Universidade Estadual de Campinas
Instituto de Computação

INSTITUTO DE COMPUTAÇÃO

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Bandwidth Management Mechanisms for Ethernet Passive Optical Networks with Multi-ONU Customers

Mecanismos para Gerenciamento de Banda Passante em Redes Ópticas Passivas Ethernet com Clientes Locatários de Múltiplas Unidades Ópticas de Redes

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Dissertação apresentada ao Instituto de Computação da Universidade Estadual de Campinas como parte dos requisitos para a obtenção do título de Mestre em Ciência da Computação.

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Resumo

As atuais redes de acesso banda larga à Internet necessitam dar suporte às altas demandas de diversas aplicações tais como voz sobre IP (VoIP), streaming de vídeo UHD, videoconferência, internet das coisas (IoT) e jogos interativos. A tecnologia de redes ópticas passivas (PONs) é considerada promissora para fornecer alta capacidade de acesso com um custo-benefício aceitável. Existem duas diferentes tecnologias que disputam o mercado das redes ópticas; Ethernet PON (EPON) e Gigabit Capable PON (GPON).

Devido ao alto custo de aquisição e manutenção de uma infraestrutura PON, muitas empresas (clientes) recorrem a fornecedores de infraestrutura (InP) para reduzir os altos custo, por meio do aluguel de uma porção dos recursos da PON. Esses clientes podem ser, por exemplo, operadores de rede móvel ou provedores de serviços virtuais, que podem adquirir múltiplas unidades da rede óptica (ONU) conectadas em uma única PON. Essa facilidade de alugar múltiplas ONUs pode gerar problemas de balanceamento de carga entre ONUs, uma vez que os atuais algoritmos de alocação de banda passante (DBA) são capazes de garantir banda para uma única ONU. Consequentemente, picos de demanda de banda passante podem ultrapassar a banda garantida em algumas ONUs e, ao mesmo tempo, subutilizar a banda garantida em outras ONUs de um mesmo cliente.

Nesta dissertação, aborda-se o problema de gerenciamento de largura de banda para clientes multi-ONU nas redes EPON. Propõe-se um algoritmo de alocação dinâmica de banda passante (DBA) (MOS-IPACT) para dar suporte ao contrato de serviço (SLA) para clientes com várias ONUs. O mecanismo proposto distribui a largura de banda agregada entre ONUs de um mesmo cliente, com o objetivo de melhorar a utilização da largura de banda. Além disso propõe-se um algoritmo DBA para EPONs (subMOS-IPACT) com o objetivo de garantir banda passante em diferentes níveis de granularidade. Este algoritmo é fundamental para clientes multi-ONU e que oferecem diversos tipos de serviços. Por exemplo, um operador da rede virtual pode alugar as ONUs de um InP para oferecer serviços corporativos e residenciais. Introduz-se, também, um algoritmo DBA para EPONs (coopMOS-IPACT) que permite a cooperação entre clientes. O algoritmo proposto permite que clientes cooperativos compartilhem banda passante não utilizada a fim de aumentar a banda disponível para alocação mas sem afetar seus SLAs individuais.

Os resultados mostram que os três algoritmos propostos são capazes de garantir banda passante para clientes multi-ONU, mesmo em condições de tráfego desbalanceadas; Além de garantir banda passante em diferentes níveis de granularidade aumentando o suporte aos requisitos de qualidade de serviço (QoS). Resultados derivados por simulação mostraram que os algoritmos distribuem eficientemente a largura de banda entre os clientes multi-ONU bem como para clientes convencionais que possuem uma única ONU. Por fim, este trabalho mostra os benefícios do modelo de clientes cooperativos para aumentar a largura de banda disponível.

Abstract

Current broadband access networks need to support the Quality of Service (QoS) requirements of diverse application such as voice over IP (VoIP), ultra-high video streaming, video conferencing, Internet of Things (IoT) and interactive gaming. Passive Optical Networks (PONs) is considered a promising solution to provides high access capacity with acceptable cost-benefit. Two different technologies share the optical access networks market: Ethernet PON (EPON) and Gigabit Capable PON (GPON).

However, the deployment of PON infrastructure involves significant costs. On the other hand, Infrastructure Provider (InP) can alleviate these costs by leasing their PONs to several enterprises (*customers*). These customers can be Mobile Network Operators (MNOs), multi-site enterprises, or virtual service providers. New scenarios are envisioned in which customers owning multiple Optical Network Units (ONUs) (multi-ONU customers) are connected to a single PON. However, current EPON Dynamic Bandwidth Allocation (DBA) algorithms are able to support only guaranteed bandwidth for individual ONUs. Consequently, peaks of bandwidth demand may surpass the guaranteed bandwidth for some ONUs and, at the same time, underutilize the bandwidth in other ONUs of a multi-ONU customer.

In this work, the bandwidth management problem for multi-ONU customers in EPON network is addressed. This dissertation proposes a mechanisms for the support of multi-ONU Service Level Agreements (SLA) in DBA algorithms for EPONs. The proposed DBA algorithms (MOS-IPACT) allows customers owning multiple ONUs to redistribute the aggregated bandwidth of the group of ONUs to better balance the bandwidth utilization. This dissertation also proposes a DBA algorithm for EPON networks (subMOS-IPACT) with the objective of assuring bandwidth at different levels of granularity. This algorithm is quite important for multi-ONU customers offering diverse type of services. For example, a virtual network operator can lease ONUs from an InP to offer enterprise and residential services to its client.This work also introduce a DBA algorithm for EPONs (coopMOS-IPACT), which allows cooperation between customers. The proposed DBA algorithm allows cooperative customers share the unused bandwidth without affecting their individual multi-ONU SLAs.

Results show that the three proposed Dynamic Bandwidth Allocation (DBA) algorithms are able to guarantee bandwidth for multi-ONU customers even in unbalancing traffic conditions. Furthermore, assuring bandwidth at different levels of granularity improves the Quality of Service (QoS) providing. Simulation results showed that the mechanisms efficiently distributes bandwidth between multi-ONU customers and traditional customers owning a single ONU. Finally, this work show the benefits of cooperative customers model in order to increase the available bandwidth.

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List of Acronyms

10G-EPON 10 Gbit/s Ethernet Passive Optical Network

AF Assured Forwarding

Alloc-ID Allocation Identify

APON ATM PON

ASIC Application Specific Integrated Circuit

ATM Asynchronous Transfer Mode

BE Best Effort

BGP Bandwidth Guaranteed Polling

BW map Bandwidth Mapping

BPON Broadband PON

CAPEX Capital Expenditure

DBA Dynamic Bandwidth Allocation

DBAM Dynamic Bandwidth Allocation with Multiple Services

DPOA Dynamic Polling Order Arrangement

DWBA Dynamic Wavelength and Bandwidth Allocation

EC Excess Control

EDP Excess Distribution Policy

EF Expedited Forwarding

eNB Evolved NodeB

EPDF Empirical Probability Density Function

EPON Ethernet PON

FE Fair Excess

FPGA Field-programmable Gate Array

FSD-SLA Fair Sharing with Dual SLAs

FTTb Fiber To The Business

FTTB Fiber To The Building

FTTc Fiber To The cell

FTTC Fiber To The Curb

FTTO Fiber To The Office

FTTH Fiber To The Home

FTTdp Fiber To The Distribution Point

FTTN Fiber To The Node

FTTP Fiber To The Premises

FTTx Fiber To The x

GEM GPON Encapsulation Method

GIANT Giga-PON Access Network

GPON Gigabit Capable PON

GSF Grant Scheduling Framework

GSP Grant Scheduling Policy

GTC GPON Transmission Convergence

GWP Grant Windows-sizing Policy

HGP Hybrid Granting Protocol

HPP High Priority Packets First

HPS High Priority Subgroup First

IC Computing Institute

IEEE Institute of Electrical and Electronics Engineers

InP Infrastructure Provider

IP Interleaved Polling

IPACT Interleaved Polling with Adaptive Cycle Time

ITU International Telecommunication Union

LLID Logical Link ID

LNF Largest Number of Frames First

LRC Network Computer Laboratory

MAC Medium Access Control

MNO Mobile Network Operator

MPCP Multipoint Control Protocol

MTP Multi-thread Polling

MTU Maximum Transmission Unit

OAM Operation Administration and Maintenance

ODN Optical Distribution Network

OLS ONU Load Status

OLT Optical Line Terminator

OMCI ONU Management Control Interface

ONU Optical Network Unit

P2MP Point-to-Multipoint

P2P Point-to-Point

PLOAM Physical Layer OAM

PLR Packet Loss Ratio

PON Passive Optical Network

QoS Quality of Service

RTT Round-Trip Time

SAR Smallest Available Report First

SLA Service Level Agreement

SMF Single-Mode Optical Fiber

SNMP Simple Network Management Protocol

SPD Shortest Propagation Delay First

STP Single Thread Polling

T-CONT Transmission Container

TDM Time Division Multiplexing

TDMA Time Division Multiple Access

TLBA Two-Layer Bandwidth Allocation

TSF Thread Scheduling Framework

TWDM Time and Wavelength Division Multiplexing

TWDMA Time and Wavelength Division Multiple Access

VNO Virtual Network Operator

WDM Wavelength Division Multiplexing

XGEM GPON Encapsulation Mode

XGPON 10 Gigabit Capable PON

Contents

Chapter 1

Introduction

Current broadband access network has unmet demands for bandwidth due to the large-scale adoption of new services and, the increasing number of Internet users. By 2022, busy hour traffic will be six times higher than the regular traffic, and global data traffic is expected to double the 2019 one [18]. Consequently, the access networks will need to support extremely unbalancing traffic and high demands of bandwidth.

Passive Optical Network (PON) is considered by academia and equipment vendors as a solution to deliver broadband access services. There are two different versions of PONs available in the market; Ethernet PON (EPON) and Gigabit Capable PON (GPON), being EPON the less expensive solution. The first generation of EPONs, which comprises 1G-EPON (IEEE 802.3ah) and 10G-EPON (IEEE 802.3av), uses Time Division Multiple Access (TDMA) whereas next-generation EPONs (IEEE 802.3ca) employ Time and Wavelength Division Multiple Access (TWDMA) to achieve higher capacity (25 Gb/s, 50 Gb/s, and 100 Gb/s), reusing the already deployed fibres [29].

The customers in the TDMA-PON network share a single wavelength dividing the channel occupancy by periods of time (time slots), however it does not exploit inter-channel statistical multiplexing. Unlike the previous access approach, the TWDMA-PON customers share multiple wavelength in both frequency and time domains by Dynamic Wavelength and Bandwidth Allocation (DWBA) algorithm. The DWBA problem of TWDMA-PONs can be divided into two sub-problems; bandwidth allocation and wavelength allocation. Thus, the conventional Dynamic Bandwidth Allocation (DBA) algorithms of the single-channel TDMA-PONs can be expanded to the transmissions on multiple channels.

In EPONs, a DBA algorithm at the Optical Line Terminator (OLT) allocates bandwidth for upstream transmissions of each ONU by using the Multipoint Control Protocol (MPCP) for signaling. This protocol employs two messages for scheduling; the Gate and Report messages, which are used, respectively, to request upstream resources and to inform the ONUs about the amount of bandwidth granted and the time that the transmission should start. DBA algorithms receive considerable attention since Quality of Service (QoS) provisioning and efficient resource utilization depend on them.

PONs offer high bandwidth capacity in the network access, however, the deployment of PON infrastructure is still high to be assumed by a single enterprise. Uncertain revenues in competitive markets are also an obstacle for the PON deployment, especially in areas with low expected bandwidth demands and/or user density [32].

There are two approaches to enhance cost-effective of the fiber-based access for PONs. The first one is a business models called PON sharing, which Infrastructure Provider (InP) leases its PONs to multiple *customers/tenants* [39]. These customers can be Mobile Network Operators (MNOs), multi-site enterprises, or virtual service providers. The second one is the deployment of Fiber To The x (FTTx) systems to deliver various type of services. FTTx access scenario includes Fiber To The Home (FTTH), Fiber To The Building (FTTB), Fiber To The Office (FTTO), Fiber To The cell (FTTc), Fiber To The Business (FTTb) and others. Moreover, these approaches have a direct correlation because one is dependent on the other, as shown in the Figure 1.1

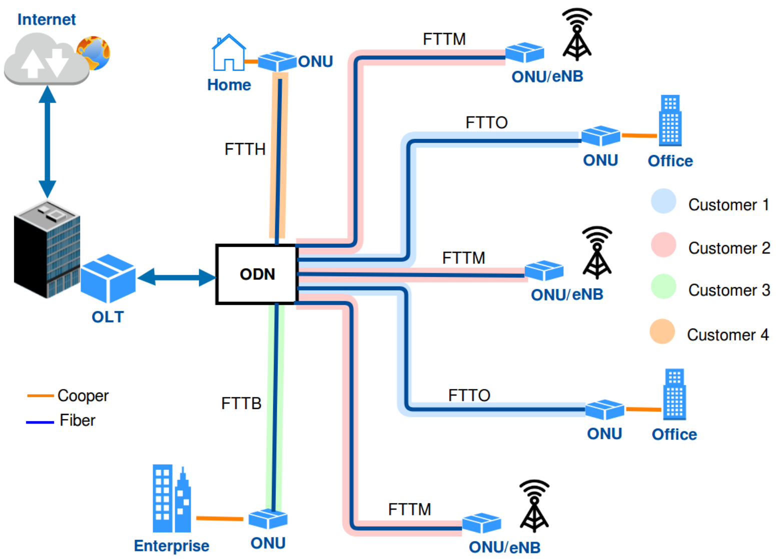


Figure 1.1: PON Sharing and FTTx system.

PON sharing reduces the Capital Expenditure (CAPEX), thus customers can enter into new markets without high investment, whereas, FTTx systems allows InP to offer different services for their customers. For example, a customer can lease ONUs from an InP to build its cellular backhauling network while other customers can lease ONUs to offer enterprise and residential services to its client. In the former, the leased set of ONUs is used by a single type of service while in the latter the set of ONUs is used by different services with diverse quality of service requirements.

Different types of customers generate bursty and unbalance traffic which limits the ability of the Medium Access Control (MAC) algorithms to satisfied the QoS demands, especially in customers owning multiple ONUs (*multi-ONU customers*). Moreover, InP are currently able to support only guaranteed bandwidth to individual ONUs with the existing DBA algorithms. Consequently, peaks of bandwidth demand may surpass the guaranteed bandwidth for some ONUs and, at the same time, underutilize bandwidth to other ONUs that belong to a multi-ONU customer.

The objective of this dissertation is to investigate the bandwidth allocation problem and QoS provisioning in EPON networks with multi-ONU customers. In this work, we introduce DBA algorithm to support *multi-ONU Service Level Agreements (SLAs)* in EPONs network. We call *multi-ONU SLA* a scheme which considers the aggregate SLAs of a group of ONUs, belonging to a customer, as a single SLA. In such approach, the OLT is able to share the unused guaranteed bandwidth of an ONU with the other ONUs belonging to the same customer by taking advantage of statistical multiplexing while maintaining isolation from the other customers.

In order to support multi-ONU customers with various types of ONUs in the same *multi-ONU SLAs*, we propose a DBA algorithm to provide bandwidth guarantee at different granularity levels: individual ONUs, multi-ONU customer and subgroups of ONUs. A subgroup is a subset of ONUs that belong to the same multi-ONU customer.

Finally, we propose a DBA algorithm to support resources sharing among customers. Thus, customers can join in a cooperative group in which the unused bandwidth is shared with others customer in order to increase the available bandwidth and network utilization without affecting their individual *SLAs*.

The remainder of this chapter summarizes the main contributions of this dissertation (Section 1.1), the publications of the results of the research developed (Section 1.2) and finally, the organization of the dissertation is delineated (Section 1.3).

1.1 Contributions

The main contributions of this dissertation are:

- Development of DBA algorithms for EPON networks to supports *multi-ONU SLAs* for multi-ONU customers, as well as, *individual SLAs* for traditional customers with a single ONU.

- Introduction of a new class of scheduling mechanisms for EPON networks, which allows isolation at different levels of granularity: individual ONUs, subgroup of ONUs and customer. The proposed DBA algorithm assures bandwidth to traditional customers, multi-ONU customers but with a single service and multi-ONU customers serving diverse type of services. The DBA algorithm also allows multi-ONU customer to support a priority bandwidth allocation in the subgroups.

- Proposal for a DBA algorithm which allows cooperation among EPON customers so that they can share unused bandwidth among themselves without affecting their guaranteed bandwidth. Thus, customers can join in a cooperative group to share unused bandwidth.

- Analysis of the impact of the diverse bandwidth distribution techniques on customers with *multi-ONU SLAs*. The performance evaluation was realize for a ONU target that belongs to a multi-ONU customer and the whole group of ONUs of the same customer based on metrics as delay, Packet Loss Ratio (PLR), wast of bandwidth and average number of overloaded ONUs.

1.2 Publications

The results obtained in this dissertation were reported in:

- Ciceri, O. J., Astudillo, C.A., Fonseca, N.L.S. Dynamic Bandwidth Allocation with Multi-ONU Customer Support for Ethernet Passive Optical Networks. IEEE Symposium on Computers and Communications (ISCC), May 2018, pp. 1–6. ***This paper received the conference Best Paper Award***.
- Ciceri, O. J., Astudillo, C.A., Fonseca, N.L.S. DBA Algorithm with Prioritized Services for 10G-EPON with Multi-ONU Customers. IEEE Latin-American Conference on Communications (LATINCOM), Nov 2019, pp. 1–6.
- Ciceri, O. J., Astudillo, C.A., Fonseca, N.L.S. DBA Algorithm for Cooperative Resource Sharing among EPON Customers. IEEE International Conference on Communications (ICC), June 2020, pp. 1–6.

1.3 Outline

This document is structured as follows:

Chapter 2 provides a background of PON networks, as well as, a classification of the existing DBA algorithms for EPON networks. Chapter 3 introduces a DBA algorithm for supporting multi-ONU SLAs in EPONs. Chapter 4 and 5 describe the design and performance evaluation of two proposed EPON schedulers based on the multi-ONU SLAs algorithm. These algorithms aims at improving the QoS provisioning for multi-ONU customers. Chapter 6 presents the conclusions and future works.

Chapter 2

Background

This chapter provides a background about PON networks. Section 2.1 describes the features, topologies and access control mechanisms proposed for PONs. Section 2.2 present a comparison of EPON and GPON. Finally, Section 2.3 shows a classification of the DBA algorithms in EPON networks.

2.1 Passive Optical Network (PON)

The PON technology does not employ any active elements in the Optical Distribution Network (ODN). Thus, along the path between the source and receiver, there is not electrical device. The only elements used in the ODN are passive optical components, such as optical fiber and optical splitters. The optical fiber is shared with the use of splitters that divide the optical signal into different signals that are transported through fibers to the optical termination points.

The only active elements in a PON are the OLT and the ONUs. These elements are at the end points of the network. The OLT resides in the central office, and multiple customers can share it (*e.g.,* service provides and MNOs), the ONUs may be located at the subscriber premises, and shared by multiple users equipment (*e.g.,* IPTV, IP Telephony, sensor networks, and Femto networks) [28]. The distance between the OLT and ONUs depends on the application type or architecture but usually ranges from 10 km to 20 km.

The scalability and the high availability of bandwidth in PONs motivated its deployment as a solution for the last mile bottleneck problem. PONs comprise the physical and link layer that allow point-to-multipoint bidirectional communication between the OLT and the ONUs.

In the downlink, the OLT send packets to ONUs using TDM. When a packet arrives, the ONUs checks if the packet is intended to it, otherwise the packet is ignored as shown in Figure 2.1. In the uplink, PONs allow multiple user access using the TDMA technique. In this mechanism, each ONU send data to the OLT at scheduled time. This means that the coordination is realized by the attribution of dedicated transmission windows for each ONU as shown Figure 2.2.

In order to increase the network bandwidth utilization, the transmissions opportunities are scheduled by the OLT executing a DBA algorithm. The DBA increases the efficiency

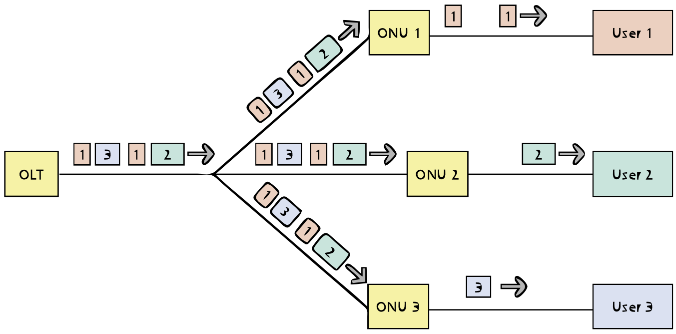


Figure 2.1: PON network using TDM in the downlink [37].

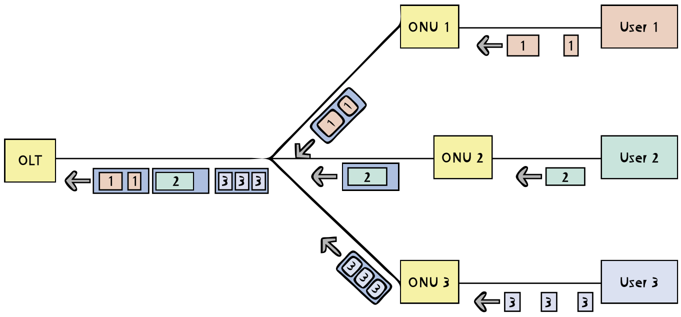


Figure 2.2: PON network using TDMA in the uplink [37].

of the available resources and QoS provisioning.

2.1.1 PONs Architecture

The PON architecture depends on the type of services offered and the distance between the optical fiber and end users. The FTTx defines the application, here "x" indicates the fiber access type. The most common models present in the optical network architectures are: FTTH (home), FTTO (office), FTTB (building), FTTN (node), FTTC (curb), FTTP (premises), FTTdp (distribution point) and FTTC (cell) as show Figure 2.3.

- Fiber To The Home (FTTH) refers to the optical architecture which an exclusive optical fiber switches directly the home.

- Fiber To The Building (FTTB) refers to the deployment of optical fiber directly to the enterprise. The internal access of clients is provided by a structured copper-cable network. FTTB demands larger bandwidths than do home users resulting in more revenue collected by the network service provider.

- Fiber To The Office (FTTO) refers to the deployment of an optical fiber direct to the office floor. The final distance (2 m - 5 m) to the end users are covered by standard twisted pair cooper-cable. FTTO does not need a floor distribution infrastructure, thus there is considerable reduction on initial investment.

- Fiber To The Node (FTTN) is also called fiber-to-the–neighborhood, or -last-amplifier. It refers to a PON architecture in which optical fiber is connected to neighborhood cabinet, located more than 1 Km of end users, being the final connections in a copper cable. This architecture is an intermediary solution to FTTH.

- Fiber To The Curb (FTTC) is very similar to FTTN, but the cabinet is closer to the end users, typically within 300 m. Coaxial cable, twisted-pair copper wires (*e.g.,* DSL), or some other transmission mediums are used to connect the curbside equipment to customers.

- Fiber To The Premises (FTTP) is use as a generic term to designate the FTTH and FTTB architectures, or when the fiber optic network includes both homes and small businesses.

- Fiber To The Distribution Point (FTTdp) is an architecture which the end of the fiber is closer to the customers that would typically be the case of FTTC or FTTN. Thus, the fiber is a few meters of the boundary of the customers which allows gigabit speeds.

- Fiber To The cell (FTTc) indicates fiber to the mobile base station. In this architecture, the PON provides the backhaul and fronthaul services for mobile communication (*i.e.,* 2G, 3G, and 4G networks).

- Point-to-Point (P2P) is another FTTH solution to offer dedicated bandwidth to the subscriber. The VIP customers can be directly connected to the OLT by optical fibers to implement end-to-end QoS.

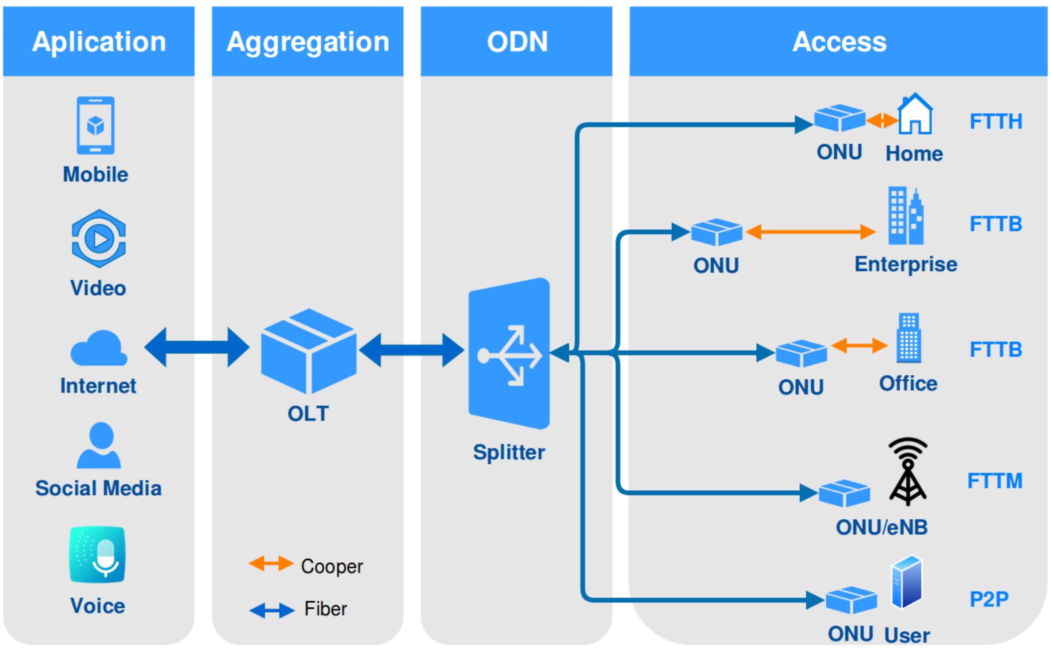


Figure 2.3: FTTx solution for different environments.

2.1.2 Optical Distribution Network (ODN) Topologies

The ODN topologies depend on the network requirements. There are several topologies suitable for the access network, the most common are: tree, tree-and-branch, ring, and bus. The deployment of the tree topology is typically use in dense areas due to the low implementation cost and the high scalability (Figure 2.4a). The bus topology has a low scalability as a result of the use of multiple splitters. However, it is usually deployed in sparse areas (Figure 2.4b). The ring topology has a backup fiber which is desirable for the network operator in case of fiber cuts (Figure 2.4c). Furthermore, the tree topology can be deployed in redundant configuration as complete or only partially redundancy, in the last case, it is called trunk of the tree (Figure 2.4d) [37].

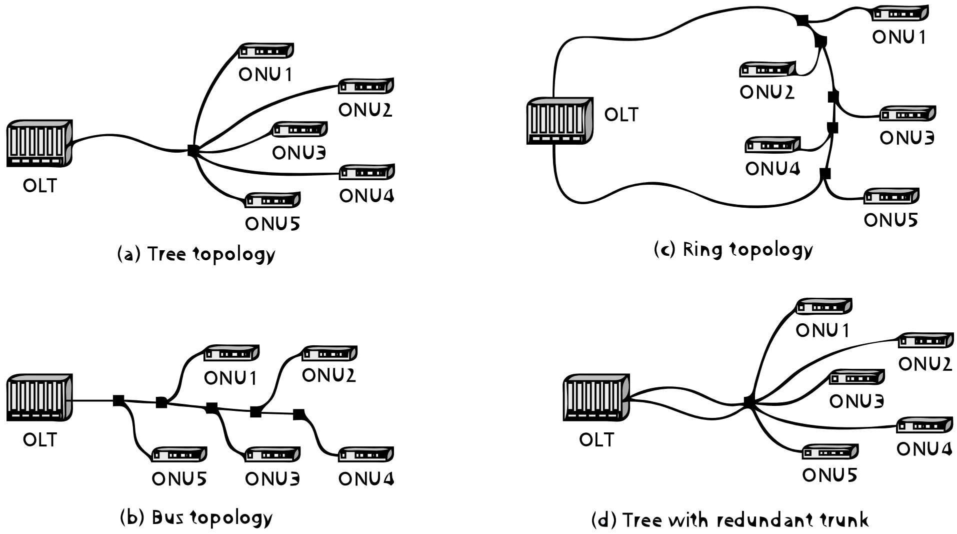


Figure 2.4: ODN topologies [37].

2.2 EPON vs GPON

Currently, two technologies have driven the PON standardization. The Gigabit Capable PON (GPON) (ITU-T G.984) and 10 Gigabit Capable PON (XGPON) (ITU-T G.9807) were standardized by the International Telecommunication Union (ITU), whereas, the first generation of Ethernet PON (EPON) which comprises 1 Gb/s EPON (IEEE 802.3ah) and 10 Gb/s EPON (10G-EPON) (IEEE 802.3av) were standardized by the Institute of Electrical and Electronics Engineers (IEEE). The 10 Gb/s PONs (*i.e.,* 10G-EPON and XGPON) have been deployed on a large scale since 2016 as a consequence of the high benefit cost ratio and the capacity to support the growing demands of bandwidth. These standards have some similarities such as wavelength plan, and applications. However, they have marked differences such as operation and services supported. An overview and comparison between those standards is presented next.

2.2.1 PON evolution

The different PON generations are defined based on the bit rates and standardization entity (*i.e.,* ITU and IEEE). ITU defines A/BPON, GPON, XG/S PON and NG-PON2, while IEEE defines EPON, 10G-EPON and NG-EPON as shown in the Figure 2.5.

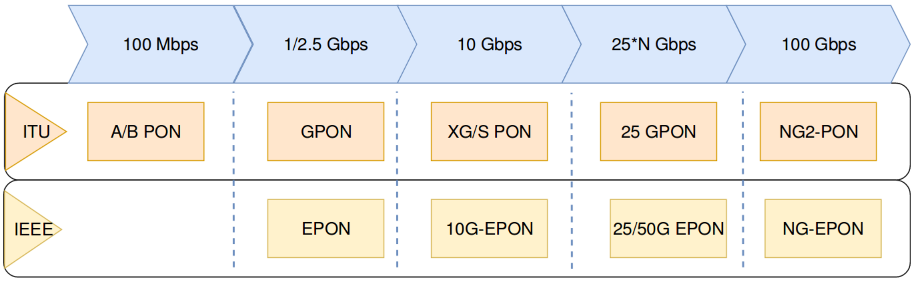


Figure 2.5: Evolution of PON networks.

In the middle of nineties, ITU launched the ATM PON (APON) and Broadband PON (BPON) standards which were based on Asynchronous Transfer Mode (ATM) framing. These standards encapsulate the data flow in ATM cells that operates at megabits per second. A few years later, the gigabit PONs (*i.e.,* GPON and EPON) emerged to take the place of APON and BPON standards. EPON offers symmetric data rate of 1.25 Gbps. However, in order to improve the available bandwidth, the Turbo Mode EPON was developed to allow a rate of 2.5 Gbps in the downlink [26]. On the other hand, GPON supports various bit rate options. GPON offer symmetric rates similar to EPON, and also offer asymmetric rates from 155 Mbps to 2.5 Gbps (*e.g.,* 2.5 Gbps in downstream and 1.25 Gbps in upstream). In this case, GPON is more flexible than the EPON technology. Furthermore, EPON has low efficiency caused by the long headers in the frames and, consequently, fewer payload bits against GPON solutions.

However, the more recent deployments are based on 10 Gb/s. The 10G-PONs (*i.e.,* IEEE 802.3av 10G-EPON and ITU G.987 XG-PON) arose to support the growing IP traffics of emergent services and replace the 1 Gb/s PON standards. 10G-EPON allows symmetric rate of 10 Gbps and asymmetric rate of 1 Gbps in the uplink and 10 Gbps in the downlink. On the other hand, XG-PON supports asymmetric rate of 10 Gbps in the downstream and 2.5 Gbps in the upstream. However, the actual available data rate is less than previously specified because it depends on the split ratio and frame headers. The bandwidth efficiency of 10G-EPON and XG-PON for different ONUs was presented in [12]. In this case, the bandwidth efficiency per user is lightly better with XG-PON. However, 10G-EPON is competitively superior because it can provide a symmetric rate of 10 Gbps inside of the asymmetric rate that supports the ITU standard. In 2015, the GPON moves to XGS-PON (ITU-T G.9807.1) in order to provide a competitive solution of 10G-EPON symmetric mode. However, it requires more expensive burst-mode lasers on the ONUs side for the upstream transmission.

The next-Generation of PONs aims at reaching 25 $^{Gb}/_{s}$, 50 $^{Gb}/_{s}$, and 100 $^{Gb}/_{s}$ reusing the already deployed fibres [29], however, it is still in the standardization process and the deployment is expected for the next five years. The ITU standardized the 40 gigabit capable PON (ITU-T G.989). This approach uses Time and Wavelength Division

Multiplexing (TWDM), which is a hybrid of conventional TDM/TDMA and WDM technologies. Meanwhile, the IEEE 802.3ca task force is working on 25G/50G/100G EPON standards development.

2.2.2 Split Ratio

The optical splitters allow a single optical fiber to be shared among multiple ONUs. A split ratio of 1:32, mean that one input fiber in the OLT can divided into 32 outputs for the ONUs.

The split ratio depends on the performance of the optical module. This means, a large split ratio increases substantially the cost of the optical module and reduces distance from the OLT to the ONUs. The typical PON configuration reaches up to 1:32 or 1:64, it means that a single fiber can serve up to 32 or 64 ONUs. Moreover, split ratios up to 1:128 are possible just in some systems.

The split ratio in the GPON has some differences with EPON. GPON supports a split ratio of 1:16, 1:32, 1:64 and 1:128. Moreover, GPON can reach a separation distance between the OLT and the ONUs up to 60 km, however, the maximum distance between the farthest ONU and closest ONU need to be 20 km. The conventional EPON standard has a split ratio of 1:32 with a maximum distance of 20 km. However, the Extended EPON specification (IEEE 802.3bk) [2] can support higher distance and/or split ratios. For example, it can reach longer distance up to 40 km without in-line amplifier with 1:16 configuration. It will also enable high split ratio up to 1:128 with maximum distance of 10 km, which is ideal for deployments in populated dense areas, or dense applications like mobile backhauling.

2.2.3 Wavelength allocation

PONs employ Single-Mode Optical Fibers (SMFs) (*i.e.,* optical fibers which carry only a single mode of light). The full duplex communication (*i.e.,* send and received data simultaneously) over the same SMF fiber is achieved by using WDM technique. WDM separates the transmission and reception into two wavelength as shown in the Figure 2.6. For example, the upstream from device A to B is achieves employing the 1310 nm wavelength, meanwhile, the downstream from the device B to A uses 1550 nm wavelength.

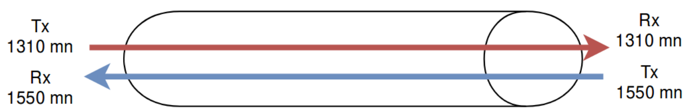


Figure 2.6: WDM technique in a SMF fiber.

The fiber attenuation is an important factor in the wavelength allocation. The attenuation causes a reduction in the power signal. Consequently, attenuation is measured in decibels per kilometer (dB/km). Optical fiber have the water peak region (*i.e.,* 1380 nm - 1430 nm), which attenuation is highest [51] [1]. Therefore, PON standards do not use this wavelength.

1G-PON and 10G-PON standards operates in separate wavelengths. 10G-PON uses wavelengths of 1577 nm for the downstream and 1270 nm for the upstream, while GPON and EPON use wavelengths of 1490 nm for the downstream and 1310 nm for the upstream. This way, 10G-PONs and 1G-PONs can coexistence over the same access network. However, it implies expensive high-speed burst lasers in the ONUs, while the OLT must employ expensive burst-mode receivers. The PON wavelength allocation is summarized in Figure 2.7.

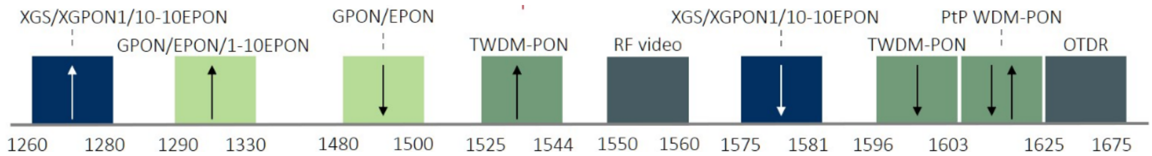
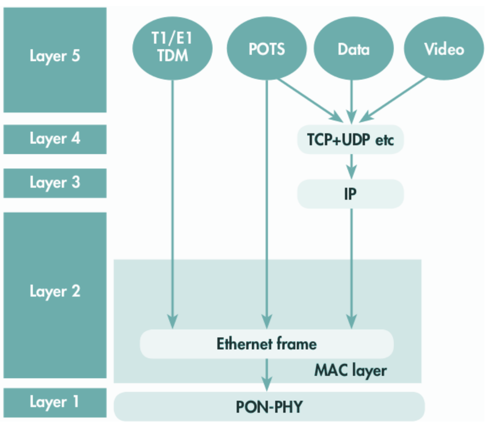


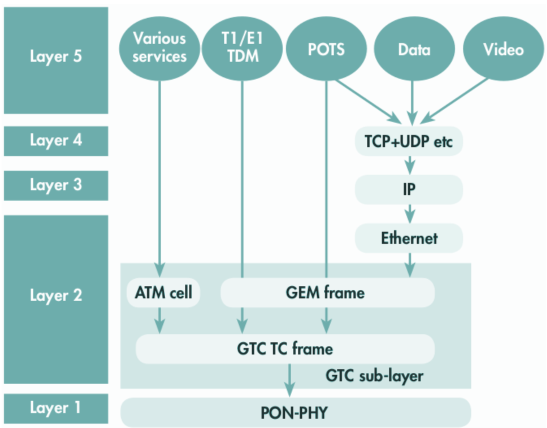
Figure 2.7: Standards and wavelength allocation in PONs [19].

2.2.4 Link Layer

The link layer in EPON networks uses a native Ethernet frame based on IEEE 802.3, as shown in the Figure 2.8a. Ethernet features are fully supported, therefore, EPON is compatible with other Ethernet standards because no protocol conversion is necessary between Ethernet-based networks. The Maximum Transmission Unit (MTU) is 1548 bytes and the smallest frame size is 64 bytes. EPONs use asynchronous frames to support data, voice and video services. EPONs also provide connectivity for any IP-based networks.



(a) EPON layering



(b) GPON layering

Figure 2.8: PON layer stack [33] [41].

On the other hand, GPON offers complex link layer, based on ATM protocol to handle ATM packets, Ethernet encapsulation to IP data, and GPON Encapsulation Method (GEM) to make possible the support of different services, as shown in Figure 2.8b. The GPON Transmission Convergence (GTC) sub-layer is responsible for mapping specific services (e.g. Ethernet) into the GPON framework. Thus, ATM cell and the GEM frames are transparently carried over GTC frames. Further, GTC frames operate in synchronous mode, every 125 us, irrespective of the traffic load. Due to synchronous naturally, GPONs need to insert idle characters in the frames.

2.2.5 Service hierarchy

PON network is a Point-to-Multipoint (P2MP) technology, thus, ONUs share a single optical fiber. For this reason, a unique identification is necessary for the OLT to recognize the ONU or data flows. EPONs use Logical Link ID (LLID) to address the ONUs. Identifier for VLAN are also available to deliver VLAN-based services. In downstream, the OLT set the LLID in the header of the frame to identify the destination ONU. Multiple LLID within a single ONU are used to provide QoS requirements and SLAs through separation of user connected to the same ONU. In the other hand, GPON is a transport oriented protocol, thus, Transmission Containers (T-CONTs) are defined between the OLT and ONUs. A T-CONT is a Point-to-Point (P2P) virtual connection that transport some data flow (*e.g.,* VoIP) with QoS services. The individual ONU in each T-CONT are identifed using multiple Port IDs. The service hierarchy of these standards is shown in Figure 2.9.

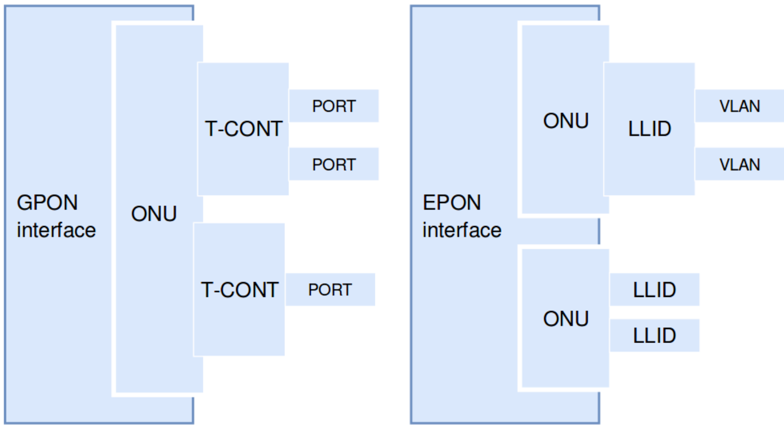


Figure 2.9: The hierarchy of GPON and EPON standards [41].

2.2.6 Control Message

The shared optical link in the upstream direction requires the scheduling of each ONU transmission to avoid collisions. Further, in PONs, the ONU receives a grant from the OLT informing when to start and terminate the transmissions.

The IEEE defines the Multipoint Control Protocol (MPCP) to support resources allocation and signaling on the uplink channel. The MPCP defines five messages for MAC: Register Request, Register and Register Ack are used in the discovery process to register new ONUs in the OLT, and Gate and Report messages are used for bandwidth allocation. The Report message is sent by ONUs to the OLT to request bandwidth. The Gate message is sent by the OLT to the ONUs to inform the size and the start time of its next transmissions windows. The grants are scheduled per LLID. The Operation Administration and Maintenance (OAM) in EPON defines a simple monitoring and support in conjunction with the Simple Network Management Protocol (SNMP).

In the other hand, GPON have three different types of control messages: ONU Management Control Interface (OMCI) message, embedded Operation Administration and Maintenance (OAM) message, and, Physical Layer OAM (PLOAM) message. PLOAM is denied for the physical layer, meanwhile, OMCI is defined for upper layer. Furthermore, OAM is employed in multiple levels. PLOAM messages have ATM format and they are used for ONU discovery, error detection and monitoring. OMCI message are used for QoS configuration, statistics and T-CONT services management. Embedded OAM messages are used for bandwidth allocation. These messages specify the allocation window for each T-CONT in the Bandwidth Mapping (BW map) field. Thus, the grants are scheduled per T-CONT by a Allocation Identify (Alloc-ID) [33].

GPON demands three link layer protocols for the support of multiple services, while, EPON have a simple link layer. In addition, EPON does not need multiple protocol conversions. These facts imply that the EPON networks are less expensive. However, the EPON management capacity is much smaller than that of GPONs.

2.2.7 Cost

The Optical Distribution Network, OLT and ONUs are important factors in the costs deployment. The cost of OLT and ONU is proportional to the optic module and the Application Specific Integrated Circuit (ASIC). The link layer circuit of GPON are mostly based on Field-programmable Gate Array (FPGA), which is more expensive than the EPON MAC layer ASIC. On the other hand, the price of the optic module in GPON is also higher than the cost of EPON. Furthermore, GPON needs Ethernet switches in front of the OLT and ONUs to provide additional Ethernet capabilities, such as VLANs. Thus, the estimated cost of a GPON networks are higher than that of EPON networks [40]. The cost of the ODN is the same for GPON and EPON, because it depends of the number of users, fiber size, optical splitter, connector, cabinet, and etc.

2.2.8 Summary

EPON has some benefits and drawbacks when compared to GPON, such as, relative cost and administration support. Thus, the deployment of those standards depends on several factors. Formerly, the decision is based on the installation/maintenance cost. However, the current cost is very similar, so the decision to use one of these two PON standard is based on the available bandwidth, service type, deployment complexity, operation complexity, spit ratio and maximum distance.

GPON offers complex layer two networks in a tree structure, based on the ATM protocol and GEM encapsulation mechanism to relay any data streams that make it possible to support different services. GPON also offers higher bandwidth based on efficiency transport mechanism. However, GPON has an addition complexity due to multiple link layers. Moreover, EPON uses native Ethernet frames to support Interleaved Polling (IP) data, voice and video services. Hence, EPON is more suitable and cost effective for IP/Ethernet services.

2.3 Dynamic Bandwidth Allocation (DBA) Algorithms in EPON

GPON and EPON standards do not specify any Dynamic Bandwidth Allocation (DBA) algorithm. This task was left for academia and equipment vendors.

The GPON DBA algorithm can not be directly employed by EPONs due to fundamental differences between these two technologies [14]. First, GPON data are transported synchronously with a constant cycle length of 125 μs, whereas EPON data are transported asynchronously in variable maximum cycle length between 1 ms and 10 ms. Second, the GPON algorithm is based on centralized QoS intelligence [57], while the OLT is responsible for QoS provisioning of individual queues at the ONUs. This scheme is attractive for small business or residential customers but not for multi-ONU customers with multiple connections at each ONU. Finally, GPON establishes virtual circuits between the OLT and the ONUs, through GPON Encapsulation Mode (XGEM) ports, and it generates groups of XGEM called T-CONTs for each type of service offered, whereas, EPON uses a native MAC to support any type of IP-based services (i.e. voice, video and data) over Ethernet without using logical connections for different type of services.

This dissertation aims at improving the bandwidth utilization for multi-ONU customer in EPON networks. For this reason, this section focus on EPON DBA algorithms.

Good surveys of DBAs for EPONs may be found in [14] [55] [27] and [62]. DBA algorithms for EPON are normally classified into three dimensions [45], however, this work considers that DBA algorithms involve 5 dimension: Grant Scheduling Framework (GSF), Grant Windows-sizing Policy (GWP), Excess Distribution Policy (EDP), Grant Scheduling Policy (GSP) and Thread Scheduling Framework (TSF), as shown in Figure 2.10.

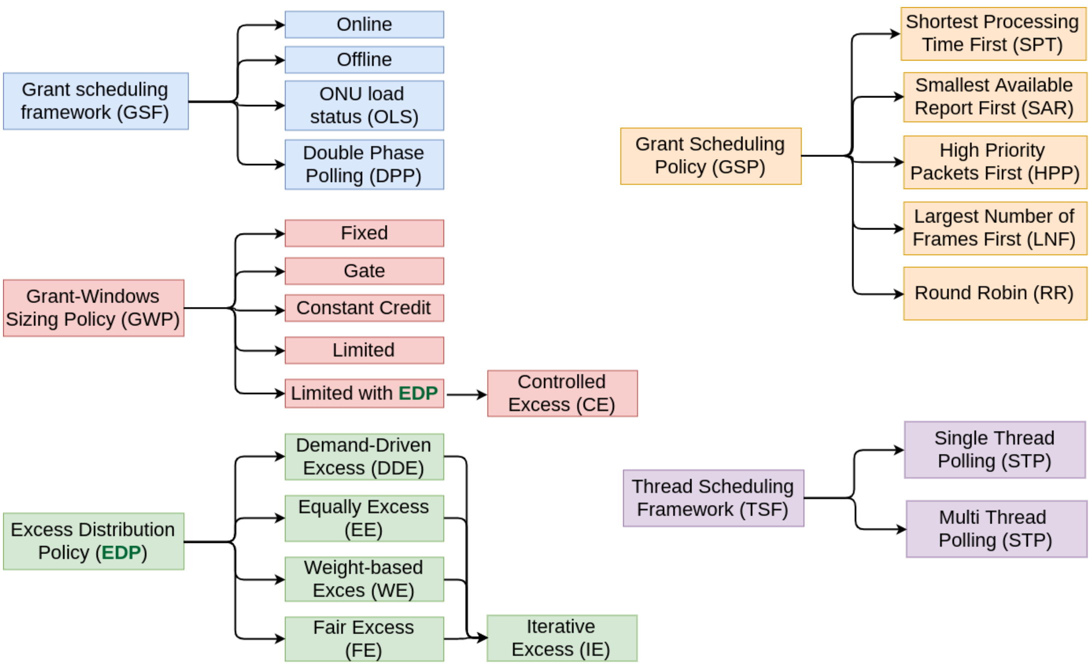


Figure 2.10: Dynamic Bandwidth Allocation (DBA) algorithms in EPON networks.

2.3.1 Grant Windows-sizing Policy (GWP)

A GWP defines the transmission window allocated to each ONU per cycle basics. The first policy is known as Fixed, which allocates transmission windows equal to a constant value ($W_i^G = C_i$). The Gated policy allocates a transmission window equal to the size of the upstream transmission request from ONU i ($W_i^G = R_i$). The Constant Credit policy allocates a transmission window equals to requested windows value plus a constant value ($W_i^G = R_i + C_i$). The idea behind of a Constant Credit policy is to compensate for the possible arrival of data in the windows time while the Report message informs the queued size and the transmission of that data in the next cycle. Load prediction techniques are employed to find an appropriate C_i value. The policy called Liner Credit works similar to Constant Credit policy; however, the size of C_i is proportional to R_i.

The most relevant policy is the Limited policy, which defines the size of the maximum transmission window (W_i^{max}) equivalent to the guaranteed bit rate for each ONU. ONU_i sends a Report message requesting a window's size higher than the allowed limit, them the OLT gives back a Gate message just with the allowed limited as

$$W_i^G = \begin{cases} R_i & if \quad R_i \leq W_i^{max} \\ W_i^{max} & if \quad R_i > W_i^{max} \end{cases} \tag{2.1}$$

An efficient policy called Limited with Excess Distributions has been proposed to avoid wastage of bandwidth. This policy shares the unused bandwidth from the underloaded ONUs with the overloaded ones. Thus, the granted window for an overloaded ONU_i is equal to ($W_i^G = W_i^{max} + E_i$), being E_i the portion of the excess bandwidth calculated with the help of the excess distribution policy, as explained next.

However, the previous policy are called uncontrolled excess because the OLT could grant a window largest than the windows required. The controlled excess technique (CE) [10] avoids such problem due to the size of the allocated window is at most the requested window size given by

$$W_i^G = \begin{cases} R_i & if \quad R_i \leq W_i^{max} + E_i \\ W_i^{max} + E_i & if \quad R_i > W_i^{max} + E_i \end{cases} \tag{2.2}$$

2.3.2 Excess Distribution Policy (EDP)

A EDP defines the distribution of unused bandwidth by the underloaded ONUs (U) to the overloaded ONUs (O) [48]. The total excess bandwidth (E^{total}) in a group of ONUs is equal to the sum of unused bandwidth of the underloaded ONUs U in that group, and it is defined as

$$E^{total} = \Sigma_{u \in U}(W_u^{max} - R_u) \tag{2.3}$$

The first excess distributing policy is called Demand-Driven Excess DBA (DDE-DBA) [7] because it uses the requested windows size (R_i). The DDE-DBA policy calculates the portion of the total excess bandwidth (E_i) to be allocated to the overloaded ONU_i as

$$E_i = \frac{R_i}{\Sigma_{o \in O} R_o} \cdot E^{total} \quad (2.4)$$

The policy called Equally Excess DBA (EE-DBA) [20] divides the E^{total} equally among the overloaded ONUs as

$$E_i = \frac{1}{|O|} \cdot E_{total} \quad (2.5)$$

The policy called Weight-based Excess DBA (WE-DBA) [10] divides the E^{total} with weights of priority as

$$E_i = \frac{\omega_i}{\Sigma_{o \in O} \omega_o} \cdot E^{total} \quad (2.6)$$

In order of improve the fairness bandwidth distribution, the policy Fair Excess DBA (FE-DBA) was proposed in [20]. FE-DBA calculates E_i according to the windows required ($W_i^{req} = R_i - W_i^{max}$) as

$$E_i = \frac{R_i - W_i^{max}}{\Sigma_{o \in O}(R_o - W_o^{max})} \cdot E^{total} \quad (2.7)$$

Iterative Excess (IE) allocation mechanics was proposed in [10] to maximize the bandwidth utilization of the CE technique. This mechanics distributes the remaining bandwidth of the successfully served ONUs between the ONUs that keep overloaded by multiple iterations, until the total excess bandwidth be complete distributed.

2.3.3 Grant Scheduling Framework (GSF)

A GSF defines the event that triggers a scheduling decision, which can be triggered by the arrival of: a Report message (online) [34], a Report messages from a group of ONUs (offline) [60], a Report message requesting a windows size less than the maximum windows size ($R_i \leq W_i^{max}$) (ONU Load Status (OLS)) [7] a Report messages of one of two independent groups of ONUs [16] or a Report message of the next cycle (compensate-in-the-next-cycle) [25]

In the online scheme, the OLT schedules a Report message after a Gate message arrived. Thus, the OLT calculates the allocated bandwidth for a ONU on the fly. This scheme is an interleaved polling, which reduces the delay. In the offline scheme, the OLT waits for the arrival of all Reports before schedule the Gate messages. This means that the OLT needs to collect the Report messages from all ONUs before making a decision about the bandwidth distribution, which generates an idle time.

The OLS scheme is an intermediate solution. This algorithm schedule the Report messages from underloaded ONUs on the fly and postpones the scheduling of Report messages from overloaded ONUs. However, the OLS scheme still introduces idle time under high loads and jeopardizes the latency and network utilization. The compensate-in-the-next-cycle scheme copes with the idle time introduced by the offline method. This scheme is an online framework with the benefits of excess distribution. In this mechanism, the excess bandwidth is distributed in the next scheduling cycle, which eliminates the idle time. However, this scheme introduces latency due to the ONUs reception of a portion of the excess bandwidth after two cycles.

2.3.4 Grant Scheduling Policy (GSP)

A GSP determines the order in which the ONUs are served by the Grant sizing policy in a granting cycle. The Smallest Available Report First (SAR) policy [13] orders the ONU requests in ascending order by queue length. The High Priority Packets First (HPP) policy [31] order the ONU requests in ascending order by different levels of priority traffic. The Dynamic Polling Order Arrangement (DPOA) policy [44] orders the ONU requests in descending order of real-time traffic loads. The Shortest Propagation Delay First (SPD) policy [46] orders the ONUs in ascending order by the smallest propagation delay. The Largest Number of Frames First (LNF) policy [47] orders the ONUs in descending order by the number of queued frames. However, the default policy is the round robin service one [7].

2.3.5 Thread Scheduling Framework (TSF)

A TSF defines the number of scheduled Reports on a cycle basis. In Single Thread Polling (STP) each Report is allocated by the OLT to the ONUs once per cycle. The delay is constraint since the ONU needs to wait for one cycle to send the data. In the Multi-thread Polling (MTP) two or more Reports are scheduled for the same ONU per cycle. MTP is commonly used in long-range PONs to reduce the delay caused by the long Round-Trip Time (RTT) time. MTP with offline scheduling and offline excess bandwidth distribution (offline MTP) was proposed in [56]; an online MTP was proposed in [50]; a dynamic adaption of the number of threads called adaptive multi-gate polling with Void filling (AMGAV) was proposed in [22]. The MTP frameworks are a suitable solution to reduce the wasted bandwidth in a scheme that generates great idle times in the OLT; however, they introduce additional complexity to coordination the many threads. Moreover, the guard times employed for the additional Reports reduce the available bandwidth. It means that MTP have a trade-off between to reduce the idle time of the offline schemes and increase the number of guard times.

Chapter 3

Bandwidth Guaranteed for Multi-ONU Customer in EPON

PONs have been deployed in broadband access networks for the past two decades. It is a solution to alleviate the bottleneck problem in access networks. Customers can rent multiple ONUs from an InP to reduce costs and maximize revenues. Those customer are called multi-ONU customers. An MNO using PON for backhauling/fronthauling is a typically use case of multi-ONU customers [8]. Another example is PON virtualization [6] [58], which allows the sharing of network infrastructure by various virtual service providers. Moreover, long-reach PONs [61] increase the geographical coverage of a PON, increasing the chance of a business customer to have more than one ONU within the footprint of a single PON.

However, InPs are currently able to support only guaranteed bandwidth to individual ONUs with the existing EPON DBA algorithms. Consequently, peaks of bandwidth demand may surpass the guaranteed bandwidth to some ONUs and, at the same time, underutilize the guaranteed bandwidth to other ONUs of the same multi-ONU customer. Such multi-ONU customer scenario creates opportunities for the InPs to employ *multi-ONU SLAs*. In this dissertation, we call *multi-ONU SLA* a scheme which considers the aggregate SLAs of a group of ONUs as a single SLA. In such approach, the OLT can share the unused guaranteed bandwidth of an ONU with the other ONUs belonging to the same customer by taking advantage of statistical multiplexing while maintaining isolation from the other customers.

This chapter introduces the *MOS-IPACT* algorithm, a novel EPON DBA algorithm which supports *multi-ONU SLAs* for multi-ONU customers such as MNOs, virtual service providers and multi-site enterprises, as well as *individual SLAs* for traditional customers owning a single ONU.

The organization of this chapter is as follows: Section 3.1 reviews the related work of DBA algorithms with support to guaranteed bandwidth in EPON networks. Section 3.2 introduces a novel EPON DBA algorithm to supports *multi-ONU SLAs*. The performance evaluation of the *MOS-IPACT* algorithm is presented in Section 3.3. The performance evaluation of *MOS-IPACT* in a multi-ONU customer is presented in Section 3.4. Finally, Section 3.5 brings the final considerations.

3.1 Related Work

Dynamic Bandwidth Allocation algorithms have received considerable attention because they allow QoS provisioning and efficient resource utilization to PON customers. Furthermore, DBA algorithms in EPON are composed by five dimensions, as explained in Section 2.3. Several DBA algorithms for EPONs have been proposed in the literature. The most popular DBA algorithm for EPONs is the $IPACT$ algorithm [34]. Besides, the majority of existing algorithms proposed so far are variation of $IPACT$ [60] [7] [16] [25].

$IPACT$ employs an online and single thread polling as show Figure 3.1. The limited policy is commonly used for providing guaranteed bandwidth in each ONU according to the SLA. Report and Gate messages are overlapped in time. $IPACT$ employees an interleaved mechanism, which reduces the wastage of bandwidth associated with polling. Finally, $IPACT$ gives transmission opportunities to each ONU using a round robin mechanism to achieve multiplexing gain.

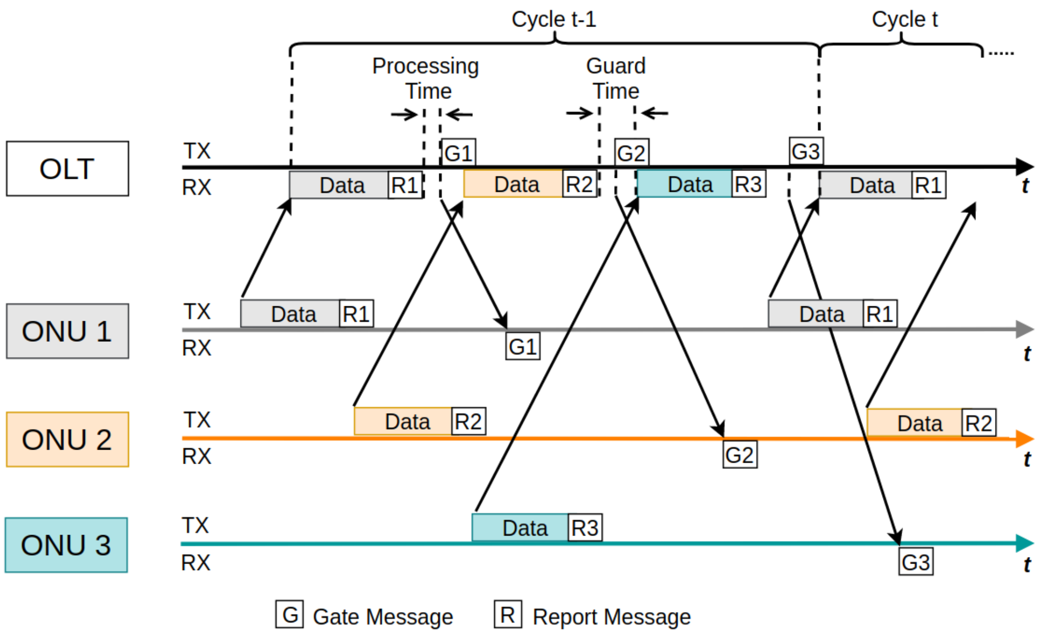


Figure 3.1: $IPACT$ DBA algorithm.

In $IPACT$, the transmission window is calculated for the next cycle in each ONU. When the OLT receives a Report message R_i in the cycle $t-1$, a Gate message G_i is sent to the ONU_i containing the granted transmission window W_i^G for the cycle t. The W_i^G is calculated as the minimum between the requested window (R_i) and the maximum allowed window size (W_i^{max}) as

$$W_i^G = min(R_i, W_i^{max}) \tag{3.1}$$

The OLT maintains the RTT of each ONU in the PON. Furthermore, it stores the start transmission time ($t^{txStart}$) and granted windows size ($W^{granted}$) of the previously ONU (ONU_{i-1}). Then, the start transmission time in the ONU_i is calculate as

$$t_i^{txStart} = t_{i-1}^{txStart} + W_{i-1}^G + GT \tag{3.2}$$

GT is guard time, and $t_{i-1}^{txStart}$ is the transmission start time of the previous scheduled ONU. Moreover, Formula 3.2 assumes that the all ONUs in the PON have the same RTT values (*i.e.,* same distance from the OLT). In a real case, the ONUs are at different distances, which creates overlapping and wastage of bandwidth, as shown in Figure 3.2.

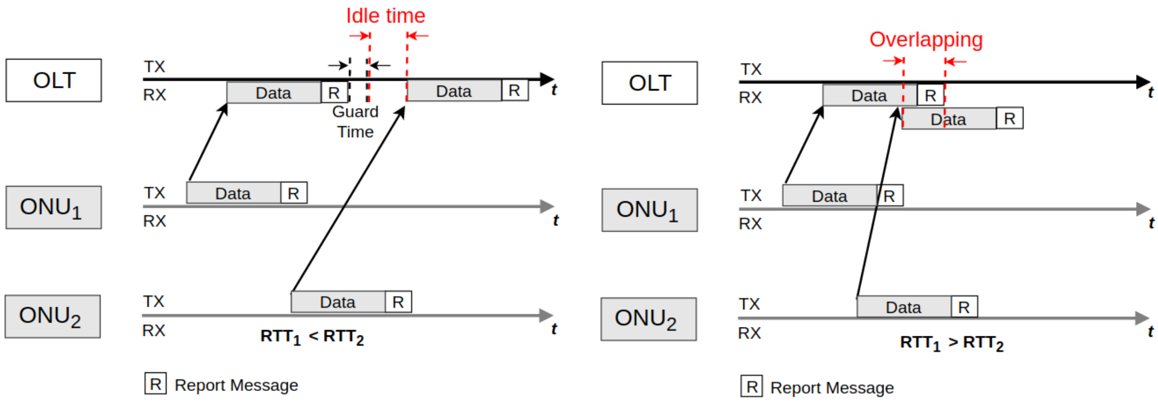


Figure 3.2: Idle time and overlapping problems.

The OLT can correct those problems taking into account the RTT value of the previously scheduled ONU (RTT_{i-1}). If the previous ONU (ONU_{i-1}) has a larger distance from the OLT than the current ONU (ONU_i). This means that the RTT_{i-1} is higher than RTT_i, then the OLT add a back off time in ($t^{txStart}$) to avoid overlapping. In the other case ($RTT_{i-1} < RTT_i$), the OLT reduce $t^{txStart}$ in the ONU_i (advance the transmission) to avoid idle times. Formula 3.3 shows the transmission start time with distance correction.

$$t_i^{txStart} = t_{i-1}^{txStart} + W_{i-1}^{G} + GT + \frac{RTT_{i-1}}{2} - \frac{RTT_i}{2} \tag{3.3}$$

Upon the arrival of a Gate message, the ONU starts an inter-ONU scheduler to distribute the received grant among the packets enqueued. When QoS differentiation is required, strict priority scheduling is typically used by the ONU. The strict priority query method gives more relevance to the highest priority traffic. Further, the OLT gives to each ONU the required bandwidth as long as the demand is lower than a threshold; the algorithm allocates bandwidth depending on both the demanded bandwidth and the SLA of each ONU.

IPACT using an excess distribution policy improves the statistical multiplexing gain. This algorithm divides the ONUs into *underloaded ONUs* and *overloaded ONUs* at every polling cycle. The former are those requesting at most the maximum transmission window (*i.e.,* $R_i \leq W_i^{max}$), whereas the latter are those with $R_i > W_i^{max}$. The excess policies distributes the unused bandwidth of *underloaded ONUs* among *overloaded ONUs*. In this algorithm, the bandwidth is distributed after the arrival of Report messages from all ONUs in the PON, being an offline scheduling framework. This generates a time frame during the OLT is unused (*i.e.,* idle time) as shown in Figure 3.3.

Let $\mathcal{R} = \{r_1, r_2, \ldots, r_n\}$ be the set of RTT values associated to the n ONUs in the PON. The idle time is equal to the minimum value in $\mathcal{R}$ as

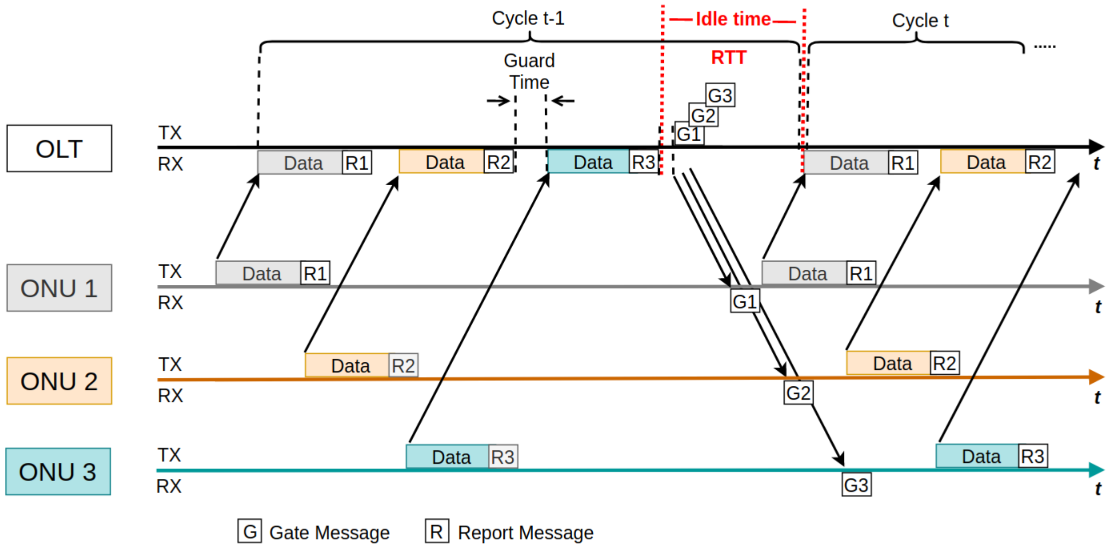


Figure 3.3: Offline GSF in EPON.

$$Idle_{time} = R_{min} = \min\{r_1, r_2, r_3, \ldots, r_n\} \tag{3.4}$$

The percentage of idle time is the relation between the idle time and cycle duration in the C cycles. The duration of a given cycle i includes the transmission windows, times guards, the processing time of the n ONUs. Furthermore, the idle time is also considered as part of the cycle. The following formula represents the percentage of file time.

$$Idle_{percent} = \frac{1}{C}\sum_{i=1}^{c} \frac{T_{DBA} + Idle_{time}}{\sum_{j=1}^{n}(W_{i,j}^{G} + GT) + T_{DBA} + Idle_{time}} \tag{3.5}$$

where $W_{i,j}$ is the transmission windows of i-th ONU at j-th scheduling cycle, C is the number of scheduling cycles, GT is the guard time period and the T_{DBA} is processing time.

The transmission bit rate (*e.g.,* 10 Gbps) has not direct relation on the idle time. A bit rate of x represents just the amount of time required to transmit the x bits into the optical link. However, this value has an direct relation with the length of the cycles. For example, EPON networks typically has maximum cycle between between 5 ms and 10 ms, meanwhile, a 10G-EPON usually employees 1 ms or 2 ms.

An approximation of the percentage of idle time is shown in Figure 3.4. It is assumed that the distance from the OLT to the closest ONUs is 10 km. Thus, the R_{min} is equal to 100 us, considering a delay of 5 us per kilometer. This graphic also excludes the T_{DBA} since this value is much shorter than the typical RTT values. Finally, it assumes that the transmission windows size is equal in all cycles and directly proportionally to the ONU load.

As shown in the previous figure, a longer length cycle implies a small idle time; thus offline schemes are recommended in optical networks operating at 1 Gbps. Moreover, the bandwidth capacity of the EPON is extremely affected in the low cycle since the idle time

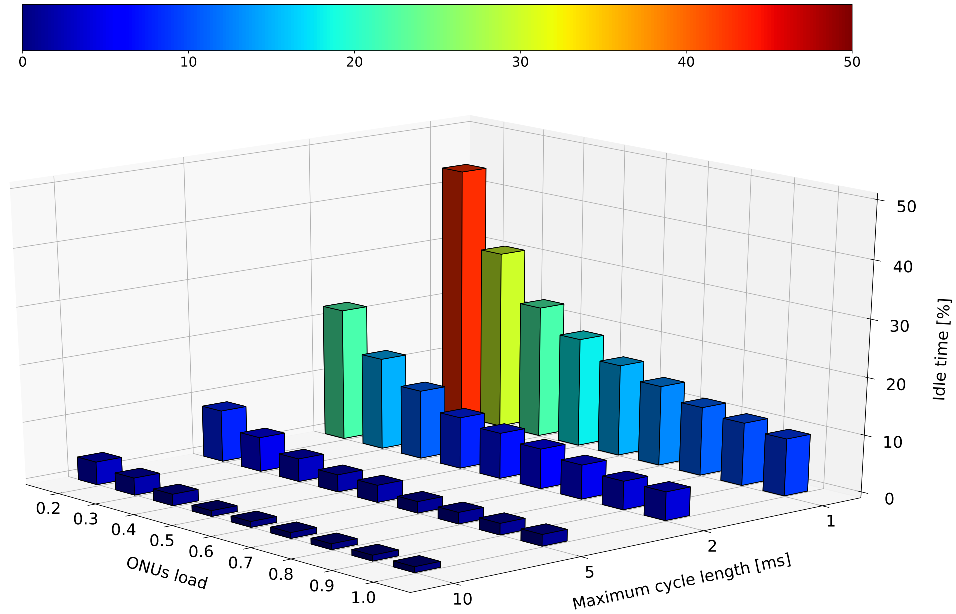


Figure 3.4: Approximate percentage of idle time for offline GSF.

can reach 45 %.

The Bandwidth Guaranteed Polling (BGP) algorithm [43] provides guaranteed bandwidth for premium subscribers and Best Effort (BE) to the others, thus, there are two groups of ONUs: bandwidth-guaranteed ONUs and non-bandwidth-guaranteed ONUs. BGP computes the transmission windows size according to the established SLAs; the remaining bandwidth is distributed to non-bandwidth-guaranteed ONUs. Thus, the is allocated for the bandwidth-guaranteed ONUs and dynamically assigned to non-bandwidth-guaranteed ONUs.

Other DBA algorithms based on IP with fixed scheduling frame size were also proposed in the EPON literature (*e.g.*, [49] and [30]). They facilitate the implementation of differentiated services supporting SLA for individual ONUs.

Indeed, no EPON DBA scheme supports *multi-ONU SLAs*. Even though an XGPON DBA algorithm supports a similar concept (group assured bandwidth), the algorithm cannot be employed by EPONs due to fundamental differences between these two technologies, as was explained in Section 2.3.

3.2 Proposed DBA algorithm

This section introduces the proposed DBA algorithm for supporting *multi-ONU SLAs* in EPONs, called Interleaved Polling with Adaptive Cycle Time (IPACT) with multi-ONU SLAs support (*MOS-IPACT*). *MOS-IPACT* allows InP to offer not only bandwidth guarantees to individual ONUs but also to groups of ONUs. The offering of a single SLA to multiple ONU belonging to the same customer increases the overall network utilization and improves the QoS provisioning. *MOS-IPACT* distributes the non-utilized bandwidth of an ONU to the others ONUs of the group it belongs to.

3.2.1 *MOS-IPACT* DBA algorithm

Currently, EPON DBA algorithms do not allow customers with more than one ONU in a PON to take advantage of the statistical multiplexing among their own ONUs. Traditionally, each ONU has an *individual SLA* specifying its guaranteed bandwidth. Conversely, in *MOS-IPACT*, a single SLA, called *multi-ONU SLA*, can be defined to a whole group of ONUs that belongs to the same customer. This *multi-ONU SLA* defines a guaranteed bandwidth per ONU, which can be aggregated with the guaranteed bandwidth of the other ONUs in the group, composing the bandwidth of the group of ONUs. This aggregated bandwidth is shared among all ONUs in the same group in a granting cycle basis. In this way, the unused bandwidth from underloaded ONUs can be redistributed among overloaded ONUs belonging to the same group by using an excess bandwidth distribution policy, increasing the network utilization.

MOS-IPACT combines the online and offline GSF. The former is used for scheduling *traditional ONUs*[1] whereas the latter is used to ONUs belonging to a *multi-ONU SLAs*. We call this framework Hybrid Polling (HP). *MOS-IPACT* also defines the GWP depending on the ONU type. The limited and limited with excess bandwidth distribution are used, respectively, for traditional ONUs and ONUs belonging to *multi-ONU SLAs*. Finally, the shortest propagation delay first GSP is used by the ONUs belonging to *multi-ONU SLAs*.

The interleaved polling proposed in the IPACT scheme is modified to wait for Report messages from all active ONUs belonging to the same *multi-ONU SLA* before sending the Gate messages to those ONUs, as illustrated in Figure 3.5. This modifies the sequence of control messages, which traditionally were organized by RTT, in such a way that Report messages from ONUs belonging to the same customer arrive one after other.

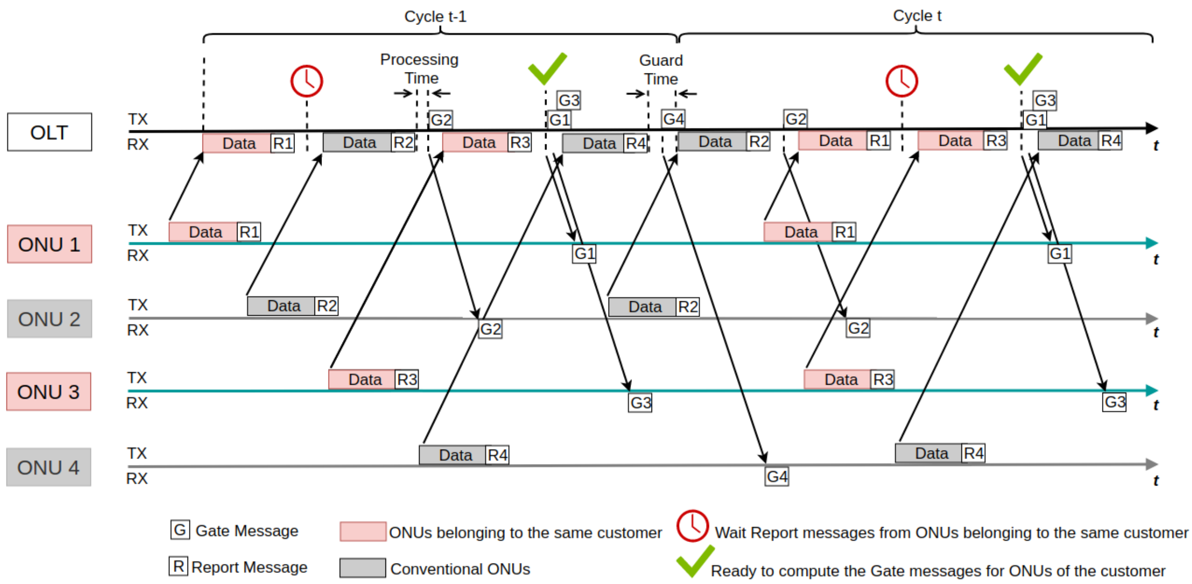


Figure 3.5: *MOS-IPACT* DBA scheme.

Algorithm 1 summarizes the *MOS-IPACT* scheme residing at the OLT. Let $\mathcal{G}$ be the set of *multi-ONU SLAs* specified for a given EPON; $\mathcal{O}$ the set of ONUs in the EPON;

[1]These are ONUs that do not belong to any *multi-ONU SLA*

$\mathcal{O}_C$ the set of ONUs that do not belong to any *multi-ONU SLA*; and $\mathcal{O}_k$ the sorted list of active ONUs belonging to the k-th *multi-ONU SLA* in increasing order of RTT value (which define the order of the Report message arrivals). $\mathcal{T}_k$ is the ordered list of expected arrival times of Report messages from active ONUs in $\mathcal{O}_k$ in increasing order of RTT values.

For each Report message R received by the OLT (Line 2), it is verified whether this message comes from an ONU in $\mathcal{O}_C$ (Line 4). If it comes from a traditional ONU, the start time $txStart$ and the transmission window $W^{limited}$ are calculated by using the legacy IPACT limited policy (Lines 5 and 6). After that, the Gate message is issued and sent to the ONU (Line 7 and 8).

However, if the Report message comes from an ONU belonging to a *multi-ONU SLA*, the Report message is added to the set of Report messages of its group k (Line 10). To cope with ONU failures, the OLT stores the expected arrival time (T) of the upcoming Report message for every active ONU in a multi-ONU SLA. The corresponding T_i value is initially updated with a value larger than the next Report message arrival time (Line 11). The maximum cycle length is used to ensure $T_i > T_{i+1}$ in any traffic condition and configuration scenario.

If the OLT has already received all the Report messages from the ONUs in that group, a grant for each ONU in $\mathcal{O}_k$ is issued (Lines 12, 14 and 24 to 31). Based on the Report messages, each ONU is classified either as *underloaded*, if the requested value (R) is less than or equal to its maximum window size ($R \leq W^{max}$), or as *overloaded* in the opposite case ($R > W^{max}$). The granted window size (W^G) is calculated by executing a limited policy with excess bandwidth distribution (*e.g.,* FE-DBA). For an *overloaded ONU*, it is first calculated the portion of the total excess bandwidth that will be allocated to the ONU, called excess bandwidth (W^{excess}). Then, the final granted window size to be attached to the Gate message of an *overloaded ONU* is calculated as $W^G = W^{max} + W^{excess}$. In this way, the total excess bandwidth from *underloaded ONUs* belonging to a given *multi-ONU SLA* is distributed among the *overloaded ONUs* belonging to the same customer in a per granting cycle basis. In the case of an *underloaded* ONU, W^{excess} is zero and the granted window size is equal to the requested value R ($W^G = R$). Finally, the OLT sends the Gate messages to the ONU (Line 28). In this fashion, all Gate messages intended to the ONUs in the same group are sent in sequence. After sending the Gate message, the corresponding T_i value for the ONU is updated with the actual Report arrival time (Line 29).

At every Report message arrival, if the previous expected Report message belongs to an ONU in a multi-ONU SLA and this message did not arrive (Line 16), the ONU is considered to be out of reach. This ONU is excluded from the active ONUs of the multi-ONU SLA (Line 17) and its corresponding expected Report arrival time is also removed from $\mathcal{T}_k$ (Line 18). Furthermore, if the received Report message comes from a traditional ONU and the expected Report has not arrived, the OLT infer that the last ONUs belonging to the group are down. Then, the OLT proceeds to send the Gate messages to the remaining active ONUs in the group (Lines 19 and 20).

Algorithm 1: *MOS-IPACT* DBA Algorithm

$\mathcal{R}_k \leftarrow \emptyset, \forall k \in \mathcal{G}$
for *each received report R from ONU i in cycle j* **do**
    Let τ be the arrival time of report R at OLT
    if *ONU* $i \in \mathcal{O}_C$ **then** /* If report message comes from a traditional customer */
        Calculate $t_{txStart}$
        Calculate $W_i^{limited}$ according to the limited policy
        $\text{Gate}_i^j \leftarrow \left(W_i^{limited}, t_{txStart}\right)$
        Send $Gate_i^j$
    else /* If report message comes from a multi-ONU customer */
        $\mathcal{R}_k = \mathcal{R}_k \cup \{R\}$ /* Save report message */
        $\text{T}_i \leftarrow (\tau + \text{maximumCycleLength})$
        if $|\mathcal{R}_k| = |\mathcal{O}_k|$ **then** /* If received all report messages from a multi-ONU customer k */
            BulkGrantGenerator()
        end
    end
    if *ONU* $i - 1 \notin \mathcal{O}_c$ *and* $\tau > T_{i-1}$ **then** /* If the expected report message of an ONU in a multi-ONU SLA did not arrive */
        $\mathcal{O}_k = \mathcal{O}_k - \{ONU_{i-1}\}$
        $\mathcal{T}_k = \mathcal{T}_k - \{T_{i-1}\}$
        if *(ONU* $i \in \mathcal{O}_c$*)* **then**
            BulkGrantGenerator()
        end
    end
end
Function `BulkGrantGenerator()`
    for *each report* $R \in \mathcal{R}_k$ **do** /* Compute and send gate messages for active ONUs of the multi-ONU customer k */
        Calculate $t_{txStart}$
        Calculate W_i^G according to grant sizing policy
        $\text{Gate}_i^j \leftarrow \left(W_i^G, t_{txStart}\right)$
        Send $Gate_i^j$
        $\text{T}_i \leftarrow \left(t_{txStart} + W_i^G + RTT_i/2\right)$ /* Save the next arrival time of the report message */
    end
    $\text{R}_k \leftarrow \emptyset$
End Function

3.2.2 Complexity Analysis

The complexity of the proposed algorithm is analyzed as follows. With the IPACT scheme, each Report is considered once per cycle, thus the allocation is performed with a time complexity of $O(n)$, where n is the number of ONUs in the PON. On the other hand, *MOS-IPACT* scheme applies the normal procedure of IPACT to receive the Report messages and the excess bandwidth allocation is calculated once for every active ONUs in the groups. Thus, the time complexity in the worst case is $O(n + l)$, where l is the total number of ONUs in the groups ($l = \sum_{i=1}^{k} l_i$).

3.3 Performance Evaluation for a Target ONU

This section assess the performance of the proposed *MOS-IPACT* DBA algorithms in a target ONU by using an EPON simulator (EPON-Sim), developed in Java and previously validated in [8], [9] and [21]. EPON-Sim implements the *IPACT* DBA algorithm together with the limited discipline introduced by Kramer *et. al* in [34]. The *MOS-IPACT* scheme with the FE-DBA policy was introduced in the EPON-Sim simulator and the new version of the simulator was validated extensively.

3.3.1 Simulation Model and Setup

The simulation scenarios include a 10G-EPON network with 1 OLT serving a set of ONUs $\mathcal{O}$ on an optical distribution network in a tree topology, with $|\mathcal{O}| = 32$. Each ONU in $\mathcal{O}$ has three different traffic classes: Expedited Forwarding (EF), Assured Forwarding (AF), and BE. The EF traffic represents voice and other delay-sensitive applications that require low end-to-end delay. It was modelled by using a constant bit rate encoding with a fixed-size packet of 70 bytes. The packet inter-arrival time (τ) depends on the ONU offered load (λ). If λ is less than 45 Mbps, τ is 125 μs, which gives 4.48 Mbps. Otherwise, τ is 12.5 μs, giving 44.8 Mbps [36]. The rest of the offered load is evenly distributed among AF and BE traffic, which typically host applications that require not only bounded delay but also bandwidth guarantees, and applications which do not have these requirements, respectively. Both AF and BE are self similar traffic simulated by using aggregation of ON-OFF sources. The ON period time and packet-burst size follow a Pareto and Bounded Pareto distributions with Hurst parameter equals 0.8, respectively [34]. The packet length follows a uniform distribution between 64 and 1518 bytes. Every ONU is assumed to receive, at least, the grant required to send a Report message (the minimum Ethernet frame size is 64 bytes) at every polling cycle. The guard time period (GT) is 1 μs and the maximum cycle length (c_{max}) is 1 ms [34]. Each simulation scenario lasted 50 s and was replicated 10 times.

It is assume that there is one costumer with multi-ONU SLA S assigned to the group of customer's ONUs $\mathcal{O}_S \subset \mathcal{O}$; $|\mathcal{O}_S| = N_{group}$ varies in the set {2,3,8}. Among the ONUs in $\mathcal{O}_S$, there is a target ONU (ONU_{target}) with guaranteed bandwidth $B_{ONU_{target}}$ of 300 Mbps. The other $N_{group} - 1$ ONUs belonging to S have guaranteed bandwidth B_i, $i \in \mathcal{O}_S \backslash \{ONU_{target}\}$, between 150 Mbps and 450 Mbps, provided that $\sum_{i \in \mathcal{O}_S \backslash \{ONU_{target}\}} B_i = (N_{group} - 1) \times 300$ Mbps. which is the effective aggregated guaranteed bandwidth of the ONU group excluding the target ONU ($A_{\mathcal{O}_S \backslash \{ONU_{target}\}}$). On the other hand, there is a set of traditional ONUs $\mathcal{O}_C \subset \mathcal{O}$, with $\mathcal{O}_C \cup \mathcal{O}_S = \mathcal{O}$ and $\mathcal{O}_C \cap \mathcal{O}_S = \emptyset$. Each ONU belonging to $\mathcal{O}_C$ has a guaranteed bandwidth B_j, $j \in \mathcal{O}_C$, equals 300 Mbps. The offered load of the target ONU ($\lambda_{ONU_{target}}$) is varied from 0 to 200 % of the $B_{ONU_{target}}$ value, corresponding to up to 600 Mbps, whereas the aggregated offered load of the ONUs in S excluding the target ONU ($\lambda_{\mathcal{O}_S \backslash \{ONU_{target}\}}$) varies from 0 to 100 % of the $A_{\mathcal{O}_S \backslash \{ONU_{target}\}}$ value. In the latter case, the individual offered load (λ_i) varies randomly between 0 and 600 Mbps. To properly assess the proposed scheme, the offered load of traditional ONUs (λ_j) equals their guaranteed bandwidth ($\lambda_j = B_j$), which is an overloaded condition for ONUs in $\mathcal{O}_C$.

Table 3.1 summarizes the main configuration parameters used in the simulation.

Parameter	Value
Optical bit rate	10 Gbps
Maximum cycle time	1 ms
Guard band	1 μs
Distance between OLT and ONUs	[10,20] km
Propagation delay in fiber	5 μs/km
OLT-ONU RTT	[100,200] μs
ONU buffer size	10 MB
Number of ONUs	32
Number of ONUs in the group	2,3,8
Aggregated guaranteed bandwidth	$N_{group} \times 300$ Mbps
Guaranteed BW of target ONU	300 Mbps
Offered load of target ONU	[0,600] Mbps
Guaranteed BW for ONUs in the group (excluding the target ONU)	[150,450] Mbps
Offered load for group of ONUs (excluding the target ONU)	[0, $(N_{group} - 1) \times 300$] Mbps
Offered load for ONUs in the group (excluding the target ONU)	[0,600] Mbps
Guaranteed BW for traditional ONUs	300 Mbps
Offered load for traditional ONUs	300 Mbps
Inter-ONU scheduler	IPACT (limited policy) MOS-IPACT (limited with FE-DBA excess distribution policy)
Intra-ONU scheduler	strict priority

Table 3.1: Simulation Parameters to Evaluated the Impact of *MOS-IPACT* in a ONU Target.

3.3.2 Simulation Results

The figures presented in this section show the mean values derived from 10 independent replications. For the sake of visual representation, confidence intervals are omitted. However, the upper bound of the confidence intervals for the delay and Packet Loss Ratio (PLR) are 4.8% and 8% of the mean values, respectively. We compare the performance of the *MOS-IPACT* scheme with the performance of traditional *IPACT* algorithm in term of the PLR and delay observed at the target ONU. To do a fair comparison, when the *IPACT* algorithm is employed the load and settings of N_{group} ONUs are the same as the ones in the multi-ONU SLA in *MOS-IPACT*, including the target ONU. The rest of ONUs have the same settings as the traditional ONUs in the *MOS-IPACT*.

Simulation results show that the delay of EF traffic experiences values less than 1 ms and no packet loss occurs because the guaranteed bandwidth is sufficient to serve the high priority traffic, which is prioritized by the intra-ONU scheduler. Similar to the EF traffic, the AF traffic do not suffer packet loss, due to its priority higher than the BE traffic one. Thus, in this section, we focus on the analysis of the PLR of the BE traffic (vulnerable to bandwidth starvation) and the average packet delay of AF traffic (delay-sensitive) in the target ONU when $\lambda_{ONU_{target}}$, $\lambda_{\mathcal{O}_S \setminus \{ONU_{target}\}}$ and N_{group} varies as explained previously.

Packet loss ratio (PLR)

The PLR of the BE traffic in the target ONU for *IPACT* and *MOS-IPACT* schemes are shown in Figures 3.6 and 3.7, respectively. When the *IPACT* scheme is employed and N_{group} equals two (Figure 3.6a), the target ONU produces packet loss for loads greater than its guaranteed bandwidth ($\lambda_{ONU_{target}} \geq B_{ONU_{target}}$).

As the N_{group} value increases (Figures 3.6b and 3.6c), the number of ONUs with a load equal to the guaranteed bandwidth decreases. Thus, the cycle length is reduced, leaving more resources to be distributed in the system. This is the reason for the slightly decreasing in the PLR as the value of N_{group} increases, despite the *IPACT* scheme providing only the individual guaranteed bandwidth. When an ONU does not use a portion of its guaranteed bandwidth, this excess bandwidth is distributed to the other 31 ONUs by the *IPACT* adaptive cycle technique.

Conversely, when the *MOS-IPACT* algorithm is employed, unused resources of an ONU in the group are first distributed to the other ONUs belonging to the same group. When the other ONUs in the group have no load, the target ONU can handle a load of up to 200 % of the $B_{ONU_{target}}$ value with very low packet loss. When the group is 100 % loaded, the target ONU presents the same packet loss previously observed in the *IPACT* scheme since there is no excess bandwidth to be distributed. Furthermore, the increase in the number of ONUs in a group has a positive effect on the packet loss (Figures 3.7b and 3.7c). As the N_{group} value increases, the excess bandwidth can be further shared among the ONUs in the group, even under high offered load. Thereby, the target ONU can have 100 % more bandwidth than its individual guaranteed bandwidth with no packet loss until 75 % of the $A_{\mathcal{O}_S \setminus \{ONU_{target}\}}$ value.

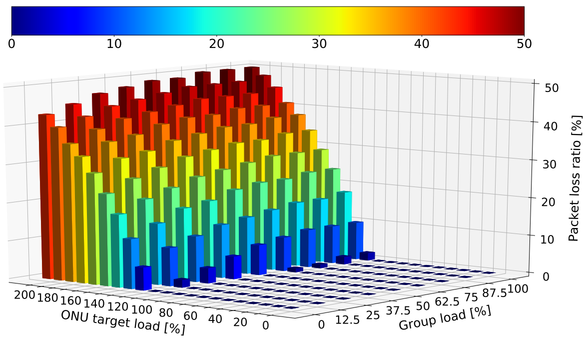
Delay

The average packet delay of the target ONU AF traffic for the *IPACT* and *MOS-IPACT* schemes are shown in Figures 3.8 and 3.9, respectively. When the *IPACT* scheme is employed and N_{group} equals two (Figure 3.8a), the target ONU produces higher delay values for loads greater than its guaranteed bandwidth ($\lambda_{ONU_{target}} \geq B_{ONU_{target}}$).

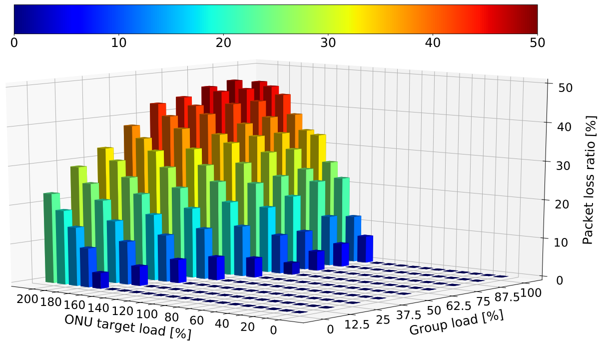
Once again, a positive impact on the network performance is observed when the number of ONUs in the group increases since the extra available bandwidth also increases, allowing the ONUs to transmit a higher number of packets in shorter periods.

Moreover, when the *MOS-IPACT* scheme is employed with group loads under 87.5 % and eight ONU in the group, the average packet delay is negligible. In the worst case, when the target ONU is under loads of 200 % and the offered group load is 100 %, the average packet delay is 5 ms with the *MOS-IPACT* scheme, whereas this value reaches 200 ms if *IPACT* is employed. This means, the average packet delay values given by *MOS-IPACT* for eight ONUs in the group are up to two order of magnitude lower than those given by *IPACT*.

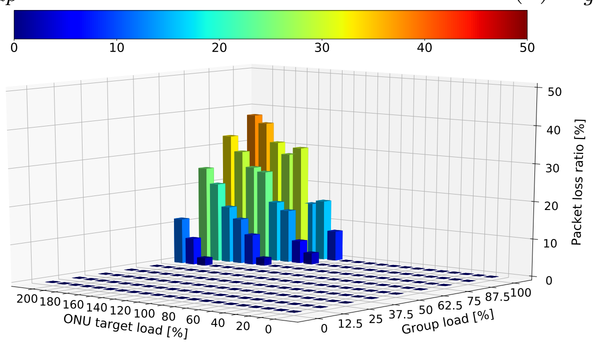
MOS-IPACT algorithm produces lower delay values in the ONU target for load lower than 100 %. These important performance improvements are because the excess bandwidth of *underloaded* ONUs is redistributed from the *overloaded* ONUs of the multi-ONU customer in a per cycle basis.



(a) $N_{group} = 2$

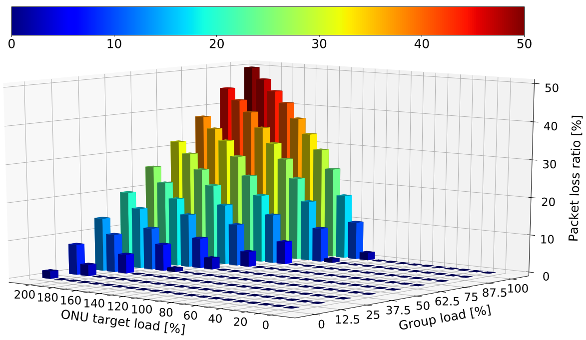


(b) $N_{group} = 3$

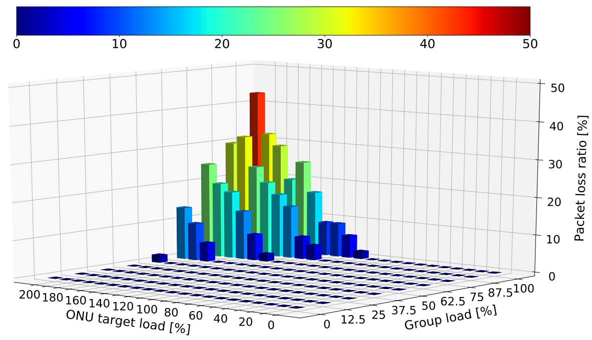


(c) $N_{group} = 8$

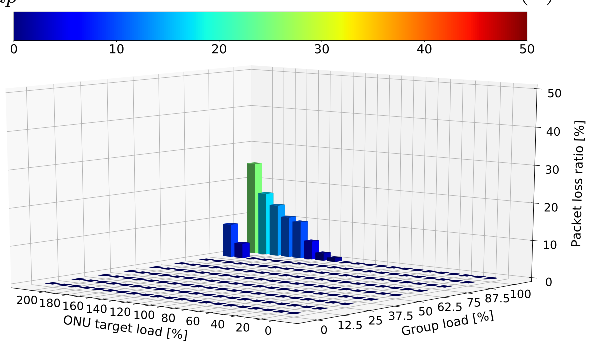
Figure 3.6: Impact of the number of ONUs in the group on the PLR of the BE traffic for the IPACT DBA algorithm.



(a) $N_{group} = 2$

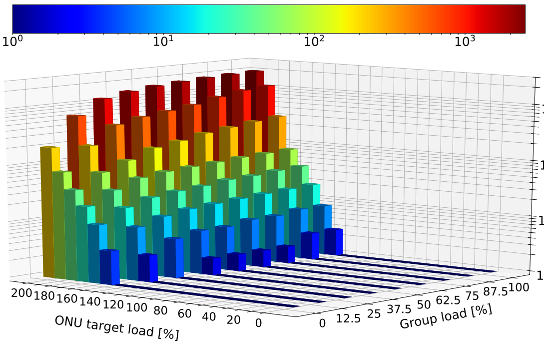


(b) $N_{group} = 3$

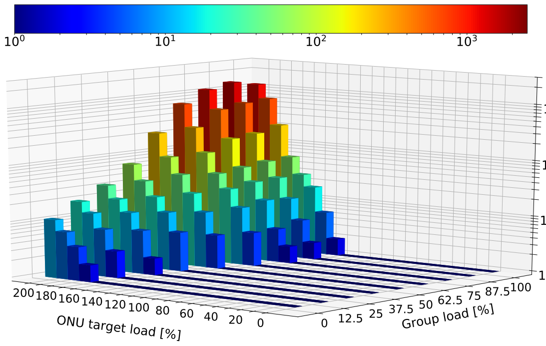


(c) $N_{group} = 8$

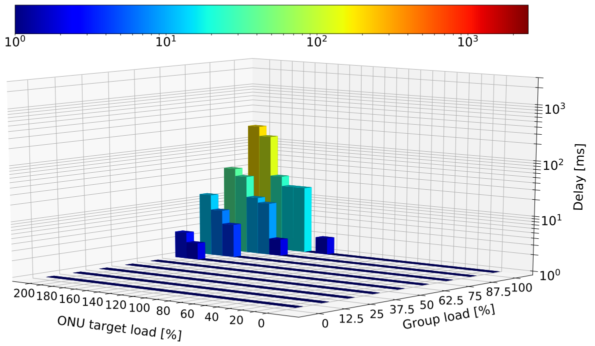
Figure 3.7: Impact of the number of ONUs in the group on the PLR of the BE traffic for the *MOS-IPACT* DBA algorithm.



(a) $N_{group} = 2$

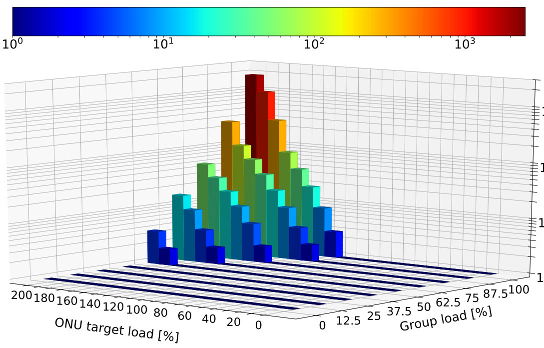


(b) $N_{group} = 3$

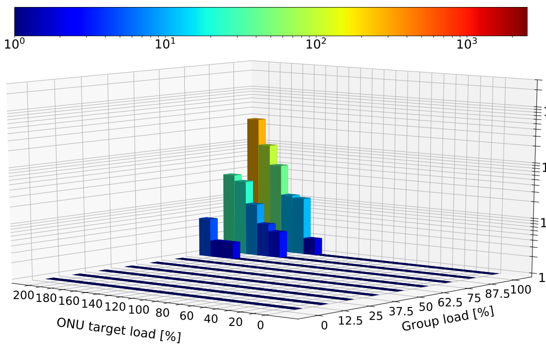


(c) $N_{group} = 8$

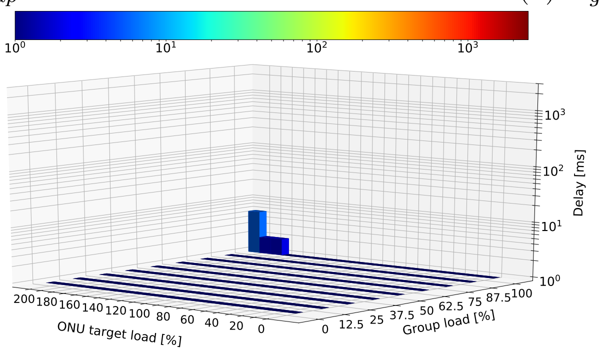
Figure 3.8: Impact of the number of ONUs in the group on the DELAY of the AF traffic for the IPACT DBA algorithm.



(a) $N_{group} = 2$



(b) $N_{group} = 3$



(c) $N_{group} = 8$

Figure 3.9: Impact of the number of ONUs in the group on the DELAY of the AF traffic for the *MOS-IPACT* DBA algorithm.

3.4 Performance Evaluation for a Multi-ONU Customer and Traditional Customers

Section 3.3 presented the performance of *MOS-IPACT* DBA algorithm for a target ONU that belongs to a multi-ONU customer, however, that section did not show the performance evaluation for the group of ONU that belongs to the multi-ONU customer and traditional customers.

In this section, we assess the performance of the proposed *MOS-IPACT* DBA algorithm for a multi-ONU customer and traditional customers by using the EPON-Sim simulator. *MOS-IPACT*, conventional *IPACT* and *IPACT* with excess distribution were compared. Different configurations in the Excess Distribution Policy (*i.e.,* FE-DBA, FE-DBA EC, EE-DBA, DDE-DBA and WE-DBA) and Grant Scheduling Framework (*i.e.,* offline and OLS) were simulated. The performance of the DBA algorithms are assessed in terms of delay, PLR, percentage of idle time and average number of overloaded ONUs, in both multi-ONU customer and traditional customers. Furthermore, the OLS policy and diverse EDPs were introduced in the EPON-Sim simulator. The new version of the simulator was validated extensively.

3.4.1 Simulation Model and Setup

The simulation scenario is almost the same as that in Section 3.3.1, except for some variations presented below. Table 3.2 shows the difference configurations of the *MOS-IPACT* and *IPACT* algorithms.

Algorithm	GFS	GWS	EDP	Acronyms
MOS-IPACT	Offline	Limited with EDP	DDE	MOF1
		Limited with EDP and EC	DDE	MOF2
		Limited with EDP	EE	MOF3
		Limited with EDP	FE	MOF4
		Limited with EDP and EC	FE	MOF5
	OLS	Limited with EDP	DDE	MOL1
		Limited with EDP and EC	DDE	MOL2
		Limited with EDP	EE	MOL3
		Limited with EDP	FE	MOL4
		Limited with EDP and EC	FE	MOL5
IPACT	Offline	Limited with EDP	DDE	IPOF1
		Limited with EDP and EC	DDE	IPOF2
		Limited with EDP	EE	IPOF3
		Limited with EDP	FE	IPOF4
		Limited with EDP and EC	FE	IPOF5
	OLS	Limited with EDP	DDE	IPOL1
		Limited with EDP and EC	DDE	IPOL2
		Limited with EDP	EE	IPOL3
		Limited with EDP	FE	IPOL4
		Limited with EDP and EC	FE	IPOL5
IPACT	Online	Limited	-	IPACT

Table 3.2: Simulated algorithms.

There is a customer with a group of ONUs $\mathcal{O}_S \subset \mathcal{O}$; $|\mathcal{O}_S| = N_{group}$ varies in the set {2,3,4,5,6,7,8}. The set of ONUs $\mathcal{O}_S$ has a mean guaranteed bandwidth (B_{mean}) of 300 Mbps, however, traditional ONUs have a guaranteed bandwidth B_{Si}, where $i \in \mathcal{O}_S$ and B_{Si} varies between 150 Mbps and 450 Mbps. Thus, the aggregate guaranteed bandwidth of the group of ONUs $A_{\mathcal{O}_S}$ is $\sum_{i\in\mathcal{O}_S} B_{Si} = N_{group} \cdot B_{mean}$. Moreover, the aggregate offered load ($\lambda_{\mathcal{O}_S}$) varies from 0 to 1.0 $\cdot A_{\mathcal{O}_S}$ [2], whereas the offered load in each ONU of the group varies randomly between 0 Mbps and 600 Mbps.

On the other hand, there is a set of traditional ONUs $\mathcal{O}_C \subset \mathcal{O}$, with $\mathcal{O}_C \cup \mathcal{O}_S = \mathcal{O}$ and $\mathcal{O}_C \cap \mathcal{O}_S = \emptyset$. Each ONU belonging to $\mathcal{O}_C$ has a guaranteed bandwidth B_{Cj}, $j \in \mathcal{O}_C$, equals $\frac{B_{real}-|\mathcal{O}_S|\cdot B_{mean}}{|\mathcal{O}_C|}$, where B_{real} refers to the real available bandwidth equal to 10 Gbps $\cdot\, (c_{max} - |\mathcal{O}| \cdot TG) \cdot \frac{1}{c_{max}}$.

To properly assess the *MOS-IPACT* DBA algorithm, the offered load of traditional ONUs (λ_j) equals their guaranteed bandwidth ($\lambda_j = B_j$), which is an overloaded condition for ONUs in $\mathcal{O}_C$. Table 3.3 summarizes the parameters of configuration used in the simulation.

Parameter	**Value**
Optical speed	10 Gbps
Maximum cycle time	1 ms
Guard band	624 ns
Distance between OLT and ONUs	[10,20] km
Propagation delay in fiber	5 μs/km
OLT-ONU RTT	[100,200] μs
ONU buffer size	10 MB
Number of ONUs ($\lvert\mathcal{O}\rvert$)	32
Number of ONUs in the group ($\lvert\mathcal{O}_S\rvert$)	2,3,4,5,6,7,8
Aggregated guaranteed bandwidth in the group of ONUs ($A_{\mathcal{O}_S}$)	$N_{group} \cdot 300$ Mbps
Guaranteed bandwidth for the ONUs in the group (B_{Si})	[150,450] Mbps
Offered load for ONUs in the group ($\lambda_{\mathcal{O}_S}$)	0,600 Mbps
Number of traditional ONUs	$\lvert\mathcal{O}\rvert - \lvert\mathcal{O}_S\rvert$
Aggregated guaranteed bandwidth in the traditional ONUs ($A_{\mathcal{O}_C}$)	$B_{real} - (\lvert\mathcal{O}_S\rvert \times B_{mean})$
Guaranteed bandwidth for traditional ONUs (B_j)	$A_{\mathcal{O}_C}/\lvert\mathcal{O}_C\rvert$
Aggregate offered load in the traditional ONUs ($\lambda_{\mathcal{O}_C}$)	$A_{\mathcal{O}_C}$
Intra-ONU scheduler	strict priority

Table 3.3: Simulation parameters to evaluated the impact of *MOS-IPACT* on a multi-ONU customer.

3.4.2 Theoretical percentage of idle time

The percentage of idle time is the relation between the idle time and cycle duration. We modified (3.5) to consider a multi-ONU customer, which is the aim scenario. Thus, (3.6) take into account the load and the number of ONUs in the multi-ONU customer as

$$Idle_{percent} = \frac{1}{C}\sum_{i=1}^{c} \frac{T_{DBA} + Idle_{time}}{\sum_{j=1}^{|\mathcal{O}_C|}(W_{i,j}^{G} + GT) + \sum_{k=1}^{|\mathcal{O}_S|}(W_{i,k}^{G} + GT) + T_{DBA} + Idle_{time}} \tag{3.6}$$

Where $j \in \mathcal{O}_C$ and $k \in \mathcal{O}_S$.

[2]For the sake of clearness and brevity, herein after, A_{Os} is omitted from the offered load values in $\mathcal{O}_S$

The idle time in *IPACT* with offline GSF is equal to RTT_{min}. In the case of *MOS-IPACT* DBA algorithm with offline GSF, the idle time depends on the load of the traditional ONUs and the RTT_{min} and cam be calculated as

$$Idle_{MOS} = \begin{cases} RTT_{min} - \sum_{j=1}^{|\mathcal{O}_C|}(W_{i,j}^G + GT) \quad if \quad RTT_{min} > \sum_{j=1}^{|\mathcal{O}_C|}(W_{i,j}^G + GT) \\ 0 \quad if \quad RTT_{min} \leq \sum_{j=1}^{|\mathcal{O}_C|}(W_{i,j}^G + GT) \end{cases} \tag{3.7}$$

The idle time in *MOS-IPACT* algorithm occurs when the traditional ONUs the time for send their data is less than the RTT_{min}. This means that the idle time depend on the load traffic in the traditional ONUs. Figure 3.10 shows this idle time in the n-th cycle when there are two traditional ONUs (ONU_1 and ONU_2) and a multi-ONU customer in the PON.

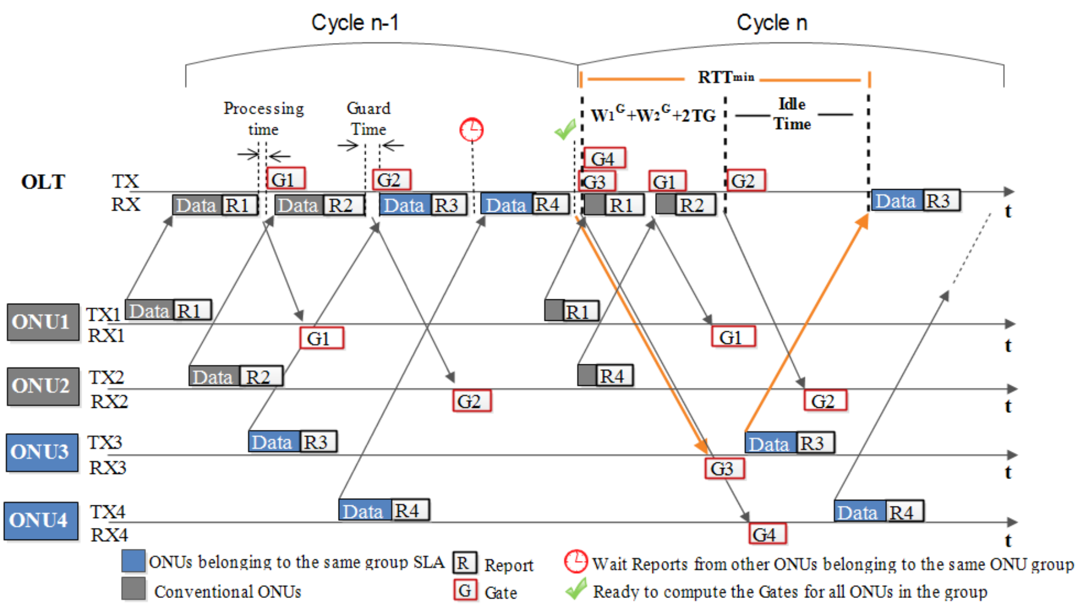
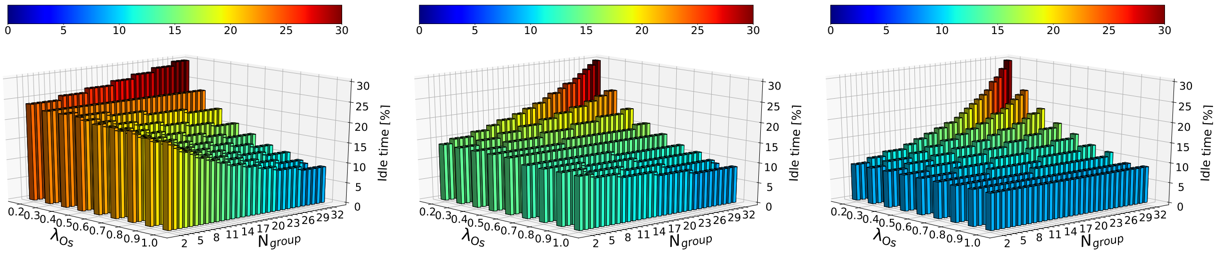


Figure 3.10: Idle time employing *MOS-IPACT* DBA algorithm.

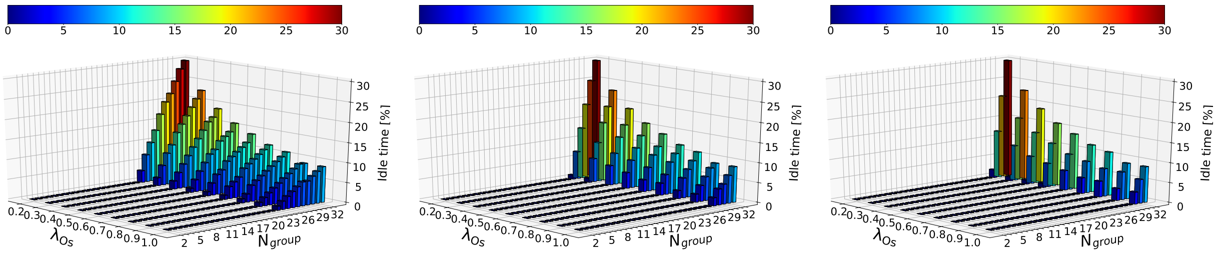
Figures 3.11 and 3.12 show an approximation of the percentage of idle time due to the use of the *IPACT* and *MOS-IPACT* DBA algorithms with offline GSF configuration, respectability. These graphics are computed by assuming a R_{min} equal to 100 μs and the granted transmission windows directly proportional to the ONU load. For example, for a load of 0.5 ($\lambda_{\mathcal{O}_S} = 0.5$), the granted transmission windows is $W^{max} \cdot 0.5 = 15$ μs. Moreover, T_{DBA} values were not consider.

Figure 3.11 reveals that the percentage of idle time employing *IPACT* has a minimum value of 9 % and a maximum value of 30 %. Consequently, this evaluation demonstrates that the *IPACT* DBA algorithm with offline GSF has low bandwidth efficiency due to the high idle time in each cycle. On the other hand, Figure 3.12 shows that MOS-*IPACT* produce no periods for customers with less than 23 ONUs and 29 ONUs, in underloaded (*i.e.,* Figure 3.12a) and overloaded conditions (*i.e.,* Figure 3.12c), respectively. This



(a) $\lambda_{\mathcal{O}_C} = 0.3$ (b) $\lambda_{\mathcal{O}_C} = 0.7$ (c) $\lambda_{\mathcal{O}_C} = 1.0$

Figure 3.11: Impact of the load of multi-ONU customer and traditional customers on the idle time for the *IPACT* DBA algorithm with offline GSF.



(a) $\lambda_{\mathcal{O}_C} = 0.3$ (b) $\lambda_{\mathcal{O}_C} = 0.7$ (c) $\lambda_{\mathcal{O}_C} = 1.0$

Figure 3.12: Impact of the load of multi-ONU customer and traditional customers on the idle time for the *MOS-IPACT* DBA algorithm with offline GSF.

results corroborate that our algorithm improve the bandwidth efficiency of *IPACT* with offline GSF.

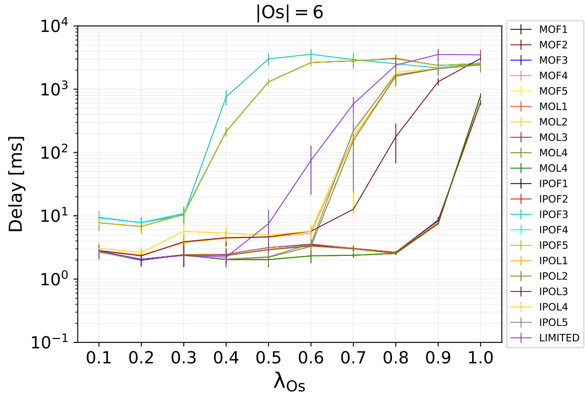
3.4.3 Simulation Results

We computed the simulation results by using the mean values derived from the independent replication method with 50 replications. We compare the performance of the *MOS-IPACT* and *IPACT* DBA algorithms in terms of PLR, delay, percentage of idle time and number of overloaded ONUs when using different EDPs and GSFs.

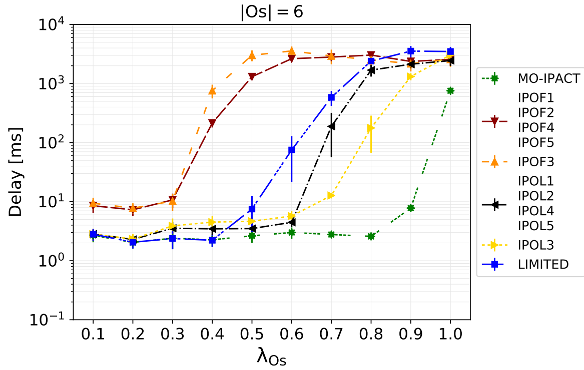
Preliminary considerations

We note that some algorithms have equivalent results in the performance of different metrics when varying both the load ($\lambda_{\mathcal{O}_S}$) and the number of ONUs $|\mathcal{O}_S|$ in the multi-ONU customer. For the sake of clearness, the figures presented in this subsection combine those values by computing their average values and their corresponding confidence intervals.

For example, Figure 3.13a shows the results of delay of the BE traffic for the ONUs of the multi-ONU customer. Note, that IPOL1, IPOL2, IPOL4, and IPOL5 algorithms produce similar delay values. Thus, they are combined in a single line as shown in Figure 3.13b. Figure 3.13a presents the 21 algorithms even though the results can be summarized in six different lines as shown in the Figure 3.13b.



(a) Delay for the 21 DBA algorithms

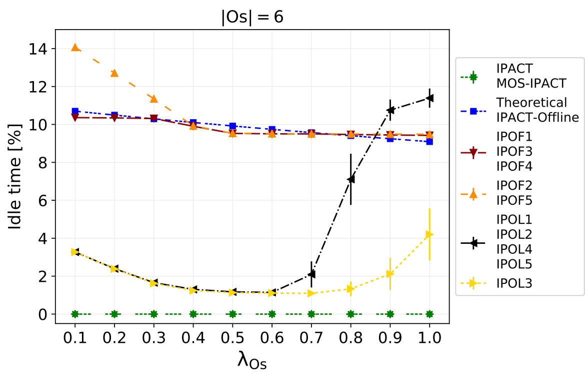


(b) Delay for the relevant behaviors

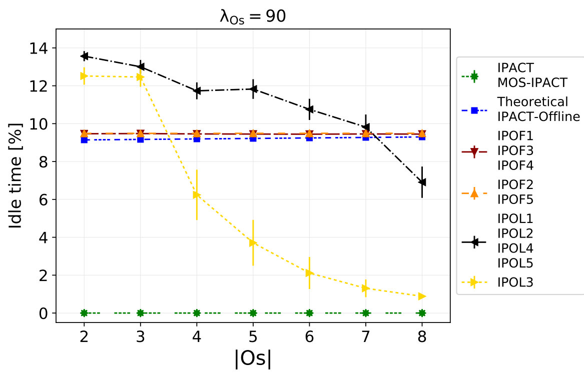
Figure 3.13: Impact of the aggregate load in the multi-ONU customer on the delay of the BE traffic.

Percentage of idle time

Figure 3.14 shows the percentage of idle time that have the OLT in the simulated scenario. The *MOS-IPACT* and *IPACT* DBA algorithms do not produce idle times. However, we can see that *IPACT* with EDPs (*i.e.,* IPO*[3]) produce high idle times in the OLT, which means a poor bandwidth utilization.



(a) Varying λ_{O_S}



(b) Varying $|\mathcal{O}_S|$

Figure 3.14: Impact of load and number of ONUs in the multi-ONU customer on the ilde time.

IPACT with offline scheduling (IPOF*) produces similar idle time values compared with the theoretical idle time. This occurs because the idle time value is fixed in all cycles. Thus, the self similar traffic does has not impact on those results. On the other hand, *IPACT* with online scheduling (IPOL*) produce a lower idle time in low traffic conditions (Figure 3.14a) than the theoretical idle time. This occurs because the OLS technique modified the arrangement of the scheduling for the ONUs in each cycle, which depend of the traffic load.

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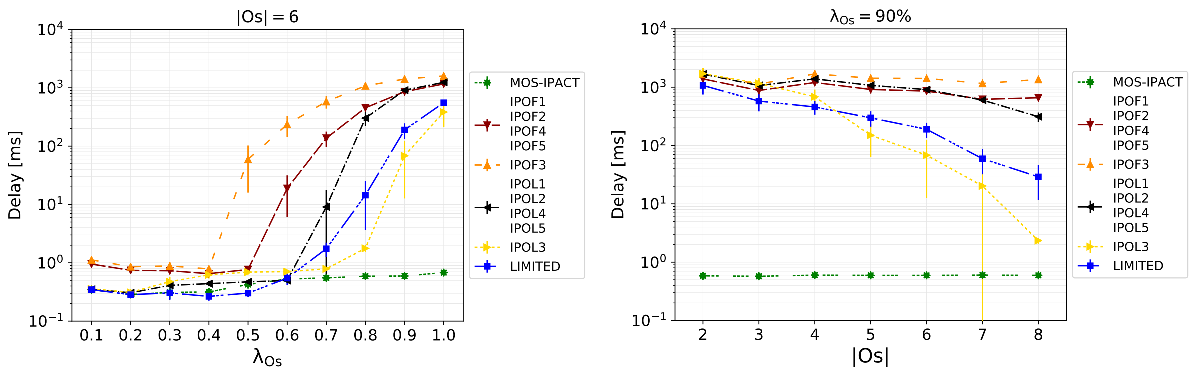
[3]For the sake of brevity, herein after, * represent the possible combinations of the algorithm. For example IPOL* represent IPOL1, IPOL2, IPOL3, IPOL4 and IPOL5.

IPACT OLS with EE policy (IPOL3) has lower percentage of idle time than other *IPACT* with EDP configuration. This occurs because when IPOL3 is employed, the OLT grants more bandwidth than the reported in the Report message, thus there are an extra bandwidth for the new data that arrive to the ONU between the Report message is sent and the Gate message is received.

Moreover, the other OLS schedulers (*i.e.,* IPOL1, IPOL2, IPOL4 and IPOL5) have a lower percentage of idle time than the IPOF* algorithms when the load of the multi-ONU customer is less than 0.9 (Figure 3.14b). This occurs because more Report messages from underloaded ONUs are scheduled on time, therefore, the idle time decreases.

Delay and PLR for the Multi-ONU customer

Figures 3.15a and 3.15b show the impact of the aggregate load (λ_{Os}) and number of ONUs in the group ($|\text{O}s|$) on the delay of the AF traffic in the multi-ONU customer.



(a) Varying the aggregate load (b) Varying the number of ONUs in the group

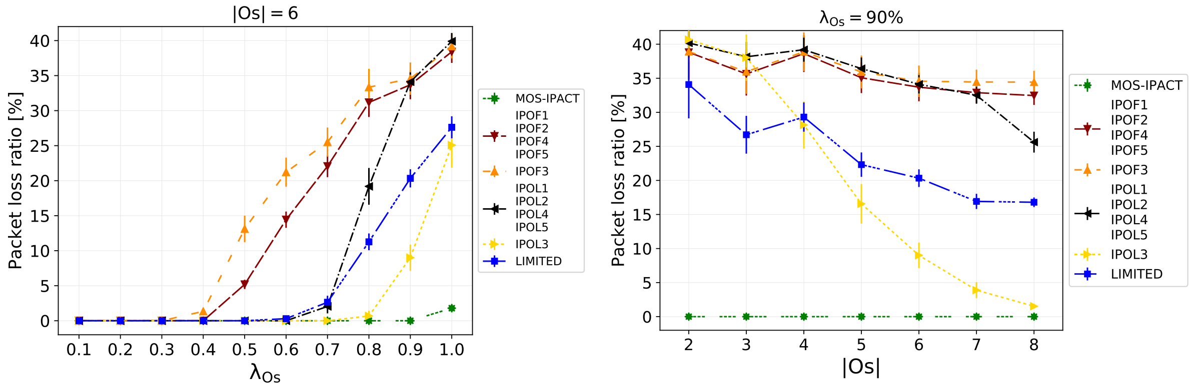
Figure 3.15: Impact of the aggregate load and number of ONUs in the group on the delay of the AF traffic in the multi-ONU customer.

Figure 3.15 shows that all configurations of the *MOS-IPACT* algorithm produces delay of the AF traffic lower than 1 ms. Moreover, these delay values are constant regardless of the load and number of ONUs in the multi-ONU customer. Thus, a multi-ONU customer, employing *MOS-IPACT* can support delay-sensitive services (*i.e.,* video conference, real-time video games) for their clients, even in unbalanced traffic conditions.

On the other hand, all configurations of the *IPACT* algorithm generate a delay of the AF traffic higher than 100 ms when $\lambda_{\text{Os}} = 1.0$. This occurs because *IPACT* does not distribute the excess bandwidth of a multi-ONU customer between their ONUs. Moreover, *IPACT* with excess bandwidth distribution generates high idle times, which reduces the available bandwidth in the PON.

Moreover, different delay values are produced when the OLT employ the diverse configurations of the *IPACT* algorithm. The IPOL3 algorithm produces lower delay values than produced by the other *IPACT* configurations. Besides, when IPOL3 algorithm is employed, the delay decreases as the number of ONUs in the multi-ONU customer increases. Thus, IPOL3 is the best configuration of *IPACT* for multi-ONU customers. In the best case (*i.e.,* $\lambda_{\text{Os}} = 1.0$ and $|\mathcal{O}_S| = 8$), the delay of the AF traffic is 2 ms employing IPOL3. However, a multi-ONU customer employing *MOS-IPACT* has lower delay values.

Figures 3.16a and 3.16b show the impact of the aggregate load (λ_{Os}) and number of ONUs in the group $|\mathrm{O}s|$ on the PLR of the BE traffic in the multi-ONU customer.



(a) Varying the aggregate load

(b) Varying the number of ONUs in the group

Figure 3.16: Impact of the aggregate load and number of ONUs in the group on the PLR of the BE traffic in the multi-ONU customer.

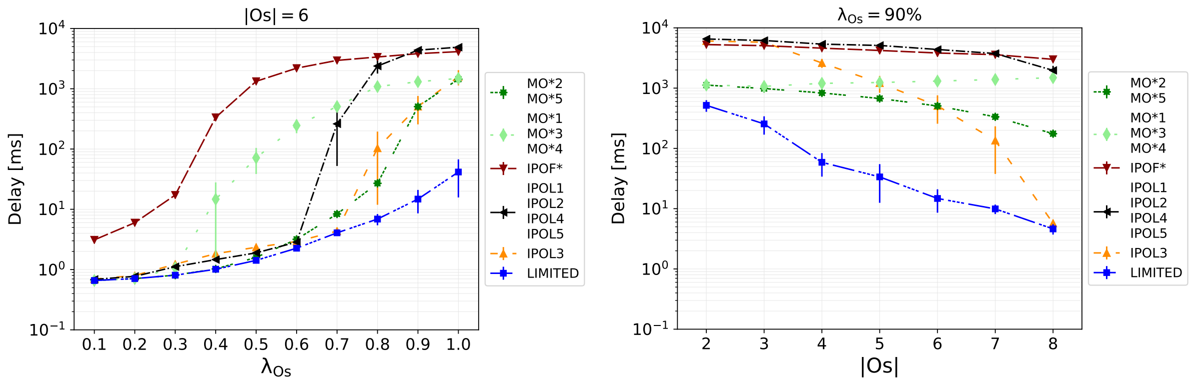
Figure 3.16 shows that the different configurations of the *MOS-IPACT* algorithm have a packet loss of the BE traffic lower than 3 %. This occurs because the multi-ONU customer can redistribute the high unbalancing loads between their ONUs, which improves the statistical multiplexing gain. For example, a ONU having a high load can use part of the available bandwidth of underloaded ONUs of the same customer.

On the other hand, the *IPACT* algorithm has PLR values higher than 25 %. Moreover, in some cases (*i.e.,* IPOF*), the PLR reaches up 35 %. This high PLR is because the *IPACT* algorithms do not guarantee bandwidth at the level of group of ONUs. Hence, overloaded ONUs cannot use the extra bandwidth of the underloaded ONUs of the same multi-ONU customer. For example, an underloaded ONU employs a window less than W^{max}, which reduces the cycle, and it benefits all ONU in the PON. Furthermore, IPOL3 produces the lowest PLR value among *IPACT* algorithms. However, *MOS-IPACT* is the best algorithm, in terms of produced PLR and delay, for multi-ONU customers.

Delay and PLR for traditional customers

We analyze the impact of the *MOS-IPACT* algorithm on the traditional customers, which have a single ONU in the PON. In our scenario, those customers share the PON with the multi-ONU customer. The delay values of the AF traffic for the traditional customer are lower than 1 ms for all algorithms. These low values occurs because the load of the traditional ONUs has the same value that the guaranteed bandwidth, which is enough to support the bandwidth demand of the medium priority traffic (*i.e.,* AF traffic). Hence, we analyze the delay of the BE traffic for those ONUs. Figures 3.17a and 3.17b show the impact of the aggregate load (λ_{Os}) and number of ONUs in the group $|\mathrm{O}s|$ on the delay of the BE traffic in the traditional customers.

The delay of the BE traffic for traditional customers employing conventional *IPACT* (limited policy) is lower than the other algorithms. This can be explained because, in the limited policy, the overloaded ONU of the multi-ONU customer cannot use the excess



(a) Varying the aggregate load (b) Varying the number of ONUs in the group

Figure 3.17: Impact of the aggregate load and number of ONUs in the group on the delay of the BE traffic in the traditional customers.

bandwidth of the underloaded ONU, which reduces the cycle, giving more opportunities to traditional customers to send data. Moreover, conventional *IPACT* has no idle times.

Moreover, *MOS-IPACT* with OLS scheduling (MO*2 and MO*5) has a delay lower than the *MOS-IPACT* with offline scheduling (MO*1, MO*2, and MO*3). The OLS scheduling reduces the idle times and time between transmission because when a Report message from an underloaded ONU arrives, the OLT sends immediately a Gate message.

MO*2 and MO*5 produce similar delay values lower than *IPACT* until 70 % of the aggregated load. For loads higher than 70 %, the delay of the BE traffic in the traditional ONUs increases when MO*2 and MO*5 are employed. This occurs because the ONUs of the multi-ONU customer share more bandwidth, which increases the size of the cycle and hence, increases the gap between transmission of the traditional ONUs. This gap does not mean that the OLT reduces the legacy transmission window in the traditional ONUs. However, the time between transmission increase [4].

Figures 3.18a and 3.18b show the impact of the aggregate load (λ_{Os}) and number of ONUs in the group ($|\mathrm{O}s)|$ on the PLR of the BE traffic in the traditional customers.

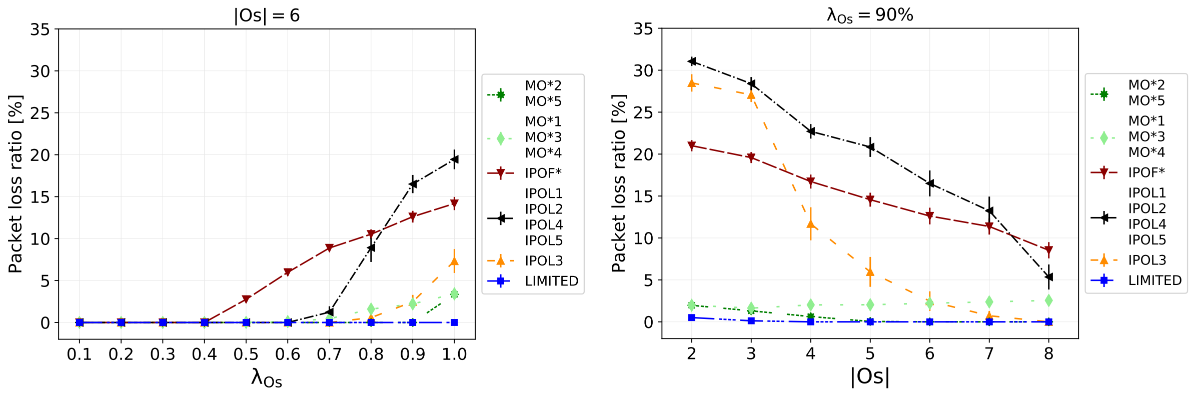
The conventional *IPACT* produces no packet losses for the BE traffic. On the other hand, MO*2 and MO*5 no produce packets loss of the BE traffic until 0.9 of the aggregated load, however, when the aggregated load is 1.0, the packets loss is 4 %. Two facts can explain this packets loss: first, traditional ONUs have a load equal to the guaranteed bandwidth. Second, the traffic is typically self-similar, which produces bigger data bursts. Thus, in overloaded conditions, the bandwidth required for a data bursts can be higher than the guaranteed bandwidth.

Moreover, when the load is 0.9, *MOS-IPACT* with offline scheduling (MO*1, MO*3 and MO*4) produce 3 % of packets loss for the BE traffic in the traditional ONUs (Figure 3.17b). This packet losses occurs because the ONUs of the multi-ONU customer employ all bandwidth. Thus, the ONUs of the traditional customers are not benefited by a reduction in the cycle.

We conclude that *MOS-IPACT* does not affect the legacy guaranteed bandwidth of

[4]The maximum gap between transmission opportunity for each ONUs is equal to the maximum cycle length (1 ms)

the traditional ONUs. The packets loss of the BE traffic in the traditional ONUs is 3 % when *MOS-IPACT* algorithm is employed. This packet losses are acceptable for a ONUs that are fully overloaded.



(a) Varying the aggregate load (b) Varying the number of ONUs in the group

Figure 3.18: Impact of the aggregate load and number of ONUs in the group on the PLR of the BE traffic in the traditional customers.

Empirical Probability Density Function (EPDF)

To compare the performances of the various *MOS-IPACT* configurations, we calculate the probability of n ONUs to be overloaded ONUs in the multi-ONU customer. Thus, we computed the number of times that n were overloaded in all cycles (x_n). Hence, the probability of the n ONUs are overloaded is calculated as

$$P(X = n) = \frac{x_n}{n_{cycles}} \tag{3.8}$$

The EPDF satisfied the Formula 3.9

$$\sum_{n=1}^{N_{group}} P(X = n) = 1 \tag{3.9}$$

The EPDF of overloaded ONUs in a multi-ONU customer with 6 ONUs and an aggregate load of 0.9 is shown in the Figure 3.19.

GSF does not affect the probability of the ONUs to be overloaded. However, this probability varies with the EDP employed. In Figure 3.19 the EE EDP (MOF3 and MOL3) reduces the probability of overloaded ONUs in the PON. For example, the probability of the multi-ONU customer to have 3 overloaded ONUs is 2 % with MOF3 and MOL3, meanwhile, this probability is greater than 15 % for the other algorithms.

The EPDF shows a specific scenario in which the load and number of ONUs are fix. Thus, we calculate the average number of overloaded ONUs for a specific scenario as

$$AverageNumber = \frac{\sum_{n=1}^{N_{group}} i \cdot P_n}{N_{group}} \tag{3.10}$$

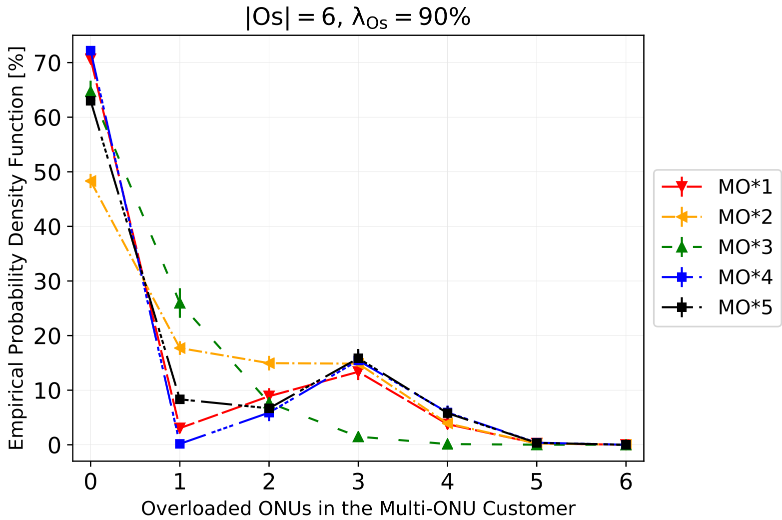
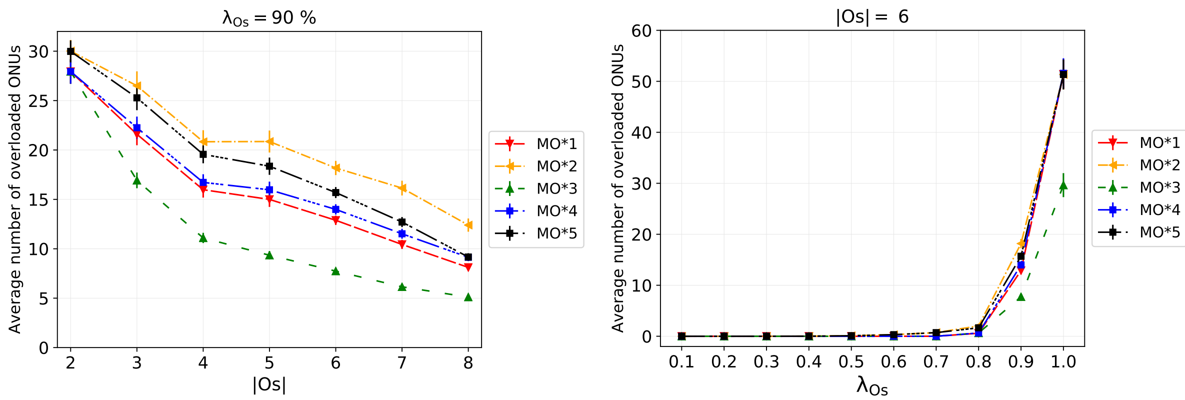


Figure 3.19: Probability of overloading in ONUs of the multi-ONU customer.

Figures 3.20a and 3.20b show the average number of overloaded ONUs in the multi-ONU customer when the number of ONUs and the aggregate load vary, respectability.



(a) Varying |Os| (b) Varying λ_{Os}

Figure 3.20: Average number of the overloaded ONUs.

The Excess Control (EC) policy (MO*2 and MO*5) increases the probability of ONUs to be overloaded. This occurs because the granted windows size is limited to the request value. Therefore, the granted windows size does not consider the new packets in the queue that arrive at the ONU between the Report message is issue and the Gate message is arrived.

On the other hand, the EE policy gives a greater window transmission than do the other algorithms, so the probability of overloaded ONUs decreases. This does not necessarily mean a positive effect on the delay and packet loss. As in the previous metrics, the best performance was presented in the configuration with excess control. Therefore, we can conclude that MOF2, MOL2, MOF5 and MOL5 algorithms presents the best benefits in terms of delay and PLR, both for the traditional customers and the multi ONU customer. However, the MOF5 and MOL5 algorithms produce lower probability of a multi-ONU customer to have overloaded ONUs than do the MOF2 and MOL2 algorithms.

3.5 Summary

This chapter introduced a novel DBA scheme that enables multi-ONU Service Level Agreement support for EPON networks. We compared the performance of our proposed scheme to that of the IPACT algorithm, which does not support Multi-ONU SLAs, when varying the number of ONU in the group as well as the offered loads of the target ONU and the group. Simulation results show that the proposed scheme provides lower packet loss ratio and delay than does the IPACT algorithm for multi-ONU customers with unbalanced traffic.

Chapter 4

Prioritized Services for Multi-ONU Customers in EPON

In the previous chapter, it was introduced the concept of a *multi-ONU SLA* which provide guaranteed bandwidth for a group of ONUs, that belongs to the same customer (multi-ONU customer). The *MOS-IPACT* algorithm allows the sharing of unused guaranteed bandwidth of an ONU with the other ONUs belonging to the same customer while maintaining isolation from the other customers. Thus, bandwidth is assured at individual ONUs level, as well as, at the group of ONUs level. However, bandwidth is not assured at subgroup level.

The *MOS-IPACT* algorithm distributes the excess bandwidth according to the requested bandwidth. Therefore, the excess bandwidth is prioritized only by the ONU load and not by the type of services that the ONU provides (*e.g.,* mobile backhauling/fronthauling, enterprise and residential services). Thereby, subgroups of ONUs in a multi-ONU customer can starve, even when the guaranteed bandwidth of the subgroup is sufficient to support the aggregate load.

In this chapter, we focus on the provisioning of bandwidth guarantee at different levels of granularity to improve QoS for multi-ONU customers. Thus, multi-ONU customers can offer diverse type of services or even a single service to its clients. For example, a multi-ONU customer can lease ONUs from an InP to build its cellular backhaul network while other customer can lease ONUs to offer enterprise and residential services to their client. In the former, the leased set of ONUs is used by a single type of service while in the latter the set of ONUs is used by different services with diverse quality of service requirements. Moreover, network as a service should provide customer isolation, customization, and efficient utilization of resources [39].

We introduce a DBA algorithm called *subMOS-IPACT* that provides bandwidth guarantee at different granularity: individual ONUs, multi-ONU customer, subgroups of ONUs as illustrated in Figure 4.1. A subgroup is a set of ONUs that belong to the same multi-ONU customer. *subMOS-IPACT* assures bandwidth to traditional customers with a single ONU, customers owning multiple ONUs but with a single service (i.e, Multiple ONUs/eNB) and customer with multiple ONUs serving diverse types of service.

Moreover, *subMOS-IPACT* provides isolation at customer, subgroup and individual ONU level. Thus, various customers can coexist in a PON without affecting the band-

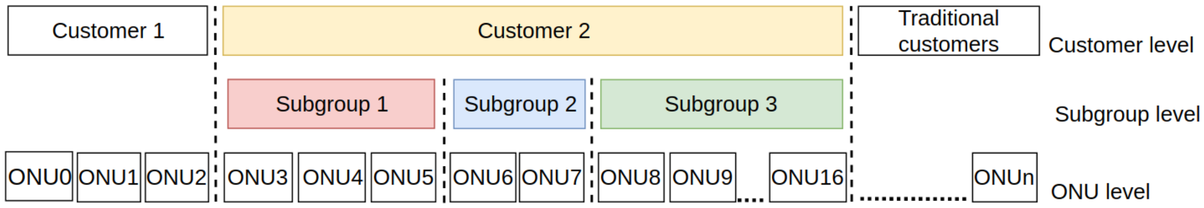


Figure 4.1: Granularity of bandwidth guarantees in *subMOS-IPACT*.

width guarantee to other customers. *subMOS-IPACT* also allows multi-ONU customer to support a priority bandwidth allocation in the subgroups.

Simulation results show that *subMOS-IPACT* provides effective bandwidth isolation and efficient channel utilization. Furthermore, it reduces the delay and PLR of overloaded high priority subgroups, and yet does not cause bandwidth starvation to low priority subgroups.

The organization of this chapter follows: Section 4.1 reviews the related work of DBA algorithms with support to guaranteed bandwidth and QoS providing in EPON networks. Section 4.2 describes *subMOS-IPACT* DBA algorithm. The performance evaluation of *subMOS-IPACT* in a multi-ONU customer is presented in Section 4.3. Finally, Section 4.4 brings final considerations.

4.1 Related Work

A variety DBA algorithms have been proposed to deliver different types of data traffic with differentiated QoS support. The IPACT algorithm [34] provides only guaranteed bandwidth for each ONU according to the SLA. In addition, the bandwidth is prioritized depending on the type of traffic (*i.e.*, EF, AF and BE).

The Hybrid Granting Protocol (HGP) algorithm [54], proposes a division in the transmission cycle to support QoS requirements of different applications (*i.e.*, voice, video and data). A sub-cycle is employed for the bandwidth allocation of the EF traffic, meanwhile, other sub-cycle is used for the AF and BE traffics. HGP employs a queue prediction mechanisms for allocating bandwidth which minimizes delay and jitter of sensitive traffic (*i.e.*, voice). The length of the EF sub-cycle is predetermined while that of the AF/BE sub-cycle depends on the traffic load of each ONU.

Fair Sharing with Dual SLAs (FSD-SLA) algorithm [11] employs two SLAs to provide fairness for both priority and no priority services. A primary SLA describes priority service requirements and a secondary SLA the lower priority. A first upstream transmissions allocates the priority services, meanwhile, the next upstream transmissions is employed to accommodate the secondary SLA services. If there is excess bandwidth in the primary SLA, FSD-SLA allocates that excess bandwidth to the secondary SLA. Furthermore, a max–min policy is adopted to fairness allocation of bandwidth between services.

Dynamic Bandwidth Allocation with Multiple Services (DBAM) algorithm [42] provides QoS for traditional customer with a single ONU with service differentiation. Instead of providing multiple services among ONUs and among end users separately, DBAM incorporates both of them into the REPORT/GATE mechanism with class based bandwidth allocation that employs bursty traffic prediction.

The Two-Layer Bandwidth Allocation (TLBA) algorithm [59] provides differentiated services and satisfies QoS demands of all ONUs. The TLBA proposes a two-layer bandwidth allocation scheme that implements weight-based priority scheduling. In the first layer, a part of transmission cycle is allocated among differentiated service. In the second layer, the partition allocated to each service is distributed to all ONUs based on a max–min fairness policy. The weight of each services prevents that high-priority traffic monopolizing the available bandwidth under heavy load condition and ensuring a minimum bandwidth allocated to each traffic class.

The previous DBA algorithm provides QoS support to deliver differentiated services, however, does not consider multi-ONU customers coexisting in the same PON. Therefore, those algorithms does not provide bandwidth guarantee for multi-ONU customer. The *MOS-IPACT* algorithm provides bandwidth guarantees for customers owning multiples ONUs, however it does not differentiate services (*e.g.,* enterprise and residential services). Thus, time-critical services covering low-latency (such as mobile backhauling service) are not prioritized in multi-ONU customers. The next section introduces the *subMOS-IPACT*, which provide bandwidth guarantees at a finer granularity including at subgroup/service level.

4.2 Proposed DBA scheme

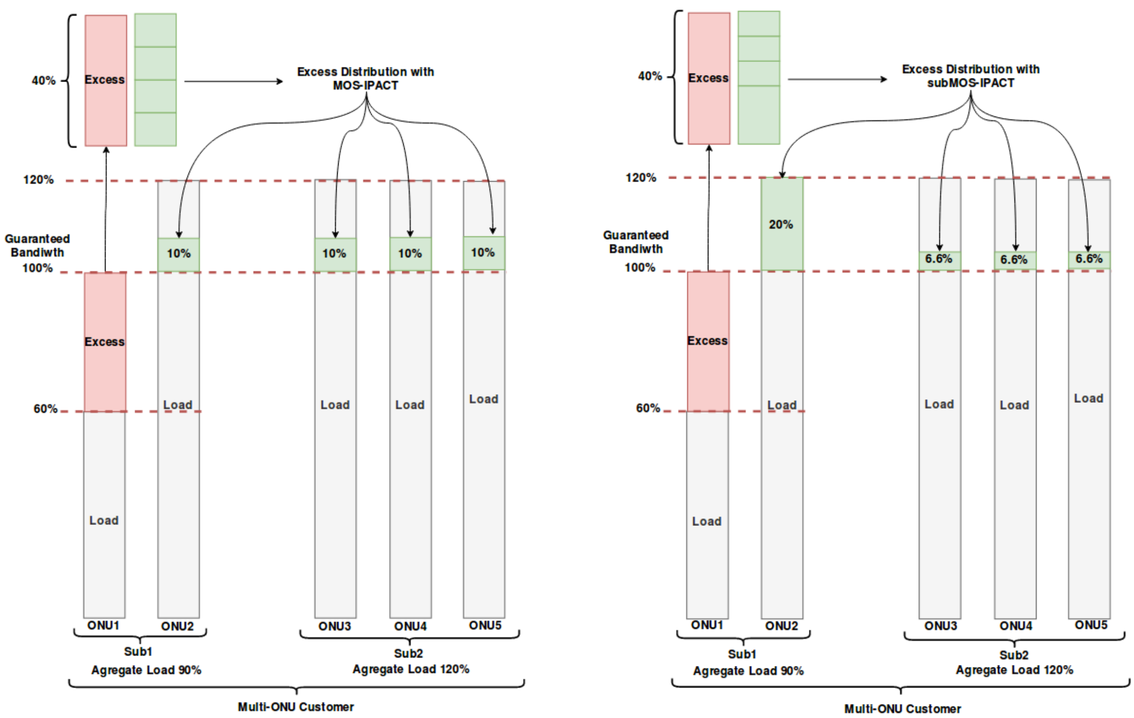
This section describes the proposed DBA that assures bandwidth at three different levels of granularity: individual ONUs, customer and subgroups of ONUs. The proposed DBA allows bandwidth guaranteed to three types of customers: i) Traditional Customer having a single SLA per ONU, ii) Multi-ONU Customer with *multi-ONU SLA* and no service differentiation and iii) Multi-ONU Customer with *multi-ONU SLA* and service differentiation.

The proposed DBA algorithm is called *MOS-IPACT* with prioritized ONU subgroup support (*subMOS-IPACT*). Furthermore, high priority subgroup, related to sensitive services (i.e., ONUs/eNBs for mobile backhauling/fronthauling), acquire more bandwidth when overloaded. *subMOS-IPACT* allows the management of the bandwidth at different levels of granularity with effective isolation.

In the MOS-IPACT algorithm, bandwidth is assured at individual ONUs level, as well as, at group of ONU level but not for differentiated services, refereed here as subgroup of ONUs with different services (*e.g.,* ONUs/eNBs, enterprise and residential ONUs). Thus, overloaded subgroups can use the aggregate guarantee bandwidth of underloaded subgroups, even when some ONUs of the underloaded subgroup have bandwidth starvation, as shown Figure 4.2a.

On the other hand, *subMOS-IPACT* algorithm distributes the total customer excess bandwidth among the subgroups based on the priority level of these subgroups and additionally maintaining the aggregate guaranteed bandwidth in each subgroup, as shown Figure 4.2b.

subMOS-IPACT calculates the windows transmission size and the next transmission



(a) *MOS-IPACT* algorithm (b) *subMOS-IPACT* algorithm

Figure 4.2: Example of excess bandwidth distribution with the proposed DBA algorithms.

time ($t_{txStart}$) at each cycle. When a Report message arrive at the OLT, *subMOS-IPACT* classifies the message coming from a traditional customer, a multi-ONU customer with no subgroups or a multi-ONU customer with subgroups.

When the Report message comes from a traditional customer, the OLT calculates the start time of the next transmission ($t_{txStart}$) and the windows size employing the Limited policy. The OLT then sends a Gate message to the corresponding ONU (online GSF).

If the Report message comes from a multi-ONU customer with a single services (without subgroups), the OLT waits for Report messages from all ONUs belonging to the same multi-ONU customer before sending the Gate messages to these ONUs (offline GSF). The window transmission size is calculated employing by the Limited with Excess policy to assure bandwidth at the customer level.

If the Report message comes from a multi-ONU customer with subgroups, the OLT waits for the arrival of each Report coming from a subgroup of ONUs before sending the Gate messages to those ONUs of that subgroup (offline GSF). The OLT then calculates the window transmission size employing the Limited with Excess policy to assure bandwidth for the subgroup. The *subMOS-IPACT* scheme also assures the bandwidth at the customer level. When the Report message from all ONUs that belongs to the same multi-ONU customer arrive at the OLT, a second Gate message is sent to the overloaded ONUs in that multi-ONU customer (MTP). The second Gate message informs the portion of the customer total excess bandwidth allocated to the overloaded ONUs. However, this thread of message consumes bandwidth due to the necessary guard time between messages. In order to reduce this waste of bandwidth and prioritize sensitive services, a new policy called High Priority Subgroup First (HPS) is proposed. HPS distributes the total customer excess bandwidth only between the overloaded ONUs of the high priority subgroup. If there is remaining bandwidth available, it is distributed between the next highest priority subgroup, until all subgroups are satisfied or all excess bandwidth is distributed.

Table 4.1 compares the *subMOS-IPACT* scheme with some principal DBA algorithms that we explained in the Section 4.1.

<table>
<tr><th></th><th>IPACT</th><th colspan="2">BGP</th><th colspan="3">MOS-IPACT</th><th colspan="4">subMOS-IPACT</th></tr>
<tr><td>PON users</td><td>Traditional Customers</td><td>Premium Subscribers</td><td>BE Subscribers</td><td colspan="2">Multi-ONU Customers</td><td>Traditional Customers</td><td colspan="3">Multi-ONU Customers</td><td>Traditional Customers</td></tr>
<tr><td>Bandwithd Guaranteed</td><td>Individual ONUs</td><td>Individual ONUs</td><td>x</td><td>Customer</td><td>Individual ONUs</td><td>Individual ONUs</td><td>Customer</td><td>Subgroup</td><td>Individual ONUs</td><td>Individual ONUs</td></tr>
<tr><td>GSF</td><td>Online</td><td colspan="2">Online</td><td colspan="2">Offline</td><td>Online</td><td colspan="3">Offline</td><td>Online</td></tr>
<tr><td>GWP</td><td>Limited</td><td colspan="2">EDA</td><td colspan="2">Limited with Excess</td><td>Limited</td><td colspan="3">Limited with Excess</td><td>Limited</td></tr>
<tr><td>EDP</td><td>x</td><td colspan="2">x</td><td>FE-DBA</td><td>x</td><td>x</td><td colspan="2">FE-DBA</td><td>x</td><td>x</td></tr>
<tr><td>GSP</td><td>Round Robin</td><td>LNF</td><td>Round Robin</td><td colspan="2">Round Robin</td><td>Round Robin</td><td colspan="2">HPS</td><td>Round Robin</td><td>Round Robin</td></tr>
<tr><td>TSF</td><td>STP</td><td colspan="2">STP</td><td>STP</td><td>STP</td><td>STP</td><td colspan="3">MTP</td><td>STP</td></tr>
</table>

Table 4.1: DBA Algorithms that support different granularity of guarantee bandwidth.

4.2.1 *subMOS-IPACT* DBA algorithm

Algorithm 2 summarizes the *subMOS-IPACT* algorithm. Let $\mathcal{G}$ be the set of multi-ONU customers and $\mathcal{S}$ the set of subgroups of a multi-ONU customer; $\mathcal{O}$ is the set of ONUs in the PON; $\mathcal{O}_C$ the set of individual ONUs that do not belong to any *multi-ONU customer*; and $\mathcal{O}_{k,s}$ the set of active ONUs which belong to the s-th subgroup of the k-th multi-ONU customer. $\mathcal{O}_k$ is the set of overloaded ONUs belonging to the k-th customer.

A transmission window $W_i^{limited}$ is calculated for each Report message R received by the OLT (Line 1) using the IPACT limited policy (Line 2), and defined as

$$W_i^{limited} = \begin{cases} R_i & if \quad R_i \leq W_i^{max} \\ W_i^{max} & if \quad R_i > W_i^{max} \end{cases} . \tag{4.1}$$

In this policy, the ONUs have a maximum windows size (W_i^{max}) equivalent to the guaranteed bit rate. For message sent by traditional ONUs (Line 3), the start time *txStart* for the next cycle is calculated, and a Gate message is sent to the ONU_i (Line 4 and 6).

If the Report message comes from an ONU belonging to a multi-ONU customer with subgroups, the Report message is added to the set of Report messages of the subgroup s that belongs to multi-ONU customer k ($\mathcal{R}_{k,s}$) (Lines 7 and 8). If the OLT has already received all the Report messages from the ONUs in that subgroup, the *BulkGrantGenerator* function is applied (Lines 9 and 10) for assuring bandwidth to the subgroup, using the same mechanism proposed in the *MOS-IPACT* scheme. When all Report messages from a multi-ONU customer with subgroups are received, a function called *MultiThreadGrantGenerator* is applied for distributing the excess bandwidth of the multi-ONU customer among the subgroups in a second scheduling thread (Lines 12 and 13).

When the Report message comes from an ONU belonging to a multi-ONU customer with no subgroups, only the *BulkGrantGenetrator* is applied since this multi-ONU customer has only one subgroup. The bandwidth is assured just for the customer and the

Algorithm 2: *subMOS-IPACT* DBA Algorithm

: $\mathcal{R'}_k \leftarrow \emptyset, \forall k \in \mathcal{G}$
: $\mathcal{R}_{k,s} \leftarrow \emptyset, \forall k \in \mathcal{G}, \forall s \in \mathcal{S}$
for *each received report R from ONU i in cycle j* **do**
  Calculate $W_i^{limited}$ according to the limited policy
  if *ONU* $i \in \mathcal{O}_C$ **then** `/* If report message comes from a traditional customer */`
    Calculate $t_{txStart}$
    $\text{Gate}_i^j \leftarrow \left(W_i^{limited}, t_{txStart}\right)$
    Send $Gate_i^j$
  else `/* If report message comes from a multi-ONU customer */`
    $\mathcal{R}_{k,s} = \mathcal{R}_{k,s} \cup \{R\}$ `/* Save report message */`
    if $|\mathcal{R}_{k,s}| = |\mathcal{O}_{k,s}|$ **then** `/* If received all report messages from the ONUs subgroup s that belongs to multi-ONU customer k */`
      BulkGrantGenerator()
    end
    if $|\mathcal{R'}_k| = |\mathcal{O}_k|$ **then** `/* If received all report messages from the multi-ONU customer k */`
      MultiThreadGrantGenerator()
    end
  end
end
$\text{R}_{k,s} \leftarrow \emptyset$
Function `BulkGrantGenerator()`
  for *each report* $R \in \mathcal{R}_{k,s}$ **do** `/* Compute and send gate messages for ONUs of subgroup s that belongs to multi-ONU customer k */`
    Calculate $t_{txStart}$
    Calculate $W_i^{granted}$
    if $R_i > W_i^{granted}$ **then**
      $\mathcal{R'}_k = \mathcal{R} \cup (i, R_i - W_i^{granted})$
    end
    $\text{Gate}_i^j \leftarrow \left(W_i^{granted}, t_{txStart}\right)$
    Send $Gate_i^j$
  end
End Function
Function `MultiThreadGrantGenerator()`
  $\mathcal{R'}_k \leftarrow sort(\mathcal{R'}_k)$ by HPS policy
  for *each report* $R \in \mathcal{R'}_k$ **do** `/* Compute and send gate messages for overloaded ONUs of multi-ONU customer k */`
    Calculate $W_i^{grantedThread}$
    if $W_i^{grantedThread} != \emptyset$ **then**
      Calculate $t_{txStart}$
      $\text{Gate}_i^j \leftarrow \left(W_i^{grantedThread}, t_{txStart}\right)$
      Send $Gate_i^j$
    end
  end
  $\mathcal{R'}_k \leftarrow \emptyset$
End Function

individual ONUs.

In the *BulkGrantGenerator* function, the OLT sends a Gate message for each Report message received from the ONUs belonging to the subgroup s and multi-ONU customer k. Each ONU is classified either as *underloaded* (if $R_i \leq W_i^{limited}$) or *overloaded* (if $R_i >$

$W_i^{limited}$). The granted window size ($W_i^{granted}$) is calculated by executing the limited policy with excess bandwidth distribution (Line 21). The FE-DBA with excess control (EC) technique [20] is used to distribute the excess bandwidth among the overloaded ONUs in a subgroup, as well as, to avoid the allocation of a granted window size larger than the request one. $W_i^{granted}$ is defined as

$$W_i^{granted} = \begin{cases} R_i & if \quad R_i \leq W_i^{max} + E_i \\ W_i^{max} + E_i & if \quad R_i > W_i^{max} + E_i \end{cases}, \tag{4.2}$$

where E_i is the excess bandwidth assigned to the overloaded ONU_i, calculated as

$$E_i = \frac{W_i^{req}}{\Sigma_{j\varepsilon O} W_j^{req}} * E_s^{total}; \tag{4.3}$$

O is the set of *overloaded* ONUs and E_s^{total} is the total excess bandwidth of *underloaded* ONUs in the same subgroup s in a given cycle. Such computation uses the required windows size ($W_i^{req} = R_i - W_i^{max}$) instead of just that allowed on the requested window size (R_i). For an *underloaded* ONU, the allocated excess bandwidth E_i is zero and the granted window size is equal to the requested windows size ($W_i^{granted} = R_i$).

The OLT then sends a Gate message with the next start time and the size of the granted transition windows for the next cycle (Lines 25 and 26). In this way, the total excess bandwidth from *underloaded ONUs* (E_s^{total}) is distributed among the *overloaded ONUs* belonging to the same subgroup in a per cycle basis.

However, if the ONU continues to be overloaded after the excess distribution process (Line 22), the Report message is added to the set of Report messages of overloaded ONUs ($\mathcal{R}'_k$) that belongs to the multi-ONU customer k. In this case, the request windows size in each Report messages in R'_k is the difference between R_i and $W_i^{granted}$ (Lines 23). Thus, the required window size W_i^{req} is equal to the requested window size. The set of Report R'_k will be schedule when executing the $MultiThreadGrantGenerator$ function, after all Reports message arrived at the OLT from the ONUs of a multi-ONU customer (Lines 12).

In the $MultiThreadGrantGenerator$ function, the total excess bandwidth of multi-ONU customer (E_k^{total}) is distributed among the ONU subgroups, beginning by the highest priority subgroup ($s1$). This is achieved by generating a list of the set R'_k sorted by their priorities (from the highest to lowest priority) (Lines 30 and 31).

Moreover, E_k^{total} is normalized considering the total bandwidth required by the given subgroup. In order to avoid affecting the guaranteed bandwidth to others, an additional guard period (TG) used for the new thread is taken into account as a part of the required windows size by overloaded ONUs as shown in Equation 4.4.

$$E_i = \frac{W_i^{req} + TG}{\Sigma_{j\varepsilon C}(W_j^{req} + TG)} * E_k^{total} \tag{4.4}$$

C is the set of *overloaded* ONUs in the subgroup.

The granted window size of the Gate message for the second thread ($W_i^{grantedThread}$)

(Lines 32) is calculated as

$$W_i^{grantedThread} = \begin{cases} B_i^{req} & if \quad B_i^{req} + TG \leq +E_i \\ B_i^{req} - TG & if \quad B_i^{req} + TG > +E_i \\ \emptyset & if \quad TG \geq E_i \end{cases} \tag{4.5}$$

and subsequently the next start time is calculated and the Gate message is sent to the overloaded ONU_i (Lines 33-36).

After distributing the customer excess bandwidth among the overloaded ONUs of the high priority subgroup, the OLT subtracts the bandwidth used from the total excess bandwidth, as shown next

$$E_k^{total} = E_k^{total} - \Sigma_{j \varepsilon C}(W_j^{grantedThread} + TG) \tag{4.6}$$

Subsequently, the overloaded ONUs of the next high priority subgroup $(s2, ..., sn)$ are processed to allocate the remaining bandwidth of the customer. When the total customer excess bandwidth is completely distributed or all overloaded ONUs in the customer receives the necessary bandwidth, the excess bandwidth allocation process is finished and the corresponding R'_k and $R_{k,s}$ are emptied (Lines 17 and 39).

4.2.2 Complexity Analysis

The complexity of the proposed algorithm is analyzed as follows. With the *MOS-IPACT* scheme, each Report is considered once per cycle to receive the Reports and the excess bandwidth allocation is calculated once for every active ONUs in the groups. *subMOS-IPACT* scheme applies receive the Reports message from all ONUs in the PON once per cycle, in addition the excess bandwidth allocation is used to distribute the excess bandwidth in each subgroup. Furthermore, *subMOS-IPACT* gives a second upstream transmission to opportunity overloaded ONUs in the same cycle. Thus, in the worst case, which all ONUs in the multi-ONU customers with service differentiation are overloaded, except one (enough underloaded to have excess bandwidth for all other ONUs), the time complexity is $O(n + l + j - s)$, where n the total number of ONUs in the PON, l is the total number of ONUs in the multi-ONU customers, j the total number of ONUs in the multi-ONU customers with service differentiation and s the total number of subgroup of ONUs.

4.3 Performance Evaluation

In this section, we assess the performance of the proposed *subMOS-IPACT* DBA scheme by using an EPON simulator (EPON-Sim) previously used in [17]. The EPON-Sim implements the IPACT DBA algorithm together with the limited discipline introduced by Kramer *et. al* in [34]. This simulation also implements the *MOS-IPACT* scheme with the FE-DBA policy. The *subMOS-IPACT* scheme was introduced in the EPON-Sim simulator and a new version of the simulator was validated extensively.

4.3.1 Simulation Model and Setup

A 10G-EPON network with a tree topology and 1 OLT that handles the upstream channel of a set of 32 ONUs ($|\mathcal{O}| = 32$) was simulated. Three different traffic classes (EF, AF and BE) were configured for each ONU in $\mathcal{O}$, as in Section 3.3. The guard time period used was 0.624 μs [52] and the maximum cycle length 1 ms. At every polling cycle, each ONU received at least the grant required to send a Report message (the minimum Ethernet frame size is 64 bytes). Each simulation scenario lasted 50 s and it was replicated 50 times.

We assume one multi-ONU customer M with three ONU subgroups ($S_i, i \in \{1, 2, 3\}$). The multi-ONU customer has a group of ONUs $\mathcal{O}_M \subset \mathcal{O}$. The ONUs of subgroup i, $\mathcal{O}_{S_i} \subset \mathcal{O}_M$ and $\mathcal{O}_{S_i} \cap \mathcal{O}_{S_j} = \emptyset \mid i \neq j$ and $i, j \in \{1, 2, 3\}$. The S_1 subgroup has the highest priority, S_2 intermediate priority and S_3 the lowest priority. The number of ONUs in the group and subgroups is fixed; $|\mathcal{O}_M| = N_{group} = 16$, $|\mathcal{O}_{S_1}| = N_{S_1} = 4$, $|\mathcal{O}_{S_2}| = N_{S_2} = 3$ and $|\mathcal{O}_{S_3}| = N_{S_3} = 9$. Each ONU j in subgroup i has guaranteed bandwidth B_j between 150 Mbps and 450 Mbps, provided that $\sum_{j \in \mathcal{O}_{S_i}} B_j = N_{S_i} \cdot 300$ Mbps $= A_{S_i}$, which is the effective aggregated guaranteed bandwidth in subgroup i. The ONUs of the multi-ONU customer can be either overloaded or underloaded since the offered load of ONU j (λ_j) varies uniformly between 0 and 600 Mbps. The aggregate offered load in the subgroup i (λ_{S_i}) satisfied ($\sum_{j \in \mathcal{O}_{S_i}} \lambda_j = \lambda_{S_i}$). On the other hand, there is a set of traditional ONUs $\mathcal{O}_C \subset \mathcal{O}$, such that $\mathcal{O}_C \cup \mathcal{O}_M = \mathcal{O}$ and $\mathcal{O}_C \cap \mathcal{O}_M = \emptyset$. Each ONU k in $\mathcal{O}_C$ has a guaranteed bandwidth B_k equals 312.5 Mbps, which is the remaining bandwidth in the network evenly distributed. The offered load of a traditional ONU k (λ_k) is equal to its guaranteed bandwidth ($\lambda_k = B_k$), which is an overloaded condition. Table 4.2 summarizes the main configuration parameters used in the simulation.

Parameter	**Value**		
Optical bit rate	10 Gbps		
Maximum cycle time	1 ms		
Guard band	0.624 μs		
Distance between OLT and ONUs	[10,20] km		
Propagation delay in fiber	5 μs/km		
OLT-ONU RTT	[100,200] μs		
ONU buffer size	10 MB		
Number of ONUs	32		
Number of ONUs in the group	16		
Aggregated guaranteed bandwidth in the group	$N_{group} \times 300$ Mbps		
Mean Guaranteed BW of ONUs in the group	300 Mbps		
Guaranteed BW for ONUs in the group	[150,450] Mbps		
Offered load for ONUs in the group	[0,600] Mbps		
Guaranteed BW for traditional ONUs	312.5 Mbps		
Offered load for traditional ONUs	312.5 Mbps		
Subgroups	$S1$	$S2$	$S3$
Number of ONUs	4	3	9
Aggregated offered load (Scenario 1)	[0.8,1.2]	0.7	1.05
Aggregated offered load (Scenario 2)	0.7	[0.8,1.3]	[0.8,1.3]
Inter-ONU scheduler	*MOS-IPACT* and *subMOS-IPACT*		
Intra-ONU scheduler	strict priority		

Table 4.2: Simulation parameters to evaluated the impact of *subMOS-IPACT*.

We compare the Packet Loss Ratio (PLR) and the delay per subgroup of the *subMOS-IPACT* scheme with those produced by the *MOS-IPACT* algorithm. The load and number of ONUs in the subgroups, and the load in the traditional ONUs are the same for *MOS-IPACT* and *subMOS-IPACT* in order to make a fair comparison. Furthermore, two scenarios were evaluated as shown in Figure 4.3

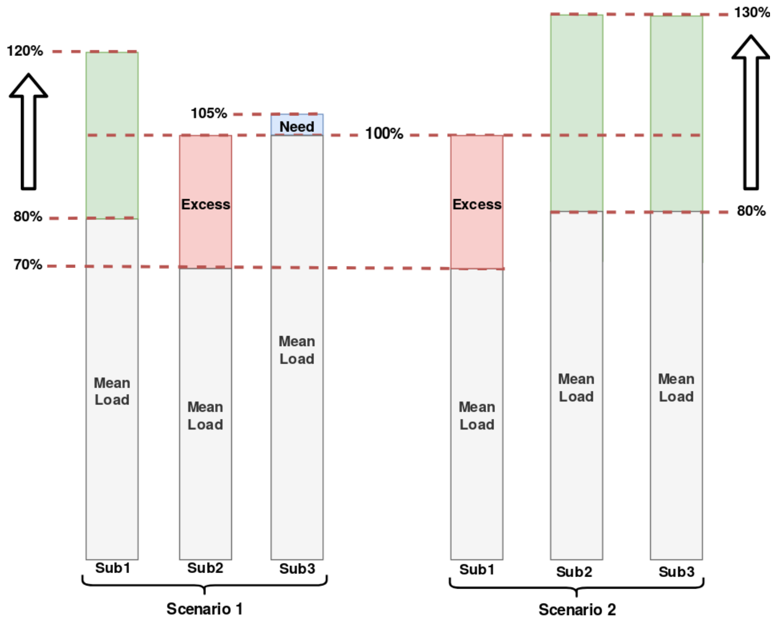


Figure 4.3: Simulation scenarios.

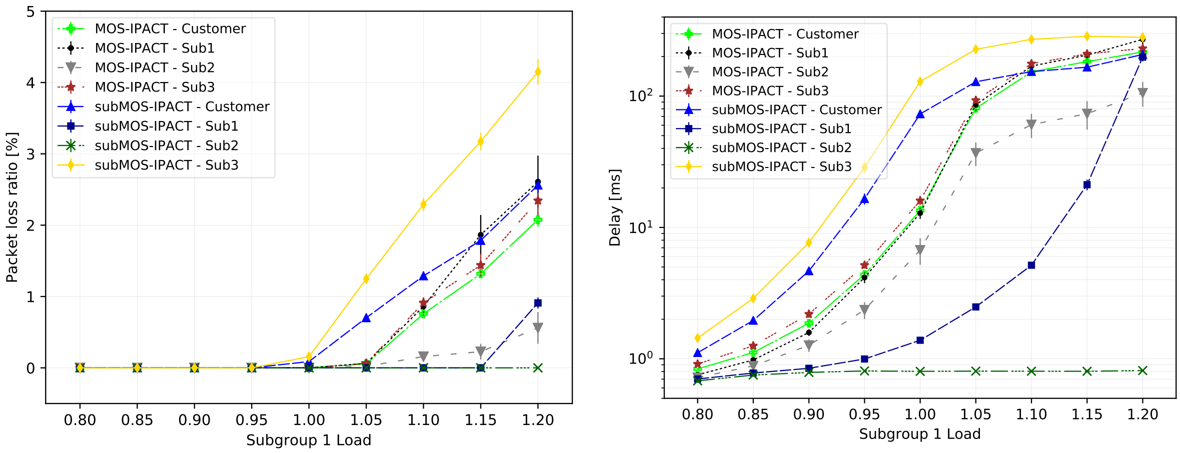
The *MOS-IPACT* algorithm is used in this comparison since the other algorithms for EPON in the literature do not provide guarantee bandwidth for a group of ONUs of a multi-ONU customer. Therefore, those algorithms generate high packet loss and produce long delays in scenarios with highly unbalanced traffics [17], like the ones proposed for in this paper. Thus, this would be an unfair comparison.

4.3.2 Scenario 1: Excess Distribution

In this scenario, the aim is to analyze how the excess bandwidth of the medium priority subgroup is distributed between the other two subgroups, when the high priority subgroup moves from underloaded to overloaded state. Thus, the aggregated offered load of S_1 (λ_{S_1}) varies from $0.8 \cdot A_{S_1}$ to $1.2 \cdot A_{S_1}$ (herein after, A_{S_i} is omitted from the offered load values), whereas S_2 is underloaded with load 0.7 and S_3 is overloaded with load 1.05.

The PLR and average delay for the subgroups and the multi-ONU customer with *MOS-IPACT* and *subMOS-IPACT* schemes are shown in Figure 4.4. No packet loss occurs when the average offered load is lower than 1.0. Thus, each subgroup is fully served.

When *MOS-IPACT* is employed and the offered load on S_1 is equal to 1.2, the delay and PLR values of the subgroup S_2 are equal to 100 ms and 0.5%, respectively. Conversely, *subMOS-IPACT* scheme yields delay values smaller than 1 ms and no packet loss regardless the S_1 load. These results show that the failure to guaranteeing bandwidth at subgroup level by *MOS-IPACT* makes the overloaded ONU subgroups (S_1 and S_3) to decrease the allocated bandwidth to the underloaded ONU subgroup (S_2), even when the aggregated offered load is equal to 0.7.



(a) Packet Loss Ratio

(b) Mean Delay

Figure 4.4: Scenario 1: Excess distribution.

The high priority subgroup (S_1) delay and PLR values increase while those of low priority subgroup (S_3) decrease when *MOS-IPACT* is employed since subgroups S_1 and S_3 dispute the excess bandwidth of the underloaded ONUs in S_2. Conversely, when *subMOS-IPACT* is employed, the high priority subgroup (S_1) has no packet loss for all offered loads. This occurs because when the S_1 is overloaded, the remaining excess bandwidth of S_2 is prioritized for S_1 without affecting the performance of S_2. However, this increases the delay and PLR of S_3. Thus, there is a tradeoff between the performance of the high and low priority subgroups.

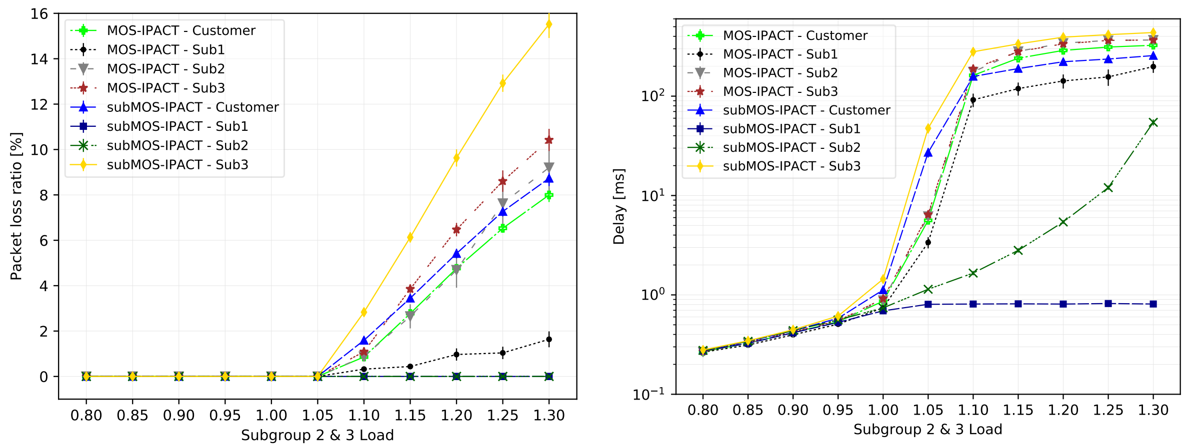
subMOS-IPACT produces around 0.5% more packet loss than does *MOS-IPACT* for the multi-ONU customer, in average. Moreover, *MOS-IPACT* produces lower delay values than those produced by *subMOS-IPACT*. This effect is the result of the extra thread scheduling in *subMOS-IPACT*, because even though it provides additional bandwidth in the same cycle to overloaded ONUs, this demands additional bandwidth for the guard periods. However, the average delay and PLR produced by *subMOS-IPACT* for S_1 are lower than those produced by *MOS-IPACT*. Thus, *subMOS-IPACT* provides traffic differentiation for high priority services.

This scenario showed that *subMOS-IPACT* distributes the excess bandwidth of the underloaded subgroups for the high priority subgroups without affecting the assured bandwidth of other subgroups. However, this implies a small loss of available resources for the multi-ONU customer due to the extra guard times used for the multi thread scheduling. Nevertheless, all subgroups have no packet losses until an aggregated load of 1.0.

4.3.3 Scenario 2: ONUs subgroup isolation

In this scenario, the aim is to analyze the isolation, especially in the high priority subgroup, as well as, to evaluate the bandwidth distribution among the low-priority subgroups. In this case, we assume that the high priority subgroup is underloaded with aggregated load equals to 0.7, and the other subgroups (medium and low priority subgroup) have an aggregated load varying from 0.8 to 1.2.

The average packet delay and the PLR of the multi-ONU customer and its subgroups with *MOS-IPACT* and *subMOS-IPACT* are shown in Figure 4.5. When the average offered load in S_2 and S_3 are lower than 1.0, both algorithms produce an average delay smaller than 1 ms and no packet loss occurs in all subgroups.



(a) Packet Loss Ratio (b) Mean Delay

Figure 4.5: Scenario 2: ONUs subgroup isolation.

The delay of the underloaded subgroup S_1 reaches 150 ms when using *MOS-IPACT*, while it reaches only 0.8 ms when using the *subMOS-IPACT*. Moreover, *subMOS-IPACT* produces no packet loss for the subgroup S_1 whereas *MOS-IPACT* yields up to 1 %. This occurs because the excess bandwidth of underloaded ONUs in the customer is distributed among all overloaded ONUs of the same customer when *MOS-IPACT* is used. Conversely, *subMOS-IPACT* assures bandwidth at subgroup level under unbalancing load conditions.

Although the aggregated load of is smaller than that of S_2, the delay values of the medium priority subgroup (S_2) using *subMOS-IPACT* are lower than those produced by *MOS-IPACT* to the ONUs with high priority services (S_1). This occurs because the medium priority subgroup (S_2) receives the unused bandwidth of S_1 when *subMOS-IPACT* is employed. However, when *MOS-IPACT* is used, the subgroups S_2 and S_3 compete for the excess bandwidth of S_1, generating packets losses in the subgroup S_2 under high loads. For instance, when the aggregated load in S_2 and S_3 are 1.10, the subgroup S_2 and S_1 have average delay lower than 2 ms when using *subMOS-IPACT*, while the subgroup S_2 experience average delays of 200 ms and S_1 experience average delays of 90 ms when using *MOS-IPACT*.

Moreover, the bandwidth used to improve the performance of the S_1 and S_2 with *subMOS-IPACT* causes performance degradation under $S3$ in overloaded condition. However, S_3 has no packets loss and produces similar delay values than those produced by the *MOS-IPACT* until loads of 1.1. This means that S_3 (low priority subgroup) supports an offered loads greater than the aggregated guaranteed bandwidth due to the use of part of the excess bandwidth of the highest priority subgroups.

This scenario showed that *subMOS-IPACT* algorithm ensures effective isolation regardless of the subgroup priority. Furthermore, if there is excess bandwidth in the highest priority subgroups, the bandwidth can be used for the lowest priority subgroup.

4.4 Summary

This chapter introduce the *subMOS-IPACT* DBA algorithm that supports priorities scheduling and guaranteed bandwidth in the ONUs subgroups of multi-ONU customers in EPON networks. We compared the performance of our proposed scheme to that of the *MOS-IPACT* scheme, when varying the aggregated average load of subgroups. Simulation results show that the *subMOS-IPACT* provides effective isolation and guarantees aggregate bandwidth at three level of granularity. Furthermore, high priority subgroups suffer lower packet loss ratio and reduced delay when compared to those produced by the *MOS-IPACT* scheme and yet guarantees bandwidth to low priority subgroups even under unbalanced traffic conditions.

Chapter 5

Cooperative Resource Sharing among EPON Customers

In chapter 3, we proposed a new DBA algorithm to guarantee the aggregate bandwidth of customers leasing multiple ONUs from the InP. In this case, the InP is responsible for the management of physical resources and allocation of bandwidth to those customers. We refer to PON customer not only the end user, but service providers which rent the PON infrastructure from the InP. PON customers can be residential subscribers, single or multi-site enterprises, or other service providers such as MNOs, Virtual Network Operators (VNOs), and tenants owning a PON slice. PON customers produce a large spatio-temporal traffic variability, which may lead to underutilization of the network resources.

Resource sharing is a common approach to enhance resource utilization and maximize revenues [53]. Service providers can take advantage of the spatio-temporal traffic variability in new business models. For instance, customers can share the network resources among themselves to increase the overall network utilization [39] [17] or even receive economic incentives [5] [4]. Hence, resource sharing can make the PON infrastructure more profitable and attractive to the customers.

PON customers usually have different traffic loads within a given time period, *i.e.*,, some customers can be *overloaded* while others are *underloaded*. In this context, cooperation among customers can increase the statistical multiplexing gain. For example, in a mobile backhauling/fronthauling scenario (Customer 1 in Figure 5.1), MNO typically has high traffic demands during the day and low traffic demands during the evening/night in commercial areas [15]. This traffic variability occurs because there is a huge density of mobile users in commercial areas during the day hours and these customers move to residential areas after business hours. MNO typically dimension its backhaul network capacity to couple with roughly 80% of the peak traffic value, underutilizing PON resources during off-the-peak periods. As mobile users usually employ indoor services (*e.g.,* WiFi, Ethernet), the residential subscribers (Customer 2 in Figure 5.1) have high traffic demands during the evening. Thus, MNOs and residential customers may cooperate and share resource to increase their network capacity.

In this chapter, we introduce a DBA algorithm called *CS-IPACT* that allows bandwidth sharing in EPONs among cooperative customers. This DBA algorithm can support

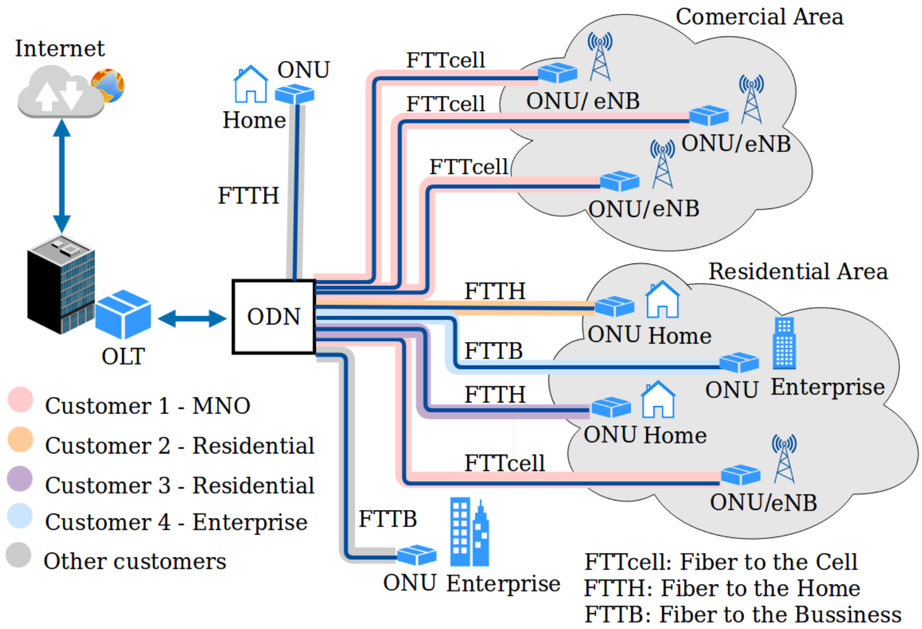


Figure 5.1: Typical PON deployment with diverse customer types.

cooperation among customers. In our proposal, customers can join a cooperative group, in which a group of customers share their unused bandwidth among them. Moreover, traditional customers with a single ONU and customers with multiple ONUs can cooperate to increase the overall available bandwidth and without compromising their individual guaranteed bandwidth are maintained.

The rest of this chapter is organized as follows. Section 5.1 discusses the related work. Section 5.2 describes the proposed DBA mechanism. Section 5.3 shows in details the simulation model, simulation scenarios and analyze the results derived from simulation. Section 5.4 brings final considerations.

5.1 Related Work

In PON networks, the DBA algorithm provides bandwidth guarantees according to SLAs. DBA algorithms that involves PON sharing provisioning, customers isolation and customization within customer have been recently proposed [39], [17], [6], [23] [3]. However, the recent research in bandwidth sharing mechanisms for PONs are focus in ITU standards.

Most relevant bandwidth sharing algorithms for GPON are presented below. Giga-PON Access Network (GIANT) is a hierarchical DBA algorithm that defines assured bandwidth, and non-assured bandwidth policy [38]. The work in [6] modifies the GIANT algorithm to support groups of ONU with assured bandwidth. The work in [39] proposes a mechanism to share frames among multiple customers, enabling bandwidth resources sharing. The work in [23] introduces virtual DBA (vDBA) in which customers have full control over the scheduling associated to its PON slices. The work in [24] proposes an algorithm to facilitate the coexistence of multiple customers in PONs. The work in [3] proposes a mechanism to motivate the cooperation and bandwidth sharing across multiple customers. However, there is no DBA algorithm that supports bandwidth sharing among customers in EPON infrastructure.

In our previous chapter, we proposed the *MOS-IPACT* DBA algorithm, which provides bandwidth guarantees for customers owning multiple ONUs. This algorithm allows multi-ONU customers to redistribute the excess bandwidth among their own ONUs. Moreover, *subMOS-IPACT* provides bandwidth guarantees at different granularity: individual ONUs, multi-ONU customer, and ONU subgroups. In this case, a subgroup is a set of ONUs that belong to the same multi-ONU customer. This DBA algorithm also allows multi-ONU customer to support a priority bandwidth allocation in the subgroups. Thus, customers have QoS support for diverse services in the same PON.

GPON and EPON differ in several aspects such as signal processing, architecture and protocols [14]. Thus, the described GPON algorithms do not support cooperative bandwidth sharing among EPON customers. The next section introduce the *CS-IPACT* scheme, which allows bandwidth sharing between cooperative customers and yet provides bandwidth isolation to traditional customers and multi-ONU customers.

5.2 Proposed DBA scheme

This section describes the proposed DBA algorithm, which allows bandwidth sharing among EPON customers. The proposed DBA algorithm is called *IPACT* with cooperative customers support (*CS-IPACT*). In the proposed algorithm, a customer can join a cooperative group to share the unused bandwidth with the other customers that belong to the same group, while guaranteeing the bandwidth in its SLA (see Figure 5.2). The unused bandwidth is distributed among cooperative customers using a policy called fair excess policy (FE-DBA) [20]. This policy distributes the excess bandwidth according to the bandwidth required by the cooperative customers. Moreover, *CS-IPACT* algorithm also guarantees bandwidth agreed in the SLAs.

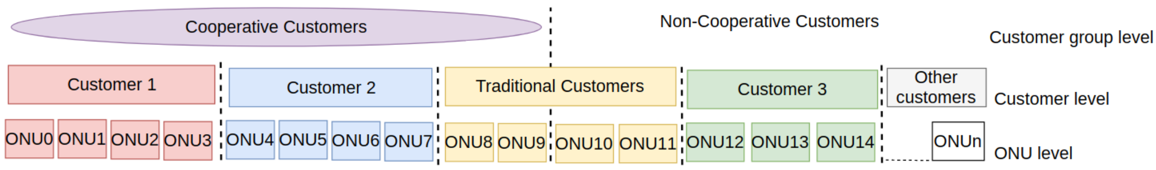


Figure 5.2: Granularity of bandwidth guarantees in *CS-IPACT*.

Currently, EPON DBA algorithms do not allow customers to share excess bandwidth with other customers. Traditionally, each customer has an *SLA* specifying its guaranteed bandwidth. Customers requiring less bandwidth than the guaranteed one leads to a reduction in the scheduling cycle, which gives more opportunities to data transmission to all the other customers in the PON.

Conversely, in the *CS-IPACT* DBA algorithm, a group of customers can share the unused resources among the customers in the same group. In this way, unused bandwidth from *underloaded* customers can be redistributed to *overloaded* customers belonging to the same cooperative group in a granting cycle basis, leading to an increase in network utilization.

CS-IPACT assures bandwidth for traditional customers and multi-ONU customers by employing the policy for bandwidth distribution of IPACT [35] and *MOS-IPACT* [17], respectively. Thus, the OLT classifies the Report messages as coming from a traditional customer or a multi-ONU customer. When a Report message comes from a traditional customer, the OLT calculates the windows transmission size and the next transmission time ($t_{txStart}$) employing the limited policy. After this process, the OLT sends a Gate message to the corresponding ONU. If the Report message comes from a multi-ONU customer, the OLT waits for Report messages from all ONUs belonging to the same multi-ONU customer before sending the Gate messages to those ONUs. The windows transmission size is calculated employing the limited with excess policy to guarantee bandwidth at the customer level.

However, *CS-IPACT* have an additional step for Report messages coming from a cooperative customer. In this case, the OLT waits for the arrival of Reports coming from all customers that belongs to the cooperative group before sending another Gate message. The second Gate message informs the portion of the excess bandwidth allocated to the overloaded ONUs that belong to the cooperative group.

5.2.1 *CS-IPACT* DBA algorithm

Algorithm 3 summarizes the *CS-IPACT* scheme. Let $\mathcal{G}$ be the set of cooperative customer groups, $\mathcal{M}$ be the set of *multi-ONU customers* and $\mathcal{O}$ the set of ONUs in the PON; $\mathcal{O}_l$ is the set of ONUs belonging to l-th cooperative group; $\mathcal{O}_T$ the set of ONUs that do not belong to any *multi-ONU customer*; and $\mathcal{O}_k$ the set of ONUs which belong to k-th multi-ONU customer.

For each Report message R received by the OLT, it is verified whether this message comes from a traditional customer $\mathcal{O}_T$ (Lines 2) or from a multi-ONU customer (Lines 5). If the Report message comes from a traditional customer, the Gate message is issued and sent to the ONU by employing the limited policy (Lines 3). However, If the Report message comes from an ONU belonging to a multi-ONU customer, the Report message is added to the set of Report messages of the multi-ONU customer k ($\mathcal{R}_k$) (Line 6). When the OLT receives all the Report messages from the ONUs in that customer, the *BulkGrantGenetrator* function is applied (Lines 15 and 19). In this function, the Gate message is issued and sent to the ONU by employing the MOS-IPACT excess distribution policy (Lines 3).

After receiving a Report message from an ONU, the OLT verifies if that Report message belongs to a cooperative customer (Lines 4 and 18). If so, the Report message is added to the set of Report messages of the l-th cooperative group ($\mathcal{R}_l$). In this case, the new requested window size is equal to the extra required window (Line 25) for overloaded ONUs or equal to zero for underloaded ONUs (Line 27).

When the OLT receives all Report messages from the customers that belongs to l-th cooperative group, a function called $MultiThreadCoop$ is applied for distributing the excess bandwidth of *underloaded* customers among the overloaded customers that belong to cooperative group (Lines 11 and 13). Thus, another Gate message is issued and sent to the overloaded ONUs in the cooperative group.

Algorithm 3: *CS-IPACT* DBA Algorithm

: $\mathcal{R}_l \leftarrow \emptyset, \forall l \in \mathcal{G}$
: $\mathcal{R}_k \leftarrow \emptyset, \forall k \in \mathcal{M}$
for *each received report R from ONU i in cycle j* **do**
  if *ONU* $i \in \mathcal{O}_T$ **then** `/* If report message comes from a traditional customer */`
    Send $Gate_i^j$ according to IPACT limited policy [35]
    SaveReportCoop()
  else `/* If report message comes from a multi-ONU customer */`
    $\mathcal{R}_k = \mathcal{R}_k \cup \{R\}$ `/* Save report message */`
    if $|\mathcal{R}_k| = |\mathcal{O}_k|$ **then** `/* If received all report messages from a multi-ONU`
      BulkGrantGenerator()
    end
  end
  if $|\mathcal{R}_l| = |\mathcal{O}_l|$ **then** `/* If received all report message from a ONUs of the cooperative group o */`
    MultiThreadCoop()
  end
end
`BulkGrantGenerator()`
  for *each report* $R_i \in \mathcal{R}_k$ **do** `/* Compute and send gate messages for ONUs of the multi-ONU customer k */`
    Send $Gate_i^j$ according to *MOS-IPACT* excess distribution policy [17]
    SaveReportCoop()
  end
  $\mathcal{R}_k \leftarrow \emptyset$
end
`SaveReportCoop()`
  if *ONU* $i \in \mathcal{O}_l$ **then** `/* If report message comes from a ONU that belong to cooperative customer */`
    if $R_i > W_i^{granted}$ **then** `/* If the ONU is overloaded */`
      $\mathcal{R}_l = \mathcal{R}_l \cup W_i^{extra}$
    else `/* If the ONU is underloaded */`
      $\mathcal{R}_l = \mathcal{R}_l \cup 0$
    end
  end
end
`MultiThreadCoop()`
  for *each report* $R_i \in \mathcal{R}_l$ **do** `/* Compute and send gate messages for overloaded ONUs of the cooperative group */`
    Calculate $W_i^{threadCoop}$ according (5.2)
    if $W_i^{threadCoop} > 0$ **then**
      Calculate $t_{txStart}$
      $\text{Gate}_i^j \leftarrow \left(W_i^{threadCoop}, t_{txStart}\right)$
      Send $Gate_i^j$
    end
  end
  $\mathcal{R}_o \leftarrow \emptyset$
end

In the $MultiThreadCoop$ function, the total excess bandwidth of the l-th cooperative group (E_l^{total}) is distributed among its cooperative customers. In order to avoid affecting the bandwidth guarantees of other customers, the additional guard period (TG) used for the new thread is taken into account as a part of the extra required window size (W^{extra})

by ONU i, which is overloaded, as shown below

$$E_i = \frac{W_i^{extra} + TG}{\Sigma_{p \in O_l^{over}} (W_p^{extra} + TG)} * E_l^{total} \tag{5.1}$$

O_l^{over} is the set of *overloaded* ONUs in the cooperative group of customers O_l. The overloaded ONUs in the cooperative group receive a portion of the excess bandwidth. Thus, the granted window size for the second Gate message ($W_i^{threadCoop}$) (Lines 33) is calculated as

$$W_i^{threadCoop} = \begin{cases} W_i^{extra} & \text{if} \quad W_i^{extra} + TG \leq +E_i \\ W_i^{extra} - TG & \text{if} \quad W_i^{extra} + TG > +E_i \\ 0 & \text{if} \quad TG \geq E_i \end{cases} \tag{5.2}$$

and subsequently the next start time is calculated and the Gate message is sent to the i-th ONU (Lines 35-37). However, if the portion of the excess bandwidth is smaller than the guard time, the corresponding ONU does not receive a second Gate message. After the scheduling of the overloaded ONUs in the cooperative group, the corresponding R_l is emptied (Line 40).

5.2.2 Complexity Analysis

The complexity of the proposed algorithm is analyzed as follows. In *MOS-IPACT* algorithm, each Report is considered once per cycle to receive the Reports. In addition, excess bandwidth allocation is calculated once for every active ONUs in the multi-ONU customers. *CS-IPACT* scheme applies the those procedures for assuring bandwidth to traditional customer and multi-ONU customers. Furthermore, overloaded ONUs in the cooperative group have a second upstream transmission opportunity in the same cycle. In the worst case, which all ONUs are overloaded in the cooperative group, except one, the time complexity is $O(n+l+c-k)$, where n is the total number of ONUs in the PON, l is the number of ONUs in the multi-ONU customers, c is the total number of ONUs in the cooperative customers and k is the number of ONUs in the cooperative group.

5.3 Performance Evaluation

In this section, we assess the performance of the proposed *CS-IPACT* DBA algorithm by using an EPON simulator (EPON-Sim). The EPON-Sim implements the *MOS-IPACT* DBA algorithm with the FE-DBA policy. The *CS-IPACT* algorithm was introduced in the EPON-Sim simulator and the new version of the simulator was validated extensively.

5.3.1 Simulation Model and Setup

A tree topology of a 10 Gbps EPON network was simulated. The OLT serves a set of 32 ONUs ($|\mathcal{O}| = 32$). The load generated by the ONUs comprises three different traffic classes as in Section 3.3.1. The guard time period between bursts of data from different ONUs is 0.624 μs. The maximum cycle length is 1 ms.

We assume that there is a group of cooperative customers $\mathcal{C}$. Let $\mathcal{O}_\mathcal{C} \subset \mathcal{O}$ be the set of all ONUs belonging to any customer in $\mathcal{C}$. Each customer $C_m \in \mathcal{C}$ is a multi-ONU customer with N_{C_m} ONUs in the PON. Each ONU n of cooperative customer C_m has guaranteed bandwidth B_n between 150 Mbps and 450 Mbps, provided that $\sum_{n \in \mathcal{O}_{Cm}} B_n = B_{C_m}, \forall C_m \in \mathcal{C}$, where B_{C_m} is the effective aggregated guaranteed bandwidth of customer C_m. The ONU offered load (λ_n) varies randomly between 0 and 600 Mbps, provided that ($\sum_{n \in \mathcal{O}_{C_m}} \lambda_n = \lambda_{C_m}$), where λ_{C_m} is the aggregated offered load of cooperative customer C_m. On the other hand, there is a set of non-cooperative ONUs $\mathcal{O}_\mathcal{N} \subset \mathcal{O}$, with $\mathcal{O}_\mathcal{N} \cup \mathcal{O}_\mathcal{C} = \mathcal{O}$ and $\mathcal{O}_\mathcal{N} \cap \mathcal{O}_\mathcal{C} = \emptyset$. Each ONU $t \in \mathcal{O}_\mathcal{N}$ has guaranteed bandwidth B_t equal to the remaining effective bandwidth in the PON divided by the number of ONUs in $\mathcal{O}_\mathcal{N}$. To properly assess the performance of the proposed algorithm, the offered load of a non-cooperative ONUs (λ_t) is equal to its guaranteed bandwidth ($\lambda_t = B_t$), which is an overloaded condition to that set of ONUs.

Figure 5.3 illustrates the proposed simulation scenario which aims at assessing the effect of cooperation among EPON customers. There is one cooperative group with three cooperative customers, representing, for instance, MNOs with backhauling/fronthauling services, and virtual network operators with residential and enterprise ONUs. The offered load of one cooperative customer varies from an *underloaded* to an *overloaded* condition, while there are two cooperative customer with fixed loads; one *overloaded* and the other *overloaded*. Customer 1 has an aggregated offered load varying from $0.7 \cdot B_{C_1}$ to $1.2 \cdot B_{C_1}$[1], whereas Customer 2 and Customer 3 have an aggregated offered load of 0.7 (*underloaded*) and 1.2 (*overloaded*), respectively. Table 5.1 summarizes the main configuration parameters used in the simulations.

We compare the performance of *CS-IPACT* to that of *MOS-IPACT*. The *MOS-IPACT* algorithm is employed because it is the only mechanisms in the literature that support guaranteed bandwidth for multi-ONU customers. As shown in [17], traditional algorithms such as IPACT generates high packet losses and produces long delays in scenarios with highly unbalanced traffics, like the ones proposed for our simulations. The offered load and guaranteed bandwidth values of the ONUs for *MOS-IPACT* and *CS-IPACT* scheme are the same to make a fair comparison. We present the average throughput per ONU and the average delay for each cooperative customer, the cooperative group, and the non-cooperative customers for both algorithms.

5.3.2 Simulation Results and Discussion

The average packet delay values given by *CS-IPACT* for the cooperative group are up to one order of magnitude lower than those given by *MOS-IPACT* (Figure 5.4a). Moreover, the *CS-IPACT* algorithm produces up to 5% higher average throughput values per ONU that belongs to the cooperative group than does the *MOS-IPACT* algorithm (Figure 5.4b). These important performance improvements are because of the cooperation among

[1]For the sake of clearness and brevity, herein after, B_{C_i} is omitted from the offered load values of Customer C_i

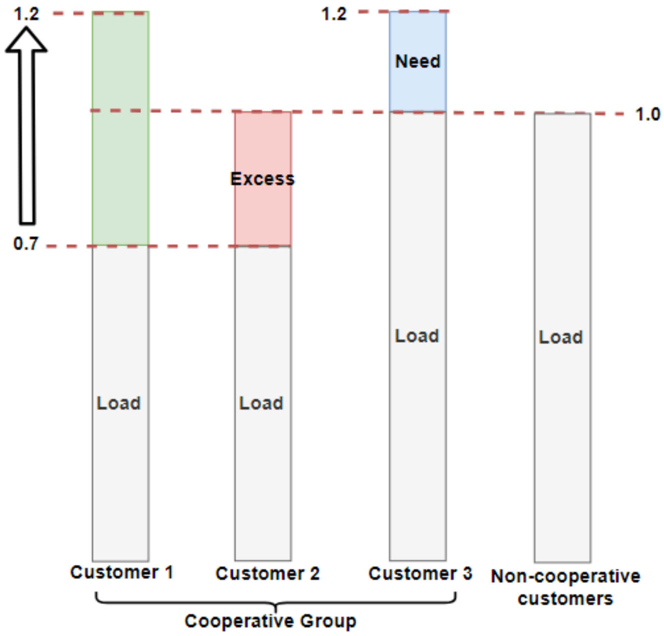
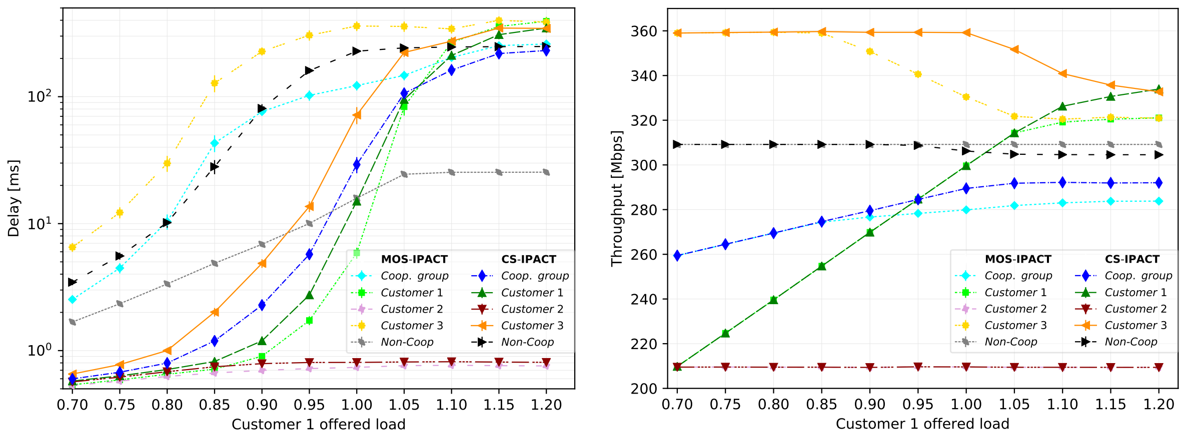


Figure 5.3: Simulation scenario.

<table>
<tr><th>Parameter</th><th colspan="3">Value</th></tr>
<tr><td>Optical speed</td><td colspan="3">10 Gbps</td></tr>
<tr><td>Maximum cycle length</td><td colspan="3">1 ms</td></tr>
<tr><td>Guard band</td><td colspan="3">0.624 μs</td></tr>
<tr><td>Distance between OLT and ONUs</td><td colspan="3">[10,20] km</td></tr>
<tr><td>Propagation delay in fiber</td><td colspan="3">5 μs/km</td></tr>
<tr><td>OLT-ONU RTT</td><td colspan="3">[100,200] μs</td></tr>
<tr><td>ONU buffer size</td><td colspan="3">10 MB</td></tr>
<tr><td>Total number of ONUs ($|\mathcal{O}|$)</td><td colspan="3">32</td></tr>
<tr><td>Guaranteed BW for each ONU in cooperative customer group (B_n)</td><td colspan="3">[150,450] Mbps</td></tr>
<tr><td>Aggregate guaranteed BW of cooperative customer (B_{C_m})</td><td colspan="3">1200 Mbps</td></tr>
<tr><td>Average guaranteed BW for ONUs of each cooperative customer</td><td colspan="3">300 Mbps</td></tr>
<tr><td>Offered load for each ONU in cooperative customer group (λ_n)</td><td colspan="3">[0,600] Mbps</td></tr>
<tr><td>Guaranteed BW for each non-cooperative ONUs (B_t)</td><td colspan="3">310 Mbps</td></tr>
<tr><td>Offered load for each non-cooperative ONUs (λ_t)</td><td colspan="3">310 Mbps</td></tr>
<tr><td>Number of ONUs in the cooperative group ($|\mathcal{O}_\mathcal{C}|$)</td><td colspan="3">12</td></tr>
<tr><td>Customer ID
Number of ONUs of C_i (N_{C_i})
Aggregated offered load of C_i (λ_{C_i})</td><td>C_1
4
[0.7,1.2]</td><td>C_2
4
0.7</td><td>C_3
4
1.2</td></tr>
<tr><td>Inter-ONU scheduler</td><td colspan="3">CS-IPACT
MOS-IPACT</td></tr>
<tr><td>Intra-ONU scheduler</td><td colspan="3">strict priority</td></tr>
</table>

Table 5.1: Simulation parameters to evaluated the impact of *CS-IPACT*.

a group of cooperative customers that our proposal provides. Under our proposal, the excess bandwidth of cooperative customers in the same cooperative group is redistributed from the *underloaded* to the *overloaded* cooperative customers in a per cycle basis. Conversely, any unused bandwidth in a PON cycle cannot be explicitly redistributed to other customers when *MOS-IPACT* is used because existing EPON DBA algorithms do not allow cooperation among customers.



(a) Average delay (b) Average throughput per ONU

Figure 5.4: Impact of cooperation among EPON customers.

In fact, existing DBA algorithms can adapt the cycle length to the offered load dynamically [35] so that the frequency of transmission opportunities increases as the offered load of the entire network decreases. However, in this case, the distribution of the unused bandwidth from a customer is performed among all other customers in the same PON. In addition, DBA algorithms with excess bandwidth distribution can redistribute unused bandwidth from *underloaded* to *overloaded* ONUs, but the redistribution is also performed among all ONUs.

To better understand the overall gain obtained by the cooperative group with our proposal, the performance metrics for each cooperative customer are analyzed next. For the *overloaded* customer (Customer 3) when $\lambda_{\mathcal{C}_1} \leq 1$, *CS-IPACT* produces delay values much lower than those given by *MOS-IPACT*. *MOS-IPACT* produces slightly lower delay values for the other two cooperative customers than does *CS-IPACT* due to the higher throughput provided by the latter (Figure 5.4b). For $\lambda_{\mathcal{C}_1} \geq 1.05$, the delay values produced by the two DBA algorithms are in the same order. On the other hand, the average throughput per ONU produced by *CS-IPACT* can be 5% to 10% higher than that produced by *MOS-IPACT* when $\lambda_{\mathcal{C}_1} \geq 0.85$ for the *overloaded* customer (Customer 3). Moreover, *CS-IPACT* produces throughput values up to 5% higher for the varying load customer (Customer 1) under *overloaded* condition ($\lambda_{\mathcal{C}_1} > 1$).

The above-described results show the impact of sharing resources among customers in a cooperative way on the delay and throughput. *CS-IPACT* allows the *overloaded* ONUs to use the excess bandwidth of the *underloaded* ONUs in the same cooperative group, in a per cycle basis. In our scenario, this sharing of resources is most frequently from ONUs belonging to the *underloaded* customer and the varying load customer (for $\lambda_{\mathcal{C}_1} \leq 1$) to ONUs belonging to the *overloaded* customer. As expected, all these gains are obtained without affecting the throughput (Figure 5.4b) and delay (Figure 5.4a) of the *underloaded* cooperative customers. This means that ONUs of a cooperative customer support higher bit rates than those guaranteed in the SLA even under high and unbalanced traffic loads without affecting other cooperative customers.

Moreover, the throughput of Customer 3 decreases as the load of Customer 1 increases when *CS-IPACT* is used for ($\lambda_{\mathcal{C}_1} \geq 1$) because our mechanism employs the Fair Excess policy to distribute the excess bandwidth between overloaded customers. Note that, when Customer 1 and Customer 3 have the same offered load value ($\lambda_{\mathcal{C}_1} = 1.2$), *CS-IPACT* produces the same throughput for these cooperative customers. This shows that a fair distribution of the excess bandwidth is provided to the cooperative customers by the proposed distribution policy.

Even though *CS-IPACT* can produce a slightly decrease in the throughput for non-cooperative customers when the varying load customer changes from *underloaded* to *overloaded*, *i.e.,* $\lambda_{\mathcal{C}_1}$ value goes from 0.95 to 1.0, the throughput stabilizes for $\lambda_{\mathcal{C}_1} \geq 1$ because a minimum bandwidth is always guaranteed. Note that, in our simulation scenario, the non-cooperative customers are in an *overloaded* condition. Thus, the delay produced by *CS-IPACT* can be up to 10 times higher than that of *MOS-IPACT* for non-cooperative customers. This delay degradation results from a overloaded conditions, in which the additional bandwidth gain obtained by the cooperative customers comes from the unused bandwidth of other cooperative customers ONUs. The excess bandwidth is distributed among all ONU in the PON when *MOS-IPACT* is used (ONU level), and among the cooperative customers when *CS-IPACT* is employed (customer level). Both *MOS-IPACT* and *CS-IPACT* can guarantee the QoS requirements in *underloaded* traffic conditions for ONUs.

5.4 Summary

This chapter has introduced a novel DBA scheme which supports bandwidth sharing among customers in EPON networks. Our proposal enables customer cooperation, which can maximize revenues for service providers and increase network utilization for cooperative customers. We compared the performance of our proposed scheme to that of the *MOS-IPACT* scheme, which promotes bandwidth sharing at the intra-customer level. Simulation results show that the proposed scheme provides higher throughput and lower delay than does the *MOS-IPACT* scheme for customers that belong to a cooperative group even under unbalanced traffic loads. As future work, we plan to compare the performance of different excess bandwidth distribution policies under cooperative scenarios. We also plan to develop a scheme for a competition model in which customers buy/sell bandwidth in auctions.

Chapter 6

Conclusion

6.1 Final Consideration

The assumption that the optical link capacity in the access networks is always higher than the bandwidth requirement can no longer be sustained due to the ever growing traffic. Thus, new mechanisms need to deal with high peak traffic rates and limited available bandwidth.

This dissertation studied the problem of bandwidth management in EPON networks. We reviewed PON broadband access network technologies. Several features were analyzed such as infrastructure cost, available bandwidth, wavelength allocation, link layer protocol and service hierarchy. We also conducted a comprehensive study of the EPON DBA algorithms and we considered five main components of those algorithms: Grant Scheduling Framework (GSF), Grant Windows-sizing Policy (GWP), Excess Distribution Policy (EDP), Grant Scheduling Policy (GSP) and Thread Scheduling Framework (TSF).

This dissertation proposed three Dynamic Bandwidth Allocation algorithms to the IEEE 802.3ah standard. The *MOS-IPACT* DBA algorithm allows multi-ONU customers to have a *multi-ONU SLAs* to aggregate the individual SLAs of his ONUs as a single SLA. *MOS-IPACT* assures the bandwidth for both: the individual ONUs and the group of ONUs, despite the traffic variability. This improves the statistical multiplexing gain and bandwidth utilization of the multi-ONU customers without affecting the traditional customers with a single ONU. IPACT and other DBA algorithms in the literature do not consider bandwidth guaranteed for multi-ONU, as a results, multi-ONU customers have their QoS requirements degraded. In the evaluation, the *MOS-IPACT* algorithm proved to be quite effective to assures the bandwidth for multi-ONU customers even when the access network is congested.

A modification of the *MOS-IPACT* algorithms was made in order to cope with multi-ONU customers offering diverse services to its clients. Those customers have subgroups of ONUs with diverse QoS requirements (*e.g.,* mobile backhauling and residential services). *subMOS-IPACT* assures the bandwidth at three different levels of granularity: individual ONU, subgroup ONU and customer level. The *subMOS-IPACT* algorithm provides effective isolation for the traditional customer, multi-ONU customer with a single services and multi-ONU customer with diverse services. Furthermore, the excess bandwidth is prioritized for delay sensitive services such as mobile backhauling. A reduction in the delay and Packet Loss Ratio for high and medium priority services. In addition, the low priority services maintains the assured bandwidth.

An improvement of *MOS-IPACT* algorithm has been implemented to allow bandwidth sharing among customers in EPON networks. *CS-IPACT* assures the bandwidth for multi-ONU customers and traditional customers. Moreover, customers can join in a cooperative group, which unused bandwidth is shared among cooperative customers without affecting his SLAs. Thus, the OLT can redistribute the unused bandwidth per cycle-basics employing a fair excess distribution policy and extra Gate message. As a result, a considerable gain over throughput was observed.

6.2 Future works

As future works, the following suggestions are presented:

- The proposed DBA algorithms can be extent to TWDM PON networks, considering that the bandwidth allocation is performed in time and wavelength domain.

- All the proposed algorithm are based on IPACT, we plan to consider other schemes such as compensate in the next cycle scheme or double phase polling scheme. Furthermore, we could use other Excess Distribution Policy that takes into account traffic prediction.

- We also plan to integrate the *MOS-IPACT* scheme in an EPON-based mobile backhauling scenario such as that in [8] and [9], in which EPON are used as backhaul link.

- Since *subMOS-IPACT* and *CS-IPACT* algorithms employ only FE-DBA policy for the bandwidth distribution, we plan to compare the impact of different excess bandwidth distribution policies on those algorithms.

- The energy efficiency is an important factor in current broadband access network, hence it is require a study about energy usage of the proposed DBA algorithms.

- A realistic model in which customer contend for excess bandwidth need to be study. In this scheme customers buy/sell bandwidth in an auction market.

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