Optimisation Analytics for Bandwidth Resource Management in Converged IP Networks

By

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Dedication

This thesis is dedicated to my parents: Mohammad and Zohreh.

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Abbreviations

AF	Assured Forwarding
AI	Artificial Intelligence
ANN	Artificial Neural Network
AP	Access Point
ATM	Asynchronous Transfer Mode
AWG	Arrayed Waveguide Grating
BA	Bandwidth Allocation
BE	Best Effort
B3G	Beyond-Third-Generation
BGP	Bandwidth Guaranteed Polling
BN	Bandwidth Negotiation
BPR	Bidirectional Path-Protection Ring
BRAN	Broadband Radio Access Network
BS	Base Station
CapEx	Capital Expenditure
CC	Central Controller
CM	Cable Modem
CN	Concentration Node

CO	Central Office
COB	Combined ONU-BS
CS	Central Scheduling
CSs	Client Stations
CWDM	Coarse Wavelength Division Multiplexing
DBA	Dynamic Bandwidth Allocation
DBRu	Dynamic Bandwidth Report upstream
DSL	Digital Subscriber Line
DWDM	Dense WDM
EA	Evolutionary Algorithms
EDFA	Erbium Doped Fibre Amplifier
EF	Expedited Forwarding
EGS	Emergency Grant Service
EPON	Ethernet Passive Optical Network
ertPS	Extended Real-time Polling Service
ETE	End-To-End
ETSI	European Telecommunications Standards Institute
FCC	Federal Communication Commission
FDM	Frequency Division Multiplexing
FiWi	Fibre-Wireless
FSC	Free Space Optical
FTTB	Fibre-To-The Building
FTTC	Fibre-To-The-Curb
FTTH	Fibre-To-The-Home

FTTPC	Fibre-To-The-PC
3G	Third-Generation
4G	Fourth-Generation
GA	Genetic Algorithm
GBR	Grant Before Report
GEM	GPON Encapsulation Method
10GEPON	10 Gb/s Ethernet Passive Optical Network
GPON	Gigabit Passive Optical Network
HDTV	High-Definition TV
HFC	Hybrid Fibre Coaxial
HOB	Hybrid ONU-BS
HPWFS	Hybrid Priority Weighted Fair Scheduling
HWMP	Hybrid Wireless Mesh Protocol
IEEE	Institute of Electrical and Electronics Engineers
IEEE EFM TF	IEEE Ethernet in the First Mile Task Force
IOB	Independent ONU-BS
IPACT	Interleaved Polling with Adaptive Cycle Time
IPTV	Internet Protocol Television
IS	Independent Scheduling
ISM	Industrial and Scientific Medical
ISP	Internet Service Provider
ITU-T	International Telecommunications Union - Telecommunication Standardisation Sector
JC	Joint Controller

LAN	Local Area Network
LD	Laser Diode
LED	Light Emitting Diode
LOS	Line of Sight
LP	Linier Programming
LTE	3GPP Long Term Evolution
MAC	Media Access Control
MC	Mission Critical
MC-FiWiBAN	Mission-Critical Fibre-Wireless Broadband Access Network
MCN	Mobile Client Node
ML	Machine Learning
MOF	Microwave-over-Fibre
MPCP	Multipoint Control Protocol
MPCP Ext.	MPCP Extension
MS	Mobile Subscriber
MZI	Mach Zehnder Intensity
NGN	Next Generation Networks
NGSSs	Next Generation Satellite Systems
NLOS	Non-Line Of Sight
OA	Optical Amplifier
OADM	Optical Add-Drop Multiplexer
OBP	Onboard Processing
OBRC	Onboard Routing Capabilities
OLT	Optical Line Terminal

ON	Optical Network
ONU	Optical Network Unit
OOW	Optical-Optical-Wireless
OpEx	Operating Expense
OR	Operational Research
OW	Optical Wireless
PC	Personal Computer
PCB	Printed Circuit Board
PCBd	Physical Control Block downstream
PE-DBA	Prediction based DBA
P2MP	Point-to-Multi-Point
PON	Passive Optical Network
QoS	Quality of Service
RF	Radio Frequency
RFOG	Radio Frequency Over Glass
RM	Resource Management
RN	Resource Negotiation
RoF	Radio over Fibre
RS	Resource Scheduling
rtPS	Real-time Polling Service
SA	Simulated Annealing
SBA	Static Bandwidth Allocation
SCM	Subscriber Multiplexing
S-DBA	slotted-DBA

SLA	Service Level Agreement
SOA	Semiconductor Optical Amplifier
SONET	Synchronous Optical Networking
SSs	Subscriber Stations
SST	Server Station
TDM	Time Division Multiplexing
TS	Tabu Search
UGS	Unsolicited Grant Service
VOB	Virtual ONU-BS
VoD	Video-on-Demand
VoIP	Voice over Internet Protocol
VP	Virtual Path
WAP	Wireless Access Point
WDM	Wavelength Division Multiplexing
WE-Bridge	WiMAX - EPON Bridge
WG	Wireless Gateway
WiFi	Wireless Fidelity
WiMAX	World Wide Interoperability for Microwave Access
WLAN	Wireless Local Area Network
WMAN	Wireless Metropolitan Area Network
WMN	Wireless Mesh Network
WMR	Wireless Mesh Router
WOBAN	Wireless Optical Broadband Access Network
WPAN	Wireless Personal Area Network

WRR	Weighted Round Robin
WWAN	Wireless Wide Area Network

Abstract

The Internet Protocol (IP) based converged Next Generation Networks (NGN) [130] appears in order to provide an efficient, cost-aware and reliable network infrastructure in support of emerging sophisticated and bandwidth hungry applications and services [129]. Addressing the International Telecommunications Union - Telecommunication Standardisation Sector (ITU-T) [132], the NGN brings significant advantages to telecom companies as well as Subscriber Stations (SSs) such as support for End-to-End (ETE) Quality of Service (QoS), mobility features, converged services and applications as well as converged infrastructure between fixed and mobile networks. The ultimate goal of the NGN is to provide the Internet applications and services wherever, whenever and in whatever format with reasonable costs for both SSs and telecom companies as well as the satisfactory coverage, capacity, speed and maintenance.

Optical technology, as a best nominee for the next generation fixed broadband access networks, is tied up and restricted to the fixed infrastructure but wherever it goes it provides the huge bandwidth with relatively lower cost for both SSs and telecom companies. On the other hand, wireless technology supports flexibility as well as mobility features and is not tied up to the fixed infrastructure but it is highly restricted to the capacity, transmission power as well as the transmission range.

Taking into consideration the converged infrastructure of the NGN [132], the future broadband applications and services must leverage on both fixed and wireless technologies which forms the idea for development of the integrated fixed, particularly optical, and wireless access networks. However, in order to successfully integrated these two technologies there are some technical concerns in terms of architectural aspects, physical layer issues and Media Access Control (MAC) related topics which need to be addressed effectively and efficiently in order to provide the smooth End-to-End (ETE) integrated structure and optimum or near optimum utilisation of network resources. This thesis takes up the challenge of addressing these issues by providing a detailed converged framework with support of a distributed, real-time, dynamic, scalable and intelligent wavelength and bandwidth allocation algorithm for the converged scenario of the NGN.

The conventional works related to optical and wireless technology, where a traditional single channel optical network has been employed as a backhaul solution for the wireless counterpart, do have some shortcomings in providing the level of capacity, scalability and intelligence which is required in the current NGN environment [131]. The integrated scenario between the multi-channel optical network and wireless counterpart has gained popularity as the foundation of providing the higher bandwidth and capacity due to employing the multi wavelengths over a same fibre infrastructure with great security and protocol transparency [24]. On the other hand optimisation techniques [84] have attracted huge attention particularly in telecommunication field as the foundation of compilation speed, real-time support, low error level, scalability, CPU overhead and memory usage. Once appropriately coded they can provide the selection of the optimum or near optimum elements from some set of the available alternatives with relatively low error levels. Hence, the overall objective of this thesis is design, development and evaluation of an intelligent and dynamic resource (wavelength/bandwidth) allocation algorithm for multi-channel optical network integration with wireless technology with the support of optimisation techniques. In the pursuit of fulfilling the addressed objectives of this thesis, a Genetic Algorithm (GA) optimisation technique emerged as an efficient solution to the identified resource allocation problems.

A framework is proposed which details all the ETE functional modules along with the component specifications, distance arrangements as well as the running sequences and running orders from the central management office all the way to the wireless subscriber stations. The key functional modules, on which this PhD thesis is focused, are highlighted and then evaluated through conducted simulation experiments employing different wavelength and bandwidth allocation algorithms (static/dynamic), simulation parameters and traffic patterns which give expected results.

An Inter-channel and Intra-channel Dynamic Wavelength/Bandwidth Allocation (IIDWBA) algorithm is proposed in order to provide the full dynamic wavelength/bandwidth allocations across the multi-channel PON integration with wireless technology. The proposed algorithm works in three phases and is capable of identifying the excess bandwidth across all the channels associated with a given Server Station (SST), collecting them, scheduling them and then distributing them fairly among the heavily loaded Client Stations (CSs) once per service cycle. The IIDWBA algorithm is detailed with support of algorithms and flowcharts for each phase and is evaluated by employing different traffic patterns and network scenarios.

A popular optimisation technique termed Genetic Algorithm (GA) is also employed in order to optimise the dynamic excess bandwidth allocations in phase three of the proposed IIDWBA algorithm. The proposed GA solver supports scalability and provides intelligent, real-time and dynamic excess bandwidth allocation decisions with low error level over the converged scenario. A mathematical and analytical treatment is also presented for the proposed GA solver. The proposed GA-based technique is capable of improving the excess bandwidth utilisations in phase three of the IIDWBA algorithm by finding the near optimum solutions per service cycle.

In summary, this thesis proposes and evaluates a GA-based resource (wavelength/bandwidth) allocation solution to incorporate real-time, intelligence and scalability features of the converged scenario between the multi-channel optical network and wireless technology for efficient NGN resource managements.

Chapter 1 Introduction

This chapter provides an overview of the thesis to follow. It starts by highlighting the motivation for the research and followed by the research objectives and summary of the key contributions which are all presented in detail in the thesis chapters. The structure of the thesis is presented next. Finally, the author's publications are presented at the end of this chapter.

1.1 Motivation

Optical and wireless technology integration has been proposed as one promising nominee for the next generation broadband access networks for quite some time [70]. An integration scheme provides satisfactory capacity and coverage with high flexibility and robustness as well as the low maintenance costs for both subscriber stations and telecom companies. It is also financially viable for the telecom operators particularly in rural areas where the optical infrastructure can be employed as a backhaul technology for the wireless counterpart and brings high speed wireless broadband access for residences located very far distances from the central management office.

Taking into consideration the emergence of the Next Generation Networks (NGN) [132], where the End-To-End (ETE) Quality of Service (QoS), mobility features, converged applications and services as well as converged infrastructure between the fixed and mobile networks are featured, the integrated scenario between the fixed and the wireless access technology comes into the spotlight. NGN is an IP (Internet Protocol) based network which supports telecommunication services using packet switching technology [130]. Employing the International Telecommunications Union - Telecommunication Standardisation Sector (ITU-T), NGN brings significant benefits such as ETE support of QoS, mobility features and converged services, applications and infrastructures [131].

However, in order to successfully integrate fixed, particularly optical as the best nominee from the fixed network, and wireless technologies there are some technical concerns which need to be addressed efficiently and effectively in order to provide smooth ETE technology integration for the NGN.

The following paragraphs focus on some of the major challenges related to the overall aims of the research study in this thesis and they comprise the specific motivations for the research work.

Comprehensive framework for the converged scenario: The architectural (physical) structure of the converged scenario between the fixed, particularly optical, and wireless networks is one of the key promises of the NGN. It includes the way two technologies connect to each other along with the ETE functional module specifications, physical structure, component specifications as well as the distance arrangements.

For instance keeping the existing infrastructures and the key components from optical and wireless technologies (independent architecture [59]), or merging then in a single box termed ONU-BS (hybrid architecture [59]).

In an independent architecture [59], each part of the converged scenario operates independently from each other part thus it benefits from the simplicity in implementation and operation. In this architecture, the structure of each element from both networks remained unchanged and the connection has been provided using the Ethernet protocol as a common standard interface [68]. The problem with this approach was that each part of the converged scenario cannot see other part's operations and performance. For instance the Optical Network Unit (ONU) cannot see the wireless Base Station (BS) packet scheduling and also the BS cannot see the ONU upstream transmission to the OLT which significantly degrades the QoS for the packets transferring over the integrated infrastructure.

In the hybrid architecture [59], the optical and wireless edge components are merged together in a single box. For instance, the ONU and the wireless BS are combined together in a virtual box termed ONU-BS [67]. This feature is expected to improve the overall network performance and QoS metrics as each part of the converged scenario has full information about packet scheduling, priority queues and available bandwidth from the other part due to the single box integration [68]. The problem with this feature is the installation cost of the virtual boxes as virtual boxes need to be replaced with the current optical and wireless key components (ONUs and BSs) which add extra cost to the telecommunication companies.

Considering the two approaches of independent and hybrid architectures, and the current infrastructures of the optical and wireless networks, there clearly lies a motivation to search for an architecture aiming to employ the current optical and wireless components in the market and taking into account the extra functional modules required with no need for the full replacement to provision converged infrastructure in the NGN environment. Therefore, this forms the first key motivation of this thesis.

Distributed, real-time, dynamic and scalable resource allocation algorithm for the converged scenario: The rate at which the telecommunication networks are expanding in size, complexity and variety, calls for a scalable and robust solution for resource allocation over the converged infrastructure of the NGN [72].

The resource (wavelength/bandwidth) allocation problems over the converged scenario have been addressed as Media Access Control (MAC) issues such as hierarchical and ETE QoS provisioning schemes, upstream bandwidth scheduling, wavelength and bandwidth negotiations (requests and allocations).

When compared to the centralised resource allocation techniques, distributed resource allocations are more robust since they are more protected for the single point of failure. They are also more scalable and generate less overhead when they are compared to the centralised approach. On the other hand, due to the dynamic nature of the Internet traffic, dynamic and real-time wavelength/bandwidth allocation techniques outperform the static allocations by taking into consideration the available resources as well as the actual need of a given network element thus provide better utilisation of network resources of the NGN.

These advantages are the driving force to study the real-time, dynamic and scalable wavelength/bandwidth allocation algorithm in a distributed scenario. Therefore, this forms the second key motivation of this thesis.

Intelligent resource allocation algorithm for the converged scenario: It is common knowledge that dynamic resource allocation algorithms have been used with the focus on QoS performance and optimum or near optimum network utilisation. They were designed in order to provide the robust and real-time resource allocation decisions taking into consideration the available resources, requested resources and the required QoS for different applications and services. This necessitates the need to devise an intelligent solution for resource allocation decisions taking into consideration the telecommunication trade-off metrics such as error level, CPU overhead, memory usage, speed of compilation and real-time support. Therefore, this forms the third motivation of this thesis.

To summarise, the factors which motivate the research study presented in this thesis are: a detailed converged framework based on the available infrastructure with support of a distributed, real-time, dynamic, scalable and intelligent wavelength and bandwidth allocation algorithm for the optical and wireless integrated scenario. These motivating factors form the basis for the research which are presented in the next section.

1.2 Research Objectives

The key motivations, identified in the previous discussion, provide the starting point for defining the objectives of this research to address the needs and requirements for the converged structure of the NGN.

As such, the broad objective of this research is to devise distributed, real-time, dynamic, scalable and intelligent resource allocation algorithm for the converged infrastructure of the current NGN operation and maintenance. As mentioned earlier, the primary reason for deployment of the NGN is to provide a converged infrastructure as well as the converged application and services with support of ETE QoS and mobility features that both subscribers and telecommunication companies can benefit from [130]. Taking into consideration the converged infrastructure of the NGN between fixed (particularly optical) and wireless networks, the traditional single channel optical networks, which has been proposed as a backhaul solution for the wireless networks, do have some shortcomings in terms of level of level of capacity, scalability and intelligence which is required in the current NGN environment. The integrated scenario between multi-channel optical networks with wireless technology has gained popularity as the foundation of providing higher bandwidth and capacity due to employing multi-wavelength over a same fibre infrastructure with great security and protocol transparency when compare to the single channel approach [24]. On the other hand, optimisation techniques [84] have gained attention, particularly in telecommunication area, with the sole focus on compilation speed, real-time support, error level, scalability, CPU overhead and memory usage. Once appropriately coded, they can guarantee to provide the selection of the optimum or near optimum solutions from some set of the available parameters with relatively low error level. Therefore, the overall objective of this research is to concentrate on design, development and evaluation of a distributed, real-time, dynamic and scalable wavelength/bandwidth allocation algorithm for multi-channel optical network with wireless technology with support of optimisation techniques and a comprehensive framework. To recall from the previous section (chapter 1, section 1.1), these objectives are a direct outcome of the motivation factors which are mentioned earlier. Special emphasis will be given to the intelligent aspect which is supported by employing the optimisation techniques particularly the GA methods. A related objective will also be to design a comprehensive framework for the converged scenario with the sole focus on the available network components in the market. In order to derive or near optimum or near optimum benefits for the proposed solutions, due consideration will be given to the distributed, real-time, dynamic, scalable and intelligence aspects. Therefore, the following clear objectives are identified for this thesis, which are related to the design, implementation and performance evaluation of the proposed solutions.

1. The solutions should be able to work in *distributed* manner in order to provide the robust and less complex environment with focus on single point of failure protection.

2. The solutions should be capable of working in a *real-time* having the low latency and fast reaction.

3. The solutions should be *dynamic* given the dynamic nature of the Internet traffic.

4. The solution should be *scalable* taking into consideration the different types and number of available resources.

5. The solutions must have *intelligent* features which can make decisions wisely and in a logical manner.

In order to summarise the identified objectives of this thesis, a comprehensive representation is provided through Figure 1.1. The identified objectives are distributed over the thesis chapters which go further into the detailed discussions and evaluations.

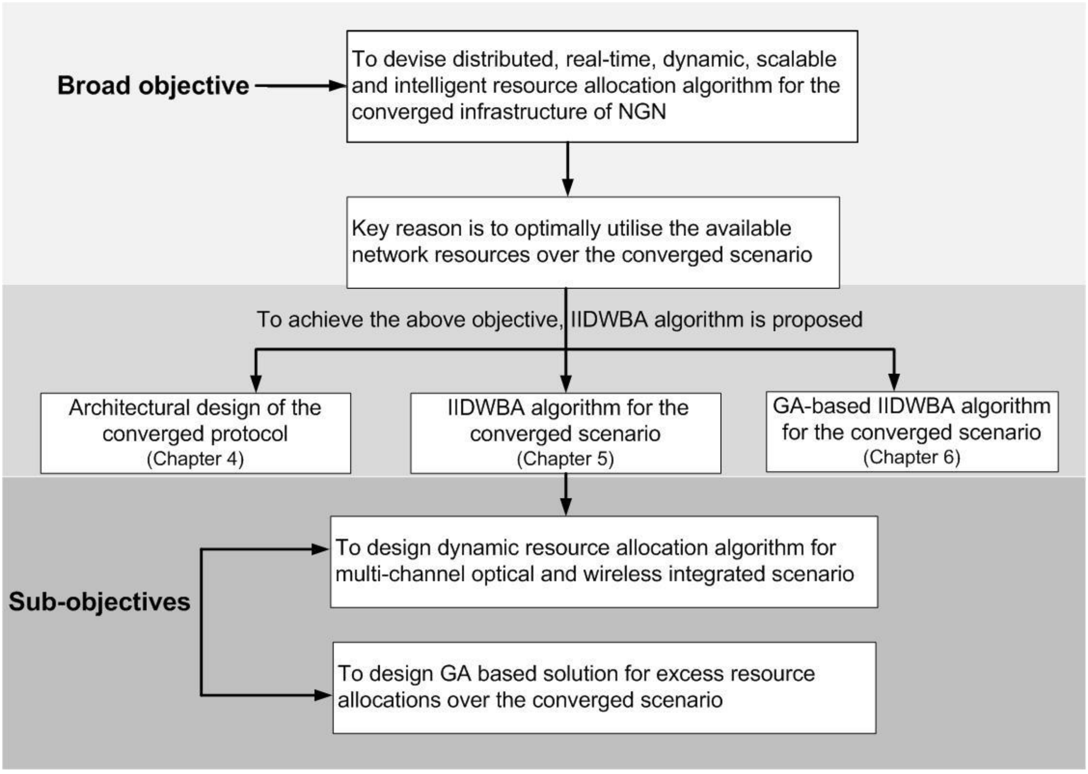

Figure 1.1 Research objectives of this thesis

1.3 Summary of Key Thesis Contributions

The thesis objectives identified in previous section, can now be utilised to look into the details of the specific solutions which thesis proposes. Therefore, the following paragraphs clearly list and describe the key contributions of this thesis.

1. A framework is proposed for the successful integration of optical and wireless technologies. This is the structure that is used for all the experiments in this thesis and includes the ETE functional modules specified inside each component of the converged scenario from the far-end central management office all the way to the front-end subscriber stations. The key functional modules, on which this PhD project is focused, alongside their roles and their running orders (e.g. dependencies

and relationships) are all identified. The performance of the proposed architecture is evaluated through the simulated scenarios employing different load values, traffic patterns and bandwidth allocation algorithms which show the expected results.

2. An Inter-channel and Intra-channel Dynamic Wavelength/Bandwidth Allocation (IIDWBA) algorithm which works over the converged scenario through three different phases is proposed. The three phases are termed as Initialisation, Inter-channel bandwidth allocations and Intra-channel bandwidth allocations. The proposed algorithm starts with Initialisation phase during which a given channel will be allocated among different Client Stations (CSs). The number of the CSs sharing a single channel is set in phase one but can be changed employing two other phases when the traffic starts building up on the CSs. Phase two of the IIDWBA algorithm is responsible for allocating bandwidth among the local CSs sharing a single channel. Phase three of the IIDWBA algorithm is provided in order to make a real-time framework for the dynamic wavelength and dynamic bandwidth allocations between different channels associated with a given SST. By employing phase three, the IIDWBA algorithm is capable of identifying the available excess bandwidth over different channels, collecting it and then distributing it fairly among all the heavily loaded CSs which may exist over various channels associated with a given SST. The IIDWBA algorithm is evaluated as a function of different load values, traffic patterns and scenarios. The advantages of using the IIDWBA algorithm becomes more obvious as the requests for the excess bandwidth increase when the converged network load increases.

3. A Genetic Algorithm (GA) - based dynamic excess bandwidth allocation algorithm, executed in phase three of the IIDWBA algorithm, is proposed in order to optimise the excess bandwidth allocation from all the channels associated with a given SST among all the CSs which are identified as heavily loaded during a given service cycle. The performance of the GA-based IIDWBA algorithm is evaluated through the simulated scenarios which show good performance with relatively low error percentages in output decisions from the GA solver.

To summarise the building blocks of this thesis which have been presented above they are *architectural design of the converged scenario*, *IIDWBA algorithm* and *GA-based IIDWBA algorithm* solutions. As mention earlier these solutions are from the core chapters of this thesis and they are further outlined in the following section.

1.4 Thesis Outline

In order to provide a comprehensive structure for the outline of this thesis, the seven thesis chapters are grouped into four major categories of: *Thesis Introduction, Thesis Background, Thesis Contribution* and *Thesis Conclusion*. A graphical view of the organisation and flow is presented in Figure 1.2 and the reminder of the thesis is structured as follows:

Chapter 2 provides a general introduction about the elements of the research domain including the optical and wireless technologies. It offers a comprehensive review of key topics embracing the state-of the art technologies, future developments and challenging issues from both optical and wireless components. The review includes a history of Optical Networks (ONs) and particularly the Passive Optical Networks (PONs) and their market demands and requirements. It addresses the deficiencies in previous broadband access technologies which are unable to provide sufficient capacity and essential speed for the forthcoming traffic growth and the huge demands of emerging sophisticated and bandwidth hungry applications and services. This is followed by the Resource Management (RM) issue which is the most challenging issue in the optical networks comprising Resource Negotiation (RN), Bandwidth Allocation (BA) and Resource Scheduling (RS).

The state-of the-art for the wireless technology alongside the future developments are presented next. Chapter 2 is concluded by highlighting a nominee from the wireless technology for the optical domain and the needs as well as the requirements for such a candidate.

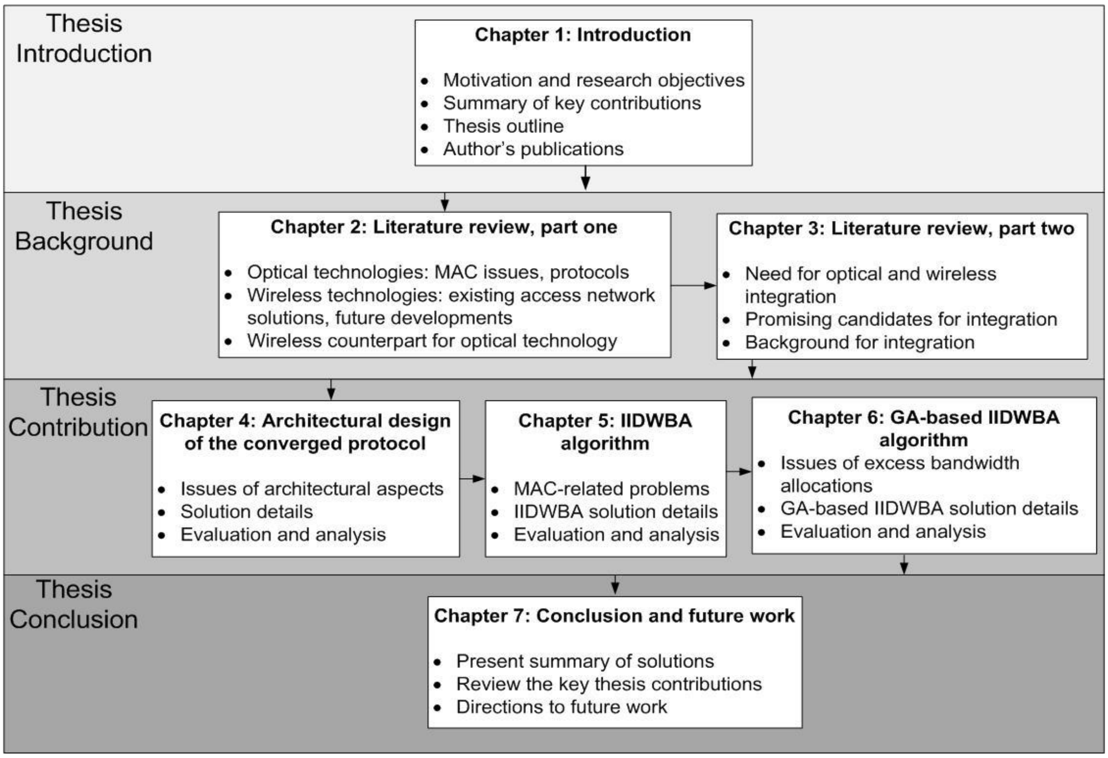

Figure 1.2 Thesis structure and organisation

Chapter 3 provides a general review of the history of optical and wireless technology integration embracing the benefits such as flexibility, robustness, capacity, and coverage along with the needs and the requirements followed by the techniques which have been used for such integration to date and the specific benefits. Promising nominees from the optical domain and the wireless domains are highlighted followed by a comprehensive review of the existing techniques which have been employed in order to provide the successful End-to-End integration between the two carrier technologies. The background of the existing technologies for the converged scenario is reviewed in the two most popular categories of Architectural aspects and Media Access Control (MAC) issues. The former includes the possible ways and the structures that two technologies can be connected to each other while the latter one considers critical MAC related issues such as the ETE bandwidth requests, ETE bandwidth allocation, Quality of Service (QoS) provisioning schemes and upstream scheduling techniques.

Chapter 4 provides detailed information about the proposed architectural aspects of the converged scenario including the specification of the network components from the central management office all the way to the front-end customer premises. This is followed by the ETE functional modules which are provided inside all the components of the converged scenario form Optical Line Terminal (OLT), located at the far-end central management office, all the way to the wireless subscriber stations situated at the front-end customer premises. It also includes the discussions about the role, the running order and the reason of the existence for each component as a part of the converged scenario highlighting the key functional modules on which this PhD work is focused. The previous work related to the architectural aspects of the converged scenario are also discussed and detailed followed by justifications for the approach that is employed for the optical and wireless integrated scenario in this thesis. The ETE functional modules particularly the key functional modules, on which this PhD work is focused, are evaluated through the simulated experiments employing the different traffic patterns and load values which give the expected results and performances.

Chapter 5 provides detailed discussions about the hierarchical wavelength and bandwidth allocations from the OLT in the central management office to the ONUs and then from the ONUs all the way to the associated BSs over the converged scenario. It is followed by our proposed Inter-channel and Intra-channel Dynamic Wavelength/Bandwidth Allocation (IIDWBA) algorithm which is identified through three phases termed as Initialisation, Inter-channel bandwidth allocations and Intra-channel bandwidth allocations. While a given DBA algorithm is capable of executing bandwidth allocations over a single channel, the IIDWBA algorithm is capable of dealing with multiple channels associated with the OLT or a given ONU. During the phase one of the IIDWBA algorithm (Initialisation phase) a group of ONUs/BSs will be associated with a single channel which will be shared among them through phase two of the IIDWBA algorithm (Intra-channel bandwidth allocations phase). Through the phase three of the IIDWBA algorithm (Inter-channel bandwidth allocations phase) the IIDWBA algorithm collects and schedules the excess available bandwidth from all the channels and then distributes it among the channels which requested extra bandwidth during a given service cycle. The proposed algorithm has complete real-time knowledge about all the channels associated with the OLT or to a given ONU through an entity termed global scheduler. For instance a given global scheduler on a given SST knows the excess available bandwidth on each channel or excess requested bandwidth from each channel during a given service cycle. The global schedulers are distributed all over the converged scenario, one global scheduler per SST; therefore they provide a distributed approach over the integrated scenario. Chapter 5 is concluded by evaluating the performance of the proposed IIDWBA algorithm through the network scenarios employing the simulated network components available in the market, different traffic patterns and load values.

Chapter 6 provides a review of the most popular optimisation techniques and their roles in telecommunications for instance the areas that the different optimisation methods have been employed in order to improve the various performances such as queuing delay, bandwidth utilisations, memory usage and calculation time. It is followed by the trade off for the four most popular optimisation techniques and the detailed specifications of the Genetic Algorithm (GA) method that is employed for the problem domain in this PhD work. Next, it provides detailed descriptions about implementing the GA techniques as a part of the phase three of the IIDWBA algorithm (Inter-channel bandwidth allocations phase) including the mathematical model and all the essential steps. Chapter 6 is concluded by the captured results and the performance evaluations that employ the GA techniques.

Chapter 7 concludes this thesis by summarising and highlighting the research contributions made, followed by a discussion about the potential future research developments stemming from this work.

1.5 Author's Publications

1. N. Moradpoor, G. Parr, S. McClean, B. Scotney and G. Owusu (BT Adastral Park), "A GA Based Dynamic Excess Bandwidth Allocation Algorithm for Integrated Hybrid PON with Wireless Technologies for Next Generation Broadband Access Networks," submitted to Optical Switching and Networking (OSN)/Elsevier on September 2012.

2. N. Moradpoor, G. Parr, S. McClean, B. Scotney and G. Owusu (BT Adastral Park), "An Inter-channel and Intra-channel Dynamic Wavelength/Bandwidth Allocation (IIDWBA) Algorithm for Integrated Hybrid PON with Wireless Technologies for Next Generation Broadband Access Networks," submitted to Optical Switching and Networking (OSN)/Elsevier on September 2012.

3. N. Moradpoor, G. Parr, S. McClean, B. Scotney and G. Owusu (BT Adastral Park), "The TDM/WDM - PON Integrations with Wireless Technologies for Next Generation Broadband Access Networks," submitted to Optical Switching and Networking (OSN)/Elsevier on September 2012.

4. N. Moradpoor, G. Parr, S. McClean and B. Scotney, "Interleaved Polling with Adaptive Cycle Time (IPACT) Implementations Using OPNET, " published at OPNET's annual technology conference (OPNETWORK2011), conference information at: http://www.opnet.com/opnetwork2011/index.html.

5. N. Moradpoor, G. Parr, S. McClean, B. Scotney and G. Owusu (BT Adastral Park), "Hybrid Optical and Wireless Technology Integrations for Next Generation Broadband Access Networks," published at 6th IFIP/IEEE International Workshop on Broadband

Convergence Networks (BcN 2011), conference information at: http://www.ieee-im.org/cfpworkshops.html.

6. N. Moradpoor, A. Bashar, G. Parr, S. McClean, B. Scotney and G. Owusu (BT Adastral Park), “Using Bayesian Belief Networks for Burst Detection in Ethernet Passive Optical Networks,” published at 2011 International Conference on Wireless and Optical Communications (ICWOC 2011), conference information at: http://www.http://www.icwoc.org/.

7. N. Moradpoor, G. Parr, S. McClean, B. Scotney and K. Sivalingam (IIT Madras), “Simulation and Performance Evaluation of Bandwidth Allocation Algorithms for Ethernet Passive Optical Networks (EPONs),” published at OPNET's annual technology conference (OPNETWORK2010), conference information at: http://www.opnet.com/opnetwork2010/index.html.

8. N. Moradpoor, G. Parr, S. McClean, B. Scotney and G. Owusu (BT Adastral Park), “Real Time Data Analytics in Support of Network Resource Management Protocols,” published at Conference on the Convergence of Telecommunications, Networking & Broadcasting (PGNET 2009), conference information at: http://www.cms.livjm.ac.uk/pgnet2009/Proceedings.

Chapter 2 Literature Review, Part One

This chapter provides a general background about the components of the research domain including the optical and wireless technologies. It starts by introducing the history of optical technologies. It then describes Optical Networks (ONs) and in particular Passive Optical Networks (PONs) and their role in telecommunication infrastructures. This is followed by Media Access Control (MAC) techniques and state-of-the art protocols particularly for PONs. It then discusses the need for Resource Management (RM) for PONs comprising Resource Negotiation (RN), Bandwidth Allocation (BA) and Resource Scheduling (RS). Then it provides a detailed description of various BA algorithms employed for PONs. Next, it presents the state-of-the-art technologies for wireless access networks, along with future developments. Finally, it highlights the need for a wireless counterpart to optical technologies.

2.1 History of the Optical Technologies

Digital Subscriber Line (DSL) [15] and Cable Modem (CM) networks [16][17], which are improvements over 56 kb/s modems, are the most widely deployed copper-based solutions for the telecommunication broadband access networks. DSL services are offered on ordinary telephone lines by telephone companies and provide data, video and voice services over the existing copper telephone line where the broadband services and analogue phone are simultaneously supported. CM networks take advantages of the high bandwidth provided by Hybrid Fibre-Coaxial (HFC) [133] and Radio Frequency over Glass (RFoG) [134] infrastructures in order to deliver broadband Internet access in the format of the cable Internet.

However, as both of these technologies are built on the infrastructures that are mainly used to carry analogue voice and analogue TV signals, they are not optimal solutions to carry broadband data traffic.

DSL and CM problem domains can be categorised as follows:

Physical Distance: DSL performance depends on distance from the Central Office (CO) and it cannot support the subscribers located more than 5.5 km from the CO.

Time of Access: DSL performance also depends on time of access which can provide various performances, during different hours of the day, for a given subscriber.

Internet Traffic Growth and Capacity: Everyday more and more new subscribers register to different Internet Service Providers (ISPs) while current users upgrade their services requesting for higher bandwidth and 24/7 availability. A typical broadband connection at home termed telhome service includes at least three phone lines (requesting ~64 kb/s bandwidth per connection), two high-definition TV (HDTV) channels (requesting ~8 Mb/s bandwidth per connection) and two Personal Computer (PC) connections (requesting ~1 Mb/s bandwidth per connection) for Internet access, Table 2-1, [14]. On the other hand, current and future telecommunication applications and services such as: video conferencing, online-banking, real-time Internet games, Internet Protocol Television (IPTV), High Definition TV (HDTV), High Definition

Table 2-1 Bandwidth assumption of telhome [14]

Connection	Number of connections	Bandwidth per connection
Phone	≥3	~64 kb/s
HDTV	≥2	~8 Mb/s
PC	≥2	~1 Mb/s

Medical Imaging and social networking require bandwidth far beyond of the bandwidth provided by DSL and CM networks.

This is the point where Optical Networks (ONs) and particularly Passive Optical Networks (PONs) come into prominence. To gain a deeper understanding and appreciation of ONs, the following sections provide a comprehensive review for the history, challenging issues (particularly MAC related problems), state-of-the-art protocols as well as the resource management topics (negotiation, allocation and scheduling) related to exiting ONs.

2.1.1 Optical Networks and Passive Optical Networks

Optical Networks (ONs) and particularly Passive Optical Networks (PONs) are the solutions for the problem domains of the DSL and CM networks. For instance, PONs offer services to the subscribers located beyond 20 km from CO and provide bandwidth far ahead of the bandwidth available by DSL and CM networks [2].

A PON is a point-to-multi-point (P2MP) fibre network architecture which can be in the following formats: fibre-to-the-curb (FTTC), fibre-to-the building (FTTB), fibre-to-the-home (FTTH) and fibre-to-the-PC (FTTPC), [21], [22] and [36]. However, FTTC has been considered as the most economical deployment among the FTTX solutions [2] [18] [36]. A PON includes the Optical Line Terminal (OLT), an 1: N passive

Splitter/Combiner and a number of Optical Network Units (ONUs), Figure 2.1. The OLT is seated inside the CO and connects the optical network to the Synchronous Optical Networking (SONET), Asynchronous Transfer Mode (ATM) or Internet Protocol (IP) backbone. The 1: N passive splitter is placed between the OLT and the ONUs and typically splits a single fibre into 16, 32, or 64 channels. The ONUs are located near to the customer premises, either inside the curb (FTTC) or inside the customer premises (FTTH, FTTB, FTTPC) and provide triple broadband services (voice, video and data) to the end-users.

A PON can be in at least four architectures: ring, bus, tree or redundant configurations such as ring with double loop or tree with double trunk topologies [2], [9]. However, a PON with a tree topology configuration has been mostly favoured in the telecommunication industry.

A PON is an inexpensive and simple technology [19] as it provides cost-aware fibre deployment solutions by minimising the fibre development in both local loop and local exchange. It is also a scalable solution as it can be upgraded to higher bit rates and additional wavelengths easily added. A PON is also an energy-aware solution for broadband access networks as it eliminates the necessity for installing the active components such as multiplexers and de-multiplexers all the way from the CO to the customer premises. Therefore, a PON has been viewed as an attractive solution by the telecommunication industry for the first mile/last mile bandwidth bottleneck problems among other ON technologies. There has been a great effort to develop economical subscriber networks based on optical technologies [2] and [20]-[23].

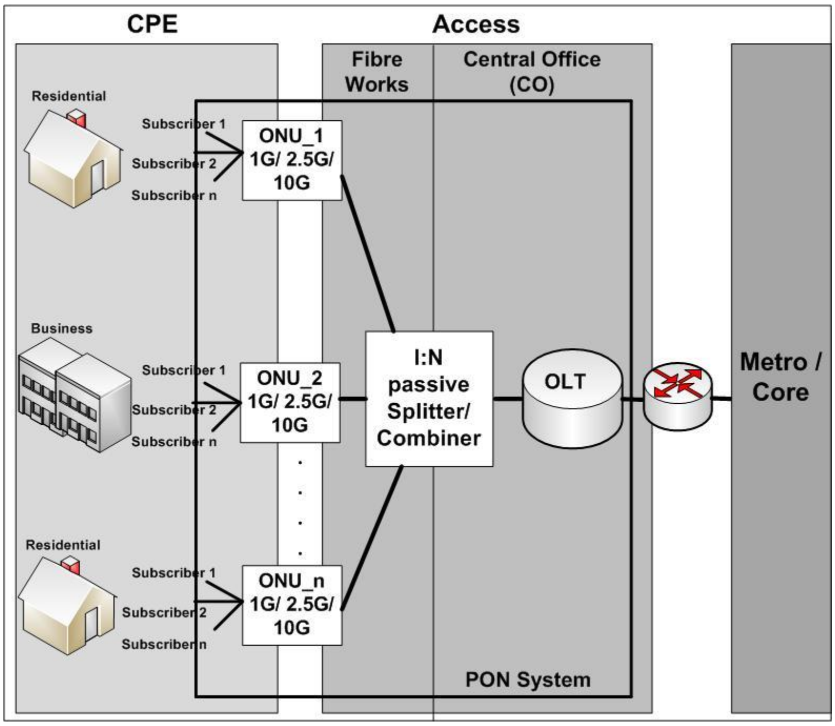

Figure 2.1 Market view architecture for PON

Media Access Control (MAC) for PONs is a challenging issue in which the upstream channels among ONUs and OLT (trunk of the tree-topology PON) should be separated in order to avoid data colliding while it is being transmitting over the upstream shared medium. The ONUs in the same optical domain may start transmitting data at the same time and may reach the trunk of the PON simultaneously, thus they may collide. The next section is dedicated to study about MAC techniques for PONs.

2.1.2 Media Access Control (MAC) Techniques for PONs

Time Division Multiplexing (TDM), Wavelength Division Multiplexing (WDM) and Hybrid Multiplexing [24] (combination of TDM and WDM) are the most commonly deployed solutions for the MAC issue in a PON [2].

In a TDM-PON, each ONU will be allocated with a time-slot by the OLT in order to access the upstream shared fibre. Each time-slot specifies a unique and permanent time of access during which a given ONU can transmit its buffered data over the shared medium. For a PON with N ONUs, each N time-slots compose a frame termed service cycle during which N ONUs can get a chance to transmit their associated data.

Each ONU should buffer the data packets received from subscribers and then wait for its allocated time-slot to arrive. A given time-slot is capable of carrying several Ethernet frames. When a time-slot arrives on a given ONU, the ONU will burst the buffered data with the full channel capacity not being more than the length of the associated window, as seen in Figure 2.2 and Figure 2.3.

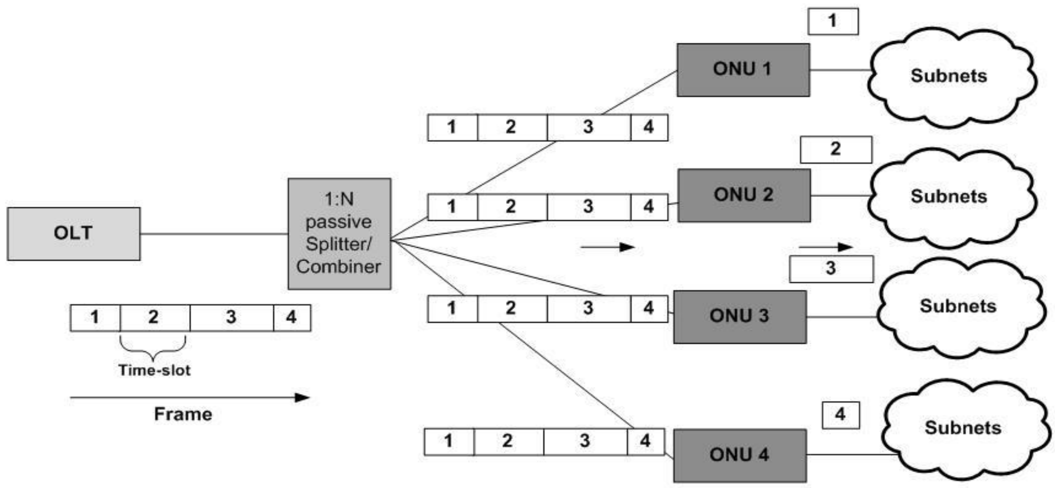

Figure 2.2 Downstream transmissions over TDM-PON

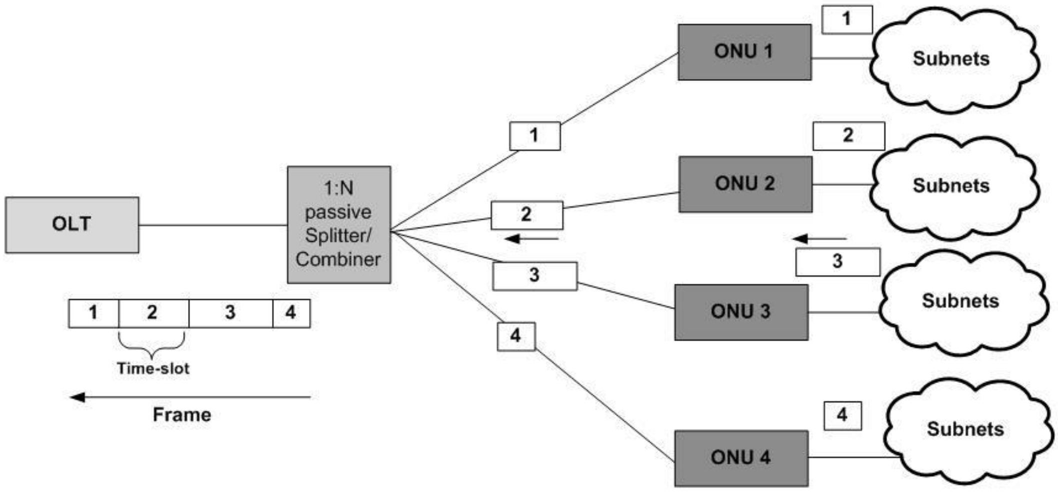

Figure 2.3 Upstream transmissions over TDM-PON

There are several ways to allocate time-slots from the OLT to ONUs as follows:

Fixed time-slot allocations: The OLT allocates fixed-length time-slots to the ONUs during each service cycle without considering the ONUs' actual need (buffer length), Figure 2.4.

Dynamic time-slot allocations: The OLT allocates dynamic-length time-slots to the ONUs by taking into account the ONUs' buffer statuses which are reported during the previous service cycle, Figure 2.5.

Quality of Service (QoS) -aware time-slot allocations: The OLT allocates time-slots to the ONUs based on the Service Level Agreements (SLA) which can be specified per ONU and/or per service class (video, voice or data), Figure 2.6. Three service classes have been identified for the PONs termed Expedited Forwarding (EF) services e.g. voice, Assured Forwarding (AF) services e.g. video and Best Effort (BE) services e.g. email services.

A WDM-PON provides multiple wavelength channels over the same fibre infrastructure with great security and protocol transparency [24]. In a WDM-PON, each ONU can be allocated to a single wavelength channel, thus the ONUs can transmit the buffered data simultaneously with no risk of collisions.

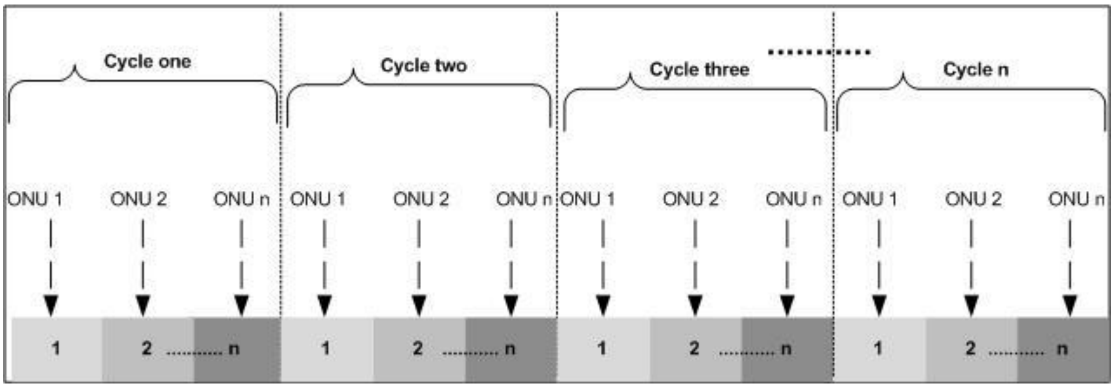

Figure 2.4 Fixed time-slot allocations

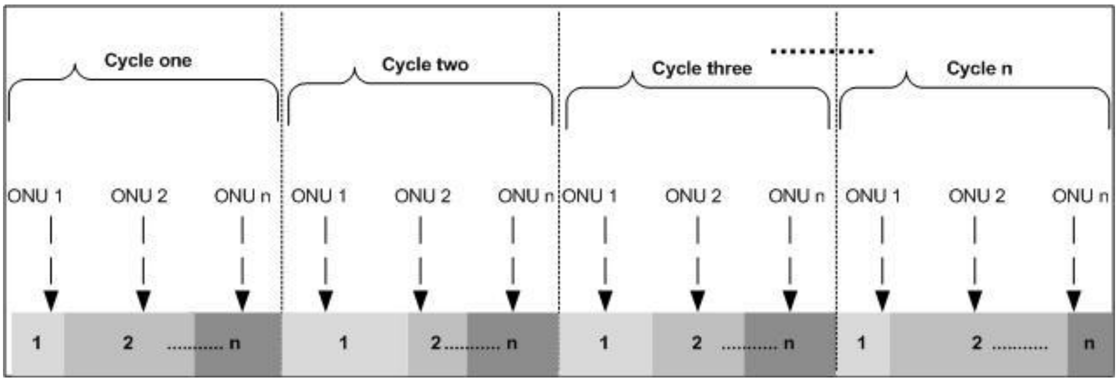

Figure 2.5 Dynamic time-slot allocations

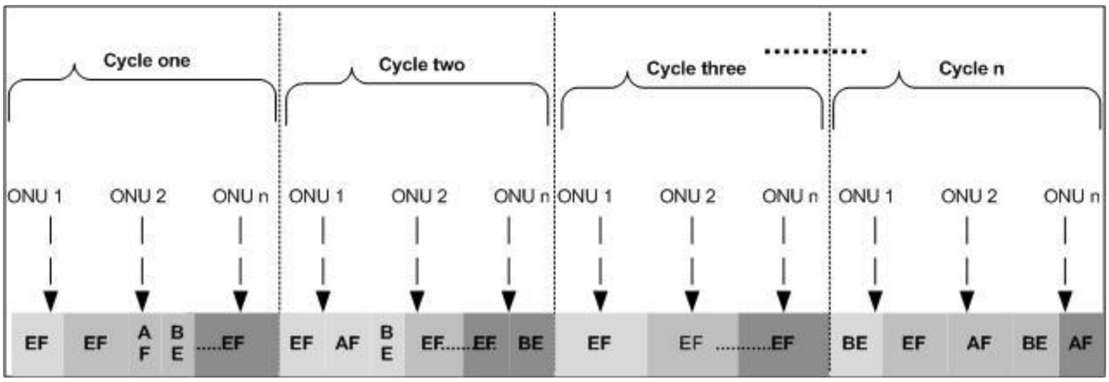

Figure 2.6 QoS-based dynamic time-slot allocations

In a WDM-PON the WDM transmitter, particularly on the customer side, is the most critical component and it is essential that the associated transmitter should be precisely aligned with the allocated channel [24]. Many WDM-PON architectures and components have been proposed in order to support multi-channel structures in WD-PON [26]-[28].

Assigning a single wavelength channel to each ONU in a WDM-PON provides much higher bandwidth and supports a greater number of subscribers than a single channel TDM-PON. A TDM-PON divides the maximum available bandwidth per subscriber and limits the number of subscribers to a maximum of 32 [24]. However, a WDM-PON needs one transmitter per wavelength channel (per ONU) in the OLT. Therefore, there will be an OLT with an array of wavelengths in the CO and ONUs with a wavelength-specific laser close to the customer side which will be more costly than a traditional TDM-PON [25]. In a TDM-PON, only one transmitter is needed inside the OLT regardless of the number of ONUs. It also needs only one type of transmitter in the ONUs [2]. However, as ONUs need to be synchronised in order to be able to transmit over the shared medium of a TDM-PON, TDM-PON, this makes a TDM-PON a more complex technique of implementation when compared to a WDM-PON.

A WDM-PON and a TDM-PON can also be combined (Hybrid-PON) in which different wavelength channels will be available over the same fibre infrastructure (WDM approaches) and then each single channel will be shared among a number of ONUs (TDM approaches). For instance, when home users and business users are separated from one another, each group can be allocated to a single wavelength channel (WDM-PON) and inside each channel the medium can be then shared (TDM-PON). A given Hybrid-PON, which is considered in this thesis, benefits from both features of high capacity (provided by the WDM-PON due to availability of multiple wavelengths over a single fibre infrastructure) and resource sharing (provided by the TDM-PON).

The next section provides a comprehensive review for the state-of-the-art protocols which were standardised and defined by Institute of Electrical and Electronics Engineers (IEEE) and International Telecommunications Union - Telecommunication Standardisation Sector (ITU-T) for PONs.

2.1.3 State-of-the-Art Protocols for PON

Ethernet Passive Optical Networks (EPONs) [29] and Gigabit Passive Optical Networks (GPONs) [30] are the current state-of-the-art standards which are recommended widely and commercially deployed for TDM-based PONs. They have defined specific control messages, data units, frame or cell fields and maximum upstream and downstream speeds in order to provide bandwidth negotiations between the OLT and the ONUs.

An EPON [81], which is standardised by IEEE 802.3ah [29], provides a maximum symmetric speed of 1Gb/s for upstream and downstream directions and uses the Ethernet frame as its data unit. The 10 Gb/s EPON (10 GEPON) was initiated by IEEE 802.3av Task Force [33]. The 10 GEPON proposed, by the Task Force, consisted of a symmetric and an asymmetric solution to upgrade the existing EPON as follows. The symmetric 10 Gb/s upstream and downstream transmission speed and the asymmetric 1 Gb/s upstream and 10 Gb/s downstream transmission speed.

The Multipoint Control Protocol (MPCP) was introduced by IEEE 802.3ah [29] to settle the real-time bandwidth negotiations over the TDM-based PONs (EPONs). It includes five 64 bytes Media Access Control (MAC) messages embracing both auto-discovery and registration messages (REGISTER_REQUEST, REGISTER, REGISTER_ACKNOWLEGE) and bandwidth request/grant messages (REPORT and GATE), Figure 2.7. The ONUs generate REPORT messages in order to report the status of their queues to the OLT. The OLT uses the reported queue lengths in order to set up the upstream data transmission among the ONUs. The OLT's arbitration decisions will be included in GATE messages and sent downstream, broadcasting to all the ONUs.

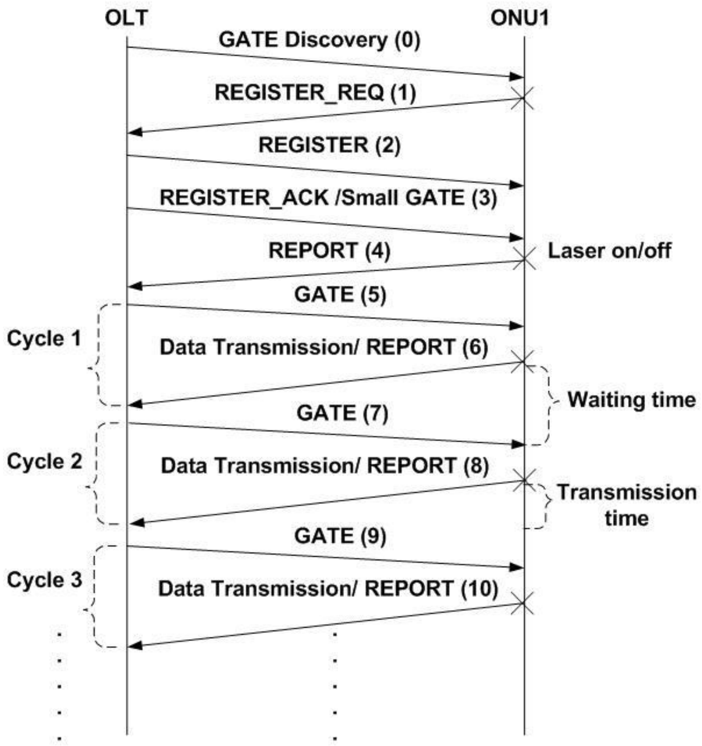

Figure 2.7 MPCP resource negotiations

While the MPCP provides time-slot assignment features, MPCP Extension (MPCP Ext.) [32] supports the wavelength assignments inside the conventional TDM-based PON. MPCP Ext. enables the OLT to schedule the transmission to and reception from a given ONU on any available upstream channel supported by both the OLT and the ONU.

A GPON, which is standardised by the ITU-T G.984 [30], provides asymmetric maximum upstream and downstream speeds of 1.244 Gb/s and of 2.488 Gb/s, respectively. A GPON supports Asynchronous Transfer Mode (ATM) cells and uses the GPON Encapsulation Method (GEM) in order to support Ethernet frames as well as Time-Division Multiplexing (TDM) units. In the GPON, the ONUs use the Dynamic Bandwidth Report upstream (DBRu) field in order to inform the OLT about their queue statuses. Bandwidth allocation decisions will be then placed in a Physical Control Block downstream (PCBd) field by the OLT and sent off inside the GPON frames, notifying the ONUs about the upstream transmission decisions.

EPONs are expected to increasingly become more popular than GPONs in the near future because of the following reasons:

1. Ethernet is inexpensive, scalable (100Mbps, 1Gbps, 10Gbps) and is also a simple technology.

2. Ethernet with 500 million ports deployed worldwide is a ubiquitous and off-the-shelf technology. In every office, at least a network device can be found which can support Ethernet. More than 95 percent of all Local Area Networks (LANs) components and more than 85 percent of all installed network connections are Ethernet based [13].

3. The emerging telecommunication applications and services are also moving towards Ethernet technology.

4. The PON upstream and downstream behaviours resemble the Ethernet Bus technology and Ethernet broadcasting behaviour, respectively.

Taking into consideration that EPONs are expected to increasingly attract more attention than GPONs in the near future, due to the reasons mentioned above, EPON is selected as a standard protocol in this thesis in order to provide the required communications over the optical infrastructure.

In order to achieve this purpose the MPCP, which was introduced by IEEE 802.3ah [29] to settle the real-time bandwidth negotiations over the EPONs and includes five 64 bytes MAC messages embracing both auto-discovery and registration messages, Figure 2.7, were implemented and published by the author of this thesis [126] using OPNET Modeller [79] simulator.

The next section provides a comprehensive review of resource management which is the most challenging issue in PONs.

2.1.4 Resource Managements for PONs

Resource Management (RM) over PONs (TDM-PONs/WDM-PONs) is a critical issue which needs to be considered efficiently and effectively in order to provide the guaranteed End-to-End (ETE) QoS for different service classes (voice, video or data). It includes all the required negotiations to grant access to the particular channel (wavelength allocations) and/or to the particular portion of a given channel (bandwidth

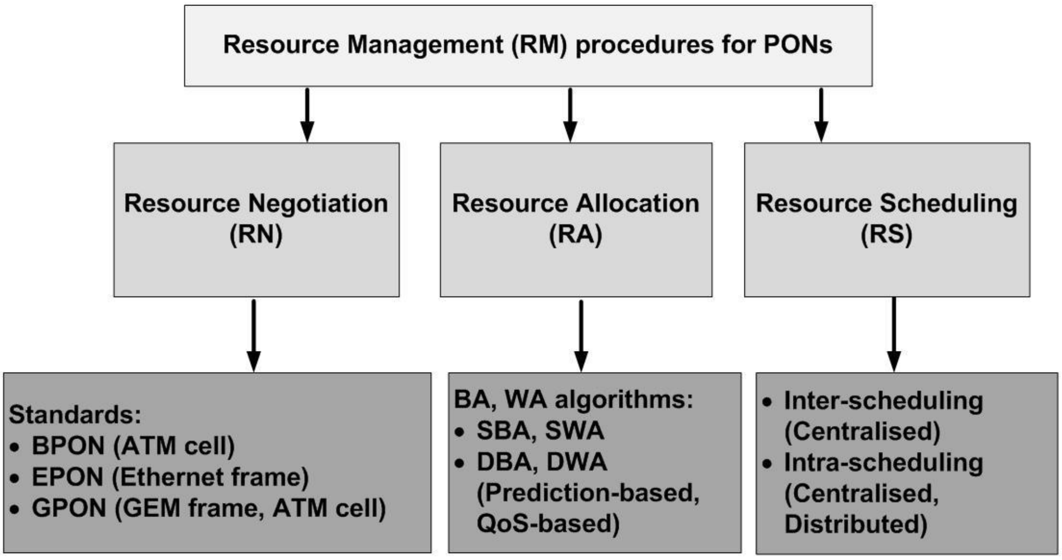

Figure 2.8 Resource Management (RM) procedures for PONs

allocations). An efficient resource management procedure includes the following three steps: Resource Negotiation (RN), Resource Allocation (RA) and Resource Scheduling (RS), Figure 2.8.

RN is between the OLT and a given ONU in order to update the OLT about the ONU's latest queue status (traffic behaviour) in every service cycle. The status of the queues received from all the ONUs helps the OLT to make adequate resource allocation decisions among the different ONUs. In order to provide RNs between the OLT and the ONUs, particular control messages, frame fields and frame structures have been defined for PONs [29] - [31].

The RA step runs immediately after the RN step has been completed in the OLT and allows the OLT to decide the allocation of the available resources (wavelength/bandwidth) to the ONUs based on the implemented RA techniques/algorithms. In RA, the OLT identifies the time of access and the length of access to the shared upstream medium (bandwidth allocation) as well as the associated channel identifier (wavelength allocation) for a given ONU. After receiving the RA decision, a given ONU will extract the following information: the transmission start time, the transmission duration and the associated channel ID over which the buffered data can be transferred with no risk of collisions. Many RA algorithms have been proposed in literature and some of them, [1]-[8] and [10]-[12], are discussed in the next section.

RS will be executed right after RA in order to arbitrate the upstream transmission orders among different priority queues, which were developed inside a given ONU (intra-ONU scheduling) [4], [5] and [9], or among different ONUs which may have different SLA requirements (inter-ONU scheduling) [2], [6], [34] and [35]. Inter-ONU scheduling is a centralised approach which needs to be implemented inside the OLT in the CO whilst Intra-ONU scheduling can be centralised (implemented inside the OLT) or de-centralised (implemented in the ONUs).

Taking into consideration the RA issues (Figure 2.8), in which this PhD thesis is more focused on, the next section provides a comprehensive review for the existing RA, particularly bandwidth allocation techniques, as follows.

2.1.5 Bandwidth Allocation Algorithms for PONs

Many wavelength and bandwidth allocation algorithms have been proposed, particularly for TDM-based and WDM-based PONs, in order to improve resource (wavelength/bandwidth) utilisation and guarantee the required ETE QoS for different service classes.

As the majority of the work in this thesis deals with the TDM-PON, only TDM-based bandwidth allocation algorithms are considered in this section and grouped into two general categories of Static Bandwidth Allocation (SBA) algorithms and Dynamic Bandwidth Allocation (DBA) algorithms. DBA algorithms are then split into prediction and non-prediction based DBA where they can be QoS-based or non-QoS-based, Figure 2.9.

SBA [2] is the simplest BA technique to implement, where each ONU is granted a fixed length time-slot by the OLT regardless of its actual need. In SBA, because the time-slot allocation is fixed, there is no need for Bandwidth Negotiations (BNs) between the OLT and the ONUs, and therefore the network overheads are reduced significantly. However, bandwidth can be assigned to a given ONU even if it does not have any buffered data to transmit. Moreover, the transmission order is also fixed so there is no prioritisation among the ONUs that may carry various service classes with different QoS requirements.

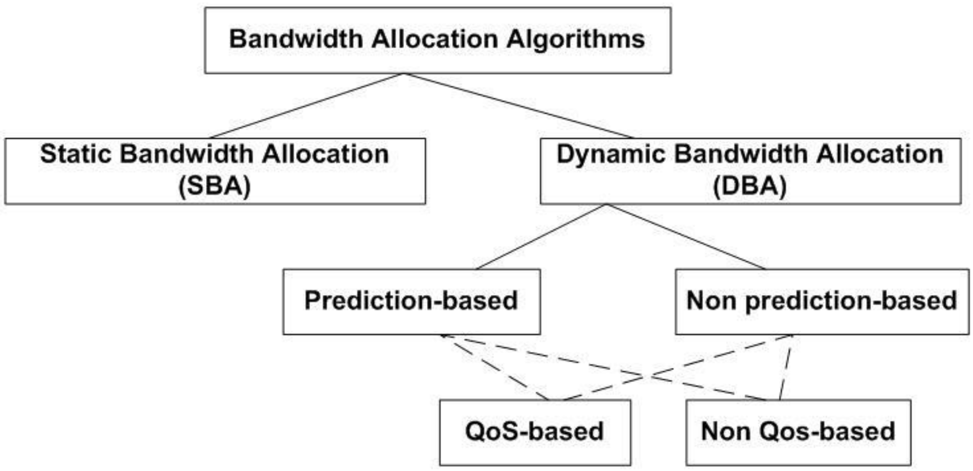

Figure 2.9 Bandwidth allocation algorithms for TDM-PON

Generally speaking, although SBA is the simplest BA algorithm to implement and can reduce the network overhead significantly, it reduces the bandwidth utilisation, increases the transmission delay, increases the queuing delay and it does not support QoS.

In comparison with the SBA algorithm, DBA algorithms allocate bandwidth according to the ONU's actual need and take into account the short-length time-slot allocations for ONUs with zero queue lengths. They can also change the transmission order among ONUs with different traffic types in order to support QoS provisioning schemes [37] e.g. by putting higher priority on ONUs with higher class of services such as voice to let them send traffic earlier than other ONUs which carry the lower service classes such as video or data. Therefore, the DBA algorithms provide higher bandwidth utilisation, reduce the queuing delay and support QoS in comparison with the SBA algorithm.

However, implementing a DBA algorithm is more complex than the SBA algorithm as DBA needs to re-adjust and re-arrange the time-slot lengths and/or time-slot allocation orders in every service cycle. It also increases the network overhead due to BN between the OLT and the ONUs which are required in every service cycle.

Many DBA algorithms have been proposed which are reviewed in the following groups as: Prediction-based and non-Prediction-based algorithms and each of which can also be considered in two groups of QoS-based and non-QoS-based DBA algorithms. The existing proposals relating to each category are as follows.

In a given ONU, the data arriving between two consecutive time-slots will experience two time-slot delays as they will be reported to the OLT at the end of the next allocated time-slot and will get transmitted in two time-slots [125]. Therefore, they may be dropped due to the buffer occupancy and the bursty nature of the Internet traffic pattern. Prediction-based DBA algorithms predict the number of the packets arriving between two consecutive time-slots; therefore, they may get a chance to be transferred in the next immediate allocated time-slot. Prediction-based DBA algorithms will diminish the QoS degradation by avoiding the buffer overflow and improving the network performance particularly queue length and queuing delay for a given ONU.

Based on whether the existing DBA algorithms support the required QoS for different class of services or not, the existing DBA algorithms can also be classified into subcategories of QoS and non-QoS DBA algorithms, Figure 2.9. There are three classes of services which are identified for PON in literature as: Expedited Forwarding (EF) e.g. voice traffic, Assured Forwarding (AF) e.g. video traffic and Best Effort (BE) service classes e.g. data traffic. ISPs need to guarantee the delay and bandwidth for EF traffic and bandwidth for AF traffic. However, there is no delay or bandwidth guarantees for BE service classes.

Table 2-2 provides a brief discussion about some of the existing BA techniques and algorithms in categories of SBA, DBA with/without prediction and DBA with/without QoS provisioning schemes. In Table 2-2, the majority of the BA algorithms have been compared with Interleaved Polling with Adaptive Cycle Time (IPACT) [1] algorithm as it is the first standard DBA algorithm which was proposed for TDM-based PON.

Generally speaking, a PON has been viewed as an attractive candidate for the problem of the first/last mile bandwidth bottleneck for many years as it is capable of providing the huge bandwidth and supporting more subscribers in a longer distance for the CO.

Table 2-2 Comparison of BA algorithms for TDM-PON

<table>
<tr><th rowspan="2">Algorithm</th><th rowspan="2">SBA</th><th colspan="4">DBA</th><th rowspan="2">Delay</th><th rowspan="2">Utilisation</th></tr>
<tr><th>prediction -based</th><th>Non prediction -based</th><th>QoS-based</th><th>Non QoS-based</th></tr>
<tr><td>Kramer et al. [2]</td><td></td><td>-</td><td>-</td><td>-</td><td>-</td><td>High</td><td>Low</td></tr>
<tr><td colspan="8">1. Fixed time-slot allocations.
2. Fixed transmission orders.
3. BNs are not required as BA lengths are fixed so it reduces the network overhead.
4. Simple to implement.
5. Bandwidth will be allocated even to the ONU with zero queue length so it reduces the bandwidth utilisation, increases the queuing delay, packet loss and transmission delay.
6. Does not support QoS.</td></tr>
<tr><th rowspan="2">Algorithm</th><th rowspan="2">SBA</th><th colspan="4">DBA</th><th rowspan="2">Delay</th><th rowspan="2">Utilisation</th></tr>
<tr><th>prediction -based</th><th>Non prediction -based</th><th>QoS-based</th><th>Non QoS-based</th></tr>
<tr><td>Kramer et al. [1]</td><td>-</td><td>-</td><td></td><td>-</td><td></td><td>Medium</td><td>Medium</td></tr>
<tr><td colspan="8">1. Flexible time-slot length allocations so it provides better bandwidth utilisations, queuing delay, packet loss and transmission delay than SBA.
2. The flexible bandwidth is upper bounded by SLA in order to avoid heavy loaded sources dominating the network.
3. Fixed transmission orders.
4. BNs are required so it has higher network overhead that SBA.
5. Does not support QoS.</td></tr>
<tr><th rowspan="2">Algorithm</th><th rowspan="2">SBA</th><th colspan="4">DBA</th><th rowspan="2">Delay</th><th rowspan="2">Utilisation</th></tr>
<tr><th>prediction -based</th><th>Non prediction -based</th><th>QoS-based</th><th>Non QoS-based</th></tr>
<tr><td>Banerjee et al. [3]</td><td>-</td><td>-</td><td></td><td></td><td>-</td><td>Compatible with [1]</td><td>Compatible with [1]</td></tr>
</table>

1. Two levels of SLA are proposed: Primary SLA for higher priority CoS e.g. voice and Secondary SLA for lower priority CoSs e.g. video and data.
2. Bandwidth allocation order: first to primary SLA and then to secondary SLA.
3. If the remained bandwidth, after primary SLA allocations, is not enough for secondary SLA allocations, max-min allocations will be applied in order to distribute the fairness.

Algorithm	**SBA**	**DBA**				**Delay**	**Utilisation**
		prediction -based	**Non prediction -based**	**QoS-based**	**Non QoS-based**		
Naser et al. [4]	-	-			-	**Higher than [1]**	**Higher than [1]**

1. Two leaky bucket credit pools are provided inside OLT one for *K* CoS and the other for *m* ONUs.
2. OLT grants bandwidth from the highest CoS to the lowest CoS of each ONU. For each bandwidth allocation, the granted bandwidth will be issued if there is enough credit in the pool.
3. After each allocation, the granted bandwidth will be subtracted from the credit pool.

Algorithm	**SBA**	**DBA**				**Delay**	**Utilisation**
		prediction -based	**Non prediction -based**	**QoS-based**	**Non QoS-based**		
Shami et al. [5]	-		-		-	**Lower than [1]**	**Higher than [1]**

1. A transmission cycle divided into two sub-cycles of EF and AF-BE.
2. The EF sub-cycle with deterministic allocated length followed by the AF - BE sub-cycle which has a flexible length based on the AF and BE's reported load in previous service cycle.
3. Uses the grant-before-report (GBR) fashion for the EF service classes which guarantees the delay and jitter for the EF. The flexible length of the second sub-cycle also guarantees the QoS for the AF and BE service classes.

Algorithm	**SBA**	**DBA**				**Delay**	**Utilisation**
		prediction -based	**Non prediction -based**	**QoS-based**	**Non QoS-based**		
Byun et al. [8]	-		-	-		**Lower**	**Higher than [1]**

						than [1]	

1. Predicts the number of the packets arriving between two consecutive time-slots.
2. Keeps the queuing delay and buffer length low but it doesn't consider QoS requirements for different CoS.

Algorithm	**SBA**	**DBA**				**Delay**	**Utilisation**
		prediction -based	**Non prediction -based**	**QoS-based**	**Non QoS-based**		
Luo et al. [7]	**-**		**-**		**-**	**Lower than [1]**	**Higher than [1]**

1. Authors proposed a QoS-based and prediction-based DBA algorithm.
2. Uses prediction in order to estimate data arrive during the waiting time for three service classes (EF, AF and BE) in order to reduces the packet loss and packet delay for all service classes.

Algorithm	**SBA**	**DBA**				**Delay**	**Utilisation**
		prediction -based	**Non prediction -based**	**QoS-based**	**Non QoS-based**		
Ma et al. [11]	**-**	**-**			**-**	**Lower than [1]**	**N/A**

1. A Bandwidth Guaranteed Polling (BGP) algorithm was proposed where the ONUs are divided into two groups of bandwidth guaranteed ONUs, e.g. business customer, and non-bandwidth guaranteed ONUs, e.g. residential users.
2. Bandwidth will be guaranteed for the first group while the second group will be served with the best effort service.

Algorithm	**SBA**	**DBA**				**Delay**	**Utilisation**
		prediction -based	**Non prediction -based**	**QoS-based**	**Non QoS-based**		
An et al. [10]	**-**	**-**			**-**	**Lower that conventional slot-size BA**	**N/A**

<table>
<tr><td colspan="8">1. A given service cycle is divided into steady and non-steady parts.
2. The steady part of the service cycle is used for the highest class of service, e.g. voice, and the non-steady part is used for lower classes of services e.g. video and data.
3. Fairness is applied to the non-steady part of the service cycle among lower service classes by taking into account the queue lengths and weighting factor.
4. The fixed length frame size reduces the network efficiency.</td></tr>
<tr><th rowspan="2">Algorithm</th><th rowspan="2">SBA</th><th colspan="4">DBA</th><th rowspan="2">Delay</th><th rowspan="2">Utilisation</th></tr>
<tr><th>prediction -based</th><th>Non prediction -based</th><th>QoS-based</th><th>Non QoS-based</th></tr>
<tr><td>Assi et al. [6]</td><td>-</td><td></td><td></td><td></td><td>-</td><td>Lower than [1]</td><td>Higher than [1]</td></tr>
<tr><td colspan="8">1. Due to the delay-sensitive characteristic of EF service class, a prediction based DBA algorithm is proposed in which the waiting data is estimated for EF traffic, e.g. voice.
2. No estimations were considered for AF and BE service classes to which domain the overall access traffic load.</td></tr>
<tr><th rowspan="2">Algorithm</th><th rowspan="2">SBA</th><th colspan="4">DBA</th><th rowspan="2">Delay</th><th rowspan="2">Utilisation</th></tr>
<tr><th>prediction -based</th><th>Non prediction -based</th><th>QoS-based</th><th>Non QoS-based</th></tr>
<tr><td>Hwang et al. [12]</td><td>-</td><td></td><td></td><td></td><td>-</td><td>Lower than [19] and [6]</td><td>N/A</td></tr>
<tr><td colspan="8">1. Authors proposed early DBA with prediction-based fair excessive bandwidth reallocation scheme in EPON.
2. The proposed scheme reduces the idle time and provides more accurate predictions to ensure fairness for all ONUs which improves the overall network performance in comparison with [19] and [6].</td></tr>
</table>

However, taking into account the fixed infrastructure of the PON, a PON is unable to provide flexible wireless access services with mobility features for the subscriber stations in front-end customer premises. Taking into consideration the ultimate goal of the NGN, which is to provide the connectivity with satisfactory capacity and speed for the telecommunication applications and services whenever, wherever and in whatever format [130], the need for a PON wireless counterpart comes into focus.

Before concluding this chapter with discussions about the needs and the benefits of having the wireless counterpart for the optical technology, the next section provides a review for the history of the wireless technologies as follows.

2.2 History of the Wireless Technologies

Considering the supported distance and coverage area, wireless networks can be categorised as Wireless Local Area Networks (WLANs), Wireless Metropolitan Area Networks (WMANs) and Wireless Wide Area networks (WWANs) each with different topologies, standards and technologies. However, some of the standards and technologies fit in more than one category.

WLANs are designed in order to provide wireless services for Local Area Networks (LANs) termed access networks e.g. offices, university campuses or home subscribers in an area with cell radius no more than hundred meters. A typical WLAN includes an Access Point (AP) and number of Client Stations (CSs) where the AP is responsible for providing communications and connectivity for CSs. WLAN can work in two modes: Centralised and Distributed. In Centralised mode, the AP is a central authority and provides communications to/from CSs while the Distributed approach CSs can also communicate with each other. The IEEE 802.11 [44] family and HiperLAN family by ETSI [52] are the available technologies for WLANs which are both united under Wireless Fidelity (WiFi) standards. WiFi technology will be discussed in more detail in next section.

WMANs are designed in order to provide wireless services for a larger area than WLANs e.g. entire cities.

The IEEE developed a cell based technology termed IEEE 802.16 [39] in order to provide broadband wireless access technology for Line of Sight (LOS), non-Line Of Sight (NLOS) and Mobile Subscribers (MSs). In order to cover a larger area, IEEE 802.16 supports multiple cells in which a central authority termed Base Station (BS), in the middle of the cell is responsible for providing broadband services to the Subscriber Stations (SSs) residing in a same cell. IEEE 802.16 technology will be discussed in more detail in next section.

On the other hand, Broadband Radio Access Network (BRAN) was developed by ETSI [52] in 1997 in order to provide broadband radio access for subscribers. BRANs developed two standards termed HiperAccess for LOS and HiperMAN for both LOS and NLOS users.

WWANs were designed in order to provide wireless services for a larger area than WMANs e.g. entire countries.

Satellite systems provide the required wide coverage for WWANs. Whilst most of the current satellite services are capable of providing one direction communications (downstream communications), the Next Generation Satellite Systems (NGSSs) are expected to provide both upload and download supports as well as Onboard Processing (OBP) and Onboard Routing Capabilities (OBRC).

IEEE 802.20 [41] is another emerging technology for WWANs where mobile vehicles that have speeds up to 250 kmph, e.g. trains, are supported. However, due to the high speed of the mobile vehicles IEEE 802.20, IEEE 802.20 is expected to support lower throughput in comparison with WLAN or WMAN technologies such as 802.11 or 802.16. As the work in this thesis is to provide the optical backhaul for the wireless access networks, the next section discusses the state-of-the art technologies for wireless access networks as follows.

2.2.1 State-of-the-Art Technologies for Wireless Access Networks

Wireless access networks may employ technologies such as Wireless Fidelity (WiFi), World Wide Interoperability for Microwave Access (WiMAX) and Cellular Networks which have different characteristics, advantages and disadvantages as follows.

Wireless Fidelity (WiFi) is developed by IEEE 802.11 a/b/g groups [44] with maximum data bit rate of 54/11/54 Mb/s, respectively with restricted 100 metres coverage. WiFi is a popular wireless access technology for WLANs due to its low cost, technical maturity and high product penetration [54]. It works in two operational modes termed *Infrastructure* mode and *Ad Hoc* mode. While in Infrastructure mode a management node termed AP is required in order to provide the central management authority, in Ad Hoc mode subscriber stations are self-managed with no need for a central authority. WiFi uses unlicensed bands named Industrial and Scientific Medical (ISM) bands. The

ISM radio bands are reserved for use of Radio Frequency (RF) in industrial, scientific and medical purposes other than communications. However, in recent years ISM reaches the short-range and low power communication systems such as cordless phones, Bluetooth devices and wireless computer networks. Although WiFi aggregated throughput is 11 Mbps per AP, there are WiFi devices in market which support data rates up to 108 Mbps using various techniques [51].

World Wide Interoperability for Microwave Access (WiMAX, IEEE 802.16 [39]), is aimed to reduce the equipment, operation and maintenance costs, provides low-cost, wide coverage, fixed and mobile broadband access connections with a QoS provisioning scheme [40] and uses both licensed and unlicensed (ISM) frequency bands. It supports up to 75 Mb/s data rates with a 20 MHz channel over 3-5 km distance (under optimal conditions). Thus, WiMAX is also suitable for WMANs due to its ability to provide high bandwidth and support long distances. WiMAX works in two operational modes: *Point-to-Multi-Point (P2MP)* mode and *Mesh* mode. In P2MP mode, communications are only provided among central management node termed the Base Station (BS) and Subscriber Stations (SSs). However, in Mesh mode, SSs can also communicate with one another. Due to high data bit rates and wide coverage support, WiMAX can also provide wireless access services for rural areas.

Cellular Networks provide low bit-rates up to 2Mb/s which are mainly employed for voice applications and are unsuitable for data services. Cellular network technology began with 3GPP UMTS/WCDMA in 2001 and has advanced into current UMTS/HSPA networks. Third-Generation networks (3G), Beyond-Third-Generation (B3G) and Fourth-Generation (4G) networks [49] and [50], which are the most advanced technology of Cellular networks, brought data application supports into the Cellular networks by supporting higher bit rate for both downstream and upstream transmissions. For instance, 3G networks support 5Mb/s and 14 Mb/s data delivery for both upstream and downstream transmissions, respectively. A more advanced version can support up to 40 Mb/s and 10 Mb/s for downlink and uplink speeds, respectively. Considering the huge demands and rapid growth such as music and video downloading, online gaming and social networking, in cellular networks, 3GPP Long Term Evolution, referred to as LTE and marketed as 4G-LTE, has been proposed as the evolution step for the 4G networks [47] in order to increase the capacity and speed. The main purpose of the LTE proposal is to achieve higher bit rates, lower delays, lower cost, simpler operational functions as well as better spectrum efficiency by making use of multi-antenna techniques and inter-cell interface coordination. The LTE requirements have been presented first in the 3GPP Release 8 [48] and demand the following specifications. Peak rates of 100 Mbps (downlink) and 50Mbps (uplink), increased cell-edge bit rates, a radio-access network, latency of less than 10ms, two to four times the spectrum efficiency of 3GPP Release 6 (WCDMA/HSPA), support of scalable bandwidths, 1.25, 2.5, 5, 10,15, and 20MHz, support for FDD and TDD modes, smooth operation with an economically viable transition from existing networks. The next section discusses future developments in wireless access networks.

2.2.2 Future Developments

Integration of different wired and/or wireless access technologies have been considered in the literature review.

For instance, in [38], authors proposed the integration of WiMAX and WiFi access technologies where the license of the WiMAX spectrum is shared with WiFi Access Points in order to provide Internet connectivity for WiFi mobile users. They have also discussed the protocol adaptations, QoS support along with a model for pricing the bandwidth sharing in the WiMAX and WiFi integrated scenario.

In order to overcome the limitations of single hop communications in WLAN (IEEE 802.11) [44], where the transmission power and transmission range are limited, wireless data packets need to travel over multiple wireless hops which forms the Wireless Mesh Networks (WMNs). In WMNs, the wireless communications are extended from offices or university campuses to city-wide developments by supporting multi-hop wireless communication. WMNs are proposed in order to address the limitations and to improve the performance of ad hoc networks, WLANs, Wireless Personal Area Networks (WPANs), and WMANs [46]. WMNs employ multiple communications in order to forward traffic to and from the wired Internet entry points [53]. They consist of mesh routers with minimum mobility and mesh clients. The mesh routers provide the Internet connectivity for both mesh clients and conventional clients and are used for bridging the integration with the other networks e.g. IEEE 802.11, IEEE 802.15 and cellular networks by executing the associated functions and protocols. The WMNs are able to work in three operation modes: *Infrastructure, Client* and *Hybrid*. In Infrastructure mode, a central management node (wireless mesh router) with no mobility is developed in order to provide routing facilities and configurations (mesh functions) for the associated SSs. In Client mode, SSs provide mesh functions themselves; therefore, there is no need for central authority. Hybrid mode is a combination of Infrastructure mode and Client mode in which a central management (wireless mesh router) and client nodes both can provide mesh functions including routing facilities and configurations.

IEEE 802.11s [42] has been outlined in order to define standards for wireless mesh networks based on IEEE 802.11 standards and definitions. IEEE 802.11s provides amendment to IEEE 802.11 and addresses the security, forwarding and routing capabilities at MAC layer as well as a new data frame that can be used for data transmissions over WMNs. It also defines a default mandatory routing protocol termed Hybrid Wireless Mesh Protocol (HWMP) [42] as well as an on-demand routing protocol in order to address the mobility features. In [43] and [45], authors provided insights into IEEE 802.11s standards and specifications and explained how it fits into the 802 series of network standards. They have also presented the key technical aspects of mesh networks including the topology, security, power efficiency, routing and media access control.

Taking into consideration the above discussions for the history of the wireless technology (chapter 2, section 2.2), the state-of-the-art technologies for wireless access networks (chapter 2, section 2.2.1) and the future developments for the wireless technology (chapter 2, section 2.2.2), the next section discusses a need for the wireless counterpart for optical technology as follows.

2.3 Wireless Counterpart for Optical Technology

An ON and particularly a PON has been viewed as an attractive candidate for the first/last mile bandwidth bottleneck problem for many years. A PON provides huge bandwidth and supports subscribers located in a longer distance from the CO in comparison with other fixed broadband access technologies such as DSL, CM or T1-E1 networks. It is an inexpensive broadband access solution as it eliminates the necessity of installing the active components such as multiplexer and de-multiplexer all the way from the OLT in the CO to the ONU near the customer premises which covers the area beyond 20 km. Instead of active network components, a PON has passive network components, e.g. 1:N passive Splitter/Combiner, which can be buried into the ground with no need for a supplementary power supply. This is another strong point of a PON which differentiates it from other fixed access technologies for the telecommunication companies in terms of cost and maintenance.

The need for a PON wireless counterpart comes into focus since a PON, which is a fixed network technology, is unable to provide flexible wireless access services with mobility features for subscriber stations. Moreover, extending the expensive fibre cables from the OLT in the CO to the rural area in order to provide fibre-based broadband access services is not physically possible for relatively long distances or is not beneficial for the network operators.

Generally speaking, optical fibres do not go everywhere due to the restrictions in fixed infrastructure, but where it goes, it provides huge bandwidth at relatively low cost. On the other hand, wireless technology goes almost everywhere due to the flexible infrastructure and mobility features, but it is highly restricted in transmission power, transmission range and channel capacity.

Given the fact that the ultimate goal in telecommunication networks is to provide Internet services and applications wherever, whenever and in whatever format at reasonable cost, with excellent coverage and satisfactory bandwidth, then future broadband services must leverage on both optical and wireless technologies and this led to the development of Fibre-Wireless (FiWi) access networks.

In the next chapter, possible candidates from optical and wireless domains will be discussed in order to form attractive nominees for FiWi access networks which includes the mutual benefits that such a convergence brings for both technologies and the need for it in future broadband access networks.

2.4 Chapter Summary

This chapter provided detailed background about the components of the research domain including the optical and wireless technology generations. The main goal of this chapter was to highlight the needs, desires and requirements for the optical and wireless technology integration and to distinguish the possible nominees from each domain for a successful integrated scenario. To achieve this aim, this chapter presented a background summary for the Optical Networks (ONs) and particularly Passive Optical Network (PONs) and their roles in telecommunication world. This was followed by the most challenging issues of the PON's Media Access Control (MAC) and resource management techniques, a detailed description of the PON's various Bandwidth Allocation (BA) algorithms and the PON's state of the art protocols. This chapter also presented a literature review for the wireless technology generations including the state-of-the-art technologies along with the future developments in order to bring to light the possible candidates from the wireless domain for the optical and wireless converged scenario.

Chapter 3 Literature Review, Part Two

This chapter provides a general background about the history of the optical and wireless technology integrated scenarios. It starts with the benefits such as flexibility, robustness, maintainability, satisfactory speed, capacity and coverage as well as the needs and requirements for optical and wireless technology integration. This is followed by highlighting the promising nominees from each domain in order to provide a successful ETE integrated scenario based on the standards, technology specifications, the mutual as well as the individual aspects from each domain. Then it provides a detailed description of various techniques that have been employed in order to provide the converged scenarios in terms of architectural aspect, e.g. the way two technologies can be connected to each other, along with the MAC related issues, e.g. the ETE bandwidth requests/allocations, QoS provisioning schemes and upstream scheduling techniques. The identified gap in the area of the architectural design as well as the MAC related issues of the converged scenario are addressed next. An overview of the key thesis contributions is presented and detailed which is concluded by the chapter summary at the end.

3.1 The Need for the Optical and Wireless Technology Integration

Optical and wireless technology integration had been proposed as one of the most promising nominees for the next- generation broadband access networks for quite some time. The future broadband access networks for NGN [132] will undoubtedly be a mixture of the optical and wireless technologies capable of providing wherever, whenever and in whatever format broadband access services with satisfactory coverage, capacity, cost, maintainability, flexibility and robustness for both subscriber stations and telecommunication companies.

Providing sufficient bandwidth with relatively low cost for an ever increasing demand for bandwidth-intensive applications and services such as instant on-line games, on-line banking, HDTV, social networking, video conferencing, Voice over Internet Protocol (VoIP), High Definition Medical Imaging, IPTV and video conferencing wherever, whenever and in whatever format would be out of the scope of individual wireless and fixed (particularly optical) domains.

For instance, optical networks bring large bandwidth with satisfactory cost, maintainability and robustness for both subscriber stations and service providers; however the supported coverage area of the optical network is limited as they are tied to the fibre-optic infrastructure which cannot go everywhere. Moreover, given the fact that the current telecommunication services and applications are moving toward the flexibility, mobility that wireless connectivity supports, the lack of wireless and mobility features in fibre-based broadband optical networks provides a huge impediment to the emergence of the NGN.

On the other hand, wireless networks, go everywhere, provide low-cost and wide-coverage broadband access services with flexible features and mobility support; however they are highly restricted in transmission power, transmission range, packet loss and channel capacity. Moreover, wireless and mobile backhaul technology is still a controversial and challenging issue. For instance, DSL and T1-E1 services are the current copper-based solutions for mobile backhaul problem domain but have huge drawbacks e.g. DSL capacity and coverage distances are limited and the performance depends on the time of access as well as the distance from the CO. On the other hand T1-E1 are not cost effective, high-capacity or flexible backhaul solutions.

Based on the above discussions, the wireless and optical converged scenario brings lots of advantages for each domain individually. For instance, it extends the coverage area of the optical domain by bringing flexibility and mobility features to the fibre-optic robust infrastructures. It also offers the robustness and huge bandwidth for the wireless counterpart and provides a promising candidate for the wireless backhaul problem domain.

The convergence scenario also brings lots of advantages and profits to the telecommunication companies in terms of Capital Expenditures (CapEx) and Operating Expense (OpEx) costs. For instance, when the optical network is used as a robust backhaul technology solution for its wireless counterpart, telecom companies will be able to provide high-speed wireless broadband access services for relatively more subscribers in rural area where the other copper-based access technologies such as DSL, CM, T1-E1 or even pure optical networks are either inaccessible or too costly to extend to. Therefore, the convergence scenario reduces the fibre extension costs, supports more subscribers with a wider coverage and provides relatively high bandwidth for the subscribers in rural area. It is also a cost-aware solution for the telecom companies in terms of energy consumption as passive optical components such as 1: N passive Splitter/Combiners can be buried under ground and there is no need for supplementary power supplies. However, the telecom companies still need to provide power supplies for the two end-points of the optical networks, the OLT in the CO and the ONU near to the customer premises, as well as the wireless components such as the BS.

To gain a deeper understanding and appreciation of the optical and wireless integrated aspects, the next section provides the best nominee from each domain for the converged infrastructure of the NGN which is then followed by the history, functions and standards related to work in the area.

3.2 Promising Candidates from the Optical and Wireless Domains

In the last decade, we have witnessed a huge development of broadband access technologies in both fixed and mobile broadband network infrastructures. It is because of the necessity to scale up the bandwidth capacity of the subscriber access networks, which connect residential and business users to the core networks in order to utilise the full capacity of the core networks. This is the so called first/last mile bandwidth bottleneck problem where the capacity of the subscriber access networks needs to be enlarged in order to benefit from the huge capacity provided by the core network. By tackling the first/last mile bandwidth bottleneck problem, the increasing bandwidth demands of the subscriber access networks will be met and emerging bandwidth-intensive applications and services such as video-conferencing, HDTV, VoIP, instant on-line games and social networking will be supported.

In the fixed access network, ONs and particularly PONs have received much attention from both industry and academia and are viewed as attractive solutions in terms of capacity, speed, cost, scalability, robustness and maintainability in comparison with other fixed broadband access technologies such as DSL, T1-E1 or CM networks.

Great efforts have been made by both IEEE Ethernet in the First Mile Task Force (IEEE EFM TF) and ITU-T in order to provide different flavours of PON such as EPON [29], BPON [31] and GPON [30].

An EPON [29], which is a primary type of PON, appears to be the preferred choice among other PON technologies such as BPON and GPON. An EPON, which is developed and standardised by the IEEE 802.3ah [29], is based on the Ethernet standard and protocol which is a ubiquitous, off-the-shelf, inexpensive and scalable (100 Mbps, 1Gbps and 10Gbps) technology. Ethernet dominates most of the LANs and today 95 percent of all LANs and 85 percent of all installed network connections are Ethernet-based [13]. The emerging sophisticated and bandwidth-intensive applications and services [128] in telecommunication e.g. Video-on-Demand (VoD) and HDTV are also moving towards Ethernet technology. EPON bus technology and EPON broadcast behaviour also resemble the PON upstream and downstream behaviours, respectively. BPON [31] employs an ATM cell in order to encapsulate the data transmitted between the OLT and the ONU. Taking into consideration the priority queues which can be easily implemented in the OLT and the ONU, ATM technology can provide better policies and QoS requirements for real-time traffic (e.g. video and voice) in PONs; however ATM cells add extra cost and complexity to the network by breaking up the IP packets at the source and then reassembling them at the destination. Moreover, the total maximum upstream and downstream speed of an EPON [29] (symmetric 1 Gb/s) is more than the maximum speed provided by a BPON [31] (1.22 Gb/s downstream and 622.08 Mb/s upstream). Moreover, the GPON [30], which is the evolution of the BPON, supports both ATM cells and Ethernet frames and provides more than twice the upstream and downstream transmission speeds (symmetric 2.448 Gb/s) in comparison with an EPON (symmetric 1 Gb/s). However, the 10 Gbps EPON (10 GEPON) proposed by IEEE 802.3av Task Force [33], which provides two solutions: symmetric (10 Gbps upstream and downstream transmission speed) and asymmetric (1 Gbps upstream and 10 Gbps downstream transmission speed), can compensate for the lower speed of the EPON and thus provides higher overall upstream and downstream transmission speeds than the GPON. Moreover, the GPON [30] maps the Ethernet frames into GEM frames which adds extra complexity and cost to the overall network expenditure.

On the other hand, IEEE 802.16 (WiMAX) [39] has achieved huge commercial success in wireless broadband access networks and is viewed as a potential counterpart nominee for the PON technology particularly the EPON.

IEEE 802.16 [39] provides high bandwidth capacity, wide network coverage, a strong QoS provisioning scheme with relatively inexpensive network equipment and maintenance costs and has many potential applications [77] and [78].

WiMAX uses both licensed and unlicensed frequency spectrums and provides up to 75 Mb/s data rate [59] within a 20 MHz channel over 3-5 km in optimal situations and works in two modes: *P2MP* and *Mesh* mode. In P2MP mode, wireless communications are only provided between a central authority termed Base Station (BS) and the wireless subscriber stations. However, in Mesh mode wireless subscriber stations can also communicate with each other.

However, WiMAX backhaul technology is still a controversial and challenging issue. T-1/E-1 and DSL are widely used as popular backhaul technologies for WiMAX which carry many drawbacks as follows. For instance, T1-/E-1 are capable of providing a transmission rate of about 2 Mbps and they are also successful in supporting a QoS provisioning scheme for different CoS. However, T-1/E-1 hire and maintenance charges are expensive which make them inadequate in terms of cost and scalability for WiMAX backhaul technologies. Moreover, DSL supports high-speed Internet using the existing telephone line with a relatively affordable cost; however DSL performance depends on the subscriber distance from the CO as well as the time of access. Taking into consideration the emerging broadband applications and services which are moving towards more sophisticated data applications with increasing bandwidth demands [128] as well as the massive cost and limited scalability [55], T-1/E-1 and DSL solutions remain unable to satisfy the mobile backhaul problem domain.

This is the point where PONs and particularly EPONs [29] come into play and where an EPON can be replaced with the current WiMAX [39] backhaul technology solutions in order to provide huge bandwidth, robust and scalable infrastructure at a relatively lower cost.

Supporting Ethernet as a common standard interface and having almost the same bandwidth request and allocation methods has made the WiMAX-EPON convergence scenario feasible.

Moreover, WiMAX- Base Station (WiMAX- BS) and EPON- Optical Network Unit (EPON- ONU) have almost the same channel capacity which avoids generating bottlenecks at the convergence point between the two technologies. In an EPON, which is a TDM-base PON, channel capacity (symmetric 1 Gbps) is shared among a group of ONUs (typically 16 ONUs), [2] and [24], which provides each ONU with capacity of ~65 Mbps (1 Gbps divided by 16) which almost matches the WiMAX channel capacity (75 Mbps) [59]. However, each ONU can only support a single BS which limits the total number of supported BSs for the whole system to 16 BSs. A solution for such a problem is hybrid-PON (combination of TDM and WDM PON) in which ONUs share multiple channels thus more bandwidth will be available per ONU which results in supporting a greater number of BSs for the whole converged scenario. For instance, if the OLT supports four channels over the same fibre infrastructure, 4×65 Mbps will be available per ONU in a group of 16 ONUs. Therefore, each ONU can backhaul up to 4 BSs which increases the total number of supported BSs to 64 (16 ONUs $\times$ 4 BSs).

However, supporting different numbers of service classes and different method of providing QoS are the challenging issues for the EPON-WiMAX converged scenario. For instance, WiMAX [39] has five service classes such as Unsolicited Grant Service (UGS) e.g.T1/E1 or VoIP without silence suppression, Real-time Polling Service (rtPS) e.g. streaming audio or streaming video, Extended Real-time Polling Service (ertPS) e.g. VoIP with silence suppression, Non Real-time Polling Service e.g. File transfer and

Best Effort services e.g. E-mail. However, EPON has three service classes such as Expedited Forwarding (EF) services e.g. VoIP, Assured Forwarding (AF) services e.g. video stream and Best Effort (BE) services e.g. E-mail. Moreover, taking into account the implemented queues inside the OLT and the ONUs, the EPON is capable of providing a queue-based QoS provision scheme while WiMAX supports connection-oriented QoS scheme.

The objective of the above discussions is to bring into play the best possible nominees from fixed and wireless technologies which form the basis of the converged scenario for the NGN. Having seen the evaluation of the fixed and mobile converged infrastructure through the last decade, now it is essential that a detailed study should be carried out for the various techniques which have employed for the integrated scenario. The following section is dedicated to this study.

3.3 History of the Optical and Wireless Technology Integration

In order to successfully integrate the optical and wireless technologies, there are some technical concerns, which need to be addressed efficiently and effectively in order to guarantee the ETE QoS for different classes of services and provide smooth ETE connections between the two technologies.

To date, a wide range of research has been carried out towards the successful integration of the optical and wireless technologies in order to establish the inexpensive, reliable and robust connections for the front-end customers and save the CapEx and OpEx costs for telecommunication companies.

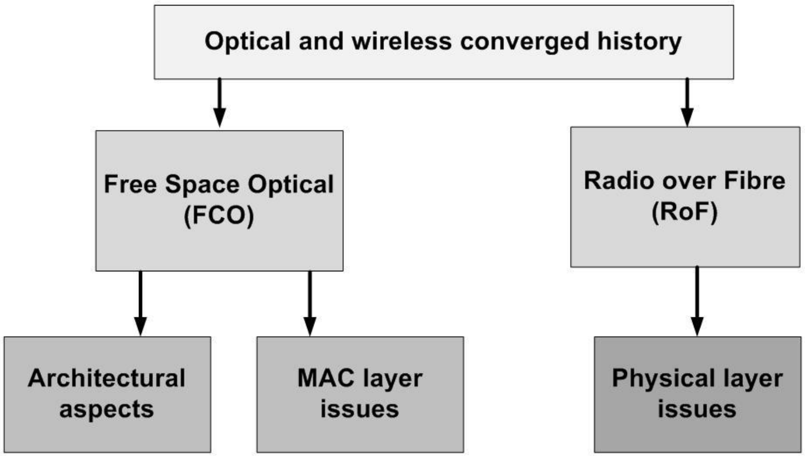

Figure 3.1 Optical and wireless converged history

Currently, there are two techniques which are used in order to implement the fibre – wireless networks termed Free Space Optical (FSO) [56], which is also known as Optical Wireless (OW) technique, and Radio over Fibre (RoF) [58] technique, Figure 3.1.

FSO provides point-to-point communications by modulating visible or infrared beams and offers high bandwidth and reliable communications over short distances [56]. In FSO, the transmission source can be either a high-power Light Emitting Diode (LED) or a Laser Diode (LD) and the destination a photo detector. FSO does not require a spectrum license and works in full-duplex mode with transmission rate from 100 Mbps to 2.5 Gbps which largely depends on the weather conditions. For instance, FSO has a high availability in rainy weather and a low availability in foggy weather with sunlight also causing interference to the system.

On the other hand, RoF [58] provides both point-to-point and point-to-multipoint communications in order to increase the transmission range. It requires a license for communications and similar to FSO its performance largely depends on weather conditions; however compared to FSO, RoF has a high availability in foggy weather and a low availability in rainy weather and electromagnetic signals can present as a huge interference to the system. In order to increase the transmission range and transmission power, an RoF transmission source typically deploys a Mach Zehnder Intensity (MZI) modulator in conjunction with an oscillator and Erbium Doped Fibre Amplifier (EDFA). Recently, a full-duplex ROF in the millimetre-wave-band has been proposed which is capable of supporting 2.5 Gbps data transmission over 40 km with less than 2 dB power attenuation [57].

While the FSO category includes the Architectural aspects and MAC layer issues of the converged scenario, the RoF category is more focused on Physical layer issues related to the optical and wireless integrated scenarios, Figure 3.1.

Architectural aspects include the way two technologies connect to each other along with the ETE functional modules specifications, physical structure, component specifications as well as the distance arrangements.

In Physical layer issues, most of the work is focused on providing the cost-effective and reliable RoF systems e.g. providing RoF systems in order to use a single modulator for both wired and wireless services simultaneously [58].

MAC layer features include the ETE resource negotiations, resource requests and resource allocations such as wavelength/bandwidth requests and allocations, upstream scheduling techniques as well as the ETE QoS support.

As this PhD work is focused on Architectural aspects as well as MAC-related issues of optical and wireless integrated networks (FCO category, Figure 3.1) the existing work related to these two aspects are considered and discussed in detail as follows.

3.3.1 Architectural Aspects

In terms of architectural aspects, integration of the optical and wireless technologies can be carried out in several ways. In this section the existing work related to FiWi integrations is discussed first where the integration occurs mostly between single-channel/multi-channel PONs and WMNs. In FiWi integrations, PONs are mostly employed in order to backhaul WMNs. WMNs include Wireless Gateways (WGs), Wireless Mesh Routers (WMRs) and WiFi technology comprising wireless APs, Mobile Client Nodes (MCNs) and cell phones. The EPON and WiMAX integrated scenarios are then particularly discussed in terms of architectural aspects as well as the MAC related issues which are more related to this PhD work.

FiWi architectures based on WiFi technology have been studied as follows.

In [60], the authors proposed a structure in which the CO interconnects with multiple Wireless Access Points (WAPs) using an optical unidirectional fibre ring, Figure 3.2. A WAP provides wireless services for a number of MCNs within the associated ring and the CO is responsible for acting as a gateway to other networks as well as a transmission manager between the MCNs and the associated WAP. The MCNs periodically send the information about the beacon power received from neighbours to the associated WAP therefore, a given WAP can estimate the distance between MCNs and compute the routes. The proposed implementation in [60] is capable of supporting advanced path discovery techniques using both multiple relaying and transmission via several WAPs.

In [61], the authors proposed a Bidirectional Path-Protection Ring (BPR) in two levels for Dense WDM (DWDM)/subscriber multiplexing (SCM) broadband FiWi networks. In their proposed architecture, Figure 3.3, the CO is interconnected to several remote nodes through a dual-fibre ring. Each remote node was also interconnected to the WAPs through several Concentration Nodes (CNs) employing a dual-fibre ring. Each CN can support several WAPs and each WAP provides channel bandwidth of at least 5 MHz for up to 15 MCNs by means of Frequency Division Multiplexing (FDM). Under normal conditions, the CO manages the downstream signal transmissions in the counter-

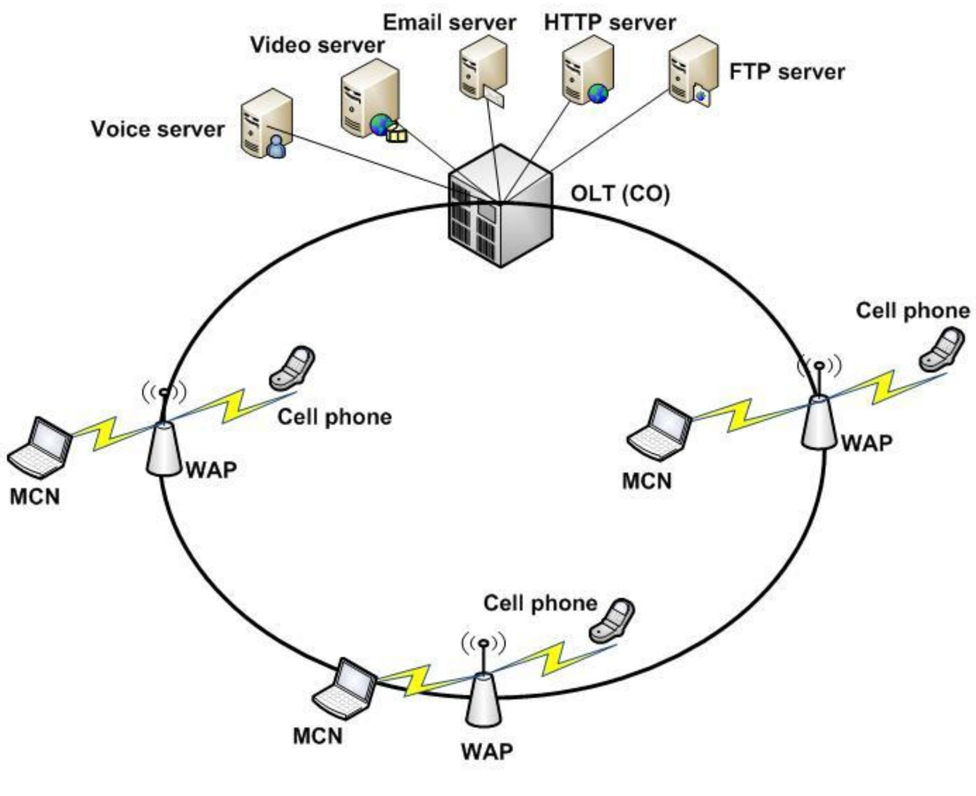

Figure 3.2 Unidirectional optical ring integrated with WAP-based access network [60]

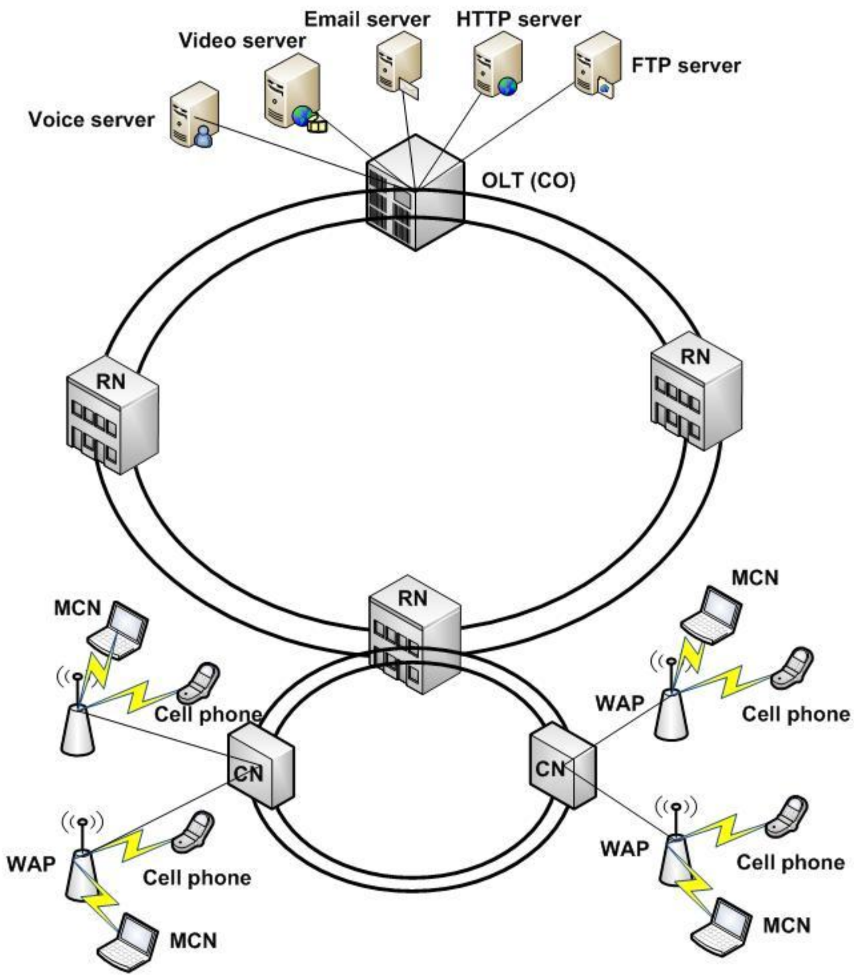

Figure 3.3 Bidirectional optical rings integrated with WAP-based access network [61]

clockwise direction through the remote nodes and CN. However, if a fibre cut occurs between the remote nodes or between the CNs, the associated controllers distinguish the failure and switch to the clockwise protection ring. The proposed structure in [61] provides a robust FiWi architecture in terms of reliability, flexibility, capacity, and self-healing.

In [62], the authors proposed a FiWi system where optical ring and optical star networks are interconnected. Each optical ring includes several WAPs and each WAP is responsible for providing wireless services to the number of MCNs. A given optical ring is connected to the CO and two optical switches in a neighbour through a single optical switch. The FiWi network is monitored periodically in order to establish the load balancing on different light paths. For instance, when the traffic load increases, if the utilisation on the established light paths is low, the load on the existing light paths will be increased by means of load balancing. Otherwise, if the established light paths are heavily loaded, new light paths need to be established.

In [63], the authors proposed a FiWi system where multiple single channels or multiple multi-channels PONs are attached to an optical WDM backhaul ring. An Optical Add-Drop Multiplexer (OADM) is employed in order to connect the OLT of each PON to the WDM backhaul ring. WGs are used in order to bridge optical and wireless networks. Each WG is also connected to a WMR each of which provides wireless services to a number of MCNs. The WMRs can also communicate with each other. In the downstream direction, data packets travel from the CO to the WG and then passes to the MCNs through one of the WMRs. In the upstream direction, data packets travel from the MCNs to a WMR which are then transmitted in the direction of one of the WGs and forwarded to the CO on one of the wavelength channels of the optical backhaul WDM ring. When some PONs are heavily loaded and others are lightly loaded, in order to balance the total network traffic among them, some of the ONUs associated with the heavily loaded PONs will be assigned to the lightly loaded PONs by turning their optical transceivers to the wavelengths assigned to the lightly loaded PONs. The proposed structure in [63] provides a cost - aware architecture with high flexibility, high scalability, high bandwidth efficiency and wide coverage.

In [64], the authors proposed a hybrid Wireless Optical Broadband Access Network (WOBAN) in order to save the network design and network deployment costs. The optimal placement of the ONU, which is the tail end of the optical part of the converged scenario and communicates directly with the wireless base stations, is investigated in WOBAN by taking into account several optimisation algorithms. Network connectivity, network set up and fault tolerance are also considered for WOBAN.

In [65], the authors proposed a hybrid optical wireless access network that consists of reconfigurable optical backhaul and WMNs. They also proposed an integrated routing algorithm that can dynamically choose the optimum or near optimum route in order to balance the total network load when congestion happens in the WMN part. Their proposed integrated routing algorithm shows improvements in throughput in comparison with a minimum hop routing algorithm with single gateway association of the WMNs.

Beside the aforementioned architectures, which were focused on FiWi architectures based on WiFi technology, the optical and wireless technology integration, particularly for the EPON and WiMAX, has been studied as follows.

The authors in [59] proposed four architectures for EPON and WiMAX integrated scenario termed Independent Architecture, Hybrid Architecture, Unified Connection-Oriented Architecture and Microwave-over-Fibre Architecture.

In Independent Architecture [59], Figure3.4, which is the most straightforward approach for the integrated scheme, each part of the converged structure operates independently from each other part. This structure benefits from the simplicity in operations as

WiMAX - BS acts as a generic user attached to the EPON - ONU and the Ethernet protocol is used as a common standard interface for the communications. However, as each part of the integrated scheme works independently, the ONU cannot see the BS packet scheduling and also the BS cannot see the ONU upstream transmissions to the OLT. Thus, the whole system may not take full advantage of the bandwidth allocations especially over the optical domain.

In Hybrid Architecture [59], Figure 3.4, EPON - ONU and WiMAX - BS are integrated in a single box termed ONU - BS. In this structure, as the two devices (ONU and BS) are combined together in a single box, the cost of the network set up operations and maintenance are reduced. Moreover, due to the single box integration structure, each part of the network (optical and wireless) has the full information about packet scheduling, priority queues and available bandwidth from the other part. Thus Hybrid Architecture is expected to improve the overall network performance and QoS metric.

In [67], the authors presented the concepts of the ONU-BS box termed Virtual ONU-BS (VOB) for the converged scenario. It is termed virtual as there is no such integrated box physically in the market. It includes an EPON - ONU, WiMAX - BS and a WiMAX - EPON Bridge (WE-Bridge) which is placed between the ONU and the BS in order to coordinate the joint resource allocations, Figure 3.4. The ONU and the BS are connected together by the Ethernet interface and both are also connected to the WE-Bridge. Generally speaking, employing the proposed architecture from [67], which was termed a combined architecture, requires replacing the current EPON - ONU and WiMAX - BS with an integrated ONU - BS which adds additional cost and complexity to the network.

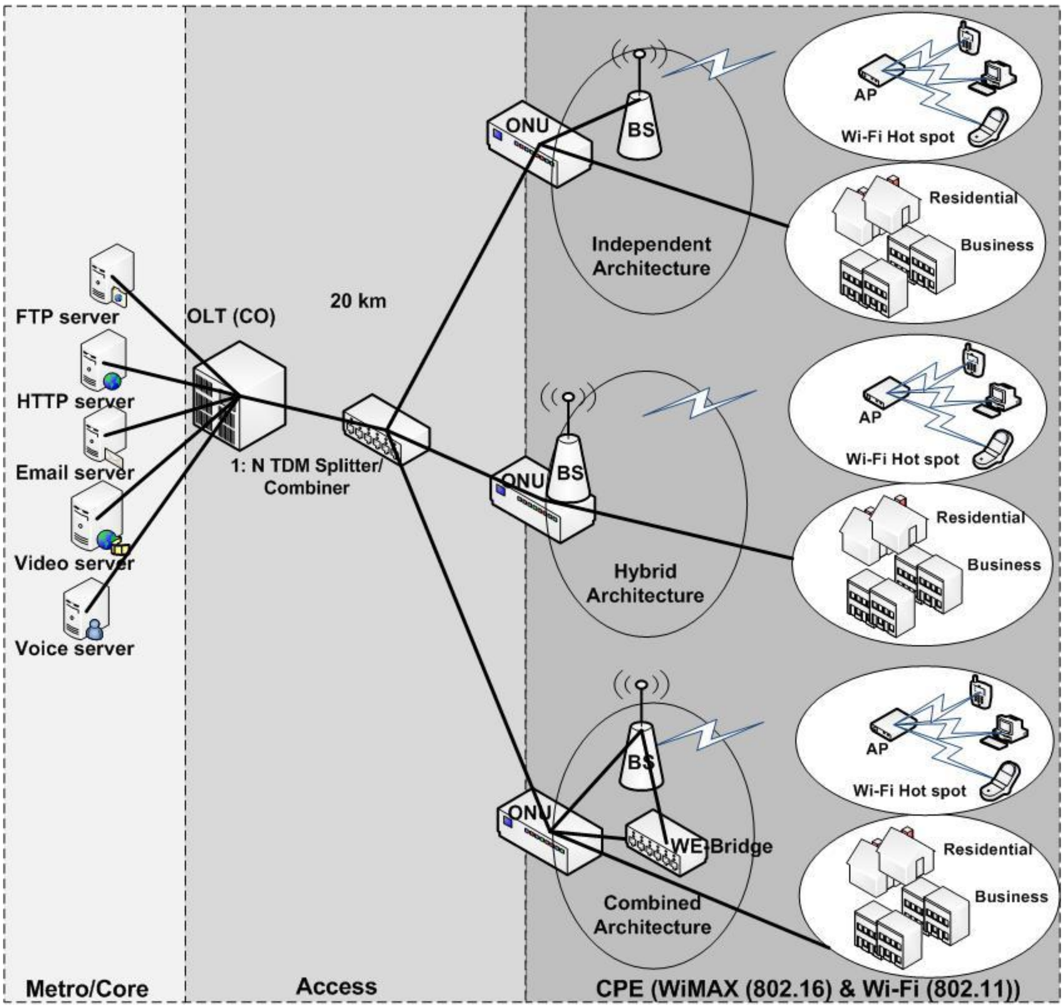

Figure 3.4 Independent, Hybrid and Combined Architectures of EPON and WiMAX Convergence [59]

For Unified Connection - Oriented Architecture, the authors in [59] proposed an integration scheme where the MAC layer of the EPON is modified in order to support connection-oriented services. The reason behind their proposal is that the connection-oriented bandwidth allocations, which are also supported in WiMAX, can provide more predictable QoS when compared to the queue-based bandwidth allocations in an EPON. For this purpose, the EPON Ethernet frames need to be encapsulated inside WiMAX MAC PDUs and then travel in the upstream and downstream directions of the EPON. However, their proposed solution has not been approved as a standard architecture.

In Microwave-over-Fibre Architecture [59], each remote node includes a single ONU and a dump antenna which is responsible for relaying WiMAX radio signals from and to its associated microcell. The EPON signal, which occupies frequencies up to 1.25 GHz, and the WiMAX signal, which is modulated over wireless frequencies, are then multiplexed and modulated into a wavelength (optical frequency) and then transmitted to the upstream central node. Modulation of the WiMAX frequency over the optical frequency (wavelength) is termed Microwave-over-Fibre (MOF).

In [68], the authors investigated three integrated scenarios termed: Independent ONU-BS (IOB), which is almost as the same as Independent Architecture discussed in [59], Combined ONU-BS (COB), which is almost as same as VOB in [67], and Hybrid ONU-BS (HOB). Therefore, HOB is only discussed as follows. In HOB, the functional modules of the ONU, BS and Joint Controller (JC), where JC is almost as same as WE-Bridge in [67], are all combined together in a few printed circuit boards (PCBs) in a single box. HOB is functionally equivalent to COB plus integrated traffic management due to the JC component. The functional modules, which were facilitated inside COB and HOB, share and process information between the two networks (optical domain and wireless domain) in order to provide the ETE QoS from SS in front-end customer premises up to the OLT in the back end central office.

In [66], the authors proposed an Optical-Optical-Wireless (OOW) architecture for the EPON-WiMAX integrated scenario in order to extend the service coverage range of the optical networks beyond 25 km which allows for the support of more end users. In the OOW architecture, an intermediate network is inserted between the backhaul and front end networks in which the OLT is connected to a group of sub-OLTs instead of ONUs.

A given sub-OLT performs the functions of the OLT in its associated network segment. Each sub-OLT was connected to the group of ONUs through a hybrid (TDM/WDM) splitter. Each single ONU was also connected to BS(s) and a given BS supports a number of subscriber stations at the front end customer premises. In the OOW architecture, two separate routers were placed inside the OLT with which each sub-OLT was connected and these are termed as primary and secondary gateways, respectively. A given sub-OLT always sends packets to its associated primary gateway unless its connection with the primary gateway is down or the network is highly congested with this gateway. Moreover, when the OLT wants to send packets to a given sub-OLT, it also checks the connection between the sub-OLT and its associated primary gateway. If it is highly congested or if the connection is down, packets will be forwarded through a secondary gateway to the associated sub-OLT.

In [69], the authors proposed two cases for optical and wireless integrated scenarios.

Case one, termed optical fibre and WiMAX integrated scenario, in which the optical fibres run from the OLT to the WiMAX - BS antennas so that each may service a large number of subscribers in a relatively large cell. In this case, network management is centralised at the OLT which was equipped with multiple optical interfaces in order to support their deployment.

Case two, termed the PON and WiMAX integrated scenario, in which each ONU is combined with a WiMAX antenna in order to facilitate wireless communications. This structure was also equipped with the network management at the edge; however unlike case one, case two can operate with a single optical interface to support data delivery over the PON due to employing the splitter between the edge node and the integrated

ONU-BS. Thus, case two was successful in reducing the network costs as compared with case one. The performance of both cases was compared by conducting simulation experiments in which case one outperformed case two in terms of throughput and ETE delay.

Generally speaking, the architectural design of the converged scenario between the optical and wireless technologies described above can be summarised into four main groups: Independent structure, Hybrid structure, Unified Connection-Oriented structure and Microwave-over-Fibre structure. As the last approach (Microwave-over-Fibre structure) is not related to the work in this thesis, this section is concluded by discussing the first three approaches (Independent structure, Hybrid structure and Unified Connection-Oriented structure) as follows.

As discussed above, the Independent structure, similar to work proposed in [59] and [68], is the simplest approach to implement for the converged scenario between the optical and wireless technologies where the WiMAX- BS acts as a generic user of the EPON- ONU. Although this approach benefits from simplicity, it is not successful in providing the required ETE QoS. This is because in the Independent structure, each part of the converged scenario acts independently from one another thus they do not know about the functionality and the performance of the other part. For instance WiMAX- BS cannot see the upstream transmission from the EPON- ONU or EPON- ONU cannot see the upstream packet scheduling of a given WiMAX- BS which results in ETE QoS degradation.

In the Hybrid structure, similar to the work proposed in [59], [67] and [68], the EPON-ONU and WiMAX- BS are integrated in a single box termed ONU – BS. When it is compared with the Independent structure [59] and [68], the Hybrid structure is expected to improve the overall network performance as each part of the converged scenario knows about the functionality and performance of the other part. It is to be noted that the concept of the ONU- BS adds extra cost and complexity to the telecommunication companies as it is required to be replaced with the current optical and wireless network elements. Moreover, to the best of our knowledge there is no such a box the market at the moment.

In the Unified Connection-Oriented structure, similar to the work proposed in [59], the MAC layer of the EPON is modified in order to support the connection-oriented services as in WiMAX systems. The reason for such a configuration is that connection-oriented services are capable of providing better QoS when compared with the queue-oriented services supported by EPON. However, to the best of our knowledge such an approach has not been standardised as yet.

In the Microwave-over-Fibre structure [59], each ONU has a dump antenna which is responsible for relaying the WiMAX radio signal from and to its associated microcell. The modulation of the WiMAX frequency over the optical frequency is termed Microwave-over-Fibre (MOF).

The shortcomings discussed above brought a new approach of semi-independent structure for the architectural design of the converged scenario which will be clearly discussed in chapter 4 of this thesis. In semi-independent structure of the converged scenario, each part of the integrated domain (e.g. EPON- ONU or WiMAX- BS) acts independently from another part based on their specific characteristics and standard functionalities. However, the new modules, approaches and functions take into consideration each part of the converged domain in order to let them work as part of the integrated infrastructure of NGN. Although this approach is not as simple as the Independent architecture [59], it benefits from reduced cost and complexity when compared with the hybrid approach proposed in [59], [67] and [68] as in the semi-independent approach there is no need for the full replacement of the existing components from both domains.

The following section will identify another challenging issue for the integrated infrastructure of the NGN, namely, MAC related issues, which forms the second contribution of this thesis.

3.3.2 Media Access Control (MAC) Aspects

In an optical and wireless integrated scenario, particularly with EPON and WiMAX technology integration, the MAC related issues include all the required ETE bandwidth negotiations (bandwidth requests and allocations) between the OLT - ONU, the ONU - BS and finally the BS and wireless subscriber stations. It also includes the upstream scheduling and QoS mapping techniques from a given BS to an ONU and then from the ONU up to the OLT.

MAC related issues for the integrated scenario of the EPON and WiMAX are discussed for the first time in [59] where the authors raised several issues about bandwidth allocations, packet scheduling, QoS support and user mobility (e.g. handover operations).

In [70], the authors demonstrated the major building components of the ONU-BS layer 2 integration including the core components of the packet processing engine, protocol processing, packet classification, DBA scheduling and QoS modules. The major difference between ONU-BS layer 2 and ONU-BS layer 3 integration is as follows. With layer 3 integration the ONU and the BS are connected physically through the Ethernet link which is very easy to implement. However, unlike the layer 3 integration, the layer 2 integration makes integrated dynamic resource scheduling (e.g. MAC) possible.

In [67], the authors proposed a QoS aware DBA algorithm in order to support bandwidth fairness at the converged point as well as class of service fairness at the 802.16 subscriber station point. Performance evaluation of the proposed DBA algorithm is carried out against two other DBA algorithms, DBA1 and DBA2. In DBA1, both OLT and VOB allocate bandwidth to the associated client stations in a static manner regardless of their individual bandwidth requests and QoS requirements. DBA2 goes between their proposed DBA algorithm and DBA1 in which the static bandwidth allocations from DBA1 is applied to the optical part of the converged network, the OLT and VOB, while their proposed algorithm is only applied to the 802.16 part. The proposed DBA algorithm performs better in terms of throughput, delay, utilisation and service differentiation when compared to DBA1 and DBA2.

In [71], the authors investigated the scheduling techniques in hybrid optical and wireless access networks aiming to guarantee the QoS for different class of service. They proposed a centralised scheduling technique in which the edge nodes act as a Central Controller (CC) and collect the resource information and service requests from the associated users. The CC nodes then prioritise the user traffic according to the class of service (e.g. voice video, or data traffic) and employ prioritisations in the scheduling decisions in order to guarantee the required QoS for different classes of service. Centralised scheduling provides a better performance when compared to distributed scheduling (multi-hop scheduling) in terms of delay for all service classes as well as throughput. However, no QoS mapping mechanism or detailed scheduling have been discussed.

In [124], the author of this thesis investigated possible challenging issues for hybrid PON integration with WiMAX and Wi-Fi technologies. To reduce the ETE delay and provide the required QoS for diverse service classes, six existing upstream scheduling mechanisms are compared in two levels which are distributed on APs from the Wi-Fi domain and the BSs from the WiMAX domain. Performance evaluations of the existing scheduling techniques for three popular service classes (Quad-play) are carried out which show the strong impact of using an efficient up-link scheduler in a converged scenario.

In [73], the authors deployed three models for the WiMAX and EPON integrated scenario from [59] (Independent Architecture, Hybrid Architecture and Unified connection-oriented Architecture) and focused on the key analysis of bandwidth allocations as well as QoS support for different service flows for all three structures. Based on the simulation results, The Hybrid Architecture as well as the Unified connection-oriented Architecture show better QoS performance particularly delays for different service classes when they are compared to an Independent Architecture. However, the Unified connection-oriented Architecture shows the most reliable QoS in comparison with two other architectures where the MAC layer of the EPON is modified in order to support connection-oriented services in WiMAX. Therefore, the Unified connection-oriented Architecture is capable of allocating the bandwidth more efficiently and scheduling upstream transmission in a more accurate way.

In [74], the authors proposed an intra ONU-BS scheduling algorithm termed Hybrid Priority Weighted Fair Scheduling (HPWFS) in order to progress the QoS performance of the EPON and WiMAX integrations without bandwidth starvation for the low priority class of service. HPWFS allocates bandwidth between the ONU-BS associated priority queues in the following orders. First the bandwidth will be allocated to the two highest priority queues and then the bandwidth allocations will be considered for the BE priority queue. The remaining bandwidth will then be recalculated and distributed among the third and the fourth priority queues based on an equation which takes into account their priority factor and weighting. HPWFS works along with the Prediction based executive DBA (PE-DBA) algorithm and the QoS mapping mechanism in order to improve the QoS performance of all traffic classes in an EPON - WiMAX integrated network.

In [70], the authors proposed slotted-DBA (S-DBA) algorithm for the EPON and IEEE 802.16 converged scenario which can work as part of the existing DBA algorithm and can be applied to one part of the integrated scenario (either the optical or wireless part) or both parts. The S-DBA algorithm increases bandwidth utilisation by reducing the signalling overhead caused by cascading bandwidth requests and grants in both optical and wireless parts of the converged scenario.

In [75], the authors presented an Emergency-Aware Mission-Critical Fibre-Wireless Broadband Access Network (MC-FiWiBAN) that leverages the layer 2 VPNs over the EPON-WiMAX integrated network to provide the mission-critical service support. They have presented a resource allocation framework to achieve a guaranteed QoS level for the MC services based on the VPN SLA definitions. The Mission Critical (MC) traffic will be mapped to one of the WiMAX CoSs based on its type and the QoS requirements in order to support the ETE QoS. However, as the emergency traffic requires QoS protection and immediate transfer, they proposed a new IEEE 802.16 CoS termed Emergency Grant Service (EGS). The EGS has the highest priority over all other service classes and will be reported to the ONU-BS whenever the associated emergency event occurs which will be placed in a separate buffer. The simulation results demonstrate that MC- FiWiBAN extends the MC coverage to the rural area while providing a robust and reliable connection for the MC services and guarantees the QoS requirements for different types of services.

In [76], the authors proposed a QoS-base DBA algorithm and scheduling scheme for an EPON – WiMAX integrated scenario. They designed two steps scheduling process in which five service classes of WiMAX will be mapped into three service classes of EPON. They applied Weighted Round Robin (WRR) to the mapped priority queues in such an order that the highest traffic type has more chance to be transmitted in hybrid architecture which improves the QoS metric in terms of ETE packet delay, average queue length and packet drop probability.

In [66], the authors proposed a DBA algorithm for the planned OOW architecture which will be executed in three levels of WiMAX - BS, ONU - BS and sub-OLTs. The simulation experiments show improvements in terms of average throughput as well as average and maximum delay for different classes of service.

In [68], the authors evaluated the performance of the integrated scenario under two scheduling mechanisms: Independent Scheduling (IS) and Central Scheduling (CS). In IS, data will be transmitted separately between the EPON and WiMAX without sharing information such as bandwidth reservations and QoS mapping which would induce longer ETE packet delay. However, the CS mechanism reduces the ETE packet delay as well as the transmission delay by sharing the status of the bandwidth reservation and providing the QoS mapping between the optical and wireless domains.

To the best of our knowledge, the traditional single channel PON has been addressed in most of the existing work related to the optical and wireless technology integrated scenario.

In conventional TDM-PON the 1Gb/s symmetric channel capacity is shared by group of ONUs (typically 16) each supplied with ~ 65 Mb/s of channel capacity (1Gb/s divided by16) which almost matches the total capacity offered by an IEEE 802.16 BS which is about 70 Mbps over a 20 MHz channel [39]. Therefore, providing services to a single BS by a single ONU from a conventional TDM-PON is feasible as the total channel capacity will be almost matched. Thus, there will be no bandwidth bottleneck problem at the converged point (ONU-BS). However, the number of BSs supported by a single ONU is limited to one BS and total number of supported BSs for the whole converged scenario is limited to 16 BSs (1 BS × 16 ONUs).

A solution for such a problem is to provide the OLT in CO with multiple wavelengths over the same fibre channel which resembles the conventional WDM-PON structure. An OLT with multiple channels provides higher bandwidth for each ONU which results in supporting more number of BSs and finally more number of SSs at the front-end customer premises.

However, providing an OLT and ONU with multiple wavelengths brings many challenging issues. For instance, OLT-ONU and ONU-BS real-time and dynamic wavelength and bandwidth allocation techniques, light source requirements on OLT, ONUs and BSs, the number of ONUs and BSs allocated per channel per service cycle are some of the challenges.

By taking into consideration the above discussions, a distributed, real-time, dynamic and scalable resource (wavelength/bandwidth) allocation algorithm, which will be fully detailed in chapter 5, is proposed by the author of this thesis for the resource allocation issues over the converged infrastructure of the NGN.

The following section identifies the proposed solutions (three contributions of this thesis), which will be clearly discussed and detailed from chapter 4 to chapter 6, for the converged infrastructure of the NGN in the two main categories of architecture (first contribution) and MAC- related issues (second and third contributions).

3.3.3 Proposed Solutions for the Converged Infrastructure of the NGN

Taking in to consideration the motivation of this thesis (chapter 1, section 1.1), objectives of this thesis (chapter 1, section 1.2) and the stated challenges and issues in this chapter, this section presents an overview of the proposed solutions as follows.

Comprehensive framework for the converged infrastructure of the NGN: A semi-independent structure for the architectural design of the converged protocol is proposed, developed and evaluated. It employs the available fixed (particularly optical) and wireless network components in the market by taking into account additional functionalities and features with no need for full replacement. In the semi-independent structure of the converged protocol each component of the converged model works independently from other part based on the defined standards, protocols, characteristics and specifications and also works as a part of the converged scenario by upgrading it with extra functionalities and features with no need for a full substitution. The proposed framework is supported with all the specific and required ETE functional modules which need to be run in the appropriate sequence in order to provide a smooth ETE data transmission between optical and wireless infrastructure of the NGN. The proposed framework is evaluated with respect to its key functional modules, on which this PhD thesis is focused, as a function of the exiting resource (wavelength/bandwidth) allocation algorithms (static/dynamic).

Distributed, real-time, dynamic and scalable resource allocation algorithm for the converged infrastructure of the NGN: An Inter-channel and Intra-channel Dynamic Wavelength/Bandwidth Allocation (IIDWBA) algorithm is proposed in order to provide the ETE dynamic wavelength/bandwidth allocations across the converged infrastructure of the NGN. While a given bandwidth allocation algorithm (static/dynamic) deals with the issue of the bandwidth allocations over a single channel, the IIDWBA algorithm deals with the resource (wavelength/bandwidth) allocations over multi-channels. The proposed algorithm works in three phases termed as Initialisation phase, Intra-channel bandwidth allocations phase and Inter-channel bandwidth allocation phase and capable of identifying the possible excess bandwidth over all the channels associated with given SST, collecting them, scheduling them and then distributing them across all the CSs with higher bandwidth demands which may be scattered over different channels. The performance of the proposed algorithm is evaluated with respect to the optimum or near optimum resource utilisation that it brings to the converged infrastructure of the NGN through various traffic pattern configurations, simulation parameters as well as the different scenarios.

Intelligent resource allocation algorithm for the converged infrastructure of the NGN: The basis of the proposed IIDWBA algorithm is explored in order to put forward a GA-based IIDWBA algorithm for optimum or near optimum bandwidth utilisation over the converged infrastructure of the NGN. The main objective of using the GA techniques, which run in phase three of the proposed IIDWBA algorithm, is to maximise the total allocated excess bandwidth from all the channels associated with a given SST to all the heavily loaded CSs which may be scattered over different places. The GA-based excess bandwidth allocation occurs once per service cycle and in such a way that the allocated bandwidth is not more than the requested excess bandwidth by a given CS and is also not more than the available excess bandwidth on a given channel.

The proposed solutions listed above are described and detailed in the next three chapters of this thesis (chapter 4 to chapter 6). The next chapter (chapter 4) presents the design, implementation and evaluation of the proposed architectural design of the converged protocol for the NGN. Similarly, chapter 5 is about the proposed IIDWBA algorithm whereas chapter 6 deals with the GA-base solutions for the proposed IIDWBA algorithm.

3.4 Chapter Summary

This chapter presented the general background about the history of the optical and wireless converged scenarios mostly in area of the ETE architectural aspects and MAC related issues. The needs, benefits, requirements and challenging issues for such integration were highlighted next. Promising nominees from each domain along with the individual challenging aspects and mutual characteristics were also identified in order to provide an smooth converged infrastructure of the NGN. The identified gap in the area of the architectural design as well as the MAC related issues of the converged scenario were then emphasized which brought the key contributions of this thesis termed as: architectural design of the converged protocol, a distributed, real-time, dynamic and scalable resource allocation algorithm for the converged scenario as well as the Intelligent resource allocation algorithm for the converged scenario. An overview of the key thesis contributions was presented and detailed at the end of the chapter.

Chapter 4 Architectural Design of the Converged Protocol

This chapter represents the first key contribution of this thesis, namely, architectural design of the converged protocol. It first justifies the need for such a design for the converged infrastructure of the NGN. It then presents the related work in the area of the architectural aspects of the converged scenario between fixed, particularly optical, and wireless technologies. It then describes the detail of the proposed architectural design of the converged protocol along with the ETE component specifications and functional modules from the OLT at the far-end central office all the way to the WLAN subscriber stations at the front-end customer premises. This is followed by discussions about the key functional modules of the integrated scenario on which this PhD work is focused. Finally, it evaluates the performance of the proposed architectural design of the converged protocol through simulation experiments which is followed by a summary of the chapter.

4.1 The Need for Architectural Design of the Converged Scenario

To date, a wide range of research has been done for the successful design of the converged scenario which saves CapEx and OpEx costs and provides reliable and robust connectivity for the next generation broadband access networks.

Taking into consideration the key goals of the NGN [132], the converged scenario, particularly between optical and wireless technologies, has been studied in the three categories of Architectural aspects, MAC-related issues and Physical layer features.

The Architectural aspects include the way two technologies connect to each other along with the ETE functional modules, physical structure, component specifications as well as the distance arrangements.

The MAC-related issues include the ETE resource negotiations, resource allocations and resource scheduling such as wavelength/bandwidth requests and allocations, upstream scheduling techniques as well as ETE QoS support.

In Physical layer features, most of the work has focused on providing the cost-effective and reliable Radio over Fibre (RoF) systems, for instance providing RoF systems in order to use a single modulator for both wired and wireless services simultaneously [57] [58].

Taking into consideration the architectural infrastructure of the converged NGN (the first key contribution of this thesis), there are some keys and challenging issues which need to be addressed efficiently and effectively in order to provide the smooth ETE integration between the two technologies for the NGN. For instance, keeping the existing infrastructure and the key elements from two technologies or merging the key components from each technology in a single box. Moreover, the ETE functional modules, the key functional modules as well as the running sequences and running orders along with the distance requirements and component arrangements need to be explored in detail. These problems are addressed in this chapter along with the requirements of the proposed architectures of the converged protocol. The next section provides a review of the architectural designs for the converged scenario which have been proposed in literature.

4.2 Existing Architectural Designs for the Converged Scenario

In terms of architectural design of the converged scenario, particularly for the EPON (from the optical domain) and WiMAX (from the wireless domain), the authors in [59] proposed four structures termed Independent structure, Hybrid structure, Unified Connection-Oriented architecture and Microwave-over-Fibre structure. These four structures were fully discussed in chapter 3 (section 3.3.1)

In this chapter, a semi-independent structure for the architectural design of the converged protocol is developed aimed to employ the optical and wireless components and infrastructures which are available in the market by taking into consideration adding the extra functional modules with no need for full replacement. In the semi-independent structure, which will be discussed in detail later in this chapter, each part of the converged scenario such as the ONU and the BS, which are termed advanced ONU and advanced BS respectively, can work independently from other parts based on the standard characteristics and specifications and also work as part of the converged scenario by upgrading with extra modules and functionalities. This is the main difference between the architectural design of the converged protocol, which is proposed in this chapter, and the Independent structure work which was proposed in [59].

The next section provides a detailed description about the proposed architectural design of the converged protocol for the NGN.

4.3 Proposed Architectural Design of the Converged Protocol

In this section, the proposed semi-independent structure for the architectural design of the converged scenario for the NGN is discussed in detail. It includes the ETE component specifications based on the existing components in the market, proposed ETE functional modules and proposed ETE key functional modules on which this PhD is focused.

The full proposed ETE function modules are presented later in this chapter (Figure 4.3) with support of arrows which run periodically and in sequence one after another and will be discussed in detail later in this chapter.

The next section discusses the ETE components of the converged scenario which exist in the market and form the basic infrastructure for the proposed architectural design of the converged protocol.

4.3.1 ETE Existing Components of the Converged Network Model

The ETE existing components of the converged scenario include the elements as follows: Optical Line Terminal (OLT) in CO, Arrayed Waveguide Grating (AWG), Optical Amplifier (OA), Optical Network Unit (ONU), 1 : N passive Splitter/Combiner, Light sources and wireless Base Stations (BSs). These are the optical and wireless network components which exist in the market and each of them plays a different role in the proposed architectural design of the converged protocol in this chapter.

They are discussed briefly as follows in order to know their functionalities before moving to the architectural design of the proposed converged protocol.

Generally speaking, the converged infrastructure consists of the two incorporated domains of the optical (fixed part) and the wireless domain.

The components of the fibre-optic network are utilised in order to form the optical domain which are more sophisticated than a conventional copper-wired system. It includes the OLT, AWG, OAs, ONUs, 1:N passive Splitters/Combiners, light sources and fibre ducts.

The components of the wireless domain include network elements such as the BS, which acts as a wireless gateway between the optical and wireless domains, and the wireless domain of which a given BS is responsible for providing wireless services.

The components of the optical domain are discussed as follows. They are the existing components in the market which are then followed by the component specifications for the wireless part of the integrated infrastructure.

A. Optical Line Terminal (OLT)

OLT [105] is one of the key components of the optical domain which is seated inside the central control room and features the network management functions. The OLT has the highest authority over the converged scenario in terms of allocating resources (wavelengths/bandwidth) to the associated ONUs and is termed the ultimate server station over the converged simulated scenario. From the OLT's point of view, the converged scenario, which is started from the AWG and ended at the WLAN users at the front-end customer premises, acts as a PON.

B. Arrayed Waveguide Grating (AWG)

The AWG is a successful device in WDM-PON industry which has been used for many long-reach WDM systems. It is capable of routing each wavelength to a unique out port, separating the multiple wavelengths from each other as well as combining and sorting different channels. Moreover, it can be a multiplexor as well as a de-multiplexor at the same time based on the cyclic wavelength property features.

An $N \times N$ AWG is usually called AWG router as it can realize $N \times N$ optical wavelength routing using only a single component [106]. When the free-spectral range of $N \times N$ AWG is N times, it is capable of processing $N \times N$ optical interconnections in a non-blocking way because of the cyclic property of the output wavelengths [107].

An AWG can be "pumped" with different numbers of wavelengths with same/different bit rates each supplied for a single out port. For instance, if N wavelengths are pumped into a given $N \times N$ AWG all with the same capacity of 1Gb/s, each out port will ideally pick up one of the input wavelengths with the equal capacity of 1Gb/s.

C. Optical Amplifier (OA)

In a traditional single channel TDM-PON, the maximum distance between OLT and ONU is set as 20 km and 10 km to support a maximum number of 16 and 32 ONUs, respectively [24]. Implementing AWG reduces the power budget by 4dB and the distance by 16 km (~0.25 dB power loss per km). In order to compensate for the attenuation losses, an OA [108] should be set up between OLT and ONU which helps to extend the PON reach and capacity. Semiconductor Optical Amplifiers (SOAs) and Earth Dependence Fibre Amplifier (EDFA) [109] are the most practical OAs to date. In this thesis, the OAs are assumed to be co-located with AWGs which are seated between OLT and ONUs and a given ONU and BSs.

D. Optical Network Unit (ONU)

An ONU is the user side, economic and high efficient optical element which plays an important role in FTTX fibre optic networks and provides many types of broadband service such as VoIP, HDTV, Video on Demand (VoD) and video conferencing to the front-end subscriber stations.

An ONU is capable of converting optical signals received from the OLT to electronic signals at the user side which provides the smooth and reliable ETE connection from the front-end customer premises all the way to the OLT in the CO [105].

In this thesis, a given ONU which is seated between the OLT and BSs, is responsible for providing resources (wavelength/bandwidth) for the associated BSs. If an ONU uses a different wavelength for the upstream and downstream transmissions, the same AWG port can be assigned for both directions. Coarse Wavelength Division Multiplexing (CWDM) then needs to be employed as a filter inside each ONU in order to separate

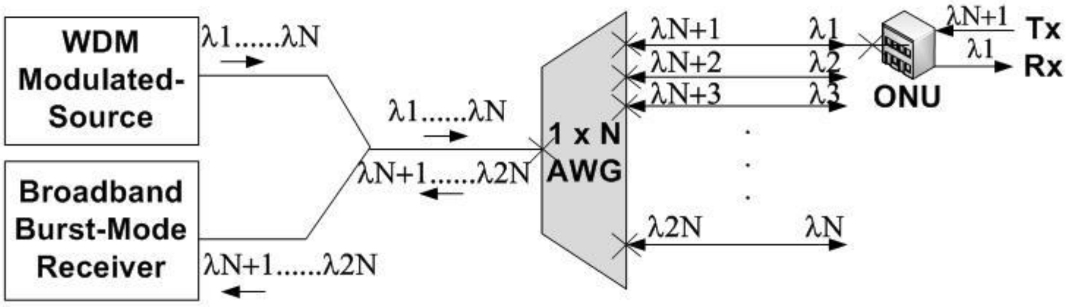

Figure 4.1 Bidirectional transceivers on the AWG and ONU

both wavelengths (bidirectional transceivers [110] at ONUs and AWG), Figure 4.1. However, if an ONU uses same wavelength for both directions (sharing resources) then two different ports should be assigned for each direction (unidirectional transceivers [110] at ONUs and AWG), Figure 4.2.

E. 1 : N Passive Splitter/Combiner

A 1: N passive splitter/combiner is one of the key components in FTTX world which includes the typical parameters such as: input cable length, output cable length, splitting ratio, connector types and working wavelengths [105].

A 1: N passive splitter/combiner is a plain power splitter in which the input power will be equally divided based on the number of the available/supported/active out ports. For instance, if a plain 1:16 passive splitter/combiner is pumped in with the transmission capacity of 1Gb/s, each out port will identically receive about 62.5 Mb/s bit rates (1 Gb/s divided by 16).

F. Light sources within the OLT, ONU and BS

The light sources over the converged scenario inside the OLT, ONUs and BSs can be in

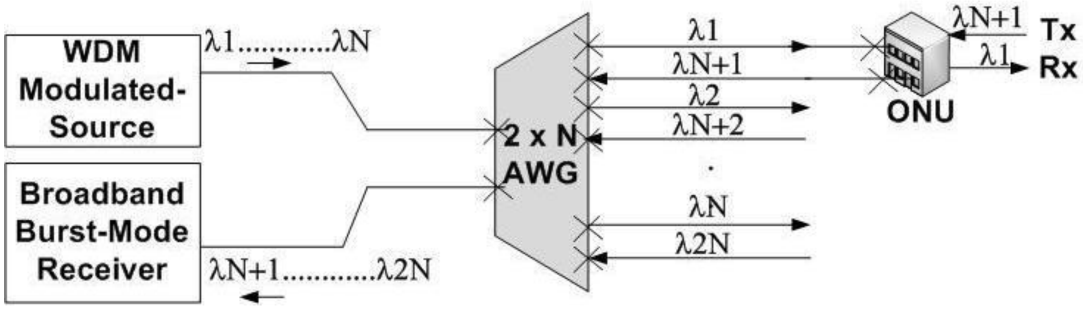

Figure 4.2 Unidirectional transceivers on AWG and ONU

the following four formats [110]. They are provided in order to align the associated transmitter from each network component with the allocated channel.

1. With a fixed wavelength: A given device can only choose a fixed wavelength for transmission. A cost-effective Fabry-Perot (FP) laser can serve as a light source here.

2. With two or more wavelengths (FPs): A given device can choose one of the wavelengths for transmission.

3. With a Tuneable Laser (TL): A given device can choose any of the available upstream wavelengths.

4. With an Array of Single-Wavelengths Laser (Multiple Wavelength Laser Array): A given device can simultaneously send/receive traffic to/from any of the available channels.

For more information about the optical elements please refer to [108], [105], [106] and [107].

G. *Wireless domain*

The wireless domain of a given converged model can be a Wireless Mesh Network (WMN) [54] which may employ technologies such as World Wide Interoperability for Microwave Access (known as WiMAX [39]), Wireless Fidelity (known as WiFi [44]) and Cellular Network [47], [48], [49] and [50] each has different characteristics. A full discussion about the wireless technologies was provided in chapter 2.

In this thesis, the wireless domain of the integrated scenario includes wireless components such as IEEE 802.16 BSs, IEEE 802.11 APs and finally number of wireless workstations at the front-end customer premises. 802.16 BS acts as a wireless gateway as it connects the optical and wireless domains to each other. It also provides wireless services for a number of 802.11 APs which are located after a given BS. A given 802.11 AP provides wireless services to the number of wireless workstations at the front-end customer premises.

Generally speaking, in this thesis, BSs are connected to the corresponding ONUs through N : N AWG and 1 : N Splitters/Combiners from one side and to the number of 802.11 APs as well as number of wireless workstations from the another side.

Taking into consideration the above discussions about the existing components from the fixed domain, particularly optical, and the wireless technologies, the required ETE functional modules, which form the proposed architectural design of the converged protocol are discussed in next section.

4.3.2 Proposed ETE Functional Modules

The ETE functional modules for the proposed architectural design of the converged protocol includes all the modules which need to be provided inside OLT, ONUs, BSs, APs as well as the WLAN subscriber stations in order to develop an infrastructure for the multi-channel PON convergence with wireless technologies of NGN.

Taking into consideration the proposed ETE functional modules presented in Figure 4.3, this PhD work is focused on the shaded modules termed key functional modules including all the fundamental modules which are required for the ETE wavelength/bandwidth requests and allocation processes over the converged scenario of the NGN.

As Figure 4.3 reveals, all the proposed functional modules are marked with arrows which run periodically (runs once for static allocation or more for dynamic allocation), and also in sequence one after another. Based on the dynamic/static nature of the converged scenario, the functional modules can run only either once or once per service cycle. A service cycle is the maximum time duration that a given ONU or BS can wait before it gets a chance to transmit the buffered data in the directions of the OLT or the ONU, or both respectively. All the proposed functional modules in Figure 4.3 are detailed as follows.

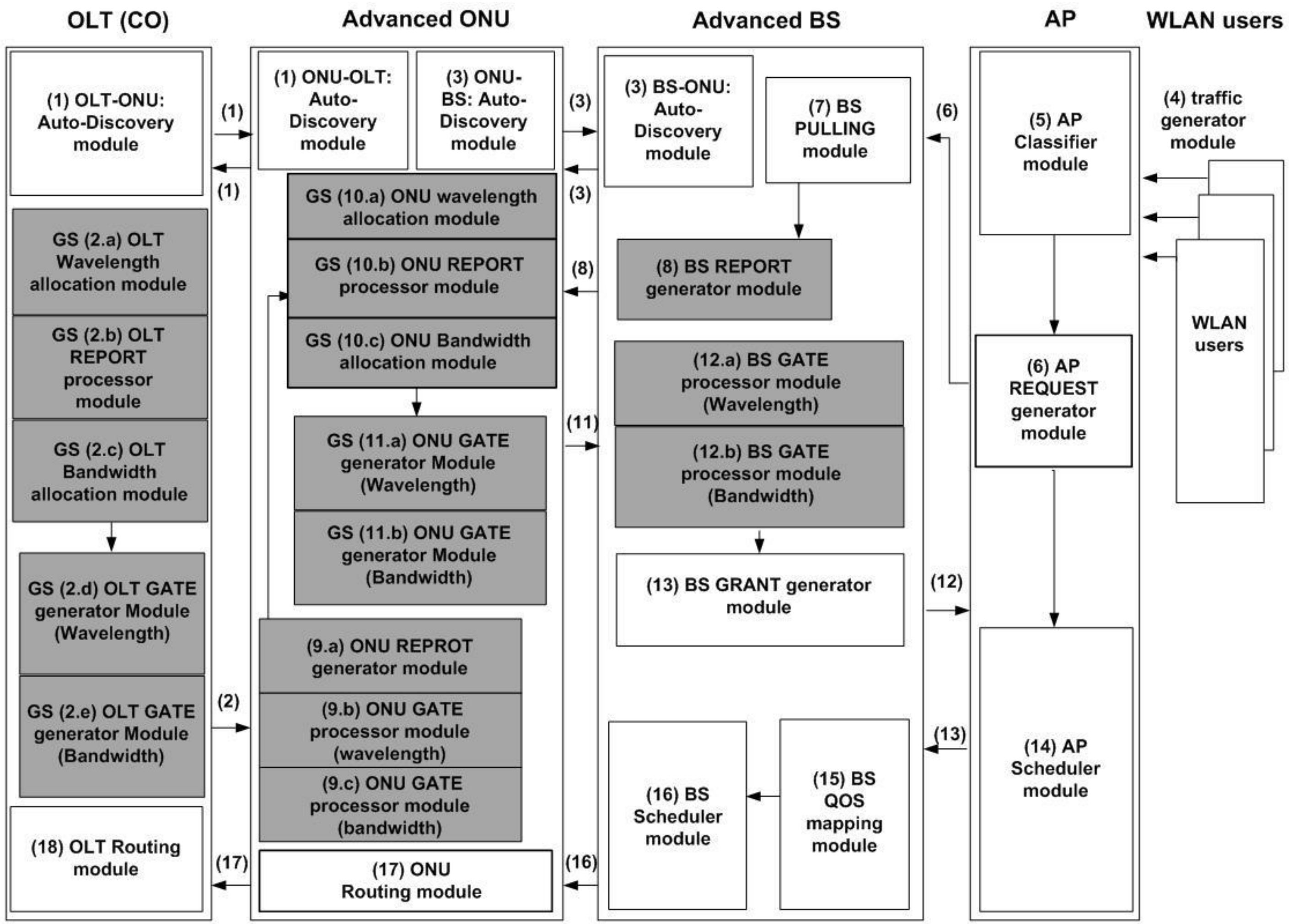

Figure 4.3 Proposed functional modules for the converged scenario: GS represents the components of the Global Scheduler

1) OLT-ONU and ONU-OLT -> Auto-Discovery modules: these modules are employed in order to discover and then register the existing ONUs into the OLT's optical domain. The fundamental waveband architecture, Table 4-1, MAC address as well as the RTT delay will be identified for each ONU at this stage by employing the MPCP Extension protocol.

   MPCP was developed by IEEE 802.3ah [29] in order to settle the real-time bandwidth negotiations in traditional TDM-based PON. It includes five 64 bytes control messages embracing both auto-discovery and bandwidth negotiations messages termed REGISTER_REQUEST, REGISTER, REGISTER_ACKNOWLEDGE, REPORT and GATE. While the MPCP provides time-slot assignment features, the MPCP Extension [32] adds wavelength assignment support to the conventional MPCP protocol which enables the OLT to schedule transmission to and from a given ONU on any available and supported wavelength. In the OLT-ONU and the ONU-OLT -> Auto-Discovery modules, the first three MPCP Ext. control messages termed REGISTER_REQUEST, REGISTER and REGISTER_ACKNOWLEDGE will be executed in order to register the available ONUs into the OLT's optical domain.

2) OLT-> wavelength / bandwidth allocation modules: OLT-> wavelength allocation module, module 2.a, allocates a wavelength (channel) to a given ONU based on the ONU's waveband architecture, which were collected by module 1, the OLT's supported and available wavelengths as well as the network load per channel, for instance, the number of ONUs associated with a given channel or traffic load on a given channel.

Table 4-1 MPCP Extension protocol [32] as part of the converged scenario

Name	Number of Bits	Values
transmitter and receiver type	2 bits each	no WDM (0), fixed-tuned (1), tuneable (2) and reserved (3)
transmitter and receiver tuning time	16 bits each	integer multiple of unit time (e.g. 2 for 2 microsecond)
wavelength id type	1 bit	two-level hieratical encoding (0) and flat encoding (1)
transmitter and receiver wavelength band	4 bits each	N/A
transmitter and receiver supported wavelengths	16 bits each If wavelength_id_type = 0 128 bits if the wavelength_id_type = 1	N/A

The wavelength allocation module needs a wavelength allocation algorithm (static/dynamic) to be implemented and installed in module 2.a placed inside the OLT. Moreover, the OLT allocates the bandwidth (channel portion) to a given ONU employing the implemented bandwidth allocation algorithm (static/dynamic) seated inside module 2.c. In dynamic bandwidth allocation, the bandwidth will be granted based on the ONU's actual need, which is reported in every service cycle and processed by module 2.b, the OLT's available bandwidth and also the DBA boundaries. The OLT-> GATE generator modules (wavelength/bandwidth) will be executed immediately after module 2.c in order to occupy the decided channel ID, which is the output from module 2.a, as well as the allocated bandwidth, transmission start time and transmission duration, which are the outputs from module 2.c, inside the MPCP Ext. GATE protocol. The generated GATE message will be broadcast immediately to all ONUs. Generally speaking, the MPCP Ext. REPORT and MPCP Ext. GATE messages are employed through module 2 in order to accomplish the OLT-> wavelength / bandwidth allocation processes.

3) The ONU-BS and BS-ONU -> Auto-Discovery modules: these modules are employed in order to determine the number of BSs in the ONU's optical domain. Information such as: Round Trip Time (RTT), individual MAC address as well as the waveband boundaries will be collected from each BS during this stage. The MPCP Ext. protocol particularly REGISTER_REQUEST, REGISTER and REGISTER_ACKNOWLEDGE messages are employed for such purposes. This information will be employed for future wavelength/bandwidth allocations from a given ONU to the corresponding BSs. The functionalities of the ONU-BS and BS-ONU -> Auto-Discovery modules are the same as the OLT-ONU and ONU-OLT -> Auto-Discovery modules, module 1. In Figure 4.3, a given ONU and BS are termed as "advanced ONU" and "advanced BS", respectively, as not all the functional modules that are presented are supported by the ONUs or BSs in the current market. For instance, to the best of our knowledge, in today's market, there is no BS that is capable of supporting optical connectivity and also there is no ONU that can function like an OLT.
4) WLAN users-> traffic generator module: This module, which is the only source to generate the network traffic, produces traffic with different priorities as soon as WLAN users start their Internet connections.
5) AP-> Classifier module: User traffic, which is generated by module 4, is immediately received by the associated AP and passed through the AP Classifier module. It classifies different traffic types by buffering them based on the traffic

priorities e.g. the first priority belongs to the voice traffic, the second priority belongs to the video traffic and the lowest priority is associated with the email traffic.

6) AP-> REQUEST generator module: as soon as the AP's buffers are occupied with data traffic from the associated WLAN users, the AP REQUEST generator module sends bandwidth requests to the associated BS. Bandwidth requests from a given AP will be issued per priority queue and will be classified based on the priority queue and the requested bandwidth inside the associated BS.
7) BS-> PULLING module: It pulls the AP bandwidth requests and goes to the next module immediately.
8) BS-> REPORT generator module: The BS needs to send the regular MPCP Ext. REPORT messages in order to ask for bandwidth from the associated ONU. The BS generalises the different bandwidth requests received from the associated APs based on the connection ID, requested amount of bandwidth (bits) as well as the Class of Service (CoS) inside Bandwidth Request Table (BRT). The REPORT generator module is responsible for tailoring the requested bandwidth (bits) from all APs associated with a given BS at the end of the latest received MPCP Ext. GATE message from the ONU. The BS then needs to wait for the next MPCP Ext. GATE message to arrive before sending any data to the ONU. The MPCP Ext. is able to report on up to eight different priority queues inside each single MPCP Ext. REPORT message.
9) ONU-> REPORT generator and GATE processor (wavelength/bandwidth) modules: The ONU-> REPORT generator module, module 9.a, is provided inside the ONU for the purpose of bandwidth requests from the OLT which is capable of reporting

up to eight priority queues in every service cycle. The ONU-> GATE processor (wavelength/bandwidth) modules, modules 9.b and 9.c, are also presented in order to find out the wavelength/bandwidth allocation decisions from the OLT including channel ID, amount of allocated bandwidth (channel portion), transmission start time and transmission duration in every service cycle.

10) ONU-> wavelength/bandwidth allocation modules and ONU-> REPORT processor module: These features require the wavelength/bandwidth allocation algorithms (static/dynamic) to be installed inside the ONU, inside modules 10.a and 10.c respectively, in order to allocate the wavelength and bandwidth, respectively, from a given ONU to the associated BSs. The ONU-> REPORT processor module, module 10b, also helps the wavelength/bandwidth allocation processes by processing the bandwidth requests received from the associated BSs in every service cycle.

11) ONU-> GATE generator modules (wavelength /bandwidth): The wavelength/bandwidth allocation decisions, which are decided by modules 10a and 10.c, respectively, reside inside the MPCP Ext. GATE messages by the ONU-> GATE generator modules (wavelength /bandwidth) and are broadcast immediately to all BSs. The MPCP Ext. GATE messages carry the allocated channel ID, allocated bandwidth (channel portion) as well as the transmission start time and transmission duration for all the associated BSs of a given ONU in a given service cycle.

12) BS-> GATE processor modules (wavelength /bandwidth): The wavelength and bandwidth allocation decisions, which are generated by module 11 and received at a given BS in the format of the MPCP GATE message, need to be processed by the GATE processor module installed inside a given BS, modules 12.a and 12.b,

respectively. First, the MAC address should be checked; obviously, non-match MPCP Ext. GATE messages will be discarded as they are meant to be for other BSs in the same optical domain. If the MAC address is matched, the wavelength ID, transmission start time and transmission duration will be captured in order to schedule the transmission of the data traffic from a given BS over the allocated channel ID.

13) BS-> GRANT generator module: This module distributes the latest received GATE message among all the bandwidth requests which have previously arrived from the associated APs on a given BS. The bandwidth requests were pulled from the APs previously and stored inside the BS BRT during module 7 and 8 executions. The GRANT messages will be received by the APs after the execution of the BS-> GRANT generator module and they will be sent to the SCHEDULER inside a given AP (module 14) immediately.

14) AP-> SCHEDULER module: This is the only module inside a given AP which has access to different priority queues and decides which queue, for how long and in what order should start sending traffic. It will be executed immediately right after the granted bandwidth arrives on a given AP from the associated BS after module 13 execution.

15) BS-> QoS mapping module: This module maps traffic types with different QoS requirements from the wireless domain into the optical domain in order to provide smooth ETE data transmission. For instance, WiMAX supports five service classes termed UGS, rtPS, ertPS, nrtPS and BE while an EPON supports three service classes termed EF, AF and BE. Therefore, some mapping techniques need to be provided in order to map different classes of services travelling between the two

technologies. For instance, as the EPON supports up to eight priority queues, a possible solution is the one to one mapping technique in which each class of service in WiMAX will be mapped into a priority queue in the EPON. Another solution is to map WiMAX UGS to the EPON EF, WIMAX rtPs and WiMAX nrtPS to the EPON AF and WiMAX nrtPS and WiMAX BE to the EPON BE services.

16) BS-> Scheduler module: This module specifies which queue in what order and for how long should start sending data traffic to the ONU. BS-> Scheduler module is executed immediately after the QoS mapping module, module 15.

17) ONU-> ROUTING module: The data traffic which arrives from a given BS on a given ONU will be forwarded to the OLT immediately using the ONU-> ROUTING module. This is the traffic which was originally generated from the WLAN users, module 4.

18) OLT-> ROUTING module: Finally, data bursts which arrived from WLAN users respectively on a given AP, BS, ONU and OLT will be directly forwarded to the Internet using the OLT-> ROUTING module.

Table 4-2 has summarises all the possible ETE delays that a given packet experiences during the journey from a WLAN subscriber station at front-end customer premises to the associated AP and BS and then from a given BS to the associated ONU and then finally to the OLT in the far-end central office. The whole process is divided into five stages as WLAN, AP, BS, ONU and OLT and the possible delays in every phase are identified.

The next section discusses the proposed key functional modules, among module 1 to module 18 (Figure 4.3). They are termed key functional modules as they have key roles as part of the resource (wavelength/bandwidth) allocations over the converged scenario, on which this PhD is focused.

4.3.3 Proposed ETE Key Functional Modules

In this section, the key functional modules of the converged infrastructure of the NGN from Figure 4.3 are discussed. They are called key functional modules as the main work in this PhD project is focused on them.

In Figure 4.3, the key functional modules (module 2,8,9,10,11 and 12) are specified from the other modules by colour. They are termed key functional modules as they have key roles as part of the wavelength/bandwidth allocations from the OLT to the ONUs and then from a given ONU to the associated BSs. The key functional modules can run periodically e.g. once per service cycle or run only once at the beginning of the network

Table 4-2 ETE delays for the integrated scenario

WLAN	Media access delay
AP	Classification delay, Queuing delay, Media access delay, REQUEST generator delay, GRANT processor delay, Scheduling delay
BS	REQUEST processor delay, REPORT generator delay, GATE processor delay (wavelength), GATE processor delay (bandwidth), GRANT generator delay, QoS mapping delay, Queuing delay, Scheduling delay
ONU	REPORT processor delay, REPORT generator delay, GATE processor delay (wavelength), GATE processor delay (bandwidth), Wavelength allocation algorithm delay, Bandwidth allocation algorithm delay, GATE generator delay (wavelength), GATE generator delay (bandwidth), Queuing delay
OLT	REPORT processor delay, Wavelength allocation algorithm delay, Bandwidth allocation algorithm delay, GATE generator delay (wavelength), GATE generator delay (bandwidth)

setup stage. This is how the dynamic or static nature of the ETE wavelength/bandwidth allocations is formed.

For instance, if the OLT allocates channel (wavelength) to a given ONU during the OLT-ONU and ONU-OLT -> Auto-Discovery stages only once, the OLT -> wavelength allocation module runs only once. However, if the allocated channel from the OLT to a given ONU is changed during the simulation run time based on e.g. channel load or channel availability, the OLT -> wavelength allocation module (module 2.a) will need to run periodically, e.g. once per service cycle, in order to provide the dynamic wavelength allocations for the associated ONUs.

The next section will evaluate how the dynamic or static nature of the OLT-ONUs and ONU-BSs wavelength/bandwidth allocations can affect the QoS performance for the integrated scenario. The proposed key functional modules are detailed in Table 4-3 considering each of them running periodically, e.g. once per service cycle, in order to provide the OLT-ONUs as well as ONU-BSs full dynamic wavelength/bandwidth allocations over the converged scenario.

4.4 Overview of Experiments

An overview of the experiments, which will be conducted in this chapter in order to evaluate the performance of the proposed architectural design of the converged protocol, is presented in Figure 4.4. It includes the investigation details along with the simulation coding and settings, key figures as well as the relevance of the results to the objectives of this thesis. It is to be noted that the experiments will be conducted only for the key functional modules on which this PhD project is focused.

Table 4-3 Key functional modules for the converged scenario

Module	Module name	Converged Scenario (Full Dynamic) (Each module runs once per service cycle)
(2.a)	OLT -> wavelength allocation	This module runs once in every service cycle in order to allocate a wavelength id from the OLT to a given ONU. The allocated wavelength may change per service cycle based on the load per channel as well as the total network load taking into account the available wavelengths on the OLT as well as the supported wavelengths on the OLT and a given ONU.
(2.b)	OLT -> REPORT processor	This module runs once in every service cycle in order to capture the queue status of a given ONU which may be different in every service cycle based on the dynamic nature of the Internet traffic.
(2.c)	OLT -> bandwidth allocation	This module runs once in every service cycle in order to allocate bandwidth from the OLT to a given ONU by taking in to account the actual need of a given ONU (captured from module 2.b), traffic status on other ONUs (network traffic) and bandwidth allocation boundaries e.g. the minimum guaranteed bandwidth for each ONU and maximum transmission window.
(2.d)	OLT -> GATE generator (wavelength)	This module runs once per service cycle in order to insert the wavelength allocation decisions (module 2.a outputs) inside the MPCP Ext. GATE messages and immediately goes to module 2.e.
(2.e)	OLT -> GATE generator (bandwidth)	This module runs once per service cycle in order to insert the bandwidth allocation decisions (module 2.c outputs) inside the MPCP Ext. GATE messages which will broadcast immediately to all the ONUs.
(8)	BS-> REPORT generator	This module runs once per service cycle in order to report the queue status of a given BS (buffer length) to the associated ONU. The reported queue status may be changed per service cycle based on the dynamic nature of the Internet traffic.
(9.a)	ONU-> REPORT generator	This module runs once per service cycle in order to update the OLT about the buffer length (queue status) which is associated with a given ONU.
(9.b)	ONU-> GATE processor	This module runs once per service cycle in order to disclose the channel ID allocated from the OLT to a given ONU

	(wavelength)	which may be different in each service cycle based on the network load, channel supports and availability as well as the waveband boundaries.
(9.c)	ONU-> GATE processor (bandwidth)	This module runs once per service cycle in order to reveal the amount of the allocated bandwidth from the OLT on associated channel ID (outputs from module 9.b) along with the transmission start time and transmission duration for a given ONU.
(10.a)	ONU-> wavelength allocation	This module runs once per service cycle in order to allocate a channel ID from the ONU to a given BS which may be different in each service cycle based on the load on a given BS, total channel load, supported channels and available channels.
(10.b)	ONU-> REPORT processor	This module runs once per service cycle in order to unveil the buffer length (queue status) associated with a given BS in a given service cycle before deciding any bandwidth allocations from a given ONU to the associated BSs.
(10.c)	ONU-> bandwidth allocation	This module runs once per service cycle in order to allocate bandwidth (channel portion) from a given ONU to the associated BSs based on the bandwidth allocation boundaries, available bandwidth as well as the queue status of a given BS (output from module 10.b).
(11.a)	ONU-> GATE generator (wavelength)	This module runs once per service cycle in order to insert the allocated channel ID (outputs from module 10.a) into the MPCP Ext. GATE messages and then goes straight to module 11.b.
(11.b)	ONU-> GATE generator (bandwidth)	This module runs once per service cycle in order to insert the bandwidth allocation decisions from the ONU (outputs from module 10.c) inside the MPCP Ext. GATE messages, which also carry the allocated channel id for a given BS (inserted by module 11.a). The generated GATE messages will then broadcast immediately to BSs of a given ONU.
(12.a)	BS-> GATE processor (wavelength)	This module runs once per service cycle in order to disclose the allocated channel id assigned from a given ONU to the associated BS by module 10.a during the latest service cycle.
(12.b)	BS-> GATE processor (bandwidth)	This module runs once per service cycle in order to capture the allocated amount of bandwidth, transmission start time, transmission duration as well as the occupied MAC address assigned from a given ONU (outputs from module 10.c) to the associated BS.

Investigation Details
To demonstrate the performance of the proposed architectural design of the converged protocol with the sole focus on the key functional modules for the integrated structure of the NGN

Simulation coding and settings
OPNET coding (C++): ETE key functional modules for Multi-channel converged scenario between optical and wireless technologies are implemented, an existing static wavelength allocation and two existing dynamic bandwidth allocations and MPCP protocol are also implemented in order to evaluate the performance of the key functional modules
Simulation setting: bursty traffic pattern (different ON/OFF state time, different traffic, different start /stop time, different packet size and different load pattern)

Key results and figures
Performance of the key functional modules from the proposed framework are represented through Figure 4.7 to Figure 4.18

Relevance of results to the thesis
A comprehensive framework for the converged infrastructure of the NGN, between optical and wireless technologies, is implemented and the key functional modules from the proposed framework are evaluated through conducted simulated experiments

Figure 4.4 Overview of experiments for chapter 4

They are termed key functional modules as they have key roles as part of the resource (wavelength/bandwidth) allocations over the converged scenario and are differentiated in Figure 4.3 from the rest of the functional modules by grey colour.

The next section presents the evaluation results of the proposed architectural design of the converged protocol by conducting the experiments listed here. Some of the following content is published by the author of this thesis in [124].

4.5 Simulation Results

This section provides the details of the experimental setup to evaluate the proposed architectural design of the converged protocol whose functional modules with sole focus on the key functional modules along with the specification of the running orders and running sequences that were presented in the previous section.

The next section discusses how the wavelength allocation is hierarchically handled over the proposed architectural design of the converged protocol taking into consideration the specific proposed functional modules for this task.

4.5.1 Hierarchical Wavelength Allocation Issues over the Converged Scenario

Before discussing the hierarchical OLT-ONUs and ONU-BSs wavelength/bandwidth allocation techniques, the meaning of the Server Station (SST) and Client Station (CS) are distinguished as follows.

A given SST is a network component which is responsible for providing resources (e.g. wavelength or bandwidth) for the associated CSs and a given CS is a network entity which requests resources periodically from the associated SST. For instance, in the converged scenario, the OLT at the far-end CO is the ultimate SST and a given WLAN subscriber station at the front-end customer premises is the ultimate CS. A given SST can be a CS and a given CS can be an SST at a given time. For instance, a given ONU is an SST in terms of providing resources for the associated BSs and a CS in terms of requesting resources from the OLT. A given BS is also an SST in terms of providing resources for the associated WLAN subscriber stations and a CS in terms of requesting resources from the associated ONU. Generally speaking, in this thesis, the OLT and ONU are addressed as SST and ONU/BS addressed as CS.

As it is depicted in Figure 4.3, the converged framework is provided with the functional modules required for the OLT-ONUs as well as the ONU-BSs wavelength allocation processes.

The key functional modules for this purpose are termed as: OLT -> wavelength allocation, OLT -> GATE generator (wavelength), ONU-> GATE processor (wavelength), ONU-> wavelength allocation, ONU-> GATE generator (wavelength) and BS-> GATE processor (wavelength) modules (modules 2.a, 2.d, 9.b, 10.a, 11.a and 12.a), Figure 4.3 and Table 4-3.

OLT -> wavelength allocation and ONU-> wavelength allocation modules, modules 2.a and 10.a, require a wavelength allocation algorithm in order to assign the available wavelengths from the OLT to the ONUs and then from a given ONU to the associated BSs, respectively. A given channel ID can be assigned based on the available wavelengths on the SSTs, supported wavelengths on the SSTs and CSs as well as the load per channel. The rest of the modules (2.d, 9.b, 11.a and 12.a) are provided in order to convey as well as distinguish the wavelength allocation decisions between the OLT and ONUs as well as a given ONU and the associated BSs.

For instance, the OLT wavelength allocation decisions will be included in the MPCP Ext. GATE messages by employing module 2.d which are then retrieved by the associated ONUs using module 9.b. Moreover, a channel will be allocated from a given ONU to the associated BSs by employing an ONU-> wavelength allocation module, module 10.a, and will be acknowledged to the BSs employing module 11.a. The allocated channel ID will then be revealed by a given BS employing module 12.a.

Due to comprehensive functionalities, the proposed structure, Figure 4.3, can be evaluated by employing different resource allocation techniques such as: static wavelength and static bandwidth allocations, static wavelength and dynamic bandwidth allocations, dynamic wavelength and static bandwidth allocations and dynamic wavelength and dynamic bandwidth allocations. In this chapter, the performance of the key functional modules is evaluated based on the static wavelength (channel) allocations and static/dynamic bandwidth allocations (channel portions) where a given channel will be allocated once from a given SST to associated CSs at the beginning of the network set up stage. The allocated channel will remain with the associated CSs permanently and will not be de-allocated and/or re-allocated to any other CSs. However, the granted channel will be shared among a number of CSs employing different bandwidth allocation algorithms (static/dynamic) which will be discussed in the next section.

The OLT-ONUs and ONU-BSs static wavelength allocations must be carried out before any bandwidth allocations are processed between the OLT and ONUs as well as between a given ONU and the associated BSs.

For these stages, a flowchart is provided, Figure 4.5, assuming that the number of available/supported channels on all SSTs and CSs is the same. It is also assumed that the total number of the CSs per SST is fixed. This stage is termed the Initialisation phase as it needs to execute at the network setup stage before the processing of any bandwidth allocations between the OLT and ONUs and between a given ONU and the associated BSs. The Initialisation phase is defined as follows.

Initialisation phase, which is the earliest stage for the OLT-ONUs and ONU-BSs wavelength/bandwidth allocation processes, includes the auto-discovery and registration steps during which a given CS joins the associated SST's domain and a default channel ID is assigned to it. However, after receiving the allocated channel ID, a given CS needs to wait in order to receive temporary access to the allocated channel in the form of a time-slot from the associated SST. A given SST may employ different bandwidth allocation algorithms for such an access.

In the Initialisation phase, first a given SST waits to receive all the registration requests from the associated CSs. Then, based on the total number of CSs in a given SST's domain, the available/supported wavelengths on a given SST and the supported wavelengths on the associated CSs, the SST starts allocating wavelengths to all CSs one at a time. The simplest way is to divide the total number of the CSs by the total number of the available/supported wavelengths on a given SST which gives the average number of CSs per channel. This allocation results in fair channel assignment at the beginning of the network setup stage in which the total number of the CSs sharing a single channel will be same for all the channels associated with a given SST. The output from this phase is multiple MPCP Ext. GATE messages which carry the associated MAC addresses of the CSs and the allocated channel IDs. The initialisation phase, which runs on all SSTs over a converged scenario, is the first part of the proposed algorithm which will be detailed in terms of algorithm specifications and mathematical descriptions in chapter 5.

The next section discusses how the bandwidth allocation is hierarchically handled over the proposed architectural design of the converged protocol taking into consideration the specific proposed functional modules for this task.

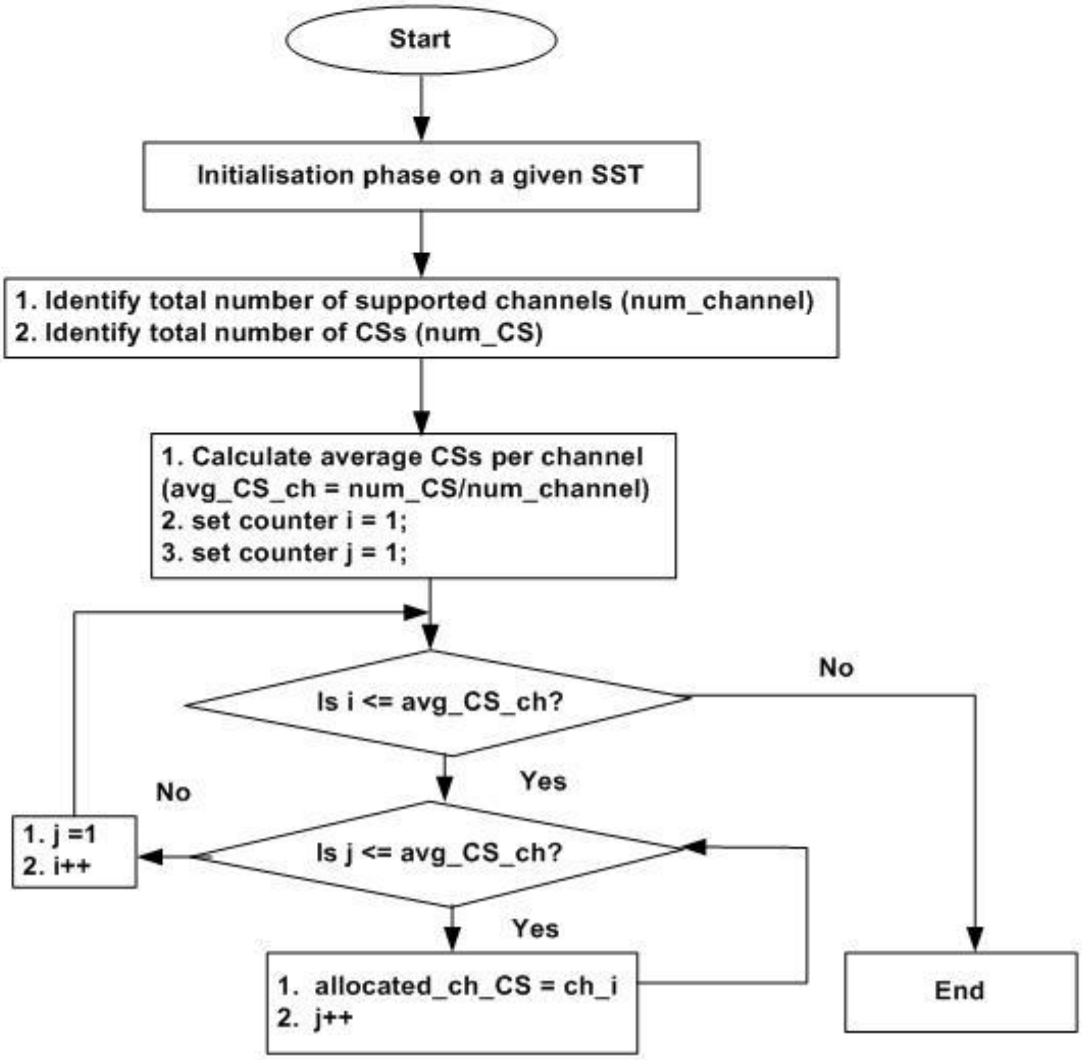

Figure 4.5 Flowchart for Initialisation phase

4.5.2 Hierarchical Bandwidth Allocation Issues over the Converged Scenario

Three existing bandwidth allocation algorithms termed *Fixed*, *Gated* and *Limited* from the literature review [2][80] and [6] are employed in order to evaluate the performance of the key functional modules in terms of the OLT-ONUs and ONU-BSs bandwidth allocation processes over the proposed framework as follows.

In the *Fixed allocation scheme*, fixed transmission windows will be allocated to each CS per service cycle regardless of the actual need.

In the *Gated allocation scheme*, a given CS will be granted whatever queue size it has reported in the latest service cycle.

In the *Limited allocation scheme*, there is an upper bound on the bandwidth allocation that a given CS will be granted. The CS will be granted the requested bandwidth if it is less than or equal to the upper bound limitation or else the upper bound limitation will be allocated.

Therefore, if B_i^{req} and B_i^{grant} are the requested bandwidth received from a given CS in $Cycle_{n-1}$ and the granted bandwidth to a given CS in $Cycle_n$, respectively:

In the *Fixed allocation scheme*, $B_i^{grant} = \alpha$, where α is the fixed granted transmission window in millisecond.

In the *Gated allocation scheme*, $B_i^{grant} = B_i^{req}$, as a given CS will be granted whatever bandwidth is requested in the latest service cycle.

In the *Limited allocation scheme*, if $B_i^{req} \leq B_i^{MIN}$, B_i^{req} will be granted to a given CS, therefore $B_i^{grant} = B_i^{req}$. However, If $B_i^{req} > B_i^{MIN}$, B_i^{MIN} will be granted, therefore $B_i^{grant} = B_i^{MIN}$.

The minimum guaranteed bandwidth, B_i^{MIN}, for a given CS is calculated as follows [6] (1).

$$B_i^{MIN} = \frac{(T_{cycle} - N\ x\ \ Guard\ time)\ x\ R_N\ x\ K\ x\ w_i}{8} \tag{4.1}$$

T_{cycle} is the total time during which *N* CSs get a chance to send their data traffic and/or REPORT messages to the associated SST. Guard time is the gap between two consecutive allocated time-slots. R_N is the transmission speed and *K* is the total number of available wavelengths in the system. w_i is the allocated weighting given to a CS based on the SLA definitions where ${}_{i=1}^{N} w_i = 1$. In case of no SLA classification w_i = *w* = *1/N* therefore:

$$B_i^{MIN} = \frac{(T_{cycle} - N\ x\ \ Guard\ time)\ x\ R_N\ x\ K\ x\ w_i}{8\ x\ N} \tag{4.2}$$

Table 4-4 reveals the sequence of the executions for the key functional modules (presented in Figure 4.3) for *Fixed*, *Gated* and *Limited allocation schemes*.

For instance, in the *Fixed allocation scheme*, as the bandwidth will be allocated from a given SST to the associated CSs regardless of the reported queue statuses, a given SST does not need to process the reported messages received from the associated CSs.

Table 4-4 Running sequences for the key functional modules in Fixed, Gated and Limited allocation schemes

Module	Module name	Run for Fixed?	Run for Gated / Limited?
(2.a)	OLT -> wavelength allocation	Once	Once
(2.b)	OLT -> REPORT processor	N/A	Once per service cycle
(2.c)	OLT -> bandwidth allocation	Once per service cycle	Once per service cycle
(2.d)	OLT -> GATE generator (wavelength)	Once	Once
(2.e)	OLT -> GATE generator (bandwidth)	Once per service cycle	Once per service cycle
(8)	BS-> REPORT generator	N/A	Once per service cycle
(9.a)	ONU-> REPORT generator	N/A	Once per service cycle
(9.b)	ONU-> GATE processor (wavelength)	Once	Once
(9.c)	ONU-> GATE processor (bandwidth)	Once per service cycle	Once per service cycle
(10.a)	ONU-> wavelength allocation	Once	Once
(10.b)	ONU-> REPORT processor	N/A	Once per service cycle
(10.c)	ONU-> bandwidth allocation	Once per service cycle	Once per service cycle
(11.a)	ONU-> GATE generator (wavelength)	Once	Once
(11.b)	ONU-> GATE generator (bandwidth)	Once per service cycle	Once per service cycle
(12.a)	BS-> GATE processor (wavelength)	Once	Once
(12.b)	BS-> GATE processor (bandwidth)	Once per service cycle	Once per service cycle

Therefore, module 2.b and 10.b are not applicable in the *Fixed allocation scheme*. However, in the *Gated* and *Limited allocation schemes*, as the reported queue status from a given CSs to the associated SST will be considered in the bandwidth allocation process, module 2.b and 10.b need to be run once per service cycle. Moreover, as the available wavelengths will be allocated from a given SST to the associated CSs only once, and will remain unchanged after this, module 2.a and 10.a only run once at the network setup stage for all three algorithms.

The network topology, which is employed for the evaluation of the proposed architectural design of the converged protocol, is discussed next.

4.5.3 Network Topology

In order to evaluate the performance of the key functional modules as part of the proposed framework, a network topology, which is represented in Figure 4.6, is developed by employing the OPNET Modeler [79]. OPNET Modeler [79] is one of the leading discrete event network simulators which provides a comprehensive framework for modelling wired and wireless network scenarios. It provides rich libraries of models for both wired and wireless network scenarios and has been employed and approved by the commercial as well as the research communities all around the world. OPNET is capable of supporting custom wired and wireless models by allowing the user to either extend the functionality of the basic and standard models which are part of the OPNET standard libraries or to develop their models using their own developed network models, node models and process models following the particular standards or vendor specifications. As there is no network model, node model or process model in OPNET standard libraries for the optical networks being considered, custom network models, process models and node models along with the standard protocols and configurations for a given optical network scenario are developed in this thesis which were published

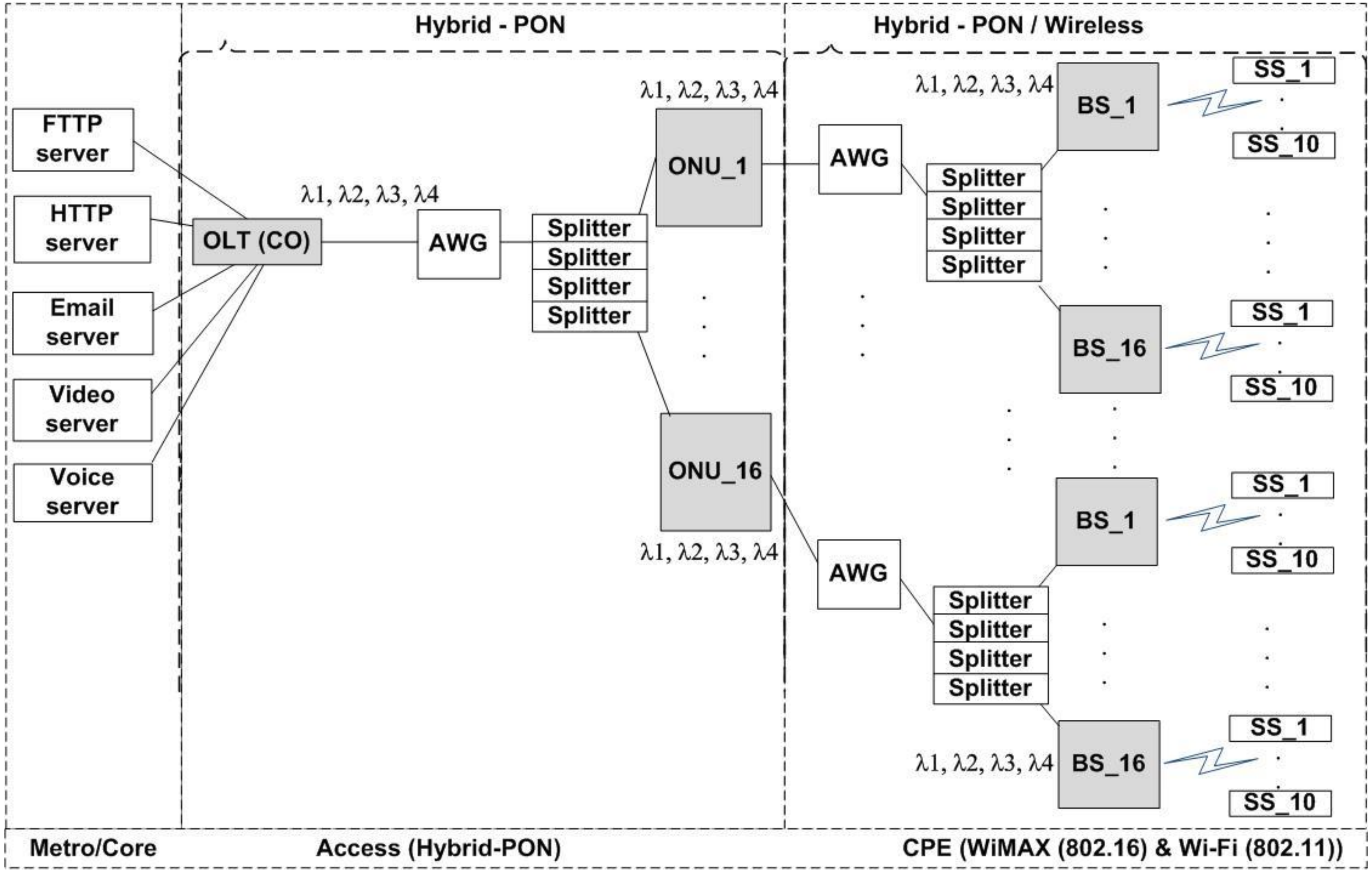

Figure 4.6 Network topology for evaluating the key functional modules

by the author in [123] and [126]. The implemented custom model is evaluated in different scenarios and is employed for all the experiments in this thesis. As represented in Figure 4.6, the implemented network topology includes a single OLT in the central office, 16 ONUs, 16 BSs per ONU and a number of SSs per BS. The wavelength/bandwidth allocation algorithms, which were discussed in previous sections, are implemented over all SSTs (OLT and all ONUs). The full MPCP Ext. protocol is implemented which works over the converged scenario and includes all the required control messages for the auto-discovery and registration stages as well as the wavelength/bandwidth negotiation processes. The summary of the key components of the network topology are as follows.

A single OLT in the central office which is related to 16 ONUs supports four channels and connects the converged scenario to the Internet.

A 4:4 sized Arrayed Waveguide Grating (AWG) which is placed after the OLT. An AWG is a successful device in the WDM-PON industry which has been used for many long-reach WDM systems for some time. It can route each input wavelength to a unique output, separating multi-wavelengths from each other as well as combining and sorting different channels. AWG can be a multiplexer and a de-multiplexer at the same time based on the cyclic wavelength property. It can be pumped in with a different number of wavelengths with the same/different bit rate and each can be reserved for a single output port. As the OLT in the CO supports four different channels with the same capacity of 1Gbps, a 4:4 sized AWG is employed here where it will be pumped in with four channels from the OLT through four input ports. Each output port then identically picks up one of the input wavelengths with the same bit rate of 1Gbps.

Four 1:16 sized Splitter/Combiners, which are placed after the AWG, each carries a single wavelength received from a given output port of the AWG. A given 1:N Splitter/Combiner is a plain power splitter in which the pumped in power will be divided equally between the available output ports. For instance, when a given 1:16 Splitter/Combiner is pumped in with an input transmission power of 1Gb/s, each output port will receive the identical bit rates of 62.5 Mb/s (1Gb/s divided by 16).

16 ONUs have been provided for the whole converged scenario; each of them supports the same four channels, which are also supported on the OLT, and are associated with the 16 BSs.

The same 4:4 sized AWG as well as four 1:16 sized Splitter/Combiners are placed between a given ONU and the associated BSs. Employing AWGs and 1:16 Splitter/Combiners between the OLT, ONUs and a given ONU and the associated BSs helps to extend the coverage of the converged scenario by up to 300 km.

A given BS also supports the same four channels in the upstream direction which are also supported by the OLT and the ONUs. However, it is provided with a fixed channel in the direction of the associated SSs. Each BS also supports a number of SSs which are gradually increased from 10 to 100 SSs in stages of 10 in order to distinguish the performance of the converged scenario under different load values.

Generally speaking, the implemented network topology, Figure 4.6, includes a single OLT in the CO, 16 ONUs, 256 BSs (16 ONUs × 16 BSs), 2560 to 25600 SSs (256 BS × 10 SS to 256 BS × 100 SS) and four supported channels on OLT, ONUs and BSs termed $w_1,\ldots,w_4$.

The next section describes the simulation parameters as well as the traffic pattern characteristics which are employed to configure the proposed architectural design of the converged protocol.

4.5.4 Simulation Parameters and Traffic Pattern Characteristics

Table 4-5 shows the simulation parameters with which the proposed architectural design of the converged protocol is configured in order to evaluate the performance of the key functional modules. It specifies the traffic pattern, ON and OFF state times, traffic start and stop times, packet size, number of supported channels on components of the converged scenario, load pattern per channel, number of SSs per BS, traffic class, simulation time, seed, and value per statistic as well as the update interval.

In order to provide uneven traffic the simulated scenario is supplied with four supported channels with different traffic loads. It should also be noted that the total number of SSs per BS is gradually increased from 10 to 100 in stage by 10 in order to distinguish the performance of the key functional modules under the different load values. Based upon the widely used configurations for the converged scenario and traditional TDM-based PON [68] and [80] the following arrangements are employed.

Moreover, different seed values of 128, 166 and 90 are employed during the simulation run time. However, we depicted the average plots from three seed values in this chapter. The buffer sizes inside the ONUs and BSs are set to 10 Mbytes and the maximum cycle time is considered as 2 ms. The maximum cycle time is the maximum time that a given CS (ONU/BS) gets to perform upstream data transmissions in the direction of the associated SST (OLT/ONU), respectively. A fixed 192μs is also considered as the RTT delay for each CS (ONU/BS) in every service cycle. Moreover, 100 Mb/s and 1Gb/s are the upstream data rates between a given BS and the associated ONU as well as a given ONU and the OLT, respectively. The guard time, which is the separation between two consecutive time slots, needs to be considered in order to accumulate several factors such as laser switching delay, ranging inaccuracy, and clock-recovery preamble. The lower bound for the guard time is laser switching time, which is about 10ns, as optical light sources need to be turned off completely when they are not transmitting.

Table 4-5 Simulation parameters for evaluating the key functional modules

Traffic pattern	Burst (uneven across SSs)
ON state time (sec)	20% of simulation time
OFF state time (sec)	80% of simulation time
Traffic start time	even across all SSs
Traffic stop time	Never
Packet size	500 bytes (constant)
Number of channels supported on OLT, ONUs and BSs for upstream transmissions	4 channels (w_1,…,w_4)
Packet interval time per SS per ONU on channel one (w_1)	0.05 sec (Exponential distributed)
Packet interval time per SS per ONU on channel two (w_2)	0.05 sec (Exponential distributed)
Packet interval time per SS per ONU on channel three (w_3)	0.5 sec (Exponential distributed)
Packet interval time per SS per ONU on channel four (w_4)	1 sec (Exponential distributed)
Number of SSs per BS	10 to 100 BY 10
Traffic class	Best Effort (BE)
Simulation time	30 sec
Seed	128, 166, 99
value per static	1600
update interval	300000

Therefore, a guard time of sub-μs is reasonable [10]. In this chapter, a fixed guard time of 5μs for light sources on the ONUs and BSs are assumed. Moreover, MPCP Ext. protocol is also employed in order to support communications among all the components of the converged scenario.

At the network setup stage, when all the CSs (ONUs/BSs) start to join the converged scenario one at a time, the Initialisation phase, which is implemented on all SSTs (OLT/ONUs) and addressed in chapter 4 (chapter 4, section 4.5.1), starts accepting them and associating each of them with a channel ID. As the number of supported channels is fixed to four channels on the OLT and the total number of ONUs is 16 for the whole system, the Initialisation phase associates four ONUs per channel on the OLT in the CO. A total number of the connected BSs per ONU is 16 and the total number of the supported channels per ONU is four, the Initialisation phase associates four BSs per channel per ONU. Generally speaking, when the initialisation phase is finished, each of the four ONUs and each of the four BSs share a single channel together in the direction of the OLT and associated ONU, respectively. Sharing a single channel among a number of ONUs/BSs needs a central authority in order to avoid data colliding while travelling over the shared medium. This is the point where bandwidth allocation techniques come into play. Three existing bandwidth allocation algorithms termed *Fixed*, *Gated* and *Limited* (addressed in chapter 4, section 4.5.2) along with a wavelength allocation algorithm (addressed in chapter 4, section 4.5.1) are employed in order to evaluate the performance of the key functional modules (showen in Figure 4.3) in terms of wavelength/bandwidth allocation processes as part of the proposed converged framework.

It is also to be noted that, the network load is only increased on a single channel (w_1) by increasing the number of SSs connected to the associated BSs while the load on the other three channels ($w_2,\ldots,w_4$) stays fixed. The reason behind such a configuration is to distinguish how the unused and excess bandwidth on the three channels ($w_2,\ldots,w_4$) can be utilised and employed by the CSs associated with w_1 in order to improve the individual channel performance which results in improving the total network performance.

The next section describes the four simulated scenarios which are developed for the performance evaluation of the proposed key functional modules as a function of the existing resource (wavelength/bandwidth) allocation algorithms detailed in chapter 4, section 4.5.1 and section 4.5.2.

4.5.5 Simulated Scenarios

Table 4-6 reveals the hierarchical wavelength/bandwidth allocation algorithms that are implemented between OLT-ONUs and ONU-BSs in the four scenarios.

The performance of the proposed key functional modules, which is discussed in the next section, is captured between the OLT and ONUs as well as the ONU and BSs for each scenario employing different load values as well as uneven traffic patterns.

4.5.6 Captured Results

Taking into consideration the previous discussions about the simulation parameters, traffic pattern characteristics and four different scenarios, which are employed in this chapter, the performance of the proposed key functional modules are captured as follows. In Figure 4.7, the average queuing delay for all ONUs associated with channel one (w_1) employing the Fixed and Gated allocation schemes under different load values

Table 4-6 Different scenarios for evaluation of the key functional modules

Scenario name	**OLT-ONUs and ONU-BS wavelength allocations**	**OLT-ONUs bandwidth allocations**	**ONU-BSs bandwidth allocations**
Scenario one (Full Static)	Fixed	Fixed	Fixed
Scenario two (Semi Dynamic)	Fixed	Fixed	Gated / Limited
Scenario Three (Semi Dynamic)	Fixed	Gated / Limited	Fixed
Scenario Four (Full Dynamic)	Fixed	Gated / Limited	Gated / Limited

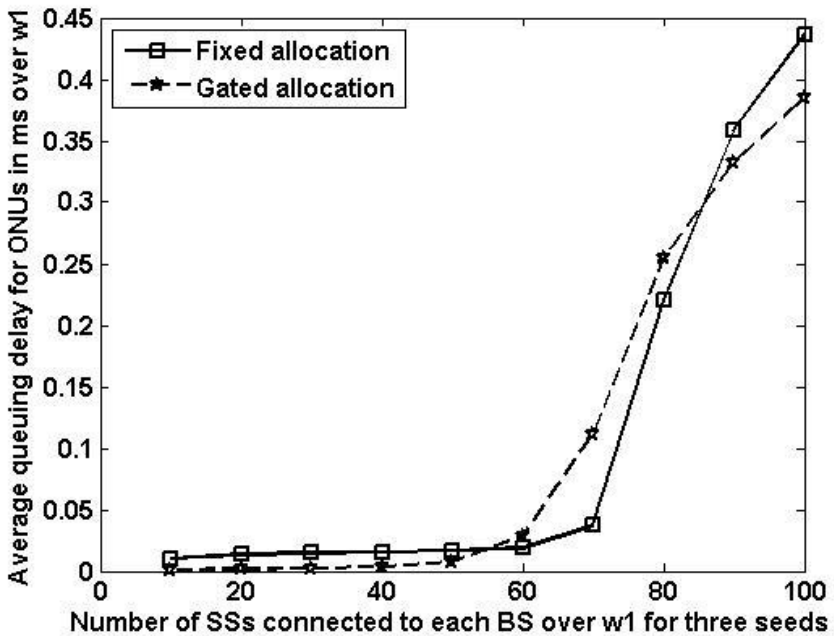

Figure 4.7 Average queuing delay for the ONUs associated with channel one employing the Fixed and Gated allocation schemes

are captured. As it is depicted in Figure 4.7, when the number of SSs per BS is up to 60, the average queuing delay for the ONUs over w_1 employing the Gated allocation scheme outperforms the Fixed allocation scheme. It is because when the number of SSs is up to 60, the granted bandwidth (bits) in the Fixed allocation scheme is not as much as the requested bandwidth (bits), Figure 4.8. Allocating bandwidth less than the actual need results in increasing the average queuing delay for all ONUs associated with w_1 in comparison with the Gated allocation scheme in which the bandwidth is allocated based on the actual requested bandwidth (bits) of a given ONU, Figure 4.9. However, when the total number of SSs per BS goes beyond 60 SSs the average queuing delay for both Fixed and Gated allocation schemes starts to increase dramatically, Figure 4.7. It is because in the Fixed allocation scheme, the fixed granted bandwidth (bits) is very small

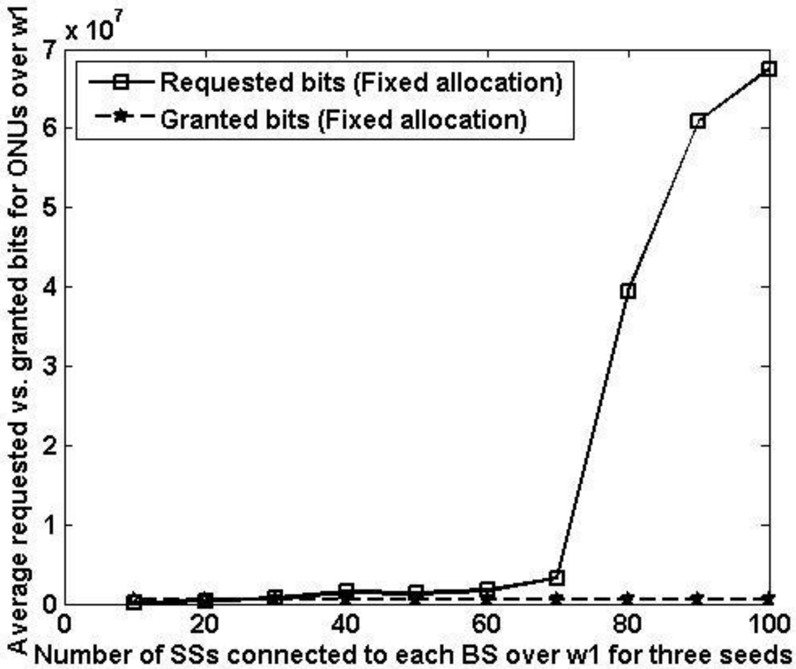

Figure 4.8 Average requested bandwidth (bits) vs. granted bandwidth (bits) for ONUs associated with channel one employing the Fixed allocation scheme

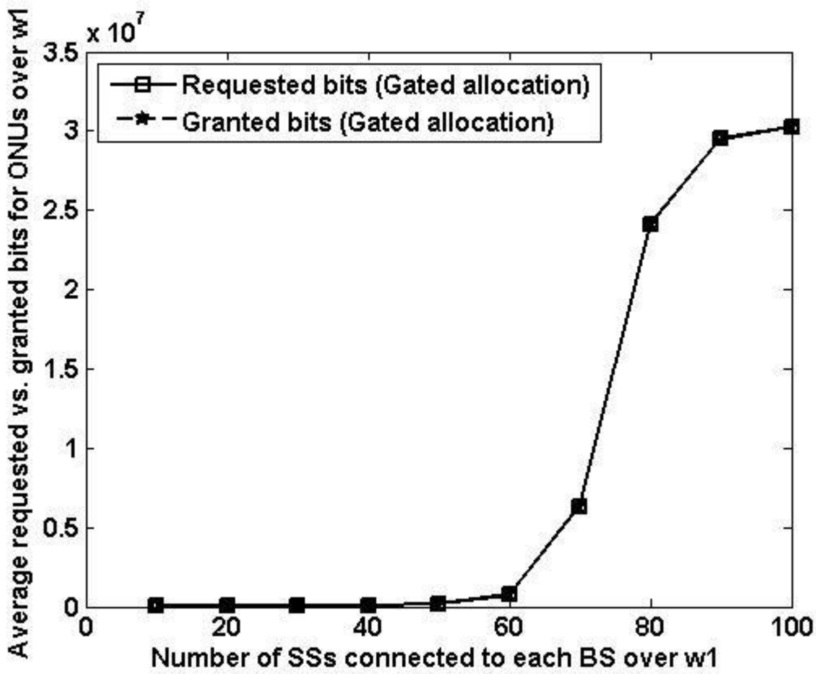

Figure 4.9 Average requested bandwidth (bits) vs. granted bandwidth (bits) for the ONUs associated with channel one employing the Gated allocation scheme

when it is compared to the requested bandwidth (bits), Figure 4.8, which results in the accumulation of more packets per service cycle leading to a significant increase in the queuing delay. In Gated allocation scheme, the granted bandwidth (bits) to the ONUs is the same as the requested bandwidth (bits) per service cycle, Figure 4.9. However, when the network is heavily loaded (when the number of SSs connected per BS is beyond 60) allocating as much as the requested bandwidth (bits) to the ONUs results in increasing the total average queuing delay for all the ONUs in the same service cycle, Figure 4.7.

The average queuing delay for all BSs associated with w_1 employing the Fixed and Gated allocation schemes are captured in Figure 4.10. This is the average queuing delay for a packet inside a queue of a given BS over w_1 before reaching the associated ONU. As Figure 4.10 reveals, the average queuing delay employing the Gated allocation scheme outperforms the Fixed allocation scheme. This is because in the Gated allocation scheme the bandwidth will be granted based on the actual need of a given BS which was reported to the associated ONU in the last service cycle while in the Fixed allocation scheme the granted bandwidth may be more or less than the reported queue length. Granting more bandwidth than the actual needs of a given BS results in increasing the average queuing delay for all BSs in the same service cycle. As Figure 4.10 reveals, when the number of SSs associated with each BS is less than 40 employing the Fixed allocated scheme, as the fixed granted bandwidth is far more than the actual need of a given BS, the average queuing delay is almost twice that compared to when the number of SSs goes beyond 40. This is because when the number of SSs passes more than 40, the fixed allocated bandwidth is getting closer to the reported queue length from a given BS. However, it is still more than the actual need therefore

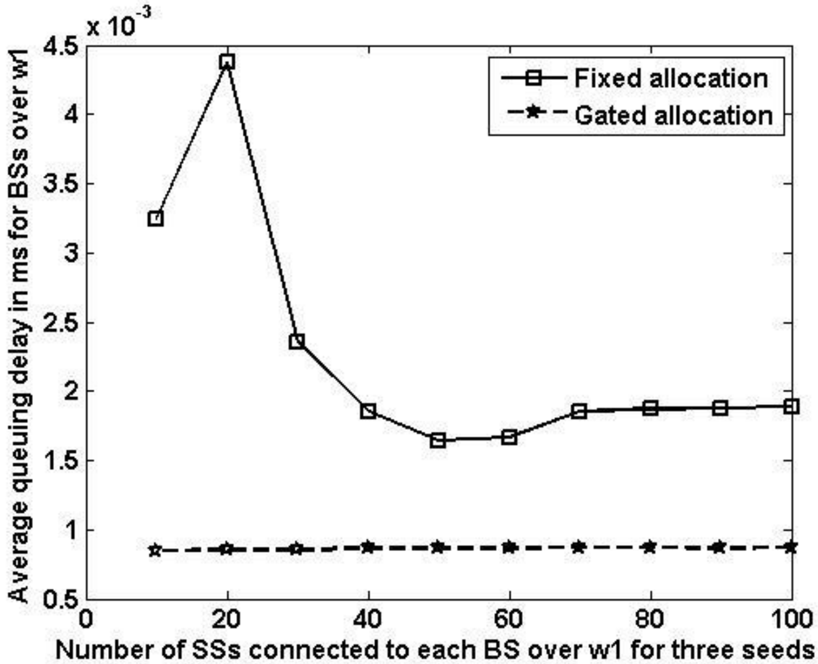

Figure 4.10 Average queuing delay for the BSs associated with channel one employing the Fixed and Gated allocation schemes

in such as case the average queuing delay is almost four times more than the Gated allocation scheme where the reported queue length will be considered before granting any bandwidth to a given BS. The ETE average queuing delay that a packet experiences all the way from a given BS to the OLT in the CO which includes the average queuing delay inside the associated BS and the average queuing delay inside the associated ONU, respectively are captured in Figure 4.11. As the average queuing delay inside a given BS, Figure 4.10, is almost negligible when compared to the average queuing delay inside a given ONU, Figure 4.7, the ETE average queuing delay is almost as the same as the average queuing delay inside the ONUs employing the Fixed and Gated allocations schemes.

In Figure 4.12, the average queuing delay for the ONUs associated with w_1 employing

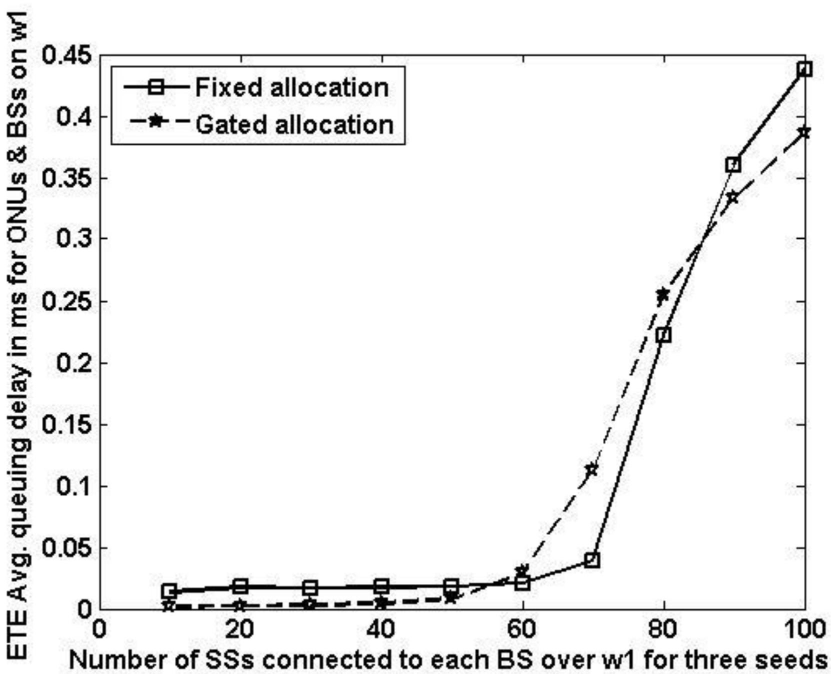

Figure 4.11 ETE average queuing delay for the ONUs and BSs associated with channel on employing the Fixed and Gated allocation schemes

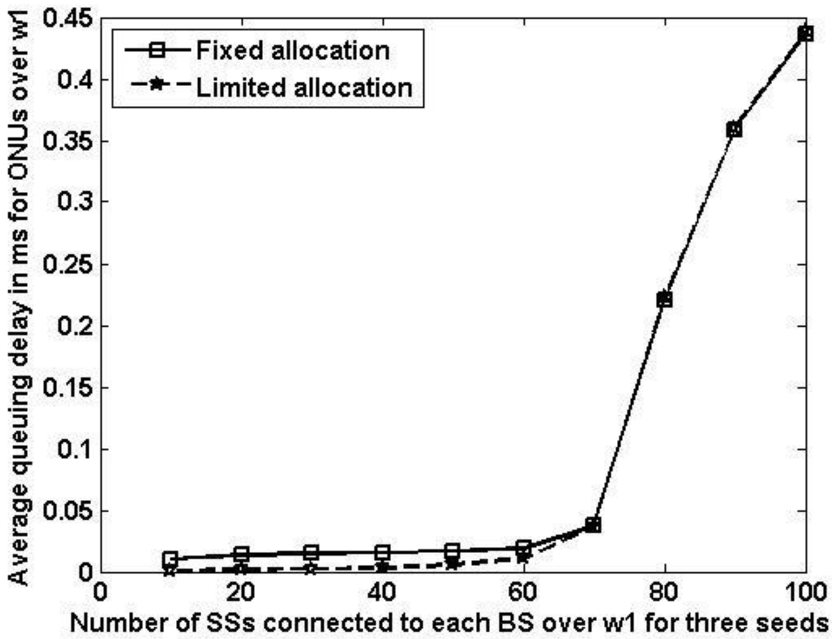

Figure 4.12 Average queuing delay for the ONUs associated with channel one employing the Fixed and Limited allocation schemes

the Fixed and Limited allocation schemes under different load values are compared. As depicted in Figure 4.12, the averaged queuing delay for the ONUs associated with w_1 in the Limited allocation scheme outperforms the Fixed allocation scheme when the number of SSs connected to each BS is upto 60. This is because in the Limited allocation scheme with up to 60 SSs per BS, the requested bandwidth is less than the minimum guaranteed bandwidth. Therefore, the requested bandwidth, which is the actual need of a given ONU, will be granted, as seen in Figure 4.15. However, in the Fixed allocation scheme, the fixed bandwidth will be allocated which is more than the actual need of a given ONU and results in increasing the queuing delay for all ONUs associated with w_1, Figure 4.12.

However, when the total number of SSs connected per BS goes beyond 60, the average queuing delay for both allocation schemes starts increasing constantly, Figure 4.12. The reason for such an increment is that the granted bandwidth is far lower than the requested bandwidth in both Fixed and Limited allocation schemes, as seen from Figure 4.8 and Figure 4.15, respectively. Also, the reason for the same output results from both allocation schemes is because in the implemented scenario the fixed allocated bandwidth is the same as the minimum guaranteed bandwidth. Therefore, when the number of SSs connected per BS goes beyond 60 both allocation schemes grant the same number of the bits to the ONUs which is equal to the minimum guaranteed bandwidth.

The average queuing delay inside BSs associated with w_1 is captured in Figure 4.13 in which the Limited allocation scheme outperforms the Fixed allocation scheme.

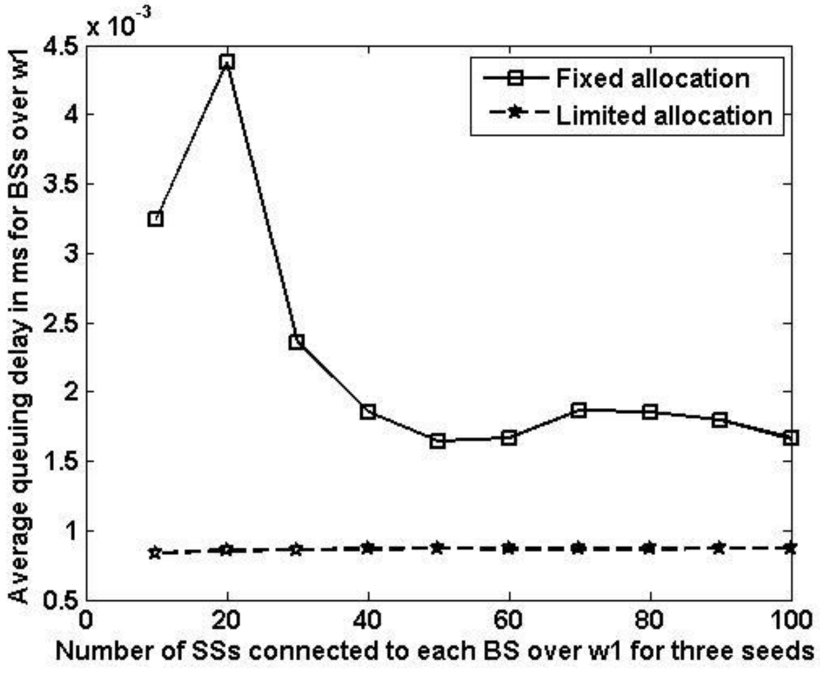

Figure 4.13 Average queuing delay for the BSs associated with channel one employing the Fixed and Limited allocation schemes

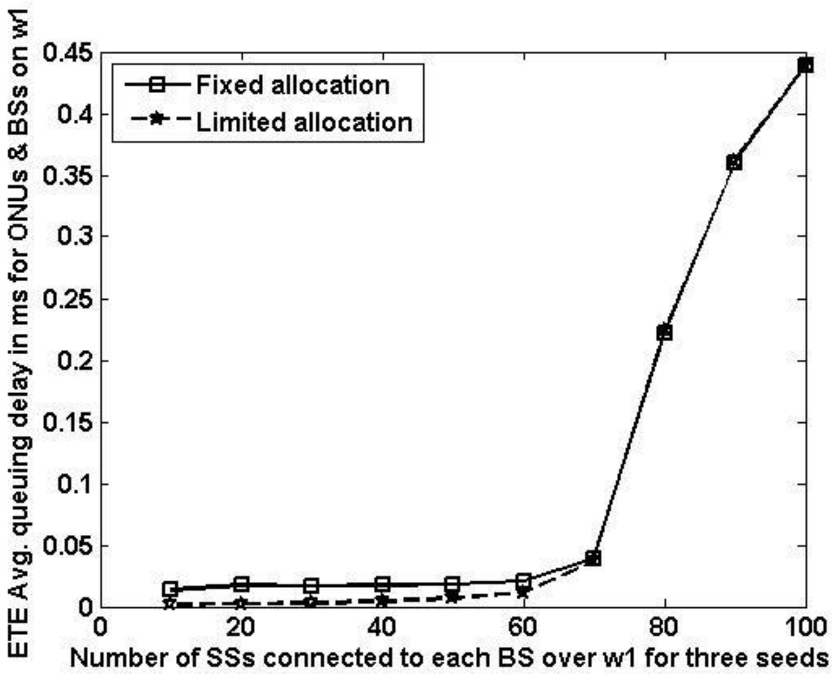

Figure 4.14 ETE average queuing delay for the ONUs and BSs associated with channel one employing the Fixed and Limited allocation schemes

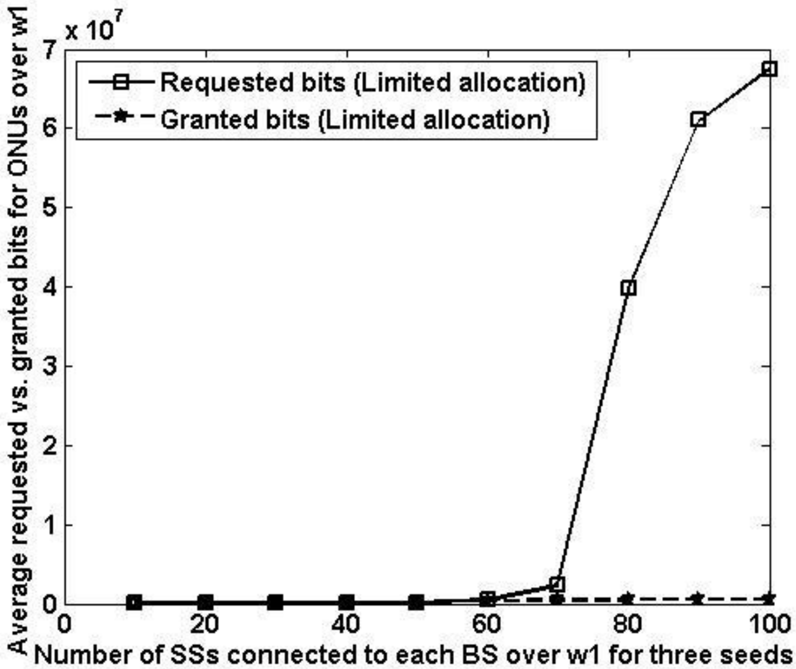

Figure 4.15 Average requested bandwidth (bits) vs. granted bandwidth (bits) for the ONUs associated with channel one employing the Limited allocation scheme

The output from Fixed and Limited allocation schemes, Figure 4.13, is the same as the output from Fixed and Gated allocation schemes, Figure 4.10. The reason the same output is obtained is because in the Limited allocation scheme if the requested bandwidth is less than the minimum guaranteed bandwidth (light load) the requested bandwidth will be granted which matches the Gated allocation scheme. However, if the requested bandwidth is more than the minimum guaranteed bandwidth (heavy load) the minimum guaranteed bandwidth will be granted which distinguishes it from the Gated allocation scheme. In this group of experiments the number of SSs connected per BS is increased to no more than 100. Obviously when they go beyond 100 the average queuing delay for the Limited and the Gated allocation scheme will not be the same. Moreover, as the average queuing delay inside BSs over w_1, Figure 4.13, is negligible when compared to the average queuing delay inside the ONUs over the same channel employing Limited allocations scheme, Figure 4.12. The ETE average queuing delay from a given BS to the OLT in the CO, Figure 4.14, is almost the same as the average queuing delay that a given packet experiences inside the queue of the associated ONU, Figure 4.12. In Figure 4.16, Figure 4.17 and Figure 4.18, the extra available bandwidth (bits) per channel ($w_{1,...,}w_4$) after employing the Fixed, Gated and Limited allocation schemes when the number of connected SSs per BS is gradually increased only on a single channel (w_1) are captured. Obviously, when the total number of connected SSs per BS is gradually increased on w_1, the number of extra available bandwidth (bits) will decrease dramatically and reach almost zero when it passes 60 SSs per BS, Figure 4.16. As Figure 4.16 reveals, the extra available bandwidth (bits) on a single channel (w_1) in the Fixed allocation scheme is less than the two other allocation algorithms,

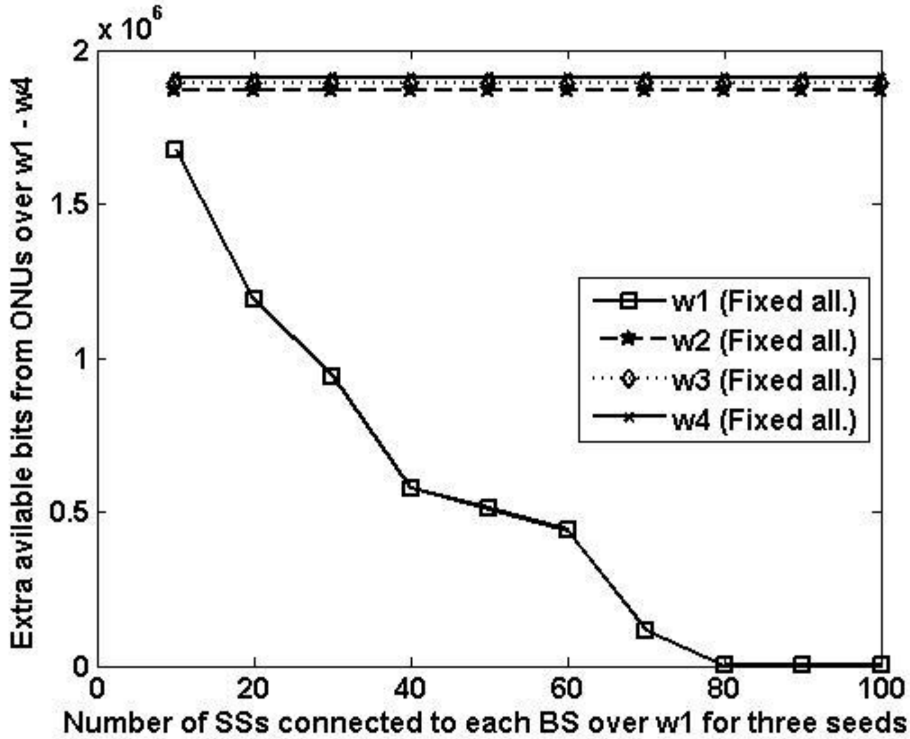

Figure 4.16 Extra available bits over four channels employing the Fixed allocation

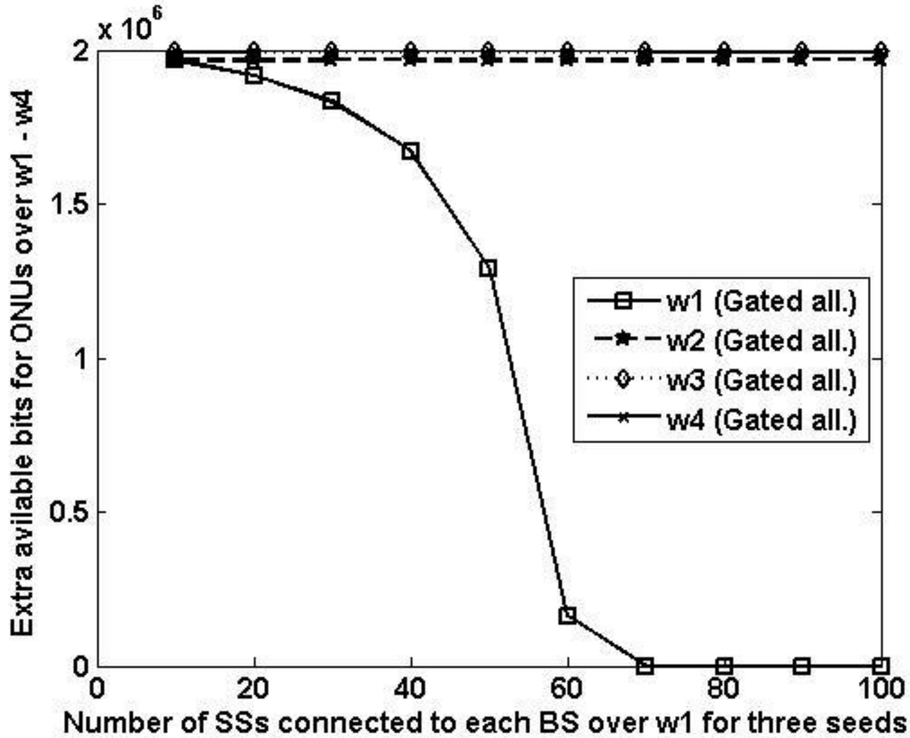

Figure 4.17 Extra available bits over four channels employing the Gated allocation

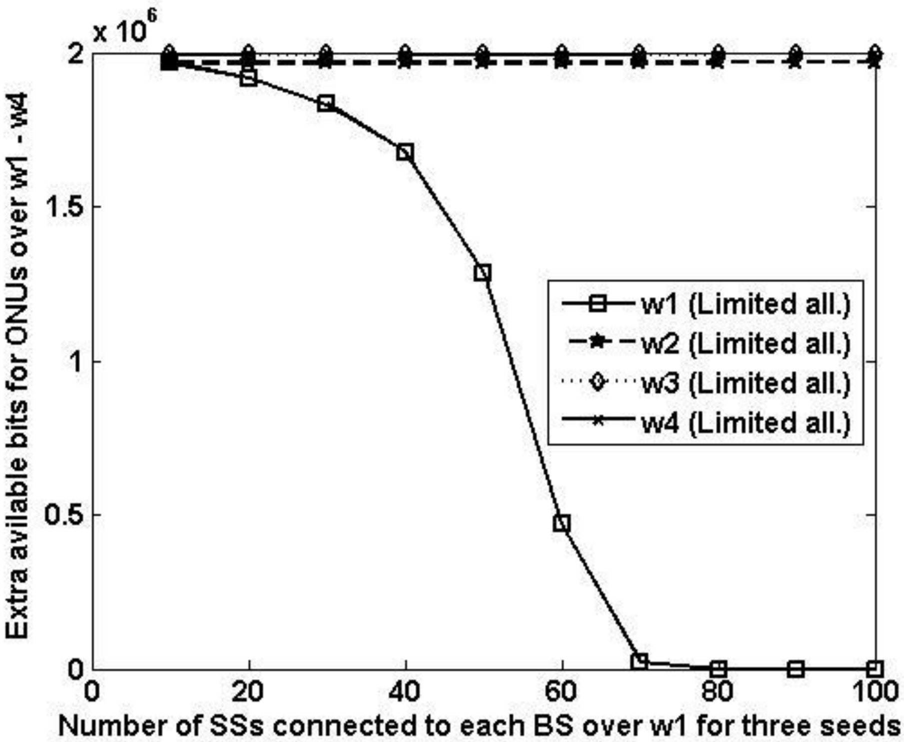

Figure 4.18 Extra available bits over four channels employing the Limited allocation

Figure 4.17 and Figure 4.18, particularly when the number of connected SSs per BS is less than 60. It is because in the Gated and Limited allocation schemes the bandwidth will be granted based on some boundaries. For instance, in the Gated allocation scheme, the actual need of a given ONU will be granted per service cycle or in the Limited allocation scheme the allocated bandwidth will not be more than the minimum guaranteed bandwidth while in the Fixed allocation scheme the fixed amount of bandwidth will be granted regardless of the actual need. Therefore, the extra available bandwidth for the Fixed allocation scheme on w_1 is less than the other two allocation schemes.

Moreover, as they are depicted in Figure 4.16, Figure 4.17 and Figure 4.18, the extra available bandwidth (bits) on other channels ($w_2,\ldots,w_4$) is unchanged as on each of them we kept the traffic load fixed by associating only 10 SSs per BS. The extra available bandwidth (bits) from ($w_2,\ldots,w_4$) can be employed for the ONUs associated with w_1 in order to improve the individual channel performance e.g. average queuing delay, queue length and packet drop as well as the total network performance e.g. utilisation and throughput. For this purpose, an Inter-channel and Intra-channel Dynamic Wavelength/Bandwidth Allocation (IIDWBA) algorithm is proposed, which will be discussed in detail in chapter five, in which the extra available bandwidth (bits) from all channels associated with a given SST will be collected per service cycle. The collected bandwidth will then be passed to a global scheduler in order to schedule and distribute fairly among heavily loaded CSs scattered over different channels.

4.6 Chapter Summary

In this chapter, an architectural design of the converged protocol was proposed. It is the converged scenario which employed in this PhD work for all the simulation experiments and embraces the way optical and wireless technologies are connected to each other along with the ETE component specifications, functional modules and physical structures.

The component specifications and proposed ETE functional modules from the OLT at the far-end central office all the way to the WLAN subscriber stations at the front-end customer premises, which are required in order to provide the smooth ETE transmissions from the wireless domain over the optical infrastructure, were fully detailed.

It is then followed by the proposed key functional modules which were provided in order to progress the ETE wavelength/bandwidth allocation over the converged scenario. These modules were called key functional modules as they have key roles as part of the ETE wavelength/bandwidth allocations over the integrated scenario.

The proposed key functional modules were evaluated in terms of wavelength/bandwidth allocation algorithms, different traffic patterns and load values which gave the expected results. At the end we put forward the problem domain on which this PhD work is focused. The same simulation environment is employed for the further experiments which will be described in next chapter for different scenarios.

Chapter 5 Inter-channel and Intra-channel Dynamic Wavelength/Bandwidth Allocation (IIDWBA) Algorithm

This chapter is dedicated to the second key contribution of this thesis, namely, the Inter-channel and Intra-channel Dynamic Wavelength/Bandwidth Allocation (IIDWBA) algorithm for the resource (wavelength/bandwidth) allocations over the converged infrastructure of the NGN environment. It starts with the motivation and need for the robust wavelength/bandwidth allocation algorithm for the converged infrastructure of the NGN. Then it presents the details of the proposed Inter-channel and Intra-channel Dynamic Wavelength/Bandwidth Allocation (IIDWBA) algorithm which is identified through three phases termed as Initialisation phase, Intra-channel bandwidth allocations phase and Inter-channel bandwidth allocations phase. The IIDWBA algorithm is capable of identifying the excess bandwidth from all the available channels associated with a given SST per service cycle and then collecting them, scheduling and distributing them among those CSs which are not satisfied by the minimum guaranteed bandwidth. This chapter then evaluates the proposed IIDWBA algorithm through the simulated scenarios employing network elements that exist in the market, different traffic patterns and load values which is then followed by the captured results and summary of the chapter at the end.

5.1 Issues of Resource Allocations in Converged Architecture

The Internet as well as telecommunication networks and infrastructure, telecommunication applications and services are growing at the rapid pace and so is their bandwidth consumption. It has been found that the worldwide international bandwidth has grown from 10 Tbps in 2007 to almost 70 Tbps in 2011 with a rate of 80% [129]. Moreover, with the global deployment of the NGN [130] and the increasing demand for the emerging bandwidth hungry applications and services, the rate of the used international bandwidth is expected to increase further in the near future. This issue calls for a scalable and robust solution for the resource (wavelength/bandwidth) allocation problems with the sole focus on the optimum or near optimum resource utilisation over the converged infrastructure of the NGN [131]. This problem is explored in this chapter along with a proposed solution based on a distributed, real-time, dynamic and scalable wavelength and bandwidth allocation algorithm for the converged infrastructure of the NGN.

One of the tasks of a real-time and dynamic resource allocation algorithm is to monitor the resource usages (e.g. bandwidth) on a regular basis. Due to the dynamic nature of the Internet traffic, it is quite possible that based on this observation a given real-time and dynamic resource allocation algorithm finds groups of CSs, which may be scattered over different locations (e.g. different channels), requesting more bandwidth (termed heavy loaded CSs) while the other groups have significant reductions in their regular bandwidth requests (termed lightly loaded CSs). This brings the excess resource allocation issues where the unused resources (e.g. unused bandwidth) from the lightly loaded CSs can be identified and collected over certain time (e.g. once per service cycle) and then scheduled as well as distributed for the heavily loaded CSs in order to satisfy their high resource demands. This issue is explored in this chapter in which the excess bandwidth allocation is considered per channel per heavily loaded CS during each service cycle.

In order to provide robust ETE dynamic resource (wavelength/bandwidth) allocations over the converged scenario of the NGN, a Dynamic Wavelength Allocation (DWA) algorithm and a Dynamic Bandwidth Allocation (DBA) algorithm are required to be implemented inside the core elements of the converged scenario (e.g. inside the OLT in the far-end central office as well as inside the ONU and BS as a given optical gateway and a wireless gateway, respectively, across the converged scenario). While the DWA algorithm identifies what channel ID should be granted from a given SST to a given CS per service cycle, the DBA algorithm identifies what portion of the granted channel should be allocated. The DWA decisions will be made based on the available wavelengths on the SSTs and the supported wavelengths of both SSTs and CSs. The DBA decisions will be made based on the available bandwidth on the SSTs as well as the DBA boundaries such as minimum guaranteed bandwidth and maximum transmission window. With support of the standard protocols (e.g. MPCP [29] and MPCP Ext [32].) the DWA and DBA decisions will be carried to the associated CSs once per service cycle. For instance, when CS_i receives $GATE_j$ message during $Cycle_n$, it starts sending traffic on channel k (the allocated channel), after α ms (transmission start time) for β ms duration (transmission duration). k, α and β are specified by the DWA and DBA algorithms, then placed inside a MPCP Ext. GATE message and finally broadcast to all CSs associated with a given SST.

The question which has to be answered is: can a given real-time and dynamic bandwidth allocation algorithm, which works over a single channel over the converged infrastructure of the NGN, be made intelligent enough for the issues of the resource (wavelength/bandwidth) allocations over the multi-channel integrated scenario in order to support the optimum or near optimum resource utilisation of the NGN?

5.2 Existing Approaches for Resource Allocations in A Converged Architecture

The resource (wavelength/bandwidth) allocation problems over the converged scenario have been addressed as Media Access Control (MAC) issues such as hierarchical and ETE QoS provisioning, upstream bandwidth scheduling, wavelength and bandwidth requests as well as the wavelength/bandwidth allocations.

The MAC-related issues for the integrated scenario were discussed for the first time in [59]. The authors raised several issues concerning bandwidth allocations, packet scheduling, QoS support and user mobility (e.g. handover operations) for the converged scenario. In [71], the authors investigated scheduling techniques in hybrid optical and wireless access networks aimed at improving performance and guaranteeing QoS for different classes of service. The proposed centralized scheduling provides better performance when compared to distribute scheduling (multi-hob scheduling) in terms of delay for all service classes as well as throughput. However, no QoS mapping mechanism or bandwidth scheduling has been discussed. In [70], the authors proposed slotted-DBA (S-DBA) algorithm for the integrated passive optical and IEEE 802.16 networks which aimed to increase the bandwidth utilization by reducing the signalling overhead caused by cascading bandwidth requests and grants in both optical and wireless parts of the converged scenario. In [74], the authors proposed an intra ONU-BS scheduling algorithm termed Hybrid Priority Weighted Fair Scheduling (HPWFS) in order to improve the QoS performance of the EPON and WiMAX integrated system without bandwidth starvation for the lower priority classes of service. In [66], the authors proposed a DBA algorithm for the suggested Optical-Optical-Wireless (OOW) architecture. The proposed DBA algorithm is executed in three levels of WiMAX BS, integrated ONU and sub-OLTs. The sub-OLTs connect to the OLT in a point-to-multipoint manner, thus, the OLT does not need to run a bandwidth allocation algorithm. The simulation experiments show the improvements in average throughput and average and maximum delay for different classes of service.

To the best of our knowledge, TDM-PON has been addressed in most of the existing work related to the optical and wireless integrated scenario.

Using a traditional single channel TDM-PON where a group of ONUs (typically 16 [24]) sharing a single channel as a backhaul for 802.16 BS, provides each BS with ~ 62.5 Mb/s capacity which is almost matched 802.16 channel capacity (~ 70 Mb/s over a 20 MHz channel [59]). However, 62.5 Mb/s does not seem to be enough when a given ONU is used as a backhaul for more than a single BS. This is the point where WDM-PON comes into play where multiple wavelengths are available over a same fibre channel, thus higher bandwidth can be provided by the OLT for a given ONU and more BSs and finally more SSs can be supported.

Providing multiple wavelengths over a single channel in the OLT or in a given ONU carries many challenging issues. For instance, wavelength management on the OLT and ONU, bandwidth management on the OLT and ONU per channel per service cycle, the number of ONUs sharing a single channel (static/dynamic), the number of BSs sharing a single channel (static/dynamic), channel allocation de-allocation and re-allocations for a given ONU and BS.

Addressing the above motivation and challenges, an Inter-channel and Intra-channel Dynamic Wavelength/Bandwidth Allocation (IIDWBA) algorithm is proposed in this chapter in order to provide the ETE dynamic wavelength/bandwidth allocations across the converged scenario. While a given DBA algorithm deals with the dynamic bandwidth allocation issues over a single channel, the IIDWBA algorithm works on top of a given DBA algorithm and deals with multi-channels. The proposed algorithm has real-time and global knowledge about the local DBA algorithm associated per channel thus it is capable of collecting excess bandwidth from all the available channels and passing them to an entity termed the global scheduler. The global scheduler then schedules and distributes the excess bandwidth from all channels among those channels which are not satisfied by the minimum guaranteed bandwidth.

The next section provides a detailed description for the proposed IIDWBA algorithm and its functionalities.

5.3 Proposed Inter-channel and Intra-channel Dynamic Wavelength/Bandwidth Allocation (IIDWBA) Algorithm

In this section, the IIDWBA algorithm is proposed in order to provide full dynamic wavelength/bandwidth allocations from the OLT in the CO to the ONUs and then from a given ONU to the associated BSs for multi-channel PON integration with wireless technologies. IIDWBA has global and real-time knowledge about the available resources (wavelength/bandwidth) per service cycle all across the converged scenario and is capable of identifying the excess bandwidth per channel per service cycle, collecting them and distributing them fairly among the CSs which are not satisfied with minimum guaranteed bandwidth and may be distributed across different channels.

The IIDWBA algorithm needs to be implemented over all the SSTs across the converged scenario including the OLT in the CO, which provides resources (wavelengths/bandwidth) for the ONUs, and all ONUs which provide resources (wavelength/bandwidth) for the associated BSs.

In order to save space and avoid repetition, the OLT or a given ONU termed a Server Station (SST) as they are responsible for providing resources for the ONUs or BSs, respectively. A given ONU or BS also termed as a Client Station (CS) as they are requesting resources periodically from the OLT or the associated ONU, respectively. A requested resource or a granted resource can be a given wavelength (channel id) or portion of a given channel termed bandwidth. Generally speaking, the OLT is an ultimate SST over the converged scenario. However, the ONUs and BSs termed SSTs in terms of providing resources for their associated CSs and termed CSs in terms of requesting resources from their associated SSTs.

The IIDWBA algorithm works in three phases termed Initialisation phase, Intra-channel bandwidth allocations phase and Inter-channel bandwidth allocations phase.

During the Initialisation phase, a temporary channel ID will be allocated to each group of CSs per SST. The allocated channel will then be shared among the local CSs using phase two of the IIDWBA algorithm. Phase three will be issued across all channels associated with a given SST in order to identify the possible excess bandwidth which may not be utilised with the local CSs of a given channel. The local excess bandwidth from all channels will be collected and passed to the global scheduler in order to schedule and distribute fairly among all the CSs which may not be satisfied by the minimum guaranteed bandwidth. The associated CSs may exist across different channels.

The objectives of the IIDWBA algorithm for each phase (phase one, phase two and phase three) are shown in Figure 5.1. It includes all the specific tasks which need to be done during each stage, either per SST or per channel per SST, during the full IIDWBA execution time.

The three phases of the IIDWBA algorithm, with the support of the flowcharts and algorithms, are detailed phase by phase as follows.

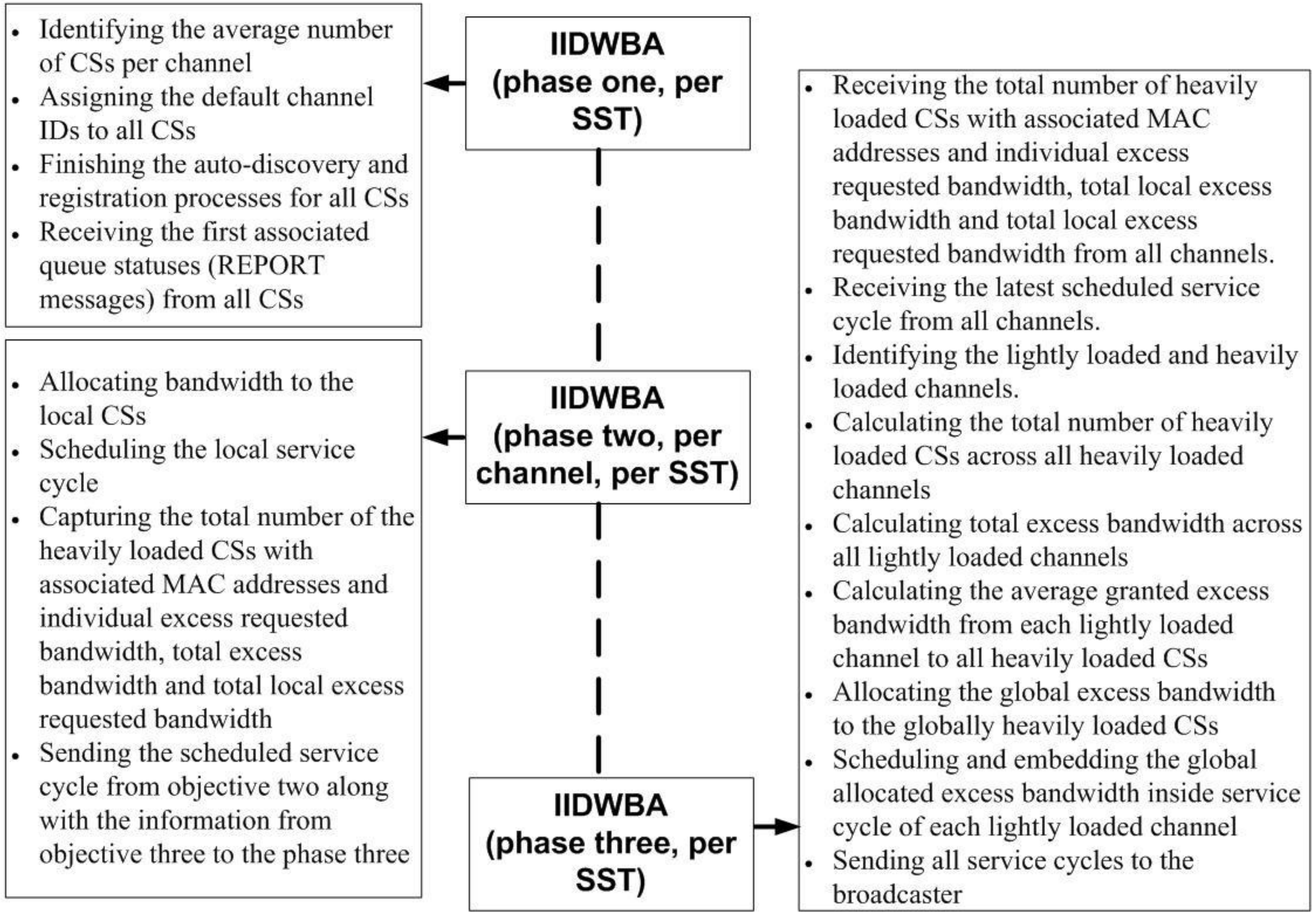

Figure 5.1 Specific tasks for each phase of the IIDWBA algorithm

5.3.1 Initialisation Phase of the IIDWBA Algorithm

Phase one of the IIDWBA algorithm is termed Initialisation phase during which a given CS joins the domain of the associated SST and a channel ID will be allocated to it. The Initialisation phase includes all the required steps in order to get a given CS discovered and registered and then send the first MPCP Ext. REPORT message (buffer length) or the first group of data traffic to the associated SST. Based on the number of CSs in the domain of a given SST, the number of available wavelengths on a given SST as well as the supported wavelengths on CSs, multiple CSs can share a single channel after executing the Initialisation phase. The number of CSs sharing a single channel can be changed during phase three of the IIDWBA algorithm after the traffic has been built up on each channel which will be discussed in section 5.3.3 of this chapter.

The Initialisation phase runs on all SSTs including the OLT in the CO and the ONUs all over the converged scenario at the network setup stage. It helps a given CS to send the first REPORT message or the first group of buffered traffic on the channel, which is allocated during the Initialisation phase, to the corresponding SST immediately after getting registered to the associated domain. All the auto-discovery and registration processes will happen over the negotiation channel, W_0, which is separated from the data channels, $W_{i=1,\dots n}$.

Taking into consideration the specific tasks which need to be done during the phase one of the IIDWBA algorithm, an algorithm and a flowchart, Figure 5.2, are developed for the phase one of the IIDWBA algorithm as follows.

A. *Algorithm for the Initialisation phase*

An algorithm for the Initialisation phase of the IIDWBA algorithm is defined as follows.

Given:

1) α : Total number of supported wavelengths on a given SST
2) β : Total number of CSs associated with a given SST

Define:

1) μ : Average number of CSs per channel for a given SST

$$\mu = \beta / \alpha \tag{5.1}$$

The μ is the default value which is calculated by Initialisation phase of the IIDWBA algorithm during the network setup stage in order to let a given CS send the first buffer length (REPORT message) or the first group of data traffic to the associated SST. It is assumed that α and β both are even numbers for simplicity.

2) N_{CS}: Number of CSs per channel on a given SST

The Initialisation phase of the IIDWBA algorithm gives the fixed number of CSs, N_{CS} , per channel per SST. The total number of CSs sharing a single channel on a given SST will be changed during phase three of the IIDWBA algorithm which will be discussed in section 5.3.3 of this chapter.

The number of CSs sharing a single channel on a given SST can be restricted to the average number of CSs per channel and the total number of associated CSs, therefore:

$$\mu \le N_{CS} \le \beta \tag{5.2}$$

Generally speaking, the objectives of the Initialisation phase are as follows:

1) Identifying the average number of CSs per channel per SST.
2) Assigning the default channel IDs to all CSs associated with each SST.
3) Finishing the auto-discovery and registration processes for all CSs and receiving the first associated queue statuses (REPORT messages) from them.

A flowchart for phase one of the IIDWBA algorithm is presented next.

B. Flowchart for the Initialisation phase of the IIDWBA algorithm

As shown in Figure 5.2, the Initialisation phase of the IIDWBA algorithm first identifies the total number of the supported channels as well as the total number of the CSs associated per SST over the converged scenario. The average number of the CSs per channel will be calculated next. Then it starts randomly allocating the channel IDs to all the CSs in such a way that the number of CSs per channel on a given SST will be the same. Finally, the allocated channel IDs will be acknowledged to all the CSs associated with a given SST.

Generally speaking, the allocated channel IDs are the default channels which will be granted in order to let a given CS sending the first group of data traffic or the first MPCP Ext. REPORT messages to the associated SST. The number of CSs sharing a single channel, which is the same in this stage, can be changed dynamically during phase three of the IIDWBA algorithm based on the load on the CSs. This will be discussed in section 5.3.3 of this chapter. The next section provides a detailed discussion for phase two of the IIDWBA algorithm as follows.

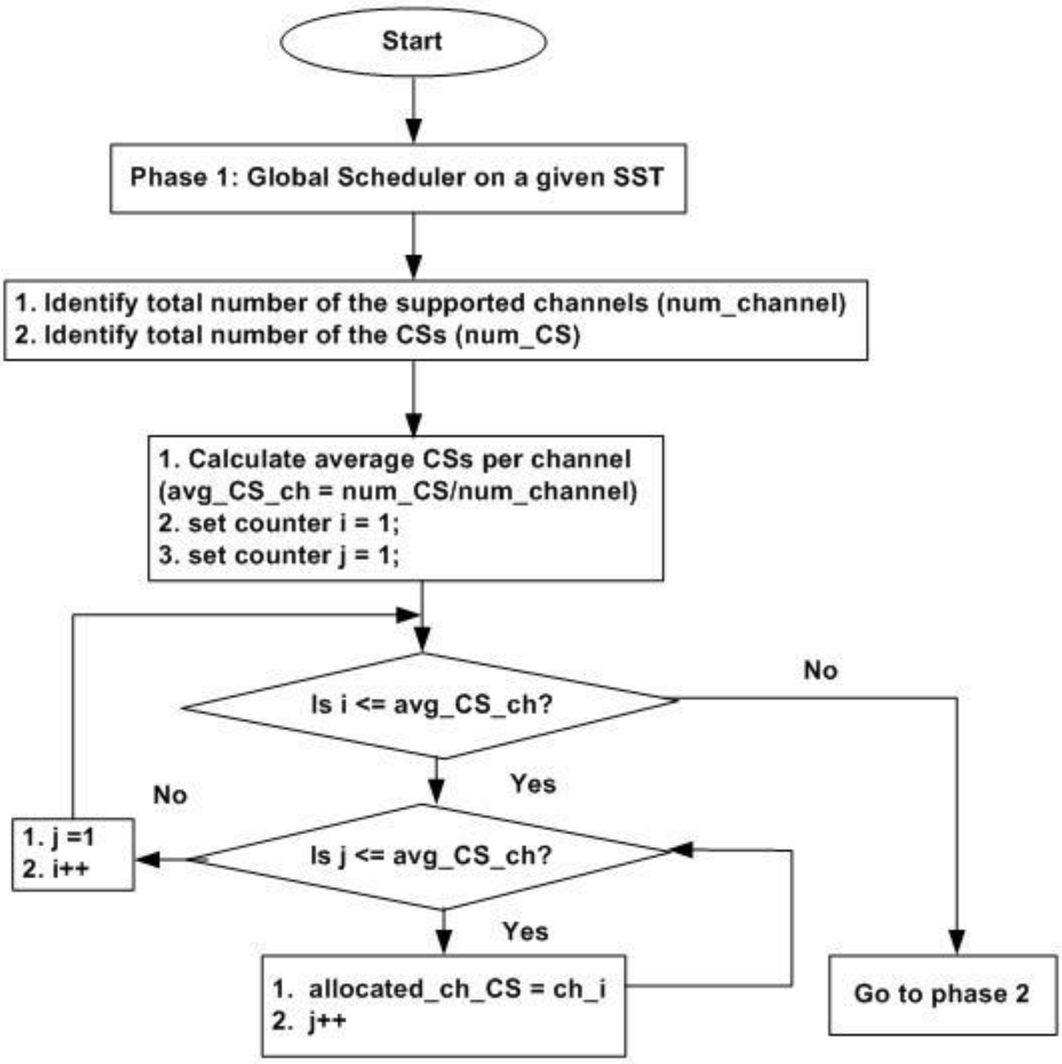

Figure 5.2 Flowchart for Initialisation phase of the IIDWBA algorithm

5.3.2 Intra-channel Bandwidth Allocations Phase of the IIDWBA Algorithm

Phase two of the IIDWBA algorithm, which is termed Intra-channel bandwidth allocations phase, will be executed right after the Initialisation phase (phase one) of the IIDWBA algorithm inside all channels associated with a given SST which will be accomplished once per service cycle. Phase two of the IIDWBA algorithm is responsible for allocating bandwidth inside a given channel per CS per service cycle considering the actual need of the local CSs as well as the minimum guaranteed bandwidth.

At the end of a given bandwidth allocation cycle, phase two of the IIDWBA algorithm will pass the local information to the global scheduler such as total number of heavily loaded CSs along with the associated MAC addresses and individual excess requested bandwidth, total excess bandwidth, total requested excess bandwidth and the generated service cycle to phase three. A global scheduler is an entity associated with each SST over the converged scenario which has global knowledge about the available resources as well as the requested resources per channel per service cycle. It is responsible to collect the extra bandwidth per CS per channel per service cycle and then schedule and distribute fairly among all the CSs which may not be satisfied by the minimum guaranteed bandwidth. The associated CSs may exist across different channels.

Taking into consideration the specific tasks which need to be done during phase two of the IIDWBA algorithm, Figure 5.1, an algorithm and a flowchart, Figure 5.3, are developed for phase two of the IIDWBA algorithm as follows.

A. *Algorithm for the Intra-channel bandwidth allocations phase of the IIDWBA algorithm*

An algorithm for phase two of the IIDWBA algorithm is defined as follows.

Given:

1) T_{cycle} : Maximum cycle duration which is the maximum time during which all CSs get a chance to send data traffic and/or REPORT messages to a given SST
2) G : Guard time (gap) between two consecutive time-slots
3) R_N : Channel rate between a given SST and the associated CS

4) w_i: Allocated weighting to CS_i based on the SLA definitions where:

$$\sum_{i=1}^{N} w_i = 1 \tag{5.3}$$

in case of no SLA classification w_i = w = 1/ N.

5) *N*: Number of CSs associated with a given SST

6) H_j: Total number of the heavily loaded CSs on a given channel *j*

7) MAC_{j}^{i}: MAC address associated with a given heavily loaded CS_i on a given channel *j*

8) $B_{min_j}^{i}$: Minimum guaranteed bandwidth for a given CS_i on a given channel *j* where: *j* = 1, …., α and *i* = 1, …., *N*. We require that:

$$\sum_{j=1}^{j=\alpha} \sum_{i=1}^{i=N} B_{min_j}^{i} < R_N \tag{5.4}$$

9) $B_{req_j}^{i}$: Requested bandwidth from a given CS_i on a given channel *j*

10) $B_{gra_j}^{i}$: Granted bandwidth to a given CS_i on a given channel *j*

11) $B_{total\_excess_j}$: Total excess bandwidth collected from a given channel *j*

12) $B_{avg\_excess_j}^{i}$: Average granted excess bandwidth to a given heavily loaded CS_i on a given channel *j*

13) $B_{total\_excess\_requested_j}$: Total extra requested bandwidth on a given channel *j*

14) $CS_{t\_duration}^{i,n,j}$: Allocated transmission duration to a given CS_i during a given service cycle *n* on a given channel *j*

15) $CS_{t\_start\_time}^{i,n,j}$: Allocated transmission start time to a given CS_i during a given service cycle *n* on a given channel *j*

16) RTT_j^i: Round trip time for a given CS_i on a given channel *j*

Define:

1) $B_{min_j}^i$: Minimum guaranteed bandwidth for a given CS_i on a given channel *j*.

The same formula from [6] is used in order to calculate $B_{min_j}^i$ as follows:

$$B_{min_j}^i = \frac{(T_{cycle} - N\ x\ G)\ x\ R_N\ x\ w_i}{8} \quad (5.5)$$

2) A given SST needs to generate a service cycle which includes the transmission start time and transmission duration for all the associated CSs at the end of each bandwidth allocation cycle as follows.

   a. Transmission duration for a given CS_i during a given service cycle *n* on a given channel *j* is calculated as follows where 64 bytes is the required bytes to transmit the next MPCP Ext. REPORT message:

$$CS_{t\_duration}^{i,n,j} = \left(\frac{B_{gra_j}^i + 64\ bytes}{R_N}\right) + RTT_j^i \quad (5.6)$$

   b. Transmission start time for a given CS_i during a given service cycle *n* on a given channel *j* has been considered by taking into account the granted transmission duration to the previous CS (CS_{i-1}) (5.6) as well as the guard time, *G*, between two consecutive allocated time-slots as follows:

$$CS_{t\_start\_time}^{i,n,j} = CS_{t\_duration}^{i-1,n,j} + G \quad (5.7)$$

Objectives:

1) Allocating bandwidth to the local CSs on a given channel *j*.
2) Scheduling the local service cycle.

3) Capturing the total number of the heavily loaded CSs with associated MAC addresses and individual excess requested bandwidth, total excess bandwidth and total local excess requested bandwidth on a given channel *j*.
4) Sending the scheduled service cycle from objective 2 along with the captured information from objective 3 to the global scheduler.

In order to distinguish how the bandwidth will be granted from a given SST to the associated CSs during a given service cycle *n* on a given channel *j*, the *Limited Bandwidth Allocation scheme* which has been studied in [80] and [81] are discussed as follows. In the *Limited Bandwidth Allocation scheme*, if the requested bandwidth is less than the minimum guaranteed bandwidth, the requested bandwidth will be granted or else the minimum guaranteed bandwidth will be issued. This approach provides the excess bandwidth remains from the CSs which requested bandwidth less than the minimum guaranteed bandwidth for what they are termed as lightly loaded CSs. One solution is to distribute it fairly among the heavily loaded CSs which requested bandwidth more than the minimum guaranteed bandwidth similar to the work which is proposed in [6].

However, the difference between the work in this thesis and the work proposed in [6] is that in this thesis the local excess bandwidth from a given channel *j* during a given service cycle *n* will be used globally if it is not employed by the local CSs on the corresponding channel during phase two and phase three of the IIDWBA algorithm.

Following are the possible cases that may occur during the execution of phase two. It is to be noted that at the first stage of phase two, all the CSs are grouped into the lightly loaded CSs and heavily loaded CSs. The lightly loaded CSs are those where requested bandwidth is less than the minimum guaranteed bandwidth while the heavily loaded CSs are those that requested bandwidth greater than the minimum guaranteed bandwidth. At the second stage, a given SST starts granting bandwidth to the lightly loaded CSs and then the heavily loaded CSs in sequence as follows.

Case I: The requested bandwidth from a given CS_i on a given channel j is less than or equal to the minimum guaranteed bandwidth, i.e.

$$B_{req}{}_j^i \leq B_{min}{}_j^i \tag{5.8}$$

In such a case, the requested bandwidth will be granted and excess bandwidth will be collected, therefore:

$$B_{gra}{}_j^i = B_{req}{}_j^i \tag{5.9}$$

$$B_{total\_excess_j} = {}_{i=1}^{i=N} B_{min}{}_j^i - B_{req}{}_j^i \tag{5.10}$$

Case II: The requested bandwidth from a given CS_i on a given channel j is more than the minimum guaranteed bandwidth, i.e.

$$B_{req}{}_j^i > B_{min}{}_j^i \tag{5.11}$$

Therefore:

$$B_{total\_excess\_requested_j} = {}_{i=1}^{i=N} B_{req}{}_j^i - B_{min}{}_j^i \tag{5.12}$$

In such a case, the minimum guaranteed bandwidth and the average of the total excess bandwidth (5.13) will be considered to be allocated, i.e.

$$B_{avg\_excess}{}_j^i = B_{total\_excess_j} / H_j \tag{5.13}$$

It brings the following two cases:

Case II. A: The requested bandwidth from a given heavily loaded CS_i on a given channel j, is less than or equal to the sum of the minimum guaranteed bandwidth and the average of the total excess bandwidth, i.e.

$$B_{req}{}_j^i \leq B_{min}{}_j^i + B_{avg\_excess}{}_j^i \tag{5.14}$$

In such a case, $B_{req}{}_j^i$ will be granted and the excess will be collected. As a result, the corresponding CS will not be considered as a heavily loaded CS anymore, therefore:

$$B_{gra}{}_j^i = B_{req}{}_j^i \tag{5.15}$$

$$H_j \text{ --} \tag{5.16}$$

$$B_{total\_excess_j} += {}_{i=1}^{i=N} B_{min}{}_j^i + B_{avg\_excess}{}_j^i - B_{req}{}_j^i \tag{5.17}$$

$$B_{total\_excess\_requested_j} -= {}_{i=1}^{i=N} B_{req}{}_j^i - B_{min}{}_j^i \tag{5.18}$$

Case II. B: The requested bandwidth from a given heavily loaded CS_i on a given channel j, is more than the sum of the minimum guaranteed bandwidth and the average of the total excess bandwidth, i.e.

$$B_{req}{}_j^i > B_{min}{}_j^i + B_{avg\_excess}{}_j^i \tag{5.19}$$

In such a case, ($B_{min}{}_j^i + B_{avg\_excess}{}_j^i$) will be granted, and the corresponding CS will remain heavily loaded, therefore:

$$B_{gra}{}_j^i = B_{min}{}_j^i + B_{avg\_excess}{}_j^i \tag{5.20}$$

$$B_{total\_excess\_requested_j} \text{ - } = B_{avg\_excess}{}^{i}_{j} \quad (5.21)$$

In this stage, the local scheduler which is associated with a given channel j passes the total number of local heavily loaded CSs (H_j), the associated MAC address of each heavily loaded CS (Mac^{i}_{j}), the total of the local excess requested bandwidth ($B_{total\_excess\_requested_j}$), the total of the local excess bandwidth ($B_{total\_excess_j}$) and the latest schedule service cycle (T_{cycle_j}) to the global scheduler on a given SST in order to execute phase three of the IIDWBA algorithm termed Inter-channel bandwidth allocations which will be discussed next.

Unlike the local scheduler, which has control over a single channel, the global scheduler has control over all channels associated with a given SST and thus it has real-time knowledge about the load, excess bandwidth as well as the excess requested bandwidth per channel per service cycle.

A flowchart for phase two of the IIDWBA algorithm is represented next.

B. *Flowchart for the Intra-channel bandwidth allocations phase of the IIDWBA algorithm*

As depicted in Figure 5.3, at the first step, each CS will be identified either as a lightly loaded or a heavily loaded CS. The lightly loaded CSs will be granted the requested bandwidth and the excess bandwidth will be collected from them at the same time. Then the bandwidth will be allocated to the heavily loaded CSs such that it is no more than the minimum guaranteed bandwidth plus the average amount of excess bandwidth which is collected from the lightly loaded CSs. After allocating bandwidth to all CSs, including the lightly loaded and heavily loaded CSs, the local information such as total number of local heavily loaded CS and associated MAC addresses as well as the individual excess requested bandwidth along with the total excess bandwidth, total excess requested bandwidth and current scheduled service cycle will be passed from phase two to phase three of the IIDWBA algorithm.

Generally speaking, the above information passes between phase two and phase three of the IIDWBA algorithm from a given local scheduler, which is associated with a given channel on a given SST, to a single entity termed global scheduler, which is associated with a given SST. In section 5.3.2 part C, we identify an example of three phases of the IIDWBA algorithm operations with clear positions of the local schedulers and global scheduler inside a given SST.

The next section provides a detailed discussion for phase three of the IIDWBA algorithm as follows.

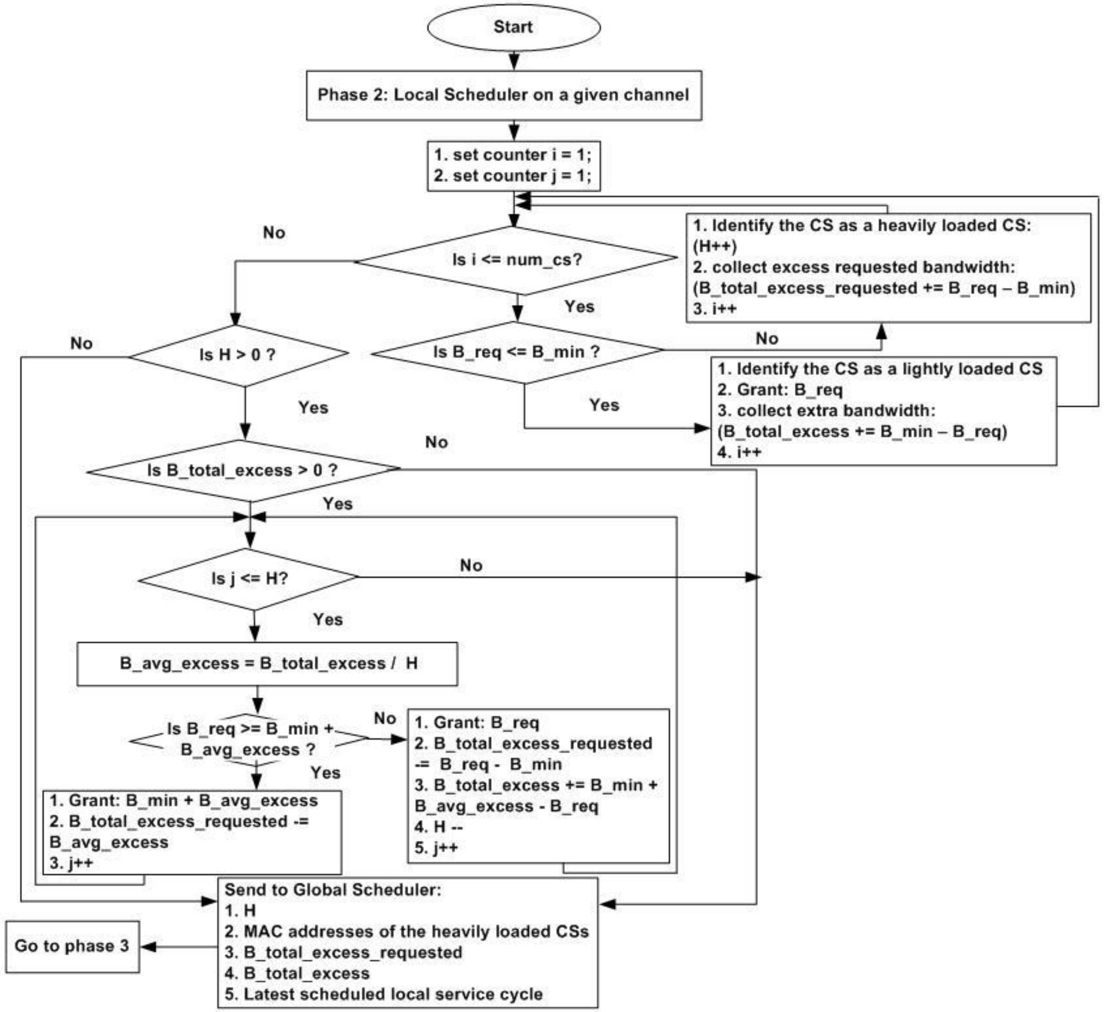

Figure 5.3 Flowchart for Intra-channel bandwidth allocations phase of the IIDWBA algorithm

5.3.3 Inter-channel Bandwidth Allocations Phase of the IIDWBA Algorithm

Phase three of the IIDWBA algorithm is termed Inter-channel bandwidth allocations phase and will be executed right after phase two. While phase two of the IIDWBA algorithm deals with a single channel, phase three deals with all channels associated with a given SST and includes three real-time stages of *Collect*, *Schedule* and *Distribute* as follows.

In the *Collect* stage, phase three starts collecting the local information from each channel associated with a given SST including the total number of the heavily loaded CSs along with the associated MAC addresses and individual excess requested bandwidth, total excess bandwidth, total excess requested bandwidth as well as the latest scheduled service cycle.

In the *Schedule* stage, based on the total number of the heavily loaded CSs over all channels (globally heavily loaded CSs), the total excess bandwidth and total excess requested bandwidth, phase three of the IIDWBA algorithm will schedule the total excess bandwidth collected from all channels among the globally heavily loaded CSs.

The proposed scheme provides fair allocations as the scheduled excess bandwidth from each channel is no more than the excess requested bandwidth per heavily loaded CS. The proposed scheme also supports the weighing method in which specific heavily loaded CSs or specific types of traffic will be treated in different way based on the associated SLA agreement. For instance, based on the SLA agreement a given heavily loaded CS can benefit from bigger portion of the excess available bandwidth.

In the *Distribute* stage, the globally scheduled excess bandwidth will be distributed among all globally heavily loaded CSs inside the associated service cycles and immediately broadcast to all channels.

Generally speaking, the main concern in phase three of the IIDWBA algorithm is to find and collect the real-time excess amount of bandwidth from all the channels associated with a given SST during each service cycle and spend (schedule and distribute) them immediately on those CSs which are identified as globally heavily loaded CSs in the latest service cycle.

Taking into consideration the specific tasks which need to be done during phase three of the IIDWBA algorithm, Figure 5.1, an algorithm and a flowchart, Figure 5.4, are developed for phase three of the IIDWBA algorithm as follows.

A. Algorithm for the Inter-channel bandwidth allocations phase of the IIDWBA algorithm

An algorithm for phase three of the IIDWBA algorithm is defined as follows.

Given:

1) MAC_j: All MAC addresses associated with the heavily loaded CSs on a given channel *j*
2) T_j : Latest scheduled service cycle associated with a given channel *j*
3) $T^{j}_{last\_t\_start\_time}$: Last transmission start time allocated inside the latest service cycle associated with a given channel *j*
4) $T^{j}_{last\_t\_duration}$: Last transmission duration allocated inside the latest service cycle associated with a given channel *j*

5) ${B_{excess\_requested}}_j^i$: Excess requested bandwidth from a globally heavily loaded CS_i on a given channel j

Define:

1) H_{global}: Total number of the heavily loaded CSs across all channels:

$$H_{global} = \sum_{j=1}^{j=\alpha} H_j \tag{5.22}$$

2) B_{excess_global}: Total excess bandwidth collected from all channels:

$$B_{excess\_global} = \sum_{j=1}^{j=\alpha} {B_{total\_excess}}_j \tag{5.23}$$

3) ${B_{avg\_excess\_global}}_i$: Average global excess bandwidth available for a given globally heavily loaded CS_i:

$${B_{avg\_excess\_global}}_i = B_{excess\_global} / H_{global} \tag{5.24}$$

Objectives:

1) Receiving the total number of heavily loaded CSs with associated MAC addresses and individual excess requested bandwidth, total local excess bandwidth and the total local excess requested bandwidth from all channels.
2) Receiving the latest scheduled service cycle from all channels.
3) Identifying the lightly loaded and heavily loaded channels.
4) Calculating the total number of heavily loaded CSs across all heavily loaded channels (globally heavily loaded CSs).

5) Calculating total excess bandwidth across all lightly loaded channels (global excess bandwidth).
6) Calculating the average granted excess bandwidth from each lightly loaded channel to a given globally heavily loaded CS.
7) Allocating the global excess bandwidth to the globally heavily loaded CSs according to their actual need.
8) Scheduling and embedding the global allocated excess bandwidth inside service cycle of each lightly loaded channel.
9) Sending all service cycles for all channels to broadcaster.

In this stage, the global scheduler received required information including: the number of the heavily loaded CSs, H_j , and associated MAC addresses and individual excess requested bandwidth, Mac_j^i and $B_{excess\_requested}{}_j^i$, along with the total excess bandwidth, $B_{total\_excess_j}$, total excess requested bandwidth, $B_{total\_excess\_requested_j}$, as well as the latest scheduled service cycle from each channel.

Following are the possible cases that may occur during phase three.

Case I: There is no heavily loaded CS across all channels.

$$H_{global} = 0 \tag{5.25}$$

Case I brings two other cases as follows.

Case I. A: All CSs across a given channel j: $j = 1, \ldots, \alpha$ are lightly loaded which means they are all requesting bandwidth equal to or less than the minimum guaranteed bandwidth.

Case I. B: Some of CSs across a given channel j: $j = 1, \ldots, \alpha$ are heavily loaded and some are lightly loaded. However, the local heavily loaded CSs are satisfied with excess bandwidth collected from the local lightly loaded CSs. Therefore, the local heavily loaded CSs are not globally heavily loaded.

In such cases, **Case I. A** and **Case I. B**, the global scheduler passes all the received service cycles from all channels to the Broadcaster which will then broadcast to all channels immediately.

Case II: There are heavily loaded CSs across some or all channels but there is no global excess bandwidth.

$$H_{global} > 0 \tag{5.26}$$

$$B_{excess\_global} = 0 \tag{5.27}$$

Case II brings two other cases as follow.

Case II. A: All CSs across a given channel j: $j = 1, \ldots, \alpha$ are heavily loaded. Therefore, there is no local excess bandwidth available from a given channel j: $j = 1, \ldots, \alpha$ to satisfy local demands for the excess requested bandwidth.

Case II. B: Some of CSs across a given channel j: $j = 1, \ldots, \alpha$ are heavily loaded and some are lightly loaded. However, the local heavily loaded CSs are not satisfied with excess bandwidth collected from the local lightly loaded CSs. Therefore, some of or all of the local heavily loaded CSs are also globally heavily loaded.

In such cases, **Case II. A** and **Case II. B**, the global scheduler passes all received service cycles from all channels to the Broadcaster which will then broadcast to all channels immediately.

Case III: There are heavily loaded CSs across all channels and the global excess bandwidth is available.

$$H_{global} > 0 \tag{5.28}$$

$$B_{excess\_global} > 0 \tag{5.29}$$

In such a case, the global scheduler allocates the global excess bandwidth among globally heavily loaded CSs scattered across all channels. In the first step, average global excess bandwidth (5.24) will be calculated by the global scheduler for all heavily loaded CSs which may not be located in a same channel. In the second step, the global scheduler compares the average global excess bandwidth with excess requested bandwidth from each globally heavily loaded CS which brings the following two cases:

Case III. A: The average global excess bandwidth calculated for a given heavily loaded CSs on a given channel *j: j = 1,…., α,* is more than or equal to the excess requested bandwidth from the associated CS:

$$B_{excess\_requested}{}_j^i \leq B_{avg\_excess\_global_i} \tag{5.30}$$

In such a case, $B_{excess\_requested}{}_j^i$ will be granted.

Case III. B: The average global excess bandwidth calculated for a given heavily loaded CS on a given channel *j: j = 1,…., α,* is less than excess requested bandwidth from the associated CS:

$$B_{excess\_requested}{}_j^i > B_{avg_{excess_{global_i}}} \quad (5.31)$$

In such a case, $B_{avg\_excess\_global_i}$ will be granted.

The granted bandwidth will be then scheduled inside the appropriate service cycle, T_j, by global scheduler taking into account: $T^{\,j}_{last\_t\_start\_time}$ and $T^{\,j}_{last\_t\_\,duration}$ as well as MAC_j. At the end, the global scheduler passes all service cycles to the Broadcaster which will broadcast to all channels immediately.

A flowchart for phase three of the IIDWBA algorithm is presented next.

B. *Flowchart for the Inter-channel bandwidth allocations phase of the IIDWBA algorithm*

As it is shown in Figure 5.4, phase three of the IIDWBA algorithm first receives local information from all the channels associated with a given SST which includes the total number of heavily loaded CSs, their associated MAC addresses and individual excess requested bandwidth, the total excess bandwidth, the total excess requested bandwidth and the latest scheduled service cycles. Then it distributes the total excess bandwidth, which is collected from all channels, among all globally heavily loaded CSs. The distributed global excess bandwidth will be scheduled inside the appropriate service cycles associated with the lightly loaded channels and will be passed to the Broadcaster in order to immediately broadcast to all CSs scattered over all channels.

The next section explains the full IIDWBA operations through an example in order to help understanding of its functionality during each phase.

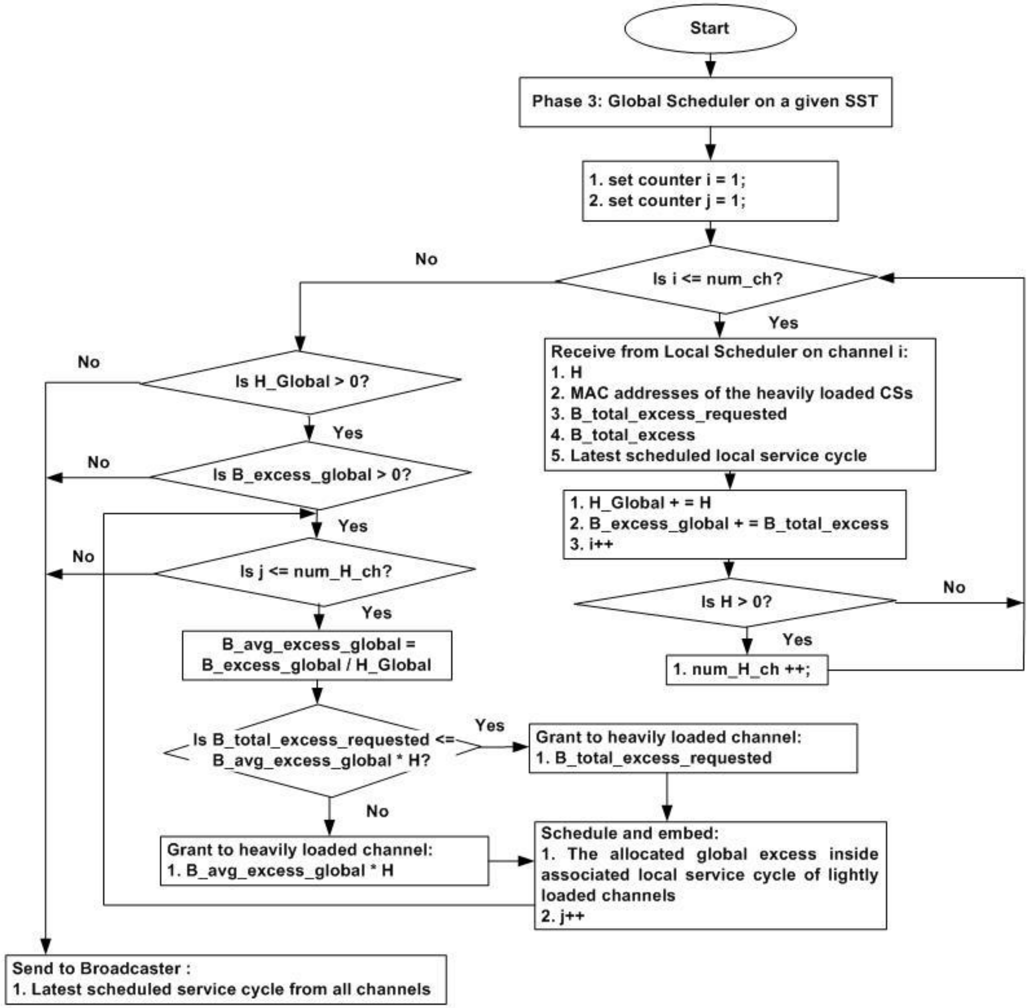

Figure 5.4 Flowchart for Inter-channel bandwidth allocations phase of the IIDWBA algorithm

C. An example of the three phases of the IIDWBA algorithm operations

As it is depicted in Figure 5.5, on a given SST, e.g. the OLT in the CO, each channel is associated with a scheduler termed a local scheduler which is responsible for allocating the bandwidth from the local channel among all CSs assigned to it. A given local scheduler also deals with the master scheduler termed a global scheduler on a given SST. While a local scheduler is only in charge of allocating bandwidth among its associated CSs, a given global scheduler deals with all the channels on a given SST and responsible for allocating the global excess bandwidth from all channels among the globally heavily loaded CSs which may exist over different channels.

Generally speaking a local scheduler on a given SST is responsible for the following tasks: 1) Identifying the local lightly/heavily loaded CSs 2) Granting bandwidth to the lightly loaded CSs 3) Collecting bandwidth from the lightly loaded CSs 4) Distributing the local excess bandwidth among local heavily loaded CSs 5) Passing the following information to the global scheduler: the total number of the heavily loaded CSs along with their associated MAC addresses and individual excess requested bandwidth, the total excess bandwidth, the total requested excess bandwidth along with the latest scheduled service cycle. This information is termed clarification data.

When the global scheduler receives the clarification data from all the associated channels on a given SST, it first starts counting the number of the heavily loaded CSs, which may be scattered across different channels, along with the total excess bandwidth and total requested excess bandwidth collected from all channels. A given globally heavily loaded CS will be allocated with the global excess bandwidth in such a way that it will be guaranteed the average portion of the total excess bandwidth collected from all

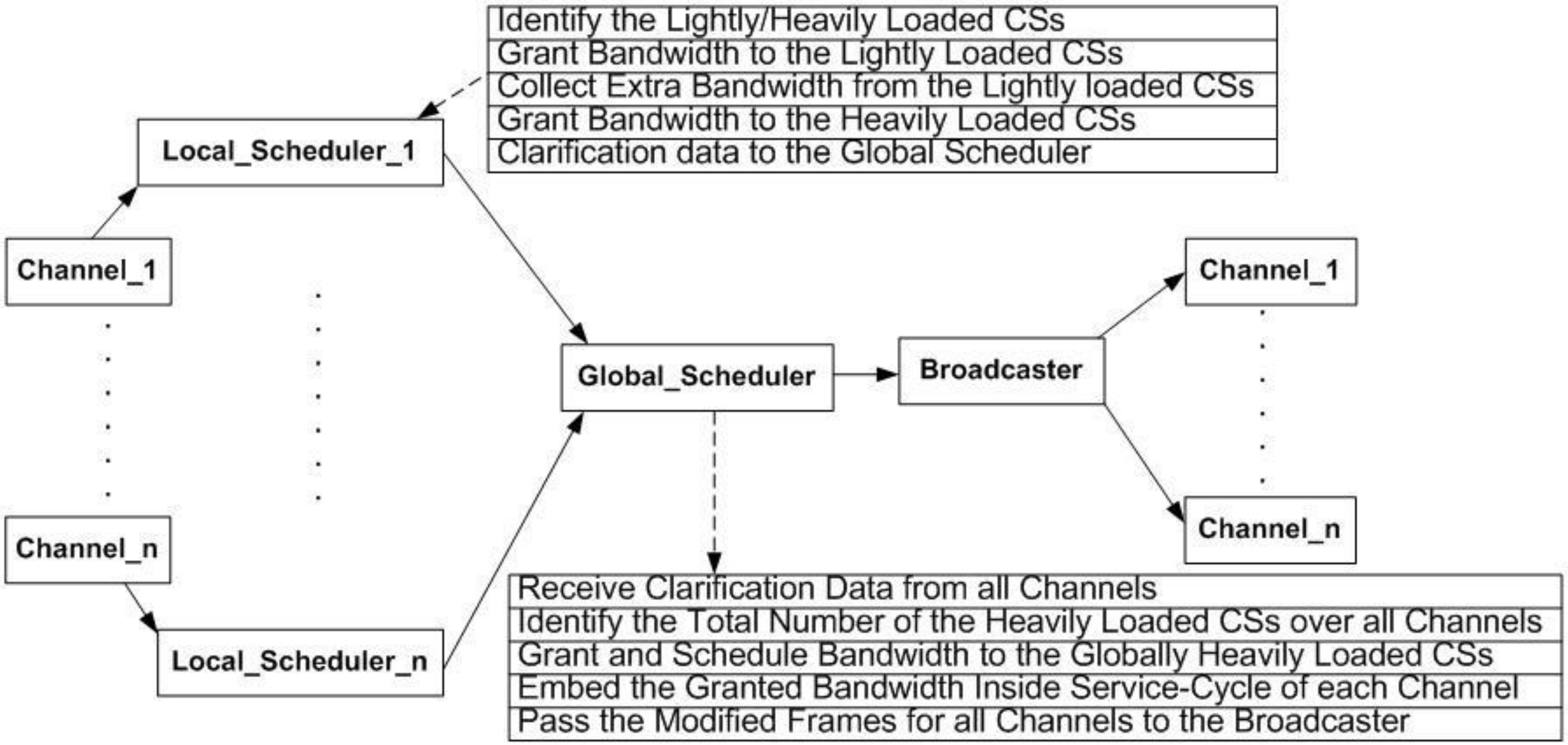

Figure 5.5 Execution of the IIDWBA algorithm inside a given SST

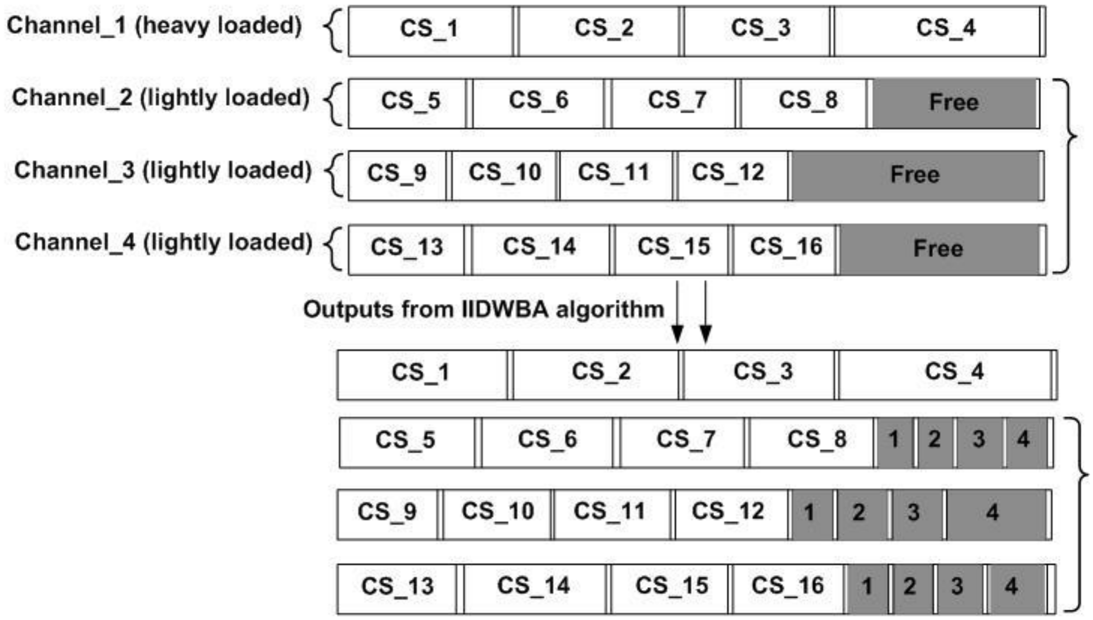

Figure 5.6 Output from IIDWBA algorithm (modified service cycles)

channels and will not receive bandwidth more than its requirements. The allocated global excess bandwidth to the globally heavily loaded CSs will be scheduled and embedded inside the service cycle associated with the lightly loaded channels. After finishing the service cycle modifications, all the service cycles will be passed to the Broadcaster which will be then broadcast to all channels associated with a given SST, Figure 5.5. In order to show the output of the IIDWBA algorithm after the execution of all three phases, a scenario is made of a given SST with four associated channels (*channel_1* to *channel_4*) each of them is assigned to four CSs, Figure 5.6. In a given service cycle *T*, the SST identifies *channel_1* as a heavily loaded channel and three other channels (*channel_2* to *channel_4*) as lightly loaded channels. Thus, IIDWBA algorithm starts collecting the available excess bandwidth from (*channel_2* to *channel_4*) in order to distribute them among CSs associated with *channel_1*. A given modified service cycle which will be passed to the Broadcaster at the end of the

IIDWBA algorithm executions includes the allocated time slots for the local CSs as well as the extra allocated time-slots which are allocated to the globally heavily loaded CSs associated with *channel_1*. When a modified service cycle is broadcast to the CSs, a given heavily loaded CS, which is locally registered to *channel_1* in above example, will find itself with multiple time-slot assignments on the local registered channel, *channel_1*, as well as three other lightly loaded channels, *channel_2* to *channel_4*, Figure 5.6. The required messages, which need to be passed during the execution of the IIDWBA over a given service cycle in order to provide the successful execution of the proposed algorithm and meet the second objective of this thesis, are shown in Figure 5.7. The next section evaluates the performance of the IIDWBA algorithm through different simulated scenarios and traffic pattern configurations as follows.

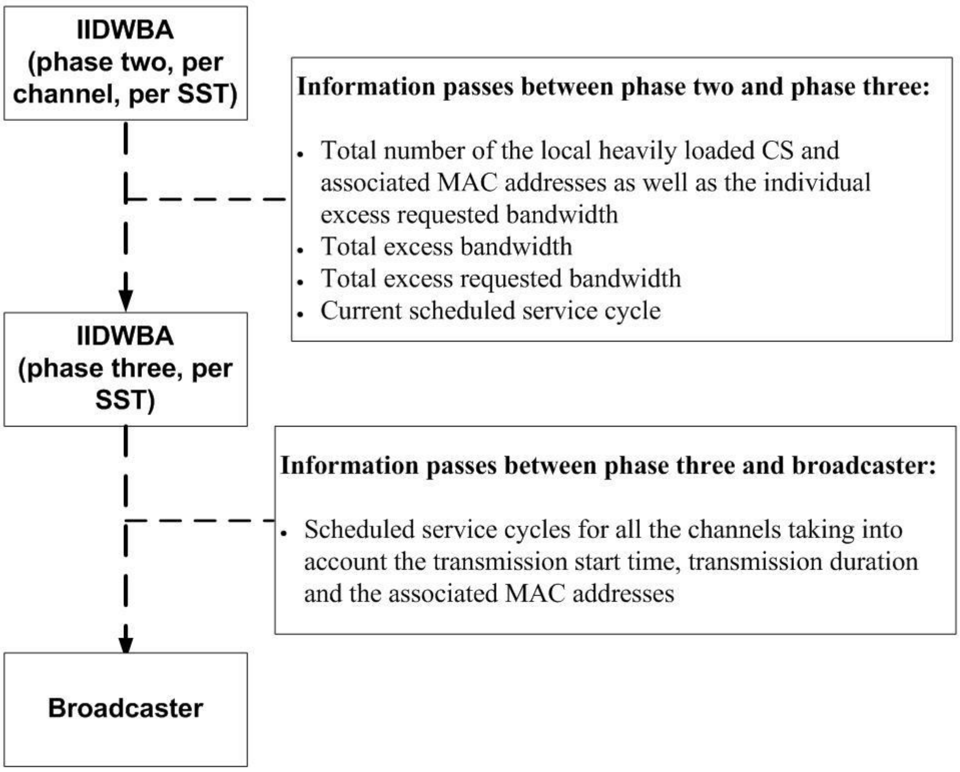

Figure 5.7 Required information passes over the execution of the IIDWBA algorithm

5.4 Overview of Experiments

An overview of the experiments, which will be executed in this chapter in order to evaluate the performance of the proposed IIDWBA algorithm, is presented in Figure 5.8. It includes the investigation details along with the simulation setting and traffic pattern configuration as well as the key results along with the relevance of the captured results to this thesis.

It is to be noted that the results, which will be discussed later in this chapter, are captured after all three phases of the IIDWBA algorithm are executed. It is because all three phases of the IIDWBA algorithm are chained together and run one after another through the simulation run time. Therefore, it is almost impossible for an isolated evaluation of each phase.

The next section discusses in detail the experimental set up to evaluate the performance of the IIDWBA algorithm as follows.

5.5 Simulation Results

This section provides the details of the experimental set up including the network topology, simulation parameters and traffic pattern characteristics which are employed in order to distinguish the performance of the proposed IIDWBA algorithm over the converged infrastructure of the NGN.

The next section describes in detail the network topology employed for the evaluation of the IIDWBA algorithm as follows.

Investigation Details To demonstrate the performance of the proposed distributed, real-time, dynamic and scalable resource allocation algorithm, namely, Inter-channel and Intra-channel Dynamic Wavelength/Bandwidth Allocation (IIDWBA) algorithm with the sole focus on the resource utilisation over the converged infrastructure of the NGN
Simulation coding and settings OPNET coding (C++): The implemented architectural design of the converged scenario with the core focus on the ETE key functional modules for Multi-channel converged scenario between optical and wireless technologies along with the implemented MPCP protocol are re-employed from chapter 5 in order to develop the proposed Inter-channel and Intra-channel Dynamic Wavelength/Bandwidth Allocation (IIDWBA) algorithm Simulation setting: bursty traffic pattern (different ON/OFF state time, different traffic, different start /stop time, different packet size and different load pattern)
Key results and figures Performance of the proposed IIDWBA algorithm are represented through Figure 4.13 to Figure 4.21
Relevance of results to the thesis A distributed, real-time, dynamic and scalable resource allocation algorithm, namely, Inter-channel and Intra-channel Dynamic Wavelength/Bandwidth Allocation (IIDWBA) algorithm for the converged scenario of the NGN is proposed and evaluated through conducted simulated experiments

Figure 5.8 Overview of experiments for chapter 5

5.5.1 Network Topology

The same network topology, which was employed in chapter 4 (section 4.5.3), is re-employed in this chapter, Figure 5.9, in order to provide a robust infrastructure for evaluating the performance of the proposed IIDWBA algorithm.

It includes an OLT in the CO, which supports four channels ($w_1, \ldots, w_4$) and is related to 16 ONUs, a 4:4 sized AWG with co-related amplifier and four 1:16 sized TDM Splitters/Combiners. AWG and TDM Splitters/Combiners are seated between the OLT and the ONUs. A given ONU, which supports the same four channels, is also related to 16 BSs and each BS supports 10 wireless subscriber stations. The number of SSs per BS will be increased to 100 in stages of 10 in order to evaluate the performance of the IIDWBA algorithm under different load values.

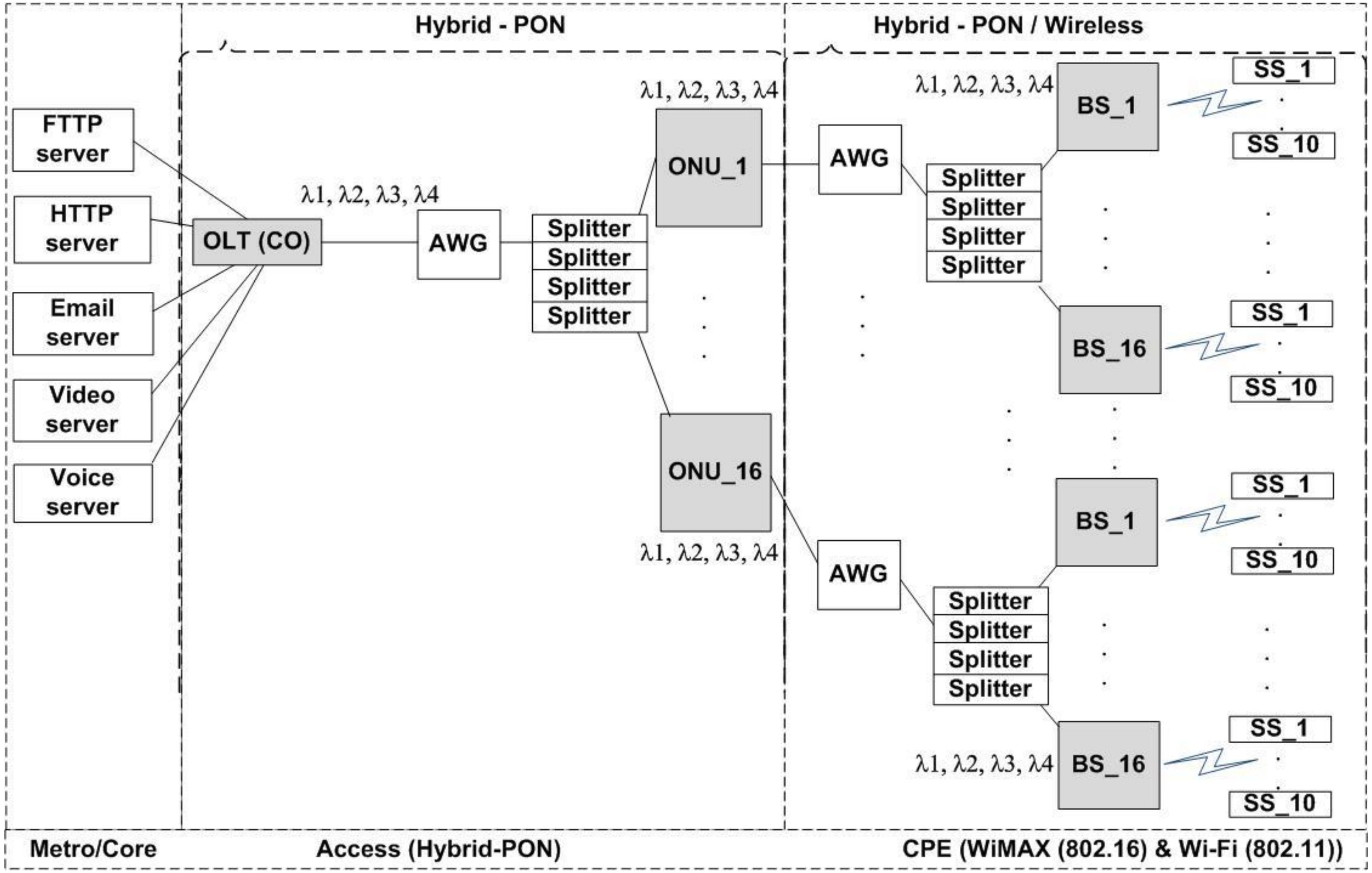

Figure 5.9 Network topology for evaluating the IIDWBA performance

A 4:4 sized AWG with co-located amplifier and four 1:16 sized Splitters/Combiners are also seated between a given ONU and the related 16 BSs. A given BS supports the same four channels in the direction of the associated ONU however it uses a fixed wavelength in the downstream direction (to the SSs). Therefore, the total number of the ONUs, BSs and SSs are 16, 256 (16 ONUs × 16 BSs) and 2560 to 25600 (256 BS × 10 SS to 256 BS × 100 SS), respectively for the whole converged scenario. The total distance supported with the implemented converged scenario is nearly 300 km due to employing AWG with co-located amplifier as well as TDM Splitters/Combiners between the OLT and the ONUs and between the ONUs and the BSs. The next section discusses the simulation parameters employed for the evaluation of the proposed IIDWBA algorithm as follows.

5.5.2 Simulation Parameters

Simulation parameters, Table 5-1, are used for the experiments over the converged scenario. Based on the Table 5-1 specifications, traffic flows with: burst pattern, different ON/OFF state time as well as Start/Stop time, constant packet size and different exponentially distributed packet interval time over four channels are used for the simulated experiments. This is the same simulation parameters that were employed in chapter 4 for a different performance evaluation. Based upon the widely used configurations for the converged scenario and traditional TDM-based PON [68], [80], following configurations are employed. The buffer sizes inside the ONUs and BSs are set to a finite 10 Mbytes and the maximum cycle time is considered as 2 ms. Maximum cycle time is the maximum time that a given CS (ONU/BS) needs to wait before getting a chance for the upstream data transmissions in the direction of the associated SST

(OLT/ONU), respectively. As all the CSs are placed in a same distance from their associated SST, the RTT delay can be considered as a fixed value. The RTT is the length of time it takes for a packet to be sent plus the length of time it takes for an acknowledgment of that packet to be received. We measured this value in our simulated scenario for a single node which gives us 192µs. Therefore, a fixed 192µs has been considered as the RTT delay for each CS (ONU/BS) in every service cycle. Moreover, 100 Mb/s and 1Gb/s are the upstream data rates between a given BS and the associated ONU as well as a given ONU and OLT, respectively.

Table 5-1 Simulation parameters for evaluating the IIDWBA algorithm

Traffic pattern	Burst (uneven across SSs)
ON state time (sec)	20% of simulation time
OFF state time (sec)	80% of simulation time
Traffic start time	even across all SSs
Traffic stop time	Never
Packet size	500 bytes (constant)
Number of channels supported on OLT, ONUs and BSs for upstream transmissions	4 channels (w_1,…,w_4)
Packet interval time per SS per ONU on channel one (w_1)	0.05 sec (Exponential distributed)
Packet interval time per SS per ONU on channel two (w_2)	0.05 sec (Exponential distributed)
Packet interval time per SS per ONU on channel three (w_3)	0.5 sec (Exponential distributed)
Packet interval time per SS per ONU on channel four (w_4)	1 sec (Exponential distributed)
Number of SSs per BS	10 to 100 BY 10
Traffic class	Best Effort (BE)
Simulation time	30 sec
Seed	128, 166, 99
value per static, update interval	1600, 300000

The guard time, which is gap separating two consecutive time slots, needs to be considered in order to support several factors such as laser switching delay, ranging inaccuracy, and clock-recovery preamble. The lower bound for the guard time is the laser switching time, which is about 10ns, as optical light sources need to be turned off completely when they are not transmitting. Therefore, the guard time is reasonable as it is sub-μs [10]. In this implementation, a fixed guard time of 5μs for light sources on the ONUs and BSs is considered. Moreover, the MPCP Ext. protocol is also employed in order to support the communications among all the components of the converged scenario. Moreover, different seed values of 128, 166 and 90 are employed during the simulation run time. However, we depicted the average plots from three seed values in this chapter.

The next section describes the traffic pattern characteristics chosen for the IIDWBA performance evaluation along with the reason for such configurations.

5.5.3 Traffic Pattern Characteristics

In order to evaluate phase three of the IIDWBA algorithm, uneven traffic across all four channels, $w_{1},...,w_{4}$, is made where lightly loaded and heavily loaded channels always exist during the simulation run time. Lightly loaded channels are those channels that related to CSs which requested bandwidth less than the minimum guaranteed bandwidth and the heavily loaded channels are those channels that related to CSs which requested bandwidth more than the minimum guaranteed bandwidth.

The simulation experiments are configured with following traffic pattern specifications termed as the *first traffic pattern* and the *second traffic pattern* as follows, Table 5-2.

In the *first traffic pattern*, the load on w_1 is gradually increased from 10 SSs to 100 SSs per BS keeping the number of SSs on the other channels ($w_2,\dots,w_4$) fixed, up to 10 SSs per BS, in order to distinguish how CSs on w_1 benefit from the available free bandwidth on other channels ($w_2,\dots,w_4$) when the traffic builds up by employing the IIDWBA algorithm.

In the *second traffic pattern*, the load on all channels, $w_1,\dots,w_4$, is increased simultaneously by gradually rising the number of SSs per BS from 10 to 100 and distinguish the performance of the CSs associated with w_1 in comparison with the results captured from the first traffic pattern .

Due to the simplicity of the downstream transmission, the experiments in the upstream directions to the OLT are only considered. Due to similarity of the results the OLT and ONUs captured results are only depicted in this chapter. However, all three phases of the IIDWBA algorithm are implemented over all SSTs (OLT and ONUs) across the converged scenario.

For each phase of the IIDWBA algorithm a single algorithm is also implemented using OPNET Modeler [79] as follows.

5.5.4 Implemented Algorithm for Phase One of the IIDWBA

The associated algorithm for the Initialisation phase of the IIDWBA algorithm (phase one) is represented in Figure 5.10.

Table 5-2 Traffic pattern configurations for evaluating the IIDWBA algorithm

<table>
<tr><th>Traffic pattern</th><th>Number of SSs on w_1</th><th>Number of SSs on $w_2,\ldots,w_4$</th><th>Generated traffic per SS on $w_1,\ldots,w_4$</th></tr>
<tr><td>First traffic pattern</td><td>Gradually increased from 10 SSs to 100 SSs per BS (total of 160 to 1600 SSs per ONU)</td><td>Fixed 10 SSs per BS (total of 160 SSs to 1600 SSs per ONU)</td><td rowspan="2">w_1 : 80 kb/s per SS (exponentially distributed)
w_2: 80 kb/s per SS (exponentially distributed)
w_3: 8 kb/s per SS (exponentially distributed)
w_4: 4 kb/s per SS (exponentially distributed)</td></tr>
<tr><td>Second traffic pattern</td><td>Gradually increased from 10 SSs to 100 SSs per BS (total of 160 to 1600 SSs per ONU)</td><td>Gradually increased from 10 SSs to 100 SSs per BS (total of 160 to 1600 SSs per ONU)</td></tr>
</table>

As Figure 5.10 reveals, the Initialisation phase of the IIDWBA algorithm first fills the array of the supported channels, *SST_ch_arry[α]*, for a given SST, Line 1. When CSs start join the converged scenario, a given SST starts accepting them, counting them and calculating the number of CSs per channel, Line 2 and Line 3. A given SST then allocates channel IDs to the associated CSs and a copy of the granted channel will be kept inside the array of wavelengths for CSs, *CS_ch_arry[α][μ]*, Line 4. The allocated channel IDs will then be placed inside the MPCP Ext. GATE messages and broadcast to all CSs, Line 5. A given MPCP Ext. GATE message carries an allocated channel ID along with the associated MAC address of a given CS. Finally, the Initialisation phase of the IIDWBA algorithm waits to receive the first MPCP Ext. REPORT messages from all the associated CSs and straightaway goes to phase two which is termed Intra-channel bandwidth allocations phase, Line 6 and Line 7.

The implemented algorithm for phase two of the IDIWBA algorithm is presented next.

Given:

1) *SST_ch_arry[α]:* array of channel IDs for a given SST
2) *CS_ch_arry[α][μ]:* array of channel IDs for all CSs associated with a given SST
3) α : total number of the supported wavelengths on a given SST
4) β : total number of CSs on a given SST

To:

1) Fill the *SST_ch_arry [α]* with supported channel IDs
2) Calculate μ: average number of CSs per channel on a given SST
3) Assign channel ID temporarily to each CS and fill the *CS_ch_arry[α][μ]*
4) Broadcast allocated channel IDs to all CSs

Algorithm:

1) Fill *SST_ch_arry[α]* with the supported channel IDs
2) Capture REGISTER_REQUEST from CS_i (i is the local loop variable: $i = 1; i \leq \beta; i{+}{+}$)
3) Find an average number of the CSs (μ) for $Channel_j$ (j is the local loop variable: $j = 1; j \leq \alpha; j{+}{+}$)
4) Allocate a temporary channel ID to CS_i and fill the associated cell in *CS_ch_arry[α][μ]*
5) Fill $GATE_i$ message for CS_i with allocated channel ID and send to all CSs
6) Wait to receive the first REPORT message from all CSs
7) Go to phase two (Intra-channel bandwidth allocations)

Figure 5.10 Algorithm for phase one of the IIDWBA algorithm

5.5.5 Implemented Algorithm for Phase Two of the IIDWBA

The implemented algorithm for the phase two of the IIDWBA algorithm, Intra-channel bandwidth allocations, is represented in Figure 5.11. As it reveals in Figure 5.11, phase two of the IIDWBA algorithm first makes an array for the MAC addresses associated with the CSs on a given channel *j*, Line 1. All CSs will be then sorted in ascending order based on the requested bandwidth and will be counted, Line 2 to Line 4. CSs will be granted by the requested bandwidth if the requested bandwidth is less than or equal to the minimum guaranteed bandwidth, Line 5. The excess bandwidth will then be collected from them, Line 6. The number of heavily loaded CSs will be calculated in the next stage, Line 7. These are CSs which are requesting bandwidth more than the minimum guaranteed bandwidth in the current service cycle. The average amount of the bandwidth which can be granted from the excess bandwidth to each heavily loaded CS will be calculated next, Line 8, taking into account the total number of the heavily loaded CSs along with the total collected excess bandwidth on the associated channel. The heavily loaded CSs will be then sorted in ascending order based on the requested bandwidth, Line9 and the total excess requested bandwidth from them will be calculated, Line 10. A portion of the collected excess bandwidth will be considered for each heavily loaded CS, Line 11, in such a way that the granted bandwidth will be no more than the minimum guaranteed bandwidth plus an average portion of the excess collected bandwidth. When the bandwidth is allocated and scheduled for all the CSs associated with a given channel *j*, the local information such as the latest scheduled service cycle, total number of heavily loaded CSs and the associated MAC addresses and individual excess requested bandwidth along with the total excess bandwidth and total requested excess bandwidth will be then passed to phase three of the IIDWBA algorithm, Line 12. The implemented algorithm for the phase three of the IDIWBA algorithm is presented next.

Given:

1) $T_{cycle}, G, R_N, w_i, N, RTT$
2) *MAC [N]:* array of MAC addresses for all CSs associated with a given SST on a given channel *j*

To:

1) Calculate B_{min} : Minimum guaranteed bandwidth
2) Allocate bandwidth to the lightly loaded CSs taking into account B_{min}
3) Allocate bandwidth to the heavily loaded CSs taking into account B_{min} and B_{avg_excess}
4) Schedule local service cycle
5) After allocating bandwidth to all CSs, re-calculate B_{total_excess} and $B_{total\_excess\_requested}$
6) Pass to the global scheduler: number of the heavily loaded CSs with associated MAC addresses, B_{total_excess}, $B_{total\_excess\_requested}$ and local scheduled service cycle

Algorithm:

1) Fill *MAC[N]* with MAC addresses of all CSs associated with a given channel *j* on a given SST
2) Sort CSs in ascending order of $B_{request}$

3) Select CS_i in which $B_{request} \leq B_{min}$

4) Count them: j

5) Grant $B_{request}$

6) Collect excess: B_{total_excess}

7) Calculate H $(H = N - j)$ (H is total number of the heavily loaded CSs, N is total number of the CSs and j is total number of the lightly loaded CSs)

8) Calculate B_{avg_excess} taking into account H and B_{total_excess}

9) Sort CS_H in ascending order of $B_{request}$ (CS_H is a heavily loaded CS)

10) Calculate $B_{total\_excess\_request}$

11) Grant bandwidth to all CS_H no more than: $B_{min} + B_{avg\_excess}$

12) If bandwidth is allocated to all CSs:

    a) Calculate $CS_{t\_start\_time}$ for each CS

    b) Calculate $CS_{t\_duration}$ for each CS

    c) Generate service cycle

    d) Reload: H, MAC_H [] (MAC addresses of the heavily loaded CSs) , $B_{total\_excess\_request}$ and B_{total_excess} and send them to global scheduler along with the generated service cycle

Figure 5.11 Algorithm for phase two of the IIDWBA algorithm

5.5.6 Implemented Algorithm for Phase Three of the IIDWBA

The implemented algorithm for the phase three of the IIDWBA algorithm, Inter-channel bandwidth allocations, is represented in Figure 5.12. As it reveals in Figure 5.12, phase three of the IIDWBA algorithm first sorts all the globally heavily loaded CSs based on the excess requested bandwidth, Line 1. The excess bandwidth will be then allocated in ascending order based on the excess requested bandwidth, Lin 2 and Line 3. When the bandwidth allocations are finished for all the globally heavily loaded CSs, phase three of the IIDWBA algorithm schedules the allocated bandwidth and embeds each of them inside the associated service cycle related to the lightly loaded channels. All the service cycles will then be passed to the Broadcaster and broadcast to all channels immediately, Line 4.

The next section describes the captured results from the above implementations as follows.

5.5.7 Captured Results

This section presents the results which are collected between the OLT, an SST, and the ONUs, CSs, where a given ONU requested bandwidth from OLT in CO in order to schedule the upstream transmissions to the OLT for the associated BSs. Due to similarities between the OLT-ONUs and the ONU-BSs captured results we only discuss the results collected among the OLT and all associated ONUs in this section.

As discussed before, the IIDWBA algorithm allocates a single channel to a given ONU_i during the Initialisation phase which will then be shared among number of ONUs

Given:

1) $MAC_j, T_j, T^{\,j}_{last\_t\_start\_time}, T^{\,j}_{last\_t\_\,duration}$

To:

1) Calculate H_{global}: Total number of the heavily loaded CSs
2) Calculate B_{excess_global}: Total global excess bandwidth across all channels
3) Calculate $B_{avg\_excess\_global_i}$: Average global excess bandwidth for each globally heavily loaded CSs
4) Allocate the global excess bandwidth to globally heavily loaded CSs
5) Re-schedule the local service cycle associated with all lightly loaded channels
6) Broadcast all service cycles to all channels

Algorithm:

1) Sort heavily loaded CSs in ascending order of $B_{total\_excess\_requested}$
2) Select heavily loaded CSs in which $B_{excess\_requested}{}^{i}_{j} \leq B_{avg\_excess\_global}$ and grant $B_{avg\_excess\_global}$
3) Select heavily loaded CSs in which $B_{excess\_requested}{}^{i}_{j} > \mathrm{B}_{\mathrm{avg\_excess\_global}}$ and grant $B_{avg\_excess\_global}$
4) If bandwidth is allocated to all globally heavily loaded CSs:
   a) Calculate $CS_{t\_start\_time}$ for each globally heavily loaded CS
   b) Calculate $CS_{t\_duration}$ for each globally heavily loaded CS
   c) Embed the $CS_{t\_start\_time}$ and $CS_{t\_duration}$ inside the appropriate

Figure 5.12 Algorithm for phase three of the IIDWBA algorithm through phase two. Phase three of the IIDWBA algorithm will be executed if a given ONU_i requests bandwidth more than the minimum guaranteed bandwidth where the excess bandwidth from the local channel is either not enough or not available. In such a case, the IIDWBA algorithm tries to collect the excess bandwidth from the neighbouring channels and distribute it fairly among all the heavily loaded ONUs which may not be situated in the same channel.

In order to evaluate the performance of the IIDWBA algorithm the collected results after employing the first traffic pattern are discussed first which is then followed by the captured results after employing the second traffic pattern.

First traffic pattern- In the first traffic pattern, the load on a single channel (w_1) is gradually increased by increasing the total number of SSs per BS from 10 to 100 in steps of 10 while it is fixed to 10 per BS on other channels ($w_2,...,w_4$). The reasons for such a configuration is to distinguish how the IIDWBA algorithm collects the extra available and unused bandwidth from three channels ($w_2,...,w_4$) and spends them on overcrowded channel, w_1, when the load builds up across it.

As Figure 5.13 reveals, the IIDWBA algorithm is successful in decreasing the average queuing delay to almost 14% for the ONUs associated with w_1 when it is compared with the scenario without employing IIDWBA algorithm but under the same load values. The reason for this is that when the number of SSs per BS starts increasing, e.g. more than 60 per BS, phase three of the IIDWBA algorithm starts to look for excess bandwidth from neighbouring channels which will then be collected and distributed among CSs associated with w_1. Associating extra time-slots from neighbouring channels to CSs on channel one helps to reduce the queue length which results in the reduction of the average queuing delay. In Figure 5.14, the average queuing delay for the ONUs associated with $w_2, \ldots, w_4$ are captured with and without employing IIDWBA algorithm applying the first traffic pattern. As it is depicted in Figure 5.14, executing IIDWBA algorithm has almost zero negative effect in terms of average queuing delay for the ONUs associated with $w_2, \ldots, w_4$ as the allocated bandwidth from those channels are the excess bandwidth which is not used by the local ONUs. The fluctuations that we can see in average queuing delay between two scenarios under the same load values, Figure 5.14, is due to the uneven traffic pattern which was generated by the exponentially distributed packet inter-arrival time over $w_2, \ldots, w_4$.

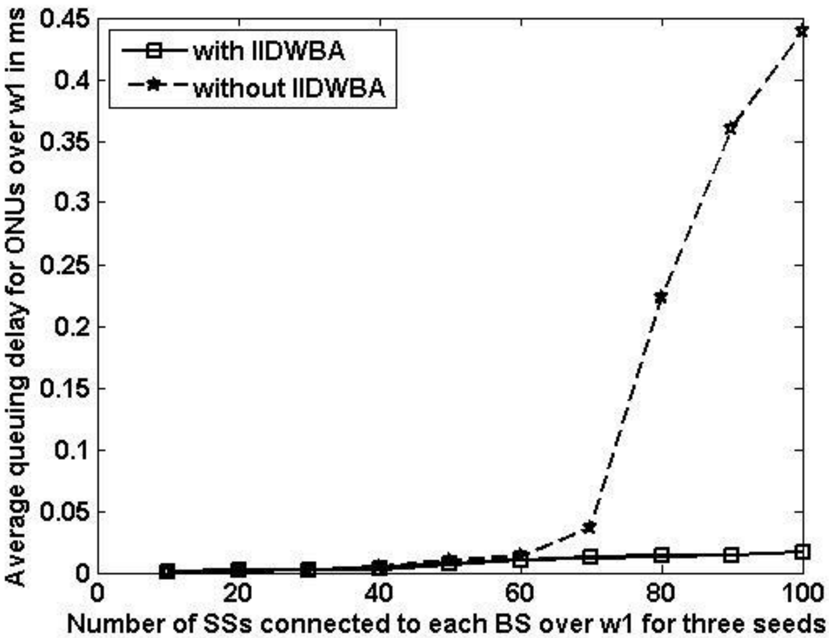

Figure 5.13 Average queuing delay for the ONUs associated with channel one employing the first traffic pattern with IIDWBA and without IIDWBA [6]

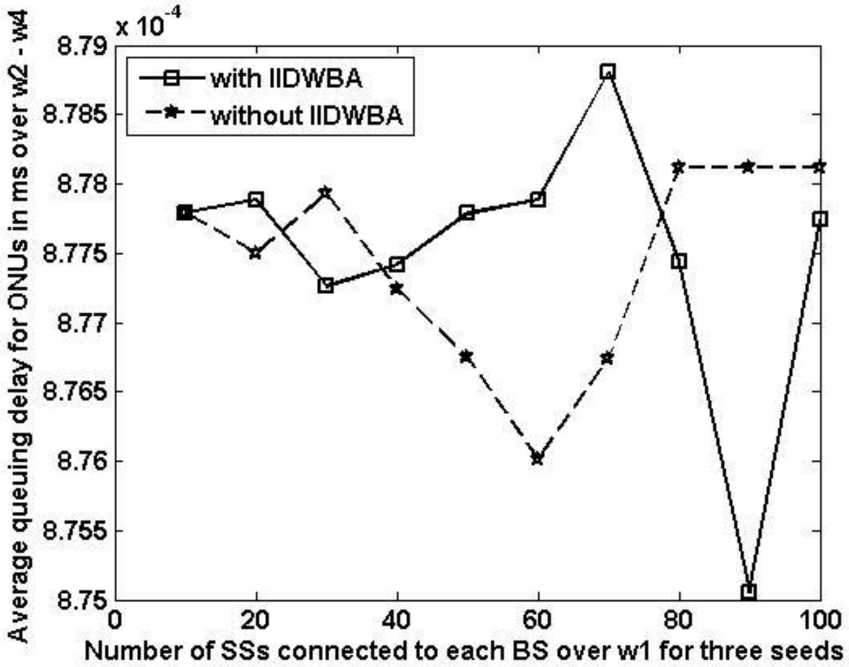

Figure 5.14 Average queuing delay for the ONUs associated with channel two to four employing the first traffic pattern with IIDWBA and without IIDWBA [6]

Figure 5.15 presents the average extra requested bits from ONUs associated with w_1 with and without the IIDWBA algorithm after employing the first traffic pattern. As Figure 5.15 reveals, IIDWBA algorithm is capable of keeping the average extra requested bits from the ONUs associated with w_1 under the minimum guaranteed bandwidth by allocating the available excess bandwidth from other channels, $w_2,...,w_4$, to them during each service cycle. For instance, when the number of SSs is increased to 70 for each BS, then the ONUs on w_1 start requesting more bandwidth from the OLT. The requested bandwidth is more than the minimum guaranteed bandwidth, therefore IIDWBA starts looking for available excess bandwidth on other channels which will be collected and then allocated in the next immediate service cycle. This process results in reducing the queue lengths for the ONUs on w_1 as it is depicted in Figure 5.13. However, only the minimum guaranteed bandwidth will be allocated to the ONUs on

w_1 without applying the IIDWBA algorithm which results in accumulating more bits, increasing the queue length, Figure 5.13, and raising the requested bits from the ONUS assigned to w_1 in every service cycle, Figure 5.15.

In the second traffic pattern, the load on all channels is gradually increased by raising the total number of SSs connected per BS from 10 to 100 in steps of 10 in order to distinguish how the increased load on the three channel, $w_2, \ldots, w_4$, will affect the performance of the ONUs over w_1.

The system throughput and the system utilisation between the OLT and ONUs are also captured employing the first traffic pattern with and without applying the IIDWBA algorithm in Figure 5.16 and Figure 5.17, respectively.

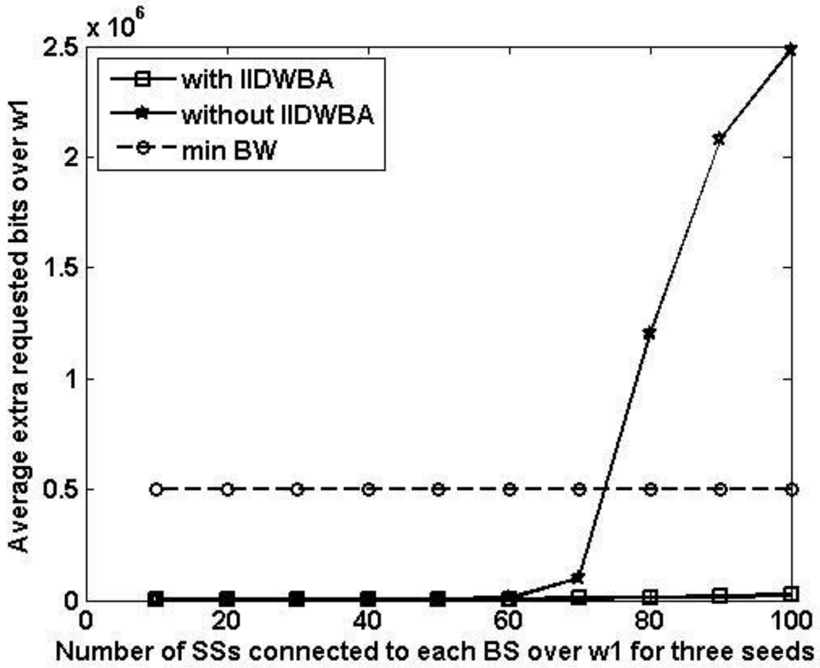

Figure 5.15 Average extra requested bandwidth from the ONUs associated with channel one employing the first traffic pattern with IIDWBA and without IIDWBA [6]

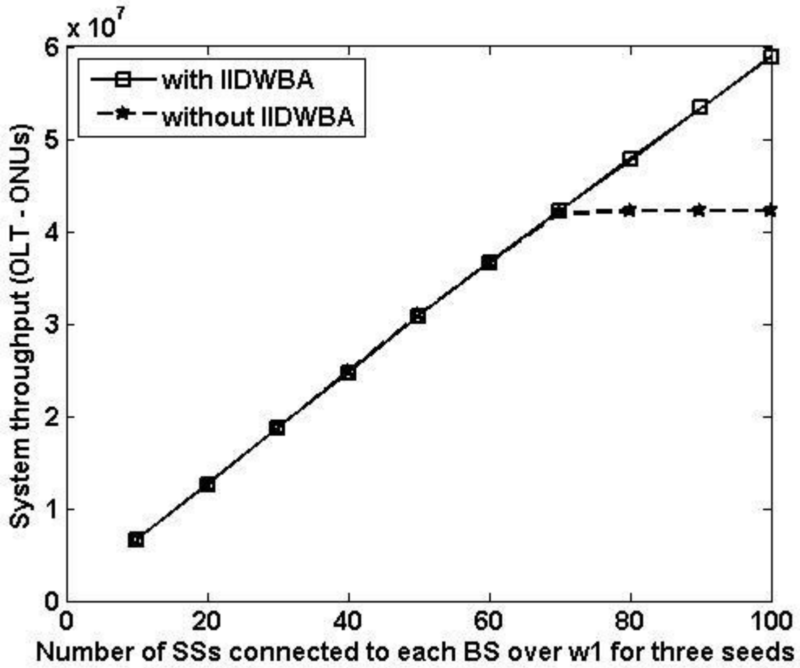

Figure 5.16 System throughput, OLT-ONUs, employing the first traffic pattern with IIDWBA and without IIDWBA [6]

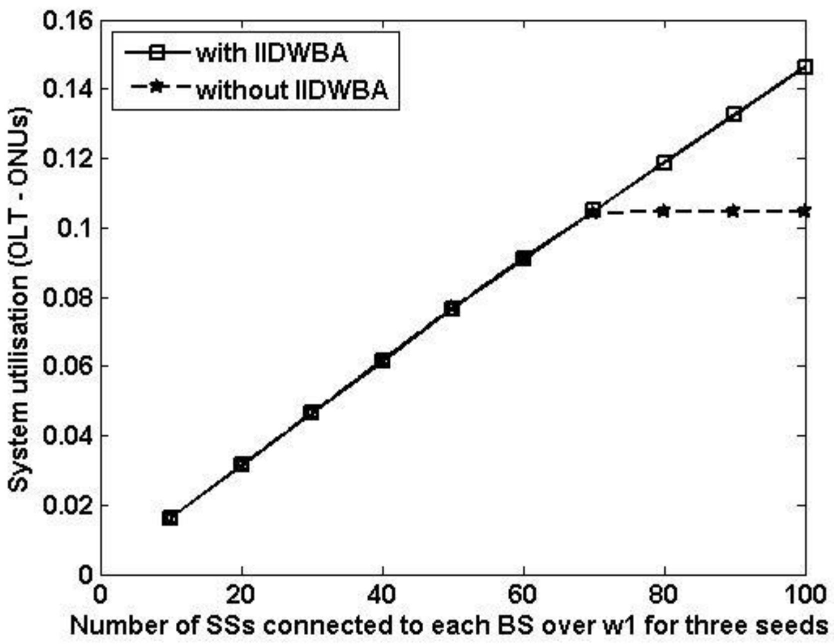

Figure 5.17 System utilisation, OLT-ONUs, employing the first traffic pattern with IIDWBA and without IIDWBA [6]

As Figure 5.16 and Figure 5.17 reveal, when the total number of SSs associated per BS on w_1 reaches 100, employing the IIDWBA algorithm improves the system throughput and utilisation between the OLT-ONUs to almost 1.5% in comparison with the scenario without employing IIDWBA algorithm. The reason behind these improvements is because of the way in which phase three of the IIDWBA algorithm execution collects the excess bandwidth from $w_{2},\ldots,w_4$ and distributes it among the ONUs associated with w_1 when the loads starts building up.

Second traffic pattern- In the second traffic pattern, the load on all channels simultaneously is increased in order to evaluate the performance of the IIDWBA when the global excess bandwidth starts to reduce. The captured results are as follows. As Figure 5.18 reveals, when the number of SSs connected per BS on all channels reaches 60, the queuing delay inside the ONUs associated with w_1 starts increasing constantly and climbs to 0.03 sec when it gets to 100 SSs per BS. The reason behind this degradation is because when the load on the three channels, $w_{2},\ldots,w_4$, is increased gradually the IIDWBA algorithm cannot find as much excess bandwidth for the ONUs associated with w_1 as compared to the first traffic pattern where the loads on the three channels were almost fixed. However, the queuing delay for the ONUs over w_1 under second traffic pattern is still much lower than the scenario when the IIDWBA is not employed, Figure 5.13.

The average extra requested bandwidth (bits) over w_1 when the second traffic pattern is employed is also captured and compared with the results from the first traffic pattern. As Figure 5.19 reveals, when the number of SSs connected per BS is gradually increased from 50 to 100 SSs in steps of 10 on all channels, the average extra requested

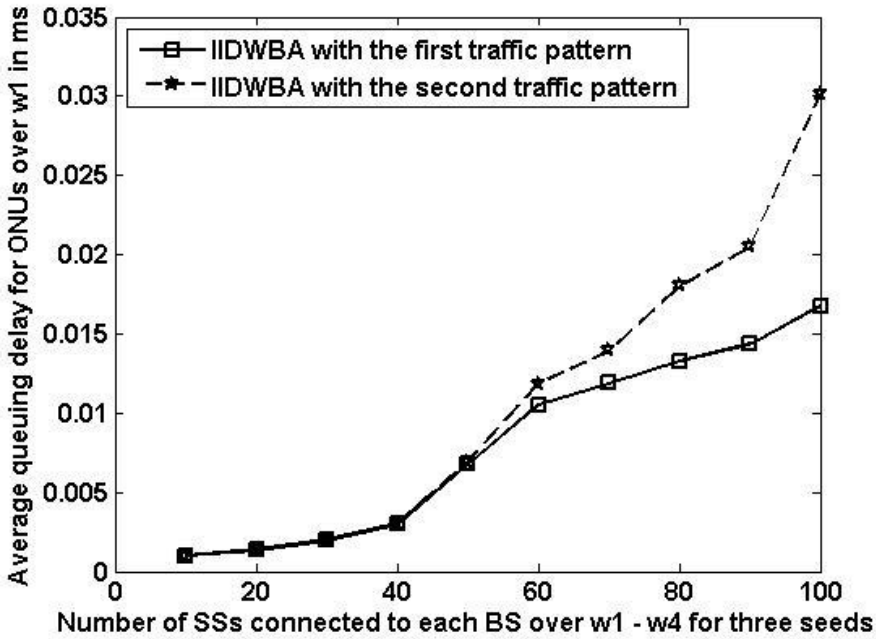

Figure 5.18 Average queuing delay for the ONUs associated with channel one employing the first and second traffic patterns

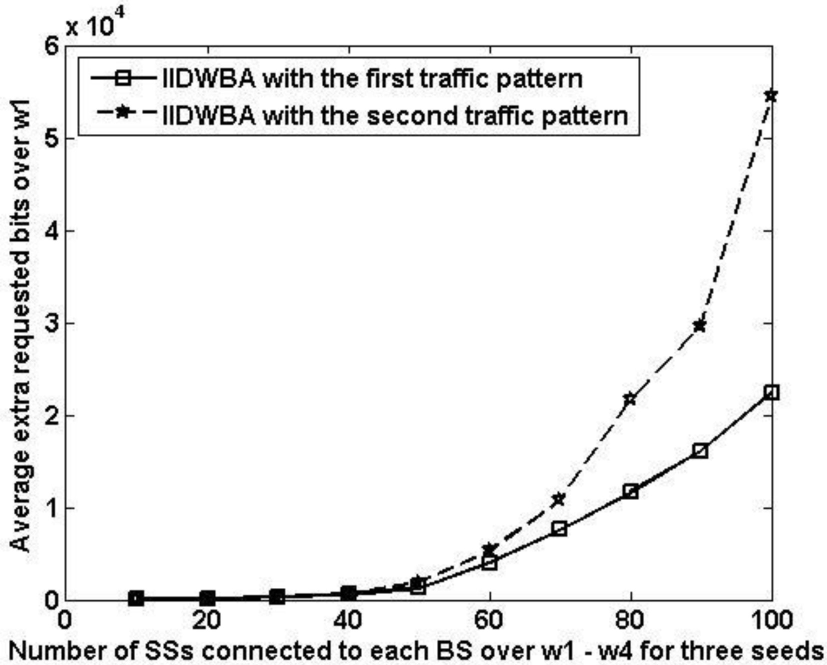

Figure 5.19 Average extra requested bandwidth from the ONUs associated with channel one employing the first and second traffic pattern

bits over w_1 starts raising almost twice much as the first traffic pattern scenario.The reason for such a result is as follows. When the second traffic pattern is employed, the load on all channels starts building up gradually therefore the IIDWBA algorithm cannot find as much excess bandwidth for the ONUs associated with w_1 over $w_{2,\ldots,}w_4$ when it is compared to the first traffic pattern. This behaviour results in the accumulation of more packets in the queues associated with the ONUs over w_1 thus leading to longer queuing delays and larger average extra requested bits will be produced.

The average allocated bits from all the available channels to the ONUs associated with w_1 by employing the first and second traffic patterns is captured in Figure 5.20 and Figure 5.21. As Figure 5.20 reveals, when the first traffic pattern is employed, as the load on $w_{2,\ldots,}w_4$ is fixed, the average allocated bits from them to ONUs on w_1 is more than the scenario where the second traffic pattern is employed, Figure 5.21. The larger bit allocations under the first traffic pattern result in shorter average queue size for the ONUs on w_1 when it is compared to the scenario where the second traffic pattern is employed, Figure 5.21. For instance, as Figure 5.21 shows, the average allocated bits from w_2 to the ONUs on w_1 is almost zero, when we employed the second traffic pattern, while it is almost 4000 bits per service cycle, when we employed the first traffic pattern, Figure 5.20. The shorter available excess bits on w_2 increases the average queue size on ONUs associated with w_1, Figure 5.21, when it is compared to the average queue size captured on Figure 5.20.

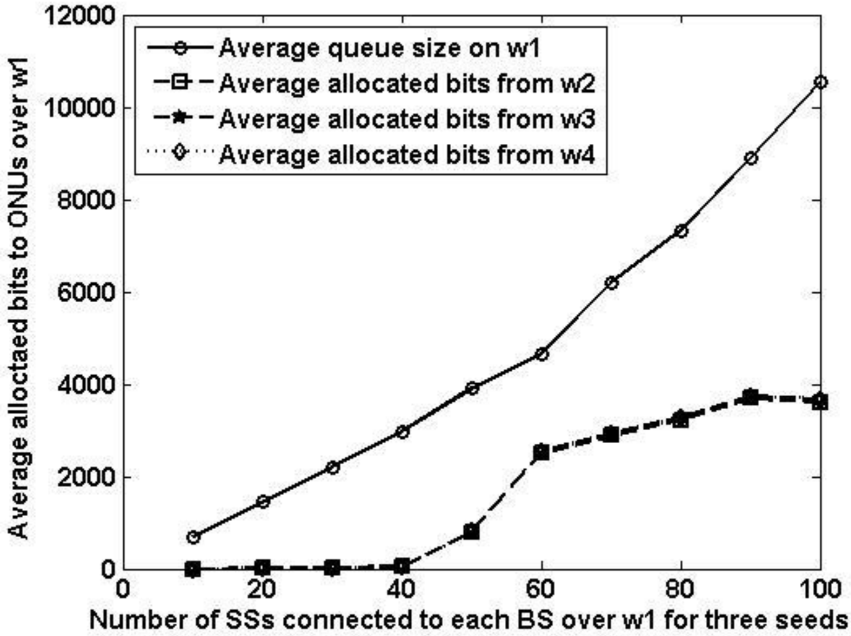

Figure 5.20 Average allocated bits to the ONUs associated with channel one from other channels employing the first traffic pattern

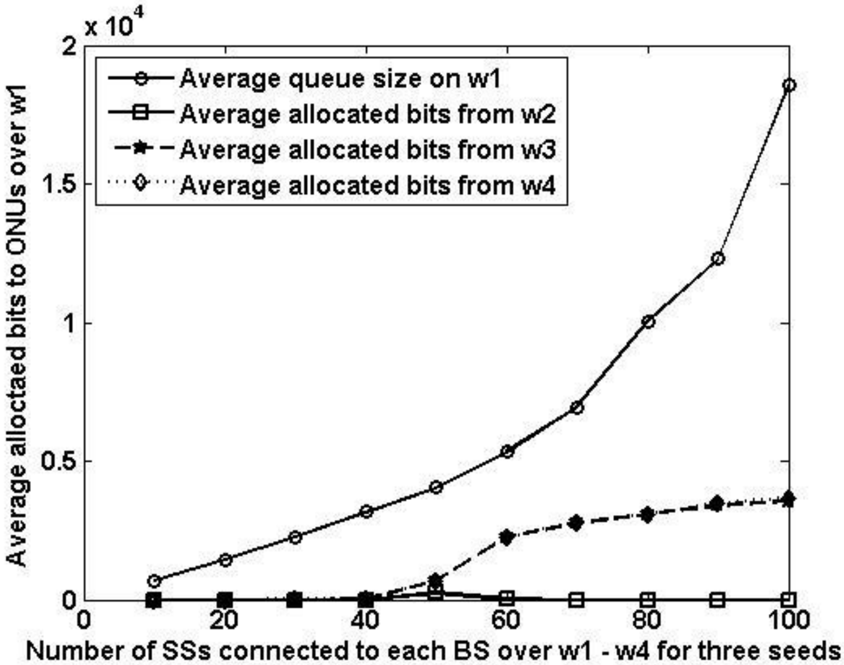

Figure 5.21 Average allocated bits to the ONUs associated with channel one from other channels employing the second traffic pattern

5.6 Chapter Summary

In this chapter, a distributed, real-time, dynamic and scalable resource allocation algorithm termed as Inter-channel and Intra-channel Dynamic Wavelength/Bandwidth Allocation (IIDWBA) for multi-channel PON integration with wireless technologies was proposed which works in three phases, namely, Initialisation phase, Intra-channel bandwidth allocations phase and Inter-channel bandwidth allocations phase.

Through conducted simulation experiments, it was shown that the proposed algorithm was capable of collecting the excess bandwidth from lightly loaded channels and spreading them fairly across heavily loaded CSs which may be scattered over different channels.

The proposed algorithm showed better performance in terms of average queuing delay, utilisation and throughput when compared with the same simulation scenario but without employing the IIDWBA algorithm from work presented in [6].

Chapter 6 Employing GA Optimisation Techniques to the IIDWBA Algorithm

This chapter is dedicated to the third key contribution of the thesis, namely, a GA-based IIDWBA algorithm for the converged scenario. It starts with the motivation and need to optimise the resource utilisation in telecommunication area. Then it presents the details of the proposed GA-based solution which works in conjunction with phase three of the IIDWBA algorithm and is capable of maximising the excess resource allocations over the converged scenario. Next, it presents the related architecture, framework and mathematical model for the GA-based IIDWBA algorithm. It then describes the details of implementation and evaluation through the simulated experiment results. Finally, it concludes with the summary of key findings and a discussion.

6.1 Issues of Optimisation Techniques

Operational Research (OR) or optimisation (alternatively, mathematical programming or mathematical optimisation) is a group of mathematical modelling, statistical techniques and algorithms which result in optimum or near optimum solutions for a complex problem. It also refers to the selection of the best elements from some set of the available alternatives [82]. The optimisation solutions can be applied to industry or non-industry fields e.g. mathematics, computer science and management science in order to maximise for example the profits or minimise the objectives such as time and cost [83].

With the sole focus on telecommunication area, optimisation techniques have been employed in order to find the best, optimum or near optimum solutions for problems such as resource management. A resource can be bandwidth (capacity), energy which is consumed by a given IP network or a network device, CPU time of a network device, connection identifier, labels in a given MPLS domain or fibre ducts implementations and arrangements in a given optical network.

With the global deployments of the NGN [130] and the forthcoming demands from the subscriber stations for multimedia rich and bandwidth hungry applications and services [129], the demand for bandwidth requests is expected to increase further in the near future.

Taking into consideration the NGN features and infrastructures with the key aspect of optimum or near optimum resource utilisation, this chapter explors the benefits of using optimisation techniques, particularly Genetic Algorithm (GA), in combination of the proposed IIDWBA algorithm towards the NGN. The question which has to be answered is: can GA optimisation techniques be made intelligent enough to come up with the optimum or near optimum resource utilisation as part of the proposed IIDWBA algorithm without compromising on telecommunications trade-off metrics such as CPU overhead, memory usage, error level, processing time, power consumption, link utilisation, service cycle length, scalability and real-time support?

6.2 Existing Approaches for Optimisation Techniques in Telecommunications

Many techniques and algorithms have been proposed in order to solve optimisation problems which can be grouped into four major categories of Mathematical Programming Techniques, Stochastic Process Techniques, Statistical Methods and Heuristic Methods [84]. Some of these optimisation techniques are summarised in Table 6-1. Some of the following content is published by the author of this thesis in [127].

Table 6-1 Optimisation techniques

Mathematical Programming Techniques	**Stochastic Process Techniques**	**Statistical Methods**	**Heuristic Methods**
Calculus methods	Statistical decision theory	Regression analysis	Simulated annealing
Calculus of variations	Markov processes	Cluster analysis, pattern recognition	Genetic algorithms
Nonlinear programming	Queuing theory	Design of experiments	Artificial Neural networks
Geometric programming	Renewal theory	Discriminate (factor) analysis	
Quadratic programming	Simulation methods		
Linear programming	Reliability theory		
Dynamic programming			
Integer programming			
Stochastic programming			
Separable programming			
Multi objective programming			
Network methods: CPM and PERT			
Game theory			

Linier Programming (LP) [85], Dynamic Programming (DP) [83] and [90] and Heuristic Methods such as Simulated Annealing (SA), Tabu Search (TS) [91], [94], [97-98], Artificial Neural Network (ANN) [86] and Genetic Algorithm (GA) [87], [88], [89], [92], [100], [102-104] and [117] are some of the most popular optimisation techniques.

With the sole focus on telecommunications, optimisation techniques generally focus on improving just a couple of key metrics such as CPU overhead, memory usage, processing time, power consumption, link utilisation, service cycle length, scalability and real-time support. These key metrics need to be traded-off in order to identify when some parameters are improved what are the expenses on the other parameters. For instance, the processing time will be improved when the size of the cache memory is increased. However, it increases memory usage.

LP, DP, GA and ANN, which are the four most popular optimisation techniques, support scalability and provide optimum or near optimum solutions. However, in terms of CPU overhead, memory usage, speed of execution and real-time support they are different. For example, DP does not provide the real-time support whilst the other three techniques are able to generate the optimisation solutions in real-time and a regular manner.

The authors in [93] proposed an algorithm base on LP and ANN in order to maximise the buffer memory and bandwidth utilisation in 3G networks. The authors in [99] applied GA techniques for spectrum assignments in cognitive radio networks. The authors in [101] utilized the GA techniques for the problem of antenna arrangements in mobile network and proposed a parallel GA model for multi-objective optimisation. The authors in [96] employed TS in order to allocate wavelengths in the optical networks and authors in [119] utilised TS techniques for peak to average power ratio reduction in power line communication channel. The authors in [95] employed TS techniques to minimise the maximum interaction time and distance in order to find the optimal locations for the hubs in a switch network.

The approach adopted in this chapter differs from the above research by using the optimisation techniques, particularly GA, for the problem of optimum or near optimum resource utilisation over the converged infrastructure of the NGN.

The next section describes in detail the general operation of a GA solver followed by the justifications for employing such an approach.

6.2.1 Genetic Algorithm (GA)

In computer science, particularly in the field of the Artificial Intelligence (AI), a given Genetic Algorithm (GA) is a heuristic search method that imitates the process of natural evolution. GA belongs to the larger group of Evolutionary Algorithms (EA) which use techniques and methods inspired by natural evolution, such as inheritance, mutation, crossover and selection.

A given GA provides an efficient and effective technique for optimisation and Machine Learning (ML) applications where genes and chromosomes (sequences of genes) are the basic instructions for building a given GA [111], [112] and [113]. The life cycle for a given GA includes *Initialisation*, *Selection*, *Reproduction*, *Evaluation*, *Deletion* and *Termination* which are briefly discussed as follows.

Initialisation: The *Initialisation* stage, which randomly generates many individual solutions, typically includes hundreds or thousands of possible solutions for the problem area. The population size depends on the nature as well as the size of the problem.

Selection: During the *Selection* process, part of the population of the existing generation will be selected in order to make a new generation. The fitness of the individual solutions, which are generated by the *Initialisation* phase, will be measured using a function termed a *Fitness Function*. The fitter solutions will more likely to be selected and appear in the next generation in order to generate a new population of solutions.

Reproduction: The *Reproduction* phase needs to be employed in order to generate a second generation population of solutions from the *Selection* phase. Mutation and Crossover are the most popular GA operators which are employed at this stage in order to generate a new population, [114], [115], [116] and [117]. It is also possible to use other GA operators such as regrouping, colonisation-extinction, or migration.

***Evaluation*:** The generated population from the *Reproduction* phase will be passed to the *Evaluation* phase in order to evaluate whether they will appear in the next population based on the defined fitness function as well as defined constraints.

Deletion: The fitter solutions from the *Evaluation* phase will survive in order to generate a next population and the less fit solutions will be discarded by *Deletion*.

Termination: The GA life cycle will be finished if any of the termination conditions is met. The followings are some possible termination conditions:

- A satisfactory solution is found.

- The available budget (e.g. time and memory) runs out.

- Some criteria are reached, for instance reaching the maximum allowed number of generations.

The next section describes in the advantages of employing GA in comparison with four other popular optimisation techniques: LP, DP, TS and ANN.

6.2.2 Genetic Algorithm (GA) vs. Liner Programming (LP), Dynamic Programming (DP), Tabu Search (TS) and Artificial Neural Network (ANN)

In Table 6-2, the four most popular optimisation techniques are compared in terms of their good points and weak points. The motivation for employing GA rather than the other three optimisation methods are as follows.

DP is a fast and reliable method in which the optimisation problem is broken up into simpler problems. It then tries to find an optimum or near optimum solution for each stage one at a time which can be an entry to the next stage or the next sub-problem. At the end by finding the optimum or near optimum solution for the last sub-problem it can find the optimum, near optimum or best solution from the entire problem space. However, DP optimisation techniques are not applicable for problems changing over a time. With the sole focus on the dynamic nature of the Internet traffic, where the requested resources (bandwidth) and the available bandwidth change per unit of time, the DP is not applicable for the problem of optimum or near optimum bandwidth utilisation being considered in this thesis.

TS is a meta-heuristic method that can be used to find a solution for combinational optimisation problems like the travelling salesman problem. TS is capable of using the short term memory and records of the most recently visited solutions and then backtrack in order to find the best solution. However, it needs to determine potential solutions in order to start working which adds extra complexity.

LP is a reliable and popular optimisation technique for a linear objective function subject to linear equality and liner inequality constraints. However, it is a time consuming method which is only applicable for liner objective functions and needs very detailed information in order to solve a given optimisation problem.

ANN is a self-organised, powerful and flexible optimisation technique with capability of supporting real-time operations due to its parallel architecture. ANN can model the complex relationship between the inputs and outputs to find the patterns of data. However, the output decisions from ANN can be unpredictable as it finds the solution for the problem itself and cannot be programmed for a specific task. Moreover, as ANN uses examples to learn the patterns, if the examples are not carefully selected, the ANN decisions will be very slow or the network will be functioning incorrectly.

On the other hand, GA is a robust and reliable optimisation technique which requires little information to find optimum or near optimum solutions (unlike LP). It is also applicable for non-stationary problems which change over time (unlike DP optimisation techniques) and can start working with no potential solution (unlike TS). It can also be programmed in order to do the specific task and does not have unpredictable behaviour (unlike ANN). However, one of the GA’s potential problems is identifying the population size which needs to be estimated correctly before running a given GA solver.

Table 6-2 Comparisons for some optimization method

Name	Good points	Weak points
LP	-It is a reliable technique. -There are many programs in the market to solve the LP problems mostly based on the simplex method.	-It is only applicable to linear objective function. -It needs to define upper and lower bounds for all variables. -The variables cannot be infinite. -The variables can only be non-negative. -It uses slack and surplus for non-equivalents which add extra variables to the problem that need to be solved. -It needs very detailed information in order to solve the problem. -The LP software consumes more computer cycles than the software which is employed for other optimisation methods. -The LP technique is not a fast method.
DP	-It is a fast and reliable technique. -It solves each sub-problem only once.	-It is not applicable if a problem changes over time. -It is not applicable if a problem is not stationary.
TS	-It is good for solving combinational optimization problem like the travelling saleman problem. -It escapes the trap of local optimality or cyclic behaviour by using the short term memory which records the most recently visited solutions. -It is capable of backtracking to the previous solutions to find the best answer.	-In order to start working it needs to determine the potential solutions, e.g. solution generated from the neighbouring algorithm.
GA	-It is a robust optimisation technique. -It is a good alternative solution when the existing solutions are too	-It cannot find the best solution when the population is small. -When the population is very big, it consumes a long waiting time for a

	slow or too complicated. -It requires little information to find the best available answer. -It is useful for non-linear problems. -It is simple and easy to develop. -It is easy to exploit the previous or the alternative solutions when we use the GA. -There are many ways to improve the GA speed as the knowledge about the problem domain is gained. -It is a good technique when we want to hybridise the captured solution with an existing solution.	significant improvement. -It cannot find the best solution when the mutation is too low or too high.
ANN	-It is a powerful technique. -It is a flexible method as it learns by examples. -It can model the complex relationship between the inputs and outputs to find the patterns in data. -It has real-time operation due to the fast computation and quick respond because of its parallel architecture. -It is good for the real-time systems due to its real time operation. -It is self organised. -It is able to learn how to do tasks by using the initial examples. -It is a good method to identify the patterns so that they are good for prediction and forecasting in areas like telecommunication, data validation, risk management and target marketing.	-Its operation can be unpredictable as it finds solutions for the problem itself. -It cannot be programmed in order to perform the specific task. -As it uses the examples to learn the patterns, if the examples are not selected carefully it will be very slow or the network may be functioning incorrectly.

For instance, GA cannot find the best solution if the population size is too small or the mutation is too low or too high. These factors have a great influence on the GA performance.

Taking into consideration the above motivations to use a GA solver as a robust and reliable optimisation technique, the next section describes and discusses in detail the general framework for using such an approach as a part of the proposed IIDWBA algorithm for optimum or near optimum bandwidth utilisation.

6.3 Proposed GA-based IIDWBA Framework

The proposed GA-based IIDWBA framework is shown in Figure 6.1, which is a specialised case of the IIDWBA algorithm already presented in chapter 5 (section 5.3).

By taking into consideration the dynamic bandwidth and the dynamic wavelength allocations provided by the IIDWBA algorithm over the converged scenario, there are two scenarios where GA techniques can be employed as follows:

Scenario one: GA can be employed as a part of phase two of the IIDWBA algorithm (Intra-channel bandwidth allocations phase) between the OLT and the associated ONUs and/or a given ONU and the associated BSs. This can be implemented in order to find the best, optimum or near optimum solutions for the bandwidth allocations among the CSs which are associated with each channel of a given SST. Thus, an independent GA solver can be implemented per channel of a given SST for the scenario one implementation.

Scenario two: GA can be employed as a part of phase three of the IIDWBA algorithm (Inter-channel bandwidth allocations phase) between the OLT and the associated ONUs and/or a given ONU and the associated BSs. This can be implemented in order to find the best, optimum or near optimum solutions for the excess bandwidth allocations between a given SST and all the associated CSs which can be scattered among different channels. Thus, a single GA solver needs to be developed per SST for the scenario two implementation.

In phase one of the IIDWBA algorithm (Initialisation phase), as the options are limited e.g. a given SST does not have knowledge about the traffic pattern on the associated CSs as the CSs that just started generating the traffic, the GA solution cannot be employed. However, when the traffic starts building up on the CSs, the GA optimisation techniques can be employed through phase two and phase three of the IIDWBA algorithm in order to find the best, optimum or near optimum solutions for the dynamic wavelength and the dynamic bandwidth allocations from a given SST to the associated CSs.

Generally speaking, the main purpose of employing the GA solver during the ***scenario one*** and/or ***scenario two*** is to provide the optimum or near optimum bandwidth utilisation over the converged scenario of the NGN in intra-channel and inter-channel manner, respectively.

In this section, employing the GA techniques for phase three of the IIDWBA algorithm (***scenario two***) is discussed, during which the IIDWBA algorithm tries to find, schedule and then distribute the excess bandwidth which may remain unutilised over different channels associated with a given SST.

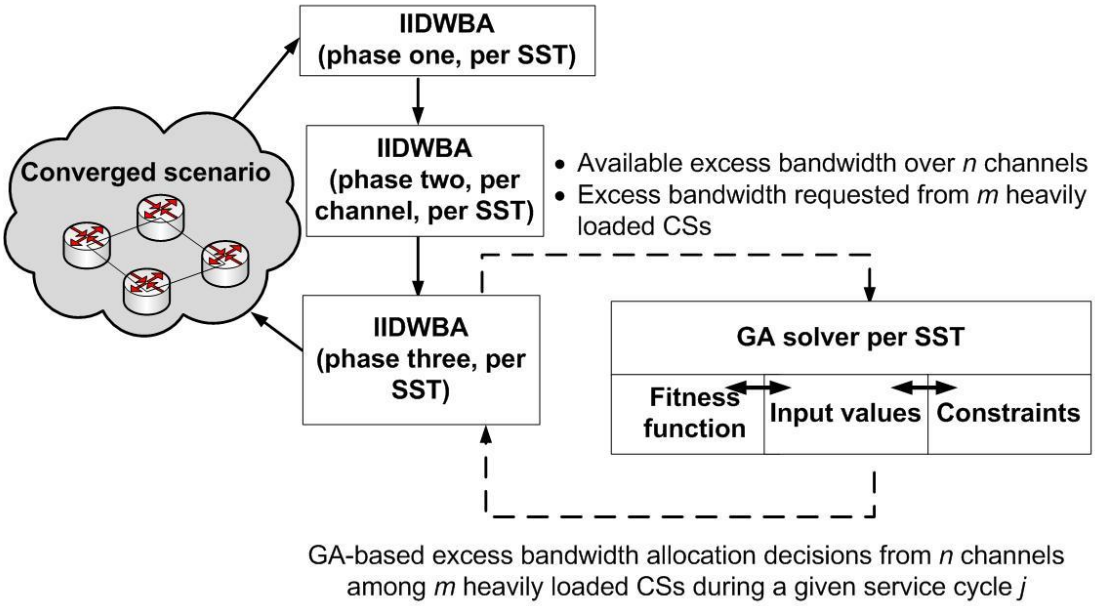

Figure 6.1 The GA-based IIDWBA framework

As shown in Figure 6.1, the GA solver runs as a part of phase three of the IIDWBA algorithm once per service cycle per SST and is fed with real-time parameters such as available excess bandwidth of each channel associated with a given SST as well as the excess requested bandwidth from each heavily loaded CS which may be scattered over the same or different channels of a given SST. These are the values which need be collected from a real/simulated network model and fed into the GA solver on a regular basis (e.g. once per service cycle).

The GA solver can also run over the phase two of the IIDWBA algorithm in conjunction with phase three in order to provide a comprehensive GA-based IIDWBA algorithm. This is the work in progress which is addressed and clarified in chapter seven of this thesis.

The input parameters then pass to the fitness function of the GA solver which has the sole propose on maximising the excess bandwidth allocation from all the channels to all the heavily loaded CSs associated with a given SST. The constraints also need to be passed to the GA handler over which the GA output decisions can be restricted. For instance, the GA output decisions should be in such a way that a given heavily loaded CS will not receive more than it actually needs or a given channel will not grant bandwidth more than the available excess bandwidth. The GA output decisions are then passed back to the real/simulated network and immediately sent to the corresponding heavily loaded CSs per service cycle, Figure 6.1.

In Figure 6.2, the actual place of the GA solver in context of phase three of the IIDWBA algorithm is revealed. The GA techniques work on top of the excess bandwidth allocations which occur during the phase three of the IIDWBA algorithm. They try to find the best, optimum or near optimum combinations of the available excess bandwidth from each channel on a given SST and the excess requested bandwidth from the heavily loaded CSs in every service cycle. The GA-based dynamic excess bandwidth allocation decision is aimed at maximising the excess bandwidth utilisations in every service cycle. A mathematical treatment of the proposed GA-based IIDWBA algorithm is discussed in the next section.

6.3.1 Mathematical Model

The mathematical model for the GA optimisation algorithm is as follows:

Given:

- W_i : Excess available bandwidth (bits) on a given channel *i* during a given service cycle *k*, where $i = 1, \ldots., n$.

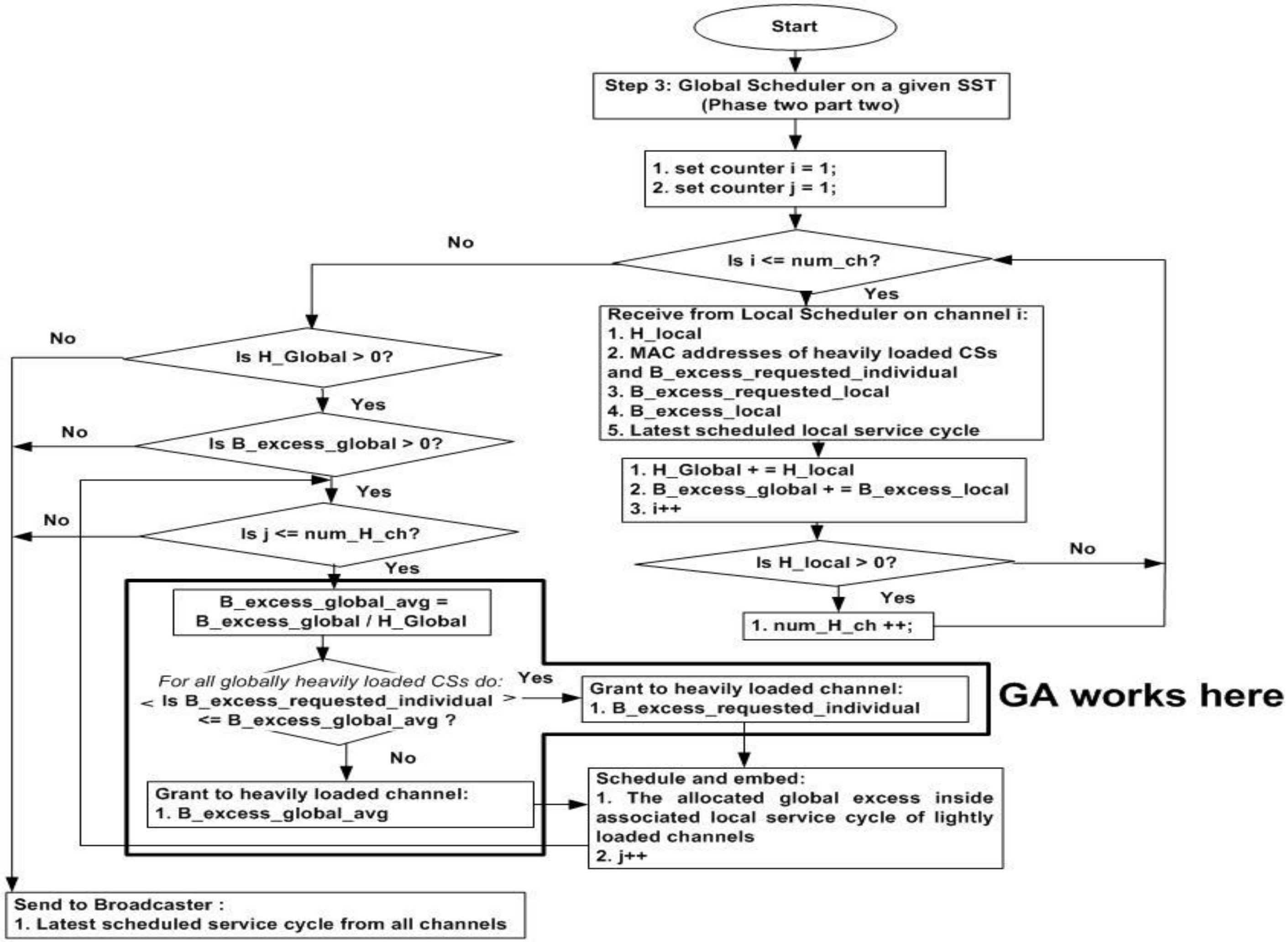

Figure 6.2 Employing GA techniques for phase three of the IIDWBA algorithm (Inter-channel bandwidth allocations phase)

- H_j : Excess requested bandwidth by a given heavily loaded source *j* during a given service cycle *k*, where *j = 1,…., m*.

  $x_{i\,j}$: Excess bandwidth granted by a given channel *i* to a given heavily loaded source *j* during a given service cycle *k*, where *i: i = 1,…., n* and *j: j = 1,…., m*.

- It is assumed that a given heavily loaded source *j* during a given service cycle *k*, where *j = 1,…., m*, can receive excess bandwidth from all the available channels.

- It is assumed that a given channel *i* during a given service cycle *k*, where *i = 1,…., n*, can allocate the associated excess bandwidth to all the available heavily loaded sources.

Define:

- The excess bandwidth will be allocated from a given channel *i* to a given heavily loaded source *j* during a given service cycle *k* not more than the actual need of the heavily loaded source *j*, where *i = 1,…., n* and *j = 1,…., m*.

So: $$\sum_{i=1}^{n} x_{i\,j} \le H_j \qquad for:\ j = 1,\ldots, m \tag{6.1}$$

- The excess bandwidth will be allocated from a given channel *i* to given heavily loaded source *j* during a given service cycle *k* not more than the available bandwidth (bits) of the channel *i*, where *i = 1,…., n* and *j = 1,…., m*.

So: $$\sum_{j=1}^{m} x_{i\,j} \le W_i \qquad for:\ i = 1,\ldots, n \tag{6.2}$$

- $W_i \ge 0,\ H_j \ge 0,\ x_{i\,j} \ge 0$

- If $W_i = 0$, it means there is no excess bandwidth available from given channel i during a given service cycle k, where $i = 1, \ldots., n$.

- If $H_j = 0$, it means a given source j during a given service cycle k is not heavily loaded, where $j = 1, \ldots., m$.

- If $x_{i\,j} = 0$, it means no excess bandwidth is allocated from a given channel i to a heavily loaded source j during a given service cycle k, where $i = 1, \ldots., n$ and $j = 1, \ldots., m$.

Objective (fitness function):

$$\text{i.e. maximise:} \quad \sum_{i=1}^{n} \sum_{j=1}^{m} x_{i\,j} \tag{6.3}$$

The main objective of using GA is to maximise the total allocated excess bandwidth from all the channels to all the heavily loaded sources. The GA tries to find the best, optimum or near optimum combinations of the allocated excess bandwidth from each channel to each heavily loaded source taking into account the available excess bandwidth (bits) per channel and the requested excess bandwidth from each heavily loaded source.

The next section discusses the implementation of the GA-based IIDWBA algorithm as follows.

6.4 Implementation of the GA-based IIDWBA Algorithm

This section describes the assumptions made for implementing the GA-based IIDWBA algorithm which forms the core of the solution.

6.4.1 Key Assumptions

For the purpose of the proof of concept, a converged topology of optical and wireless network scenarios are considered, as will be described later in this chapter. To demonstrate the practically of the proposed GA-based IIDWBA algorithm, the implementation starts with a scenario in which multi channels are available on all the SSTs over the converged scenario (e.g. multi-channel OLT and ONUs). Also it is assumed that the traffic is un-evenly distributed over different channels associated with a given SST e.g. some channels are lightly loaded and some are heavily loaded. Finally, it is assumed that the load is gradually increased on all the channels (both lightly loaded and heavily loaded channels) by the same regular amount. Thus, the excess bandwidth is always available over different service cycles (due to the uneven traffic pattern over all the channels) and the excess requested bandwidth changes per service cycle (due to the regular load increments over all the channels). These assumptions are made in order to distinguish the performance of the GA solver in more a critical way in combination with the IIDWBA algorithm where GA input parameters of the excess available bandwidth and excess requested bandwidth are dynamically changed over each service cycle.

Investigation Details
To demonstrate the detailed off-line modelling of the GA-based IIDWBA algorithm for the optimum resource utilisation over a converged scenario of the NGN

Simulation settings
OPNET (C++): Multi-channel converged scenario between optical and wireless technologies, bursty traffic pattern with different exponentially distributed packet inter-arrival time over different channels.
MATLAB (C++): GA handler, fitness function and constraints

Key results and figures
GA decision output results for the problem of resource utilisation: Figure 6.6 to 6.11
GA decision output errors: Figure 6.12 to 6.15

Relevance of results to the thesis
Off-line modelling of the GA techniques in conjunction with the on-line modelling of the IIDWBA algorithm were achieved through a converged simulated scenario. The GA solver showed significant solutions for the optimum resource utilisation over the phase three of the IIDWBA algorithm with negligible error percentages.

Figure 6.3 Overview of experiments for chapter 6

6.5 Overview of Experiments

An overview of the experiments is presented here in order to appreciate the content to follow in the evaluation and results section. Figure 6.3 presents the summary of experiments in this chapter.

The next section presents the evaluation of the GA-based IIDWBA algorithm by conducting the experiments listed here.

6.6 Simulation Results

The domain under consideration for the proposed work in this chapter is shown in Figure 6.4. The topology, which is re-employed in this chapter from chapter 5, includes an OLT in the CO which supports four channels ($w_1,\ldots,w_4$) and is related to 16 ONUs, a 4:4 sized AWG with co-related amplifier and four 1:16 sized TDM passive Splitters/Combiners. A 4:4 sized AWG with co-related amplifier and four 1:16 sized TDM passive Splitters/Combiners are located between the OLT in CO and the associated ONUs. Each ONU supports the same four channels, which are also supported by the OLT ($w_1,\ldots,w_4$), and related to 16 BSs. A given BS is connected to 10 SSs which are gradually increased to 100 in steps of by 10 in order to evaluate the network performance under the different load values. A 4:4 sized AWG with co-related amplifier and four 1:16 sized TDM passive Splitters/Combiners are also located between a given ONU and the associated 16 BSs. A given BS supports the same four channels as OLT and ONUs ($w_1,\ldots,w_4$) in the direction of the related ONU however it employs a fixed wavelength in the downstream direction to the associated SSs.

Employing the AWG with co-related amplifier and the TDM passive Splitters/Combiners between the OLT and ONUs as well as the ONUs and the associated BSs help to extend the total coverage distance for the integrated scenario up to 300 km.

Therefore, there are a single OLT, 16 ONUs, 256 BSs (16 ONUs × 16 BSs) and 2560 to 25600 SSs (256 BS × 10 SS to 256 BS × 100 SS) existing in the whole converged topology domain.

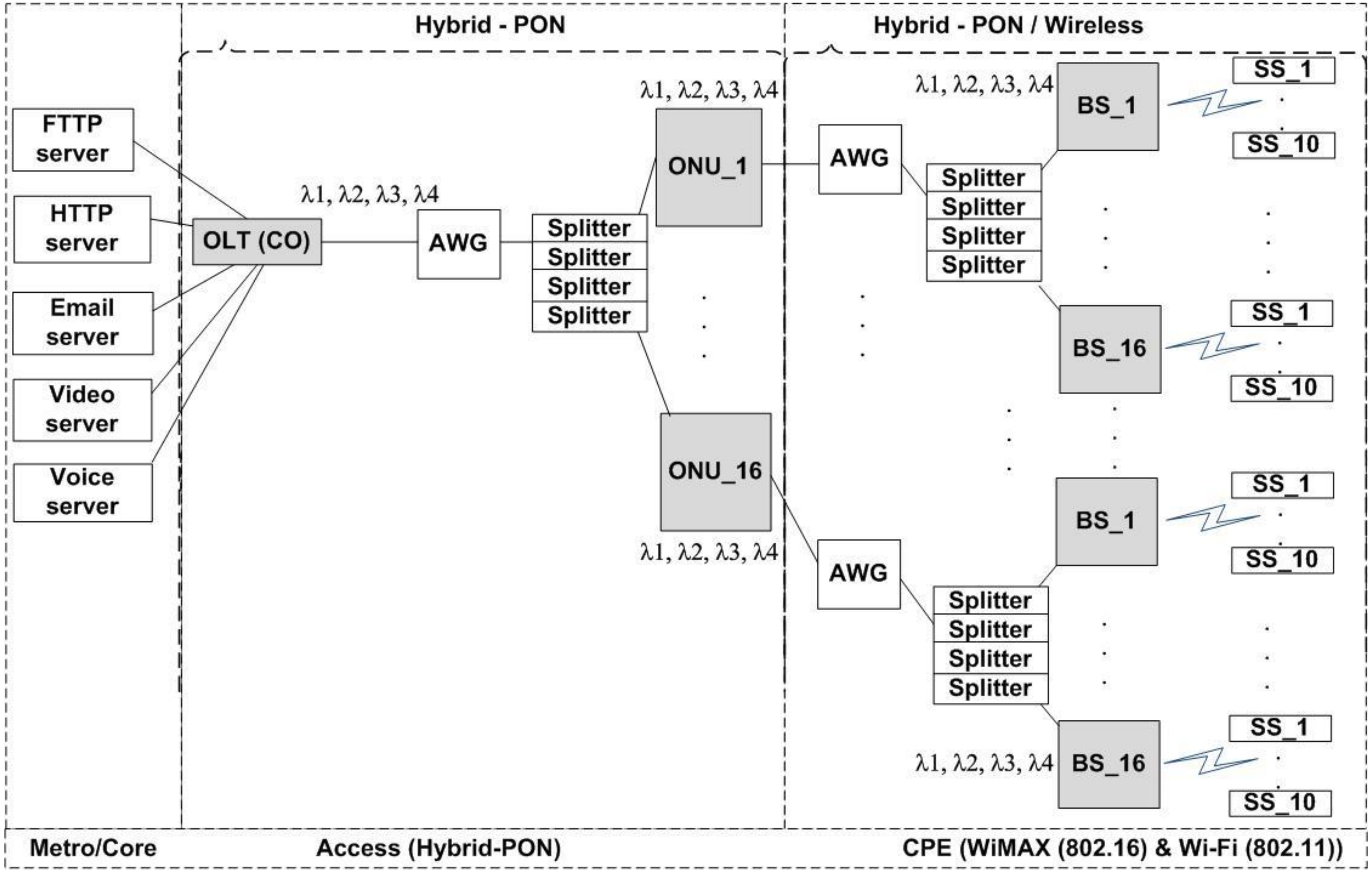

Figure 6.4 Network topology for evaluating the GA-based IIDWBA algorithm

6.6.1 The Simulation Setup MATLAB

MATLAB [118], which is popular software for the numerical calculations and formulas with vast library of functions and algorithms, was used for implementing and coding the requirements of the GA techniques such as the fitness function and the required constraints. The GA solutions are employed in off-line and regular bases for the input parameters from the simulated scenario in OPNET once per service cycle in order to evaluate the GA influence over the IIDWBA algorithm.

The GA implementation in MATLAB, which includes the requirements of the GA techniques such as fitness function, necessary constraints and chromosome encoding, is defined for our implementation as follows.

[v,fval] = ga (ObjectiveFunction,nvars,A,b,[],[],LB,[],[],opts) (6.4)

ObjectiveFunction = @(v) ResourceAllocation (v, x_1, x_2 , x_3, x_4 , x_5 , x_6 , x_7 , x_8, w_1 , w_2 , w_3 ,w_4); (6.5)

%opts = gaoptimset (opts,'TolFun',1e-12,'PopulationSize',100); (6.6)

nvars = 32; (6.7)

A= (6.8)

```
[1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1,1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1 ;
 1, 1, 1, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0 ;
 0, 0, 0, 0, 1, 1, 1, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0;
 0, 0, 0, 0, 0, 0, 0, 0, 1, 1, 1, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0 ;
 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1, 1, 1, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0 ;
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 0, 0, 0, 1, 0, 0, 0, 1, 0, 0, 0, 1, 0, 0, 0, 1, 0, 0, 0, 1, 0, 0, 0, 1, 0, 0, 0, 1, 0, 0, 0, 1 ];
```

b=[w1+w2+w3+w4;x1;x2;x3;x4;x5;x6;x7;x8;w1;w2;w3;w4]; (6.9)

$$LB = [0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0]; \tag{6.10}$$

Where:

- ga: It is the GA function available in MATLAB library.

- ObjectiveFunction: It is the fitness function described in formula (6.3) in which the objective of using GA is to maximise the total allocated excess bandwidth from all the channels to all the heavily loaded sources.

- nvar: It is the total number of variables for our fitness function. In our implementation as we considered eight heavily loaded CSs and four available channels (four donors), the total number of variables is 32 (eight multiple by four).

- A: It is the array of constraints. It was defined based on 6.1 and 6.2 formulas. For instance, as we discussed before all the heavily loaded resources can benefits from the excess bandwidth on all the available channels. However, the total allocated excess bandwidth to all the heavily loaded resources should not more than the excess bandwidth on all four channels. So, we can define this constraints as follows where $x_{i\ j}$ is excess allocated bandwidth from channel *j* to heavily loaded source *i*:

  $$x_{1\,1} + x_{1\,2} + x_{1\,3} + x_{1\,4} + x_{2\,1} + x_{2\,2} + x_{2\,3} + x_{2\,4} + x_{3\,1} + x_{3\,2} + x_{3\,3} + x_{3\,4} + x_{4\,1} + x_{4\,2} + x_{4\,3} + x_{4\,4} \leq W_1 + W_2 + W_3 + W_4$$

  This can be encoded as 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1,1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1 (first row of the A array).

- b: It defines the relationships between variables (heavily loaded resources and available donors).

- LB: It is the lover bound for the constraints. In MATLAB implementation, we considered this value as zero in order to provide only integer values (non-negative values) for the excess resource allocation.

- opts: It defines the population size (GA iteration value) for the GA solver which is 100 in our simulation. We considered this value as we captured extremely small improvements after the population size goes beyond 100.

- x_1, x_2, x_3, x_4 , x_5 , x_6 , x_7 , x_8: They are the amount of excess bandwidth requested from eight heavily loaded resource. We have considered eight out of sixteen resources because based on our captured values from OPNET simulation only eight resources became heavily loaded during the simulation run time. However, the model can be extended easily in order to support any number of heavily loaded resources. x_1, x_2, x_3, x_4 , x_5 , x_6 , x_7 , x_8 values need to capture constantly once per service cycle and feed in to the GA solver in order to provide GA-based dynamic excess bandwidth allocation decisions based on the real time traffic pattern

- w_1 , w_2 , w_3 ,w_4: They are the four available channels (available resources with possible excess bandwidth). This is one of the key assumptions in our simulation scenario in which we configured our OPNET simulation components assuming each CS/SST supports four identical channels. However, it can be extended easily in order to support more number of channels. w_1 , w_2 , w_3 ,w_4 values need to capture constantly once per service cycle and feed in to the GA solver in order to provide GA-based dynamic excess bandwidth allocation decisions based on the real time traffic pattern.

6.6.2 The Simulation Setup OPNET

The OPNET Modeler [79], which is popular network simulation software, was used to simulate the converged topology as shown in Figure 6.4.

Figure 6.5 reveals the essential steps in order to employ the MATLB [118] decision outputs in off-line bases for the OPNET simulated scenarios.

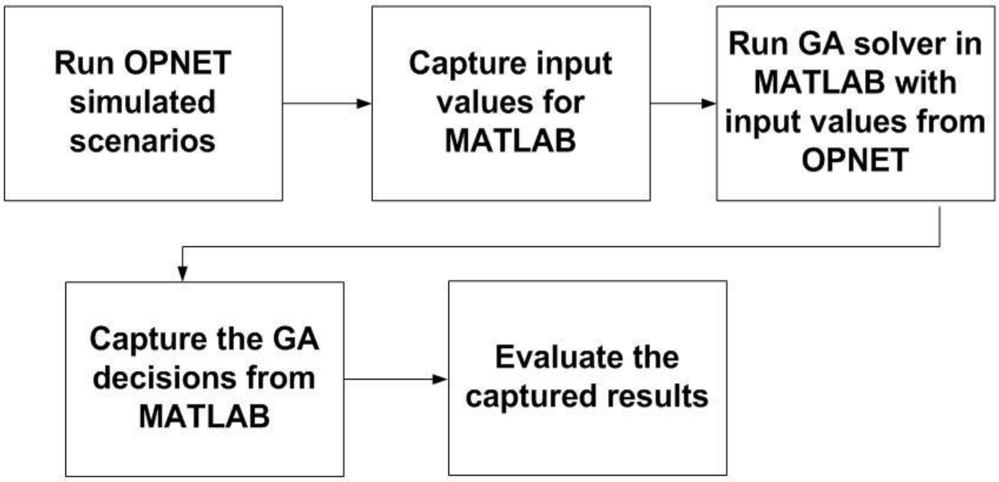

Figure 6.5 Employing the MATLAB decisions for the converged simulated scenario implemented in OPNET

6.6.3 Traffic Characteristics and Simulation Parameters

For the traffic pattern configurations, the second traffic pattern from chapter 5 is employed in order to provide the uneven network load across all the channels ($w_1, \dots, w_4$) associated with all the SSTs over the converged scenario.

As addressed in chapter 5, unlike the first traffic pattern, in the second traffic pattern the network load on all the channels is gradually increased by raising the number of SSs connected per BS from 10 to 100 in steps of 10.

The reason for selecting the second traffic pattern and avoiding using the first traffic pattern is to evaluate the performance of the GA decisions under the different values for the available excess bandwidth and excess requested bandwidth per load rate per service cycle. Employing the second traffic pattern provides different input values for the GA decisions and helps to evaluate the GA's influence on overall network performance in a more critical way. However, in the first traffic pattern as the network load is fixed over lightly loaded channels, the available excess bandwidth over them is the same thus the GA decision outputs would be almost the same.

Table 6-3 and Table 6-4 reveal the simulation parameters and traffic pattern configuration, respectively, which are employed to evaluate the performance of the GA-based IIDWBA algorithm. Moreover, different seed values of 128, 166 and 90 are employed during the simulation run time. However, we depicted the average plots from three seed values in this chapter.

Table 6-3 Simulation parameters for evaluating the IIDWBA algorithm with the GA techniques (OPNET)

Traffic pattern	Burst (uneven across SSs)
ON state time (sec)	20% of simulation time
OFF state time (sec)	80% of simulation time
Traffic start time	even across all SSs
Traffic stop time	Never
Packet size	500 bytes (constant)
Number of channels supported on OLT, ONUs and BSs for upstream transmissions	4 channels (w_1,…,w_4)
Packet interval time per SS per ONU on channel one (w_1)	0.05 sec (Exponential distributed)
Packet interval time per SS per ONU on channel two (w_2)	0.05 sec (Exponential distributed)
Packet interval time per SS per ONU on channel three (w_3)	0.5 sec (Exponential distributed)
Packet interval time per SS per ONU on channel four (w_4)	1 sec (Exponential distributed)
Number of SSs per BS	10 to 100 BY 10
Traffic class	Best Effort (BE)
Simulation time	30 sec
Seed	128, 166, 99
value per static	1600
update interval	300000
Traffic pattern name	Second traffic pattern

Table 6-4 Traffic pattern configurations for evaluating the GA-based solutions for the IIDWBA algorithm (OPNET)

Traffic pattern	**Number of SSs on w_1**	**Number of SSs on $w_2,\ldots,w_4$**	**Generated traffic per SS on $w_1,\ldots,w_4$**
Second traffic pattern	Gradually increased from 10 SSs to 100 SSs per BS (total of 160 to 1600 SSs per ONU)	Gradually increased from 10 SSs to 100 SSs per BS (total of 160 to 1600 SSs per ONU)	w_1 : 80 kb/s per SS (exponentially distributed) w_2: 80 kb/s per SS (exponentially distributed) w_3: 8 kb/s per SS (exponentially distributed) w_4: 4 kb/s per SS (exponentially distributed)

6.6.4 Experiments for the GA-based IIDWBA Algorithm

The objective of this experiment is to demonstrate the overall influence of the proposed GA-based solution which works as a part of the proposed IIDWBA algorithm (phase three) for optimum or near optimum resource utilisation over the converged scenario.

In Table 6-5 and Table 6-6, groups of input values for the GA solver including the excess requested bandwidth from a number of heavily loaded CSs in a random service cycles as well as the excess available bandwidth on four channels associated with a given SST are collected from the OPNET converged scenario for the six load values. In Table 6-7 to Table 6-9, the GA solver output decisions based on the input values, from Table 6-5 and Table 6-6, for all six loads values from 50 to 100 in steps of 10 are shown. For instance, as Table 6-5 and Table 6-6 reveal, when the number of the SSs per BS is 50 in a given service cycle j, the excess bandwidth only exists on two channels (w_3 and w_4) and the excess bandwidth is only requested from four CSs (CS_1 to CS_4) with different values. Based on these input parameters, the GA solver allocates bandwidth in such a way that the allocated bandwidth will not be more than the excess requested bandwidth from each CS and not more than the excess available bandwidth on two channels. For instance, no bandwidth is allocated to (CS_5 to CS_8) as they did not request any excess bandwidth during the service cycle *j* or the allocated bandwidth is not more than the available bandwidth on (w_3 and w_4), Table 6-7.

Table 6-5 Excess available bandwidth for six load values over all channels on a given service cycle *j* (OPNET)

Load values	**Excess available bandwidth on w_1**	**Excess available bandwidth on w_2**	**Excess available bandwidth on w_3**	**Excess available bandwidth on w_4**
50	0	0	1998000	1978000
60	0	0	1974000	1886000
70	0	1102000	1998000	1998000
80	0	0	1998000	1966000
90	0	0	0	1962000
100	0	0	0	1998000

Table 6-6 Excess requested bandwidth for six load values from all heavily loaded CSs on a given service cycle *j* (OPNET)

Load	**Num. HL**	**CS_1 REQ.**	**CS_2 REQ.**	**CS_3 REQ.**	**CS_4 REQ.**	**CS_5 REQ.**	**CS_6 REQ.**	**CS_7 REQ.**	**CS_8 REQ.**
50	4	380500	144500	224500	284500	0	0	0	0
60	8	2396500	2348500	2564500	2636500	2492500	1988500	2972500	2732500
70	2	436666.7	0	0	452666.7	0	0	0	0
80	8	2568500	2304500	3064500	2360500	2320500	1952500	2816500	2336500
90	8	952500	560500	552500	544500	328500	372500	616500	364500
100	4	0	0	0	0	132500	316500	68500	436500

Table 6-7 GA decision outputs for load values of 50 and 60 for each heavily loaded CS on each channel on a given service cycle *j* (MATLAB)

Allocated to CSs	**50**				**60**			
	$\mathbf{w_1}$	$\mathbf{w_2}$	$\mathbf{w_3}$	$\mathbf{w_4}$	$\mathbf{w_1}$	$\mathbf{w_2}$	$\mathbf{w_3}$	$\mathbf{w_4}$
To CS_1	0	0	76553	303946	0	0	6824	119622
To CS_2	0	0	117332	27167	0	0	212848	134566
To CS_3	0	0	63014	161485	0	0	48123	186590
To CS_4	0	0	183373	34166	0	0	94880	71792
To CS_5	0	0	0	0	0	0	0	115536
To CS_6	0	0	0	0	0	0	106867	223435
To CS_7	0	0	0	0	0	0	109892	1005431
To CS_8	0	0	0	0	0	0	1394562	29025

Table 6-8 GA decision outputs for load values of 70 and 80 for each heavily loaded CS on each channel on a given service cycle *j* (MATLAB)

Allocated to CSs	**70**				**80**			
	$\mathbf{w_1}$	$\mathbf{w_2}$	$\mathbf{w_3}$	$\mathbf{w_4}$	$\mathbf{w_1}$	$\mathbf{w_2}$	$\mathbf{w_3}$	$\mathbf{w_4}$
To CS_1	0	64595	63845	308225	0	0	988722	137387
To CS_2	0	0	0	0	0	0	110476	93601
To CS_3	0	0	0	0	0	0	89569	127739
To CS_4	0	69059	76500	307106	0	0	134155	12642
To CS_5	0	0	0	0	0	0	206422	210226
To CS_6	0	0	0	0	0	0	42191	1215150
To CS_7	0	0	0	0	0	0	337644	15277
To CS_8	0	0	0	0	0	0	88818	153973

Table 6-9 GA decision outputs for load values of 90 and 100 for each heavily loaded CS on each channel on a given service cycle j (MATLAB)

Allocated to CSs	**90**				**100**			
	$\mathbf{w_1}$	$\mathbf{w_2}$	$\mathbf{w_3}$	$\mathbf{w_4}$	$\mathbf{w_1}$	$\mathbf{w_2}$	$\mathbf{w_3}$	$\mathbf{w_4}$
To CS_1	0	0	0	952500	0	0	0	0
To CS_2	0	0	0	122627	0	0	0	0
To CS_3	0	0	0	321731	0	0	0	0
To CS_4	0	0	0	49805	0	0	0	0
To CS_5	0	0	0	64077	0	0	0	132500
To CS_6	0	0	0	46574	0	0	0	316500
To CS_7	0	0	0	40183	0	0	0	68500
To CS_8	0	0	0	364500	0	0	0	436500

The average of the GA output decisions for the dynamic excess bandwidth allocations are captured and depicted in Figures 6.6 to 6.11 for the six load values from 50 to 100 SSs per BS in steps of 10.

In this chapter, the GA output decisions for the dynamic excess bandwidth allocations for the load values under 50 SSs per BS are not depicted as under the light load values there are no excess bandwidth requests from the CSs all over the channels associated with a given SST. Generally speaking, the dynamic excess bandwidth allocation decisions from the GA solver only come into play when both factors of there being heavily loaded CSs and excess bandwidth is available in the network. When the number of the SSs per BS gradually increases from 50 to 100 in steps of 10 the heavily loaded CSs will start appearing in the network on all the channels associated with a given SST.

As is revealed in Figures 6.6 - 6.11, the GA solver is capable of providing the dynamic excess bandwidth allocation decisions very close to the excess requested bandwidth for all the six load values from 50 to 100 SSs per BS.

It is also revealed that the GA output decisions are not more than the excess requested bandwidth from the heavily loaded CS and also not more than the excess available bandwidth on all the channels. This is because of the boundaries which are defined for the GA solver in order not to allocate bandwidth more than the actual need of a given heavily loaded CS or more than the available excess bandwidth on a given channel (mathematical model in chapter 6, section 6.3.1).

In Figures 6.6 - 6.11, the average of the GA output decisions are also compared with the scenarios in which the GA solver is not employed over the identical simulation run time. As shown in Figures 6.6 - 6.11, when the numbers of SS per BS is increased from 50 to 100, due to increased load per SS, the average excess available bandwidth is decreased while the average excess requested bandwidth is increased. However, under almost all the load values the GA solver is capable of providing a better average for the dynamic excess bandwidth utilisation, closer to the average excess requested bandwidth, by maximising the excess bandwidth allocations when compared with the scenarios where the GA solver is not employed.

Addressing the simulation parameters, Table 6-3, the ON state time is 20% of simulation run time (30 seconds) which is equal to 6 seconds (20% multiple by 30 seconds). We considered ON time at the last 6 seconds of simulation run time which is from 24^{th} to 30^{th} seconds. The ON time is the period over which wireless nodes start sending traffic and therefore start requesting bandwidth from their associated SSTs over the converged scenario. As it is depicted in almost all the figures in this chapter, Figures 6.6 - 6.15, the simulation scenario became stable after the first second of simulation run time (after 25^{th} seconds). This is the reason for observing the significant reductions in variables such as excess requested bandwidth and error percentages for excess allocation bandwidth after the first send of the ON time period. For instance, as it is depicted in Figure 6.6 the average excess requested bandwidth is in its maximum value between 24^{th} and 25^{th} second of simulation run time. It is because all the wireless nodes stars sending the traffic on 24^{th} second and it took one second for the converged scenario to response to all the bandwidth requests and reach to its steady situation.

Figures 6.12 and 6.13 reveal the average for percentages of the error in GA-based dynamic excess bandwidth allocation decisions versus the excess requested bandwidth for the load values of 50 and 100 SSs per BS. As shown, both GA and no-GA output decision errors became stable after the first second of the simulation run time (from 25^{th} second onward). As it was described before, it is because all the wireless nodes stars sending traffic on 24^{th} second and it took one second for the converged scenario to response to all the bandwidth requests and becomes established.

As Figure 6.12 reveals, the GA solver shows the better performance in terms of percentage error in the excess bandwidth allocation decisions when it compares with the scenario without employing the GA solver. However, when the load is gradually increased to 100 SSs per BS, Figure 6.13, the error of the excess bandwidth allocation decisions is almost same in both scenarios due to the increments in the excess bandwidth requests from the heavily loaded CSs which are scattered over all the channels. The average of the dynamic excess bandwidth allocation errors for both GA

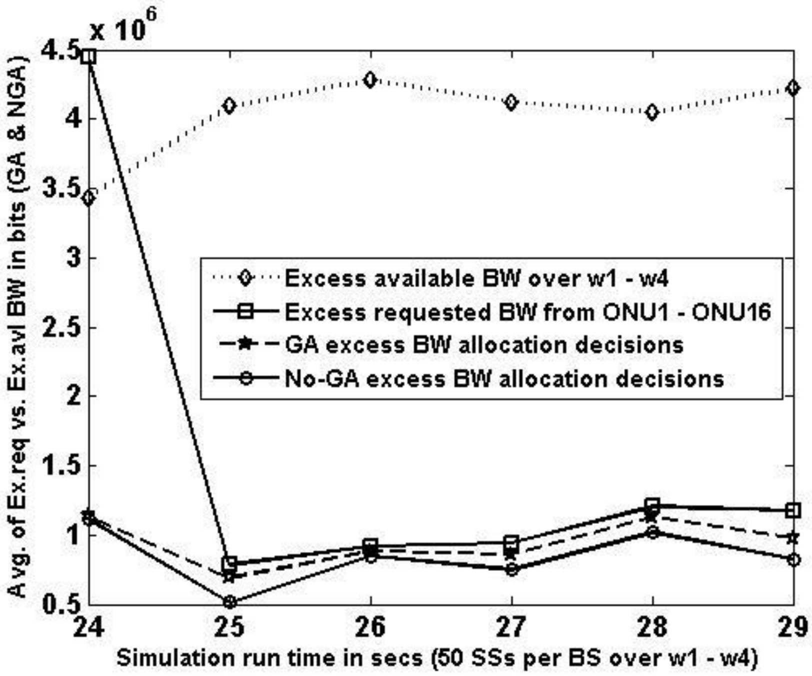

Figure 6.6 Average of GA and no-GA-based excess bandwidth allocation decisions vs. the excess requested and available bandwidth when the number of the SS connected per BS over w_1 to w_4 is 50

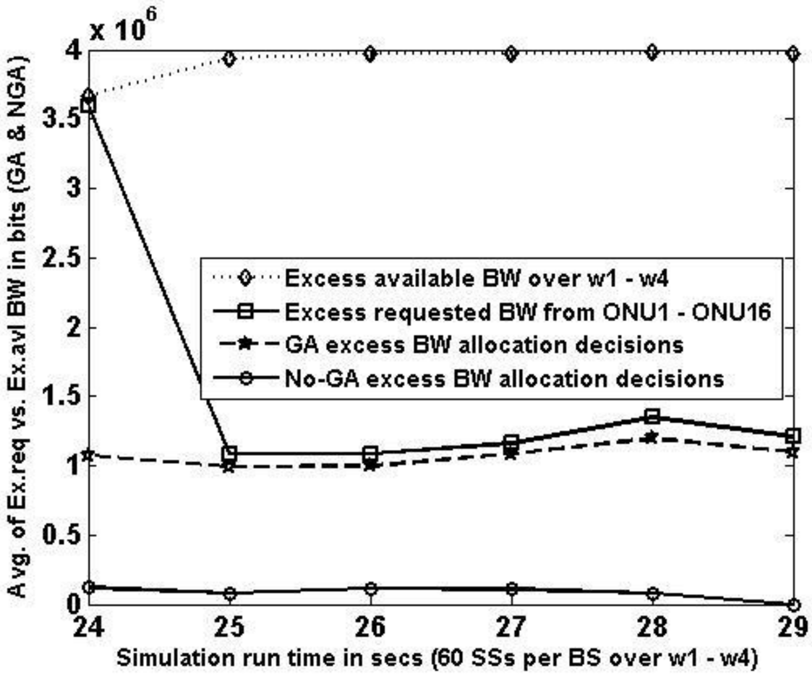

Figure 6.7 Average of GA and no-GA-based excess bandwidth allocation decisions vs. the excess requested and available bandwidth when the number of the SS connected per BS over w_1 to w_4 is 60

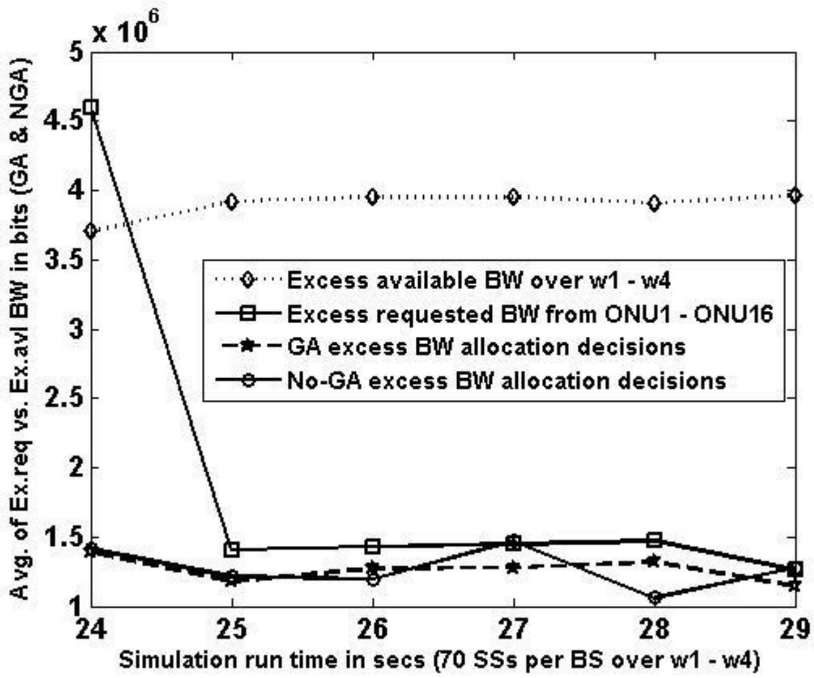

Figure 6.8 Average of GA and no-GA-based excess bandwidth allocation decisions vs. the excess requested and available bandwidth when the number of the SS connected per BS over w_1 to w_4 is 70

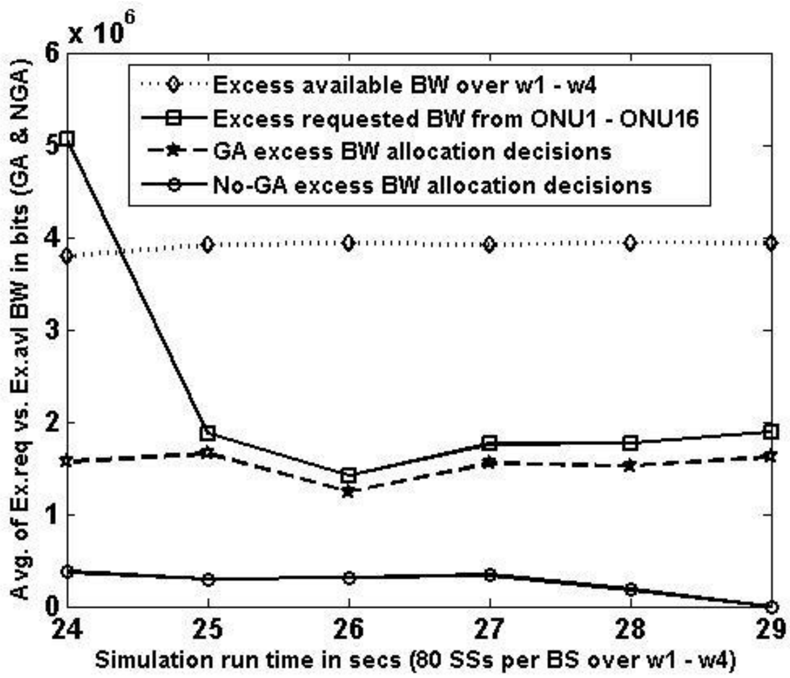

Figure 6.9 Average of GA and no-GA-based excess bandwidth allocation decisions vs. the excess requested and available bandwidth when the number of the SS connected per BS over w_1 to w_4 is 80

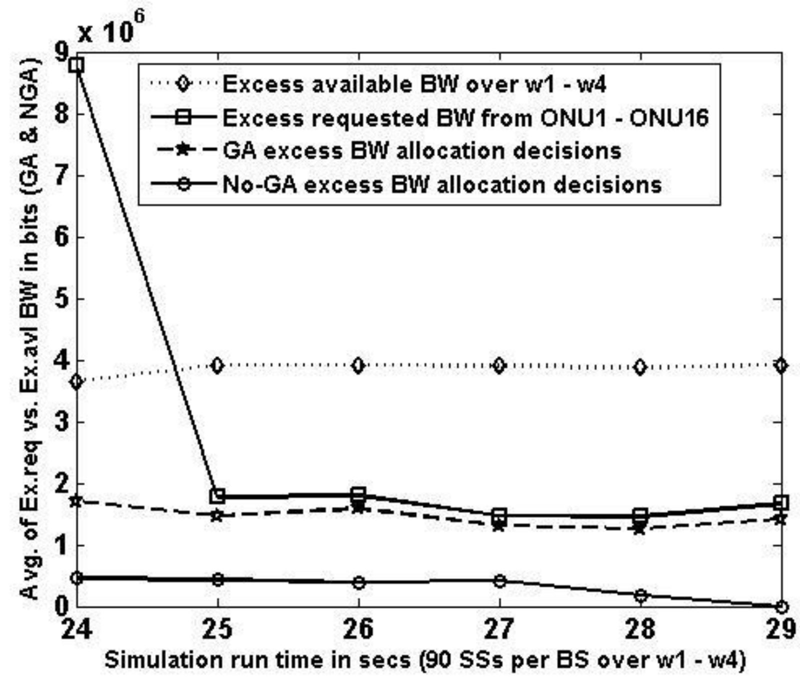

Figure 6.10 Average of GA and no-GA-based excess bandwidth allocation decisions vs. the excess requested and available bandwidth when the number of the SS connected per BS over w_1 to w_4 is 90

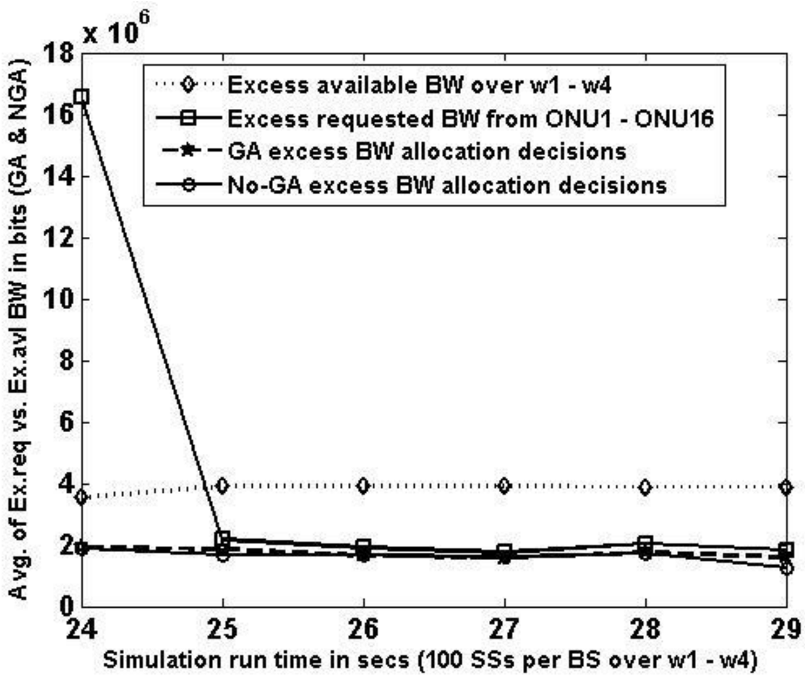

Figure 6.11 Average of GA and no-GA-based excess bandwidth allocation decisions vs. the excess requested and excess available bandwidth when the number of the SS connected per BS over w_1 to w_4 is 100

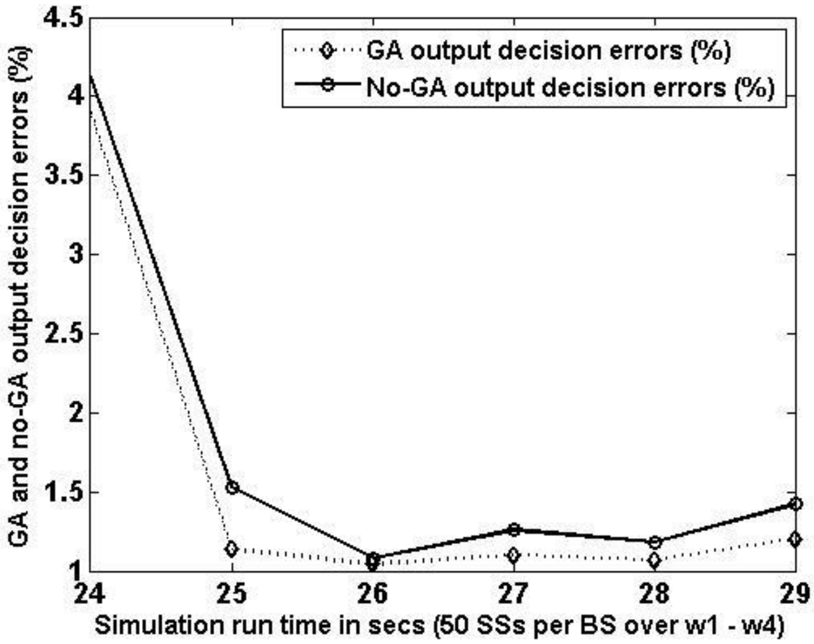

Figure 6.12 GA and no-GA-based excess bandwidth allocation decisions errors when the number of the SS connected per BS over w_1 to w_4 is 50

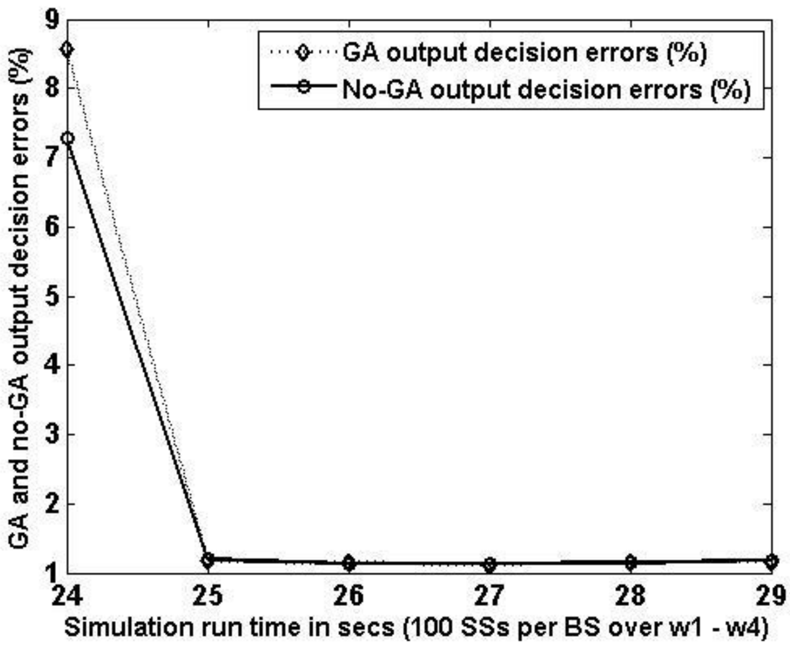

Figure 6.13 GA and no-GA-based excess bandwidth allocation decisions errors when the number of the SS connected per BS over w_1 to w_4 is 100

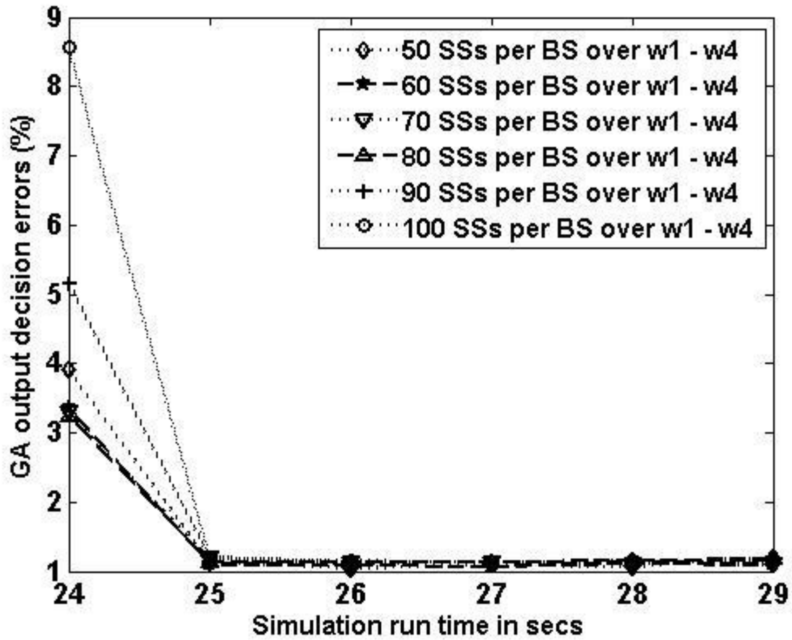

Figure 6.14 GA-based excess bandwidth allocation decisions errors when the number of the SS connected per BS over w_1 to w_4 is increased from 50 – 100

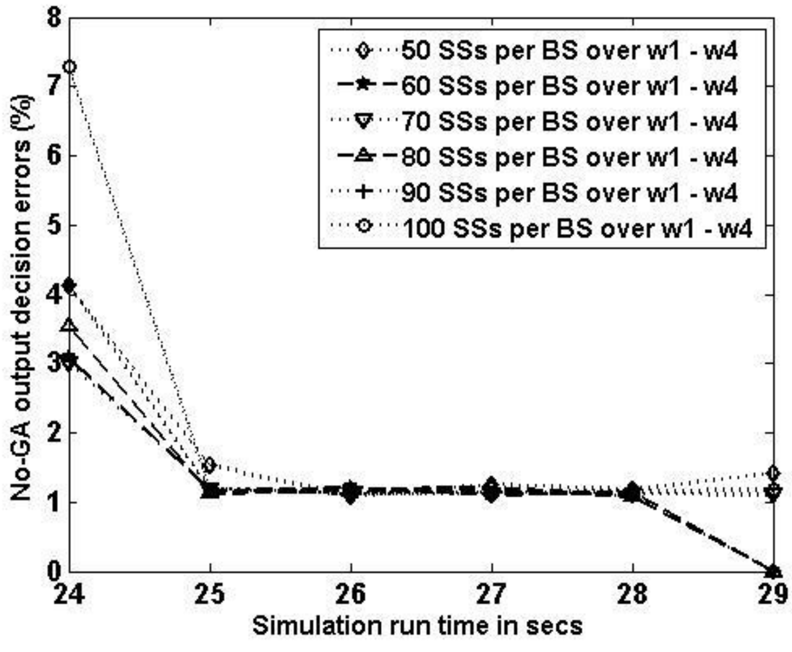

Figure 6.15 No-GA excess bandwidth allocation decisions errors when the number of the SS connected per BS over w_1 to w_4 is increased from 50 - 100

and none-GA scenarios are captured in Figure 6.14 and 6.15, respectively. Addressing the captured results, it is concluded that although the both scenarios show very small errors in the excess bandwidth allocation decisions, the GA solver shows a negligible and more constant error level in comparison with the none-GA solution.

6.7 Chapter Summary

This chapter presented the novel concept of using a GA approach for providing an intelligent solution for the optimum or near optimum resource utilisation over the converged scenario of the NGN.

In this chapter, GA was applied to phase three of the proposed IIDWBA algorithm, from chapter 5, to find the optimum, near optimum or the best solutions for the dynamic excess bandwidth allocations among all the heavily loaded CSs associated with a given SST once per service cycle. The heavily loaded CSs may be scattered over the different channels related to a given SST and may have different excess bandwidth requests.

The excess bandwidth data was collected at the end of phase two of the IIDWBA algorithm (Intra-channel bandwidth allocations phase) and passed to the global scheduler located on a given SST. The global scheduler has all the updates about all the channels related to a given SST e.g. number of the heavily loaded CSs per channel, the excess available bandwidth per channel and the excess requested bandwidth per channel per heavily loaded CS per service cycle.

After receiving the excess available bandwidth as well as the excess requested bandwidth from all the channels associated with a given SST, phase three of the

IIDWBA algorithm employed the GA in order to find the best, optimum or the near optimum solutions for the dynamic excess bandwidth allocations from all the available channels among all the heavily loaded CSs which may be scattered over the different channels.

Employing GA as a part of phase three of the IIDWBA algorithm helped to improve the total network performance in the converged scenario between the optical and wireless technologies particularly the excess bandwidth utilisations. For instance, as it was depicted in Figure 6.6, the average excess bandwidth allocation is 1.14% improved when the GA techniques were employed in comparison with non-GA based excess bandwidth allocation scenario.

Addressing the captured results, the GA solver was also capable of providing excess bandwidth allocation decisions with the negligible error percentages when it was compared with the actual excess requested bandwidth from all the heavily loaded CSs per service cycle. For instance, as it was depicted in Figure 6.12, the decision error for excess bandwidth allocation is around 1.57E+00% when GA techniques were employed. Moreover, as it was depicted in Figure 6.12, the decision error for excess bandwidth allocation is 8.79E-01% improved when GA techniques were employed in comparison with non-GA based excess bandwidth allocation scenario.

Chapter 7 Conclusions and Future Work

This chapter brings this thesis to a conclusion. In doing so, first it reviews the motivation and the objectives in company with a summary of the key contributions of the research work in this thesis. Secondly, it acknowledges and discusses possible future directions which come forward from the research presented in this thesis.

7.1 Summary of Thesis Contributions

The research presented in this thesis is an outcome of the motivations and objectives associated with the forthcoming traffic growth and the huge demands of emerging sophisticated and bandwidth hungry applications and services [129]. Taking into consideration the emergence of the NGN [130], where the Internet services and applications are to be provided wherever, whenever and in whatever format, the converged infrastructure of the NGN comes into the spotlight. Conventional work related to the fixed, particularly optical, and wireless converged scenarios have some shortcomings in providing the level of capacity, scalability and intelligence which is required in the current NGN environment. This forms the prime motivation for the work presented in this thesis to bridge this gap. NGN, with significant advantages of supporting ETE QoS, mobility features as well as converged services, applications and infrastructure, also brought forward specific challenges like the resource management over the converged scenario as well as the converged infrastructure. These motivating factors formed the inputs to the design and develop a comprehensive converged framework with support of a distributed, real-time, dynamic, scalable and intelligent wavelength and bandwidth allocation algorithm for the converged scenario of the NGN. The primary reason for the extensive development of the NGN is to provide a reliable, robust Internet service wherever, whenever and in whatever format with sole focus on ETE QoS and converged support for a wide variety of fixed, mobile and wireless applications and services.

Taking into consideration the converged infrastructure of the NGN, the traditional single channel optical network has been mostly employed for the integrated scenario between the fixed and wireless scenario. However, the traditional single channel optical networks do have some shortcomings in terms of the level of coverage support, capacity and scalability. The integrated scenario between the multi-channel passive optical network and wireless technology has gained popularity as the function of providing relatively higher bandwidth, capacity and coverage due to supporting the multi-wavelengths over the same fibre infrastructure with great mobility and protocol transparency. On the other hand optimisation techniques have gained great attentions in telecommunication area in terms of providing the optimum or near optimum solutions from some set of available alternatives with relatively low error level.

As such, to support the essential requirement of scalability, high capacity and coverage multi-channel optical networks were identified as a suitable nominee for the fixed part in converged infrastructure of the NGN. A distributed, real-time, dynamic, scalable and intelligent wavelength/bandwidth allocation algorithm with support of the optimisation techniques, particularly GA was proposed to address the problem of resource allocations over the converged scenario. Hence, the overall objectives of this research was the design, development and evaluation of an intelligent and dynamic resource (wavelength/bandwidth) allocation algorithm for multi-channel optical network integration with wireless technology with support of optimisation techniques. A Genetic Algorithm (GA) based technique was put forward as an efficient solution to the identified resource allocation problem. This resulted in the following key thesis contributions which are presented and summarised next.

Comprehensive framework for the converged scenario: In support of the first objective of the thesis (i.e. architectural design of the converged protocol), a comprehensive framework for the converged scenario between multi-channel optical network and wireless technology (as detailed in chapter 4) was designed, implemented and evaluated. It detailed the way two technologies can be integrate together based on the available optical and wireless components in the market along with proposed ETE functional module specifications, physical structure, component specifications as well as the distance constraints. The proposed ETE key functional modules, on which this PhD project was focused, alongside their roles and their operations were all identified and then evaluated through the comprehensive simulated experiments employing different traffic patterns, load values and parameters which showed expected results.

After the framework was found to be appropriate for the converged scenario in terms of providing the reliable infrastructure for the key functional modules with the focus on resource allocation including the ETE wavelength and bandwidth allocation, the same scenario is employed for all subsequent experiments in this thesis.

Distributed, real-time, dynamic and scalable resource allocation algorithm for the converged scenario: To realise the second objective of the thesis (i.e. devise a resource allocation algorithm for the converged scenario), an Inter-channel and Intra-channel Dynamic Wavelength/Bandwidth Allocation (IIDWBA) algorithm was proposed which was a solution for the resource allocation problem over a multi-channel optical network converged with wireless technology (as detailed in chapter 5). The proposed solution worked in three phases termed Initialisation, Intra-channel bandwidth allocations and Inter-channel bandwidth allocations. It started with the Initialisation phase during which a given channel is allocated to a number of CSs associated with a given SST. During phase two of the IIDWBA algorithm the allocated channel from phase one is shared among local CSs associated with a given SST. Phase three of the IIDWBA algorithm was provided in order to make a real-time framework for the dynamic wavelength and dynamic bandwidth allocations between different channels associated with a given SST. Phase three of the IIDWBA was capable of identifying the available excess bandwidth as well as the requested excess bandwidth in real-time which was followed by collecting the excess bandwidth over a given service cycle across all the channels associated with a given SST, scheduling them and finally distributing them among all the heavily loaded CSs which may exist over different channels. The IIDWBA algorithm is evaluated through simulations employing different traffic patterns and load values in terms of throughput, utilisation and queuing delay. The benefits of employing the IIDWBA algorithm became more obvious when the converged simulated scenario is more heavily loaded.

GA-based intelligent resource allocation algorithm for the converged scenario: In support of the third objective of this thesis (i.e. an intelligent resource allocation algorithm for the converged scenario) a popular optimisation technique termed Genetic Algorithm (GA) was employed in order to improve the excess bandwidth utilisations over the converged scenario, which occurred once per service cycle during phase three of the IIDWBA algorithm (as detailed in chapter 6). Addressing the captured results, the GA solver was capable of providing the optimum or near optimum solutions for the dynamic excess bandwidth allocation over the integrated scenario taking in to account the actual needs of each heavily loaded CSs and the available excess bandwidth per channel per service cycle. The GA decision outputs were constrained such that the excess allocated bandwidth was not be more than the actual need of a given heavily loaded CS and was also not be more than the available excess bandwidth on a given channel with relatively low error percentages.

The three solutions (architectural design of the converged protocol, IIDWBA algorithm and GA-based IIDWBA algorithm) provided a proof of scalability and applicability to solve the problems of the converged infrastructure of the NGN. For instance, the proposed IIDWBA algorithm is independent from the numbers of supported/available channel over a given converged scenario which means it can run on any converged scenario with support of *1* to *n* channels per SST per CS. Moreover, the proposed IIDWBA algorithm is independent from the excess resource availability per channel per service cycle which means if there is no excess bandwidth from all the channels associated to a given SST on a given service cycle, the proposed algorithm is still capable of providing the minimum guaranteed bandwidth per CS.

7.2 Directions for Future Research

The work presented in this thesis motivates further potential research which is worthy of a detailed investigation. Certain issues related to the optimisation techniques could not be addressed in this thesis because of the time limitations and the capabilities of the tools which were used. This section provides potential pointers for further research.

Full GA-based IIDWBA algorithm: This thesis presented the performance of the GA-based excess resource allocation algorithm for the optimum or near optimum resource utilisations over the converged scenario of NGN. The GA solver employed in phase three of the proposed IIDWBA algorithm (Inter-channel bandwidth allocations phase) in order to find the best, optimum or near optimum solutions for the excess resource allocations once per service cycle. The full GA-based IIDWBA can immensely benefit from the optimum or near optimum resource utilisation both on a intra-channel and inter-channel basis. This is the work which could not be addressed in this thesis due to time limitations. However, it needs to be noted that the initial preparations for employing the GA solver for phase two of the IIDWBA algorithm (Intra-channel bandwidth allocations phase) is done. This needs to be evaluated through simulation experiments in conjunction with phase three of the IIDWBA algorithm (Inter-channel bandwidth allocations phase) in order to assess the performance of the GA decision outputs over the full IIDWBA algorithm steps.

As a way of clarifying the full GA-based IIDWBA algorithm, a pictorial representation is provided in Figure 7.1. It reveals the necessary factors which need to be passed to the GA solver in each phase (phase two and phase three) in order to provide a full GA-based IIDWBA algorithm for the converged scenario of NGN. To achieve this objective, the GA solver needs to be implemented on each channel associated with a given SST (sub-GA solvers) for phase two of the IIDWBA algorithm and on a given SST (global GA solver) for phase three of the IIDWBA algorithm.

Comprehensive online performance evaluation: The second pointer for further research is to employ the GA solver in an online basis inside the converged simulated scenario in order to distinguish the influence of the GA solutions on overall network performance such as queuing delay, queue lengths and link utilisation. This is another

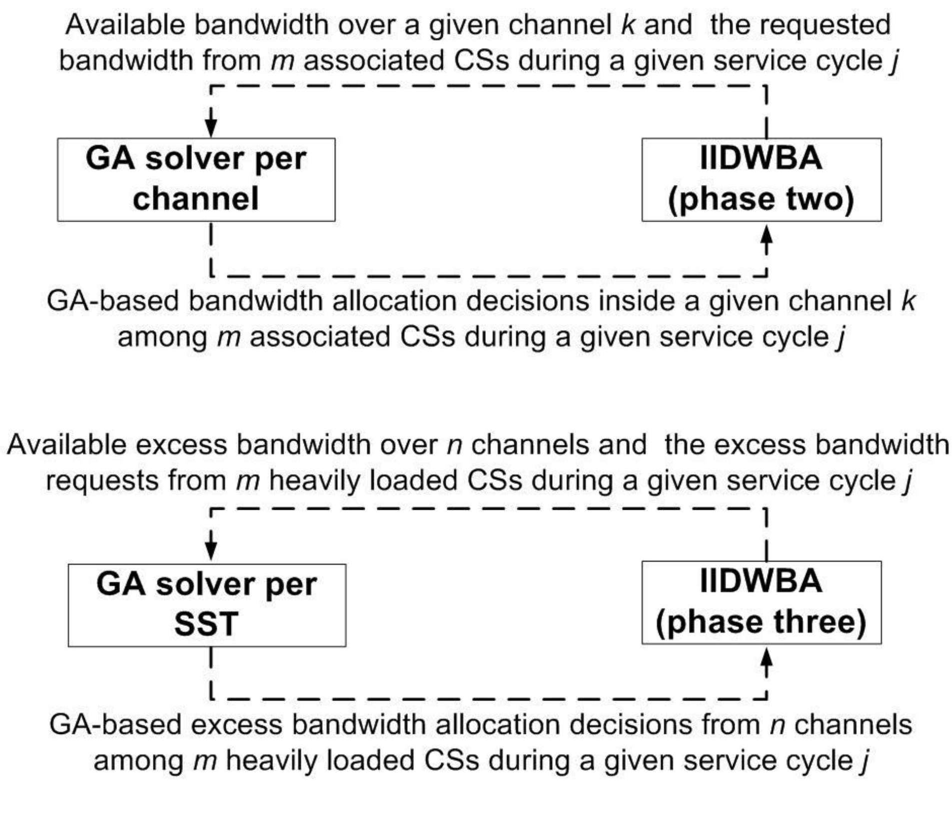

Figure 7.1 Full GA-based IIDWBA algorithm

work which could not be addressed in this thesis due to the time limitations and complexity of the task as it involves integration between two popular tools which employed in this thesis, OPNET and MATLAB. Integration of OPNET and MATLAB provides a unique platform for employing the developed functions and algorithms from MATLAB over an implemented scenario in OPNET. Another approach for employing the GA techniques inside the OPNET simulation scenarios in an online basis is to implement the GA solver inside OPENT which is not unreachable due to custom model supports in OPNET.

Comparison with other optimisation techniques: In this thesis, GA, which is one of the most popular optimisation techniques, is employed in combination with the proposed IIDWBA algorithm in order to provide the best, optimum or near optimum solution as a function of optimum or near optimum resource utilisation of the NGN. An interesting study might involve comparison with other popular optimisation techniques such as LP, DP, and ANN. The real challenge in such a scenario could be to find the suitable solutions which guarantee all/majority of the trade-off factors in telecommunication area such as CPU overhead, memory usage, speed of compilation and real-time support. In this thesis the GA solver was capable of providing the output decisions for the problem of the resource utilisations with significant low error percentages.

Real network and testbed evaluation: The important characteristics of solutions presented in this thesis is the way in which they were modelled, coded, implemented and evaluated in a simulated environment of OPNET and MATLAB. These solutions can be verified practically through either a real network (e.g. as a part of a real converged development from a telecommunication company) or a testbed with appropriate facilities of a converged network. This will add further value to the proposed solutions in this thesis, because it can test the effectiveness of the solution for a real network environment.

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