Enhanced dynamic bandwidth algorithms for passive optical networks

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PhD program in Network Engineering

Enhanced Dynamic Bandwidth Algorithms for Passive Optical Networks

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Dedication

This research work is dedicated to the memory of my late father.

Prince Timothy Aderibigbe Haastrup

September 23, 1936 to January 29, 2023

Abstract

The telecommunications industry is currently undergoing a significant transformation with the focus being the rapid deployment of 5G networks. These next-generation wireless technologies promise unprecedented bandwidth, minimal latency, and impeccable end-to-end quality of service, revolutionizing our interaction with technology. As the proliferation of smart devices continues to grow and the demand for higher bandwidth increases, it becomes crucial to streamline the network architecture, simplify the management of the network, and optimize resource utilization for improved cost-effectiveness.

Passive Optical Networks (PONs) have emerged as a highly viable and flexible solution for delivering broadband access to both residential and commercial sectors. PONs provide benefits such as energy efficiency, robust security, and high performance, making them an ideal candidate for serving radio access networks (RAN) in mobile communications, both in the fronthaul and backhaul. However, the current bandwidth capacities of PONs fall short of the demands imposed by 5G and future mobile communication networks.

To address this pressing challenge, leading organizations such as the Institute of Electrical & Electronics Engineers (IEEE) and the International Telecommunication Union - Telecommunication (ITU-T) are diligently developing standards aimed at increasing the bandwidth capacity of the next generation of PONs to 25Gbps, 40Gbps, 80Gbps, and 100Gbps. However, managing PON installations has become more complex due to the escalating demand for bandwidth. In response to these challenges, there is a growing need for innovative mechanisms to efficiently manage PONs, ensuring optimal resource allocation, quality of service (QoS), energy saving, and low latency. Dynamic bandwidth allocation (DBA) algorithms play a key role in achieving the aforementioned goals, as these algorithms dynamically allocate bandwidth in response to the traffic demands of each Optical Network Unit (ONU), thereby ensuring efficient resource usage.

Traditional DBA algorithms face limitations when confronted with the increasing demand for higher bandwidth and low latency in PONs. This thesis addresses some of these limitations. The novel enhanced DBA algorithms introduced in this research are specifically designed to enhance bandwidth utilization, and reduce latency. Leveraging techniques such as the Longest Processing Time (LPT) scheduling method to

minimize queue delays, our research also considers the concept of laser tuning time to bring a practical, real-world approach to our system.

The main contributions of this thesis are:

- Introducing an innovative algorithm for PONs employing techniques such as LPT to minimize queue delay and enhance throughput. The utilization of LPT resulted in a notable reduction (up to 73%) of queue delay.
- Incorporating the often-overlooked laser tuning time (LTT) concept in our analysis of DBA for TWDM PONs, therefore obtaining more realistic results.
- Developing a Distance Weighted DBA (DWDBA), specifically tailored for Long-Reach PONs (LRPON), aimed at preventing the penalization of ONUs located farther from the OLT.

The effectiveness of our proposed algorithms is thoroughly validated through comprehensive simulation studies, demonstrating their potential to align with the demands of future networks.

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List of Abbreviations

1G-EPON	1G Ethernet Passive Optical Network
10G-EPON	10G Ethernet Passive Optical Network
4G	4th Generation (of Mobile Communications)
5G	5th Generation (of Mobile Communications)
Alloc-ID	Allocation Identifier
AON	Active Optical Network
AON AS	AON Active Star
APON	Asynchronous Transfer Mode PONs
ATM	Asynchronous Transfer Mode
AWG	Arrayed Waveguide Grating
BPON	Broadband Passive Optical Network
CO	Central Office
C-OLT	Client OLT
CPRI	Common Public Radio Interface
C-RAN	Centralized Radio Access Network
CU	Centralized Unit
DBA	Dynamic Bandwidth Allocation
DBRu	Dynamic Bandwidth Report unit
DBWA	Dynamic Wavelength and Bandwidth Allocation
DDSPON	Distributed Dynamic Scheduling for EPON

Diffserv	Differentiated Services
DSL	Digital Subscriber Line
DU	Distributed Unit
eCPRI	evolved Common Public Radio Interface
EFT	Earliest Finish last transmission Time
EFT-OS	Earliest Finish last transmission Time - Optimal Switching
EPON	Ethernet Passive Optical Networks
FSAN	Full-Service Access Network
FTTH	Fiber-To-The-Home
FTTP	Fiber-To-The-Premise
FTTx	Fiber-To-The-X
GEM	GPON Encapsulation Method
GPON	Gigabit Passive Optical Network
GPS	Generalized Processor Sharing
GTC	GPON Transmission Convergence
GTG	Gate-to-Gate
HDTV	High-Definition Television
HSP	Higher Speed PON
HS-PON	Higher Speed PON
IEEE	Institute of Electrical & Electronics Engineers
IoT	Internet of Things
IPACT	Interleaved Polling with Adaptive Cycle Time

IPTV	Internet Protocol Television
ITU	International Telecommunication Union
ITU-T	International Telecommunication Union – Standardization Sector
JIT	Just-In-Time
LAN	Local Area Network
L-OLT	Line OLT
LPT	Longest-Processing-Time-first
LRPON	Long Reach Passive Optical Networks
LS	List scheduling
LTT	Laser Tuning Time
MAC	Media Access Control
MAM	Media Access Management
MCCP	Multi-Channel Control Protocol
MDU	Multi-Dwelling Units
MFH	Mobile fronthaul
MPCP	Multi-Point Control Protocol
NASC	Next Available Supported Channel
NG-EPON	Next Generation Ethernet Passive Optical Network
NG-PON1	Next-Generation PON—Part I
NG-PON2	Next-Generation PON—Part 2
OAN	Optical Access Network
OAM	Operations, Administration, and Maintenance

OCDM	Optical Code Division Multiplexing
ODN	Optical Distribution Network
OLO	Other Licensed Operators
ONT	Optical Network Terminals
ONU	Optical Network Unit
ONU OMCI	ONU Management and Control Interface
OSI	Open Systems Interconnections
P2MP	Point-to-Multipoint
PAPR	Peak-to-Average Power Ratio
PCS	Physical Coding Sublayers
PDH	Plesiochronous Digital Hierarchy
PHY	Physical Layer
PLOAM	Physical Layer Operation Administration and Maintenance
PLR	Packet Loss Ratio
PMA	Physical Media Attachments
PMD	Physical Media Dependent
PON	Passive Optical Networks
PtP	Point to Point
QoS	Quality of Service
RAN	Radio Access Network
RF	Radio Frequency
RG	Residential Gateway

RN	Remote Nodes
RoF	Radio-over-Fiber
RTS	Request-to-Send
RTT	Round-Trip Time
SDH	Synchronous Digital Hierarchy
SIEPON	Service Interoperability in Ethernet Passive Optical Networks
SLA	Service Level Agreements
SONET	Synchronous Optical Networking
SR	Status Report
Super-PON	Super Passive Optical Networks
T-CONT	Transmission Container
TDM	Time-Division Multiplexing
TDMA	Time Division Multiple Access
TWDM-PON	Time Wavelength Division Multiplexing PON
UDP	User Datagram Protocol
WDM	Wavelength Division Multiplexing
WDM/TDM	Wavelength Division Multiplexing / Time Division Multiplexing
XG-PON1	10 Gigabit Symmetrical PON 1
XG-PON2	10 Gigabit Symmetrical PON 2

Chapter 1
Introduction

This chapter presents a high-level introduction to the Ph.D. thesis, covering the background, motivation, problem statement, and objectives of the work. It also discusses the contribution of the thesis and provides an outline of its structure. The chapter aims to offer a concise introduction, emphasizing the main research goals and providing an overview of the topics covered in the dissertation.

1.1 Motivation

The growing demand for bandwidth, driven by the proliferation of smart devices and the increasing demand for high-speed internet, needs the development of next-generation networks, such as 5G and 6G, capable of providing significantly higher bandwidths. To fully realize the potential of these networks, it is essential to optimize network architecture, streamline management processes, maximize resource utilization, and minimize costs. Passive Optical Networks (PONs) present an attractive solution due to their cost-effectiveness, flexibility, and energy-saving features, making them well-suited for broadband residential access, and also as fronthaul and backhaul infrastructure for mobile communication networks (5G and beyond) [1, 2].

Current Challenges and Need for Enhanced Dynamic Bandwidth Allocation (DBA) Algorithms:

Currently, PONs provide capacities ranging from 1Gbps to 10Gbps, shared among 32 to 64 users [3, 4]. However, the escalating bandwidth requirements of emerging services and 5G networks demand higher bandwidth rates. To address this need, the Institute of Electrical & Electronics Engineers (IEEE) and the International Telecommunication Union - Telecommunication (ITU-T) are actively working on standards to increase the bandwidth capacity of next-generation PONs to 25Gbps, 40Gbps, 80Gbps, and 100Gbps [1, 3]. Additionally, there is a growing need to expand the reach of PONs across broader geographical regions. This has led to the development of Long-Reach Passive Optical Networks (LRPONs), which extend coverage from the conventional 20 km in traditional PONs to 100 km [4, 5]. LRPONs facilitate high-speed, long-distance data transmission through optical fibers, offering cost savings by minimizing the need for central offices [5, 6].

Despite these advancements, the increasing demand for bandwidth has presented significant challenges in PON installations. To address these challenges, there is a pressing need to develop mechanisms to manage PONs effectively, ensuring efficient resource allocation and utilization, end-to-end quality of service (QoS) support, energy-saving, and optimized service for real-time provisioning of traffic flows [7, 8]. Dynamic bandwidth allocation (DBA) algorithms have been proposed as one solution to optimize resource utilization and minimize delay in PONs. These algorithms dynamically allocate bandwidth based on the traffic demand of each ONU, ensuring efficient resource utilization [7, 9, 10].

Limitations of Existing DBA Mechanisms and the Need for Novel DBA Techniques:

Existing DBA mechanisms have limited capabilities in handling the increasing demand for higher bandwidth in PONs. They have proven inadequate in adapting to the dynamic changes and evolving traffic patterns caused by emerging mobile applications, the Internet of Things (IoT), IPTV, and cloud-based services [11, 12, 13]. These limitations are evident in their struggle to cope with the dynamic nature of network traffic and the growing demand for bandwidth. As new applications and services continue to shape traffic patterns, existing DBAs fail to keep up, resulting in suboptimal resource management and network performance [14].

To address the challenges posed by the evolving networking landscape and fully harness the potential of PONs, both in the residential access and as support of advanced mobile networks, novel DBA technologies are necessary. These advanced solutions should simplify management processes, optimize resource allocation, and dynamically adapt to traffic demands in real-time.

Proposed Approach:

In this context, the use of multi-wavelength DBA algorithms emerges as a promising approach to enhance network performance. The enhanced DBA algorithms proposed in this thesis incorporate the often-overlooked concept of laser tuning time (LTT) delay, capturing the time spent on frequency reconfiguration during transmitter operations, specifically associated with wavelength switching [15, 16, 17, 18]. This incorporation provides the algorithms with a realistic perspective on the dynamic nature of Time Wavelength Division Multiplexing PON (TWDM-PON) systems. This is crucial in our DBA approaches, where we optimize wavelength switching based on tuning times, ensuring effective coordination of wavelength changes among ONUs. LTT becomes a significant consideration in our DBA design for the proper exploitation of these mechanisms.

Furthermore, we use the Longest Processing Time (LPT) [19] scheduling scheme to optimize the packet delay by sorting the ONUs' bandwidth requests in descending order, with the largest request being processed first, thereby minimizing overall delay. The LPT scheme is recognized for its efficiency and effectiveness, as it helps reduce task completion time, resulting in decreased delays [15].

Finally, we extend our work to Long Reach PONs that offer coverage over large geographical areas [6, 20]. LRPONs have the capability to extend the distance covered by PONs from 20 km to 100 km, resulting in cost savings by reducing the number of central offices. However, LRPONs face challenges in dynamic bandwidth allocation due to increased propagation delay. Traditional DBA schemes are inefficient in LRPONs due to longer round-trip times (RTT). To address this, we propose the Distance-Weighted Bandwidth Allocation (DWDBA) algorithm, specifically designed for multi-wavelength LRPONs. The DWDBA algorithm optimizes bandwidth utilization by assigning weight vectors to ONUs based on their distance from the OLT, ensuring fair resource allocation without penalizing ONUs based on distance. This mitigates the performance degradation caused by increased propagation delay in LRPONs.

1.2 Objectives

In summary, the objectives of the thesis have been:

- To investigate the existing DBA algorithms for Passive Optical Networks and identify their limitations in meeting the requirements of broadband access and advanced mobile networks.
- To propose and develop Enhanced Dynamic Bandwidth algorithms for PONs that can efficiently manage and allocate resources to meet the traffic demands. This includes the use of novel techniques such as LPT scheduling.
- To evaluate the performance of the proposed algorithms through simulation and compare it with existing DBA algorithms in terms of queue delay, and throughput.
- To extend the proposed Enhanced DBA algorithms to cover Long-Reach Passive Optical Networks.

The algorithms are designed to efficiently manage and allocate resources, ensure and accommodate the requirements of emerging applications and services. Additionally, the goal is to achieve low queue delay, higher throughput, and improved bandwidth utilization. By leveraging these innovative techniques such as LPT scheduling the proposed enhanced DBA algorithms achieve reduced latency, and higher throughput.

1.3 Thesis Contributions

As has been described above, the main contribution of this thesis is the development and evaluation of Enhanced Dynamic Bandwidth Allocation algorithms for Passive Optical Networks. What follows is a summary of the thesis contributions:

1. Development of an improved DBA algorithm for PONs, featuring the capacity to minimize overall delay through the utilization of the LPT technique. Results demonstrate a notable enhancement over the Interleaved Polling with Adaptive Cycle Time (IPACT) algorithm, of up to 73% reduction of queue delay. The results have been published in a journal [16].
2. Development of a Distance Weighted DBA considering distinctive characteristics of LRPON like distance and extended propagation delay. DWDBA involves assigning higher weights to distant ONUs, preventing penalization of those farthest away. Results demonstrate a queue delay reduction of up to 30% and a 10% improvement in queue delay and throughput respectively over IPACT. The results have been published in a conference [21], and a journal [22].
3. Incorporation of Laser Tuning Time into our analysis due to its realistic impact on TWDM-PON systems, an aspect often neglected in other studies. Despite LTT being a drawback in Time Wavelength Division Multiplexing (TWDM) networks, an LTT-aware DBA can lead to better results than those obtained by classic DBAs (such as IPACT). The results have been published in conferences [23, 21] and journals [16, 22].

The contributions have been carried out in collaboration with Mohammad Zehri, another PhD student of the Department. In some cases, the publications have been led by the author of this thesis, Adebanjo Haastrup, as first author [22, 23] and Mohammad Zehri as second author, or vice versa [15, 21].

1.4 Thesis Organization

This thesis is organized in six chapters. The background materials of the fields related to our research are provided in the first two chapters, while the rest of the document presents our contributions. The contents of each chapter are as follows:

- Chapter 1 introduces the context and motivation for the research. The chapter offers an overview of the thesis, outlining its objectives, contributions, and organization.

- Chapter 2 presents a comprehensive overview of the role of PONs, covering their architecture, components, standards, and associated implementations and technologies. This includes their contribution to delivering broadband access and supporting mobile backhaul networks.
- Chapter 3 explores important topics related to resource allocation in PONs. It discusses the implementation of DBA algorithms in PONs and explores the coexistence of IEEE and ITU operations in this context. The chapter also covers multiplexing techniques, including time- and wavelength-division multiplexing. It provides an overview of tunable lasers and highlights the significance of their delay. Additionally, the chapter includes a discussion of related work in the field.
- Chapter 4 presents the details of the proposed enhanced DBA algorithms for PONs. The chapter describes the LPT scheduling technique used to achieve reduced queue delay, and the tuning time delay used to give the system a realistic approach. The chapter also explains how these techniques are combined to achieve efficient resource utilization. Additionally, the results of the simulations conducted to evaluate their performances against traditional DBAs are presented.
- Chapter 5 introduces a novel Distance-Weighted DBA algorithm designed specifically for Long-Reach Passive Optical Networks. It addresses the limitations of existing DBA algorithms in the context of LRPON technology. The chapter presents simulation results that compare the performance of the new algorithm with traditional DBAs like IPACT.
- Chapter 6 concludes the thesis, with a summary of the contributions of the research and the key findings of the study, and a description of future research possibilities.

Chapter 2
Optical Access Networks

2.1 Introduction

The importance of broadband and multimedia telecommunications for society is growing rapidly, driving the need and, consequently, creating great business opportunities for network providers. Although the core and metro segments of networks are currently capable of providing adequate resources, the access portion of the network remains a bottleneck in terms of bandwidth and quality of service [24]. As a result, research and development efforts are increasingly focused on the access segment of the networks. Optical access networks have specific goals and limitations that set them apart from the core network. The primary focus of the access network is to enhance capacity while ensuring a low cost per user. This objective necessitates the development of innovative approaches to optimize performance within the constraints posed by existing infrastructure, services, and coverage areas [25].

A variety of broadband technologies have been developed for the access network, including Digital Subscriber Line (DSL), coaxial cable, wireless, and optical fiber. While DSL, coaxial cable, and wireless technologies are cost-effective and widely used, they struggle to cope with the exponential growth of internet traffic and the emergence of bandwidth-intensive services such as Video-On-Demand, High-Definition Television (HDTV), interactive gaming, and two-way video conferencing. These demanding applications require high bandwidth, prompting a rising interest in optical fiber as a solution to meet the escalating demand for high-speed internet services.

Optical fiber, known for its capability to provide significantly higher bandwidth compared to other technologies, has gained popularity as a preferred option for delivering broadband services [2]. Optical fibers have traditionally been favored for use in backbone and core networks due to their ability to transmit data at high bandwidths over long distances with minimal loss. However, in recent times, they have also become increasingly popular as a preferred choice for last-mile connections in access networks. This shift is driven by their suitability in meeting the growing demands of current online applications, which require higher bandwidth and low latency. Moreover, optical fibers are capable of accommodating future needs, making them an ideal solution for addressing the evolving requirements of modern communication networks. Optical access network systems are being installed under the deployment of Fiber to the x (FTTx, where x stands for home, building, curb, node, etc.) [26, 27] with fiber extending from the central office.

Fiber-to-the-home (FTTH) networks are commonly implemented using/under two main architectures, namely Active optical network (AON) and Passive Optical Network. AON is built on a point-to-point network architecture in which each subscriber has its own fiber-optic line that is terminated on an optical concentrator [28]. AON involves the use of electrically powered switching equipment, such as a router or a switch aggregator, to manage signal distribution and direct signals to specific customers [29]. The switch directs the incoming and outgoing signals to the proper place by opening and closing in various ways.

AON is an Ethernet-based technology that relies on active Ethernet switches, making interoperability among vendors easy [30]. AONs are deployed in two variants: point-to-point (PtP) and active star (AS). PtP is also referred to as "homerun," where each subscriber has a dedicated fiber that connects the residential gateway (RG) or optical network unit, located near the subscribers/end users, to the Ethernet switch with an optical line terminal located in the central office (CO) [31], as shown in Figure 2.1. This architecture is simple and straightforward but not very cost-effective because it requires a dedicated transceiver and fiber for each end-user in the central office. Moreover, each connection requires two interfaces, which can result in high power consumption and a large footprint.

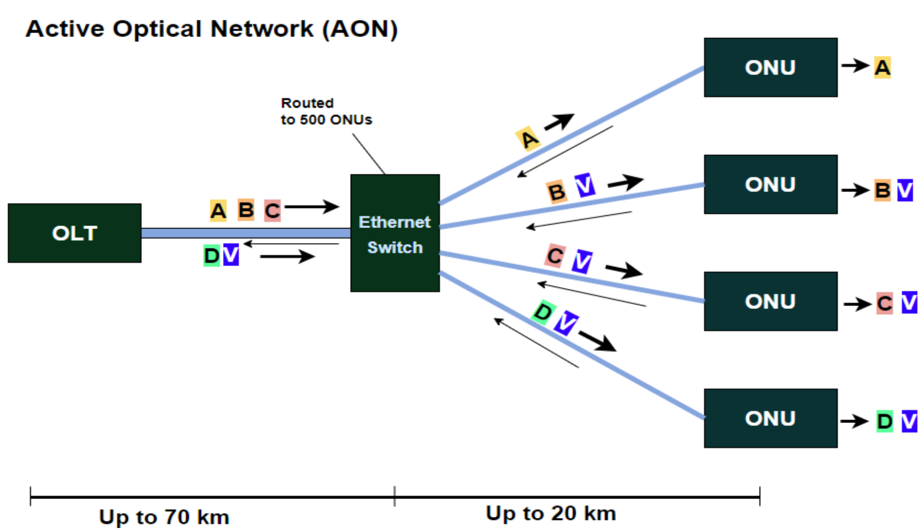

Figure 2.1: Active Optical Network (AON).

The AON Active Star (AON AS) uses a point-to-multipoint topology and employs active remote nodes (RNs) to connect the central office with multiple households. The remote nodes can be placed either in a cabinet or inside a building, such as a basement in a multi-dwelling unit. An Ethernet switch is present in the RN, which aggregates the traffic from a group of subscribers and connects through a feeder fiber to another Ethernet switch at the CO [31]. Two or more feeder fibers can be used to provide redundancy, but the number of fibers required in the AON AS architecture is significantly lower compared to the point-to-point (PtP) case.

2.2 Passive Optical Networks

Passive Optical Networks are highly efficient and reliable fiber optic networks that have gained popularity for access networks, offering numerous advantages over AON [32]. PONs utilize a passive architecture, eliminating the need for active electrical equipment between the central office and subscriber premises. This simplification not only reduces costs and power consumption but also enhances reliability and scalability [33].

In a PON, a point-to-multipoint topology is employed, with a passive splitter located between the Optical Line Terminal and Optical Network Units [2]. The trunk fiber extends from the central office to the passive optical splitter in the Optical Distribution Network (ODN), and optical drop fibers connect the subscriber nodes. These components are arranged in a tree-like architecture, as shown in Figure 2.2, to connect end-users to the central office. Unlike AON, PON uses a passive optical splitter that distributes the optical signal among the ONUs without requiring electrical power. PONs offer a converged infrastructure capable of carrying various services, including traditional telephone services that are converted and encapsulated in a single packet type for efficient transmission over the fiber [34].

PONs offer significant advantages, including simplified network deployment, reduced costs and power consumption, improved operational efficiency, and scalability. They are ideal for delivering high-speed broadband services with high capacity, low latency, enhanced reliability, and improved security. PONs support a wide range of ultra-high-bandwidth applications, such as cloud/edge networking, ultra-high-definition video streaming services, and upcoming technologies like 3D holographic communications.

Efficiency and reliability are key features of PONs, as they eliminate the need for outdoor active devices and perform all signal processing functions at the end terminating equipment located at the central office and user's premises. This "passive" nature distinguishes PONs from other optical network technologies, contributing to their efficiency and reliability. PONs are resistant to electromagnetic interference, ensuring signal integrity over long distances and making them a reliable solution for the last mile connection [32].

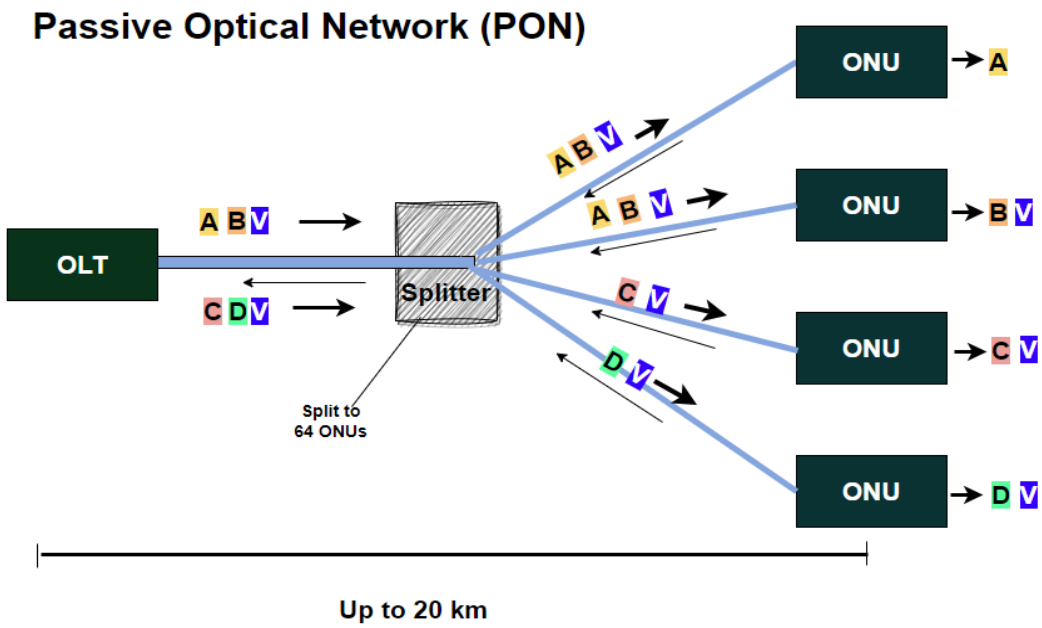

Figure 2.2: Passive Optical Network (PON).

Telco carriers are particularly interested in PONs due to their minimal fiber infrastructure, efficiency, and elimination of powering equipment in the outside plant. PON networks achieve efficiency through the utilization of splitters, allowing a single fiber optical strand to serve multiple users. This technology solves the first mile problem by reducing the number of optical transceivers, central office terminations, and fiber deployment, ultimately reducing costs [31]. PONs stand out as highly efficient, reliable, and cost-effective fiber optic networks with numerous advantages and applications. Their passive architecture simplifies network deployment, reduces costs and power consumption, and enables seamless scalability, positioning them as a promising solution for modern access networks.

2.3 PON Architecture

2.3.1 PON Components and Devices

A PON network consists of three main parts as shown in Figure 2.3: Optical Line Terminal, Optical Network Units and Optical Distribution Network.

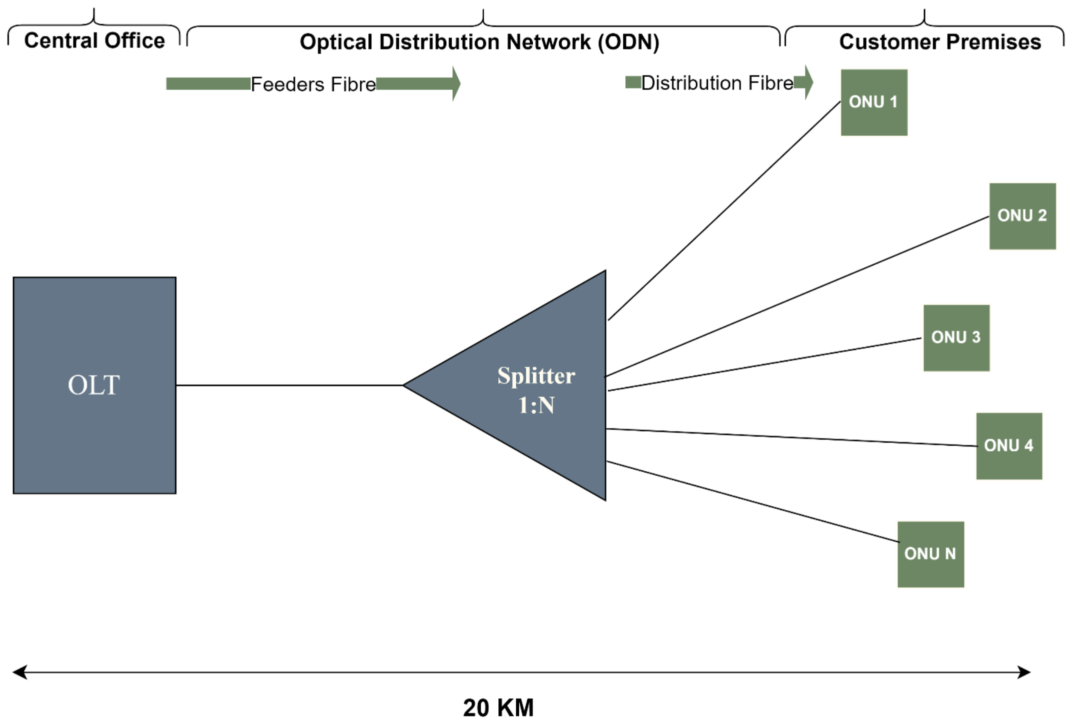

Figure 2.3: Elements of a Passive Optical Network (PON).

2.3.1.1 Optical Line Terminal (OLT)

The Optical Line Terminal is a crucial component of the optical access network that serves as the endpoint for the service provider. It functions as a multi-service platform and performs the functions of a layer 2 (L2) switch in a traditional communication network. At the central office side, the OLT converges signals carrying various services, sends them over the network through the Optical Distribution Network in a specific format, and transmits them to the Optical Network Units. Additionally, the OLT receives signals from subscribers and forwards them to various service networks based on service types. The OLT connects multiple ONUs through optical splitters, initiates, manages, and controls the ranging process, and records the ranging information [32].

The OLT, located at the root of the tree-like PON architecture, serves as the central command center, providing instructions to each ONU for the delivery of cost-effective and high-speed communication services to subscribers. Its primary role is the allocation of network resources to the ONUs and controlling the starting time and transmission window size of the ONU's transmitted data.

2.3.1.2 Optical Network Units (ONUs)

The Optical Network Units are located at the subscriber side and work together with the OLT to implement layer 2 (L2) functions. They convert optical signals transmitted from the OLT via the optical fiber to electrical signals and provide voice, data, and multimedia services to individual subscribers. In addition to this, the ONUs are responsible for sending, aggregating, and grooming different types of data coming from the customers and sending it to the OLT in the upstream direction.

The main functions of the ONUs can be summarized as follows:

- Filter and accept data sent from the OLT.
- Respond to management instructions from the OLT and make adjustments accordingly.
- Buffer the Ethernet data from subscribers and transmit the data upstream in transmission windows allocated by the OLT.
- Implement other subscriber management functions.

Furthermore, the ONU device includes both Multi-Dwelling Units (MDUs) and Optical Network Terminals (ONTs), with MDUs typically deployed in corridors and street-side cabinets, while ONTs are usually deployed in users' homes [35].

2.3.1.3 Optical Distribution Network (ODN)

The Optical Distribution Network is the optical information transmission channel between the central office and terminal users. It is an integral part of the PON system and facilitates the transmission and distribution of data between the OLT and ONUs over distances of up to 20 km (or more, in the case of Long-Reach PONs [5, 6]).

The ODN is responsible for connecting the central office to end-users through a five-segmented network. These segments consist of the feeder fiber, optical distribution point, distribution fiber, optical access point, and drop fiber, which work together to establish an optical information transmission channel capable of transmitting and distributing data between the OLT and ONUs over long distances. The quality of the ODN is critical for the performance, reliability, and scalability of the PON system. Therefore, careful planning is required during its design and installation [36].

2.3.1.4 Splitter/Combiner

A critical component of the optical distribution network in PON networks is the passive optical splitter [37]. Its purpose is to split the optical signal from the OLT into multiple signals to be distributed to the ONUs. The use of the passive optical splitter is one of the key advantages of the PON system, as it eliminates the need for any active device in the ODN, thereby reducing the number of cables required. In the upstream direction, the splitter combines the signals coming from the ONUs into one signal, which is then sent to the OLT. This passive combining function means that all signal processing functions are completed in the switches and user premises equipment. The splitting ratio is a key parameter of optical splitters, and there is a growing interest in finding ways to increase the splitting ratio [38].

2.4 PON Standards

The PON network has been developed over the years to become a future-proof infrastructure capable of meeting evolving demands and standards that specify higher data rates. The Institute of Electrical & Electronics Engineers (IEEE) and the International Telecommunication Union (ITU) have been the active players at the forefront of developing standards based on point-to-multipoint passive optical networks over the past 20 years. These standards help to ensure interoperability between PON equipment and promote adoption of the technology [2].

There are several alternative PON architectures that have been standardized and deployed commercially in the field. These PON architectures differ in organization, specification, bearer protocol, data formats, and signaling rates. Four variations of PON have been developed, which can be grouped into two different architectures. The first architecture is based on Asynchronous Transfer Mode (ATM) and includes three variations: Asynchronous Transfer Mode Passive Optical Network (APON), Broadband Passive Optical Network (BPON), and Gigabit Passive Optical Network (GPON) [33]. The second architecture is based on

Ethernet Passive Optical Network (EPON). Out of all the PON variations, EPON and GPON have become the most popular due to their cost-effectiveness, high data rates, and ease of deployment.

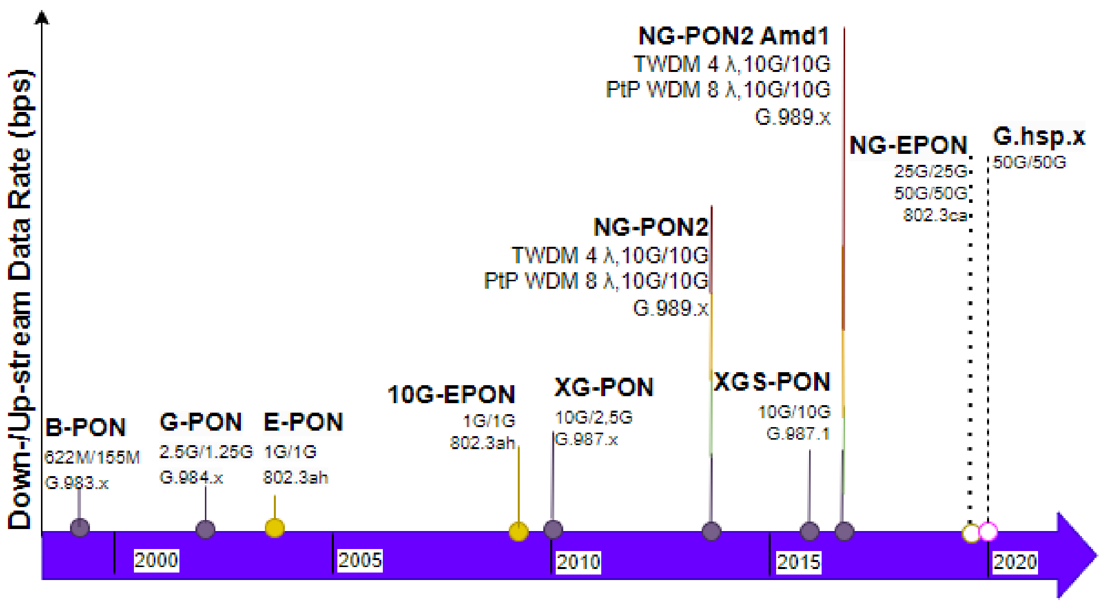

Figure 2.4: PON Standards Development in ITU-T and IEEE (based on Fig.11 of [39]).

Parameters	**EPON**	**GPON**
Standards	IEEE 802.ah	ITU-T G.984
Transmission speed	Downstream: 1.25 Gbps Upstream: 1.25 Gbps	Downstream: 1.244/2.488 Gbps Upstream:1.5/6.2/1.244/2.488 Gbps
Max Split ratio	16 (up to 32)	64 (up to 128)
Line code	8B/10B	Non return to zero (NRZ)
Protocol	Ethernet and TDM	ATM, Ethernet and TDM
Security	Not Specified	Advanced encryption standard (AES)
Quality of Service (QoS) Support	Poor	Good
Data Encapsulation mode	Ethernet	GEM/ATM
Forward Error Correction (FEC)	Optional RS (255,239)	Optional RS (255,239)

Table 2.1: IEEE 802.ah vs ITU-T G.984 PON Standards

The two leading standards bodies, IEEE and ITU, each have different philosophies. IEEE is responsible for developing the EPON, which is based on simple standards with less stringent hardware requirements. In contrast, ITU developed GPON, which is based on a relatively complex set of standards with tighter hardware requirements and a larger focus on QoS assurance. While the two philosophies have some similarities, they differ in the message syntax, guard times, overheads, and other parameters that affect bandwidth utilization within the two systems. Despite these differences, both PON architectures offer advantages in terms of cost savings, bandwidth efficiency, and scalability, and are widely used in access networks [2]. The roadmap for the development of both standards is summarized in Figure 2.4, while Table 2.1 summarizes the defferences between EPON IEEE 802.ah and GPON ITU-T G.984 standards.

2.4.1 IEEE PON Standards

2.4.1.1 Ethernet Passive Optical Network (EPON)

Ethernet Passive Optical Network is an access network technology that uses Ethernet frames to transmit data, voice, and video. The EPON standards are being developed by the IEEE 802.3 working groups. EPON has gained popularity in the access network space due to its cost-effective technology that is compatible with many legacy systems [40]. The IEEE 802.3 standard primarily focuses on the physical and data link layers of the Open Systems Interconnections (OSI) reference mode. EPON uses Ethernet Media Access Control (MAC) and physical layer (PHY) chip sets, making it a reliable technology. EPON combines the high bandwidth capability of optical networks with the well-known Ethernet architecture and frame format, enabling efficient transmission of data, voice, and video.

In an EPON system, the transmission of customers' Ethernet frames occurs when the ONUs send the frames to the OLT during the assigned transmission time slot in the upstream direction, thus requiring a careful planning and synchronization in order to ensure that transmissions from ONUs do not collide. On the other hand, in the downstream direction, a broadcast method is used to transmit the Ethernet frames to the ONUs. This broadcast transmission is achieved by using MAC addresses that are attached to the Ethernet packets [12]. All ONUs within the EPON system receive the packet that contains the data of all ONUs. However, each ONU only extracts the data frames that are meant for it and forwards them to the appropriate user, while disregarding any frames that are not addressed to it.

In 2004, the first generation of EPON standard was established by the IEEE 802.3ah standard, which specified a network infrastructure based on EPON and allowed for the transport of data traffic in Ethernet frames at a symmetric rate of 1.25 Gbps [40]. The use of 8B/10B line encoding limited the bit rate for data transmission to 1 Gbps [41]. As the number of users continued to grow and more bandwidth-intensive applications emerged, the IEEE 802.3 committee formed a study group in 2006 to develop a 10 Gbps EPON specification. This group, known as IEEE 802.3av, aimed to standardize the requirements for the next generation 10G EPON, with the requirement of maintaining backwards compatibility with the original EPON standard. This backward compatibility presented several technical challenges to the specification process, but ultimately allowed for a smooth transition to the faster network standard.

This standard introduces some modifications to the reconciliation sublayer (RS), physical coding sublayers (PCSs), physical media attachments (PMAs), and physical media dependent (PMD) sublayers. It supports two physical layer modes, including symmetric transmission at 10 Gbps data rates and asymmetric transmission at 10 Gbps downstream and 1 Gbps upstream data rates. The use of Time-Division Multiplexing (TDM) in EPON allows for backward compatibility with 1 Gbps EPON equipment while enabling the deployment of both EPON and 10G-EPON in the same network [42]. In 10G EPON, a different line coding scheme of 64B/66B is used, with a higher line rate of 10.3125 Gbps, compared to the 8B/10B line coding with a line rate of 1.25 Gbps in 1G EPON. The guard time is assumed to be the same in time units in both EPON versions, and control messages (REPORT/GATE) used for the (upstream/downstream) communications from the ONUs to the OLT are also the same for the 1G and 10G versions [43].

One notable difference between 1G-EPON and 10G-EPON is that the latter supports both symmetric and asymmetric data rates, whereas 1G-EPON provides only a 1 Gbps symmetric data rate. Specifically, 10G-EPON allows for 10 Gbps data rates in both the downstream and upstream directions for symmetric transmission, and 10 Gbps downstream and 1 Gbps upstream for asymmetric transmission. Additionally, the different line coding reduces the bit-to-baud overhead to 3% in 10G-EPON due to the usage of 64 B/66 B, while the 8 B/10 B used in 1G-EPON incurs a higher overhead of 25%. The burst signal format is similar for both systems, but the receiver settling time for 10G-EPON is twice as long as that for 1G-EPON, at 800 ns and 400 ns, respectively [44]. These differences in data rates, line coding, and receiver settling time are important considerations for network designers when selecting which system to use for a particular application.

2.4.1.2 Next Generation Ethernet Passive Optical Network (NG-EPON)

In 2014, the IEEE 802.3 Working Group established an ad-hoc group to examine service provider requirements, economic and technical feasibility, and bandwidth requirements for the next generation of EPON, in anticipation of the continued growth in access network bandwidth demand. The findings of this ad-hoc group were published in the IEEE 802.3 Industry Connections Feasibility Assessment for the Next Generation of EPON report [45], which provided strong evidence for the need for a new EPON technology standard [46]. Consequently, the IEEE-802.3ca (Project Authorization Request) PAR 100G EPON Task Force was approved with the goal of standardizing a low-cost solution to support point-to-multipoint topologies for the next generation of 100G EPON. The task force aims to standardize 25G, 50G, and 100G PON, based on 25Gbps per channel transmission, that support point-to-multipoint topologies on optical fiber while maintaining coexistence with 10G EPON.

However, unlike some other network technologies, NG-EPON does not support wavelength tunability. This means that all 25G channels will operate on fixed wavelengths, limiting the flexibility of network design. The NG-EPON network is designed to support four wavelength channels, with each channel capable of operating at a data rate of 25Gbps. In response to increasing customer demands, multiple ONUs can request to use higher logical data rates, such as 50Gbps, 75Gbps, or 100Gbps [46]. Bandwidth-intensive ONUs can transmit their data on multiple wavelength channels in parallel to achieve higher capacity. This is achieved by scheduling frames on different designated channels. One of the main technologies addressed by the IEEE-802.3ca PAR 100G EPON Task Force is Channel Bonding, which aims to deliver higher data rates of 50Gbps and 100Gbps [47]. This technology allows multiple channels to be bonded together to increase capacity and improve performance. However, the single 25G channel is optimized for cost, while 50 Gbps and 100Gbps may cost more. Despite this, the NG-EPON standard maintains backward compatibility with 10G EPON, ensuring that previous investments in access network infrastructure are protected.

Channel bonding is a technique that has recently been introduced to the point-to-multipoint (P2MP) Ethernet scenario, though it has been in use for some time in the classical point-to-point (PtP) Ethernet network. This technique allows the combination of multiple wavelengths to achieve higher data rates. It is achieved through the use of the Multi-Channel Control Protocol (MCCP) in conjunction with the Multi-point Control Protocol (MPCP) [47]. By coordinating upstream transmissions on one or more wavelengths simultaneously using the dynamic bandwidth allocation, the channel bonding mechanism enables an ONU to operate on multiple wavelengths simultaneously, resulting in higher aggregated line rates to accommodate the increase in customers and bandwidth demand [48].

The NG-EPON implementation is taking a generational approach, in which a single standard is developed to cover multiple generations, unlike the previous PON standards rollout that defined a single generation at a time. This shift is considered more efficient and effective than the prior approach, as it allows for more forward-thinking and better planning [47]. The deployment is expected to occur one generation at a time, starting with the 25G first-generation system, followed by the 50G second generation, and the 100G third generation. The coexistence of multiple generations on the same network is planned, and backward compatibility of ONUs is deemed highly beneficial. The deployment of 25G symmetrical services is primarily driven by business applications, such as mobile front and backhaul technologies. The generational approach is set to offer channel bonding, providing 50G for the 2nd generation PON and 100G for the 3rd generation PON, using four wavelength pairs as illustrated in Figure 2.5. This approach will enable higher capacity and more efficient use of network resources to meet the growing bandwidth demand from customers.

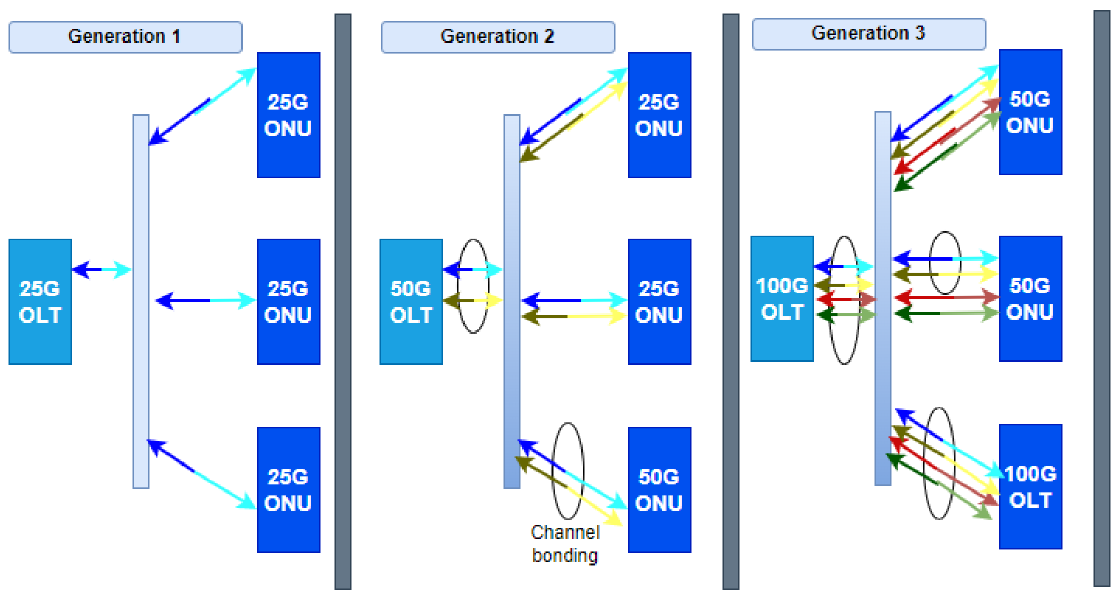

Figure 2.5: Generational Approach of 25/50/100G EPON by means of Channel Bonding (based on Fig 7 of [47]).

2.4.1.3 Super-PON

Another PON architecture worthy of mention is the Super-PON concept proposed by IEEE with the aim of increasing the reach and customer aggregation of PONs [49]. To standardize the Super-PON, the IEEE 802.3 Working Group formed the P802.3cs task force in November 2018. However, this effort did not produce any standardization or significant commercial deployments, as a project with nearly identical objectives was later initiated in ITU-T Q2/SG15 [49]. The Super-PON is designed to operate on a FTTH architecture that supports a longer reach between the central office and the customer, increasing from the current 20km to 50km. The extended reach is achieved by incorporating downstream and upstream amplification, which increases the optical signal strength and helps overcome the progressive losses that limit the reach on weaker signals.

Moreover, the Super-PON architecture supports up to 1,024 customers per fiber, compared to just 64 with today's PON architectures. This significant increase in capacity leads to a reduction in the number of central offices required to support PON services in access networks that provide connectivity to end-users in a particular area [50]. The Super-PON is based on Wavelength Division Multiplexing (WDM) multiplexing technique, which enables one fiber to carry multiple PON instances by mapping each instance to a different wavelength. This allows for an increased number of customers, leading to a significant cost reduction as the cost of the central office is spread across more customers, thus lowering the overhead for each of them. While the Super-PON has not yet seen significant commercial deployment, it has the potential to revolutionize the way PON services are delivered, offering increased capacity and reach, which could benefit users and service providers alike.

2.4.2 ITU Standards

A series of ITU-T standards for PONs have been defined over the decades by the full services access network (FSAN) group of companies, following a point-to-multipoint passive optical networks topology. FSAN is a forum for the world's leading telecommunications services providers, independent test labs, and equipment suppliers to work towards a common goal of truly broadband fiber access networks [51, 52]. Their first initiative came in the mid-90s with the development of Asynchronous Transfer Mode PONs (APONS). APON uses Asynchronous Transfer Mode (ATM) for packet communication and utilizes centralized and statistical multiplexing combined with the sharing effect of passive splitters on fiber and OLT [53]. Its strategy was to utilize a common broadband access system for provisioning of broadband

and narrowband services. The APON format was adopted by International Telecommunications Union (ITU) under (ITU – T Rec.G.983) standards [53]. Its main focus was primarily in residential places and to make provisions for video delivery over the PON. APON required separate fiber for the transmission of video while voice and data could share the same fiber.

APON was succeeded by Broadband PON (BPON) which is an enhancement after the APON standard, but it is also based on the ATM protocol. BPON was specified in ITU-T recommendations G.983.1, G.983.2 and G.983.3 [54]. A major characteristic of BPON is that it is backward compatible with APON [53]. Both standards are based on ATM as transport protocol providing 32 splits and a span of 20km each. They both equally used broadcast for downstream and time-division multiple access (TDMA) upstream like all other TDM PONs. The downstream frame consists of 56 cells of 53 bytes each [9]. The major difference between APON and BPON is that BPON can be supported by some extra overlay capabilities which can be used for services related to broadband and video. BPON has uplink and downlink speeds of 155 and 622 Mbps, respectively, plus dynamic bandwidth allocation, protection and other functions and maximum reach of 20km. It can provide services such as Ethernet access, video transmission, and high-speed leased lines [54].

2.4.2.1 Gigabit Passive Optical Network (GPON)

Gigabit Passive Optical Network (GPON) is an upgraded version of BPON with increased data rates. GPON systems use Wavelength Division Multiplexing technology to transmit data bi-directionally (upstream and downstream) over a single optical fiber [55]. To separate the transmit and receive signals of different users over the same optical fiber, GPON uses broadcast for downstream data transmission while TDMA technology is used for upstream transmission [55]. Its frame comprises 38880 bytes and a fixed frame duration of 125µs traditionally used in Synchronous Digital Hierarchy (SDH) and Plesiochronous Digital Hierarchy (PDH), leading to a downstream rate of 2.488Gbps [9]. This frame duration provides certain efficiency advantages over EPON, as messages (control, buffer report, and grant messages) can efficiently be integrated into the header of each 125µs frame [56]. In terms of bandwidth, GPON has an advantage of allowing higher bandwidth efficiency and higher data rates over EPON, thereby making it more suitable to relieve bottlenecks for core and access networks [33]. It was well accepted by operators due to its advantages in providing better QoS efficiency and typically shorter polling cycles, which provides a better pre-reporting delay. It has support for variable data rates while the typical data rates of 2.4Gbps (downstream) and 1.2Gbps (upstream) are what most vendors implement [1].

Traditionally, GPON incorporates two layers of encapsulation, including the use of Asynchronous Transfer Mode (ATM). The Ethernet frame is initially encapsulated into a transport protocol known as GPON Encapsulation Method (GEM). This GEM frame is then encapsulated into a GPON Transmission Convergence (GTC) frame. The GTC frame contains both pure ATM cells and TDM [57]. GEM, functioning within the GPON transmission convergence layer, serves as the data transport scheme. It is a modified version of the G.7041 Generic Framing Procedure, which facilitates the transmission of IP packets over SDH or Synchronous Optical Networking (SONET) [9]. GEM employs a connection-oriented, variable-length framing mechanism to transport data services over the PON. The use of variable-length frames allows for the accommodation of different types of services [9]. Consequently, GEM enables the simultaneous transmission of data and TDM traffic over the same fiber, making GPON systems highly effective in handling high-bandwidth scenarios when compared to other data-centric protocols [42].

In terms of management, GPON offers physical OAM (Operations, Administration, and Maintenance) functions for critical signal timing. It utilizes the ONU Management and Control Interface (OMCI) to facilitate statistical data collection, service provisioning, and fault management. While GPON boasts robust management capabilities, its configuration and service provisioning are primarily static. This implies that the bandwidth allocated to each ONU cannot be dynamically changed on demand as it is fixed in principle [58].

The advancement of the GPON is categorized into three generations: The first generation, next generation stage 1 (NG-PON1) and next generation stage 2 (NG-PON2). NG-PON technologies are categorized into two groups: evolutionary and revolutionary (disruptive). Evolutionary NG-PONs aim to improve performance, such as increasing data rates, while also co-existing with legacy PONs on existing optical distribution networks. Revolutionary NG-PONs, on the other hand, provide enhanced services on new distribution networks, and employ technologies such as optical code division multiplexing (OCDM). For the purposes of this discussion, the focus is on the evolutionary NG-PON technologies that are expected to replace current GPON and EPON solutions in the near- to mid-term. By upgrading the current infrastructure, these NG-PONs can provide improved performance, higher data rates, and new capabilities, while also maintaining backward compatibility with legacy PONs. This allows for a smoother transition to the new technology, with a lower risk of disruption to the existing service. Overall, the adoption of evolutionary NG-PON technologies offers a practical and cost-effective solution for service providers to meet the growing demand for bandwidth and enhanced services [57].

2.4.2.2 NG-PON1

NG-PON1 is termed as an evolutionary growth of gigabit PON, which supports coexistence with GPON on the same ODN [37]. Its coexistence feature enables seamless upgrade of individual customers to NG-PON on a live ODN without disrupting services of other customers. It is a mid-term upgrade compatible with the first generation GPON offering a higher capacity, longer reach, larger bandwidth, and support for more users. The next generation PON stage1 is subdivided into 2: XG-PON1 and XG-PON2. XG-PON1 is an asymmetric 10 Gigabit PON system with bandwidth capacity of 10Gbps and 2.4Gbps for downstream and upstream respectively, defined under ITU-G987x standards that marks the beginning of next stage of development [59]. The selected wavelength is between 1575 nm and 1580 nm for the downstream and 1260 nm to 1280 nm for the upstream transmission. The main goals of introducing NG-PON1 are to achieve an increase in the data-transfer speed at a minimal cost, and to ensure interoperability [37].

The XG-PON2, also known as (XGS-PON), is a 10-Gigabit-capable PON system which is an update to the XG-PON1 standard in order to deliver symmetrical capacity defined under ITU-T G.9807.1 standards [60]. It offers an increase in the upstream transmission speed from 2.5 Gbps to 10 Gbps, enabling the symmetrical transmission speed of 10Gbps in the upstream and downstream direction. XG-PON2 operates at the same wavelengths for upstream and downstream with XG-PON1, this is the only case where there is a reuse of the same wavelengths in successive standards [61]. XGS-PON has support for 64 subscribers over 20 km. The 20 km distance limitation is due to optical power budget constraints which is also related to the split ratio of the ODN [49]. PON's upper layer protocols are able to support longer distances (e.g., up to 60 km for the G-PON transmission convergence (TC) layer [61]) and larger split ratios (e.g., up to 1:1024 for the XGS-PON TC layer [62]).

2.4.2.3 Next Generation PON stage 2

Next-Generation Passive Optical Network 2 (NG-PON2) is a 2015 telecommunications network standard for the second stage of the Next generation Passive Optical Networks [63]. It comes with further improvement to NG-PON1 towards achieving higher data rates, and higher split ratios specified under the ITU-T G.989 standard series [59]. The general requirements for NG-PON2 point to supporting at least 40 Gbps of aggregate bandwidth capacity in downstream for residential and commercial applications, mobile backhaul and other applications. It facilitates a multi-wavelength transmission that can scale up to higher capacities, with the ability to reach up to 80 Gbps. As per the ITU-T G.989 standards, the specified reach distance for NG-PON2 spans from 20km to 60km [64]. One major requirement of NG-PON2 and NG-PON1 is the coexistence with the already developed GPON systems and the reuse of the outside plant, considering that the ODN costs 70% of the sum of investments in the PON rollout.

NG-PON2, offers spectral flexibility in the ODN, enabling the coexistence of different customer types on the same network. This flexibility allows operators to transition smoothly by utilizing new wavelength bands as legacy systems are phased out, ensuring a seamless integration [65]. Unlike its predecessor, NG-PON2 utilizes four wavelengths instead of one, resulting in improved efficiency and enhanced QoS without disrupting existing connections. To effectively manage these multiple wavelengths, tunable devices are introduced at the ONUs. By employing TWDM techniques and stacking multiple NG-PON1 systems on the fiber network, NG-PON2 optimizes resource utilization and simplifies the network architecture. This approach combines different laser light wavelengths, transmitting multiple signals over a single optical fiber and dividing transmission into time slots, ultimately boosting the network's overall capacity [66]. Figure 2.6 illustrates the multiplexing techniques used in NG-PON2.

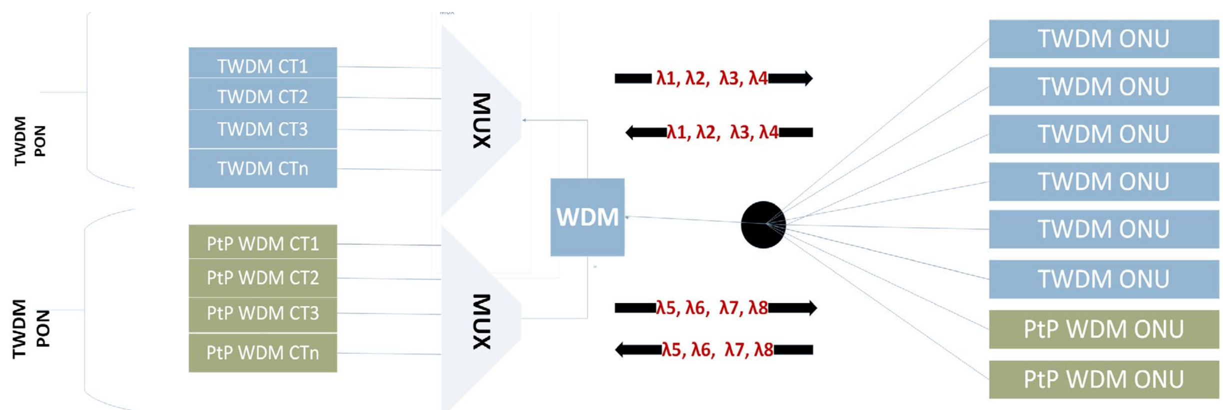

Figure 2.6: Multiplexing Techniques for NG-PON2 (based on Fig 4 of [63]).

TWDM, a hybrid multiplexing technique, leverages the benefits of Time Division Multiplexing and Wavelength Division Multiplexing. By transmitting TDM frames across multiple wavelengths, TWDM enables the simultaneous delivery of services to multiple users, maximizing network efficiency [67]. The selection of TWDM for the NG-PON2 standard was driven by its technological maturity and compatibility with the existing ODN infrastructure, including the ability to reuse power splitters from previous PON generations. This eliminates the need for costly replacements such as arrayed waveguide grating (AWGs), resulting in significant cost savings [3].

In TWDM, four bi-directional channels with Dense Wavelength Division Multiplexing (DWDM) spacing are utilized, each operating at a downstream line rate of 10 Gbps and an upstream line rate of 2.5 Gbps. This configuration aggregates a downstream capacity of 40 Gbps and an upstream capacity of 10 Gbps by consolidating four 10GPON systems over a single fiber. TWDM effectively addresses the growing demand for high-bandwidth services while optimizing resource utilization [4]. Notably, TWDM stands out for its lower risk, cost-effectiveness, and minimal disruption compared to alternative solutions, making significant contributions to the standardization and adoption of NG-PON2.

2.4.2.4 Higher Speed PON (HSP)

A Higher Speed PON (HSP) was launched by ITU/-T SG15/Q2 study group under the G.sup.HSP project in 2016, researching various key technologies and technical feasibility for PON networks providing higher speeds. The project describes the characteristics of optical transmission of up to 50Gbps per wavelength between the OLT and the ONU [50]. The HSP 50 Gbps line rate is a next generation of PON system defined under ITU-T G.9804 standard project series.

The HSP systems can meet the needs of a wide range of networks in diverse markets and it is deployable in numerous applications ensuring easier convergence between residential, business, and mobile networks in an efficient manner. One of its goals is to promote backward compatibility with existing ODN that comply with the legacy recommendations. It focuses on the ability to re-use established technical capabilities as much as possible, and to ensure smooth migration scenarios from legacy PON systems to HSP systems [50, 63]. HSP system includes both single-channel 50 Gbit/s systems to succeed XG(S)-PON and multi-channel 50 Gbit/s systems to succeed NG-PON2 (40G PON, at 10Gbit/s per wavelength) specifying both symmetric and asymmetric nominal line rates. The symmetric nominal line rate is capable of achieving, approximately 50 Gbps in the downstream and upstream directions to ensure support of the maximum service rate of at least 40 Gbps [50]. For asymmetric nominal rates, one option is to achieve approximately 50 Gbps in the downstream and 25 Gbps in the upstream. Another option is to achieve approximately 50 Gbps in the downstream and 12.5 Gbps or 10 Gbps in the upstream per wavelength. It supports the maximum fiber distance of at least: 20 km for general applications, 10 km for applications that are latency sensitive (e.g., a case where the PON network is used as fronthaul or backhaul for Ultra-Reliable Low Latency service as defined by 5G) [68].

The higher speed PON systems have one or more wavelength channel pairs which are separated in the wavelength domain. The architecture can be split between TDM/TDMA based and point to point based. The TDM/TDMA based system with a single wavelength channel pair is the single channel TDM PON [69]. While the higher speed PON TDM/TDMA system with more than one wavelength channel pairs is the TWDM-PON. TWDM-PON system supports ONU tunability, wavelength channel bonding, and makes use of a wavelength multiplexer at the OLT. The operational principles of TDM and TDMA apply in an individual wavelength channel pair in both higher speed PON TDM/TDMA systems. The higher speed PON point-to-point systems are non TDMA based and typically have multiple wavelength channel pairs [69]. HSP is the first PON standard to enable the use of Digital Signal Processing (DSP) in order to meet high bitrate performances [70].

2.4.3 Long-reach Passive Optical Networks (LRPONs)

Long-reach PONs have revolutionized the capabilities of conventional TDM and WDM PONs by significantly increasing their range and split ratio, opening up new possibilities for network deployments and service offerings [71]. These advanced PON architectures are designed to extend the reach of traditional optical access networks beyond their typical distance limit of 20 km [5, 71], enabling the delivery of high-speed broadband services to areas that were previously considered challenging due to their distance from the central office.

State-of-the-art long-reach PONs span lengths of up to 100 km. This extensive reach allows them to serve a larger geographical area, making them ideal for deployments in rural and suburban regions where the distance between the central office and end users is significant. In addition to the extended reach, long-reach PONs also support a substantial split ratio, accommodating up to 17 power-splitting TDM PONs within the same network infrastructure [72]. Each of these TDM PONs operates on a distinct pair of upstream and downstream wavelength channels, ensuring efficient utilization of the available spectrum.

The scalability of long-reach PONs is further demonstrated by their ability to serve a large number of colorless ONUs (i.e. an ONU that can work on any wavelength). With the potential to support up to 256 ONUs per TDM PON, the overall capacity of long-reach PONs is truly remarkable. In fact, when considering the entire network, the total number of colorless ONUs that can be served by long-reach PONs can reach 4352 units. This scalability enables service providers to cater to a wide range of customers and deliver high-quality broadband services to a large subscriber base.

One of the significant advantages of long-reach PON technologies is their capability to integrate optical access and metro networks, effectively bridging the gap between these two domains. By combining the functionalities of these networks, long-reach PONs provide a seamless and efficient solution for delivering high-speed connectivity from the central office to the end users. This integration not only simplifies network architecture but also results in substantial cost savings by reducing the number of required optical-electrical-optical (OEO) conversions and the number of equipment interfaces. However, it should be noted that the integration of optical access and metro networks in long-reach PONs necessitates the incorporation of optical amplifiers to compensate for propagation and splitting losses, ensuring reliable signal transmission over longer distances [73]. LRPONs are commonly used in access networks providing residential broadband access in FTTH and also as in Cloud Radio Access Networks (C-RAN) technologies for mobile networks (4G, 5G and beyond) for connecting the baseband unit (BBU) to the remote radio heads (RRH) [74]. More details about C-RAN are provided in Section 2.5.2.

2.5 Other PON Related Implementations and Technologies

2.5.1 Service Interoperability in Ethernet Passive Optical Networks (SIEPON)

The Service Interoperability in Ethernet Passive Optical Networks (SIEPON) is a set of standards proposed under IEEE 1904.1 standard for managing PONs networks [75]. It builds upon the IEEE 802.3ah (1G-EPON) and IEEE 802.3av (10G-EPON) Physical layer and Data Link layer standards to create an open, system-level and network-level standard.

SIEPON helps to provide multivendor interoperability accommodating varied nature of the existing deployments and standards supporting multiple service models, multiple provisioning and management concepts, and diversity of deployment environments and regulatory requirements. The standards are to enable plug and play, and interoperability between ITU-T GPON and IEEE EPON standards thereby eliminating the need for each of the bodies to create unique interoperability specifications that needlessly fragment the market. SIEPON defines a generalized and flexible architecture for EPON systems, and specifies the precise behavior of MAC, MAC control, and OAM clients.

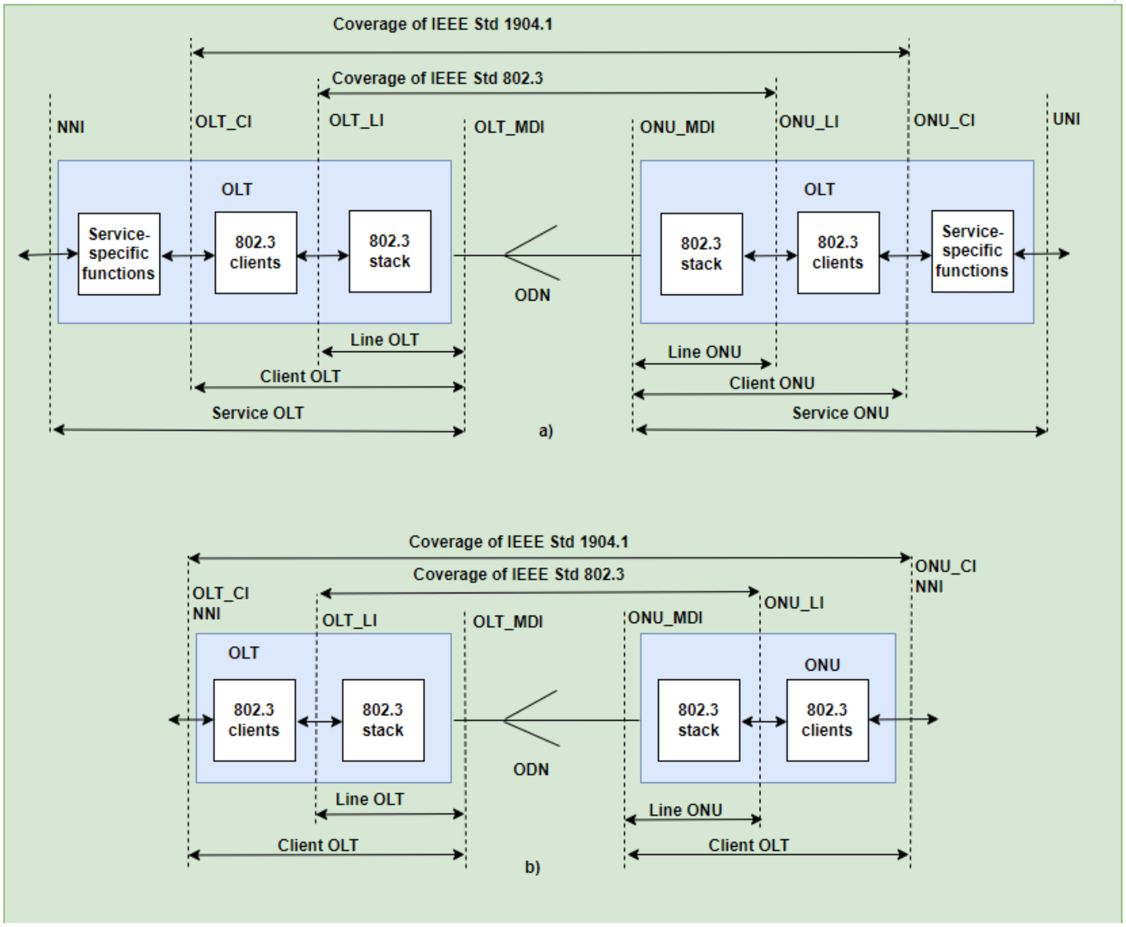

Figure 2.7: Target EPON System Architecture: a) OLT and ONU with service-specific functions; b) OLT and ONU without service-specific functions (based on Figure 1 of [76]).

SIEPON's goals can be summarized into four categories:

- Service configuration and provisioning
- Performance requirements and service quality
- Service Survivability
- System/device maintenance and management

The scope of SIEPON standardization includes physical (PHY), MAC, and upper layers to support functions related to the data path: such as multicast delivery, tunnels, VLANs, and quality of service (QoS) management. The architecture model of SIEPON is separated into: (1) Line OLT (L-OLT)/Line ONU (L-ONU) with their functions covered by the IEEE 802.3 standards; (2) Client OLT (C-OLT)/Client ONU (C-

ONU) with their functions covered by the SIEPON standards; and (3) Service OLT (S-OLT)/Service ONU (S-ONU) with additional functions defined by operators or vendors as shown in Figure 2.7

In summary, the amalgamation of multiple standards under a common framework, together with reliable and complete third-party testing and certification, ensures a healthy and balanced competitive environment for all sectors of the PON ecosystem.

2.5.2 Centralized Radio Access Network (C-RAN)

Centralized Radio Access Network is a network architecture for mobile communication systems that separates the radio hardware from the signal processing and control functions [77]. In C-RAN, the base station is split into three parts: the Centralized Unit (CU), the Distributed Unit (DU) and the Remote Unit (RU). The CU is responsible for higher layer protocol functions, such as mobility management, while the DU handles the lower layer protocol functions, such as modulation and coding. The RU is responsible for the final digital and analog radio frequency (RF) processing. C-RAN architecture is designed to improve network efficiency and reduce operational costs by centralizing the baseband processing functions, while distributing the radio frequency functions. This approach enables multiple RUs to share the same DU and CU, which can result in lower equipment costs, reduced power consumption, and easier network management [78].

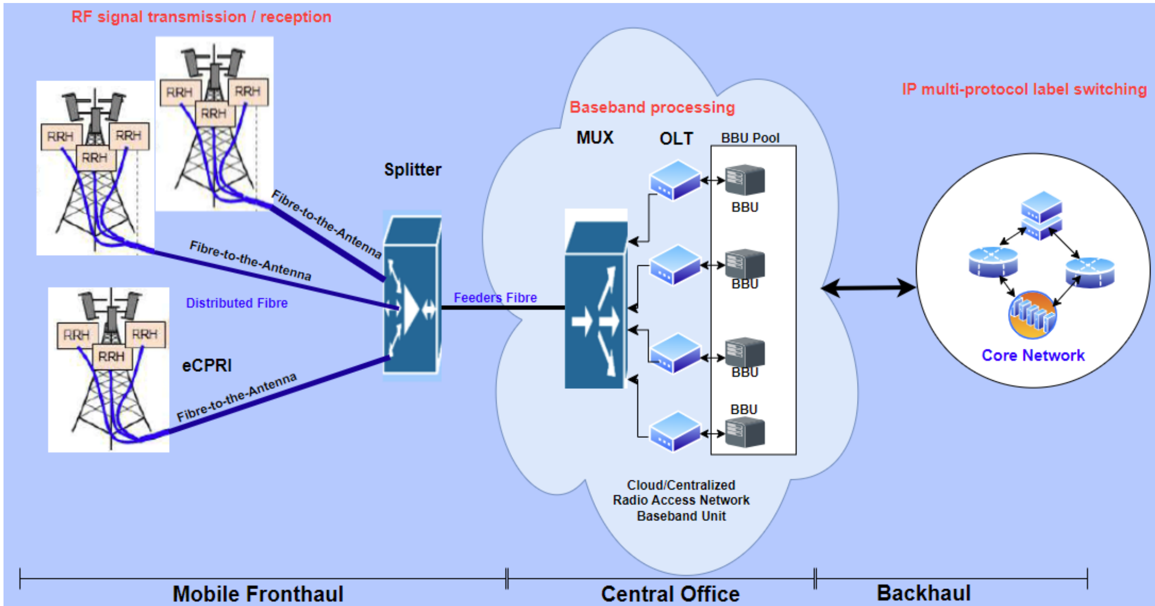

Figure 2.8: Centralized Radio Access Network architecture.

To enable C-RAN architecture, a mobile fronthaul (MFH) network is used to connect the DU and RU units to the CU. The MFH network is typically based on the Radio-over-Fiber (RoF) technology, which uses optical fibers to transport the high-bandwidth digital signals between the DU, RU, and CU. The different initiatives and alliances of equipment manufacturers, operators, and academy have proposed different transmission and control management protocols for MFH, such as Common Public Radio Interface (CPRI) and enhanced CPRI (eCPRI), which are used in 4G/LTE and 5G technologies [11]. PONs are a promising solution for supporting 5G MFH in a C-RAN architecture as illustrated in Figure 2.8. They are widely deployed Fiber-To-The-Premise (FTTP) technology, and they have the lowest deployment cost when compared to the point-to-point fiber alternative. Additionally, PONs benefit from their inherently centralized architecture, which makes them suitable for MFH in a C-RAN architecture. PONs have the potential to provide high transmission bandwidth, low latency, and synchronization, which are essential requirements for transport networks supporting advanced mobile networks (5G and beyond).

2.6 Summary

In this chapter, we have delved into the world of optical access networks, particularly focusing on PON technologies and FTTx. PONs are considered to be one of the key technologies in delivering high-speed broadband residential services and have been also widely deployed as part of the infrastructure of mobile networks. We provided a comprehensive overview of PON technologies, including the architecture of the popular ones. Furthermore, we have presented the standards from the two leading standardization bodies - IEEE and ITU and emphasized the need for the amalgamation of these standards. We also touched on the evolution of these standards over the generations, highlighting their crucial roles in 5G networks.

The chapter also provided a detailed description of the architecture and topology of PONs, and how they have been deployed in practice. We also discussed other related implementations of PON technologies, as well as their roles in the C-RAN mobile fronthaul.

Overall, the chapter aimed to provide readers with a fundamental understanding of PON technologies and FTTx. This knowledge is essential for understanding the subsequent chapter, which will delve deeper into the principles of resource allocation in PONs. We will describe the main standards, principles, and protocols for the exchange of communications among the PON components, which will allow readers to gain a deeper understanding of how these technologies work.

Chapter 3
Resource Allocation in PONs

3.1 Introduction

One of the major challenges being faced by PON is the efficient allocation of the network resources between the OLT and the ONUs connected to the system. PON is built on P2MP topology with many ONUs competing for network resources in real-time in the shared medium. Time slots and wavelength are the two main resources shared by the ONUs in the PON system. Classic PONs, with only one wavelength, allocate bandwidth to users by assigning time slots. Next-generation PONs have introduced the use of multiple wavelengths. Therefore, the design of the allocation of time slots and assignment of wavelength among the ONUs wanting to transmit in the PON system has been a major challenge of the PON networks.

In the downstream direction, network resources are communicated from the OLT to the ONUs in a broadcast manner and the ONUs will accept the data sent to it while discarding others. In the upstream direction, the channel is shared among the ONUs and thus prone to collision as they tend to transmit at the same time. ONUs are not able to detect collision occurring in the shared medium due to the difficulty in implementing carrier-sense multiple access with collision detection [79]. In order to prevent data collisions and to fully utilise the network potential, it is imperative to design a mechanism that arbitrates the allocation of resources to the ONUs in the shared medium. The resource or bandwidth allocation mechanism is responsible for coordinating the transmission of data based on the load from customers in order to avoid transmission conflict in the upstream direction [8].

Bandwidth allocation techniques can be broadly categorized into static and dynamic, and further categorized as shown in Figure 3.1. The static bandwidth allocation mechanism was popular in the earlier days of PON, where bandwidth allocation was implemented by granting constant data rate to all the ONUs [80]. If an ONU needed more resources than granted, the transmission would not be possible. If an ONUs needed less bandwidth than apportioned, then the excess bandwidth will be wasted due to non-usage. The resources specified for ONUs are static with predetermined fixed-size time slots for each allocation, and do not change during the transmission. Underutilization of upstream channel bandwidth, undesirable packet delay, and packet loss all tend to occur under static bandwidth assignment due to the bursty behavior of network traffic. It is therefore a very simple implementation, but it does not perform optimally [81].

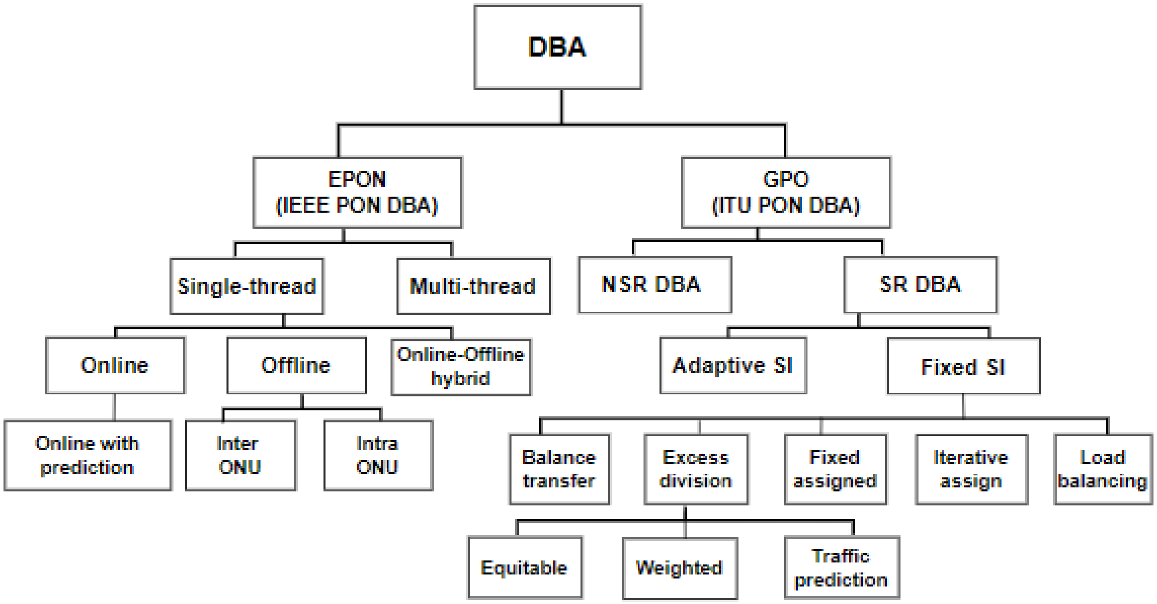

Figure 3.1: Classification of DBA Algorithms (based on Fig 1 of [12]).

The development and evolution of PON, coupled with the limitations of the static bandwidth allocation algorithm, has led to the development of more flexible, efficient bandwidth algorithms. A Dynamic Bandwidth Allocation algorithm allows bandwidth allocated to the ONUs to be varied according to load and usage of the link. The bandwidth is allocated dynamically to the ONUs as the need arises, thereby allowing some ONUs that need more resources than existing can take from ONUs with excess resources. DBA can be implemented in 2 ways: 1) centralized DBA where the DBAs are exclusively performed at the OLT in the central office; 2) distributed DBA where both the OLT and the ONUs play a contributory role in the scheduling.

3.2 Centralized Dynamic Bandwidth Allocation

A centralized bandwidth allocation scheme is concentrated in the OLT and implemented in a centralized manner following a logical tree-like topology. In the centralized approach, the ONU's reports have to travel to the OLT over the ODN to inform the OLT about the ONU upstream bandwidth needs. It has the advantage of having a centralized intelligence for the bandwidth assignment algorithm in which the OLT knows the traffic status of the entire PON. Hence it can perform dynamic and adaptive resource allocation to provide better support for differentiated services. In addition, with the centralized approach, the ONUs' configuration can be simplified thus reducing the network cost [82, 83]

A foremost example of the centralized dynamic bandwidth allocation algorithm designed for EPON is Interleaved Polling with Adaptive Cycle Time [84]. In IPACT, the scheduling and bandwidth allocation algorithms are implemented at the OLT. IPACT uses an interleaved polling scheme to schedule data transmission of ONUs, so the other ONUs are able to transmit their data between two adjacent transmissions of an ONU thereby reducing the idle time. The OLT polls the ONUs individually in a round-robin fashion to dynamically allocate the bandwidth in accordance with the requested bandwidth of each ONU. The ONU's request is granted by the OLT, based on the previous polling cycle. This reduces the wait time (time that each ONU must wait for the next transmission) and cycle time (time taken to poll all ONUs on the network), thereby minimizing the overall transmission delay. Accordingly, IPACT lacks support for service level agreements (SLA) and does not support QoS for services that are sensitive to time delay and therefore, it is not a suitable algorithm for some traffic types [85].

Figure 3.2 illustrates the operations of IPACT. At time t_0, the OLT sends a control message called a Grant to ONU1, allowing it to send 6000 bytes of data. Upon receiving the Grant, ONU1 starts sending data up to the granted window size. ONU1 also generates its own control message called a Request, indicating the number of bytes in its buffer (550 bytes in this case). The OLT knows when the last bit of ONU1's transmission will arrive by considering the RTT and the authorized data size. It then schedules a Grant to ONU2 (3200 bytes), ensuring a small guard interval between the transmissions. The OLT repeats the process for ONU2, calculating the time when the last bit from ONU2 will arrive and scheduling a Grant to ONU3 (1800 bytes) accordingly. ONU2 generates its Request (5700 bytes) and informs the OLT. The OLT updates its table again, and the process is repeated for all the ONUs.

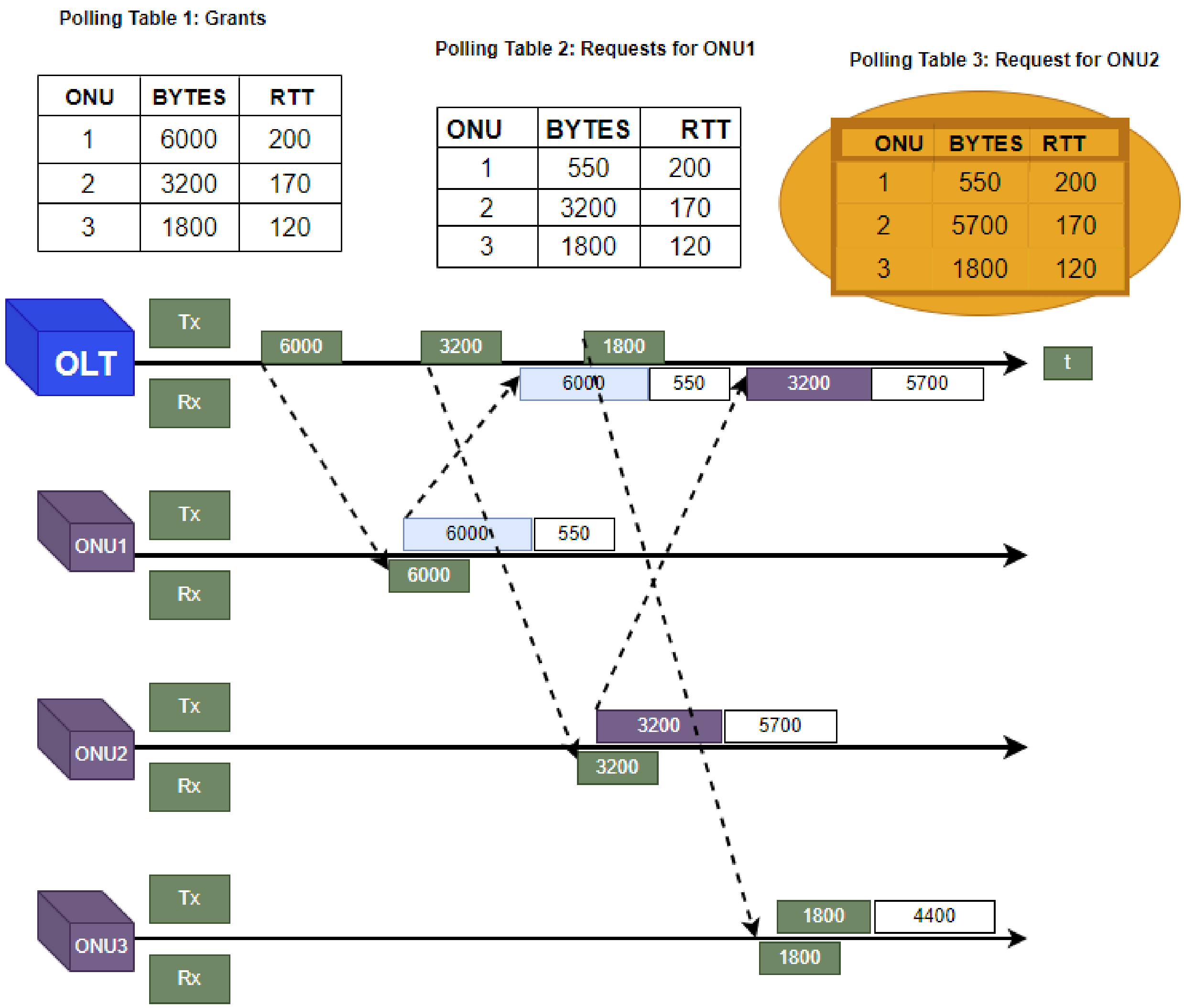

Figure 3.2: IPACT operation (based on Figure 5 of [84]).

3.3 Distributed Dynamic Bandwidth Allocation

A Distributed DBA allows the DBA functionalities and implementation to be decentralized and distributed between the ONUs and the OLT. It involves the cooperation of the OLT and the ONUs whereby the ONUs play active roles in the DBA process. The computation of the DBA is distributed among the ONUs, and the ONUs can update their bandwidth requests directly without the intervention of the OLT, thus allowing a faster response time than a centralized scheme [86]. A prominent example of the distributed DBA is the

Distributed Dynamic Scheduling for EPON (DDSPON) [87]. In DDSPON, each ONU is able to estimate the global free capacity of the upstream channel and proportionally perform requests based on the state of its queues and those reported by the other ONUs [86, 88].

DDSPON, illustrated in Figure 3.3, builds upon the basic IPACT algorithm by adding extra information in the GATE messages, specifically the weight vector that provides information about the load distribution across all ONUs. This extra information allows the ONUs to schedule transmission window sizes [87]. Additionally, each ONU transmits a Report message to the OLT, including an extra parameter - its weight. The OLT utilizes this weight information to update the weight vector, which is then distributed to all the ONUs, thus making them aware of the fraction of bandwidth assigned to them.

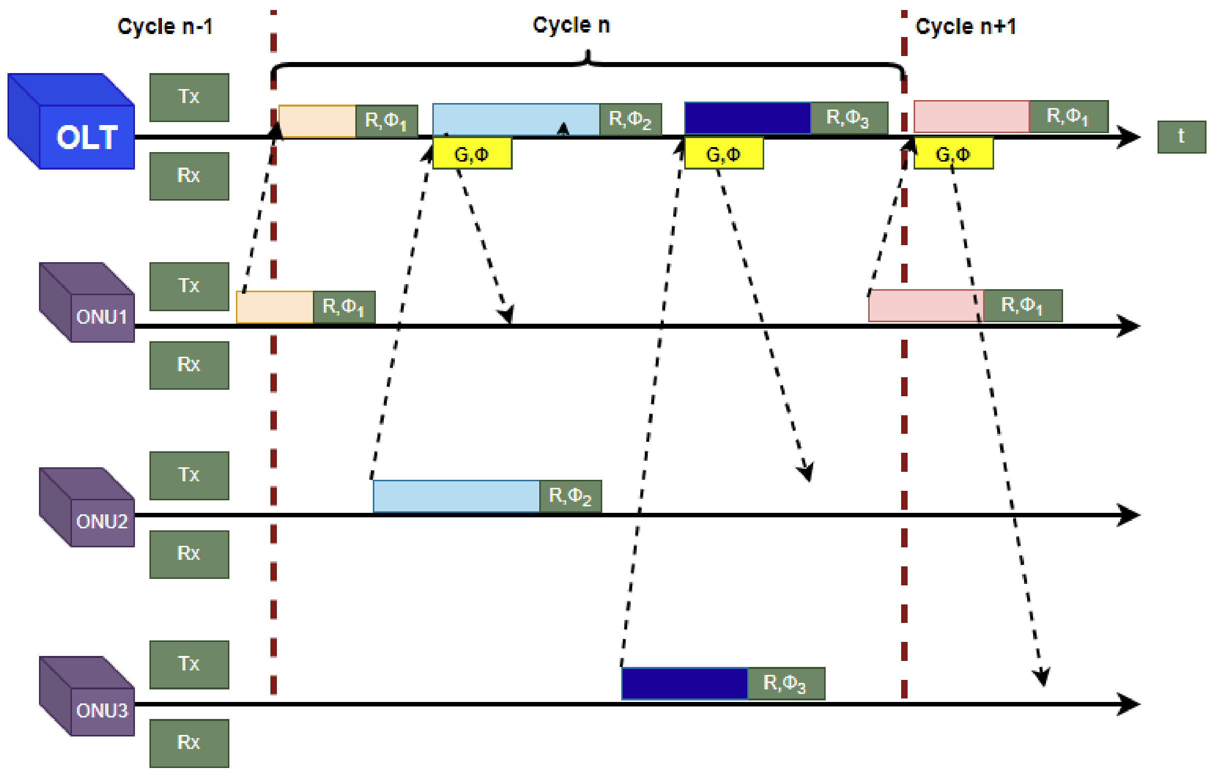

Figure 3.3: Distributed Bandwidth Allocation Scheme (DDSPON Polling Mechanism) from [86].

The scheduling process in DDSPON is performed on-the-fly, eliminating the need for the OLT to wait for all Report messages to arrive before initiating the scheduling algorithm [85]. Additionally, ONUs independently calculate the appropriate number of bytes that can fit within the maximum transmission window size, ensuring efficient utilization of bandwidth. Unlike IPACT, which requires the OLT to be notified of queue thresholds in ONUs, DDSPON eliminates this dependency, as ONUs dynamically determine the size of their transmission windows based on the real number of bytes in each Ethernet frame without fragmenting data [88].

3.4 DBA implementation in GPON and EPON

EPON and GPON which are the two popular standards setting the framework for the DBA operations embrace different philosophies. While EPON is based on a simple standard with looser hardware requirements, GPON is based on a relatively complex standard with tighter hardware requirements and a larger focus on QoS assurance [2]. They both have different guard times, overheads, and other parameters that affect the bandwidth utilization on both systems. These underlying differences would determine how DBAs are designed in each system in order to cope with the imposed traffic requirements and fairness policies while still maintaining efficient utilization of the PON's shared upstream channel [12]. Due to this, the DBA algorithm in IEEE EPON is not suitable for ITU-T GPON and vice versa, because their frame structures are entirely different due to the significant differences of the MAC layer.

3.4.1 Dynamic Bandwidth Allocation in EPON

The upstream channel is managed by the MAC protocols operation in the data link layer. The primary function of the MAC is to prevent collision between Ethernet frames of different connected ONUs that are transmitting simultaneously as it is difficult to implement a carrier-sense multiple access with collision detection [89]. MAC protocols should be capable of introducing low overhead, making efficient use of the resources and guaranteeing the requested QoS for different types of traffic [34]. The MAC sublayer defines a set of medium independent functions, enabling MAC clients to exchange data with their link peers. MAC supports general data encapsulation (including framing, addressing, and error detection) and medium access (collision detection and deferral process for shared medium environment) [12]. The MAC sublayer is designed in order to facilitate the implementation of various DBA algorithms.

A functionality of the Multi-Point MAC control sublayer is the Multi-Point Control Protocol, which is responsible for managing the communication between the OLT and ONUs during the initial registration phase, and during normal operations. MPCP was developed and standardized by the IEEE 802.3ah task force with the purpose of arbitrating the upstream transmission among the ONUs. MPCP controls operations such as synchronization and ranging (Round-Trip Time computation), bandwidth arbitration, time slot assignment to ONUs, and discovery functions. It performs real time control and manipulation of MAC operation, and exchange of messages between the OLT and ONUs. MPCP defines a state machine, messages, and several timers to control access to the upstream channel. The MPCP does not dictate a specific dynamic bandwidth allocation scheme but facilitates the implementation of DBA schemes by enabling the exchange of information that the OLT needs to allocate bandwidth to each ONU [12].

The MPCP functions include assignments of ONUs transmission slot, ONUs auto-discovery and reporting bandwidth requirements to the upper layer to dynamically assign bandwidth [90]. There are two modes of operation of MPCP: the auto-discovery, or initialization, and normal operation. The auto-discovery mode is used by the OLT to detect newly connected ONUs, and to learn the round-trip delays between the OLT and the new ONU. It is also used to learn the MAC address of the ONU, as well as assign a unique ONU ID to the new ONU. Under the normal mode of operation, registered ONUs request certain shares of the bandwidth, and are granted such requests by the OLT in a collision free manner [12].

MPCP relies on some Ethernet control messages during the initial registration and normal operation modes to provide the signaling infrastructure/control plane for coordinating upstream data transmission. The initial registration process is to complete the discovery of newly connected ONUs and register them. For the initial registration phase as seen in Figure 3.4, the following messages are defined:

- REGISTER_REQ: unregistered ONUs use this message to respond to discovery GATE messages. In the downstream channel, the OLT sends GATE messages, which all ONUs receive (broadcast mode).
- REGISTER: the OLT uses this message to assign a unique identifier to a newly registered ONU.
- REGISTER_ACK: sent by the ONUs to the OLT as a final registration acknowledgment.

The contention zone is the period where multiple ONUs engage in competition to register with the OLT, ensuring collision avoidance.

The OLT periodically opens a discovery time window in order to allow unregistered ONUs to attempt register. The OLT broadcasts a discovery message, which includes the starting time and length of the discovery window. When ONUs receive this message, they wait for a random time (in order to avoid collision, in case all receivers answered at the same time) and then transmit a register message to the OLT. The offline ONUs, after receiving the discovery message, will be registered during the previously established window. This window is unique because this is the only time that ONUs can communicate with the OLT without a specific grant window [91].

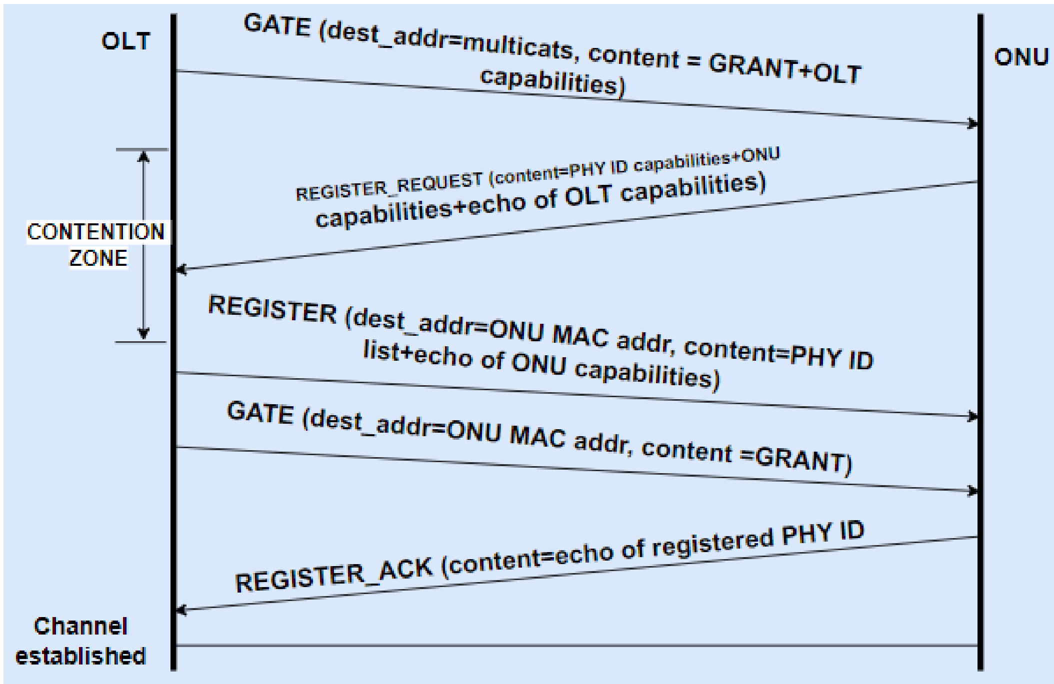

Figure 3.4: OLT and ONUs Registration Procedures.

During normal operations, GATE and REPORT messages are both used to request bandwidth from the OLT and allocate the required bandwidth to each ONU. The GATE message is used by the OLT to allocate a transmission window to an ONU. The REPORT message is used by an ONU to report its local conditions and make bandwidth requests to the OLT in the upstream direction, as shown in Figure 3.5.

After receiving the GATE message, the ONU will program its local registers with "transmission start" and "transmission length" and update its local clock to match the timestamp of the received message. When the "start timer" expires, the ONU will begin its transmission, which may consist of multiple Ethernet frames. The bandwidth assignment process is summarized in the following 3 steps:

- REPORT message: The ONU sends a REPORT message to the OLT, including a timestamp and queue status. This message provides information about the ONU's current status and bandwidth requirements.

- GATE message: The OLT calculates the RTT based on the timestamp received from the ONU. Using this RTT, the OLT sends a GATE message to the ONU, which includes the timestamp, grant start time, and grant length. The grant start time indicates when the ONU can start transmitting data, and the grant length specifies the duration of the allocated time slot.
- Data transmission: Upon receiving the GATE message, the ONU updates its local time based on the timestamp provided by the OLT. The ONU then transmits data within the allocated time slot, ensuring efficient utilization of the available bandwidth.

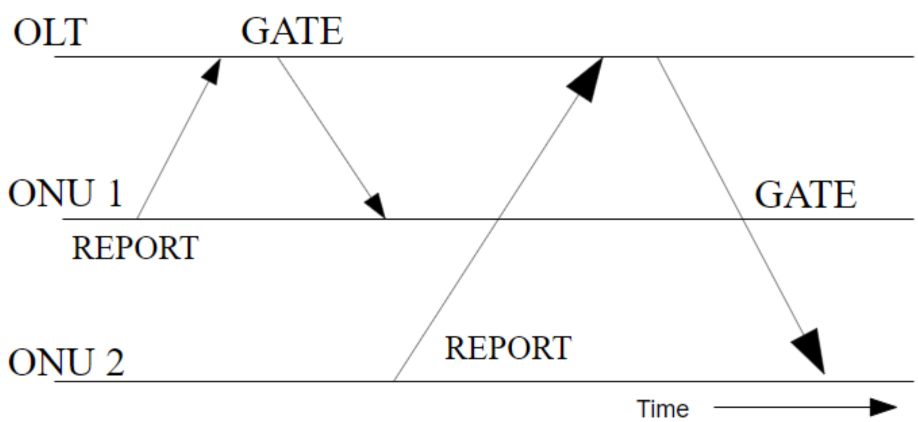

Figure 3.5: Exchange of GATE and REPORT messages between OLT and ONUs.

Packet fragmentation is not allowed, so any frames that do not fit within the allocated time slot will be deferred to the next time slot. This ensures that the ONU remains in sync with the OLT and avoids any potential clock drift [89]. In summary, the MPCP is designed for the assistance of dynamic bandwidth allocation operation in EPONs. Since there is no mandatory DBA algorithm specified in MPCP, it provides a framework for facilitating the implementation of various allocation algorithms in EPON [12].

3.4.2 Dynamic Bandwidth Allocation in GPON

The GPON standards introduce GPON Transmission Convergence Layer (GTC), a protocol layer of the GPON protocol suite that is positioned between the physical media dependent layer and the GPON clients [2]. The GPON protocol is based on a partitioning of the upstream and downstream transmission into 125 µs GTC frames [92]. The GTC layer is composed of GTC framing sub-layer and GTC adaptation sub-layer. GPON uses a GPON Encapsulation Method (GEM) to handle the transport of other protocol like

Ethernet, IP, or T1/E1 circuits, among others. The GPON packet size ranges from 53 bytes to 1518 bytes allowing service differentiation [12, 35].

GPON uses Transmission Containers (T-CONT), an ONU object representing a set of GEM ports that appears as a single entity for the purpose of upstream bandwidth assignment on the PON [2, 59, 92], as shown in Figure 3.6. T-CONT is a logical queue at the ONU associated with specific QoS requirements.

A T-CONT allows different GEM slots of an ONU to be aggregated and identified by a single allocation identifier (Alloc-ID) to distinguish between different traffic types and allocates bandwidth accordingly during ONU initialization [60]. A T-CONT can only be used by one ONU per PON interface on the OLT [93]. In the downstream direction, the GEM frames are carried in the GTC payload over one or more T-CONTs, which arrive at all the ONUs. The ONU framing sub-layer extracts the frames, and the GEM TC adapter filters the frames based on their 12-bit Port-ID. Only frames with the appropriate Port-IDs are allowed through to the GEM client function. In the GPON upstream direction, the bandwidth is dynamically assigned to the users. T-CONTs are identified by Alloc-ID and each T-CONT bandwidth is assigned differently according to DBA and SLA [94]. There are five types of T-CONT, labelled 1 to 5:

- T-CONT 1: Fixed bandwidth.
- T-CONT 2: Assured bandwidth.
- T-CONT 3: Assured and Non-assured bandwidths.
- T-CONT 4: Best-effort bandwidth.
- T-CONT 5: Fixed, Assured and Non-Assured.

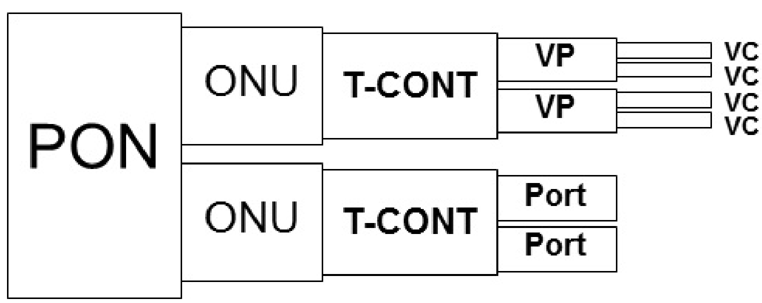

Figure 3.6: GPON’s T-CONT structure.

The GPON standard defines status report (SR) messages, used by the ONUs to communicate instantaneous T-CONT occupancy information to the OLT, while grant messages (BW map) are used by the OLT to communicate scheduling information back to the ONUs.

The BW map contains T-CONT scheduling information for the particular upstream GTC frame. Hence, a BW map is broadcasted to the ONUs in the header of every downstream GTC frame [95]. The SR messages are integrated in the header of each T-CONT for each upstream ONT burst and are issued upon request from the OLT [96]. Figure 3.7 shows a schematic view of the GPON DBA process with the OLT-ONT communication resulting in an updated bandwidth assignment. Upon request, the T-CONT issues a SR containing buffer occupancy information [96].

The complete DBA algorithm process is implemented in such a way that the DBA module which is usually located inside the OLT continuously collects the status report information. The OLT does the calculations, and the results are sent to the ONUs in the form of BW map in the downlink frame. Each ONU sends uplink data in the time slot allocated to it according to the BW map information, occupying uplink bandwidth. The OLT dynamically adjusts and allocates the uplink bandwidth to the ONU according to the upstream burst traffic demand of the ONU [97].

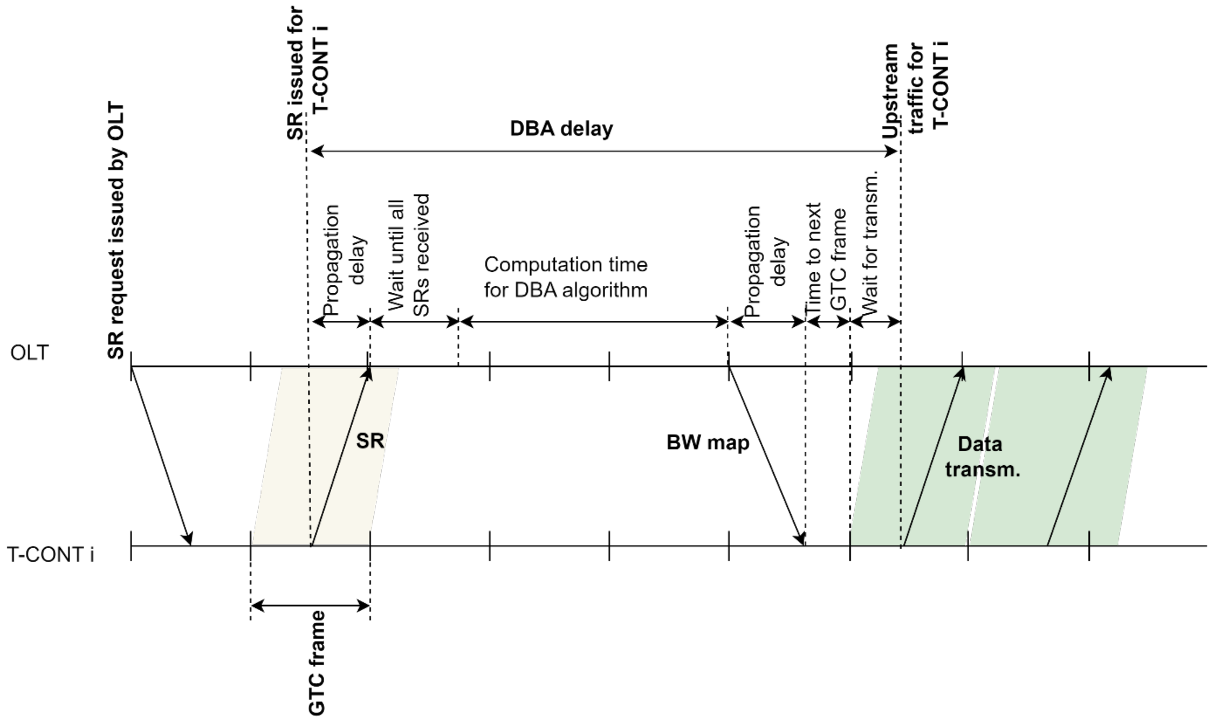

Figure 3.7: Schematic view of the DBA process in GPON.

3.5 Multiplexing techniques used in PONs

The two first PON standards, namely IEEE 802.3ah Ethernet PON (EPON) and ITU-T G.984 Gigabit PON (GPON), consist both of a single upstream wavelength channel and a separate single downstream wavelength channel, whereby both channels are operated with TDM. EPON and GPON are expected to coexist for the foreseeable future as they evolve into Next-Generation PONs [98], some of which are based in other multiplexing techniques, among them Wavelength Division Multiplexing, Orthogonal Frequency Division Multiplexing (OFDM) and Optical Code Division Multiplexing (OCDM) [99], as described in the following sections.

3.5.1 Time-Division Multiplexing

In Time-Division Multiplexing, time is fragmented into slots which are assigned to ONUs to enable the upstream transmission [100, 101]. Multiplexing in time domain involves intermittent, periodic transmission of ONUs connected to each OLT. However, the fixed assignment of TDM slots is inefficient in cases where ONU capacity requirements are not homogeneous, leading to underutilization of available bandwidth [102]. TDM is the simplest technique for sharing the optical carrier capacity, and a majority of the deployed PONs, such as the first generation of EPON and GPON use it [55]. The basic TDM-PON architecture is shown in Figure 3.8.

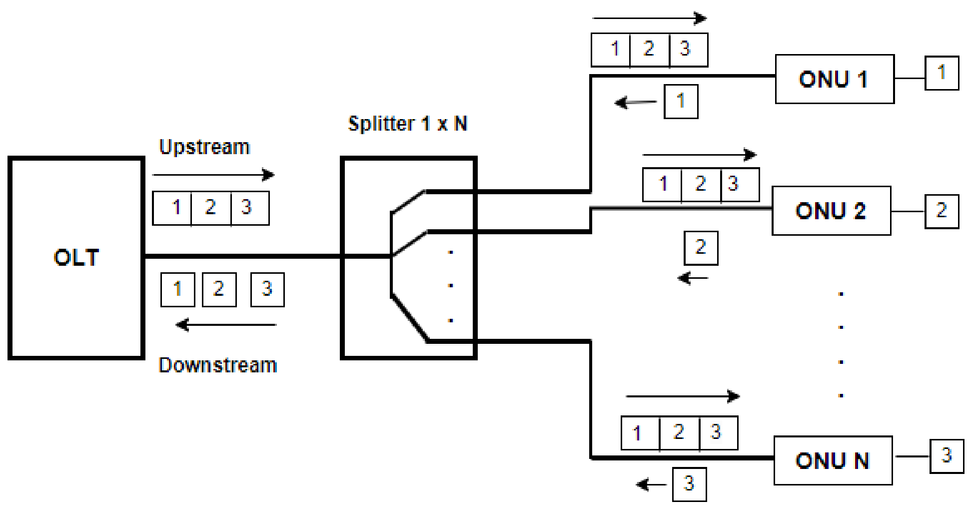

Figure 3.8: TDM-PON architecture.

TDM has been a popular choice for PONs due to its simplicity and flexibility. By dynamically allocating more time periods to signals that require more bandwidth and reducing the time periods for signals that do not require it, TDM can provide greater efficiency [103]. However, one of the main drawbacks of TDM-PON solutions is that, using only one optical carrier, they cannot fully exploit the vast bandwidth capacity of optical fibers, which may not be sufficient to meet the increasing demands for higher bandwidth from future network applications [55]. TDM operates by allocating time periods during which only one channel can transmit at a given time, which can lead to some data delay, although typically only for a few milliseconds. To address the limitations of TDM, recent PON implementations have combined it with other multiplexing techniques to form hybrid multiplexing approaches such as TDM/WDM, TDM/OCDM, and TDM/OFDM, which can achieve better performance [104].

3.5.2 Wavelength-Division Multiplexing (WDM)

WDM enables the transmission of multiple channels of data through a single optical fiber by using different wavelengths of light for each channel [101]. WDM is implemented in PONs by assigning an individual wavelength to each end user. It has the capability of delivering at higher bandwidth and lower transmission loss as compared to TDM-PON [105].

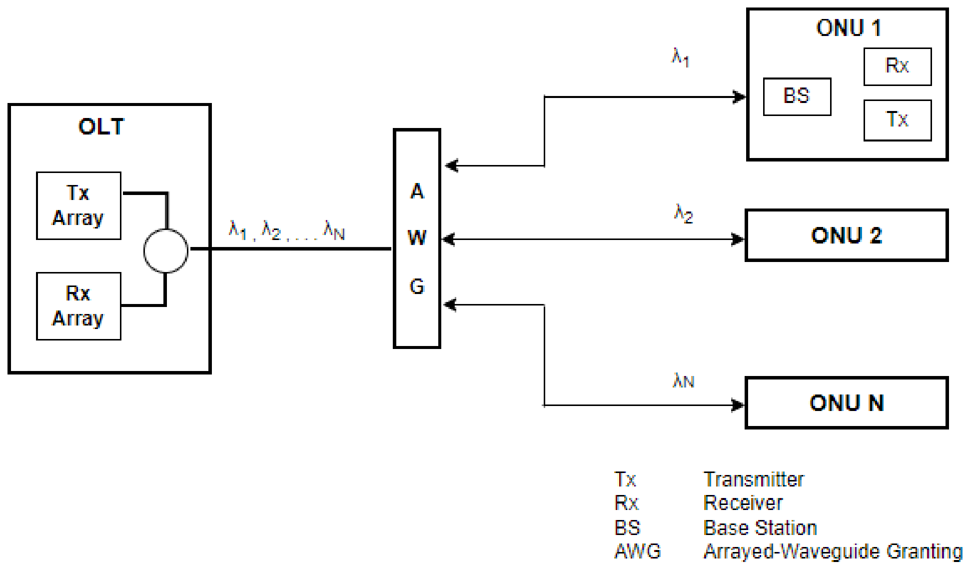

Figure 3.9: WDM-PON architecture.

As shown in Figure 3.9, in the downstream direction of the WDM-PON the wavelength channels are routed from the OLT to the ONUs by a passiveAWG router [106]. The AWG is deployed at the ODN which is where the passive splitter in a TDM-PON is normally placed [55]. As shown in the figure, data is transmitted to all ONUs by assigning a particular wavelength. A multiwavelength source at the OLT is used for transmitting multiple wavelengths to the various ONUs. In the upstream direction, the OLT employs a WDM demultiplexer along with a receiver array for receiving the upstream signals. One of the requirements of a WDM-PON is scalability in bandwidth as well as in the number of users. To satisfy this requirement, the optical devices that are needed for the architecture should not only be economically feasible but also be able to use multiple wavelengths over the same fiber infrastructure [101].

Unlike other multiplexing techniques, WDM is inherently transparent to the channel bit rate [107]. Additionally, it allows for multiple AWGs or optical filters to be employed in a single deployment, thereby increasing the number of wavelengths that can be used [108]. However, one of the drawbacks of WDM-PON is its wavelength allocation based on fixed channel intervals, making it challenging to adapt to services with different rate requirements [107]. If the bandwidth of a service is less than the capacity of one wavelength, the entire wavelength must be allocated, resulting in spectrum waste [109]. On the other hand, if the bandwidth of a service is greater than the capacity of one wavelength, multiple wavelengths must be allocated to carry this service, which also leads to unnecessary spectrum waste [79]. WDM offers better latency compared to TDM because in WDM, channels can transmit at any time [110].

3.5.3 Optical Code Division Multiplexing (OCDM)

In OCDM, multiple users use unique optical codes to send their data from the transmitter to the receiver simultaneously [111]. OCDM has some unique features that make it particularly useful in PONs, including full asynchronous transmission, low latency access, soft capacity on demand, and optical layer security [112]. There are two different approaches for the multi-user coherent OCDMA system: synchronous and asynchronous OCDMA. In the synchronous OCDMA, proper timing coordination is required to carefully avoid the overlaps between signal and interferences [112, 113]. In contrast, the asynchronous capability is essential in practical OCDMA systems. Asynchronous OCDMA systems have no specific timing requirements for users, which simplifies the system design and makes it more practical for use in PONs [112, 114].

One of the main advantages of OCDMA is its ability to achieve a higher level of security. With this technique, data is sent using unique codes assigned to each user. The receiver then uses these codes to filter out the signals, ensuring that only the intended recipient can access the information. This level of security makes it an attractive option for transmitting sensitive information such as banking transactions [111]. Finally, the capacity of OCDMA systems can be easily increased by simply adding more codes.

3.5.4 Orthogonal Frequency Division Multiplexing (OFDM)

OFDM has been identified as a strong candidate for multiplexing in PONs due to its ability to overcome the effects of fiber dispersion, provide high spectral efficiency, and enable dynamic bandwidth allocation for multiple services provisioning [115, 116]. OFDMA PON has the potential to increase the system reach and transmission rates without increasing the required cost or complexity of optoelectronic components. It provides fine granularity of bandwidth allocation, which further improves its applicability and versatility [80]. However, its implementation is not yet common as there are still many topics on OFDM-PON that require further research [116, 117]. OFDM multicarrier transmission aims to support high data rate speeds and is proposed as a solution to overcome the dispersion of single carrier transmission [118, 119]. While OFDM has many advantages, such as spectral efficiency and dynamic bandwidth allocation, its main disadvantage is the peak-to-average power ratio (PAPR), which can lead to issues related to sensitivity to phase noise and frequency offset [4, 120]. Nonetheless, the potential benefits of OFDM in PONs make it an area of active research and development.

3.5.5 Time and Wavelength Division Multiplexing (TWDM)

Hybrid multiplexing techniques have been increasingly popular over the past few decades in the development of PONs. These techniques combine multiple multiplexing technologies to take advantage of their unique benefits, leading to more efficient use of the available network capacity [121]. Among the various available multiplexing techniques, TWDM has attracted the majority of support from global vendors and has become the multiplexing technique of choice in newer PON deployments.

TWDM leverages the huge capacity provided by TDM and the large wavelengths and low latency provided by WDM [55]. Therefore, TWDM has the capability to accommodate more bandwidth than the traditional TDM and WDM, and completely eliminates unused bandwidth in PON [122]. In addition, it helps to provide improved scalability by allowing large splitting ratio of up to 1:1024, which helps in achieving lower cost and power consumption per user [44, 123]. Moreover, it inherently supports the high flexibility of resource allocation, which allows it to efficiently adapt to the varied traffic demands from the end user [4, 124].

TWDM was selected by the Full Service Access Network community as a primary solution to Next-Generation PON 2 (NG-PON2) to enable different customers and services to coexist on the same network within different wavelengths [125]. It is backward compatible with earlier ITU-T PONs such as GPON and XG-PON and allows service convergence and resource sharing [64]. With TWDM, different wavelengths can be assigned to different operators, facilitating co-investment in common infrastructure and promoting sharing of costs and risks [37, 126].

This architecture offers the advantage of increasing overall PON capacity while maintaining TDM-PON flexibility, with the ability to balance loads by moving end-users across wavelength channels [127]. Additionally, TWDM-PON enables network sharing, with possibilities such as assigning wavelengths to Other Licensed Operators (OLOs) and dynamically assigning ONUs to different OLTs for load balancing

[128]. This flexibility has also led to other ideas for network sharing, such as the multi-OLT and multi-wavelength optical access network proposed in [129], which allows ONUs to be shared among all operators. However, this solution does not support simultaneous time and wavelength allocation and, in the upstream, each service operator uses an individual wavelength [129].

In TWDM-based PON systems, the DBA algorithms are two-dimensional, considering both the time and wavelength dimensions of the network. These algorithms can be implemented in two main ways: separate-time-and-wavelength scheduling (STWS) algorithms and joint-time-and-wavelength scheduling (JTWS) algorithms. STWS algorithms handle wavelength assignment and time slot allocation independently, making them relatively straightforward to implement. However, they may not offer the same level of efficiency and scalability as JTWS algorithms. JTWS algorithms, on the other hand, integrate wavelength assignment with time slot allocation, resulting in a more efficient and scalable utilization of network resources. However, the combined approach also adds complexity to the algorithms. Overall, JTWS algorithms are more efficient and scalable compared to STWS, but they require a higher level of complexity in their implementation [59]. One key point of TWDM-PON is its use of tunable transceivers into the ONUs for switching from one wavelength to the other [37], as described in the next section.

3.6 Tunable lasers

The typical architecture of a TWDM-PON involves a tree topology, with the OLT located at the root and the ONUs positioned at the leaves. The OLT is equipped with a set of laser diodes operating at different wavelengths that serve as the laser source. The laser source is the heart of the PON, as it is responsible for transmitting and receiving data signals in the network. The wavelengths used in a TWDM-PON are typically spaced at intervals of 20nm, which allows for the transmission of up to 40 different wavelengths in both the upstream and downstream directions.

In the ODN, the splitter allows signals on all wavelengths to be distributed to all the ONUs, making it possible for all the ONUs to receive signals from the OLT on all wavelengths in the downstream direction. Consequently, the ONUs must be equipped with tunable wavelength selection devices that allow them to access all wavelengths.

The ONUs contain a tunable laser, a wavelength selection device that can correctly select the appropriate wavelength [130], and a tunable receiver [131]. The tunable transmitter allows transmission on any available wavelength in the upstream direction, while the tunable receiver receives signals on all the TWDM-PON downstream wavelengths. At the tunable receiver, is a tunable filter that can tune to any wavelength and filters out signals by allowing only the signal on the desired downstream wavelength to the receiver. An ONU that can work on any wavelength, i.e., a colorless ONU, is preferred by operators for easier network laying and maintenance [130].

Tunability has over the years gained interest from Telecom operators as the tunable lasers facilitate the statistical multiplexing of traffic from all ONUs, thus potentially yielding improved system performance. Tunable lasers enable the color-free property of ONUs, which further facilitates the simplified inventory management, reduced costs, flexibility and ease of management [15].

Class	**Laser Tuning Time**
Class 1	<10µs
Class 2	10µs to 25ms
Class 3	25ms to 1s

Table 3.1: Classes of Laser Tuning Time.

The introduction of tunable lasers to facilitate the switching of wavelengths by the ONUs introduces a delay called Laser Tuning Time [59]. The tuning time is the time delay experienced by the laser while tuning from one wavelength to another. It has become an important parameter and a key consideration for choosing tunable lasers. There are several types of tunable laser devices, which are categorized based on the speed at which they can switch from one wavelength to another [59, 126]. Three classes are defined by ITU-T [59] are slow, moderate, and fast-switching lasers as shown in Table 3.1.

The switching of lasers between wavelengths can take between a few seconds and nanoseconds. While slow lasers are considerably cheap, fast-switching lasers are very costly and energy-consuming [10], but a higher tuning speed can yield a better system performance. The authors of [132] claim that tuning times in the range of microseconds offer good network performance at data rates of 2.5 Gbps. However, the higher the tuning speed, the more sophisticated the technology is needed, and consequently, the higher the tunable laser cost [15].

3.7 Related work

Many research studies have been carried out on the DBA algorithms for TWDM-PONs, referred to as dynamic wavelength and bandwidth allocation (DWBA) algorithms. This is also known as upstream scheduling and wavelength assignment (USWA) algorithms [133]. A variety of algorithms exists that explore the problem of scheduling and wavelength assignment in TWDM-PONs [10].

The main challenge for designing a DWBA scheme is the selection criteria according to which the wavelength switching will be performed [134]. A load proportional wavelength assignment scheme has been presented for multi wavelength PON with slight variations by different authors. A comparative discussion of EPON compliant DWBA schemes is available in [7]. The main idea of all these approaches is to keep all the wavelengths initially deactivated and start activating them one by one with the increase of traffic load. This approach cannot work for ITU based TWDM-PONs as the standard requires simultaneous activation of all the wavelengths due to its synchronous nature. Moreover, the wavelength switching mechanism is performed using Physical Layer Operation Administration and Maintenance (PLOAM) messages. This requires a hand shaking process between OLT and ONU and, thus, requires tuning time for the tuning of ONU laser transceiver to the desired wavelength.

Most of the available DWBAs are mainly focused on the assignment and scheduling of multi-wavelengths and bandwidth allocation, while ignoring the tuning and switching time of lasers at the ONUs. These algorithms, however, allow unlimited switching of wavelengths. Earliest finish last transmission time (EFT) algorithm for example, does not take into account the tuning and the switching time of lasers (and receivers) at the ONUs, leading them to changing wavelengths more frequently [10]. Therefore, wavelength switching will increase the guard bands due to the tuning and the switching time of components, thereby limiting channel utilization and increasing packet delays.

Some research works have identified the effect of laser tuning time on the performance of DWBA. The work of [18] concludes that while laser tuning time will degrade the performance of an EFT-based DWBA, it can efficiently exploit the bandwidth in presence of very different propagation delays within the same network [135]. In the same vein, the work of [15] focuses on investigating the effect of laser tuning (wavelength switching) time on DBA algorithms, and consequently the system performance.

Laser tuning time constitutes an important consideration factor in designing DBA algorithms. When the laser tuning time is infinity, lasers have to stay on the same wavelengths all the time, and requests from

ONUs can only be scheduled on the wavelengths their respective corresponding lasers stay [16]. No statistical gain can be exploited among ONUs that can support different wavelengths. When the laser tuning time is zero, requests can be scheduled on any wavelength at any time [23]. When the laser tuning time is different than zero, proper DBA algorithms are desired to exploit the statistical gain among requests to the best under the condition that lasers are given enough time to switch wavelengths [15].

The work of [136] is on equipping each ONU with a tunable laser to facilitate a fully flexible dynamic bandwidth allocation in the upstream direction [137]. An architecture that equips ONUs with tunable lasers with the focus on the laser tuning range was described in [138]. The impact of Laser tuning range, an important parameter of tunable lasers, was investigated on the network capacity. They designed WDM PONs by selecting lasers with proper tuning ranges to minimize the capital investment of the PON. Consequently, earliest finish last transmission time - optimal switching (EFT-OS) algorithm which extends the EFT algorithm to switch wavelengths optimally considering the switching and tuning time of laser was proposed. EFT-OS adapts the wavelength switching to the laser tuning times, and thus obtains high performance [10].

3.8 Summary

In this chapter, we have delved into the intricacies of resource allocation in Passive Optical Networks, which are crucial for delivering high-speed broadband services. We presented various bandwidth allocation techniques and wavelength allocation techniques, and we categorized and discussed each technique in detail.

We also explored the communication protocols used in IEEE PONs, with a particular focus on the MCPC protocol that is exchanged between the OLT and ONUs. Moreover, we discussed multiplexing techniques used in PONs, including the hybrid multiplexing technique that combines the strengths of two multiplexing techniques. We introduced tunable devices used in multi-wavelength PONs and the associated laser tuning time delay incurred while changing from one wavelength to another.

Lastly, we provided insights into the state of the art of resource allocation in PONs. Resource allocation techniques are evolving to meet the increasing demands of high-speed broadband services, and new approaches are being developed to ensure efficient resource utilization.

In the next chapter, we will focus on our contributions to the field of resource allocation in PONs. We will present our proposed techniques, protocols, and algorithms that can enhance the efficiency of resource allocation in PONs and improve the quality of service for end-users. Our contributions will build upon the foundation established in this chapter, leveraging existing techniques and protocols while introducing new approaches to address the challenges facing resource allocation in PONs.

Chapter 4
An LTT-aware DBA for TWDM-PONs based on LPT

4.1 Introduction

This chapter describes a first contribution on PON DBAs, where the author of this thesis actively participated alongside another researcher, Mohammad Zehri, who was the first author. Our shared goal is to address the challenge of optimizing available bandwidth to meet the increasing demand for fast, low-latency communication. We achieve this by developing DBA algorithms based on TWDM-PON technology to optimize bandwidth utilization and reduce delays, based on the LPT scheduling discipline, and laser-tuning-time concept [16, 23]. Subsequent chapters will delve into further work on DBAs for LRPON, building upon this research to advance the field.

Our DBA builds upon our previous work in [139] primarily rooted in IEEE standards. Considering the advancements in ITU-T standards, including multiwavelength and laser tuning time introduced in NG-PON2, we have extended our work to accommodate these features for emerging standards like IEEE 802.3cs (Super-PON).

TWDM-based PONs introduce a two-dimensional resource allocation process, comprising wavelength and time slot allocation in the upstream link. Managing multiple wavelengths during operation poses challenges for TWDM-PON media control. The use of tunable transceivers in ONUs introduces complexities and inefficiencies, including laser tuning time delays arising from coordinating wavelength changes among ONUs [130]. Therefore, effective management of bandwidth allocation and wavelength assignments, including ONU switching, is crucial. We consider laser tuning time as a critical element in the evaluation.

In this chapter, we start by explaining essential elements of the DBA, including grant sizing and scheduling. We then introduce LPT scheduling into the DBA to reduce queue delay, and delve into our specific DBA implementation in TWDM PONs. We conclude this chapter by evaluating and presenting the results obtained from extensive simulations.

4.2 Grant Sizing and Grant Scheduling Subproblems in Resource Management

Our resource management and allocation mechanism is a multi-channel process for managing and allocating resources, consisting of two subproblems: grant sizing and grant scheduling. The grant sizing problem involves determining the length of the transmission window assigned to each ONU per polling cycle, while the grant scheduling problem involves determining the order in which ONUs receive their grants during a given cycle [44]. The grants are sized according to various existing techniques in the DBA, and we use a multi-layered approach to tackle the grant scheduling aspect of the DBA process for multi-channel passive optical networks.

4.2.1 Grant Sizing

The DBA system relies on the REPORT messages sent by EPON ONUs to track the current status of each device. These messages are attached to the back of each transmission grant and include information about the current size of the device's buffer, or queue, in bytes. The size of the queue is affected by the rate at which new data frames arrive and are added to the queue for later transmission as upstream traffic. The OLT can use the information provided by the ONUs in their REPORT messages to improve the efficiency of the network's bandwidth usage [140]. This includes using an adaptive algorithm to determine the size and scheduling of transmission grants based on the current status and arrival rate of data frames in the ONUs' buffers. Therefore, the ONUs transmit their queue content, which consists of new data packets, over one or multiple wavelengths, depending on the grant size.

The grant size is the main parameter that determines the ONU cycle time, which in turn affects the number of new packet arrivals that will be granted transmission in the next cycle [141]. A longer cycle time means a larger queue size and vice versa. In one cycle time, all ONUs transmit their requested queued packets over several wavelengths using TWDM. The time slot for each ONU on a given wavelength is proportional to the allocated bandwidth on that wavelength. At the end of the cycle, all ONUs report the size of their queue, which includes new packet arrivals, to be scheduled and transmitted in the next cycle time. The grants are scheduled with regards to the corresponding round-trip times and granted window sizes. As a result, the order of grants may be different in every cycle [91].

4.2.2 Grant Scheduling

Grant scheduling in TWDM-PON is a problem similar to the scheduling of computational tasks in a multiprocessor environment with identical processors acting in parallel. The bandwidth allocation problem in TWDM-PONs is modeled into a multiprocessor scheduling problem by mapping ONUs' requests as jobs and wavelength channels as machines [142]. Jobs and machines in this particular problem have their own unique characteristics, with the assumption that data rates are the same on all wavelengths. Scheduling theory aims to efficiently schedule a set of jobs with specific processing times on a set of machines according to an optimization criterion. Although the wavelength channels are modeled as parallel machines, they may not be available at the same time [15].

To solve the bandwidth allocation problem in a single DBA cycle, a schedule of the minimum length that allows all requests to be fulfilled while also giving lasers enough time to switch wavelengths is created. This process considers the laser tuning time, requests from n ONUs, the available time of m wavelength channels, and the wavelength initially tuned by each laser. Each ONU can be viewed as representing a job, its grant size as defining its processing time, and the channels used for transmission on the PON as representing the machines whereby the jobs have to be scheduled on available machines. We propose solution techniques for this model that result in a set of possible scheduling policies for producing a schedule given a set of ONU grants.

We model the grant scheduling in our DBA implementation following a layered approach introduced as proposed in [143] that divides the problem of scheduling into two layers to address the issues surrounding when and how the OLT performs DBA, respectively. The first layer is called the scheduling framework, and the second layer is referred to as the scheduling policy. The scheduling framework is the system that determines when the OLT should make scheduling decisions, while the scheduling policy is the strategy that the OLT uses to create the schedule.

The OLT has the option of either creating a schedule using partial information about the ONU transmissions that need to be scheduled or waiting to receive all the information about the ONU transmissions before creating the schedule [34]. The scheduling policy is used by the OLT to create a schedule once it has received a set of transmission requests from ONUs.

The scheduling framework determines when the OLT makes scheduling decisions and affects the delay between receiving a grant request and scheduling the next grant for an ONU (REPORT-to-Schedule, (RTS))

[15] as depicted in Figure 4.1. On the other hand, the scheduling policy determines the timing of when an ONU's grant is transmitted on a channel, which impacts the Schedule-To-GRANT delay. Therefore, scheduling framework provides a technique for determining when the OLT produces a schedule, thereby resulting in a set of possible scheduling policies for producing a schedule given a set of ONU grants.

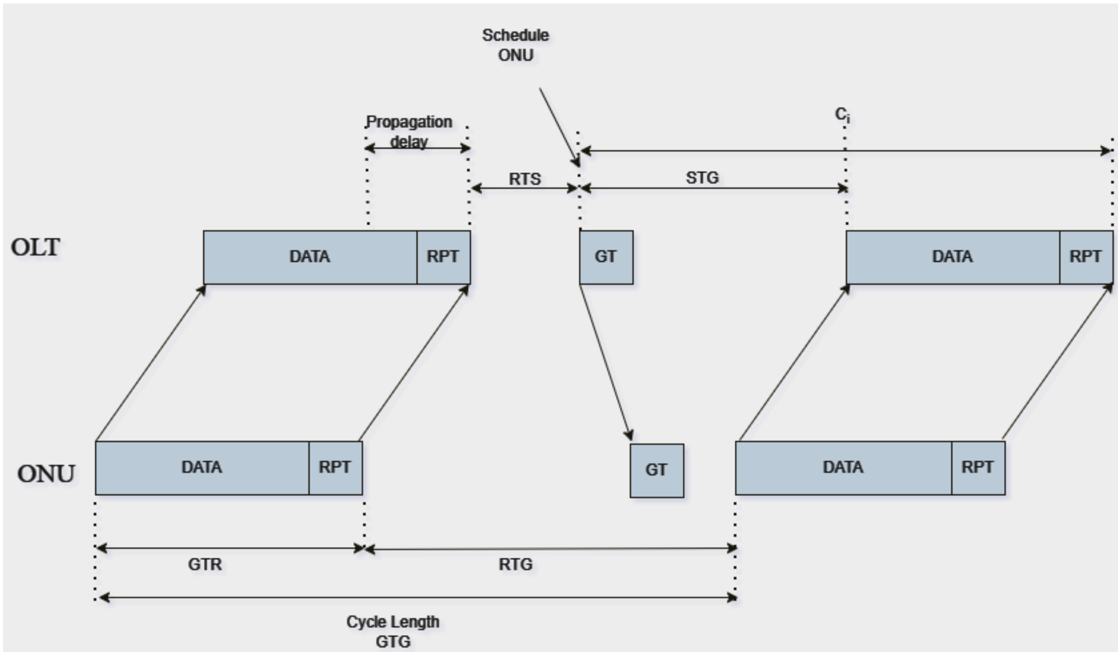

Figure 4.1: Illustration of various delays of a scheduling cycle.

The scheduling frameworks can be categorized into three categories, based on the level of control the DBA has on the system: online scheduling, offline scheduling, and just-in-time scheduling [143]. Online scheduling refers to the operation where OLT determines the bandwidth allocation to an ONU immediately after receiving the ONU's request. Offline scheduling refers to the operation that the DBA is performed by the OLT after receiving queue requests from all ONUs. The choice of scheduling framework depends on the level of control that is needed by the scheduler, as both online scheduling and offline scheduling have their own benefits and drawbacks.

Online scheduling enables ONUs to get immediate grants as the dynamic bandwidth allocation is activated as soon as request from an ONU is received by the OLT. However, the system may result in unfairness for other ONUs with upcoming requests because the bandwidth allocation decision is made based on only one ONU's request [144]. This is the scheduling framework that is at the far end of the online side of the scheduling framework continuum depicted in Figure 4.2. This scheduling approach avoids wasted channel capacity by not keeping any channels idle while there is an ONU grant request message for the OLT to act on.

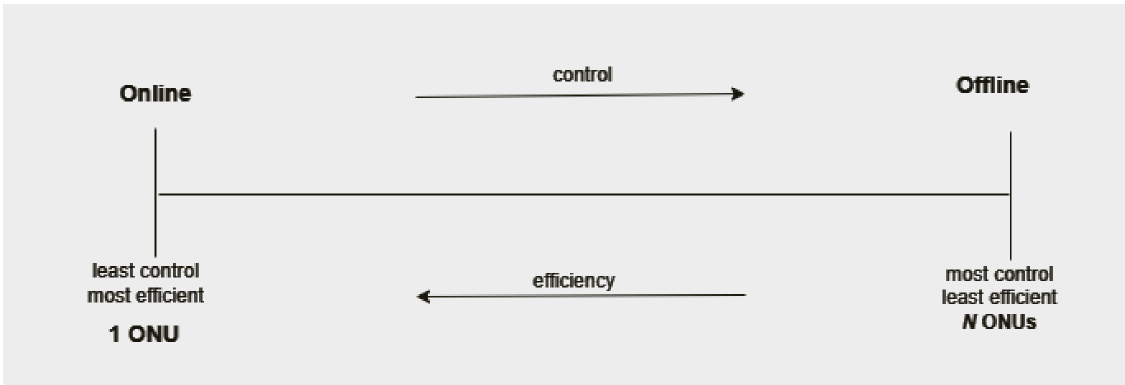

Figure 4.2: Scheduling Framework Spectrum (N: number of ONUs).

In an offline scheduling framework, the OLT receives request messages from all ONUs in a multi-channel PON before making scheduling decisions [145]. This allows the OLT to consider the current bandwidth needs of all ONUs while determining the size and timing of grants for transmission. The scheduling process begins after the OLT receives the end of the last ONU's gated transmission window. The scheduling pool consists of all ONUs, allowing the OLT to take a comprehensive approach to scheduling. The REPORT-to-Schedule (RTS) delay for the last ONU will be minimal, but the RTS delay may not be insignificant for the other ONUs. This RTS delay can cause additional queueing delays in the ONUs because it increases the cycle length, GATE-to-GATE (GTG, time between back-to-back grants) delay which also includes the propagation delay (the delay between the ONU and OLT) for an ONU [143]. Waiting for all ONU's grant request messages to be received can result in unused capacity on the channels. The amount of unused capacity increases with the number of channels.

To address the limitations of both online and offline scheduling for multi-channel PONs, the authors of [143] proposed a Just-In-Time scheduling solution. This approach involves the OLT delaying its decision-making until one channel is about to become idle, in order to balance the immediacy of online scheduling with the efficiency of offline scheduling [15]. Just in time scheduling is a hybrid approach that combines the benefits of online and offline scheduling. It can help to minimize the wasted channel capacity of offline scheduling while also avoiding the near-sightedness of online scheduling. It allows the OLT to make scheduling decisions at a time that is later than in online scheduling, but earlier than in offline scheduling. This results in better utilization of channel capacity and reduced queue delays for the ONUs.

4.3 Scheduling Policy

The scheduling policy in a multi-channel PON is responsible for determining how DBA should be performed. This policy is implemented after the OLT has received the end of the last ONU's gated transmission window. While the request-to-send (RTS) delay for the last ONU may be small and negligible, it may be significant for other ONUs [143]. This RTS delay can cause additional queueing delays for the ONUs, as it increases the cycle length (GTG) for an ONU. When the OLT waits for all ONU GRANT requests to be received, it can result in wasted channel capacity, which increases as the number of channels increases [16].

In a multi-wavelength PON environment, the dynamic bandwidth allocation involves both wavelength assignment and time allocation. A commonly proposed approach for wavelength assignment is the earliest-channel-available-first rule, which assumes that each ONU can support all wavelengths [79]. This scheduling model has been suggested as a useful way to find the best scheduling policy for a multi-wavelength PON that supports the evolution from single-channel PONs to multi-channel PONs. Once the OLT has identified which ONU grants need to be scheduled, it uses a specific scheduling policy to determine the order in which they should be transmitted. We have chosen to use a modified version of the earliest-channel-available-first rule, called Next Available Supported Channel (NASC) [146].

The NASC scheduling policy is designed for use in multi-channel PONs. It allows ONUs to be scheduled for upstream transmission on the wavelength channel that is available earliest among the channels that the ONU supports. Channel availability is determined using the "horizon approach," in which each channel is considered busy until the end of the last scheduled reservation [17].

4.4 LPT and Job Scheduling

One of the goals of scheduling is to minimize the completion time of the latest jobs and equalize the usage of the channels in the network. This is because it is assumed that the wavelengths are not loaded equally, and ONUs assigned to a heavily loaded wavelength may experience longer waiting times compared to those using other wavelengths. To address this, the ONUs are scheduled on the wavelengths as soon as they become available, following the NASC policy [146]. When all wavelengths become idle at the same time, requests from most of the ONUs are collected and scheduled by the scheduler, ensuring fairness among the ONUs. However, if one wavelength becomes idle much earlier than the others, only a few requests will arrive at the scheduler before the decision-making time, leading to unfairness and an increase in the frequency of calculating bandwidth allocation. To reduce delays, ensure fairness, and enforce load balancing, we consider minimizing the latest job completion time as the scheduling objective. To achieve this, we introduce the concept of scheduling algorithms [147].

One of the fundamental problems in scheduling is the non-preemptive assignment of n independent jobs (tasks) to $m \geq 2$ parallel machines (processors) in order to minimize the schedule makespan, i.e., the overall completion time [148]. This problem is NP-hard [149]. A variety of heuristics and approximation algorithms have been proposed to tackle it. One such heuristic is list scheduling (LS), which puts the jobs in a priority list and assigns the first job in the remaining list to the first available machine [150]. List scheduling (LS) is a greedy algorithm used for scheduling identical-machines. It takes as input a list of jobs that need to be performed on a set of m machines. The list is arranged in a specific order, such as by priority or by order of arrival. The algorithm has a running time of complexity of order (O(n)), where n is the number of jobs. The algorithm always returns a set of jobs whose makespan is at most α times the optimal makespan, where α is a constant factor dependent on the algorithm. This is because the length of the longest job and the average length of all jobs provide lower bounds for the optimal makespan. The algorithm can also be used as an online algorithm when the order of arrival of items cannot be controlled. It has been shown that LS has a worst-case performance ratio of $2-1/m$, where the worst-case performance ratio of a heuristic H is the infimum of all those ρ such that, for any problem instance, the makespan of the schedule generated by H is no more than ρ times the minimum one [151].

In the context of multi-channel PONs, [146] proposed the use of the longest-processing-time-first (LPT) rule to minimize the makespan in the case where ONUs can access all wavelengths. LPT is a derivative of LS that prioritizes jobs according to their non-increasing processing times. It has been successfully applied to various scheduling environments and is known for its good balance between efficiency and effectiveness as a heuristic. The LPT algorithm works by sorting the ONUs' bandwidth requests in descending order, with the largest request being processed first. This helps to minimize the frame makespan and reduce delays, while also ensuring fair allocation of resources through the use of the bin-packing method, where items of varying sizes are packed into containers (bins) to minimize unused space similar to the MULTIFIT algorithm used in IPACT [15]. Overall, the use of the LPT algorithm in DBA can help to improve the performance of multi-channel PONs and ensure fair resource allocation among ONUs.

The choice of LPT scheduling algorithm is majorly due to its simplicity to solve the problem of scheduling the requests on multiple wavelengths to achieve minimal makespan of the requests' processing [146]. LPT is a greedy algorithm for job scheduling that is based on a sequencing rule that prioritizes jobs to be scheduled according to an order of their non-increasing times. The LPT principle works by first sorting the requests in order of increasing processing time, with the longest processing time requests placed at the front of the queue. This is based on the assumption that longer processing time requests are likely to be more resource-intensive and will therefore require more bandwidth to complete. By giving these requests priority in the scheduling process, we are able to ensure that they are able to make use of the available bandwidth as efficiently as possible. The requests are then scheduled on the available wavelengths in this order, with the longest processing time requests being given priority.

By minimizing the makespan, LPT is able to reduce the overall delay, and thus it has been successfully applied to various scheduling environments in delivering a near minimum-makespan schedule, such as in multi-stage scheduling with parallel machines, where each job has to be processed in some stages at different time periods and each stage consists of a number of parallel machines [152].

We integrated our LPT approach with the IPACT DBA. With LPT, ONU requests during a cycle i are sorted based on the time required for processing, $J_1(i), J_2(i) \ldots J_M(i)$, with the longest time request being processed first and the shortest being processed last, such that $L_r(i) \geq L_s(i) \geq \ldots \geq L_{m,}(i)$ being r, s, and $m \leq M$. The advantage of LPT is that it schedules loads on the wavelengths almost equally, preventing situations where some wavelengths are idle. The approximation ratio of the upper limit of LPT, Cmax(LPT), to Cmax(OPT), $\frac{C_{max}(LPT)}{C_{max}(OPT)}$ is shown in (1), where $C_{max}(LPT)$ represents the maximum makespan of the LPT heuristic, $C_{max}(OPT)$ represents the maximum makespan of an optimal scheduler and M is the total number of tasks or jobs in a given scheduling cycle [153].

$$\frac{C_{max}\ (LPT)}{C_{max}(OPT)} \leq \frac{4}{3} - \frac{1}{3M} \qquad (1)$$

At the start of each cycle, the number of connected ONUs with non-empty queues is determined by the algorithm. The reported jobs from these connected ONUs (J_m) are then sorted in descending order based on their lengths. The ONUs are assigned to the available wavelengths ω based on the following criteria: ONU m with job $J_m(i)$ having the longest processing time $L_m(i)$ is scheduled first, followed by the next ONU assigned to the minimally loaded channel. If the sum of the processing times of all ONUs $\sum_0^M L_m$ is less than or equal to the maximum time δ_{max}, then the requested time is granted for the connected ONUs in cycle (i). Otherwise, δ_{max} is granted, and some jobs with lower processing times have to wait for cycle $(i + 1)$.

4.5 Description of the DBA

4.5.1 Introduction to the Algorithm and List of Parameters

Our work builds on the original IPACT dynamic bandwidth allocation algorithms, which were first introduced in [91]. The IPACT algorithm has an adaptive cycle time feature, which allows it to adjust the length of the polling cycles based on the workload of the system [84]. During network congestion, cycle time increases to provide ONUs more transmission time, while it decreases during non-congestion to reduce delay. Real-time adaptation to changing traffic conditions ensures system efficiency and responsiveness to varying workloads. Additionally, IPACT prioritizes fairness, distributing available bandwidth equally among ONUs to prevent resource monopolization and ensure all users have necessary access.

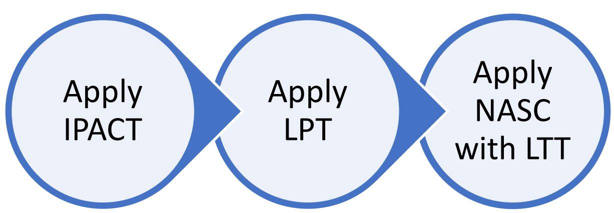

Figure 4.3: Complete sequence of the algorithm.

In our enhanced IPACT algorithm, designed to support multiple wavelengths in a TWDM-PON system [139], optimal scheduling of ONUs' requests on the four wavelengths becomes a key concern [16]. To achieve optimal performance and utilize available bandwidth effectively, factors such as traffic conditions on each wavelength, link utilization, and QoS guarantees are carefully considered.

The introduction of the LPT scheme optimizes delay in the TWDM-PON system, delivering high-quality service. Time slot allocation and wavelength assignment procedures follow the Joint Time and Wavelength Scheduling (JTWS) scheme from [10]. In addition to JTWS, our algorithm adopts the NASC scheduling policy [143]. NASC ensures ONUs are assigned to the next available wavelength where their requests will be processed. To further optimize performance, the LPT scheme arranges ONUs' requests in descending order before scheduling on assigned wavelengths.

Parameter	**Description**
M	Number of ONUs
ω	Assigned wavelength, $0 \leq \omega \leq 3$
i	Cycle number i, $0 < i < \infty$
$J_m(i)$	The job requested by ONU m at cycle i, $1< m <M$
$L_m(i)$	Length of job $J_m(i)$ requested by ONU m at cycle i
τ	Laser tuning time
ω_i	The wavelength assigned for ONU m during cycle i
$\theta(\omega, i)$	Waiting time for a job $J_m(i)$ on a wavelength ω during cycle i
δ_{max}	Maximum allowed cycle length in bytes or windows in a cycle
φ_ω	The completion time of the last job on wavelength ω
k	Counter of the number of non-empty connected ONUs

Table 4.1: Parameters of the LTT-aware QoS based algorithms for TWDM PON.

Choosing NASC aligns with Just-in-Time and LPT principles, assigning a free wavelength to the longest job not yet assigned when available [154]. This ensures efficient resource use and faster job completion. Following the Just-in-Time principle allows the algorithm to adapt to changing network conditions and adjust bandwidth allocation in real-time, enhancing network efficiency [16]. Figure 4.3 illustrates the steps in the application of our algorithm, and Table 4.1 includes a list of parameters that will appear in the description of the algorithm in the following subsections.

4.5.2 LPT Algorithm

What follows is the pseudocode, *Pseudocode 4.1* of the LPT Heuristic Non-Preemptive Scheduler.

// Initialize k before counting connected ONUs

k = 0;

// Loop through all ONUs to find connected ones with non-empty queues

for *m = 1:M*

  if *(ONU_m is connected && Queue $\neq 0$)*

    Consider ONU;

    k = Connected_ONUs++; // Increment k for each connected ONU

  end if

end for

//after this point k will be the number of connected ONUs

for *m = 1: k*

  //sort J_m in descending order based on their length;

  $L_r \geq L_s \geq L_t \geq \cdots \geq L_m$

  // If the summation of requests is greater than the maximum allowed window, jobs with excess lengths are dropped and granted in the next cycle before sorting new jobs

end for

if *($\sum_0^k L_m \geq \delta_{max}$)*

    δ_{max} is granted in cycle i;J_m that are not assigned will be processed first in cycle $i+1$

  //Jobs that are not assigned will be processed in the next cycle

  Process remaining jobs in cycle i+1

end if

Pseudocode 4.1: LPT algorithm executed at the OLT for each cycle i.

The algorithm begins by acknowledging the number of connected ONUs that have non-empty queues. This is an important step as it allows the algorithm to understand the number of ONUs that need to be serviced in the current cycle. Once the number of connected ONUs with non-empty queues is known, the algorithm then sorts the jobs reported by these ONUs based on their lengths. This is done in descending order, with the job that has the longest processing time being listed first. This ordering ensures that the jobs with the longest processing times are given priority, which results in more efficient use of resources and faster completion of jobs. The next step in the algorithm is to assign the ONUs to the respective available wavelengths. This is done in such a way that the ONU with the longest processing time is processed first, and the next one is assigned to the channel with the least load. This ensures that the most critical jobs are processed as soon as possible.

Once the ONUs have been assigned to the respective wavelengths, the algorithm then checks if the sum of the processing times of all connected ONUs is less than or equal to the maximum time δ_{max}. If this is the case, the requested time is granted for the connected ONUs in the current cycle(i). However, if the sum of the processing times exceeds the maximum time δ_{max}, then the maximum time δ_{max} is granted, and certain jobs with shorter lengths have to wait for the next cycle ($i + 1$).

Our algorithms also take into account the Laser Tuning Time when deciding whether or not to switch to a new wavelength [59, 155]. The channel is considered busy until the end of the last scheduled reservation, and the OLT checks the time needed for a wavelength to become free before deciding to switch to a new wavelength. The pseudocode of the Wavelength Assignment-NASC with LTT presented is presented in *Pseudocode 4.2.*

The algorithm guarantees fairness in the sharing of resources among ONUs, and by considering the LTT, it also ensures efficient utilization of the available wavelengths [23]. When the OLT assigns a new wavelength to an ONU, it compares the newly assigned wavelength with the wavelength that the ONU is currently tuned to. If the newly assigned wavelength is the same as the current wavelength, then no LTT is added. However, if the newly assigned wavelength is different from the current wavelength, the ONU checks the time required for its current wavelength to become free and adds the LTT to it. This process happens continuously whenever GATE and REPORT messages are exchanged during the lifetime of the communication between the OLT and the ONUs.

//If the wavelengths in the present and previous cycle are the same, then there is no laser tuning time added

if $(\omega_i = \omega_{i-1})$

No tuning

τ *is not considered*

queue_delay += $\theta(\omega, i)$

end if

//if the wavelength in the present cycle is different from the wavelength in the previous cycle, then the laser tuning time is compared with the waiting time on the current wavelength for the current job to finish processing.

else

if$(\omega_i \neq \omega_{i-1})$

// if the tuning time τ *is greater than the waiting time on the current wavelength, then no tuning takes place and the waiting time* $\theta(\omega, i-1)$ *is added to delay calculations*

if ($\boldsymbol{\tau} \geq \theta(\omega, i-1)$***)***

No tuning

τ *is not considered*

$(\omega_i = \omega_{i-1})$

queue_delay += $\theta(\omega, i)$

end if

else

//else the tuning time is smaller, then tuning occurs and LTT is added to the delay calculations

//Laser tunes

τ *is considered*

queue_delay += τ

end else

end else

Pseudocode 4.2: Wavelength assignment using NASC and LTT executed at the OLT for each cycle i.

4.6 Evaluation Methodology

To evaluate the effectiveness of the DBA algorithms, extensive simulations were conducted using a simulation network model developed with OPNET Modeler [156]. This model allowed for the examination of the algorithms' behavior under various network conditions, including different traffic loads and varying numbers of ONUs. We first describe how we evaluate the metrics, namely throughput and queue delay, followed by the description of the simulation scenarios.

4.6.1 Definition of Metrics

In our simulations we evaluate throughput and queue delay. Throughput is calculated by taking the total number of bits that are successfully transmitted by the ONUs, including the Ethernet header (for both destination and source addresses) and trailer (frame check sequence), and dividing it by the time it takes to transmit those bits.

In a PON system, the end-to-end delay is measured as the time it takes for a packet of data to travel from the ONUs to the OLT. It includes several components, such as the time it takes for the packet to be processed by the ONU, and the propagation delay caused by the physical distance the packet travels, among other factors. One of the most important components of delay in a PON system is the ONUs' queue delay, i.e., the time a packet spends waiting in a buffer at the ONU before it is processed and transmitted. It is a variable component of delay, which means it can change based on network conditions and traffic patterns. This is particularly important because it provides insight into how well the network is handling traffic loads. Our simulations measure the delay from the time a packet enters the transmitter channel queue at the ONU to the time the last bit of the packet is transmitted.

4.6.2 Simulation Scenarios

The setup consists of multiple customer premises-based ONUs a centralized OLT and an ODN that emulates a passive optical splitter/combiner that splits the optical fiber cable running from the OLT to the ONUs. To assess the impact of the number of ONUs in the PON system on our algorithms, we have created three different scenarios with 8, 16, and 64 ONUs randomly distributed between 18 and 20 km from the OLT, that we will call Scenario 8, 16a and 64, respectively. A fourth scenario with 16 ONUs is added in order to evaluate the influence of the relative distance between the ONUs: Scenario 16b, where the 16 ONUs are located within 2 km and 20 km from the OLT, also randomly distributed.

In the downstream communication, the OLT sends data to all ONUs, and each ONU filters the data sent to it and discards the rest. The upstream channel has a total capacity of 4 Gbps across four wavelengths, each with a rate of 1 Gbps, managed dynamically by the DBA. All ONUs are connected to their respective traffic sources and equipped with a packet generator with a 1 Gbps link to prevent any bottlenecks. The maximum cycle time (δmax) is 1 ms, and the sources generate self-similar traffic [157] with a Hurst parameter H of 0.75 and an adjusted mean packet rate based on the varying offered load. The frame size follows a uniform distribution with a minimum of 512 bits and a maximum of 12,144 bits, representing Ethernet traffic in a realistic manner.

Multiple scenarios are created to evaluate the effect of the algorithms for LPT scheduling, and laser tuning time. A specified percentage of the system's total bandwidth capacity is allocated as a guaranteed weight to some ONUs, giving them different QoS. A laser tuning time of 10 µs is selected, based on the ITU-T G.989.2 specifications class 2 devices [59]. The traffic load varies from 5% to 100% of the total load, with a maximum global offered load of 4 Gbps. The simulated algorithm sets are categorized as IPACT and LPT, depending on the configuration:

- Set 1: IPACT with four wavelengths and laser tuning time (LTT) of 0 and 10 µs.
- Set 2: LPT over IPACT with four wavelengths and laser tuning time (LTT) of 0 and 10 µs.

In our simulations, we aim to determine the impact of the IPACT and LPT algorithms on the system. Both algorithms are used to facilitate communication between the ONUs and the OLT, with the ONUs being assigned an equal share of the total bandwidth and communication occurring through four different wavelengths. In order to evaluate the performance of our new DBA algorithm (LPT), we focus on two metrics, throughput and queue delay, as defined in Section 4.7.1. To assess the performance of the DBA algorithm relative to another algorithm, we implemented an extended version of IPACT specifically tailored for four-wavelength operation and compared it head-to-head with DBA.

4.7 Results

In the following section, we present the results of our simulations and provide a comprehensive discussion on each metric.

4.7.1 Throughput

We first wanted to check that the introduction of LPT does not affect the total throughout. We started with scenario 16a. The results for IPACT and LPT transmitting on all four wavelengths for all ONUs with no LTT are presented in Figure 4.4 (left). In this scenario, all ONUs are given an equal share of the system's bandwidth, which amounts to 250 Mbps for each ONU. The results show that both IPACT and LPT perform similarly, as they both transmit an equal amount of throughput up to 220 Mbps before reaching saturation at an offered load of 210 Mbps. We conclude that the introduction of LPT scheduling has no significant impact on the performance of IPACT in terms of throughput.

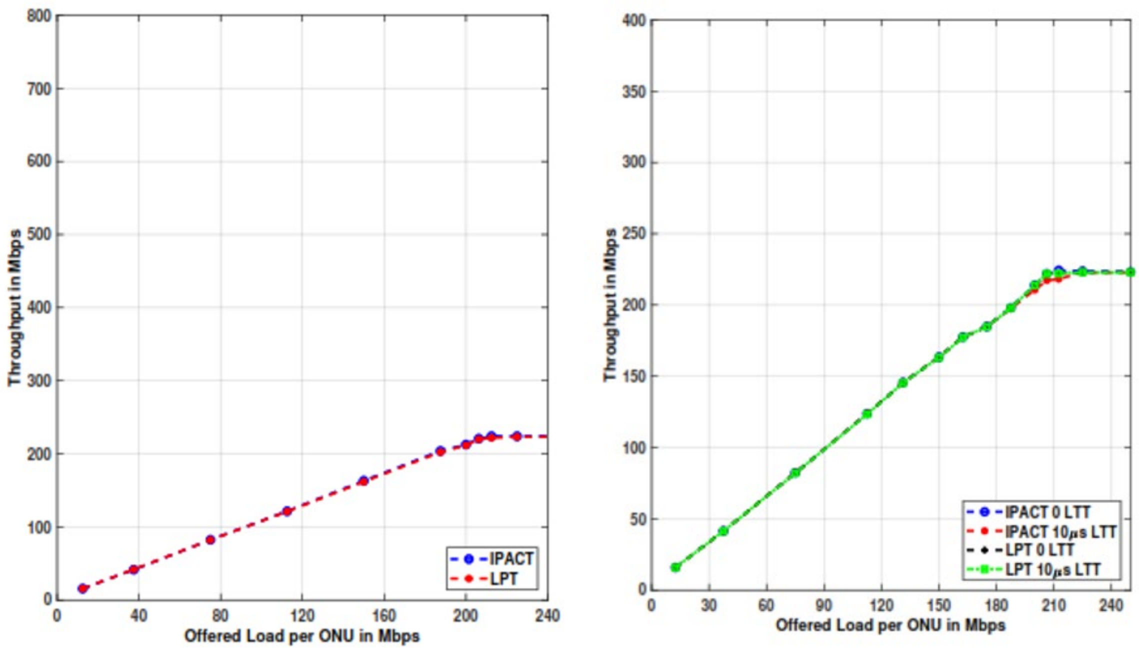

Figure 4.4: Left: Average throughput for the 16 ONUs with LTT = 0 μs in scenario 16a, IPACT vs. LPT. Right: Throughput for ONU 1 with LTT = 0 μs and 10 μs, scenario 16a, IPACT and LPT.

In order to evaluate the impact of LTT on our algorithms, we present the results in Figure 4.4 (right). This figure compares the performance of the IPACT and LPT algorithms for a single ONU (ONU1) under two different LTT scenarios: LTT = 0 μs and LTT = 10 μs. All ONUs in the system have an equal allocation of 250 Mbps of the total bandwidth, and they transmit on all four wavelengths. The results indicate that there is no significant difference in the throughput of IPACT and LPT under the two different LTTs. Both algorithms exhibit a maximum throughput of 225 Mbps, regardless of the laser tuning time. These results suggest that LTT does not have a significant impact on the throughput when the ONUs have an equal allocation of resources.

We also wanted to check the influence of the number of ONUs. In Figure 4.5, the results of the comparison between the performance of the PON system with different numbers of ONUs are presented. The results for the LPT and IPACT algorithms are shown for 8 ONUs and 16 ONUs with LTT = 10 µs.

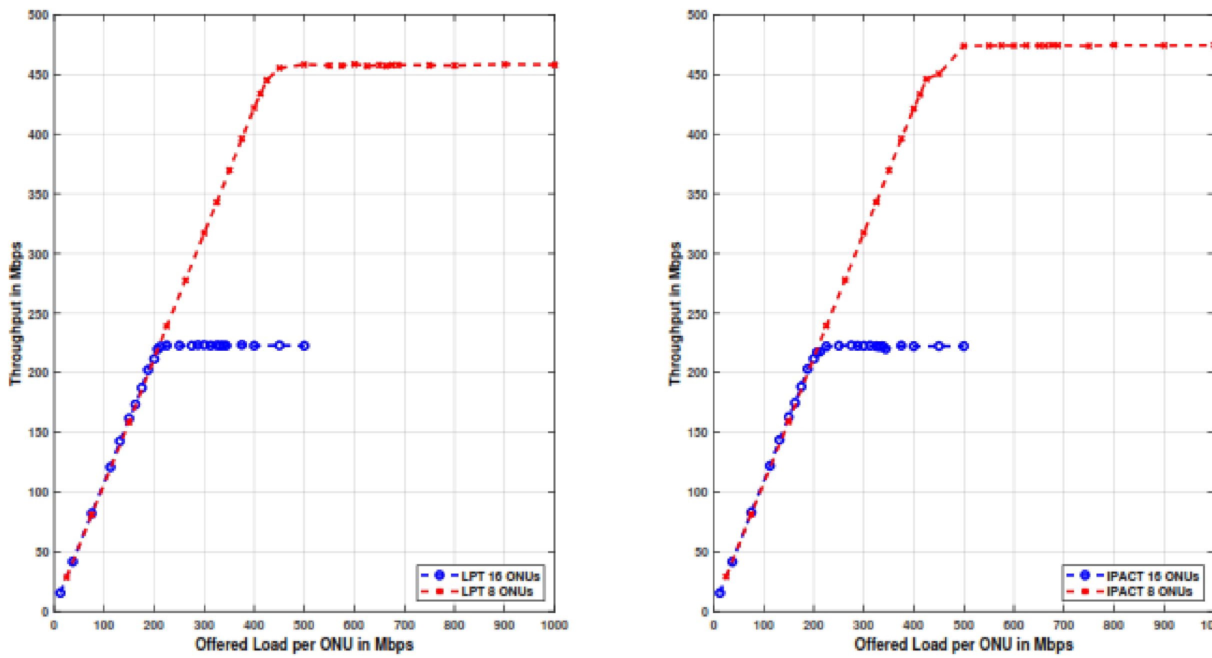

Figure 4.5: Average throughput of the ONUs with LTT = 10 µs in the scenarios with 16 ONUs and 8 ONUs; LPT (left) and IPACT (right).

The left plot of Figure 4.5 demonstrates that the throughput under the LPT algorithm reaches 465 Mbps in the 8-ONU system and 225 Mbps in the 16-ONU system. Similarly, the right plot of Figure 4.5 shows that the throughput reaches 465 Mbps with 8 ONUs and 225 Mbps with 16 ONUs under the IPACT algorithm. The results indicate a proportional increase in throughput from 225 Mbps to 465 Mbps when the number of ONUs decreases from 16 to 8. These results suggest that the number of ONUs in the PON system does not have a significant impact on the behavior of LPT and IPACT.

To examine the impact of the distance between the OLT and the ONUs on the performance of our algorithms, we conducted a comparison between the results of two sets of ONUs with varying distances from the OLT. In scenario 16a the ONUs were within a range of 18-20 km from the OLT, while in scenario 16b ONUs were scattered within a range of 2-20 km. In order to gain a deeper understanding of the results, we focused on the performance of the LPT algorithm. The results are presented in Figure 4.6 (left) and show the throughput for the LPT algorithm in both scenarios. It can be seen that LPT performs similarly in both cases, as it is able to transmit up to 220 Mbps before reaching saturation at an offered load of 210 Mbps at LTT = 10 µs. This indicates that the distance between the OLT and the ONUs does not significantly impact the throughput under LPT algorithm, and that it is capable of providing reliable and consistent performance in both scenarios.

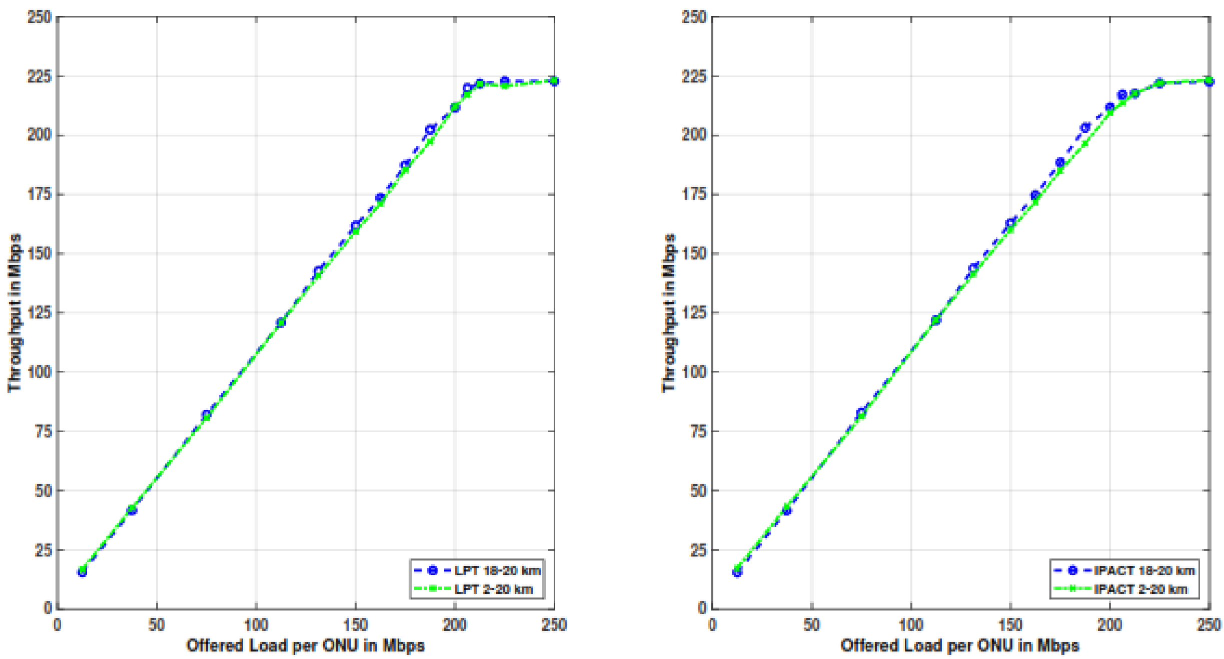

Figure 4.6: Throughput for all ONUs at LTT = 10 µs for a range of 18–20 km (scenario 16a) vs. 2–20 km (scenario 16b) for LPT (left) and for IPACT (right).

In Figure 4.6 (right) we present the results for the IPACT algorithm, which are based on the comparison between the ONUs that are located within 18–20 km and those within 2–20 km from the OLT. The experiments were performed with the LTT set to 10 µs. From the results, it is evident that the IPACT algorithm behaves similarly within both distance ranges. Regardless of the distance, the ONUs are able to transmit an equal amount of throughput, reaching a maximum of 222 Mbps before the system becomes saturated at an offered load of 225 Mbps. Again, IPACT and our algorithm do not show significant differences.

Further results of the impact of the LPT algorithm on the throughput as a function of the distance and load are presented in Figure 4.7. This figure focuses on the two ONUs located at the opposite ends of the distance range in scenario 16b, with ONU 1 situated 2 km away from the OLT and ONU 4 located 20 km away. The cumulative distribution function (CDF) of the throughput for IPACT and LPT at low load and high load are shown for two values of offered load.

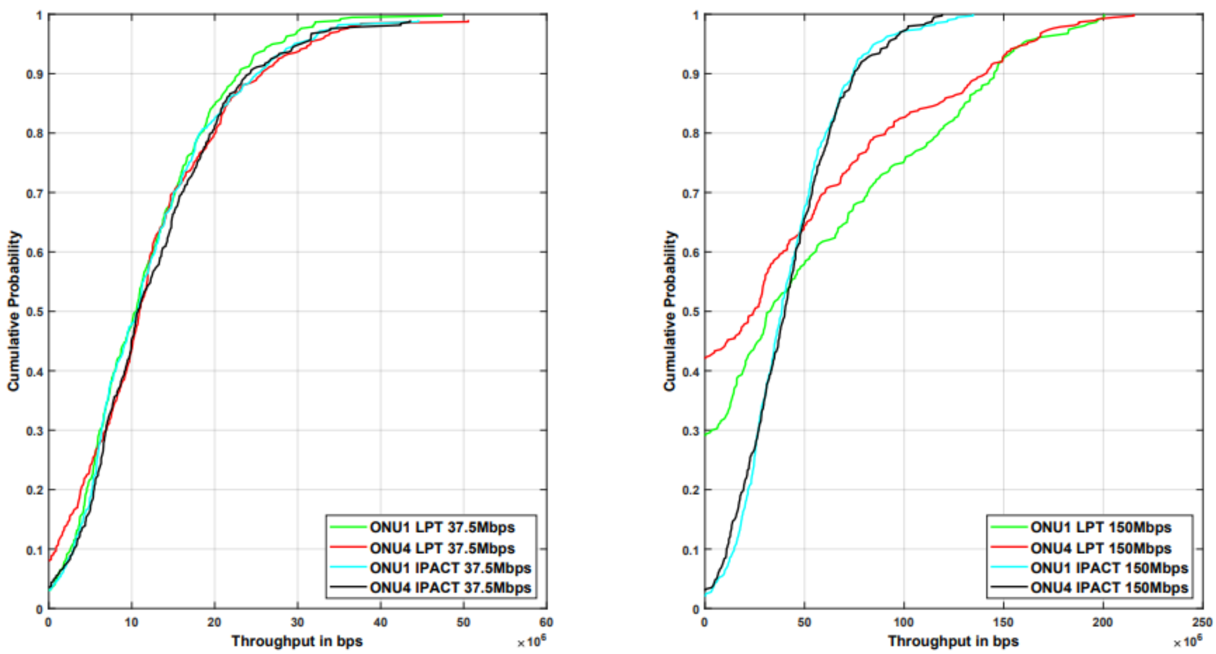

Figure 4.7: CDF of the throughput for ONU 1 and 4 in scenario 16b with LTT = 0 µs; IPACT vs. LPT at low load (left) and heavy load (right).

The findings indicate that the distance between the ONUs and the OLT does not have any significant impact on the throughput of the system at low load levels. As the load increases, the behavior of the ONUs closest to the OLT remains consistent for both IPACT and LPT. However, for the ONUs located further away from the OLT, LPT has a slightly lower deviation compared to IPACT, with a deviation of less than 10%. Our interpretation is that the LPT algorithm reduces the delay of frames even when the system is operating under heavy loads.

4.7.2 Queue Delay

In Figure 4.8 (left), we present the comparison of the average queue delay between IPACT and LPT algorithms in scenario 16a when the ONUs have equal system share with each ONU having a share of 250 Mbps and are transmitting on all four wavelengths at 0 LTT. The results indicate that the ONUs experience a significantly lower delay of 0.08 ms with the LPT algorithm compared to 0.3 ms with the IPACT algorithm. Additionally, it is observed that both algorithms reach saturation at a similar offered load of approximately 200 Mbps.

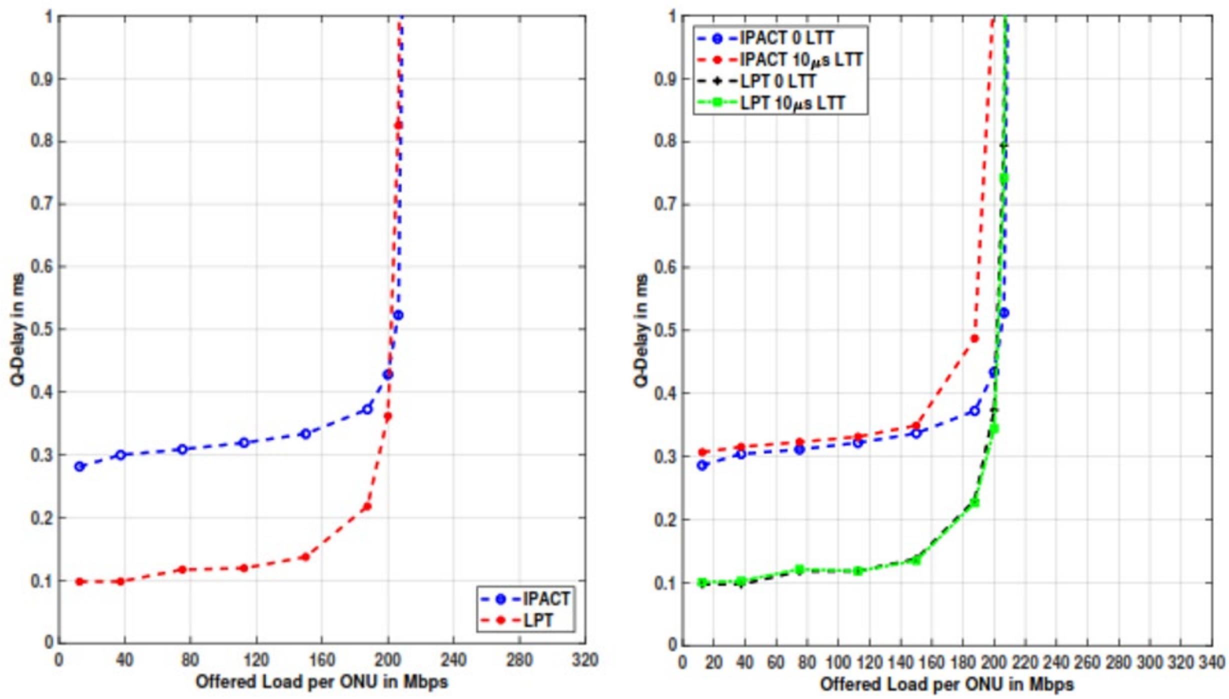

Figure 4.8: Left: Average queue delay for all ONUs at LTT = 0 μs, scenario 16a, IPACT vs. LPT. Right: Queue delay for ONU 1, in scenario 16a, for both LTT = 0 μs and LTT = 10 μs, IPACT and LPT.

Figure 4.8 (right) illustrates the impact of LTT on the queue delay of the two algorithms, LPT vs IPACT, in relation to the offered loads. The results are for ONU 1, and the results are shown for IPACT and LPT under both LTT = 0 μs and LTT = 10 μs conditions. From the results, we can observe that when LTT = 0 μs, the queue delay for IPACT is slightly lower (0.281 ms) compared to when LTT = 10 μs (0.296 ms).

Figure 4.9 compares the behavior of the IPACT and LPT algorithms when different numbers of ONUs are connected. It shows the results of simulations run to check the queue delay for three scenarios with 64 ONUs, 16 ONUs, and 8 ONUs at LTT = 10 µs. The results indicate that the number of ONUs has limited impact on the behavior of the algorithms, and the LPT and IPACT algorithms perform similarly. Figure 4.9 illustrates that the queue delay under the LPT algorithm remains around 0.1 ms to 0.15 ms in all three scenarios until reaching saturation at an offered load of approximately 50 Mbps for 64 ONUs, 200 Mbps for 16 ONUs, and 400 Mbps for 8 ONUs.

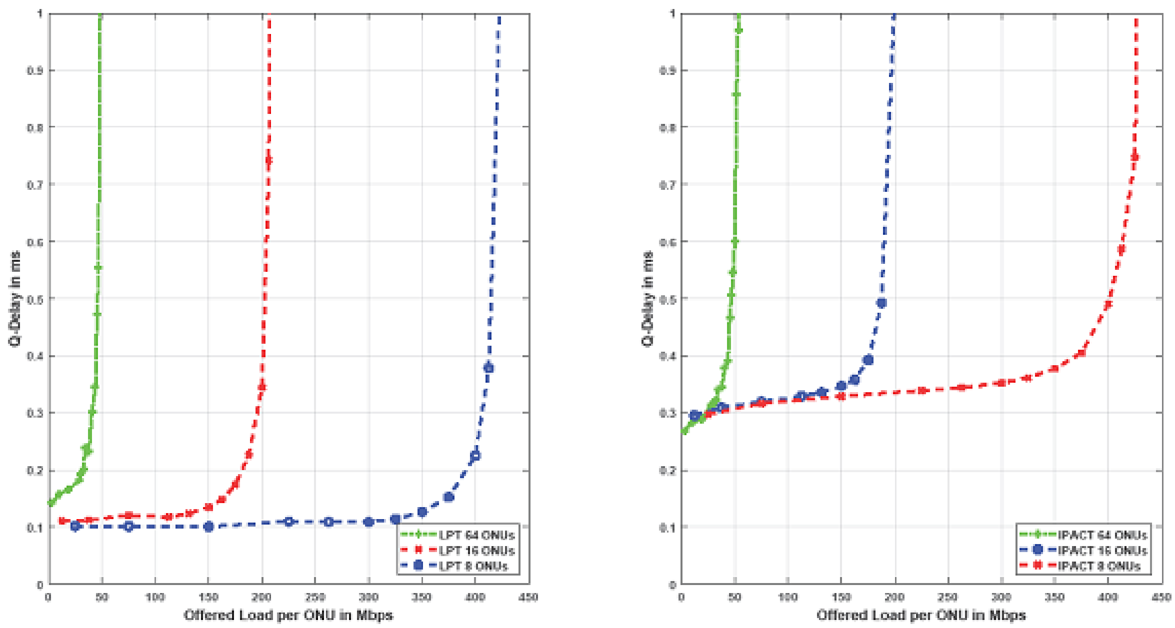

Figure 4.9: Average queue delay for all ONUs at LTT = 10 µs for 64 ONUs, 16 ONUs and 8 ONUs; LPT (left) and IPACT (right).

Figure 4.10 compares the performance of the LPT and IPACT algorithms in two different scenarios with 16 ONUs. In the first scenario, the ONUs are spread over a distance range of 2 to 20 km from the OLT, while in the second scenario, the distance range is 18 to 20 km. The results for the LPT algorithm are shown in the left side of Figure 4.10. It is clear that the behavior is consistent in both distance ranges, with the queue delay being kept at approximately 0.11 ms before reaching saturation at an offered load of 190 Mbps.

The results in Figure 4.10 (right) reveal the impact of distance on the queue delay performance of the IPACT algorithm. The queue delay increases as the ONUs are farther away from the OLT, as seen in the scenario with ONUs in the 18-20 km range where the queue delay goes from 0.3 ms to 0.35 ms near saturation, while in the scenario with ONUs in the 2-20 km range the queue delay only increases from 0.2 ms to 0.3 ms near saturation. This highlights the importance of considering the distance between the ONUs and the OLT when evaluating the performance of the IPACT algorithm.

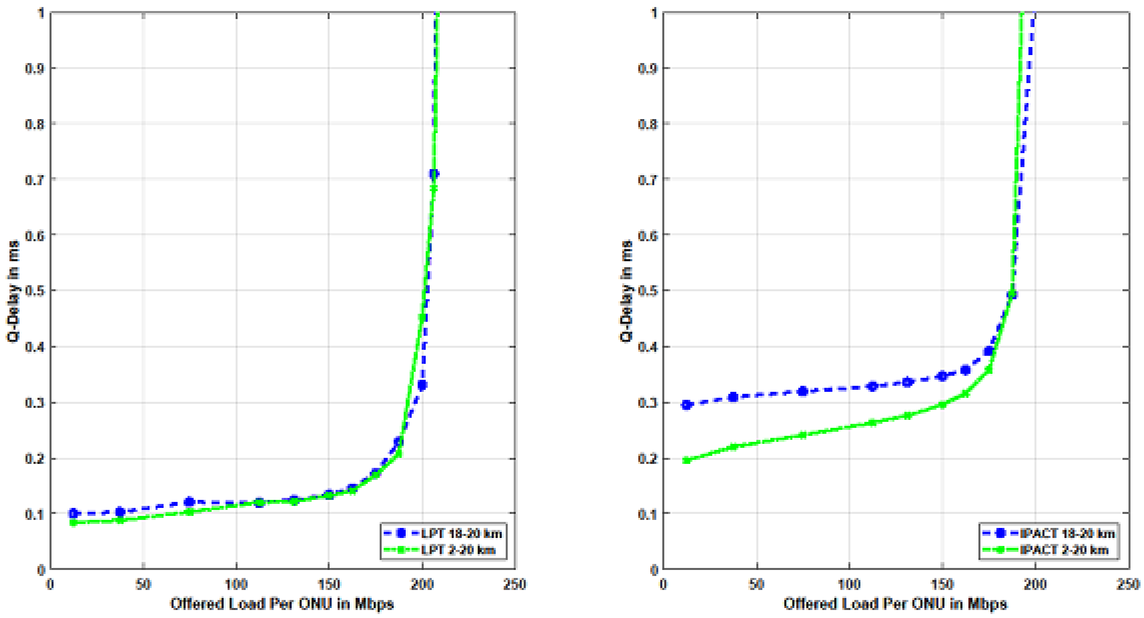

Figure 4.10: Queue delay for a 16-ONU system with a distance range of 2–20 km vs. 18–20 km at LTT = 10 µs; LPT (left) and IPACT (right).

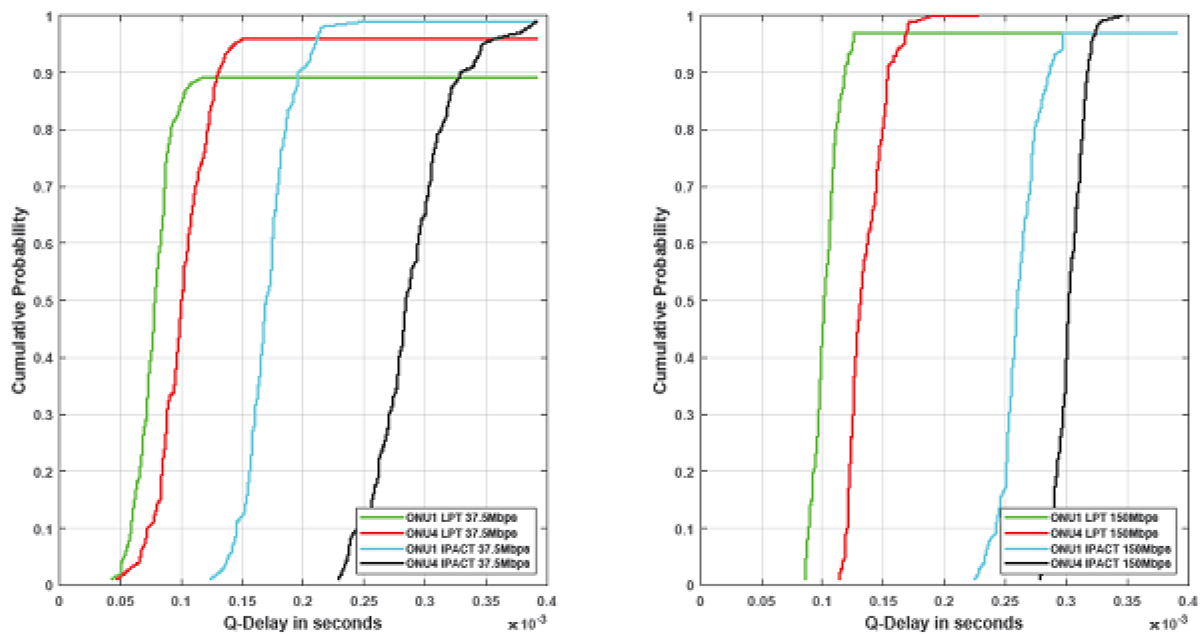

Figure 4.11: CDF of the queue delay for ONU 1 and ONU 4 under the IPACT and LPT algorithms for LTT = 10 µs at offered loads of 37.5 Mbps (left) and 150 Mbps (right).

Figure 4.11 presents the results of the Cumulative Distribution Function (CDF) of the queue delay for two ONUs, ONU 1 and ONU 4, under the IPACT and LPT algorithms for an offered load of 37.5 Mbps and 150 Mbps with LTT = 10 µs. ONU 1 and ONU 4 are located 2.61 km and 17.43 km from the OLT, respectively, in a 16-ONU scenario. The results, as shown in Figure 4.11 (left), indicate that the LPT algorithm provides a margin of improvement over IPACT of between 50 µs to 100 µs at low loads. The impact of the distance on the LPT algorithm is limited to less than 25 µs.

Figure 4.11 (right) compares the queue delay for ONU 1 and ONU 4 at an offered load of 150 Mbps. The results demonstrate that LPT has a more pronounced advantage over IPACT when the load is heavy, as the difference between them increases by 150 µs. Despite the increase in distance between the ONU and OLT, the variability of the queue delay at heavy loads and different distances remains around 40 µs, which is comparable to the low loads. These results indicate that as the offered load increases, the difference in queue delay narrows, even with an increase in distance.

4.8 Discussion of the Results

The results show four key findings. Firstly, our analysis focuses on the effect of LTT on the IPACT algorithm, in terms of throughput and queue delay, as a function of system load and the distance between the ONUs and the OLT. Secondly, the LPT algorithm optimizes queue delay more effectively than IPACT in all scenarios.

The average bandwidth efficiency in the upstream link is about 85%, meeting the minimum efficiency requirement. The inefficiency in the system is caused by overhead from encapsulation such as control message overhead, guard band overhead, discovery overhead, and frame delineation overhead, which consume up to 16.37% of the bandwidth, with the minimum throughput being 836.3 Mbps on a 1 Gbps link.

The introduction of a realistic LTT of 10 µs causes a noticeable decrease in throughput and an increase in queue delay. The impact on throughput is only visible at high loads, above 320 Mbps (80% offered), with the delay caused by the LTT reducing the throughput capability of the ONUs by 10% compared to when there is no LTT, resulting in lower bandwidth utilization of the system. The effect of LTT is not apparent at lower loads since the system is not operating at full capacity and can therefore transmit at the maximum allowable throughput. The impact of LTT on queue delay is only noticeable at high loads, when the queue delay begins to skyrocket, which occurs at a much higher offered load when there is no LTT compared to when there is a LTT of 10 µs. At lower loads, the queue delay remains minimal and comparable to when there is no LTT applied.

The number of ONUs connected to the OLT does not affect the performance of the DBA algorithms with regards to queue delay and throughput. The algorithms allocate resources equally among the ONUs in the PON, resulting in similar values of throughput and queue delay for each ONU. The distance between the ONU and the OLT, within the maximum allowed distance of 20 km in the PON, does not affect the throughput. Regardless of the location of the ONU in the PON, the throughput remains the same. However, the queue delay does change and decreases as the ONUs get closer to the OLT. But the impact of the distance between the ONU and the OLT decreases as the offered load increases.

These findings highlight the importance of considering the LTT when designing and evaluating the performance of DBA algorithms, in order to accurately model the behavior of a system that must meet delay requirements within a range of 1 ms to 100 ms. The LPT scheme is designed to minimize the total finish time when scheduling requests on multiple wavelengths. When LPT is applied to the IPACT algorithm, it reduces the queue delay by 73%, but there is no significant effect on throughput.

4.9 Summary

In this chapter, we presented a contribution in the field of DBAs for TWDM-PONs, conducted in partnership with a fellow researcher. Though not being the first author, this collaboration forms the foundational groundwork for the subsequent research on DBAs in Long-Reach PONs, which will be the focus of the next chapter.

We began by highlighting the critical role of DBA algorithms in enhancing bandwidth allocation efficiency within PONs. We provided a detailed explanation of DBA techniques, including grant sizing and grant scheduling, which are essential for optimizing network resource utilization in PONs. Given the complexity and the NP-hard nature of scheduling problem in TWDM-PONs, we then shifted our focus to the scheduling policy. Specifically, we proposed LPT scheduling as a solution, showcasing how LPT effectively addresses the NP-hard complexity by prioritizing the scheduling of ONUs with longer processing times. This strategic approach contributes to achieving near-optimal solutions, ultimately reducing delays and enhancing the efficiency of data transmission in PONs.

Finally, we provided a comprehensive explanation of the implementation of the DBA algorithm, including LPT and NASC with LTT. We provided pseudocode for each algorithm to help better understand how they contribute to optimizing DBA algorithms in PON.

Subsequently, we conducted an assessment of the proposed algorithms, particularly LPT. Our evaluation centered on two key performance indicators: throughput and queue delay. The implementation of LPT resulted in enhanced performance, achieving a significant reduction in queue delay by up to 73% when compared to IPACT.

Chapter 5
DBA for Long Reach PONs

5.1 Introduction

This chapter describes a contribution to the development of DBAs for Long Reach Passive Optical Networks. Over the past few years, there has been a rising demand to extend the coverage of PONs across larger geographical areas. To meet this demand, LRPONs have emerged, offering coverage expansion from 20 km to 100 km. LRPONs provide high-speed, long-distance data transmission over optical fibers, resulting in cost savings by reducing the need for central offices [72].

Additionally, there is a growing demand to streamline telecom networks by integrating the metro and access networks. LRPON serves as an effective solution for achieving this simplification, as depicted in Figure 5.1. In conventional telecoms networks, three components exist: the access network, the metropolitan-area network, and the backbone network. However, with the advancements in LRPON technologies, it becomes possible to consolidate the metro network into the access network. This consolidation leads to a simplified network hierarchy, with the access headend situated in close proximity to the backbone network [158].

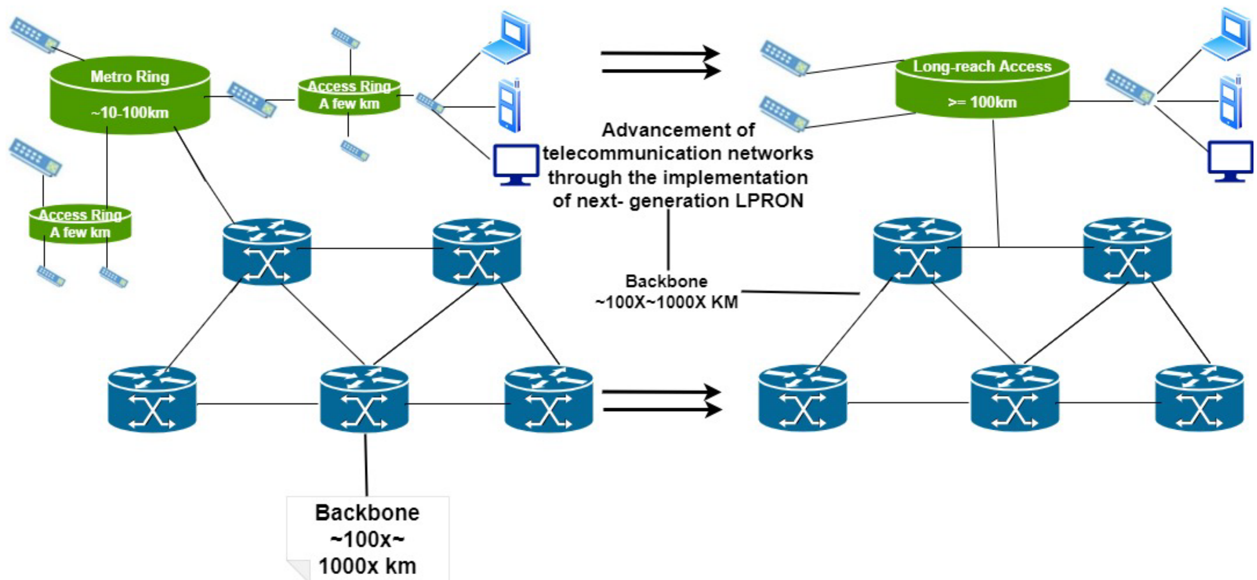

Figure 5.1: Evolution of LRPON (based on Fig 1 of [159]).

However, the extended reach of LRPONs introduces new challenges, particularly in the area of DBA algorithms. The traditional DBA algorithms used in standard PONs such as IPACT and LPT may not be as efficient for LRPONs due to increased propagation delays and RTT between the Optical Line Terminal and Optical Network Units.

To address these challenges, we propose a novel DBA algorithm in this chapter: the Distance Weighted Dynamic Bandwidth Allocation algorithm. Factors such as laser tuning time and ONU distances are taken into account to enhance overall network performance, improve efficiency, and reduce congestion. This work, whose first author is Adebanjo Haastrup was also performed in collaboration with Mohammad Zehri as second author.

The chapter is organized as follows. In Section 5.2, we provide background studies and review related work on DBA in LRPONs. In Section 5.3, we introduce the DWDBA, a multi wavelength algorithm, which utilizes a unique scheduling policy to assign weight vectors to ONUs based on their distances from the OLT. This approach ensures fairness among ONUs without penalizing those located farther away. Section 5.4 describes the evaluation of the algorithm with simulation scenarios. Section 5.5 presents the results, demonstrating DWDBA's effectiveness in terms of bandwidth utilization and queue delay, and outperforming the existing IPACT algorithm, as discussed in Section 5.6.

5.2 Related Work on LRPON

The use of Next Generation Passive Optical Networks is rapidly gaining popularity as a high-speed backbone network solution, facilitating the seamless delivery of mobile cloud services. However, to achieve extended reaches and larger splitting ratios in these networks, the incorporation of Optical Amplifiers (OAs) becomes essential. Consequently, OAs and splitters serve as internal nodes within the Optical Distribution Network structure of LRPONs, enabling the support of more ONUs with extended reach. The ITU-T G.984.6 recommendation for LRPONs involves extending the reach capability up to 60 km and accommodating a split ratio of 1:128. A typical implementation of an LRPON comprises a single wavelength channel with a reach of 100 km, supporting a maximum split ratio of 1000 ONUs. The network operates at downstream speeds of 10 Gbps and upstream speeds of 2.5/10 Gbps. [159].

Recent research on DBA algorithms for LRPONs has been concentrated on devising efficient methods to allocate bandwidth to ONUs, taking into account various constraints such as QoS requirements, energy efficiency, and fairness. In a comprehensive study [160], a range of DBA algorithms designed for LRPONs was reviewed and their fundamental properties were briefly compared. To assess the performance of these algorithms, an OPNET-based simulation platform was utilized, focusing on key metrics like average packet delay and channel utilization in LRPONs. The outcomes of these simulations offered valuable insights for the development and optimization of DBA algorithms tailored for LRPONs.

As suggested by [20], the introduction of a multi-threaded DBA algorithm is considered a potential solution to address performance degradation. The utilization of multi-threading enables an ONU to have more opportunities for upstream channel access, as it allows for further GATE allocations before the OLT receives the REPORT message from the ONU for the previous allocation. The impact of multi-threading on DBA performance was investigated in both Gigabit PON and Ethernet PON systems [95]. The study concluded that multi-threading can effectively mitigate performance degradation caused by extended reach in both standards. However, to achieve optimal efficiency, novel approaches for coordinating multiple threads are required in long reach PON systems.

A DBA scheme known as Multi-thread Polling (MTP) was specifically designed for implementation in LRPONs [161]. While this scheme has been thoroughly examined from various perspectives, it has encountered certain challenges. In response to these issues, a novel technique called Parallel Polling has been introduced. The main objective of Parallel Polling is to improve the delay performance of MTP in

LRPONs by addressing the identified challenges and providing an effective solution. To achieve this, Parallel Polling utilizes the idle time in each cycle to serve the second thread concurrently through parallel polling.

In the context of LRPONs, an online multi-thread polling DBA scheme is proposed by [162], incorporating an online excess bandwidth distribution mechanism. This scheme differs from offline multi-thread polling as it enables the OLT to process bandwidth requests as soon as it receives the REQUEST message, rather than waiting for all requests from a given thread. In the context of multi-threaded DBA algorithms for LRPONs, a common issue known as the "over-granting problem" is observed, where the allocated time slot size is larger than necessary for ONUs [163]. This problem arises due to overlapping polling cycles in multi-threaded DBA and the use of predefined or calculated maximum thresholds for time slot sizes assigned to each ONU for upstream transmission. The resulting over-granting leads to inefficient bandwidth utilization and is not adequately addressed by existing DBA algorithms. To address this challenge, researchers in [163] propose an enhanced version of IPACT called Enhanced IPACT with limited service for multi-thread DBA in Long-Reach EPON. This modified algorithm adjusts the reported time slot size to the OLT and ensures that previously reported data by an ONU in one parallel thread is not reported again by another parallel thread, thus mitigating the over-granting problem.

An alternative DBA, designed to resolve the problem of over-granting in conventional online MTP-based schemes, is presented in [158]. This work introduces a novel online MTP-based DBA algorithm known as the Slotted MTP (S-MTP) scheme. S-MTP effectively reduces end-to-end packet delay and mitigates over-granting in LRPON systems with lower computational complexity. It achieves this by dividing the reach time cycle into multiple grant scheduling slots, where multiple request and grant messages are processed simultaneously, and utilizing frame-by-frame information in both the request and grant messages.

In [164], a comprehensive review of recently proposed DBA schemes for Long Reach PONs is provided, with a focus on reducing delay. The authors introduce a novel approach to enhance quality of service in LRPONs by integrating inter- and intra-ONU scheduling mechanisms. This proposal combines the Priority Swapping (PS) scheme with the efficient inter-thread scheduling (EIS) mechanism, resulting in notable improvements to QoS in LRPON. The combined scheme effectively reduces the delay of delay-intolerant traffic and enhances the delay performance of delay-tolerant traffic. Additionally, the authors of [165] propose an efficient inter-thread scheduling (EIS) method specifically tailored for LRPONs. This method integrates key elements from existing inter-thread scheduling algorithms and addresses the challenge of inadequate communication between overlapping threads, which can lead to reduced efficiency and inferior performance in multi-thread DBA compared to traditional single-thread algorithms.

A new DBA protocol called GPON Redundancy Eraser Algorithm for Long-Reach (GREAL) to overcome inefficiencies in DBA upstream protocols for LRPONs is proposed by [166]. GREAL effectively removes redundancy caused by an ONU polling cycle or Scheduling Interval (SI) that is smaller than the RTT while providing multi-service quality of service. This algorithm's efficiency is independent of the SI and relies on real data queuing information, leading to improved bandwidth utilization. Moreover, the combination of prediction techniques with GREAL further enhances the DBA protocol and improves bandwidth management.

The impact of idle time on performance degradation in LRPONs has been challenging to analyze. Idle time refers to unutilized time slots that are caused by long propagation delays in LRPONs. Previous studies have only considered scenarios without idle time, using modified OLTs and ONUs. However, [167] introduces a novel exact solution for calculating the mean packet delay in LRPONs while considering the presence of idle time. The results show a close match between the proposed analytical solution and the simulated mean packet delay. This contribution is crucial as it enables the analysis of LRPON performance in the presence of idle time, a significant factor to be considered in the design and optimization of these networks.

In [6], an enhanced Service Interval-based (SIBA) dynamic bandwidth allocation algorithm for LRPONs with fiber distances of up to 140 km is introduced. This algorithm aims to enhance the mean delay for different traffic classes, especially at maximum offered load. The study highlights the significance of the number of assigned service intervals in ensuring the stability of the allocation process in LRPONs. Comparative results indicate that the proposed SIBA algorithm outperforms other DBA algorithms, demonstrating greater stability and efficiency as the fiber length increases.

In [168], a decentralized medium access control scheme for LRPON networks is proposed, allowing direct inter-ONU communication through an (N+1)x(N+1) star coupler. The scheme incorporates a novel DBA method called profit-weight-based-plus (P-DBA+), which efficiently distributes excess bandwidth while ensuring QoS provisioning. Extensive simulations demonstrate that the proposed scheme achieves exceptional system performance under diverse traffic loads and burstiness. It provides fair, efficient, and robust scheduling, meeting the QoS requirements effectively.

After conducting an extensive review of DBA schemes in LRPONs, it becomes evident that the efficiency of these schemes plays a vital role in mitigating performance degradation in these networks. LRPONs present unique challenges due to the varying distances and propagation delays of each ONU, requiring careful consideration in scheduling transmission requests. In response to these challenges, we have developed an enhanced Distance-Weighted DBA algorithm tailored for LRPON, which incorporates the laser tuning time, NASC and LPT techniques already described in Chapter 4.

5.3 DWDBA Algorithm Description

The DWDBA algorithm is an extension of the original IPACT algorithm, an online DBA, which has been enhanced to handle multiple wavelengths in TWDM-PON systems [139]. Our DWDBA algorithm is specifically designed for LRPON systems, taking into account their unique characteristics and constraints, such as the distance and propagation delay of each ONU during transmission request scheduling. It involves assigning weights to ONUs based on their distances from the OLT, with farther ONUs receiving higher weights. The ONUs are then sorted in descending order by weight and polled cyclically, starting with the highest-weighted ONU. The cycle time, representing the time interval between consecutive allocation decisions, is adjusted according to the number of active ONUs in the system. A higher number of active ONUs results in an increased cycle time, while a lower number decreases it. The ultimate goal of DWDBA is to optimize the transmission process by prioritizing ONUs based on their distances, queue lengths, and available wavelengths for transmission.

The DWDBA algorithm is shown in the flowchart presented in Figure 5.2. The algorithm begins by checking if an ONU is connected and if its queue contains data. If both conditions are satisfied, the algorithm proceeds to retrieve the distance of the ONU from the pre-assigned distance vector. To ensure comparability, this distance is normalized by subtracting the minimum distance and dividing it by the range of distances (distance between the farthest and the nearest ONU). The normalization process scales all connected ONUs' distances to a common range, facilitating easier comparison.

Next, the algorithm arranges the ONUs in descending order based on their normalized distances. By sorting the ONUs in this manner, the algorithm ensures that those with the longest distances and, consequently, the highest priorities are processed first. This approach prioritizes ONUs that are further away from the OLT, optimizing the transmission process in the LRPON system.

In the DWDBA algorithm, each connected ONU is granted a queue length based on both the maximum allowed length and the current length of the ONU's queue. If the queue length exceeds the maximum allowed length, the algorithm grants the maximum allowed length and leaves the remaining packets in the queue for processing in the next cycle. On the other hand, if the queue length does not exceed the maximum allowed length, the DBA grants the entire queue length to the ONU.

Once the queue length is granted, the DBA proceeds to assign wavelengths to the ONUs using the NASC principle [143]. This scheduling policy ensures that the next available wavelength is assigned to the ONU with the highest weight. The wavelength assignment is performed in offline scheduling mode, allowing scheduling decisions to be made with complete knowledge of all the tasks to be scheduled for a specific cycle. In this mode, the OLT gathers all the ONUs with REPORT messages and includes them in a scheduling pool. Subsequently, the scheduling is carried out after the ONUs have been sorted in descending order based on their weights and priorities following bubble sort. This offline scheduling framework offers greater control over the scheduling process.

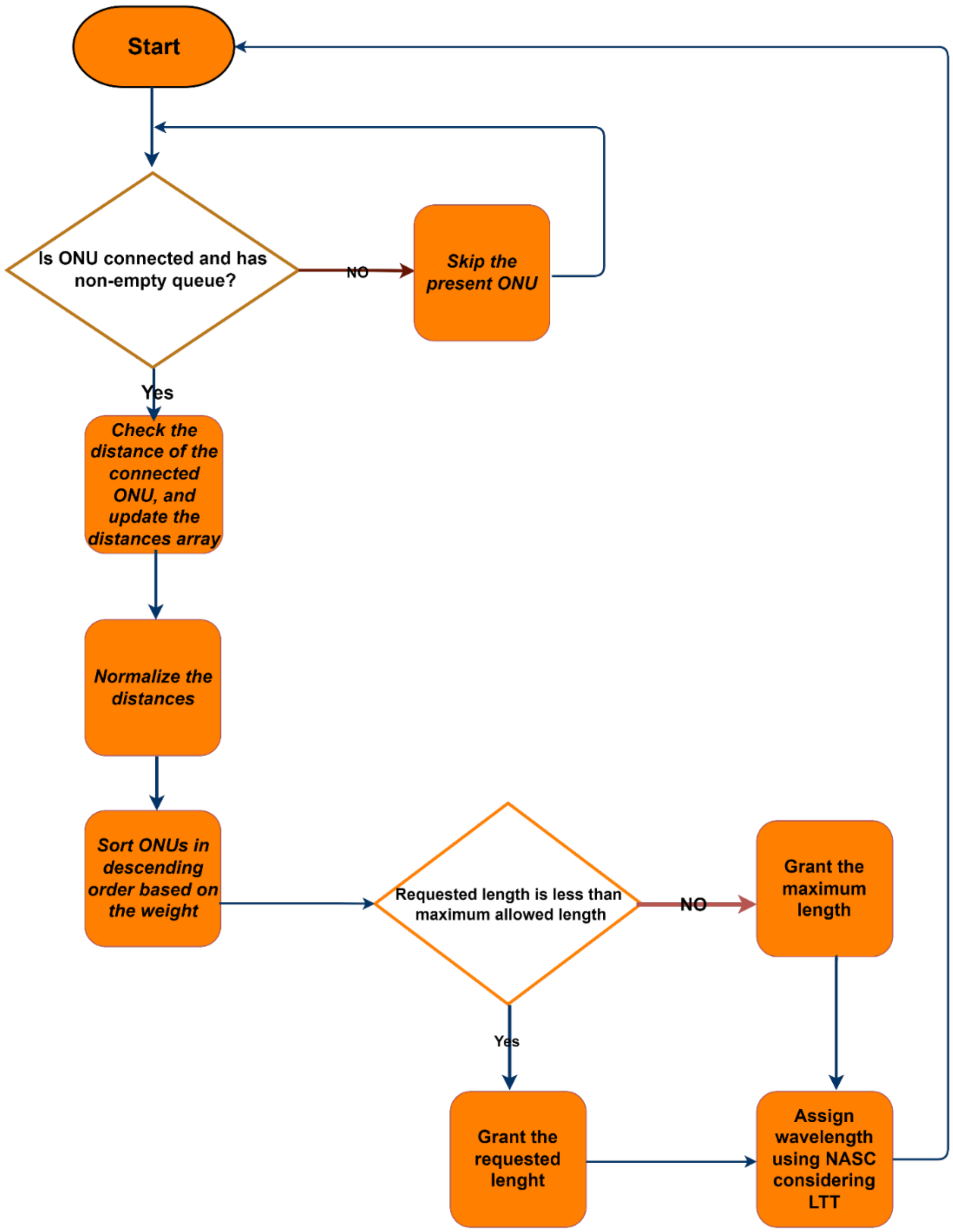

Figure 5.2: Flowchart of the DWDBA algorithm.

To provide a comprehensive understanding of the DWDBA and NASC algorithms, the pseudocodes for both are presented in *Pseudocode 5.1* and *Pseudocode 5.2*, respectively. These pseudocodes detail the step-by-step process that the algorithms follow to efficiently manage transmission requests and wavelength assignments in the LRPON system. For a detailed explanation of the parameters and variables used in the pseudocodes, please refer to Table 5.1.

Parameter	Description
ONU i	Individual ONU in the network
distance[i]	Distance measure form the OLT to each ONU i
min_distance	Minimum distance from the OLT among the ONUs
max_distance	Maximum distance from the OLT among the ONUs
normalized_distances[i]	Normalized distance values for each ONU
Total_ONUs_Number	Total number of ONUs in the network
queue_length	The queue length of a connected ONU
length_of_ONU_i's_queue	The current length of the queue for ONU i
max_allowed_length	Maximum allowed length for an ONU’s queue
wavelength	Available wavelength
find_empty_wavelength(wavelengths)	Function that finds an empty wavelength
wait_time	Time an ONU waits for a wavelength to become available
get_wait_time(wavelengths)	Function that calculates the wait time until a wavelength becomes available
laser_tuning_time	The time required to tune the laser to a new wavelength
tune_laser_to_empty_wavelength(wavelengths)	Function that tunes the laser to an empty wavelength
transmit_packets(i, wavelength)	Function that transmits packets from ONU i on the given wavelength

Table 5.1: Parameters of the DWDBA algorithm for TWDM LRPON

```
// Check for connected ONUs with non-empty Queues
for each ONU i:
    if ONU i is connected and its queue is non-empty:
        distance[i] = get_distance(distance_vector, i)
        // Update min_distance if the current distance is smaller
         min_distance = min(min_distance, distance[i])
    end if
end for
// After finding the minimum distance, normalize distances
for each ONU i:
    if min_distance == max_distance:

        normalized_distances[i] = 1

    else:

        normalized_distances[i] = (distance[i] - min_distance) / (max_distance - min_distance)

    end if
end for
// Special case: if distance[1] is the min_distance, set normalized_distances[1] accordingly
if distance[1] == min_distance:
    normalized_distances[1] = min_distance / (max_distance – min_distance)
end if

// Sort ONUs based on normalized distances in descending order
for i from 1 to Total_ONUs_Number:
     for j from i+1 to Total_ONUs_Number:
        if normalized_distances[i] < normalized_distances[j]:
            swap ONUs i and j
            swap normalized_distances[i] and normalized_distances[j]
        end if
    end for
```

```
end for

// Grant queue lengths to connected ONUs
for each connected ONU i:
        // Calculate the allowed queue length for ONU i
        queue_length = min (length_of_ONU_i's_queue, max_allowed_length)
        if length_of_ONU_i's_queue > max_allowed_length:
                grant max_allowed_length to ONU i
                //leave remaining packets in the queue for the next cycle
        else:
                grant to the ONUi its requested queue length
        end if
end for
```

Pseudocode 5.1: Algorithm 1 - DWDBA executed at the OLT for each cycle i.

Additionally, our DWDBA algorithm incorporates the consideration of Laser Tuning Time (LTT) when making decisions regarding wavelength assignment as shown in Algorithm 2 (Pseudocode 5.2). The DBA checks if the wavelength currently tuned by the ONU is available for transmission. If it is available, the DWDBA assigns the wavelength to the ONU, and packet transmission can occur without any additional delay due to laser tuning time.

However, if the wavelength currently tuned by the ONU is not available, the algorithm proceeds to check the wait time for the wavelength to become available and the LTT for the next available wavelength. The DBA calculates the sum of the LTT and the time needed to wait for the next available wavelength to be ready. If this sum is greater than the wait time for the currently tuned wavelength to become available, the ONU stays on the current wavelength and waits for it to be available for transmission.

On the other hand, if the sum of LTT and wait time for the next available wavelength is less than the wait time for the currently tuned wavelength, the ONU switches to the next available wavelength, and the Laser Tuning Time is applied. By employing this approach, the algorithm minimizes waiting time for an available wavelength, optimizing the utilization of network resources and reducing transmission delays.

```
//Transmit packets on next available supported channel
for each connected ONU i:
        wavelength = find_empty_wavelength(wavelengths)
        // See definition of the find_empty_wavelength function below
        if pre-assigned wavelength is available
                transmit_packets(i, wavelength)
        else:
                wait_time = get_wait_time(wavelengths)
                if wait_time < laser_tuning_time:
                        wait(wait_time)
                else:
                        tune_laser_to_empty_wavelength(wavelengths)
                        wait(laser_tuning_time) for each ONU i:
        end if
end for
// Function to find an empty wavelength
function find_empty_wavelength(wavelengths):
        for i from 0 to 3:
                if wavelengths[i] is empty:
                        return i
                end if
        end for
        // no empty wavelength found
        return -1
end function
```

Pseudocode 5.2: Algorithm for assigning NASC on DWDBA

DWDBA leverages IPACT's overlapping and interleaving nature, enabling simultaneous polling requests and resulting in improved bandwidth utilization and reduced transmission delays. Unlike traditional

TDMA-based DBAs, DWDBA eliminates the need for ranging, a process that attempts to make ONUs appear equidistant from the OLT by delaying their responses by specific amounts of time. The purpose of ranging is to account for the varying distances and propagation delays of ONUs in the network [84].

In summary, the communication process begins with connected ONUs sending REPORT messages to the OLT, containing their queue status and bandwidth requests. The DBA algorithm then checks the distance of these ONUs from the OLT and updates the distance array. Next, the distances are normalized to calculate weights, and the requests are sorted in descending order based on these weights. If an ONU's requested length is within the maximum allowed, the OLT grants that length; otherwise, it grants the maximum length. Subsequently, the wavelength is assigned following the NASC principle, considering the LTT. This process continuously occurs during the communication between the OLT and the ONUs, with GATE and REPORT messages being exchanged. Figure 5.3 illustrates the steps of the algorithm.

Figure 5.3: DWDBA Algorithm Sequence Diagram.

5.4 Evaluation Methodology

In order to evaluate the effectiveness of these algorithms, we conducted extensive simulations using a simulation network model developed using OPNET Modeler, under various network conditions, such as different traffic loads and different numbers of ONUs. The metrics, namely throughput and queue delay, are defined as in Section 4.8.

5.4.1 Simulation Model

Our simulation setup emulates a realistic LRPON network, comprising 16 ONUs, an OLT, and an ODN with a splitter. Similar to the simulation scenarios described in Section 4.7, in the downstream the OLT distributes data to all connected ONUs via a 1Gbps broadcast link from the OLT through the passive splitter. For the upstream channel, we have allocated a total capacity of 4 Gbps, distributed across four wavelengths, each operating at a rate of 1 Gbps. The dynamic management of the upstream channel is handled by the DWBA algorithm.

Every ONU is connected to its respective traffic source, generating self-similar traffic with a Hurst parameter (H) of 0.75 [157]. The mean packet rate is adaptively adjusted based on the changing offered load. The maximum cycle time (δmax) is set at 1 ms. Ethernet frames are uniformly distributed from 64 bytes to 1518 bytes, as prescribed in [16]

5.4.2 Simulation Scenarios

To assess the influence of distance on the DWBA algorithm, we have designed several simulation scenarios that alter the ONUs' distance from the OLT. These simulations will enable us to examine the effect of distance on our algorithm's performance, specifically in relation to throughput and queue delay. Furthermore, these scenarios will offer a deeper understanding of our algorithm's response to diverse network setups and its adaptability to changing traffic conditions and distances.

The simulation scenarios and the rationale behind them are described below:

- **Scenario 1—ONUs Distributed Between 50 km and 75 km from the OLT**. This scenario depicts a typical deployment situation where the ONUs are in close proximity to the OLT, albeit at different distances. This setup enables us to scrutinize the DWDBA algorithm's performance when the ONUs are within a limited distance range, but still with varying propagation delays.
- **Scenario 2—ONUs Distributed Between 70 km and 100 km from the OLT**. In this setup, the ONUs are situated at a greater distance from the OLT, illustrating a longer-reach deployment scenario, so propagation delays are bigger than in Scenario 1.
- **Scenario 3—ONUs Distributed Between 17 km and 100 km from the OLT**. This scenario covers a broad spectrum of distances, incorporating both short-reach and long-reach ONUs.
- **Scenario 4—ONUs Distributed Between 50 km and 100 km from the OLT.** This scenario covers from medium to long-reach distances.

The details of the ONUs distributions in the aforementioned distance ranges are presented in Table 5.2.

To ensure our simulation accurately reflects real-world conditions, we have chosen an LTT of 10 µs, aligning with the specifications outlined in ITU-T G.989.2 for class 2 devices [59].

Simulations are executed under diverse traffic loads, ranging from 5% to 100% of the maximum global offered load, which is set at 250 Mbps, a value gotten by dividing the total bandwidth capacity of the system (4Gbps) by the number of the ONUs (16) in the system. We gathered data from 100 simulations for each offered load, and to ensure reliability and precision, the process was repeated with 5 different seeds defined in OPNET. For each of the scenarios, there are 16 ONUs with all of them having equal access to the system but we have decided to present results for a subset of the ONUs for ease of analysis and presentation.

ONU #	**Scenario 1 (50-75km)**	**Scenario 2 (70-100km)**	**Scenario 3 (17-100km)**	**Scenario 4 (50-100km)**
ONU1	50	75	100	50
ONU2	50	70	99	50
ONU3	50	71	100	50
ONU4	60	80	56	60
ONU5	74	82	17	80
ONU6	76	87	37	80
ONU7	70	100	27	100
ONU8	70	91	24	90
ONU9	60	78	90	60
ONU10	50	71	80	50
ONU11	61	80	71	61
ONU12	69	100	46	100
ONU13	75	82	38	81
ONU14	70	78	31	90
ONU15	70	93	31	90
ONU16	75	100	20	100

Table 5.2: ONUs distribution for the different simulation scenarios.

5.5. Results

Our evaluation focused on throughput and queue delay, particularly considering the distances between the ONUs and the OLT. The findings are illustrated in the subsequent sections with figures showcasing the comparative performance of the DWDBA and modified IPACT algorithms.

5.5.1 Throughput

Figure 5.4 presents the outcomes obtained from scenario 1, where the ONUs are located between 50km and 75km from the OLT. We will focus our analysis on some specific ONUs: ONU1 at 50km, ONU4 at 60km, and ONU16 at 75km. From the figure, it is evident that with DWDBA, the ONUs can achieve higher throughput, exceeding 230Mbps, with a maximum throughput of 225Mbps, even at higher offered loads. Under the IPACT algorithm none of the ONUs can transmit beyond an offered load of 210Mbps. Specifically, ONUs 4 and 16 achieve a maximum throughput of 150Mbps and 180Mbps, respectively.

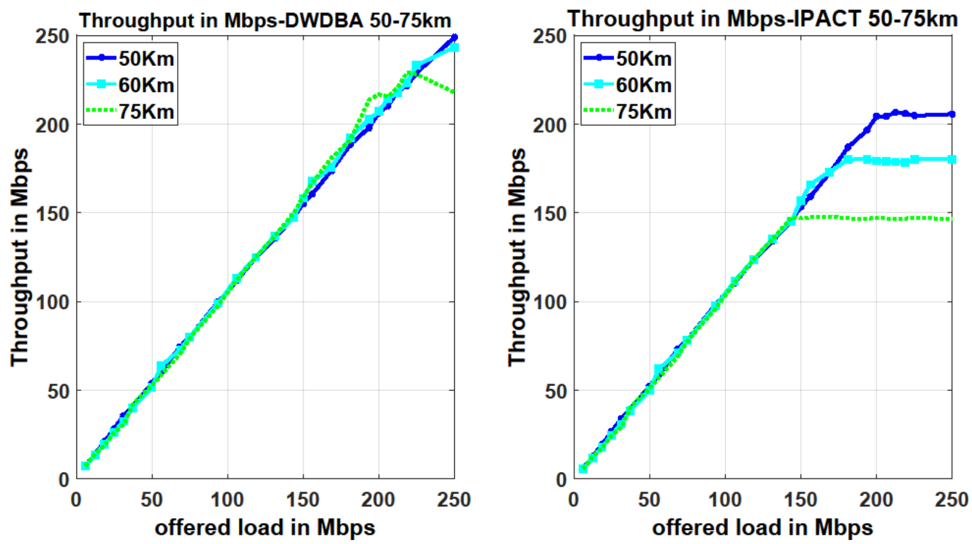

Figure 5.4: Throughput for scenario 1 (50km to 75km) for DWDBA (left) and IPACT (right).

In Figure 5.5, we present the comparison of throughput for ONUs in scenario 2, where the distances between ONUs and OLT range from 70km to 100km (ONU2 at 70km, ONU4 at 80km, and ONU16 at 100km). The figure shows that with our DWDBA algorithm, the ONUs can achieve a maximum throughput of 200Mbps. Specifically, ONUs 2 and 4 demonstrate the ability to transmit beyond an offered load of 225Mbps, while ONU 16 achieves a maximum transmission of 190Mbps.

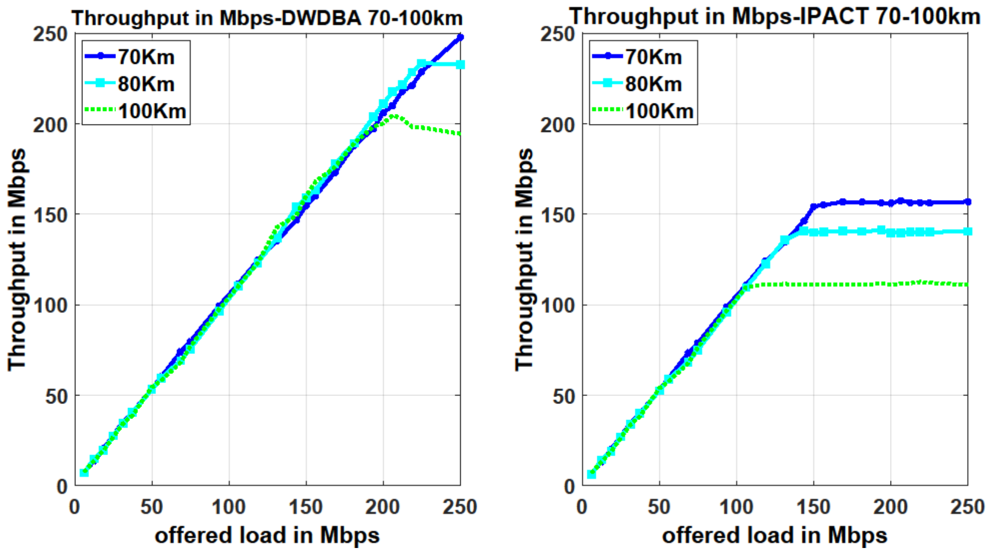

Figure 5.5: Throughput for scenario 2 (70km to 100km) for DWDBA (left) and IPACT (right).

In contrast, the ONUs operating under the IPACT algorithm, the maximum transmission rates are limited, with ONU 2 reaching 110Mbps, ONU 4 achieving 130Mbps, and ONU 16 reaching 160Mbps. Additionally, the transmission rates for ONU 2, ONU 4, and ONU 16 do not exceed 105Mbps, 140Mbps, and 150Mbps, respectively.

In Figure 5.6, the comparison of throughput for ONUs in scenario 3 is presented. The distances between ONUs and OLT range from 17km to 100km, with specific distances for each ONU: ONU5 at 17km, ONU6 at 37km, ONU4 at 56km, ONU11 at 71km, and ONU1 at 100km. On the left side of Figure 5.6, the results for our DWDBA algorithm are displayed. The ONUs exhibit similar behavior, achieving a maximum throughput of 245Mbps at an offered load of 230Mbps. In contrast, the right side of the figure showcases the performance of ONUs under the IPACT algorithm. In this case, only the ONUs located closer to the OLT (17km and 37km) are capable of achieving a throughput of 240Mbps at higher offered loads. However, the ONUs situated at greater distances (100km, 71km, and 56km) experience limitations in their transmission capabilities, with maximum throughputs of 110Mbps, 150Mbps, and 180Mbps, respectively.

In scenario 4, the ONUs are positioned as follows: ONU1 at 50km, ONU4 at 60km, ONU5 at 80km, ONU8 at 90km, and ONU16 at 100km. Figure 5.7 (left) showcases the performance of our DWDBA algorithm, indicating that all ONUs can achieve a maximum throughput of 230Mbps when the offered load exceeds 220Mbps. Conversely, Figure 5.7 (right) displays the performance of the IPACT algorithm. It is evident that none of the ONUs can attain a throughput of 200Mbps. Furthermore, the ONUs located at greater distances (80km, 90km, and 100km) transmit at speeds below 150Mbps.

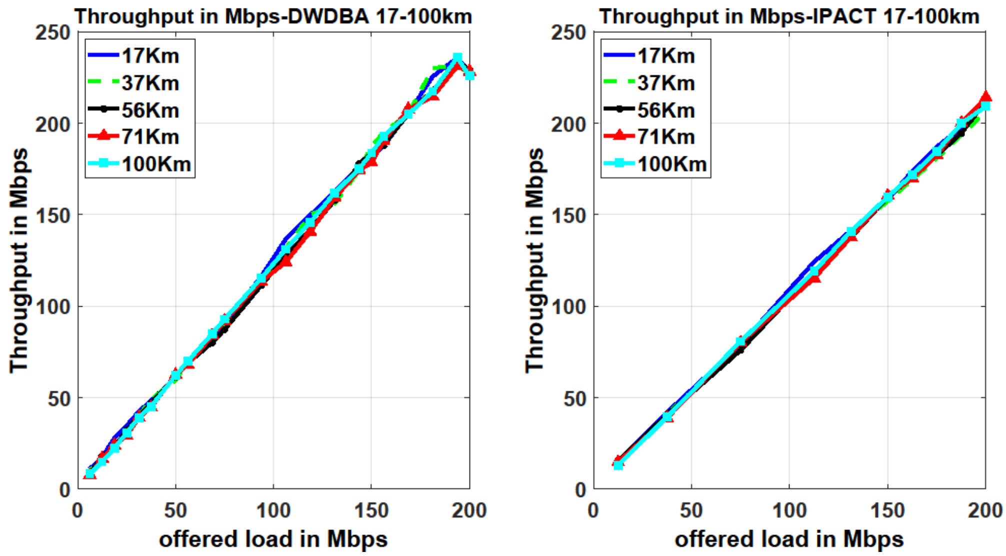

Figure 5.6: Throughput for scenario 3 (17km to 100km) for DWDBA (left) and IPACT (right).

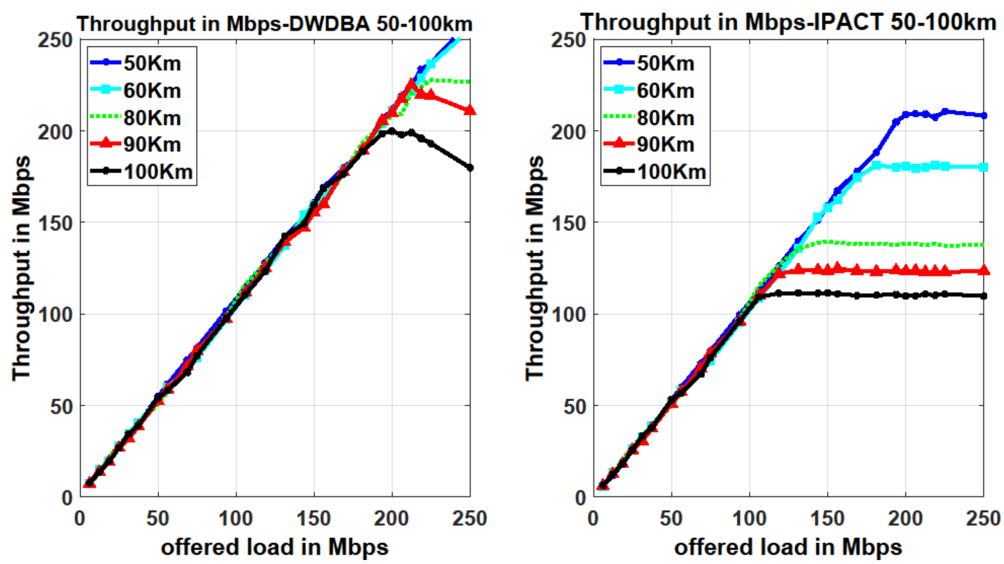

Figure 5.7: Throughput for scenario 4 (50km to 100km) for DWDBA (left) and IPACT (right).

From these findings, it can be inferred that the DWDBA algorithm demonstrates superior performance compared to IPACT when ONUs are located at very long distances. The ONUs located at farther distances are still capable of achieving higher maximum throughputs, and they are not penalized by the algorithm.

5.5.2 Queue delay

Queue delay results for scenario 1 (ONU1 at 50km, ONU4 at 60km, and ONU16 at 75km) are presented in Figure 5.8. For DWBA, ONUs demonstrate remarkably low queue delay, even when handling offered loads exceeding 200Mbps. In contrast, for IPACT a higher queue delay is observed, and at higher offered loads (200Mbps, 170Mbps, and 130Mbps for ONU1, ONU4, and ONU16 respectively), the ONUs reach a state of saturation.

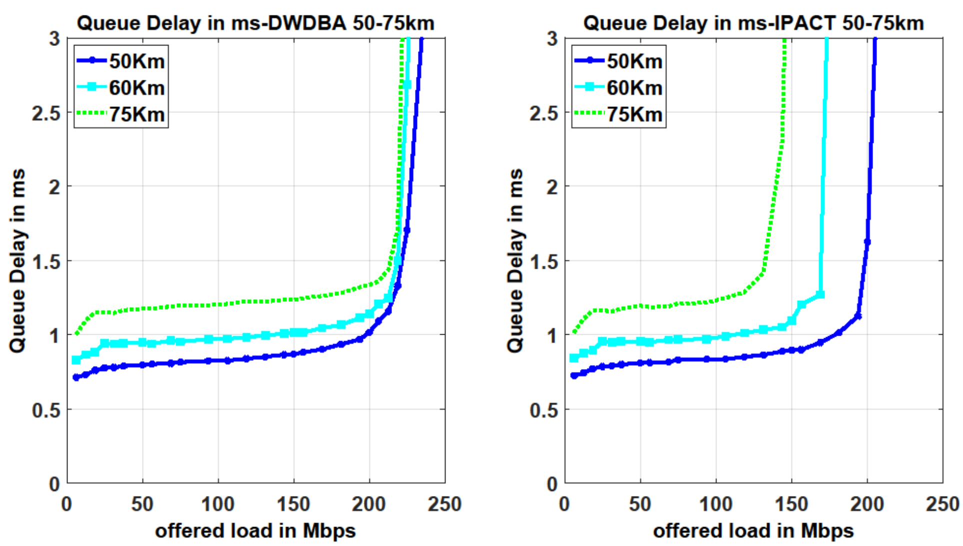

Figure 5.8: Queue delay for scenario 1 (50km to 75km) for DWDBA (left) and IPACT (right).

The results for scenario 2 (with ONU2 at 70km, ONU4 at 80km, and ONU16 at 100km) are presented in Figure 5.9. In the DWDBA case, ONUs exhibit low queue delay, which is sustained up to an offered load of 180Mbps for ONU16, 220Mbps for ONU4, and 225Mbps for ONU2. In contrast, for IPACT, considerably higher queue delay is observed. Furthermore, the ONUs under IPACT reach saturation at lower offered loads, with ONU16 saturating at 85Mbps, ONU4 at 125Mbps, and ONU2 at 145Mbps.

In scenario 3 (ONU5 at 17km, ONU6 at 37km, ONU4 at 56km, ONU11 at 71km, and ONU1 at 100km), the results confirm again the reduction in queue delay of DWDBA compared to IPACT, as shown in Figure

5.10, Notably, even the farthest ONU (ONU1 at 100km) is able to maintain a queue delay below 1.5ms up to an offered load of 150Mbps under DWDBA, while under IPACT, it is unable to achieve the 1.5 ms delay even at a load below 50Mbps.

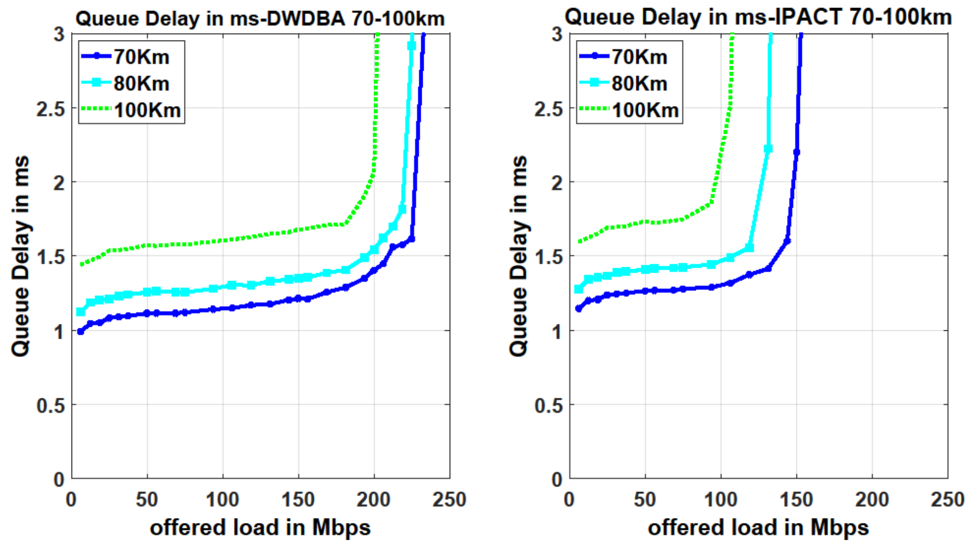

Figure 5.9: Queue delay for scenario 2 (70km to 100km) for DWDBA (left) and IPACT (right).

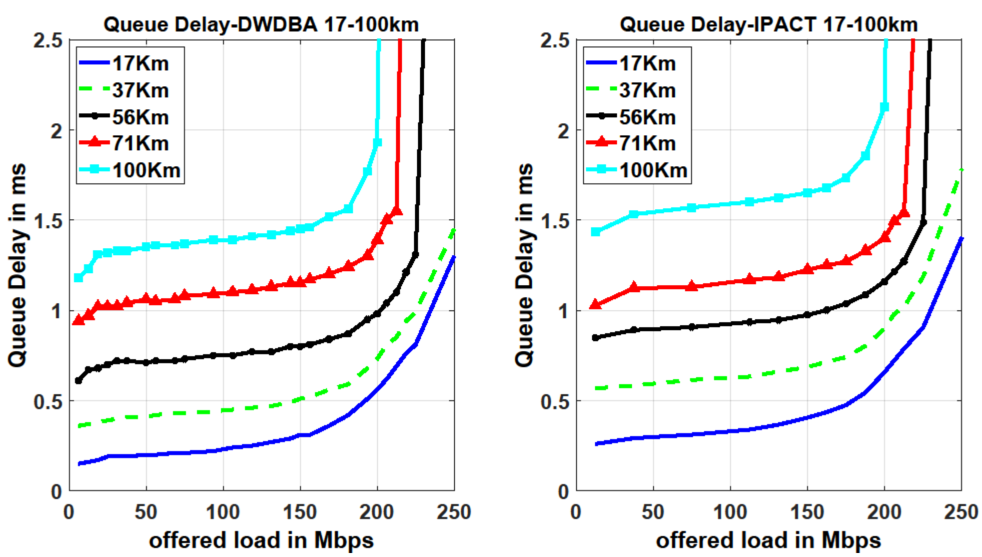

Figure 5.10: Queue delay for scenario 3 (17 Km to 100Km) for DWDBA (left) and IPACT (right).

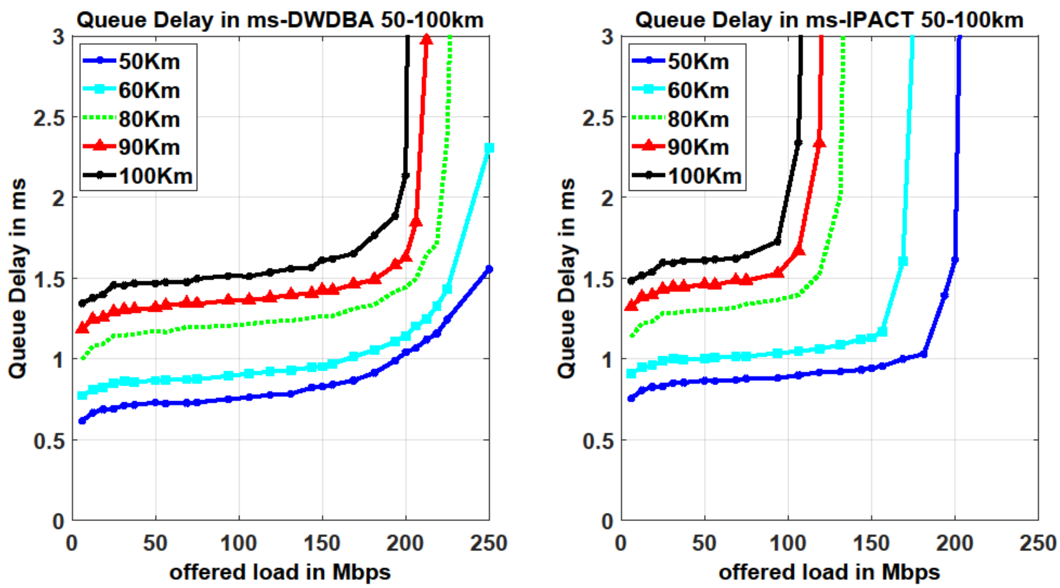

Figure 5.11: Queue Delay for scenario 4 (50km to 100km) for DWDBA (left) and IPACT (right).

Finally, Figure 5.11 presents the results from scenario 4, where ONUs are positioned between 50km and 100km from the OLT. Again, DWDBA obtains lower queue delays that are proportional to their distances from the OLT, even at higher offered loads. The figure also shows that under the IPACT algorithm, the ONUs closer to the OLT display lower queue delays than the ONUs positioned farther away, which is a similar behavior the DWDBA algorithm. ONUs under the IPACT algorithm are unable to sustain low queue delays beyond an offered load of 100 Mbps, whereas the DWDBA algorithm allows the ONUs to maintain low queue delays even at offered loads of up to 200 Mbps.

5.6 Discussion of Results

The results of our study show a comprehensive comparison between the DWDBA algorithm and the IPACT algorithm in terms of both queue delay and throughput. We investigated the influence of varying distances between the ONUs on the performance of the LRPON algorithms. Overall, DWDBA achieved an average bandwidth efficiency of approximately 85% in the upstream link, meeting the minimum efficiency standard set in [169]. The results consistently showed that the DWDBA algorithm outperformed the IPACT algorithm in terms of both queue delay by 30% reduction and throughput by up to 45% under high loads.

The DWDBA algorithm enabled ONUs, even those located farther from the OLT, to achieve higher throughput at higher offered loads.

In queue delay performance, the DWDBA algorithm demonstrated significant reductions, particularly at higher offered loads, making it well-suited for LRPON. In comparison to IPACT, it achieved a more than 30% reduction in queue delay while maintaining stability under increased offered loads. Even in scenarios where ONUs were dispersed, the DWDBA algorithm consistently outperformed IPACT. Our study observed that queue delay increased in proportion to the distance between ONUs and the OLT, as expected due to longer transmission paths. However, the implementation of the DWDBA algorithm effectively addressed this issue by ensuring that ONUs were not penalized based on their distances from the OLT.

Furthermore, the DWDBA algorithm demonstrated its ability to handle increased network traffic loads without becoming overwhelmed. It was able to effectively manage and allocate resources even when the network's traffic load exceeded 200 Mbps before any noticeable degradation in performance occurred. This highlights its capacity to handle higher traffic demands without compromising the quality of service. In contrast, the IPACT algorithm exhibited limitations in maintaining acceptable queue delay and throughput, especially at higher offered loads.

5.7 Summary

This chapter has discussed the challenges and solutions related to DBA in LRPONs. LRPONs have emerged as a promising solution to extend the coverage of PONs across larger geographical areas. However, the increased propagation delays in LRPONs pose significant challenges for traditional DBA algorithms, such as IPACT.

We reviewed related work on DBA in LRPONs, covering recent research on DBA algorithms for LRPONs, focusing on devising efficient methods to allocate bandwidth to ONUs, taking into account various constraints such as QoS requirements, energy efficiency, and fairness. In response to these challenges, we introduced a novel DBA algorithm, DWDBA, specifically tailored to address the unique requirements of LRPONs. DWDBA incorporates distance-based prioritization and LTT considerations to optimize bandwidth allocation and minimize transmission delays.

We presented the DWDBA in detail, with a flowchart and pseudocode provided for a comprehensive understanding. We conducted an evaluation using OPNET Modeler and demonstrated the superior performance of DWDBA compared to IPACT, particularly for ONUs located farther from the OLT. DWDBA significantly enhances throughput and reduces the queue delay by more than 30%, thereby, ensuring fair and efficient bandwidth distribution across the network.

Chapter 6
Conclusions and Future Work

6.1 Conclusions

This report describes our contributions regarding the development of DBA algorithms for PONs. In Chapter 1, we established the foundation for our research by outlining the motivations and objectives that drive the significance of this thesis. We have chosen to focus specifically on PONs and LRPONs as they play a crucial role in modern network infrastructure.

In the second chapter, we examined the legacy mechanisms that have significantly contributed to the evolution of optical networks. Additionally, we surveyed the latest progress in optical networks, with a focus on next-generation networking technologies, and we highlighted ongoing research initiatives and implementations that are shaping the future of optical communication. We discussed the state-of-the-art solutions, considering the latest advancements in 5G networks and beyond.

In Chapter 3, we discussed how resources are allocated in optical networks to make the best use of the network and improve data transmission. Our research focused specifically on resource allocation in GPON and EPON technologies, looking at how they can work together and be integrated to improve multiplexing techniques in future networks. One important aspect of resource allocation is the laser tuning, which allows for flexibility and adaptability in choosing the wavelength for transmission. We thoroughly explored the concept of laser tuning time and how it affects network performance and response time. We also reviewed different DBA solutions in detail, analyzing their strengths and limitations. Furthermore, we examined the latest developments in DBA solutions, which provided valuable insights into the current advancements and challenges in this important area.

Chapter 4 describes our first set of original contributions, in collaboration with another researcher. Our research focused on DBAs in multiwavelength PONs, always considering the laser tuning time. We introduced the Longest Processing Time technique, which helps reduce the average queue delay. We built a simulation model to test the feasibility and effectiveness of the proposed DBA techniques, and compared them with IPACT as baseline. With the introduction of the LPT technique, we achieved improved performance with a reduction in queue delay of up to 73% compared to IPACT.

Building upon this foundation, in Chapter 5 we further extended our work to create a DBA specifically tailored for Long-Reach PONs. The DBA for LRPONs addresses the unique challenges faced by extended reach networks, ensuring that ONUs located at greater distances from the OLT are not disadvantaged. We investigated the limitations of traditional DBAs in addressing the complexities of LRPONs and developed the DWDBA algorithms, which assigns weight vectors to ONUs based on their distance from the OLT. This method takes into account the challenges of long RTT in long-distance optical networks without penalizing any ONU based on its distance. The results underscore the potential of our proposed DBAs in managing LRPONs. Compared to IPACT, our DWDBA algorithm achieved a reduction of over 30% in queue delay while maintaining stability at higher loads. Moreover, the algorithms demonstrated robustness and adaptability to changing network conditions. Overall, our optimized algorithms for LRPON present a promising and effective solution for enhancing bandwidth utilization and reducing queue delay in LRPONs, setting them apart from existing DBAs.

What follows is a list of publications generated during this thesis.

- **Haastrup, Adebanjo**, Mohammad Zehri, David Rincón, José Ramón Piney, and Ali Bazzi. "A Distance-Weighted Dynamic Bandwidth Allocation Algorithm for Improved Performance in Long-Reach Passive Optical Networks for Next Generation Networks", Photonics, vol. 10, no. 8, 923, pp. 1-21. MDPI, 2023.

  This publication includes the results described in Chapter 5, related to LRPON. The journal is ranked as Q3 in the Journal of Citation Reports (JCR) in its 2022 edition, and as Q2 in the Scimago Journal Rank (SJR) in 2022 (the 2023 data is not available at the time of writing this thesis).

- **Haastrup, Adebanjo**, Mohamad Zehri, David Rincón, and José Ramón Piney. "Optimizing Resource Allocation in Long-Reach PONs for Improved Performance in 6G Networks", 23rd International Conference on Transparent Optical Networks (ICTON) 2023, pp. 1-4. IEEE, 2023.

This publication includes the results described in Chapter 4, related to LRPON. The ICTON conference is indexed by JCR (WoS Core Collection) and Scopus. Google Scholar reports 1 citation.

- Zehri, Mohammad, **Adebanjo Haastrup**, David Rincón, José Ramón Piney, Sebastià Sallent, and Ali Bazzi. "A QoS-aware dynamic bandwidth allocation algorithm for passive optical networks with non-zero laser tuning time", Photonics, vol. 8, no. 5, 159, pp. 1-22. MDPI, 2021.

  This publication includes the results described in Chapter 4, related to the LTT-aware DBA. The journal is ranked as Q3 in JCR 2021 and as Q2 in SJR 2021. JCR reports 4 citations (3 when self-citations are excluded), Scopus reports 5 citations (3 without self-citations), and Google Scholar reports 7 citations (5 without self-citations).

- Zehri, Mohamad, **Adebanjo Haastrup**, David Rincón, José Ramón Piney, Sebastià Sallent, and Ali Bazzi. "Leveraging SDN-Based Management for Improved Traffic Scheduling in PONs", 22nd International Conference on Transparent Optical Networks (ICTON), pp. 1-4. IEEE, 2020.

  This publication includes the results described in Chapter 4, related to the realistic introduction of LTT. The ICTON conference is indexed by JCR (WoS Core Collection) and Scopus. Scopus and Google Scholar report 1 self-citation.

6.2 Future work

As we conclude this thesis, the insights gained, and contributions made pave the way for exciting future directions in the field of optical networks. Future work for this research could focus on several areas to further advance the field of optical access networks, as described in the following subsections.

6.2.1 Hardware implementation of the algorithms

A natural extension of this work is the implementation of the algorithms in real hardware. Among the technologies available today, the most promising is P4 (Programming Protocol-Independent Packet Processors) [170, 171], an open-source programming language for network equipment. P4 is aligned with the Software-Defined Networking (SDN) [75] paradigm, which promotes the separation of the control and data planes in network devices and a centralized controller entity that has a global view of the network and its state. P4 could be used to implement the data plane of PON OLT and ONUs around a programmable P4 switch, following a similar approach to that described in [23, 75, 172] for OpenFlow, a legacy and less powerful SDN protocol. This integration of PON and SDN would enhance the adaptability of PON devices, especially as OANs progress towards network slicing and on-demand service provisioning [173].

Although this was one of our initial goals in this thesis, due to resource constraints, we changed our focus to the algorithmic and simulation fields, but we presented a first design of a P4-PON architecture in a couple of conferences [174] [175] in 2018. In our proposal, the introduction of a P4 programmable switch at the OLT facilitates the virtualization of the MPMC sub-layer, with some functionality transferred to the P4ON controller on the ONOS controller, and the remainder integrated with the P4-enabled switch within the P4-based OLT. This enables the P4 runtime to deliver MAC and software-defined functionalities to the PON system through matching and acting on specific tables.

As far as we know, besides our work, only one other research team has ventured into this field of study. Their research, outlined in [173, 176], details the execution of DBA on a programmable P4 pipeline. The mechanism divides the DBA scheduling into two segments. The first segment operates according to standard DBA procedures, where the bandwidth map is computed after receiving all necessary grant requests for a given cycle. The second segment, known as Fast Intercept, operates in the P4 hardware NIC, spoofing upstream low latency Dynamic Bandwidth Report unit (DBRu) requests and storing them until the next bandwidth map (BWMAP) arrives from the downstream frame. It then alters the BWMAP by adding grants from the low latency DBRus to the unallocated portion of the BWMAP. This approach achieves latency reduction between 37% and 43%, compared to standard and virtual PONs.

6.2.2 Distributed DBA algorithms

A promising area for research is the development of more sophisticated DBA algorithms that follow a distributed approach, building on existing work [88, 172]. This decentralized approach would place greater responsibilities on ONUs for scheduling and computing their bandwidth allocation, particularly in the context of multiwavelength PONs and LRPONs. Under this distributed approach, each ONU would be able to proportionally schedule its transmission window size based on its own queue requirements and the requirements of the other ONUs. This is achieved by utilizing the weight vector, a piece of information about the bandwidth consumed by other ONUs that is included in the GATE message received from the OLT.

The work in [177] indicates that distributed DBA algorithms can outperform centralized approaches, particularly under bursty traffic conditions. For instance, a distributed algorithm, DDSPON [87] demonstrates higher throughput allocation efficiency and significantly lower instantaneous delays compared to IPACT, a centralized DBA algorithm.

Thus, the combination of the techniques used in our work, specifically LPT and NASC with DDSPON, could further decrease the average delay, and in a second phase, one could think of a TWDM version of DDSPON, evaluated under realistic conditions by taking in consideration the laser tuning time. To the best of our knowledge, there has been no previous integration of distributed DBA with TWDM, making this a novel and unexplored research direction.

6.2.3 Energy awareness

A critical area for future research is the exploration of energy-efficient solutions for optical networks as current access networks (including customer's premises equipment) consumes about 80% of the energy consumed on the Internet [17]. To address this, it is important to develop DBA algorithms that prioritize energy conservation while ensuring efficient resource utilization. In the context of TWDM-PON, there are interesting opportunities to save energy both at the OLTs and ONUs. The wavelengths at the OLT can be used at a high utilization by turning off idle ones, and ONUs can exploit sleep modes due to a bursty and slotted transmission.

One proposal for energy-saving DBA is the sleep-based DBA (SB-DBA) algorithm [178]. In this scheme, both the OLT and ONUs enter power-saving modes to reduce overall energy consumption, reaching up to 98% energy savings. Another notable algorithm is the hybrid sleep mode aware (HSMA) algorithm [17]. HSMA minimizes energy consumption at both the OLT and ONUs by combining sleep modes and the load-dependent use of transceivers at the OLT. HSMA utilizes a two-phase scheduling approach: wavelength minimization and assignment (WMA) and time slot assignment (TSA). WMA addresses traffic variability over a period, while TSA distributes bandwidth among ONUs on a per-cycle basis. HSMA has been shown to reduce average energy consumption by 31% and decrease delay compared to conventional algorithms.

Additionally, a novel energy-saving DBA algorithm was presented in [88] to enhance the energy efficiency of the DDSPON algorithm, combining the benefits of distributed DBAs (reduced delay) with energy-saving features. It incorporates doze and sleep modes to reduce energy consumption by the ONUs. By analyzing ONUs' queue sizes and switching them to doze/sleep mode when there is no upstream/downstream traffic, respectively, the algorithm achieves improved energy efficiency. It has been demonstrated to improve energy efficiency by over 78% on average for each ONU compared to the DDSPON algorithm.

One interesting research path would be to integrate the on-off technique used for energy saving, with the laser tuning time constraints, which might be jointly optimized. The impact of LPT on the scheduling of the on-off periods is another aspect that could be explored. This concept is not limited to traditional PONs but can be extended to LRPONs, with particular attention to the challenges posed by the extended RTT inherent in LRPON architectures. By fine-tuning the DBA mechanisms to leverage the synergies between on-off periods, LPT scheduling, laser tuning time constraints, and considerations for LRPON features, there is potential to enhance the overall efficiency and performance of PONs while conserving energy.

6.2.4 C-RAN scenarios

In the context of C-RAN architecture, a promising avenue for future research direction is the enhancement of DBA algorithms for the Mobile fronthaul (MFH) [11]. DBA plays a critical role in efficiently allocating bandwidth resources between the baseband unit (BBU) and remote radio heads (RRHs) within MFH setups.

One potential area of exploration could revolve around the development of DBA algorithms specifically designed to handle the unique characteristics and requirements of MFH in C-RAN. This includes considering the dynamic nature of MFH traffic, which can vary based on the number of RRHs and their associated traffic patterns. The algorithms should be able to adapt and allocate bandwidth resources in real-time to meet the changing demands of the RRHs.

One recent proposal in this realm is a novel DBA mechanism based on the concept of a dynamic service interval for XG-PON in mobile fronthaul [179]. This scheme capitalizes on the dynamicity of the service interval, resulting in variable allocation bytes that can provide dynamic grants based on variable demand. The results of this proposed DBA scheme have demonstrated its ability to meet the latency requirements of LTE RRHs, showcasing improvements in mean delay, packet loss ratio (PLR), and grant-request ratio.

Integrating LPT and NASC techniques into MFH DBA schemes under a realistic non-zero LTT can potentially enhance the performance of C-RANs. This integration has the potential to significantly reduce average delays and provide high throughput, ensuring that C-RANs can effectively meet the demanding requirements of future traffic. To the best of our knowledge, there has been no previous implementation of these algorithms in the context of PONs applied to C-RAN.

Another promising future direction involves integrating these techniques with deep learning models, such as the intelligent DBA proposed in [180]. By leveraging the power of deep learning, we can further optimize performance and adapt to real-time traffic patterns, enabling C-RANs to operate at an even higher level of efficiency.

In addition, we suggest exploring the application of the aforementioned techniques (subsections 6.2.1, 6.2.2, and 6.2.3) within the context of MFH. These techniques can play a crucial role in optimizing bandwidth allocation and improving network performance in the Mobile Fronthaul (MFH) domain. As these techniques continue to evolve, they are poised to play a pivotal role in shaping the future of C-RANs.

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