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Dynamic Connection Provisioning in Fiber-Wireless Access Networks using Tuning-Based ROADMs

Submitted in partial fulfillment of the requirements for the degree of

Master of Science in Computer Science

Shadrack Omondi Anyuo

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Supervisor: Prof. Dr. Noélia Correia

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Acknowledgment

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Acronyms

FiWi	Fiber Wireless
ROADM	Reconfigurable Optical Add/Drop Multiplexer
FOADM	Fixed Optical Add/Drop Multiplexer
OADM	Optical Add/Drop Multiplexer
WiMAX	Worldwide Interoperability for Microwave Access
WoF	Wireless over Fiber
WDM	Wavelength Division Multiplexing
DWDM	Dense Wavelength Division Multiplexing
OXC	Optical Cross Connect
O-E-O	Optical-to-Electrical-to-Optical
FTTH	Fiber To The Home
AON	Active Optical Networks
PON	Passive Optical networks
W&F	Wireless and Fiber
CO	Central Office
OLT	Optical Line Terminal
ONU	Optical Network Unit
ONT	Optical Network Terminal
TDM	Time Division Multiplexing
ATM	Asynchronous Transfer Mode
EPON	Ethernet PON
GPON	Gigabits PON
A/B PON	ATM/Broadband PON
AP	Access Point
BS	Base Station
MR	Mesh Router
MGR	Mesh Gateway Router
WMN	Wireless Meshed Network
FSO	Free Space Optics
OZS	Optical Multipoint Units
OR	Optical Router
WAP	Wireless Access Point

SCM	Subcarrier Multiplexing
MCS	Mobile Client Station
CN	Concentration Node
RN	Remote Node
OS	Optical Switch
BTS	Base Transceiver Station
RAU	Remote Antenna Units
SONET	Synchronous Optical Network
FBG	Fiber Bragg Grating
RWA	Routing and Wavelength Assignment
TR	Tuning Range
LAN	Local Area Network
TH	Tuning Head / Tunable Head
A*	A Star
AHT	Average Holding Time
AIT	Average Inter-arrival Time

Resumo

Temos assistido recentemente a uma enorme procura por serviços de banda larga, procura essa que tem sido incentivada pela queda dos preços dos dispositivos com capacidades de banda larga. Este aumento na procura trouxe também desafios para os operadores de telecomunicações, uma vez que a largura de banda oferecida necessita de acompanhar o aumento da procura. Apesar da existência de soluções em redes de transporte para transmissão de grandes quantidades de trafégo através de fibra-óptica, as redes de acesso até ao operador não estão aptas para oferecer grande largura de banda aos utilizadores finais.

Mais recentemente, uma nova e eficaz solução para redes de acesso, que combina os benefícios das redes ópticas e sem fios, tem sido investigada. Espera-se que esta solução híbrida, conhecida por *hybrid fiber-wireless* (FiWi), venha a ser uma plataforma de suporte para aplicações e serviços futuros.

Nesta tese, é discutido o fornecimento de ligações dinâmicas em redes de acesso FiWi. Para reduzir o custo total da rede de acesso, é proposto o uso de *reconfigurable add/drop optical multiplexers* (ROADMs) sintonizáveis na interface sem-fios - fibra óptica. Para estabelecer as ligações dinâmicas, é proposta uma heurística que procura minimizar a probabilidade de bloqueio através de um eficiente encaminhamento e atribuição de comprimento de onda e através do reajuste eficiente do posicionamento das cabeças nas ROADMs.

Abstract

There has been a continuous demand for broadband services in the recent past majorly attributed to the fall in pricing of high end devices with broadband capabilities. This has brought challenges to network operators since the offered bandwidths need to match the ever increasing demand. While there has been solution for transport network to carry huge traffics through fiber optics technology, access networks have not been able to deliver this huge bandwidth to the end users.

More recently, a new powerful access solution, combining the strength of both optical and wireless technologies, is under strong research. This hybrid fiber-wireless (FiWi) access solution is expected to become a powerful platform for the support of future applications and services.

In this thesis, dynamic connection provisioning in FiWi access networks is discussed. In order to reduce the overall network costs in the access networks, the use of tunable reconfigurable add/drop optical multiplexers (ROADMs) at the wireless-optical interface is proposed. To achieve dynamic connection provisioning, a heuristic is proposed that minimizes the overall connection blocking probability through efficient routing & wavelength assignment and tuning-based head re-positioning at ROADMs.

Chapter 1

1 Introduction

1.1 Focus

There has been a continuous demand for broadband services in the recent past majorly attributed to the fall in pricing of high end devices with broadband capabilities. This has brought challenges to network operators since the offered bandwidths need to match the ever increasing demand. While there has been solution for transport network to carry huge traffics through fiber optics technology, access networks have not been able to deliver this huge bandwidth to the end users.

We have seen a tremendous advancement in access networks with the deployment of fiber –to the-home/offices/premises and wireless technology to offer the last mile connectivity. Both technologies have been running independently with the main aim of availing the much needed bandwidth. Fiber optics technology has really done well as it has the capacity to offer unlimited bandwidth but the cost of installation is still high and cannot offer much mobility to the users. Wireless technology on the other hand offers affordability and mobility to the user but cannot rival optical technology in bandwidth capacity. These challenges have made these two technologies to complement each other and have led to new evolution of technological advancement in access network known as fiber-wireless access networks. This technology which tries to take the strengths of both fiber optics and wireless technology is expected to be a major success in the last mile connectivity.

Due to the increasing importance of fiber wireless networks in the access, we envision that innovation in allocation of resources and fairness use of resources will become necessary. This is based on the fact that resource allocation decisions relating a specific service will influence the performance of others. Also, when granting access to shared resources, fairness among users/services/operators should be achieved.

This dissertation focuses on resource allocation in fiber-wireless networks under a scenario where connections generated by wireless nodes arrive dynamically to the optical section.

1.2 Objectives

The first goal of this work is to study fiber-wireless technology and the existing architectures in literature. A key aspect that needs to be applied in the access network, is the cost effectiveness of the solution. A careful analysis of the architectures was undertaken and ROADM-based architectures using tunable devices were selected and further analysis carried out and detailed herein.

The second goal is to develop an efficient heuristic algorithm for dynamic connection provisioning to be applied on the chosen architecture. For this purpose an A star based algorithm was developed.

The third objective is to determine the effect of the number of tunable heads per ROADM on the network performance. As the number of tuning heads per ROADM approaches the total number of wavelengths, the more such tuning based ROADM architecture approaches switching based ROADM architecture.

The last objective is to analyze the performance obtained through using the A star based algorithm with the chosen architecture and compare it with traditional algorithm such as Dijkstra. This result analysis is also discussed in detail in this dissertation.

1.3 Main Contributions

The main contributions of this study are as follows:

- Analysis of cost effectiveness of fiber-wireless access network architectures.
- Development of a heuristic algorithm for dynamic connection provisioning in fiber-wireless access networks using tuning-based devices.
- Analysis of the effect of the number of tuning heads per ROADM node to the network performance.
- Performance analysis of the proposed heuristic algorithm when compared to traditional Dijkstra algorithm.

1.4 Organization

This dissertation is organized into seven chapters. The first chapter gives the overview of the dissertation, its main focus areas, the objectives to be achieved, main contributions and the general organization of this dissertation.

The second chapter focuses on both optical and wireless as standalone architectures. This chapter reviews the optical networks with emphasis to both optical transport networks and optical access networks. Under optical networks different implementation forms are discussed such as point-to-point, ring and meshed while on the optical access networks both active and passive optical approaches are presented. Their implementation strategies are discussed together with both merits and demerits of each. On wireless standalone architectures, single-hop and multi-hop infrastructure-based networks and worldwide interoperability for microwave access (WiMAX) are detailed.

In chapter three, fiber-wireless access networks is presented. It details various implementation scenarios for this technology through the use of both optical and wireless networks such as using wireless meshed networks, EPON and WiMAX integration, radio over fiber, free space optics and other hybrid integration of fiber-wireless networks.

Chapter four presents a detailed view of the adopted network architecture. It discusses the different devices used in the architecture; the network topology employed and also gives the background information on routing and wavelength assignment strategies.

In chapter five, the proposed routing and wavelength assignment heuristic algorithm is introduced and discussed. The heuristic formulation and implementation is presented together with the pseudo code. This chapter also outlines the routing, wavelength assignment and tuning head parking and re-parking strategies for the adopted architecture.

Chapter six discusses performance analysis of the proposed heuristic algorithm. A comparison of the proposed algorithm with traditional heuristic such as Dijkstra, under different network scenarios, is presented. Analysis of the effect of the number of tuning head per node on the network blocking probability is also discussed. These results are compared in terms of the network blocking probability.

Chapter seven basically concludes the thesis. It also points out the potential future research areas which can be explored further.

Chapter 2

2 Optical and Wireless Standalone Architectures

Due to the continuous growth in demand for bandwidth by network users, optical technologies and optical networks have become a focal point of interest to both researchers and practitioners as they have offered a way by which this demand can be met. In theory a single-mode fiber has the potential to offer over 30 terabits per second of bandwidth, this is much better than the current electronic processing speed of few gigabits per second [1]. Apart from this huge bandwidth capability, fiber optics has low signal attenuation, low signal distortion and low error bit rate. In implementation of optical networks, a technology called wavelength division multiplexing (WDM) has been explored. This technology combines multiple wavelengths and transmits them at the same time over a single fiber, each at a rate of a few gigabits per second thereby increasing the usable bandwidth of a fiber. We will look at optical and wireless as standalone architectures in order to understand how fiber-wireless access networks integration will emerge.

2.1 Optical Networks

2.1.1 Optical Transport Networks

This layer is also referred to as the core or backbone network. It is characterized by higher capacity and covers larger geographical areas such as inter-continents, inter-cities or within a city. Here optical network can be implemented in the form of point-to-point, ring or meshed optical networks [2].

2.1.1.1 Point –to – Point Optical Link

This network is made up of a single fiber that offers connection between two points. It is made up of a multiplexer used to combine different wavelengths ($\lambda_1, \ldots, \lambda_W$) into an optical signal, thereby inserted into a single fiber at the transmission end, and a de-multiplexer used to separate the incoming optical signal into the original wavelengths at the receiver side. In between these two devices, depending on the distance, there can exist other various components such as repeaters /amplifiers to boost the signal strength as it can suffer attenuation.

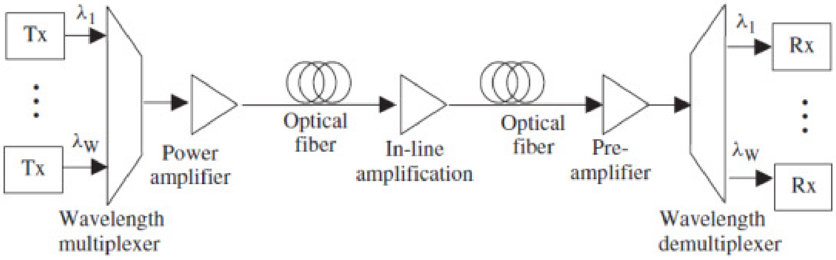

Figure 1: WDM point-to-point link

2.1.1.2 Ring Network

This optical network is implemented by the use of optical cross connects (OXCs) or optical add/drop Multiplexers (OADMs) into a form of a ring topology. OXC is a type of optical switch with a certain number of equal input and output ports. It has the capability of switching incoming wavelength(s) to specific output port(s) and to convert them to other wavelength(s). The latter can be achieved when the OXC is equipped with converters, where conversion can be done all-optically, or using O-E-O conversion. Recent research has shown that using OXC in optical domain has enabled cost reduction through removal of the costly and power consuming electrical stage [42-43]. They also reduce the deployment times for new services and provide additional network robustness by offering fast protection switching and restoration.

Therefore, OXC at the optical layer of communication networks provides additional network management options so that features such as load balancing and traffic routing can be achieved economically. This factor has shaped the current and future research on optical networks. The OADMs can also be used to add/drop one or more optical signals on a given wavelength(s) in an input/output port.

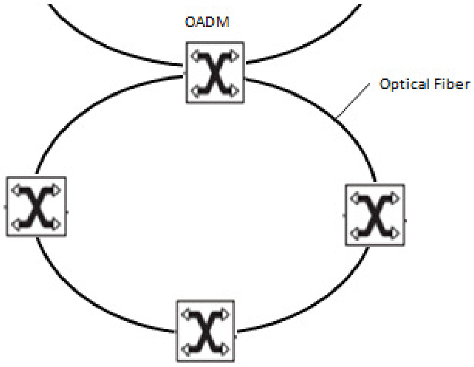

Figure 2: Optical ring network

Optical ring networks range from simple static to advanced dynamic rings with reconfigurable devices.

2.1.1.3 Mesh Optical Network

This network is formed by arbitrary interconnection of OXCs that might include optical rings, as shown in Figure 3 below.

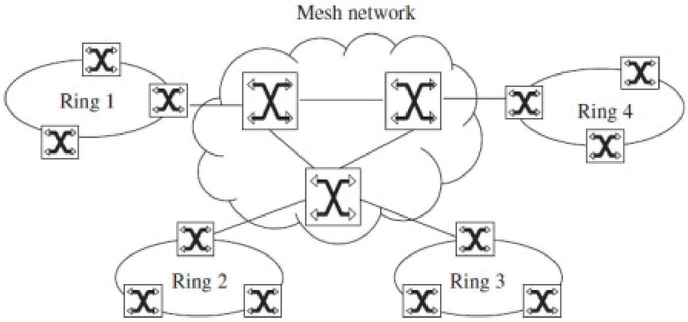

Figure 3: Mesh optical network

In the implementation of the above mentioned optical networks, many components are used [3]. These networks are also associated with very high traffic flows and, therefore, their availability is of very great concern. To ensure no failures, different protection schemes are implemented as shown in [3].

2.1.2 Optical Access Networks

These networks concern with the final delivery of traffic to the end users either at home, in the offices or on the move. It is always referred to as first/last mile or access networks. Here, implementation of Fiber-To-The-X (X – homes, offices, building) has played a major role in meeting the increasing bandwidth demand caused by the increasing sophistication of end user applications such as Voice over IP, video on demand, interact gaming, HDTV among others.

These networks can be grouped into two major categories namely: - active optical networks (AONs) and passive optical networks (PONs). In AONs, the components of the optical network are power consuming. They include amplifiers, switches, regenerators which tend to be more expensive in terms of maintenance costs. On the other hand PONs have passive elements with low installation and maintenance cost but able to offer high reliability at shorter distances. The elements include couplers, splitters and filters. PON have provided a better alternative to deploy optical access networks and will, therefore, be discussed in detail next.

2.1.2.1 Passive Optical Networks

As explained earlier PONs have passive elements but still offer high reliability. It is always implemented in a tree topology to deliver traffic to the end users which also lowers cost through infrastructure sharing.

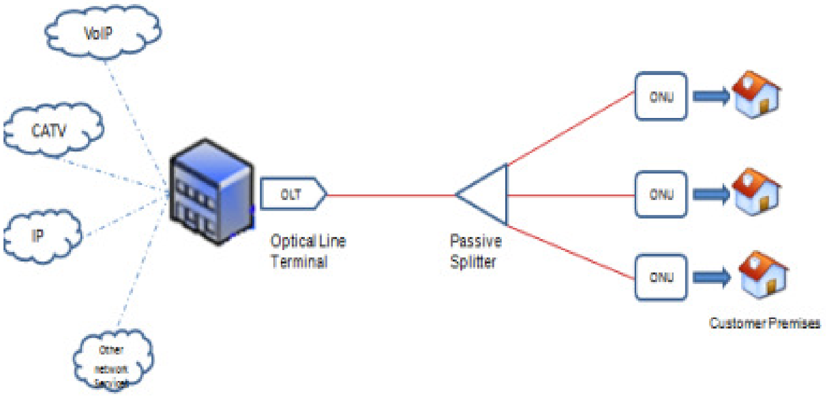

Figure 4: PON network

As shown in Figure 4 above, the central office (CO) is where the central processing is done, It has optical line terminals (OLTs) that can manage two way shared connections in PONs. The passive splitter is used to split/combine optical power. The optical network unit/terminal (ONU/ONT) is the user side equipment. ONU is used together with OLT to provide the user with many kinds of broadband services. Between OLT and ONU there is an optical fiber which is used to carry traffic to the users. At the splitter point, the optical power will be divided equally to the ONTs at the user premises. On the upstream the scenario is different in that, the single fiber to the OLT will not carry the sum of the optical power from the various user ONTs but rather just one fraction of the total power for each fiber coming into the splitter. This is actually a set back to PON implementation.

Again on the upstream since there are different users sending traffic to the OLT, there is need to have some form of multiplexing. Two kinds of multiplexing have been implemented in PONs namely, time division multiplexing (TDM) and WDM. Most PONs have been working on TDM but, due to increased bandwidth need, it has proved not to be very efficient, thus the need to use WDM.

In TDM PON, the bandwidth is shared in time domain, that is, every ONU has a specific time slot to send data packets, the management of this time slot allocation is done by the OLT as per the ITU-T G.983.4 specifications [4]. It also uses two wavelengths each for upstream and downstream respectively. One major limitation of TDM-PON is that all the users share only one wavelength and this really reduces performance when demand increases.

There are more standards under TDM-PON. The ATM/Broadband PON (A/B-PON) which was standardized to carry ATM cells traffic by ITU-T G.983 [5] thus guaranteeing quality of service. The other one is the Ethernet PON (EPON) based on the Ethernet standardization IEEE802.3ah [6] and is well-suited to carry packetized traffic. It allows for utilization of the economies-of-scale of Ethernet, and provides simple, easy-to-manage connectivity to Ethernet-based IP equipment, both at the customer premises and at the central office [7]. The last one is the gigabits PON (GPON), which was standardized by ITU-T G.984 [8]. Its main objective is to bridge both A/B-PON and EPON by trafficking both ATM cells and Ethernet frames while offering high efficiency and flexibility [9].

Due to the increased number of users and emergence of high bandwidth demand user applications, TDM-PONs can no longer offer the much needed capacity. With WDM-PON the capacity can be boosted and performance increased. The main challenge has been how to shift commercial networks from TDM-PON to WDM-PON in terms of the costs. Some researchers have proposed an initial coexistence of both technologies with gradual replacement of components as a solution [10][11][12].

There are two standards for WDM-PON; dense WDM-PON ITU-T G.694.1 and coarse WDM-PON ITU-T G.694.2 [13-14]. There are a range of issues associated with WDM-PONs deployments as shown in [15].

2.2 Wireless Networks

2.2.1 Infrastructured Wireless LAN

This is also referred to as single-hop infrastructured networks and is composed of a set of access points (APs) and a set of wireless users. Each AP has a fixed transmission range and can only serve users within its range. The AP connects to the internet directly or through a backbone network. It is defined in IEEE 802.11 standardization [58]. The infrastructured wireless LAN's easy installation and low infrastructure cost make it ideal for network access in offices, campuses, airports, and hotels. Figure 5 below shows an infrastructured wireless LAN.

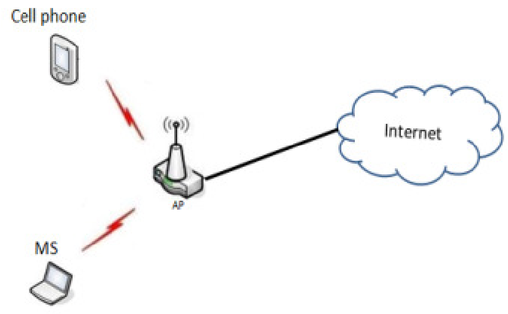

Figure 5: Infrastructured wireless LAN

2.2.2 Wireless Meshed Networks (WMN)

It is also referred to as multi-hop infrastructure-based networks and consists of a number of mesh routers (MR) and mesh gateway routers (MGR). The MR is used to connect to end users and relay their traffic to the MGR which connects to the Internet directly or through backbone networks [16-17]. These features bring many advantages to WMNs such as low up-front cost, easy network maintenance, robustness, and reliable service coverage. WMN can also easily be integrated with other wireless networks as shown in Figure 6 below (source http://www.cnri.dit.ie/images/mustafa.gif).

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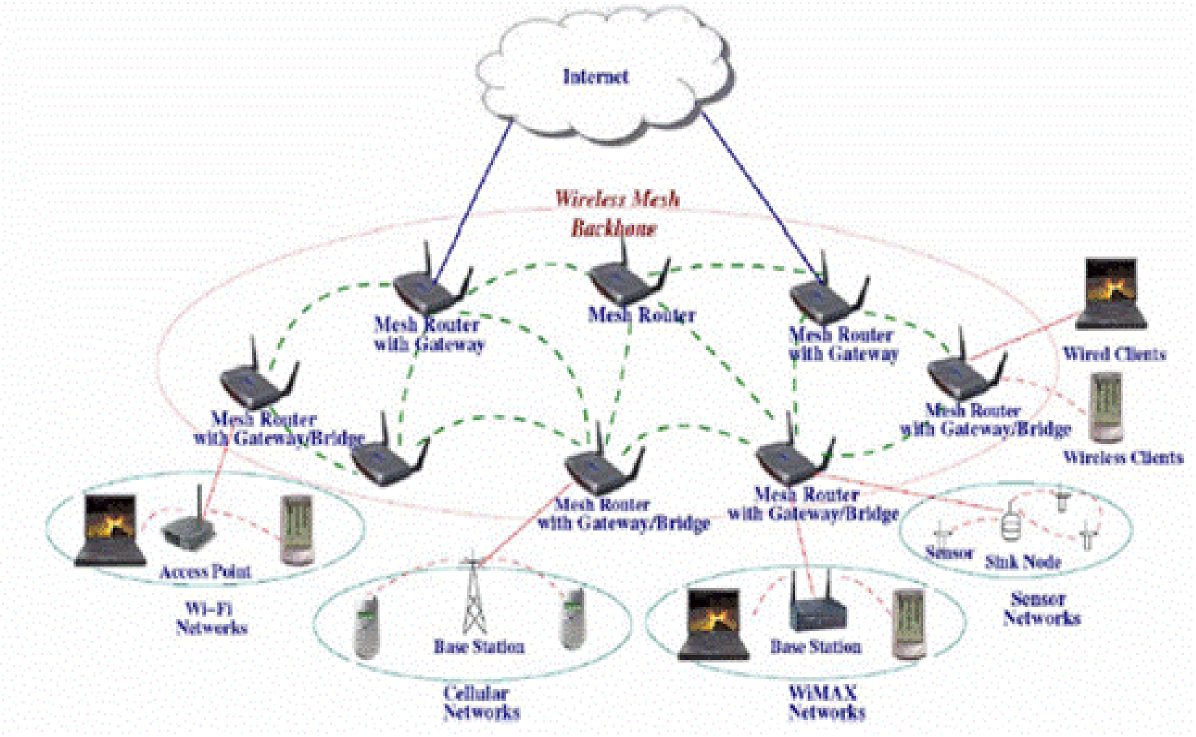


Figure 6: Wireless mesh network

2.2.3 Worldwide Interoperability for Microwave Access (WiMAX)

This technology is used to offer broadband service up to 50km for fixed stations and 3-5 km for mobile stations. WiMAX protocol allows for more efficient bandwidth use, interference avoidance, and is intended to allow higher data rates over longer distances. It provides for both point-to-point connection or point-to-multipoint connection and can easily integrate with Wi-Fi networks. It was first standardized in 2004 [18] with further amendments [19] meant to provide more features. In [20] these features are analyzed and their benefits pointed out. There is also the WiMAX Forum which is an industry-led, not-for-profit making organization formed to certify and promote the compatibility and interoperability of broadband wireless products based upon the harmonized IEEE 802.16/ETSI HiperMAN standard [21]. Other design issues have been addressed to enhance WiMAX network to better support existing and potential services that are crucial for service providers. In particular, proposals have been made to design a new network layer that can efficiently support multi-hop communications in a WiMAX network and that can fully exploit the features of WiMAX while enhancing security [22 - 23]. This technology is illustrated in Figure 7 (source http://docs.cpuc.ca.gov/published/Graphics/45539-12.gif)

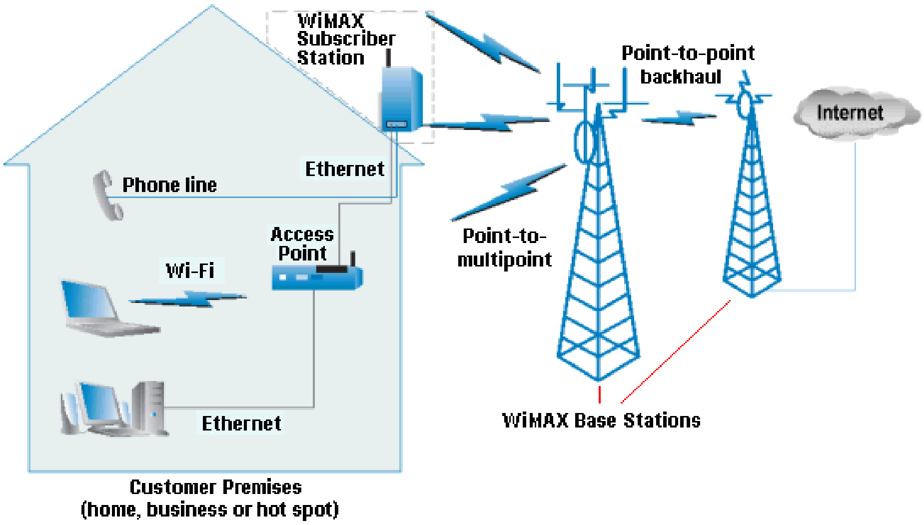


Figure 7: A simple WiMAX network

Chapter 3

3 Fiber Wireless Networks

After looking at both optical access networks and wireless access networks we can say that there is one goal both technologies are intended to fulfill: give end users the much needed bandwidth with ease of accessibility while keeping costs down. Optical networks can provide the required bandwidth but with limited flexibility while wireless networks can offer flexible accessibility for mobile users but with limited bandwidth. We can easily point that the two technologies have eventually met at the access segment and can solve the puzzle of how to satisfy end users bandwidth demands with flexible accessibility. This has eventually evolved into the new access network paradigm called fiber wireless (FiWi) access network.

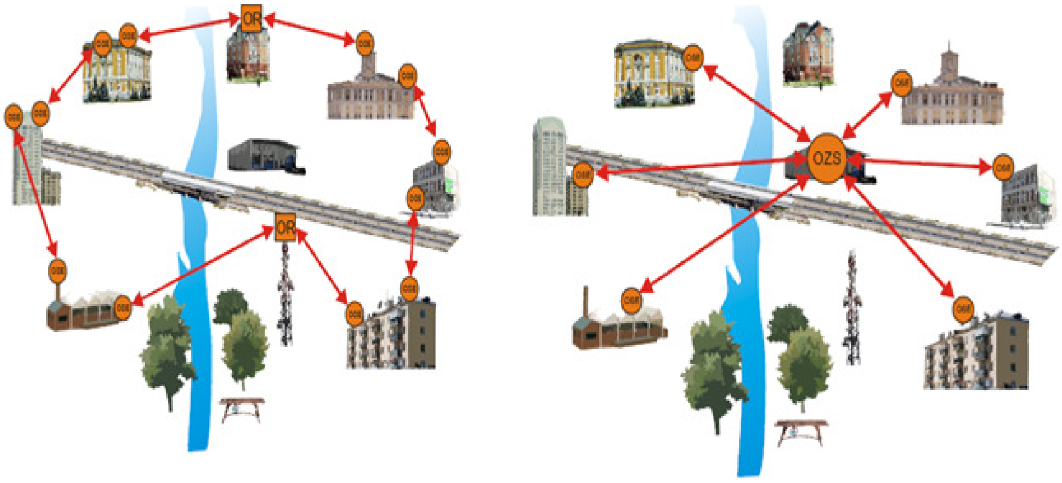
In this paradigm, the optical network is used as the backbone to transport the traffic at the back-end while the wireless network is used at the access level to connect to the end users at the front end. This paradigm offers two scenarios: one is wireless and fiber (W&F) while the other one is referred to as wireless over fiber (WoF).

In the W&F both wireless and fiber technologies are used independently with different management. For interfacing, specific devices such as ONUs are used. This paradigm provides challenges in the network management as services run independently on two distinct networks. On the other hand, WoF promises a different approach where radio frequency signals from the wireless network are inserted into the fiber, using antennas, and transported to the central office in the form of optical signals with no prior processing. The central office acts as the processing center. This offers a centralized approach to management of resources and services unlike the W&F. With this centralized management this paradigm may offer efficient and fair ways of allocating resources within the entire network, it is also cheaper as not very sophisticated antenna are needed. We will look at some of the FiWi architectures proposed in existing literature.

3.1 Fiber Wireless Network Implemented Using Free Space Optics

Free space optics (FSO) consist of an optical transmitter, modulator and telescope for the transmitter end; the receiver end has a detector, decoder and telescope. FSO has been used to provide last mile broadband wireless solution within metropolitan areas. It offers high data rate point-to-point or point-to-multipoint connectivity from the backbone network to the access network for end users. In [24] both ring and star network architectures, implemented using FSO to offer fiber wireless access, have been proposed.

The FSO equipments are installed on roof tops with failure protections to offer high speed network access. Within these architectures an optical repeater (OR) is used in ring topology while optical multipoint units (OZS) are used to act as repeaters in star topology thus improving line of sight transmission of signals. Both architectures are shown in Figure 8 below (source [24]).



(a) Optical Wireless (Ring Architecture)

(b) Optical Wireless (Star Architecture)

Figure 8: FSO wireless architecture

In the star architecture of Figure 8 (b), failure of the OZS might lead to a whole network failure, which can be avoided by having another OZS as a backup even though this might be costly.

The best solution to maximize availability, proposed in [24], is to have a meshed network with both ring and star architectures together. Even though FSO offers high data rates, which is a major step in the last mile effort, it still has some major challenges as shown in [25]. At the access point it can be connected to other wireless technologies, such as Wi-Fi or even WMN, to offer flexible wireless access while on the other end it connects to optical backbone network. FSO can also be used to solve frequency interference in both Wi-Fi and WMN as shown in [26].

3.2 Hybrid Integrated Fiber Wireless Network

This architecture shown in Figure 9, is implemented using Wi-Fi networks to offer access to users and optical network as the backbone. In the proposal of [27], a single fiber optic cable is used to connect to a Wi-Fi network with different wireless access points (WAP). These WAPs offer wireless access to mobile users within the coverage area. The fiber cable forms a ring like topology running from the CO and back to CO. The CO acts as the central point for the network management. It assigns radio frequency to every WAP and also acts like a gateway to other networks.

This architecture is capable of supporting multi-hop relay which is coordinated by the CO using radio control channels. It also supports path diversity where the CO is able to send a similar signal to a mobile user through different WAPs simultaneously, which will allow the intended user to extract data more accurately. Another enhancement on this architecture is the support for multiple services by the same infrastructure such as WLAN and even cellular radio network.

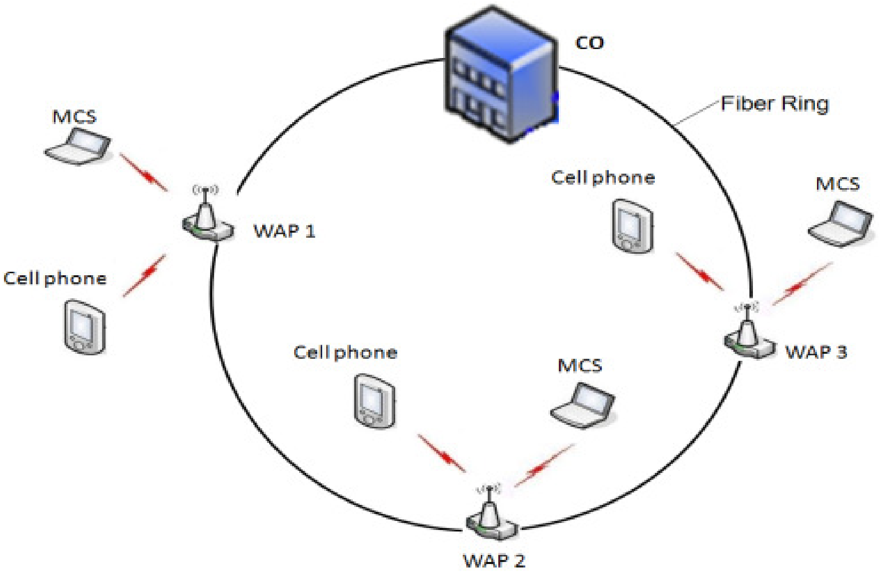


Figure 9: FiWi access network ring topology architecture

In another architecture proposed in [28] and shown in Figure 10, a hybrid FiWi implementation using Wi-Fi networks has been proposed with two-level bidirectional path-protected ring architecture for DWDM/subcarrier multiplexing (SCM) broad-band fiber-wireless access networks.

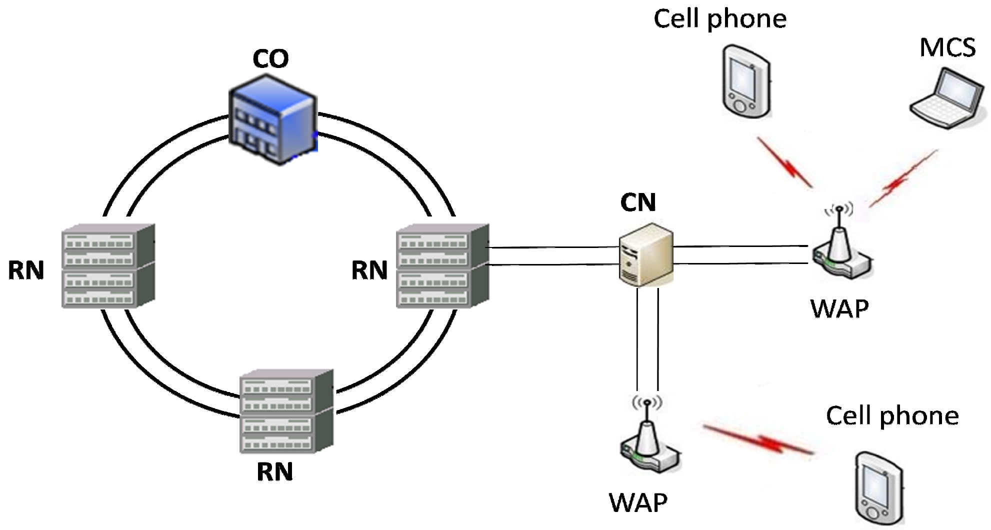


Figure 10: Two-level bidirectional path-protected ring architecture

The CO connects many remote nodes (RN) via a dual-fiber ring. The CO has two devices to offer protection with only one working at a time. Each RN cascades many wireless access points (WAP) through concentration nodes (CN) and the RN has a protection unit; a bidirectional wavelength add/drop multiplexer based on dielectric interference filter. The WAPs allow for wireless attachment of cell phones and mobile client stations (MCS). Due to distributed controllers placed at each RN and CN, this architecture can perform self-healing functions on any link failure.

The other FiWi architecture proposed in [29] is a combination of both star and ring optical networks integrated with Wi-Fi as shown in Figure 11 below.

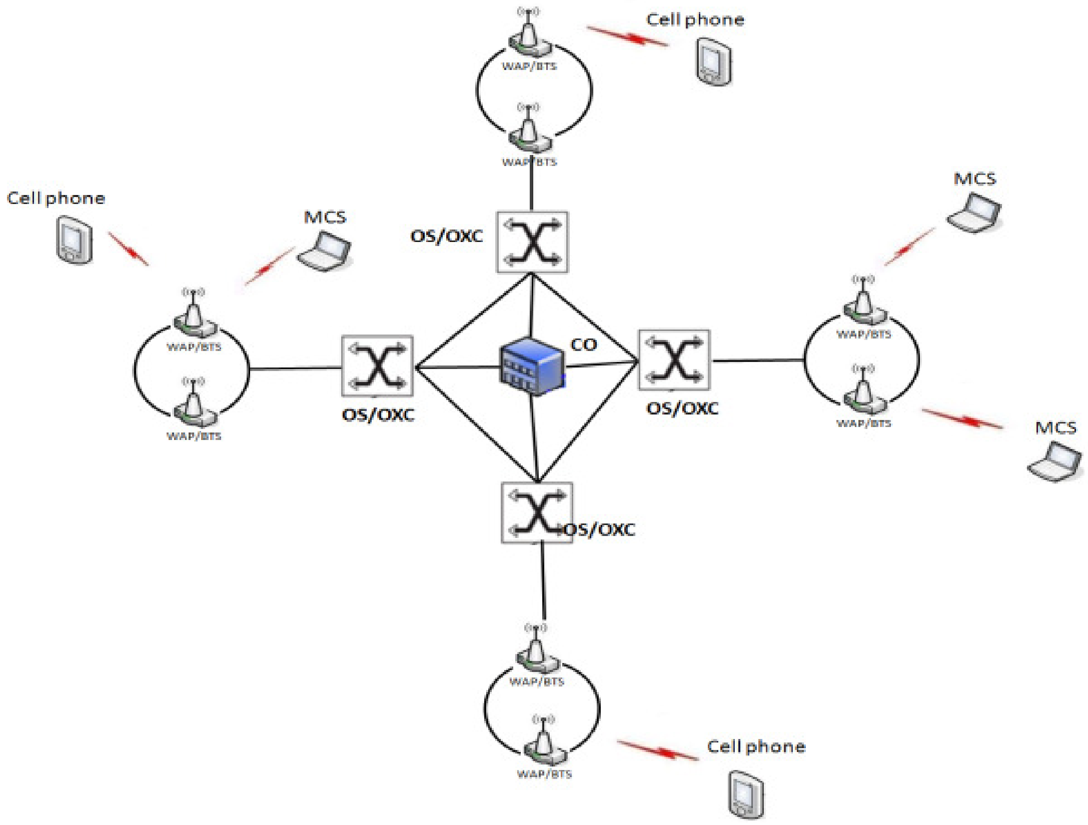


Figure 11: FiWi star-ring access network architecture

This architecture divides the coverage area into sections which are then served by smaller optical rings depending on the traffic. The rings are then connected to CO through optical switches (OS)/OXC using optical fiber. This forms the optical part. The sub rings have either base transceiver stations (BTS) or WAPs to offer wireless access to users. This implementation offers both static and dynamic configuration to meet bandwidth need from the users. The number of BTSs or WAPs depends on the number of transceivers on the OS/OXC and this can be based on traffic demands.

For dynamic configuration, this can be achieved by the use of lightpaths between the BTS/WAP to the OS/OXC and every lightpath has its own wavelength. The lightpaths can either be added or dropped depending on the traffic demand. This architecture exploits the advantages of both ring and star optical networks.

3.3 FiWi Network Implemented Using WMN

In this architecture, as shown in Figure 12, there is an optical fiber ring connecting different optical backhaul nodes to the central office. There are mesh gateway routers (MGR) which are connected to mesh routers (MR) at every backhaul node. The MR provides wireless access to the end users. The optical network based on TDM-PON technology can be implemented using EPON [30].

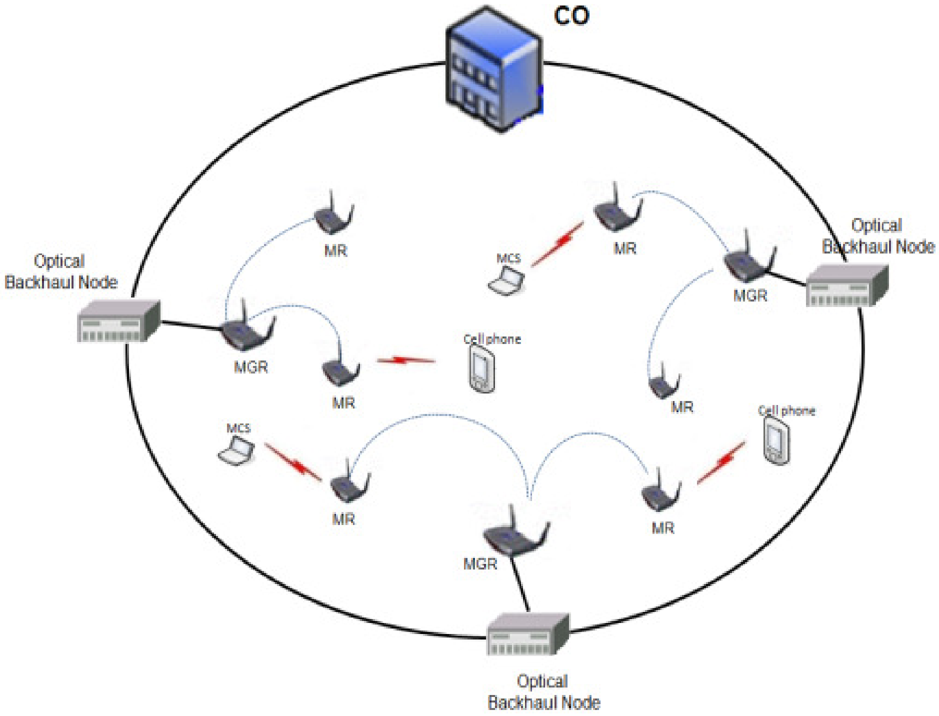


Figure 12: FiWi ring WMN architecture

3.4 FiWi Network Implemented through Integration of EPON and WiMAX

In this architecture we have an integration of both EPON and WiMAX technologies. While WiMAX might suffer from limited wireless spectrum thereby limiting bandwidth capacity to capacity hungry users, EPON offers a broadband feeder with huge capacity to interconnect many wireless access points to the CO. The integration of these technologies can be done in any of the four ways discussed next [31].

3.4.1 Independent Architecture

In this architecture both EPON and WiMAX operate independently where a WiMAX BS is connected to EPON's optics network unit (ONU) through a common interface. The ONU doesn't only serve the BS but also offers FTTH functionality. The main disadvantage with this arrangement is that both ONU and BS do not have full visibility of each other's packet scheduling activities and therefore benefits of the two technologies cannot be fully exploited. The architecture is shown in Figure 13 (source [31])

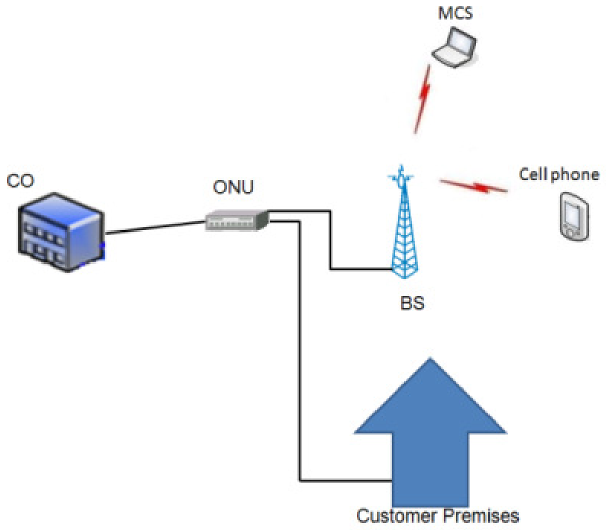


Figure 13: Independent architecture

3.4.2 Hybrid Architecture

In this architecture both the ONU and the BS are merged into one piece of equipment called ONU-BS both in hardware and software. This implementation offers full exploitation of the strength of both technologies and can offer a reduction in equipment costs. The architecture is shown in Figure 14 (source [31])

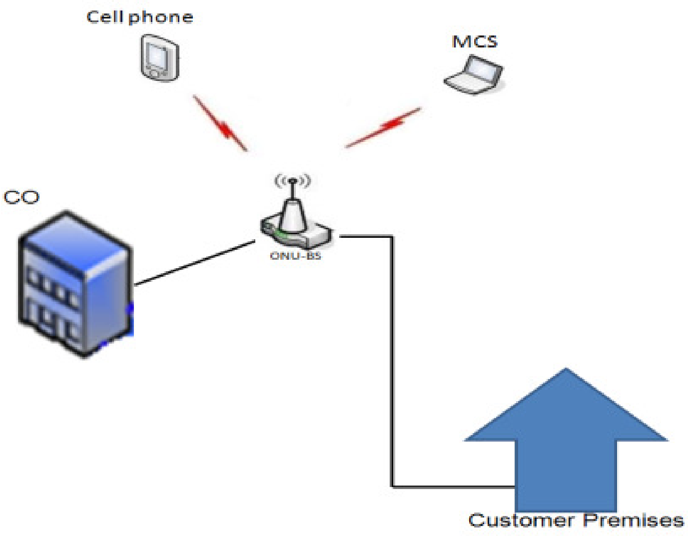


Figure 14: Hybrid architecture

3.4.3 Unified Connection –Oriented Architecture

It has a similar layout as the hybrid architecture with common ONU-BS; the main difference is that the MAC layer protocol of EPON is modified to support connection-oriented services as in WiMAX systems. This will allow the Ethernet frames to be encapsulated as client data in the WiMAX MAC PDUs. It is also viable to adapt a WiMAX network to run the EPON MAC protocols to enable WiMAX devices to operate under the Ethernet technique with unified Ethernet interfaces.

3.4.4 Microwave over Fiber Architecture

This architecture promises to reduce more the cost on the boundary of the EPON and WiMAX systems as well as better utilize the transmission capacity of fiber. In this implementation there are both ONU and BS on remote nodes to carry EPON traffic and WiMAX radio signals respectively. The WiMAX signal is modulated at radio frequency and then both EPON signal and WiMAX modulated signal are multiplexed and modulated on one optical wavelength then transmitted to CO which has OLT and Macro-BS for processing EPON signals and WiMAX signals respectively. The modulation of a WiMAX carrier frequency over an optical frequency is termed microwave-over-fiber.

3.5 FiWi Networks Implemented Using Radio over Fiber

RoF technology deploys two distinct domains into one robust system. It uses fiber optics network to deliver data from central office to remote antenna units (RAUs) which work on radio frequency and relay signals to users within the coverage area. RoF allows for the transmission of modulated radio frequency signals on optical link [32-33]. RoF can be implemented in different topologies as shown in [34].

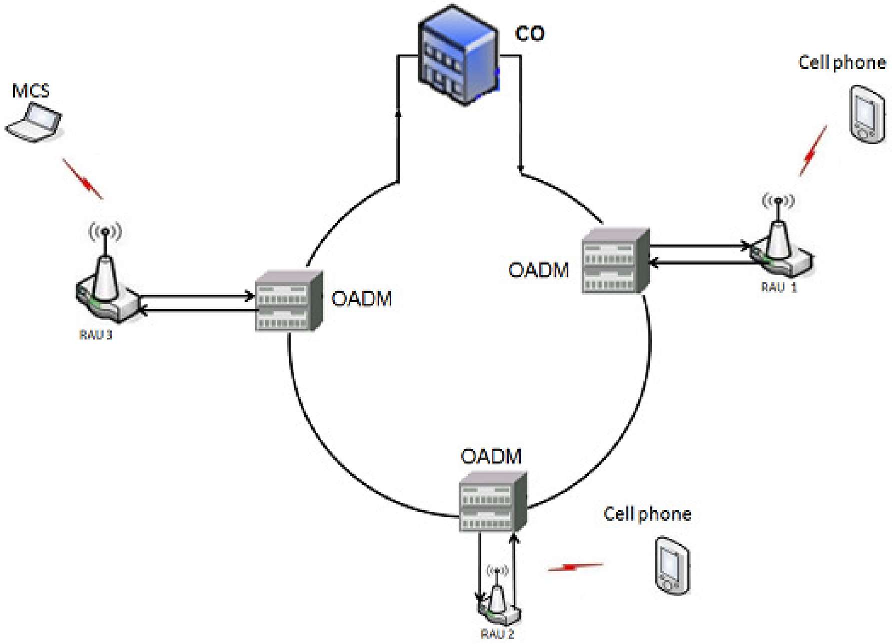


Figure 15: Fiber radio ring network topology

From Figure 15 above which shows a generic RoF ring topology, the CO has WDMs devices for multiplexing and de-multiplexing of the outgoing and incoming wavelengths. At every point we have OADM connected to RAUs. The OADM is to either add / drop wavelength for individual RAUs which offer wireless connectivity to end users through radio frequency signals. Here the CO does all the management functions such as wavelength assignment, multiplexing, carrier modulation, frequency up conversion among others since RAUs just insert radio signals into fiber and no protocol interpretation/translation is required at RAUs. This centralized management offers system simplicity at the RAU level. Other RoF implementations are shown in [35-39].

Chapter 4

4 Adopted Network Architecture and Related RWA Problem

4.1 The Adopted Network Architecture

After looking at some of the existing proposals on FiWi architectures, a network architecture has been adopted whose characteristics and challenges are discussed. This network architecture provides high bandwidth at the access and allows dynamic resource allocation.

As shown in Figure 16, a reconfigurable OXC is integrated at each CO to offer dynamic channel switching, depending on the network traffic at different access points. The COs are connected in a ring topology that will enable them to easily balance processing loads. The ring configuration also allows easy integration with SONET implementations. Rings also have self-healing properties in case of failures, making them attractive for metro and access use.

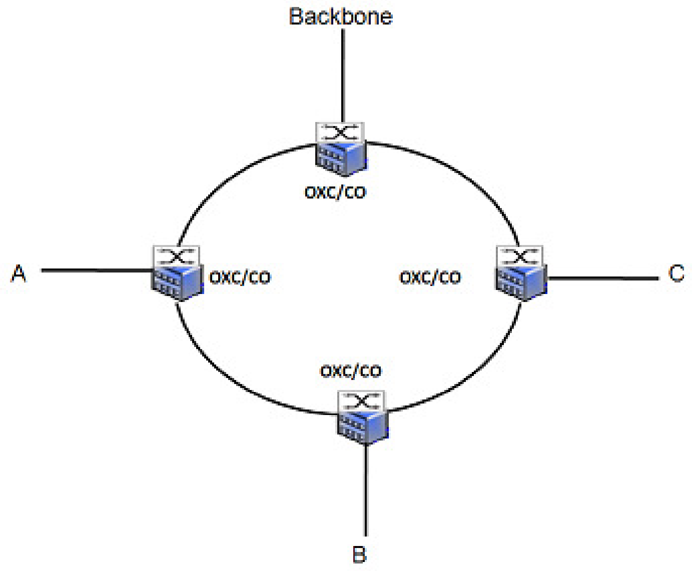


Figure 16: Adopted network architecture: connecting central offices

The letters A, B and C represent connections to rings made up of ROADMs more near the users, shown in Figure 17.

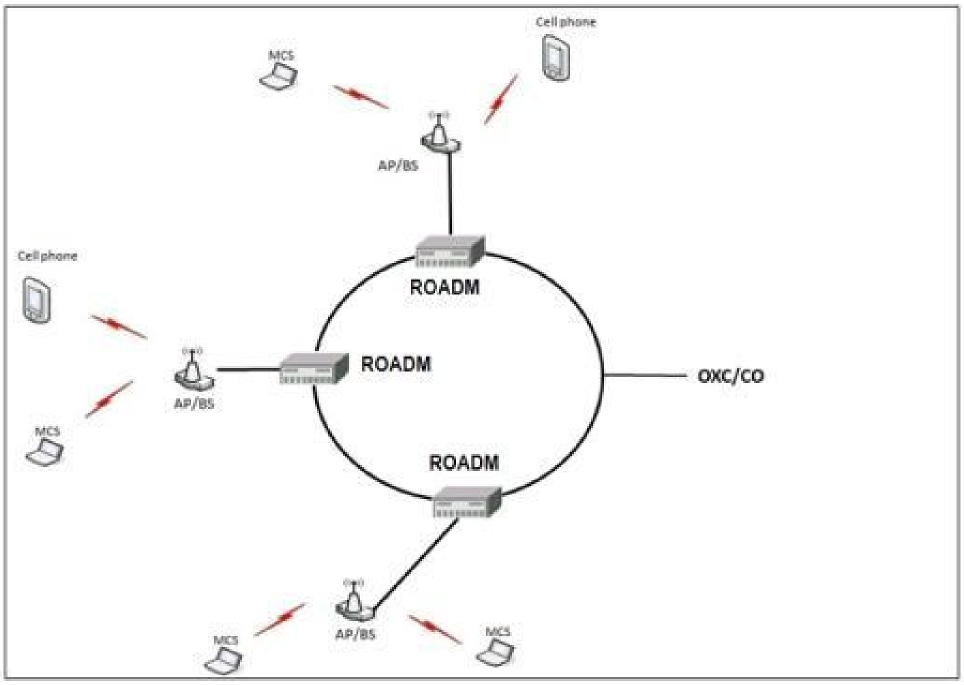


Figure 17: Adopted network topology: the ROADM ring

The use of dynamically reconfigurable OADMs provides flexible insertion and dropping of wavelengths to and from the AP/ BS offering wireless connectivity to end users. Thus the COs form the core part of the network, while the ROADM rings form the access part of the network. The ROADMs offer the connection interfaces to the AP/ BS which acts as the clients' attachment points to the network.

4.1.1 Key Attributes of Reconfigurable Optical Add/Drop Multiplexers

The key attribute of optical bypass in transport networks is the means to implement cost effective multi-point connectivity in DWDM ring or mesh networks without unnecessary O-E-O transitions. An intelligent OADM implements optical bypass with particular benefits in ease of use and deployment, fitting also into existing operational deployment models. Dynamically reconfigurable OADM is seen as the most efficient solution for multi-point metro WDM transport networks. They provide the compelling solution for lowering the cost of metro core and regional networks through extension of transmission distance and for lowering operational costs. They have quickly become the most promising technology on the market by streamlining networks while addressing dynamic traffic [40, 41, 42, 43, 61].

Key attributes for dynamically ROADM solutions include:

- Optical bypass which eliminates intermediate regeneration points and lowers the capital cost of the network compared with multiple point-to-point systems
- Dynamically reconfigurable add/drop eliminates the need for intermediate network touch points for service provisioning, lowers installation and management costs and reduces chances for configuration errors.
- They also perform the fundamental protection techniques of span switching in case of a transmission fiber break and ring switching in the event of an optical equipment failure of a certain node in a ring network architecture. As a result, the dynamic ROADM provides network protection functionality similar to that of the SONET standard, which has been provided only in the electrical domain. This functionality enables the network element intelligence to migrate from the electrical layer to the optical layer, giving way to low-cost, less-complex time-division-multiplexed electronic transmission equipments.

4.1.2 Classification of ROADM Architectures

ROADM architectures can be classified into two categories: i) switching-based architecture and ii) tuning-based architecture [44].

Switching-Based ROADM Architectures

This kind of ROADM, shown in Figure 18, uses switching technology to add/drop traffic. They are implemented through the use of one optical multiplexer and de-multiplexer, switches and tunable transmitters and receivers. The implementation cost is associated with the number of wavelengths in the network and the number of wavelengths that can be added/dropped at the same time. In access networks where small number of wavelengths is added/dropped at a node, switching-based architecture is not cost effective [44].

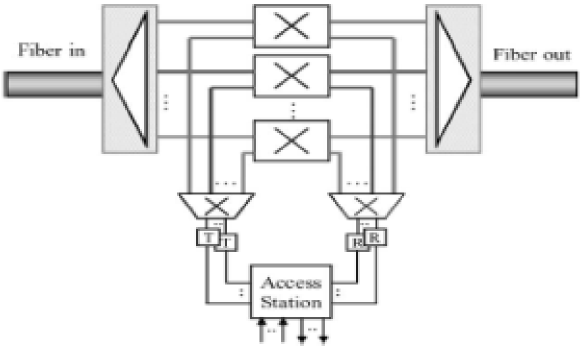


Figure 18: Switching-based ROADM architecture

Tuning-Based Architectures

This ROADM is implemented as shown in Figure 19, where a group of wavelengths come from the incoming fiber, enters circulator C_1 then comes out to the fiber with the tunable fiber bragg gratings (FBGs). Let's take one of the tunable FBGs to be operating on a wavelength, say λ_i, then λ_i will be reflected back to circulator C_1 and dropped to the receivers while all other wavelengths will bypass the FBG. This implements the drop part of the ROADM. To add traffic on λ_i, one of the tunable transmitters transmits traffic on λ_i, which enters circulator C_2 and comes out to the fiber with FBGs. Since one of the tunable FBGs is working on λ_i, λ_i will be reflected back to circulator C_2, and, finally, enter the outgoing fiber, along with all the bypassing wavelengths. If the FBG is tuned to another wavelength λ_j ($i \neq j$), the ROADM will add/drop λ_j instead of λ_i.

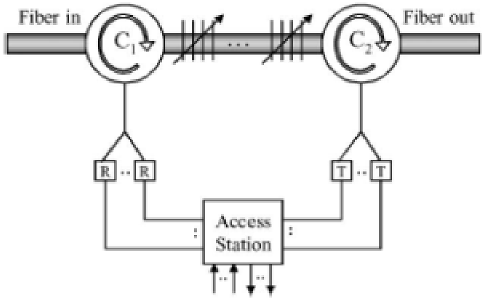


Figure 19: Tuning-based ROADM architecture

This architecture is insensitive to the number of wavelengths in the network; it has better scalability, simpler and cheaper, especially when there are many wavelengths in the network and each node may access only a few wavelengths [44]. Tuning-based ROADMs, each having a set of FGBs, can be used in an access ring topology.

Even though, this architecture is preferred, it has one characteristic that needs better management; it is referred to as *tuning constraint*. That is, when a connection request arrives, the tuning heads of the ROADMs at the source and destination should be tuned to a similar free wavelength before the connection is set up. As the tuning process is virtually continuous, the tuning head will pass through all the wavelengths between the starting and ending position. However, if the tuning process at the source or destination node causes the tuning head to pass through some wavelength carrying existing traffic, it will cause service disruption to the traffic on that wavelength and, in such a scenario, the connection should be blocked since tuning is not possible.

Figure 20 below illustrates the tuning constraint. Let the current positions of the tuning heads of ROADM 1 and ROADM 2, assuming for simplicity a single head per ROADM, be on wavelengths λ_1 and λ_4 respectively and a connection needs to be set up between these two ROADMs. Suppose there is traffic on wavelength λ_3. Since the tuning heads of the ROADMs are on opposite sides of wavelength λ_3, the two ROADMs cannot tune to the same wavelength without crossing wavelength λ_3, so the connection has to be blocked [44]. In the adopted architecture of this thesis, tuning-based devices are used. These devices provide the desired flexibility and enable fast provisioning of dynamic traffic, saving capital expenditure and operational expenditure.

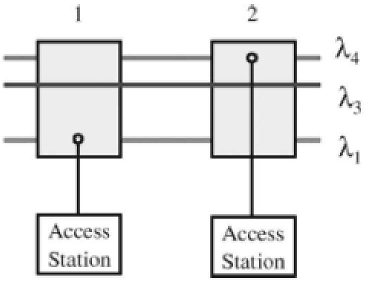


Figure 20: Illustration of tuning constraint

For the scenarios analyzed in this thesis, many heads per ROADM are assumed

4.2 Routing and Wavelength Assignment

The large bandwidth of WDM can be divided into different wavelengths and these wavelengths are the ones used to establish optical connections between pairs of nodes in the network. That is, to establish a connection path, a lightpath must be created from the source node to the destination [45]. These lightpaths can traverse multiple physical links and their formation depends on the availability of wavelengths along the desired path. Given a network, with either links associated with some costs or not, and a set of lightpath requests (connection requests), then the problem of setting up lightpaths by routing and assigning a wavelength to each request is called Routing and Wavelength Assignment (RWA) problem.

RWA attempts to determine an efficient way to establish a route for each lightpath request, and to assign wavelengths to these routes. The objective of the RWA problem is often to minimize the number of wavelengths used, or to maximize the number of successful connections established subject to a limited number of wavelengths, that is to minimize the blocking probability. RWA can be classified into two major categories, namely: static (offline) and dynamic (online). In static RWA, the traffic patterns in the network are reasonably well-known in advance and any traffic variations take place over long time scales. Static RWA is appropriate for provisioning a set of semi permanent connections [60]. In dynamic RWA, connections arrive dynamically over time and during that time the network state plays a very important role. In practical situations the average call arrival follows a Poisson distribution while the average holding time for every request follows an exponential distribution. With these informations, then the RWA algorithm should be able to check the network status before execution and to update network status after execution. A connection can be blocked when there is no route or wavelengths along the desired path. Note that when wavelength converters are not available at intermediate nodes, the same wavelength must be available along all the route links. This is the case assumed in this thesis as wavelength converters are still expensive.

4.3 State of the Art

So many approaches have been proposed to solve RWA problems as shown in [46, 47, 48, 49]. In most cases the RWA problem is divided into two sub problems: routing sub problem and wavelength assignment sub problem. The routing sub problem can either be static, where the route is pre-determined and adaptive where the route it determined dynamically as the connection requests arrive at the nodes. In ring networks, like the one assumed in this work, choosing a route implies choosing to go right or left and usually the shortest path is used.

The wavelength assignment sub problem can also be solved either through offline or online strategies similar to routing problem. Some of the wavelength assignment heuristics discussed in literature, considering the wavelength continuity constraint, are:

- **Random Wavelength Assignment (R).** This scheme determines free wavelengths on the desired route then chooses one of the available wavelengths at random. The probability of choosing any wavelength is uniform. R-WA tends to ensure fairness as wavelength usage is balanced due to random distribution of traffic.
- **First-Fit (FF).** In this scheme the wavelengths are indexed, to assign a wavelength the lower indexed wavelengths are considered first in the list of free wavelengths. Since it favors low indexed wavelengths, the high indexed wavelengths will always have low utilization rate. The main advantage of this scheme is that it does not require global information and compared to Random scheme, it has low computational cost due to low complexity and low overhead.
- **Least-Used (LU)/SPREAD.** LU selects the wavelength that is the least used in the network in order to try to balance the load among all the wavelengths. This scheme ends up breaking the long wavelength paths quickly; hence, only connection requests that traverse a small number of links will be serviced in the network. The performance of LU is worse than Random, while also introducing additional communication overhead (global information is required to compute the least-used wavelength). The scheme also requires additional storage and computation cost; thus, LU is not preferred in practice.
- **Most-Used (MU)/PACK.** This strategy attempts to select the most-used wavelength in the network. That is, the free wavelength that is used on the greatest number of links in the network is assigned to the request. It outperforms LU significantly [50] and FF slightly, as it seeks to establish connections with few wavelengths while maintaining idle capacity of wavelengths less used and these wavelengths can be used for connections

with longer routes. The communication overhead, storage, and computation cost are all similar to those in LU.

Tuning constraint for the tuning-based ROADM architecture was first introduced in [44], where its impact on online connection provisioning has been investigated. Different heuristics are also proposed to help solve the tuning constraint problem. The researchers found out that tuning constraint has a severe impact on the network performance and have recommended for more research work to develop more efficient heuristics for performance improvement and the importance of knowing the optimal number of tuning heads per node in terms of network performance and cost. Other previous work, addressing the RWA problem in architectures with tuning-based devices, is not known.

In this work, a heuristic will be proposed to solve the RWA problem by taking into account wavelength continuity on a route and network load status at the wavelength level. This work will address the issue of network performance when using tuning-based ROADM architecture, analyze how the number of tuning heads per node affects network performance and try to determine the trade off on cost and performance when deploying tuning-based ROADMs in the network.

Chapter 5

5 Proposed Routing and Wavelength Assignment Algorithm

Wavelength is a very vital resource in optical networks and its management determines network efficiency and the overall throughput. Also, heuristic approaches typically use special knowledge about the domain of the problem being represented by a graph to improve the computational efficiency of solutions to particular graph-searching problems [51]. Having these aspects in mind, a heuristic algorithm has been proposed to solve the RWA problem that takes into consideration the particularities of the adopted access network architecture. For ease of tackling, the RWA problem has been divided into two parts: i) routing sub-problem and ii) wavelength assignment sub-problem.

5.1 Routing Sub-Problem

In solving the routing sub-problem the A star algorithm is used to determine the best route to use when a request arrives in the network. This is dynamic and always takes the status of the network into consideration before assigning a route for any connection request.

5.1.1 A Star Algorithm

Even though this algorithm has majorly been used in path finding applications such as games, it can equally be applied in network routing problems. The A star Algorithm (A*) combines both Dijkstra and Best-First (BF) search algorithms. The Dijkstra algorithm is guaranteed to find a shortest path from the starting point to the goal (destination), as long as none of the edges have a negative cost, while the BF algorithm works in a similar way, except that it has some estimate (*heuristic*) of how far from the destination a given vertex (node) is. Instead of selecting the vertex closest to the starting point, it selects the vertex closest to the goal. BF search algorithm is not guaranteed to find the cheapest/least expensive path. However, it runs much quicker than Dijkstra algorithm because it uses the heuristic function to guide its way towards the goal very quickly. This is a very important issue under dynamic traffic scenarios, especially in the access where demands can arrive quite frequently.

A* Algorithm combines the pieces of information that Dijkstra algorithm uses (favoring vertices that are close to the starting point) and information that BF search uses (favoring vertices that are close to the goal), also avoiding the shortest path from becoming overloaded (over utilized).

It has three main properties:

- It may return the least expensive path if a path exists to the destination, other algorithms may find a path faster but it is not necessarily the "best".
- It uses a heuristic (a "guess") to search nodes considered more likely to lead to the destination first, allowing us to find the best path without having to search the entire network and making the algorithm much faster.
- It is also based on the idea that each node has some cost associated with it. If the costs for all nodes are the same then the best path returned by A* will also be the shortest path but A* can easily allow us to add more intelligence taking into account different network status in evaluating and assigning costs to the nodes.

Suppose the network is represented as a graph $G(V, E)$, the vertices V will be the nodes while the edges E will be links between the nodes.

So let:

- $\mathrm{g}(v)$ be a function representing the cost of the path from the starting point to any vertex $v \in V$
- $\mathrm{h}(v)$ be a function representing the heuristic estimated cost from vertex $v \in V$ to the goal (goal is when the final destination is reached).
- Then the objective function will be $\mathrm{f}(v) = \mathrm{g}(v) + \mathrm{h}(v)$, which during the algorithm steps must be kept minimum.

The general pseudo code of the A* Algorithm

The A* algorithm maintains two lists of nodes: CLOSED and OPEN. OPEN is sorted in ascending order of the evaluation function f() and contains nodes (vertices) which their function f() value can still change and are yet to be considered as candidate nodes to be included in the path. The CLOSED list has nodes which their function f() value will not change and have been considered as part of the desired path. The algorithm repeatedly picks nodes from the top of the OPEN list and checks if the node picked is the final destination. If this is not the case, it generates its neighboring nodes and calculates their f() value unless the node is already in the CLOSED list. When there is a tie in the f() values of neighboring nodes then both nodes have the same probability of being sorted in the OPEN list. The algorithm terminates when the destination node is added to the CLOSED list or when the OPEN list is empty. That is, no route/path to the desired destination exists [55, 56, 57,59].

Algorithm

1) Create two empty lists (open and closed lists)
2) Add the starting vertex v (node) to the open list.
3) Repeat the following:
    a) Look for the node with the lowest $f(v)$ cost on the open list. We refer to this as the current node.
        - v= current node
    b) Move v to the closed list.
    c) Get neighbor nodes of the current node v
    d) For each of the neighbors of v do
        - If it is on the closed list, ignore it. Otherwise do the following
            - If it is on the open list, check to see if the path from the source to that neighbor is better, using $f(v)$ cost as the measure. A lower $f(v)$ cost means that this is a better path. If so, change the $f(v)$ cost and parent of the neighbor to the current node v.
            - Else if it isn't on the open list, add it to the open list. Make v the parent of this neighbor. Record the $f(v)$, $g(v)$, and $h(v)$ costs of the neighbor.
    e) Stop when:
        - the goal node is added to the closed list or
        - the open list is empty.

4) Save the path. Working backwards from the goal node, go from each node to its parent node until you reach the starting node. That is the path.

5.1.2 Heuristic Applied to the Adopted FiWi Access Network Architecture

When using A* algorithm, the heuristic function may be chosen based on multiple criterions, for example, the minimum distance (or the minimum hops), the link-state, the power saving, the quality of service, wavelength availability among other constraints [52]. In the adopted FiWi access network architecture, network load and continuous availability of wavelengths will be used as criterions for route selection.

Let Figure 21 below represent a ring graph example of the adopted network architecture with ROADMs marked 1, 2 and 3 and the CO. Connection requests can originate from any node in the network and can terminate in any node.

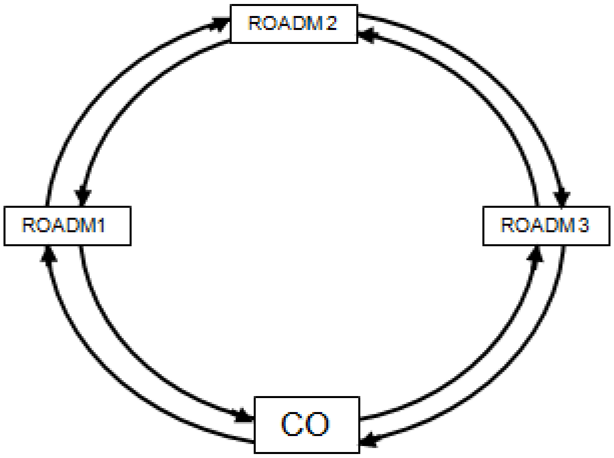


Figure 21: Ring graph example of the adopted network architecture

Considering Figure 21, the network graph shall be denoted by $G = (V, E)$ where V is the set of vertices (nodes) and E is the set of edges (links). The number of elements in these sets are given by $|V|$ and $|E|$ respectively. The adopted network has two links between adjacent nodes, one for upstream and the other for downstream transmission. That is two links $e_i = \{v \rightarrow v'\}$ and $e_j = \{v' \rightarrow v\}$, having same end nodes, will be used for transmission in both directions. The wavelength availability at some link e_i is stored in a vector,

$$\boldsymbol{\lambda}^{e_i} = \left[\lambda_1^{e_i}, \lambda_2^{e_i}, \dots, \lambda_{|W|}^{e_i}\right], \forall\, e_i \in E \ , \tag{1}$$

where W is the set of usable wavelengths in the network, $\lambda_w^{e_i} = 0$ if wavelength $w \in W$ is not available on link e_i and $\lambda_w^{e_i} = 1$ otherwise available.

Let the number of connections in the network be C_N and the average number of hops per connection be H_c. Therefore, the network load at a particular time will be given by:

$$\rho_N = \frac{C_N H_c}{|E||W|} \tag{2}$$

We can see $1 - \rho_N$ as an approximation for the probability of finding a specific wavelength free on a particular link $e_i \in E$ of the network.

Formulation of the heuristic $\mathrm{h}(v)$

Suppose a connection c has $s(c)$ and $d(c)$ as source and destination nodes, respectively. Let Z be a connected series of links, such that $Z\colon v \in V \rightarrow \cdots \rightarrow d(c) \in V$, where v and $d(c)$ are the intermediate and destination nodes of the connection, respectively. The heuristic $\mathrm{h}(v)$, will estimate an approximation for the probability of finding a free continuous wavelength from node v until the destination node. Suppose ϕ is the total number of wavelengths continuously available from source until node v, therefore the estimated cost $\mathrm{h}(v)$ will be given by:

$$\mathrm{h}(v) = \frac{1}{\phi(1 - \rho_N)^{|Z|}} \tag{3}$$

The lower part of expression (3) is an approximation for the probability of finding wavelengths, that were available from $s(c)$ to node v, still free when destination node is reached. The higher this probability is the lower the cost will be.

Note that in meshed networks, $|Z|$ can be used as the maximum number of hops from node v until the destination node. This value can be pre-computed in advance, not adding overhead to the algorithm.

Formulation of the function $\mathrm{g}(v)$

Suppose $\mathcal{P}$ is a connected series of links, such that $\mathcal{P}: s(c) \in V \rightarrow \cdots \rightarrow v \in V$, where $s(c)$ and v are source and intermediate nodes of the connection, respectively. The cost of using the links in $\mathcal{P}$ will be summation cost of using each individual link in the series of links. This summation cost will be denoted by $\mathrm{g}(v)$. In order to determine the right cost that should be associated with network links, let H_{max} be the maximum number of hops that might eventually be used when establishing the connection c from source node $s(c)$ until destination node $d(c)$, which can also be pre-computed. The cost associated with any link $e_i \in E$ will be given by:

$$\mathrm{C}(e_i) = \frac{1}{\left(\frac{|W||E| - C_N H_c}{|E|}\right)\left(\frac{(1-\rho_N)^{H_{max}}}{H_{max}}\right)} \tag{4}$$

While $(1-\rho_N)^{H_{max}}$ is an approximation for the probability of finding a specific wavelength available in the largest possible route from source node to destination node, $\frac{(1-\rho_N)^{H_{max}}}{H_{max}}$ will be per hop related approximation value. When multiplied by $\frac{|W||E|-C_N H_c}{|E|}$, we get a per link approximation value that takes into consideration the current availability of wavelengths at links, therefore approximating the $\mathrm{h}(v)$ and $\mathrm{g}(v)$ scales.

Therefore,

$$\mathrm{g}(v) = \sum_{e_i \in \mathcal{P}} \mathrm{C}(e_i) \tag{5}$$

After determining both $\mathrm{g}(v)$ and $\mathrm{h}(v)$ functions, then the objective function $\mathrm{f}(v)$ will be given by the summation of the two functions in equations (5) and (3).

$$\mathrm{f}(v) = \mathrm{g}(v) + \mathrm{h}(v) \tag{6}$$

Below is the implementation pseudo-code for the routing functionality.

Routing Pseudo-code

```
Routine: Routing Computation
Inputs: Open_List,Closed_List,source_node,destination_node
Outputs: Final_Cost_List,Path_List
****************************************************************************************
Explanations of Inputs and Outputs                                                     *
Open_List:List of nodes to be visited which are sorted from the least interms of their cost.     *
Closed_List:List of nodes which have already been visited  and will not be visited again.     *
source_node: Is the node which the connection starts.                                  *
destination_node: The node which the connection terminates.                            *
Path_List: Contains the route from source node to destination node.                    *
Final_Cost_List: Contains the f(v) values for every node and candidate nodes to be used in path   *
                                  construction .                                       *
****************************************************************************************
Empty (Closed_List)
Empty (Open_List)
Empty (Final_Cost_List)
Empty (Path_List)
Open_List  <- source_node
WHILE !Empty(Open_List)
        current_node = Remove(Top_Element(Open_List))
        IF (current_node == destination_node)
                Path_List = PathConstruction(Final_Cost_List,current_node)
                RETURN (Path_List)
        ELSE
                Closed_List  <- current_node
                Neighbor_List = GenerateNeighborNodes(current_node)
                FOREACH neighbor_node IN (Neighbor_Node_List)
                        IF  neighbor_node !IN (Closed_list)
                                current_G_cost = GetCommulativeGCost(current_node,neighbor_node)
                                heuristic_cost = ComputeHeuristicCost(neighbor_node,destination_node)
                                final_cost = current_G_cost + heuristic_cost
                                Final_Cost_List <- UpdateFinalCost(current_node,neighbor_node,final_cost)
                        END IF
                END FOREACH
        END IF
        Open_List <- UpdateOpenList(Final_Cost_List)
END WHILE
RETURN ("No path Found")
```

5.2 Wavelength Assignment Sub-Problem

In the previous section, only the route has been determined and specific wavelength has not been chosen. In the wavelength assignment sub-problem, there are three issues to be tackled: Wavelength Assignment (WA), ROADM tuning head Assignment (RA) and re-parking of free ROADM tuning heads. WA deals with choosing the wavelength to be assigned for a connection, RA deals with choosing a head at (source and/or destination nodes) to be tuned to the chosen wavelength, without causing interference on already established connections, and re-parking of ROADM tuning heads ensures that the free heads, on every node in the network, are re-parked before establishing a connection in such a way that the probability of not blocking a future connection is increased. Re-parking depends on how the tuning ranges of the free heads will be affected by the current connection. This phenomenon is discussed in details here after. The first two issues are related in that, after choosing the wavelength to be used for a connection, there is need to determine which parked head at the source node or/and the destination node should be tuned to the chosen wavelength in-order to set up connection, as there may be more than one head available at the source/destination node. In wavelength assignment, the most used wavelength assignment strategy is implemented, this is because it has been shown to be giving better results when compared to other wavelength assignment strategies [50]. In head assignment, the head which will least affect the tuning range of other heads will be selected for tuning. To illustrate the concept of tuning range, ROADM tuning head re-parking will be analysed first.

5.2.1 ROADM Tuning Head Re-parking

As mentioned earlier, initially all the ROADM heads will be parked randomly. As more connections arrive into the network, there is need to have a strategy which minimizes the possibility of future connections being blocked due to tuning constraint. To achieve this, the tuning range of every head will be analysed. Tuning Range (TR) is the set of all positions to which a tuning head can be parked to without interference with already established connections. At the beginning, this set has $2 * |W| + 1$ positions. That is, initially all the head parking positions are available and the TR size is given by:

$$TR\ Size = 2 * |W| + 1, \tag{7}$$

where $|W|$ is the total number of wavelengths in the network. This is because parking can be done at any wavelength, between two consecutive wavelengths or below/above the first/last wavelength on the wavelength range.

As connection requests arrive to the network and are established, the TR of tuning heads might be redefined and most likely will reduce as the nodes might have different bypassing traffic on different wavelengths. When a connection terminates, the affected tuning heads will have their tuning ranges expanded. Figure 22 below illustrates the changes in TR.

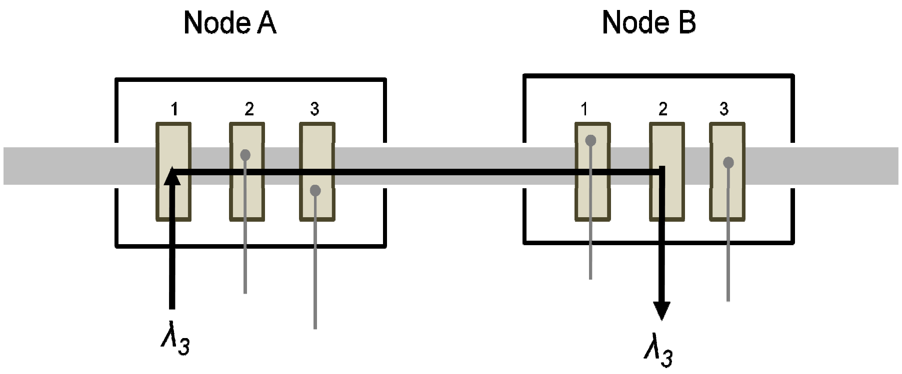


Figure 22: A simple illustration of tuning range

Let the position of head k within a particular node/ROADM r, be denoted by p_k^r**.** Therefore the parking head positions in node/ROADM r will be represented by a vector $\boldsymbol{p}^r$ such that,

$$\boldsymbol{p}^r = [p_1^r, p_2^r, \dots, p_{|H|}^r], \tag{8}$$

where H is the set of tuning heads which can be adjusted voluntarily and r is the node/ROADM number.

Suppose nodes A and B are part of a ring network, each having three tunable heads marked 1, 2 and 3. Suppose there are four wavelengths marked as $\lambda_1 - \lambda_4$ in the network and there is a connection c_1 from node A to node B established at head 1 in node A and head 2 in node B, these heads being tuned to positions p_1^A and p_2^B, which is λ_3 . As shown in Figure 23 above, then other heads parked at positions p_2^A , p_3^A, p_1^B and p_3^B are still free. Initially, before the connection c_1 is set, the TR for all the tuning heads is the same, that is $2 * |W| + 1 = 2 * 4 + 1 = 9$. After the connection establishment all the free heads apart from p_3^B will be bypassed by the connection c_1 and therefore their new parking positions can either be below or above λ_3 . According to the decision of re-parking the head above or below λ_3, a new TR with size smaller than 9, will become available. For the tuning head 3 in node B parked at position p_3^B which is not bypassed by the connection c_1 , its TR still remains the same and is unaffected.

When the connection is terminated, the TR of the affected heads change and therefore need to be determined again. The decision on how to re-park the tuning heads according to tuning ranges before a connection set-up, may potentially have significant impact on the solution for future connections. In order to reduce the probability of blocking a future connection due to tuning constraint, the tuning heads whose tuning ranges have been affected by the current connection (either in source, intermediate or destination node) need to be carefully re-parked before setting up the current connection, and tuning ranges need to be computed again when the connection terminates, so that future connection requests have a smaller probability of being blocked.

The adopted approach for head re-parking, executed before a connection is established, is to be applied to all available heads at nodes traversed by the connection, source and destinations nodes included. Their tuning ranges will be determined and the larger tuning range is chosen when parking the free tuning heads within the nodes. The determination of the new tuning ranges will depend on how the connection to be established divides the whole tuning range in that node. For example, as shown in Figure 22, head 2 in node A will have its tuning range divided in to two sets of 3 and 6 parking positions respectively. So, before the connection is established, head 2 in node A should be parked at any position on the larger tuning range excluding the chosen wavelength position. Similar re-parking approach should be applied to all tuning heads whose tuning ranges have been affected by this connection.

5.2.2 Wavelength and ROADM Tuning-Head Assignment

In the implementation of this functionality, for every link on the route, free continuous wavelengths are identified and then the most used wavelength in the network will be assigned to the connection. By continuous we mean that the chosen wavelength must meet the *wavelength continuity constraint,* where a common wavelength is used on every link on the specified route.

In determining the most used wavelength in the network, wavelength utilization on every link in the network will be analysed as it is necessary to determine how many links are being used by each wavelength. So let $\mathbf{\Psi} = \left[\psi^1, \psi^2, \ldots, \psi^{|W|}\right]$ be a wavelength utilization vector, where

$$\psi^w = \sum_{i=1}^{|E|} \boldsymbol{\lambda}^{e_i}\left[\lambda_w^{e_i}\right], \forall\, w \in \{1,2,\ldots,|W|\} \tag{9}$$

That is, ψ^w will give the total number of links with wavelength w not available in the network. Therefore, the most used wavelength will be given by:

$$w_{max} = \underset{w \in \{1,2,\ldots,|W|\}}{\arg\max} \{\psi^w\} \tag{10}$$

Whenever the most used wavelength is not free on the route, the subsequent most used wavelengths will be tried until an available wavelength is found; otherwise the connection will be blocked. The same procedure will be performed when the chosen wavelength does not allow for head tuning.

After choosing the right wavelength, a parked head will also be chosen for tuning to that wavelength. Assuming that, after a connection arrival, the direction of the connection is identified (clockwise/anti-clockwise), by the route computation approach previously discussed, then choosing the head to tune will be done as follows:

i) The tuning heads in each node are numbered/indexed in a clockwise direction (ascending order).

ii) If the direction of the connection is clockwise, the head to be chosen at the source node will be the one with the highest index, while the head to be chosen at the destination node will be the one with the lowest index. Tuning at the source/destination node will only happen if the connection starts/terminates at a ROADM node, otherwise it will not be necessary. As shown in Figure 23 below, suppose node A is the source node, node B is the destination node and both nodes are ROADMs. Then, by tuning head 3 at node A to the selected wavelength, the tuning ranges for both heads 1 and 2 at node A are not affected. At node B, when head 1 is tuned to the selected wavelength, then again tuning ranges for heads 2 and 3 will not be affected as the connection does not bypass any of them.

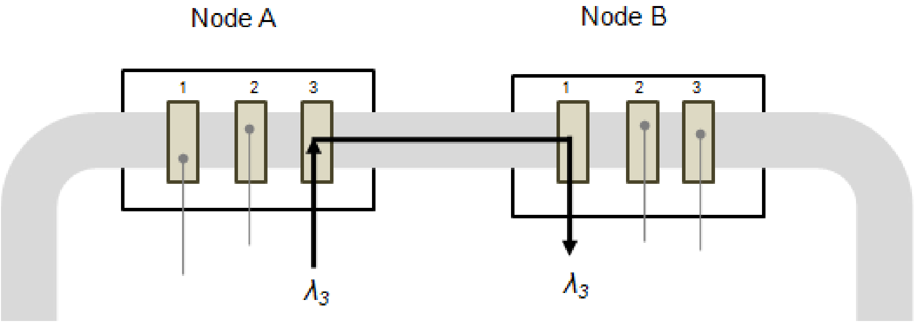


Figure 23: Clockwise direction head assignment

iii) If the direction of connection is anti-clockwise, the head to be chosen at the source node will the one with the lowest index, while the head to be chosen at the destination node will be one with the highest index. This will depend on whether the source/destination node is a ROADM node; otherwise it will not be required. In Figure 24, suppose the connection is from node B (source node) to node A (destination node). Then, head 1 will be tuned at node B while head 3 will be tuned at node A. By doing this the tuning ranges of heads not bypassed by the connection are not affected.

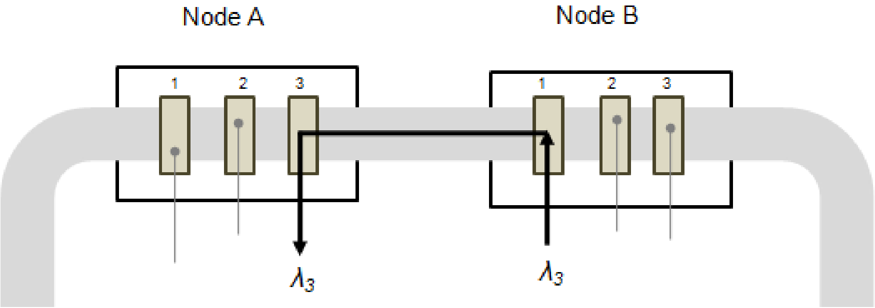


Figure 24: Anti-clockwise direction head assignment

In a case where the last /first indexed heads are not free, the subsequent heads will be tried until a free head is found; otherwise the connection will be blocked (tuning not possible). After the right head has been selected for tuning then re-parking of other heads, whose tuning ranges might be affected by this connection, is done before the heads are tuned to the chosen wavelength. On termination of a connection, re-parking will not be done but the tuning heads whose tuning ranges were affected by this particular connection will be determined and their tuning ranges adjusted accordingly. As for the tuning heads which were assigned to the terminated connection, their parking position will be at the position of the wavelength on which they were previously tuned to. The wavelength that was assigned to the connection will also be returned to the free wavelength pool for future assignment.

Since only the tuning range of the affected heads will be redefined and not all heads at a node, the tuning-head assignment strategy will have a reduced computational overhead.

Wavelength Assignment Pseudo-code

```
Routine: Wavelength and Tuning Head Assignment
Inputs: Path_List,Wavelength_Matrix,source_node,destination_node,Head_Parking_Positions_List,Wavelength_Utilization_List
Outputs: wavelength_to_assign,Heads_To_Assign_List,Head_Parking_Positions_List,Wavelength_Matrix
****************************************************************************************************
Explanations of Inputs and Outputs                                                                 *
Path_List:List of nodes visited in the form of links connection ie "node1-node2".                  *
Wavelength_Matrix: Contains the network wavelength either being used (0) or free (1).              *
Wavelength_Utilization_List: It contains a list of wavelength sorted in ascending order from the   *
                             the most used to the least used in the whole network.                 *
wavelength_to_assign: Is the Wavelength on which a connection will be established.                 *
Common_Wavelength_List: Contains the wavelengths that are common along a given path and are free.  *
Head_Parking_Positions_List: Contains the parking position for every head in every node.           *
Heads_To_Assign_List: Contains the heads to be used in establishing a connection.                  *
source_node: Is the node from which the connection starts.                                         *
destination_node: The node to which the connection terminates.                                     *
Free_Wavelengths_on_Link: Contains the free available wavelengths on a link.                       *
link: This is the edge connecting any two adjacent nodes.                                          *
****************************************************************************************************
EMPTY(Common_Wavelength_List)
EMPTY(Free_Wavelengths_on_Link)
FOREACH link IN (Path_List)
        Free_Wavelengths_on_Link  = GetFreeWavelengths(link)
        IF EMPTY(Free_Wavelengths_on_Link)
                RETURN ("Connection blocked, No wavelength on link")
                BREAK FOREACH
        ELSE
                IF EMPTY(Common_Wavelength_List)
                        Common_Wavelength_List = Free_Wavelengths_on_Link
                ELSE
                        Common_Wavelength_List = WavelengthContinuityChecker(Free_Wavelengths_on_Link,Common_Wavelength_List)
                        IF EMPTY (Common_Wavelength_List)
                                RETURN ("Connection blocked, Wavelength contuinity not possible")
                                BREAK FOREACH
                        END IF
                END IF
        END IF
END FOREACH
FOREACH wavelength IN (Wavelength_Utilization_List)
        IF wavelength IN (Common_Wavelength_List)
                wavelength_to_assign = wavelength
                Heads_To_Assign_List = HeadAssignment(wavelength_to_assign,source_node,destination_node,
                                       Head_Parking_Positions_List)
                IF EMPTY (Heads_To_Assign_List)
                        RETURN ("Connection blocked, Head tuning not possible")
                        BREAK FOREACH
                ELSE
                        Head_Parking_Positions_List = ReparkAndUpdateTuningHeadsPositions(wavelength_to_assign,source_node,
                                                      destination_node,Heads_To_Assign_List,Head_Parking_Positions_List)
                        Wavelength_Matrix = UpdateWavelengthMatrix(wavelength_to_assign,Wavelength_Matrix,Path_List)
                        RETURN (wavelength_to_assign,Heads_To_Assign_List,Head_Parking_Positions_List,Wavelength_Matrix)
                END IF
                BREAK FOREACH
        END IF
END FOREACH
```

Chapter 6

6 Performance Analysis

The implementation of the algorithm and simulations were done using Perl language, where functions were developed to simulate inter-arrival times, holding time, routing and wavelength assignment functionalities. Both the inter-arrival time (IAT) and the holding time (HT) follow exponential distributions [53]. In all simulations, the average HT is set to 180 seconds since this is the average HT used, in general, by many businesses [54]. A connection request can originate from any node and can also terminate at any node in the network. Uniform distribution is used when selecting source and destination nodes of connections.

The proposed A* based algorithm will be run, for each connection request, to identify an appropriate route from source to destination. Then, wavelength assignment, tuning head re-parking and tuning head assignment will be done as shown in previous sections. A connection can be blocked when there is no free continuous wavelength from source to destination node or when tuning of the free ROADM heads at source node or/and destination node to the chosen wavelength is not possible. The final output of the simulations is the ratio of blocked connection requests to the total number of connection request that arrive to the network. This is the blocking probability. The adopted constant parameters used during the simulations are shown in Table 1.

Parameter	**Value**
Number of wavelengths (W)	16
Maximum tuning range size	2 * W + 1
Number of requests	10000
Average HT	180
Number of nodes in the ring	20

Table 1: Simulation constant parameters

Other parameters used were: the number of tunable heads per ROADM and the average IAT. These two parameters were not constant and different values were used for different simulations, as shown in Table 2.

Parameter	Value
Number of tunable heads per node	4,6,8,10,12,14 and 16
Average IAT	70,60,50,40,30,20 and 10

Table 2: Simulation non-constant parameters

The network adopted for all simulations has a ring topology with twenty nodes (19- ROADM nodes and 1- CO node). The network has two links between adjacent (neighbor) nodes, one for upstream and the other for downstream transmission.

The performance of the proposed routing and wavelength assignment strategies will now be evaluated. While the number of wavelengths was kept constant for all simulations done, different values for the number of tuning heads in the ROADMs and traffic load (offered load measured as Average HT divided by Average IAT) were tested in the adopted network architecture. The objectives were:

i) To determine the effect of the number of tunable heads per ROADM on the network throughput. As the number of tuning heads per ROADM approaches the total number of wavelengths, the more such tuning based ROADM architecture approaches switching based ROADM architecture.
ii) To determine the performance of the proposed A* based algorithm in the adopted architecture under different traffic load scenarios. For this purpose a comparison was done between the proposed A* based algorithm and the traditional Dijkstra algorithm.

6.1 Tuning Head Analysis

The effect of the number of tunable heads per ROADM on the network throughput is analysed next. Figure 25 shows the performance of the proposed A* based algorithm where TH is the number of tunable heads per ROADM.

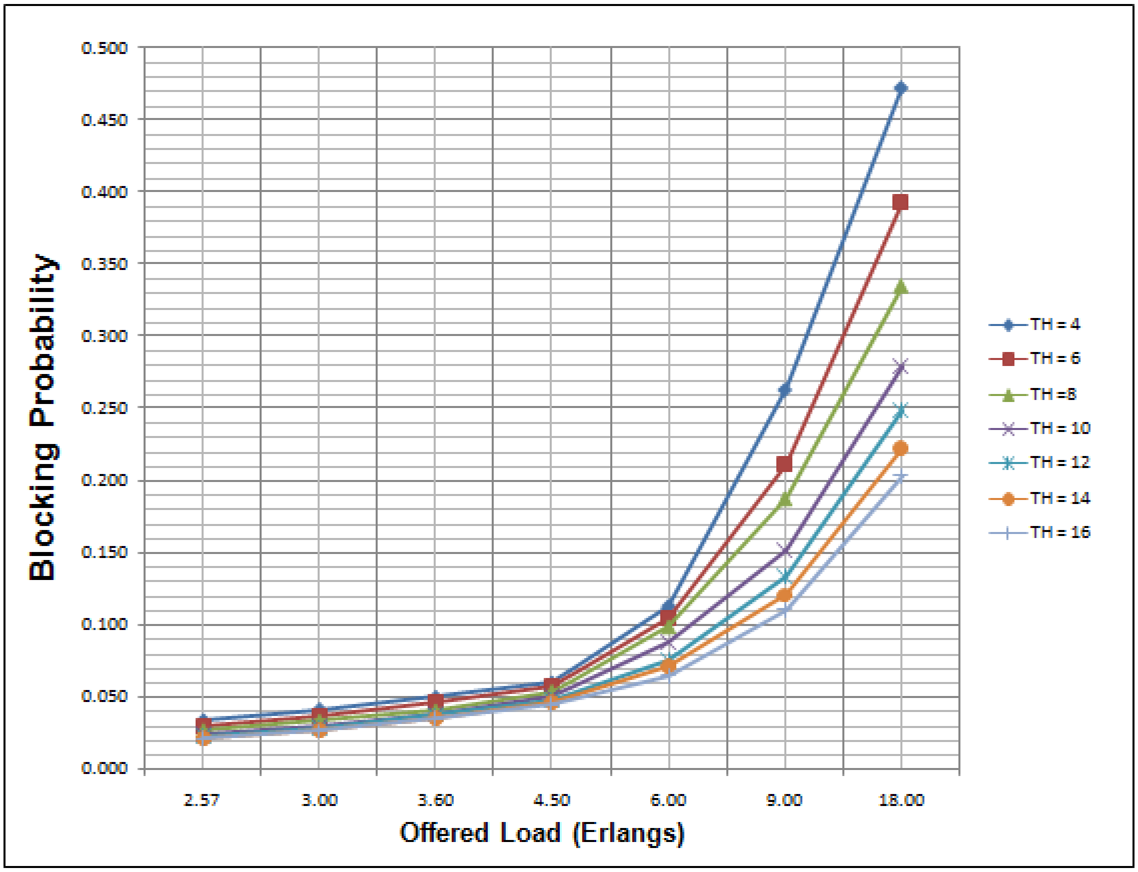


Figure 25: Performance of the proposed heuristic algorithm

As shown in Figure 25, the blocking probability increases exponentially when the traffic load increases irrespective of the number of tuning heads used per node. This is because an increase in traffic load in the network with no increase in bandwidth will always cause more chances of blocking a connection request.

As the number of tunable heads per node increases, the exponential growth of the blocking probability becomes smoother. That is, when the number of tuning heads per node edges closer to the total number of wavelengths, from 12 until 16, the difference between the curves is smaller. This shows that, as the number of tunable heads gets closer to the number of wavelengths the effect of head tuning on performance becomes less significant. To illustrate this further, a sample of some traffic loads (6 – 18 Erlangs) is shown in more details in Figure 26.

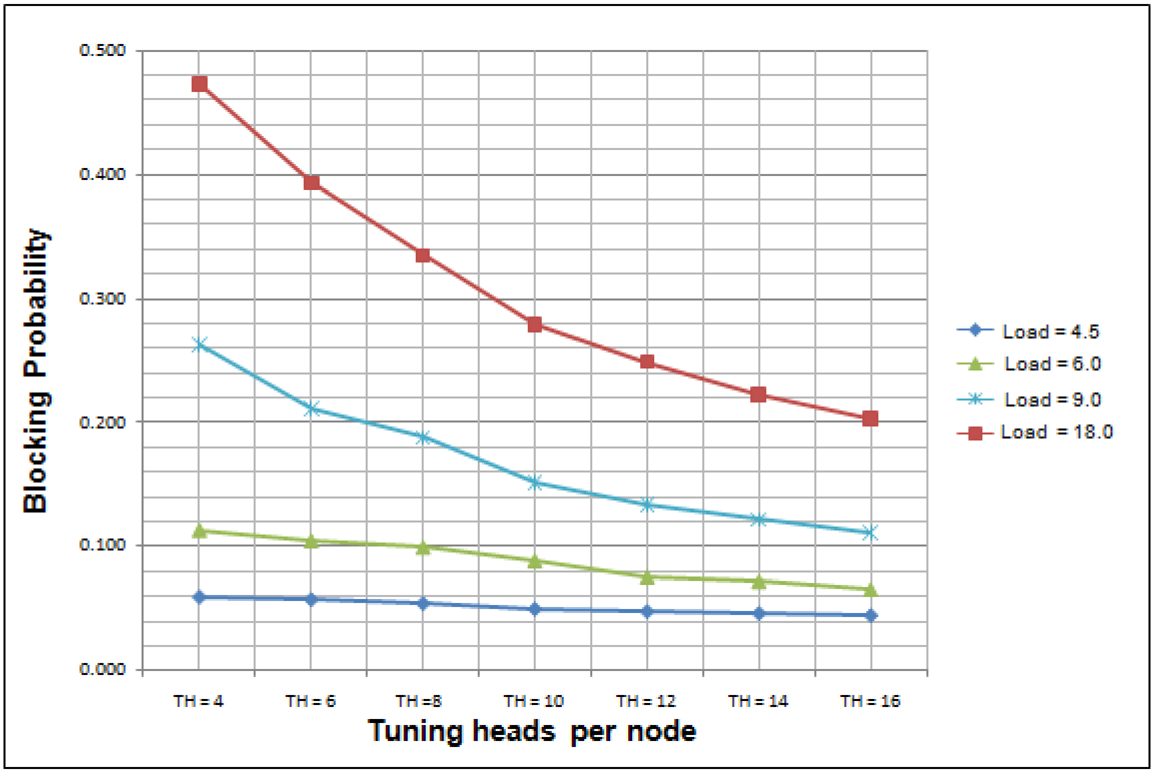


Figure 26: Reduction in blocking probability with an increase in tuning heads per node

As shown in Figure 26, there is a gradual reduction in blocking probability, for every traffic load, as the number of tuning heads per node increases. But after the number of tuning head per node reaches 12, the reduction in blocking probability decelerates. This indicates that the number of tuning heads per node affects the blocking probability up to a certain point, after which the effect on network performance is minimal. This is further illustrated in Figure 27 and Table 3, where the reduction in blocking probability is analysed when the tuning heads change from 4 until 12 and from 12 until 16.

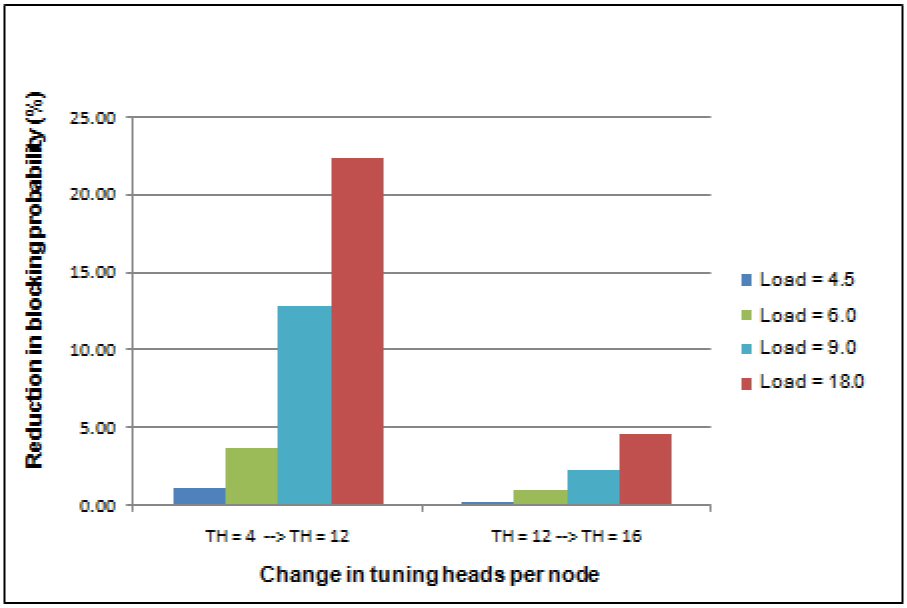


Figure 27: Reduction in blocking probability with a change in tuning heads per node

When the tunable heads per node increases from 4 until 12, the blocking probability is greatly reduced for every sample of traffic load. While an increase from 12 until 16 of tunable heads per node offers a small reduction of the blocking probability. Table 3 shows the blocking probability reduction in percentages as the tuning heads change for every sampled traffic load.

Traffic Load	TH = 4 --> TH = 12	TH = 12 --> TH = 16
4.5	1.16%	0.31%
6.0	3.80%	1.00%
9.0	12.95%	2.33%
18.0	22.39%	4.60%

Table 3: Reduction in blocking probability with change in number of tuning heads per node

From this, it is evident that during network dimensioning it is of essence to ration the number of tuning heads per node to the total number of wavelengths. The number of tuning heads per node should not be too low compared to the total number of wavelengths; this will not offer good network performance. It should also not be too close or equal to the number of wavelengths. Even though this might offer slightly better performance, it is not economically viable due to cost implication more so at the access network where small amount of traffic is either added or dropped.

6.2 Performance of the Proposed A* based Algorithm

When comparing the proposed A* based algorithm with Dijkstra, the proposed algorithm gave better results irrespective of the number of tuning heads per ROADM as shown in Figures 28 and 29.

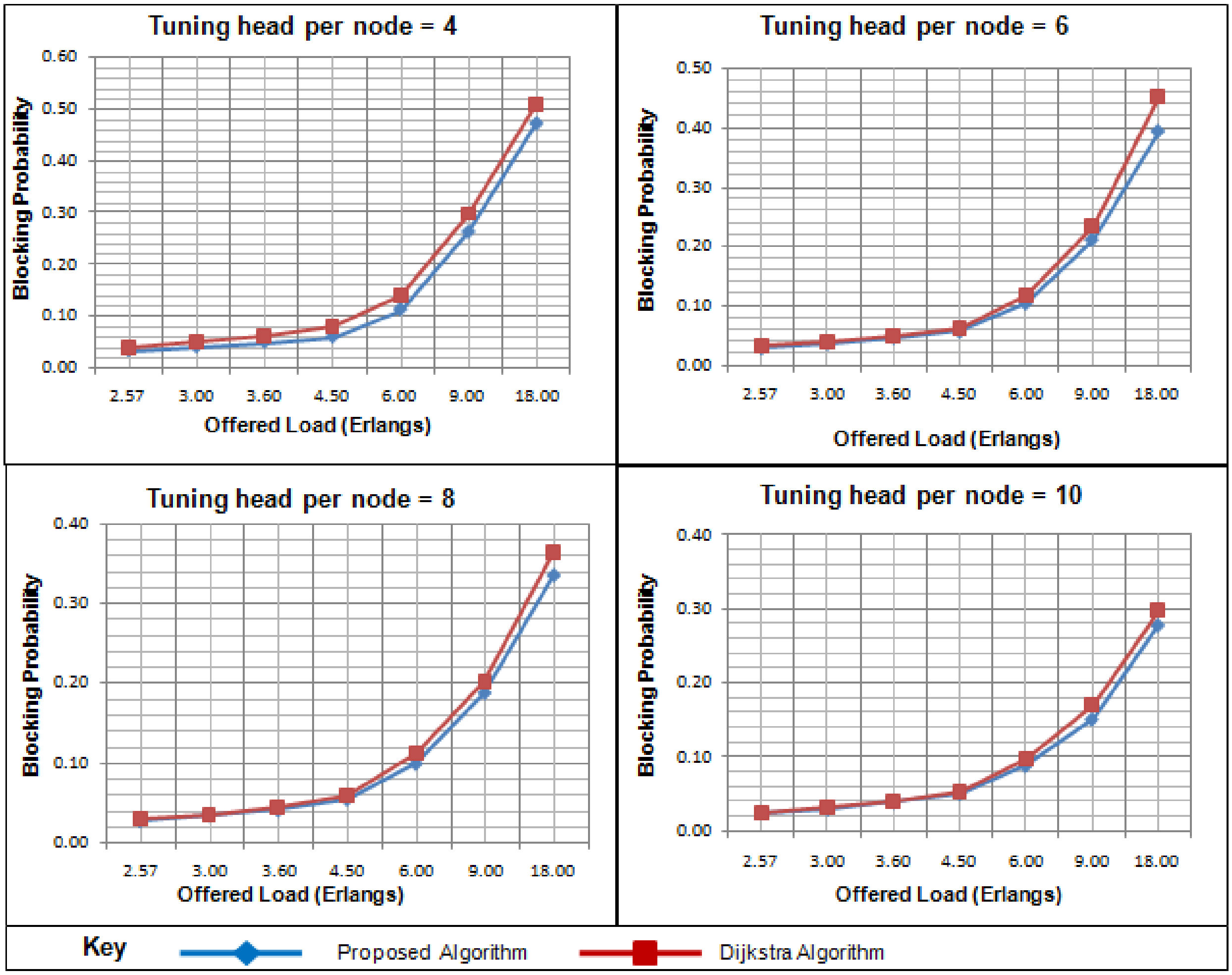


Figure 28: Comparison of proposed algorithm with Dijkstra (TH equals to 4, 6, 8 and 10)

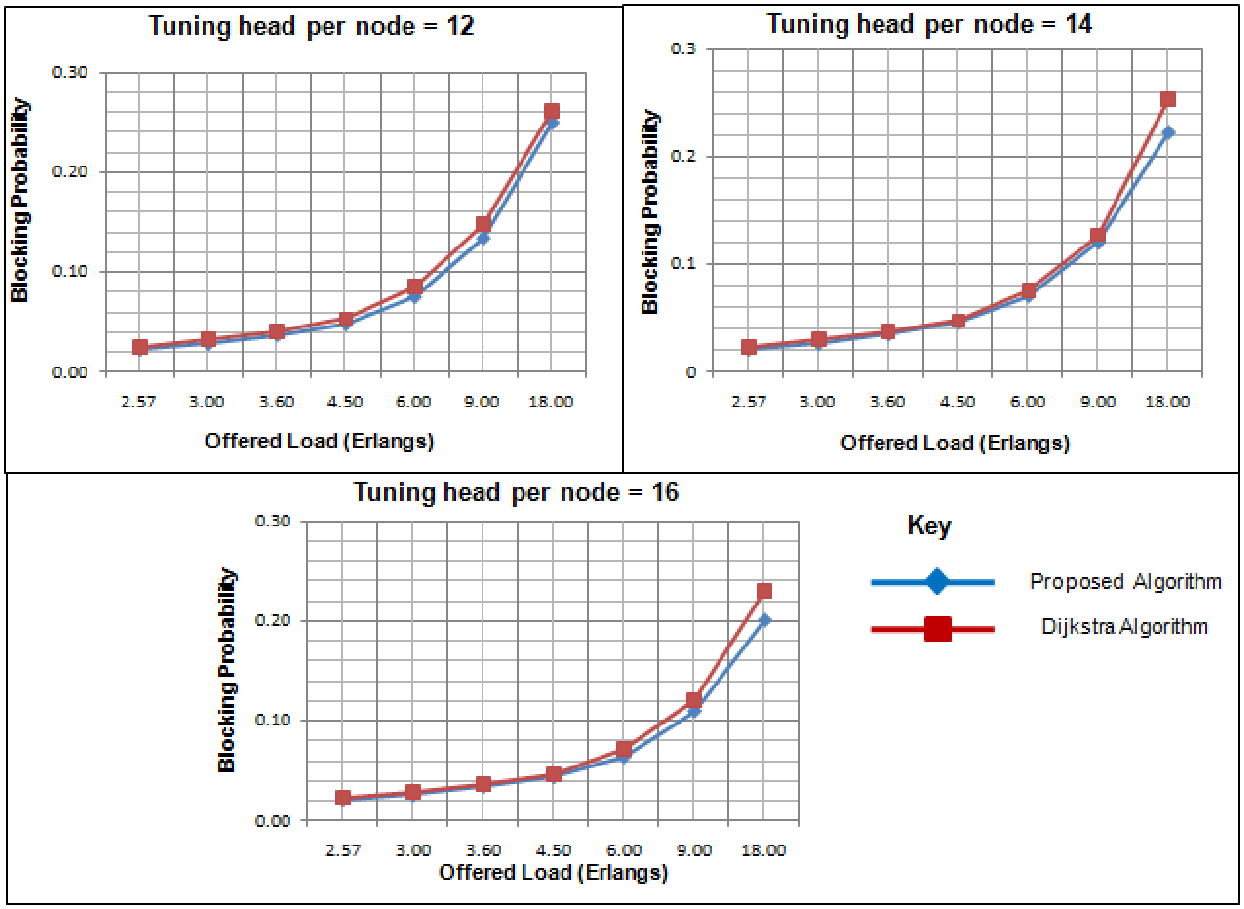


Figure 29: Comparison of proposed algorithm with Dijkstra (TH equals to 12, 14 and 16)

The advantage of the proposed A* based algorithm can be attributed to the fact that it incorporates the whole network status before making a routing decision and can find alternative routes depending on the network load status at the wavelength level. The routes might not be optimal in length but guarantees a connection establishment, unlike Dijkstra algorithm which observes optimality in length with no guarantee of connection establishment. The heuristic takes into account wavelength continuity before assigning a route to a request. This ensures less chance on connection blockage due to wavelength constraints. It also ensures that wavelength usage is evenly distributed in the network as it will offer routes with more free wavelengths. This again reduces blocking probability for future connection requests. Dijkstra, on the other hand, only evaluates the cost of a particular link at a time with no regard to what happens on other links between source and destination nodes. This makes Dijkstra blind to wavelength continuity when assigning routes, leading to higher blocking chances for connection requests.

The results also show that when the traffic load in the network is small the algorithms offer almost similar performances but, as the network traffic increases, the blocking probability for Dijkstra algorithm increases more than that of the proposed A* based algorithm in all cases. This confirms that by observing optimality, Dijkstra may be overloading (over utilizing) shortest paths thereby leading to higher blocking of connection requests. This over utilization of shortest paths also leads to poor distribution of wavelength usage in the network thus enhancing chances for future connection requests being blocked.

It should be emphasized that being the tested network a ring topology, which is very rigid in terms of routing alternatives, having any improvement beyond Dijkstra is very difficult. Therefore the results achieved can be considered very positive. Higher improvements beyond Dijkstra are expected in more connected networks.

In all the simulations a smaller blocking probability is obtained when the number of tuning heads is equal to the total number of wavelengths in the network. At this point, the ROADM is acting like a switch. Even though this gives better results, the cost of deploying ROADM as switches might increase the network cost in terms of initial implementation and maintenance, more so at access networks where only small amount of traffic need to be added/dropped at a node. The computational overhead is also increased since there are many heads to be re-parked at a node every time a connection is set or dropped with no major performance boosting. The essence of using tunable ROADMs in the adopted architecture is to reduce cost.

Chapter 7

Conclusion and Future Work

As reviewed in this dissertation, FiWi networks technology promises to solve the bottle neck problem at the junction of transport and access networks by offering higher bandwidth to end users with flexibility. FiWi access networks have shown the potential to offer a solution to the bandwidth congestion experienced at the network access points.

Different proposed FiWi access network architectures have been discussed in this thesis and a network architecture has been adopted which promises high bandwidth at the access level and allows dynamic resource allocation. In this architecture, the COs are connected in a ring topology which can enable easy sharing of processing loads, the ring topology also possesses self-healing properties in case of failures, making it attractive for metro and access networks.

Through the use of both OXC and tunable-based ROADMs the architecture promises network reconfiguration at the wavelength level for restoration and accommodation of changes in bandwidth demand. The architecture also promises to keep network costs low since tunable-based ROADMs are cheap, easy to maintain and implement all optical network elements with no O-E-O conversion.

A routing and wavelength assignment algorithm has been proposed that reduces the blocking probability when compared with Dijkstra, thus enhancing network performance. This enhancement is possible due to the use of a heuristic which takes into consideration the wavelength continuity on the route and network load status at the wavelength level. Besides being more efficient in performance, it is also faster because it uses the heuristic function for route/path computation. This is a very important issue under dynamic traffic scenarios, especially in the access network where demands can arrive more often. The tuning-head assignment strategy used also reduces computational overhead as only the tuning range of the affected heads will be redefined and not all tuning heads in the network.

In this thesis it has also been shown that, when using tunable ROADMs, the head tuning constraint can affect the network blocking probability and the number of tuning heads per node greatly affects the network performance. It is important to ration the number of tuning heads per node to the total number of wavelength in the network accordingly as this can greatly improve network performance. When tuning heads per node are too few compared to the total number of wavelengths in the network, blocking probability increases. On the other hand, when the tuning heads per node are more close to the number of wavelengths in the network, the blocking reduces. Even though this offer better results, the cost implication associated with an increase of each tuning head and the computational overhead might overshadow the performance benefit. More so at the access network where small amount of traffic is either added or dropped. Thus, it is of essence to strike a balance between cost and performance during network optimization and dimensioning.

This thesis has focused on how to grant access to network resources through dynamic connection provisioning. Further analysis of the dynamic connection provisioning problem should be done with assumption that ongoing connections can change the wavelength they are working on.

The access network architecture adopted also promises a possibility of ensuring load balancing among the central offices. Therefore, future work should be carried out to propose heuristics which can offer a fair load balancing at the central offices.

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