ADVERTIMENT. La consulta d'aquesta tesi queda condicionada a l'acceptació de les següents condicions d'ús: La difusió d'aquesta tesi per mitjà del servei TDX (www.tesisenxarxa.net) ha estat autoritzada pels titulars dels drets de propietat intel·lectual únicament per a usos privats emmarcats en activitats d'investigació i docència. No s'autoritza la seva reproducció amb finalitats de lucre ni la seva difusió i posada a disposició des d'un lloc aliè al servei TDX. No s'autoritza la presentació del seu contingut en una finestra o marc aliè a TDX (framing). Aquesta reserva de drets afecta tant al resum de presentació de la tesi com als seus continguts. En la utilització o cita de parts de la tesi és obligat indicar el nom de la persona autora.

ADVERTENCIA. La consulta de esta tesis queda condicionada a la aceptación de las siguientes condiciones de uso: La difusión de esta tesis por medio del servicio TDR (www.tesisenred.net) ha sido autorizada por los titulares de los derechos de propiedad intelectual únicamente para usos privados enmarcados en actividades de investigación y docencia. No se autoriza su reproducción con finalidades de lucro ni su difusión y puesta a disposición desde un sitio ajeno al servicio TDR. No se autoriza la presentación de su contenido en una ventana o marco ajeno a TDR (framing). Esta reserva de derechos afecta tanto al resumen de presentación de la tesis como a sus contenidos. En la utilización o cita de partes de la tesis es obligado indicar el nombre de la persona autora.

WARNING. On having consulted this thesis you're accepting the following use conditions: Spreading this thesis by the TDX (www.tesisenxarxa.net) service has been authorized by the titular of the intellectual property rights only for private uses placed in investigation and teaching activities. Reproduction with lucrative aims is not authorized neither its spreading and availability from a site foreign to the TDX service. Introducing its content in a window or frame foreign to the TDX service is not authorized (framing). This rights affect to the presentation summary of the thesis as well as to its contents. In the using or citation of parts of the thesis it's obliged to indicate the name of the author

Universitat Politècnica de Catalunya
Department of Telematics Engineering

Resource Optimization in Passive Optical Networks:
Dynamic Bandwidth Allocation, Evolution, and Cost-Effective Capacity Upgrades

Marilet De Andrade Jardin

Directors:

Prof. Sebastià Sallent Ribes, Universitat Politècnica de Catalunya

Prof. Biswanath Mukherjee, University of California at Davis

A dissertation submitted to
Universitat Politècnica de Catalunya
in partial fulfillment of the requirements
for the degree of Doctor

Barcelona, October 14, 2010

ABSTRACT

This thesis is a result of contributions to optimize or improve resource allocation in Passive Optical Networks (PON). The contributions are related with resource allocation during PON operation and with the upgrade process to allocate more capacity to the network in an “as-needed” fashion. We first address algorithms for Dynamic Bandwidth Allocation (DBA) in the upstream channel of Ethernet-based PONs through providing a state-of-the-art survey and proposing two algorithms. The proposed DBA results demonstrate improved performance and fairness among users. Then we introduce the problem of allocating new capacity to an existing PON through addition of wavelength (channels) and line-rate upgrades. In this regard, we first analyze possible strategies for PON evolution, and then we provide a new cost-based method to optimize the upgrade process in a per-period basis. The results on PON evolution analysis and our capacity-upgrade method contribute to cost reductions while optimizing new channel allocation, maximizing network capacity usage, and assuring minimum disturbances.

Keywords: Passive Optical Networks, Dynamic Bandwidth Allocation, PON evolution, capacity upgrade, migration, WDM, optimization

Esta tesis es el resultado de contribuciones para optimizar o mejorar la distribución de recursos en Redes Ópticas Pasivas (PONs). Las contribuciones están relacionadas con el uso de los recursos durante la operación de las PONs y con el proceso de incremento en la capacidad en la red de forma gradual. Primero enfocamos el estudio en algoritmos de Distribución Dinámica de Ancho de Banda (DBA, por las siglas en inglés) sobre el canal ascendente de las redes PON basadas en Ethernet, para lo cual proveemos un resumen del estado del arte y proponemos dos nuevos algoritmos. Los resultados de evaluar los DBA propuestos demuestran mejoras en el rendimiento y mayor justicia entre los usuarios. Posteriormente se introduce el problema de asignar más capacidad a una PON existente mediante la implementación de nuevas longitudes de onda (canales) y aumento de la tasa de línea. Finalmente se plantea un método que minimiza las inversiones en el proceso de migración de las redes PON. Los resultados en el análisis de la evolución de las PONs y nuestro método basado en costos para incrementar la capacidad, contribuyen a reducir la inversión a la vez que se optimiza la implementación y asignación de nuevos canales, maximizando el uso de la capacidad de la red, y asegurando mínimos cortes de servicios.

Palabras Clave: Red Óptica Pasiva, Distribución Dinámica de Ancho de Banda, Evolución de las PON, aumento de capacidad, migración, WDM, optimización

To my mother
Maria Ezequiel

ACKNOWLEDGMENTS

First, I would like to thank my advisors Prof. Sebastian Sallent from UPC and Prof. Biswanath Mukherjee from UC Davis, for their help, concern, and valuable advice. Without their support this dissertation would not have been finished. Their understanding and ease of cooperation has helped a lot. I thank them from the bottom of my heart.

Second, I extend my thanks to my paper co-authors, whom I have learned a lot from. In this regard, I thank Dr. Massimo Tornatore for spending good amount of time working together at UC Davis and for the fruitful discussion. I also thank Prof. Lluis Gutiérrez, and Paola Garfias for the very fruitful work together at UPC, and I also thank coauthors Prof. Cristina Cervellò and Prof. David Rincón. I especially want to thank the collaboration at University Simón Bolívar with Prof. Mónica Huerta, and her students Anny Martínez, Dayana Sánchez and Pedro Vizarreta, who did an excellent job during their visit to UPC. It was a great experience to work with Prof. Lena Wosinska and Dr. Jiajia Chen in KTH, and I thank them for their collaboration. I thank Dr. Glen Kramer for his contribution and for the important knowledge he brought into my work.

Special deep thanks go to my fiancé Dr. Iyad Al Khatib for believing in me and for his strong support and encouragement to go for my dreams. He has been a major force to get this work done.

It is my pleasure to thank my colleagues Xavier, André, Alberto, Mari Carmen, Elena, Pedro, and Yury. I thank them for giving me help when I needed it, and for being supportive and fun to be around. Special thanks are for my lab-mate Eduard Garcia for the very interesting discussions, nice work environment, and help. I also thank all lab-mates at UC Davis, who have been such a great company, and were so very open to give help. At UC Davis I thank Avishek, Sayeem, Eiman, Pulak, Menglin, Lei, Ming, Rajesh, Yee, Dragos, Marwan, and many others. I want to thank my kind mates at KTH: Amo, Jawwad, and Paolo.

Many thanks are to my friend Sophie for her great help, understanding and support in many of my hard times in Spain. I also thank my friends Thais and Mar for the great time, true friendship, and understanding. I thank my friend Jad for being there for me and cheering me up all the times. I thank my friends from the church choir for opening their hearts and becoming a second family for me in Spain. I thank especially Leo for being like a second mother for me. I also thank Cari, María, Pili, Tere, Cova, Carolina, and all the priests at the “Sagrados Corazones” church.

I would like to extend many special and deep thanks to my friend and roommate Amber Norgaard for her endless support and help. Without Amber many issues in my life in the US would have been much harder, and more time consuming. I also thank my friend Shareghe a lot for her support and help. Shareghe´s help was always great and she was always there when I needed her. I thank both Amber and Shareghe for being honestly very true friends.

I thank my friends in Stockholm for their support; especially I thank Bassam, Khaled, Adel, Jad, Zaidoon, Omar, Fadi, and Cicek.

Many thanks to Margaret Hellwarth at UC Davis, who has enlightened many days, helped me in many practical issues, and for being a wonderful friend.

I also would like to thank the professors, colleagues, and administration in the Telematics Engineering Department at UPC! I appreciate their help many times, and I appreciate the nice Christmas and “Guardiola” dinners together.

I also have very special thanks to my great friends Eiman, Talal, Bader, and Omar who made me part of their family in CA, USA.

Before I end this, I want to thank Prof. Mukherjee and all at UC Davis for the wonderful Potluck gatherings that helped me always regain energy and charge for more work!

Finally, and again I remain grateful to my family, who never hesitated to help me. I acknowledge the lessons of my father to fight for what I want, and I thank my brother for taking over many of my father’s responsibilities after he left us. They cannot celebrate this achievement with me now, but I am sure they feel very proud of me.

I also want to thank my best friend Mascoli Cécil for her unconditional support and care.

For all those who helped and I may have forgotten to mention, please forgive me and I thank you in this sentence.

CONTENTS

Page

LIST OF FIGURES

Page

LIST OF TABLES

Page

ABBREVIATIONS

ADSL	Asymmetric Digital Subscriber Line
APON	ATM-based PON
AWG	Arrayed Waveguide Grating
BPON	Broadband PON
CAPEX	Capital Expenditure
CATV	Cable Television
CDM	Code Division Multiplexing
CSMA/CD	Carrier Sense Multiple Access with Collision Detection
CWDM	Coarse Wavelength Division Multiplexing
DBA	Dynamic Bandwidth Allocation
DDSPON	Dynamic Distributed Scheduling for EPON
DFB	Distributed Feedback laser
DPSK	Differential Phase-Shift Keying
DWDM	Dense Wavelength Division Multiplexing
E-OLT	Enhanced OLT
EPON	Ethernet-based PON
FTTB	Fiber To The Business
FTTCab	Fiber To The Cabinet
FTTEx	Fiber To The Exchange
FTTH	Fiber To The Home
FTTN	Fiber To The Node
GEM	Generic Encapsulation Method
GPON	GEM-based PON
GPS	Generalized Processor Sharing
HD	High Definition
HDTV	High Definition Television
IEEE	Institute of Electrical and Electronics Engineers
IPHDTV	Internet Protocol High-Definition TV

IPTV	Internet Protocol Television
ITU	International Telecommunication Union
LR-PON	Long-Reach PON
MAC	Medium Access Control
MILP	Mixed Integer Linear Programming
MUX/DEMUX	Multiplexer/Demultiplexer
NGA	Next-Generation Access
NRZ	Non-Return-to-Zero
NTE	Network Terminal Equipment
OCDM	Optical CDM
OFDM	Optical Frequency Division Multiplexing
OLT	Optical Line Terminal
ONT	Optical Network Terminal
ONU	Optical Network Unit
OPEX	Operational Expenditure
PON	Passive Optical Network
QoS	Quality of Service
RN	Remote Node
RSOA	Reflective Semi-conductor Optical Amplifier
SDM	Sub-carrier Division Multiplexing
SMB	Small/Medium Business
SLA	Service Level Agreement
SP	Service Provider
TDM	Time Division Multiplexing
U-DWDM	Ultra Dense Wavelength Division Multiplexing
VDSL	Very high bit-rate Digital Subscriber Line
WDM	Wavelength Division Multiplexing
XGPON	10-Gbps GPON

Chapter 1 Introduction

This chapter briefly introduces the problem we aim at solving and the motivation behind our goals. The main problems lie in efficiency limitations of bandwidth allocation algorithms for PONs and a need to upgrade existing PONs in a gradual way by considering cost-effective optimization requirements. The solutions proposed consist of two algorithms and one method which, through simulations and optimization tool, illustrated good properties.

This chapter consists of three sections: Section 1.1 describes the motivation of the problems we intend to solve in this dissertation, Section 1.2 states our contributions, and Section 1.3 outlines the organization of the remainder of this dissertation.

1.1. Motivation

The socio-economic factors related to data-exchange on communication networks are a major driver for the growth of such networks and the consequent knowledge-based economy. The *social* factors are coupled to network traffic growth. This traffic accretion calls for better solutions that leverage network infrastructure to be able to meet current and future demands while respecting the *economic* side, i.e. being cost effective. This draws our attention to investigate current communication networks, study their progress, and look for potential solutions. So much so, we seek optimal bandwidth usage and evolution paths for these technologies.

In this respect, rapidly increasing bandwidth demands and increasing number of Internet users have led to the development of broadband access networks. In particular, the Passive Optical Network (PON) has been considered to be a cost-effective solution for the last mile, since all the network elements in the signal path within the network are passive. Nowadays international technical organizations such as IEEE and ITU-T promote and release standards for different types of PONs. Some years ago, when the standards were first released, one of the main issues that was not covered was the bandwidth allocation algorithm, which defines when and for how long user devices are allowed to transmit considering that one of the channels (upstream channel, from user to head-end node) was shared in time. Many researchers and companies worked on trying to propose bandwidth allocation mechanisms with diverse properties like fairness and channel efficiency, which is the first motivation of this dissertation.

Subsequently, as traffic continued to grow more concerns were placed on building the next-generation PON. Many companies, providers, and telecom operators gave an important attention to find and propose the best candidate technology for a migration to a next-generation PON from existing legacy ones. Now, the standardization processes have to deal with backward compatibility issues and specific requirements to facilitate the placement of future PON generations without hurdles. This context has led us to evaluate possible evolution strategies, and this constitutes our second motivation.

Assuming that PON evolution may go through a combination of TDM and WDM technologies, the problem that arises here is how to gradually upgrade the exiting and deployed PONs in a gradual manner, accomplishing all the required bandwidth demands, while achieving reduced cost and disruptions. This is the third problem that motivated this part of the work in this dissertation.

1.2. Contributions

This dissertation aims at providing a contribution to the solution for each problem reported in the previous section. The first contribution is a review of the state of the art in Dynamic Bandwidth Allocation (DBA) algorithms proposed for a particular type of PON: Ethernet-based PON or EPON. Our work is intended to facilitate other research works and ours in the research for new algorithms for EPON. Consequently, we propose a taxonomy of DBA algorithms.

The second contribution of this dissertation is the proposal of two DBA algorithms that fall in two different types of solutions according to our aforementioned taxonomy. The first algorithm is a centralized one, and it is part of our first findings, whose aim is to satisfy fairness among users. However, this scheme is not very satisfying due to some extra delays to run it. These delays are based on the premise that, before running the algorithm, the central node needs to have all the network state from bandwidth-requirements point of view in order to provide fairness. We propose and evaluate a new algorithm that would overcome the previous problem, while providing fairness and less delay. The second proposed DBA algorithm is decentralized.

The third contribution is the qualitative and quantitative analyses of the evolution strategies for PONs. In this contribution, we also propose three technology-encompassed and smooth migration phases, and their most suitable candidate under the light of basic evolution requirements for an as-needed PON capacity upgrade.

Finally, our fourth contribution is a multi-step method to calculate the optimal capacity upgrades needed by a PON based on traffic demands over multiple time periods. The aim is to minimize capital expenses and system disruptions, while ensuring guaranteed resource usage. Our method calculates optimal capacity upgrades for PONs using Mixed Integer Linear Programming and proposed pricing policies. It can be adapted to the specific requirements of an operating PON that needs to be upgraded and a Service Provider can customize this method by changing its parameters to its specific network values.

1.3. Organization of the Dissertation

The rest of the dissertation is organized as follows: *Chapter 2* reviews the background knowledge of related fields and research, *Chapter 3* presents two Dynamic Bandwidth Allocation algorithms for Ethernet-based PON; *Chapter 4* discusses an analysis of evolution strategies for PONs; *Chapter 5* presents an optimal capacity upgrade method for PON and analysis results; *Chapter 6* concludes the dissertation; and finally, *Chapter 7* examines open issues, presents ongoing research, and lists topics for future research work.

References are listed alphabetically and numbered accordingly using Arabic Numerals. Within the dissertation text, numbers between *parentheses* correspond to *equations*.

Chapter 2 Background

This chapter provides the background of the research issues treated in this dissertation. We provide a general introduction to Passive Optical Networks (PON) based on different technologies and standards, the state of the art of Dynamic Bandwidth Allocation (DBA) algorithms, and literature on PON evolution, with focus on next-generation PONs.

The chapter is organized as follows: Section 2.1 introduces the concepts and standard-related fundamentals of PON. Section 2.2 provides a classification and describes some of the most important algorithms that have been proposed for Ethernet-based PONs. In Section 2.3, next-generation PON and some background of its evolution are discussed. Section 2.4 is devoted to briefly explain some of the DBA tendencies for WDM-based PONs. Finally, the chapter ends with a summary in Section 2.5.

2.1. Passive Optical Networks

It is widely accepted that Passive Optical Networks (PON) are the most promising cost-effective and high-performance access network solution, and they can support bandwidth-intensive applications [28]. A PON is a subscriber access network technology that provides high bandwidth capacity over fiber. It is a point-to-multipoint network with a logical tree topology in many cases, as shown in Figure 1. The terminal equipment connected at the trunk of the tree is referred to as the Optical Line Terminal (OLT) and typically resides at the service provider's facility. The OLT is connected to a passive optical splitter (known also as the Remote Node, RN) using an optical trunk fiber, which fans out at the splitter to multiple optical drop fibers to which Optical Network Units (ONUs) are connected.

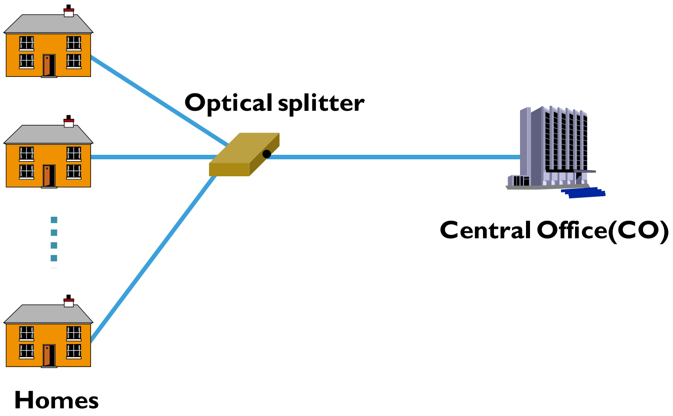


Figure 1. A passive optical network (PON).

An ONU typically resides at the subscriber premises, which can be end-user locations or curbs resulting in different fiber-to-the home, business or curb (FTTx) architectures (where x may mean Home, Business/Building or Curb, among other possibilities) as presented in Figure 2. In FTTB and FTTH, the ONU or ONT (Optical Network Terminal) is located at end-user's premises (Business or House). In FTTEx, FTTCab, FTTC, the ONU is located at the Local Exchange, Cabinet and Curb, respectively, and the connection to the user is through ADSL or VDSL, according to the distance left till the user. The device inside the user's facility is often called Network Terminal Equipment (NTE), except in the case of FTTH/B. The distances covered are usually 10-20 km. Legacy PONs, also known as TDM-PON, employ two wavelength channels: an upstream channel (from ONUs to OLT shared in time domain) and a downstream broadcast channel (from OLT to ONUs) [24][29].

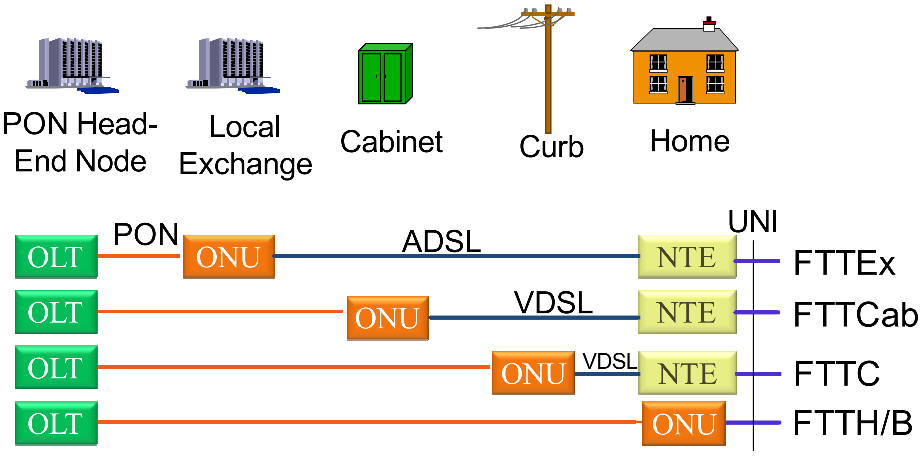


Figure 2. Fiber To The x (FTTx): different approaches according to where the ONU or ONT are located.

2.1.1. GPON / EPON Review

The PON standards being currently deployed around the world are: APON/BPON (ITU G.983), GPON (ITU G.984 [34]); and EPON (Ethernet PON) born in 2004 (IEEE 802.3 ah [38]). Their basic physical features are very close to each other but what differentiates them more is the encapsulation of the information carried by the network: while the APON/BPON and GPON carries the information using ATM (Asynchronous Transfer Mode) or GEM (Generic Framing Protocol) frames respectively, EPON carries bursts of pure Ethernet frames.

Current legacy PON or TDM-PON are single channel networks, where the downstream is a broadcast channel but the upstream channel is a multi-access channel shared in time among the ONUs. Each ONU transmits a burst of data which cannot be interfered by any other burst of a different ONU in the window allocated to it.

The main challenge is to develop appropriate scheduling algorithms (known as Dynamic Bandwidth Allocation, DBA) to efficiently allocate the bandwidth over the upstream channel to the ONUs. The scheduler must be efficient, support the Quality of Service (QoS) that each traffic flow (real- and non-real time traffic) requires, allocate fair bandwidth to users by reducing delay and jitter, be computationally simple, and fulfill the Service Level Agreement (SLA). Such process usually runs centralized at the OLT, but it is also possible to develop distributed scheduling algorithms running at the user equipment. A survey of the most relevant algorithms is available in [80]. IPACT (Interleaved Polling Adaptive Cycle Time) is considered to be a key DBA used as reference for performance comparisons in most of the studies [32].

Each ONU performs the intra-scheduling to provide the QoS to each traffic type. The QoS in GPON is ensured by using 4 types of connections with differentiated treatment as the ATM model, and in the EPON standard there can be up to 8 queues of priority, and the transmissions are ordered from the higher to the lower priority following the IEEE 802.1P/Q standards.

2.1.2. GPON / EPON Comparison

Given the synchronous transmission nature of ATM- and GEM-oriented PON, they can easily adapt circuit emulation traffic, whilst the performance of Ethernet-oriented PON may be optimal when the traffic is mostly composed by Internet applications. Anyway, it is not simple to make a definitive statement about their performance, because the data collected depends on many parameters. For instance, in a detailed performance comparison between GPON and EPON with real traffic traces [75] , the authors state that EPON is more efficient than APON and GPON in the setting evaluated. A good comparison analysis of EPON vs. GPON from the point of view of Dynamic Bandwidth Allocation is presented in [7]. Table 1 summarizes the basic features of both standards.

Table 1. Basic features of GPON and EPON standards.

Feature	GPON	EPON
Standard	ITU G.984	IEEE 802.3 ah
Capacity Downstream (DS)	1244 / 2488 Mbps	1000 Mbps
Capacity Upstream (US)	155 / 622 / 1244 / 2488 Mbps	1000 Mbps
DS/US wavelength	1490 / 1310 nm	1490 / 1310 nm
Typical split ratios	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

2.1.3. Ethernet-Based PON Fundamentals

One of the most beneficial properties of PON is that the same fiber infrastructure can support different data transmission technologies [54]. Ethernet protocol is highly deployed in local area networks (LAN) and it is also becoming an emerging technology for metropolitan and wide area networks (MAN and WAN). Thus, Ethernet is an attractive protocol choice for the access network due to its technological simplicity and customer familiarity.

According to IEEE 802.3ah standard, an EPON supports a nominal bit rate of 1000 Mbps, shared among ONUs, which can be at a maximum distance of 20 km. The OLT and the ONUs transmit Ethernet frames over the fiber using 8B/10B encoding.

Due to directional properties of the splitter/combiner (splitting the optical signal in the downstream direction and combining the optical signals in the upstream direction) in the PONs, the downstream channel (from the OLT to the ONUs) will be broadcast in nature while the upstream channel (from the ONUs to the OLT) will be shared in time. In an EPON, all downstream Ethernet frames transmitted by the OLT, reach all ONUs. ONUs will discard frames that are not addressed to them by checking the logical id/MAC address. In the upstream direction, the signal transmitted by an ONU is received only by the OLT. Since the upstream channel is shared in time between all ONUs, it must be controlled to guarantee no collisions. The OLT arbitrates the upstream transmissions from ONUs by granting transmission windows or timeslots which can have variable lengths. An ONU is only allowed to transmit during the timeslot allocated to it. The OLT informs the duration and starting time of the allocated timeslot to the ONUs by means of a Gate message. In order to inform the OLT about ONUs' bandwidth requirements, the ONUs use Report messages that are also transmitted (along with the data) in the allocated timeslot. According to the standard, there are more control messages, besides the Gate and the Report messages for different purposes, but we do not cover them in this chapter (see [38] for more information). Control frames are also encapsulated in Ethernet frames. Frames are never fragmented in EPON, therefore, the IEEE working group introduced the concept of threshold reporting in order to achieve a higher bandwidth efficiency.

For EPON, the access to the medium has been established as time division multiplexing (TDM), because of its low-cost implementation. However, in the future, other PON implementations such as WDM and CDMA can be considered. We focus on WDM-based schemes for the next-generation PON later in this chapter.

2.2. Bandwidth Allocation Algorithms for EPON

One of the issues not included in the EPON standard is how and when to distribute the network bandwidth among ONUs. This can be solved by a good design of a Dynamic Bandwidth Allocation (DBA) algorithm. There are several DBA algorithms proposed in the literature. DBA algorithms can be classified as intra-ONU if any resource management is done inside each ONU, or inter-ONU if such management is done outside the ONUs (for example in the OLT). Inter-ONU mechanisms could be centralized or non-centralized/distributed according to where the algorithm is executed. Many schemes include both a centralized inter-ONU DBA algorithm and an intra-ONU scheduling. With advances and standardization efforts for EPON, non-centralized schemes are also becoming popular. DBA schemes frequently define a cycle or repetition period for transmissions from ONUs. The cycle can have fixed or variable length. If the cycle is constant, more time-based restrictions can be accomplished such as per-packet delay and circuit emulation. However, with a variable cycle, we can take advantage of the bursty nature of Internet traffic, and channel efficiency can be improved by adapting the cycle size to the instantaneous traffic load.

The scheduling framework can be offline or online. Offline scheduling means that the ONUs are scheduled for transmission once the OLT has received current Report messages from all ONUs before the computation of bandwidth allocation to each ONU takes place. This means that a gap between scheduling cycles is introduced, the so-called inter-scheduling cycle gap (ISCG). The length of ISCG on a wavelength channel is computed by adding: a) the computation time of the schedule; b) the transmission time for the Grant; and c) the round-trip time (due to propagation delay) to the first ONU scheduled on the wavelength in the next round. It is well-known that the ISCG impacts negatively on the efficiency of the algorithm [8][87].

On the other hand, online scheduling policies are *on-the-fly* methods, where an ONU is scheduled for upstream transmission as soon as the OLT receives that very ONU's Report message and without waiting to receive the rest of the Report messages from other ONUs. In many settings, the online schemes perform better than the offline ones, but with less control from fairness point of view. In Figure 3, we present a summary of EPON DBA taxonomy.

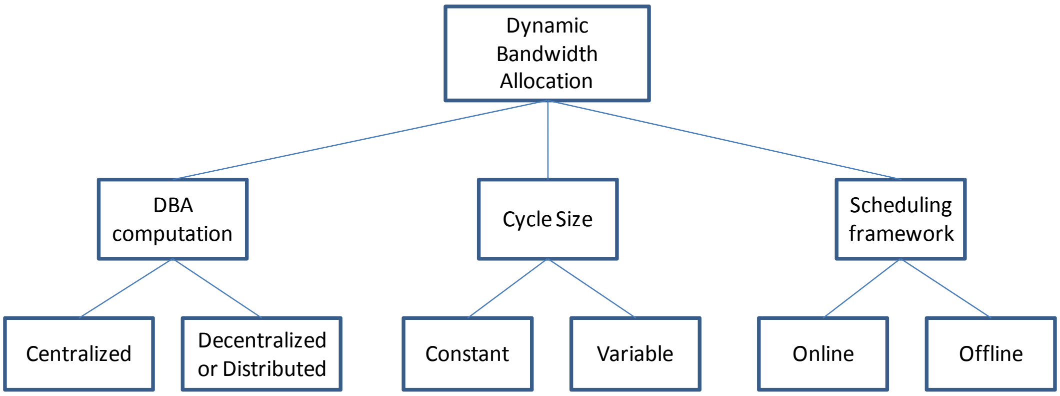


Figure 3. Bandwidth allocation taxonomy for EPON.

2.2.1. *Non-Centralized Schemes*

When considering the use of Ethernet in PON, the commonly-used medium-access protocol, CSMA/CD (Carrier Sense Multiple Access with Collision Detection), could be one of the first options for a decentralized scheme. However, its efficiency would decrease with distance. According to [28], the main reason why a medium-access mechanism with collision detection (CSMA/CD) is very difficult to implement in EPON is that, due to the directional characteristics of the optical splitter, ONUs cannot detect a collision which happened at the OLT. Although the OLT can inform the respective ONUs of the occurrence of a collision, this would imply larger propagation delays and EPON's efficiency would be reduced.

In [10], the authors perform experiments using a star-type network EPON using CSMA/CD's scheme, and obtain a good efficiency on medium usage. These results are based on optical re-routing of an OLU's data towards the rest of ONUs such that collisions can be detected. To resolve the problem described in [28], the authors in [10] do not include the OLT in the collision-detection process. Here, CSMA/CD is only applied between ONUs, using distances (between splitter-ONU) in the range of 100 meters, which gives an efficiency of 99%. Although it is an interesting result, it does not express the efficiency for a more realistic case in which the distance between ONUs and splitter is relatively larger (several kilometers). Moreover, the CSMA/CD mechanism is not deterministic (transmission time for the traffic of a given ONU is unknown), and so it is incompatible when providing guaranteed services.

An alternative is the FULL-RCMA (Full Utilization Local Loop - Request Contention Multiple Access) protocol presented by Foh et al. [11]. This mechanism needs a change in the physical structure of the EPON. In the splitter they incorporate an opto-coupler feedback that is sent back to ONUs through an additional fiber between the splitter and the ONUs. Then, the authors propose a communication protocol among the ONUs to manage the arbitration of the channel. In this way, the ONUs can know what is transmitted to the medium and if its own transmission has collided with another ONU or not. The OLT is not involved in the bandwidth management process. ONUs administer transmission times without data collisions. In this case, like the above, it is not possible to offer guaranteed services.

2.2.2. Centralized Schemes with Fixed Cycle

The first idea related to centralized schemes was proposed by Kramer et al. [31] and we refer to it as fixed TDMA. This simple approach assigns fixed timeslot to every ONU in the EPON. Obviously, fixed TDMA decreases utilization since light-loaded ONUs will underutilize their allocated slots. Moreover, this mechanism does not take into account particular bandwidth needs of ONUs.

An interesting fixed-cycle scheme is BGP (Bandwidth Guaranteed Polling), designed by M. Ma et al. [77]. BGP divides a cycle into a fixed number of elements that the authors call bandwidth unit. The number of units granted to an ONU depends on delay requirements and bandwidth. If there is a unit not used by any bandwidth-guaranteed ONU, it is granted to best-effort ONU. Also there could be units not reserved for a bandwidth-guaranteed ONU that are granted to best-effort ONUs in a round-robin fashion within each cycle. This protocol obtains controlled guarantees and is able to offer some QoS in the EPON. One problem we found is that the algorithm for uniform distribution of bandwidth units over a cycle can be computationally heavy and time consuming for the calculations over each cycle. The algorithm should be executed every time a connection status changes, and so it could be time consuming. A second disadvantage is related to the "guard time"[1]. Since the BGP mechanism allows any ONU to transmit several times inside a cycle, a larger amount of time is spent to complete the required guard times, which consequently leads to reduce the channel utilization.

Another fixed cycle mechanism called HSSR (Hybrid Spot-Size/Rate) was proposed by F. Hsueh et al. [90]. HSSR divides a cycle in two parts: a first fixed part for guaranteed services, and a second part that is granted dynamically to ONUs without guaranteed services. The dynamic part can be shared between several ONUs depending on the traffic load. If traffic load is high, only one or two ONUs without guaranteed services could transmit. With this operation, the authors intended to reduce guard time overload during high traffic load. One disadvantage is the need for traffic load measurement. In addition, we find in this approach the same problem in fixed TDMA, because there could be underutilization inside the static part of a cycle transmission. At intra-ONU level, the authors propose priority queuing. When any priority queue fills up, new packets are directed to the next lower priority queue. As this method generates some disorder of packets, authors introduce a new queue stage to manage reordering.

2.2.3. Centralized Schemes with Variable Cycle

2.2.3.1. Interleaved Polling with Adaptive Cycle Time (IPACT)

Kramer et al. [32] designed a DBA algorithm called IPACT (Interleaved Polling with Adaptive Cycle Time), which has been considered as the reference mechanism for EPON DBAs. By using the information received in

---

[1] Guard time is the time between subsequent transmissions of two ONUs, such that the remaining laser signal from the previous ONU does not interfere with the next ONU's laser signal. The guard time is set by standard and it deals with turn-off and turn-on times of the lasers.

the Report messages, the OLT fills a table with the ONUs' queue requirements and round-trip time (RTT), as shown in Figure 4. Roughly speaking, this algorithm works as follows: all ONUs get a timeslot in a cyclic order, and during each timeslot an ONU will transmit some data as well as a Report message to update the OLT's table which stores all ONUs' bandwidth requirements. The timeslot length allocated to ONU$_i$ is completely determined by the contents of the Report transmitted in the previous timeslot of that ONU$_i$. However, the OLT will usually grant (limited service case) the requested amount of bandwidth if it is equal or less than a predefined maximum (plus the size of a report message). If the requested bandwidth surpasses the maximum allowed; then, just the maximum value is allocated. This approach offers good channel utilization and it is highly efficient; however, there may be some issues related to delay and jitter because of the variable polling cycle times.

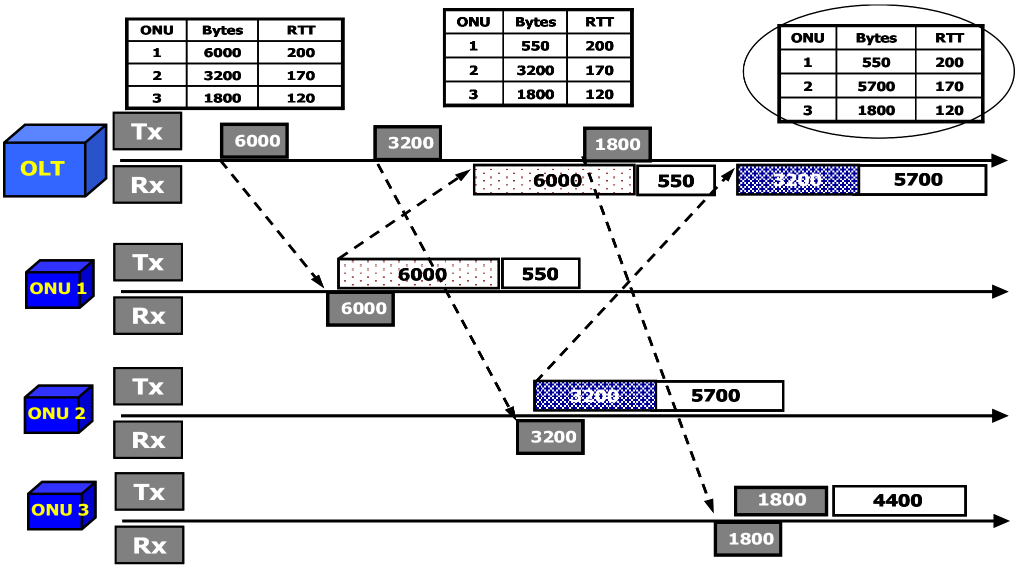


Figure 4. Interleaving polling mechanism in IPACT's DBA algorithm.

The IPACT algorithm was extensively studied and improved in order to support differentiated services in [33]. The authors point out that queuing delays for some traffic classes increase when the network load decreases, and they called this problem *light-load penalty*. To solve it, IPACT incorporates a two-stage queuing system at intra-ONU level. The first stage system classifies and schedules packet transmission based on strict priority. The second queuing stage provides fairness according to the arrival time of packets. Another solution to light-load penalty problem is the CBR credit-based scheme, which gives an extra transmission time to CBR sources based on knowledge of its constant rate. CBR credit partially solves the penalty but requires knowledge of the arrival process. In a further extension of this algorithm, a hierarchical scheduler is proposed in [30].

2.2.3.2. Other Schemes

Nikolova et al. [16][17] study the effect of threshold reporting on delay and efficiency of IPACT mechanism. They are the only ones to make use of the thresholds reporting mechanism. They allocate bandwidth up to the same threshold for all requesting ONUs in the cycle. They also impose a restriction on the minimum length of the cycle, which solves some undesirable effects such as the light-load penalty.

Choi [87] suggests a Cyclic Polling-based Dynamic Bandwidth Allocation Algorithm similar to IPACT. However, Gate messages are sent periodically only at the end of each cycle in order to schedule transmissions and try to maintain a nearly-fixed cycle. This idea helps in getting some of the advantages offered by fixed-cycle schemes.

The algorithm proposed by Assi et al. [8][9] is similar to that in [87]. The main difference is a condition for sending a grant immediately or at the end of the cycle. If bandwidth requested by any ONU is smaller than the maximum permitted, the OLT grants immediately the requested transmission window. If the requested bandwidth is greater than the maximum, then this request enters into a scheduler that proportionally distributes the remaining bandwidth according to bandwidth requirements and priority. The authors obtain a better performance in terms of per-packet delay and throughput compared with IPACT.

In some cases, the DBA might be based on prediction-oriented or non-prediction-oriented approaches. Some examples of prediction-oriented algorithms are: [35][92][93][6].

2.3. Next-Generation PON

The FTTH infrastructure, mainly in the form of PON networks, is being deployed on a large scale in Asia and the U.S.A., and is beginning to pick up pace also in Europe. Due to traffic demand growth, operators need to consider the future migration from legacy PON systems to next-generation access (NGA) systems upon the current PON fiber infrastructure. Not only such upgrade will provide higher bandwidth or further reduce the cost of delivering existing services, but also NGA will be the backhaul of mobile networks (WiFi, WiMAX); attaching the Base Station to the PON to easily access the metro and core networks.

The extant PON networks are TDM-PON with a single channel but the next-generation PON (NG-PON) will be based on WDM techniques (WDM-PON). The goal is to migrate gradually from existent TDM-PON to the WDM-PON by facilitating the operators to replace the users' network equipment. Such upgrade is driven by the IEEE and ITU-T, which have developed a new standardization for PONs that starts with line-rate upgrade. NTT has demonstrated that the evolution through 10-Gbps is more suitable than WDM-PON [83] for a next-generation migration step.

2.3.1. 10-Gbps GPON

The FSAN group together with the ITU is upgrading the former GPON from 2.5 to 10 Gbps. The first enhancement of GPON is in recommendation ITU G.983.3, which allocates some space in the optical spectrum to host video services or additional digital services by using appropriate subcarrier multiplexing techniques. The current upgrade goes in three directions [24]:

- Higher data rates: The downstream rate would likely be 10 Gbps, but the upstream rate is still an open question. It can be 2.5, 5, or 10 Gbps.
- Blocking filters to be supported at G-PON ONUs to ensure that next-generation ONUs could be installed on currently-deployed G-PON side by side with legacy G-PON ONUs.
- The extension of a G-PON's optical budget. Such enhancement will allow the deployment of longer reach and higher split ratio in current PONs.

2.3.2. 10-Gbps EPON

The TDM-EPON is being upgraded also to 10 Gbps by the IEEE 802.3av standard. This standard was finished in September 2009. Its potential market is very wide and the standard goes after the objectives listed below [39]:

- Support subscriber access networks using point-to-multipoint topologies on optical fiber.
- Two different data rate channels: 10 Gbps DS/1 Gbps US, single SM fiber; or 10 Gbps DS/10 Gbps US, single SM fiber.
- Define up to three optical power budgets that support split ratios of 1:16 and 1:32, and distances of at least 10 and at least 20 km.

The goal is to upgrade the channel capacity for both upstream and downstream channels gracefully, while maintaining the logical layer intact, taking advantage of the already existing communication protocols and DBA agent specifications, which will remain compatible with legacy 1Gbps-EPON. Moreover, 10Gbps-EPON can keep on utilizing the analog video delivery systems before such service shifts gradually to an IP-based distribution system.

2.3.3. WDM-PON and PON Evolution

Due to continued increase in bandwidth demands in the access networks, more capacity upgrades in PONs have been proposed over the recent years. One of the most relevant ones is related to the use of WDM in PONs in order to increase the number of wavelength channels and multiply the PON capacity.

Many architectures have been proposed [1] based on the provision of one or more dedicated wavelength channels to each ONU. In many of the cases, the optical splitter needs to be replaced by an Arrayed Waveguide Grating (AWG). An AWG can be described as a fixed-wavelength passive optical router. From one side, the AWG will receive multiple wavelengths from one fiber and route each of them towards a different output fiber. This device is purely optical (it does not require electrical power supply), and its optical power loss is relatively lower than the optical splitters. This is a good characteristic that may be used to extend the PON reach.

Reference [78] presents the future applications and services that can be served with WDM-PONs, especially presenting a survey of metro-access architectures.

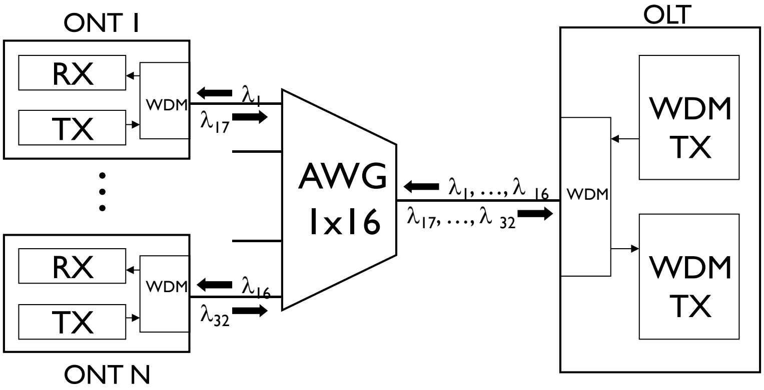


Figure 5. Basic architecture scheme of a WDM-PON.

Now, the concern is more related to a WDM-based evolution approach from the current and deployed PONs. In [44], [50] and [52], PON upgrades from current-state PON are proposed through a user-by-user evolution, where the network grows in capacity according to new user traffic needs. In the proposed evolution scenario, new 3-port wavelength-band splitters (active devices) are required in the OLT and RN. At the RN, this device is used to separate the incoming optical signal into two output ports. These two output ports are connected to the existent passive splitter and to the new AWG, respectively. ONUs connected to the AWG form the new WDM-PON and the ONUs connected to the passive splitter form the legacy and already-deployed PON. New users in this case will be added to the WDM-PON. The new RN structure is formed by a number of devices that require a control unit, which makes this proposal a very complex one. Moreover, the remote node composition is not passive any more, which may not be convenient from OPEX (Operational Expenditures) viewpoint. In [45] and [51], the same authors introduce the possibility to reuse the analog video overlay band for PON upgrade over the proposed architecture outlined before. When we do not need analog overlay video services in the future, the overlay video band can be reused in WDM-PON by reconfiguring the RN remotely from the OLT. This procedure allows more capacity in the WDM-PON and consequently it can handle more users. In this case, it is required to add a CWDM filter to the RN structure and OLT and use a four-port wavelength-band splitter at the OLT instead of a three-port one.

Reference [91] has a similar policy, where the new users will be added to a WDM-PON attached to the existing legacy PON. In this case, the architecture is simpler because it uses one of the splitter's ports to connect an optical multiplexer/demultiplexer (MUX/DEMUX), instead of an ONU. New ONUs will be attached to this MUX/DEMUX. The attached WDM-PON system is based on the use of a separate wavelength band (1550 nm) with DPSK/NRZ modulation from the OLT, and upstream remodulation to achieve colorless ONUs[2] in WDM-PON. Here also the required changes imply to have an active RN, where we lose the advantages of passive devices in terms of cost.

Authors of [88] propose an evolution scenario of broadband access network using WDM-PON and hybrid TDM/WDM-PON. In the first stage of evolution, WDM-PON is being deployed (by placing an AWG at the RN) in the form of a hybrid WDM-PON/twisted-pair copper network, where the optical signal in each wavelength is converted to electrical signals at the ONU. This is a cost-effective solution since the cost of the optical channel can be shared among several users. The first stage is solving a FTTN/C/B scenario where the ONU serves several users. However, every ONU is getting one or more wavelength channels, whose capacity is not being shared through the rest of the PON. The second stage proposed is related to existing legacy PONs (also known as TDM-PONs), where an AWG is placed at the CO in order to combine several TDM-PONs. New ONUs will include transceivers that are based on Reflective Semi-conductor Optical Amplifiers (RSOA). The new hybrid WDM/TDM OLT is placed at the edge of the node of the core network. In addition, previous hybrid WDM-PON/twisted-pair copper network would migrate to a WDM/TDM PON, by replacing the copper wire with optical fiber.

Other tendencies [42] tackle PON upgrading issues by adding a new node whose interface looks to the legacy OLT as another ordinary ONU. Reference [42] suggests the use of a wavelength-conversion node (with ONU interface) for an economic PON evolution. Instead of making each ONU have a unique wavelength, all ONU upstream signals are routed through the RN toward the wavelength-conversion node, where wavelengths are changed to a unique value, and then sent to the OLT. The authors propose specific RN and wavelength-conversion node. In any case, it is required to have an AWG at the RN. This proposal makes economic ONUs since they all transmit on the same wavelength channel. Authors do include in this study the issues concerning added delays due to accumulated propagation delays: from ONU to RN, from RN to wavelength-conversion node, and finally, from wavelength-conversion node to OLT.

Authors in [53] introduce the most common options to upgrade a TDM-PON through WDM technology, including the previously-discussed WDM-PON, and the use of RSOA-based ONUs. Another option mentioned is the broadcast-and-select WDM-PON, which uses a splitter as the RN. Authors point out that careful attention should be paid to high splitting ratios, because sometimes they may lead to high power losses that cannot be tolerated. In [21], three different possibilities to implement WDM-PON are presented and evaluated: using tunable lasers at the ONUs, remotely seeded devices using RSOAs at the ONUs, and remodulation techniques using also RSOAs at the ONUs. The later offers the possibility to double the system capacity. In [26][27], the WDM-PON-based evolution architectures are evaluated through experiments in a testbed. Authors propose two technology evolution stages and evaluate them with respect to tunable-laser-based WDM-PON: WDM-PON with up to 2.5 Gbps and 10 Gbps per wavelength. A number of options are considered inside each evolution stage using RSOAs in the case of 2.5-Gbps stage, Reflective Electro-Absorption Modulator (EAM) in the case of 10-Gbps stage, and different modulation techniques.

Reference [58] presents a possible evolution path from legacy PON, which is fulfilled in three phases from a cost-effective point of view: partial CWDM upgrade, full CDWM upgrade, and DWDM upgrade. CWDM is

---

[2] A colorless ONU is one, whose transceivers are made of identical components regardless of the working wavelength. For instance, ONUs using tunable lasers, array of fixed-wavelength lasers, and Reflective Semi-conductor Optical Amplifier (RSOA) can be considered colorless ONUs.

considered as a potentially low-cost option of WDM due to the possibility to use uncooled lasers and passive elements with relaxed specifications. However, authors consider that although the migration should be gradual and smooth, OLT, ONUs and RN will require a complete change. Most of this work deals with protection options within the upgrading process.

2.3.4. Long-Reach-PON (LR-PON)

The next step in future Next-Generation PON is the so-called Long-Reach PON (LR-PON). The LR-PON can simplify the network, reducing the number of equipment interfaces, network elements, and even nodes, thus the LR-PON is a very cost-effective solution. Basically, the strength of an LR-PON is its ability to displace electronics and simplify the network. The access and metro networks can be combined into an integrated system through the use of an extended backhaul fiber, possibly 100 km in length, to increase drastically the split ratio of up to 1024 ONUs, and incorporate protection paths and mechanisms. Moreover the overhead at the interface between access and metro could be reduced significantly, and the PON head-end and all higher-layer networking functions can now be located further upstream.

LR-PON is being investigated recently, but these systems are not commercially available yet although many experimental networks are already being developed.

Among others, SUPERPON [37] is the most well-known successful prototype of a LR-PON developed under the European PLANET project in the mid-1990s. It targeted 100 km and 2048 ONUs. There are some more recent developments also under the European projects, i.e., the PIEMAN and MUSE II. Both projects target similar figures, including additionally the WDM dimension. Finally, recent developments point to extending the GPON physical layer to a logical reach of 60 km and split ratio of 128 ONUs.

And finally, the current FP7 framework of the European Union is funding the project called Single-fiber Advanced Ring Dense Access Network Architecture (SARDANA). Its goals are quite ambitious, and the consortium expects to achieve figures such as: up to 1024 users per PON and 10 Gbps data rate, remote passive amplification, and wavelength-agnostic customer equipment [46].

In long-reach scenarios, previously developed DBA algorithms might not be directly applicable since the waiting times needed to start running the DBA algorithm could be relatively long. The DBAs at this level might face efficiency problems, since the RTT will be very long. Many of the DBA algorithms for legacy PONs require that any ONU (user device) to send a Report message indicating the bandwidth needed instantaneously. A very good approach has been proposed recently in [36]. The authors introduce a new multi-thread DBA that runs more than one time (thread) inside a cycle, hence, shortening the waiting time of data in ONU’s queues.

2.4. Bandwidth Allocation Algorithms for WDM-Based PON

The new challenge of a DBA is to allocate bandwidth to ONUs in both time and wavelength, maximizing the efficiency of the entire network. Here we consider the type of WDM-based PONs that combines a TDM/WDM hybrid, where different numbers of ONUs may support a different number of wavelengths in the upstream channel. In such a case, ONUs supporting the same wavelength will be sharing in time their transmission over such a wavelength channel. Two main approaches are possible: improve and extend an existing DBA, e.g., IPACT [22]; or develop new mechanisms, for instance, applying a well-known scheduling theory [82].

The backward compatibility with protocols in the standard is mandatory, but some extensions must be implemented to run the upgraded DBA, e.g., extensions to the Gate (also known as Grant) message.

The scheduling in DBA algorithms is usually broken into two separate problems: a) grant sizing, and b) bandwidth assignment.

2.4.1. Grant Sizing: Online / Offline

Online and offline scheduling are two broad paradigms to allocate bandwidth dynamically for upstream transmissions [79]. As described in Section 2.2, online scheduling for each ONU is calculated once the OLT receives each ONU's Report message, while the offline scheduling involves a general knowledge of the network state (after receiving all or many Report messages) before taking a decision. The simplest online policy is to assign the next available supported channel (NASC) to the ONU. On the other hand, the scheduling theory may help us to make a better decision when assigning the wavelength [81]. An offline scheme is LFJ (Least First Job), which schedules first the transmissions of ONUs that support the fewest number of wavelength channels, at the earliest available time on the supported channels. The LFJ policy is optimal in that it minimizes the length of the schedule under certain conditions and thus, is the best candidate to be applied. Nevertheless, there are many other candidate scheduling algorithms that might be evaluated or tested, like SPT (Shortest Path First) and LPT (longest Path First), in an online or offline setting [82].

The so-called online just-in-time (JIT) scheduling is a new enhancement hybrid between offline and online scheduling. The ONUs not yet allocated are scheduled together across all wavelengths as soon as a wavelength becomes available. The online JIT scheduling framework gives the OLT more opportunity to make better scheduling decisions [81].

Below we summarize some of algorithms developed for hybrid WDM/TDM EPONs. Some of them claim to be backward compatible with the legacy PON.

- Reference [57] presents the WDM IPACT with a single polling table (WDM IPACT-ST), it is basically an upgrade of the former IPACT.
- Reference [22] presents Simultaneous and Interleaved Polling with Adaptive Cycle Time (SIPACT), which is also an algorithm derived from the former IPACT.
- Reference [2] presents different algorithms: Static and Dynamic Wavelength Dynamic Time for the WDM-EPON architecture. They also propose an upgrade of a former DBA developed in the past for the TDM-EPON.
- Reference [81] presents the online and Just-in-time (JiT) scheduling algorithms discussed before.
- Finally, [15] presents the algorithm called Byte Size Clock (BSC). It claims to be backward compatible with both: APON and EPON.

2.5. Summary

This chapter presented the fundamentals of Passive Optical Networks (PON), and the different types available, with special attention to Ethernet-based PON. We then described the most relevant Dynamic Bandwidth Allocation (DBA) algorithms for Ethernet-based PONs in the literature. We also classified them in centralized and non-centralized algorithms, as well as fixed-cycle and variable-cycle schemes [66][65].

In this chapter, we surveyed the next-generation access networks that are an evolution of the legacy TDM-PON to 10 Gbps. Then, we reviewed how WDM techniques can be used to enhance the current PONs. WDM-based PON will become an important and scalable broadband access technology that will provide high bandwidth to end users. One of the keys of WDM-PON's development is significant advance in optical devices design, and in particular the development of colorless ONUs. Another interesting topic in current research is the proposal of new DBA algorithms for hybrid TDM/WDM PONs that we have outlined. Finally, we briefly discussed the research on LR-PON to extend the physical reach and increase the splitting ratio in a PONs. All these topics have been discussed in [61][62].

Chapter 3 Dynamic Bandwidth Allocation in EPON

In this chapter, we propose and evaluate two new Dynamic Bandwidth Allocation (DBA) algorithms, whose objectives are to provide a fair distribution of bandwidth and control the delay experienced by user traffic. First, we discuss a centralized scheme that includes cycle-based ordering, and present some initial studies. However, we focus our study later on a distributed scheme, where ONUs (user devices) also participate in the scheduling process. The results show a significant improvement in terms of delay and queue size for high network loads when compared to one of the most popular schemes.

The chapter is organized as follows: in Section 3.1, we provide a brief introduction and motivation to the development and design of new DBA mechanisms for EPONs. In Section 3.2, we introduce the first findings of our study on a centralized DBA that we designed to include time-based ordering of the transmissions. Section 3.3 is the central part of this chapter, where we propose and provide detailed simulation results of a distributed DBA scheme. Finally, we summarize the chapter in Section 3.4.

3.1. Introduction

Ethernet-based PON is an attractive broadband access network because data therein is transported using Ethernet frames. The Ethernet protocol is highly deployed in local area networks (LANs) and it is becoming an emerging technology for metropolitan and wide area networks. Ethernet is an attractive protocol choice for the access networks because of its technological simplicity and customer familiarity.

An open issue in the standard IEEE 802.3ah (EPON standard) is the Dynamic Bandwidth Allocation (DBA) algorithm. DBA schemes have been considered as a way of handling bandwidth, fairness, and QoS requirements in EPON. In Chapter 2, we have presented a classification of DBA algorithms and we have discussed their virtues and disadvantages. Most of the works are based on a centralized algorithm that runs at the OLT and allocates transmission windows to every active ONU. In that way, we present a new centralized DBA algorithm proposal, which is designed to improve EPON performance by reducing per-packet delays and providing fairness. Later, we propose a distributed scheduling mechanism in order to allocate bandwidth fairly and efficiently in an EPON. The control of the channel is centralized because it is done by the OLT. However, the scheduling process is distributed among the active ONUs over the PON.

3.2. Ordering-Based DBA Algorithm

The most common scheduling schemes proposed in literature employ a round-robin mechanism since the order of ONUs' transmissions is constant. In an initial study [67], we have shown that, by using Time-Dependent-Priority-based [86] scheduling, we can improve EPON's delay performance. This has repercussion in the ONU's traffic delay, according to a time-based priority. However, this scheme would increase control complexity at the OLT and the ONUs. We then proposed a simpler ordering scheduling within cycles in [68] in order to improve the delay in the EPON performance. Later, Zheng and Mouftah [49] proposed an ordering scheme combined with IPACT's limited service for the bandwidth distribution. At the OLT, each ONU's request is queued for further decision on the order of ONU's data transmissions. In a more mature stage, we combined the ordering approach with proportional bandwidth distribution such that the cycle size remains as constant as possible at medium to high network loads, in order to optimize EPON's delay performance [60], [64]. The proposed algorithm consists of two parts working in parallel: bandwidth assignment and ordering scheduling. Both schemes run at the OLT which, by means of Gate messages, allocates the transmission window size to every ONU, and decides the transmission order of all ONUs within a cycle.

3.2.1. Bandwidth Assignment

The proposed algorithm takes the reported information on ONU$_i$'s queue size and compares it with its corresponding predefined guaranteed window size W_i, which is setup according to the contracted traffic rate. The algorithm guarantees a transmission window size up to the value of W_i. When a requested transmission window is less than the corresponding guaranteed minimum, the remaining time (that takes to complete W_i) is later distributed fairly between the ONUs whose requests exceeded their guaranteed window size.

We define the queue size variation for ONU i at cycle n as follows:

$$\Delta q_i(n) \equiv W_i - Q_i(n) \tag{3.1}$$

where $Q_i(n)$ is the reported queue size in cycle n.

When $\Delta q_i(n)<0$ implies that ONU i will have a larger request for bandwidth in its Report message than the guaranteed timeslot size. So, in this case we are talking about overloaded ONUs. On the other hand, when $\Delta q_i(n)>0$, it implies that ONU i will have a smaller bandwidth request than the guaranteed amount in its Report message. Consequently, ONU i is lightly loaded and the capacity that it is not using can be allocated to overloaded ONUs. We define the total excess variation $\Delta q^{exc}(n)$ as the total queues' sizes variation for all overloaded ONUs, and the total minimum variation $\Delta q^{min}(n)$ to be the total queues' sizes variation for all lightly-loaded ONUs Here, the equations of total variations are:

$$\Delta q^{\min}(n) = \sum_{\forall i | \Delta q_i(n)>0} \Delta q_i(n) \tag{3.2}$$

$$\Delta q^{exc}(n) = \sum_{\forall i | \Delta q_i(n)<0} \left|\Delta q_i(n)\right| \tag{3.3}$$

The proposed algorithm works as discussed below.

When the OLT receives all the request messages from ONUs by the end of every cycle, it runs the following bandwidth allocation algorithm:

1. For those ONUs that reported queue sizes lower than their corresponding W_i, the OLT will grant a transmission window $G_i(n+1)$ with size $Q_i(n)$ for the next cycle.

2. The OLT calculates $\Delta q_i(n)$ for all ONUs in step 1. Then, the OLT calculates $\Delta q^{min}(n)$ and $\Delta q^{exc}(n)$.

3. Then, the algorithm distributes the remaining bandwidth to the rest of ONUs whose requirements exceed the guaranteed maximum as shown in the following conditionals:

If $\Delta q^{exc}(n) \le \Delta q^{\min}(n)$ then

$$G_i(n+1) = Q_i(n)$$

If $(\Delta q^{exc}(n) > \Delta q^{\min}(n))$ AND $(\Delta q^{exc}(n) > 0)$ then

$$G_i(n+1) = W_i + \Delta q^{\min}(n)\left(\frac{\Delta q_i(n)}{\Delta q^{exc}(n)}\right)$$

considering that $\Delta q^{min}(n)$ and $\Delta q^{exc}(n)$ are always equal to or larger than zero. This allocation algorithm distributes proportionally the available bandwidth according to the excess amount of bytes required by each overloaded ONU. By filling up the cycle, we expect the delay to be more stable and lower for the case of overloaded ONUs, while accomplishing every cycle with the guaranteed service for every ONU. Waiting till the end of a cycle to run a DBA algorithm leads to more delays at low network loads if compared to IPACT's limited service. However, from the point of view of fairness, our algorithm can be superior.

4. After allocating the timeslot size for every ONU at the end of the cycle, the OLT proceeds to apply the scheduling mechanism for the next cycle, which can be round-robin (newDBA) or delay-based ordering (newDBA+ordering).

3.2.2. Ordering Scheduling

Here, the scheduling refers to the order in which the ONUs' transmissions will take place in a cycle. Ordering decision is based on a time-based mark that we call σ_i. In each cycle, after all requests of ONUs have arrived at the OLT and bandwidth is assigned, the OLT calculates a mark for each request in order to decide which one will be gated first (intra-cycle algorithm).

The scheduler also requires a timestamp in each report message, containing arrival time of the reported group of packets or burst waiting inside the ONU's queue. It is possible to incorporate arrival time information in the PAD/Reserved field of Report messages, instead of filling it with zeros as suggested by the IEEE 802.3ah standard.

Let us define $T_{ac}(k)$ as the virtual time accumulated in cycle n, which will be evaluated each time k that a decision is taken over a request. Assuming that T_i is the equivalent transmission time to $G_i(n)$ in bytes for ONU$_i$, the expression for T_{ac} when it is evaluated inside a cycle is the following:

$$T_{ac}(k)=T_{ac}(k-1)+T_i \tag{3.4}$$

where k is an integer meaning that each time the OLT evaluates T_{ac}. We assume $T_{ac}(0)=0$. In the virtual time k, one request is granted (or served) with its corresponding bandwidth assigned before. The integer i is the index of the last ONU that was granted in (k-1). Periods of general inactivity must be added to T_{ac}.

One mark $\sigma_i(k)$ has to be calculated at time k for every request not served in the current cycle, based on $T_{ac}(k-1)$, as can be seen in the equation below:

$$\sigma_i(k)=\frac{T_{ac}(k-1)-Tarrival_i}{\Delta D\max_i} \tag{3.5}$$

where $Tarrival_i$ is the arrival time of the burst requested for transmission by ONU$_i$, and $\Delta D\max_i$ is a known parameter that stands for maximum delay permitted for that ONU in a cycle. The calculation of T_{ac} and $\sigma_i(k)$ has to be repeated until every request i in the cycle is served.

The relation expressed by (3.5) compares the virtual delay given by the difference between accumulated time and burst arrival time, with maximum delay. If $\sigma_i(k)$ is higher than 1, it implies that ONU$_i$ is experiencing a high delay, and the lower the value of $\sigma_i(k)$ is, the lower its delay is. Therefore, $\sigma_i(k)$ helps the OLT in taking scheduling decisions. OLT will select the request of ONU$_i$ that has the highest value of $\sigma_i(k)$ to be granted at time k. Doing this, we can give higher priority of transmission to ONUs experiencing higher delays with their traffic.

In summary, the steps for the ordering scheduling are as follows:

1. When the OLT receives all the Report messages from all ONUs at the end of a cycle n, it proceeds to extract the values of $Tarrival_i$.

2. Then, for the initial time k set at the beginning of next cycle $n+1$, the OLT calculates $\sigma_i(k)$ for every ONU using (3.5).

3. The OLT selects the next transmission over the upstream channel for the ONU with highest $\sigma_i(k)$. Then, the OLT deletes that ONU from the scheduling process in the current cycle. OLT also increments the value of k and updates $T_{ac}(k)$ using (3.4).

4. Steps 2 and 3 are repeated until all ONUs are scheduled for transmission in cycle $n+1$.

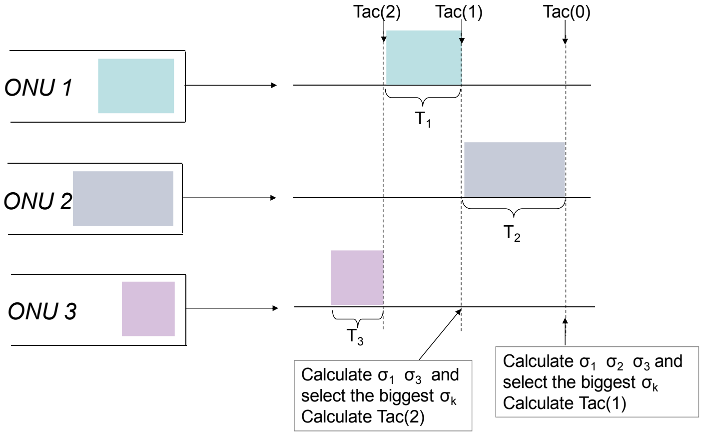


Figure 6. Process for defining the transmission order per cycle.

Figure 6 presents a non-numerical example of our proposed ordering scheme using three ONUs. After the bandwidth distribution algorithm (timeslot sizing process) has finished, we start at $T_{ac}(0)$ and the calculation of all time marks for all the ONUs ($\sigma_1(0)$, $\sigma_2(0)$, and $\sigma_3(0)$), assuming known $Tarrival_i$ and $\Delta D\text{max}_i$ for each ONU_i. In this case, we obtain that ONU_2 has the largest delay and, therefore, its timeslot is scheduled to be transmitted first. OLT calculates the next evaluation time $T_{ac}(1)$, i.e., right after ONU_2's timeslot and guard band. For $T_{ac}(1)$, OLT calculates $\sigma_1(1)$ and $\sigma_3(1)$. Since ONU_1's timeslot presents a higher value, it is scheduled to be transmitted before ONU_3's timeslot. Finally, after calculating $T_{ac}(2)$, ONU_3's timeslot is scheduled.

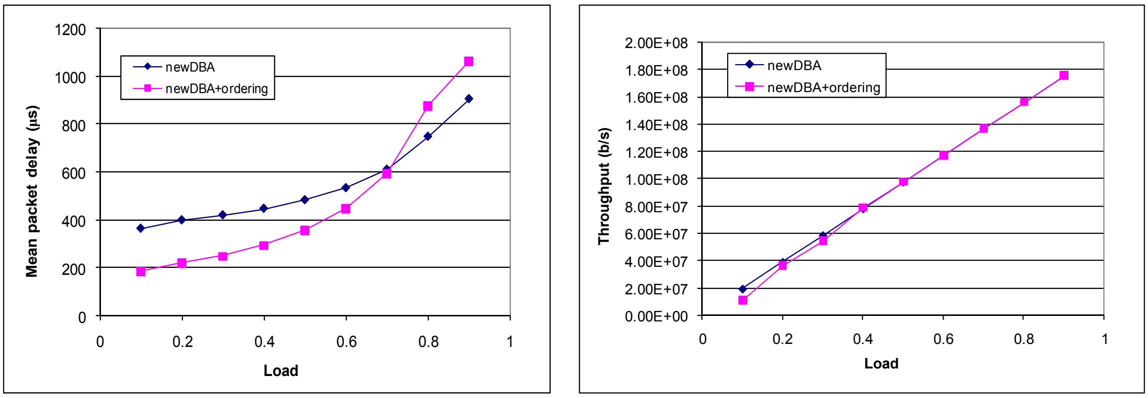
This ordering mechanism is intended to allow transmissions of ONUs following a specified order according to a timing parameter. In this case, we use a time mark $\sigma_i(k)$ that requires the OLT to make several calculations every time it schedules one ONU's data transmission slot. However, for a practical analysis, we can define the timing parameter to be the arrival time of the first frame in the head of ONU's queue. This approach deals with the frames experiencing high delays which should be served first. In general, the ordering mechanism implies that the ONU will memorize the arrival times of the first frame in the queue in every cycle and copy it in the Report message.

3.2.3. Simulations and Results

The aim of this subsection is to evaluate the performance of the proposed bandwidth allocation algorithm using round-robin scheduling (newDBA) and the same algorithm using our ordering scheduling (newDBA+ordering). For the simulations, we defined a small tree topology consisting of one OLT and five ONUs. The sources of traffic generate Ethernet frames of constant size (1470 bytes), and the inter-arrival time between frames follows a negative exponential distribution. Here, we show the most important results, mainly the ones related with mean packet delay versus the network traffic load.

Some tests have been done with an event-driven C++ program considering two scenarios. In the first scenario, all ONUs generate traffic at the same rate, while in the second scenario, ONUs have different rates. For both scenarios, each ONU has a guaranteed contracted bandwidth of 200Mbps.

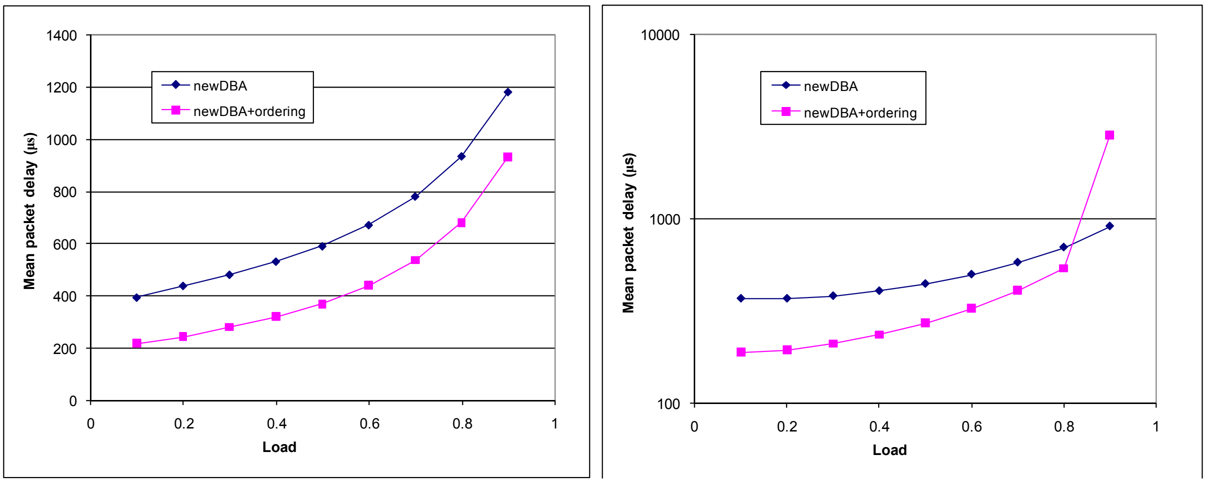
In the first case, every ONU generates traffic at an average rate of 200 Mbps. Figure 7 shows simulation results related to mean packet delay (µs) and throughput (b/s) versus network load. It can be seen that, for low network loads, the ordering approach improves the delay performance when traffic load is lower than 70%. When the traffic load surpasses 70%, the ordering approach experiences a higher mean delay. The improvement in delay of frames waiting in an ONU's queue for the ordering case causes a reduction in overall mean packet delay at low loads. Due to extra processing time (for each cycle) in ordering+newDBA case, we can see in Figure 7(b) that a slight decrease of throughput occurs in the ordering case when compared with newDBA scheme. At higher loads, ordering+newDBA algorithm is dealing with large ONU queues that have accumulated many packets in all the cases equally in average. Since in our simulation we only use the arrival time of the first packet that arrived to the queue, we are not considering all the arrival times of all packets into the ordering-based scheduling. For high network loads, it may lead to an increased delay.



(a) (b)

Figure 7. First scenario when all ONUs have the same traffic profile. Comparison of: (a) Mean packet delay, and (b) Throughput, for newDBA and newDBA+ordering schemes.

In a second scenario, each ONU has a different traffic rate with respect to the guaranteed bandwidth contracted (200Mbps). Some of them are intentionally overloaded or generating traffic at a higher rate than the contracted rate. The sources generate traffic at the following average rate: ONU_0 100Mbps, ONU_1 300Mbps, ONU_2 500Mbps, ONU_3 50Mbps, ONU_4 50Mbps. The total average bandwidth required is 1Gbps, so the algorithms should distribute the bandwidth accordingly. By having such overloaded ONUs implies that they will experience sometimes (from cycle to cycle) higher delays and the goal of this test is to evaluate which approach performs better.



(a) (b)

Figure 8. Second scenario when the EPON traffic rate from ONUs is different from maximum traffic rate contracted. Comparison of mean packet delay for newDBA and newDBA+ordering schemes: (a) the overloaded ONU_2, and (b) the light-loaded ONU_4.

In Figure 8, we show the mean packet delay comparison of newDBA and newDBA+ordering mechanisms. In order to illustrate the behaviour of these algorithms, we choose to compare the results for two of the ONUs: one with the highest traffic rate (ONU_2, Figure 8(a)) and one with low traffic rate (ONU_4, Figure 8(b)). In both cases, mean packet delay is lower using the ordering combination, except for ONU_2 (overloaded ONU) after reaching 80% of network load. Therefore, in a heterogeneous traffic load environment, the newDBA+ordering algorithm is performing better in terms of delay. In general, it can be seen that mean packet delay is higher for newDBA. For the rest of the lightly-loaded ONUs, the ordering approach also improves their delay performance.

3.3. Distributed Dynamic Scheduling for E-PON: DDSPON Algorithm

Most of the proposed algorithms for bandwidth allocation are centralized. Among the centralized approaches, the work of Kramer et al. [32] is considered as a reference with the so-called IPACT (Interleaved Polling with Adaptive Cycle Time) algorithm. This algorithm is also taken as reference in our proposal, and we describe it here briefly. By means of Gate and Report messages, the OLT fills a table with the transmission window size requirements of every ONU (among other parameters). IPACT uses an interleaved polling approach, where the next ONU is polled before the transmission of the previous one finishes.

The main idea is to keep the channel occupied as much as possible in order to use it efficiently. As the downstream channel is independent from the upstream channel, the OLT can inform an ONU the start time of its timeslot before the previous transmission ends. When the OLT receives a Report message from any ONU, it immediately computes the grant time based on a predefined maximum bandwidth. If the requested timeslot is larger than its maximum timeslot permitted (according to the maximum bandwidth), the OLT grants the maximum timeslot for that ONU, and otherwise it grants the requested timeslot. The maximum cycle time is the maximum time required for all ONUs to transmit their respective maximum predefined timeslot. In IPACT, the cycle size is variable.

In our scheme, the interleaved polling mechanism is also applied. However, in our case, the size of the transmission window for each of the ONUs is calculated by themselves. Extra information about the weight vector (Φ) for the ONUs is included in the Gate messages, as can be seen in Figure 9. Our approach is explained in more detail in the next subsection.

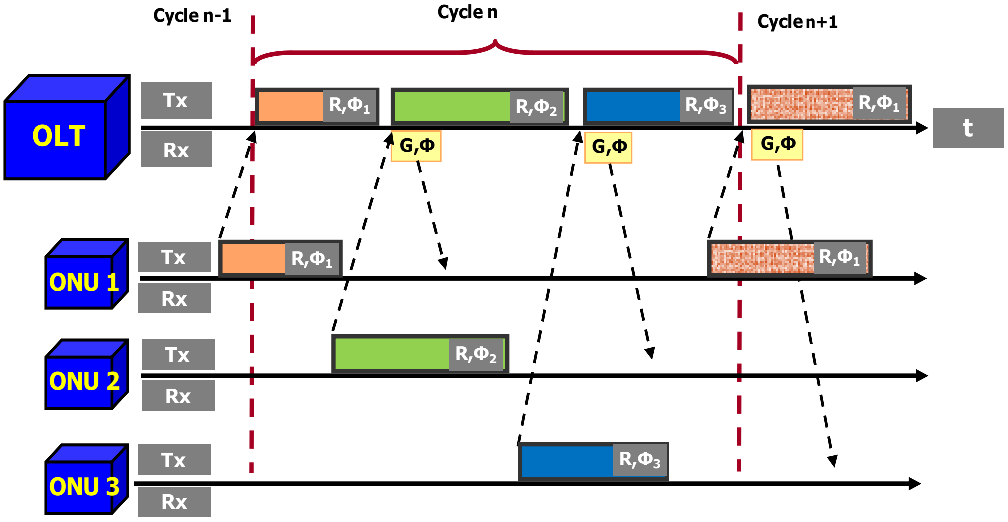


Figure 9. Illustration of the Interleaved Polling mechanism using a distributed scheduling.

3.3.1. Remote Distributed Scheduler

The bandwidth scheduling algorithm we propose is performed mainly by each active ONU in the EPON network. This is the reason why we call it a remote distributed scheduler. However, the OLT also participates in the scheduling process. Extra information (the weight vector) must be sent to the ONUs from the OLT. With this vector, each ONU calculates the instantaneous transmission window size for itself. The information needed by the ONU can be sent through the Gate message in the PAD/Reserve header fields. We call this method

Dynamic Distributed Scheduler for EPON (DDSPON) [70][71]. Each ONU will send to the OLT one extra parameter (its instantaneous weight) in the Report message so that the OLT can update the weight vector. In this chapter, we will study a case of one queue per ONU, but it can be easily extended to several queues per ONU.

In a PON system, there are N ONUs, and each ONU i has a predefined (nominal) weight $\Phi_i^{nominal}$. The nominal weight is used to define the ONU's transmission window size (in bytes):

$$W_i = \frac{\Phi_i^{nominal}}{\sum_{j=1}^{N} \Phi_j^{nominal}} W_{MAX} \tag{3.6}$$

where W_{MAX} is the maximum transmission window size that corresponds to the maximum cycle time, and can be calculated by the equation below:

$$W_{MAX} = T_{MAX} * Upstream\ rate \tag{3.7}$$

The cycle is the period during which all active ONUs have transmitted their traffic, when a new cycle starts again. So, the OLT guarantees the minimum instantaneous window size $\Phi_i^{nominal} * W_{MAX}$ if:

$$\sum_{j=1}^{N} \Phi_j^{nominal} = 1 \tag{3.8}$$

This scheme is similar to the well-known Generalized Processor Sharing (GPS) scheme, which provides a good performance for elastic services because the delay is bounded, and a minimum bandwidth is guaranteed.

The algorithm for DDSPON works as follows:

1. The OLT receives a report message (from ONU i) that contains two values: $R_i(n)$ (requested window size for cycle n) and weight $\Phi_i(n)$. Then the OLT updates its vector of weights for the cycle n, where each weight in the vector corresponds to a different ONU, as shown below:

ONU$_1$	ONU$_2$	ONU$_3$	……	ONU$_N$
$\Phi_1(n)$	$\Phi_2(n)$	$\Phi_3(n)$	……	$\Phi_N(n)$

The OLT proceeds to send a gate message to ONU i granting $R_i(n)$ and including the weight vector Φ and the time to start ONU's transmission.

If the EPON system has M service classes, the gate messages would include a (NxM) matrix:

$$\Phi(n) = \begin{pmatrix} \Phi_{11}(n) & \cdot & \Phi_{1M}(n) \\ \cdot & \cdot & \cdot \\ \Phi_{N1}(n) & \cdot & \Phi_{NM}(n) \end{pmatrix} \tag{3.9}$$

where N is the number of ONUs and M is the number of service classes. In this description, we consider M=1.

2. When ONU i receives the Gate message at cycle n, it transmits the data in the queue up to the granted window size (in bytes). Then, ONU i sets its own weight to the nominal one Φ_i, according to the corresponding value in weight vector received in the gate, and calculates the new maximum window size it can take in cycle n+1 as follows:

$$W_i(n+1) = \frac{\Phi_i^{nominal}}{\Phi_i^{nominal} + \sum_{j=1; j\neq i}^{N} \Phi_j(n)} W_{MAX} \tag{3.10}$$

where $\Phi_i^{nominal}$ is the nominal weight for ONU i.

Finally, ONU i sends to the OLT (inside the Report message) two values: $R_i(n+1)$, and the new weight for the next cycle n+1. These two variables can be calculated using the following two equations:

$$R_i(n+1) = MIN\left(Wq_i(n+1), Q_i\right) \tag{3.11}$$

$$\Phi_i(n+1) = \frac{R_i(n+1)\left(\Phi_i^{nominal} + \sum_{j=1;j\neq i}^{N} \Phi_j(n)\right)}{W_{MAX}} \tag{3.12}$$

where Q_i is the queue size in ONU *i* at the moment of calculation, and $Wq_i(n+1)$ is the number of bytes that can fit the size of $W_i(n+1)$ without fragmentation of any Ethernet frame.

The process is performed in the same way by every ONU. It should be noted that planning is carried out instantly (on-the-fly). In this case, there is no need to wait to receive all Report messages at the OLT to proceed to execute the DBA algorithm, which is the case for many centralized schemes. In this case, there is no need to wait until all the reports arrive to the OLT in order to execute the scheduling algorithm. The process is repeated in the same way for each ONU. At the initial point of operation, the weight of ONU$_i$ is set to the nominal value $\Phi_i^{nominal}$ at the beginning of the connection. In Figure 10, we summarize the DDSPON algorithm in flow diagrams for any ONU and the OLT.

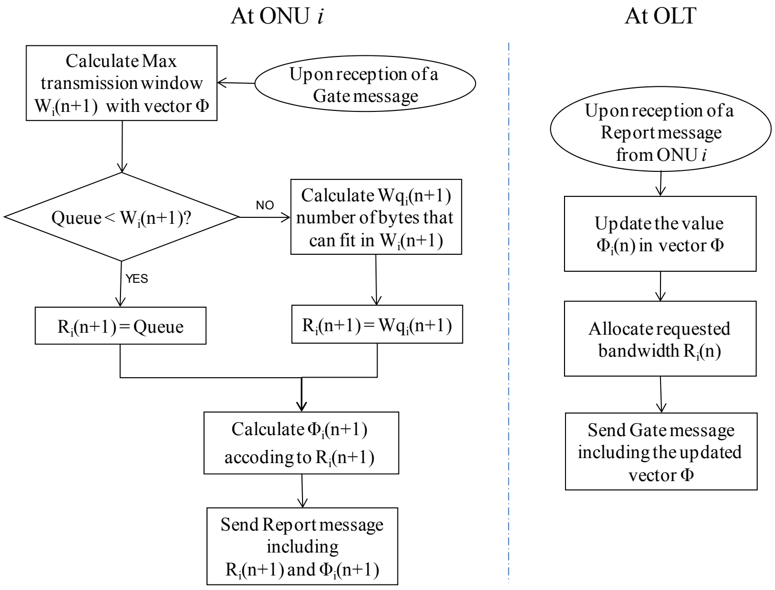


Figure 10. Flow diagrams of DDSPON algorithm for ONU$_i$ and OLT.

An important feature of this scheme is that the ONU will allocate the right timeslot size in bytes that can fit inside the maximum transmission window size after calculating (3.11). There is no over-granting, and we avoid the use of threshold information for ONU's queues. Here, the ONU is the one which schedules dynamically the size of its transmission window by fixing it to the real number of bytes in each Ethernet frame using (3.11), which cannot be fragmented.

It is also worth mentioning that the ONU assigns the precise size in bytes that can fit in the maximum transmission window computed with (3.10). In centralized schemes, the OLT usually allocates the maximum window size to an ONU when it requests a larger one. However, in such a case, the OLT does not know if the allocated window size truncates an Ethernet packet, resulting in channel underutilization. Here, an ONU plans dynamically the size of its timeslot, choosing a value that does not affect the transmission of any Ethernet frame, given that, in EPON, fragmentation is not allowed. The computation complexity is stronger at ONUs than in the OLT; however, processes or calculations required are simple enough to be implemented in the ONU nodes.

3.3.2. Simulations and Results

3.3.2.1. Simulation Setup

To evaluate the performance of the DDSPON algorithm, numerous simulations were conducted using the simulation environment OPNET Modeler. We developed an EPON featuring strict compliance with the standard IEEE 802.3ah. The network model has been developed so that it is possible to assess benefits of different schemes for bandwidth allocation easily, and to evaluate network performance by changing different parameters such as distance, cycle time, SLA parameters, etc. OPNET Modeler is a tool that allows simulation of communication systems to assess performance under different conditions.

Subsequently, we implemented IPACT and DDSPON schemes in order to compare them. Thus, it has been possible to evaluate EPON's performance. It is also possible to analyze the behaviour and validate the effectiveness of DDSPON scheme. Different scenarios have been analyzed by changing some parameters such as the ONU-OLT distance, and traffic descriptors can also be modified.

The overall network topology is a tree-type with 16 ONUs, each separated from OLT by a distance of 10km to 20km in general, as shown in Figure 11. The simulations compare the performance of DDSPON and IPACT algorithm. The latter is based on a limited-service method, i.e., the OLT allocates the requested bandwidth by an ONU without exceeding its maximum predefined transmission window. IPACT has been chosen for our comparisons because: (*i*) it is the most widely used reference in DBA performance evaluations, and (*ii*) it is the nearest to DDSPON.

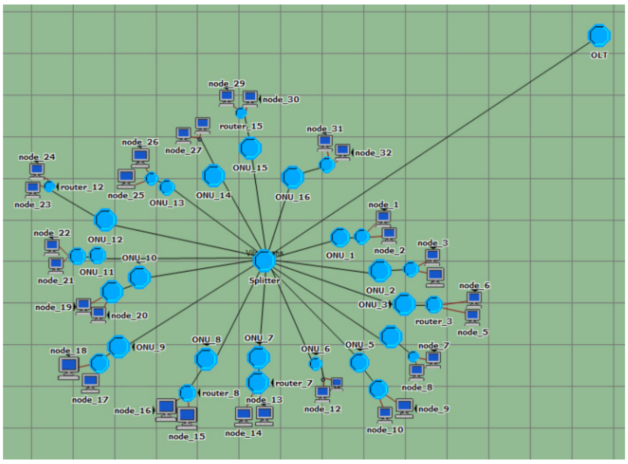


Figure 11. Simulation scenario in OPNET.

To perform an analysis of the benefits, we use a self-similar traffic source model according to [89]. We considered in this study two values for the Hurst parameter: H = 0.7 and H = 0.8. The average packet size follows a uniform distribution that varies from 64 bytes to 1518 bytes to model Ethernet frame sizes. OPNET Modeler provides a traffic generation module called Raw Packet Generator RPG in which the attributes of the traffic can be set up to generate self-similar traces.

To obtain results for different network loads, the total offered load is 1 Gbps, which is distributed equally among all active ONUs, and the mean arrival rate varies proportionally according to the network load that is assessed in the simulation. The simulations have been performed with different numbers of seeds so that samples obtained approximate the mean value of the actual value thereof. The statistics presented are mainly the average values of queue size and packet delay, only over the upstream channel.

We consider five simulation scenarios for which we have varied parameters such as distance between ONUs and OLT and Hurst parameter, which are included in [74][62]. For all scenarios, we consider a 1-Gbps EPON with 16 ONUs, each ONU with a line rate of 100 Mbps, and a queue size of 100 MB. The guard interval is 0.008 ms and the maximum size of the cycle of 1 ms. The distance between the OLT and ONUs is defined as long distances around 20km, middle distances of about 10km, and short distances around 5km approximately. Scenarios 1 and 2 represent long distances, scenario 4 represents middle distances, and scenario 5 represents short ones. Scenario 3 has a combination of different middle and long distances, where half of the ONUs are located at middle distances, and the rest at long distances. Those choices can help us assess the behaviour of the algorithms in cases where ONUs are located at heterogeneous distances. Table 2 shows the parameters considered in each simulation scenario.

Table 2. Setup parameters for each simulation scenario.

Parameters	**Sce. 1**	**Sce. 2**	**Sce. 3**	**Sce. 4**	**Sce. 5**
Number of ONUs	16	16	16	16	16
User link rate at ONU	100Mbps	100Mbps	100Mbps	100Mbps	100Mbps
Line rate at EPON	1Gbps	1Gbps	1Gbps	1Gbps	1Gbps
Number of Queues per ONU	1	1	1	1	1
Buffer size	100 MB	100 MB	100 MB	100 MB	100 MB
Guard time	0.008ms	0.008ms	0.008ms	0.008ms	0.008ms
Maximum cycle size	1ms	1ms	1ms	1ms	1ms
Distance between ONUs and OLT (km)	18<d<20	18<d<20	10<d<20	10<d<11	4<d<5
Hurst parameter	H=0.7	H=0.8	H=0.8	H=0.8	H=0.8

For simplicity of analysis, the simulations have been carried out using single-queue per ONU, but it can be extended to up to eight queues according to the IEEE 802.3ah standard. Data was evaluated for different network loads, such that obtained mean values can be displayed in terms of offered load.

3.3.2.2. Results and Discussion

The results related to queue size comparison are shown in Figure 12. It can be seen that the average queue size in scenarios 1 and 2 are very similar for the same DBA under different network loads. Variation on the Hurst parameter from 0.7 to 0.8, for the proposed values, does not affect significantly the performance in our EPON.

Both algorithms experience a similar behaviour at low network loads, but when the network load is greater than 0.7, IPACT algorithm begins to show an increase in queue size larger than that of DDSPON. When the network load reaches its maximum capacity, IPACT has an average value of approximately 427.9 KB, while DDSPON only reaches a maximum value of 146.6 KB. These results have implications for the storage size of ONU's buffers since IPACT will require more queue capacity to avoid packet losses than in DDSPON's case.

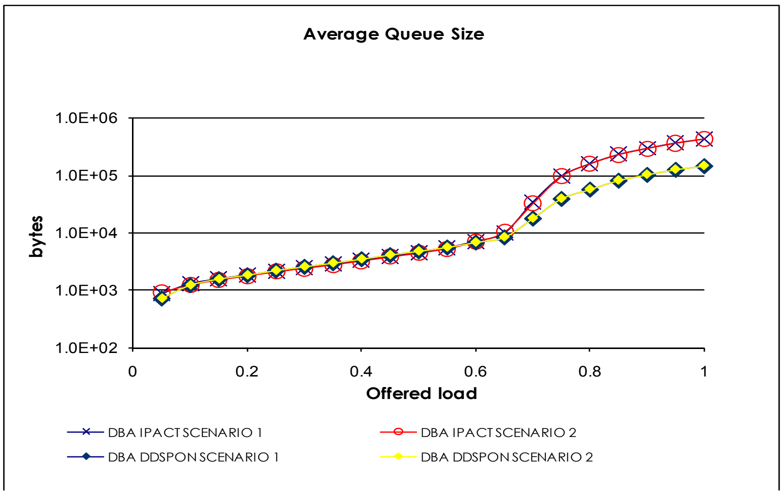


Figure 12. Average queue size for scenarios 1 and 2.

Figure 13 represents the average delay per packet. It mainly shows a delay increase when the network load is higher than 0.7. When the queue markedly increases its size, it also reflects an increase in the packet delay. DDSPON shows lower delays for high network loads compared to IPACT. As can be observed, when the network reaches its maximum load, IPACT gets a value of 0.041 seconds while in DDSPON it is less than 0.014 seconds.

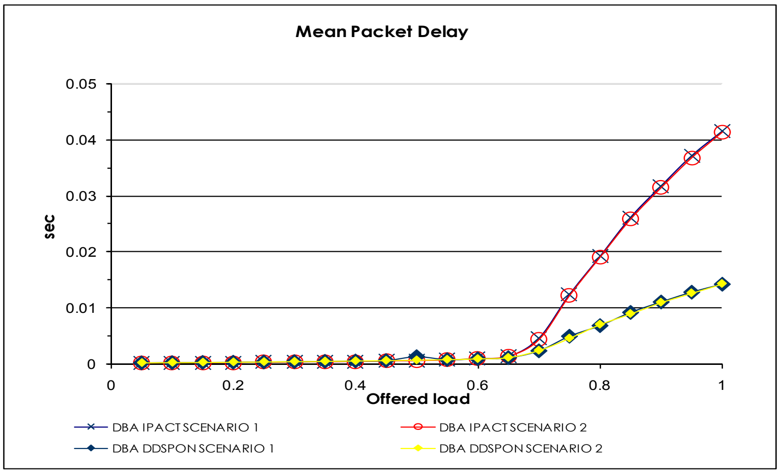


Figure 13. Mean packet delay for scenarios 1 and 2.

The average queue size and mean packet delay are shown in Table 3 and Table 4 for IPACT and DDSPON, considering scenarios 1 and 2, and with a 95% confidence interval.

Table 3. Average queue size for scenarios 1 and 2 (in bytes).

Offered Load	CONFIDENCE INTERVAL 95%											
	IPACT scenario 1			IPACT scenario 2			DDSPON scenario 1			DDSPON scenario 2		
0.05	859.4	±	53.35776	942.4606	±	52.11126	726.0358	±	98.960147	694.25328	±	58.78017401
0.2	1817.9	±	15.71684	1809.149	±	14.05234	1848.754	±	17.163988	1889.89596	±	15.90877284
0.4	3302.1	±	16.27839	3292.374	±	13.06709	3512.193	±	28.640373	3497.1409	±	31.40697411
0.6	7057.6	±	35.04878	7078.041	±	37.7841	6851.891	±	70.351379	6765.50977	±	90.46282045
0.8	158655	±	4222.854	157538.5	±	5267.572	57266.14	±	3079.5779	59306.7814	±	3134.090275
1	427966	±	4806.813	425367.1	±	4952.053	146608.7	±	3804.4181	148205.386	±	4004.284915

Table 4. Mean packet delay for scenarios 1 and 2 (in seconds).

Offered Load	CONFIDENCE INTERVAL 95%											
	IPACT scenario 1			IPACT scenario 2			DDSPON scenario 1			DDSPON scenario 2		
0.05	0.000283	±	2.26E-06	0.000286	±	2.47E-06	0.00029	±	5.686E-06	0.00029025	±	4.96606E-06
0.2	0.000374	±	1.21E-06	0.000373	±	8.29E-07	0.000406	±	5.491E-06	0.00041108	±	4.27911E-06
0.4	0.000568	±	1.35E-06	0.000567	±	1.18E-06	0.000622	±	3.074E-06	0.00062216	±	4.45099E-06
0.6	0.001049	±	2.91E-06	0.00105	±	3.45E-06	0.001015	±	9.026E-06	0.00100087	±	9.62725E-06
0.8	0.019284	±	0.000496	0.019095	±	0.000571	0.006865	±	0.0003564	0.00709164	±	0.000353267
1	0.04162	±	0.0004	0.041337	±	0.000378	0.014178	±	0.0002987	0.01431085	±	0.000366334

In the following figures, we present simulation results, where we vary distances between OLT and ONUs in order to evaluate sensitivity with respect to distance. In Figure 14, IPACT displays a similar behaviour in most of the scenarios. However, for scenario 2, where the distances are high for all ONUs, IPACT shows a higher average queue size. DDSPON's results concerning average queue size is presented in Figure 15. In this case, DDSPON also presents similar performance in most of the scenarios, except for scenario 3, where the setup combines middle and long distances. DDSPON shows a slightly higher average queue size for scenario 3.

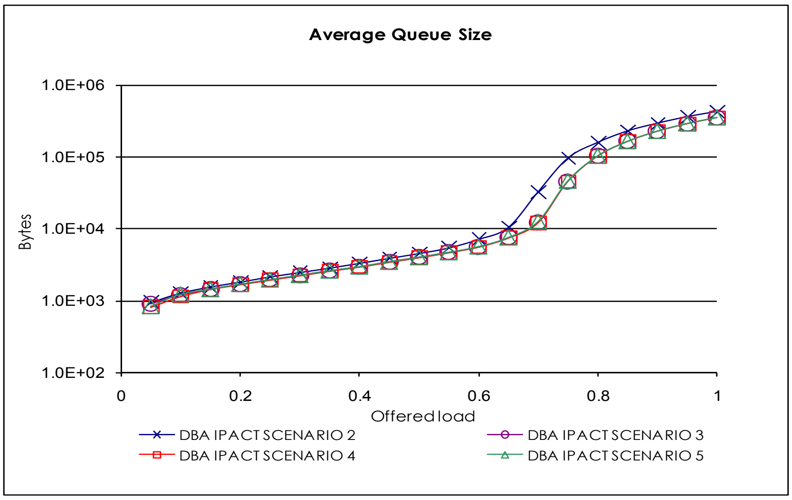


Figure 14. Average queue size for IPACT for scenarios 2, 3, 4, and 5.

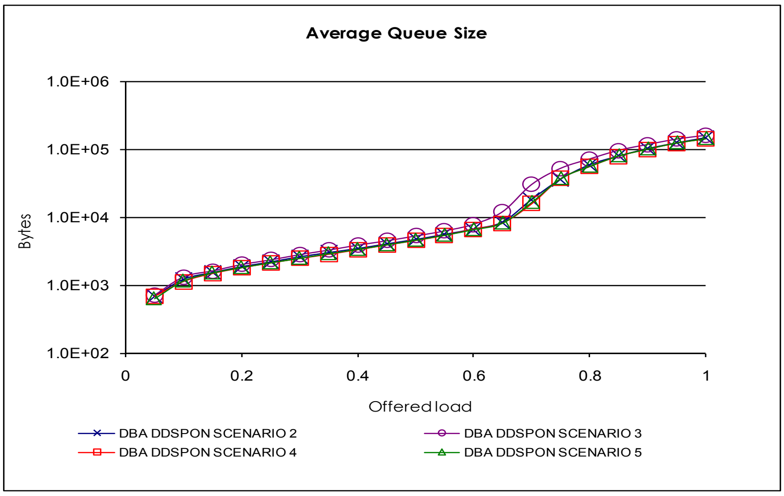


Figure 15. Average queue size for DDSPON for scenarios 2, 3, 4, and 5.

Similarly, we present mean packet delay in relation to network load for both algorithms in Figure 16 and Figure 17. The highest delay values for DDSPON are obtained in scenario 3, where for the maximum network load the mean packet delay is 0.015 seconds. The highest delay values for IPACT appear in scenario 2, with a delay of 0.0413 seconds for the maximum network load. The values obtained for both algorithms are shown in Table 5 and Table 6. There can also be appreciated the corresponding 95%-confidence intervals.

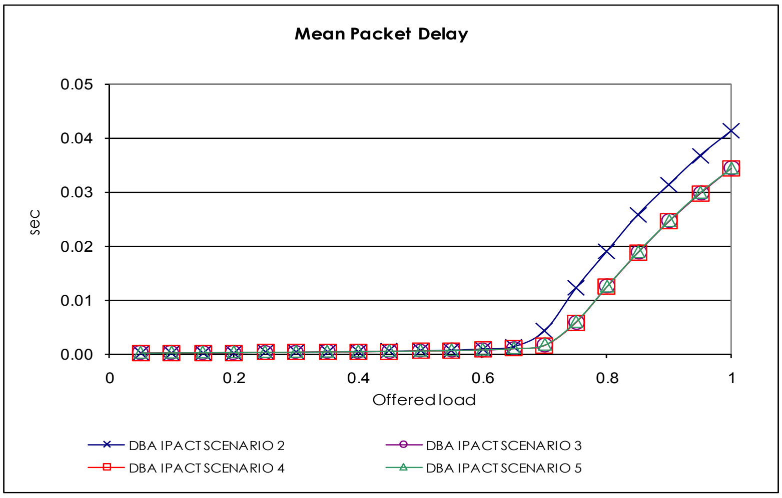


Figure 16. Mean packet delay for IPACT for scenarios 2, 3, 4, and 5.

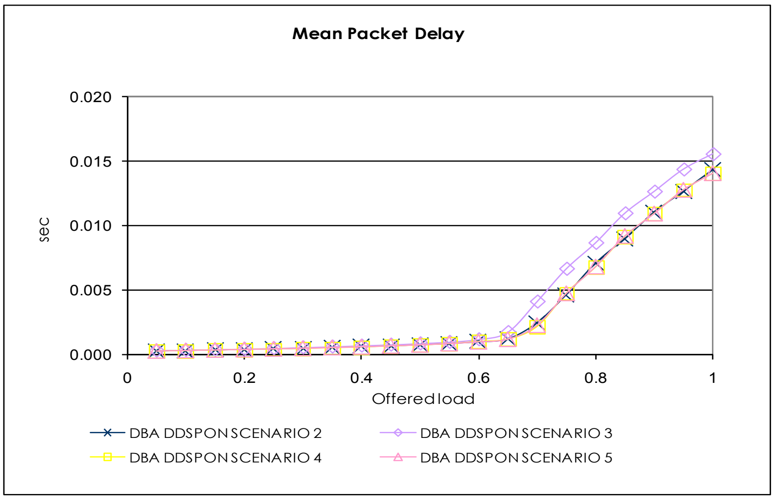


Figure 17. Mean packet delay for DDSPON for scenarios 2, 3, 4, and 5.

Table 5. Average queue size for scenarios 2, 3, 4, and 5 (in bytes).

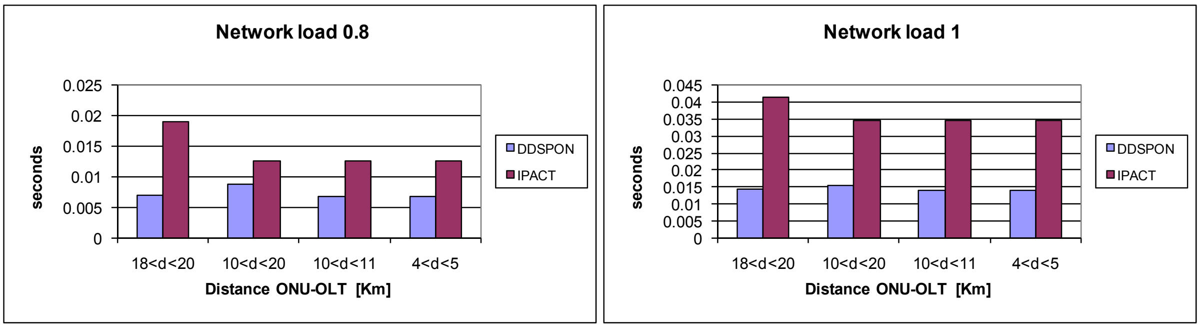
Offered Load	CONFIDENCE INTERVAL 95%																	
	IPACT scenario 3			IPACT scenario 4			IPACT scenario 5			DDSPON scenario 3			DDSPON scenario 4			DDSPON scenario 5		
0.05	898.3116	±	115.089021	814.0196	±	114.103	827.324784	±	111.49	722.23444	±	76.10661	699.0878768	±	56.0822	638.6390227	±	74.010686
0.2	1680.298	±	218.163409	1682.811	±	214.193	1685.46665	±	233.465	2032.38454	±	77.838	1839.910823	±	22.0249	1833.078027	±	34.836207
0.4	2946.477	±	386.879136	2954.2301	±	397.598	2947.97528	±	389.674	3914.01813	±	95.965	3386.044983	±	28.1863	3395.991213	±	37.11828
0.6	5512.923	±	752.306008	5628.6777	±	757.555	5614.4853	±	748.028	7954.63981	±	170.7036	6815.547673	±	74.4178	6646.902971	±	67.305459
0.8	103049.9	±	15139.5819	102879.48	±	15116.5	102992.34	±	15130.2	72505.7398	±	6929.278	56616.07043	±	3369.18	56890.03194	±	3436.8713
1	354007.7	±	50343.1104	353820.99	±	50329.9	353418.473	±	50284.8	161325.241	±	8729.929	144940.6108	±	4307.33	145150.5819	±	4387.194

Table 6. Mean packet delay for scenarios 2, 3, 4, and 5 (in seconds).

Offered Load	CONFIDENCE INTERVAL 95%																	
	IPACT scenario 3			IPACT scenario 4			IPACT scenario 5			DDSPON scenario 3			DDSPON scenario 4			DDSPON scenario 5		
0.05	0.000282	±	2.7101E-06	0.00027	±	4.29565E-06	0.000266	±	4.22846E-06	0.000334	±	2.46063E-05	0.0002713	±	3.13787E-06	0.0002675	±	4.27156E-06
0.2	0.00036	±	3.13444E-06	0.00036	±	1.69056E-06	0.000362	±	4.69176E-06	0.000474	±	3.04895E-05	0.0003868	±	1.58567E-06	0.0003858	±	1.87386E-06
0.4	0.000527	±	2.67898E-06	0.00053	±	2.4047E-06	0.000528	±	2.87499E-06	0.000725	±	2.76556E-05	0.0005889	±	2.5129E-06	0.0005904	±	3.60742E-06
0.6	0.000842	±	4.56266E-06	0.00086	±	3.54181E-06	0.000856	±	5.00712E-06	0.001214	±	3.14266E-05	0.0010064	±	8.51185E-06	0.0009798	±	8.00483E-06
0.8	0.012538	±	0.001644225	0.01252	±	0.001638312	0.01253	±	0.001646676	0.008701	±	0.000788819	0.006787	±	0.000372766	0.0068168	±	0.000384658
1	0.034447	±	0.004711822	0.03443	±	0.004699723	0.034395	±	0.004691306	0.015593	±	0.000797015	0.0140298	±	0.000396848	0.0140594	±	0.000403095

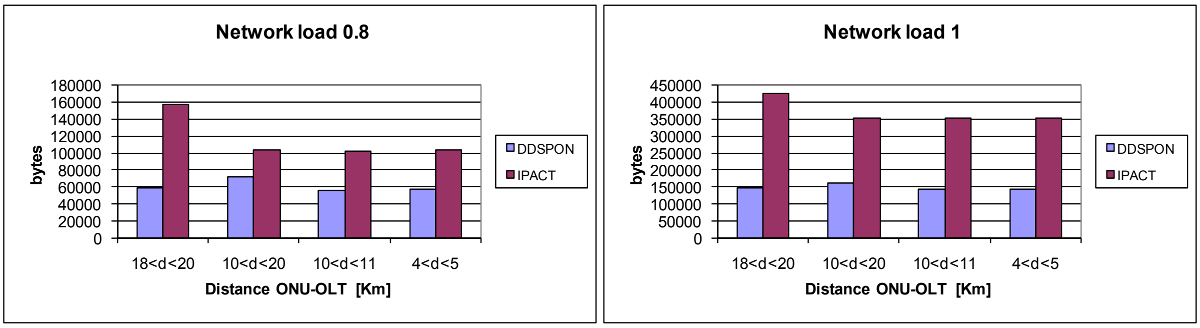
In general, high levels of packet delay and queue size are observed in all IPACT cases, when compared to DDSPON cases. The values obtained reflect that DDSPON exhibits very low variation in the outcomes with respect to IPACT values. We can see that DDSPON maintains its efficiency for high network loads regardless of the distance to the ONUs.

Figure 18 displays comparisons of mean packet delay for IPACT vs. DDSPON for critical network load such as 0.8 and 1. Similarly, comparisons for average queue size are presented in Figure 19.



(a) (b)

Figure 18. Comparison of mean packet delay between DDSPON and IPACT (a) network offered load 0.8, (b) network offered load 1.



(a) (b)

Figure 19. Comparison of average queue size between DDSPON and IPACT (a) network offered load 0.8, (b) network offered load 1.

In Figure 18 and Figure 19, we can observe three interesting aspects. First, it is possible to verify that DDSPON maintains the levels of average queue size and mean packet delay smaller than in the IPACT scheme. Secondly, DDSPON is more stable against distance variations, while IPACT, especially for longer distances, presents a high increment. Finally, it is interesting to note that DDSPON shows an increase in the average size of queue when the distances between ONUs and OLT are disparate (between 10 and 20 km) such as scenario 3. This variation is 10-21% higher (for loads of 0.8 and 1 respectively) compared to other scenarios where distances are more homogeneous. However, compared with the centralized scheme, this aspect is minimized and benefits of DDSPON are still higher. These small variations in DDSPON are due to differences in round-trip times (RTT) that can affect the acquisition of current state of the network for some ONUs, which leads to an increase in the queue waiting time affecting both queue size and network delay.

Figure 20 shows a bar chart representing the percentage difference of DDSPON over IPACT (improvement percentage) in terms of average delay per packet. The difference of average packet delay shown in percentages shows that DDSPON improves on IPACT's performance, and the values vary from 30.6% to 65.4%. This represents a considerable improvement of DDSPON when compared with the centralized scheme IPACT.

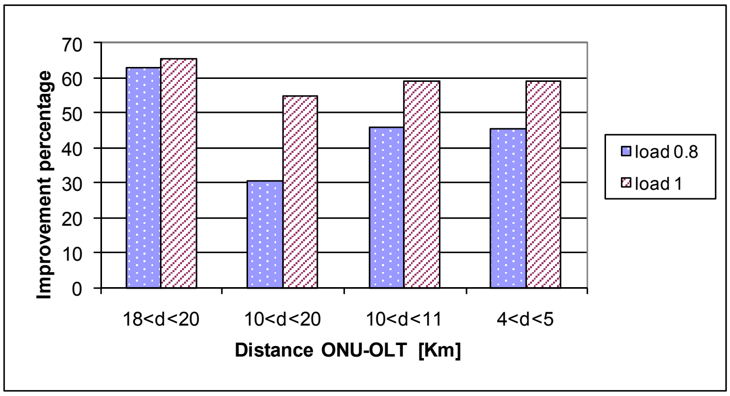
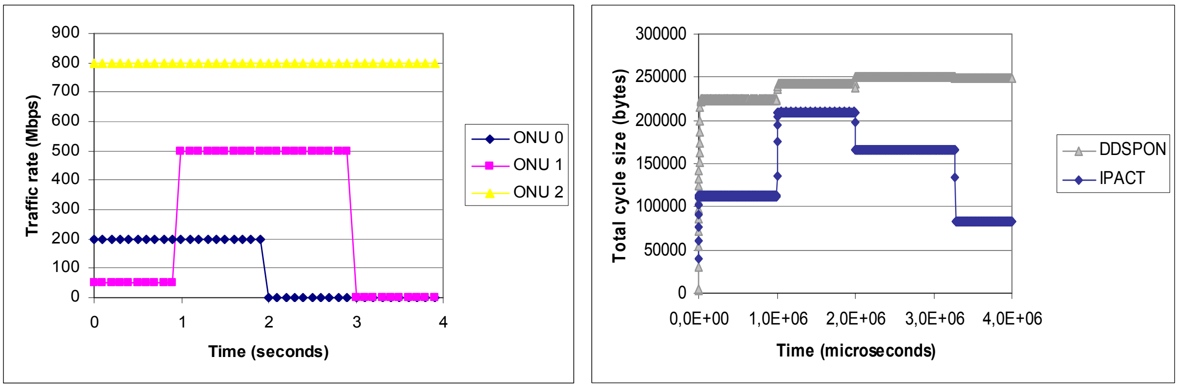


Figure 20. Improvement percentage of DDSPON over IPACT on the mean packet delay at network loads of 0.8 and 1.

The simulation results thus confirm the good performance of the DDSPON algorithm especially for high network loads compared to the reference centralized scheme in all scenarios. The main reason for this behaviour at high loads can be explained in what follows. At high loads, it is more probable to allocate the maximum window size to an ONU. However, if the ONU does not participate in the DBA calculations (as in the IPACT scheme), then most of the times the maximum transmission window size may truncate an Ethernet frame that may not be transmitted (no fragmentation is allowed in EPON). As a consequence, the OLT will be over-granting the ONUs at high loads. With DDSPON, this issue is solved.

Finally, a new simulation experiment was used to illustrate the total bandwidth distribution over a cycle time and to see the transient response of the algorithm using step functions as traffic input. In this test, we consider a tree topology with one OLT and three ONUs: ONU 0, ONU 1 and ONU 2. The cycle time is set to 2 ms. Each

ONU has a CBR source generating frames of 700 bytes, and their rates change over time according to Figure 21(a). Each ONU has a nominal weight of 1/3.



(a) (b)

Figure 21. Simulation experiment to evaluate the cycle size in DDSPON and IPACT: (a) CBR source traffic rate input over time for ONUs 1, 2 and 3, and (b) Comparison of total cycle size in bytes.

In Figure 21(b), we show the changes of the total cycle size over the simulation time. The maximum cycle size that corresponds to 2 ms is 250000 bytes including the guard times between ONUs' transmissions. In IPACT, as the algorithm only grants as a maximum 250000/3 (83333) to each ONU, when the traffic of any of the ONUs is low, then the total cycle decreases. And, as the ONU's traffic fluctuates, the cycle size also varies in the same way. For example, between 2 and 3 seconds there are only two sources generating traffic, so IPACT only allows the guaranteed window size to each ONU, giving a total of 166666 bytes. In the case of DDSPON, the distributed exchange of the changing weights creates a dynamic and fair distribution of the bandwidth for each cycle. As can be seen, the cycle size remains stable in DDSPON compared to IPACT for medium and high network loads. This also has implications on the delay variation that IPACT is imposing to the traffic flows due to the cycle time variation, whereas in DDSPON we are minimizing this aspect.

3.4. Summary

In this chapter, we have proposed and evaluated two Dynamic Bandwidth Allocation algorithms for EPON. The first was a part of our initial study on centralized DBA algorithms. This DBA scheme supports bandwidth distribution and delay control through cycle-based ordering scheduling. The scheduler runs remotely in the OLT. It is based on time marks in order to select the ONU that must transmit first within a cycle. This cycle-based algorithm gives priority of transmission to the ONU with more delayed packets. Our first results about mean packet delay show a better performance for the combination of both schemes under a network capacity of 70% when the traffic is homogeneous or balanced. When there are sources generating traffic higher than the contracted bandwidth, the proposed combination performs better in terms of delay, especially for those sources that are not misbehaving.

Our second proposal is a DBA algorithm, called Distributed Dynamic Scheduling for EPON (DDSPON). Using a simple algorithm, the ONU is able to proportionally schedule its transmission window size based on its current queue requirements and the requirements of the rest of the ONUs. The simulation results confirm that this algorithm is a good alternative to centralized schemes. Especially it outperforms the centralized schemes in terms of delay and queue size at high network loads. Also it has been shown that it fairly distributes the bandwidth when the traffic rates are changing, therefore it is suitable for elastic services and to offer differentiated services.

The proposed schemes require sending extra information inside the control messages. They also impose a higher computation capability at the ONUs, which may affect their cost. A tradeoff between these factors and the algorithm's benefits need to be considered.

Chapter 4 PON Evolution

Network evolution is a natural response to handle increasing traffic demands. The objective of this chapter is to evaluate evolution strategies to increase a PON's capacity regardless of its technology: EPON (Ethernet-based PON) or GPON (GFP-based PON). We study the requirements for an optimal migration towards higher bandwidth per user. Based on these constraints, we examine scenarios and cost-effective solutions for PON evolution, and we propose three main evolution stages.

This chapter is organized as follows. In Section 4.1, we introduce to the problem. In Section 4.2, we outline the constraints for PON evolution. In Section 4.3, we propose three migration phases and we explore different alternatives and scenarios. Finally, in Section 4.4, we summarize the chapter.

4.1. Introduction

The bandwidth supported by legacy PONs is limited: 1 Gbps upstream and downstream for EPON, and up to 2.5 Gbps downstream/1.25 Gbps upstream for GPON today. A sustained growth of Internet traffic is being observed over the past two decades. Upcoming applications such as multi-player gaming, e-health, e-learning, e-culture based on 3D full-HD (High-Definition) video and audio services will increase the bandwidth demands to unprecedented levels. Current GPON and EPON may need to be upgraded to cope with mid- and long-term needs.

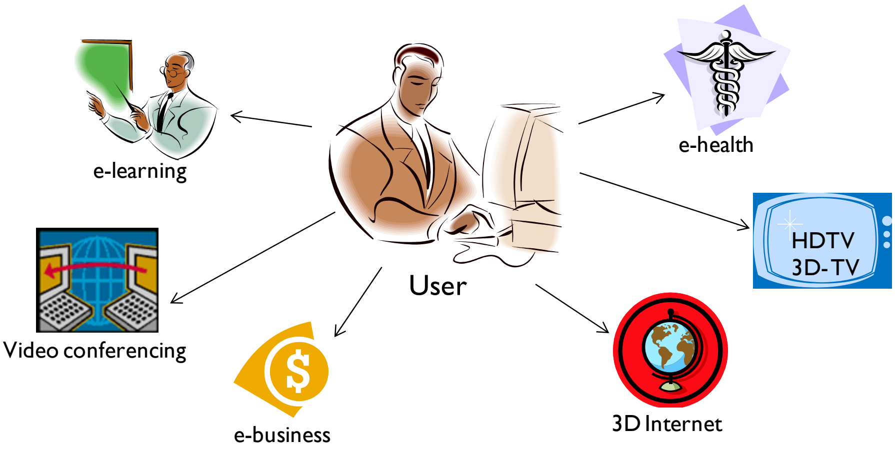


Figure 22. Upcoming applications demanding high bandwidth.

Access networks are experiencing extensive efforts to offer higher bandwidths to subscribers. A number of architectures [1] have been proposed for next-generation Passive Optical Networks (PON). Recent publications [25], [47] give an overview of the possible candidates and architectures for the next-generation GPON. In this chapter, we focus on the long-term evolution of currently-deployed PONs (EPON or GPON), and consider some basic requirements for future PON generations. In Chapter 2, we have discussed some related works in the field of PON evolution. In this dissertation, we anticipate three principal evolutionary phases, where WDM is the main technology that allows coexistence among PON generations.

4.2. Evolution Constraints

4.2.1. Traffic Growth

A sustained growth of Internet traffic is being observed over the past two decades. It is expected that new bandwidth-hungry applications and services will generate more demand and attract new users. An upcoming application is 3D TV which will require 100-Mbps bandwidth per user [84]. Many other applications are emerging such as multi-player gaming, e-health, e-education, e-training, etc. When the third dimension (3D vision, high quality sound) is added to many existing interactive Internet applications, the bandwidth demand will increase to unprecedented levels.

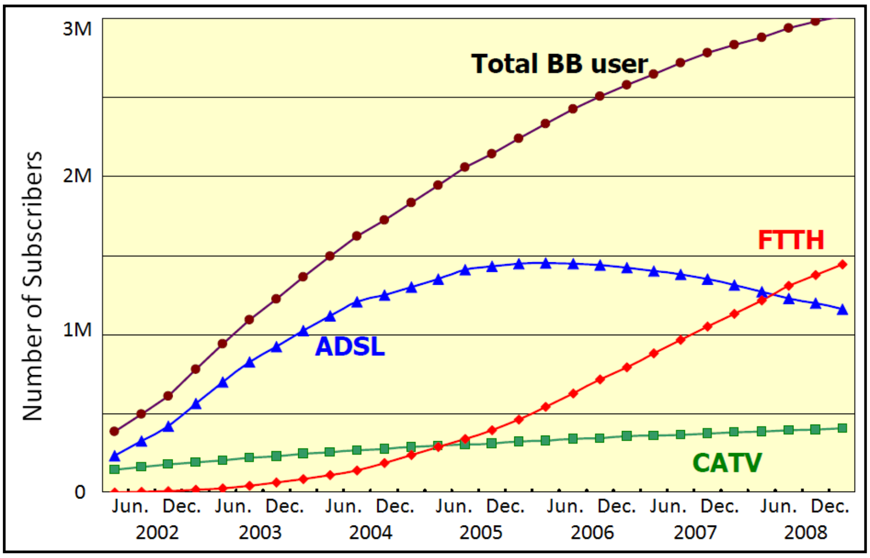
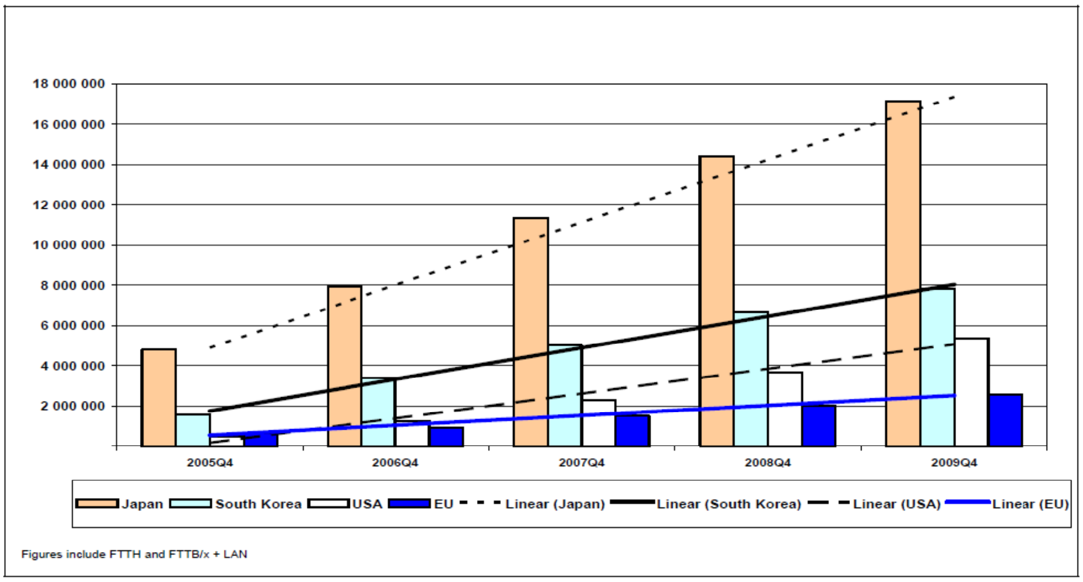


Figure 23. Broadband Access Growth, with Total Million BB (Broadband) users in the period 2002-2008. (Source: MIC, Ministry of Internal Affairs and Communications, Japan).



Figures include FTTH and FTTB/x + LAN

Figure 24. FTTx deployments in the EU, US, Japan and South Korea (source: European Commission [19]).

For example, in Figure 23, which shows the fast-growing market for broadband access to Internet in Japan, we observe that the number of subscribers has increased to more than 375% between years 2002 and 2008. Among other broadband access technologies, FTTH (Fiber-to-the-Home)is growing substantially, and it is surpassing the number of subscribers in ADSL and CATV. Although in other markets xDSL is still the dominant broadband technology deployed, Fiber-To-The-x (FTTx; where x can be Home, Building, Premises, Node, or

Curb) deployments continue to grow in many countries, as can be seen in Figure 24. FTTx implementation through the use of PON is expected to be the leading technology due to its high capacity and cost-effective deployment. In the future, capacity of current GPON and EPON may need to be upgraded to cope with mid- and long-term needs.

4.2.2. Multiple-Phase Migration Evolution

To satisfy the long-term demands, a comprehensive study of the migration alternatives is essential from cost and efficiency points of view. A selection of technology and migration strategy can directly affect the later generations. The upgrade path may present multiple evolution phases (see Figure 25). Minor phases or sub-phases will reflect the changes that might emerge smoothly as the access network increments its capacity.

The enabling technologies will influence the multi-phase migration scenario. Two relevant and useful technologies are: WDM and OCDM (Optical Code-Division Multiplexing) [3]. WDM is a key option for upgrading PON capacity today. Much work has been conducted towards WDM-PON deployment, proposing several architectures [1]. Most of these architectures are related to a fixed allocation of a wavelength per ONU. However, this is not a flexible solution for a dynamic reallocation of capacity from lightly-loaded ONUs towards overloaded ONUs. We expect that wavelength channels are going to be shared among several ONUs for better utilization of the PON capacity.

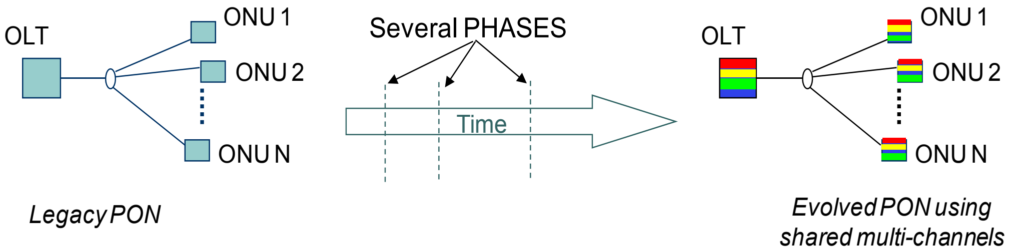


Figure 25. Multi-phase migration process.

Other promising technologies are electronic-based such as: Sub-Carrier Multiplexing (using Orthogonal Frequency-Division Multiplexing) and electronic Code-Division Multiplexing. In case of electronic technologies, all signal multiplexing processes are performed in electronics first and then sent over the optical channel (wavelength) to the end-node. Since electronic technology is more mature, it usually brings reduction in price.

4.2.3. Requirements for Future PON Generations

Future PON generations may take diverse evolution paths. To determine the optimal migration evolution, we define constraints to identify key enabling technologies and architectures for PONs. We present five main requirements for the evolutionary path (see Figure 26), as discussed below.

4.2.3.1. Minimize Equipment-Related Investments

The most important requirement operators consider while selecting any option is the required new investments. For further PON migration process, a new technology may need to be deployed, and new components and devices may be placed in the system, in addition to existing ones or as a replacement at end points (e.g., at the OLT and ONUs). Capital expenditures must be evaluated together with other current and future benefits for a cost-effective evolution path.

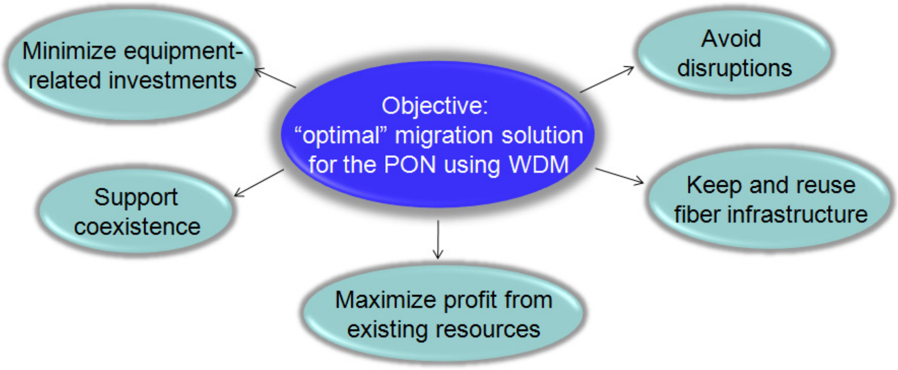


Figure 26. Constraints for PON evolution.

4.2.3.2. Support Coexistence

We consider PONs that are operating with legacy devices. Coexistence means that next-generation devices must operate on the same infrastructure without interfering with existing operation whenever possible. Backward-compatible devices also need to be considered for coexistence.

Coexistence is also related to the type of users sharing PON resources at different evolutionary stages. For instance, at certain time periods, small and medium business (SMB) users create relatively-large traffic volumes on the network while residential users generate lower traffic volumes, and vice versa. Hence, a user-coexistence strategy can achieve better resource utilization.

In PON evolution, even within one category of users, traffic demands may be different. Some users will be satisfied with minimal service and will not upgrade to newer devices or will upgrade much later, when the prices become comparable. Therefore, the network upgrades must allow coexistence among new-generation and legacy devices.

4.2.3.3. Maximize Profit from Existing Resources

Usage maximization of current and extended capacities can be achieved by dynamically allocating bandwidth among users. Efficient capacity utilization will bring revenue to the service provider and facilitate recovery of initial and subsequent investments.

4.2.3.4. Keep and Reuse Fiber Infrastructure

Another condition for cost-effective upgrade is that neither the RN should be changed, nor should more optical fiber be added to the existing PON. Most of the optical network is lying underground, so civil engineering/deployment increases the capital expenditures. Although changes to outside plant could help further upgrades, they can cause service disruptions.

4.2.3.5. Avoid Disruptions

In general, we expect some service disruptions during network migration, but we need to reduce their number and their effects depending on which devices/fibers are being replaced. A disruption occurring at the ONU only affects its users, and not the rest of the network, unlike changing the OLT where the entire PON will be affected. However, making a change at the CO is performable under a more-protected environment than replacing the RN, which is a field operation.

4.3. Main Evolution Phases and Scenarios

PON evolution depends on many factors, including technology advances and their cost of implementation. According to current efforts in standardization bodies, to introduce 10 Gbps rate on PONs, we can anticipate three principal evolutionary phases: (i) line-rate upgrade; (ii) multiple wavelength channel migration; and (iii) other future PON technologies, as discussed below.

4.3.1. Line-Rate Upgrade

A natural PON evolution is to increase existing PON capacity to a higher line rate, namely 10 Gbps. Work has been conducted by IEEE and ITU-T to standardize the next-generation 10 Gbps PONs since 2006 and 2007, respectively. The standards are influenced by the ability to coexist with legacy PONs, price, and implementation feasibility. IEEE has ratified a new standard for 10 Gbps EPON (IEEE 802.3av) in September 2009. Also, ITU-T (Question 2, Study Group 15) is releasing a series of recommendations for 10Gbps-GPON (XG-PON), namely G-987.1, G-987.2 (both approved in January 2010) and G-987.3 (waiting for approval). Both IEEE 802.3av and ITU-T-proposed architectures (in NGA1, Next-Generation Access 1) [47] are good examples including line-rate upgrades that allow coexistence with current commercial PONs.

For a longer-term PON evolution, we may consider higher line rates. Line rates up to 40 Gbps or 100 Gbps can be an option for future PONs. However, for higher line rates, it is more difficult to reach the typical PON distances without signal amplification.

This migration can occur in an “as-needed” fashion, and two sub-phases of evolution are expected: asymmetric and symmetric line-rate upgrades [47][76].

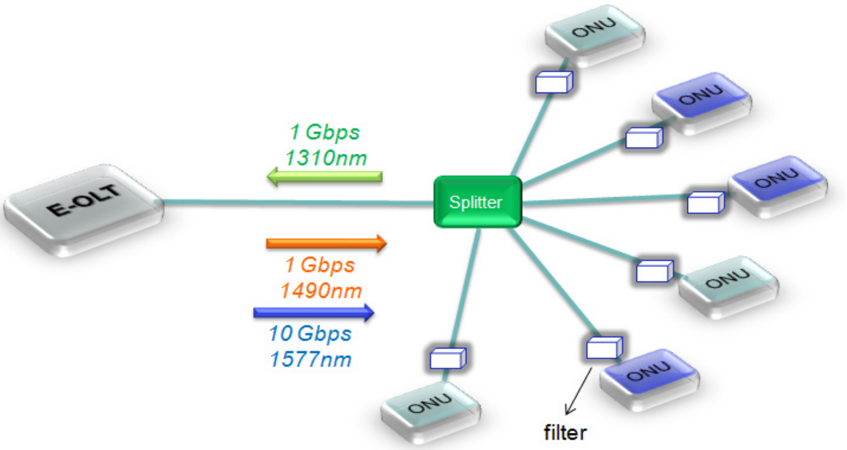


Figure 27. Asymmetric line-rate upgrade to 10 Gbps (in EPON).

4.3.1.1. Asymmetric Line-Rate Upgrade

Downstream traffic from OLT to ONUs is traditionally higher than upstream traffic. PONs are attractive due to their natural broadcast capability on the downstream channel. Thus, with imminent growth of broadcast services (e.g., due to deployment of Internet Protocol High-Definition TV, IPHDTV), we have the first part of the line-rate upgrade phase. Another reason for asymmetric migration as a first step is the fact that adding 10 Gbps upstream capability (symmetric approach) would require more expensive ONU devices.

Figure 27 shows a new downstream channel added to the PON using WDM. To not interfere with the existing legacy PON (light-colored ONUs in Figure 27), the new wavelength channel can be taken from the L-band. A new OLT card or module can manage legacy and 10 Gbps downstream services. We call this module E-OLT or

Enhanced-OLT. New ONUs (dark-colored ONUs in Figure 27) are added to the PON to support 10 Gbps service.

However, some precautions are needed to support this coexistence. New wavelength-blocking filters (boxes located next to each ONU in Figure 27) should be attached to ONUs to avoid interferences between downstream channels. Reference [59] shows that adding these filters during legacy PON deployment can significantly reduce the overall migration cost. We also observe that the addition of these filters can ease coexistence with future-generation PONs as discussed later.

An external or embedded amplifier may be needed at the OLT due to the low sensitivity of the ONUs' receivers and the low optical power level needed to reach the receiver of high-line-rate signals (at 10 Gbps). The OLT may operate at a dual rate in the downstream channel, with two MAC (Medium Access Control) layer stacks; consequently a new class of PON chipsets has to be developed [76].

4.3.1.2. Symmetric Line-Rate Upgrade

Symmetric line-rate upgrade is achieved when both downstream and upstream directions operate at 10 Gbps. This depends on the symmetry of traffic demands, e.g., new peer-to-peer communications, multimedia real-time applications, and 3D Internet services. Two approaches have been taken into consideration, namely i) TDM, and ii) WDM coexistence [23].

4.3.1.2.1. A. Symmetric Line-Rate Upgrade with TDM Coexistence

The upstream channel can be upgraded to 10 Gbps by sharing a wavelength in time and using two different line rates (see Figure 28). This approach is approved in IEEE for 10G-EPON. It can reduce deployment cost, because the legacy upstream channel is on the lower-dispersion fiber band. New ONUs can operate with commercially-available distributed feedback (DFB) lasers, and the optical transmission system can be reused to reduce cost. However, network implementation becomes more complex since an extra control mechanism is needed to manage the upstream channel with different rates, and it must also deal with time alignments.

An important challenge is imposed on the OLT's burst-mode receiver, which now has to adapt its sensitivity according to the incoming optical burst signal, to detect different-line-rate traffic arriving through the same optical channel. This problem only affects the PON at the discovery stage, when the OLT incorporates ONUs with unexpected rates. IEEE 10G-EPON standard solved the problem by allowing separate discovery windows for 1G- and 10G-services.

4.3.1.2.2. Symmetric Line-Rate Upgrade with WDM Coexistence

The alternative to a shared upstream channel upgrade is to add another upstream channel at 10 Gbps (see Figure 29). Now, independent OLTs can manage legacy (OLT) and 10 Gbps (E-OLT) services. The new optical transmission for ONUs can be slightly-more expensive because the transmission system cannot be reused as before (in the case of TDM coexistence). Now, the laser at the enhanced-ONU has to transmit at a different wavelength in C or L bands, e.g., at 1550nm [23]. However, this wavelength is currently reserved for analog video broadcasting.

Other wavelength bands may need to be explored to support coexistence. For example, in [25], two symmetric non-overlapping upstream channels are located in the O-band (1270nm and 1310nm). In such case, the current legacy ONUs (often covering the whole O-band, centered at 1310nm) would need narrower transmitters (e.g., coarse-WDM or dense-WDM transmitters) in order to not overlap with the new channel at 1270nm in the same band. Network disruption can occur due to the installation of a WDM filter (box near OLT and E-OLT in Figure 29) at the CO. The WDM filter separates wavelengths directed to the legacy OLT from the ones to the E-OLT. For guaranteed services, the OLT can be installed in a redundant way such that changes to any module do not generate disruptions since the spare OLT will be working. Many current deployments do not use protection schemes, but protection will become important in the near future.

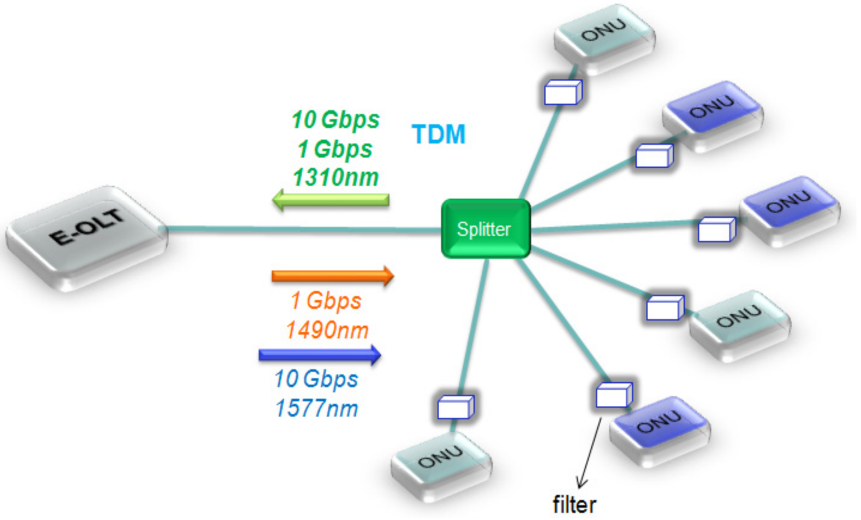


Figure 28. TDM coexistence example in symmetric line-rate upgrade to 10 Gbps.

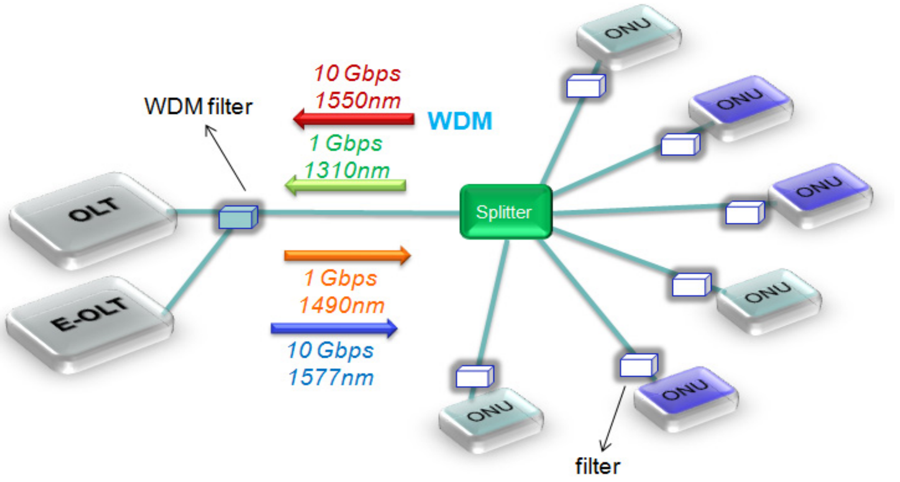


Figure 29. WDM coexistence example in symmetric line-rate upgrade to 10 Gbps.

4.3.2. *Multiple Wavelength-Channel Migration*

The natural second step for PON evolution is based on WDM technology. However, other technologies (part of the third migration phase) may change this expectation, due to reduction of their cost and better implementation feasibility. The advantage of WDM is that it allows coexistence between two or more PON generations over the same infrastructure. Provisioning multiple channels on the PON allows deployment of different migration technologies or capacity extensions transparently, where devices of a generation are unaware of the coexistence with other generations.

Today, there are concerns regarding challenges to implement WDM in PONs, especially regarding: type of transceivers at OLT and ONU, sharp filtering, and type of RN. Details of enabling technologies and challenges can be found in [1][63]. Another consideration is wavelength planning. Initially, when there are few wavelengths, they could be spaced far apart, e.g., using the 100G grid. If more wavelengths are needed, unused wavelengths from the 50G grid can be invoked. Care must be taken to ensure that closely-spaced wavelengths are operating at lower rates to reduce interference. Practical aspects such as these must be handled by the Service Provider in its actual deployment and upgrade situations.

Diverse architectures for this migration stage can be considered [1][63]. Some WDM-based PON architectures involve changes at the RN, including addition of active components, such as in [52][91]. In this dissertation, we consider changes that allow the network to remain passive (RN is fully passive), and we study two main architectures: (i) WDM-PON and (ii) Overlaid-PONs.

4.3.2.1. WDM-PON

WDM-PON has been studied by several teams of researchers. WDM is considered by many to be an ideal technology for the next migration step [5]. WDM-PON is also known as wavelength-routed or wavelength-locked WDM-based PON. It requires the replacement of the optical power splitter by an Arrayed Waveguide Grating (AWG) (see Figure 30). In upstream direction, the AWG acts as a multiplexer of different wavelengths into a single fiber; and, in downstream direction, the AWG is used as a de-multiplexer by directing a different wavelength to each fiber drop. Therefore, AWG allows a fixed assignment of two wavelengths (upstream and downstream channels) to each ONU.

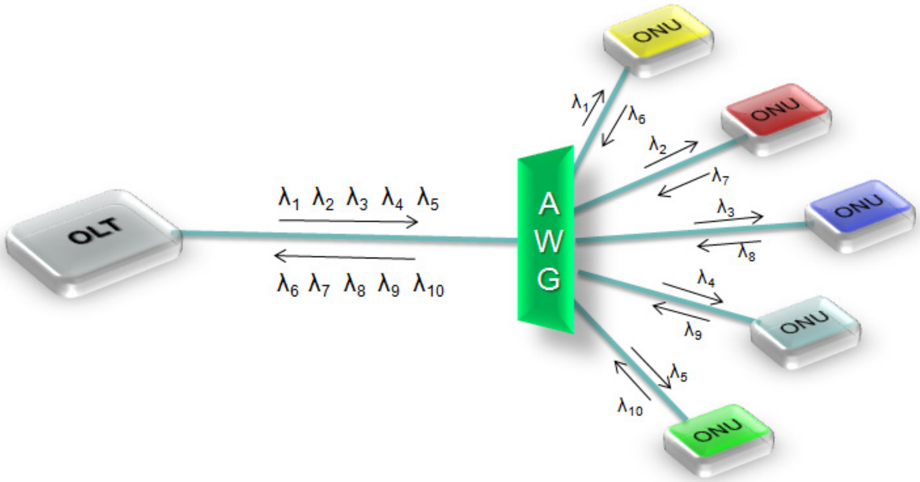


Figure 30. WDM-PON with five ONUs. Two different wavelengths have been assigned to each ONU by using an AWG.

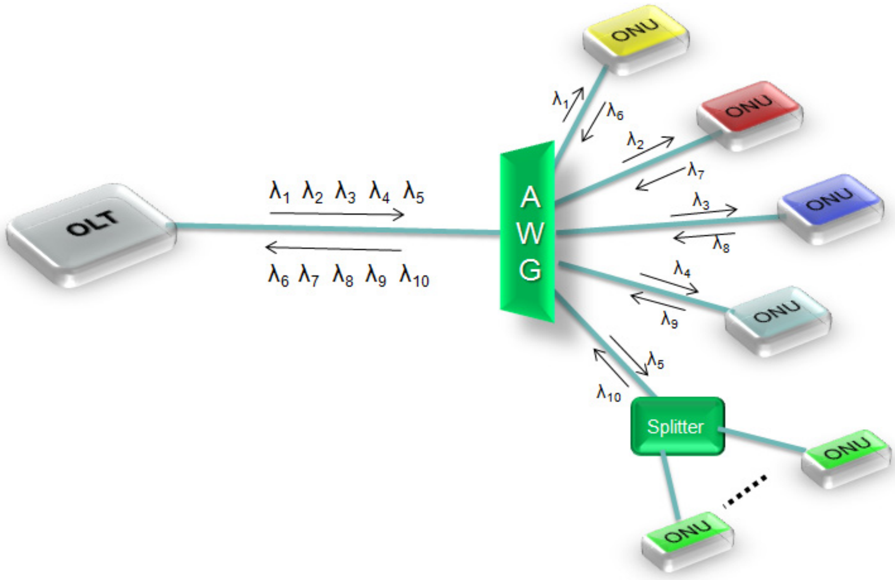


Figure 31. WDM-PON with cascaded TDM-PON, by using a combination of an AWG and a splitter.

Devoting one or more optical channels to each ONU implies a substantial increase in the offered capacity per user. However, fixed-channel assignment is inflexible and does not allow dynamic reuse of wavelengths by different ONUs for efficient capacity utilization, especially when traffic demands are bursty.

ONUs in WDM-PON will require new transmitters working on different wavelengths. A good option is to use colorless ONUs either with tunable lasers or RSOAs (Reflective Semiconductor Optical Amplifier). However, today, RSOA's price is one order of magnitude more expensive than an entire EPON-based ONU, and tunable lasers are more costly than RSOAs.

A WDM-PON with cascaded TDM-PON can dynamically allocate unused bandwidth from one ONU to other ONUs (see Figure 31). The addition of a splitter in one (or more) fiber drops allows time-sharing the dedicated wavelengths among some ONUs in that PON branch. This architecture can significantly improve the maximum number of ONUs supported by a single PON, but it does not facilitate capacity upgrades in an "as-needed" fashion by adding wavelengths.

WDM-PON is a highly-disruptive option since the RN has to be replaced by another device (AWG). This procedure will provoke a major PON disruption unless the RN is installed in a protected configuration. More importantly, all existing devices on the network must migrate at the same time to support the WDM-PON architecture; and this does not meet the coexistence requirement. A complete migration of all user devices will lead to prohibitive costs, especially when some users may not want a capacity upgrade. Although WDM-PON is considered as a next-generation PON after 10 Gbps, the above arguments suggest that it is not suitable for a smooth PON evolution.

4.3.2.2. Overlaid-PONs Using WDM

Overlaid-PONs is a valuable option for the second migration phase. They exploit WDM technology, but now the RN remains an optical power splitter, and it does not need to be replaced by an AWG as in WDM-PON. In Overlaid-PONs, PON capacity is incremented by adding more wavelength channels based on the traffic demands. If existing channels are time-shared among users, a new channel will also be time-shared by the ONUs on the new wavelength. OLT will control an ONU's usage of a wavelength at a specific timeslot. Thus, ONUs working on a new wavelength form the set of devices pertaining to the new overlaid-PON (over the legacy PON or previous-generation service), as illustrated with the example in Figure 32. Some devices might belong to two or more different overlaid-PONs according to their hardware capabilities which can lead to a flexible distribution of bandwidth. Overlaid-PONs are also known as broadcast-and-select WDM-based PON, where all wavelength channels are broadcast to all users and an ONU selects the one assigned to it. Overlaid-PONs or Stacked PONs have been included as one of the next-generation architectures for GPON in NGA1 proposal (ITU-T, Study Group 15).

When using Overlaid-PONs, some disruptions observed in WDM-PON are minimized since there is no need to replace the RN; only end-devices will require a change. Moreover, some users may need capacity extension while other ONUs may remain the same for some time. "As-needed" growth is accomplished efficiently using Overlaid-PONs. The network becomes flexible for efficient distribution of overall capacity among users which operate on the same wavelength channel(s).

The overlaid-PONs architecture requires that new ONUs and OLT operate at different wavelengths than existing ones in legacy PON and 10G-PON. Existing legacy standards, for cost reasons, allocated wide bands for upstream and downstream channels which may interfere with the new optical channels. Thus, we need blocking filters at the first migration phase for all ONUs. These filters can be costly because they should have a very steep response characteristic in order to fit into the narrow guard band left between the channels. The suggested evolution path allows migrating first towards an intermediate line-rate upgrade phase which may give time to fully migrate existing legacy ONUs, before moving to the second migration phase. New wavelengths can be targeted at the legacy bands. By that time, the filters' prices may become affordable.

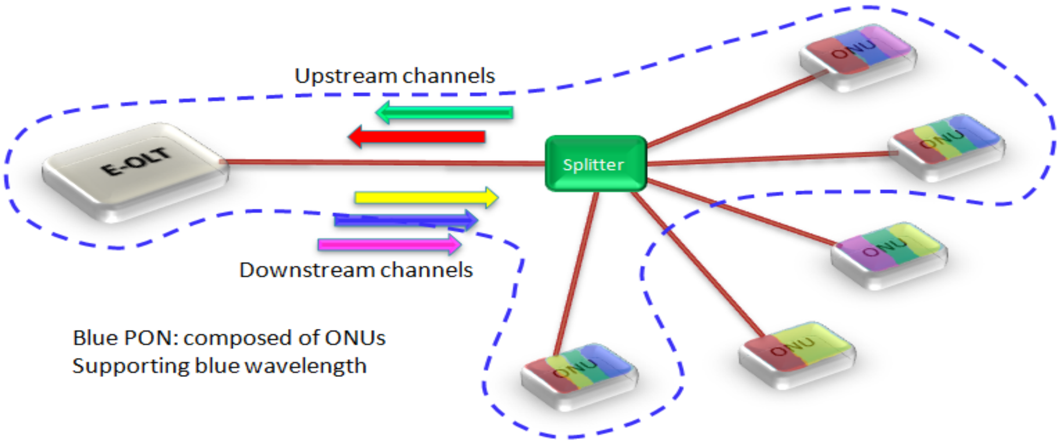


Figure 32. Example of Overlaid-PONs. Several PONs are stacked on the same infrastructure. ONUs supporting particular wavelength channels are part of such a particular PON, as in the case of the "blue" PON.

To allow an ONU's transmission over more than one wavelength, one of two methods may be used: (i) tunable lasers and (ii) fixed-wavelength laser arrays. Using tunable lasers increases network flexibility, but their price is still very high. Fixed-wavelength laser array is cheaper but less flexible compared to tunable lasers. The choice of lasers for ONUs will mainly depend on their price at the time of implementation.

Using L-band could be an immediate solution for a capacity upgrade using WDM. Future increments in number of wavelengths can be obtained through the spectral space left empty by a total migration of previous generations working at lower bands.

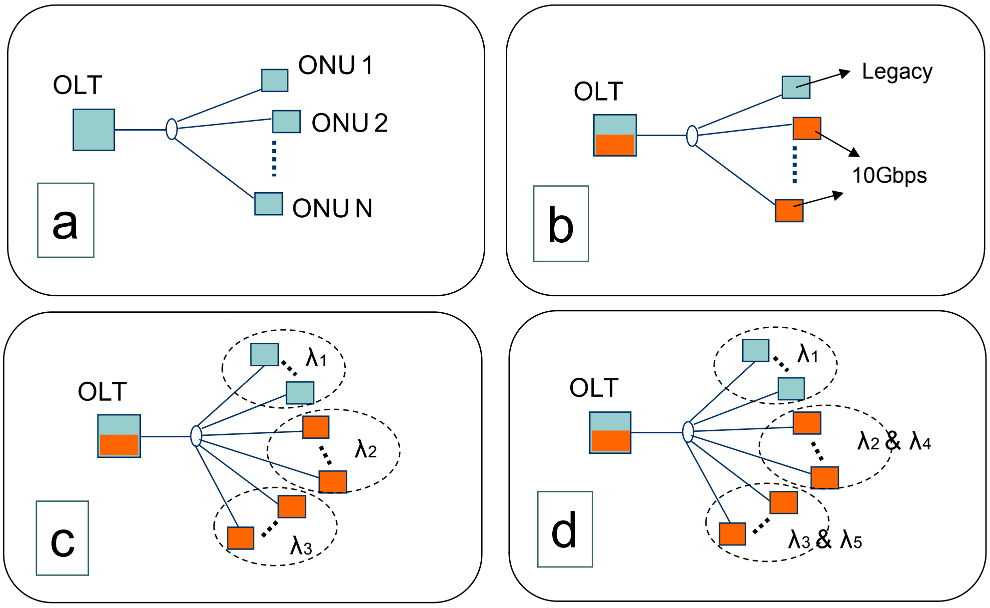


Figure 33. Evolution using Overlaid-PONs: (a) legacy PON, (b) partial upgrade to 10G-PON, (c) extending capacity by adding downstream (and/or upstream) channel to a set of ONUs, (d) extending capacity by adding more channels to sets of ONUs as needed.

The best characteristic of Overlaid-PONs is that it eases the path towards the coexistence of multiple generations on the same fiber infrastructure. A good example can be seen in Figure 33. Starting from a legacy PON (Figure 33(a)), the first evolution phase goes through a line-rate upgrade for some of the ONUs (Figure 33(b)). The previous step requires the addition of wavelengths to allow coexistence with the legacy PON. With time, some users may need more capacity which can be resolved by adding a new wavelength to any or both traffic-flow directions (Figure 33(c)). Some ONUs can share two or more wavelengths as required. Finally, for some sets of ONUs, there may be a need to increase the number of wavelengths to be shared among the ONUs (Figure 33(d)). Thus, the Overlaid-PONs approach using WDM is not only a way to increase a PON's capacity by adding wavelengths, but also a way to keep PON generations coexisting by stacking them with different wavelengths.

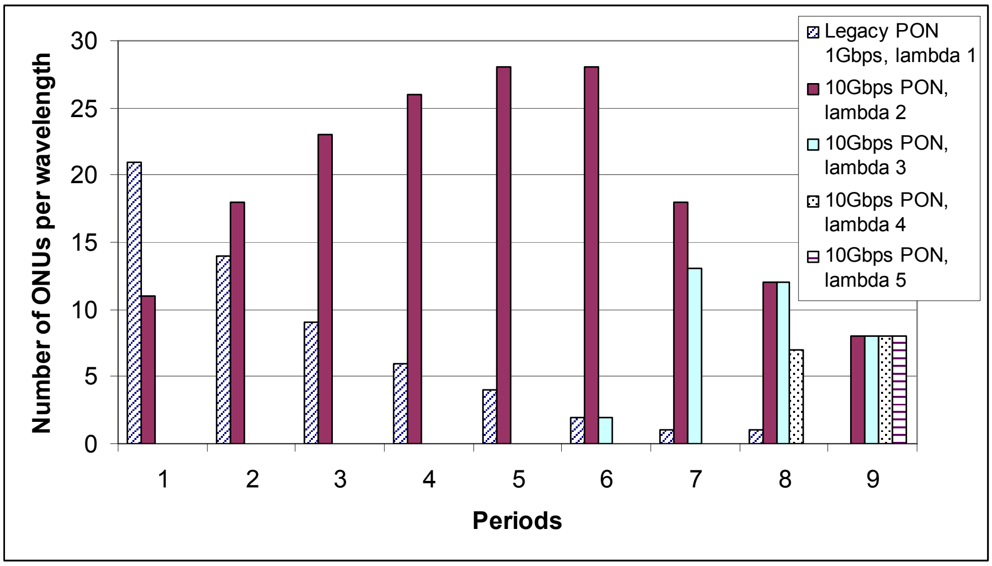


Figure 34. Number of ONUs migrating to 10-Gbps line rate and to extra optical channels per period using Overlaid-PONs approach (when each period approximates a year).

To illustrate how the migration process can be achieved using Overlaid-PONs, we now present an example of evolution through different periods. Figure 34 shows the number of ONUs per service during each period (which approximates a year). Let us consider traffic growth in this PON with a factor of 1.5 per period. The number of ONUs during these periods is constant (32 ONUs) and traffic at each ONU will grow on average in the same proportion. At the initial state of the network, just before period 1, the legacy-PON´s capacity is totally consumed (total traffic volume is 1 Gbps on average). In this PON, existing ONUs will be upgraded gradually (line-rate upgrade first, then wavelengths at 10 Gbps are added as needed) trying to utilize the available capacity in previous services as much as possible. In other words, when total bandwidth requirements surpass the available capacity, we move traffic of a minimum number of ONUs to a new wavelength such that all the requirements are committed. We choose a minimum number of ONUs to be upgraded because it would suppose a lower investment than trying to achieve load balancing, by distributing the same amount of ONUs over all wavelengths.

From Figure 34, we observe that coexistence among 1G and 10G services can last for eight periods. From period 6, additional wavelengths are needed to support the growing traffic demand. In the last period shown, there are four channels serving eight ONUs each. Note that the capacity of the four optical channels can be shared among a subset of ONUs, according to the needs. That would require colorless ONUs and a wavelength-assignment algorithm. Locating the point in time to run the provisioning and its bandwidth granularity will be a challenge for the network operator in the near future. It is important to mention that this is an illustrative example assuming a constant traffic growth factor, which leads to a 9-year interval to operate with four channels (considering only one flow-direction). Future upgrade decision periods will be affected by many other factors, namely economy and traffic-growth evolution.

4.3.2.3. WDM-PON vs. Overlaid-PON

With WDM-PON, it is mandatory to replace the RN (splitter) by an AWG, and this disrupts the entire network. Furthermore, given that a WDM-PON provides one wavelength per user, not much revenue can be achieved from an efficient use of the capacity by dynamic wavelength and bandwidth allocation. Finally, when migrating to a WDM-PON, all ONUs must be changed at the same time, and the coexistence principle is violated.

On the other hand, an Overlaid-PONs approach not only accomplishes most of the requirements but it is also the enabling approach that leads to coexistence of old and new generations. Hence, the Overlaid-PONs approach is a better solution for the second evolutionary phase and it promotes future PON generations in an "as-needed" fashion.

Below we quantitatively compare different PON upgrade approaches, and focus on WDM-PON and Overlaid-PON.

4.3.2.3.1. Optical Power Budget

PONs require higher optical power budget to compensate for increased insertion loss along the paths between the OLT and ONUs. Considering the typical insertion loss introduced by filters (around 4 dB), splitters (17.2 dB, assuming 1:32 splitting ratio), AWG (2.5 dB), and fiber links along the path (0.2 dB/km, assuming 20 km), we can calculate the lower bound of the total power loss (without adding the optical penalty required to cope with physical impairments) for different upgrade approaches, see Figure 35.

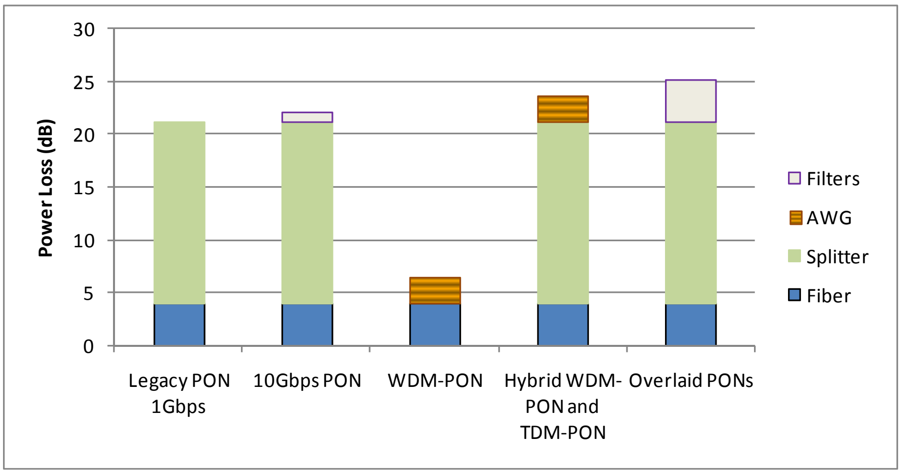


Figure 35. Optical power loss for different upgrading approaches.

As shown in Figure 35, WDM-PON offers the minimum total power loss, which means that it can support longer distance or more ONUs may be added to the architecture. WDM-PON with cascaded TDM-PON increases considerably the power loss if we assume the insertion of a 1:32 splitter. Furthermore, Overlaid-PONs and 10-Gbps PONs (TDM coexistence) experience a higher total optical power loss compared to WDM-PON and the original Legacy PON. The main reason is due to insertion of filters at the ONUs (1dB) in both cases and at the OLT (3 dB) [59] in the case of Overlaid-PONs. However, the maximum optical power budget, usually 29 dB (e.g., IEEE 802.3av, for 1:32 splitting ratio), is not reached. This is an important consideration in case of adding more devices to the system.

4.3.2.3.2. Capacity Usage

Using the example presented in Section 4.3.2.2, we evaluate the amount of unused capacity for WDM-PON and Overlaid-PONs. In periods 1 to 5, we upgrade the network using 10G-PON, and after that, we upgrade the PON either with WDM-PON (at 1 Gbps for the purpose of this example) or with Overlaid-PONs. We calculate the total unused capacity per period according to the bandwidth that each ONU consumes on average (see Figure 36). The amount of unused capacity in the case of WDM-PON is very high compared to the case of Overlaid-PONs in Figure 36. However, the extra capacity in WDM-PON cannot be shared among ONUs, unless the service provider implements a WDM-PON with cascaded TDM-PON.

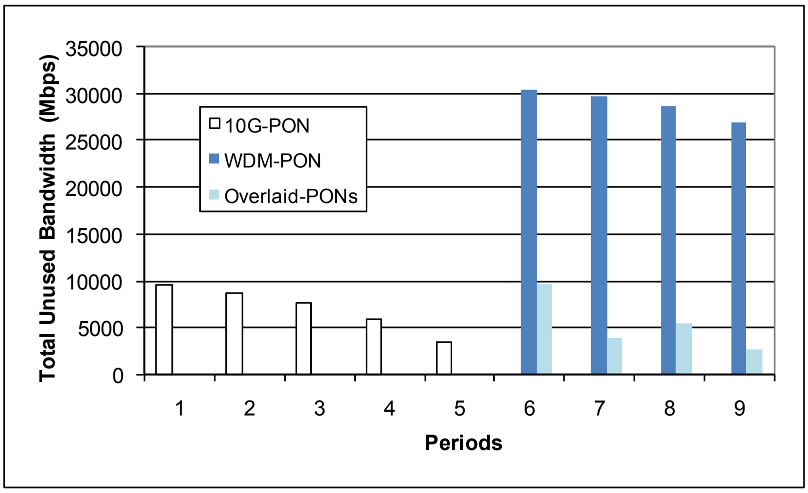


Figure 36. Total unused bandwidth per period for 10G-line rate upgrade combined with WDM-PON or Overlaid-PONs.

4.3.2.3.3. CAPEX

In this section, we analyze the cost impact that a new technology will have on the upgrade process. At the moment, WDM-PON is not a widely-deployed technology, hence the exact cost of this technology is difficult to estimate or forecast. However, some current technical challenges (type of transceivers, wavelength plan) suggest the high cost of components required to implement WDM-PON. To illustrate the CAPEX required for our example presented in Figure 34, we use the cost per device shown in Table 7 as in [40]. We assume a cost reduction of 7% per period (which approximates a year). We also assume that 10-Gbps equipment cost is in the middle between WDM-PON equipment and Legacy PON (TDM PON in [40]) equipment cost. Overlaid-PON ONU (hybrid-PON ONU in [40]) is assumed here to be the same as WDM-PON ONU cost. Costs are presented in Table 7.

Table 7. Devices' cost for CAPEX calculation.

Device	Cost ($)
OLT (Overlaid PON)	44320
OLT (WDM PON)	44320
OLT (10 Gbps)	30250
Splitter 1:32	2300
AWG 1:32	3200
ONU (Overlaid PON)	525
ONU (WDM PON)	525
ONU (10 Gbps)	440

In Figure 37, we present the capital expenses (CAPEX) needed in our example. We have basically two stages: from period 1 to 5 when we upgrade to 10 Gbps, and from period 6 to 9 when we upgrade using WDM technology (i.e., adding wavelength channels). We calculate the required CAPEX for each period, and total CAPEX for both WDM-PON and Overlaid-PONs (i.e., 10G-PON and WDM-PON, or 10G-PON and Overlaid-PONs).

According to the results presented in Figure 37, CAPEX required for Overlaid-PONs is lower than the one required for WDM-PON. The main reason for this difference is the gradual investment required by Overlaid-PONs (see Figure 37, periods 7 to 9), which results in a lower CAPEX due to cost reductions per period. It is reasonable that WDM-PON and Overlaid-PONs have comparable CAPEX totals since both are WDM-based and face similar technical challenges. Note that, in this example, ONUs' traffic grows uniformly and at a fast rate; however in a practical scenario (e.g., using different growth patterns per user), the investment for Overlaid-PONs would be distributed over several periods, leading to more cost reductions per period.

Finally, we evaluate the sensitivity of total CAPEX to variations in cost of some elements. For every network element, we increase its cost by 20% and 50%. Figure 38 shows the percentage difference between the total CAPEX in Figure 37 and the new recalculated CAPEX. We observe that, compared to the base cost (total CAPEX in Figure 37), the CAPEX is more sensitive to cost variations at the OLT, especially when its price increases by 50%. Otherwise, the effects on CAPEX is not very large (<15%). Although, in Figure 38, it may seem that combined evolution of 10G-PON and Overlaid-PONs is more expensive than combined 10G-PON and WDM-PON, note that percentage differences are calculated using their respective base total CAPEX (in Figure 37) as reference.

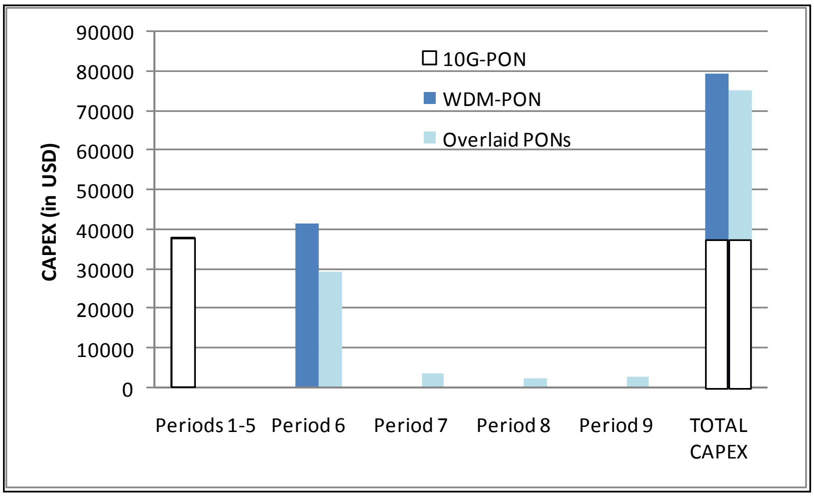


Figure 37. CAPEX for 10G-line rate upgrade combined with WDM-PON or Overlaid-PONs.

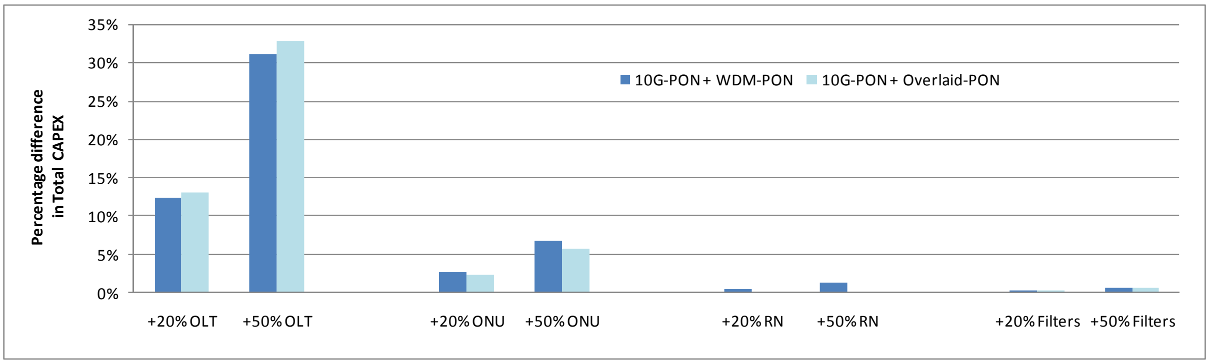


Figure 38. Percentage difference of total CAPEX between respective total CAPEX in Figure 37 and total CAPEX adding 20% and 50% to the cost of WDM-based PON elements.

4.3.3. Other Future PON Technologies

The third PON-migration phase can be based on different possibilities. For instance, it can carry different hybrids between WDM and other multiplexing technologies such as CDM (Code-Division Multiplexing) and SCM (Sub-Carrier Multiplexing) [3], or it can be an upgrade of WDM-based PONs by using Coherent PONs.

By using separate wavelengths for different PON generations (allowing coexistence), any subsequent generation can be deployed over specific wavelength channels, forming a hybrid. Below, we briefly discuss future hybrids.

4.3.3.1. CDM Hybrids

OCDM-PON (Optical-CDM PON) technology addresses capacity upgrade in PONs by adding a code-based dimension to the system. However, design of orthogonal codes to reduce interference and noise when the number of users grows is still an open issue. The coders/decoders and the corresponding transceivers are still in an early stage of development. Few orthogonal codes can be implemented to create more Overlaid-PONs (WDM/CDM), as proposed in [56]. A combination of some codes on different channels (as needed) can provide more flexibility to the network.

4.3.3.2. SCM Hybrids

With SCM, signals are separated (electronically or optically), and shifted to different subcarrier channels using modulation techniques [63]. The subscriber's baseband signal modulates an electrical carrier with an unique frequency using some modulation format (QPSK, FSK, etc.). This electric signal subsequently modulates the lightwave. In this way, electric signal are the subcarriers and lightwaves are the carriers [14]. This option may require a different wavelength to support a WDM-hybrid scenario in order to avoid interference with existing and operating services on other channels. A good example of PONs using this technology is OFDM (Orthogonal Frequency-Division Multiplexing)[18].

4.3.3.3. Coherent PON

An attractive trend for PONs is where transmitters are based on coherent lasers (using ultra-dense-WDM band, U-DWDM), and optical heterodyne or homodyne reception [41]. This may be a good candidate to be used in future U-DWDM-based PONs. To upgrade an existing WDM-PON, only end-devices (ONU and OLT) need to be replaced. Coherent PON allows longer reach (100 km) and a splitting factor of 1:1000, and can provide one different wavelength channel per user. However, complexity and cost are very high at the moment.

4.4. Summary

In this chapter, we introduced and evaluated different options for the evolution of PONs towards a higher bandwidth per user. Our contribution is a qualitative and quantitative study of possible evolutionary migrations that PONs may experience in the future [69]. The importance of such study remains on the consequences that a PON generation can lead to future migration decisions. For that reason, we proposed in this chapter three envisioned migration phases: line-rate upgrade, multi-channel migration, and future PON technologies. The first migration phase is in the process of standardization and can follow two sub-phases: asymmetric and symmetric upgrades. Asymmetric sub-phase aims at adding a new channel at 10 Gbps in downstream direction. Symmetric sub-phase delivers 10 Gbps in upstream direction also by either time-sharing with legacy services or adding a new upstream channel. The second phase is based on multiple channels (wavelengths) in both downstream and upstream directions, and the technology used is WDM. In the second phase, it is necessary to have filters at existing and new ONUs in order to select the appropriate optical signals. The quality and precision of these filters play an important role in future migration procedures over the same network, especially if they are installed at an early stage. Finally, a third migration phase includes new hybrids with previous technologies: TDM and WDM. Some possibilities are OFDM and OCDM, coexisting with previous generations. Another future technology may consider an extension of WDM technologies by deploying Coherent PONs.

Any evolution path can lead to bifurcations at different phases. The second migration phase can be chosen by using WDM-PON or Overlaid-PONs. The benefits of Overlaid-PONs over WDM-PON are disruption minimization and coexistence. In general, WDM-PON does not allow the flexibility to build different channels for different hybrids that could be shared among a number of ONUs. This lack of flexibility in WDM-PON is also clear because the wavelengths are not shared among different ONUs. Hence, WDM-PON cannot make an efficient usage of the capacity by means of a dynamic bandwidth allocation algorithm.

Overlaid-PONs ease the implementation of future generations by preserving coexistence with the previous generation through addition of new wavelengths per service and not per ONU, as in WDM-PON. The third migration phase (other future PON technologies) can be considered with many options, each of which can be implemented independently over the PON by using different channels, consequently guaranteeing coexistence. The evolution path enabled by Overlaid-PONs is more convenient when the aim is to permit coexistence between different evolution generations and technologies.

Chapter 5 Capacity Upgrade in PON

In this chapter, we address the upgrading problem of existing PONs that need to increase their capacity, in an "as-needed" fashion and at different points in time. We propose and investigate the characteristics of a method that upgrades network line-rates and enables migration of network services towards new wavelength channels based on increasing traffic demands and cost constraints. This method is intended to minimize capital expenses and system disruptions, while ensuring optimal resource usage. To do so, we have designed a multi-step model based on Mixed Integer Linear Programming (MILP) and pricing policies. We consider a typical case study for this problem, which is solved using CPLEX. Results from our illustrative numerical examples demonstrate the aforementioned attractive properties of our method.

This chapter is organized as follows. Section 5.1 gives a brief introduction to the topic. In Section 5.2, we formulate the MILP problem with pricing policies and our multi-step method. Section 5.3 describes a case study and the parameters used to test the proposed method. In Section 5.4, we present results of tests performed over our example network scenario, and we compare our results with two other PON upgrading approaches. Section 5.5 concludes the chapter.

5.1. Introduction

Due to expected increase in traffic demands, recent efforts have focused on upgrading the line-rate of current PONs (1 to 2.5 Gbps) to 10 Gbps, while keeping backward compatibility with legacy services [76][39][23][47]. Besides line-rate upgrades, WDM-based (Wavelength Division Multiplexing) PON architectures are being considered as an option for the ITU Next-Generation PON standard [25]. In such architectures, new wavelengths can be added to the PON in order to increase its capacity [1][63][45]. However, as have been discussed in Chapter 4, a dedicated wavelength is allocated to each ONU in most of the proposed architectures, and therefore the network cannot exploit statistical multiplexing to achieve efficient capacity usage. In these architectures [5], the passive optical splitter is typically substituted by an AWG (Array Waveguide Grating). Unfortunately, this procedure implies a major disruption to the network (since the remote node is connected to all the ONUs and OLT), while as studied in [47] and [59], smooth and cost-effective migration is crucial in PON evolution; and two requirements for Next-Generation PON are coexistence with the already-deployed Legacy PON, and minimization of service disruption for subscribers who are not migrating [43].

An important option to guarantee coexistence and also use WDM to add new wavelengths is to implement TDM-WDM (Time Division Multiplexing-WDM) hybrid PON [3] or Overlaid PON as presented in Chapter 4, where ONUs may support and share more than one wavelength, each of which can be shared in time among different users using TDM. In TDM-WDM hybrid PON, the passive optical splitter does not need to be replaced by an AWG. Therefore, new wavelength channels can be added on an as-needed fashion to support ONUs that require extra capacity, by changing only the end-devices that need an upgrade. However, to the best of our knowledge, no work has been done to model the system in terms of cost in order to optimize the upgrade decisions to be taken by the Service Provider (SP), and no work has been done to optimally calculate how many wavelengths should be added, when to add them, and at which line rate, in order to achieve a cost-effective and smooth PON evolution. Ref. [12] uses multiple-period analysis to upgrade line rates in optical core networks. To our knowledge, our work is the first one that proposes a method for calculating optimal capacity upgrades in PONs based on traffic demands over multiple time periods. Our method is based on a multi-step cost-and-network-upgrade model based on Mixed Integer Linear Program (MILP) formulations and pricing policies. This model allows user-by-user upgrade according to their traffic demands, while minimizing the number of disruptions to only the elements being upgraded through a new wavelength or line rate.

5.2. A method to Optimize PON Upgrade Process

Our method calculates optimal capacity upgrades for PONs using MILP and simple pricing policies. It can be adapted to the specific requirements of an operating PON that needs to be upgraded and a SP can customize this method by changing its parameters to its specific network values. Although the following analysis can be applied either to downstream or upstream channels, throughout the rest of the chapter, we assume to be working with upstream channels.

Our general problem scenario is a PON that can evolve through line-rate upgrades and/or addition of new wavelength channels. Our analysis considers a number of possible line rates for the PON and insertion of new wavelengths in the system by adding either single-wavelength transceivers at a time or multiple-fixed-wavelength arrays of transceivers.

5.2.1. MILP Problem Formulation

To choose the optimal solution over all possible upgrade options for a PON towards a TDM-WDM hybrid PON, we propose the MILP formulation below. In our method, the following MILP will be run over multiple periods of time which will be inter-related by using some constants that depend on the network status during the previous periods.

5.2.1.1. Definition of Variables

$l_{k,i,j}$ is a binary variable that is 1 if the i-th ONU is operating on wavelength j with rate k; note that an ONU, in order to support an additional wavelength j, needs to be equipped with an additional transceiver;

$c_{k,j}$ is a binary variable that is 1 if the j-th wavelength is operative on rate k;

$\beta_{i,j}$ is a binary variable that is 1 if the i-th ONU has any traffic over wavelength j;

$bw_{i,j}$ is an integer variable that represents the bandwidth in Mbps that ONU i has over wavelength j;

U_{max} is an integer variable that represents the maximum bandwidth occupation over all the wavelengths.

5.2.1.2. Definition of Constants

K is the set of line rates supported by the PON;

N is the set of ONUs existing in the PON;

L is the set of wavelengths that can be used in the PON;

α is the cost per unit of bandwidth to support load balancing over all wavelengths;

R_k is the value in Mbps of the k-th line rate;

M is a value used to obtain a binary number out of an integer, and accomplishes: $M \gg bw_{i,j}$;

F_i is the maximum number of wavelength channels that ONU i can support.

5.2.1.3. Definition of Multiple-Period Constants

The following constants will change with every period in which we apply the MILP, in order to calculate how a PON evolves. These constants will link one period to the other.

$W_{k,j}$ is cost to support wavelength j with rate k at the OLT;

$Z_{k,i,j}$ is cost to support wavelength j with rate k at ONU i;

Ω_j is the previous line-rate value of j-th wavelength before running the MILP;

B_i is the guaranteed bandwidth for ONU i;

E_i is the set of wavelengths that have not been allocated to ONU i in any previous step;

$F_{i,o}$ is the number of wavelength channels that ONU i previously supported.

5.2.1.4. Objective Function

$$\min\left(\sum_{k=1}^{K}\sum_{i=1}^{N}\sum_{j=1}^{L} Z_{k,i,j} l_{k,i,j} + \sum_{k=1}^{K}\sum_{j=1}^{L} W_{k,j} c_{k,j} + \alpha U_{\max}\right) \tag{5.1}$$

5.2.1.5. Constraints

$$\sum_{k=1}^{K} R_k c_{k,j} \geq \sum_{i=1}^{N} bw_{i,j} \qquad \forall j \in L \tag{5.2}$$

$$\sum_{k=1}^{K} R_k c_{k,j} \geq \Omega_j \qquad \forall j \in L \tag{5.3}$$

$$\sum_{j=1}^{L} bw_{i,j} = B_i \qquad \forall i \in N \tag{5.4}$$

$$\beta_{i,j} \geq \frac{bw_{i,j}}{M} \qquad \forall i \in N, \forall j \in L \tag{5.5}$$

$$\beta_{i,j} \leq bw_{i,j} \qquad \forall i \in N, \forall j \in L \tag{5.6}$$

$$\sum_{j \in E_i} \beta_{i,j} \leq F_i - F_{i,o} \qquad \forall i \in N \tag{5.7}$$

$$\sum_{k=1}^{K} c_{k,j} \leq 1 \qquad \forall j \in L \tag{5.8}$$

$$\sum_{k=1}^{K} l_{k,i,j} \leq 1 \qquad \forall i \in N, \forall j \in L \tag{5.9}$$

$$l_{k,i,j} = \left(c_{k,j}\right) \text{AND} \left(\beta_{i,j}\right) \qquad \forall k \in K, \forall i \in N, \forall j \in L \tag{5.10}$$

$$U_{\max} \geq \sum_{i=1}^{N} bw_{i,j} \qquad \forall j \in L \tag{5.11}$$

5.2.1.6. MILP Description

Eq. (5.1) is a triple-objective function. The first and second terms stand for the cost of supporting wavelength j with line rate k at the ONUs and at the OLT, respectively. Here, cost is the cost per added transceiver. The third term represents the maximum utilization among all wavelengths with lower priority (given by a small value α).

Therefore, the objective is to minimize the cost of supporting a new wavelength at a given line rate by the ONUs, minimize the cost of supporting a new wavelength at a given rate by the OLT, and, with a small priority, minimize the maximum utilization among all wavelengths in the PON (which performs load balancing). Note that cost here is associated to capital expenses to install transceivers at OLT and ONUs, but other cost may apply.

Eq. (5.2) constrains the maximum amount of traffic that can be placed on each wavelength. Eq. (5.3) restricts the possible line rate that a wavelength channel can take according to the value of the previous line rate: according to (5.3), a wavelength channel's line rate can only increase or remain the same. Eq. (5.4) ensures that the bandwidth assigned to an ONU satisfies its guaranteed bandwidth requirements.

By using (5.5) and (5.6), we associate a binary variable $\beta_{i,j}$ to the integer variable bw_{ij} introducing a "big M" inequality. Eq. (5.7) limits the number of channels that an ONU can use to support the traffic (note that second term of (5.7) accounts both the number of existing transceivers F_{io} and the newly enabled transceivers F_i). Eqs. (5.8) and (5.9) discard the possibility of having two different line rates over the same wavelength.

There is a logical relation among all the binary variables ($l_{k,i,j}$, $c_{k,j}$, $\beta_{i,j}$) in (5.10), which implies that ONU i can only operate over wavelength j with rate k if that wavelength has rate k, and that ONU has traffic flowing over wavelength j. Note that even AND operator in (5.10) is not, rigorously speaking, a linear constraint, however logical operators among binary variables can be easily linearized [85]. Finally, in (5.11), variable U_{max} takes the value of maximum traffic occupation among all wavelength channels.

So far, the problem formulation suits a PON with addition of new channels via single-wavelength transceivers. To add several wavelengths at a time (e.g., by means of multiple-fixed-wavelength array of transceivers), our problem formulation can include the following equation:

$$c_{k,v} = c_{k,v+1} = c_{k,v+2} = \dots = c_{k,v+\gamma-1} \quad \forall k \in K, \forall v \in G(n) \tag{5.12}$$

where γ is the number of fixed wavelengths in the array of transceivers, and v is the first wavelength of the group of wavelengths in any array. $G(n)$ is set of wavelengths pertaining to group n of an array of γ transceivers.

Eq. (5.12) states that, once a wavelength from the group of wavelengths included in a γ-fixed-wavelength array of transceivers is allocated in the system, the other wavelengths in that group are also automatically supported.

Solving this MILP, we can minimize cost and, secondarily, balance traffic load in an evolving PON; also, we obtain the traffic allocation over different wavelengths and the capacity upgrade needed to support the traffic at a particular point in time. But here we are dealing with a multi-step approach that considers the evolution of PON capacity and bandwidth allocation over multiple periods of time. Below, we show how this single-period formulation (basic step) can be extended to calculate how a PON evolves over multiple periods of time.

5.2.2. Capacity Upgrade over Multiple Periods

Over time, a PON will experience incremental growth in traffic demands and it must respond to those changes. The best way to deal with the problem would be by reducing the number of disruptions or service cuts for the users. Thus, we consider very few changes that would lead to a disruption. So, we propose a multi-step method to optimize network capacity upgrade, minimizing service disruptions and cost. We define the end of a period as the point of completion of a round of time when we will calculate the upgrades needed in the PON, e.g., the period could be a year. In general, the period durations need not to be constant. The SP may choose the most-suitable duration for its network. Below, we explain, step by step, our method sequence to be applied to all periods.

For current period τ, do:

5.2.2.1. Step 1: Obtain New Traffic Demands.

Before a period starts, obtain the traffic forecast or expected traffic demand at the end of the period, and determine the guaranteed bandwidth for all ONUs (constant B_i for ONU i)[3].

5.2.2.2. Step 2: Collect Historical Data.

Our upgrade calculations must consider existing resources available at every ONU and OLT at each period. Without this information, each period would be solved independently of previous changes (e.g., after more than two periods, an ONU's traffic may be totally transferred to a new wavelength, and we would lose information of the previous supported wavelength). By considering historical data, a later period may obtain an optimal solution by distributing the ONU's bandwidth over new and old supported wavelengths. So, by keeping track of prior changes, we exploit previously-supported wavelengths to optimally allocate traffic in the PON.

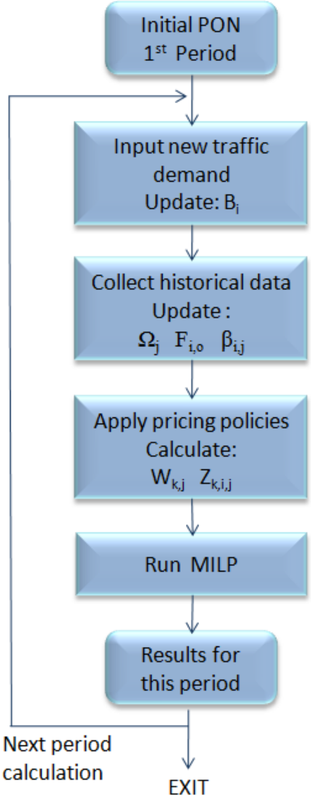


Figure 39. Flow chart of the proposed PON upgrade method.

5.2.2.3. Step 3: Apply Pricing Policies.

The cost of adding a wavelength and/or changing the line rate of a channel is not the same at every period and every device (OLT/ONU) in the network. A smaller cost should apply to a specific device if it is already supporting the wavelength channel at a given line rate. For this reason, Step 2 (collecting historical data) is essential to achieve a proper cost assignment. On the other hand, a larger cost should be assigned when upgrading a wavelength's line rate.

Pricing policies are used to calculate the cost parameters $W_{k,j}$ and $Z_{k,i,j}$, which are updated at each step and depend on previous wavelength and line-rate allocations. $W_{k,j}$ is related to cost at OLT, and its value depends on changes at the previous period (τ-1). $Z_{k,i,j}$ is related to the cost at the ONU. The calculation of $Z_{k,i,j}$ should depend

---

[3] A possible extension of this work is to devise a traffic growth model and tie the upgrade mechanism to some traffic growth parameter, but this is beyond the scope of the present work.

on the history of supported wavelengths over previous periods, such that we do not pay again for an existing service. Pricing policies assure previous-investment and existing-resources awareness for each ONU and at the OLT. In the next subsection, we provide a detailed description of our pricing policies.

5.2.2.4. Step 4: Run MILP.

Finally, we solve the MILP, and obtain the bandwidth and wavelength channel allocations per ONU for period τ.

The flow chart in Figure 39 summarizes the above steps. Here we can see the relation among bandwidth input and cost parameters with the MILP calculation. Note that some constants or parameters for multiple periods (see Section 5.2.1.3) are updated at their corresponding step.

5.2.3. *Pricing Policies*

We provide examples of pricing policies that may be used to set the cost values in the objective function of our MILP. The MILP can choose the best combination of costs that suits the objective function and fulfill all traffic demands. The following three pricing policies are examples of how we can model cost of transceivers and line interfaces in the PON. First, we propose a base case that allocates a specific cost to add/modify transceivers at the ONUs or OLT. Second, we propose a policy to properly allocate a cost when we upgrade the network using transceiver arrays. Third, we study a similar approach to the first policy which makes use of more complete historical information. We consider that our PONs can support two different line rates, namely R_1 to R_2, on wavelength j, where $R_2>R_1$. We define two different constants: C_1 and C_2. C_1 stands for the relative cost (in dollars) to add one new wavelength to the system, while C_2 is in general the cost to upgrade the line rate of a channel from R_1 to R_2. In the following pricing policies, we assume that the system has been correctly set up with proper WDM filters at an early stage (see chapter 4 and [59]). Hence, we do not consider the cost of adding filters into our pricing policies. Policies can be fine-tuned by the SP based on price trends and new devices.

5.2.3.1. Pricing Policy 1: Single-Wavelength Transceivers

In general, we give high priority (low cost) when a wavelength was already supported by the OLT or ONUs, and a low priority (high cost) whenever a new investment is needed. For a *Base Case*, we propose a simple pricing policy example to calculate $W_{k,j}$ and $Z_{k,i,j}$. To calculate $W_{k,j}$, we consider three cases to assign appropriate cost to implement any of the rates R_1 or R_2: *(i)* if the previous line rate of wavelength j is zero (i.e., j is inactive), we assign cost values $W_{1,j}$ and $W_{2,j}$ to activate j for the first time (C_1 and C_2, respectively, with $C_1<C_2$) at any of the available line rates, *(ii)* if wavelength j was active at line rate R_1, we assign a small value ε to $W_{1,j}$ (because R_1 is already active and a new investment is not required to keep R_1), and $W_{2,j}$ gets the cost value that is required to upgrade the line rate $C_2+\omega$ (ω is extra cost to perform the line-rate change, we assume $\omega = 0.5$), and *(iii)* if wavelength j was active at line rate R_2, it is not desirable to go back to a lower rate (R_1), hence $W_{1,j}$ gets a very high value (e.g., 10^6), and $W_{2,j}$ gets ε (because it is already implemented and requires no new investment). Since price tendencies for transceivers and line interfaces at ONUs are similar to those at OLT, we use $W_{k,j}$ to calculate ONU's cost. Now, $Z_{k,i,j}$ objective is to adapt the value of $W_{k,j}$ to ONU case.

To calculate $Z_{k,i,j}$, we first evaluate if ONU i was already supporting wavelength j in any previous period. If so, the cost will be $\delta * W_{k,j}$, where δ takes a small value. Otherwise, if ONU i never supported wavelength j before, then the cost will be $1*W_{k,j}$ (i.e., we assume that an ONU's cost take the same cost values as those given to the new OLT's transceivers).

$W_{k,j}=\varepsilon$ means that wavelength j is already supported in the system, and $Z_{k,i,j}$ will take the same low value (due to $Z_{k,i,j}=1* W_{k,j}$) even if ONU i was not supporting such wavelength. Thus, if a capacity upgrade is required for ONU i, this case leads or encourages our MILP to choose wavelength j. Given that the number of disruptions is proportional to cost, we set a low price to the situation that leads to lower disruption.

5.2.3.2. Pricing Policy 2: Multiple-Wavelength Arrays of Transceivers

To support multiple-wavelengths arrays of transceivers, we modify the first pricing policy. Let wavelength group n be a set of wavelengths that a transceiver array supports. Let the PON be able to support a number of wavelength groups. In our approach, a PON will first support group 1, until more capacity, i.e., more wavelengths, is needed. Then, we proceed to add wavelength group 2 to the system. After running out of capacity with the previous two wavelength groups, we can add wavelength group 3, and so on. In this context, we propose a pricing policy to obtain the values of $W_{k,j}$ and $Z_{k,i,j}$ for every k, i, and j.

We calculate a new $W_{k,j}$ that conveys historical data on which wavelength groups have been already supported in the PON. If a group is already supported, the SP does not need to invest on installation cost. However, a relatively high priority (low cost) is given to the next (in ascending order) wavelength group not used, such that we try to install that group. In this way, it is more likely to support the same groups of wavelengths in OLT and ONUs, leading to lower the OPEX due to spare devices. In what follows, we provide a detailed description of this pricing policy.

For a particular wavelength j pertaining to wavelength group n, we calculate $W_{k,j}$ by evaluating four conditions: *(i)* if all previous groups (smaller than n) have been supported by the PON, and group n is not active, we assign cost values $W_{1,j}$ and $W_{2,j}$ of C_1 and C_2, respectively; *(ii)* if any of the previous groups were not supported by the PON, then the cost would be a high value (e.g., 1000) in order to give priority to a lower-than-n wavelength group; *(iii)* if wavelength group n is being supported by the PON at line rate R_1, we assign the value of ε to $W_{1,j}$, and a value of $C_2+\omega$ to $W_{2,j}$; and *(iv)* if wavelength group n is being supported by the PON at line rate R_2, $W_{1,j}$ gets a very high value (10^6), and $W_{2,j}$ gets the value of ε.

To calculate $Z_{k,i,j}$, we first evaluate if ONU i was already supporting wavelength j in previous periods. If so, the cost will be $\delta * W_{k,j}$. Otherwise, if ONU i never supported wavelength j before, then the cost will be $C_2 * W_{k,j}$ (due to the higher cost required to implement the new type of transceiver compared to single-wavelength-transceivers).

5.2.3.3. Pricing Policy 3: Adding Line-Rate History (LRH) to the Calculation of $Z_{k,i,j}$

Note that, in Policy 1, $Z_{k,i,j}$ is calculated based on historical values of $\beta_{i,j}$, which contains information on the wavelengths that ONU i supports. But no information is given to Policy 1 about which *line rate* was supported by ONU i on its wavelengths, e.g., if ONU 1 supports wavelength 3 at 1 Gbps, the upgrade cost increases if we want to perform a line-rate upgrade (e.g., to 10 Gbps) over wavelength 3. So, an alternate pricing policy to calculate the cost parameter at the ONU can be based on the use of line-rate history as well. A solution could be to use the historical values of variable $l_{k,i,j}$, that tells if a wavelength j at rate k has been being supported by ONU i.

To calculate $Z_{k,i,j}$, we check if ONU i supported wavelength j at line rate k in any previous period. If so, the cost will be $\delta * W_{k,j}$. Otherwise, $Z_{1,i,j}$ and $Z_{2,i,j}$ will be C_1 and C_2, respectively.

This pricing policy can be also added to the ONU's cost calculation in Policy 2. In the rest of the chapter, we will refer to Policy 3 as: adding Line-Rate History (LRH).

5.3. Case Study

To test our method, we consider a practical case as follows. The PON serves a residential area with several buildings (say 10) and some houses (say six), so this PON has 16 ONUs and one OLT. Initial average load for a building (multi-dwelling unit) is 600 Mbps, and for a house, it is 100 Mbps. At this point, the PON has moved already from 1-Gbps line rate to 10 Gbps over the first wavelength (λ_1). We refer to λ_1 as the legacy wavelength channel. Here, we only consider load growth and upgrades over upstream channels.

Our model assumes a traffic growth factor of 1.5, i.e., traffic demands grow 50% every period (say a year). Real forecast of traffic growth and other growth functions and estimations could also be used by a SP. As traffic demands increase, we may add wavelength channels with two possible line rates: 10 Gbps and 40 Gbps. However, our method could also be applied to current deployed PONs using line rates of 1 Gbps / 2.5 Gbps, moving to 10 Gbps, with minor changes.

Due to difficulties to estimate the absolute cost of emerging components, we assume relative cost values. We consider that all costs in our case study will be relative to a reference cost, which is the cost required to upgrade an ONU to support a new wavelength at 10 Gbps. Then, by multiplying the reference cost to the relative costs presented in this case study, it is possible to obtain the total upgrading cost. For this reason, cost C_1 is set to 1, which corresponds to the cost of adding a new wavelength at 10 Gbps to any ONU. Now, the relative cost to add a new wavelength at 40 Gbps (C_2) can be set to 2.5 instead of 4, if we want to apply volume discount.

We test all pricing policies stated in Section 5.2.3, evaluating the addition of single-wavelength transceivers, and 4-fixed-wavelength array of transceivers. All setup parameter values are shown in Table 8.

ONUs 11 to 16 have a wavelength limit of one in order to force the system to keep some users in the legacy wavelength. This is favorable for users with low traffic that are not expected to grow drastically.

Table 8. Setup parameter values.

Parameter	Values
B_1 to B_{10}	600 Mbps
B_{11} to B_{16}	100 Mbps
F_1 to F_{10}	8
F_{11} to F_{16}	1
R_1	10000 Mbps
R_2	40000 Mbps
C_1	1
C_2	2.5
ε	0.1
ω	0.5
δ	0.1
α	10^{-6}

Next, we calculate the traffic growth forecast for the first period τ=1. The initial wavelength allocation information is used as historical data. For example, at τ=1, all ONUs support the legacy wavelength (λ_1) at 10 Gbps. Then, we update $\Omega_j(0)$ and $\beta_{i,j}(0)$ for all i and j, which are needed to apply the pricing policies. Finally, we solve the MILP using CPLEX.

After this first iteration, we apply the steps of the method for the next periods, which are six periods in our example. It is important to note that, although we are keeping constant the number of ONUs in this example, it is feasible to add new ONUs to the PON. Then, we would need to incorporate the new initial parameters to update the MILP model.

5.4. Results and Discussion

5.4.1. Evolution Analysis

5.4.1.1. Base Case: Adding Single-Wavelength Transceivers

Our first set of results using Policy 1 (Section 5.2.3.1) is presented in Table 9. Throughout this chapter, we call this policy the Base Case or ‘1x1 Tx’. For every ONU, we display the evolution of its transceiver assignment over the six periods.

The first period is able to support the traffic increment with the legacy wavelength λ_1. After that, every period adds a new wavelength channel as in periods 2, 3, 4, and 6, or changes the line rate of an existing wavelength from 10 Gbps to 40 Gbps, as in period 5. In all, we need five wavelength channels when we reach the sixth period according to this traffic growth. This shows the gradual upgrade as a primary characteristic of our method, with incremental investments on an "as-needed" basis.

From Table 9, we observe that the maximum number of wavelengths allowed per ONU is respected. ONUs 11-16 use their allocation over the legacy channel. For ONUs 1-10, maximum number of wavelengths allowed is four (see F_i in Table 8), but most of them support two channels including the legacy λ_1. ONUs 1, 2, 3, 5, 6, 7, and 9 support two wavelength channels, while ONUs 4, 8, and 10 support three. Thus, the method not only tries to minimize the total wavelengths, but it also minimizes the number of wavelengths that an ONU needs. Moreover, by using a limited number of wavelengths, we are also reducing the number of disruptions in the system.

Table 9. Wavelength allocation per ONU and Period, Base Case.

	Period 1	**Period 2**	**Period 3**	**Period 4**	**Period 5**	**Period 6**
ONU 1	λ_1[a]	λ_1	**λ_3**	λ_3	λ_3	λ_3
ONU 2	λ_1	λ_1	λ_1 **λ_2**	λ_2	**λ_2**	**λ_2**
ONU 3	λ_1	λ_1	λ_1	λ_1	λ_1	**λ_5**
ONU 4	λ_1	λ_1	λ_1	**λ_4**	λ_4	**λ_3** λ_4
ONU 5	λ_1	**λ_2**	λ_2	λ_2	**λ_2**	**λ_2**
ONU 6	λ_1	λ_1	λ_1	**λ_4**	λ_4	λ_1 λ_4
ONU 7	λ_1	**λ_2**	λ_2	λ_1	**λ_2**	**λ_2**
ONU 8	λ_1	**λ_2**	λ_2	**λ_3**	**λ_2**	**λ_2**
ONU 9	λ_1	**λ_2**	λ_2	λ_2	**λ_2**	**λ_2**
ONU 10	λ_1	λ_1	**λ_3**	λ_3	λ_3	**λ_2** λ_3
ONU 11	λ_1	λ_1	λ_1	λ_1	λ_1	λ_1
ONU 12	λ_1	λ_1	λ_1	λ_1	λ_1	λ_1
ONU 13	λ_1	λ_1	λ_1	λ_1	λ_1	λ_1
ONU 14	λ_1	λ_1	λ_1	λ_1	λ_1	λ_1
ONU 15	λ_1	λ_1	λ_1	λ_1	λ_1	λ_1
ONU 16	λ_1	λ_1	λ_1	λ_1	λ_1	λ_1

[a] Notation: λ_j represents wavelength channel j allocated to the ONU. Bold red text means that ONU is supporting a new wavelength at 10 Gbps. Bold and shadowed text denotes line rate of 40 Gbps. Two different wavelengths together indicate that this ONU is sharing bandwidth among them.

Let us observe the evolution in Table 9 in more detail. In period 2, some ONUs (5, 7, 8, and 9) change to wavelength λ_2. In period 3, when a new channel is needed to handle the new traffic demand, the ONUs chosen are different from those that already changed to λ_2 in the previous period (see ONUs 1 and 10). This behavior will emerge often during PON evolution.

In period 3, we see that ONU 2 is sharing its traffic among λ_1 and λ_2. Traffic sharing is only possible in TDM-WDM hybrid PONs. Note that, although only ONU 2 seems to be sharing its traffic over two wavelengths, this is just part of the design to accomplish capacity upgrade needs. A PON may use a dynamic bandwidth allocation algorithm that simultaneously allocates the ONU's load over different supported wavelengths according to instantaneous requests. TDM-WDM hybrid PONs can exploit statistical multiplexing to improve network performance and capacity usage.

In period 4, a new wavelength λ_4 is added to the system and it is allocated to ONUs 4 and 6. Note that these ONUs did not have changes before, thus reducing disruptions in the PON. On the other hand, ONU 8 suffers a new change to wavelength λ_3 (after a previous one in period 2). For existing wavelengths, like the case of λ_3 (before period 4), the implementation cost is smaller (given by the value of ε in Policy 1, Section 5.2.3.1)[4].

In period 5, λ_2 changes its rate from 10 Gbps to 40 Gbps. All ONUs which previously supported λ_2 change their line interface to support 40 Gbps rate, viz. ONUs 2, 5, 7, 8, and 9.

Finally, in period 6, λ_5 is added to the PON. ONU 3, which till period 5 only supported the legacy channel, now supports λ_5 also. We see that new wavelength channels are usually given to ONUs that are only supporting the legacy channel. For capacity reasons, ONUs 4 and 10 now support λ_3 and λ_2, respectively. As before in period 3 with ONU 2, now ONUs 4, 6, and 10 share their traffic among two wavelengths. By doing so, we avoid adding new wavelength channels or changing line rates, which are more expensive options.

Another property of our method is continuity in the use of an ONU's wavelengths. For ONUs 1, 2, 3, 4, 5, 6, and 9, once a new wavelength is allocated, the ONU remains operating on that channel as long as possible to reduce disruptions.

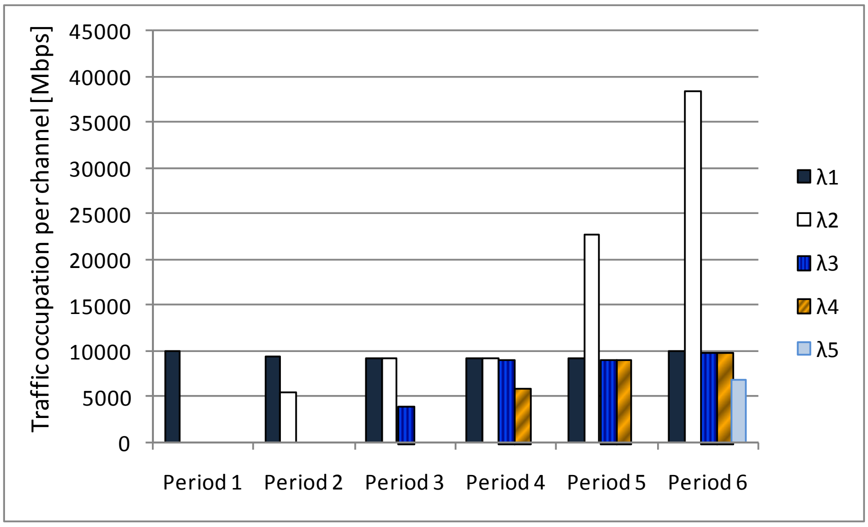


Figure 40. Number of wavelengths assigned to the PON per period and its total traffic occupation in Mbps, for the Base Case (adding single-wavelength transceivers, with no line-rate history).

Figure 40 shows the occupation in Mbps of each wavelength per period. We summarize the evolution of our PON by noting the number of wavelengths being added in each period and observing the total traffic allocation per channel. Load balancing is a secondary objective of our MILP, and its priority is set by parameter α, but we can observe that load balancing over the wavelength channels is applied in most cases. Note that in periods 5 and 6, λ_2 exhibits a very high occupation compared to the rest of the wavelengths because it has been upgraded from 10 Gbps to 40 Gbps. Traffic occupation has similar levels for the rest of the wavelength channels, which is a result of load balancing (namely balancing the fractional channel utilization). Details on bandwidth and wavelength allocation per ONU and per period are shown in Table 10 (see '1x1 Tx' fields).

---

[4] The selection of this ONU in this case depends on the overall cost calculation of the MILP, where there is no special preference among ONUs. However, it is possible to correct this effect in the pricing policy by giving a higher cost when the ONU had a change of wavelength in previous periods

5.4.1.2. Adding 4-Fixed-Wavelength Arrays of Transceivers

A new set of tests evaluated adding arrays of transceivers (4 wavelengths each) to the PON using Policy 2 in Section 5.2.3.2. In the rest of the chapter, we call this setup as '1x4 Tx'.

Table 10 ('1x4 Tx' case) shows wavelength and bandwidth allocation for all ONUs and at each period. Wavelength λ_1 remains a single transceiver in the initial setup. Once an ONU needs to be allocated with a new wavelength, it will automatically support four (array of four) transceivers. In Table 11, case '1x4 Tx', we can see more clearly when and which ONUs are getting such arrays of transceivers.

Table 10. Bandwidth and wavelength allocation details.

	Cases with WH	Period 1	Period 2	Period 3	Period 4	Period 5	Period 6
ONU 1	**1x1 Tx**	900@λ1	1350@λ1	2025@λ3	3038@λ3	4556@λ3	6834@λ3
	1x4 Tx	900@λ1	1350@λ2	2025@λ4	3038@λ4	4556@λ5	6834@λ3
	All-in-one	-	-	-	-	-	6834@**λ1**
ONU 2	**1x1 Tx**	900@λ1	1350@λ1	1011@λ1 1014@λ2	3038@λ2	4556@**λ2**	6834@**λ2**
	1x4 Tx	900@λ1	1350@λ2	2025@λ4	3038@λ2	4556@λ5	6834@λ4
	All-in-one	-	-	-	-	-	6834@**λ1**
ONU 3	**1x1 Tx**	900@λ1	1350@λ1	2025@λ1	3038@λ1	4556@λ1	6834@λ5
	1x4 Tx	900@λ1	1350@λ1	2025@λ5	3038@λ3	4556@λ3	6834@λ2
	All-in-one	-	-	-	-	-	6834@**λ1**
ONU 4	**1x1 Tx**	900@λ1	1350@λ1	2025@λ1	3038@λ4	4556@λ4	502@λ3 6332@λ4
	1x4 Tx	900@λ1	1350@λ1	2025@λ2	3038@λ5	4556@λ2	6834@**λ1**
	All-in-one	-	-	-	-	-	6834@**λ1**
ONU 5	**1x1 Tx**	900@λ1	1350@λ2	2025@λ2	3038@λ2	4556@**λ2**	6834@**λ2**
	1x4 Tx	900@λ1	1350@λ1	2025@λ1	3038@λ1	4556@**λ1**	6834@**λ1**
	All-in-one	-	-	-	-	-	3668@**λ1** 3166@λ2
ONU 6	**1x1 Tx**	900@λ1	1350@λ1	2025@λ1	3038@λ4	4556@λ4	3166@λ1 3668@λ4
	1x4 Tx	900@λ1	1350@λ1	2025@λ1	3038@λ1	4556@**λ1**	6834@**λ1**
	All-in-one	-	-	-	-	-	6834@λ2
ONU 7	**1x1 Tx**	900@λ1	1350@λ2	2025@λ2	3038@λ1	4556@**λ2**	6834@**λ2**
	1x4 Tx	900@λ1	1350@λ3	2025@λ5	3038@λ4	4556@λ4	502@**λ1** 3166@λ4 3166@λ5
	All-in-one	-	-	-	-	-	6834@λ3
ONU 8	**1x1 Tx**	900@λ1	1350@λ2	2025@λ2	3038@λ3	4556@**λ2**	6834@**λ2**
	1x4 Tx	900@λ1	1350@λ2	2025@λ5	3038@λ5	4556@λ3	6834@λ5
	All-in-one	-	-	-	-	-	6834@λ4
ONU 9	**1x1 Tx**	900@λ1	1350@λ2	2025@λ2	3038@λ2	4556@**λ2**	6834@**λ2**
	1x4 Tx	900@λ1	1350@λ1	2025@λ4	3038@λ2	4556@λ4	6834@**λ1**
	All-in-one	-	-	-	-	-	6834@λ5
ONU 10	**1x1 Tx**	900@λ1	1350@λ1	2025@λ3	3038@λ3	4556@λ3	4170@**λ2** 2664@λ3
	1x4 Tx	900@λ1	1350@λ1	2025@λ1	3038@λ3	4556@λ2	502@**λ1** 3166@λ2 3166@λ3
	All-in-one	-	-	-	-	-	6834@λ6
ONUs 11 to 16	**1x1 Tx**	150@λ1	225@λ1	338@λ1	506@λ1	759@λ1	1139@λ1
	1x4 Tx	150@λ1	225@λ1	338@λ1	506@λ1	759@**λ1**	1139@**λ1**
	All-in-one	-	-	-	-	-	1139@**λ1**

All values are in 'Mbps'. Allocated wavelength *i* is denoted by '@λ*i* '. Bold wavelengths represent that a 40-Gbps line rate is being supported.
For each ONU and at each period, the table presents the wavelength and bandwidth allocated for cases: Base Case (adding single-wavelength transceivers, or '1x1 Tx'), adding 4-fixed-wavelength arrays of transceivers (named '1x4 Tx'), and all-in-one period calculation (referred as 'All-in-one').

In period 2, there is an investment to equip four ONUs (1, 2, 7, and 8) with a 4-wavelength transceiver array. Period 2 onwards, these ONUs are supporting wavelengths: λ_2, λ_3, λ_4, and λ_5, besides the legacy wavelength. In period 3, three more ONUs (3, 4, and 9) start supporting wavelengths λ_2 to λ_5. ONU 10 gets a transceiver array in period 4. The investment is distributed in time, according to needs.

Once an ONU is supporting a group of wavelengths (by means of an array of transceivers), the OLT can allocate bandwidth over one or more of the ONU's supported wavelengths. In Table 10, we find that, for example, ONU 7 is placing its traffic over different wavelengths in different periods. It takes λ_3 in period 2, it changes to λ_5 in period 3, and then it uses λ_4 in periods 4 and 5. Finally, in period 6, ONU 7 shares the transmission of its traffic among three wavelengths (λ_1, λ_4, λ_5). All these changes are happening at no extra cost, except for the initial investment in period 2. This type of transceiver adds more flexibility to the system and facilitates an optimal distribution of bandwidth due to the fact that transmission over different wavelengths can be shared in time.

Table 11. ONUs upgraded with a 4-fixed-wavelength array of transceivers.

	Period 1	**Period 2**	**Period 3**	**Period 4**	**Period 5**	**Period 6**
1x4Tx $\lambda_{2-3-4-5}$	-	1, 2 7, 8	3, 4, 9	10	-	-
1x4Tx+LRH $\lambda_{2-3-4-5}$	-	3, 7, 8, 10	2, 4, 6	1	-	-
$\lambda_{6-7-8-9}$	-	-	-	-	5	1, 4, 6, 9, 10

ONUs indicated by their number ID at a certain period are being given a four-fixed-wavelength array of transceivers. Hence, such ONUs are supporting these four wavelengths from that period onwards.

Installing arrays of transceivers at the ONU initially saves a number of single installations of devices (single transceivers) at the ONUs. Few wavelengths supported by the system may be good enough to address the PON's traffic demands for some time, while taking advantage of the statistical multiplexing in this kind of PON (i.e., TDM-WDM PON). This upgrade scheme is more convenient from the OPEX point of view: because the same 4-wavelength array of transceivers is being installed in the ONUs, it is simpler to maintain a good inventory of similar spare devices.

5.4.1.3. All-in-One Period Analysis

An interesting comparison for our multi-step approach is to consider a single-step optimization: our model in Section 5.2 can be directly applied to the long-term traffic forecast (sixth period), and the network equipped accordingly starting from the first. The historical data only contains the setup previous to the first period. Results are presented in Table 10 (see 'All-in-one'). With this scheme, six wavelengths are needed, and the legacy wavelength changes its line rate from 10 Gbps to 40 Gbps. All-in-one-period approach requires one wavelength more than the multiple-periods Base Case, but the overall cost is less, since a single-step method leads to better optimization of capacity and traffic assignment. Nonetheless, we will see that, including cost reductions per period, i.e., depreciation, the expenses become significantly higher than the Base Case, since the equipment deployment has to be done at once, and from the first moment.

In general, we expect that the longer our unique period evaluation is, the more close the result will be to the WDM-PON, where one wavelength is devoted to each single ONU.

5.4.1.4. Adding Line-Rate History (LRH) to the ONU's Pricing Policy

We evaluate the evolution of our PON using Policy 3 (see Section 5.2.3.3), with single-wavelength transceivers ('1x1 Tx + LRH') and multiple-wavelength arrays of transceivers ('1x4 Tx + LRH'). In Table 12, we can see wavelength and bandwidth allocation details. We observe that, by adding line-rate history (LRH), the ONU's policy differs significantly with respect to other pricing policies (Policies 1 and 2, Sections 5.2.3.1 and 5.2.3.2 respectively). Table 12 shows that no wavelength is upgraded to 40 Gbps. The PON supports 8 wavelengths by Period 6 (in both studied cases), regardless of the type of transceiver used.

When we include line-rate-history awareness in the pricing policy for the ONU, changes from 10 to 40 Gbps are avoided since for every ONU it implies a higher cost. This contrasts with the previous policies (Policies 1 and 2), in the price that is being given for an already-supported wavelength regardless of the line rate at the ONU. In the LRH policy, we are pricing the already-supported wavelength with a higher value when the wavelength is changing to a higher line rate. For some scenarios, it will be more expensive to upgrade the line rate (e.g., to 40 Gbps, which is still not available for PONs at an affordable price) than adding more wavelengths. In such cases, one can choose LRH policy.

It is interesting to note for case ‘1x1 + LRH’, in Table 12, that ONUs remain in supported wavelengths for as many periods as possible, e.g., ONU 10 changes from λ_1 to λ_3 in period 3, and it remains on that wavelength for the rest of the periods. Also ONU 7 remains on λ_1 until period 4, and then it changes to and stays on λ_5. In general, our method tries to minimize disruptions while accomplishing a good bandwidth distribution according to the requirements.

Table 12. Bandwidth and wavelength allocation details

	Cases with LRH	Period 1	Period 2	Period 3	Period 4	Period 5	Period 6
ONU 1	**1x1 Tx**	900@λ1	1350@λ1	2025@λ3	3038@λ3	4556@λ1	6834@λ8
	1x4 Tx	900@λ1	1350@λ1	2025@λ1	3038@λ3	4556@λ4	6834@λ7
ONU 2	**1x1 Tx**	900@λ1	1350@λ1	2025@λ3	3038@λ3	4556@λ3	2929@λ3 3905@λ7
	1x4 Tx	900@λ1	1350@λ1	2025@λ5	3038@λ4	4556@λ3	2734@λ3 4100@λ4
ONU 3	**1x1 Tx**	900@λ1	1350@λ1	2025@λ1	3038@λ4	4556@λ4	5858@λ4 5857@λ8
	1x4 Tx	900@λ1	1350@λ4	2025@λ3	3038@λ2	4556@λ5	6834@λ3
ONU 4	**1x1 Tx**	900@λ1	1350@λ1	2025@λ1	3038@λ4	4556@λ4	3905@λ4 2929@λ8
	1x4 Tx	900@λ1	1350@λ1	2025@λ3	3038@λ3	4556@λ5	6834@λ5
ONU 5	**1x1 Tx**	900@λ1	1350@λ2	2025@λ2	3038@λ2	4556@λ2	977@λ2 5857@λ7
	1x4 Tx	900@λ1	1350@λ1	2025@λ1	3038@λ1	4556@λ6	2734@λ6 1366@λ7 2734@λ8
ONU 6	**1x1 Tx**	900@λ1	1350@λ2	2025@λ2	3038@λ2	4556@λ6	1953@λ1 4881@λ6
	1x4 Tx	900@λ1	1350@λ1	2025@λ5	3038@λ5	4556@λ4	2732@λ1 2734@λ2 1368@λ5
ONU 7	**1x1 Tx**	900@λ1	1350@λ1	2025@λ1	3038@λ1	4556@λ5	6834@λ5
	1x4 Tx	900@λ1	1350@λ5	2025@λ2	3038@λ5	4556@λ2	6834@λ6
ONU 8	**1x1 Tx**	900@λ1	1350@λ2	2025@λ2	3038@λ1	4556@λ6	1952@λ2 4882@λ6
	1x4 Tx	900@λ1	1350@λ2	2025@λ2	3038@λ2	4556@λ2	6834@λ2
ONU 9	**1x1 Tx**	900@λ1	1350@λ2	2025@λ2	3038@λ2	4556@λ2	6834@λ2
	1x4 Tx	900@λ1	1350@λ1	2025@λ1	3038@λ1	4556@λ1	6834@λ8
ONU 10	**1x1 Tx**	900@λ1	1350@λ1	2025@λ3	3038@λ3	4556@λ3	6834@λ3
	1x4 Tx	900@λ1	1350@λ3	2025@λ3	3038@λ4	4556@λ3	5468@λ4 1366@λ5
ONUs 11 to 16	**1x1 Tx**	150@λ1	225@λ1	338@λ1	506@λ1	759@λ1	1139@λ1
	1x4 Tx	150@λ1	225@λ1	338@λ1	506@λ1	759@λ1	1139@λ1

All values are in ‘Mbps’. Allocated wavelength *i* is denoted by ‘@λ*i* ’. All wavelengths in the table run at a 10-Gbps line rate, over all the periods.
For each ONU and at each period, the table presents the wavelength and bandwidth allocated using the pricing policy with line-rate history (LRH) for two cases: adding single-wavelength transceivers (‘1x1 Tx’), adding 4-fixed-wavelength arrays of transceivers (‘1x4 Tx’).

In Table 11 (see ‘1x4 Tx + LRH’), we see how and when the arrays of transceivers are allocated to ONUs. It is interesting to see that, after the capacity of the first group of wavelengths (λ_2 to λ_5) is exhausted, a new group of wavelengths appears (λ_6 to λ_9) in period 5. In period 5, only ONU 5 gets that new array of wavelengths. Note that ONU 5 was not supporting before the set of wavelength from λ_2 to λ_5. The same happens to ONU 9 in period 6. ONU 9 was not supporting the previous group of wavelengths (λ_2 to λ_5), and it is being allocated a new array of transceivers (wavelengths from λ_6 to λ_9). For capacity reasons, other ONUs (1, 4, 6, and 10) support the two groups of wavelengths: λ_2 to λ_5 and λ_6 to λ_9 by period 6. This example shows the continuity property of our method.

5.4.2. Comparing All Cases

In this section, we compare cases: 1x1 Tx, 1x4 Tx, 1x1 Tx + LRH, 1x4 Tx + LRH, and all-in-one period.

Figure 41 shows the total number of wavelengths that every case needed. When some cases (1x1 Tx and 1x4 Tx) require only five wavelengths, one of the wavelengths's line rate is 40 Gbps. On the other hand, some cases (1x1 Tx + LRH and 1x4 Tx + LRH) require 8 wavelengths at 10 Gbps. This means that the total capacity in most of the cases, except for all-in-one period, is the same: 80 Gbps. As for the all-in-one-period approach, a total of 90 Gbps was allocated to the system. The reason why our method chooses 6 wavelengths instead of 5 is related to the cost assigned in Policy 1. In the case of 6 wavelengths, the cost is 17.3, while with 5 wavelengths the cost is 17.6. This calculation will be explained later in this chapter.

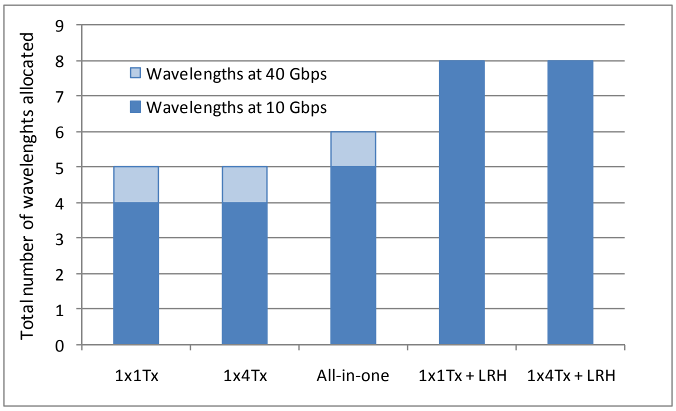


Figure 41. Total number of wavelengths needed for different cases: Base Case (adding single-wavelength transceivers 1x1 Tx), adding four-fixed-wavelength arrays of transceivers (1x4 Tx), all-in-one period (at period 6), 1x1 Tx with line-rate history (1x1 Tx + LRH) and 1x4 Tx + LRH.

In Figure 42, we compare all cases from bandwidth-usage point of view. The percentage of total PON bandwidth allocated to ONUs per period is shown. The highest capacity usage of the full PON capacity is in case '1x1 Tx + LRH'. Case '1x1 Tx' has the second best capacity usage with the exception of the last two periods. The reason for the last case's behavior is due to a line rate upgrade to 40 Gbps, performed in period 5.

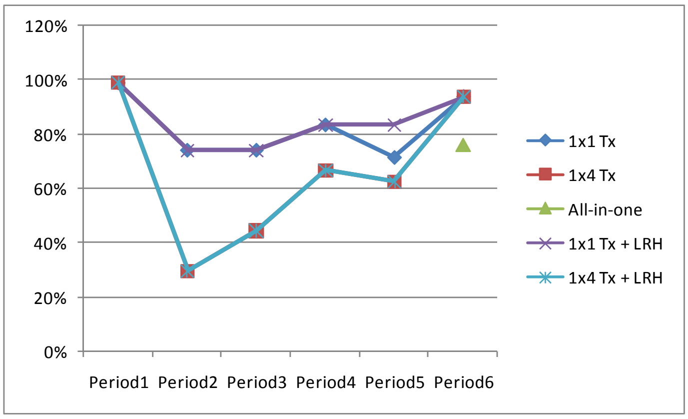


Figure 42. Percentage of total bandwidth allocated to ONUs for different cases: 1x1 Tx, 1x4 Tx, all-in-one (in period 6), 1x1 Tx + LRH and 1x4 Tx + LRH.

The plots of cases using 4-wavelength arrays of transceivers (1x4 Tx and 1x4 Tx + LRH) overlap in Figure 42. In these cases, arrays of transceivers are added at needed points. Of course, having four wavelengths increase the available capacity in these cases which is higher compared to the "1x1-Tx"-type increments at the first periods when no 40-Gbps-line-rate upgrade has been done. So, each increment will result in many times excess bandwidth, depending on the traffic growth tendencies.

Now, in the case of "1x1 Tx", we note that, in period 5, the bandwidth allocated is lower because there is an excess in bandwidth due to a 40-Gbps upgrade. This upgrade covers most of the needs, but some bandwidth in the wavelength at 40 Gbps remains unutilized.

Finally, all-in-one-period case does not present a high capacity usage because it had from the first period an excess of 10 Gbps in the total capacity compared to the other cases. When most of the cases (except all-in-one) converge with the same percentage of bandwidth in period 6, we can note that all-in one has a smaller percentage of bandwidth allocated. Over several periods, all-in-one chooses a number of wavelengths to be allocated to the system that would also cover the bandwidth requirements, but there is a part of capacity not being used.

5.4.3. Relative Cost Comparisons

For cost comparison, we compare the Base Case with all-in-one-period case and WDM PON. In the last two cases, all the investment is done in the first period. We first calculate the relative cost per period (see Figure 43) for our Base Case. We assume that cost unit is relative to the real cost in dollars required to add a new wavelength at 10 Gbps to any ONU.

To calculate relative cost per period (without cost reduction), we apply the upgrading policies presented in Section 5.2.3.1*, Policy 1*:

Relative Cost =

No._of_ new_λs @10Gbps_@OLT * C_1 +

No._of_ new_λs @40Gbps_@OLT * C_2 +

No._of_old_ λs @10Gbps_@OLT * ε +

No._of_old_ λs @40Gbps_@OLT * ε +

No._ of_old_ λs_changing from 10Gbps_to_40Gbps * $(C_2 + \omega)$ +

No._of_ONUs_using_ new_λs @10Gbps * C_1 * 1 +

No._of_ONUs_using_ new_λs @40Gbps * C_2* 1 +

No._of_ONUs_using_old_λs @10Gbps * ε * δ +

No._of_ONUs_using_old_λs @40Gbps * ε * δ +

No._of_ONUs_using_λs_changing_from_10Gbps_to_40Gbps * $(C_2 + \omega)$ * δ.

For example, for period 5 (Table 10) we can calculate the upgrade policies as follows (same order as previous equation):

Relative Cost = 0*1 + 0*2.5 + 3*0.1 + 0*0.1 + 1*3 + 0*1*1 + 0*2.5*1 + 11*0.1*0.1 + 0*0.1*0.1 + 5*3*0.1 = 4.91.

Results in Figure 43 include accumulated cost reduction of 10% per year. So, for period 5, the relative cost with cost reduction will be: $4.541*0.9^5 = 2.9$. In Figure 43, we see that the highest cost occurs in the second period. After that, the cost starts to decrease due to savings in wavelength and line-rate allocations, and due to cost reductions. Period 5's relatively high cost (especially considering no cost reduction) is due to the investment on line-rate change required for λ_2.

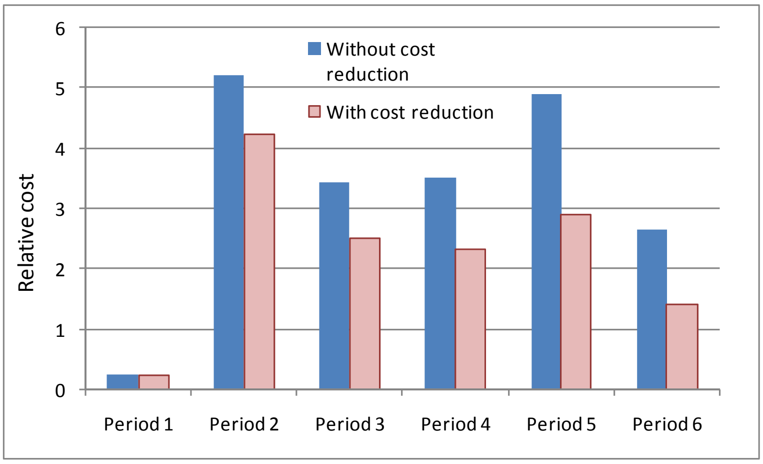


Figure 43. Relative upgrade cost for Base Case (1x1 Tx), without cost reduction and with 10% cost reduction per period. Cost unit related to cost in dollars to add a new wavelength at 10 Gbps to any ONU.

Here, we compare our multi-period study with an all-in-one-period run, and with WDM PON. In WDM PON, each ONU will be allocated a different wavelength, e.g., we need 16 wavelengths for 16 ONUs. The cost will be: 16 transceivers at the OLT*1 + 16 transceivers at the ONU*1 = 32.

Using Policy 1 also for all-in-one approach, total relative cost for the solution with 6 wavelengths is:

Relative Cost (6 wavelengths) = 5*1 + 0*2.5 + 0*0.1 + 0*0.1 + 1*3 + 6*1*1 + 0*2.5*1 + 0*0.1*0.1 + 0*0.1*0.1 + 11*3*0.1=17.3.

Another option this approach could have taken would be to use 5 wavelengths (as in multi-step-approach). But in such case, we obtain a slightly higher total relative cost as follows:

Relative Cost (5 wavelengths) = 4*1 + 0*2.5 + 0*0.1 + 0*0.1 + 1*3 + 7*1*1 + 0*2.5*1 + 0*0.1*0.1 + 0*0.1*0.1 + 12*3*0.1=17.6.

For this reason, the chosen alternative for all-in-one approach is implemented with 6 wavelengths.

Table 13. Total relative cost.

Upgrading Approach	**Cost**
Multiple periods 'Base Case' with cost reduction	13.6
Multiple periods 'Base Case' without cost reduction	20.0
All-in-one period	17.3
WDM PON	32

Table 13 shows the total relative cost comparison among the three upgrade approaches: multiple periods "Base Case", all-in-one period, and WDM PON. In particular, multiple-periods cost is presented with and without cost reductions per period. Table 13 shows that the total cost for multiple-periods case (with cost reduction) to upgrade the PON is lower than the other two approaches. By upgrading in one period (all-in-one period), we spend 27% more capital than considering multiple periods with 10% cost reduction per year, according to these results. The main reason for this difference is the lack of cost reductions in the all-in-one-period approach because all the investment is done in a first and unique period. However, our multi-periods approach without cost reduction shows a slightly higher total relative cost than all-in-one-period approach. Having a longer traffic forecast (over several periods) to apply an all-in-one-period analysis is more efficient in some cases, especially if the prices decrease little over time. WDM PON performs poorest since it requires a different wavelength per

ONU; so it is more expensive based on our pricing policies. Also using WDM PON upgrade approach means an important disruption for the entire PON since all ONUs will require a new wavelength, i.e., a new transceiver.

5.4.4. *Sensitivity Considerations*

We study the effect on variation of parameters and constants in the proposed method. In Table 14, we present the level of sensitivity for the parameters of our methods under a specified range of values.

The value of $W_{k,j}$ affects the overall cost of the PON and the number of wavelengths that it can support. $Z_{k,i,j}$ on the other hand, limits how many wavelengths an ONU will support. If $Z_{k,i,j}$ is high, then the tendency is to upgrade to or collect higher line rates. If $Z_{k,i,j}$ takes a low value, the ONUs may tend to support a higher number of wavelengths. Parameter ω directly affects the frequency we upgrade from a lower line rate to a higher one.

Table 14. Sensitivity level to parameter values.

Parameter	Range	Sensitivity
$W_{k,j}$	1 - 4	Very high
$Z_{k,i,j}$	0.1 - 4	Very high
ω	0 - 4	High
ε	$10^{-3} – 10^{-1}$	Low
δ	$10^{-3} – 10^{-1}$	Low
α	$10^{-3} – 10^{-6}$	Medium

Constants ε and δ have little impact as long as they remain at least one order of magnitude lower than the price given to add a new wavelength to the OLT or the ONU, respectively.

Finally, α has a medium level of sensitivity as it determines the cost to balance the bandwidth among all wavelengths. If α takes a high value, the method will give more priority to balancing the bandwidth than to minimizing the number of new wavelengths and line-rate upgrades. That would result in several ONUs supporting several wavelengths such that the traffic can be better balanced. Such a decision is not convenient since more cost is required to support a larger number of wavelengths in order to achieve an accurate load balancing in our PON. A very small value is enough to obtain a good level of compromise between cost and load balancing.

5.5. Summary

We proposed and evaluated a new multi-step method to upgrade an existing PON [72][73]. Given traffic demand forecast and initial PON settings, we devised a method for capacity upgrade with minimum cost and system disruption. Our solution is based on Mixed Integer Linear Programming and pricing policies that are executed over multiple periods of time.

We considered a WDM-TDM hybrid PON, where several ONUs may share in time one or more wavelengths. We showed the application of the steps of our method in a practical setting. Our results demonstrated multiple properties of this method, namely: minimization of the number of wavelengths in the PON, minimization of the number of channels supported by each ONU, minimization of disruptions per ONU and per period, minimization of capital expenses, history-aware upgrading process, load balancing over all the wavelength channels, and gradual capacity upgrade.

Different pricing policies were considered, namely: adding single-wavelength transceivers, adding multiple-wavelength arrays of transceivers, and adding line-rate history in ONU's cost calculations. Multiple-wavelength arrays of transceivers provide more flexibility, since an ONU may support multiple wavelengths at a time. However, the percentage of total network capacity usage is higher in using single-wavelength transceivers, especially if we consider historical information on wavelengths supported by each ONU and its respective line-rate.

For the same settings, we also applied our method in a unique period for a hybrid TDM-WDM PON (all-in-one period) and a WDM PON (a different wavelength channel per ONU). Our results showed that the multi-period approach has the minimum total number of wavelengths and the minimum total relative cost. Multiple-periods approach allows gradual capacity upgrading and reduced capital expenses.

Chapter 6 Conclusion

Infrastructure networks play a major role in shaping the present and future ways to exchange information and build a knowledge-based economy. We are intrigued to investigate the progress and evolution of the related technologies, especially those that have a grand potential of success, such as Passive Optical Networks. This chapter summarizes the achievements of this work in this dissertation.

In this dissertation, we have contributed to the knowledge on resource optimization in Passive Optical Networks (PONs) with focus on three issues: (i) Dynamic Bandwidth Allocation (DBA), where we extend the work to (*a*) a state-of-the-art survey and (*b*) two new algorithms, (ii) Evolution of PON that sheds light on how the scientific community can evaluate various strategies for analysis, and (iii) a multi-step method for cost-based capacity upgrades in a gradual (*as-needed*) manner. We briefly discuss the three aforementioned points.

In this respect, we first provided a survey and taxonomy of DBA algorithms for Ethernet-based PON (EPON). We also included some algorithms for hybrid TDM/WDM PON that deal with bandwidth allocation over a set of available wavelength channels. We also provided a background of the work done on evolution of PONs.

In addition, we evaluated our two proposed DBA algorithms for EPON. Our initial studies on the first algorithm inspired our second algorithm. Our first algorithm is based on the idea of fairly distributing the available bandwidth to users in the PON and providing a new scheduling of the transmission times different from the common one used in most of the works for DBA in PONs, namely round-robin scheduling. Our scheme is based on ordering the transmissions of user devices (ONUs) according to a delay parameter sent to the head-end network device (OLT) in a Report message. We ran our first algorithm with and without the transmission ordering process, and then we compared the respective outcomes. The results of our simulations show that ONUs requiring higher bandwidth than what is guaranteed suffer higher delays than ONUs requesting a bandwidth value less than or equal to the guaranteed level. However, the drawback of this scheme is that it needs to wait until the OLT receives all the Report messages in order for it to run the algorithm and provide a decision. This type of schemes is well-known to provide less efficiency in the usage of the channel.

Inspired by the first algorithm, we proposed and evaluated a second DBA algorithm for EPON that intends to provide fairness without efficiency decrement as noted in the first algorithm. We call our new scheme: Distributed Dynamic Scheduling for EPON (DDSPON). DDSPON is a distributed scheme since the OLT and all ONUs participate in the scheduling process. With a distributed scheme, we get to use all the state of the network in order to take fair decisions on the amount of traffic that each ONU can transmit. At the same time, the scheme redistributes unused bandwidth to other ONUs that may need it without sacrificing the guaranteed bandwidth of any ONU and without decreasing the delay if compared with one of the most efficient schemes, namely IPACT [32]. Another interesting property that we note in the behavior of DDSPON is that its good performance properties are maintained stable with distance, which may be useful for Long-Reach PONs.

Regarding the contribution on PON evolution, we conducted thorough work on the evaluation of the evolution possibilities in the light of the following migration constraints: backward compatibility or coexistence, reduced cost, reuse of existing infrastructure, minimization of disruptions, and maximization of available resources available. We discussed three evolution phases: (a) line-rate upgrade, (b) multiple wavelength channel migration, and (c) other future PON technologies. We compared the migration options from qualitative and quantitative viewpoints including: optical power loss, CAPEX, and unused available bandwidth. The option that requires no changes in the optical infrastructure and the remote node, which is a hybrid of TDM and WDM technologies, has been presented as a more flexible alternative for gradual and smooth migration between evolutionary stages.

Finally, regarding our multi-step method for cost-based capacity upgrade, we provided a planning tool for capacity upgrade of PONs. We proposed a novel method that optimizes the allocation of bandwidth and wavelengths, considering the addition of new wavelength channels to the system and upgrading line rate of existing channels. The method is based on MILP and Service-Provider-defined pricing policies. The cost-based method is intended to achieve an optimal and gradual capacity upgrade “period by period”. This is done while maximizing the network capacity usage and assuring- when possible- minimum number of disruptions for each ONU and for the entire system in general. We considered a typical case study for this problem, which we solved using CPLEX. We evaluated the possibility to add single or multiple transceivers to an ONU and/or OLT. The results demonstrate the attractive properties of our method such as: optimizing bandwidth/wavelength allocation, maximizing network capacity usage, and assuring minimum disturbances.

All in all, we demonstrated our proposed solutions on the current and future PON technologies that can aid companies, research organizations, and governments in optimizing, evaluating, and making better cost-effective decisions on how such technologies can be designed and implemented.

Chapter 7 Open Issues and Future Work

This chapter lists open issues in the presented research and thus suggests future work. We discuss the research points that have been left without investigation, and then look at the open issues to suggest specific future tasks of research.

In this dissertation, some issues remain open for possible future work. Below, we enumerate many of the open issues.

- Given the positive results achieved using a variation in distance, an extended work to apply our DDSPON algorithms to Long-Reach PONs may report important findings.
- It is needed to extend the proposed DBA algorithms to WDM-based PON and 10-Gbps PON to verify if similar benefits to those obtained with Legacy EPON can be achieved.
- An insightful cost analysis of future network evolution and investment is needed. There is an important OPEX impact when ONUs are not colorless. Spare specific-wavelength ONUs should all be available to solve problems at the user side. It is preferable to use colorless ONUs. Typical colorless ONUs are based on tunable lasers or RSOAs. The main challenge is to reduce their cost. Besides, more research is required to design an efficient control module for colorless ONUs.
- A control and provisioning system should be added to the PON. As multiple generations are expected to coexist on the same evolving network, a dynamic control system would make efficient use of the shared resources. Particularly, a challenge is dynamic wavelength assignment and bandwidth provisioning granularity according to user needs.
- It is important to study the type and quality of filters to be installed in the PON. The filters, when installed at early stages, will allow a smoother evolution. Although a precise filter implies extra cost, it can be better for the upgrade process by minimizing disruptions in existing generations.
- Coexistence of devices of different generations should not be the only concern for PON evolution. Another issue is the smart allocation and coexistence of new and existing users, together with a graceful combination of different types of users such as residential and SMB subscribers. Consequently, higher network revenue can be obtained by designing the best user-coexistence combination.
- An analysis of future PON technologies is needed if it can be related to cost and ease of implementation. In future technology implementations, independent OLT modules (for different generations) can be a good option for an effective upgrade without affecting or changing existing transceivers.
- Amplified PON for longer reach is an important aspect to be taken into account in PON evolution. Therefore, long-distance effects over the different technological candidates to Next- and Future-Generation PONs should be evaluated.
- It is important to analyse more study cases (scenarios) using our proposed cost-based capacity upgrade method for PON, in order to validate the properties obtained in our particular case.
- Insightful extended sensitivity analysis and different pricing policies must be applied to the optimization method for PON capacity upgrade.
- A versatile design of pricing policies is required which can cope with most of the changes needed to add a new wavelength and to upgrade line rate, since in this study we consider the cost of adding transceivers as the main investment.

References

[1] A. Banerjee, Y. Park, F. Clarke, H. Song, S. Yang, G. Kramer, K. Kim, and B. Mukherjee, "Wavelength-Division Multiplexed Passive Optical Network (WDM-PON) Technologies for Broadband Access: A Review [Invited]," *OSA Journal of Optical Networking*, vol. 4, no. 11, pp. 737-758, November 2005.

[2] A. Dhaini, C. Assi, M. Maier, and A. Shami, "Dynamic Wavelength and Bandwidth Allocation in Hybrid TDM/WDM EPON Networks," *IEEE/OSA Journal of Lightwave Technology*, vol. 25, no. 1, pp. 277-286, January 2007.

[3] A. Shami, M. Maier, and C. Assi, Editors, "Broadband Access Networks, Technologies and Deployments," *Springer*, 2009.

[4] A. Stok and E. Sargent, "The Role of Optical CDMA in Access Networks," *IEEE Communications Magazine*, vol. 40, no. 9, pp. 83-87, September 2002.

[5] B. Hesse, "Passive Optical Networking Update, WDM-PON," *IEEE Communications Magazine*, vol. 45, no. 3, pp. S6-S8, March 2007.

[6] B. Lannoo, L. Verslegers, D. Colle, M. Pickavet, P. Demeester, and M. Gagnaire, "Thorough analysis of the IPACT dynamic bandwidth allocation algorithm for EPONs," *Fourth International Conference on Broadband Communications, Networks and Systems*, pp. 486-494, 2007.

[7] B. Skubic, J. Chen, J. Ahmed, L. Wosinska, and B. Mukherjee, "A comparison of dynamic bandwidth allocation for EPON, GPON, and next-generation TDM PON," *IEEE Communications Magazine*, vol. 47, pp. S40-S48, 2009.

[8] C. Assi, Y. Ye, S. Dixit, and M. Ali, "Dynamic Bandwidth Allocation for Quality-of-Service Over Ethernet PONs," *IEEE Journal on Selected Areas in Communications*, vol. 21, no. 9, November 2003.

[9] C. Assi, Y. Ye, S. Dixit, and M. Ali, "Support of QoS in IP-Ethernet-PON," *Proc., IEEE Globecom 2003*, December 2003.

[10] C. Chae, E. Wong, and R. Tucker, "Optical CSMA/CD media access scheme for Ethernet over passive optical network," *IEEE Photonics Technology Letters*, vol. 14, no. 5, pp. 711-713, May 2002.

[11] C. Foh, L. Andrew, M. Zukerman, E. Wong, and M. Zukerman, "FULL-RCMA: a high utilization EPON," *IEEE Journal on Selected Areas in Communications*, vol. 22, no. 8, pp. 1514-1524, March 2003.

[12] C. Meusburger and D. Schupke, "Optimizing the Migration of Channels with Higher Bit-Rates," *Proc., OFC/NFOEC 2009*, March 2009.

[13] C. Michie, A. Kelly, and I. Andonovic, "Reflective Semiconductor Optical Amplifiers for passive optical networks," *11th International Conference on* pp. 1-4, 2009.

[14] C. Sierens, D. Mestdagh, G. Van Der Plas, J. Vndewege, G. Depovere, and P. Debie, "Subcarrier Multiple Access for Passive Optical Networks and Comparison to Other Multiple Access Techniques," *Proc., IEEE Globecom 1991*, pp. 619-623, 1991.

[15] C. Xiao, B. Bing, and G. Chang, "An Efficient Reservation MAC Protocol with Preallocation for High-Speed WDM Passive Optical Networks," *Proc., IEEE INFOCOM 2005*, vol. 1, pp. 444-454, 2005.

[16] D. Nikolova, B. Van Houdt, and C. Blondia, "Dynamic bandwidth allocation algorithms in EPON: a simulation study," *Proc., Opticomm 2003*, October 2003.

[17] D. Nikolova, B. Van Houdt, and C. Blondia, "QoS issues in EPON," *Proc., Community Nets and FTTH/P/x Workshop*, October 2003.

[18] D. Qian, N. Cvijetic, J. Hu, and T. Wang, "Optical OFDM transmission in metro/access networks," *Proc., OFC/NFOEC 2009*, March 2009.

[19] European Commission, "Europe's Digital Competitiveness Report," Commission Staff Working Document, vol. 1, SEC(2010) 627, May 2010. http://ec.europa.eu/information_society/digital-agenda/documents/edcr.pdf.

[20] F. An, K. Kim, Y. Hsueh, M. Rogge, W. Shaw, and L. Kazovsky, "Evolution, Challenges and Enabling Technologies for Future WDM-Based Optical Access Networks," *Proc., 2nd Symposium on Photonics, Networking and Computing*, September 2003.

[21] F. Cavaliere, F. Ponzini, M. Presi, and E. Ciaramella, "Migration towards high speed optical access enabled by WDM techniques," *Proc., Asia Communications and Photonics Conference and Exhibition (ACP)*, pp. 1-7, 2009.

[22] F. Clarke, S. Sarkar, and B. Mukherjee, "Simultaneous and Interleaved Polling: An upstream Protocol for WDM-PON," *Proc., Optical Fiber Communication Conference (OFC),* 2006.

[23] F. Effenberger and H. Lin, "Backward Compatible Coexistence of PON Systems," *Proc., OFC/NFOEC 2009*, March 2009.

[24] F. Effenberger, D. Cleary, O. Haran, G. Kramer, R. Li, M. Oron, and T. Pfeiffer, "An introduction to PON technologies," *IEEE Communications Magazine*, vol. 45, no. 3, pp. S17-S25, March 2007.

[25] F. Effenberger, H. Mukai, S. Park, and T. Pfeiffer, "Next-Generation PON-Part II: Candidate Systems for Next-Generation PON," *IEEE Communications Magazine*, vol. 47, no. 11, pp. 50 – 57, November 2009.

[26] F. Ponzini, F. Cavaliere, G. Berrettini, M. Presi, E. Ciaramella, N. Calabretta, and A. Bogoni, "Evolution Scenario Toward WDM-PON [Invited]," *IEEE/OSA Journal of Optical Communications and Networking*, vol. 1, no. 4, pp. C25-C34, 2009.

[27] G. Berrettini, L. Giorgi, F. Ponzini, F. Cavaliere, P. Ghiggino, L. Poti, and A. Bogoni, "Testbed for experimental analysis on seamless evolution architectures from GPON to high capacity WDM-PON," *Proc., 5th International Conference on Testbeds and Research Infrastructures for the Development of Networks & Communities and Workshops (TridentCom),* pp. 1-9, 2009.

[28] G. Kramer and G. Pesavento, "Ethernet Passive Optical Network (EPON): Building a Next-Generation Optical Access Network," *IEEE Communications Magazine*, vol. 40, no. 2, pp. 66-73, February 2002.

[29] G. Kramer, "Ethernet Passive Optical Networks," *McGraw-Hill*, 2005.

[30] G. Kramer, A. Banerjee, N. Singhal, B. Mukherjee, S. Sudhir, and Y. Ye, "Fair Queuing with Service Envelopes (FQSE): A Cousin-Fair Hierarchical Scheduler for Subscriber Access Networks," *IEEE Journal on Selected Areas in Communications*, vol. 22, no. 8, pp. 1497-1513, October 2004.

[31] G. Kramer, B. Mukherjee, and G. Pesavento, "Ethernet PON (ePON): Design and Analysis of an Optical Access Network", *Photonic Network Communications*, vol. 3, no. 3, July 2001.

[32] G. Kramer, B. Mukherjee, and G. Pesavento, "IPACT: A Dynamic Protocol for an Ethernet PON (EPON)," *IEEE Communications Magazine*, vol. 40, no. 2, pp. 74-80, February 2002.

[33] G. Kramer, B. Mukherjee, S. Dixit, Y. Ye, and R. Hirth. "Supporting differentiated classes of service in Ethernet passive optical networks," *OSA Journal of Optical Networking*, vol. 1, no. 8, pp. 280-298, August 2002.

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

[35] H. Byun, J. Nho, and J. Lim, “Dynamic bandwidth allocation algorithm in Ethernet passive optical networks,” *Electronics Letters*, vol. 39, no. 13, pp. 1001-1002, 2003.

[36] H. Song, B. Kim, and B. Mukherjee, “Multi-thread polling: a dynamic bandwidth distribution scheme in long-reach PON,” *IEEE Journal on Selected Areas in Communications*, vol. 27, no. 2, pp. 134-142, 2009.

[37] I. Van de Voorde, C. Martin, I. Vandewege, and X. Oiu, “The superPON demonstrator: an exploration of possible evolution paths for optical access networks,” *IEEE Communications Magazine,* vol. 38, no. 2, pp. 74–82, 2000.

[38] IEEE 802.3 ah, Standard, http://ieee802.org/3/, June 2004.

[39] IEEE 802.3av, Standard, http://www.ieee802.org/3/av/index.html/, September 2009.

[40] J. Chen, L. Wosinska, C. Mas Machuca, and M. Jaeger, “Cost vs. Reliability Performance Study of Fiber Access Network Architectures,” *IEEE Communications Magazine*, vol. 48, no. 2, pp. 56-65, February 2010.

[41] J. Fabrega, L. Vilabru, and J. Prat, “Experimental demonstration of Heterodyne Phase-Locked Loop for optical homodyne PSK receivers in PONs,” *Proc., International Conference on Transparent Optical Networks (ICTON)*, vol. 1, pp. 222-225, June 2008.

[42] J. Hyun, W. Cho, Y. Park, and B. Kim, “Economic Evolution from EPON to WDM-overlaid PON Employing a Wavelength Conversion Node,” *Proc., OFC/NFOEC 2007*, pp. 1-3, 2007.

[43] J. Kani, F. Bourgard, A. Cui, A. Rafel, M. Campbell, R. Davey, and S. Rodrigues, “Next-Generation PON-Part I: Technology Roadmap and General Requirements,” *IEEE Communications Magazine*, vol. 47, no. 11, pp. 43-49, November 2009.

[44] J. Lee, K. Choi, J. Moon, and C. Lee, “Evolution methods for next-generation access networks with reconfigurable remote nodes,” *Proc., Joint Conference of the Opto-Electronics and Communications Conference, and the Australian Conference on Optical Fibre Technology (OECC/ACOFT)*, pp. 1-2, 2008.

[45] J. Lee, K. Choi, J. Moon, and C. Lee, “Seamless Upgrades From a TDM-PON With a Video Overlay to a WDM-PON,” *IEEE/OSA Journal of Lightwave Technology,* vol. 27, no. 15, pp. 3116-3123, 2009.

[46] J. Prat, “Next-Generation FTTH Passive Optical Networks,” *Springer*, 2008.

[47] J. Zhang, N. Ansari, Y. Luo, F. Effenberger, and F. Ye, "Next-Generation PONs: A Performance Investigation of Candidate Architectures for Next-Generation Access Stage 1," *IEEE Communications Magazine*, vol. 47, no. 8, pp. 49-57, August 2009.

[48] J. Zheng and H. Mouftah, “A survey of dynamic bandwidth allocation algorithms for Ethernet Passive Optical Networks,” *Journal of Optical Switching and Networking*, 2009.

[49] J. Zheng and H. Mouftah, “Adaptive scheduling algorithms for Ethernet passive optical networks,” *Proc., IEE Communications*, vol. 152, no. 5, pp. 643-647, October 2005.

[50] K. Choi and C. Lee, “An Efficient Evolution Method of Current TDM-PON for Next-Generation Access,” *Proc., Joint International Conference on Optical Internet and the 32nd Australian Conference on Optical Fibre Technology (COIN-ACOFT),* pp.1-3, 2007.

[51] K. Choi, J. Moon, J. Lee, and C. Lee, “An Evolution Method from a TDM-PON with a Video Overlay to a WDM-PON,” *IEEE Photonics Technology Letters*, vol. 20, no. 4, pp. 312-314, 2008.

[52] K. Choi, S. Lee, M. Kim, and C. Lee, “An Efficient Evolution Method From TDM-PON to Next-Generation PON,” *IEEE Photonics Technology Letters*, vol. 19, no. 9, pp. 647-649, 2007.

[53] K. Grobe and J. Elbers, “PON Evolution from TDMA to WDM-PON,” *Proc., OFC/NFOEC 2008*, pp. 1-7, 2008.

[54] K. Kim, “On the evolution of PON-based FTTH solutions,” *Information Sciences*, 2003.

[55] K. Kim, D. Gutierrez, F. An, and L. Kazovsky, “Design and Performance Analysis of Scheduling Algorithms for WDM-PON under SUCCESS-HPON architecture,” *IEEE/OSA Journal of Lightwave Technology*, vol. 23, no. 11, November 2005.

[56] K. Kitayama, X. Wang, and N. Wada, “OCDMA over WDM PON-solution path to gigabit-symmetric FTTH,” *IEEE/OSA Journal of Lightwave Technology*, vol. 24, no. 4, pp. 1654-1662, April 2006.

[57] K. Kwong, D. Harle, and I. Andonovic, “Dynamic bandwidth allocation algorithm for differentiated services over WDM EPONs,” *Proc., IEEE International Conference on Communication Systems (ICCS)*, pp. 116-120, 2004.

[58] K. Langer, J. Grubor, and K. Habel, “Promising evolution paths for passive optical access networks,” *Proc., 6th International Conference on Transparent Optical Networks,* vol. 1, pp. 202-207, 2004.

[59] K. McCammon and S. Wong, “Experimental Validation of an Access Evolution Strategy: Smooth FTTP Service Migration Path,” *Proc., OFC/NFOEC 2007*, March 2007.

[60] L. Gutiérrez, **M. De Andrade**, and S. Sallent, “Evaluación de prestaciones de una red EPON,” *XVI Jornadas Telecom I+D 2006*, November 2006.

[61] L. Gutiérrez, **M. De Andrade**, and S. Sallent, “New trends on optical access networks: DBAs for 10G EPON and Long-Reach PONs (Invited paper),” *Proc., 14th European Conference on Networks and Optical Communications (NOC)*, June 2009.

[62] L. Gutiérrez, P. Garfias, **M. De Andrade**, C. Cervelló, and S. Sallent, “Next Generation Optical Access Networks: from TDM to WDM (book chapter),” *Trends in Telecommunications Technologies*, Book Editor: Christos J. Bouras, *IN-TECH*, March 2010.

[63] L. Kazovsky, W. Shaw, D. Gutierrez, N. Cheng, and S. Wong, “Next-Generation Optical Access Network,” *IEEE/OSA Journal of Lightwave Technology*, vol. 25, no. 11, pp. 3428-3442, November 2007.

[64] **M. De Andrade** and S. Sallent, “Cycle-based Ordering and Dynamic Bandwidth Allocation Algorithm for Ethernet Passive Optical Networks,” *Proc., International Conference on Telecommunications and Computer Networks (IADAT-tcn)*, September 2006.

[65] **M. De Andrade** and S. Sallent, “Dynamic Bandwidth Allocation algorithms for Ethernet Passive Optical Networks,” *Proc., 11th Open European Summer School (EUNICE)*, July 2005.

[66] **M. De Andrade** and S. Sallent, “Estado del Arte de los Protocolos MAC en las Redes Ethernet-PON,” *XIX Symposium Nacional de la Unión Científica Internacional de Radio*, September 2004.

[67] **M. De Andrade** and S. Sallent, “Nuevo Protocolo MAC para Redes de Acceso Ópticas Pasivas basadas en Ethernet (EPON),” *XIV Jornadas Telecom I+D 2004*, November 2004.

[68] **M. De Andrade**, D. Rincón, and S. Sallent, “Dynamic Bandwidth Allocation Algorithm with Delay Control for Ethernet Passive Optical Networks,” *IEEE INFOCOM 2005 Student Workshop*, March 2005.

[69] **M. De Andrade**, G. Kramer, L. Wosinska, J. Chen, S. Sallent, and B. Mukherjee, “Evaluating Strategies for Evolution of Passive Optical Networks,*” IEEE Communications Magazine*, under second revision submitted on October 5, 2010.

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

[71] **M. De Andrade**, L. Gutiérrez, and S. Sallent, "DDSPON: A Distributed Dynamic Scheduling for EPON," *Proc., IEEE International Conference on Signal Processing and Communication (ICSPC)*, pp. 840-843, November 2007.

[72] **M. De Andrade**, M. Tornatore, S. Sallent, and B. Mukherjee, "Capacity Upgrade of Passive Optical Networks with Minimum Cost and System Disruption," *Proc., 11th International Conference on High Performance Switching and Routing (HPSR),* June 2010.

[73] **M. De Andrade**, M. Tornatore, S. Sallent, and B. Mukherjee, "Optimizing the Migration to Future-Generation Passive Optical Networks (PON)," *IEEE Systems Journal, special issue on Broadband Access Networks*, paper accepted on August 25, 2010.

[74] **M. De Andrade**, S. Sallent, P. Garfias, L. Gutiérrez, A. Martínez, P. Vizarreta, D. Sánchez, and M. Huerta, "Algoritmo Distribuido para la Asignación Dinámica de Recursos en Redes EPON," *Proc., VIII Jornadas de Ingeniería Telemática (JITEL)*, September 2009.

[75] M. Hajduczenia et al., "EPON versus APON and GPON: a detailed performance comparison," *Journal of Optical Networking*, vol. 5, no. 4, April 2006.

[76] M. Hajduczenia, H. Da Silva, and P. Monteiro, "10G EPON Development Process," *Proc., International Conference on Transparent Optical Networks (ICTON)*, vol. 1, pp. 276-282, July 2007.

[77] M. Ma, Y. Zhu, and T. Cheng, "A Bandwidth Guaranteed Polling MAC Protocol for Ethernet Passive Optical Networks," *Proc., IEEE INFOCOM 2003*, vol. 1, pp. 22-31, March 2003.

[78] M. Maier, "WDM EPON: Future applications and services," *Proc., Second International Conference on Access Networks & Workshops (AccessNets)*, pp. 1-8, 2007.

[79] M. McGarry M. Reisslein, and M. Maier, "WDM Ethernet Passive Optical Networks," IEEE Communications Magazine, vol. 44, no. 2, pp. 15-22, February 2006.

[80] M. McGarry, M. Reisslein, and M. Maier, "Ethernet passive optical network architectures and dynamic bandwidth allocation algorithms," *IEEE Communications Surveys & Tutorials*, vol. 10, no. 3, pp. 40-60, 2008.

[81] M. McGarry, M. Reisslein, C. Colbourn, M. Maier, F. Aurzada, and M. Scheutzow, "Just-in-Time Scheduling for Multichannel EPONs," *IEEE/OSA Journal of Lightwave Technology*, vol. 26, no. 10, May 2008.

[82] M. Pinedo, "Scheduling: Theory, Algorithms, and Systems," *Prentice Hall*, 2nd ed., 2002.

[83] M. Tsubokawa and K. Kumozaki, "Evolution of Next Generation Access," *Proc., Globecom 2008*, pp. 1-3, 2008.

[84] M. Wegleitner, "Maximizing the Impact of Optical Technology," Keynote Address, *Proc., OFC/NFOEC 2007*, March 2007.

[85] R. G. Jeroslow, "Logic-based decision support: mixed integer model formulation," North-Holland, 1989.

[86] S. Chaudhry and A. Choudhary, "Time Dependent Priority Scheduling for Guaranteed QoS Systems," *Proc., International Conference on Computer Communications and Networks (ICCCN)*, pp. 236-241, September 1997.

[87] S. Choi, “Cyclic Polling-Based Dynamic Bandwidth Allocation for Differentiated Classes of Service in Ethernet Passive Optical Networks,” *Journal on Photonics Network Communications*, vol. 7, no. 1, pp. 87-96, January 2004.

[88] S. Park, Y. Choi, J. Oh, S. Koo, and D. Lee, “An Evolution Scenario of a Broadband Access Network Using R-SOA-Based WDM-PON Technologies,” *IEEE/OSA Journal of Lightwave Technology*, vol. 25, no. 11, 2007.

[89] W. Leland, M. Taqqu, W. Willinger, and D. Wilson, “On the self-similar nature of Ethernet traffic (extended version),” *IEEE/ACM Transactions on Networking (TON)*, vol. 2, no. 1, pp. 1-15, February 1994.

[90] Y. Hsueh, F. An, K. Kim, and L. Kazovsky, “A New Media Access Control Protocol with Quality of Service and Fairness Guarantee in Ethernet-based Passive Optical Networks,” *Proc., 2nd Symposium on Photonics, Networking, and Computing*, September 2003.

[91] Y. Liu, J. Liu, X. Hong, and D. Zeng, “A novel evolution method for hybrid TDM/WDM-PON based on DPSK/NRZ orthogonal modulation,” *Proc., Asia Communications and Photonics Conference and Exhibition (ACP)*, pp. 1-6, 2009.

[92] Y. Luo and N. Ansari, “Bandwidth allocation for multiservice access on EPONs,” *IEEE Communications Magazine*, vol. 43, no. 2, pp. 16-21, 2005.

[93] Y. Zhu, M. Ma, and T. Cheng, “IPACT with Grant Estimation for EPON,” *Proc., 10th IEEE Singapore International Conference on Communication Systems (ICCS),* pp. 1-5, 2006.

Appendix

Detailed Results of DBA Algorithm DDSPON

In this appendix we provided detailed results of simulations run in OPNET Modeler for two dynamic bandwidth allocation algorithms: IPACT (limited service) and DDSPON. We also present the confidence intervals according to T distribution.

The network topology is a tree-type with 16 ONUs, each separated from OLT at a distance of 10km to 20km. We use self-similar traffic source models. We considered the following Hurt (H) parameters in this study H = 0.7 and H = 0.8. The average size packet follows a uniform distribution that varies from 64 bytes to 1518 bytes as the real Ethernet frame sizes. To obtain results for different network loads, the total offered load is 1 Gbps, which is distributed equally among all active ONUs, the mean arrival rate varies proportionally according to the network load that is assessed in simulation. The simulations have been performed with different number of seeds so that samples obtained approximate the mean value the actual value thereof. The statistics collected over the upstream channel are: queue size, packet delay, and throughput. We considered five simulation scenarios for which we have varied parameters such as distance between ONUs and OLT and traffic Hurst parameter, as shown in the following table.

Parameters	Sce. 1	Sce. 2	Sce. 3	Sce. 4	Sce. 5
Number of ONUs	16	16	16	16	16
User link rate at ONU	100Mbps	100Mbps	100Mbps	100Mbps	100Mbps
Line rate at EPON	1Gbps	1Gbps	1Gbps	1Gbps	1Gbps
Number of Queues per ONU	1	1	1	1	1
Buffer size	100 MB	100 MB	100 MB	100 MB	100 MB
Guard time	0.008ms	0.008ms	0.008ms	0.008ms	0.008ms
Maximum cycle size	1ms	1ms	1ms	1ms	1ms
Distance between ONUs and OLT (km)	18<d<20	18<d<20	10<d<20	10<d<11	4<d<5
Hurst parameter	H=0.7	H=0.8	H=0.8	H=0.8	H=0.8

For all scenarios we consider a 1-Gbps EPON with 16 ONUs, each ONU with a line rate of 100 Mbps and a queue size of 100 MB. The guard interval is 0.008 ms and the maximum size of the cycle of 1 ms. The simulations have been carried out using single-queue per ONU. All the results are divided in two sections according to the parameter measured: queue size and packet delay.

Packet Delay

Packet delay per packet for IPACT, scenario 1

DBA IPACT SCENARIO 1			stddev	Confidence Intervals							
AVERAGE				99%		95%		90%		80%	
sec	ms	load		sec	ms	sec	ms	sec	ms	sec	ms
0.002133285	2.133285419	0.05	0.00022993	0.000169401	0.169401265	0.000122495	0.122495451	0.000100767	0.100767023	7.70842E-05	0.077084186
0.001719482	1.719481816	0.1	7.77861E-05	5.73089E-05	0.057308908	4.14405E-05	0.041440544	3.40898E-05	0.034089757	2.60778E-05	0.026077789
0.001431249	1.43124924	0.15	1.70338E-05	1.25496E-05	0.012549645	9.07475E-06	0.009074752	7.46506E-06	0.007465059	5.71058E-06	0.005710578
0.001260186	1.260186497	0.2	1.51406E-05	1.11548E-05	0.011154837	8.06615E-06	0.008066155	6.63537E-06	0.006635368	5.07589E-06	0.005075886
0.001169618	1.169618493	0.25	1.07208E-05	7.89855E-06	0.007898554	5.71151E-06	0.00571151	4.69839E-06	0.004698394	3.59415E-06	0.003594151
0.001125477	1.125477108	0.3	1.08956E-05	8.02734E-06	0.00802734	5.80464E-06	0.005804636	4.775E-06	0.004775001	3.65275E-06	0.003652753
0.001113864	1.113863715	0.35	8.47038E-06	6.24055E-06	0.006240552	4.51259E-06	0.004512595	3.71214E-06	0.003712144	2.83969E-06	0.002839695
0.001124739	1.124738942	0.4	9.44882E-06	6.96142E-06	0.006961419	5.03386E-06	0.00503386	4.14095E-06	0.004140946	3.16772E-06	0.003167717
0.001157302	1.157302373	0.45	7.64338E-06	5.63126E-06	0.005631263	4.07201E-06	0.004072013	3.34971E-06	0.003349713	2.56244E-06	0.002562445
0.001209032	1.20903163	0.5	9.10077E-06	6.70499E-06	0.006704989	4.84843E-06	0.004848433	3.98841E-06	0.003988411	3.05103E-06	0.003051032
0.001308408	1.308408494	0.55	8.71746E-06	6.42259E-06	0.006422586	4.64422E-06	0.004644225	3.82043E-06	0.003820425	2.92253E-06	0.002922527
0.001509769	1.509768975	0.6	7.79975E-06	5.74647E-06	0.005746465	4.15532E-06	0.004155316	3.41824E-06	0.00341824	2.61487E-06	0.002614866
0.001896797	1.896797006	0.65	1.20655E-05	8.88925E-06	0.008889247	6.42789E-06	0.006427888	5.2877E-06	0.005287699	4.04495E-06	0.004044954
0.005537078	5.537078315	0.7	0.000584436	0.000430583	0.430583309	0.000311358	0.311358342	0.000256129	0.256129128	0.000195932	0.195932208
0.014343705	14.34370482	0.75	0.000867542	0.000639162	0.639161503	0.000462183	0.462182953	0.0003802	0.380200242	0.000290843	0.290843425
0.022045763	22.04576304	0.8	0.001052887	0.000775714	0.775714404	0.000560925	0.560925482	0.000461428	0.461427672	0.00035298	0.352980324
0.029918257	29.91825747	0.85	0.000956138	0.000704434	0.704434468	0.000509382	0.509382372	0.000419027	0.419027357	0.000320545	0.320545172
0.036273353	36.27335299	0.9	0.001208163	0.000890114	0.890114022	0.000643649	0.643648789	0.000529477	0.529477394	0.000405037	0.405036615
0.042396125	42.3961247	0.95	0.000768775	0.000566395	0.566394799	0.000409565	0.409564749	0.000336916	0.336915535	0.000257732	0.257731736
0.04734747	47.34747002	1	0.00085507	0.000629973	0.629973182	0.000455539	0.455538803	0.000374735	0.374734642	0.000286662	0.286662381

Packet delay per packet for DDSPON, scenario 1

DBA DDSPON SCENARIO 1			stddev	Confidence Intervals							
AVERAGE				99%		95%		90%		80%	
sec	ms	load		sec	ms	sec	ms	sec	ms	sec	ms
0.001651952	1.651951879	0.05	0.000388096	0.00028593	0.285929765	0.000206758	0.206758171	0.000170083	0.170083094	0.000130109	0.130109201
0.001537461	1.537460685	0.1	0.000115594	8.51637E-05	0.085163657	6.15825E-05	0.061582543	5.06589E-05	0.050658938	3.87528E-05	0.038752787
0.0013797	1.379700041	0.15	3.71991E-05	2.74064E-05	0.027406405	1.98178E-05	0.019817798	1.63025E-05	0.016302487	1.2471E-05	0.012470984
0.00127015	1.27014969	0.2	2.46956E-05	1.81945E-05	0.018194519	1.31566E-05	0.013156607	1.08229E-05	0.010822868	8.27922E-06	0.008279216
0.00122319	1.223190024	0.25	2.1117E-05	1.55579E-05	0.015557942	1.12501E-05	0.011250076	9.25452E-06	0.009254521	7.07947E-06	0.007079471
0.001199298	1.199297787	0.3	1.7985E-05	1.32504E-05	0.013250422	9.58149E-06	0.00958149	7.88191E-06	0.007881911	6.02946E-06	0.006029459
0.001189785	1.189784638	0.35	1.22343E-05	9.01361E-06	0.009013611	6.51782E-06	0.006517816	5.36168E-06	0.005361676	4.10154E-06	0.004101545
0.001206327	1.20632716	0.4	1.40933E-05	1.03832E-05	0.010383212	7.50819E-06	0.007508186	6.17637E-06	0.006176373	4.72477E-06	0.004724767
0.001247041	1.247040747	0.45	1.63238E-05	1.20266E-05	0.012026554	8.6965E-06	0.008696501	7.1539E-06	0.007153902	5.47255E-06	0.005472552
0.001289659	1.289659323	0.5	1.62155E-05	1.19468E-05	0.01194676	8.6388E-06	0.008638801	7.10644E-06	0.007106437	5.43624E-06	0.005436242
0.001356455	1.356455454	0.55	2.08515E-05	1.53623E-05	0.015362317	1.11086E-05	0.011108618	9.13815E-06	0.009138155	6.99045E-06	0.006990454
0.001484334	1.484333968	0.6	2.38071E-05	1.75399E-05	0.017539911	1.26833E-05	0.012683254	1.04335E-05	0.010433479	7.98134E-06	0.007981344
0.001662948	1.662948122	0.65	2.79756E-05	2.0611E-05	0.020611015	1.4904E-05	0.014903995	1.22603E-05	0.012260302	9.37882E-06	0.009378816
0.002980786	2.980785524	0.7	0.000253801	0.000186988	0.186987964	0.000135213	0.135212539	0.000111228	0.111228334	8.50868E-05	0.085086821
0.005919872	5.919872062	0.75	0.000685252	0.000504859	0.504859334	0.000365068	0.365067947	0.000300312	0.300311643	0.000229731	0.229730698
0.008037038	8.037038271	0.8	0.000762999	0.000562139	0.562139419	0.000406488	0.406487649	0.000334384	0.334384256	0.000255795	0.255795372
0.010711092	10.71109165	0.85	0.000743762	0.000547966	0.547966288	0.000396239	0.396238941	0.000325953	0.325953479	0.000249346	0.249346044
0.012823558	12.82355756	0.9	0.001004402	0.000739993	0.739993361	0.000535095	0.535095301	0.000440179	0.440179288	0.000336726	0.336725856
0.014808504	14.80850363	0.95	0.000729928	0.000537774	0.53777434	0.000388869	0.388869059	0.000319891	0.319890878	0.000244708	0.24470831
0.016417154	16.41715423	1	0.00066676	0.000491236	0.491235612	0.000355217	0.355216522	0.000292208	0.292207679	0.000223531	0.223531373

Packet delay per packet for IPACT, scenario 2

DBA IPACT SCENARIO 2			stddev	Confidence Intervals							
AVERAGE				99%		95%		90%		80%	
sec	ms	load		sec	ms	sec	ms	sec	ms	sec	ms
0.002337777	2.337777194	0.05	0.000243753	0.000179585	0.17958505	0.000129859	0.129859431	0.000106825	0.106824769	8.17182E-05	0.081718206
0.001702418	1.702417927	0.1	5.77335E-05	4.25352E-05	0.042535189	3.07575E-05	0.030757546	2.53017E-05	0.025301726	1.93552E-05	0.019355171
0.001419938	1.419937616	0.15	3.02511E-05	2.22875E-05	0.022287497	1.61163E-05	0.016116273	1.32575E-05	0.013257544	1.01417E-05	0.010141681
0.001254916	1.254915768	0.2	2.25537E-05	1.66164E-05	0.016616444	1.20155E-05	0.012015488	9.88416E-06	0.009884162	7.56113E-06	0.007561131
0.001170607	1.170606856	0.25	1.57094E-05	1.15739E-05	0.011573903	8.36918E-06	0.008369184	6.88465E-06	0.006884646	5.26658E-06	0.005266577
0.001124723	1.12472346	0.3	1.23428E-05	9.09355E-06	0.009093549	6.57562E-06	0.006575621	5.40923E-06	0.005409227	4.13792E-06	0.00413792
0.001109137	1.109137462	0.35	9.33385E-06	6.87671E-06	0.006876714	4.97261E-06	0.004972608	4.09056E-06	0.00409056	3.12917E-06	0.003129173
0.001122588	1.122588235	0.4	8.59517E-06	6.33249E-06	0.006332495	4.57908E-06	0.004579079	3.76684E-06	0.003766835	2.88153E-06	0.002881532
0.001156962	1.15696182	0.45	6.80977E-06	5.0171E-06	0.005017101	3.62791E-06	0.003627907	2.98438E-06	0.002984384	2.28298E-06	0.002282977
0.001205705	1.205705318	0.5	6.8649E-06	5.05771E-06	0.005057714	3.65727E-06	0.003657275	3.00854E-06	0.003008542	2.30146E-06	0.002301457
0.001294018	1.294017519	0.55	1.11002E-05	8.17806E-06	0.008178063	5.91362E-06	0.005913625	4.86466E-06	0.004864657	3.72134E-06	0.003721338
0.001511098	1.511097513	0.6	9.2301E-06	6.80028E-06	0.006800279	4.91734E-06	0.004917338	4.04509E-06	0.004045093	3.09439E-06	0.003094392
0.001955093	1.955092766	0.65	1.90721E-05	1.40513E-05	0.014051337	1.01606E-05	0.010160637	8.35833E-06	0.008358328	6.39391E-06	0.006393906
0.0052351	5.235099892	0.7	0.00036933	0.000272104	0.27210414	0.000196761	0.196760747	0.000161859	0.161859029	0.000123818	0.123818002
0.014077848	14.07784793	0.75	0.001175592	0.000866117	0.866117167	0.000626296	0.626296465	0.000515203	0.515203052	0.000394117	0.394117109
0.021826986	21.82698583	0.8	0.001218901	0.000898025	0.898025141	0.000649369	0.649369384	0.000534183	0.534183262	0.000408636	0.408636483
0.029508315	29.50831507	0.85	0.000922066	0.000679332	0.6793322	0.000491231	0.491230716	0.000404095	0.404095469	0.000309123	0.309122661
0.035841564	35.84156412	0.9	0.000850603	0.000626682	0.626681789	0.000453159	0.453158769	0.000372777	0.372776782	0.000285165	0.285164669
0.041871772	41.87177245	0.95	0.000779957	0.000574633	0.574633452	0.000415522	0.415522188	0.000341816	0.341816234	0.000261481	0.261480645
0.047036025	47.03602535	1	0.000812522	0.000598626	0.598625626	0.000432871	0.432871126	0.000356088	0.356087792	0.000272398	0.27239802

Packet delay per packet for DDSPON, scenario 2

DBA DDSPON SCENARIO 2			stddev	Confidence Intervals							
AVERAGE				99%		95%		90%		80%	
sec	ms	load		sec	ms	sec	ms	sec	ms	sec	ms
0.001644652	1.644651546	0.05	0.000221555	0.000163231	0.163230572	0.000118033	0.118033373	9.70964E-05	0.097096435	7.42763E-05	0.07427628
0.001515792	1.515792157	0.1	9.18248E-05	6.76519E-05	0.067651944	4.89197E-05	0.048919679	4.02422E-05	0.040242232	3.07843E-05	0.030784275
0.001375427	1.375426587	0.15	4.93789E-05	3.63799E-05	0.036379877	2.63066E-05	0.026306589	2.16403E-05	0.021640286	1.65543E-05	0.016554263
0.001293134	1.29313414	0.2	2.8484E-05	2.09856E-05	0.020985581	1.51748E-05	0.015174847	1.24831E-05	0.012483109	9.54926E-06	0.009549258
0.001234224	1.234224245	0.25	2.26475E-05	1.66856E-05	0.016685554	1.20655E-05	0.012065462	9.92527E-06	0.009925272	7.59258E-06	0.007592578
0.001213647	1.213646619	0.3	1.4021E-05	1.033E-05	0.010329974	7.46969E-06	0.007469689	6.1447E-06	0.006144705	4.70054E-06	0.004700541
0.001201585	1.20158463	0.35	1.60933E-05	1.18567E-05	0.011856721	8.57369E-06	0.008573692	7.05288E-06	0.007052878	5.39527E-06	0.005395271
0.001213426	1.213426191	0.4	1.73845E-05	1.2808E-05	0.012808037	9.2616E-06	0.009261597	7.61876E-06	0.007618761	5.82816E-06	0.005828157
0.001239066	1.239065885	0.45	1.39442E-05	1.02734E-05	0.01027336	7.42875E-06	0.007428751	6.11103E-06	0.006111028	4.67478E-06	0.00467478
0.001285359	1.285358687	0.5	1.44298E-05	1.06312E-05	0.010631161	7.68748E-06	0.00768748	6.32386E-06	0.006323863	4.83759E-06	0.004837593
0.001356588	1.356588172	0.55	2.44944E-05	1.80463E-05	0.018046272	1.30494E-05	0.013049408	1.07347E-05	0.010734684	8.21176E-06	0.008211758
0.00146869	1.468690262	0.6	2.51524E-05	1.8531E-05	0.018531042	1.33999E-05	0.013399949	1.1023E-05	0.011023046	8.43235E-06	0.008432347
0.0016775	1.677499727	0.65	2.64112E-05	1.94585E-05	0.01945847	1.40706E-05	0.01407058	1.15747E-05	0.01157472	8.85436E-06	0.008854363
0.00305598	3.055980469	0.7	0.000252533	0.000186054	0.186053716	0.000134537	0.134536976	0.000110673	0.110672604	8.46617E-05	0.084661701
0.005506648	5.506647702	0.75	0.000582339	0.000429038	0.429037947	0.000310241	0.310240877	0.00025521	0.255209882	0.000195229	0.195229008
0.008297928	8.297928137	0.8	0.000757918	0.000558396	0.558396208	0.000403781	0.403780902	0.000332158	0.332157636	0.000254092	0.254092065
0.010476251	10.4762514	0.85	0.000845726	0.000623088	0.623088386	0.00045056	0.45056035	0.000370639	0.370639274	0.00028353	0.28352953
0.012766843	12.76684339	0.9	0.000832488	0.000613335	0.613335453	0.000443508	0.443507923	0.000364838	0.364837818	0.000279092	0.279091565
0.014686879	14.68687879	0.95	0.000818701	0.000603178	0.603177832	0.000436163	0.436162864	0.000358796	0.358795636	0.000274469	0.274469451
0.016581661	16.58166126	1	0.0008147	0.00060023	0.600230462	0.000434032	0.434031596	0.000357042	0.357042416	0.000273128	0.273128283

Packet delay per packet for IPACT, scenario 3

DBA IPACT SCENARIO 3			stddev	Confidence intervals							
AVERAGE				99%		95%		90%		80%	
sec	*ms*	*load*		*sec*	*ms*	*sec*	*ms*	*sec*	*ms*	*sec*	*ms*
0.00028189	0.28188964	0.05	5.087E-06	3.7479E-06	0.00374785	2.7101E-06	0.0027101	2.2294E-06	0.00222938	1.7054E-06	0.00170542
0.00030379	0.3037921	0.1	8.1297E-06	5.9896E-06	0.00598957	4.3311E-06	0.00433111	3.5628E-06	0.00356285	2.7255E-06	0.00272549
0.00032934	0.32934378	0.15	9.4346E-06	6.9509E-06	0.00695094	5.0263E-06	0.00502628	4.1347E-06	0.00413471	3.163E-06	0.00316295
0.00036028	0.36028364	0.2	5.8835E-06	4.3347E-06	0.00433467	3.1344E-06	0.00313444	2.5784E-06	0.00257844	1.9724E-06	0.00197244
0.00039669	0.39669481	0.25	8.8541E-06	6.5233E-06	0.00652327	4.717E-06	0.00471703	3.8803E-06	0.00388031	2.9683E-06	0.00296834
0.00043588	0.4358759	0.3	3.7315E-06	2.7492E-06	0.00274921	1.988E-06	0.00198798	1.6353E-06	0.00163535	1.251E-06	0.001251
0.00048038	0.48038177	0.35	1.4128E-06	1.0409E-06	0.00104091	7.5269E-07	0.00075269	6.1918E-07	0.00061918	4.7366E-07	0.00047366
0.00052688	0.52687735	0.4	5.0286E-06	3.7048E-06	0.00370481	2.679E-06	0.00267898	2.2038E-06	0.00220378	1.6858E-06	0.00168583
0.00059044	0.59044104	0.45	7.2198E-06	5.3192E-06	0.00531918	3.8463E-06	0.00384634	3.1641E-06	0.00316407	2.4204E-06	0.00242043
0.00066225	0.66224578	0.5	1.0627E-05	7.8296E-06	0.00782964	5.6617E-06	0.00566167	4.6574E-06	0.0046574	3.5628E-06	0.00356279
0.00073775	0.7377546	0.55	1.6199E-05	1.1935E-05	0.01193476	8.6301E-06	0.00863012	7.0993E-06	0.0070993	5.4308E-06	0.00543078
0.00084181	0.84180701	0.6	8.5644E-06	6.3098E-06	0.00630979	4.5627E-06	0.00456266	3.7533E-06	0.00375333	2.8712E-06	0.0028712
0.00110834	1.10833726	0.65	2.342E-05	1.7255E-05	0.01725452	1.2477E-05	0.01247688	1.0264E-05	0.01026371	7.8515E-06	0.00785148
0.00172638	1.72638187	0.7	0.00016371	0.00012062	0.12061596	8.7218E-05	0.0872184	7.1747E-05	0.07174747	5.4885E-05	0.05488497
0.00594548	5.94547689	0.75	0.00141429	0.00104198	1.04197774	0.00075346	0.7534627	0.00061981	0.61981235	0.00047414	0.47414053
0.01253803	12.5380252	0.8	0.0030863	0.00227383	2.27383024	0.00164423	1.6442254	0.00135257	1.35257021	0.00103468	1.03468149
0.01885808	18.8580784	0.85	0.00466517	0.00343706	3.43706383	0.00248537	2.4853692	0.00204451	2.04451065	0.001564	1.56399817
0.02464094	24.6409369	0.9	0.00625132	0.00460566	4.60566027	0.00333039	3.33039092	0.00273964	2.73964114	0.00209576	2.09575515
0.02977287	29.7728704	0.95	0.00759549	0.00559598	5.59597581	0.0040465	4.04649625	0.00332872	3.32872263	0.00254639	2.54638736
0.03444678	34.4467842	1	0.00884434	0.00651607	6.51606734	0.00471182	4.71182202	0.00387603	3.87603191	0.00296506	2.96506491

Packet delay per packet for DDSPON, scenario 3

DBA DDSPON SCENARIO 3			stddev	Confidence intervals							
AVERAGE				99%		95%		90%		80%	
sec	*ms*	*load*		*sec*	*ms*	*sec*	*ms*	*sec*	*ms*	*sec*	*ms*
0.00033397	0.33397193	0.05	4.6187E-05	3.4028E-05	0.03402846	2.4606E-05	0.02460626	2.0242E-05	0.02024156	1.5484E-05	0.01548428
0.0003833	0.38330251	0.1	5.301E-05	3.9055E-05	0.039055	2.8241E-05	0.028241	2.3232E-05	0.02323157	1.7772E-05	0.01777155
0.00041965	0.41964816	0.15	5.3957E-05	3.9752E-05	0.03975246	2.8745E-05	0.02874533	2.3646E-05	0.02364644	1.8089E-05	0.01808892
0.00047443	0.47443319	0.2	5.723E-05	4.2164E-05	0.04216449	3.0489E-05	0.03048949	2.5081E-05	0.02508122	1.9186E-05	0.01918649
0.00052173	0.52173267	0.25	5.5442E-05	4.0847E-05	0.04084688	2.9537E-05	0.02953672	2.4297E-05	0.02429745	1.8587E-05	0.01858693
0.00058459	0.58459078	0.3	5.793E-05	4.268E-05	0.04267993	3.0862E-05	0.03086221	2.5388E-05	0.02538783	1.9421E-05	0.01942103
0.00064871	0.64870674	0.35	5.8285E-05	4.2942E-05	0.04294163	3.1051E-05	0.03105144	2.5543E-05	0.02554349	1.954E-05	0.01954012
0.00072519	0.72518806	0.4	5.1911E-05	3.8245E-05	0.03824549	2.7656E-05	0.02765563	2.275E-05	0.02275003	1.7403E-05	0.01740319
0.0007999	0.79989537	0.45	5.5365E-05	4.079E-05	0.04079029	2.9496E-05	0.02949579	2.4264E-05	0.02426378	1.8561E-05	0.01856117
0.00089508	0.89508415	0.5	5.391E-05	3.9718E-05	0.03971788	2.872E-05	0.02872033	2.3626E-05	0.02362587	1.8073E-05	0.01807319
0.00100989	1.00988825	0.55	6.1149E-05	4.5051E-05	0.04505136	3.2577E-05	0.03257701	2.6798E-05	0.02679845	2.05E-05	0.02050013
0.00121421	1.21420932	0.6	5.8989E-05	4.346E-05	0.04346044	3.1427E-05	0.0314266	2.5852E-05	0.02585211	1.9776E-05	0.0197762
0.00177149	1.77149035	0.65	0.00015248	0.00011234	0.11234147	8.1235E-05	0.08123504	6.6825E-05	0.06682545	5.112E-05	0.05111975
0.00414528	4.14528303	0.7	0.00095588	0.00070425	0.70424759	0.00050925	0.50924724	0.00041892	0.41891619	0.00032046	0.32046013
0.00668795	6.68794824	0.75	0.00161913	0.0011929	1.19289529	0.00086259	0.86259242	0.00070958	0.70958447	0.00054281	0.54281391
0.00870124	8.70123767	0.8	0.00148066	0.00109087	1.09087327	0.00078882	0.78881945	0.0006489	0.64889747	0.00049639	0.4963899
0.01099562	10.9956213	0.85	0.00135805	0.00100055	1.00054682	0.0007235	0.72350365	0.00059517	0.59516748	0.00045529	0.45528785
0.01268259	12.6825915	0.9	0.00149947	0.00110473	1.10473266	0.00079884	0.7988413	0.00065714	0.65714162	0.0005027	0.50269647
0.0144043	14.4043041	0.95	0.00135422	0.00099772	0.99772451	0.00072146	0.72146282	0.00059349	0.59348865	0.000454	0.45400358
0.01559291	15.5929141	1	0.00149604	0.00110221	1.10220669	0.00079701	0.79701475	0.00065564	0.65563907	0.00050155	0.50154706

Packet delay per packet for IPACT, scenario 4

DBA IPACT SCENARIO 4			stddev	Confidence intervals							
AVERAGE				99%		95%		90%		80%	
sec	*ms*	*load*		*sec*	*ms*	*sec*	*ms*	*sec*	*ms*	*sec*	*ms*
0.00026569	0.26569227	0.05	8.0632E-06	5.9405E-06	0.00594053	4.2956E-06	0.00429565	3.5337E-06	0.00353368	2.7032E-06	0.00270317
0.00029666	0.29665948	0.1	1.2363E-05	9.1087E-06	0.00910868	6.5866E-06	0.00658656	5.4182E-06	0.00541823	4.1448E-06	0.00414481
0.0003282	0.32820452	0.15	8.6797E-06	6.3948E-06	0.00639477	4.6241E-06	0.00462411	3.8039E-06	0.00380388	2.9099E-06	0.00290987
0.00035949	0.35949219	0.2	3.1733E-06	2.3379E-06	0.00233791	1.6906E-06	0.00169056	1.3907E-06	0.00139069	1.0638E-06	0.00106384
0.0003951	0.3950952	0.25	5.7023E-06	4.2012E-06	0.00420117	3.0379E-06	0.0030379	2.499E-06	0.00249904	1.9117E-06	0.0019117
0.00043453	0.43452592	0.3	4.6593E-06	3.4327E-06	0.00343273	2.4822E-06	0.00248224	2.0419E-06	0.00204193	1.562E-06	0.00156203
0.00047934	0.47933601	0.35	2.5904E-06	1.9085E-06	0.00190851	1.3801E-06	0.00138006	1.1353E-06	0.00113526	8.6845E-07	0.00086845
0.00052909	0.52908879	0.4	4.5138E-06	3.3255E-06	0.00332551	2.4047E-06	0.0024047	1.9782E-06	0.00197815	1.5132E-06	0.00151324
0.00058594	0.58594145	0.45	4.9613E-06	3.6552E-06	0.0036552	2.6431E-06	0.00264311	2.1743E-06	0.00217427	1.6633E-06	0.00166326
0.00065929	0.65928966	0.5	1.3722E-05	1.011E-05	0.01010977	7.3105E-06	0.00731046	6.0137E-06	0.00601372	4.6003E-06	0.00460034
0.00073778	0.7377824	0.55	5.4676E-06	4.0283E-06	0.00402829	2.9129E-06	0.00291289	2.3962E-06	0.00239619	1.833E-06	0.00183303
0.00086021	0.86021176	0.6	6.6482E-06	4.898E-06	0.00489804	3.5418E-06	0.00354181	2.9136E-06	0.00291356	2.2288E-06	0.0022288
0.00109973	1.09972988	0.65	3.2635E-05	2.4044E-05	0.02404351	1.7386E-05	0.01738606	1.4302E-05	0.01430209	1.0941E-05	0.01094073
0.00171257	1.71257396	0.7	0.00015	0.00011051	0.11051125	7.9912E-05	0.0799116	6.5737E-05	0.06573676	5.0287E-05	0.05028693
0.00593288	5.93288315	0.75	0.00141753	0.00104437	1.04436759	0.00075519	0.75519081	0.00062123	0.62123393	0.00047523	0.47522801
0.01251941	12.5194106	0.8	0.0030752	0.00226565	2.26565278	0.00163831	1.63831221	0.00134771	1.34770591	0.00103096	1.03096043
0.0188875	18.8874989	0.85	0.0046854	0.00345197	3.45197169	0.00249615	2.49614919	0.00205338	2.05337848	0.00157078	1.57078182
0.02467714	24.6771401	0.9	0.00626513	0.00461583	4.61583154	0.00333775	3.33774585	0.00274569	2.74569145	0.00210038	2.10038348
0.02988601	29.8860146	0.95	0.00764719	0.00563407	5.63407069	0.00407404	4.07404297	0.00335138	3.35138307	0.00256372	2.56372202
0.03443072	34.4307231	1	0.00882163	0.00649934	6.49933505	0.00469972	4.69972277	0.00386608	3.86607884	0.00295745	2.95745107

Packet delay per packet for DDSPON, scenario 4

DBA DDSPON SCENARIO 4			stddev	Confidence intervals							
AVERAGE				99%		95%		90%		80%	
sec	ms	load		sec	ms	sec	ms	sec	ms	sec	ms
0.00027134	0.27133672	0.05	5.89E-06	4.3394E-06	0.00433943	3.1379E-06	0.00313787	2.5813E-06	0.00258127	1.9746E-06	0.00197461
0.00030776	0.30775694	0.1	3.4413E-06	2.5354E-06	0.00253537	1.8333E-06	0.00183335	1.5081E-06	0.00150815	1.1537E-06	0.00115369
0.0003481	0.3480984	0.15	2.9927E-06	2.2049E-06	0.0022049	1.5944E-06	0.00159438	1.3116E-06	0.00131157	1.0033E-06	0.00100332
0.0003868	0.38679828	0.2	2.9764E-06	2.1928E-06	0.00219285	1.5857E-06	0.00158567	1.3044E-06	0.0013044	9.9783E-07	0.00099783
0.0004313	0.43129719	0.25	3.6741E-06	2.7069E-06	0.00270688	1.9574E-06	0.00195737	1.6102E-06	0.00161017	1.2317E-06	0.00123174
0.00047805	0.47805142	0.3	1.7918E-06	1.3201E-06	0.00132012	9.5459E-07	0.00095459	7.8527E-07	0.00078527	6.0071E-07	0.00060071
0.00052777	0.52777124	0.35	4.0788E-06	3.005E-06	0.00300503	2.173E-06	0.00217296	1.7875E-06	0.00178752	1.3674E-06	0.00136741
0.00058892	0.58892008	0.4	4.7168E-06	3.4751E-06	0.00347513	2.5129E-06	0.0025129	2.0672E-06	0.00206716	1.5813E-06	0.00158132
0.00066505	0.66505081	0.45	4.5414E-06	3.3459E-06	0.0033459	2.4194E-06	0.00241945	1.9903E-06	0.00199028	1.5225E-06	0.00152252
0.00074299	0.74298738	0.5	7.1186E-06	5.2446E-06	0.00524464	3.7924E-06	0.00379244	3.1197E-06	0.00311973	2.3865E-06	0.00238652
0.00084444	0.84444477	0.55	1.0938E-05	8.0583E-06	0.00805828	5.827E-06	0.00582701	4.7934E-06	0.00479341	3.6668E-06	0.00366683
0.00100637	1.00637078	0.6	1.5977E-05	1.1771E-05	0.0117712	8.5118E-06	0.00851185	7.002E-06	0.007002	5.3564E-06	0.00535635
0.00119356	1.19355737	0.65	1.9858E-05	1.463E-05	0.01463004	1.0579E-05	0.0105791	8.7026E-06	0.00870256	6.6572E-06	0.00665724
0.0021747	2.17469624	0.7	0.0001453	0.00010705	0.10705176	7.741E-05	0.07741001	6.3679E-05	0.0636789	4.8713E-05	0.04871273
0.00475121	4.75120922	0.75	0.00055716	0.00041049	0.41049093	0.00029683	0.29682938	0.00024418	0.24417733	0.00018679	0.18678939
0.00678701	6.78700531	0.8	0.0006997	0.0005155	0.51550486	0.00037277	0.37276581	0.00030664	0.30664405	0.00023457	0.23457483
0.00915866	9.15866472	0.85	0.00063349	0.00046672	0.46672453	0.00033749	0.33749236	0.00027763	0.27762745	0.00021238	0.21237788
0.0109255	10.9254976	0.9	0.00060029	0.00044226	0.44226145	0.0003198	0.3198029	0.00026308	0.26307578	0.00020125	0.20124622
0.01275186	12.7518627	0.95	0.00061493	0.00045305	0.45305234	0.00032761	0.32760588	0.00026949	0.26949466	0.00020616	0.20615649
0.01402976	14.0297638	1	0.00074491	0.00054881	0.54880877	0.00039685	0.39684815	0.00032645	0.32645462	0.00024973	0.24972941

Packet delay per packet for IPACT, scenario 5

DBA IPACT SCENARIO 5			stddev	Confidence intervals							
AVERAGE				99%		95%		90%		80%	
sec	ms	load		sec	ms	sec	ms	sec	ms	sec	ms
0.00026615	0.26615149	0.05	7.937E-06	5.8476E-06	0.00584761	4.2285E-06	0.00422846	3.4784E-06	0.00347841	2.6609E-06	0.00266089
0.00030144	0.30143657	0.1	7.9314E-06	5.8435E-06	0.00584348	4.2255E-06	0.00422547	3.476E-06	0.00347595	2.659E-06	0.00265901
0.0003272	0.32719956	0.15	9.4653E-06	6.9735E-06	0.00697354	5.0426E-06	0.00504262	4.1482E-06	0.00414816	3.1732E-06	0.00317323
0.00036159	0.36158751	0.2	8.8067E-06	6.4883E-06	0.00648832	4.6918E-06	0.00469176	3.8595E-06	0.00385953	2.9524E-06	0.00295244
0.00039536	0.39535563	0.25	6.8957E-06	5.0804E-06	0.00508042	3.6737E-06	0.0036737	3.0221E-06	0.00302205	2.3118E-06	0.00231179
0.00043559	0.43558732	0.3	6.134E-06	4.5192E-06	0.00451921	3.2679E-06	0.00326788	2.6882E-06	0.00268822	2.0564E-06	0.00205642
0.00047869	0.47869456	0.35	2.1918E-06	1.6148E-06	0.00161478	1.1677E-06	0.00116766	9.6054E-07	0.00096054	7.3479E-07	0.00073479
0.00052764	0.52763557	0.4	5.3965E-06	3.9759E-06	0.00397588	2.875E-06	0.00287499	2.365E-06	0.00236502	1.8092E-06	0.00180918
0.00058799	0.58798958	0.45	2.5158E-06	1.8535E-06	0.00185349	1.3403E-06	0.00134027	1.1025E-06	0.00110253	8.4341E-07	0.00084341
0.00065746	0.65745525	0.5	1.1534E-05	8.4977E-06	0.00849772	6.1448E-06	0.00614477	5.0548E-06	0.0050548	3.8668E-06	0.00386679
0.00073429	0.73429143	0.55	8.0022E-06	5.8957E-06	0.00589565	4.2632E-06	0.0042632	3.507E-06	0.00350698	2.6828E-06	0.00268275
0.00085642	0.85641715	0.6	9.3986E-06	6.9244E-06	0.00692444	5.0071E-06	0.00500712	4.1189E-06	0.00411895	3.1509E-06	0.00315089
0.00110274	1.10274172	0.65	3.3168E-05	2.4436E-05	0.02443641	1.767E-05	0.01767017	1.4536E-05	0.01453581	1.112E-05	0.01111952
0.00175179	1.75178932	0.7	0.00015757	0.00011609	0.11608639	8.3943E-05	0.08394302	6.9053E-05	0.06905308	5.2824E-05	0.05282384
0.00598409	5.98409478	0.75	0.0014278	0.00105193	1.05193094	0.00076066	0.76065994	0.00062573	0.62573293	0.00047867	0.47866963
0.01253013	12.5301291	0.8	0.0030909	0.00227722	2.27721925	0.00164668	1.64667602	0.00135459	1.35458614	0.00103622	1.03622362
0.01889347	18.8934726	0.85	0.00468335	0.00345045	3.45045464	0.00249505	2.4950522	0.00205248	2.05247607	0.00157009	1.57009151
0.02466901	24.6690087	0.9	0.00622998	0.00458994	4.58993827	0.00331902	3.31902221	0.00273029	2.73028903	0.0020886	2.08860102
0.02989421	29.8942077	0.95	0.00765489	0.00563974	5.63974236	0.00407814	4.0781442	0.00335476	3.35475682	0.0025663	2.56630285
0.03439531	34.3953091	1	0.00880583	0.0064877	6.48769601	0.00469131	4.69130648	0.00385916	3.85915545	0.00295215	2.95215485

Packet delay per packet for DDSPON, scenario 5

DBA DDSPON SCENARIO 5			stddev	Confidence intervals							
AVERAGE				99%		95%		90%		80%	
sec	ms	load		sec	ms	sec	ms	sec	ms	sec	ms
0.00026746	0.26745627	0.05	8.018E-06	5.9072E-06	0.00590723	4.2716E-06	0.00427156	3.5139E-06	0.00351387	2.688E-06	0.00268802
0.0003081	0.30809535	0.1	3.0974E-06	2.282E-06	0.00228202	1.6501E-06	0.00165015	1.3574E-06	0.00135744	1.0384E-06	0.00103841
0.0003485	0.34849969	0.15	3.4459E-06	2.5387E-06	0.00253874	1.8358E-06	0.00183578	1.5101E-06	0.00151015	1.1552E-06	0.00115523
0.00038578	0.3857813	0.2	3.5173E-06	2.5914E-06	0.0025914	1.8739E-06	0.00187386	1.5415E-06	0.00154148	1.1792E-06	0.00117919
0.00042934	0.42934374	0.25	2.9296E-06	2.1584E-06	0.00215836	1.5607E-06	0.00156073	1.2839E-06	0.00128388	9.8214E-07	0.00098214
0.00047795	0.47795193	0.3	3.0815E-06	2.2703E-06	0.00227026	1.6416E-06	0.00164164	1.3504E-06	0.00135045	1.0331E-06	0.00103306
0.00053289	0.53289032	0.35	5.5515E-06	4.0901E-06	0.00409006	2.9576E-06	0.00295756	2.4329E-06	0.00243294	1.8611E-06	0.00186114
0.00059037	0.59037343	0.4	6.7713E-06	4.9888E-06	0.00498876	3.6074E-06	0.00360742	2.9675E-06	0.00296753	2.2701E-06	0.00227008
0.00066302	0.66301513	0.45	8.0582E-06	5.9369E-06	0.00593686	4.293E-06	0.00429299	3.5315E-06	0.00353149	2.7015E-06	0.0027015
0.00074321	0.74320919	0.5	8.4729E-06	6.2424E-06	0.0062424	4.5139E-06	0.00451393	3.7132E-06	0.00371324	2.8405E-06	0.00284054
0.00084159	0.84158859	0.55	1.7136E-05	1.2625E-05	0.01262473	9.129E-06	0.00912905	7.5097E-06	0.00750972	5.7447E-06	0.00574474
0.00097981	0.97981323	0.6	1.5025E-05	1.107E-05	0.01107003	8.0048E-06	0.00800483	6.5849E-06	0.00658492	5.0373E-06	0.0050373
0.00118321	1.18320762	0.65	1.9457E-05	1.4335E-05	0.01433514	1.0366E-05	0.01036586	8.5271E-06	0.00852715	6.523E-06	0.00652305
0.00226185	2.26184609	0.7	0.00018625	0.00013722	0.1372169	9.9223E-05	0.09922267	8.1622E-05	0.0816224	6.2439E-05	0.06243904
0.00473742	4.73742145	0.75	0.0005842	0.00043041	0.43041287	0.00031124	0.3112351	0.00025603	0.25602774	0.00019585	0.19585465
0.00681678	6.8167845	0.8	0.00072202	0.00053195	0.53195014	0.00038466	0.38465753	0.00031643	0.3164264	0.00024206	0.24205807
0.00919304	9.19304401	0.85	0.00063913	0.00047088	0.47088144	0.0003405	0.34049825	0.0002801	0.28010016	0.00021427	0.21426943
0.01093028	10.9302779	0.9	0.00061743	0.00045489	0.45489021	0.00032893	0.32893486	0.00027059	0.2705879	0.00020699	0.20699279
0.01277146	12.7714589	0.95	0.00063192	0.00046557	0.46556583	0.00033665	0.33665449	0.00027694	0.27693821	0.00021185	0.21185062
0.01405942	14.0594231	1	0.00075663	0.00055745	0.55744802	0.0004031	0.40309526	0.00033159	0.33159361	0.00025366	0.2536606

Queue Size

Queue size for IPACT, scenario 1

DBA IPACT SCENARIO 1			stddev	Confidence Intervals							
AVERAGE				**99%**		**95%**		**90%**		**80%**	
bits	***bytes***	***load***		***bits***	***bytes***	***bits***	***bytes***	***bits***	***bytes***	***bits***	***bytes***
6875.18977	859.398721	0.05	801.242819	590.315647	73.7894559	426.862112	53.357764	351.144665	43.8930832	268.616655	33.5770819
10243.7455	1280.468181	0.1	446.998048	329.325812	41.1657265	238.13821	29.7672762	195.896894	24.4871118	149.856096	18.7320119
12451.1553	1556.394417	0.15	191.483001	141.075101	17.6343876	102.012569	12.7515711	83.9174253	10.4896782	64.1946762	8.02433452
14543.1659	1817.895738	0.2	236.01073	173.880905	21.7351132	125.734716	15.7168396	103.431702	12.9289628	79.1225972	9.89032466
16852.8457	2106.605713	0.25	145.471485	107.176116	13.3970145	77.4999334	9.68749167	63.7528781	7.96910976	48.7693152	6.0961644
19474.7102	2434.338777	0.3	176.473244	130.016662	16.2520828	94.0161206	11.7520151	77.3393991	9.66742489	59.162655	7.39533187
22662.6763	2832.834537	0.35	174.803544	128.786511	16.0983139	93.1265881	11.6408235	76.6076532	9.57595665	58.6028881	7.32536102
26416.7107	3302.088834	0.4	244.443173	180.093508	22.5116885	130.2271	16.2783875	107.127221	13.3909026	81.9495737	10.2436967
30728.5842	3841.073019	0.45	313.922482	231.282388	28.9102985	167.242202	20.9052753	137.576528	17.1970659	105.242512	13.155314
36095.9114	4511.988928	0.5	392.307265	289.032378	36.1290472	209.001696	26.1252119	171.928659	21.4910824	131.521011	16.4401263
43645.1321	5455.64151	0.55	397.829551	293.100922	36.6376153	211.943694	26.4929617	174.348801	21.7936001	133.372357	16.6715446
56460.6767	7057.58459	0.6	526.307297	387.756901	48.4696126	280.390212	35.0487766	230.654173	28.8317716	176.444521	22.0555652
79584.639	9948.079877	0.65	873.373428	643.457873	80.4322341	465.289694	58.1612117	382.755905	47.8444881	292.798442	36.5998052
273250.761	34156.34513	0.7	31305.1668	23064.0816	2883.0102	16677.8276	2084.72845	13719.4893	1714.93617	10495.0572	1311.88214
772501.619	96562.70231	0.75	48469.0302	35709.558	4463.69475	25821.8758	3227.73448	21241.5525	2655.19406	16249.2424	2031.15529
1269242.31	158655.2883	0.8	63412.1601	46718.9089	5839.86362	33782.8283	4222.85353	27790.3792	3473.79739	21258.9267	2657.36583
1841314.33	230164.2911	0.85	64003.2353	47154.3836	5894.29795	34097.7236	4262.21545	28049.4179	3506.17723	21457.0846	2682.13558
2356113.16	294514.1449	0.9	81212.7933	59833.5255	7479.19069	43266.1156	5408.26446	35591.5067	4448.93833	27226.589	3403.32362
2918349.73	364793.7164	0.95	61482.6275	45297.3258	5662.16572	32754.8698	4094.35872	26944.7615	3368.09519	20612.0509	2576.50636
3423726.47	427965.8087	1	72181.1393	53179.4544	6647.4318	38454.5019	4806.81274	31633.3843	3954.17304	24198.7269	3024.84087

Queue size for DDSPON, scenario 1

DBA DDSPON SCENARIO 1			stddev	Confidence Intervals							
AVERAGE				**99%**		**95%**		**90%**		**80%**	
bits	***bytes***	***load***		***bits***	***bytes***	***bits***	***bytes***	***bits***	***bytes***	***bits***	***bytes***
5808.28676	726.0358449	0.05	1486.02755	1094.8308	136.853849	791.681176	98.960147	651.251573	81.4064466	498.190735	62.2738419
9894.20196	1236.775246	0.1	916.955432	675.566914	84.4458643	488.508006	61.0635008	401.855718	50.2319647	307.409308	38.4261636
12634.6907	1579.336332	0.15	428.721603	315.860641	39.4825801	228.401434	28.5501793	187.887243	23.4859053	143.728917	17.9661147
14790.0291	1848.753641	0.2	257.741729	189.891219	23.7364023	137.311906	17.1639882	112.955313	14.1194141	86.4079145	10.8009893
17750.104	2218.762994	0.25	392.661822	289.293597	36.1616997	209.190586	26.1488232	172.084044	21.5105054	131.639876	16.4549845
20677.85	2584.731249	0.3	347.814098	256.252037	32.0315046	185.297961	23.1622451	152.429528	19.0536911	116.604676	14.5755845
23935.2876	2991.910944	0.35	421.269985	310.370662	38.7963327	224.431585	28.0539481	184.621571	23.0776964	141.230763	17.6538453
28097.5446	3512.193074	0.4	430.075992	316.858487	39.6073109	229.122985	28.6403731	188.480803	23.5601004	144.182976	18.022872
33112.7787	4139.097341	0.45	568.423291	418.78586	52.3482325	302.827509	37.8534386	249.111507	31.1389384	190.563908	23.8204886
38551.9162	4818.989529	0.5	622.592415	458.694962	57.3368702	331.686109	41.4607636	272.851126	34.1063907	208.724107	26.0905134
44981.89	5622.736247	0.55	729.661474	537.578091	67.1972614	388.72715	48.5908938	319.774141	39.9717676	244.619009	30.5773761
54815.1289	6851.891111	0.6	1056.42615	778.321969	97.2902461	562.811033	70.3513792	462.978762	57.8723452	354.166868	44.2708585
67441.6312	8430.203895	0.65	1165.28998	858.527391	107.315924	620.808236	77.6010294	510.688333	63.8360416	390.663465	48.8329331
143330.598	17916.32473	0.7	14964.2378	11024.9022	1378.11277	7972.19767	996.524709	6558.0772	819.75965	5016.76071	627.095089
315264.218	39408.02724	0.75	39281.4835	28940.633	3617.57912	20927.2103	2615.90129	17215.1101	2151.88877	13169.1173	1646.13967
458129.156	57266.14455	0.8	46244.2486	34070.4501	4258.80627	24636.6234	3079.57793	20266.5419	2533.31774	15503.3843	1937.92304
655490.797	81936.34965	0.85	47009.8876	34634.5347	4329.31684	25044.5176	3130.5647	20602.0832	2575.26041	15760.0648	1970.0081
826987.949	103373.4937	0.9	74275.0668	54722.1555	6840.26943	39570.0418	4946.25523	32551.048	4068.881	24900.7161	3112.58952
1013878.84	126734.8549	0.95	53109.9772	39128.7757	4891.09696	28294.3404	3536.79255	23275.4475	2909.43094	17805.1199	2225.63998
1172869.78	146608.7226	1	57128.7561	42089.6111	5261.20138	30435.3448	3804.4181	25036.6774	3129.58467	19152.4155	2394.05193

Queue size for IPACT, scenario 2

DBA IPACT SCENARIO 2			stddev	Confidence Intervals							
AVERAGE				**99%**		**95%**		**90%**		**80%**	
bits	***bytes***	***load***		***bits***	***bytes***	***bits***	***bytes***	***bits***	***bytes***	***bits***	***bytes***
7539.685	942.460625	0.05	782.52475	576.525109	72.0656387	416.89006	52.1112575	342.941472	42.8676839	262.341422	32.7926778
10143.1034	1267.88792	0.1	287.823387	212.05388	26.506735	153.337909	19.1672387	126.138599	15.7673249	96.4927905	12.0615988
12365.6904	1545.7113	0.15	276.086721	203.406892	25.4258615	147.085201	18.3856501	120.995006	15.1243757	92.5580733	11.5697592
14473.1948	1809.14935	0.2	211.01596	155.466009	19.4332511	112.418753	14.0523441	92.4777446	11.5597181	70.7431007	8.84288759
17040.6561	2130.08201	0.25	220.224217	162.250192	20.281274	117.324452	14.6655565	96.5132633	12.0641579	73.8301689	9.22877111
19634.0535	2454.25668	0.3	212.835234	156.806359	19.6007948	113.387971	14.1734964	93.2750413	11.6593802	71.3530122	8.91912653
22609.1101	2826.13876	0.35	221.618283	163.27727	20.4096588	118.06714	14.7583926	97.1242127	12.1405266	74.2975295	9.28719119
26338.9937	3292.37422	0.4	196.220925	144.565767	18.0707209	104.536698	13.0670873	85.9938206	10.7492276	65.7830653	8.22288316
30878.772	3859.84649	0.45	303.081521	223.295311	27.9119139	161.46668	20.1833351	132.825477	16.6031846	101.60808	12.70101
36029.1618	4503.64522	0.5	365.180859	269.046998	33.6308747	194.550103	24.3187628	160.040511	20.0050639	122.426883	15.3033604
43097.6604	5387.20755	0.55	423.015232	311.656472	38.957059	225.361365	28.1701706	185.386425	23.1733032	141.815857	17.7269821
56624.3304	7078.0413	0.6	567.382	418.018689	52.2523361	302.272761	37.7840951	248.655162	31.0818952	190.214816	23.776852
83032.1173	10379.0147	0.65	1646.58246	1213.11963	151.639953	877.216805	109.652101	721.614763	90.2018453	552.016769	69.0020962
259270.692	32408.8364	0.7	19891.7244	14655.228	1831.9035	10597.3162	1324.66452	8717.54822	1089.69353	6668.70061	833.587576
763181.953	95397.7442	0.75	71385.4108	52593.2014	6574.15018	38030.5776	4753.8222	31284.6563	3910.58204	23931.959	2991.49487
1260307.98	157538.498	0.8	79100.0947	58276.9947	7284.62434	42140.5754	5267.57193	34665.6165	4333.20206	26518.3067	3314.78834
1819016.48	227377.06	0.85	62946.406	46375.7646	5796.97057	33534.6978	4191.83722	27586.2624	3448.2828	21102.7826	2637.84782
2331749.03	291468.628	0.9	70307.2073	51798.835	6474.85437	37456.1647	4682.02059	30812.1336	3851.5167	23570.4913	2946.31141
2868386.25	358548.282	0.95	71288.9911	52522.1642	6565.27053	37979.21	4747.40125	31242.4004	3905.30005	23899.6343	2987.45429
3402936.45	425367.056	1	74362.1326	54786.3012	6848.28765	39616.4262	4952.05327	32589.2046	4073.65058	24929.905	3116.23812

Queue size for DDSPON, scenario 2

DBA DDSPON SCENARIO 2			stddev	Confidence Intervals							
AVERAGE				**99%**		**95%**		**90%**		**80%**	
bits	***bytes***	***load***		***bits***	***bytes***	***bits***	***bytes***	***bits***	***bytes***	***bits***	***bytes***
5554.02624	694.25328	0.05	882.668028	650.30567	81.2882087	470.241392	58.780174	386.829263	48.3536579	295.914456	36.9893071
9901.33177	1237.66647	0.1	588.790936	433.791722	54.2239652	313.678371	39.2097964	258.037628	32.2547034	197.392161	24.6740201
12421.8752	1552.7344	0.15	352.373954	259.611511	32.4514388	187.727224	23.465903	154.427885	19.3034857	118.133368	14.766671
15119.1677	1889.89596	0.2	238.892882	176.004331	22.0005413	127.270183	15.9087728	104.694805	13.0868507	80.0888386	10.0111048
17772.6247	2221.57809	0.25	355.361134	261.812315	32.7265394	189.318644	23.6648305	155.737017	19.4671271	119.13482	14.8918525
21104.7452	2638.09315	0.3	386.948845	285.084561	35.6355702	206.146997	25.7683746	169.580331	21.1975414	129.7246	16.215575
24371.0239	3046.37799	0.35	420.651184	309.914759	38.7393449	224.101918	28.0127398	184.350381	23.0437976	141.023309	17.6279137
27977.1272	3497.1409	0.4	471.620446	347.466364	43.4332955	251.255793	31.4069741	206.687661	25.8359576	158.110755	19.7638443
32672.4303	4084.05379	0.45	483.40925	356.151765	44.5189707	257.536278	32.1920348	211.854104	26.481763	162.062951	20.2578689
37980.5586	4747.56983	0.5	581.519416	428.434429	53.5543037	309.804469	38.7255586	254.850884	31.8563605	194.954384	24.369298
45121.4879	5640.18598	0.55	1006.47061	741.517224	92.689653	536.197219	67.0246524	441.085746	55.1357183	337.419273	42.1774091
54124.0781	6765.50977	0.6	1358.42809	1000.82189	125.102737	723.702564	90.4628205	595.331109	74.4163887	455.413016	56.926627
68594.2009	8574.27512	0.65	1368.32698	1008.1149	126.014362	728.976196	91.1220246	599.669297	74.9586622	458.731619	57.3414523
146745.522	18343.1902	0.7	14315.284	10546.7855	1318.34818	7626.46754	953.308443	6273.67321	784.209151	4799.19896	599.899869
292037.848	36504.731	0.75	34452.4937	25382.8747	3172.85934	18354.566	2294.32075	15098.8054	1887.35067	11550.1985	1443.77481
474454.251	59306.7814	0.8	47062.8291	34673.5393	4334.19242	25072.7222	3134.09027	20625.2848	2578.16061	15777.8135	1972.22668
637497.729	79687.2161	0.85	57482.185	42349.9998	5293.74998	30623.6341	3827.95426	25191.5676	3148.94595	19270.9025	2408.86282
819938.009	102492.251	0.9	56175.7628	41387.4932	5173.43666	29927.6376	3740.9547	24619.028	3077.37851	18832.9245	2354.11556
995219.001	124402.375	0.95	57553.0774	42402.2298	5300.27873	30661.402	3832.67525	25222.6362	3152.82952	19294.6692	2411.83365
1185643.09	148205.386	1	60130.041	44300.8077	5537.60096	32034.2793	4004.28491	26351.9904	3293.99881	20158.5962	2519.82453

Queue size for IPACT, scenario 3

DBA IPACT SCENARIO 3			stddev	Confidence Intervals							
AVERAGE				**99%**		**95%**		**90%**		**80%**	
bits	***bytes***	***load***		***bits***	***bytes***	***bits***	***bytes***	***bits***	***bytes***	***bits***	***bytes***
7186.49304	898.31163	0.05	1728.22557	1273.27019	159.158773	920.712171	115.089021	757.394855	94.6743569	579.387622	72.4234527
9579.54847	1197.44356	0.1	2072.44752	1526.87571	190.859464	1104.09642	138.012052	908.250125	113.531266	694.78803	86.8485038
11565.7586	1445.71982	0.15	2793.89627	2058.40308	257.300385	1488.44824	186.05603	1224.42504	153.05313	936.653725	117.081716
13442.3834	1680.29792	0.2	3276.0343	2413.61827	301.702284	1745.30728	218.163409	1435.72203	179.465254	1098.2905	137.286313
15551.1041	1943.88802	0.25	4040.00734	2976.47541	372.059426	2152.31391	269.039239	1770.53322	221.316652	1354.41246	169.301557
17977.1968	2247.14959	0.3	4482.68336	3302.61697	412.827121	2388.14956	298.518695	1964.53598	245.566998	1502.8196	187.85245
20789.9229	2598.74036	0.35	4655.54143	3429.97015	428.746268	2480.2397	310.029962	2040.29103	255.036379	1560.77026	195.096283
23571.8124	2946.47654	0.4	5809.54123	4280.1795	535.022438	3095.03309	386.879136	2546.03145	318.253931	1947.6487	243.456087
27739.2721	3467.40901	0.45	6361.91885	4687.14371	585.892964	3389.31227	423.664033	2788.11093	348.513867	2132.83329	266.604162
32058.7402	4007.34252	0.5	8101.72349	5968.94478	746.118098	4316.19319	539.524149	3550.58032	443.82254	2716.1028	339.51285
37531.0465	4691.38081	0.55	8952.79782	6595.97379	824.496724	4769.60304	596.20038	3923.56364	490.445455	3001.42547	375.178183
44103.3809	5512.92261	0.6	11296.9462	8323.02508	1040.37814	6018.44806	752.306008	4950.88665	618.860832	3787.3012	473.41265
60025.6169	7503.20212	0.65	15248.0102	11233.9715	1404.24644	8123.37743	1015.42218	6682.44047	835.305058	5111.89542	638.986927
98965.2373	12370.6547	0.7	25623.3689	18878.0171	2359.75213	13650.8498	1706.35622	11229.4414	1403.68018	8590.23443	1073.7793
367109.574	45888.6967	0.75	108137.476	79670.2856	9958.7857	57610.2405	7201.28006	47391.2489	5923.90612	36253.0889	4531.63611
824398.956	103049.869	0.8	227342.384	167494.502	20936.8127	121116.655	15139.5819	99632.7999	12454.1	76216.5343	9527.06679
1314381.12	164297.639	0.85	352631.883	259801.54	32475.1925	187864.636	23483.0795	154540.923	19317.6153	118219.839	14777.4798
1823340.73	227917.592	0.9	487918.632	359474.052	44934.2565	259938.651	32492.3314	213830.34	26728.7925	163574.721	20446.8402
2323542.61	290442.826	0.95	622227.436	458426.064	57303.258	331491.667	41436.4583	272691.174	34086.3967	208601.748	26075.2185
2832061.74	354007.718	1	755973.503	556963.478	69620.4348	402744.883	50343.1104	331305.387	41413.1734	253440.117	31680.0146

Queue size for DDSPON, scenario 3

DBA DDSPON SCENARIO 3			stddev	Confidence Intervals							
AVERAGE				**99%**		**95%**		**90%**		**80%**	
bits	***bytes***	***load***		***bits***	***bytes***	***bits***	***bytes***	***bits***	***bytes***	***bits***	***bytes***
5777.87552	722.23444	0.05	1142.84915	841.99411	105.249264	608.852884	76.1066105	500.853639	62.6067049	383.140177	47.8925221
10702.2837	1337.78546	0.1	830.547907	611.906171	76.4882713	442.474398	55.3092997	363.98762	45.4984525	278.441186	34.8051482
13123.5124	1640.43904	0.15	888.403324	654.531149	81.8163936	473.296871	59.1621089	389.342757	48.6678446	297.837214	37.2296518
16259.0764	2032.38454	0.2	1168.84839	861.149053	107.643632	622.703981	77.8379976	512.247808	64.030976	391.856423	48.9820529
19038.9421	2379.86777	0.25	1048.6536	772.595536	96.574442	558.670203	69.8337753	459.572438	57.4465548	351.561118	43.9451397
22689.732	2836.21651	0.3	1470.52443	1083.40887	135.426109	783.421888	97.927736	644.457329	80.5571662	492.993314	61.6241642
26509.54	3313.69251	0.35	1685.96508	1242.13477	155.266847	898.197897	112.274737	738.874197	92.3592747	565.219794	70.6524742
31312.1451	3914.01813	0.4	1441.0511	1061.6944	132.7118	767.719975	95.9649969	631.540646	78.9425808	483.112382	60.3890478
36288.8038	4536.10048	0.45	1901.27388	1400.76353	175.095441	1012.90366	126.612957	833.233277	104.15416	637.402068	79.6752584
42721.3918	5340.17398	0.5	2035.18715	1499.42414	187.428017	1084.24596	135.530745	891.92077	111.490096	682.296493	85.2870617
50729.6185	6341.20231	0.55	2684.03364	1977.46178	247.182723	1429.91892	178.739865	1176.27774	147.034718	899.822278	112.477785
63637.1184	7954.63981	0.6	2563.35723	1888.55344	236.06918	1365.62856	170.703571	1123.39131	140.423913	859.365511	107.420689
97337.5703	12167.1963	0.65	8692.43736	6404.15322	800.519153	4630.896	578.862	3809.46067	476.182584	2914.13962	364.267453
244021.976	30502.747	0.7	55784.5872	41099.2946	5137.41183	29719.2388	3714.90486	24447.5954	3055.94942	18701.7829	2337.72286
422311.835	52788.9794	0.75	105111.806	77441.1233	9680.14041	55998.3148	6999.78935	46065.2491	5758.15614	35238.733	4404.84163
580045.919	72505.7398	0.8	104052.981	76661.034	9582.62925	55434.2258	6929.27823	45601.2191	5700.15239	34883.762	4360.47025
776195.373	97024.4216	0.85	98341.5026	72453.102	9056.63775	52391.4355	6548.92944	43098.1635	5387.27044	32968.9887	4121.12359
946567.124	118320.891	0.9	115593.844	85163.7645	10645.4706	61582.6203	7697.82754	50659.0021	6332.37526	38752.8362	4844.10452
1135133.93	141891.742	0.95	106769.444	78662.3875	9832.79844	56881.421	7110.17763	46791.7086	5848.96358	35794.4559	4474.30699
1290601.93	161325.241	1	131092.319	96582.266	12072.7832	69839.4329	8729.92912	57451.2088	7181.4011	43948.6999	5493.58749

Queue size for IPACT, scenario 4

DBA IPACT SCENARIO 4			stddev	Confidence Intervals							
AVERAGE				**99%**		**95%**		**90%**		**80%**	
bits	***bytes***	***load***		***bits***	***bytes***	***bits***	***bytes***	***bits***	***bytes***	***bits***	***bytes***
6512.15679	814.019598	0.05	1713.41232	1262.35653	157.794566	912.820412	114.102552	750.902948	93.8628685	574.421479	71.8026849
9202.33523	1150.2919	0.1	2423.45457	1785.48015	223.185019	1291.09542	161.386928	1062.07896	132.75987	812.463143	101.557893
11523.2754	1440.40943	0.15	2910.46599	2144.28581	268.035727	1550.55075	193.818844	1275.51172	159.438965	975.733722	121.966715
13462.4878	1682.81097	0.2	3216.41181	2369.6914	296.211426	1713.54339	214.192924	1409.59248	176.19906	1078.30206	134.787758
15555.4946	1944.43682	0.25	3870.91399	2851.89588	356.486986	2062.22943	257.778679	1696.42806	212.053507	1297.72392	162.21549
17915.5222	2239.44027	0.3	4398.83315	3240.84032	405.10504	2343.47836	292.934795	1927.78863	240.973579	1474.70881	184.338602
20675.1585	2584.39481	0.35	5018.07065	3697.06355	462.132943	2673.37714	334.172142	2199.16946	274.896183	1682.30818	210.288523
23633.8407	2954.23009	0.4	5970.496	4398.76293	549.845366	3180.78174	397.597718	2616.56987	327.071234	2001.60878	250.201098
27470.1091	3433.76363	0.45	6628.61427	4883.63156	610.453945	3531.39425	441.424281	2904.9902	363.123775	2222.24293	277.780367
31846.133	3980.76663	0.5	8307.33964	6120.43248	765.05406	4425.73519	553.216899	3640.6916	455.08645	2785.03561	348.129452
37289.1595	4661.14493	0.55	9339.8023	6881.09934	860.137418	4975.77967	621.972459	4093.16836	511.646045	3131.16872	391.39609
45029.4219	5628.67774	0.6	11375.7599	8381.09111	1047.63639	6060.43609	757.554511	4985.42678	623.178347	3813.72351	476.715438
59713.1347	7464.14184	0.65	15218.756	11212.4185	1401.55231	8107.79226	1013.47403	6669.61982	833.702477	5102.08795	637.760994
97994.3669	12249.2959	0.7	25387.6234	18704.3315	2338.04144	13525.2563	1690.65704	11126.1259	1390.76574	8511.20073	1063.90009
366476.601	45809.5751	0.75	107904.332	79498.517	9937.31462	57486.0331	7185.75414	47289.0737	5911.13421	36174.9275	4521.86593
823035.83	102879.479	0.8	226995.661	167239.054	20904.8817	120931.939	15116.4923	99480.8486	12435.1061	76100.2955	9512.53694
1316613.75	164576.719	0.85	353040.676	260102.718	32512.8398	188082.42	23510.3025	154720.076	19340.0095	118356.887	14794.6108
1826002.09	228250.261	0.9	488781.834	360110.017	45013.7521	260398.522	32549.8153	214208.639	26776.0799	163864.11	20483.0138
2332834.34	291604.292	0.95	624126.821	459825.435	57478.1794	332503.564	41562.9455	273523.579	34190.4474	209238.517	26154.8146
2830567.93	353820.991	1	755774.54	556816.892	69602.1115	402638.886	50329.8607	331218.192	41402.274	253373.414	31671.6768

Queue size for DDSPON, scenario 4

DBA DDSPON SCENARIO 4			stddev	Confidence Intervals							
AVERAGE				**99%**		**95%**		**90%**		**80%**	
bits	***bytes***	***load***		***bits***	***bytes***	***bits***	***bytes***	***bits***	***bytes***	***bits***	***bytes***
5592.70301	699.087877	0.05	842.153832	620.456836	77.5571044	448.657454	56.0821817	369.073917	46.1342396	282.332072	35.291509
9263.12788	1157.89099	0.1	822.835717	606.224214	75.7780268	438.365728	54.795716	360.607753	45.0759691	275.855674	34.4819592
12135.0738	1516.88422	0.15	507.40862	373.833301	46.7291626	270.321942	33.7902428	222.371828	27.7964784	170.10874	21.2635925
14719.2866	1839.91082	0.2	330.735108	243.669091	30.4586363	176.199129	22.0248911	144.944661	18.1180826	110.878945	13.8598681
17322.1399	2165.26748	0.25	302.76132	223.059402	27.8824253	161.296093	20.1620116	132.685148	16.5856435	101.500732	12.6875915
20164.6397	2520.57997	0.3	304.074635	224.026987	28.0033734	161.995762	20.2494702	133.260709	16.6575886	101.941021	12.7426277
23248.0197	2906.00246	0.35	377.724609	278.288606	34.7860757	201.232785	25.1540982	165.53781	20.6922262	126.632175	15.8290219
27088.3599	3386.04498	0.4	423.257585	311.835026	38.9793782	225.490478	28.1863098	185.492637	23.1865796	141.897105	17.7371382
31848.7762	3981.09702	0.45	399.742509	294.510294	36.8137867	212.962822	26.6203527	175.187155	21.8983943	134.013676	16.7517095
37091.0431	4636.38039	0.5	582.887535	429.442392	53.680299	310.533334	38.8166668	255.450462	31.9313078	195.413046	24.4266308
44127.9636	5515.99545	0.55	674.770135	497.136897	62.1421122	359.48379	44.9354737	295.718012	36.9647515	226.216688	28.277086
54524.3814	6815.54767	0.6	1117.48971	823.310541	102.913818	595.342641	74.4178301	489.739864	61.217483	374.638424	46.829803
66936.5834	8367.07292	0.65	1502.6962	1107.11143	138.388928	800.561402	100.070175	658.556611	82.3195763	503.778902	62.9723627
128373.273	16046.6591	0.7	9680.28201	7131.94777	891.493471	5157.17024	644.64628	4242.38359	530.297949	3245.31454	405.664318
300198.56	37524.82	0.75	37445.2633	27587.7977	3448.47472	19948.964	2493.6205	16410.3866	2051.29833	12553.5245	1569.19056
452928.563	56616.0704	0.8	50593.0734	37274.4468	4659.30585	26953.4598	3369.18248	22172.4144	2771.5518	16961.3278	2120.16598
645129.122	80641.1402	0.85	48229.8064	35533.3099	4441.66373	25694.4294	3211.80367	21136.7127	2642.08908	16169.0426	2021.13032
816752.156	102094.02	0.9	48848.0951	35988.8341	4498.60426	26023.8227	3252.97784	21407.6777	2675.95971	16376.3239	2047.04049
1004831.49	125603.936	0.95	55221.0534	40684.1111	5085.51388	29419.0162	3677.37702	24200.6266	3025.07833	18512.8581	2314.10727
1159524.89	144940.611	1	64680.6589	47653.4755	5956.68443	34458.621	4307.32763	28346.2988	3543.28735	21684.1909	2710.52386

Queue size for IPACT, scenario 5

DBA IPACT SCENARIO 5			stddev	Confidence Intervals							
AVERAGE				**99%**		**95%**		**90%**		**80%**	
bits	***bytes***	***load***		***bits***	***bytes***	***bits***	***bytes***	***bits***	***bytes***	***bits***	***bytes***
6618.59827	827.324784	0.05	1674.18695	1233.45723	154.182154	891.923096	111.490387	733.71243	91.7140537	561.271174	70.1588967
9704.78074	1213.09759	0.1	2099.71412	1546.96438	193.370547	1118.6227	139.827837	920.199714	115.024964	703.929159	87.9911449
11408.516	1426.0645	0.15	2859.09429	2106.43772	263.304715	1523.18248	190.39781	1252.99807	156.624759	958.51136	119.81392
13483.7332	1685.46665	0.2	3505.81361	2582.90818	322.863522	1867.7222	233.465275	1536.42282	192.052852	1175.32401	146.915502
15551.4801	1943.93501	0.25	3966.24084	2922.12794	365.265993	2113.01481	264.126851	1738.20505	217.275631	1329.68224	166.21028
17936.383	2242.04787	0.3	4435.73078	3268.02465	408.503082	2363.13557	295.391947	1943.95902	242.994877	1487.07874	185.884843
20713.0641	2589.13301	0.35	4619.04013	3403.07782	425.384727	2460.79363	307.599204	2024.29434	253.036792	1548.5332	193.566651
23583.8022	2947.97528	0.4	5851.50973	4311.0998	538.887475	3117.39181	389.673976	2564.42414	320.553018	1961.71864	245.21483
27469.2984	3433.6623	0.45	6728.32106	4957.09054	619.636317	3584.51304	448.06413	2948.6867	368.585838	2255.66963	281.958704
31793.2715	3974.15893	0.5	8301.12848	6115.85641	764.482051	4422.4262	552.803275	3637.96956	454.746195	2782.95332	347.869165
37275.7815	4659.47269	0.55	8987.13179	6621.26934	827.658668	4787.89446	598.486807	3938.61051	492.326313	3012.93593	376.616991
44915.8824	5614.4853	0.6	11232.7114	8275.70015	1034.46252	5984.22701	748.028377	4922.73578	615.341973	3765.76651	470.720813
59900.35	7487.54375	0.65	15129.3209	11146.5271	1393.31589	8060.14569	1007.51821	6630.42487	828.803108	5072.10482	634.013102
100358.439	12544.8049	0.7	25494.1347	18782.8037	2347.85047	13582.0003	1697.75003	11172.8045	1396.60057	8546.90865	1068.36358
369457.654	46182.2067	0.75	108848.16	80193.8816	10024.2352	57988.8571	7248.60713	47702.706	5962.83825	36491.3455	4561.41819
823938.716	102992.34	0.8	227201.994	167391.069	20923.8837	121041.862	15130.2328	99571.274	12446.4092	76169.4686	9521.18357
1316999.31	164624.913	0.85	353273.414	260274.188	32534.2735	188206.411	23525.8014	154822.074	19352.7592	118434.912	14804.364
1824742.32	228092.79	0.9	488702.38	360051.478	45006.4348	260356.193	32544.5241	214173.818	26771.7272	163837.473	20479.6841
2333471.09	291683.887	0.95	624423.586	460044.077	57505.5096	332661.666	41582.7082	273653.637	34206.7046	209338.007	26167.2509
2827347.78	353418.473	1	755097.676	556318.213	69539.7766	402278.287	50284.7858	330921.556	41365.1945	253146.496	31643.312

Queue size for DDSPON, scenario 5

DBA DDSPON SCENARIO 5			stddev	Confidence Intervals							
AVERAGE				**99%**		**95%**		**90%**		**80%**	
bits	***bytes***	***load***		***bits***	***bytes***	***bits***	***bytes***	***bits***	***bytes***	***bits***	***bytes***
5109.11218	638.639023	0.05	1111.37585	818.806158	102.35077	592.085485	74.0106856	487.060467	60.8825584	372.588754	46.5735943
9322.23992	1165.27999	0.1	513.75805	378.511243	47.3139054	273.704601	34.2130751	225.154465	28.1443082	172.237386	21.5296733
12223.7619	1527.97024	0.15	574.603845	423.339383	52.9174228	306.120198	38.2650248	251.820135	31.4775169	192.635939	24.0794924
14664.6242	1833.07803	0.2	523.115257	385.405166	48.1756457	278.689653	34.8362067	229.255261	28.6569077	175.37439	21.9217987
17247.9741	2155.99677	0.25	216.173942	159.266152	19.908269	115.166668	14.3958335	94.7382301	11.8422788	72.4723141	9.05903926
20096.287	2512.03587	0.3	361.158565	266.083573	33.2604466	192.407225	24.0509032	158.277741	19.7847176	121.078409	15.1348011
23514.9607	2939.37009	0.35	405.375661	298.660519	37.3325648	215.963884	26.9954855	177.655884	22.2069855	135.902191	16.9877738
27167.9297	3395.99121	0.4	557.38384	410.652544	51.3315681	296.946241	37.1182801	244.273468	30.5341835	186.862932	23.3578666
31748.6049	3968.57561	0.45	668.566166	492.566123	61.5707653	356.178625	44.5223281	292.999122	36.6248903	224.136807	28.0171009
37114.0086	4639.25108	0.5	497.1534	366.277767	45.7847209	264.858474	33.1073092	217.877477	27.2346847	166.670677	20.8338347
43981.6405	5497.70506	0.55	887.863857	654.133697	81.7667121	473.00947	59.1261837	389.106335	48.6382919	297.656358	37.2070448
53175.2238	6646.90297	0.6	1010.68733	744.623888	93.077986	538.443673	67.3054592	442.933721	55.3667151	338.832926	42.3541158
66358.4219	8294.80274	0.65	1320.02082	972.525342	121.565668	703.241094	87.9051367	578.499126	72.3123908	442.536981	55.3171227
133475.224	16684.403	0.7	11882.2184	8754.22438	1094.27805	6330.25183	791.281479	5207.3822	650.922774	3983.5137	497.939213
299430.749	37428.8436	0.75	38862.9759	28632.2975	3579.03719	20704.2504	2588.0313	17031.6992	2128.9624	13028.8127	1628.60159
455120.256	56890.0319	0.8	51609.5178	38023.3122	4752.91403	27494.9706	3436.87132	22617.8712	2827.2339	17302.0908	2162.76135
647284.334	80910.5417	0.85	47953.12	35329.4612	4416.18264	25547.0247	3193.37808	21015.4548	2626.93185	16076.2835	2009.53543
817052.923	102131.615	0.9	50381.559	37118.6136	4639.8267	26840.7755	3355.09694	22079.7182	2759.96478	16890.4176	2111.30221
1006999.34	125874.918	0.95	56298.387	41477.8366	5184.72958	29992.9657	3749.12071	24672.7681	3084.09601	18874.0343	2359.25428
1161204.66	145150.582	1	65879.9667	48537.0655	6067.13318	35097.5523	4387.19403	28871.8954	3608.98693	22086.2588	2760.78235