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DEPARTMENT OF ELECTRICAL AND COMPUTER ENGINEERING

CONVERGED OPTICAL ACCESS NETWORKS FOR MOBILE BACKHAUL

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A Dissertation

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APPROVAL PAGE

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Converged Optical Access Networks for Mobile Backhaul

The present Doctorate Dissertation was submitted in partial fulfillment of the requirements for the Degree of Doctor of Philosophy in the Department of Electrical and Computer Engineering, and was approved on July 30, 2019 by the members of the Examination Committee.

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The present doctoral dissertation was submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy of the University of Cyprus. It is a product of original work of my own, unless otherwise mentioned through references, notes, or any other statements.

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Abstract

Over the last few years, demand for high-bandwidth access networks has been growing continuously, thus service providers are always searching for efficient and effective architecture solutions for the access arena, while also considering the integration of next-generation optical access architectures with mobile broadband access technologies that can fully support both mobile and fixed traffic. Further, wireless/mobile networks have recently received significant attention, resulting in a growing gap (imbalance) between the current fixed and future mobile components of next-generation networks; thus, as also highlighted by the ITU-T Focus Group Technologies for Network 2030 (FG NET-2030), next generation fixed access networks are required to be developed in order to support and guarantee the data throughput of the mobile services.

Combining the capacity of WDM-PONs with the ubiquity and mobility of wireless networks forms a powerful platform for the support and creation of future applications and services. In particular, PON architectures can be utilized to backhaul traffic from individual base stations (BSs) to the Radio Network Controller (RNC), which then connects to the mobile operators' core network or gateway (this mobile backhaul is also referred to as the Radio Access Network (RAN)). However, in order for the PON architectures to backhaul mobile traffic, new distributed TDM/WDM-PON-based backhaul architectures are needed, as next-generation wireless technologies require more distributed RAN architectures. Furthermore, in these types of converged optical-wireless access networks, failures occur often and sometimes with serious consequences. Even though failures cannot be avoided, quick detection and recovery of a fault are essential for highly reliable network operation. Thus, integration of WDM-PON architectures with next-generation mobile broadband access technologies presents a number of open issues, challenges, and opportunities which need to be studied in order to be able to provide innovative

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future Fiber-Wireless (FiWi) networks.

The objective of this dissertation is to study problems related to efficient wavelength sharing and scheduling for both fixed and wireless traffic in converged optical-wireless access networks, as well as novel converged access architectures and techniques for failure recovery of both fixed and wireless traffic in converged access networks. Specifically, new heuristics and optimization algorithms are proposed for converged ring-based WDM-PON optical access networks in order to support efficiently the network traffic. Also, a resilient wheel-based optical access network architecture is proposed that can efficiently support not only the fixed users but also the mobile users in both downstream and upstream operations under normal and failure scenarios, while minimizing the average traffic delivery time and without using extra redundant fibers for protection purposes.

The main objective is to provide services that are high-speed, symmetric, survivable, and with guaranteed QoS, supporting different types of traffic for both fixed and mobile users. This dissertation fills an existing void in the access arena by formulating and developing solutions for the problem of efficiently and reliably transporting fixed and wireless traffic in converged access networks.

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Περίληψη

Τα τελευταία χρόνια, η ζήτηση για δίκτυα πρόσβασης μεγάλης χωρητικότητας αυξάνεται συνεχώς, οπότε οι πάροχοι υπηρεσιών ψάχνουν πάντοτε για αποδοτικές και αποτελεσματικές λύσεις για την αρχιτεκτονική των δικτύων πρόσβασης, λαμβάνοντας επίσης υπόψη την ενσωμάτωση των αρχιτεκτονικών οπτικών ινών επόμενης γενιάς με τα ευρυζωνικά δίκτυα ασύρματης τεχνολογίας, που θα μπορούν να υποστηρίξουν πλήρως τόσο την ασύρματη όσο και τη ενσύρματη διακίνηση δεδομένων. Ως εκ τούτου, όπως επισημάνθηκε και από ομάδα της Οργάνωσης ITU-T που εστιάζεται στα Δίκτυα του 2030 (FG NET-2030), πρέπει να αναπτυχθούν νέα οπτικά δίκτυα πρόσβασης επόμενης γενιάς για να υποστηρίξουν και να εγγυηθούν τη διακίνηση δεδομένων για τις υπηρεσίες των ασύρματων δικτύων.

Ο συνδυασμός της χωρητικότητας των παθητικών οπτικών δικτύων χρησιμοποιώντας πολυπλεξία κατά μήκος κύματος με την κινητικότητα που παρέχουν τα ασύρματα δίκτυα αποτελεί μια ισχυρή πλατφόρμα για την υποστήριξη και τη δημιουργία μελλοντικών εφαρμογών και υπηρεσιών. Συγκεκριμένα, οι αρχιτεκτονικές παθητικών οπτικών δικτύων μπορούν να χρησιμοποιηθούν για την μεταφορά δεδομένων από μεμονωμένους σταθμούς βάσης στον ελεγκτή δικτύου ραδιοσυχνοτήτων. Ωστόσο, για να χρησιμοποιηθούν με τέτοιο τρόπο οι αρχιτεκτονικές παθητικών οπτικών δικτύων, απαιτείται να μπορούν να λειτουργούν με κατανεμημένο τρόπο. Επιπλέον, σε αυτά τα συγκλιόμενα οπτικά-ασύρματα δίκτυα πρόσβασης, σφάλματα εμφανίζονται συχνά και μερικές φορές με σοβαρές συνέπειες. Παρόλο που τα σφάλματα δεν μπορούν να αποφευχθούν, η γρήγορη ανίχνευση και αποκατάσταση των σφαλμάτων είναι απαραίτητη για την αξιόπιστη λειτουργία του δικτύου. Έτσι, η ενσωμάτωση των αρχιτεκτονικών παθητικών οπτικών δικτύων με πολυπλεξία κατά μήκος κύματος με τις τεχνολογίες κινητής ευρυζωνικής πρόσβασης επόμενης γενιάς παρουσιάζει μια σειρά από ανοικτά ζητήματα, προκλήσεις, και ευκαιρίες που πρέπει να μελετηθούν προκειμένου τα μελλοντικά δίκτυα οπτικής-ασύρματης πρόσβασης να μπορούν να παρέχουν υπηρεσίες αποτελεσματικά και αξιόπιστα.

Σκοπός της παρούσας διατριβής είναι η μελέτη προβλημάτων που σχετίζονται με την

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αποτελεσματική κατανομή μήκους κύματος και τον προγραμματισμό τόσο της σταθερής όσο και της ασύρματης κίνησης δεδομένων σε οπτικά-ασύρματα δίκτυα πρόσβασης, καθώς και καινοτόμες αρχιτεκτονικές και τεχνικές για την αποκατάσταση τόσο της σταθερής όσο και της ασύρματης κίνησης δεδομένων σε αυτά τα δίκτυα. Συγκεκριμένα, προτείνονται νέοι αλγόριθμοι για την αποτελεσματική υποστήριξη της κυκλοφορίας του δικτύου. Επίσης, προτείνεται μια νέα, ευέλικτη αρχιτεκτονική δικτύου οπτικής πρόσβασης η οποία μπορεί να υποστηρίξει αποτελεσματικά όχι μόνο τους σταθερούς χρήστες αλλά και τους χρήστες των ασύρματων δικτύων κάτω από κανονικές συνθήκες λειτουργίας του δικτύου και σε περιπτώσεις που υπάρχουν σφάλματα στο δίκτυο, ελαχιστοποιώντας τον μέσο χρόνο παράδοσης των δεδομένων και χωρίς να χρησιμοποιούνται επιπλέον οπτικές ίνες για λόγους προστασίας του δικτύου.

Ο κύριος στόχος είναι η παροχή υπηρεσιών υψηλής ταχύτητας, συμμετρίας, ανθεκτικών στα σφάλματα και με εγγυημένη ποιότητα εξυπηρέτησης, για τους σταθερούς και κινητούς χρήστες του δικτύου. Αυτή η διατριβή συμπληρώνει ένα υπάρχον κενό στην αρένα δικτύων πρόσβασης με τη διατύπωση και την ανάπτυξη λύσεων για το πρόβλημα της αποτελεσματικής και αξιόπιστης μεταφοράς σταθερής και ασύρματης κίνησης δεδομένων σε συγκλιόμενα οπτικά-ασύρματα δίκτυα πρόσβασης.

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2. D. Monoyios, K. Manousakis, C. Christodoulou, et al., “Indirect Crosstalk-aware Routing and Wavelength Assignment in Transparent Optical Networks with the Use of Genetic Algorithms”, *Proc. IEEE International Conference on Transparent Optical Networks (ICTON)*, July 2016.

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List of Acronyms

ADC	Analog-to-Digital Converter
APON	Asynchronous Transfer Mode Passive Optical Network
APS	Automatic Protection Switch
ASIC	Application-Specific Integrated Circuit
AWG	Array Waveguide Grating
BS	Base Station
BPON	Broadband Passive Optical Network
CDMA	Code Division Multiple Access
CO	Central Office
CMDC	Control and Management Data Center
CWSA	Cooperation-Based Wavelength Selection Algorithm
DAC	Digital-to-Analog Converter
DBA	Dynamic Bandwidth Allocation
DPSK	Differential Phase Shift Keying
DS	Downstream
DSL	Digital Subscriber Line
EPON	Ethernet Passive Optical Network
FTTB	Fiber-To-The-Building
FTTC	Fiber-To-The-Curb
FTTH	Fiber-To-The-Home
FTTx	Fiber-To-The-x
FiWi	Fiber-Wireless
FSAN	Full Service Access Network
FF	First-Fit

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GPON	Gigabit Passive Optical Network
HPSA	High Priority Scheduling Algorithm
IPACT	Interleaved Polling with Adaptive Cycle Time
LAN	Local Area Network
LTE	Long Term Evolution
LL	Lightly-Loaded
LRD	Long-Range Dependence
MAC	Media Access Control
MAN	Metro Access Network
NG-PON	Next Generation PON
OCS	Optical Carrier Suppression
ODN	Optical Distribution Network
OFDM	Orthogonal Frequency Division Multiplexing
OLT	Optical Line Terminal
ONU	Optical Networking Unit
OOL	ONU Offered Load
OSW	Opto-mechanical Switch
P2MP	Point to Multipoint
PDC	Phasor Data Concentrator
PEV	Pluggable Electric Vehicles
PON	Passive Optical Network
QAM	Quadrature Amplitude Modulation
QoS	Quality-of-Service
RN	Remote Node
RNC	Radio Network Controller
RAN	Radio Access Network
RF	Radio Frequency
Rx	Receiver
SC	Star Coupler
SCADA	Supervisory Control And Data Acquisition
SBR	Sharing Backup Radios
SLA	Service Level Agreement

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SP	Service Providers
TDM	Time Division Multiplexing
TDMA	Time Division Multiple Access
Tx	Transmitter
US	Upstream
WDM	Wavelength Division Multiplexing
WiFi	Wireless Fidelity
WiMAX	Worldwide Interoperability for Microwave Access
WMN	Wireless Mesh Networks
WSaS	Wavelength Selection and Scheduling
WS-ASK	Wavelength-Shifted Amplitude Shift Keying
WSN	Wireless Sensor Network

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Chapter 1

Chapter 1

1.1 Background

Over the last few decades there has been a tremendous growth in the development of both high-capacity backbone and Metro Access Network (MAN) architectures. In both these architectures the emergence of intelligent optical networks played a crucial role, as nowadays optical network architectures not only provide transmission capacities to higher transport levels, but also the intelligence required for fast lightpath provisioning and fast and efficient failure restoration. In these networks optical switches (optical cross-connects, reconfigurable optical add-drop multiplexers, etc.) can be utilized to provision the traffic and enable the network to recover in the case of a failure event. Wavelength division multiplexing (WDM) has been the norm for these networks in the last two decades, even though recently, because of the increasing traffic demand in backbone networks, orthogonal frequency division multiplexing (OFDM)-based networks have been proposed. These networks are called flex-grid (or elastic optical networks) because they can "elastically" allocate spectrum, contrary to the fixed grid utilized in WDM networks. Specifically, in these networks, due to orthogonality, the spectrum is split into finer granularity slices (e.g., of 25, 12.5, and 6.25 GHz) compared to the 50 GHz spacing of fixed grid networks and this way each demand can be allocated a number of spectrum slices, leading to better utilization of the network's resources.

Generally, backbone networks are provisioned for operation under worst-case scenarios of link failures, and thus backbone links are lightly loaded most of the time. In addition, high capacity routers and ultra-high capacity fiber links have

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created a true broadband architecture. However, large backbones are not the whole the equation; distribution of that connectivity to individual enterprises and homes is just as critical for meeting the huge demand for more bandwidth. Even though the technology has progressed significantly in the backbone and metro-area arena, access technologies/networks represent a significant bottleneck in bandwidth and service quality between a high-speed residential/enterprise network and a largely overbuilt core backbone network, as the end users are constantly becoming more and more sophisticated, using rich multimedia and high-bandwidth applications and real-time services that have to be accommodated by these access networks. This in turn makes it difficult to support end-to-end Quality of Service (QoS) for a wide variety of applications, particularly non-elastic applications such as voice, video, and multimedia that cannot tolerate variable or excessive delay or data loss.

Bridging this emergent gap between the capacity provided by the backbone and metro networks on one side and the actual capacity experienced by end-users on the other, with the last-mile bottleneck in between, is one of the most significant challenges facing service providers and local carriers. Passive optical network (PON) is a technology viewed generally as the most promising access solution poised to break the last-mile bandwidth bottleneck, as PON access networks can deliver future high data rates (10Gbits/s and beyond) in both the downstream and upstream directions.

PONs are point-to-multipoint fiber networks with no active elements in the signal's path, consisting of the Optical Line Terminator (OLT) on the service provider side and Optical Networking Units (ONUs) on the user side connected to the OLT through one shared fiber. A PON architecture has a number of advantages, as it allows for longer distances between central offices and customer premises, it minimizes fiber deployment in both the local exchange and the local loop, provides higher bandwidth due to deeper fiber penetration, supports high quality triple play services (for data, voice and video), and supports high-speed Internet access and other services in a cost-effective manner [92]. PONs have in the last few year become the most popular fiber access network solution to be used in the access arena because of their service transparency, cost effectiveness, energy savings and higher security. There are in general several technologies and architectures utilized for the implementation of PON architectures, as described in detail in Chapter 2 of the thesis. Chapter 2 discusses all these different types of technologies, analyzing the

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advantages and disadvantages of each.

In addition to the fixed access infrastructure, looking at the mobile traffic arena, service providers (SPs) worldwide are being challenged to deliver new innovative offerings beyond voice and basic data services to their customers. This has led to the development/deployment of new wireless broadband access technologies including 4G and 5G networks and cellular Long-Term Evolution (LTE). A typical cellular system consists of the radio link, the backhaul access network and the mobility core network. The radio link with the backhaul network are known as the radio access network (RAN). Most of the existing backhaul networks, that support 3G and 4G systems, are using Ethernet/IP-based transmission using mostly optical fiber as the transport medium, in contrast with the older 2G and 3G systems that are using T1-based lines with time division multiplexing techniques. However, moving to 5G systems and beyond, only fiber-optic systems are envisioned to be used in the integration of the access arena with the wireless system in order to support the increasing bandwidth requirements. Thus, optical fiber networks are poised to play an important role in these networks, and particularly in the development of high-speed mobile backhaul and fronthaul, that are essential nowadays for the telecommunications industry, especially as it moves towards 5G wireless technologies. As the mobile and fixed users' data traffic is growing continuously, there is a need for new high-speed and cost-effective backhaul and fronthaul fiber access networks which will connect the cell cite to the core network in an efficient and effective manner. The service providers and local carriers are therefore challenged to find efficient solutions for the access arena to alleviate the "last mile" bottleneck problem for both the fixed as well as the mobile traffic.

1.2 Motivation

Traditional standalone optical and wireless networks have their limitations in order to support and manage the future traffic which is predicted to be more than 1000 times today's traffic volume. Many carriers are considering as an attractive solution the integration of next-generation optical access architectures with mobile broadband access technologies. In general, PONs as standalone networks provide capacity, however integrated with the mobility and ubiquity of the wireless networks they can be used to support the future growing traffic demand for all kind of users (fixed

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and mobile users). Thus, by utilizing an optical access network as a mobile wireless backhaul, generated by both mobile and fixed wireline traffic can be supported, provided that a number of challenges can be addressed. In such an architecture, the different types of traffic, both fixed and mobile users, must be fully supported and provided with high-speed protected services and guaranteed quality-of-service (QoS). This has led to the development of a number of converged optical-wireless network solutions, integrating advanced optical access networks with the mobile infrastructure.

Clearly, the integration of optical and wireless networks promises a powerful platform by building a single (integrated) network having the enormous bandwidth of the optical fiber and the mobility provided by the wireless technologies. However, integration of next-generation fiber-based access architectures with mobile broadband access technologies presents a number of open issues, challenges, and opportunities which need to be studied in order to be able to provide innovative future Fiber-Wireless (FiWi) networks. Next-Generation optical-wireless access networks need to be able to provide and guarantee services that are high-speed, symmetric, and with guaranteed QoS, supporting different types of traffic for both fixed and mobile users. In particular, fiber-based access architectures can be utilized to backhaul traffic from individual base stations (BSs) to the Radio Network Controller (RNC), which then connects to the mobile operators' core network or gateway (this mobile backhaul is also referred to as the Radio Access Network (RAN)). However, in order for the PON architectures to backhaul mobile traffic, new distributed fiber-based access architectures are needed, as the next generation wireless technologies require more distributed RAN architectures.

Even though a large amount of research work has been undertaken for converged FiWi access architectures, most of this work has utilized the typically centralized tree-based access topologies, and did not consider architectures that can support distributed control and management functionalities. Further, for priority scheduling, significant research work has been undertaken but only for tree-based access architectures. It is also important to note that the fairness problem in these architectures is a challenging issue for any type of access architecture. This thesis work investigates new distributed access architectures and techniques for the efficient utilization of network resources that ensures proper bandwidth allocation for every class of service via priority scheduling in the downstream direction, as well as traffic

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flow rerouting and sharing in the upstream direction.

Furthermore, in these types of converged optical-wireless access networks, failures occur often and sometimes with serious consequences. As fiber-optic networks are cable-based technologies, they are subject to frequent damage due to either human or hardware error or potentially malicious attacks. Furthermore, due to the fact that optical fibers can transmit an enormous amount of data, a fiber cut or equipment failure will potentially have a devastating effect on the network and its users in terms of data lost. Even though failures cannot be avoided, quick detection and recovery of a fault are essential for highly reliable network operation. Research in fault detection, isolation, and recovery techniques has been ongoing over the years, mainly focusing on backbone network architectures. However, very limited work has taken place on the protection of access networks and even in those cases the solutions have been constrained mostly by the topology of the access networks in question. Thus, the aim is to provide an access topology and recovery protocols that allow for increased reliability, while at the same time keeping the cost of the proposed solution low in terms of capital expenditure required.

1.3 Thesis Objective/Contribution

Given the preceding discussion on the two major trends in access networks, namely large capacity sessions for fixed and wireless users, as well as the need for reliable services, we now have a context for the problems and results developed in this thesis. These trends have motivated us to explore techniques that can provide efficient utilization of resources in converged optical-wireless access networks, as well as efficient failure recovery in these networks in a fast and distributed manner. As it will become apparent in Chapter 2, there has been much research work done on converged optical-wireless access networks as well as on failure recovery in general (with some but not extensive work on failure recovery in access networks). The failure recovery research focuses mainly on point-to-point systems in networks with tree-based topologies or techniques that require considerable amount of resources (duplication of network equipment) to recover from a failure.

The objective of this dissertation is to study problems related to efficient wavelength sharing and scheduling for both fixed and wireless traffic in converged optical-wireless access networks, as well as novel converged access architectures

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and techniques for failure recovery of both fixed and wireless traffic in converged access networks. The efficient resource scheduling presented in this dissertation is based on the utilization of a simple and cost-effective local access ring-based WDM-PON architecture that addresses some of the limitations of conventional tree-based architectures including supporting dynamic allocation of network resources as well as a truly shared LAN capability among end users. The proposed architecture combines the salient features of both traditional static WDM-PONs (such as the dedicated connectivity to all subscribers with bit rate and protocol transparencies, guaranteed QoS, and increased security) and dynamic WDM-PONs (that efficiently utilize network resources via dynamic wavelength allocation/sharing and scheduling among end users by using efficient scheduling mechanisms).

In addition, this dissertation proposes a novel converged access topology and novel recovery protocols that guarantee failure recovery of any single failure scenario. The recovery process proposed is fast, without the requirement to utilize redundant fibers for failure recovery. It can recover the failure in real time, independent of the connection state of the network at the time of the failure. Thus, network recovery can be accomplished without disruption of higher layer operations and while ensuring minimal loss of information. We strongly believe that the problem of failure recovery is of crucial importance in the deployment of next generation converged optical-wireless access networks, especially given the high bandwidth services that the end users will be utilizing.

This dissertation fills an existing void in the access arena by formulating and developing solutions for the problem of efficiently and reliably transporting fixed and wireless traffic in converged access networks.

1.4 Organization of the Thesis

Chapter 2, is devoted to background material and presents a survey of the existing access technologies and architectures proposed in the literature. This chapter concentrates on passive optical networks (PONs) in networks utilizing TDM and WDM technologies. It also concentrates on survivability techniques for these access architectures. The chapter concludes with a discussion on the shortcomings of the existing architectures and recovery techniques and the need for a new recovery scheme that addresses fault restoration in PONs with minimal fiber usage, utilizing

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new types of access architectures.

Chapter 3 introduces the work specific to this thesis, starting with the traffic generation model that is used throughout the thesis to obtain an accurate and realistic performance analysis of the proposed algorithms. It subsequently analyzes the existing tree-based time division multiplexed passive optical network (TDM-PON) and presents and examines different dynamic bandwidth allocation algorithms in order to avoid packet loss in the upstream direction and provide better channel utilization.

Chapter 4 extends the work of Chapter 3 by initially introducing a converged ring-based PON access architecture for backhauling mobile traffic. In turn, algorithms (heuristics and an optimization algorithm) are presented for efficient wavelength sharing and scheduling, and their performance is examined, aiming to provide QoS for both fixed and mobile end users, including cases where different priorities of traffic are considered.

In Chapter 5, a novel resilient PON-based access architecture is proposed, which differs from all previous existing fixed optical access architectures as it utilizes a new wheel-based network topology which can be integrated with wireless technologies to efficiently backhaul mobile and fixed traffic under normal and failure operating conditions. Initially, wavelength sharing and scheduling algorithms are developed and analyzed for this architecture under normal operating conditions. Chapter 6 extends the work of Chapter 5 with additional experiments in the upstream/downstream direction, under different failure scenarios. The signaling and recovery protocols are described and analyzed under different single failure scenarios, and the performance of the proposed approach is compared to the ring-based PON architecture. Chapter 6 also explores multiple failure scenarios, under different network conditions. Our analysis shows that depending on the position of the failures, multiple failures can be recovered simultaneously utilizing the proposed architecture.

Chapter 7 ends the thesis by offering some concluding remarks and emphasizing the original contributions of this work. It is important to note that converged optical-wireless access networks constitute a very active research area and a number of questions are still unanswered. A number of issues can be raised from the results of this thesis, warranting further investigation. The second part of Chapter 7, indicates some of these worthy issues and notes them as topics for future study. It also includes

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a discussion of potential directions in which this work could be extended. While these problems were not tackled in detail, it is envisioned that this thesis will serve as a basis for their more elaborate undertaking.

Part of the results presented in this thesis have also been published in [19], [21], [20], and [30]. In addition two journal papers have been submitted and are currently under the second review.

1.5 Statement of Originality

This is to certify that to the best of my knowledge, the content of this thesis is my own work. This thesis has not been submitted for any degree or other purposes. I certify that the intellectual content of this thesis is the product of my own work and that all the assistance received in preparing this thesis and sources have been acknowledged.

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Chapter 2

Passive Optical Networks and Converged Fiber-Wireless Access Networks: State of the Art

2.1 Introduction

The demand for high-bandwidth access networks is expected to grow continuously, due to the increased expansion of innovative and high-bandwidth applications like Web 2.0, mobile TV, and streaming content, that will be the dominant application in next generation mobile networks. Thus, current backbone standards are expected to become less effective for building mobile access networks. Specifically, legacy technologies such as circuit-switched T1/E1 wireline or microwave used for existing 3G network infrastructures cannot scale to the capacity requirements of mobile broadband networks [25]. Thus, mobile operators are investing heavily in upgrading their backhaul infrastructure, with fiber-optic deployments to the base stations (fiber-to-the-cell). It is generally accepted that fiber deployment to cell towers (fiber-to-the-cell) is the only future-proof solution to build mobile backhauls, which will scale to the increased capacity requirements. This will alleviate the need of using expensive RF point-to-point links (i.e., 26GHz) or even the unlicensed 60GHz WiFi band. Apart from requiring additional RF circuits and antennas, they lack the high capacity, inherent resilience, and the ubiquity offered by optical fiber networks. Among the optical network architectures, passive optical networks (PONs) meet the needs for such high-capacity access architecture. PONs is an access technology, bearing a) low

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deployment costs, avoiding active components in the field, b) bandwidth sharing between the end-users, c) scalability in terms of users and points of presence, as well as d) bandwidth granularity. Different variants of PONs have been proposed but most were conceived based on the demands and bandwidth prospects of the past. PONs architectures have slightly changed since then and only the technology has changed. These are discussed in detail in the sections that follow.

Due to their compelling advantages, many works have addressed the need for building access architectures for mobile networks, such as [8] and [94]. This chapter presents some of the basic ideas related to the general area of converged fiber-wireless access networks, starting from various architecture solutions for standalone optical access networks and then moving to converged access solutions presented in the literature. This chapter also outlines the need for fault recovery techniques at the physical layer for such architectures and discusses various failure protection techniques that have also been proposed in the literature.

The rest of the chapter is organized as follows: Initially, Section 2.2 describes the different proposed PON architectures, including TDM-PON, WDM-PON, and OFDM-PON technologies. This is followed by Section 2.3 that describes the various converged fiber-wireless access network solutions proposed in the literature. Section 2.4 then presents various fault recovery techniques proposed for passive optical networks as well as for converged fiber-wireless access networks.

2.2 Passive Optical Networks

In order to implement optical access networks, passive optical networks (PONs) emerged as the successor to DSL and cable modems that could not provide enough bandwidth for emerging real-time, high bandwidth applications and services.

A passive optical network (PON) is a point-to-multipoint fiber optical network with no active elements in the signal's path. There are several multipoint topologies suitable for PON-based access networks including tree, tree-and-branch, ring, and bus architectures (see Fig. 2.1) [39]. For example, the tree-based topology consists of a single, shared optical fiber connecting a service provider's central office (head end) to a passive star coupler (SC) (optical splitter/combiner), which is located near residential customers. The SC is intentionally positioned a substantial distance away from the central office, but close enough to the end users in order to save fiber. Each

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customer receives a dedicated short optical fiber but shares the long distribution trunk fiber.

All transmissions (duplex operation) in a PON architecture are performed between an optical line terminal (OLT) and optical networking units (ONUs). The OLT resides in the central office, connecting the optical access network to the metro backbone. The OLT hosts the active equipment, particularly, the transmitter/receiver arrays that depend on the standard deployed. On the other hand, an ONU is located near end-users, at either the curb (FTTC) or the end-user location (FTTH and FTTB). Further, the ONU provides the required service interface to all operator's customers, that is e.g., used to provide broadband voice, data, and video services. A passive feeder network, also called Optical Distribution Network (ODN) is utilized to interconnect the OLT and ONUs. The ODN uses simple optical fiber and a power splitter and typically is in the form of a tree network architecture. In the downstream direction (from the OLT to the ONUs), a PON is a point-to-multipoint network, and in the upstream direction it is a multipoint-to-point network. Thus, the number of ONUs deployed determines the splitting ratio and thus the power budget of the system. The distance between the ONUs and the OLT is also an issue for investigation, not only due to delay, but because it also may cause optical power variations and the OLT receiver will operate in burst mode [42], [111].

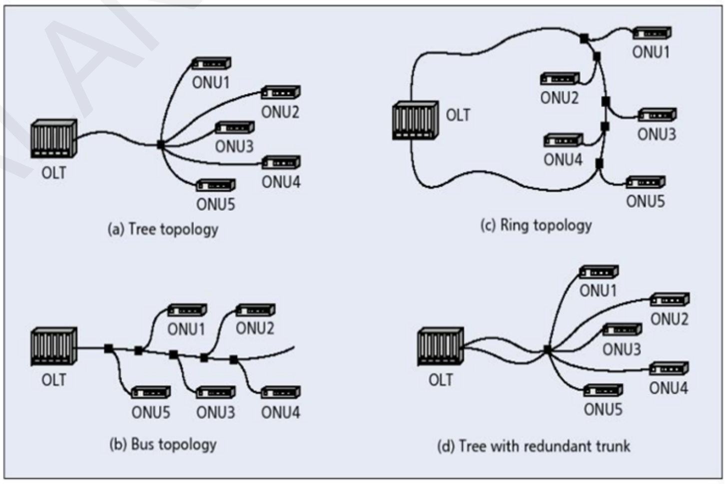

Figure 2.1: Different types of PON topologies [56].

There are several different technology options for PONs, depending on how data are multiplexed and transmitted, including time division multiplexed (TDM) PONs, where traffic from/to the OLT to multiple ONUs is time-division multiplexed over

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a single (or more) wavelength(s), wavelength division multiplexed (WDM) PONs which use discrete wavelength channels, one per ONU, and orthogonal frequency division multiplexed (OFDM) PONs, where a number of orthogonal subcarriers are employed to transmit traffic from/to the ONUs [56]. With the WDM and OFDM technology, PONs are capable of providing data rates of up to 40 Gb/s.

Even though PONs have several advantages, as it will be detailed below, they also face several challenges [78]. Significant research work has taken place over the years on PON technologies and architectures, pointing out the advantages of each proposed technique. Clearly, each multiplexing technology has its advantages and disadvantages [23], [70], [71], and the selection of which should be selected depends on several factors including the technology, the system performance, the power consumption, and the cost-effectiveness. Nowadays, the most popular PON architectures that can be found are EPON and GPON. Both architectures have the same framework and applications, however the physical and data link layers operations are different. Various research works have investigated possible architectures for next generation PONs. For example, in [29], the authors have presented a set of possible solutions for the next-generation PONs. Additionally, they have considered how the key requirements of the architecture can support the coexistence of the different multiplexing techniques in the same network/architecture and examined if this could be accommodated.

As wireless access technology is also gaining significant traction over the last few years, integrated solutions between the two access technologies must also be considered. In [101], the authors have reviewed the key enabling access technologies and progress advancements of both the optical and wireless access networks. Also, the emerging optical and wireless access technologies were also presented and compared. Nesset et al. [82], have also looked at the same problem albeit from a different angle, focusing on the requirements from network operators that are driving the standards developments and the technology selection prior to standardization, concluding that there are many challenges in the access arena in order to support the future traffic demand and stringent users/operators' requirements.

The sections that follow describe in brief the various proposed optical access networks, utilizing TDM, WDM, OFDM, or hybrid (TDM/WDM/OFDM) technologies, outlining some of the issues and limitations of the proposed solutions.

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2.2.1 Time-Division-Multiplexed Passive Optical Networks (TDM-PONs)

Time-division-multiplexed passive optical networks (TDM-PONs) allows multiple users to share the same bandwidth using a single wavelength in the upstream and downstream direction. In a typical TDM-PON, the downstream traffic is broadcasted from the OLT to all users (ONUs) as shown in Fig. 2.2 and is extracted by the assigned ONUs (each ONU extracts those packets that contain the ONUs unique Media Access Control (MAC) address). Typically, the number of ONUs that can be served ranges between 4 and 64 (depending on the technology utilized). In the upstream direction, EPON behaves as a timeshared network. This means that collisions may occur if two or more ONUs transmitters start transmitting frames simultaneously, or close enough, such that these frames may overlap at the combiner. Thus, the ONUs need to employ some arbitration mechanism to avoid collisions such that each ONU transmits within a dedicated time slot and the OLT receives a continuous stream of collision-free frames from multiple ONUs. This is shown in Fig. 2.3. Specifically, the OLT arbitrates transmissions via a Dynamic Bandwidth Allocation (DBA) module so that collision-free transmission can be guaranteed. Each ONU is assigned a specific timeslot by the OLT to sent its upstream data. In order to avoid collisions and utilize the bandwidth efficiently, different dynamic bandwidth allocation techniques have been proposed as discussed in more detail in Chapter 3 of this dissertation [34], [56], [78].

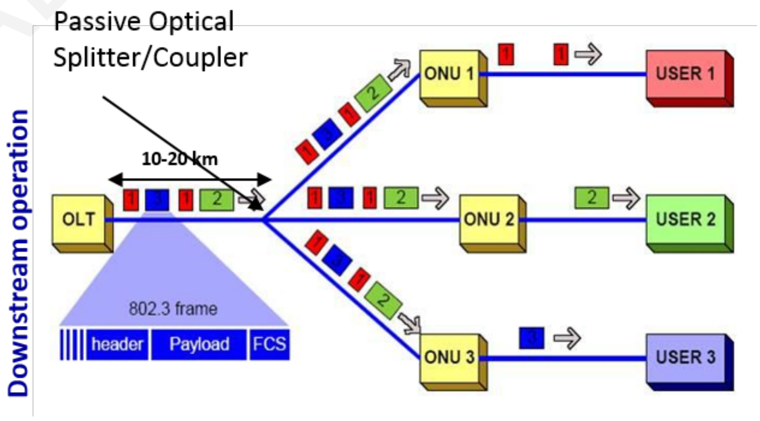

Figure 2.2: EPON downstream operation [58].

Over the years, a significant body of research and standardization work has taken place on TDM-PONs, while the most common topology investigated is the tree-based

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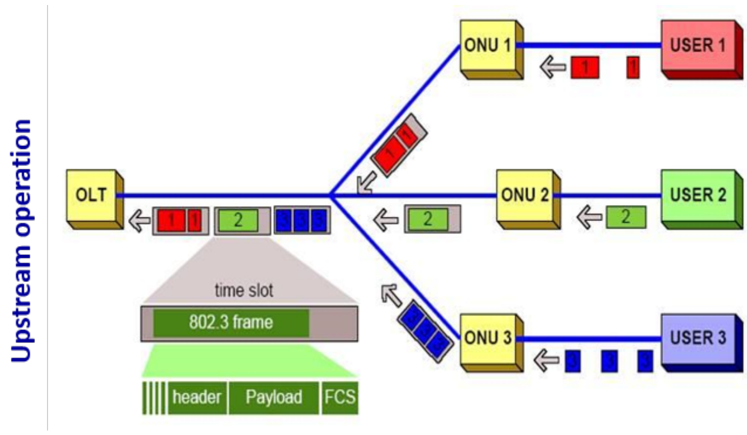

Figure 2.3: EPON upstream operation [58].

topology. In TDM-PONs, all ONUs transmit their data using the same wavelength, thus in order to avoid collisions each ONU must have its own transmission window. As all the ONUs operate on the same wavelength but send their data over different timeslots, this yields a lower bandwidth availability for each ONU. In [59], Kramer et al. discussed the advantages of using time-division multiple access (TDMA) in a PON, namely, the ability to provide a fraction of a wavelength capacity to each user, while using a single wavelength for all upstream channels, thus limiting the cost in terms of Tx/Rx equipment. Nevertheless, work also showed that a considerable amount of bandwidth was wasted due to timeslots not being filled to capacity. Further, security issues of the TDM-PONs due to the shared infrastructure of the users also needs to be investigated as it may be susceptible to possible eavesdropping and other types of network attacks. For example, an attacker can eavesdrop [55], [105] by physically tapping into the optical fiber or by observing the crosstalk interference emitted in adjacent spectrum by confidential signals [75], [76]. As this is a passive scenario, the attack can potentially go undetected for a prolonged period of time, severely compromising the data flow in the access network.

In order to lower the cost of a PON-based access network by utilizing its bandwidth more efficiently, an interleaved polling algorithm, called IPACT, was proposed for dynamic bandwidth allocation (also described in Chapter 3) [60]. This proposed technique increases the amount of best-effort bandwidth available to busy ONUs and so it can efficiently utilize the unused network capacity. Further work in [56] fully investigated the performance of the TDM tree-based Ethernet Passive Optical Networks in terms of security, protection, dynamic bandwidth allocation, fairness issues, QoS, and channel utilization and demonstrated the enormous advantages of this type of technology compared to DSL and cable-based access networks.

Among the different technologies used for TDM-PONs, the Gigabit PON and Ethernet PON (or in short GPON and EPON respectively) became the two established technologies for TDM-PON implementation. A discussion on these, as well as the rest of the PON technologies is presented below. In particular, as it will be discussed below, upgrading the TDM-PON based architectures to WDM-based, will be the next evolutionary step that will enable the efficient development of PONs and subsequently converged optical-wireless access networks.

Ethernet PON (EPON)/Gigabit PON (GPON)

The two major standards of TDM-PONs are Ethernet PON (EPON) and Gigabit PON (GPON).

Gigabit PON (GPON) is the successor architecture to the Asynchronous Transfer Mode PON standard (APON) that was defined in ITU-T G.983. Initially, Broadband PON (BPON) was proposed and standardized followed by the Gigabit-capable Passive Optical Networks (GPON) (ITU G.984), with an upgrade in terms of upstream/downstream speeds (2.488/1.244 Gbit/s). GPONs are P2MP (point-to-multipoint) architectures which eliminate active electronic components replacing them with cheaper and simpler equipment such as passive optical couplers (splitters/combiners) easier to maintain and longer lived than active components without the extra power needed for active elements. In GPON architectures, each subscriber does not require a separate fiber port in the CO, therefore the cost of expensive equipment is shared over many subscribers.

10G-PON is the next ultra-fast capability standard for GPON (ITU-T G.987), that is also known as XG-PON. In general GPON and 10G-PON are very similar with respect to framing and protocols but differ in the operating wavelengths (10G-PON uses wavelengths of 1577nm and 1270nm for downstream/upstream traffic, while GPON and EPON use wavelengths of 1490nm and 1310nm). This standard defines shared network access rates up to 10 Gbit/s over existing fiber. There are two variants of the standard: asymmetric 10G-PON (or XG-PON1) that defines 10 Gbit/s downstream line rates and 2.5 Gbit/s upstream line rates and symmetric 10G-PON, (XG-PON2), with symmetric 10Gbit/s downstream and upstream speeds. Standards for 40Gbit/s and 80Gbit/s PONs (NG-PON2 discussed below), are underway that

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utilize a hybrid architecture utilizing both TDM and WDM technologies.

Ethernet-PON (EPON) is a variant of GPON based on the Ethernet. Thus, EPON is a PON-based network that carries data traffic encapsulated in Ethernet frames as defined in the IEEE 802.3 standard. In EPON there is not a specific framing structure; Ethernet frames transmit in bursts with standard spacing between them to avoid inter-symbol interference. Also, no multiple fragmentations in packets are necessary. Packets of multiple sizes can be carried using the EPON architecture. It operates at standard Ethernet speeds of 1, 10, and 100 Gbps (GEPON/10G-EPON/100G-EPON). The Ethernet PON has been one of the successful candidates for optical access network implementation, as it can efficiently transport data, video, and voice services over a single platform.

The EPON standard 802.3ah initially proposed in 2004 has matured from a symmetrical 1Gbit/s to the new 10G-EPON standard (IEEE 802.3av), supporting both symmetric at 10 Gbit/s and asymmetric 10G/1G downstream/upstream operation. In both standards, one wavelength is used for the downstream traffic (1550nm) and one for the upstream traffic (1310nm). In case the two protocols coexist, then the 1480-1500nm and 1575-1580nm bands are used for GEPON and 10G-EPON respectively. The EPON standard continue to evolves, defining 40 and 100 Gbit/s speeds for a variety of different reaches (IEEE 802.3ba standard). Furthermore, work on 400GbE and 1TbE is also underway.

In previous years, a few research groups have addressed some of the requirements of the next-generation passive optical networks [12], comparing the two main architectures (i.e., EPON and GPON). In [85], the authors have compared the efficiency and performance of EPON and GPON on the implemented medium access control protocol (MAC), while Kani et al. in [53] have examined the most likely future development of next generation PON technologies, providing a roadmap of evolutionary growth vs. revolutionary change. In that work, the general requirements were also reviewed, including the service, the architectural, the system, and the operational requirements for the next-generation passive optical access network.

Next-Generation PON (NG-PONs)

Next-generation PONs termed as NG-PON1 are referring to the evolution of GPON/EPON architectures, supporting both technologies on the same feeder network, while

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NG-PON2 refers to the utilization of new technologies (e.g., optical code division multiplexing) to create the next-generation of PON architectures. The NG-PON2 standard (ITU-T G.989), details the architectural and technology features for network throughput of 40 Gbps, corresponding to up to 10 Gbps symmetric upstream/downstream speeds available at each end-user.

The main NG-PON2 architecture is a hybrid TDM-WDM architecture, where a tree-based WDM network is set up and TDM is utilized within each wavelength (supporting lines rates of 2.5, 10, and 40 Gbps) to support the end user services. NG-PON2 can also support point-to-point WDM overlay, that can be used by mobile services that require low latency. The NG-PON2 uses the 1524-1544nm band for upstream transmission and the 1596-1602nm band for downstream transmission (with a reduced spectrum band for upstream traffic also possible; 1528-1540nm and 1532-1540 nm). For the TDM operation, tunable burst mode transmitters are utilized at each ONU. Thus, wavelength spacing is at 50GHz, 100GHz or 200GHz, depending on the tunable components employed at each ONU.

2.2.2 Wavelength Division Multiplexed Passive Optical Networks

Wavelength-division-multiplexed passive optical network (WDM-PON) architectures shown in Fig. 2.4 are another variant for passive optical networks. WDM-PONs solve the problems of limited bandwidth to each subscriber compared to TDM-PONs. A typical WDM-PON topology, shown in Fig. 2.4, can provide a point-to-point connection from the OLT to each ONU utilizing a dedicated wavelength (pair of dedicated wavelengths for the upstream and downstream traffic). By using WDM instead of TDM, each user has its own capacity in a dedicated wavelength without the need of extra fiber links and any impact on the allocation of resources to the rest of the users in the network. The different wavelengths may coexist on the same fiber or may be routed over different ones.

As seen in the figure, a WDM multiplexer/demultiplexer is used at the OLT and the remote node (splitting location). These are utilized to multiplex and demultiplex the wavelengths in the upstream and downstream directions. Typical technologies that are used to implement this functionality at the remote node include thin film filters, arrayed waveguide gratings (AWG), and fiber Bragg gratings. In Fig. 2.4, an AWG is depicted; AWGs are usually preferred as they have a low insertion loss

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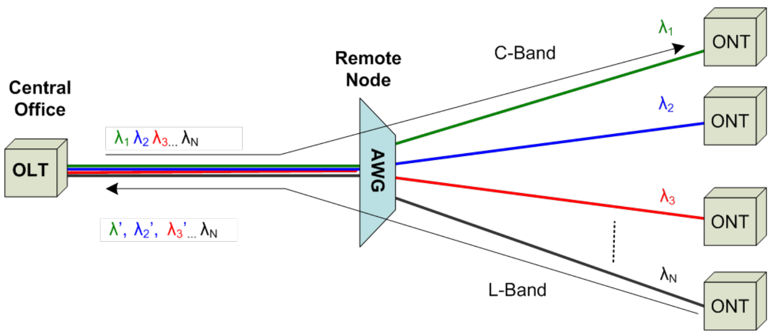

Figure 2.4: WDM-PON topology.

and thus the network can potentially accommodate a larger number of ONUs [82]. A 40-Gigabit-capable WDM-PON is being standardized by the Full Service Access Network (FSAN) forum and ITU-T Study Group 15, for the purpose of enabling cost-effective 40-Gigabit-capable transmission capacity and multiple service capability. Clearly, for these kinds of speeds, attention must also be given to physical layer impairments, such as dispersion compensation and polarization maintaining techniques.

The WDM-PON architecture offers the advantages of higher speeds, as well as scalability in capacity and network size compared to its TDM-PON counterparts. Additionally, it provides dedicated optical connectivity to each subscriber with bit rate, modulation format, and protocol transparencies, guaranteed QoS, and increased security, as it now provides dedicated connections from the OLT to each ONU and is not broadcasting to all the users. Further, utilizing WDM-PONs, since each ONU is assigned a dedicated wavelength, there is no need for bandwidth sharing between different ONUs (allowing every ONU to transmit at the peak speed). Since no sharing is now implemented, this means that there is no need for complex control and management signaling protocols and resource sharing functionalities. Finally, the bandwidth allocation mechanisms are now considerably simplified, as there is no need for dynamic bandwidth allocation (DBA) algorithms, and OLT-ONU communication is performed in a point-to-point fashion.

According on the number of wavelengths supported and the wavelength spacing between the individual wavelengths transmitted in a fiber link, the WDM-PON is classified as either dense WDM-PON (DWDM-PON) or coarse WDM-PON (CWDM-PON). The former can be utilized to increase the network capacity by minimizing the wavelength spacing and the latter can significantly reduce the network cost as lower cost equipment (transmitters, receivers, muxes/demuxes) is now required [78], [92].

Various WDM-PON architecture implementations have been presented in the literature utilizing different technologies (e.g., burst mode receivers, DFB lasers, broad-spectrum sources, etc.) and different optical topologies (topologies utilizing active components (e.g., optical amplifiers), topologies that provided reuse of a wavelength to more than one ONUs, etc.). Examples include the Composite PON (CPON), Local Access Router Network (LARNET), Remote Interrogation of TErminal NETwork (RITENET), Multistage AWG-Based WDM-PON, super-PON (SPON), and SUCCESS-DWA architectures [13].

Further, if a migration from current TDM-PON technologies to WDM-PONs is required, with the constraint that the legacy technology will remain in the network, then an appropriate migration scheme needs to be devised. In [17], Chow et al., have demonstrated such a migration scheme that transforms time-division-multiplexed passive optical networks to wavelength-division-multiplexed PONs using differential phase-shift keying (DPSK) for the downstream signal and wavelength-shifted amplitude-shift keying (WS-ASK) for the upstream signal. This scheme can be implemented to effect the said transformation utilizing the existing fiber infrastructure.

Despite the attractive features offered by WDM-PONs compared to TDM-PONs, still WDM-PON deployment is costly, mainly because of the use of active WDM sources (the number of transceivers required is almost double of TDMA architectures ($2 * N$ for TDM-PONs versus $N + 1$ for WDM-PONs)). However, as bandwidth demand increases, the economics change. In the near future, in terms of cost per bit rate, WDM-PON is projected to be more efficient and economical compared to its TDM-PON alternatives.

Nevertheless, the traditional tree-based WDM-PON architectures also suffer from several limitations similar to their TDM-PON counterparts. These limitations stem from the network topology rather than the technologies utilized. Firstly, this architecture cannot efficiently utilize the available network resources. The unused dedicated channel capacities of lightly-loaded/idle subscribers cannot be shared by any of the other heavily-loaded users attached to the PON. Additionally, it cannot provide private networking capability within a single PON and also there are no simple and cost-effective recovery capabilities which are essential in order to provide guaranteed QoS to the end-users.

To address the aforementioned limitations of traditional WDM-PONs, several

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WDM-PON architectures and protocols that dynamically manage and allocate bandwidth in both time and wavelength dimensions have been proposed [8], [33], [32], [104]. Most of these schemes, however, are costly, require many redundant components, and assume complex OLT and ONUs setups, which require tunable transceivers, or an array of fixed transceivers, or both, WDM filters, and wavelength-selective receivers at both the OLT and ONUs. Furthermore, schemes that support dynamic wavelength sharing, where additional wavelength channels are added to accommodate the fraction of bursty downstream traffic that may exceed the users dedicated downstream wavelength channel rate, are still falling short of addressing the fundamental problem of the inefficient utilization of network resources [32], [33]. This is because unused capacities of those lightly loaded, or even idle dedicated downstream wavelength channels are being wasted. Overall, each of these complex architectures has only targeted a single limitation and applied specific solutions to traditional WDM-PONs, mostly resulting in increased cost and complexity.

A ring-based architecture was subsequently introduced that more efficiently addresses the aforementioned limitations [32], [45], [46]. This architecture can support private networking capabilities, a distributed control plane, and dynamic wavelength sharing functionalities. For this type of architecture, various dynamic bandwidth allocation, as well as wavelength allocation/sharing schemes have been proposed and analyzed, demonstrating that the proposed methodologies can meet the capacity requirements of the dynamic and highly fluctuant traffic pattern of the emerging multimedia applications and services [32], [33], [44], [93], [104]. This ring-based architecture is revisited in Chapter 4, where it is now utilized as a converged optical-wireless solution, serving both fixed and wireless traffic. In addition, Chapters 5 and 6 also present and analyze a wheel-based WDM-PON topology to be used as a converged solution.

2.2.3 OFDM-PON

Orthogonal frequency division multiplexing PONs use a number of orthogonal subcarriers assigned to different ONUs and provide all the advantages of OFDM transmission, that is bandwidth flexibility, transmission performance (in terms of reach, power budget, etc.), service transparency, and cost-efficiency. In an OFDM-PON each subcarrier is modulated with a conventional m-QAM scheme at a lower

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symbol rate, thus the bandwidth is increased with very small effect on chromatic or polarization dispersion. In OFDM systems the transmission reach is significantly extended (beyond 100km) without the use of specialty fibers, optical amplification, or expensive laser sources, thus this technology can be used to implement PON architectures that cover large geographical areas. In addition, OFDM utilizes low-cost ASICs for advance signal processing with less stringent operational requirement than WDM laser sources. Also, it is worth noting that in OFDM-PONs in order to allocate bandwidth per user only the subcarrier modulation frequency and/or modulation scheme have to change, eliminating extra component cost and complex allocation techniques.

In [24], the authors present the fundamental advantages of OFDM-based PON as a candidate platform for next-generation optical access networks. In an OFDM-based PON, the subcarriers provide not only efficient spectrum use and equalization, but also transparent, finely granular resources for dynamic, multi-user bandwidth access [101]. The latter is a unique advantage for future PON systems as it leads to flexible, transparent inter-user and/or service bandwidth sharing [23].

Because of the advantages presented over the years, high-speed OFDM-based PONs have emerged as an attractive solution in the research field of passive optical access network [89], [90], [91]. Research work in [54] also went a step further, and proposed a novel optical access network architecture based on OFDMA technology and applied it on a PON topology which can be integrated with wireless technologies, as a good successor for converged access solutions utilizing TDM- and WDM-PONs.

Even though the OFDM-PON has significant advantages as mentioned above, it still is a premature technology due to the cost and requirements of some of high-speed components (ADCs/DACs) utilized. Nevertheless, it is considered as a potential successor for future optical and converged optical-wireless access networks.

2.2.4 Hybrid PONs

A final variant to PONs is hybrid PONs. Hybrid PONs are simply architectures that combine both TDM and WDM technologies (OFDM-WDM architectures have also been proposed). Hybrid PONs are useful in the sense that they can serve as a migration solution from the TDM-PON to a WDM-PON deployment and enable backward compatibility. Several hybrid architecture approaches have been proposed in the lit-

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erature, such as a tree-ring solution, where the remote nodes are interconnected together with the central office in a ring topology utilizing WDM technology, and at each remote node a tree topology interconnects the remote node to the ONUs, utilizing now a TDM technology [1], [2], [3], [115].

2.3 Converged Fiber-Wireless Access Networks

In recent years, a significant amount of research has also taken place focusing on the integration of PON and wireless broadband access technologies, mostly proposing numerous hybrid Fiber-Wireless (FiWi) network architectures that will enable the support of fixed-mobile applications and services independent of the access infrastructure [8], [39], [56]. These architectures are utilizing the fiber-based PON access network to backhaul mobile traffic.

Most of these proposed architectures are centralized architectures and can be categorized as (i) independent architectures, where both the wireless and fiber segments are operated independently, by considering the base station (BS) as another user connected to an ONU, and (ii) integrated architectures, where the ONUs and BSs are collocated and the mobile and fixed traffic are addressed in an integrated fashion. In the latter case, interconnecting the BSs and ONUs via a common standard communication interface is required to implement a next generation converged fixed-mobile access architecture. In this section both architectures are described.

Over the last few years, the benefits of the integration of the fiber infrastructure with the wireless technologies in the access arena, have been investigated. In [77], the possible challenging issues are investigated for the integrated structure of the Time Division Multiplexing and Wavelength Division Multiplexing Ethernet Passive Optical Networks (TDM EPON and WDM EPON) combined with the Worldwide Interoperability for Microwave Access and Wireless Fidelity (WiMAX and Wi-Fi) networks. Based on the same WDM/TDM-stage levels of [77], a novel hybrid wavelength division multiplexed/time division multiplexed passive optical network (WDM/TDM PON) architecture was also proposed in [63], which can support direct inter-ONU communication, a corresponding decentralized dynamic bandwidth allocation (DBA) protocol for inter-ONU communication and an algorithm to dynamically select egress ONUs. Further, in [74], the authors proposed a highly innovative optical-star architecture that integrated EPON with WiMAX in a

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distributed management system for meeting future requirements that also involve optical and wireless sensor technologies, plug-in electric vehicles (PEVs) and energy resources [62], [73].

Most of the research works in the literature have focused on the typically centralized tree-based PON topology [39], [95], [103] for the optical access part, and did not consider architectures that can support distributed control and management functionalities for providing efficiently utilization of the backhaul traffic. Significant research work has also been undertaken for priority scheduling, but only for tree-based access architectures. It is also important to note that the fairness problem in these architectures is a challenging issue for any type of PONs. Kramer et al. in [57] addressed this problem for tree-based PONs and proposed a new hierarchical scheduler that fairly divides the excess bandwidth among priority queues from different ONUs. Also, Ahmad et al. in [27] proposed a new intra-ONU bandwidth scheduling algorithm based on a Deficient Weighted Round Robin scheduling technique in order to achieve adaptive fairness among different class of service, again for tree-based PON architectures.

Furthermore, Radio over Fiber (RoF) systems were investigated for the integration of wireless and wired networks. RoF technology is the propagation of wireless signal through optical fibers in order to provide mobility and high bandwidth to the end users [49], [88]. Specifically, RoF is a technology where light is modulated with radio frequency signals and transmitted over the optical fiber to facilitate wireless access and transmission. In order to increase the capacity and coverage area of access networks, the integration of Radio over Fiber (RoF) with WDM-PON is considered as an attractive solution, where the proposed converged architecture enables to simultaneously transport RF and baseband signals through a single-mode fiber [9], [11], [83], [110].

On the other hand, all of these network architectures have their limitations in order to support today's and future mobile/wireless infrastructures. Considering the fully distributed ring-based WDM-PON architecture presented in [8], the mobile infrastructure is supported and also distributed network control as well as management operations are provided. Development of such a powerful FiWi platform in the access arena, can thus ensure that all types of traffic will be served efficiently under a distributed control plane as shown in [32]. Specifically, using the proposed WDM-PON ring-based architecture for the converged FiWi infrastructure, the network resources can be more efficiently utilized via wavelength selection and scheduling in the downstream direction, as well as traffic flow rerouting and sharing in the upstream direction , [32], [108], [103]. Additionally, simple techniques for wavelength selection and scheduling (WSaS) in the downstream direction have been previously proposed in [32], [108], [113], as well as dynamic bandwidth allocation techniques among LAN users to satisfy the traffic between ONUs/BSs that are now directly interconnected on the fiber ring. As also discussed in Chapter 7, and in [50], FiWi access networks based on passive optical network technologies converged with mobile networks can be utilized to support the rapidly growing fixed and mobile data traffic not only for the telecommunication providers, but also for emerging applications such as the smart grid. Thus, a truly integrated optical-wireless access network could also be a fundamental networking solution for other applications that will require massive transmission of information (such as the smart grid or any other intelligent critical infrastructure system that collects a vast amount of data from monitoring sensors and needs a communications infrastructure to control and manage the system). In smart grids, for example, the communication between the customers and the utility must be integrated into the power system in order to be able to control and monitor the electricity demand and also efficiently control and manage the entire power distribution network. In [114], the authors present a quality-of-service Wireless Sensor Network (WSN) integrated with PON (FTTH/FTTC/FTTx) to collect the data from the end users in the smart grid environment [73]. It is thus envisioned that the current passive optical access networks converged with the mobile/wireless technologies, could possibly be the future architecture for the deployment of smart grids , [26], [61], as it can meet the system's requirements for low latency and high bandwidth, providing both fixed and wireless connectivity to various points in the network [36].

2.4 Fault Recovery in Optical Access Networks

As also described in Chapter 1, fault recovery is essential in all types of telecommunication networks. This need is more urgent nowadays with users utilizing more and more real-time services and applications. Failures can significantly affect the delivery of data; this is clear from the discussion above that highlighted the data rates supported by PON architectures nowadays and the projected future technolo-

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gies reaching Tbps capabilities. Failures can be either cable failures (fiber cuts) or equipment failures (switches, transceivers, etc.) and can be either full failures completely disrupting the traffic flow (e.g., a fiber cut) or partial failures affecting only part of the traffic (e.g., failure of a single transceiver). These failures can be the result of human error (e.g., "backhoe effect"), equipment degradation or malfunction, or even malicious attacks.

Fault management in optical networks encompasses the entire range of functionalities, including fault detection, fault identification/isolation, as well as fault recovery. In most networks, the essential functionalities are fault detection and subsequent recovery of the affected traffic (these usually fall under the control functionalities of the network that are performed quickly to accommodate the network when a change in the network state occurs). Usually fault identification/isolation is a slower process that will take place after the failure has been recovered (a slower process falling under the management functionalities of the network).

There are a number of performance metrics that need to be considered during failure recovery. Quick failure detection and recovery is essential as the more time it takes for the failure to be restored, the more data is lost. Further, the restoration capacity of the network (capacity that is reserved and utilized only when a failure has occurred) must be kept low, as this is capacity only to be used in the event of a failure and cannot be utilized to send working traffic (unless this is a low-priority traffic that can be preempted when a failure occurs). In addition, the signaling and control protocols, as well as any rerouting algorithms employed, must also be simple and with low computational complexity.

In general, one of the following two approaches has been used for fault recovery: protection techniques, where the recovery path is pre-planned and is calculated prior to the occurrence of a failure, and restoration, where the recovery path is calculated after a failure has occurred.

Protection techniques utilize mostly built-in redundant facilities such as extra (protection) fibers that are used only in the event of a failure occurrence [15], [106]. In this case, upon a failure event, the traffic is automatically switched to the protection facility and is quickly recovered. Such approaches are very fast and simple to implement. Nevertheless, they require a large amount of protection capacity (reserved resources for protection).

On the other hand, dynamic restoration techniques do not utilize redundant facilities; rather they use redundant capacity (usually reserved for recovery purposes) to direct the affected traffic to its destination [15], [106]. In this case, the path that the affected traffic has to follow is not pre-planned but is calculated after the failure has occurred. This approach will require less redundant capacity than the aforementioned pre-planned technique, however it is also a slower and more complex recovery technique that in order to be implemented usually requires a more elaborate signaling protocol.

The rest of the section concentrates on optical layer recovery techniques in access networks that have been proposed in the literature, followed by a discussion on the shortcomings of the existing recovery techniques presented in this chapter. It ends with a discussion advocating the need for new recovery techniques/architectures for passive optical networks.

2.4.1 Protection Techniques in Tree-Based PONs

In a tree-based PON topology, the fiber links and the network components should be protected. There are two main types of pre-planned protection schemes known as 1+1 and 1:1 protection. In order to protect the network components, such as the optical transceivers of a tree topology, usually redundant backup units (1:N or 1+1) are used for protection purposes. If there is also the need to protect the fiber links, usually backup redundant fiber links and switches are used to divert the affected traffic to the protection paths when a failure is detected. Most of the existing protection network architectures assume only a single failure scenario at a time and this is the assumption that we will follow throughout this thesis.

ITU-T G.983.1 [5] suggests four different pre-planned protection architectures for tree-based topologies using extra redundant fiber links and backup components: 1) protect the feeder fiber, 2) protect the feeder fiber and the OLT, 3) protect all the components (fiber links, ONUs and OLT), and 4) protect only the feeder fiber and the branch fiber links. Further, in order to ensure and increase the network reliability for tree-based PONs, standards ITU-T G983.5 and 983.6 proposed two different approaches: (a) Duplicate PON, (b) Duplicate OLT. In the first configuration, the protection redundant path is obtained by duplicating every single element or component in the network and sharing the outputs of the optical splitters between different user groups to allow, in case of failure, switching from one PON network

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to the second one. In the splitting section, the solution could be provided simply by multiplying the number of components requested or by using a more integrated approach, such as an integrated splitter array solution. In the second configuration, the protection redundant path is obtained between the CO and the point-of-presence due to a $2 \times N$ optical splitter. Among the optical layer protection schemes, automatic protection switching (APS) is a good candidate for fault recovery, whereby the optical path of the transported signals is switched to a predetermined path upon detection of a fiber break or an equipment failure by means of hardware. Fault detection and switching can be performed at the CO, a process however that can be slower, more complex, and requires a lot of changes at each ONU for a successful restoration of a signal transport, or distributively, in which case the process will be faster and simpler.

An APS scheme was proposed, whereby in the event of a distribution fiber break, its detection and subsequent protection switching to a predetermined protection path is carried out at the affected ONU. The state of the distribution fiber is monitored with a channel that is used to communicate with other users in the PON. This protection mechanism was experimentally demonstrated in conjunction with two different LAN-emulation techniques, whereby scheme one enabled the recovery of the downstream traffic from the CO to the ONUs, upstream traffic from the ONUs to CO, and LAN traffic that is transmitted among customers within the PON, while scheme two recovered the conventional upstream and downstream transmissions between the CO and the ONUs but not the LAN-traffic transmissions [81]. In this protection architecture, adjacent ONUs are interconnected in a bus topology using an additional length of fiber, and each ONU incorporates an opto-mechanical switch (OSW) that switches transmissions from the normal to the protection path. Under normal operating conditions, the OSW is in "bar" state. Each ONU monitors the state of its distribution fibers through the redirected upstream frames which could include upstream traffic, LAN traffic and/or periodically transmitted monitoring frames. In the event of a distribution fiber break, the OSW switches to the "cross" state and both downstream and upstream transmissions are restored through the adjacent ONU. It is important to note that with this scheme, the PON is capable of recovering the transport of conventional downstream and upstream access traffic between the OLT and ONUs but not the LAN traffic between the ONUs. Nonetheless, multiple adjacent ONUs can be simultaneously protected by a single ONU at full bandwidth

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usage, and failure detection and automatic protection switching can be performed independently by each ONU in a distributed manner, thus reducing the processing complexities and associated delays at the OLT.

Additional works reported in [6], [86], [109], [87], and , also propose various 1:N protection schemes to protect not only the ONUs and the fiber links of the tree topology but also the OLT which resides at the central office. Also, work in [79] and [80] proposed several protection architecture solutions for the tree-based topologies with extra fiber links for protection and optical protection switches to be used only when a failure has occurred.

Further work on tree-based PON protection techniques was also reported in Dixit et al. [28], where authors proposed several reliable architectures for wavelength division multiplexed (WDM) PON and time and wavelength division multiplexed (TWDM) PON architectures. Concurrently, in [72], the authors proposed a hybrid PON architecture that offer different degrees of resilience depending on the user profiles such as partial and full protection for residential and business access. Additionally, in [51] and [52], a novel method for N:1 optical line terminal (OLT) protection on wavelength-division-multiplexing/time-division-multiplexing passive optical networks (WDM/TDM-PONs) was proposed.The proposed protection scheme was based on in-service wavelength tuning (λ - tuning) at optical network units (ONUs) and showed that it can provide reliable and cost-effective protection without the need for equipment specific to OLT protection on either the ONU or OLT side.

Finally, optical carrier suppression (OCS) technique is another simple scheme that can be used to protect both upstream and downstream links in WDM-PONs [18]. This scheme employs only N units of laser diodes at the CO for both working and protection mode. This self-survivable protection scheme detects and restores all types of network failures at feeder/distribution fibers, remote nodes, and transmitters in CO and ONUs. In this architecture, at the CO, N wavelength channels (λ_1, ..., λ_N) are used to provide both the downstream (DS) and upstream (US) light sources for N ONUs. For each λ_i ($i = 1, ..., N$), two sub-wavelength channels (λ_{id} and λ_{up}) are generated using an optical carrier suppression (OCS) technique. However, only one OCS unit is used for N-wavelength channels to generate their respective sub-wavelength channels. A clockwise wavelength sharing scheme among the ONUs is used to provide centralized light sources for US and DS directions both in the

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working and protecting mode. In the normal working mode, the sub-wavelength channels λ_{id} and λ_{up} generated at wavelength λ_i are used to provide both DS and US channels, respectively, for the i-th optical network unit (ONU$_i$) for $i = 1, ..., N$. However, in the protection mode, ONU$_i$ is served by the wavelength channel λ_{i-1} (i.e., $\lambda_{(i-1)d}$ and $\lambda_{(i-1)u}$ for $i = 2, ..., N$ and for $i = 1$, ONU$_1$ is served by wavelength channel λ_N (i.e., λ_{Nd} and λ_{Nu})). After the OCS, the working and protection channels designated for ONU$_i$ are fed into respective network unit controllers (NUC$_i$) using an array waveguide grating filter and 3dB splitters. The NUC$_i$ performs protection switching and transceiver functions for ONU$_i$. At NUC$_i$, an optical switch is used to select the appropriate wavelength channel based on the mode of operation (working or protection) of ONU$_i$, which is determined by the optical power monitor (M$_i$). An interleaver filter (IL) is used to separate the DS and US carriers.

2.4.2 Protection Techniques for Ring-Based PONs

In ring-based PON topologies, ONUs are interconnected around a ring. Protection in a ring topology is more important compared to a tree-based architecture, as a single failure on the ring can disconnect several ONUs. Nevertheless, ring-based PONs have inherent resilience capabilities due to the topology of the network. In [46] and [47], a cost-effective protection scheme for a novel ring-based EPON architecture is proposed (utilizing 1+1 protection). Additionally, in [116], a novel ring-based WDM-PON architecture with a self-healing function is proposed, where the optical line terminal (OLT) and the optical networking units (ONUs) can automatically switch to protection links when a fiber failure occurs by using cost-effective components within the ONUs. Also, in [16], an architecture based on a central single-fiber ring and secondary trees for large-scale networks is presented and demonstrated. The proposed architecture, can provide both protection and dynamic wavelength assignment, utilizing the central ring to provide protection for the feeder fiber and the remote node (RN) to provide the function of dynamic wavelength assignment.

Specifically, for the ring-based protection scheme depicted in Fig. 2.5, the APS module attached to each ONU is the basic building block of the proposed self-healing mechanism that monitors the state of its adjacent distribution fiber paths and the ONU to which it is attached and performs both fault detection and automatic switching process. APS is performed using a 4×4 bidirectional optical switch

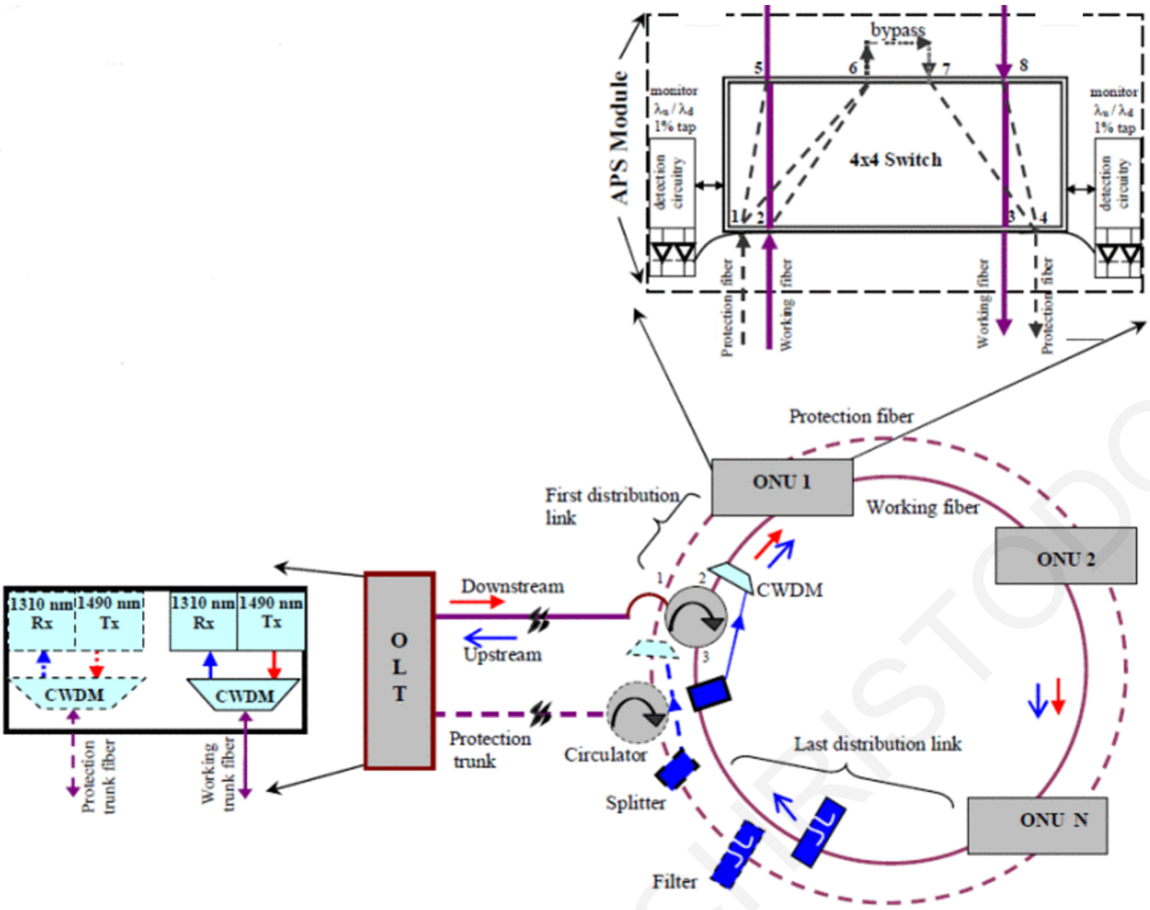

Figure 2.5: Protected ring-based passive optical network [47].

that can switch any input port to any output port. In order to initiate the APS process, detection circuits are utilized that monitor the LAN signal as well as the downstream/upstream signal. For this types of architecture, it was shown that all different classes of failure, namely trunk failures, general link/node failures can be recovered. In addition, some multiple failure scenarios can also be recovered.

2.4.3 Protection Techniques in Converged Fiber-Wireless Access Networks

Finally, some preliminary work has also appeared in the literature examining the protection of the converged optical-wireless access network, rather than just the standalone PON architecture.

Authors in [96] and in [97]proposed different techniques (DARA and RADAR algorithms) for protecting the wireless front end from different types of failures, having as an aim to reduce the packet delays. Further, work in [35] improved on RADAR by assigning backup ONUs (with deployed backup fiber among the backup

ONUs) so that the traffic always will reach any ONU given any primary fiber cut. This is again in turn improved in [66] (OBOF algorithm - optimizing backup ONU selection and backup fiber deployment) utilizing simulated annealing to deploy the backup ONUs and a heuristic algorithm to deploy the backup fiber amongst the backup ONUs from each segment. One of the aims was to efficiently use the residual capacity of the remote segments, while the second was to limit the recovery time. A further improvement was also reported in [65], in terms of finding the optimum path with the least delay.

Additional work has been reported [68] for converged optical and data center networks, where the authors proposed placing wireless routers and configuring backup radios to be used for failure protection, utilizing an algorithm called WRBR (Wireless rerouting and backup radios). In this case, backup ONUs are designated for primary ONUs via backup radio paths. Mathematical formulation and heuristic algorithms are used to allocate the backup ONUs and wireless backup routers, considering only single failure scenarios.

For multiple failure scenarios, in [64], a ring-based protection approach is considered. Now the backup ONUs from each segment are connected in a ring configuration utilizing backup fibers, thus offering two paths for each segment to reroute the affected traffic. A second more recent work on multiple failures was also presented in [14]. Again, a tree-based access network is considered, and in this scenario backup ONUs from each segment are connected in a fully mesh fashion in order to be able to support multiple failures, making it a viable protection scheme candidate for networks that are heavily loaded.

Further work in [67] proposed various algorithms to protect against different network failures; a sharing backup radios (SBR) algorithm is used to protect against ONU failures (utilizing a backup radio path to connect to the backup ONU) and a shortest protection ring (SPR) algorithm is used to protect failures that occur in the network side from the OLT to the ONU. In this case, a genetic algorithm approach or a backtracking technique are used to determine the shortest ring path for connecting the backup ONUs.

Finally, additional work appeared in [112], where the authors investigate FiWi access networks with integrated small cell and WiFi (ICSW) in a tree-based configuration. In this case, the WiFi function can be utilized to create wireless mesh networks (WMNs) providing the connectivity to address the failure of network components

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(i.e., it provides the redundant mesh connectivity to transmit data from primary to backup ISCWs when a distribution fiber is cut). The objective of the proposed formulation is to optimize the deployment and maximize the coverage of survivable FiWi access networks with ISCW, while ensuring that all constraints (capacity and delay demands) are satisfied.

Clearly, as standalone optical access networks and converged optical-wireless access networks support different types of traffic from different types of users, with different classes of service and priorities, as well as different Service Level Agreements (SLAs) between the network providers and the users, the choice of the protection/restoration technique adopted, if any, will depend strongly on these SLAs as well as on the failures that the network needs to protect against, the available network resources, and the economics of each PON/converged fiber-wireless deployment scenario.

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Chapter 3

Tree-Based Passive Optical Access Networks

3.1 Introduction

As also described in detail in Chapter 2 of this thesis, there are several multipoint topologies suitable for PON access networks including tree, tree-and-branch, ring and bus. The most commonly used topology is the tree-based PON as it can in a straightforward way effect bi-directional communication between the OLT to the ONUs. In the downstream direction (from OLT to ONUs) a tree-based PON is a point-to-multipoint network, and in the upstream direction it is a multipoint-to-point network.

Depending on how data are multiplexed and transmitted, in downstream (from OLT to ONU) and upstream (from ONUs to OLT) mode, there exist three different technology options. The most popular one is time division multiplexing (TDM) PON [34], where traffic from/to the OLT to multiple ONUs is TDM multiplexed over a single (or more) wavelength(s). Thus, depending on the technology used to implement the tree (e.g., EPON, GPON, etc.), in the upstream direction, from the users to the network, data streams may collide if all users are allowed to send their data whenever they have data to send (as a single wavelength is utilized to transmit all information that is time-division multiplexed on that channel). Therefore, some channel separation mechanism or scheduling process should be employed in order to fairly allocate the channel capacity and the network resources while avoiding any collisions. As an example, Fig. 3.1 shows upstream and downstream operation for

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an EPON architecture. In the downstream direction, Ethernet packets transmitted by the OLT pass through a $1 \times N$ passive splitter and reach each ONU utilizing a broadcast and select approach. In the upstream direction from the ONUs to the OLT, packets from each ONU are combined through a passive optical combiner and reach the OLT. In a tree-based PON topology, the upstream direction behaves like a point-to-point network but data packets from different ONUs are transmitted simultaneously. Therefore, a collision avoidance technique is required in order to share the capacity of the channel among the different ONUs. This is in contrast to WDM PONs which use discrete wavelength channels, one per ONU. In such architecture capacity is not shared, as in TDM-PON, and thus a bandwidth allocation technique is not required.

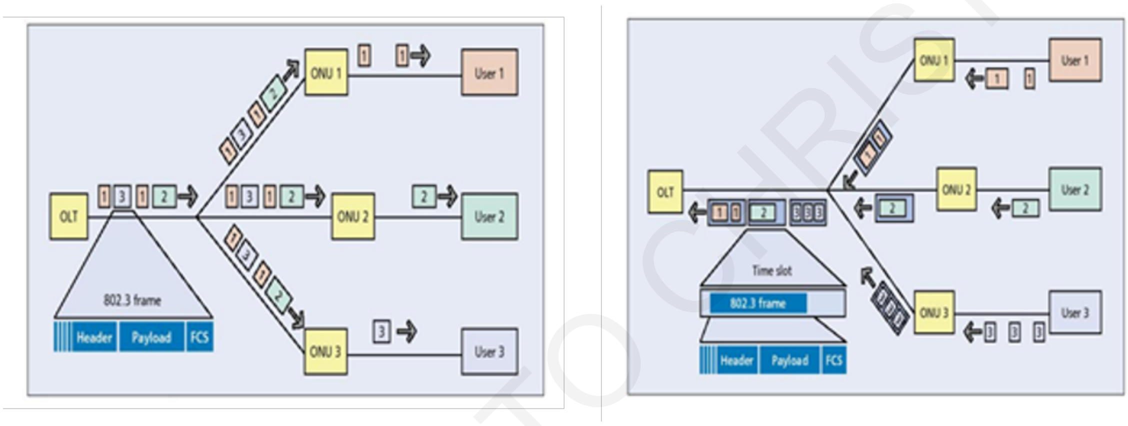

Figure 3.1: Tree-based upstream and downstream operation [56].

In this chapter different dynamic allocation algorithms will be presented and examined in a tree-based TDM-PON access network in order to avoid data collision in the upstream direction and provide better network performance in terms of channel utilization. These bandwidth allocation algorithms are developed and evaluated in this chapter so as to ascertain the dynamic bandwidth allocation algorithm that will be subsequently used in Chapters 4-6 for the inter-ONU/BS communication utilizing a common wavelength (λ_{LAN}).

The rest of the chapter is organized as follows: Initially, Section 3.2 describes the different bandwidth allocation algorithms. This is followed by Section 3.3 that describes the traffic generation model that is used for the tree-based PON networks and for the rest of the converged architectures throughout the thesis. This is followed by channel utilization results for different traffic loads and different bandwidth allocation techniques. Finally, Section 3.4 offers some concluding remarks.

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3.2 Bandwidth Allocation Algorithms

A number of bandwidth allocation techniques have been reported in the literature ranging from static bandwidth allocation to more dynamic bandwidth allocation schemes that are based on the amount of data in each queue at every ONU [56], [84]. The simplest technique, albeit the most inefficient as it does not allow for any statistical multiplexing, is the static bandwidth allocation technique where every ONU is assigned a fixed timeslot [69]. This technique was followed by other dynamic bandwidth allocation techniques where the OLT centrally assigns bandwidth for each ONU transmission, utilizing the information that is receiving by each OLT. For such an approach to be implemented, an OLT-based polling scheme was proposed, namely the interleaved polling with adaptive cycle time (IPACT) scheme [56]. This approach is based on the exchange of messages between the OLT and the ONUs prior to the transmission by the ONUs. The term interleaving in this case just implies that the next ONU is polled before the transmission from the previous one has arrived. Clearly, the dynamic bandwidth allocation techniques are expected to be more efficient in capacity utilization, as they allow for statistical multiplexing between the ONUs.

Thus, for the tree-based PON network under consideration IPACT was used [56], [60] to deliver data encapsulated in Ethernet packets from a collection of optical network units (ONUs) to a central optical line terminal (OLT) over the PON access network. In this case the OLT should determine the granted window size that each ONU by using one of the approaches described below, to avoid any data collision.

Four different bandwidth allocation approaches (Fixed, Limited, Gated, and Elastic) have been implemented and presented below by using the IPACT allocation scheme in order to decide the maximum allocation size granted to each ONU and compare the channel efficiency for different ONU offered loads in the tree-based network TDM-PON [59], [60].

3.2.1 Fixed Service Algorithm

The fixed service network model uses fixed timeslots for each ONU; each ONU is assigned a static timeslot which cannot change during the transmission procedure. All N timeslots together compose a frame. Any two adjacent timeslots have a guard interval G between them. A set of N timeslots together (a frame) with their

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associated guard intervals is called a cycle, i.e., a cycle is the time interval between two successive timeslots assigned to one ONU.

This scheduling service ignores the window size that each ONU has requested in the upstream direction and always grants the maximum window. This yields a constant and maximum cycle time T_{max} (where a cycle is defined as the time that elapses between two executions of the scheduling algorithm).

$$W_{i,k} = W_{max} \tag{3.1}$$

3.2.2 Limited Service Algorithm

The Limited Service Algorithm does not use static slot assignment (SSA) such as in the Fixed Service. This scheduling discipline grants the requested number of bytes, which should be no more than the maximum transmission window. In this work, the maximum transmission window is W_{max}. Therefore, the frames of the Limited Service approach are changed throughout the transmission process depending on the number of bytes requested by each ONU. The timeslots are also changed through the transmission process according to the frame size that is requested. Transmission windows (timeslots) in the limited service approach have a specific maximum capacity of W_{max}. The frames can be less than W_{max} bytes but cannot be more than the maximum transmission window size W_{max}.

$$W_{i,k} = min(W_{i,k}^{Req}, W_{max}) \tag{3.2}$$

Depending on the number of bytes which need to be sent to an ONU, transmission windows are created which are responsible to carry these packets in order to be delivered to their respective destinations. This means that also the time cycle is not static (fixed) but cannot exceed the maximum cycle time T_{max} corresponding to the maximum transmission W_{max}. It is the most conservative scheme and has the shortest cycle of all the schemes.

Note that W_{max} is determined by the maximum cycle time T_{max}.

$$W_{max} = \frac{1}{N}[R(T_{max} - (N * T_G))] \tag{3.3}$$

where N is the number of ONUs, T_G is the guard band slot, and R is the system's line rate.

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3.2.3 Gated Service Algorithm

The Gated Service Algorithm does not have any limits on the cycle time or the granted window size such as the fixed and limited service algorithms. This service will always authorize an ONU to send as much data as it has requested. The fact that there are not any limiting parameters will result to an increasing time cycle, especially if the offered load exceeds the network capacity. In this scheme, a limiting factor that is used is the buffer size Q. So, an ONU cannot store more than Q bytes in the buffer and thus it will never request more than Q_{max} bytes.

As there is only the limiting factor of the buffer size Q_{max}, each ONU can exceed W_{max} but it cannot grant more than Q_{max} size bytes. Each packet is checked to ascertain to which ONU it should be sent to. If the packet does not belong to the first frame which belongs to ONU_1, it will be placed in the buffer and will wait for the next cycle of frames in order to be checked again and sent if it belongs to this ONU's frame. This process continues for each ONU until all the packets (data) waiting in each Q_i^{ONU} buffer are transmitted.

$$W_{i,k} = W_{i,k}^{Req} \tag{3.4}$$

3.2.4 Elastic Service Algorithm

The Elastic Service Algorithm does not have any limits on the maximum granted window size but the only limiting factor is the maximum cycle time T_{max}. Each ONU is authorized to send as much data as it has requested in such a way that the accumulated size of the last ONU (ONU_N) does not exceed $N * W_{max}$ bytes. This means that if one ONU has data to send, the maximum window size allowed is equal to the entire transmission window which belongs to all the ONUs within the network.

The elastic algorithm attempts to eliminate the fixed maximum window limit W_{max} by using the maximum cycle time T_{max} as the limiting parameter. The requested window is compared with $N * W_{max} - \sum_{n=1}^{i-1} W_{n,k}$ (where N is the number of ONUs and $W_{n,k}$ is the granted window for the k^{th} packet of the n^{th} ONU). By using the elastic algorithm a window size of $N * W_{max}$ is possible, if only one ONU has data to send. Thus, the window granted for the elastic algorithm will be as follows:

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$$W_{i,k} = min(W_{i,k}^{Req}, (N * W_{max} - \sum_{n=1}^{i-1} W_{n,k})) \quad (3.5)$$

3.3 Traffic Generation in Passive Optical Access Network

Initially, a traffic generation model has to be devised that will be used to simulate downstream and upstream traffic in the performance analysis for the tree-based architecture, as well as the rest of the converged architectures used throughout the thesis. A traffic generation model is a stochastic model of the traffic flows or data sources in a communication network used to analyze the performance and capacity of a network topology/architecture and the protocols and algorithms that will be used. Depending on the type of the network and the data that would need to be generated, different traffic generation models can be chosen to be used for the generation of the traffic of the network that will be examined (e.g., Poisson traffic model, the long-tailed or heavy-tailed traffic models, etc.).

3.3.1 Generator of Self-Similar Traffic

As there is a lack of real data traffic for access networks from telecommunication providers, the only realistic way to generate traffic for this type of networks is to use a distribution that shows properties close to real network traffic characteristics. In the case of optical access network, it was shown in [107] that the access network traffic flows are characterized by self-similarity and long-range dependence (LRD). Thus, in this thesis, in order to obtain an accurate and realistic performance analysis of our proposed algorithms, we simulate our system with the appropriate traffic having the aforementioned self-similarity and long-range dependence characteristics. Further, it was also shown [107] that self-similar or long-range-dependent (LRD) network traffic can be generated by multiplexing several sources of Pareto-distributed ON and OFF periods. In the context of a packet data network the ON periods correspond to a packet train with packets transmitted back to back, or separated only by a relatively small preamble (as defined in IEEE standard 802.3, for example) and the OFF periods are the periods of silence between packet trains as shown in Fig. 3.2.

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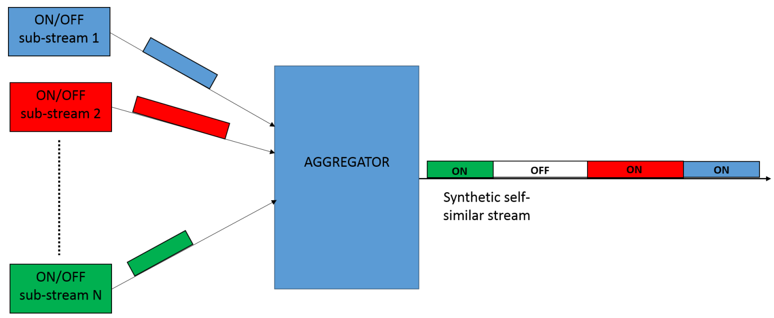

Figure 3.2: Self-similar traffic ON/OFF sources.

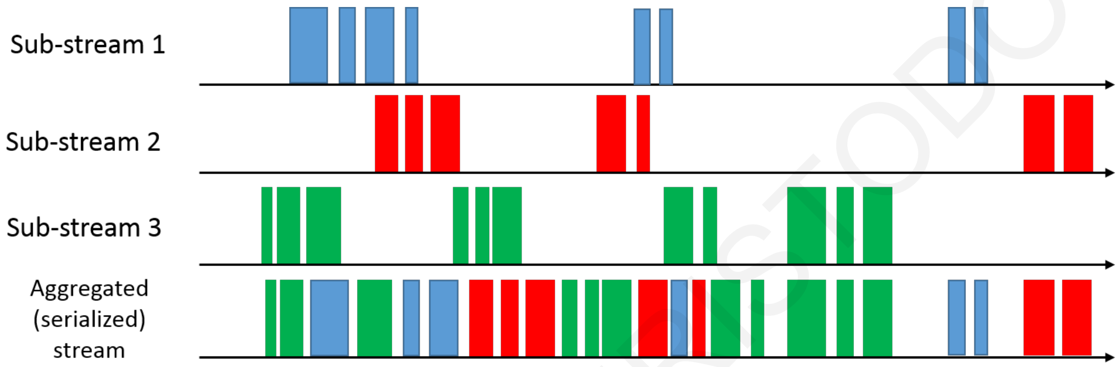

Figure 3.3: Self-similar traffic obtained by aggregating multiple sub-streams.

In this work, multiple sources (as shown in Fig. 3.2) are contributing to the resulting synthetic traffic trace and may be thought of as individual flows (connections). It is reasonable to assume that packet sizes within a connection remain constant. Different connections, however, will have packets of different sizes. To generate a Pareto-distributed sequence of ON periods, one can generate a Pareto distributed sequence of packet train sizes. The minimum train size is 1, which corresponds to a single packet transmitted. More specifically, the Pareto distribution is a heavy-tailed distribution with a probability density function (pdf):

$$f(x) = (\alpha * b^{\alpha})/x^{(\alpha+1)}, x \geq \alpha \tag{3.6}$$

where α is a shape parameter and b is a location parameter. For self-similar traffic, α must be $1 < \alpha < 2$, and affects the shape of the distribution rather than simply shifting it as the parameter b does. The effect of the location parameter is simply to shift the graph left or right on the horizontal axis (e.g., a location parameter of 5 units will shift the graph 5 units to the right on the horizontal axis).

Subsequently, the generation of self-similar traffic is an aggregation of multiple streams, each consisting of alternating Pareto-distributed ON/OFF periods. In order to create the ON/OFF periods, ON/OFF sources are used (with the number of sources utilized ranging from 8 to 32 depending on the simulated network). Each one of these sources generates windows of bytes which are later filled with multiple Ethernet packets of size 64 to 1518 bytes as shown in Fig. 3.4.

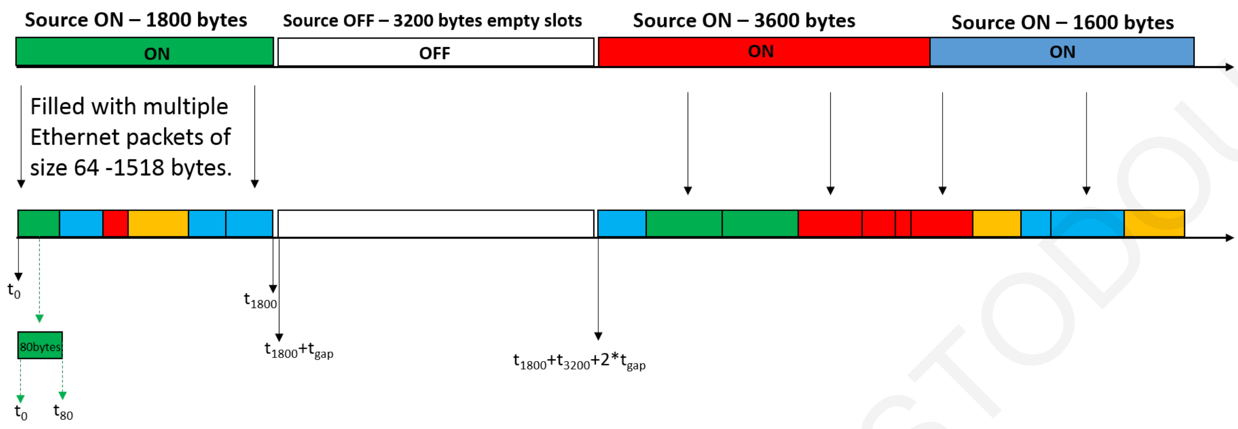

Figure 3.4: Self-Similar traffic obtained by aggregating multiple sub-streams of Ethernet packets.

To generate the Pareto values, we used the Pareto expected formula

$$E(x) = b * \alpha/(\alpha - 1) \tag{3.7}$$

while, to generate a Pareto distribution we used the following formula,

$$X_{pareto} = b/U^{1/a} \tag{3.8}$$

where U is a uniform distribution U[0,1]. It is desirable to generate a synthetic traffic of a predefined network load. The resulting load L is the sum of the loads L_i generated by each source i. The number of sources assumed to be k is defined according the simulated network, so that the load can then be defined by

$$L = \sum_{i=1}^{k} L_i \tag{3.9}$$

In the simulation scenarios considered in this thesis it is also important to be able to get a good estimation of the load generated by one source, as we use a predefined load of each source in our network model in order to examine the performance of the access network. The load generated by one source is the mean size of a packet train divided over the mean size of the packet train and the mean size of the inter-train gap, or alternative it is the mean size of the ON period over the mean size of the ON and OFF periods.

$$L_i = \frac{\overline{ON}}{\overline{ON} + \overline{OFF}} \tag{3.10}$$

$$E_{on} = b_{on} * \alpha_{on}/(\alpha_{on} - 1) \tag{3.11}$$

$$E_{off} = b_{off} * \alpha_{off}/(\alpha_{off} - 1) \tag{3.12}$$

It is reasonable to examine the performance of the network using specific fix load sources at each time. So, from equations 3.9-3.12:

$$L = k * \frac{b_{on} * \alpha_{on}/(\alpha_{on} - 1)}{b_{on} * \alpha_{on}/(\alpha_{on} - 1) + b_{off} * \alpha_{off}/(\alpha_{off} - 1)} \tag{3.13}$$

Using eq. 3.13, we will analyze the network for different loads, by varying the load from 0.1 to 1.0 in 0.1 steps on all sources.

The values used for the shape parameters were α_{on} = 1.4 for the ON period and a_{off} = 1.2 for the OFF period [107]. For the location parameter, b_{on} = 1518 was used (maximum size of Ethernet packet in bytes) for the ON period and for the OFF period the location parameter was calculated using the following equation:

$$b_{0ff} = k * \frac{(\alpha_{on} - 1) * b_{on} * \alpha_{on}}{(\alpha_{on} - 1) * L * \alpha_{off}} \tag{3.14}$$

where the offered load L is randomly generated in the range of 0.1 to 1.2.

The above self-similar traffic model was used in the development of our packet generator to examine the performance of different optical access network topologies/architectures.

In our model we use as ON/OFF sources, in the upstream and downstream direction, the users of the network. The users are assumed to be 10 to 20 per ONU depending of the simulated network model (10 users (sources) per ONU assuming a lightly-loaded network and 20 users(sources) per ONU assuming a heavily-loaded network).

Using eq. 3.14 we get:

$$b_{0ff} = 3.5/6 * 1518 * [\frac{(K * N)}{OL} * \frac{R_U}{R_N} - 1] \tag{3.15}$$

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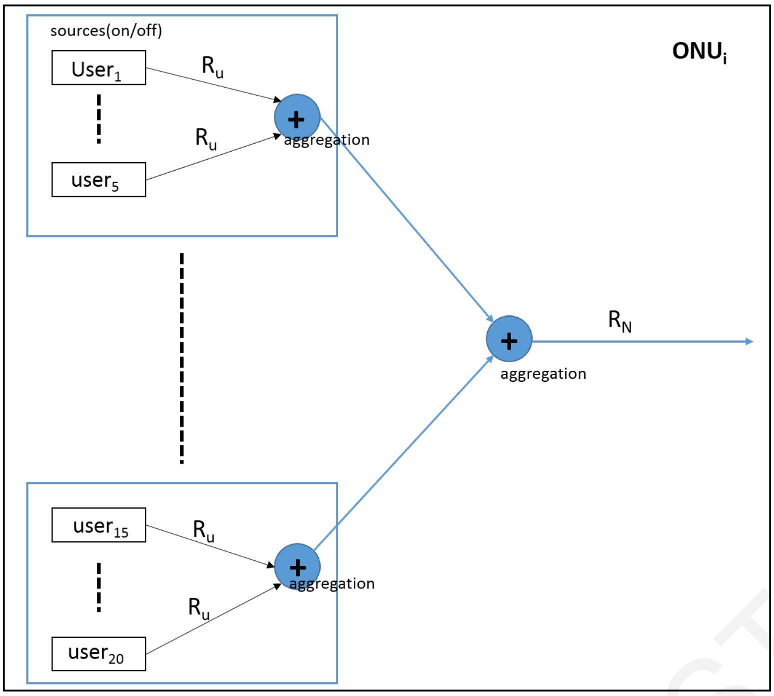

Figure 3.5: ON/OFF users (sources) aggregation model.

where K is the number of ON/OFF users (sources) per ONU, N is the number of ONUs in the simulated network (from 8 to 32 ONUs) and OL is the simulation offered load which varies from 0.1 to 1.0. R_U is the transmission rate at the user level and R_N is the transmission rate at the ONU level.

3.3.2 Tree-Based TDM-PON Simulation Model

In order to obtain an accurate and realistic performance analysis of the various bandwidth allocation techniques, the system is simulated with the appropriate traffic. As explained above, the most appropriate network traffic flows are characterized by self-similarity and long-range dependence (LRD). This type of traffic can be generated by multiplexing several sources of Pareto-distributed ON and OFF periods as explained in the section above.

The network model simulated consists of N ONUs. The number of ONUs are in the range of 4 to 64, especially for the TDM-PON topologies where passive splitters are being used. Note that commercial PON-based FTTH network systems commonly use the 1×8, 1×16 or 1×32 splitting ratio, as this ratio affects the power budget of the system. A higher splitting ratio means that the attenuation of the optical signal that reaches the ONUs is increased considerably, thus active components (such as optical amplifiers) may be needed.

The data rate of the access link from a user to an ONU is R_U in Mbps and R_N in Mbps is the rate of the upstream link from and an ONU to the OLT. Line rates for a link are the same in the upstream and downstream directions. In this model, the system parameters that were used for simulating all dynamic bandwidth allocation algorithms (DBAs) discussed in Section 3.2 are presented in Table 3.1 below.

PARAMETER	DESCRIPTION	VALUE
N	Number of ONUs	16
R_U	Line rate of user-to-ONU link	100Mbps
R_N	EPON line rate	1000Mbps
Q_{max}	Buffer Size in ONU	1Mbyte
G	Guard Interval	$1\mu s$
T_{max}	Cycle time	2ms
W_{max}	Timeslot Size	15500 bytes

Table 3.1: Tree-based TDM-PON system simulation parameters.

Simulation experiments were performed for the different dynamic bandwidth allocation techniques with all 16 ONUs having the same load in each simulation instance (for each different ONU offered load). All the other simulation parameters used are shown in Table 3.1 above and remain the same for all different experiments utilizing different ONU offered loads.

Fig. 3.6 above shows the results of the channel utilization versus the ONU offered load for the Fixed, Limited, Gated, and Elastic dynamic bandwidth allocation techniques for a tree-based TDM-PON when there is only traffic in the upstream direction (from the ONUs to the OLT) that requires the use of a collision avoidance mechanism.

It is observed that the best performance is achieved utilizing the Gated and Elastic DBA schemes for a channel utilization around 0.98, compared to the Limited and Fixed techniques that reach a channel utilization around 0.9. This performance is achieved at higher loads, where the traffic per ONU increases and all services reach the maximum channel utilization and the maximum buffer occupancy.

Additionally, simulation experiments were also performed in order to examine the average delivery time of the traffic per ONU for each load using the four different dynamic bandwidth allocation algorithms.

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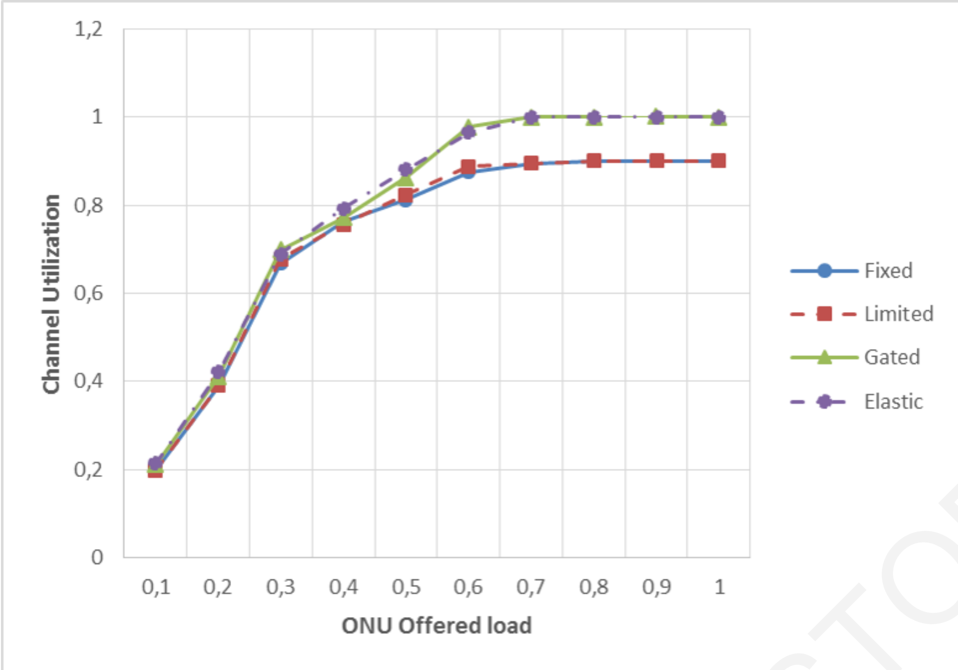

Figure 3.6: Performance results for different dynamic bandwidth allocation schemes.

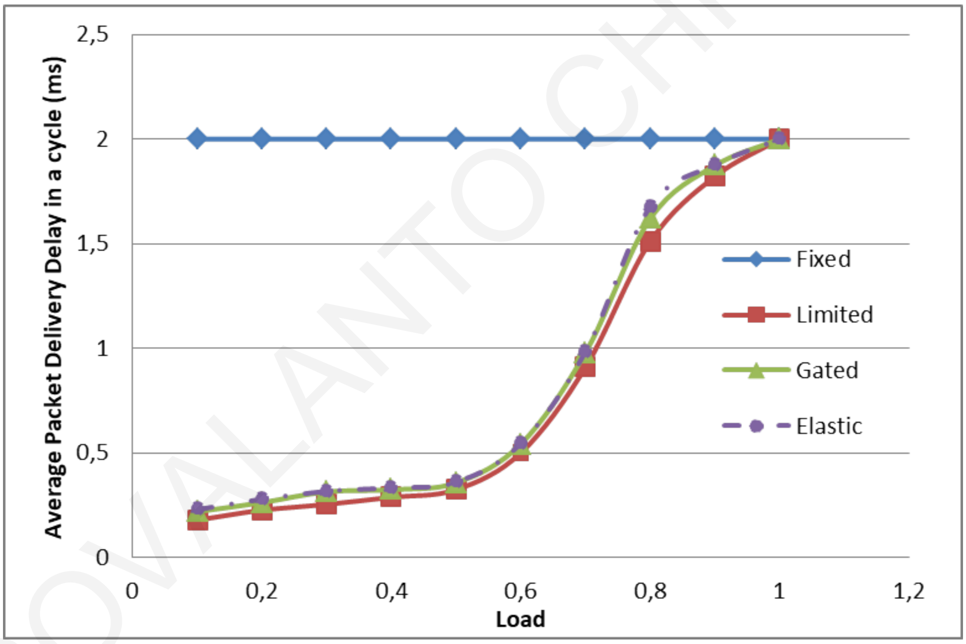

Figure 3.7: Average delivery time of the traffic per ONU in a cycle.

The reader should note that even though in the results presented above the gated and elastic approaches have better performance in terms of capacity utilization, amongst all algorithms, other considerations (such as packet latency and fairness) must also be taken into consideration. The limited approach (where the OLT grants the requested number of bytes, but no more than a given predetermined maximum) is the most conservative scheme and has the shortest cycle of all the schemes, thus

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it is preferred amongst all bandwidth allocation approaches and will be utilized throughout the rest of the thesis.

All of the dynamic bandwidth allocation schemes examined in this chapter are centralized and the assignment of the bandwidth occurs at the OLT. Such an approach however has some limitations that do not allow for the optimal use of the network resources. The first limitation is that the bandwidth allocation is not globally optimized, as the OLT does not take into account all ONU requests when deciding what to allocate to a single ONU (this decision is based only on the state of that specific ONU during the previous cycle). In addition, the traffic considered is bursty, and this may create significant variations in the amount of traffic that each ONU has to transmit. In this case, one ONU may have excess capacity that can be used to accommodate another overloaded ONU, but this capacity is wasted due to the previous aforementioned limitation.

Thus, it is clear that a distributed control plane is required in order to accommodate these limitations and have a better utilization of network resources. By utilizing a distributed control plane, the bandwidth allocation computation can be performed after receiving and processing the requests for all ONUs, leading to a more efficient decision (globally optimized without now having any excess bandwidth that is not allocated to overloaded ONUs). This global optimized solution can also be extended to the ONU and/or priority level. In addition, the order of ONU transmission (in each cycle) can now be set according to the traffic demand and traffic priorities.

In addition, it is clear that traditional tree-based TDM-PON architectures suffer from several limitations. Firstly, TDM-PON is based on a fixed number of well synchronized time slots, so it is not easily scalable. Also, this architecture does not provide any inherent protection capabilities and is also less secure as it uses a broadcast and select operation mechanism which allows other ONUs to possibly "listen" to time slots that do not belong to them. In addition tree-based architectures do not allow for direct inter-ONU communication and they also require a centralized control plane, limiting the control flexibility of the network and its utilization of resources. Due mostly to the capacity utilization and security issues, WDM-PON tree-based models were subsequently proposed as the possible successors to TDM-PON tree-based architectures, where the ONUs do not share wavelength capacity, with each ONU possessing its own wavelength, directly routing its traffic to the OLT (i.e., a separate pair of dedicated upstream/downstream wavelength channels is provided to each subscriber with Gb/s of dedicated bandwidth per subscriber).

The WDM-PON architecture offers the advantages of higher speed, as well as scalability in capacity and network size. Additionally it provides dedicated optical connectivity to each subscriber with bit rate and protocol transparencies, guaranteed QoS, and increased security. Finally, the bandwidth allocation mechanisms are now considerably simplified, as there is no need for DBA algorithms, and OLT-ONU communication is performed in a point-to-point fashion. However, despite these attractive features, WDM-PON installation is costly, mainly because of the use of active WDM sources. However, as bandwidth demand increases, the economics change. In terms of cost per bit rate, WDM-PON is projected to be more efficient and economical compared to the TDM-PON alternatives.

Nevertheless, the traditional tree-based WDM-PON architectures also suffer from several limitations similar to their TDM-PON counterparts. These limitations stem from the network topology rather than the technologies utilized. Firstly, this architecture cannot efficiently utilize the available network resources. The unused dedicated channel capacities of lightly-loaded/idle subscribers cannot be shared by any of the other heavily-loaded users attached to the PON. Additionally, it cannot provide private networking capability within a single PON. Finally, there are no simple and cost-effective recovery capabilities which are essential in order to provide guaranteed QoS to the end-users.

Thus, an alternative architecture solution is needed for the converged optical-wireless access networks. Initially, the ring-based WDM PON architecture is examined in Chapter 4 in terms of efficient utilization of the network resources, followed by a novel wheel-based architecture that is discussed in Chapters 5 and 6 that investigate both wavelength scheduling, as well as the protection capabilities of such an architecture.

3.4 Conclusion

This chapter discusses and presents various bandwidth allocation techniques for TDM-PON architectures, utilized for collision avoidance in the upstream direction, including their performance comparison in terms of capacity utilization. TDM-PON limitations are also discussed leading to the conclusion that WDM-PON architectures must be considered. However, even though WDM-PONs solve the problems

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of limited bandwidth to each subscriber compared to TDM-PONs, the tree-based architectures utilized nowadays face a significant number of limitations when considered as a converged solution for backhauling both fixed and mobile traffic. In the chapters that follow ring- and wheel-based WDM-PON architectures are described that aim to alleviate all these limitations. For these architectures a number of networking issues are addressed such as downstream wavelength selection and scheduling techniques, priority scheduling algorithms for QoS support, as well as fault recovery techniques.

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Chapter 4

Wavelength Scheduling in WDM PON-Based Mobile Backhaul Networks

4.1 Introduction

As described in detail in Chapter 2, a large amount of work has taken place over the years on converged optical-wireless access networks and several viable solutions for the optical access topology have been proposed, with the main topology being a tree-based WDM-PON architecture as also described in Chapter 3. In several publications in the more recent years, a standalone ring-based initially EPON [104] and later WDM-PON [32], [33] architecture has been proposed as a solution to the optical access arena that provides dedicated connectivity to all subscribers with bit rate and protocol transparencies, guaranteed QoS, and increased security. Additionally, the ring-based architecture, as described in [31], provides resiliency capabilities, compared to the conventional tree-based solutions.

Another major advantage of the ring architecture is that it can enable the usage of efficient schemes for dynamic allocation of wavelengths and sharing traffic among end-users, by allowing underutilized wavelengths to serve destinations whose dedicated resources are overloaded. This is made possible by this specific architecture that allows inter-nodal communication on the ring, as well as a distributed control mechanism for allocating bandwidth for inter-nodal communication. The reader should note that even though the proposed wavelength sharing and scheduling

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approach utilized in this work is based on a centralized manager (control module) located at the OLT to make decisions on which wavelengths to use (utilizing also information from the ONUs/BSs made available through control communication), the actual implementation of the technique requires the usage of the λ_{LAN} for inter-nodal communication, and that process relies on a distributed LAN control plane.

In this chapter we extend on this architecture, proposing a converged ring-based WDM PON architecture in which the ONUs are integrated with the BSs and can serve both mobile and fixed users. Thus, this architecture can be utilized for backhauling mobile traffic. Initially this architecture and its operation are described in detail, followed by the description of wavelength sharing and scheduling algorithms when classes of service are also present and when all traffic is indistinguishable, without any assigned priorities (as first presented in [19] and [21]). The performance of the proposed algorithms is subsequently examined and analyzed, aiming to provide QoS for both fixed and mobile end users. The performance metric considered here is the transmission delay for both fixed and mobile traffic in the downstream direction.

Specifically, in this chapter, different heuristic and optimization algorithms are proposed for downstream wavelength scheduling in ring-based WDM-PON mobile backhaul networks, where optical networking units (ONUs) are integrated with base stations (BSs). The main objective of the work is to improve the time delay of the packet delivery from the infrastructure to the end-users for both fixed and wireless traffic. This is achieved through dynamic wavelength scheduling and sharing techniques in a converged ring-based WDM-PON access architecture by taking into account the priorities of the data sent and also the cooperation area for mobile users between adjacent ONUs/BSs. The proposed heuristic algorithms are examined under different traffic load scenarios and compared with the optimization algorithm for varying traffic loads.

The rest of the chapter is organized as follows: Section 4.2 describes the ring-based WDM PON architecture, the operation of this architecture, and how traffic flows in this network in the upstream and downstream direction. Subsequently, Section 4.3 describes the wavelength selection and scheduling algorithms for traffic with and without priorities, as well as for the downstream traffic destined to mobile users within the cooperation area. This is followed by the performance evaluation section (Section 4.4) that presents several experiments and scenarios to ascertain the performance of the proposed solutions in terms of the maximum data delivery time.

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Finally, Section 4.5 offers some concluding remarks.

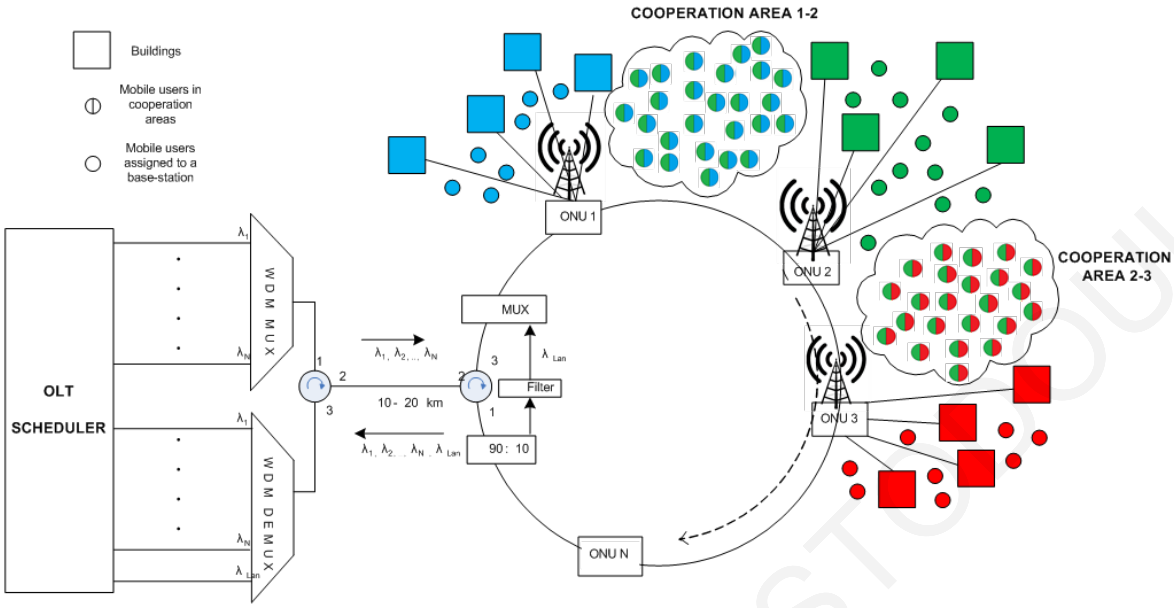

Figure 4.1: Converged ring-based WDM-PON architecture with integrated ONUs/BSs.

4.2 Converged Ring-based WDM-PON Architecture

The proposed converged optical-wireless ring-based WDM-PON architecture with integrated ONUs and BSs is shown in Fig. 4.1. In this architecture the OLT is situated within the central office of a service provider at a distance of around 10 – 20 km from the end users and it is connected to the ONUs/BSs via a trunk fiber. The ONUs/BSs are interconnected through a short distribution fiber ring with diameter 1 – 2 km (unidirectional ring with traffic flowing in the clockwise direction) so as to cover the same local access area as in the tree-based architecture. As can be seen in Fig.4.1, the trunk fiber from the OLT is connected to the distribution ring through two passive 3-port optical circulators that allows traffic to flow from the trunk fiber onto the ring and from the ring to the trunk fiber and eventually the receiver array at the OLT.

Assuming that there are N ONUs/BSs on the ring, then the OLT houses N fixed transmitters (TXs) and $N + 1$ fixed receivers (RXs). Each TX/RX pair in the OLT corresponds to one TX/RX pair at the ONU/BS on the distribution ring (as this is a WDM-PON architecture, one dedicated wavelength is assigned for communication between the OLT and each ONU/BS). The extra RX at the OLT serves to receive the

λ_{LAN} wavelength from the distribution ring as it is explained below. The wavelengths utilized for upstream and downstream communications, as well as the LAN wavelength, can in the 1530 – 1565 nm standard C-band (spaced 200 GHz apart). Clearly, the wavelengths used will mostly depend on the number of ONUs/BSs on the ring. For example, for $N = 16$, these wavelengths can also be allocated over the 1270 – 1610 nm CWDM spectrum (with 20-nm spacing), reducing the overall capital expenditure by utilizing low-cost CWDM components. Scaling the ring to larger numbers of ONUs/BSs will depend on the power budget considerations as also detailed in [44].

The 3-port circulator is utilized to allow downstream traffic from the OLT to get onto the ring and at the same time to allow upstream traffic from the ring to enter the trunk fiber and reach the OLT. On the ring side, it couples the WDM signal to the ring which is recombined with the re-circulated LAN signal via a 2×1 WDM combiner (mux). Then, the combined signal circulates around the ring in a drop/add and pass-through fashion via the N ONUs/BSs. Thus, traffic arrives at the OLT from metro and backbone networks, and this traffic is sent to the end users (mobile or fixed) through the ONUs/BSs. In order to be able to share and schedule wavelengths, the OLT also houses N queues, a flow scheduler module, and a low-cost WDM multiplexer/demultiplexer, which are responsible for scheduling the packets to their assigned destinations as is explained in this chapter.

On the distribution fiber ring, the N ONUs/BSs are interconnected with point-to-point unidirectional fiber links, forming a ring, where traffic flows only in the clockwise direction. As mentioned above, each ONU/BS houses a TX/RX pair which is matched to the corresponding TX/RX pair at the OLT in order to receive and transmit downstream and upstream traffic on a dedicated wavelength (λ_i, $i = 1, ..., N$). In addition, each ONU/BS also houses an extra TX/RX pair for transmitting and receiving the local LAN wavelength λ_{LAN}. This wavelength, λ_{LAN}, is used for inter-ONU/BS communication within the ring. Inter-ONU/BS communication is used when an end user connected to an ONU (or BS) (either via wireline or through a wireless connection) wants to send information to another end user connected to another ONU (or BS) (either via wireline or through a wireless connection) that resides on the same ring. In addition, as it will be explained in more detail below, inter-ONU/BS communication is utilized when a dedicated connection cannot be made between the OLT and an ONU/BS, and the λ_{LAN} is employed as a "transient" wavelength in

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order to send the data to its final destination. Finally, the λ_{LAN} is also used to carry control information between the ONUs/BSs and the OLT. As this is a single fiber ring, with only one wavelength utilized for inter-ONU/BS communication, time-division multiplexing is used. Thus, a bandwidth allocation technique (as the ones described in the Chapter 3 for the tree-based PONs) is required to establish all connections on the ring.

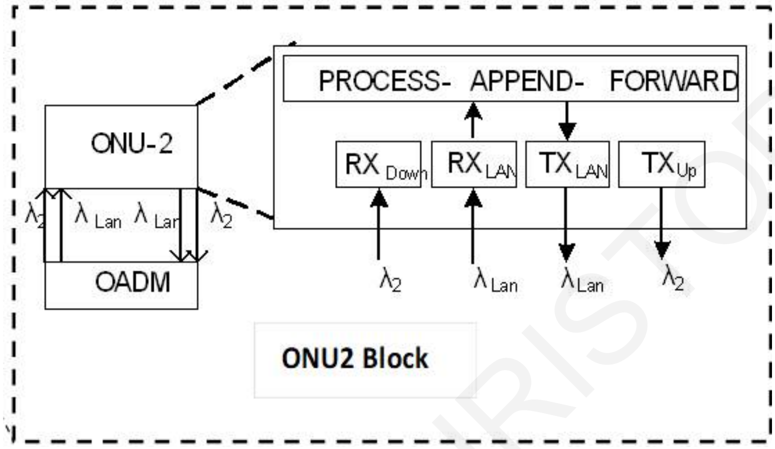

Figure 4.2: Converged node architecture.

As the fiber ring that connects the N ONUs/BSs is unidirectional, both downstream and upstream signals are transmitted in one direction only as a combined signal. The LAN wavelength channel λ_{LAN} is terminated, regenerated, and retransmitted at each ONU/BS [8]. Figure 4.2 shows a detailed view of the ONU/BS node, that includes a low cost optical add-drop multiplexer (OADM), where the dedicated wavelengths assigned to each node (downstream, upstream, and LAN wavelengths) are dropped and added at each node. After the final (N^{th}) ONU/BS on the ring, a 1×2 90:10 passive splitter is utilized, together with a filter and a multiplexer located on the ring after the circulator and before the 1st ONU/BS, to allow the λ_{LAN} traffic (10% of the signal) to circulate around the ring after recombining with the downstream signal that originated at the OLT utilizing the 2×1 WDM multiplexer, while filtering out all upstream traffic. The upstream traffic (90% of the signal) reaches the circulator and is directed to the trunk fiber, destined for the OLT, where it is received by an array of N optical receivers (each receiver detects its corresponding upstream signal). The λ_{LAN} traffic also reaches the OLT and there it is received by a λ_{LAN} receiver and subsequently used for control purposes. Wavelength λ_{LAN} can also potentially carry upstream traffic, downstream traffic, and dedicated LAN traffic.

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The upstream traffic is received and forwarded to the appropriate destination, while the downstream and dedicated LAN traffic will be discarded. The reader is referred to [8] for a detailed description of the ring-based WDM-PON architecture.

In addition, in Fig.4.1, the *cooperation area* is defined as the area located between two adjacent ONUs/BSs that are connected around the fiber ring. The mobile users within this area can be served by both ONUs/BSs. Note that each ONU/BS serves both fixed and mobile users; an ONU/BS serves the fixed users that are connected directly with it, the mobile users that are within an area near the ONU/BS, and also the mobile users that are within the cooperation area with an adjacent ONU/BS around the ring.

4.2.1 Inter-ONU/BS Communication

For inter-ONU/BS communication, during a given cycle, at each assigned time slot, each integrated ONU/BS transmits a control message (denoted as REPORT). This control message is transmitted from node to node around the ring, directly informing all nodes on the ring of its control information, where this information relates to the desired size of the next time slot based on the data that this specific ONU/BS has to transmit (based on the data in the ONU buffer at that time). Eventually, this control message reaches the node where it originated, where at that point it is removed from the ring. In addition, as λ_{LAN} traverses around the ring, control information from each node is appended to the data, and this way, in a distributed manner, all nodes on the ring are aware of the state (amount of information that each node on the ring wishes to transmit in the next cycle) of the rest of the nodes on the ring. A control module located at each node can subsequently use this information to calculate a new set of time slot assignments at each cycle (each ONU independently runs the same bandwidth allocation algorithm once all control information has reached all network nodes). This way, a unique set of time slot assignments can be calculated for the next cycle, without depending on the OLT for these calculations, as it was the prior state of the art. In turn, the ONUs/BSs sequentially can transmit their data based on this assignment without any collisions.

Clearly, precise time synchronization between ONUs/BSs is required for this scheme to operate correctly. This is feasible for these types of architectures, as in PONs synchronization for the ONUs is implemented utilizing a synchronization

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marker (one byte code transmitted every 2 ms) that is embedded in the downstream traffic from the OLT to the ONUs.

As it will become apparent below, as well as in Chapter 5, the data carried on λ_{LAN} may include inter-ONU/BS communication data, downstream traffic, as well as upstream traffic. In this case, downstream/upstream traffic will be traffic that is utilizing λ_{LAN} because it could not be accommodated by the dedicated downstream/upstream wavelength channel.

Clearly, as also discussed in Chapter 3, an efficient bandwidth allocation algorithm is required for this architecture. A discussion on the choice of the dynamic bandwidth allocation algorithm utilized in this work is included in both Chapter 3 and Chapter 5 of this thesis.

4.3 Wavelength Selection and Scheduling Algorithm

As mentioned in the introductory chapter, there has been a tremendous growth in the development of both high-capacity backbone and metro access network (MAN) architectures and service providers are continuously trying to find more efficient solutions for the access arena to alleviate the "last mile" bottleneck problem and deliver data to the end users efficiently, while meeting certain QoS constraints.

Using the ring-based WDM-PON architecture for the converged FiWi infrastructure as described above, provides an efficient way for the network resource utilization via wavelength selection and scheduling (both in the downstream as well as the upstream direction). This chapter extends the state of the art on wavelength selection and scheduling in ring-based WDM-PON architectures [32], [33] by also considering mobile users in a now converged architecture. Further, priority scheduling also needs to be taken into consideration as these networks carry traffic for various classes of service. Significant research work has taken place for priority scheduling, but only for tree-based access architectures, mostly proposing schedulers that fairly divide the excess bandwidth among priority queues from different ONUs [56], [57], [60]. This chapter also examines priority scheduling, again in the context of converged FiWi infrastructures, utilizing ring-based WDM-PON architectures.

Specifically, the presented ring-based converged WDM-PON architecture shown in Fig. 4.1 uses a wavelength selection and scheduling algorithm to efficiently schedule the traffic that reaches the OLT and is destined for the ONUs/BSs. The goal is

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to achieve good resource utilization and minimize the traffic delivery time for both fixed and mobile users in the downstream direction of the proposed WDM-PON architecture under different traffic scenarios.

In the ring-based WDM-PON architecture, when the traffic reaches the OLT destined for different ONUs, this traffic will be carried downstream utilizing specific wavelengths. This wavelength selection and scheduling process takes place within the OLT flow scheduler as shown in Fig. 4.1. To accommodate this process, the OLT houses N queues, one queue per ONU. Each queue (e.g., Q_i^{OLT}) is assigned to a specific ONU (e.g., ONU_i) and is connected to a dedicated downstream wavelength (e.g., λ_i). The downstream traffic from the OLT which is destined to ONU_i is sent through its dedicated wavelength via its assigned queue Q_i^{OLT}. Also, at each ONU, two more queues are utilized, one queue, $Q_{i,up}^{ONU}$, which is assigned to the dedicated upstream wavelength, λ_i, and a second queue $Q_{i,LAN}^{ONU}$, which is assigned to the LAN/control traffic.

In the normal wavelength selection and scheduling operation, if queues Q_i^{OLT} and $Q_{i,LAN}^{ONU}$ have available space for ONU_i/BS_i's downstream traffic, the traffic will be sent through the dedicated downstream wavelength, λ_i. However, if a downstream dedicated wavelength, λ_i, with traffic destined to ONU_i/BS_i, is overloaded and its corresponding Q_i^{OLT} is congested, the scheduler at the *OLT* will divert the traffic to a different ONU, by sending the traffic to a different (not overloaded) queue that corresponds to a different downstream wavelength. The LAN wavelength is subsequently used in the ring to ultimately deliver the traffic to the correct destination (where the traffic was originally destined to). The decision of which wavelength will be selected for the transmission of the packets of the overloaded wavelength, depends on which of the scheduling algorithms the scheduler at the OLT is utilizing.

For example, assume that a downstream dedicated wavelength, λ_i, with traffic destined to ONU_i/BS_i, is overloaded and its corresponding Q_i^{OLT} is congested. The algorithm finds a suitable alternative (underutilized) wavelength (say λ_j) that is destined to ONU_j/BS_j and puts the data for ONU_i/BS_i on this wavelength. This data will eventually be terminated at ONU_j/BS_j, where it will be initially buffered at the corresponding ONU_j's LAN queue and then λ_{LAN} will be subsequently used to carry the traffic to its final destination (ONU_i/BS_i), utilizing the bandwidth allocation algorithm discussed above (carry the data via TDM on the time slots granted for ONU_j/BS_j's LAN traffic). Note that at node ONU_j/BS_j, both LAN traffic and down-

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stream traffic are terminated. The node's control module then decides which data to pass on to the end users (downstream traffic destined for that specific node) and which data to pass through (transient LAN traffic as well as transient downstream traffic). This decision can be based on specific traffic identifiers such as the MAC address of the Ethernet frames, etc.

Wavelength Selection and Scheduling Process: The process described in short above consists of the following steps:

- The OLT periodically (at the end of each cycle), checks to determine whether the queue for each dedicated wavelength (and its LAN queue at the corresponding ONU/BS node) is congested or is available to transmit information. Clearly, the threshold for the capacity of the queues can vary. One easy approach to this is to limit the packet delay in the queue (thus the threshold can be easily found, as the data rate of each channel is known). The reader should note that the status of the LAN queues is reported via the LAN REPORT messages transmitted to the OLT (utilizing λ_{LAN}). Since it takes some time for these control messages to reach the OLT, the information on the occupancy of the LAN queues may be slightly outdated. To be as accurate as possible, at each cycle, the REPORT message that arrives last to the OLT within the current cycle must be utilized, as it comprises of the most up-to-date information on the occupancy of the LAN queues.

- When a new traffic flow arrives at the OLT, destined to end users, the OLT scheduling module has to make a decision whether to admit and route, or drop the flow. If the dedicated queue for that flow is not a congested queue, it can be utilized to transmit the information. If, on the other hand, it has been identified as a congested queue, the scheduling algorithm will make a determination of how many flows should be rerouted and to which alternate queue. If such a queue cannot be found, it drops the flow.

Note that utilizing a similar process, upstream traffic at a specific (overloaded) node can also utilize λ_{LAN} to transport the traffic to the OLT, provided that the LAN queue of that specific node has available capacity to accommodate the excess flow for the overloaded upstream dedicate wavelength. In this case, the excess traffic will be buffered in the LAN queue and transmitted together with dedicated LAN traffic and/or transient downstream traffic as explained above. Utilizing the 90:10 splitter on the ring, λ_{LAN} will also reach the OLT, where the transient downstream and dedicated LAN traffic will be discarded and the control traffic and transient upstream traffic will be received and processed. Subsequently, the transient upstream traffic will be sent to its appropriate destination. In the same manner, the LAN traffic will pass through the 90:10 splitter, the filter, and the combiner and will be re-injected on the ring (combined with the downstream traffic from the OLT). The transient upstream traffic will be eventually removed from the LAN channel when it reaches the source ONU/BS (the ONU/BS where this particular traffic first originated). Chapter 5 includes more details on the upstream wavelength assignment and scheduling scheme, including performance results for both fixed and mobile traffic.

4.3.1 Downstream Wavelength Selection and Scheduling Algorithms

Two heuristic algorithms are implemented for the downstream wavelength selection and scheduling (WSaS), namely the first-fit and the lightly-loaded heuristics [21]. For the first-fit WSaS heuristic algorithm, if a dedicated downstream wavelength channel, λ_i, which is destined to ONU_i/BS_i is overloaded, the following steps are executed: (i) The scheduler at the OLT searches for the first available downstream wavelength channel, λ_j, $j > i$, that can accommodate λ_i's excess flow – without searching if the channel is heavily or lightly loaded; (ii) If the search is successful and the scheduler at the OLT finds an underutilized downstream wavelength channel, λ_j, whose corresponding queue has some available space that can accommodate one or more of λ_i's excess traffic, then λ_j is selected if and only if its corresponding LAN queue at ONU_j, $ONU_{j,LAN}$, has also available space to accommodate the excess flow.

For the Lightly-Loaded WSaS heuristic, if a dedicated downstream wavelength channel, λ_i, which is destined to ONU_i is overloaded, the scheduler at the OLT initially searches for another underutilized downstream wavelength channel, λ_j, whose corresponding queue has the maximum available space in comparison to all the other wavelengths that can accommodate one or more of λ_i's excess downstream traffic flows. If the search is successful, the available channel with the maximum capacity, λ_j, is selected if and only if its corresponding LAN queue at ONU_j, $ONU_{j,LAN}$, is also available (e.g., it can accommodate the excess traffic originally destined for wavelength λ_i). Figs. 4.3 and 4.4 demonstrate the scheduling of the packets when

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the first-fit and lightly-loaded heuristics are utilized respectively.

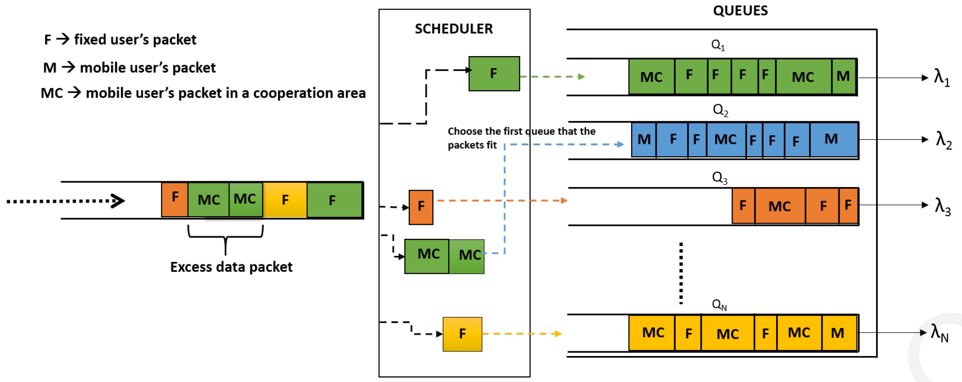

Figure 4.3: Scheduling of the packets when the first-fit heuristic is utilized.

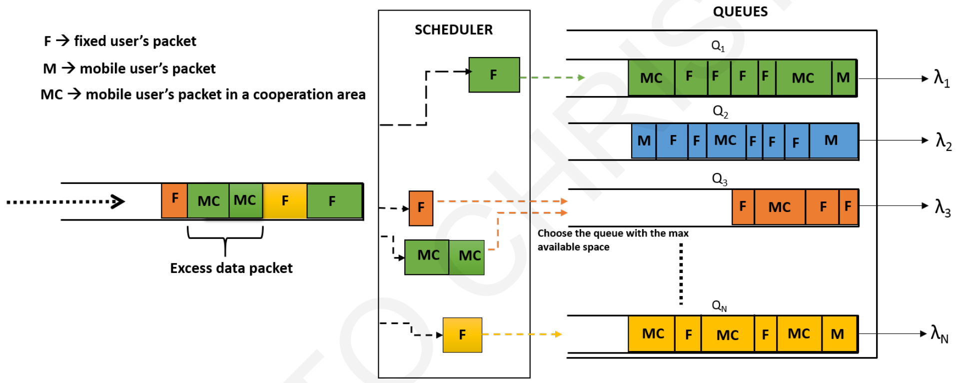

Figure 4.4: Scheduling of the packets when the lightly-loaded heuristic is utilized.

Apart from the two heuristics, a novel Integer Linear Program (ILP) formulation for the wavelength selection of packets that cannot be sent through their dedicated wavelength is presented. The ILP is formulated in order to find the best scheduling for the packets, in terms of time delay, that need to be routed through different wavelengths than the ones that correspond to their dedicated ONUs/BSs. This optimization is used for benchmarking the performance of the network under different traffic conditions. Note that the optimization algorithm developed addresses an inherently dynamic problem by considering snapshots of a dynamic scenario during which offered traffic and current queue status are known and fixed. The following parameters and variables are used to formulate the problem.

Parameters:

- $w \in C$: an available wavelength, $|C| = N$

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- U: the set of ONUs.
- α_{ip}: the requested transmission time of a packet p that corresponds to destination ONU$_i$.
- P: the set of packets that will use different wavelength (λ_i) to reach destination ONU$_i$,
- t_{offset}: the required time to deliver a packet from ONU$_i$ to ONU$_j$
- T_Q: the maximum available queue time at the queue of an ONU.
- Q_{total}: the maximum queue time that corresponds to the queue size.
- Q_w: the occupied time at queue Q_i^{OLT}. This is the time required by the packets that are sent through their dedicated wavelength.
- M: a large constant.

Variables:

- X_{ip}^{w}: a Boolean variable, equal to 1 if packet p occupies wavelength w to reach destination ONU$_i$, 0 otherwise.
- f_w: a Boolean variable, equal to 1 if wavelength w is used to deliver packets to ONU$_i$, $i \neq w$.
- g_w: an integer variable equal to the number of extra cycles that may be required for the packets to wait in queue Q_i^{OLT}, $i = w$, in order for the packets to be delivered to their destination. (Extra cycles are required to deliver a packet due to limited-size queues at the ONUs. The time of a cycle is equal to t_{offset}.)
- F_w: a variable equal to the required time to deliver all the packets that use wavelength w to their destination.
- F_{max}: a variable equal to the maximum required time to deliver all the packets to their destination.

The formulation of the problem is then as follows:

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Objective: *Minimize*:

$$F_{max} \tag{4.1}$$

Subject to the following constraints:

Demand constraint:

$$\sum_{w} X_{ip}^{w} \alpha_{ip} = \alpha_{ip}, \forall p \in P, \forall i \in U \tag{4.2}$$

Packets on different w (OLT queue):

$$\sum_{i} \sum_{p} X_{ip}^{w} \leq f_w M \forall w \in C, \forall i \neq w \tag{4.3}$$

Maximum capacity for each wavelength (OLT queue):

$$\sum_{i} \sum_{p} X_{ip}^{w} \alpha_{ip} \leq Q_{total} - Q_w, \forall w \in C \tag{4.4}$$

Extra cycles needed due to limited-size queues at ONUs:

$$\sum_{i} \sum_{p} X_{ip}^{w} \alpha_{ip} \leq T_Q + g_w T_Q, \forall w \in C \tag{4.5}$$

Time capacity for each wavelength :

$$\sum_{i} \sum_{p} X_{ip}^{w} \alpha_{ip} + (f_w + g_w) t_{offset} + Q_w = F_w, \forall w \in C \tag{4.6}$$

Maximum delivery time:

$$F_w \leq F_{max}, \forall w \in C \tag{4.7}$$

The objective is used in order to minimize the total time required to deliver all the packets to their corresponding destinations (ONUs). The total time is determined by the most-loaded queue in the OLT in combination with the queues in the ONUs. Constraint 4.2 corresponds to the packet delivery constraint, ensuring that the packets of a destination (ONU) will be delivered using any available wavelength (any available OLT queue). At the same time, this constraint ensures that each packet can

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be assigned only to one wavelength (one OLT queue). This constraint differentiates one packet from the other. Constraint 4.3 is used to activate the Boolean variable f_w. This variable is enabled when packets that correspond to ONU$_i$, will use wavelength w, to reach their destination. The large constant M is used to activate the variable with at least one packet that uses wavelength w to reach the destination ONU$_i$. This variable is useful in order to count the extra time a packet requires to reach its destination. The extra time is added due to the fact that this packet has to be dropped at a different ONU and then added again to reach its destination ONU using λ_{LAN}. Constraint 4.4 prohibits the use of a wavelength (OLT queues) that exceeds the maximum capacity of the corresponding queue. Q_w is the available size in the queue that uses wavelength w and can be used by the packets to reach their destination. Constraint 4.5 counts the extra cycles that are required due to the limited-size queues at the ONUs. The queue at an ONU corresponds to the size of the available time that can be used by an ONU in order to receive packets using λ_{LAN}. If this queue is full, extra cycle(s) are required to receive all the packets. Variable g_w counts the required cycles. Constraint 4.6 counts the required time in order for all the packets of a queue to reach their destination. This time is equal to the time required by the packets that are sent through their dedicated wavelength (Q_w) plus the required time for the packets that use a different wavelength to reach their destination. The packets that use a different wavelength require at least one extra cycle. This is taken into account by the Boolean variable f_w. Moreover, the extra cycles required due to the queues at the ONUs are taken into account by the variable g_w. Constraint 4.7 is used to find the queue that requires the maximum time in order to deliver the packets to their corresponding destinations.

4.3.2 Priority Scheduling Algorithms for QoS Support

In this section, heuristic algorithms are presented for priority-based scheduling techniques for QoS support in ring-based WDM-PONs, focusing on the downstream direction. The focus of these algorithms is on not only achieving a good resource utilization of all the packet/traffic in the downstream direction but also improving the time delay of the high-priority packet delivery from the infrastructure to the end-users (mobile or fixed users). This is achieved through dynamic packet reordering and scheduling in different priority queues and wavelengths [19]. The heuristic

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algorithms implementing dynamic scheduling are compared in terms of the high-priority packet delay for varying traffic loads.

As discussed previously, in the proposed architecture traffic from the OLT to the ONUs/BSs is carried downstream utilizing specific queues according to the destined ONU. This queue selection and scheduling process takes place within the OLT scheduler. To accommodate this process, the OLT houses N queues, one queue per ONU/BS. Each queue (e.g., Q_i^{OLT}) is assigned to a specific ONU (e.g., ONU_i/BS_i) and is connected to a dedicated downstream wavelength (e.g., λ_i). Each queue also houses 3 priority sub-queues ($Q_{i,p0}^{OLT}$, $Q_{i,p1}^{OLT}$, $Q_{i,p2}^{OLT}$), each one belonging to a different packet priority class (priority 0, 1, and 2 corresponding to high, medium, and low priorities respectively). Thus, downstream traffic from the OLT, which is destined to ONU_i is sent through its dedicated wavelength via its assigned queue Q_i^{OLT}. Also, at each ONU_i, two more queues are utilized, one queue, $Q_{i,up}^{ONU}$, which is assigned to the dedicated upstream wavelength, λ_i, and a second queue, $Q_{i,LAN}^{ONU}$, which is assigned to the LAN/control traffic.

The process of scheduling and sharing downstream priority queues is implemented jointly at both the OLT and the ONUs. Two different priority scheduling algorithms are proposed in this work, namely High Priority Scheduling Algorithm A (HPSA-a) and High Priority Scheduling Algorithm B (HPSA-b).

For HPSA-a, if a dedicated downstream high priority queue, $Q_{i,p0}^{OLT}$, serviced by its dedicated wavelength, λ_i, which is destined to ONU_i is overloaded, the scheduler at the OLT searches for another underutilized downstream queue, initially investigating the queues of different priorities for ONU_i (e.g., $Q_{i,p1}^{OLT}$, $Q_{i,p2}^{OLT}$) and subsequently examining lower priority queues for other ONUs (e.g., $Q_{j,p1}^{OLT}$, $Q_{j,p2}^{OLT}$), in order to ascertain which queue has available space to accommodate one or more of $Q_{i,p0}^{OLT}$'s excess downstream traffic flows. Note that the scheduler does not search the rest of the high-priority queues (dedicated to the other ONUs) so as not to affect the high priority traffic of the other ONUs. If the search is successful, the available queue, e.g., $Q_{j,p1}^{OLT}$, is selected, if and only if its corresponding LAN queue at ONU_j, $Q_{j,LAN}^{ONU}$, can also accommodate the excess traffic originally destined for wavelength ONU_i.

On the other hand, in the case of HPSA-b, if a dedicated downstream high priority queue, $Q_{i,p0}^{OLT}$, is overloaded, the following steps are executed: (i) The scheduler at the OLT searches for a high priority downstream queue, $Q_{j,p0}^{OLT}$, $j \neq i$, that can accommodate $Q_{i,p0}^{OLT}$'s excess flow (ii) If the search is successful and the scheduler

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at the OLT finds an underutilized high priority downstream queue, $Q_{j,p0}^{OLT}$, whose corresponding queue has the maximum available space in comparison to all the other high priority downstream queues that can accommodate one or more of $Q_{i,p0}^{OLT}$'s excess downstream traffic flows, $Q_{j,p0}^{OLT}$, is selected, if and only if its corresponding LAN queue at ONU$_j$, $Q_{j,LAN}^{ONU}$, has also available space to accommodate the excess flow. The pseudocode of this algorithm is shown below (Alg. 4.3.2).

The scheduler, for both techniques, redirects one, some, or all of $Q_{i,p0}^{OLT}$'s excess flow(s) to the selected queue, $Q_{j,px}^{OLT}$, and it is then transmitted, along with ONU$_j$'s native downstream traffic to ONU$_j$ over its dedicated wavelength channel λ_j. Then, ONU$_j$ terminates all of λ_j's downstream traffic including both native downstream traffic destined to ONU$_j$ and traffic destined to ONU$_i$, and performs the following two functions: (i) The native downstream traffic that matches ONU$_j$'s address is copied and delivered to the end-users and (ii) the transient traffic destined to ONU$_i$ is redirected to ONU$_j$'s LAN queue and then retransmitted to its final destination (utilizing wavelength λ_{LAN}), within the proper designated LAN timeslot of ONU$_j$.

Algorithm 1 High Priority Scheduling Algorithm B

---

while Excess High Priority Flow $p_0 > 0$ **do**
    if ($Q_{i,p0}^{OLT}$ - Packet Size of p_0) $\geq Q_{max,p0_{available}}$ ($i \neq j$) **then**
        if ($Q_{j,LAN}$ + Packet Size of p_0) $\leq Q_{j,max}^{LAN}$ **then**
            $T_{j,p0}^{Delay} = T_{j,p0}^{Delay} + t_{PacketTransmissionP0}$
        else
            Check for next available $Q_{i,p0}^{OLT}$
        end if
    else
        Check for next available $Q_{i,p0}^{OLT}$
    end if
end while

4.3.3 Wavelength Scheduling Algorithm for ONU/BS Cooperation Area

Two new heuristic algorithms are presented for the proposed architecture of Fig. 4.1 that can utilize not only the fixed traffic but can also efficiently utilize the backhaul

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mobile traffic by taking into account the cooperation area of mobile users between adjacent ONUs/BSs as defined in Section 4.2.

The process of dynamically assigning and sharing downstream wavelengths is again implemented jointly at both the OLT and ONUs. Initially, all the fixed traffic destined to ONU_i and the mobile traffic destined to BS_i that can be served by BS_i and does not lie within the cooperation areas of BS_i and BS_{i+1}/BS_{i-1} are served first, and placed in the corresponding queue Q_i^{OLT}. Subsequently, the mobile users that are in a cooperation area are served by queue Q_i^{OLT} if it has available space. If the downstream queue, Q_i^{OLT}, with traffic destined to ONU_i/BS_i, is overloaded (with the fixed traffic and the mobile traffic that is destined to users outside the cooperation area), the scheduler at the OLT will use one of two different scheduling heuristic algorithms for the ONU/BS cooperation area to find an alternative available queue: a) Lightly-loaded wavelength scheduling and b) Cooperation-based wavelength scheduling heuristic algorithm, to divert the excess traffic in other available buffers/queues.

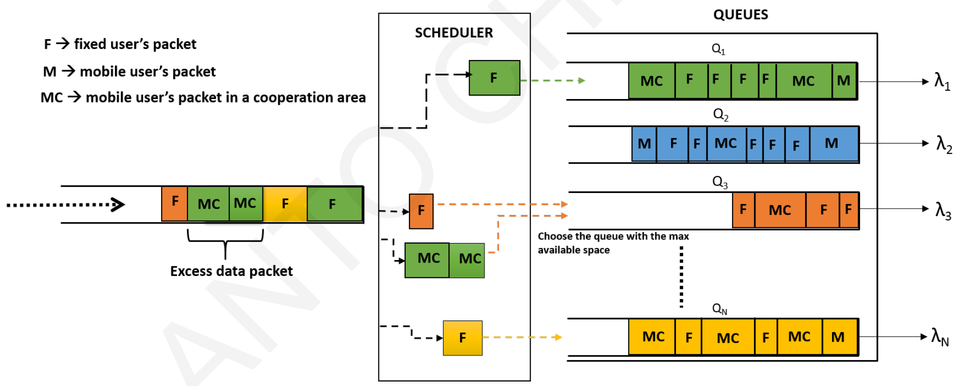

Figure 4.5: Lightly-Loaded wavelength scheduling algorithm.

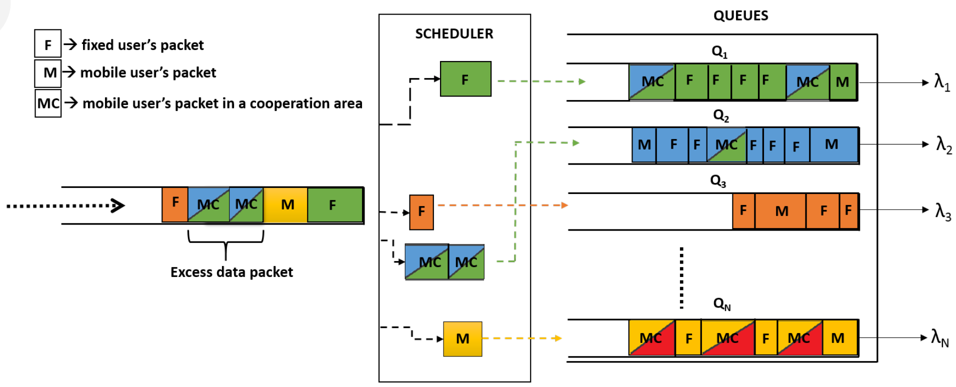

Figure 4.6: Cooperation-based wavelength scheduling algorithm.

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For the lightly-loaded wavelength scheduling algorithm (LLWSA), if a dedicated downstream queue, Q_i^{OLT}, which is assigned to a dedicated wavelength λ_i, destined to ONU_i/BS_i, is overloaded with fixed and mobile users' data, the following steps are taken: (i) The scheduler at the OLT searches for another downstream queue Q_j^{OLT} (with buffer $B_{j,mob_{coop}}$), where $j < i$, that has the maximum available space in comparison to all the other queues that can accommodate one or more of $B_{i,mob_{coop}}$'s (mobile data) excess downstream traffic flows. (ii) If the search is successful the underutilized downstream queue, Q_j, is selected and the excess mobile traffic of $B_{i,mob_{coop}}$ is diverted to the $B_{j,mob_{coop}}$ buffer of Q_j. Subsequently, the packets arrive to the mobile end-user through wavelength λ_j, as shown in Fig. 4.5.

For the cooperation-based wavelength scheduling algorithm (CWSA), if a dedicated downstream queue, Q_i^{OLT}, which is assigned to a dedicated wavelength λ_i, destined to ONU_i/BS_i, is overloaded with fixed and mobile users' traffic, the following steps are executed: (i) The scheduler at the OLT searches for the cooperator's downstream queue Q_{i+1}^{OLT} (which has available space that can accommodate one or more of $B_{i,mob_{coop}}$'s (mobile data) excess downstream traffic flows, without searching if the channel is heavily or lightly loaded; (ii) If the search is successful the underutilized downstream buffer, $B_{i+1,mob_{coop}}$ is selected and the excess mobile traffic of Q_i^{OLT} is diverted to the $B_{i+1,mob_{coop}}$ of Q_{i+1}^{OLT} and the packets arrive to the mobile end-user through Q_{i+1}^{OLT}, using wavelength λ_{i+1}, without adding any extra cycle delay time, as ONU_{i+1}/BS_{i+1} is in the cooperation area of ONU_i/BS_i (Fig. 4.6).

Another scenario that needs to be considered is the case where the queues of the ONU/BS within the cooperation area have no available space to accommodate the excess traffic. In order not to drop this excess mobile traffic and loose the data, the scheduler executes additional steps: (iii) If the search is not successful, the scheduler at the OLT searches for other downstream queue Q_j^{OLT} (with buffer $B_{j,mob_{coop}}$), where $j > i$, that has the maximum available space in comparison to all the other queues that can accommodate one or more of $B_{i,mob_{coop}}$'s (mobile data) excess downstream traffic flows. (vi) If this search is successful the underutilized downstream queue, Q_j, is selected and the excess mobile traffic of $B_{i,mob_{coop}}$ is diverted to the $B_{j,mob_{coop}}$ buffer of Q_j^{OLT} and the packets arrive to the mobile end-user through wavelength λ_j (with an extra delay equal to T_{cycle} ($2ms$)).

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Algorithm 2 Excess Mobile Cooperation (MC) Traffic

while Excess High Priority Flow MC > 0 **do**
  if (Q_{i+1}^{OLT} - PacketSizeMC) ≥ $Q_{max,i+1}^{OLT}$ **then**
    $Q_{i+1}^{OLT} = Q_{i+1}^{OLT}$ + PacketSizeMC
    $T_{i+1}^{Delay} = T_{i+1}^{Delay} + t_{TransmisisonPacketMC}$
  else
    Check for any Q_j^{OLT} with max availability
  end if
  MC packet flow = MC packet flow+1
end while

4.4 Performance Evaluation

All proposed heuristics and the ILP were implemented for a converged ring-based WDM-PON backhaul network shown in Fig. 4.1, with 16 integrated ONUs/BSs, interconnected in a ring configuration, where an OLT including a scheduler function was connected to the ring utilizing a 20 km bidirectional trunk fiber. An output file is generated, with the packets that cannot be accommodated by their respective dedicated queues, which is used as the input for the ILP in order to redirect them to other available queues. To solve the ILP formulation, the Gurobi library was used [4].

The downstream flows are generated by aggregating multiple sub-streams, where each sub-stream is modeled as an ON/OFF source, with Pareto distribution [107], to generate packets according to a self-similar process, with a Hurst parameter $H = 0.7$. The system parameters used in the simulation are the following: (i) All the channels (downstream, upstream, and LAN) are operating at 1 Gbps; (ii) Each ONU/BS houses a LAN queue (Q_i^{LAN}) with maximum size equal to 100 kbytes; (iii) The OLT houses 16 downstream queues, each one corresponding to a given ONU/BS with a maximum size of Q_{max} equal to 100 kbytes; (iv) The maximum access LAN link rate from users to an ONU is 200 Mbps; and (v) The maximum LAN cycle T_{cycle} is equal to 2 ms.

4.4.1 Downstream Wavelength Selection and scheduling

The First-Fit and the Lightly-Loaded heuristic algorithms are implemented with a variable downstream load destined to each ONU that is incremented from 0.1 to 1.0

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in 0.1 steps. Note that whereas the two heuristics are scheduling all the arriving packets at the available queue, by using a first-in first-out order, the ILP is trying to find the best match to redirect them in the available queues (not necessarily in a first-in first-out order), so as to improve the transmission delay of the packets for a transmission cycle (T_{cycle}). Fig. 4.7 shows the maximum delay time per ONU offered load (OOL) (averaged over 10 runs), which is needed in order to transmit the last packet to its destination within a transmission cycle, assuming a strict priority scheduling mechanism at each LAN queue and zero upstream traffic. It can be seen from this figure that, as expected, as the OOL increases, the maximum time delay also increases. By increasing the OOL of each ONU, many more packets are generated, so that the occupancy of each queue is higher, thus the transmission time for each packet is becoming higher as well. Additionally, in Fig. 4.7 it is shown that for higher loads, from 0.6 to 1.0, the time delay increases considerably and it almost reaches the maximum queue time. Finally, it is clear that the ILP improves the transmission delay of the packets, compared with both the First-Fit and the Lightly-Loaded WSaS heuristics. Results demonstrate that the First-Fit approach produces high delays and that, even though the Lightly-Loaded technique has better performance results,it is still far from the optimal, especially for low-to-medium traffic loads.

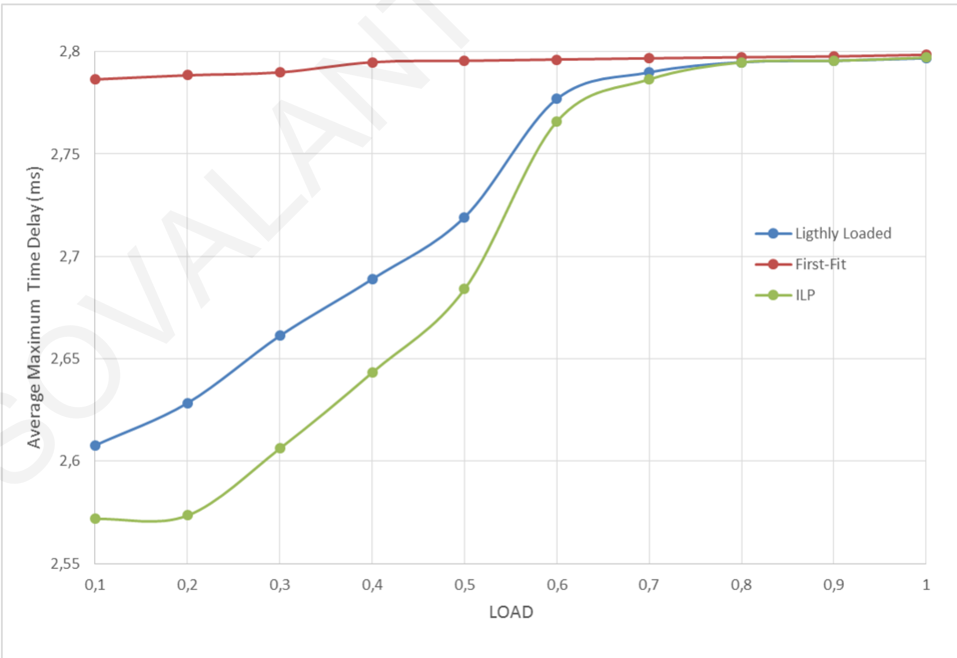

Figure 4.7: Maximum packet delay vs. ONU offered load.

Furthermore, simulations were also performed with a fixed (light) traffic load

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of 0.6, a fixed (small) number and size of packets generated, but different size of queues so as to ascertain the effect of the queue size on the optimization algorithm and the proposed heuristics. In Fig. 4.8, it can be observed that for smaller queues, the maximum time delay is higher, because there are many more packets that need to be shared, as there are many congested queues. However, as the size of the queues increases, the maximum time delay decreases, as the number of packets that need to be shared also decreases. For larger queues, it can be observed that the maximum time delay is the same for all algorithms, as now the queues can accommodate all their assigned packets, with no congestion, thus no sharing is required and there are no dropped packets in the network. It is observed that, this is true only for the case of light traffic load and small number of packets. As the traffic load and the number and size of packets increases considerably, even for queues with larger sizes, the network will experience considerable congestion and there will be a need for wavelength sharing and scheduling so as to minimize the maximum traffic delay as well as to avoid having packets dropped in the network.

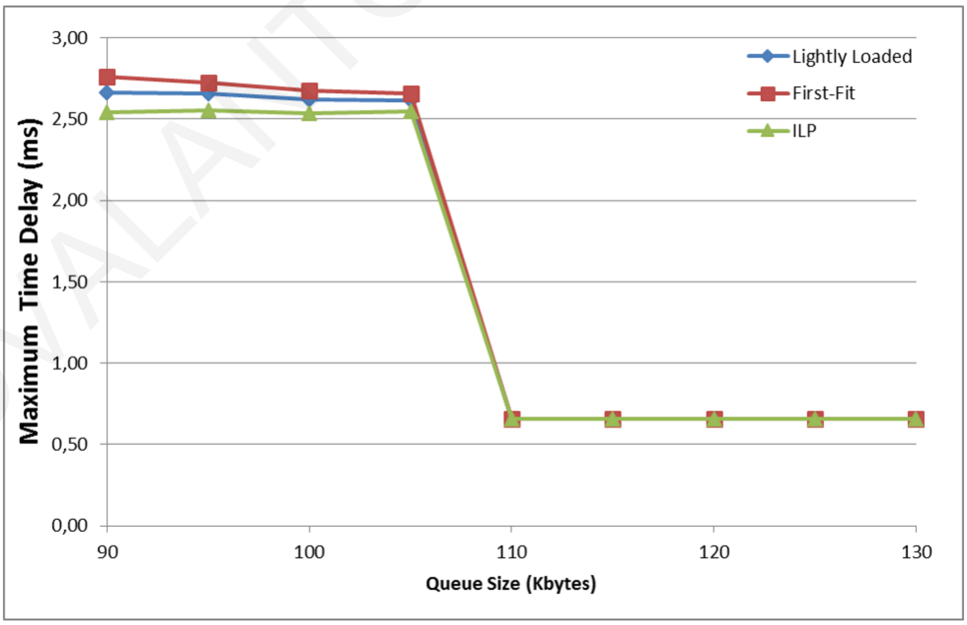

Figure 4.8: Maximum packet delay vs. queue size.

4.4.2 Priority Scheduling Algorithms for QoS Support (HPSA-a and HPSA-b)

The two HPSA algorithms are implemented with a variable downstream load destined to each ONU that is incremented from 0.1 to 1.0 in 0.1 steps. The OLT houses 16 downstream queues, each one corresponding to a given ONU and additionally each queue houses 3 priority sub-queues ($Q^{OLT}_{i,p0}$, $Q^{OLT}_{i,p1}$, $Q^{OLT}_{i,p2}$) with a maximum size of 30 Mbytes and each one belongs to different packet priority class.

Both heuristics schedule all the arriving packets at the available queue according to their priority and when the need arises they also redirect the high priority traffic in the available queues, utilizing one of the two aforementioned techniques (HPSA-a and HPSA-b). The metric used in this work to ascertain the performance of the algorithms is the transmission delay of the high priority packets for a transmission cycle (T_{cycle}).

Fig. 4.9 shows the Maximum Delivery Delay Time per ONU Offered Load (OOL) (averaged over 10 runs), which is needed in order to transmit the last high priority packet to its destination within a transmission cycle, assuming a strict priority scheduling mechanism at each LAN queue and zero upstream traffic. In this scenario, it is assumed that the packets are prioritized as 30% high priority, 35% medium priority and 35% low priority packets of the generated traffic in the network. For comparison purposes, the two additional wavelength sharing algorithms discussed in Section 4.3.1 were also implemented. These two algorithms (first fit and lightly loaded) essentially redirect downstream traffic to other wavelengths if a wavelength queue is overloaded, without taking into consideration the priority of the packets for the traffic in question.

As it can be seen from Fig. 4.9, as expected, as the OOL increases, the maximum time delay also increases for all techniques investigated. By increasing the OOL of each ONU, many more packets are generated, so that the occupancy of each queue is higher, thus the transmission time for each packet is increasing as well. For higher loads, from 0.6 to 1.0, the delay of the high priority packets increases considerably and it almost reaches the maximum queue time. However, it is clear that both HPSAs improve the transmission delay of the high priority packets, compared to the two algorithms that only use wavelength sharing without taking into account the priority of the packets. Further, the results in Fig. 4.9 demonstrate that HSPA-b

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performs better than HPSA-a; this is due to the fact that when HSPA-b is utilized, the packets will be redirected to high priority queues (destined for other ONUs) that will be forwarded faster to their destination compared to HPSA-a where the packets are redirected to lower priority queues (mostly destined to other ONUs) that are forwarded to their destination after the high priority queues are accommodated. For this scenario, in Fig. 4.9, it was showed that HPSA-b performs better compared to HPSA-a in terms of maximum time delay for both high and low traffic loads (in contrast to the scenario presented in Fig. 4.10 below). This is due to the fact that since the three classes have about an equal share of the total traffic, there are many more packets that need to be redirected as not only high priority queues are congested but also all the other queues of the network especially at higher loads (the resources are exhausted).

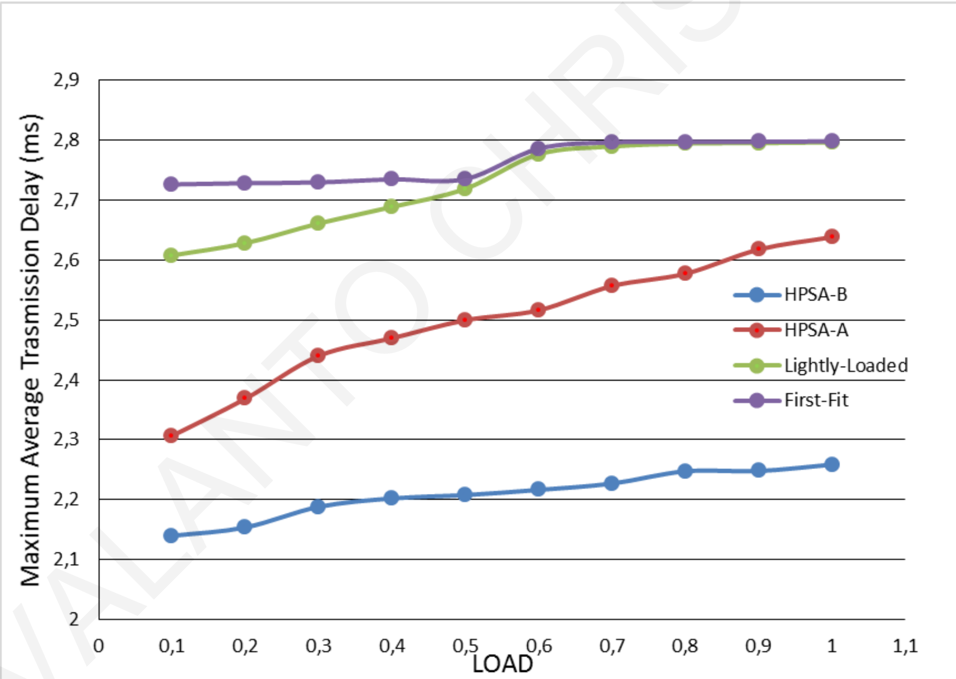

Figure 4.9: Maximum high priority packet delivery delay vs. ONU offered load.

Further, for heavily-loaded high priority traffic networks, where high priority traffic reaches up to 50% of the total number of packets in the network (Fig. 4.10), it can be observed that the maximum time delay for both algorithms is increased (compared to the results of Fig. 4.9), while at higher loads the two algorithms perform almost the same (with HSPA-b slightly outperforming HSPA-a), as now the high-priority queues are much more congested. Thus, clearly, as the traffic load and the number and size of packets increases considerably, even for queues with larger sizes, the network will experience considerable congestion and there will be a need for appropriate priority scheduling mechanisms so as to minimize the maximum high priority traffic delay as well as to avoid having packets being dropped in the network (especially for high priority services/users).

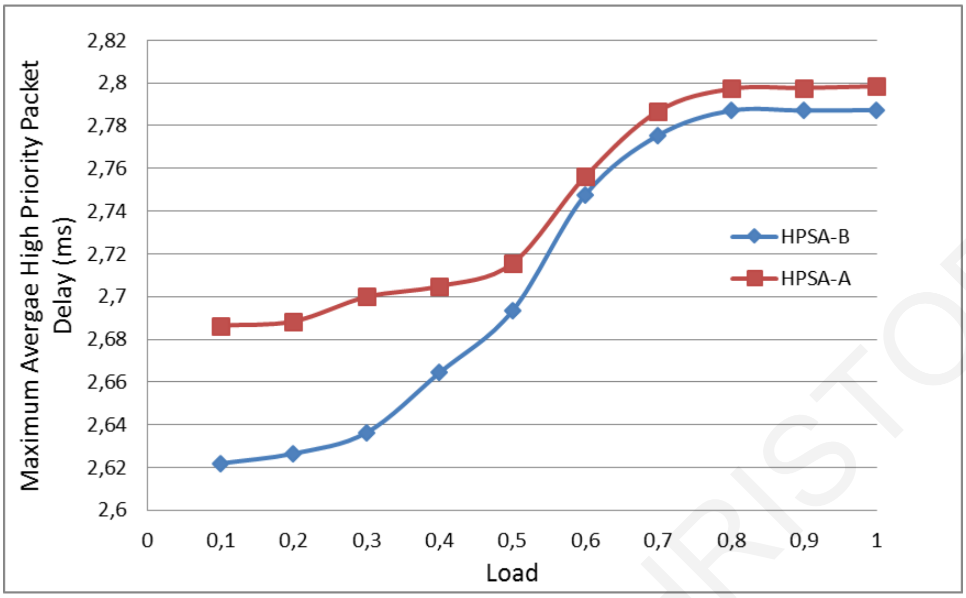

Figure 4.10: Maximum average high priority packets (heavily-loaded network with up to 50% high priority traffic) vs. Load.

4.4.3 Wavelength Selection Algorithms Utilizing Base Station Cooperation for Mobile Users

The lightly-loaded and cooperation-based wavelength scheduling heuristic algorithms are implemented in a network with 8 ONUs, with a variable downstream offered load destined to each ONU/BS that is incremented from 0.1 to 1.0 in 0.1 steps. The scheduler accommodates 3 extra buffers per ONU/BS ($B_{i,fixed}$, $B_{i,mob}$, $B_{i,mob-coop}$), each one corresponding to the different type of users (fixed, mobile, mobile in a cooperation area). These buffers have unlimited size.

Two different simulation scenarios were performed in order to examine the performance of both heuristic algorithms under different network conditions. For the first scenario, we assume that the data packets for all the fixed users and the mobile users that do not fall in the cooperation areas are allocated to their corresponding queues (without dropping any packets) and the following assumptions hold concerning the available space within the queues: (i) Q_1 has 10% availability, (ii) Q_2 has

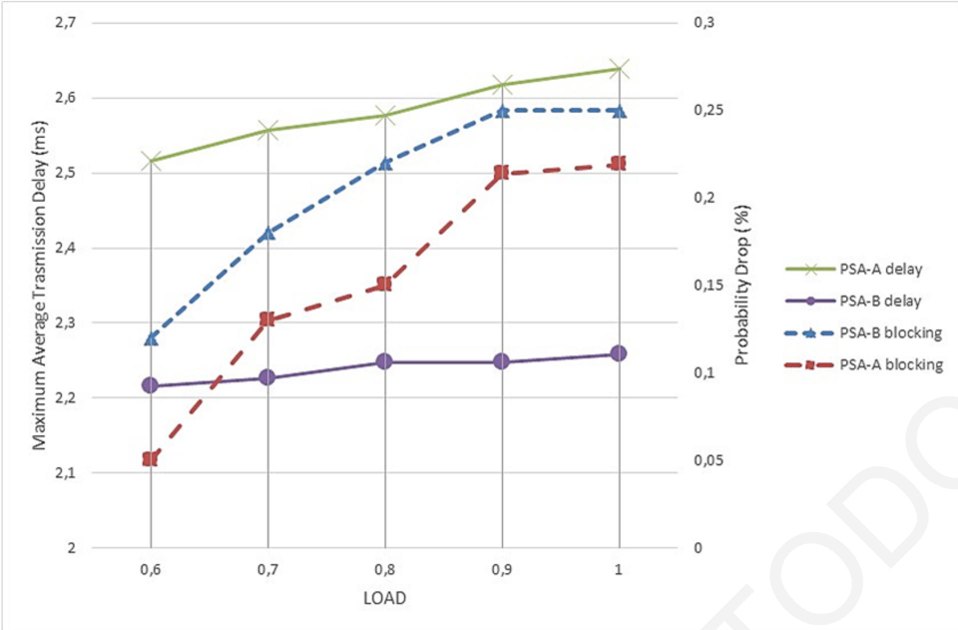

Figure 4.11: Traffic blocking vs Load.

50% availability, (iii) Q_3 has 70% availability, (iv) Q_4 is full, (v) Q_5 has 30% availability , (vi) Q_6 has 80% availability, (vii) Q_7 has 10% availability - may not be possible to allocate all or any packets, (viii) Q_8 has 90% availability. Given this network state, the scheduler then tries to schedule at the available queues only the data packets of the users that fall within the cooperation areas, utilizing one of the two heuristics algorithms described above. The aim is to direct the traffic to the most appropriate queues, so as to minimize the transmission delay of the packets for a transmission cycle (T_{cycle}).

Fig. 4.12 shows the maximum delay time of the mobile cooperation packets per ONU offered load (OOL) (averaged over 10 runs). This is the time required in order to transmit the last packet to its destination (destined to a mobile user within a cooperation area) within a transmission cycle, assuming a strict priority scheduling mechanism at each LAN queue and zero upstream traffic. It can be seen from Fig. 4.12 that, as the OOL increases, the maximum time delay also increases. By increasing the OOL of each ONU, many more packets are generated, so that the occupancy of each queue is higher, thus the transmission time for each packet is becoming higher as well. Additionally, in Fig. 4.12 it is shown that for higher loads, from 0.5 to 1.0, the time delay increases considerably when the lightly-loaded wavelength selection algorithm (LLWSA) is used and it almost reaches the maximum queue time. Comparing the maximum average time delay observed for the two

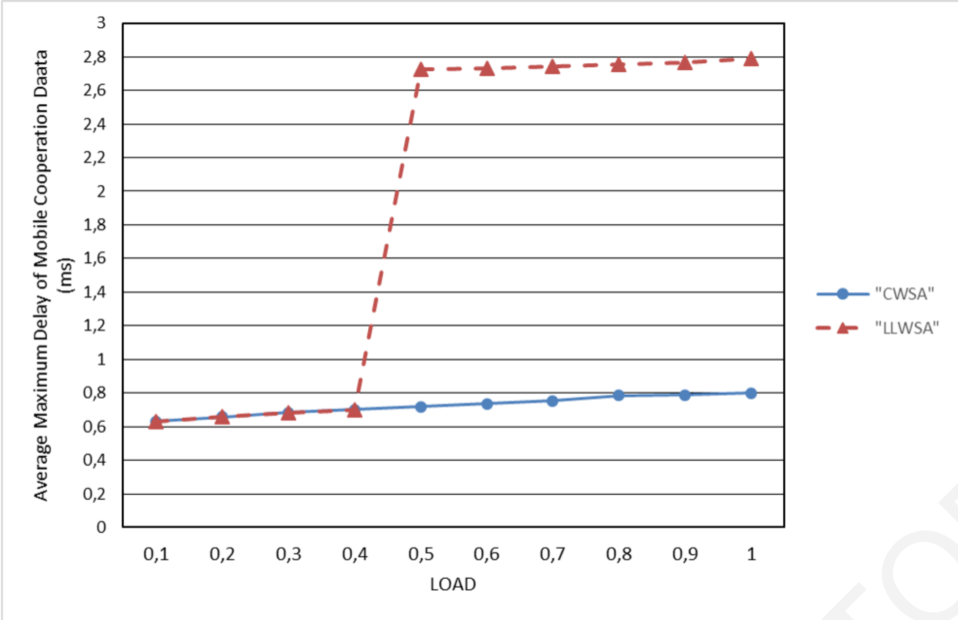

Figure 4.12: Scenario 1: Maximum time delay for mobile cooperation data vs. Load.

heuristics, it is noted that for loads greater than 0.5, the cooperation-based wavelength selection algorithm (CWSA) improves significantly the transmission delay of the packets destined to users within a cooperation area. This is the case, as the CWSA approach favors, for the excess mobile cooperation packets, the cooperation wavelength (queue) over any other queue, even when the cooperation queue did not have the maximum available space. On the other hand, utilizing the LLWSA approach, the excess mobile cooperation packets are transmitted via the queue that has the maximum availability space (and not the cooperation queue), resulting in additional delay (extra time cycle) for the data to reach its destined end-user.

For the second simulation scenario, again the assumption is that the data packets for all the fixed users and the mobile users (that do not fall in the cooperation areas) are allocated to their corresponding queues and the queue availability is as follows: (i) Q_1 is full with all types of packets, (ii) Q_2 is full with all types of packets, (iii) Q_3 has 30% available space, (iv) Q_4 has 10% available space, (v) Q_5 has 30% availability, (vi) Q_6 is full, (vii) Q_7 has 80% availability, (viii) Q_8 has 100% availability. Again, as it can be seen from Fig. 4.13, by increasing the offered load of each ONU, many more packets are generated, so the occupancy of each queue is higher, thus the transmission time for each packet is increasing for both heuristic algorithms. In this scenario it is observed that as the occupancy of the cooperation queues is higher and most of them are already congested from the fixed and mobile users (that do not fall in the cooperation areas), both heuristic algorithms result in higher time delays compared to the previous scenario. Also, it is again noted that the CWSA heuristic performs better than the LLWSA approach, but for this scenario higher average maximum time delays are observed for the data of the cooperation mobile users. This can be easily explained, since the cooperation ONU/BS's queues are now congested, forcing the scheduler to find other available queues to divert the excess mobile cooperation data. Nevertheless, the CWSA approach still provides better packet delays compared to the LLWSA technique. This is a direct consequence of the diversion strategy of the CWSA technique that tries to utilize the cooperation queues as much as possible in an effort to minimize the packet transmission delay.

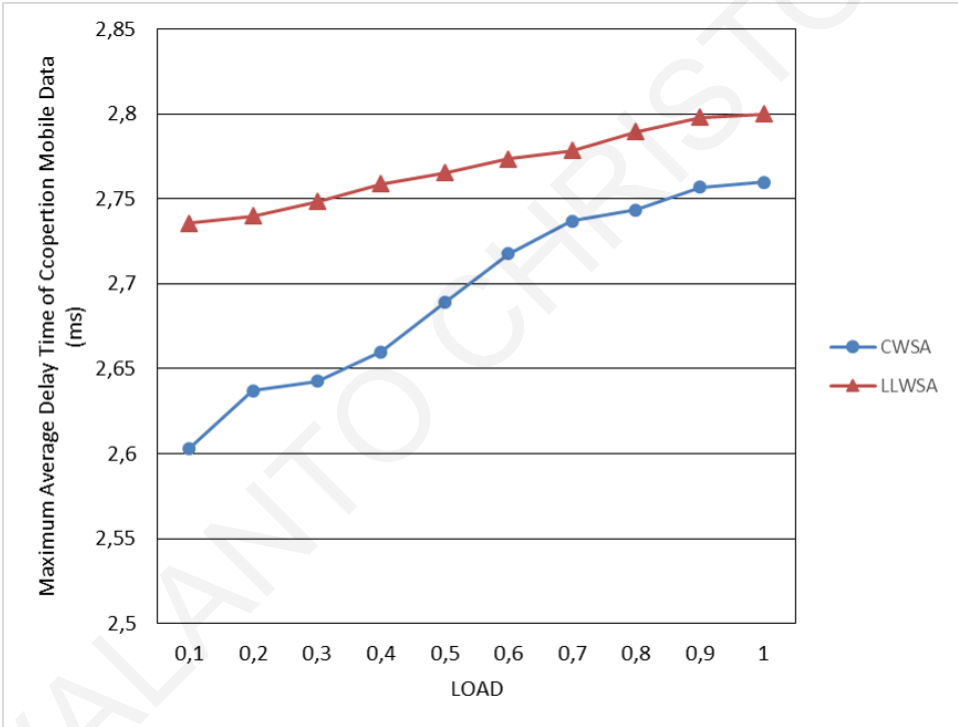

Figure 4.13: Scenario 2: Maximum time delay for mobile cooperation data vs. Load.

4.5 Conclusion

This chapter presents wavelength scheduling algorithms for converged ring-based WDM-PON architectures that can better utilize the network capacity and provide QoS (in terms of the data delivery time) for both mobile and fixed users. The ring-based WDM-PON topology was chosen as it can be used to support dynamic allocation of network resources, a truly shared LAN capability among the end users, as well as inherent survivability capabilities. Heuristic algorithms as well as an ILP formulation were presented for wavelength selection and scheduling for the case where the downstream packets do not have any priorities, as well as the case where priorities are present. Performance evaluation results indicate that utilizing the proposed algorithms improves on the maximum time required to transmit the last packet to its destination within a transmission cycle, especially when the HSPA-b and CWSA heuristics are utilized for the case of high priority traffic and traffic destined to the mobile users within a cooperation area, respectively. Future work involves additional experiments on the wavelength selection and scheduling techniques in the presence of both upstream and downstream traffic (including inter-ONU traffic carried with λ_{LAN} and implemented via dynamic bandwidth allocation techniques).

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Chapter 5

Resilient Wheel-Based Converged Access Network Architecture

5.1 Introduction

As detailed in the previous chapters, demand for high-bandwidth services and applications has been growing steadily and service providers are always on the lookout for efficient and effective architecture solutions for the access arena in order to accommodate this demand. At the same time, service providers need to also consider the integration of next-generation optical access architectures with mobile broadband access technologies that can fully support both mobile and fixed traffic. As wireless/mobile networks have recently received significant attention, this has resulted in an imbalance between the current fixed and future mobile components of next-generation networks; thus, as also highlighted by the ITU-T Focus Group Technologies for Network 2030 (FG NET-2030), next generation fixed access networks are required to be developed in order to support the data throughput for broadband mobile networks.

Even though in recent years significant work has taken place for several multipoint topologies suitable for converged optical wireless access networks, including TDM/WDM tree, tree and-branch, and TDM/WDM ring-based access network architectures [8], [31], [33] an attempt was never made to propose an access architecture with a topology that will not only provide the advantages of the proposed WDM ring-based architecture (dedicated connectivity, guaranteed QoS, efficient utilization of network resources, along with increased resilience capabilities), but will also

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support efficiently both fixed and mobile users under normal and failure operating conditions with minimum fiber usage and efficient scheduling solutions. This is precisely the focus of this chapter that proposes a novel access architecture which differs from all previous architectures in the literature as it utilizes a new *wheel-based* optical access network architecture which can be integrated with wireless technologies to efficiently backhaul mobile and fixed traffic under normal and failure operating conditions.

Specifically, in this chapter, a wheel-based converged optical-wireless access network architecture for backhauling network traffic is initially described, followed by an analysis for downstream traffic flow as well as wavelength scheduling under normal operating conditions. As it will become apparent in Chapters 5 and 6, this resilient architecture can efficiently support not only the fixed users but also the mobile users in the downstream and upstream direction under normal and failure circumstances/scenarios, while minimizing the average traffic delivery time and without using extra redundant unused capacity (fiber) for protection.

The rest of the chapter is organized as follows. Section 5.2 describes the proposed architecture, followed by Section 5.3 that describes the operation of the proposed architecture (traffic flow) under normal operating conditions (including wavelength scheduling schemes under normal conditions). A timing analysis is subsequently presented in Section 5.4, followed by the performance evaluation of the proposed architecture in Section 5.5. Finally, Section 5.6 offers some concluding remarks.

5.2 Proposed Wheel-Based Optical Access Network Architecture

The proposed wheel-based optical access network architecture with resiliency capabilities is shown in Fig. 5.1. In this architecture the OLT is situated within the central office of a service provider at a distance of around $0.5 - 1$ km from the end users and it is directly connected to each ONUs/BSs via two directed fiber links. The ONUs/BSs are interconnected through a short distribution fiber ring with diameter $1 - 2$ km (unidirectional ring with traffic flowing in the clockwise direction) so as to again cover the same local access area as in the tree-based architecture. Additionally, the OLT block includes a scheduler and switches to divert the traffic to the appro-

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priate queue according to the scheduling procedure under different network traffic conditions.

Each ONU/BS is assigned a dedicated wavelength λ_i for both downstream and upstream transmissions and a wavelength λ_{LAN} for monitoring and control and for inter-ONU/BS communication purposes. Thus, assuming that there are N ONUs/BSs on the ring, then the OLT again houses N fixed transmitters (TXs) and N fixed receivers (RXs). Each TX/RX pair in the OLT corresponds to one TX/RX pair at the ONU/BS on the distribution ring (one dedicated wavelength is assigned for communication between the OLT and each ONU/BS). The extra RX at the OLT serves to receive the λ_{LAN} wavelength from the distribution ring as it was explained previously in Chapter 4. Again, if we assume that $N = 16$, then these wavelengths can also be allocated over the $1270-1610$ nm CWDM spectrum (with 20-nm spacing). As in the process described in Chapter 4, in order to be able to share and schedule wavelengths, the OLT also houses N queues and a flow scheduler module which is responsible for scheduling the packets to their assigned destinations.

On the distribution fiber ring, the N ONUs/BSs are interconnected with point-to-point unidirectional fiber links, forming a ring, where traffic flows only in the clockwise direction. Each ONU/BS houses a TX/RX pair which is matched to the corresponding TX/RX pair at the OLT in order to receive and transmit downstream and upstream traffic on a dedicated wavelength (λ_i, $i = 1, ..., N$), as well as a TX/RX pair for transmitting and receiving the local LAN wavelength λ_{LAN} (again used for inter-ONU/BS communication within the ring for dedicated LAN traffic or for transient downstream or upstream traffic, as well as for control communication between the ONUs/BSs and the OLT). As shown in the figure, the LAN wavelength channel λ_{LAN} is terminated, regenerated, and retransmitted at each ONU/BS. Wavelength sharing of λ_{LAN} involves the aggregation of packets per destination ONU/BS in separate queues. Again, cooperation areas are also defined as the area located between two adjacent ONUs/BSs that are connected around the fiber ring, where the mobile users within this area can be served by both ONUs/BSs.

The proposed architecture does not have any redundant fiber capacity that will be used only under failure scenarios; depending on the failure, the proposed architecture will operate in such a way that the traffic will diverted through different fiber paths (via the OLT or via another ONU/BS) in order to recover from the failure (see Chapter 6). Specifically, for this architecture, the OLT is directly connected with two

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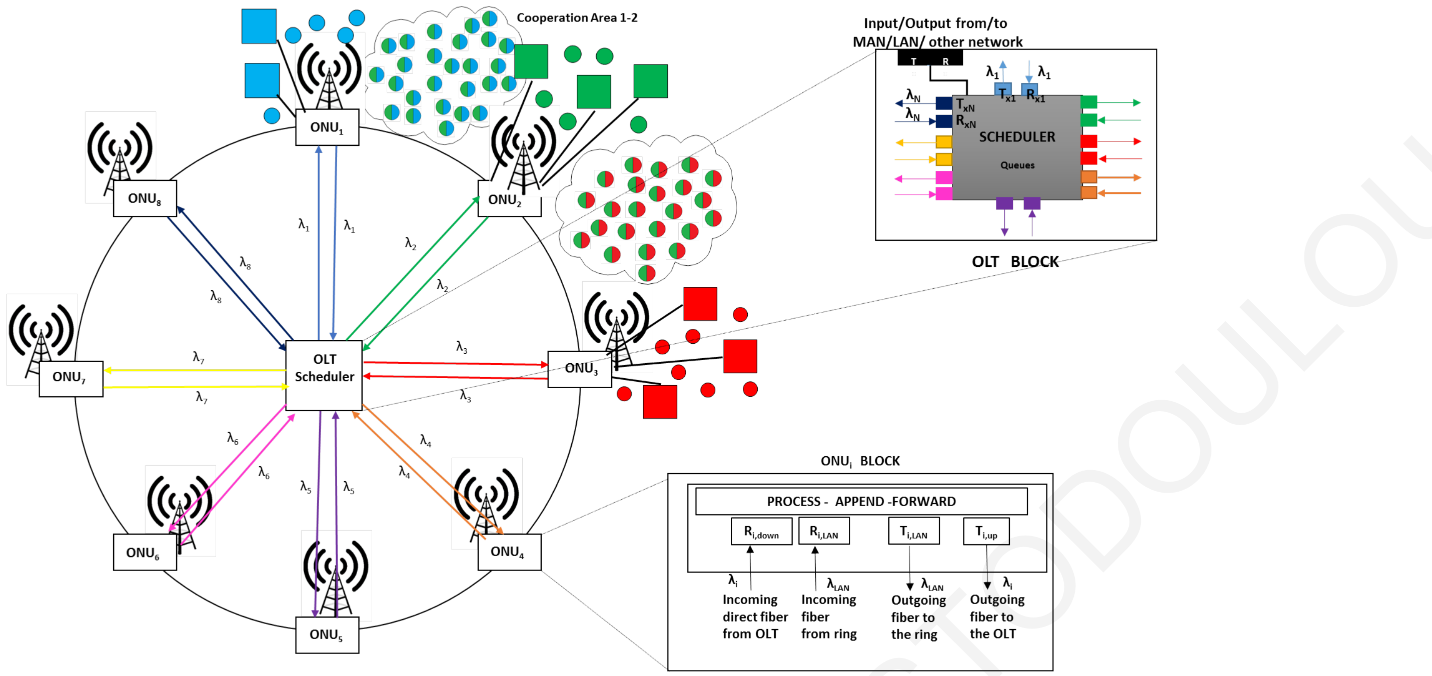

Figure 5.1: Proposed wheel-based converged access network architecture.

fiber links (upstream and downstream) to each ONU and the ONUs are connected on a fiber ring.

Table 5.1: Fiber usage for architectures with no protection capabilities (in km).

Tree-based PON	Ring-based PON	Wheel-based PON
$D = t + N * s$	$D = t + 2 * pi * r$	$D = N * s * 2 + 2 * pi * r$

In Table 5.1, the fiber usage of the optical access architectures with no extra protection fibers (only working fiber paths) is shown. For the tree-based PON architecture, the maximum distance from ONU to OLT is calculated using the distance of the fiber trunk from the OLT to the slitter/combiner t (approximately 20 km) plus the distance from the splitter/combiner to the ONUs (assuming a distance s of approximately 1 km) for a total of $t + N * s$ km. For the ring-based PON, the total fiber usage D is the maximum fiber distance from OLT to the last ONU on the ring. If we assume again that the trunk fiber has distance t and that the ONUs are connected on a fiber ring with diameter d km, which gives a circumference of $2 * pi * r$, where $r = \frac{d}{2}$, the total fiber usage will be $D = t + 2 * pi * r$. Finally, for the wheel-based optical access architecture, the OLT is directed connected with two fiber links (upstream and downstream) to each ONU with distance s (approximately 0.5 km), requiring $N * 2 * s$ km of fiber. Additionally, the ONUs are interconnected via a fiber ring

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with diameter of d km (approx. 1 km diameter), resulting in a total fiber usage of $N * s + 2 * pi * r$. Clearly, the proposed wheel-based architecture requires the least amount of fiber even in the case when the rest of the architectures do not provide protection capabilities. As it will be further shown in Chapter 6, this advantage is strengthened when protection operation is considered, since, contrary to the tree- and ring-based topologies, the proposed wheel-based architecture does not require any additional redundant fibers for protection purposes (unlike the ring- and tree-based architectures that need a trunk fiber as well as redundant fibers for protection purposes [47]).

5.3 Network Operation under Normal Conditions

5.3.1 Signaling Process

A scheduler/controller is located in the OLT and controls the traffic flow in the proposed architecture. A signaling protocol between the ONUs/BSs and the OLT is further utilized (report their status, queue capacities, etc.), in order to avoid traffic collisions, packet drops, and loss of data due to failures. ONUs/BSs also exchange control signals periodically through the LAN wavelength to report their status (online/offline). Specifically, the signaling process between the OLT and the ONUs/BSs during the normal network operation is as follows:

- Each ONU/BS (ONU_i/BS_i) sends to the OLT a REPORT signal to inform on its status (online/offline). Subsequently, the OLT sends back a GATE signal acknowledging reception of the status signal. When this signal is received by the ONU/BS, then the ONU/BS sends a new REPORT signal with its queue size (data destined to the OLT) and also the status of its adjacent ONU/BS (ONU_{i-1}/BS_{i-1}).

- When the OLT receives the second REPORT message from each ONU/BS, it schedules the packet data to each ONU/BS according to the information received.

- Subsequently, the OLT informs with a GATE message each ONU whether it can transmit data to its adjacent ONU (ONU_{i+1}/BS_{i+1}) and to the OLT.

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The exchange of control signals under normal network operation (when no failure has occurred in the network) are shown in Fig. 5.2 below.

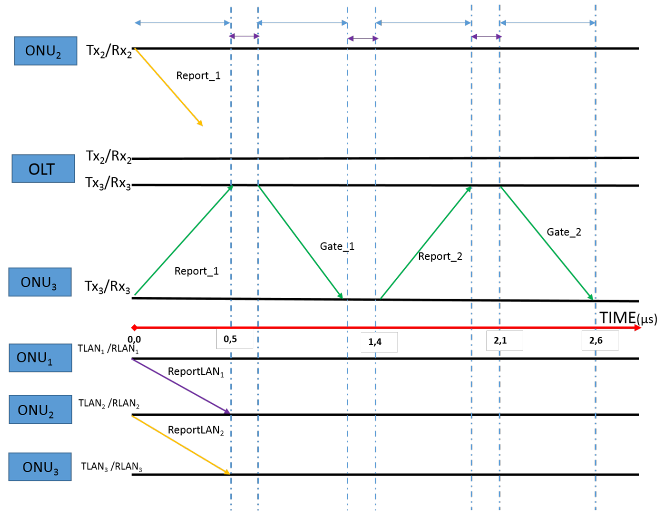

Figure 5.2: Control signaling under normal network operation.

5.3.2 Traffic Flow

The operation of the proposed architecture is based on scheduling algorithms in order to serve both downstream and upstream traffic. Specifically, for the downstream traffic, according to the end user the traffic is destined to, the scheduler places the data packets to the corresponding ONU/BS downstream queue located at the OLT and then transmits them via its dedicated wavelength to its destination ONU/BS. For the upstream direction, there exist two types of traffic from an ONU/BS, namely traffic that is destined to another ONU/BS, and also traffic destined to other networks (MAN/LAN) through the OLT. For inter-ONU/BS communication, the ONUs/BSs exchange control messages and data in a distributed manner though the LAN wavelength on the fiber ring. The control messages are processed, regenerated, and then retransmitted by each ONU/BS around the ring. Each ONU/BS removes/discards its own control message after a cycle on the fiber ring and transmits an updated one. The upstream LAN traffic destined to other ONUs/BSs, also passes through the rest of the ONUs/BSs on the ring, regenerated and retransmitted along with each ONU/BS's own upstream LAN traffic within the allocated timeslots for each ONU/BS until it reaches its destination. ONUs/BSs exchange data for inter ONU/BS communication in the upstream direction though the LAN wavelength around the ring, utilizing TDM. In this case, the LAN traffic can pass through multiple ONUs/BSs, but each one can receive only its own data for security and privacy purposes [48], and can also send data only in its own time-slot/transmission window. A common bandwidth allocation approach in this case is to allow each ONU to send data in its own time-slot that cannot exceed the maximum transmission window size W_{max} [56].

$$W_{i,k} = \min\,(W_{i,k}^{Req}, W_{max})$$

Thus, the proposed network architecture can support direct communication between all ONUs/BSs on the fiber ring in a distributed manner. On the other hand, the upstream traffic destined from an ONU/BS to other networks (MAN/LAN) is transmitted through the OLT in a centralized way, via the direct fiber link connections and utilizing a dedicated upstream wavelength λ_i. However, if a connection from an ONU/BS to the OLT is required and the corresponding dedicated upstream wavelength channel is overloaded, the control module scheduler at ONU/BS may redirect the excess upstream flow to the local LAN queue and utilize the λ_{LAN} wavelength to send the information to the OLT, provided that the LAN queue has available capacity and it can fully or partially accommodate the excess flow. This process is performed independently at each ONU via its control module and is triggered at the end of each LAN cycle:

- Each ONU's control module (flow scheduler) periodically (at the end of each LAN cycle) checks the status of the LAN traffic queue and the upstream traffic queue.
- If an upstream traffic queue is overloaded, the process of potentially utilizing the LAN wavelength is triggered.
- The ONU's control module then checks if the corresponding LAN traffic queue is available. A LAN traffic queue will be available if the aggregated incoming traffic rate to Q_{LAN} is lower than the outgoing traffic rate (and also the capacity of the queue is below a threshold that can be set according to various traffic engineering constraints). If the LAN queue is available the control module partially or fully redirects the excess flow to this queue and the information is sent as transient upstream traffic. Otherwise, the excess flows that cannot be accommodated are dropped.
- This is a revertive process; once the upstream queue becomes available again, the control module may redirect parts of the flow back to the upstream queue.

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Thus, once the excess flow is placed in the LAN queue it becomes transient upstream traffic and is transmitted together with the directed LAN traffic and the transient downstream traffic (if any) utilizing a TDM-based dynamic bandwidth allocation process (for example the limited approach mentioned above). At the OLT, the transient upstream traffic is received while the transient downstream traffic and dedicated LAN traffic are once again discarded. In addition, the transient upstream traffic will be taken off the ring once it reaches again the originating ONU/BS node.

Depending on the data traffic load in the downstream direction, the scheduler at the OLT can use different wavelength selection and scheduling algorithms to avoid collisions, loss of data, and also minimize the average delay to the end users.

Wavelength Selection and Scheduling Process (WSaS)

The process of dynamically assigning and sharing downstream wavelengths is implemented jointly at both the OLT and the ONUs. Initially, all the fixed traffic destined to ONU_i and the mobile traffic destined to BS_i that cannot be served by the cooperation areas' BSs are served first, and placed in the corresponding queue Q_i^{OLT}. Subsequently, the mobile users that are in a cooperation area are served by queue Q_i^{OLT} if it has available space; if not, the scheduler runs the wavelength scheduling algorithms [21] to find an alternative available queue. If the downstream queue, Q_i^{OLT}, with traffic destined to ONU_i/BS_i is overloaded (with the fixed traffic and the mobile traffic that is destined to users outside the cooperation area), the scheduler at the OLT will use one of the following heuristic algorithms: a) First-fit scheduling algorithm, b) Lightly-loaded wavelength scheduling, and c) Cooperation-based wavelength scheduling heuristic algorithm, to divert the excess traffic to other available queues.

For the first-fit (FF) WSaS heuristic, if a dedicated downstream wavelength channel, λ_i, which is destined to ONU_i is overloaded, the following steps are executed: (i) The scheduler at the OLT searches for the first available downstream wavelength channel, λ_j, $j > i$, that can accommodate λ_i's excess flow, without searching if the channel is heavily or lightly loaded; (ii) If the search is successful and the scheduler at the OLT finds an underutilized downstream wavelength channel, λ_j, whose corresponding queue has some available space that can accommodate one or more of λ_i's excess traffic, then λ_j is selected if and only if its corresponding LAN queue at ONU_j has also available space to accommodate the excess flow.

For the lightly-loaded (LL) WSaS heuristic, if a dedicated downstream wavelength, λ_i, which is destined to ONU$_i$ is overloaded, the scheduler at the OLT initially searches for another underutilized downstream wavelength channel, λ_j, whose corresponding queue has the maximum available space in comparison to all the other wavelengths that can accommodate one or more of λ_i's excess downstream traffic flows. If the search is successful, the available channel with the maximum capacity, λ_j, is selected, if and only if its corresponding LAN queue at ONU$_j$, is also available (e.g., it can accommodate the excess traffic originally destined for λ_i).

For the cooperation-based wavelength scheduling algorithm (CWSA), if a dedicated downstream queue, $Q_i{}^{OLT}$, which is assigned to a dedicated wavelength λ_i, destined to ONU$_i$/BS$_i$, is overloaded with fixed and mobile users' traffic, the following steps are executed: (i) The scheduler at the OLT searches for the cooperator's downstream queue Q_{i+1}^{OLT} which has available space that can accommodate one or more of $B_{i,mob_{coop}}$'s (mobile data) excess downstream traffic flows $j > i$, without searching if the channel is heavily or lightly loaded; (ii) If the search is successful the underutilized downstream buffer, $B_{i+1,mob_{coop}}$ is selected and the excess mobile traffic of Q_i^{OLT} is diverted to the $B_{i+1,mob_{coop}}$ of Q_{i+1}^{OLT} and the packets arrive to the mobile end-user through Q_{i+1}^{OLT}, using wavelength λ_{i+1} without adding any extra cycle delay time, as ONU$_{i+1}$/BS$_{i+1}$ is in the cooperation area of ONU$_i$/BS$_i$.

Another scenario that needs to be considered is the case where the queues of the ONU/BS within the cooperation area have no available space to accommodate the excess traffic. In order not to drop this excess mobile traffic and loose the data, the scheduler executes the following additional steps: (iii) If the search is not successful, the scheduler at the OLT searches for another downstream queue Q_j^{OLT} (with buffer $B_{j,mob_{coop}}$, where $j > i$), that has the maximum available space in comparison to all the other queues that can accommodate one or more of $B_{i,mob_{coop}}$'s (mobile data) excess downstream traffic flows; (vi) If this search is successful, the underutilized downstream queue, Q_j is selected and the excess mobile traffic of $B_{i,mob_{coop}}$ is diverted to the $B_{j,mob_{coop}}$ buffer of Q_j^{OLT} and the packets arrive to the mobile end-user through wavelength λ_j (with an extra delay equal to T_{cycle} (2ms)).

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5.4 Timing Analysis

The delivery time for each packet to its destination is defined as the time required from the time the packet is generated (or arrives at the OLT/scheduler from another network) till the time the packet arrives at its destination ONU/BS. The reader should also note that the control signals exchanged between ONUs are sent at the same time as the control signals exchanged between the ONUs and the OLT, so there is no extra delay that affects the packet delivery time due to signaling. Thus, the total delivery time is calculated as follows:

(i) Delivery time under normal operation: $T_{TotalDelay} = T_{delay_{RG}} + T_{PacketTransmission} + T_{Q_i^{OLT}} + T_{PropagationData}$

(ii) Delivery time under rescheduling due to congestion or link failure scenario: $T_{TotalDelay} = T_{delay_{RG}} + T_{PacketTransmission} + T_{PropagationData} + T_{Q_j^{OLT}} + T_{Q_j^{LAN}} + T_{rescheduling}$

(iii) Delivery time under rescheduling due to component failure: $T_{TotalDelay} = T_{delay_{RG}} + T_{PacketTransmission} + T_{PropagationData} + T_{Q_{i-1}^{LAN}} + T_{Q_j^{OLT}} + T_{Q_j^{LAN}} + T_{rescheduling}$

where $T_{delay_{RG}}$ is the control signal delay given by $T_{delay_{RG}} = t_{REPORT1} + t_{GATE1} + t_{REPORT2} + t_{GATE2} + 4 * t_{process} + 4 * T_{PropagationControl}$, with the transmission delay of each control message given by $t_{REPORT} = t_{GATE} = (B * 8)/R$, where R is the rate of the line and B is the size of the control messages (bytes), and $t_{process}$ is the processing time associated with each control message; $T_{PacketTransmission} = PacketSize(bits)/R(Gbps)$ is the packet transmission time; $j \neq i$ is the number of the ONU/BS that the scheduler redirects the excess traffic due to congestion or failure; $T_{rescheduling}$ is the rescheduling time at the controller; and $T_{PropagationControl}$, $T_{PropagationData}$ are the propagation delays for the control and data respectively, that depend on the distance traveled.

The reader should note that the network operation under fault conditions and the delivery time under component failure is explained in detail in the following chapter (Chapter 6). Nevertheless, for completeness, it is added in this section, together with the timing analysis for the network under normal operating conditions.

5.5 Performance Evaluation

The proposed architecture and scheduling heuristics were implemented for a converged optical-wireless backhaul network, with $N = 8$ integrated ONUs/BSs, inter-

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connected in a wheel-based configuration, with an OLT that includes a scheduler function. Note that only 8 ONUs/BSs are used, as the execution of the simulation model is computationally intensive and complex.

An event-driven wheel-based PON simulator was developed using C, with the simulator executing WDM/TDM-based downstream/upstream scheduling algorithms at the OLT/ONU for downstream and upstream traffic provisioning respectively, as well as executing TDM-based distributed LAN dynamic bandwidth allocation at each ONU in order to accommodate the directed LAN traffic as well as the transient downstream and upstream traffic.

The traffic model used here is the same as the one used in Chapter 4 and detailed in Chapter 3. Specifically, for the simulation experiments, traffic flows are generated by aggregating multiple sub-streams, where each sub-stream is modeled as an ON/OFF source, with Pareto distribution [107], to generate packets according to a self-similar process, with a Hurst parameter $H = 0.7$. To simplify the analysis, and without loss of generality, in all scenarios some component of the traffic was assumed to be zero, so as to reduce the complexity of the simulation.

Further, the system parameters used in the simulation are the following: (i) All channels (downstream, upstream, and LAN) are operating at 1 Gbps; (ii) Each ONU/BS houses a LAN queue ($Q_{i,LAN}^{ONU}$) with maximum size equal to 100 Kbytes; (iii) The OLT houses 8 downstream queues, each one corresponding to a given ONU/BS with a maximum size Q_{max} equal to 100 Kbytes; (iv) Maximum access LAN link rate from users to an ONU is 200 Mbps; and (v) Maximum LAN cycle $T_{cycle} = 2$ ms.

5.5.1 Downstream Operation

Simulations were performed with the same traffic generation under normal conditions where no failures occurred for the proposed wheel-based optical access network architecture and for the ring-based WDM-PON architecture. In this scenario, to simplify the analysis, and without loss of generality, the upstream traffic in all scenarios is assumed to be zero so as to reduce the complexity of the simulation. Ten (10) different executions were performed for each traffic load for each topology to provide an average of the maximum delivery delay of the traffic per load during normal and faulty network conditions.

The proposed wheel-based architecture is compared to the WDM-PON ring-

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based architecture, as it is a converged fixed-mobile optical access network architecture that provides both efficient utilization of network resources, along with increased resilience capabilities.

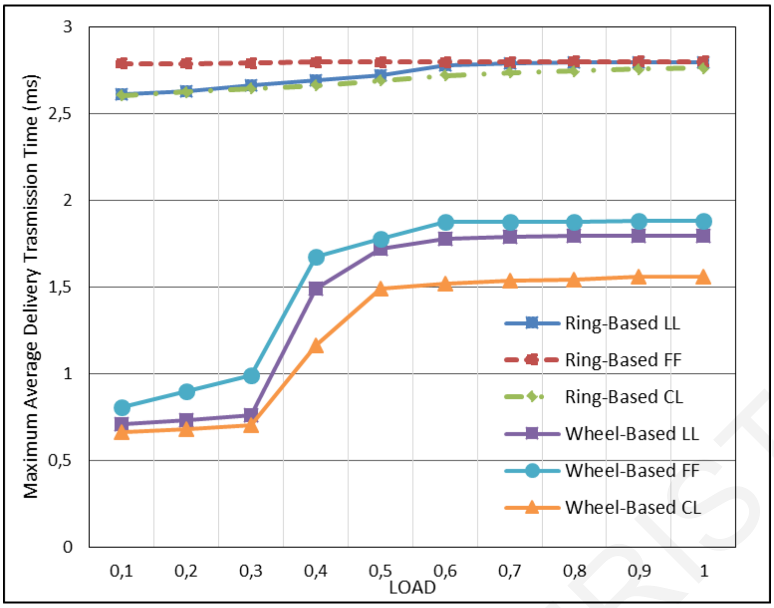

Figure 5.3: Maximum downstream delivery delay vs network load under normal network operation.

From the results under normal operation, clearly shown in Fig. 5.3, the proposed wheel-based optical access network architecture outperforms the existing ring-based WDM-PON in terms of the delivery delay of the traffic in the downstream direction. Even at lower loads, when using any of the proposed scheduling algorithms, it is observed that the maximum delivery delay is significantly lower than that of the ring-based WDM-PON architecture. The same data packets may be re-scheduled due to congestion in both architectures, but the distance that the packets need to propagate is significantly shorter in the proposed wheel-based architecture. While all previous works place the OLT at the provider's site (10 – 20 km away from the end users), utilizing the proposed architecture, the OLT can be placed at the center of a coverage area (away from the provider), allowing it to serve an entire area more efficiently.

5.5.2 Upstream Operation

Also, simulations were performed with the same traffic generation under normal conditions in the upstream direction when no failures occurred for the proposed wheel-based optical access network architecture and for the ring-based WDM-PON architecture [31]. In this simulation scenario, the downstream traffic was assumed to be zero so as to reduce the complexity of the network and examine only the operation of the traffic in the upstream direction (traffic send between ONUs on the ring and from an ONU to the OLT). The upstream traffic generated from each ONU/BS is destined for another user in this access network (to another ONU/BS) or for the OLT (to another network MAN/LAN/access network). Thus, the generated traffic in both architectures is either sent through the LAN wavelength ($Q_{i,LAN}^{ONU}$) in a TDM manner (ring- and wheel-based architectures), or though the directed upstream fiber links ($Q_{i,up}^{ONU}$) (wheel-based architecture). For the inter-ONU communication, the limited service was used for the dynamic bandwidth allocation of each ONU/BS's data, since it was shown in [56] that this scheme has the shortest cycle between all DBA schemes.

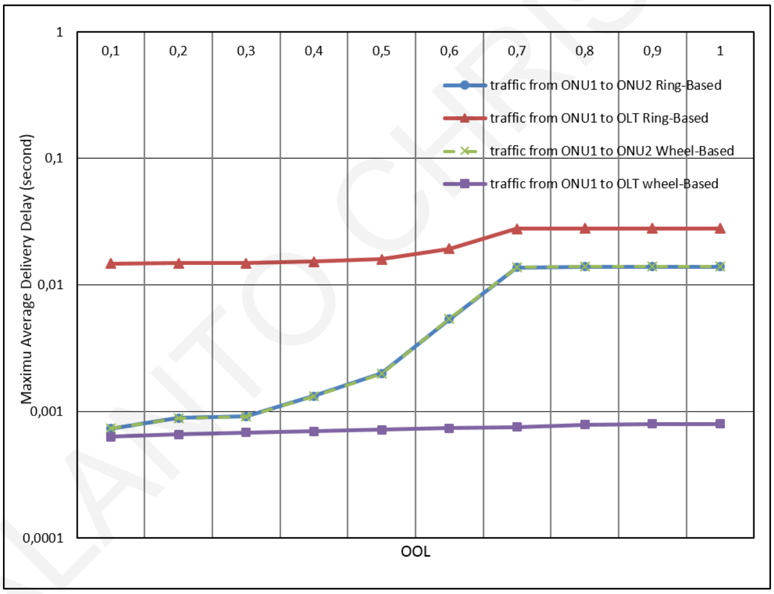

Figure 5.4: Maximum upstream delivery delay vs ONU offered load under normal network operation.

From the results shown in Fig. 5.4, the proposed wheel-based optical access network architecture outperforms the existing ring-based WDM-PON in terms of the delivery delay of the traffic in the upstream direction when the ONU data is destined for the OLT. Even at lower loads, it is observed that the maximum delivery delay using the wheel-based architecture, is significantly lower than that of the ring-based WDM-PON architecture. Again, this is due to the fact that in the wheel-based topology the data from the ONU to the OLT propagate only though the directed fiber links, contrary to the ring-based architecture, where the data needs to traverse a long trunk fiber. Thus, the proposed wheel-based architecture minimizes the propagation distances and serves an entire area more efficiently.

5.6 Conclusion

In this work, a novel wheel-based converged optical-wireless access network architecture was proposed that can support both fixed and mobile users in the downstream and upstream direction under normal network conditions in an efficient manner compared to the analogous ring-based architecture, while being more economical, in terms of fiber usage, in comparison with other PON access network topologies. The signaling protocol, as well as the traffic scheduling procedures are described, followed by an extensive performance analysis that demonstrates the effectiveness of this architecture in terms of the time delay in delivering the traffic, compared to the ring-based topology.

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Chapter 6

Fault Protection in Wheel-based Optical Access Networks

6.1 Introduction

In Chapter 5 a wheel-based optical access network architecture for backhauling network traffic was proposed. It was further shown that this architecture can efficiently support not only the fixed users but also the mobile users in the downstream and upstream direction under normal network operation, while minimizing the average traffic delivery time. In this chapter, the resiliency of this architecture is investigated.

As outlined in Chapter 1 and described in detail in Chapter 2, fault management (detection, isolation, and recovery) is essential for the proper operation of any telecommunications network. Over the years, the issue of network survivability has received increased attention as more and more users and services are expecting high-availability and guaranteed QoS.

In optical access networks, as in all telecommunications networks, the fault management and failure protection/restoration are highly important aspects. In the case of any failure scenario (e.g., equipment failure or fiber cut), there should be available resources to effectively and efficiently recover the affected traffic. If a fault goes unattended for a prolonged period of time this may cause the loss of a huge amount of traffic. Thus, it is very important to provide effective traffic recovery techniques at the physical layer that quickly and efficiently restore the traffic after a failure has occurred. In general, as described in detail in Chapter 2, redundant protection/restoration resources/paths are required to accommodate the affected traf-

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fic; this is possible in optical access networks by essentially duplicating fiber links, equipment and other network components.

Even though significant amount of work has taken place on protection and restoration in backbone networks, access networks have not been at the forefront of fault management research, mainly due to their topologies (generally tree-based topologies) that do not provide for many possibilities on how to protect the affected traffic in the event of a failure. Nevertheless, even if the backbone (and metropolitan area) networks are fully and highly protected, if the traffic does not reach the end user due to lack of protection in the access arena, then this negates the protection functionalities offered at other parts of the network.

Thus, designing a survivable optical access network architecture, is essential, especially when we consider the optical access network for backhauling wireless traffic as well. The decision of which protection scheme should be used, depends on the optical access network topology and network parameters of interest such as traffic delivery delay, the fiber usage (capital expenditure), the type of failures that can detected and recovered, the complexity of the protection technique (operational expenditure), etc. In this chapter, we expand on the wheel-based architecture proposed in Chapter 5, that uses dynamic wavelength assignment/sharing and rerouting to recover from possible network failures.

The rest of the paper is organized as follows. Section 6.2 describe the operation of this architecture under fault operating conditions (including signaling and fault recovery protocols). This is followed by the performance evaluation of the proposed architecture under single and multiple failures for both upstream and downstream traffic in Section 6.3. Finally, Section 6.4 offers some concluding remarks.

6.2 Network Operation Under Failure Conditions

In this section the operation of the wheel-based optical access network architecture is described under component and fiber failure conditions. Prior to this analysis we present a table with the fiber usage for various proposed optical-wireless access architectures with protection capabilities.

For the tree-based PONs, conventional 1 + 1 protection is assumed for the trunk fiber and the fiber from the splitter/combiner to each ONU, while for the ring-based PONs, conventional 1 + 1 protection is assumed for the trunk and ring fibers. A

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Table 6.1: Fiber usage for architectures with protection capabilities (in km).

Conventional Tree with 1+1 Protection (km)	Conventional Ring with 1+1 Protection (km)	Ring with Tree Protection (km)	Wheel Based (km)
$2*t+2*N*s$	$2*t+4*pi*r$	$2*t+N*s$ $+2*pi*r$	$N*s*2$ $+2*pi*r$

third architecture is also considered here, namely a hybrid ring-tree architecture, where the tree links are used for protection purposes. For all architectures, a trunk fiber of 20 km is assumed, as well as rings with 1 km diameter, distances from splitter/combiner to ONUs of 1 km, and distances from ONU to OLT (wheel-based architecture) of 0.5 km. As demonstrated, the proposed architecture requires the least amount of fiber, due to its inherent resilient topology that does not require any additional redundant fibers for protection purposes.

Table 6.2: Characteristics of different access topologies.

	Fiber Usage (km) (no protection)	Protection Techniques	Fiber Usage (km) (for protection)	Network Control
Tree-Based	28	1+1 protection	56	Centralized (OLT-based)
Ring-Based	23	1+1 protection	46	Hybrid (Centralized and Distributed)
Wheel-Based	11	Scheduling Algorithms	11	Hybrid (Centralized and Distributed)

As shown in Table 6.2 and also discussed at length in the preceding chapters, the ring- and wheel-based topologies are more flexible and efficient than the tree-based solution. They can provide a hybrid control plane (centralized control for wavelength selection and scheduling and distributed control for inter-ONU/BS communication) and at the same time the wheel-based approach provides an additional advantage compared to the ring-based topology, in terms of enabling more economical protection capabilities.

Signaling Process

In an optical access network, the failures are divided in two categories: i) fiber cuts and ii) component failures. In order for the network to be able to recover the traffic,

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the controller in the OLT should be able to recognize the type of failure and where the failure has occurred. Different failure scenarios with the appropriate signaling processes are described below.

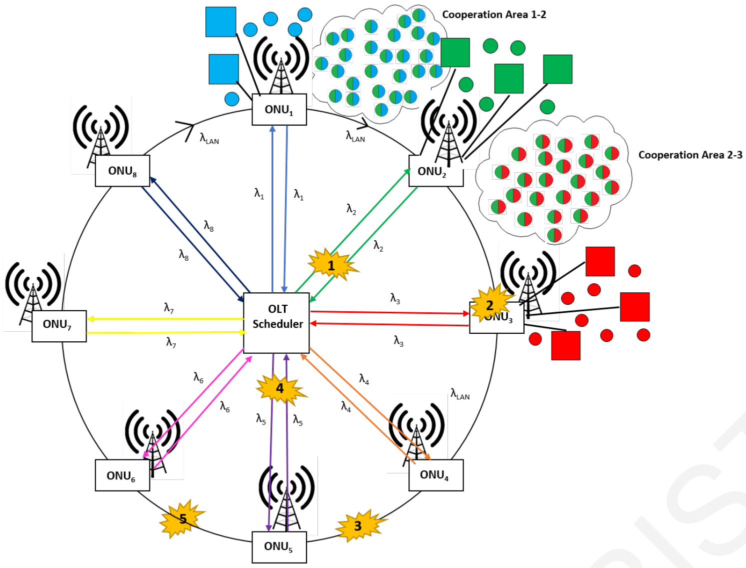

Figure 6.1: Wheel-based optical access network architecture under failure conditions.

1. Fiber cut between an ONU and OLT: Assuming a fiber cut between ONU_2 and OLT (failure 1 in Fig. 6.1), according to the signaling process previously described, ONU_2 will send the first control signal (REPORT) to the OLT and will not receive any acknowledgment back in a fixed time period (T_{delay}). Additionally, ONU_2 will also not receive any control signal from the OLT informing it about its downstream queue size (Q_2^{OLT}). In the same timing interval, ONU_2 will send to ONU_3 a REPORT signal informing about its Q_{LAN} size and its active status. Subsequently, ONU_3 will receive ONU_2's REPORT signal and will inform the controller about its status, its queue size, and the active status of ONU_2. Clearly, from this sequence of control signals, the controller can easily ascertain that the failure has occurred on the directed fibers between ONU_2 and OLT and will execute the scheduling process to send the downstream data traffic to ONU_2 through other queues/wavelengths/ONUs. At the same time, ONU_2 will direct traffic that is destined to OLT, to other ONUs that can subsequently forward the traffic to the OLT, through the fiber ring/directed links by using λ_{LAN}.

2. Component failure: Assuming that ONU_3 has completely failed (failure 2 in Fig. 6.1), according to the signaling process previously described, the OLT will not receive any REPORT signal from ONU_3 in a fixed time period (T_{delay}). In the same

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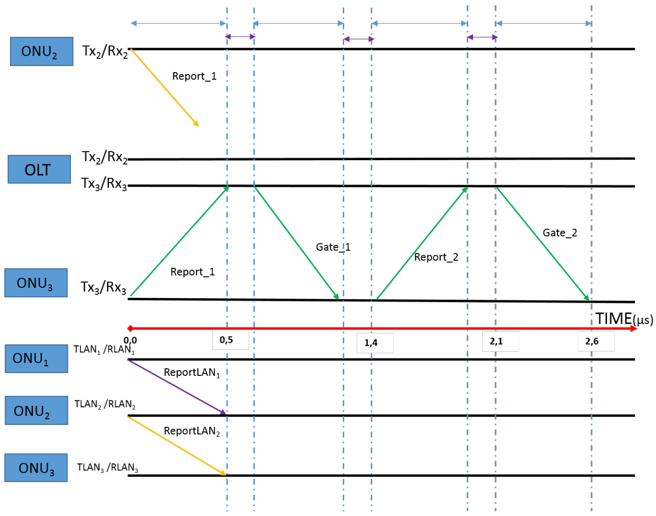

Figure 6.2: Control signaling when a fiber cut between ONU$_2$ and OLT has occurred.

timing interval, ONU$_2$ will send to ONU$_3$ a REPORT signal informing of its Q_{LAN} size and its online status. ONU$_4$ should also receive from ONU$_3$ a REPORT signal for its status and its Q_{LAN} size. As the OLT will not receive any control message from ONU$_3$, as well as from ONU$_4$ on the status of ONU$_3$, it can ascertain that ONU$_3$ has failed or that there are multiple fiber cuts, between ONU$_3$ and ONU$_4$ around the fiber ring and also on the directed fiber between OLT and ONU$_3$. The OLT will execute the scheduling process to send the mobile data traffic of ONU$_3$ through other queues/wavelengths/(ONUs/BSs) and finally will inform ONU$_2$ to divert the LAN traffic through the OLT. The fixed traffic associated with ONU$_3$ cannot be recovered in this case as ONU$_3$ has suffered a complete failure.

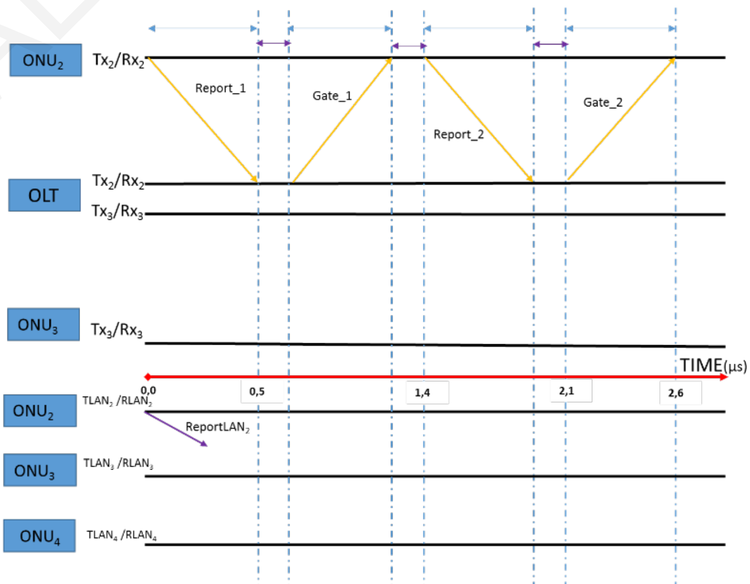

Figure 6.3: Control signaling under a component failure (ONU$_3$) scenario.

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3. Fiber cut on the fiber ring: Assuming that a fiber cut now occurs on the fiber ring between ONU_4 and ONU_5 (failure 3 in Fig. 6.1), according to the signaling process previously described, ONU_4 will send its first control signal to the OLT with its online status and at the same time will send through the fiber ring (λ_{LAN}) another REPORT signal to ONU_5 informing it of its online status and Q_{LAN} size. ONU_5 will also send a control signal with its status to OLT, and at the same time, using the fiber ring and the LAN wavelength, it will send a REPORT signal to ONU_6 informing it of its online status and Q_{LAN} size. Clearly, in this failure scenario, ONU_4 will received a status signal and Q_{LAN} size from ONU_3, but ONU_5 will not receive such a signal from ONU_4. Since each ONU sends a REPORT signal to the OLT controller, informing it of the status of its previous ordered ONU, the controller can easily ascertain that a fiber cut has occurred between ONU_4 and ONU_5. To recover the traffic, the controller will divert all the traffic of ONU_4's LAN queue via the directed fiber links and through the OLT to its destinations by using other available queues/wavelengths.

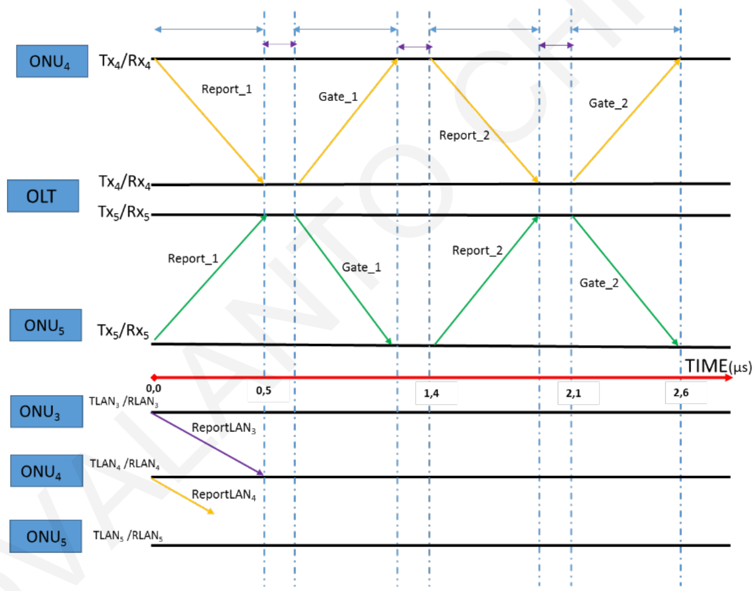

Figure 6.4: Control signaling under a ring fiber cut scenario (between ONU_4 and ONU_5).

4. Multiple Failures: The proposed architecture can recover from specific multiple scenarios as well. For example, in Fig. 6.1 we assume a multiple failures scenario, where a fiber cut now occurs on the fiber ring between ONU_1/BS_1 and ONU_2/BS_2 and a fiber cut also occurs between ONU_2/BS_2 and the OLT. According to the signaling process previously described, ONU_2/BS_2 will send its first control signal to the OLT with its online status and at the same time will send through the fiber ring (λ_{LAN})

another REPORT signal to ONU_3/BS_3 informing it of its online status and Q_{LAN} size. ONU_1/BS_1 will also send a control signal with its status to OLT, and at the same time, using the fiber ring and the LAN wavelength, it will send a REPORT signal to ONU_2/BS_2 informing it of its online status and Q_{LAN} size. Clearly, in this failure scenario, ONU_2/BS_2 will not received a status signal and Q_{LAN} size from ONU_1/BS_1, but ONU_3/BS_3 will receive such a signal from ONU_2/BS_2. Also, the OLT will not receive any REPORT signal from ONU_2/BS_2. Since each ONU sends a REPORT signal to the OLT controller, informing it of the status of its previous ordered ONU, the controller can easily ascertain that a fiber cut has occurred between ONU_1/BS_1 and ONU_2/BS_2 and also on the directed fiber link between the OLT and ONU_2/BS_2. It can also easily recognize that this is not an ONU_2/BS_2 full component failure as ONU_3/BS_3 has received a control signal from ONU_2/BS_2. To recover the traffic, the controller will divert all the traffic of ONU_1/BS_1's LAN queue via the directed fiber links and through the OLT to its destinations by using other available queues/wavelengths. Similarly, it will also try to forward all the affected cooperation mobile traffic to its destination. The reader should note here that not all multiple failure scenarios can be recovered. Nevertheless, the proposed architecture is flexible enough to allow recovery from several multiple (mostly dual) failure scenarios.

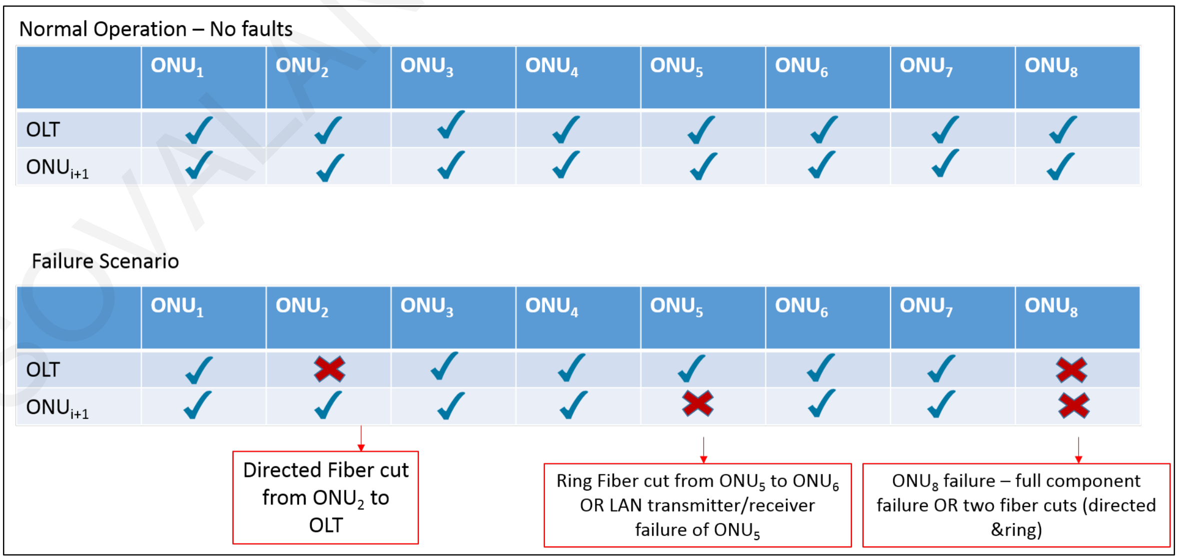

Figure 6.5: Table illustrating REPORT-GATE signaling during normal operation and after specific failure events.

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Traffic Flow under Failure Conditions

As described in the previous section, the failures can easily be detected and isolated via the control messages that are exchanged periodically between the ONUs/BSs and the OLT. Once this is done, the scheduler, using the CWSA algorithm, can divert the traffic to its destination.

(i) Fiber Cut between ONU and OLT: Assuming there is a fiber cut between OLT and ONU_i, the scheduler at the OLT will run the CWSA algorithm without taking into account the faulty fibers. Initially, the scheduler will try to divert the traffic destined to ONU_i/BS_i to the previous ordered ONU/BS (ONU_{i-1}/BS_{i-1}), if and only if its Q_{i-1} and $Q_{i-1,LAN}$ have available space to accommodate ONU_i/BS_i's traffic. If both queues have available space then the traffic will reach ONU_i/BS_i through ONU_{i-1}/BS_{i-1} utilizing λ_{i-1} and the *LAN* wavelength along the fiber ring. If there is no available space, then the scheduler at the OLT will repeat the process until it finds previously ordered ONUs/BSs with availability in their queues to divert the traffic.

(ii) Component Failure: Assuming ONU_i fails, the scheduler at the OLT will run the CWSA algorithm to divert the mobile traffic within the cooperation areas of the faulty node through the cooperating ONUs/BSs (ONU_{i+1}/BS_{i+1} and ONU_{i-1}/BS_{i-1}) to its destination mobile users. All LAN traffic that arrives to ONU_{i-1}/BS_{i-1} and is destined to other ONUs will be diverted to the OLT and the scheduler will then direct it to its destination via the directed fiber links.

(iii) Fiber Ring Cut: Assuming a fiber cut has occurred on the fiber ring between ONU_i/BS_i and ONU_{i+1}/BS_{i+1}, the scheduler at the OLT will run the CWSA algorithm to divert the traffic destined from ONU_i/BS_i to ONU_{i+1}/BS_{i+1} or to any other ONU_j/BS_j ($j > i$) to its destination via the directed fiber links through the OLT.

As described in Chapter 5, the delivery time for each packet to its destination (i.e., the time required from the time the packet is generated (or arrives at the OLT/scheduler from another network) till the time the packet arrives at its destination ONU/BS) will be $T_{TotalDelay} = T_{delay_{RG}} + T_{PacketTransmission} + T_{PropagationData} + T_{Q_j^{OLT}} + T_{Q_{j,LAN}^{ONU}} + T_{rescheduling}$ for the case of a link failure scenario and $T_{TotalDelay} = T_{delay_{RG}} + T_{PacketTransmission} + T_{PropagationData} + T_{Q_{i-1,LAN}^{ONU}} + T_{Q_j^{OLT}} + T_{Q_{j,LAN}^{ONU}} + T_{rescheduling}$ if a component has failed.

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6.3 Performance Evaluation

The proposed architecture was implemented for a converged optical-wireless backhaul network, with $N = 8$ integrated ONUs/BSs, interconnected in a wheel-based configuration. Once again, for the simulation experiments, downstream traffic flows are generated by aggregating multiple sub-streams, where each sub-stream is modeled as an ON/OFF source, with Pareto distribution [107], to generate packets according to a self-similar process, with a Hurst parameter $H = 0.7$. The rest of the system parameters used in the simulation are the following: (i) All channels (downstream, upstream, and LAN) are operating at 1 Gbps; (ii) Each ONU/BS houses a LAN queue ($Q_{i,LAN}^{ONU}$) with maximum size equal to 100 Kbytes; (iii) The OLT houses 8 downstream queues, each one corresponding to a given ONU/BS with a maximum size Q_{max} equal to 100 Kbytes; (iv) Maximum access LAN link rate from users to an ONU is 200 Mbps; and (v) Maximum LAN cycle $T_{cycle} = 2$ ms.

6.3.1 Single Failure Network Operation

Downstream Operation

To simplify the downstream operation analysis, and without loss of generality, the upstream traffic in the following scenarios is assumed to be zero so as to reduce the complexity of the network. Simulations were also performed assuming single failure scenarios in both the wheel-based and ring-based architectures. In the first scenario, a fiber cut failure is assumed on the link that connects ONU_2 with the OLT. In the ring-based WDM-PON architecture the fiber cut is assumed to be on the fiber ring between ONU_1 and ONU_2. Even though the failures are at different locations, they affect the same traffic in the downstream direction from the OLT to ONU_2 in order to accurately compare the delivery delay in both architectures.

Additionally, simulations were also performed assuming the same component failure (ONU_3/BS_3) in both topologies. In this case, the downstream traffic lost is the traffic destined to the faulty node (all the fixed and mobile users except the users in the cooperation areas of ONU_3/BS_3). The rest of the traffic assigned to other ONUs/BSs and the mobile traffic that is located in the cooperation area of the faulty node are affected only in their delivery time, as can be seen in Fig. 6.6, especially for the ring-based topology. This is the case, as in the ring-based architecture, when

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a node fails, its optical switch is reconfigured to the bypass mode by switching the incoming signal directly to the outgoing protection fiber and this switching process adds extra delay on the transmission of the data packets [33].

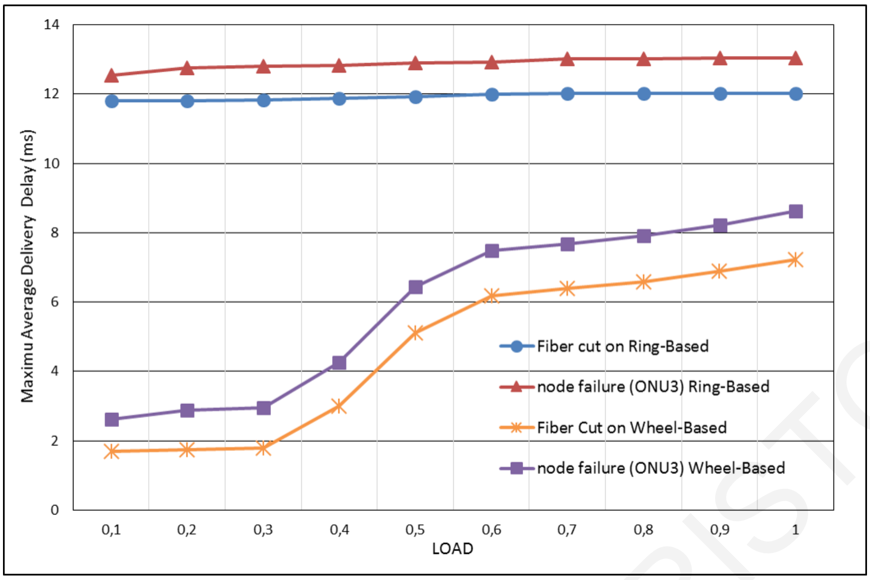

Figure 6.6: Maximum delivery delay vs downstream offered load for a single failure scenario.

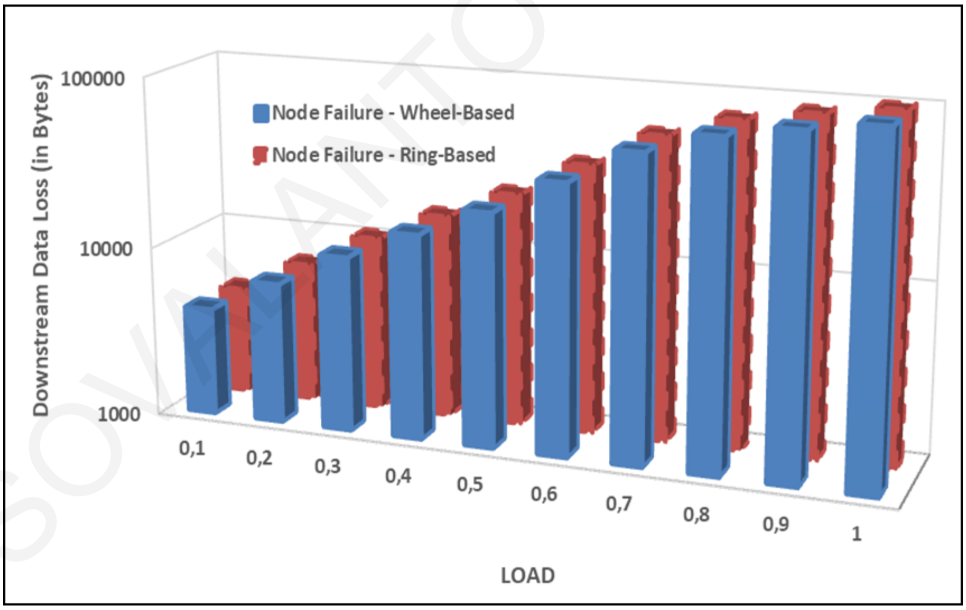

Figure 6.7: Data loss in bytes vs downstream offered load for a single failure scenario.

For the above failure scenarios, the simulations were executed 10 times for each load (0.1 to 1.0) for each topology per single failure. From Fig. 6.6 it is clear that the wheel-based architecture again outperforms the ring-based WDM-PON under a fiber-cut scenario as it uses a more efficient way to redirect the data traffic that is affected due to the failure. The ring-based WDM-PON [46] is an 1 + 1 architecture which uses optical switches and backup redundant capacity to restore the failure. This switching process incurs extra delay for the packets to arrive at their destination ONU, while the proposed wheel-based architecture uses scheduling algorithms to re-schedule and re-direct the packets to their destinations (via also the use of the LAN wavelength). As can be observed from Fig. 6.7, due to the component failure, in both topologies (architectures) the same amount of data (in bytes) is lost and this is the traffic destined to the faulty node (all the fixed and mobile users' data destined to the faulty node except the data from the users in the cooperation area that can be redirected to adjacent ONU/BS).

Upstream Operation

Again, in order to simplify the upstream operation analysis, and without loss of generality, the downstream traffic in the following scenarios is assumed to be zero. The simulations were again executed 10 times for each load (0.1 to 1.0) for each topology for the same single failure in order to evaluate the average performance of each topology under the same traffic scenarios. Simulations were performed assuming single failure scenarios in both the wheel- and ring-based architectures.

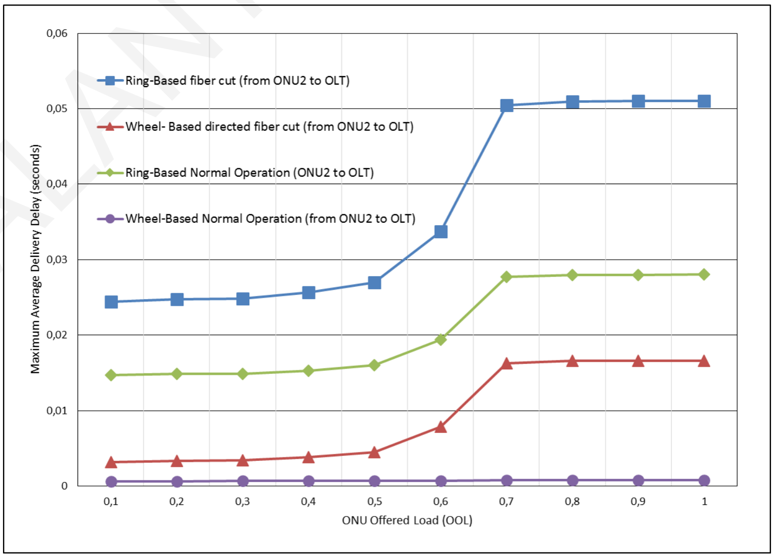

Figure 6.8: Maximum delivery delay vs upstream offered load for single failure scenario (fiber cut from ONU_2 to OLT).

In the first scenario, for the wheel-based topology, a fiber cut is assumed on the directed fiber link that connects ONU_2 with the OLT, while in the ring-based WDM-

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PON topology, the fiber cut is assumed to be on the fiber ring between ONU_2 and ONU_3 (again affect the same traffic for both topologies in the upstream direction).

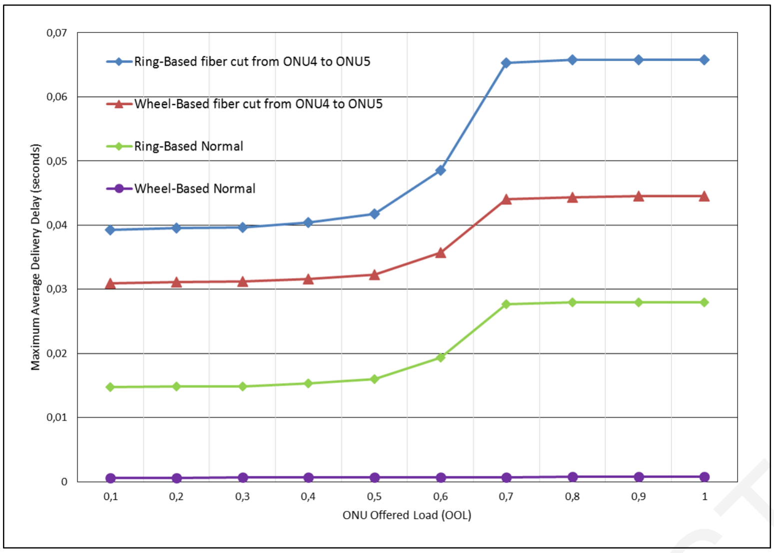

Figure 6.9: Maximum delivery delay vs upstream offered load for a single failure scenario (fiber cut on the ring between ONU_4 and ONU_5).

In both topologies the traffic that is affected due to the fiber cut is the upstream traffic destined from ONU_2 to *OLT* and the LAN traffic. From Fig. 6.8 it can be observed that the maximum delivery delay increases for both topologies due to the failure compared to the maximum delay observed under normal operation. Also, it is clear that the same amount of traffic experiences additional delay in the ring-based topology, in comparison with the wheel-based architecture, mainly due to the switching time of the optical switches on the protection path for the recovery of the traffic in the ring-based topology.

A second failure scenario is also investigated for both topologies, that is a fiber cut on the fiber ring that connects ONU_4 with ONU_5. From Fig. 6.9 it can be seen that the same amount of traffic in the ring-based topology requires considerably more time to arrive at its destination compared to the proposed wheel-based architecture.

Additionally, simulations were also performed assuming the same component failure (ONU_3/BS_3) in both topologies. The downstream traffic is assumed to be zero and the upstream traffic that is lost is all the upstream traffic that needs to be sent from ONU_3/BS_3 to any other ONU/BS or to the OLT (all the fixed and mobile users' traffic except the upstream traffic from the users in the cooperation areas of ONU_3/BS_3). The rest of the upstream traffic from other ONUs/BSs and the mobile traffic that is located in the cooperation area of the faulty node is affected only in

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their delivery delay as can be seen in Fig. 6.10, especially for the ring-based topology.

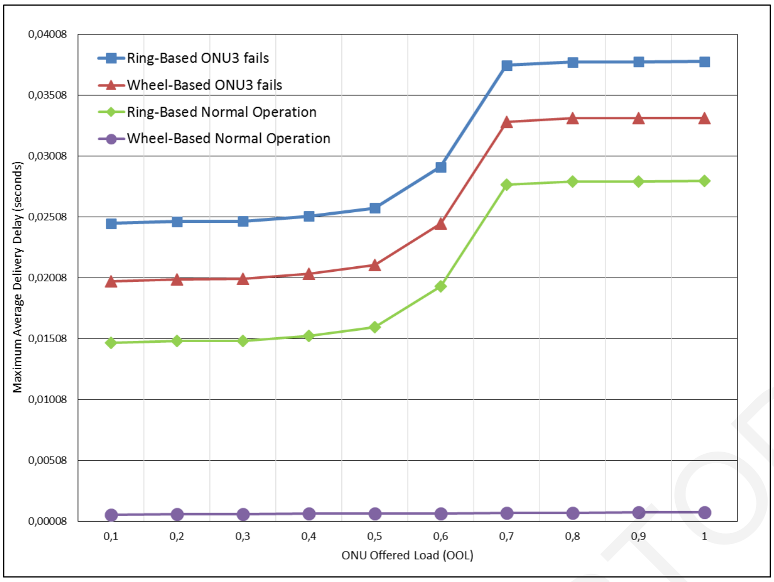

Figure 6.10: Maximum delivery delay vs upstream load under single component failure (ONU_3/BS_3) scenario.

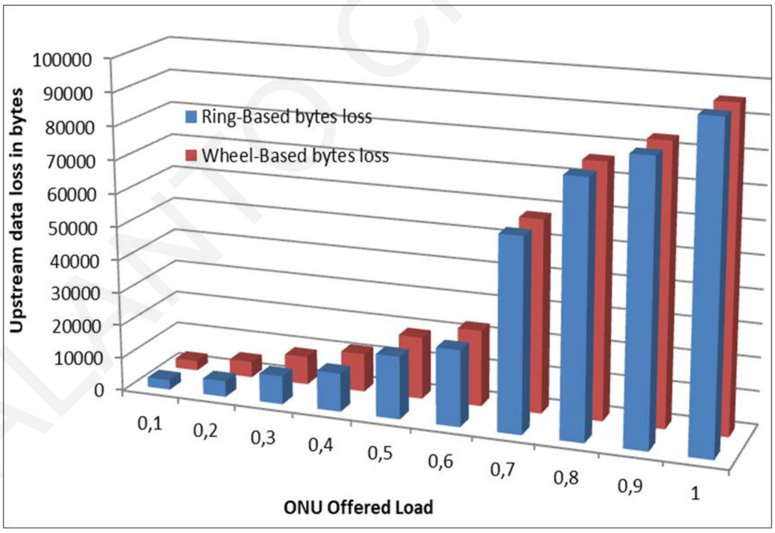

Figure 6.11: Data loss (in bytes) vs upstream load under single component failure (ONU_3/BS_3) scenario.

In the wheel-based topology, when a node fails, all the affected traffic is rescheduled and is sent through the directed fiber links to the OLT and then to its destination. Thus, the extra delay incurred is due to the rescheduling process as well as due to congestion in the queues. On the contrary, in the ring-based topology [46], when a node fails, its optical switch is reconfigured to access the protection fiber, adding extra delay on the transmission of the data packets. In both architectures, the data

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destined to the faulty node (all the fixed and mobile users' data except the data from the users in the cooperation area), is lost as cannot be served through the faulty node.

6.3.2 Multiple Failure Operation

Additional simulations were performed assuming multiple failure scenarios in both wheel-based and ring-based architectures. In this scenario, a fiber cut is assumed on the directed fiber links that connects the OLT with ONU_2/BS_2 and simultaneously a fiber cut is assumed on the ring between ONU_4/BS_4 and ONU_5/BS_5 in the wheel-based architecture. In the ring-based WDM-PON architecture the fiber cut is assumed to be on the fiber ring between OLT and ONU_2/BS_2 and between ONU_4/BS_4 and ONU_5/BS_5. Even though the failures are at different locations, they affect the same traffic in the upstream direction from the OLT to ONU_2 and from ONU_4/BS_4 to ONU_5/BS_5. Thus, we can accurately compare the delivery delay in both architectures.

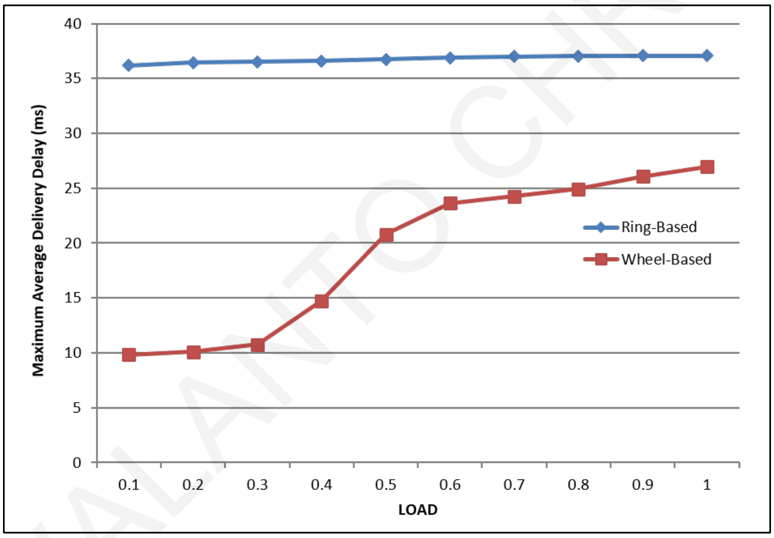

Figure 6.12: Maximum delivery delay in the downstream vs load under multiple failures.

In the wheel-based topology, when a failure occurs anywhere in the network, then the affected traffic is rescheduled to be sent through any other available fiber links. In this scenario, when more than one failures occur simultaneously, they will detected by collecting and processing the REPORT/GATE messages at the OLT as previously explained. Then, the scheduler at the OLT will try to reschedule the excess data through the available unaffected fiber links. However, in the ring-based topology [46], when multiple failures occur, the relevant optical switches are reconfigured to the bypass mode in order re-route the traffic to the protection fiber.

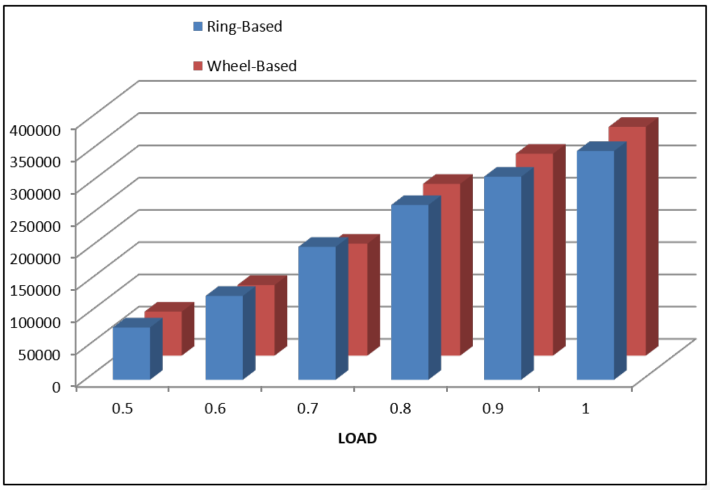

Figure 6.13: Data loss (in bytes) in the upstream direction vs load under multiple failures.

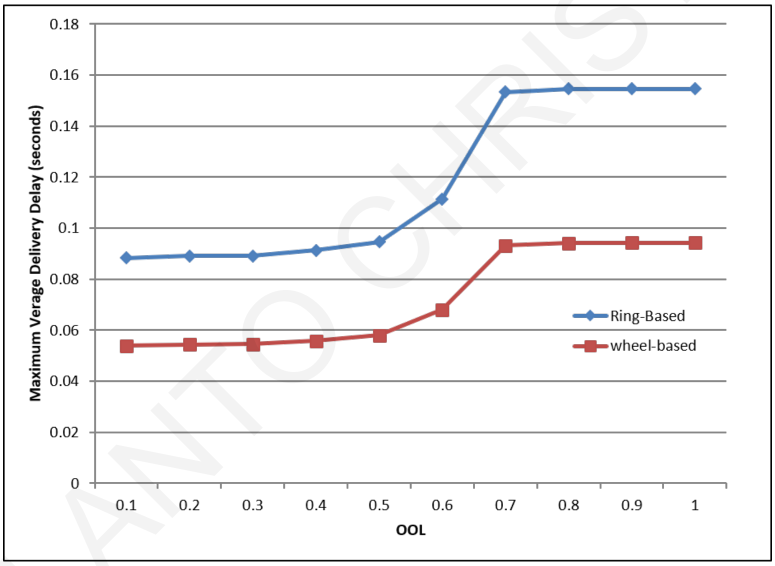

Figure 6.14: Maximum delivery delay vs upstream load under multiple failures.

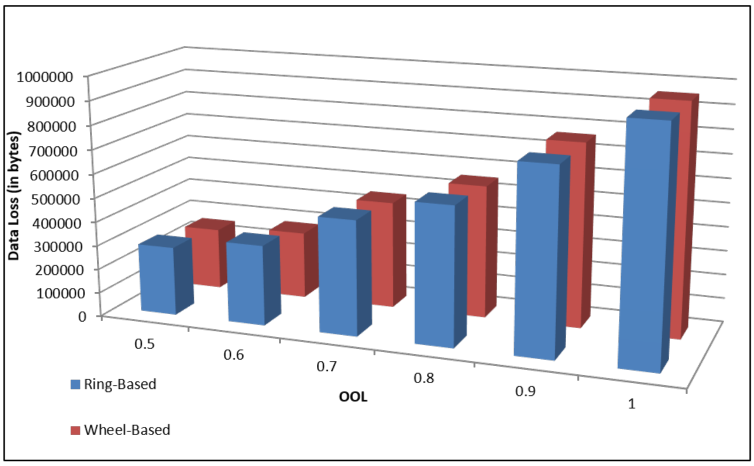

Figure 6.15: Data loss in bytes vs upstream load under multiple failures.

Figures 6.12-6.15, illustrate the delay in delivering the data, as well as the data lost under the prescribed multiple failure scenario. Clearly, both topologies manage to recover the same amount of data. Nevertheless, the wheel-based topology again performs better in terms of delay in data delivery as it uses a faster recovery approach compared to its ring-based counterpart.

6.4 Conclusion

In this chapter, the wheel-based optical-wireless access network architecture that was proposed in Chapter 5 is investigated under failure conditions (including link, component, and multiple failures). The signaling protocol, as well as the fault recovery procedures are described, followed by an extensive performance analysis that demonstrates the effectiveness of this architecture in terms of the time delay in delivering upstream and downstream traffic under different network load conditions, when a failure has occurred, compared to the ring-based topology.

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Chapter 7

Conclusions and Future Directions

7.1 Conclusions

The main focus of this dissertation was to develop new converged optical-wireless architectures that can efficiently support both wired and wireless traffic, while at the same time providing fault recovery capabilities. The basic motivation behind the proposed work was discussed in Chapter 1 and included such reasons as the tremendous increase of the high-speed services and applications, the need for mobility, and the vulnerability of fiber-optic cables and switching equipment.

The optical access architectures reported in the literature, as well as the converged optical-wireless access architectures, have a number of significant disadvantages, making them undesirable for use in the next generation converged architectures for backhauling mobile traffic. Chapter 2 discussed these disadvantages in an attempt to illustrate the need for a new and better architectural solution.

Active research in fiber-wireless access networks has for years centered around architectures that rely on centralized control and management planes and treat the fixed and wireless users independently. This thesis has been devoted to the problem of an integrated solution, where the mobile and fixed users are considered together, utilizing novel architectures that support a distributed control and management plane.

The thesis achieved its intended objectives. The research took advantage of the wide body of results available for optical access networks to develop new architectures and methodologies for solving the wavelength sharing and scheduling as well as fault recovery problems in converged fiber-wireless access networks. These

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techniques, in conjunction with the novel architecture topologies proposed were the main contributions of this dissertation.

Initially, in Chapter 3, the thesis discussed the tree-based PON architecture and the dynamic bandwidth allocation algorithms that can be implemented for such a topology demonstrating the limitations of these types of topologies for supporting the converged optical-wireless access architectures.

This is followed in Chapter 4 with the description of a converged ring-based WDM PON architecture in which the ONUs are integrated with the BSs and can serve both mobile and fixed users. This ring architecture tries to solve some of the limitations and a number of networking issues that were identified for tree-based topologies. Novel wavelength sharing and scheduling algorithms (heuristics as well as an ILP) were subsequently proposed for converged ring-based WDM-PON architectures that can better utilize the network capacity and provide QoS (in terms of the data delivery time) for both mobile and fixed users. Performance evaluation results indicate that utilizing the proposed algorithms improves on the maximum time required to transmit the last packet to its destination within a transmission cycle, especially when the HSPA-b and CWSA heuristics are utilized for the case of high priority traffic and traffic destined to the mobile users within a cooperation area, respectively.

The second major contribution of this dissertation was the proposition of a new access topology, namely a wheel-based converged aceess architecture that is described in Chapter 5 together with wavelength scheduling algorithms for downstream and upstream traffic. Specifically, in this work, a simple and cost-effective local access wheel-based optical-wireless access architecture is presented that addresses some of the limitations of conventional tree-based PONs and ring-based WDM-PON architectures, combining the salient features of both traditional static and dynamic PONs. The work of this thesis comprises of efficient resource allocation techniques, utilizing novel wavelength selection and sharing and priority scheduling techniques.

Significant work on protection and restoration has been undertaken in backbone (and metropolitan area) optical networks, but in access networks limited work has taken place considering the protection of the traffic against faults or malicious attacks. It is important to note that even if the backbone networks are fully and highly protected, it is also critical that the traffic reaches the end user. Thus, protection in the access arena is also essential. The thesis concludes in Chapter 6 with a

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description of simple and cost-effective protection techniques for single and multiple failures without the need for extra redundant fiber usage. Thus, it is proved that the proposed wheel-based architecture can not only support both fixed and mobile users in the downstream and upstream direction in an efficient scheduling manner (for both normal and faulty operational conditions), but it is also a more economical topology (in terms of fiber usage) in comparison with existing PON access network topologies.

We strongly believe that resource allocation and fault protection are fundamental research topics that will have significant impact in the successful deployment of converged access networks as well as for other critical infrastructure applications as it is discussed in the section that follows. This dissertation has hopefully provided a framework for addressing these issues in an efficient manner.

7.2 Future Directions

During the course of the thesis work several other interesting ideas and future avenues of research were considered. However, since not all of the ideas can be addressed in the thesis there are noted in this section as topics of future work.

In both the ring- and wheel-based solutions proposed in this thesis, all performance results presented were based on simulations of the proposed architectures to demonstrate the advantages of these architectures in terms of QoS and resilience. Nevertheless, physical layer implementation of the proposed architectures is further required to demonstrate the viability of these architectures and techniques. Thus, one avenue of future research is the implementation of the proposed architectures in a testbed environment, including implementing the signaling and control protocols, as well as conducting experiments on the physical layer impairments in these types of architectures. Further, by physically implementing the proposed architectures the scalability issue can also be investigated in terms of the number of nodes that can be included on the distribution ring.

There are also several important issues that need to be considered regarding the security of the data transmitted in these types of architectures. As the data in the proposed architectures can potentially reach different nodes, before the final destination node where the data is delivered to the end user, there must exist additional security provided for the transmitted data. Security at the physical layer has gained signifi-

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cant traction recently, as it can further enhance data security (over and above of the security offered at higher layers) [37], [40]. By protecting the data at the optical layer one can potentially protect mainly the integrity of the data against malicious attacks, as well as the confidentiality of the data against eavesdropping attacks (tapping the optical fiber to access the information) [37], [40], [55]. For the case of eavesdropping attacks, several solutions have been proposed including Quantum Key Distribution (QKD) [98] and optical encoding [38]. For example, various spread spectrum techniques including optical code division multiple access (OCDMA) have been shown to effectively implement optical encoding [38], [41], [99], [100], [102].

Clearly, there are also several other extensions to the work presented in the areas of (i) creating an integrated module for the ONU/BS, (ii) creating a unified distributed control and management plane, and (iii) providing QoS support and mapping.

In terms of the integrated ONU/BS module, integration in both hardware and software is required, including support of a common standard interface and being able to differentiate between fixed and wireless users. Initial thoughts on this topic were presented in [103] [104] with three control modules, an ONU control module, a BS control module, and a common control module. Each module runs its own protocols (optical and wireless respectively) and the common module manages and coordinates jointly the network resources, as well as runs the bandwidth allocation and wavelength scheduling algorithms proposed in this work. As far as the unified distributed control plane is concerned, utilizing the integrated module mentioned above that includes a common control module, this enables the support of an integrated control and management plane that can manage and control jointly the optical and mobile radio network resources (including implementing admission and congestion control algorithms for both wired and wireless traffic). This, in turn, will provide the most efficient allocation of resources and it will provide support for better QoS. Finally, providing QoS support and mapping requires a mapping mechanism between PON and wireless technology so as to correctly identify and map traffic flows and store them in the appropriate priority queues for further handling. This, in turn, will ensure that the queue management schemes and scheduling algorithms are implemented the same for both wired and wireless upstream/downstream traffic.

Clearly, there is also much work to be done in the area of mobility management that was not investigated in this thesis. The proposed converged architecture must

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be able to support initially a registration procedure (managed by the OLT/RNC) and then support handoff procedures that conform to the wireless technology in use. In the proposed architectures there can be a handoff between two nodes that are on the same ring and managed by the same OLT/RNC (intra-OLT handoff), as well as a handoff between nodes located on different adjacent rings, where each BS is managed by a different OLT/RNC (inter-OLT handoff). It is clear that due to inter-ONU/BS communication in the proposed architecture, there are significant advantages in the implementation of at least intra-OLT handoff, that could potentially reduce handoff latency. Nevertheless, modeling of intra- and inter-OLT handoff is required, as well as extensive simulation results, in order to ascertain the advantages of the proposed architectures in the context of mobility management.

Future work stemming from this thesis is also possible in other application areas, where this technology is not currently under consideration. As an example, in the following years, power grids worldwide are expected to undergo major paradigm shifts. The Internet technology and renewable and conventional power technologies are beginning to merge in order to create the infrastructure for the so-called "third industrial revolution economy", which goes well beyond current measures and has been officially endorsed by the European Commission as an economic growth roadmap towards a competitive low-carbon society by 2050 [50]. Thus, the communication infrastructure must be able to accommodate all the future growth in data traffic not only for the telecommunication users but also for the communication infrastructure of the smart grids utilized for control and monitoring purposes.

The Smart Grid (SG), is a well-known term used nowadays, describing the communication and control facilities integrated with the conventional power grid. As the SG infrastructure involves smart metering and various other monitoring and control functionalities [50], there is a pressing need for an intelligent telecommunication infrastructure that is capable of providing accurate and real-time control of the system. The power and telecommunication industries are thus challenged to provide intelligent, reliable, and sustainable integrated power and communication systems to support the future high-level traffic for both systems. The evolution of telecommunication technologies in the power system [10] is shown in Fig. 7.1 below.

The most important achievements in SGs is the advanced metering infrastructure (AMI) [22], which is an integrated system of smart meters, communications networks, and data management systems that are used to measure and analyze the

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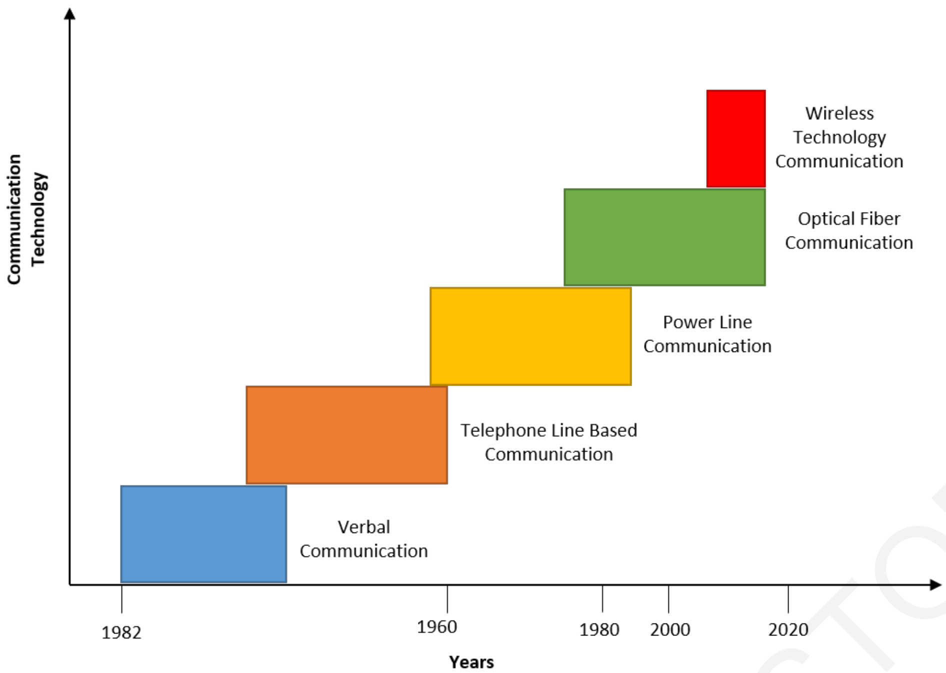

Figure 7.1: Communication technology evolution for smart grid communication.

data concerning energy consumption and power quality for each consumer. As the number of consumers is very large and growing steadily, the future power grid applications require to support a massive number of connected devices with low latency and reliability. Thus, in order to support this high-level communication in the smart grid, there is a need for point-to-point fibers between the devices and the controller. The best successor solution, is the optical fiber networks and specifically the fiber-to-the-home solution converged with wireless technology that can be either a dedicated private network owned and controlled by the power providers, or commercial fixed/mobile networks controlled by the telecommunication providers. However, developing dedicated fiber networks only for the SG purposes, will be not only costly but also the fiber capacity will be underutilized.

Nowadays, the commercial converged optical-wireless access network has received significant attention as the successor solution for the converged grid communication architecture [7], [43]. This is the case since, as discussed throughout the thesis, standalone optical fiber networks provide high data rates, high bandwidth, low attenuation, high reliability and negligible interference, while at the same time wireless communication infrastructure provides mobility and it is one of the fastest growing technologies in the world. Thus, the results of the integration of both technology systems can easily meet the future requirements of the smart grid systems.

An architectural model solution that is proposed and presented in Fig. 7.2, is a wheel-based optical access network architecture converged with current wireless technologies which could be integrated with the power grid system to support both the needs of the telecommunication providers as well as all required functionalities of the smart grid.

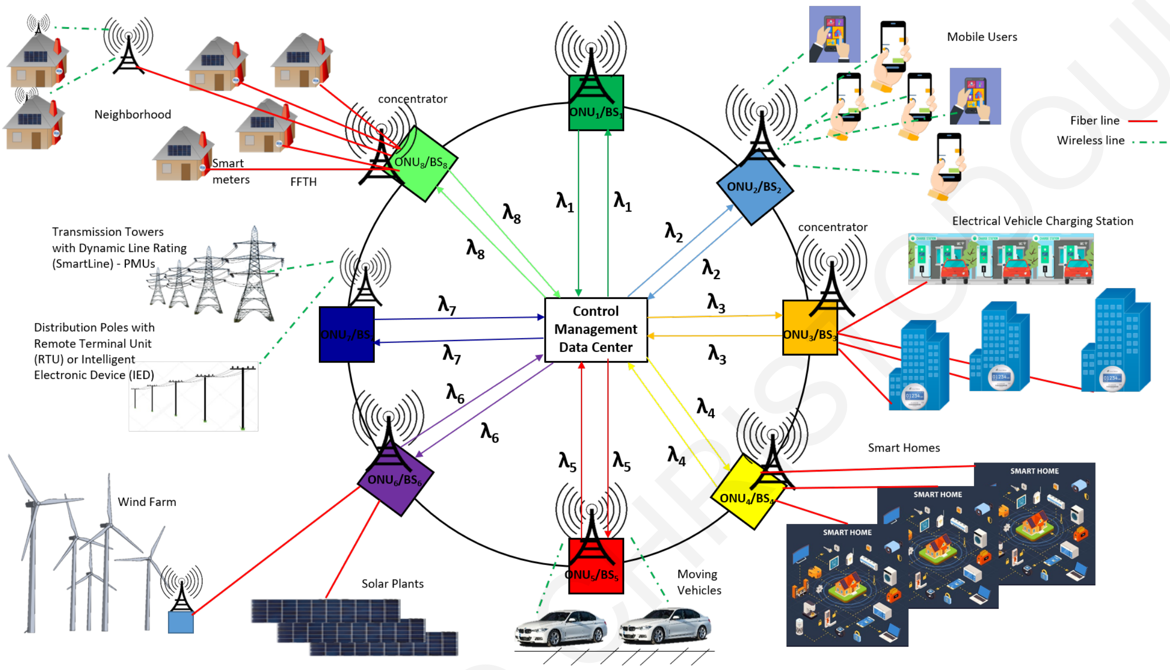

Figure 7.2: Converged optical-wireless technology architecture for future smart grid systems.

As shown in Fig. 7.2, the control and management data center (CMDC) is located at the center of a fiber ring where N ONUs/BSs are interconnected in a closed loop around the access ring. The CMDC includes the OLT for the telecommunication services, data buffers, and the data concentrators required for the power system communication. The CMDC includes a pair of dedicated transceivers that are directly connected to each ONU/BS with two fiber links (incoming and outgoing fibers). As described in Chapter 5, each ONU/BS is assigned a single-dedicated wavelength λ_i for both downstream and upstream transmissions and a wavelength λ_{LAN} for monitoring and inter-communication among the ONUs/BSs. The *cooperation area*, is the area located between two adjacent ONUs/BSs around the fiber ring, where the mobile users, the smart meters and any wireless devices within this area can be served by both ONU/BSs. Each ONU/BS serves both fixed and mobile users and the communication of wireless and wireline devices within the power system; an ONU/BS serves the fixed users and the communication power systems devices that are connected directly with it, the mobile users and wireless communication power system devices that are within an area near the ONU/BS, and also those that are within the cooperation area with an adjacent ONU/BS around the ring. The downstream and upstream traffic in the fiber-wireless access network could be either fixed or mobile users traffic but also data traffic from metering and control functionalities of the power devices.

All communications related to the power supervisory control and data acquisition (SCADA) system are thus served though the wheel-based optical access network integrated with wireless technologies. For example, the phasor measurement units (PMUs) are placed at the power transmission towers in order to provide fine-grained measurements pertaining to the power system dynamics. The data from the PMU is sent wirelessly to the ONUs/BSs and subsequently are carried as an optical signal via the optical fibers to the phasor data concentrator (PDC) which is located at the CMDC. At the PDC, the optical signal is converted back into electrical signal and received by the power system managers for additional processing. Additionally, except from PMUs, remote terminal units (RTUs) can be added in the network for more intelligent control of the power system by collecting measurements and other data at remote or inaccessible points. The RTUs are electronic devices controlled by a microprocessor that are placed at the power system distribution network poles in order to collect the telemetry data. These data, is subsequently sent via the proposed communications architecture to the CMDC for processing. Further, smart meters are placed at the premises (houses, building, etc.) as are shown in Fig. 7.2 in order to record electricity consumption and communicate this information for monitoring and billing. The communication from the meter can be either wirelessly, or via the fixed fiber connections to a data concentrator at the ONU/BS and then to the CMDC through the optical access network. Finally, in the proposed converged architecture shown in Fig. 7.2, sensors are placed at wind farms and solar plants for metering and control of the renewable power generation. Again, the sensors' information can be sent to the data concentrators through the wireless or fiber technologies (ONUs/BSs), and then to the SCADA center through the optical access network to be collected and processed.

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