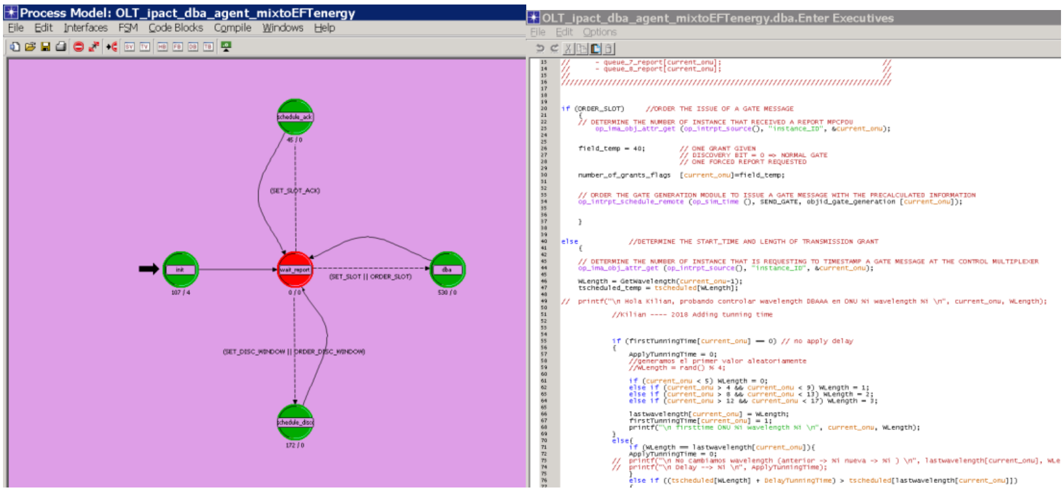

Fig. 7.4 Process Model, visual editor and state programming

Process model is a visual editor represented by state diagrams (STDs) and the states are programmable in Proto-C language (based in C) (see Fig. 7.4). States' connections are called transactions and they can be conditional or unconditional. These transitions define a condition to pass to the next state. Fig. 7.5 shows edit configuration for defining the transactions' condition.

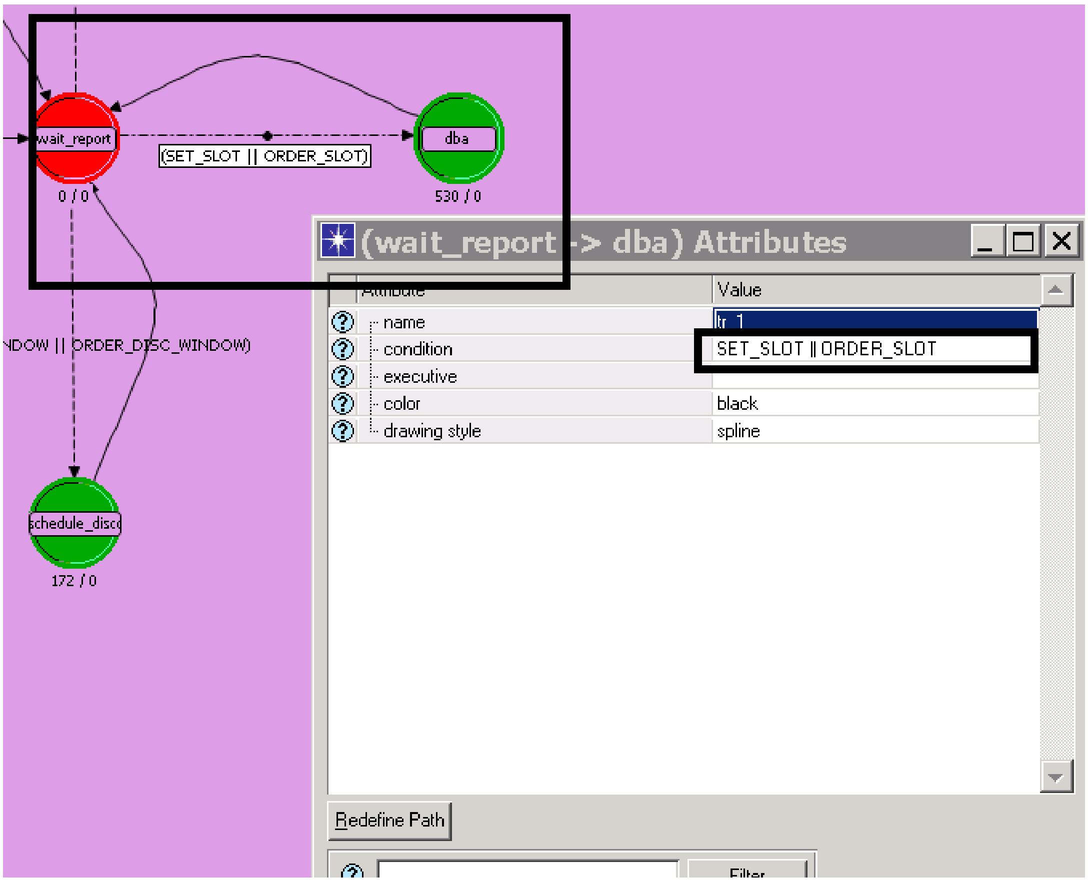

Fig. 7.5 Edit attributes menu of transactions in process model

7.5.1. Forced and unforced states

In process model there are two kind of states, forced and unforced. They are differentiated by its colour. The green states are forced and the red states are unforced, as shown in Fig. 7.6 and 7.7. The states differ in execution.

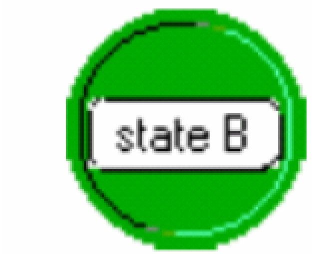

Fig. 7.6 Unforced State

Fig. 7.7 Forced state

First of all, let’s see which components have the states (see Fig. 7.8). One state has two C codes into it, the enter executive code and the exit executive code. Enter executive code is executed when the module enters in a state and exit executive code is executed when the module leaves of the state.

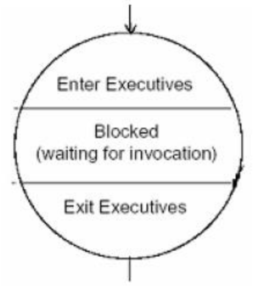

Fig. 7.8 State. Executives codes

The forced state does not return the control of the simulation. When it receives an invocation immediately executes the enter and exit executives and moving to next state. On the other hand, the unforced state returns the controls of the simulation kernel after executing the enter executive. The unforced state waits for an invocation to execute the exit executives moving to next state.

7.5.2. Variables definition in process modeler

The functions in OPNET needs variables. Some of these variables and functions might be shared between states. Thus, the variables and functions are defined on different blocks depending on their needed (see Fig. 7.9).

The variables can be categorized such as: State variables (SV) or temporary variables (TV). Being the states variables just for this process and the temporary just for iterating some data.

In header block (HB) are global variables, macros and libraries.

In Function Block (FB) are the functions and they can be called from any state of the process model. Normally, this function receives data as parameter and returns result data, after doing some operations.

In diagnostic block (DB) are the functions about the simulation state.

In termination block (TB) are the functions to execute at the end of the simulation.

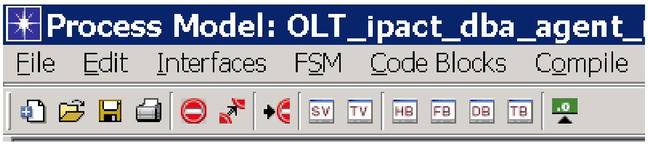

Fig. 7.9 Variables definition

7.5.3. Statistic Data Collection

OPNET software collects the simulation results in a statistic data vectors with the values desired.

Three statistic data collection are used in this document: the average queue delay, the average queue size and the throughput.

The average queue delay describes the average delay since a packet is introduced in the queue, till the packet is transmitted by the ONU, it is expressed in seconds.

The average queue size collects number of packets in the queue versus in different moment of the simulation. When the packet is transmitted, it is eliminated. It is expressed in packets or bits.

The throughput collects the average bit rate of one channel, it is expressed in bits per seconds.

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