

1-13-2016

# Energy Efficient Anycast Routing for Sliding Scheduled Lightpath Demands in Optical Grids

Darshil Rami  
*University of Windsor*

Follow this and additional works at: <http://scholar.uwindsor.ca/etd>

---

## Recommended Citation

Rami, Darshil, "Energy Efficient Anycast Routing for Sliding Scheduled Lightpath Demands in Optical Grids" (2016). *Electronic Theses and Dissertations*. Paper 5662.

This online database contains the full-text of PhD dissertations and Masters' theses of University of Windsor students from 1954 forward. These documents are made available for personal study and research purposes only, in accordance with the Canadian Copyright Act and the Creative Commons license—CC BY-NC-ND (Attribution, Non-Commercial, No Derivative Works). Under this license, works must always be attributed to the copyright holder (original author), cannot be used for any commercial purposes, and may not be altered. Any other use would require the permission of the copyright holder. Students may inquire about withdrawing their dissertation and/or thesis from this database. For additional inquiries, please contact the repository administrator via email ([scholarship@uwindsor.ca](mailto:scholarship@uwindsor.ca)) or by telephone at 519-253-3000ext. 3208.

**Energy Efficient Anycast Routing for  
Sliding Scheduled Lightpath Demands in Optical Grids**

By

**Darshil Rami**

A Thesis

Submitted to the Faculty of Graduate Studies  
Through the School of Computer Science  
In Partial Fulfillment of the Requirements for  
The Degree of Master of Science at the  
University of Windsor

Windsor, Ontario, Canada

2016

© 2016 Darshil Rami

**Energy Efficient Anycast Routing for**

**Sliding Scheduled Lightpath Demands in Optical Grids**

By

**Darshil Rami**

APPROVED BY:

---

Dr. Mohammed Khalid, External Reader

Electrical & Computer Engineering

---

Dr. Imran Ahmad, Internal Reader

School of Computer Science

---

Dr. Arunita Jaekel, Advisor

School of Computer Science

Jan 7, 2016

## DECLARATION OF ORIGINALITY

I hereby certify that I am the sole author of this thesis and that no part of this thesis has been published or submitted for publication.

I certify that, to the best of my knowledge, my thesis does not infringe upon anyone's copyright nor violate any proprietary and that any ideas, techniques, quotations, or any other material from the work of other people included in my thesis, published or otherwise, are fully acknowledged in accordance with the standard referencing practices. Furthermore, to the extent that I have included copyrighted material that surpasses the bounds of fair dealing within the meaning of the Canada Copyright Act, I certify that I have obtained written permission from the copyright owner(s) to include such material(s) in my thesis and have included copies of such copyright clearances to my appendix.

I declare that this is a true copy of my thesis, including any final revisions, as approved by my thesis committee and the Graduate Studies office, and that this thesis has not been submitted for a higher degree to any other University or Institution.

## ABSTRACT

Optical grids have been thought as an answer to support large-scale data intensive applications. Data centers and Optical grids are largest and fastest growing consumers of electricity. Energy efficient routing schemes and traffic models can answer the problem of energy consumption. In Optical Grids, it is possible to select destination node from the set of possible destinations which is known as anycasting. We propose ILP formulations for flexible sliding scheduled traffic model, where setup and tear down times may vary within larger window frame. The problem of energy consumption is addressed by switching off ideal network components in low utilization periods. Our proposed novel formulation that exploits knowledge of demand holding times to optimally schedule demands achieved 7-13% reduction in energy consumption compared to previously best known model.

## DEDICATION

To my loving Family:

Father: Kamleshkumar Rami

Mother: Jyotsnaben Rami

## ACKNOWLEDGEMENTS

Masters of Science at Windsor University has not only polished my technical skills and intellectual thinking but also helped me to develop many life skills like patience and perseverance.

I would like to express my deepest gratitude to Dr. Arunita Jaekel for her guidance, providing me the opportunity to train myself through tackling the challenges during the research. I am grateful to her for giving me the freedom to apply and test my ideas and making it possible. I would like to thank my thesis committee members Dr. Imran Ahmad and Dr. Mohammed Khalid for their valuable comments and suggestions for writing this thesis. I would like to thank the entire computer science faculty members and Graduate secretary for all the support they provided throughout my Graduation.

I offer my heartfelt gratitude to my Parents and my Family for always encouraging me to live my life undefeated by anything and for teaching me to create value out of even the most difficult circumstances. A special thanks to my friend Yomini S. for her continuous support throughout my work.

Above all I thank to God for giving me the strength and for everything that I have.

## TABLE OF CONTENTS

DECLARATION OF CO-AUTHORSHIP/ PREVIOUS PUBLICATION	iii
ABSTRACT	iv
DEDICATION	v
ACKNOWLEDGMENTS	vi
LIST OF TABLES	viii
LIST OF FIGURES	ix
LIST OF ABBREVIATIONS/ SYMBOLS	xii
1. INTRODUCTION	1
1.1. OVERVIEW	1
1.1.1. OPTICAL NETWORK AND OPTICAL GRID COMPUTING	1
1.2. MOTIVATION	4
1.3. PROBLEM STATEMENT AND SOLUTION OUTLINE	5
1.4. THESIS ORGANIZATION	6
2. BACKGROUND	7
2.1. OPTICAL NETWORK	7
2.1.1. OPTICAL FIBERS	7
2.1.2. LIGHTPATH AND TOPOLOGIES	13
2.2. WAVELENGTH DIVISION MULTIPLEXING	16
2.3. ROUTING AND WAVELENGTH ASSIGNMENT	17
2.4. ANYCAST ROUTING	18
2.5. TRAFFIC DEMAND ALLOCATION MODELS	20
2.6. LITERATURE REVIEW	22
3. ENERGY EFFICIENT ANYCAST ROUTING FOR SLIDING SCHEDULED LIGHTPATH DEMANDS	29



3.1. INTRODUCTION	29
3.2. NETWORK ENERGY MODEL	29
3.3. SOLUTION APPROACH	31
3.4. PROPOSED INTEGER LINEAR PROGRAM	33
3.4.1. JUSTIFICATION OF THE ILP	37
3.4.2. MODIFICATION FOR FIXED WINDOW MODEL	41
3.5. AN ILLUSTRATIVE EXAMPLE	41
4. EXPERIMENTATION AND RESULTS	45
4.1. SIMULATION PARAMETERS	45
4.2. COMPARISON OF ENERGY CONSUMPTION FOR ILP FORMULATIONS	48
4.3. COMPARISON OF SOLUTION TIMES	54
5. CONCLUSION AND FUTURE WORK	56
5.1. CONCLUSION	56
5.2. FUTURE WORK	57
REFERENCES/BIBLIOGRAPHY	58
VITA AUCTORIS	64

## LIST OF TABLES

Table 2.1	Literature review summary	28
Table 3.1	Power consumption of network devices	30
Table 3.2	Illustrative example	43
Table 3.3	Number of active nodes and links for each case	44

## LIST OF FIGURES

Figure 1.1	Optical Grid Computing	3
Figure 2.1	Cross-section of Optical Fiber	8
Figure 2.2	Total internal Reflection inside Optical Fiber	9
Figure 2.3	Principle of Total Internal Reflection	10
Figure 2.4	Add-drop Multiplexer	11
Figure 2.5	Static Optical Cross Connect and Dynamic Cross Connect	12
Figure 2.6	Lightpath set-ups in Optical Network	14
Figure 2.7	Physical Topology	15
Figure 2.8	Logical Topology	16
Figure 2.9	Wavelength Division Multiplexing	17
Figure 2.10	Routing and Wavelength Assignment	18
Figure 2.11	Anycast Routing	19
Figure 2.12	Fixed Window Demand Allocation	21
Figure 2.13	Sliding Scheduled Demand Allocation	22
Figure 3.1	Energy Efficient Solution Approach	32
Figure 3.2	Illustrative example of possible start times	42
Figure 3.3	Possible destination and routes for demand P3	42
Figure 4.1	11-node network with 24 links (COST-239)	47
Figure 4.2	14-node network with 21 links (NSFNET)	47
Figure 4.3	24-node network with 43 links	47
Figure 4.4	Comparison of energy consumption for 11-node topology	50
Figure 4.5	Comparison of energy consumption for 14-node topology	51
Figure 4.6	Comparison of energy consumption for 24-node topology	51

Figure 4.7	Comparison of energy consumption for different networks	52
Figure 4.8	Improvement by EA_anycast_SSLD in %	53
Figure 4.9	Comparison of execution time	54

## LIST OF ABBREVIATIONS/SYMBOLS

- ILP – Integer Linear Programming
- RWA – Routing and Wavelength Assignment
- WDM – Wavelength Division Multiplexing
- SLD – Scheduled Lightpath Demand
- LHC – Large Hadron Collider
- Tbps – Tera bits per second
- SETI – Search for Extra Terrestrial Intelligence
- LP – Lightpath
- EOE – Electrical to Optical to Electrical
- IP – Internet Protocol
- LAN – Local Area Network
- MAN – Metropolitan Area Network
- WAN – Wide Area Network
- Gbps – Giga bits per second
- LED – Light Emitting Diode
- MUX – Multiplexer
- DEMUX – Demultiplexer
- OADM – Optical Add Drop Multiplexer
- OXC – Optical Cross Connect
- NSFNET – National Science Foundation Network
- COST-239 – European network topology
- EA-RWA – Energy Aware Routing and Wavelength Assignment
- IBM – International Business Management

ILOG CPLEX – Optimization Software Package

*EA\_anycast\_SSLD* – Energy aware *anycast sliding* scheduled traffic model

*EA\_anycast\_FW* – Energy aware *anycast fixed* window traffic model

*EA\_unicast\_SSLD* – Energy aware *unicast sliding* scheduled traffic model

*EA\_unicast\_SSLD* – Energy aware *unicast fixed* window traffic model

# CHAPTER 1

## INTRODUCTION

### 1.1.Overview

Internet is growing rapidly because of today's technological advancement. The numbers show that over 3 billion people in the world are using Internet nowadays which is over 40% of the total population [1]. Many applications such as weather modeling applications, e-science applications like LHC computing grid [15], search engines and social networking sites require tremendous amount of data. A large amount of power supply is needed to satisfy the processing requirements of these data intensive applications, which generally supports speed in *Tbps* [17]. Optical networks are attractive candidates for meeting the needs of such high speed applications with low power consumption.

#### 1.1.1. Optical Network and Optical Grid Computing

An optical network is a communications network which supports transmission of data through optical fibers in the form of optical signals. At the early stage of Internet, copper cables were used for the transmission of data between nodes, which led to many problems like low speed, high cost, distance, etc. With the introduction of optical fibers, it started new era of high speed computing with low cost. In optical networks the electrical signals at the node are converted to optical signals and then they are transmitted over optical fibers, using the principle of *total internal reflection* [14]. At the receiving end, the optical signal is converted back to an electrical signal. In optical networks, it is

not necessarily required that all the network components work in optical domain. Typically, the transmission components work in optical domain and switching components work in either electrical domain or optical domain.

There is a large amount of heterogeneous computing and storage resources available around the world, much of which remain under utilized [19]. Grid computing refers to high performance computing resource sharing using optical backbone networks to support data-intensive applications. Grid computing provides a solution to better utilize these resources, for applications where the physical location of the resource is not important. Grids provide a form of distributed computing [22] whereby a super virtual computer [16] is composed of many networked ‘loosely coupled’ computers, acting together to perform large tasks [16].

Optical grid computing is a high performance computing architecture which consists of optical backbone network to support the data intensive applications with the capability of resource sharing. The grid computing can be heterogeneous or homogeneous and also geographically dispersed. The computing grid can support data transmission up to hundreds of *Gbps* [17] and some large grid applications process data in Peta Bytes per year [15]. Some examples of the grid are Bitcoin Network [16], SETI@Home project [16], MilkyWay@Home project [16] and LHC computing grid [15].

For the grid computing the basic requirement is high speed with low delay time. Optical communications technology with WDM networks fulfills the requirements for optical grid computing as it can carry large amount of data with reliability. Thus optical



networks will be very much important for the future of grid computing. In the Figure 1.1 the example of optical grid or photonic grid is shown.



Figure 1.1: Optical Grid Computing [11]

Some fundamental concepts of optical networking, which are integral to the remainder of thesis, are introduced in the following sections.

The concept of *wavelength division multiplexing* (WDM) [17] was introduced in order to effectively utilize the tremendous bandwidth available in a single optical fiber. The technology of using multiple optical signals on the same fiber is called *wavelength division multiplexing* (WDM) [3]. The *routing and wavelength assignment* or RWA solves the problem of assigning lightpaths in WDM networks. The RWA problems are considered as the NP-complete problems [3]. In many applications the physical location of the server or other network resources remains hidden from the user as it is not important. In this scenario, it is possible to select the best destination from the set of

possible destinations to execute a job. This phenomenon is known as *anycasting*. Intelligent resource allocation strategies can be used to exploit inherent possibilities of *anycast* principle.

There are mainly three different demand allocations models exist for WDM optical networks. In static traffic model, the set of demands are fixed and known in advance. For dynamic traffic, the set up time and the duration of the demands are not known in advance, they are generated based on certain distributions. Scheduled traffic model is predictable and periodic in nature. In scheduled traffic demands the set up time and the tear down time for the demand is known in advance. The scheduled traffic model is further divided into two different models, known as fixed window traffic model and sliding scheduled traffic model.

## **1.2.Motivation**

Due to increase in Internet traffic, the power consumption by Internet is also increasing at the rate of 9% per year, which is not directly proportional to the rate of growing traffic increasing at 40% per year according to a study presented by Mario Pickavet of iMinds [5]. However the resources like power stations and power grids which provide electricity for that are increasing at the rate of 3% per year, which shows the 6% gap between requirement and supply for the electricity [5]. The Internet consumes 5% of world's total electricity generation at present time and this is expected to rise to 8% by the year 2020 [5].

These Figures show that the energy consumption can become the bottleneck for the high speed data communication. The development of energy efficient schemes is very

important at all levels of network infrastructure to address this problem. Efficient routing schemes and resource allocation both in optical and electrical domain can provide the answer to the problem of energy consumption. A transparent IP-over-WDM network can be utilized to allow traffic to optically bypass the electronic components, which consumes more power like IP routers and switches [6]. In recent years, various research works have been published in the field of energy efficient WDM networks. A number of different approaches have been proposed, including switching off or slowing down unused network elements [19], [23], [24], reducing electrical-optical-electrical (E-O-E) conversions [22], putting selected network components in sleep mode [21], and using intelligent traffic grooming techniques [6]. Although energy aware routing for WDM networks has received significant attention in recent years, the idea of utilizing the *anycast* concept for energy minimization [19], [23] has been less well studied.

### **1.3. Problem statement & Solution outline**

The Internet and specially data center networks consume a large amount of electrical power throughout the world. In this research work, we are trying to minimize the energy consumption of a network by switching off ideal network elements using *anycast* routing scheme.

Several researches show that routing schemes can affect the overall energy consumption of a network [19] - [24]. In this thesis, we address the problem of energy efficient routing of scheduled traffic demands. Rather than using the traditional *unicast* routing, our proposed approach uses the *anycast* principle to select the most suitable destination for a given demand. Furthermore, we present a novel approach that jointly routes and schedules demands in time. We have developed a new integer linear program (ILP)

formulation to solve this integrated routing and scheduling problem. We consider power consumption at both network nodes (e.g. in IP routers, optical switches) and along fiber links.

In order to evaluate the performance of our ILP, we compare the solutions generated by the ILP with the solutions obtained using the *unicast* principle, as well as *anycast* routing with fixed start and end times for each demand. We have performed simulations on different network topologies and with different demand sets. The results demonstrate that our proposed approach can lead to significant reductions in energy consumption, compared to traditional routing schemes.

#### **1.4. Thesis organization**

The rest of the thesis is organized as follows: Chapter 2 describes literature review of previous works including most important papers. It also delivers the definitions and overview about research area in optical networks. In chapter 3, we describe our proposed approach which uses *anycasting* scheme for sliding scheduled traffic model in WDM network. Chapter 4 discusses the simulation results of our experimentation and analysis of our obtained results. Finally chapter 5 concludes the research work and gives directions about the future work.

# CHAPTER 2

## BACKGROUND

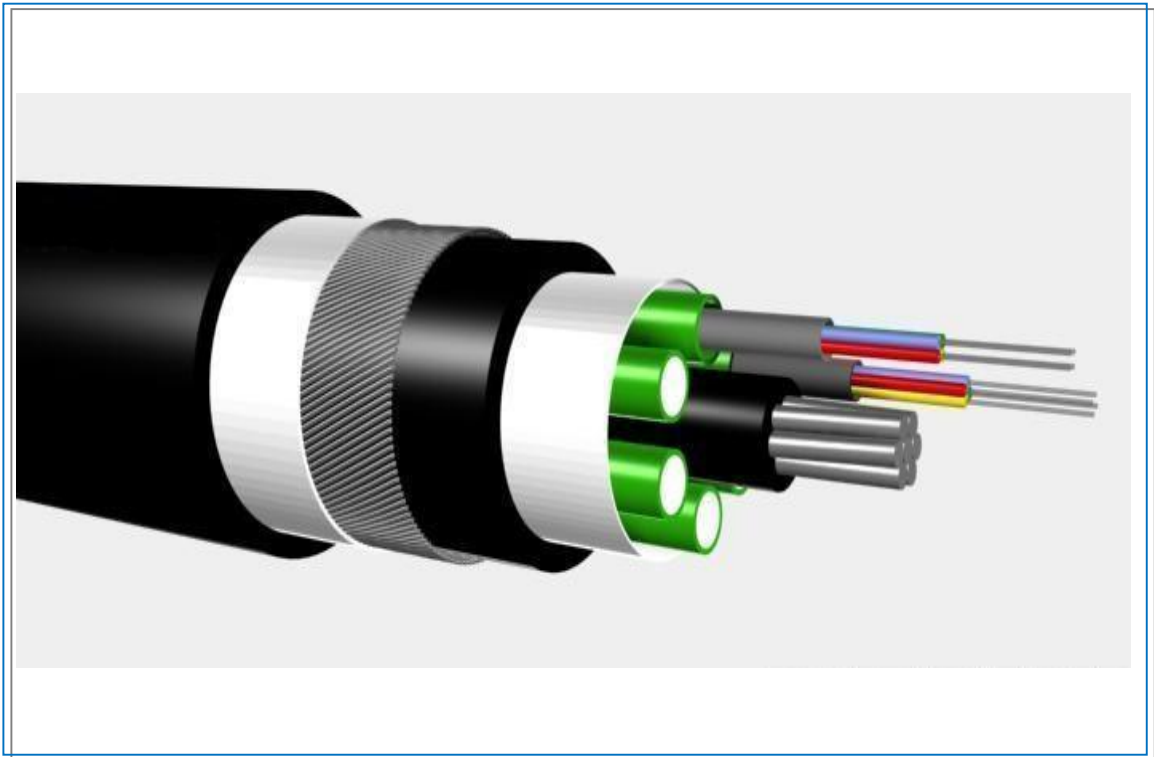
### 2.1. Optical Networks

Optical networking is a means of communication that uses signals encoded onto light to transmit information among various nodes of a telecommunications network [7]. It utilizes optical fiber cables for communicating between nodes. Optical fibers are thin cylinders made up from glass or silica, which are able to carry information in the form of light. Optical network can be operated over wide variety of networks like LAN (Local Area Network), MAN (Metropolitan Area Network) and WAN (Wide Area Network). In the following sections we will review the basic concepts of the optical networks.

#### 2.1.1. Optical Fibers

In the past decade, the number of Internet users has increased significantly [1]. Furthermore, the emergence of web applications including video streaming is requiring high speed data transmission, which is placing greater demands on the bandwidth resources of the network infrastructure. Optical fibers provide the best answer to this problem by supporting speed up to hundreds of *Gbps* [17]. Optical fibers have low signal attenuation and low signal distortion compared to traditional copper cables; optical fibers consume less energy and require less space. Also, they provide protection from electromagnetic interference, which means more secure data transmission compared to copper cables.

Optical fibers can be of two types: single mode and multi-mode fibers. In single mode fibers generally the inner core has small size and it transmits the signal using infrared lasers [13]. Multi-mode fibers have a larger core and they transmit the signal using infrared LED lights [13].



**Figure 2.1: Cross-section of Optical Fiber [8]**

Optical fibers consist of two layers of thin glass like material which are called core and cladding. Information is transmitted through the core, which is made up from glass or silica. The core is surrounded by another layer called cladding also made up from silica but having lower refractive index compared to inner layer. The outer most layer is called buffer, which provides protection to fibers from physical damages as shown in Figure 2.2.

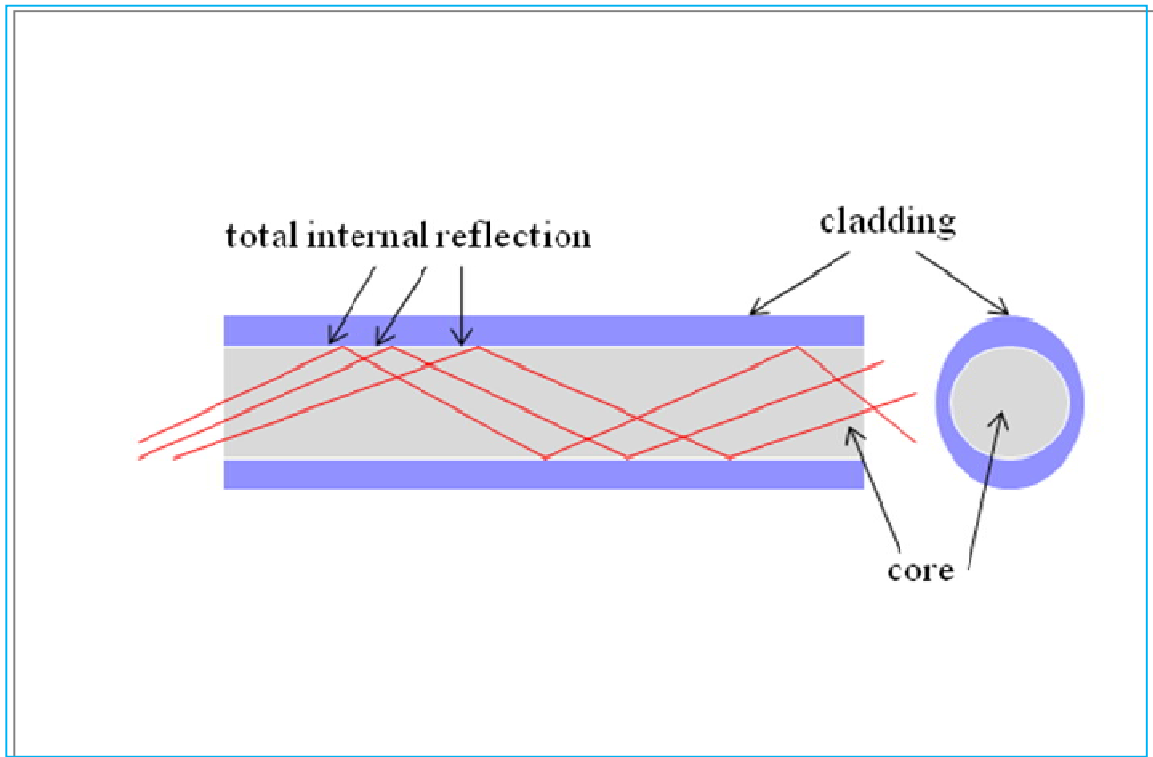


Figure 2.2: Total Internal Reflection inside Optical Fiber

Optical fibers basically work on the principle of *total internal reflection* [13]. Total internal reflection is a phenomenon in which the light strikes the surface at an angle larger than *critical angle* with respect to the normal of the surface, and is reflected back entirely into the first medium [14]. Critical angle is the angle of incidence above which the total internal reflection occurs [14]. The signal must be sent at the angle greater than critical angle defined as  $\sin^{-1} \mu_1 / \mu_2$ , where  $\mu_1$  and  $\mu_2$  are the refractive indexes of the mediums. As shown in Figure 2.3, there are two mediums water and air with refractive indexes  $\eta_1$  and  $\eta_2$ ,  $\theta_1$  and  $\theta_2$  are angle of incident and angle of refraction. The Figure 2.3 shows three different cases of reflection for different angle of incident. In the first case when the angle of incident is smaller than critical angle it penetrates to second medium with a different angle of refraction. It gets reflected on the edge of two mediums in second case, when it is exactly same as critical angle  $\theta_c$ . In third case the signal gets

reflected to the same medium, when angle of incident becomes larger compared critical angle.

Optical signal propagates inside the optical fiber through the series of total internal reflections. In data transmission, generally the input carrier signal is in the band of 1450 to 1650 nm. At the source end, the data is modulated with the carrier signal and transmitted through one or more optical fiber. At the receiving end, the demodulator extracts the data from carrier signal.

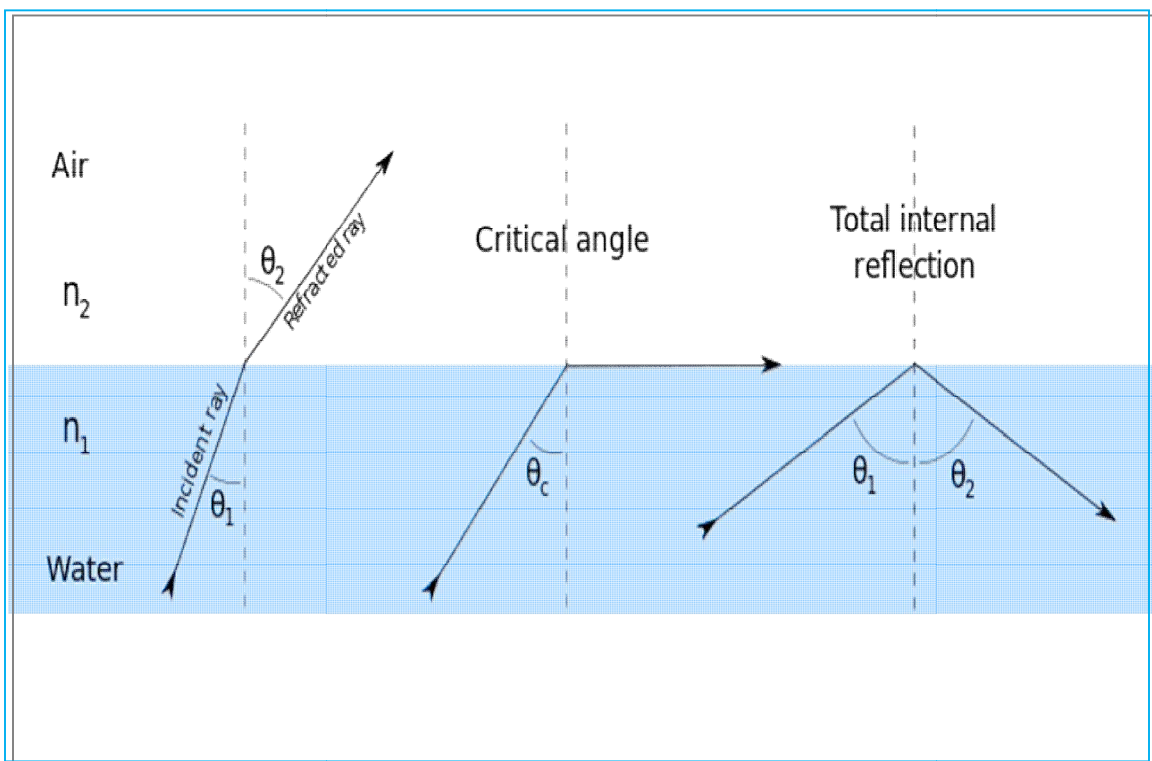


Figure 2.3: Principle of Total Internal Reflection [9]

“A multiplexer (MUX) is a device allowing one or more low-speed analog or digital input signals to be selected, combined and transmitted at a higher speed on a single shared medium or within a single shared device. Thus, several signals may share a single device or transmission conductor such as a copper wire or fiber optic cable. A MUX functions as a multiple-input, single-output switch [25]”. “Demultiplexer is the reverse of



multiplex process- combining multiple unrelated analog or digital streams in to one signal over a single shared medium, such as single conductor of copper wire or fiber optic cable [25]”. Demultiplexer or DEMUX is a device which accepts a combined input from the fiber and separates it into its constituent channels. Optical add-drop multiplexer or OADM is a pair of multiplexer and demultiplexer, which allows to add or drop traffic with having some of the outputs of demultiplexer not connected to the inputs of multiplexer. Each output of demultiplexer, which is not connected to multiplexer is connected to the receiver. Also each input not coming from demultiplexer, is directly connected to transmitter as explained in Figure 2.4.

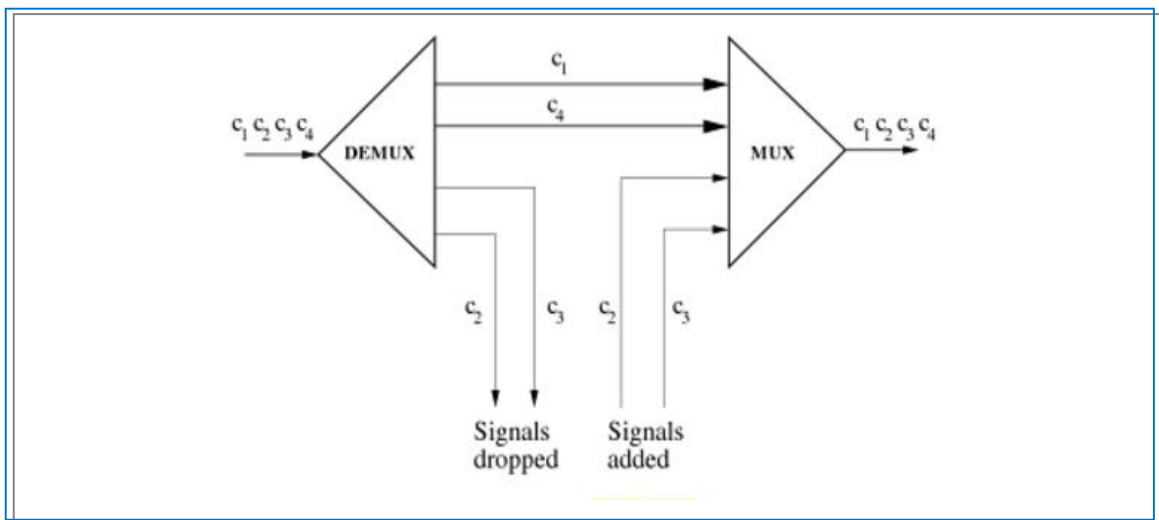
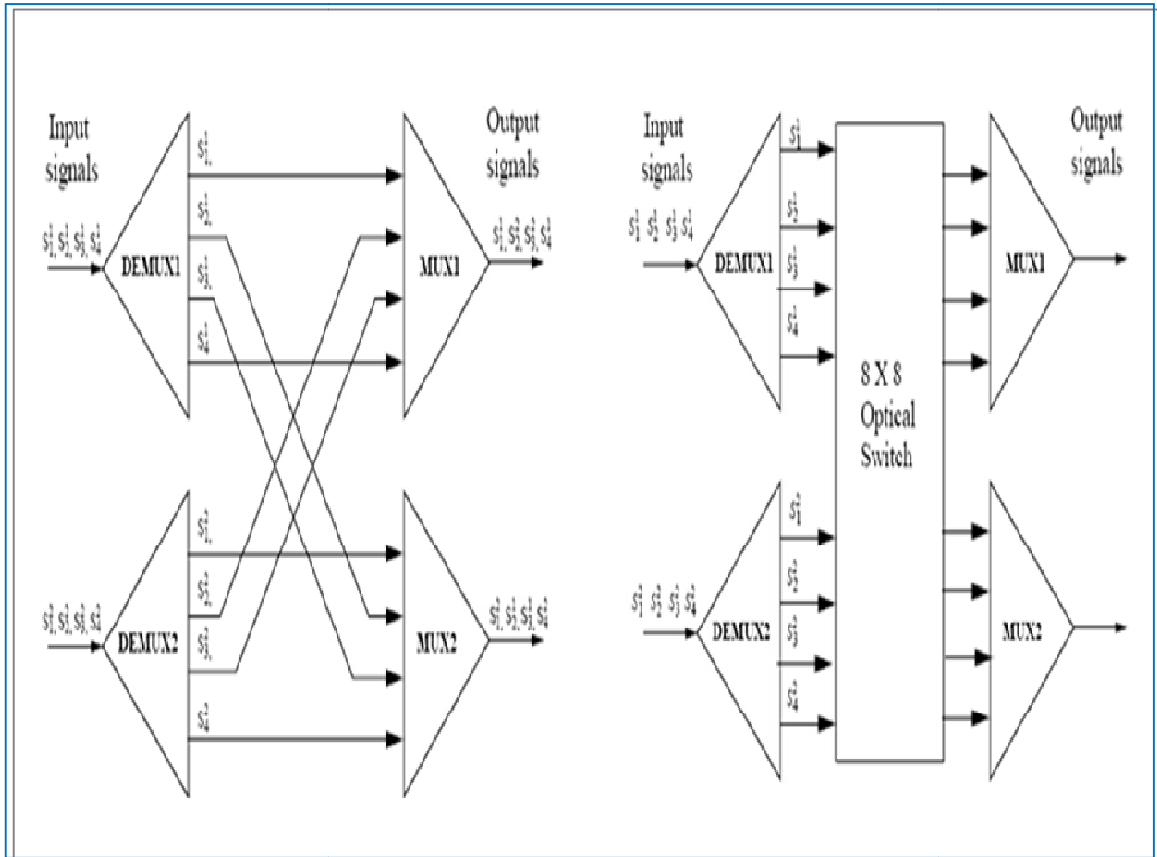


Figure 2.4: Add-drop multiplexer

“In optical networks optical cross-connect switches or OXC play an important role for routing the optical signals throughout the network. An  $m \times n$  optical cross-connect switch has  $m$  number of inputs and  $n$  number of outputs. If the  $i_{th}$  input to optical cross-connect switch is carrying signal  $s_{ij}$  using channel  $c_j$ , then the signal  $s_{ij}$  may be routed to the  $p_{th}$  output provided that no other signal using channel  $c_j$  is routed to the  $p_{th}$  output, for all  $i, j$ ,  $1 \leq i \leq m$ ,  $1 \leq j \leq N$ , where  $N$  is the maximum number of channels allowed on a fiber [3]”.

The connections inside the optical switch determine how the routing of optical signals will be done. There are mainly two types of the optical cross-connect switches static OXC and dynamic OXC.



**Figure 2.5: Static Optical Cross Connect and Dynamic Optical Cross Connect**

In Figure 2.5, the internal working of the optical cross-connect switch is shown for both static and dynamic case. In static OXC the routing is always fixed between switches like the outputs  $s_2^1$  and  $s_3^1$  of DEMUX1 are always connected to the inputs of the MUX2. On the other hand in dynamic OXC the connections can be modified based on current traffic requirements.

Apart from optical cross-connect switches, the devices like amplifiers, transceivers and transponders consume a sufficient amount of energy during data transmission. An

amplifier is a device which is used in optical networks to amplify the signal, when the signal power falls below a specific threshold [4]. There are mainly three types of amplifiers used in optical networks: inline amplifiers, pre and post amplifiers. Some of the amplifiers are capable of amplifying the signal directly in optical domain without converting them in to electrical domain first. The transceivers are used to terminate the lightpaths at the end [26]. Transponders are devices used to send and receive signals from the optical fibers and have the capability of converting one wavelength to another.

### **2.1.2. Lightpath & Topologies**

A lightpath refers to an end to end optical channel from source to destination, which may traverse through multiple fibers [3]. A lightpath may or may not have multiple wavelengths from source to destination, which depends on the wavelength conversion capability of the network.

The Figure 2.6 shows the example of physical topology with lightpaths. There are 6 nodes in the network and each node is connected to one or more nodes in the network by bidirectional links called edges. The lightpaths in the following examples are:

Lightpath 1: node 0 → node 3

Lightpath 2: node 2 → node 4

Lightpath 3: node 5 → node 4

Lightpath 4: node 0 → node 5

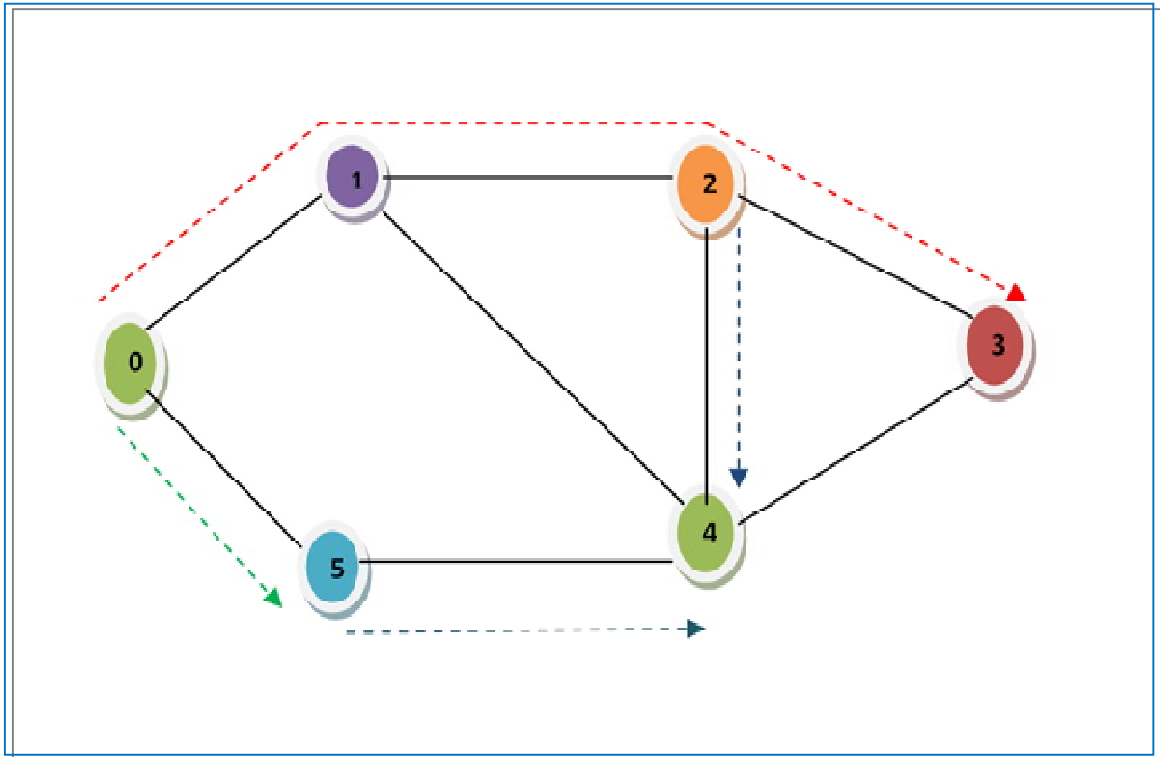


Figure 2.6: Lightpath set-up in Optical Network

A physical topology refers to the actual connectivity, using optical fibers, between the nodes in the network. In the graphical representation, the physical topology is represented by a graph  $G(N, E)$ , where  $N$  is the set of nodes in the network and  $E$  is the set of edges in the network. Each bi-directional link in the physical topology is actually implemented using two unidirectional optical fiber links, as shown in Figure 2.7.

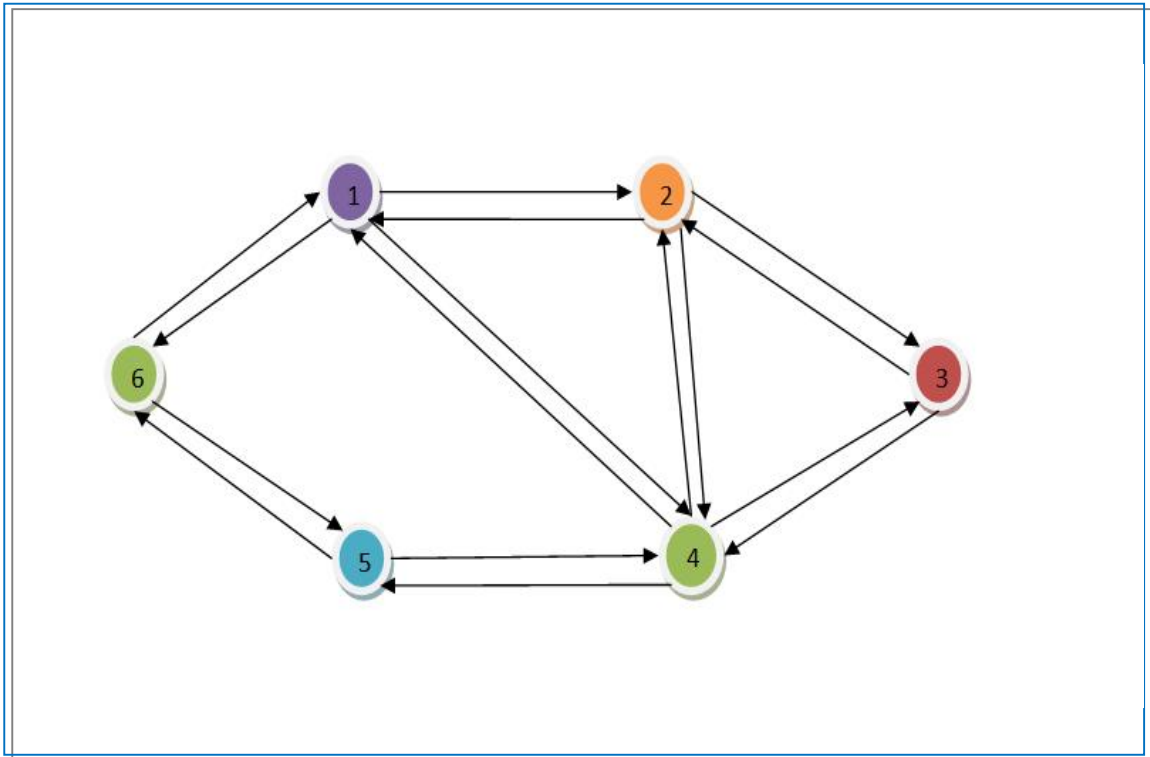


Figure 2.7: Physical Topology

A logical topology or virtual topology is the graphical representation of connectivity between nodes using lightpaths. There may be many different logical topologies corresponding to a given physical topology. The set of nodes for the logical topology is the same as the nodes of the physical topology. However, the links in the logical topology correspond to lightpaths established over the network, rather than physical links. So, it is possible for two nodes to be directly connected in the logical topology, even to there is no physical link between them. Conversely, two nodes that are directly connected in the physical topology may not be connected in the logical topology. The logical topology corresponding to the network and set of lightpaths in Figure 2.6 is shown in Figure 2.8.

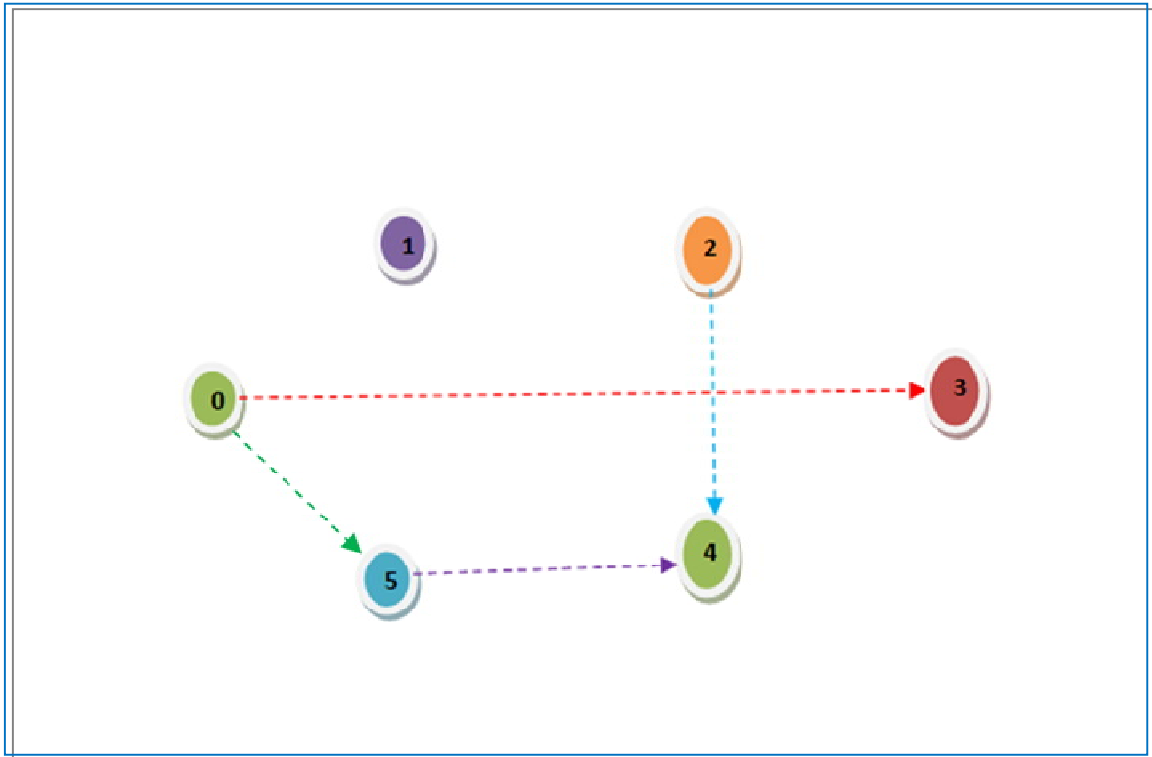


Figure 2.8: Logical Topology

## 2.2. Wavelength Division Multiplexing

The concept of *wavelength division multiplexing* (WDM) [18] was introduced in order to effectively utilize the tremendous bandwidth available in a single optical fiber. WDM allows multiple optical signals to be carried on a single optical fiber at the same time [3]. In WDM networks a fiber transmits the signal on the bandwidth which is already in use instead of providing a new bandwidth to each signal. The entire bandwidth of the optical fiber is divided in to the number of *channels*, and each channel is assigned a specific *wavelength*. Each channel can be routed independently of each other, and can carry many low speed demands, which leads to better utilization of the bandwidth. Figure 2.9 illustrates the concept of WDM. There are four different optical signals having different

wavelengths  $\lambda_1$  to  $\lambda_4$  and they are combined using multiplexer and transmitted over a single fiber.

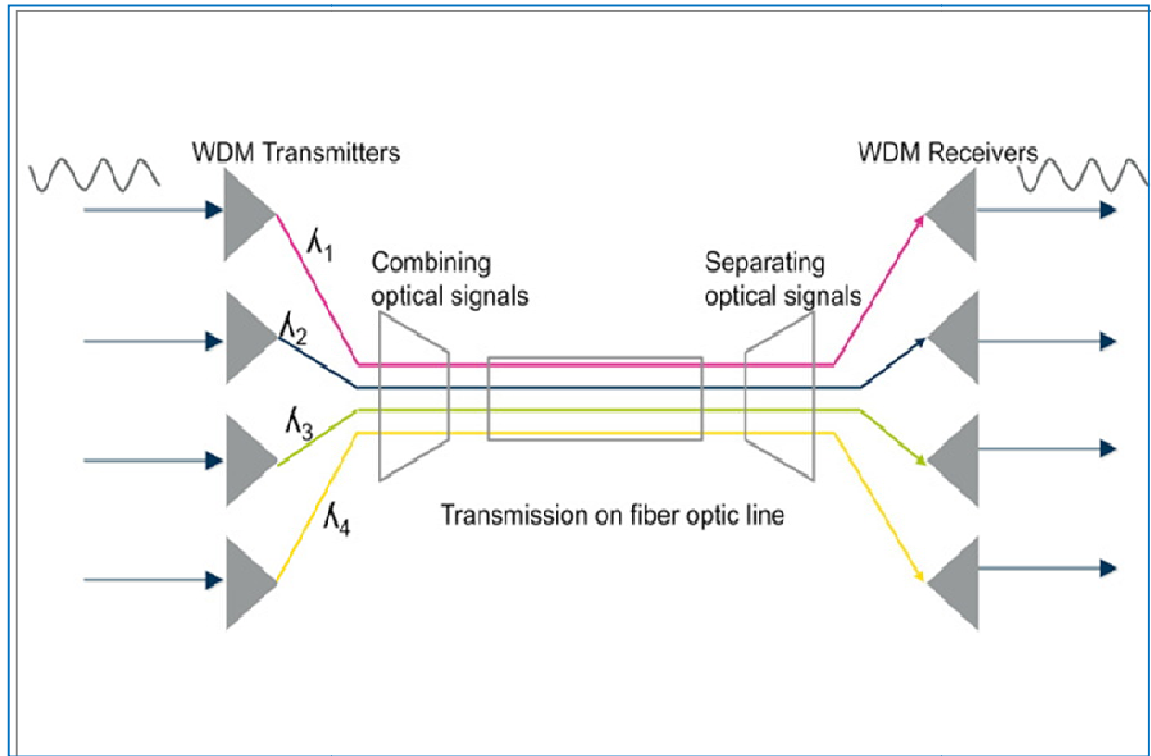


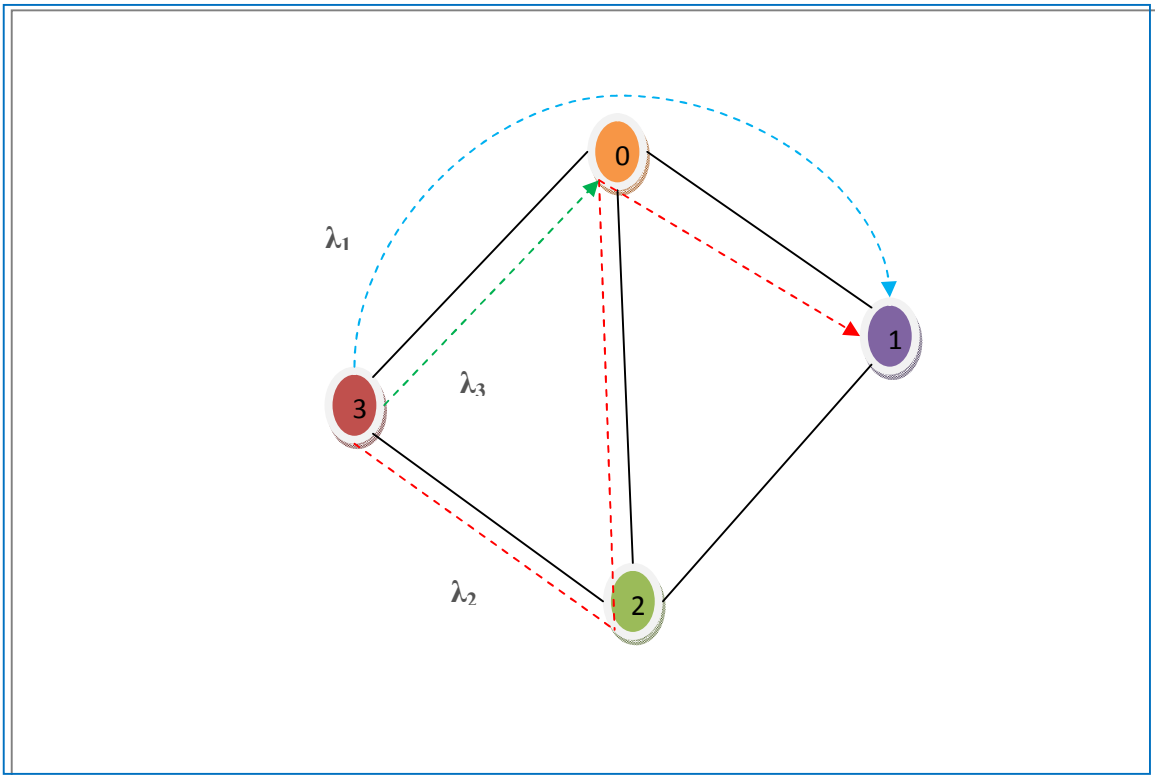
Figure 2.9: Wavelength Division Multiplexing (WDM) [17]

### 2.3. Routing and Wavelength Assignment

Routing and wavelength assignment (RWA) problem is to determine a route over physical topology and available channel on each edge of the selected route for each lightpath [7]. The objective of routing and wavelength is typically to minimize the amount of resources required to accommodate a given set of lightpaths. So in RWA we assign using which link, using which fiber and using which wavelength the source and destination node will be connected as shown in Figure 2.10.

There are two main constraints that should be satisfied for a valid RWA:

- i. Wavelength continuity constraint
- ii. Wavelength clash constraint



**Figure 2.10: Routing and Wavelength Assignment (RWA)**

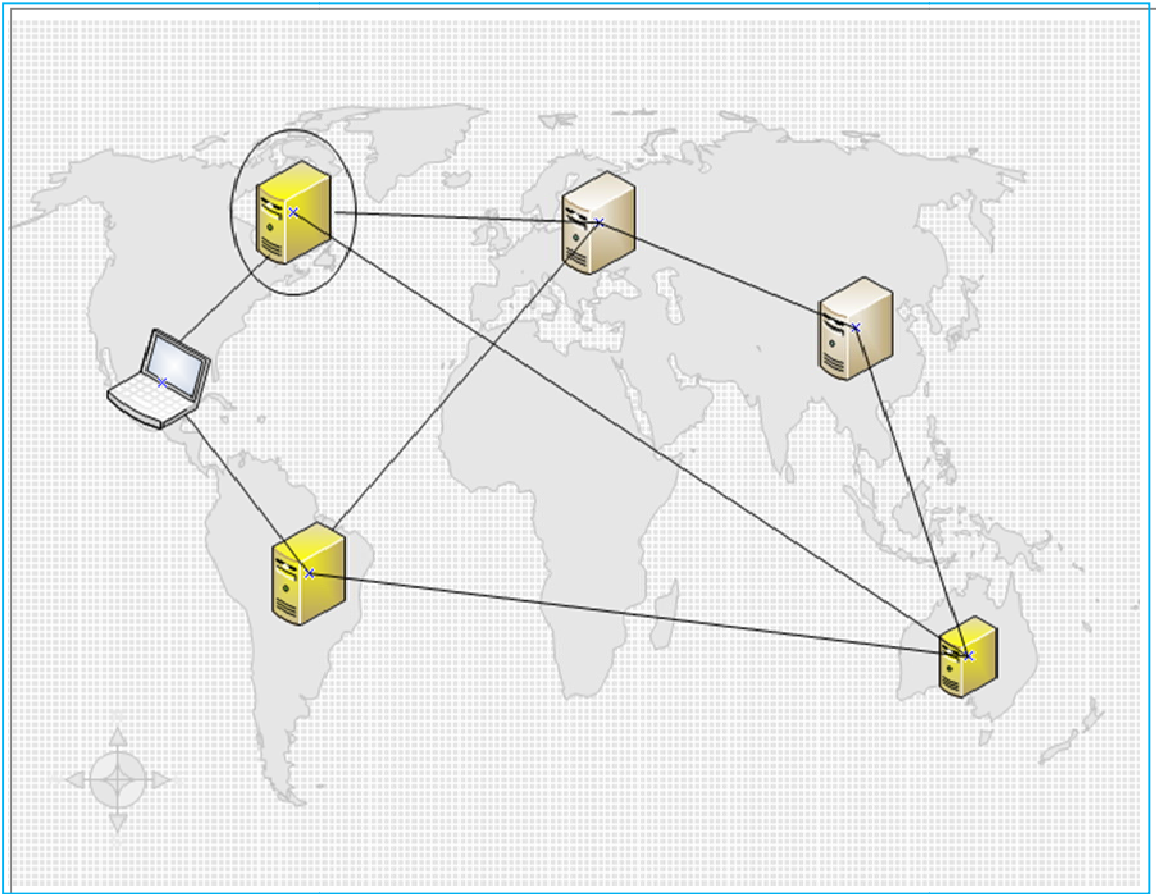
Wavelength continuity constraint states that a given lightpath must be assigned the same wavelength on each link it traverses [3]. This is necessary when there are no ‘wavelength converters’ available at the network nodes, which is typically the case. The wavelength clash constraint ensures that the same wavelength cannot be assigned to more than one lightpath on same link, at the same time.

## **2.4. Anycast Routing**

In grid computing the main goal is the completion of a task efficiently without necessarily considering the location where the job executes. The idea of *anycast* routing can be illustrated by the example of a power grid [18]. In a power or electrical grid the users do not care about the location of the power station from where they get electricity,



similarly, for the computing grid the users often may not where the computation takes place as long as their job is being executed. In *unicast* routing the source node and the destination node for each demand is fixed. In *anycast* routing the destination gets selected from the set of possible destinations.



**Figure 2.11: Anycast Routing**

Figure 2.11 shows an example of *anycast* routing. The user has a task that can be executed at one of three possible destinations, which are colored yellow. And out of these possible destinations one destination is selected, which is circled on the top. Our approach is to minimize the energy consumption of a network by efficiently selecting the destination node through anycasting.

## 2.5. Traffic Demand Allocation Models

In optical communication technology, there are three types of traffic demand allocation models:

- i) *Static traffic demand*
- ii) *Dynamic traffic demand and*
- iii) *Scheduled traffic demand*

The scheduled traffic demand model is further divided to *fixed window traffic model* and *sliding scheduled traffic model*. In static traffic demands the set up time and tear down time of a demand is known in advance and it is fixed for long time generally in months or years compared to other demand allocation models [23]. On the other hand, for dynamic lightpath demands the setup and tear down times are not known in advance. Connection requests (for lightpaths) arrive randomly and are serviced on demand, as they arrive [24]. The duration of dynamic lightpath is generally shorter than static lightpath demands. When a connection (lightpath) is no longer needed, the resources allocated to that lightpath are released and can be used for other lightpaths. In scheduled demand allocation the setup and tear down times are known in advance.

The scheduled lightpath demands are not permanent like static demand allocation but they are periodic in nature and also known in advance. Many of the real time applications such as e-science or banking applications use scheduled traffic demand allocation which requires scheduled and dedicated connections at predetermined times. The *scheduled traffic model* [24] further divides in to two categories: *fixed window demand allocation* [24] and *sliding window demand allocation* [24].

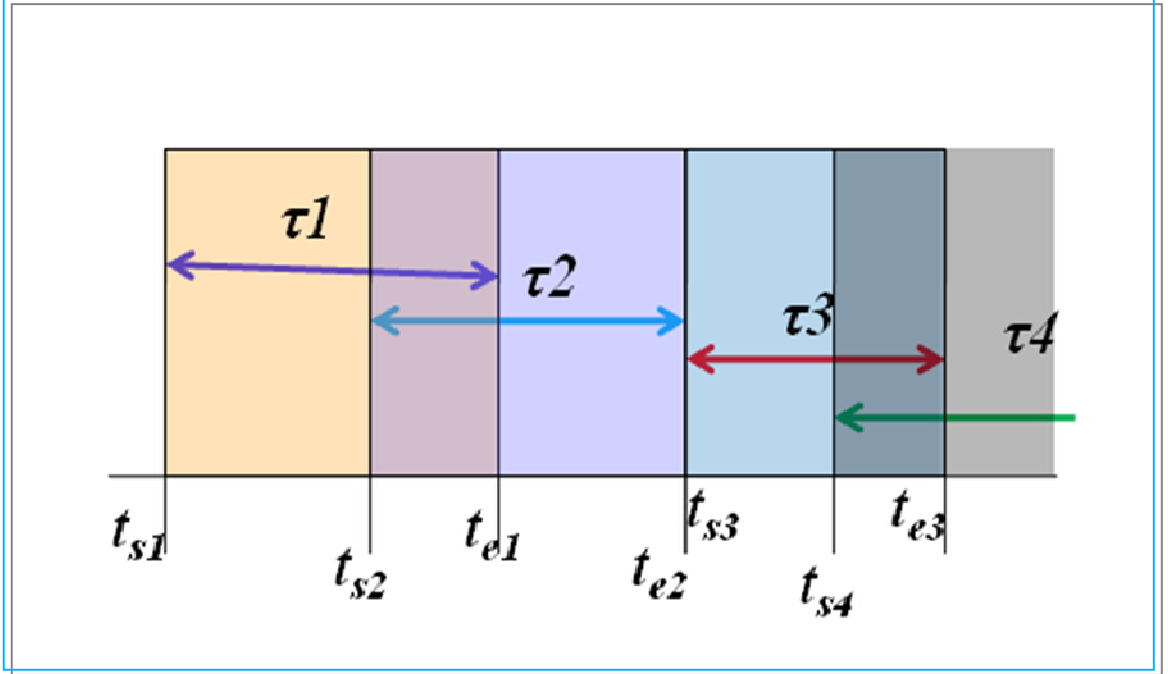


Figure 2.12: Fixed Window Demand Allocation

In the Figure 2.12 the fixed window demand allocation model is explained. In fixed window traffic model each traffic demand is represented by a tuple  $(s, d, n, t_s, t_e)$ , where  $s$  and  $d$  are source and destination nodes for demand.  $n$  represents the bandwidth requirement in terms of the number of lightpaths needed, and  $t_s$  and  $t_e$  are the setup and tear down times for the demand.

In sliding scheduled traffic demand model instead of starting and end time for demand, a larger window is specified for each demand, during which the demand must be serviced. The lightpath request for sliding scheduled demand can be represented by a tuple  $(s, d, n, \alpha, \omega, \tau)$ ; where  $s(d)$  is the source (destination)node,  $n$  is the number of required lightpaths,  $(\alpha, \omega)$  specifies the larger window and  $\tau$  denotes the holding time for each demand, where  $\tau \leq \omega - \alpha$ . The sliding window demand allocation model is explained in the Figure 2.13. In Figure 2.13, there are two different demands scheduled for larger window  $(\alpha_1, \omega_1)$  and  $(\alpha_2, \omega_2)$ . They are active during the holding times  $\tau_1$  and  $\tau_2$ . These demands can

slide inside their larger window size, so if we assign a lightpath to these demands when they are overlapping maximum with each other while sliding inside their specified window, it will be efficient utilization of resources.

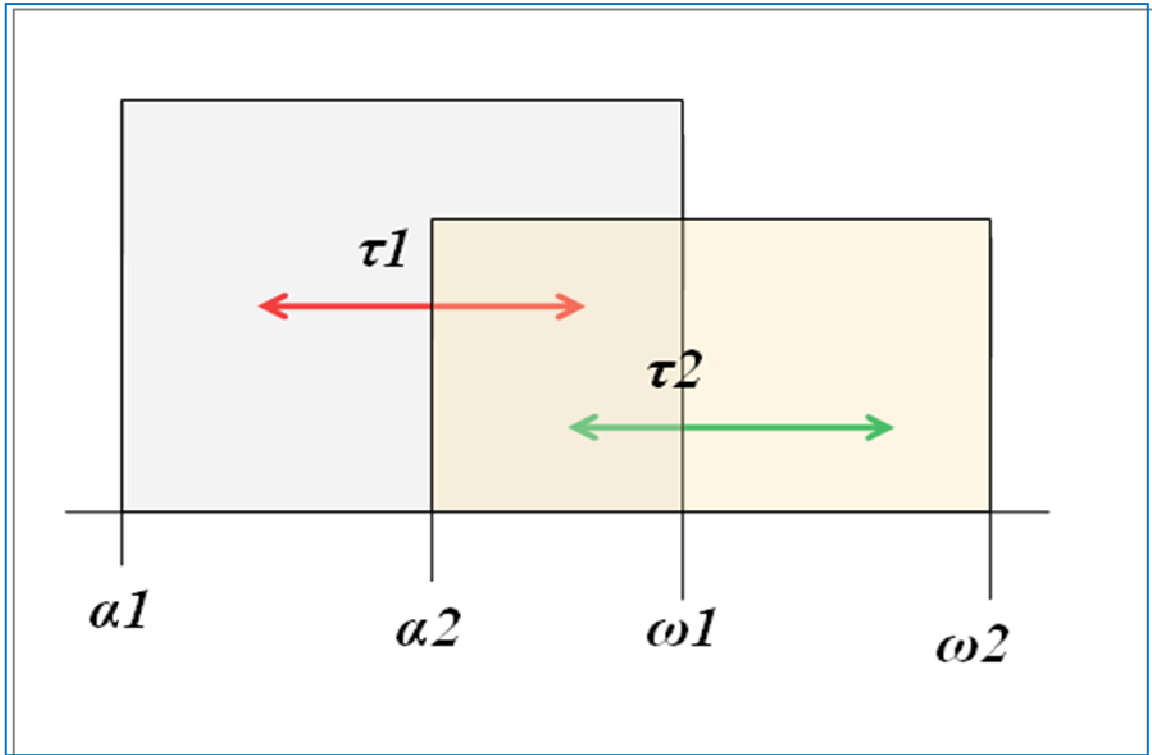


Figure 2.13: Sliding Scheduled Demand Allocation

## 2.6.Literature Review

The tremendous growth in high-bandwidth applications in the past decade has led to a corresponding increase in power consumption in today's core/transport networks. It has been predicted that “energy consumption rather than the cost of the component equipment may eventually become the barrier to continued growth” [28] for such networks. Consequently, energy efficiency of core wavelength division multiplexing (WDM) networks has received significant research attention in the last few years [20, 21]. Energy aware *unicast* routing in WDM networks has received considerable research

attention in the last ten years [23]. More recently, energy aware approaches (both heuristics and optimal formulations) using *anycast* routing has been considered in [20, 23, and 24]. The goal is to reduce both the static and dynamic (load dependent) portions of power consumption as much as possible, although static power consumption typically dominates for most network components [24]. In this section we will review in detail the most relevant papers for this thesis, which directly address the problem of energy aware *anycast* routing in optical networks.

In [19] the authors propose exploiting *anycast* principle to reduce energy in optical networks and server systems. Their proposed approach evaluates power consumption on networks with wavelength conversion and without conversion. The approach they used to solve the problem was to intelligently select the destination through *anycast* routing from the set of possible destinations by switching off unused network elements. The authors evaluate possible energy saving for optical network through allowing full wavelength conversion capability.

The inputs of the problem formulation are the network topology with optical cross connects and fiber links, which are used to connect them, along with source sites and candidate destinations. The goal is to find routes in the topology in such a way that it reduces the overall power consumption. The authors compare their proposed *anycast* routing scheme with *unicast* routing; further they compare the results for wavelength conversion and wavelength continuous networks. The authors conducted experimentation on COST-239 European networks with having 11 nodes and 26 links [19]. The numbers of candidate server destination sites are 3 and each fiber supports 16 wavelengths. The authors claim that the power consumption in fiber links accounts for 30%, while OXC

and other network node consumes 70% of total power consumption. The results obtained by authors depicts 23% less power consumption for *anycast* and 28% less power consumption for *unicast* with energy aware routing compared to shortest path routing. The authors also claim to have 20% energy consumption reduction and 29% reduction of wavelength resource usage with anycasting compared to traditional unicasting approach.

In “Reducing power consumption in wavelength routed networks by selective switch off of optical links” [20], the authors state that the growth of internet users and higher bandwidth services increased the requirement for more transmission and switching equipment with more capacity.

The authors propose ILP formulations and heuristic for their proposed scheme to reduce power consumption by selective switching off of optical links. The authors used network model of a transparent circuit switched optical network with WDM transmissions with no wavelength conversion. The client signals are assumed to be at the speed of 10 Gbps and transponders perform forward error correction operations. A lightpath can traverse through a number of OXC from source site to destination; the path also includes multiplexers, demultiplexers and amplifiers. The authors propose ILP formulations and heuristic for selective switching off of optical links. The authors claim that their proposed scheme saves between 28% to 33% energy on an average by mediating the results on daily traffic variability and also the power consumption reduces with the increase in number of wavelengths. Their model reduces power consumption by switching off unused fiber links through routing them on alternative links.

In [21], the authors state that the power consumption through Information and Communications Technology will increase tremendously in the next decade, so it is very much important to solve the energy consumption issue for the internet. They also talk about the schemes proposed like green routing, energy efficient packet forwarding, energy efficient design and selective turn off for access, metro and backbone networks in internet.

In this paper the authors consider a transport network topology defined as graph  $G(V, E)$ , where  $V$  is the set of nodes and  $E$  is the set of links. The connection requests follow the *anycast* paradigm and energy saving is done by switching off network nodes. In this paper the authors count the energy consumption on the basis of erbium doped fiber amplifiers, energy consumption due to wavelength utilization and energy consumption due to ON state of a node. In the proposed energy efficient distributed framework a node can go to sleep mode and refuse to accept transient traffic, but is still required to handle the traffic associated with already established lightpaths. The simulation results are obtained using the standard NSFNET topology, consisting of 14 network nodes and 21 links each comprising 16 number of wavelength channels. The authors claim that their proposed model reduces energy consumption of a network by 6% at all traffic loads. The results obtained by authors also depict that the average end to end network delay is maximum for sleep mode scheme compared to energy unaware and adaptive sleep mode scheme. In their proposed model each node stores two predetermined thresholds that trigger the node switching between sleep and active modes, depending on traffic load. The drawback of this model is it can drop lightpath requests due to isolated nodes.

In [22], the authors state that grid computing with resource sharing capacity is the future for large scale, data intensive applications using geographically distributed resources. They state that optical networks are ideal candidates for to fulfill the requirements of grid computing, since they have much lower per bit energy cost compared to electrical processing. The authors propose a new approach to energy aware resource allocation for optical grids with using *anycast* principle. They also propose ILP formulations for minimizing the energy consumption of a set of lightpath demands using anycasting model and a fast two stage ILP capable of generating near optimal results for larger networks.

In this paper the authors consider an IP-over –WDM network architecture [22], where each node consists of OXC connected to an IP router. In proposed model the traffic can be switched directly in optical domain if routing is not required in electrical domain, otherwise it is sent to associated router via transponders. The model considers traffic granularity at lightpath level and does not consider sub wavelength demands grooming. The authors consider power consumption at IP routers and optical switches. The authors consider various topologies ranging from 6 nodes to 14 nodes, including NSFNET and COST-239 topologies, with the number of demands ranging from 15 to 150. The authors compared their results with energy aware *unicast* algorithm and energy unaware *anycast* algorithm. The authors claim that their proposed scheme performs 35% better with 40 lightpath demands and 15% better with 120 demands. The energy savings decrease with increase in number of demands because of less availability of nodes to switch off with higher number of demands. They also claim that the optical switch requires less energy compared to IP routers and optical amplifiers in NSFNET and COST-239 topology.



In [23] the authors state that WDM optical networks can fulfill the requirements for the growing speed demands with reliability of internet, and propose an ILP formulation for energy efficient routing under the fixed window scheduled traffic model, using *anycast* principle. Each scheduled lightpath demand has a specified source node, bandwidth requirement (number of required lightpaths), starting time and ending time. In this paper the destination node is selected from the set of possible destinations. The authors consider power consumption at IP routers, optical switches and pre, post and inline amplifiers. The authors conducted experiments on standard 14-node NSFNET and 11-node COST-239 topology. The authors compared their results with energy aware *unicast*, energy unaware *anycast* and energy aware but holding time unaware *anycast* routing approaches. The authors claim that their proposed approach reduces energy 21% to 27% compared to next best technique, which was energy aware *unicast* routing. Their approach considers applications with periodic bandwidth demands and demand holding time to reduce energy consumption.

- **Summary of related work**

The following table summarizes the most related papers to this work.

**Table 2.1: Literature review summary**

Reference	Traffic Model	Traffic Granularity	Routing Scheme	Solution Approach
Buysee et al. 2011	Static traffic model	Sub- wavelength	Anycasting	ILP
Coiro et al. 2011	Static traffic model	Sub- wavelength	Unicasting	ILP/ Heuristic
Tafari et al. 2012	Dynamic traffic model	Lightpath	Manycasting	ILP
Chen et al. 2013	Static traffic model	Lightpath	Anycasting	ILP
Chen et al. 2014	Fixed Window traffic model	Lightpath	Anycasting	ILP

## CHAPTER 3

# Energy Efficient Anycast Routing for Sliding Scheduled Lightpath Demands

### 3.1. Introduction

This chapter introduces the proposed ILP using *anycast* principle for sliding scheduled lightpath demands allocation. The objective here is to minimize the network's energy consumption to accommodate the demand set. The global power consumption of electricity for Internet is growing at the rate of 9% per year; however the resources like power stations or power grids which supply electricity to this are increasing at the rate of 3% per year [2]. This shows there is a 6% gap between demand and supply for electricity [2]. Energy requirements become bottleneck for designing many high speed data communication applications.

### 3.2. Network Energy Model

We consider a transparent IP-over-WDM network, which consists of optical cross connect switches connected to IP router. We consider power consumption both at network nodes and fiber links. The total power consumption by IP router, optical switch and fiber links can be calculated using following equations.

$$P_{IP} = P_{IP\_low} + P_{IP\_ON} + P_{IP\_dyn} * t_{IP} \quad (3.1)$$

$$P_{SW} = P_{SW\_low} + P_{SW\_ON} + P_{\lambda} * t_{\lambda} \quad (3.2)$$

$$P_{\text{link}}^e = P_{\text{pre}} + P_{\text{post}} + P_{\text{inline}} \quad (3.3)$$

In both cases  $P_{\text{IP}}$  and  $P_{\text{SW}}$ , the first term  $P_{\text{IP}_{\text{low}}}$  and  $P_{\text{SW}_{\text{low}}}$  define the power consumption of a device at a low power state or inactive state when no traffic passing through it. The second terms denotes the *static* power consumption for turning the device on, so that it can carry some traffic. The third term is the *dynamic* component of the power consumption, which increases with the amount of traffic passing through the node. The last equation  $P_{\text{link}}^e$  represents the power consumption of an active fiber link. It is the addition of power consumption of all active pre, post and inline active amplifiers. Each fiber link  $e$  has one pre and one post amplifier and one or more inline amplifiers, depending on the length of the link. Table 3.1 shows the power consumption of different network devices considered in this thesis.

Table 3.1: power consumption of network devices [22]

Device	Symbol	Power Consumption
IP router (static)	$P_{\text{IP}_{\text{on}}}$	150W
IP router (dynamic)	$P_{\text{IP}_{\text{dyn}}}$	17.6W per $\lambda$
Electronic control system	$P_{\text{SW}_{\text{ON}}}$	100W
Optical switch	$P_{\lambda}$	1.5W per $\lambda$
Pre-amplifier	$P_{\text{pre}}$	10W
Post-amplifier	$P_{\text{post}}$	20W
In-line amplifier	$P_{\text{ILA}}$	15W
Transponder	$P_{\text{TR}}$	34.5W

### **3.3.Solution Approach**

To solve the energy consumption problem, there are mainly two schemes: hardware improvement schemes and efficient routing schemes [25]. For the hardware improvement, the solution can be introduction of the photonic routers or improvement of laser energy efficiency [25]. Lasers are used in optical networks to transmit the information through fiber. The introduction of energy efficient lasers can be a useful solution towards reducing the energy consumption in optical networks. The introduction of photonic routers allows routing of lightpaths directly in optical domain without need of optical-electrical couplers.

Our approach to addresses the energy minimization problem by developing energy efficient routing schemes. We consider a set of sliding scheduled lightpath demands originating from different sources, and select the route and destination for each demand in such a way that the overall energy consumption is minimized.

The main idea is to select a destination node and routing path for each demand, such that the components required establishing the lightpath can be shared by other lightpaths as much as possible. For example in Figure 3.1, suppose the circled destination node and highlighted path is already ‘active’. If a new demand is to be established and we select a different destination and path, this will require turning ‘on’ additional network components. On the other hand, if we select the destination which is circled, then all the network components connecting the source to the destination is already turned on, and the additional traffic load on these components will only increase the energy consumption incrementally. The notable thing here is that the power requirement of adding extra traffic on a node or link is significantly lower compared to turning on additional network

components [22]. Existing work on energy efficient RWA focused on static, dynamic or fixed window demand allocation [23, 24]. Unlike the previous work, we address the problem of *sliding scheduled demand allocation* based on *anycast* principle for WDM optical networks.

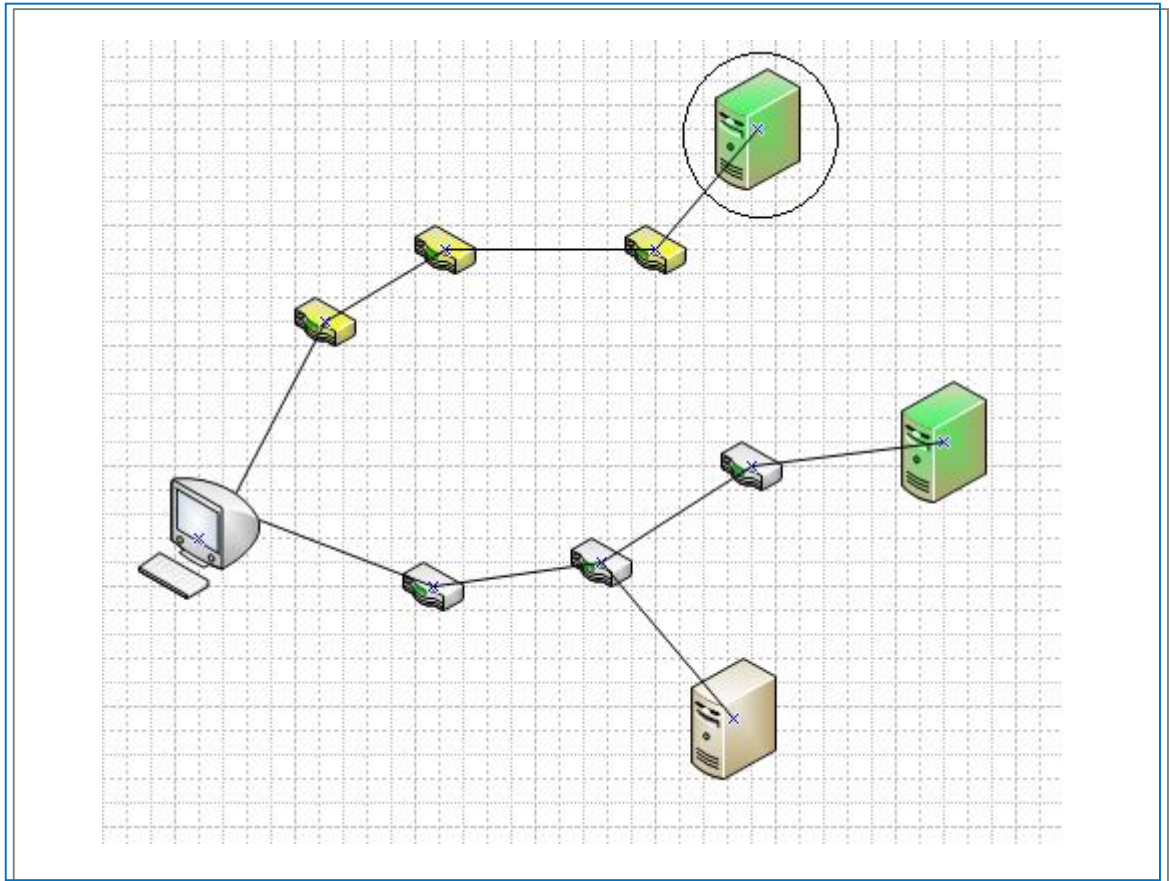


Figure 3.1: Energy Efficient Solution Approach

The ILP performs EA-RWA (Energy aware routing and wavelength assignment) for sliding scheduled traffic model. The objective of the ILP is to find the total energy consumption of the network by reducing it through energy efficient routing. The constraints find route to destination based on *anycast/ unicast* and try to minimize the number of active network components.

### 3.4. Proposed Integer Linear Program

In this section we present our ILP formulation for energy aware RWA of scheduled lightpath demands under the sliding window traffic model. The following parameters are given as input to the ILP.

Inputs

- Physical topology  $G[N,E]$
- $N$ : Set of nodes in the network
- $E$ : Set of edges in the network
- $P$ : Set of scheduled lightpath demands to be routed over the physical topology.
- $(i, j)$ : edge in the network from node  $i$  to node  $j$
- $D_p$  = set of candidate destination nodes for lightpath demand  $p$
- Set of lightpath demand requests  $(s_p, D_p, n_p, \alpha_p, \omega_p, \tau_p)$ , where  $s(d)$  is the source (destination) node,  $n$  is the number of required lightpaths,  $(\alpha, \omega)$  specifies the larger window and  $\tau$  denotes the holding time for each demand, where  $\tau \leq \omega - \alpha$ .
- $K$  = Set of channels available on each fiber link
- $m = 1, 2, 3..m_{max}$ ,  $m$  is the number of intervals ( $0 \leq m \leq 23$ )
- $M$  = a large constant,  $M$  is the large constant that represents the entire time interval from the beginning of the earliest window to the end of the final window.
- $C_{ip}^s$  = static component of IP router power consumption
- $C_{ip}^d$  = dynamic component of IP router power consumption
- $C_{sw}^s$  = static component of optical switch power consumption
- $C_{sw}^d$  = dynamic component of optical switch power consumption

➤  $C_{link}^e$  = power consumption of link e

There are following three types of variables are defined as binary variables.

- a) Channel assignment variables:  $\omega_{k,p}$  for wavelength continuous network
- b) Route assignment variables:  $r_{i,m}$ ,  $s_{i,m}$  and  $t_{e,m}$ ,  $x_{e,p}$
- c) Scheduling variables:  $st_{p,m}$  and  $a_{p,m}$

It is well known that the computational complexity of an ILP increases exponentially with the number of integer variables [23]. Therefore, all remaining variables are defined as *continuous* variables; however some of them are restricted to take only *integer* values, by careful use of constraints.

### ***Binary variables***

- $r_{i,m} = 1$ , if IP router at node i is being used during interval m.
- $s_{i,m} = 1$ , if optical switch at node i is being used during interval m.
- $t_{e,m} = 1$ , if link e is being used during interval m.
- $y_{p,i}(x_{e,p}, \omega_{k,p}) = 1$ , if LP uses node i (link e, channel k).
- $d_{p,i} = 1$ , if node i is selected as destination node for LP p.
- $a_{p,m} = 1$ , if LP p is active during interval m.
- $st_{p,m} = 1$ , if m is the starting interval for LP p.

### ***Continuous variables***

- $r_{i,m}^p = 1$ , if LP uses IP router at node i during interval m.
- $s_{i,m}^p = 1$ , if LP uses optical switch at node i during interval m.



- $a_{k,e}^p = 1$ , if LP  $p$  uses channel  $k$  on link  $e$ .
- $t_{e,m}^p = 1$ , if link  $e$  is being used during interval  $m$ .

**ILP formulation**

$$\text{Minimize } \sum_m [\sum_{i \in N} (C_{ip}^s \cdot r_{i,m} + \sum_{p \in P} C_{ip}^d \cdot r_{i,m}^p) + \sum_{i \in N} (C_{sw}^s \cdot s_{i,m} + \sum_{p \in P} C_{sw}^d \cdot s_{i,m}^p) + \sum_{e \in E} C_{link}^E \cdot t_{e,m}] \quad (1)$$

**Subject to:**

*Destination node selection constraints:*

$$\sum_{i \in D_p} d_{p,i} = 1, \forall p \in P \quad (2a)$$

$$d_{p,i} = 0, \forall i \notin D_p, \forall p \in P \quad (2b)$$

*Route selection constraints:*

$$\sum_{e: i \rightarrow j \in E} x_{e,p} - \sum_{e: j \rightarrow i \in E} x_{e,p} = \begin{cases} 1 & \text{if } i = S_p \\ -d_{p,i} & \text{otherwise} \end{cases} \quad \forall i \in N, p \in P \quad (3)$$

$$y_{p,i} = \sum_{j: (e: i \rightarrow j \in E)} x_{e,p}, \forall i \in N, p \in P \quad (4)$$

*IP router usage constraints:*

$$d_{p,i} + a_{p,m} - r_{i,m}^p \leq 1, \forall p \in P, \forall i \in D_p, \forall m, \alpha_p \leq m \leq \omega_p \quad (5a)$$

$$d_{p,i} \geq r_{i,m}^p, \forall p \in P, \forall i \in D_p, \forall m, \alpha_p \leq m \leq \omega_p \quad (5b)$$

$$a_{p,m} \geq r_{i,m}^p, \forall p \in P, \forall i \in D_p, \forall m, \alpha_p \leq m \leq \omega_p \quad (5c)$$

$$\frac{\sum_p r_{i,m}^p}{M} \leq r_{i,m}, \forall p \in P, \forall i \in D_p, \forall m \quad (5d)$$

$$r_{i,m} \leq \sum_p r_{i,m}^p, \forall p \in P, \forall i \in D_p, \forall m \quad (5e)$$

*Optical switch usage constraints:*

$$a_{p,m} + (y_{p,i} + d_{p,i}) - s_{i,m}^p \leq 1, \forall p \in P, \forall i \in D_p, \forall m, \alpha_p \leq m \leq \omega_p \quad (6a)$$

$$a_{p,m} \geq s_{i,m}^p, \forall p \in P, \forall i \in D_p, \forall m, \alpha_p \leq m \leq \omega_p \quad (6b)$$

$$(d_{p,i} + y_{p,i}) \geq s_{i,m}^p, \forall p \in P, \forall i \in D_p, \forall m, \alpha_p \leq m \leq \omega_p \quad (6c)$$

$$\frac{\sum_p s_{i,m}^p}{M} \leq s_{i,m}, \forall p \in P, \forall i \in D_p, \forall m \quad (6d)$$

$$s_{i,m} \leq \sum_p s_{i,m}^p, \forall p \in P, \forall i \in D_p, \forall m \quad (6e)$$

*Fiber link usage constraints:*

$$x_{e,p} + a_{p,m} - t_{e,m}^p \leq 1, \forall p \in P, \forall e \in E, \forall m, \alpha_p \leq m \leq \omega_p \quad (7a)$$

$$a_{p,m} \geq t_{e,m}^p, \forall p \in P, \forall e \in E, \forall m, \alpha_p \leq m \leq \omega_p \quad (7b)$$

$$x_{e,p} \geq t_{e,m}^p, \forall p \in P, \forall e \in E, \forall m, \alpha_p \leq m \leq \omega_p \quad (7c)$$

$$\frac{\sum_p t_{e,m}^p}{M} \leq t_{e,m}, \forall p \in P, \forall e \in E, \forall m \quad (7d)$$

$$t_{e,m} \leq \sum_p t_{e,m}^p, \forall p \in P, \forall e \in E, \forall m \quad (7e)$$

*RWA constraints:*

$$\sum_{k \in K} \omega_{k,p} = 1, \forall p \in P \quad (8)$$

$$\omega_{k,p} + x_{e,p} - a_{k,e}^p \leq 1, \forall k \in K, \forall e \in E, \forall p \in P \quad (9)$$

$$\omega_{k,p} \geq a_{k,e}^p, \forall k \in K, \forall e \in E, \forall p \in P \quad (10)$$

$$x_{e,p} \geq a_{k,e}^p, \forall k \in K, \forall e \in E, \forall p \in P \quad (11)$$

$$a_{k,e}^p + a_{p,m} + a_{k,e}^q + a_{q,m} \leq 3, \forall k \in K, \forall e \in E, \forall p, q \in P, \forall m, \alpha_p \leq m \leq \omega_p \quad (12)$$

*Demand scheduling constraints:*

$$\sum_m st_{p,m} = 1, \forall p \in P, \forall m, \alpha_p \leq m \leq \omega_p \quad (13)$$

$$\sum_m a_{p,m} = \tau_p, \forall p \in P, \forall m, \alpha_p \leq m \leq \omega_p \quad (14)$$

$$a_{p,m+j} \geq st_{p,m}, \forall p \in P, 0 \leq j < \tau_p, \forall m, \alpha_p \leq m \leq \omega_p \quad (15)$$

### 3.4.1. Justification of the ILP

The objective function in (1) tries to minimize the total number of active network components.  $C_{ip}^s$  and  $C_{sw}^s$  are the *static* components of power consumption in IP routers and optical switches respectively. The variables which  $r_{i,m}(s_{i,m})$  will be set 1 if the IP router (optical switch) at node  $i$  is being used during interval  $m$ .  $C_{ip}^d$  and  $C_{sw}^d$  represent the *dynamic* component of power consumption of an IP router and optical switch

respectively. In other words  $C_{ip}^d(C_{sw}^d)$  represents the *incremental* power consumption for each lightpath routed through the router (optical switch). Therefore,  $\sum_{p \in P} C_{ip}^d \cdot r_{i,m}^p$  ( $\sum_{p \in P} C_{sw}^d \cdot s_{i,m}^p$ ) represents the *total* dynamic power consumption for all lightpaths  $p$  that are using the router (optical switch) at node  $i$  during interval  $m$ .  $C_{link}^e$  is the power consumption of an *active* link  $e$ , i.e. a link which has at least one lightpath using the link. This value does not depend on the number of lightpaths using the link. The variable  $t_{e,m}$  is set to 1 if link  $e$  is active during interval  $m$ . So,  $\sum_{e \in E} C_{link}^e \cdot t_{e,m}$  represents the *total* power consumption for all links, during interval  $m$ . Similarly,  $\sum_{i \in N} (C_{ip}^s \cdot r_{i,m} + \sum_{p \in P} C_{ip}^d \cdot r_{i,m}^p)$ , ( $\sum_{i \in N} (C_{sw}^s \cdot s_{i,m} + \sum_{p \in P} C_{sw}^d \cdot s_{i,m}^p)$ ) represents the total power consumption for all IP routers (optical switches) during interval  $m$ . Finally, the outer summation ( $\sum_m$ ) in the objective function gives the total power consumption over all intervals.

Constraint (2a) selects exactly one destination for demand  $p$ . Constraint (2b) sets the value of  $d_{p,i} = 0$ , if  $i \notin D_p$ . This ensures that destination nodes are selected only from the set of candidate destinations for each demand  $p$ . Constraint (3) is the standard flow conservation constraint, which is used to find a feasible path from source node  $s_p$  to the selected destination  $d_{p,i}$  for each demand  $p$ .

Constraint (4) identifies the nodes that are used along the selected path of a demand  $p$ . The optical switches at all these nodes will be used by demand  $p$ , during the intervals in which it is active.

Constraint (5a)-(5c) are used to set the value of  $r_{i,m}^p = 1$ , if router at node  $i$  is being used by demand  $p$  during interval  $m$ . Constraint (5a) states that if  $d_{p,i} = 1$ , (i.e. node  $i$  is the

selected destination node for demand  $p$ ) and  $a_{p,m} = 1$ , (i.e. node demand  $p$  is active during interval  $m$ ) then  $r_{i,m}^p = 1$ . Constraints (5b) and (5c) state that if either  $d_{p,i} = 0$  or  $a_{p,m} = 0$ , then  $r_{i,m}^p$  must be set to 0. In constraint (5d) if there is at least one demand  $p$  which uses the IP router at node  $i$  during interval  $m$  (i.e.  $r_{i,m}^p = 1$ ), then the left hand side of the constraint will be greater than 0. This forces  $r_{i,m} = 1$ , since it is a *binary* variable. On the other hand constraint (5e) states that if  $\sum_p r_{i,m}^p = 0$ , (i.e.  $r_{i,m}^p = 0, \forall p \in P$ ), then  $r_{i,m} = 0$ . In other words, constraints (5d) and (5e) together set the value of  $r_{i,m} = 1$ , if the IP router at node  $i$  is being used by at least one demand (possibly more than 1) during interval  $m$ , and set  $r_{i,m} = 0$  otherwise.

Constraints (6a) - (6e) are very similar to constraints (5a) – (5e) and are used to determine if the optical switch at node  $i$  is being used by at least one lightpath demand during interval  $m$ . These constraints together set the value of  $s_{i,m} = 1$ , if the optical switch at node  $i$  is being used by at least one demand (possibly more than 1) during interval  $m$ , and set  $s_{i,m} = 0$  otherwise. Similarly, constraints (7a) - (7d) together set the value of  $t_{e,m} = 1$ , if fiber link  $e$  is being used by at least one demand (possibly more than 1) during interval  $m$ , and set  $t_{e,m} = 0$  otherwise.

Constraint (8) enforces the *wavelength continuity constraint*, which states that a lightpath demand  $p$  can be allocated exactly 1 wavelength in along its entire route. Constraints (9)-(11) ensures that  $a_{k,e}^p$  is restricted to take on values of 0 or 1. This lowers the number of integer variables in the ILP, which leads to less complexity of the ILP. Constraints (9)-(11) set the value of  $a_{k,e}^p$  to 1, if the lightpath  $p$  uses channel  $k$  on link  $e$ , and set it to 0, otherwise.

Constraint (12) enforces the *wavelength clash constraint*, which states that two lightpaths demands  $p$  and  $q$  cannot use same channel  $k$  on the same link  $e$  during the same interval  $m$ . If two demands  $p$  and  $q$  both use the same channel  $k$  on a link  $e$ , then we will have  $a_{k,e}^p = 1$  and  $a_{k,e}^q = 1$ . This will be a valid assignment if and only if demands  $p$  and  $q$  are time disjoint, i.e. they are never active during the same time interval. If there is at least one time interval  $l$ , during which both  $p$  and  $q$  are active, then we will have  $a_{p,l} = 1$  and  $a_{q,l} = 1$ , during interval  $l$ . In this case, the left hand side of constraint (12) will have a value of 4, which would violate constraint (12). Hence, such an assignment will not be allowed.

In the *fixed window* traffic model, it is trivial to determine the start and end times of demands because they are specified in inputs. In *sliding window* model the ILP itself determines the most suitable start time for each demand, based on other demands' start times and durations. Constraints (13)- (15) find best starting interval for each lightpath demand and consequently determines the value of  $a_{p,m}$  for each time interval, i.e. they determine the intervals during which a demand  $p$  will be active. Constraint (13) sets the actual starting time for demand  $p$  during interval  $m$ , and states that there can be exactly one starting interval for each demand. Constraint (14) sets the number of active intervals for each demand  $p$  to its demand holding time  $\tau_p$ . Finally, constraint (15) states that demand  $p$  will be active for  $\tau_p$  consecutive time intervals, beginning with the selected starting interval of  $st_{p,m}$  for demand  $p$ .

### 3.4.2. Modification for fixed window model

For *fixed window* model, the actual start time for the demand is same as the starting time of its window. This means  $\tau_p = \omega_p - \alpha_p + 1$  and  $st_p = \alpha_p, \forall p \in P$ . So in *fixed window* model, the starting time is known in advance. This can be easily handled by the proposed ILP, by simply adding an extra constraint as follows:

$$St_{p,\alpha_p} = 1, \forall p \in P \quad (16)$$

Constraint (16) states that  $\alpha_p$  will be automatically selected as the starting interval for demand  $p$ , i.e. the ILP do not have the option of selecting any other time interval as the starting interval for  $p$ . Once the starting interval is set, all other constraints function in a similar manner as for *sliding window* model.

### 3.5. An Illustrative Example

In order to illustrate the effectiveness of the proposed approach, we consider a simple four node topology with three lightpath demands. As shown in the Figures 3.2 and 3.3, the topology has four nodes and five bi-directional links. There are three lightpath demands, the first demand  $p_1$  is specified as  $p_1 = (2, \{1\}, 2, 4, 2)$ . This demand has source node  $s_1=2$ , the set of possible destinations  $D_1 = \{1\}$ , the demand must be scheduled within intervals  $\alpha_1 = 2, \omega_1 = 4$  and the demand holding time  $\tau_2=2$  intervals. The second demand  $p_2$  is specified as  $p_2 = (1, \{3\}, 1, 4, 3)$  and third demand is  $p_3 = (2, \{3, 4\}, 3, 5, 2)$ . Based on this demand set the ILP routes the lightpaths as shown in the Figure 3.3(a, b, c) and schedules demands as shown in Figure 3.2(a, b).

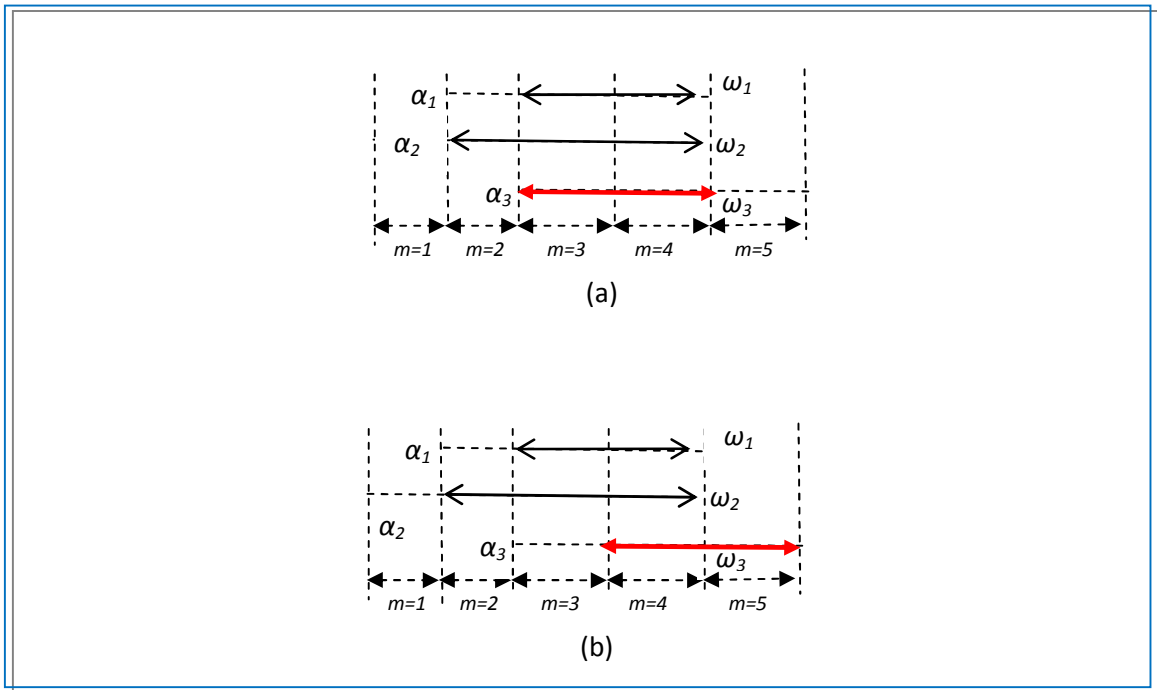


Figure 3.2: Illustrative Example for possible start time for  $P_3$

As shown in Figure 3.3 there are three possible alternative routes for demand  $p_3$ . Also demand  $p_3$  is active during either  $m=3$  and  $m=4$  or  $m=4$  and  $m=5$  with its holding time 2 as shown in Figure 3.2. So demand  $p_3$  can have two possible starting times  $m=3$  and  $m=4$ , as  $m=5$  is not possible as starting time.

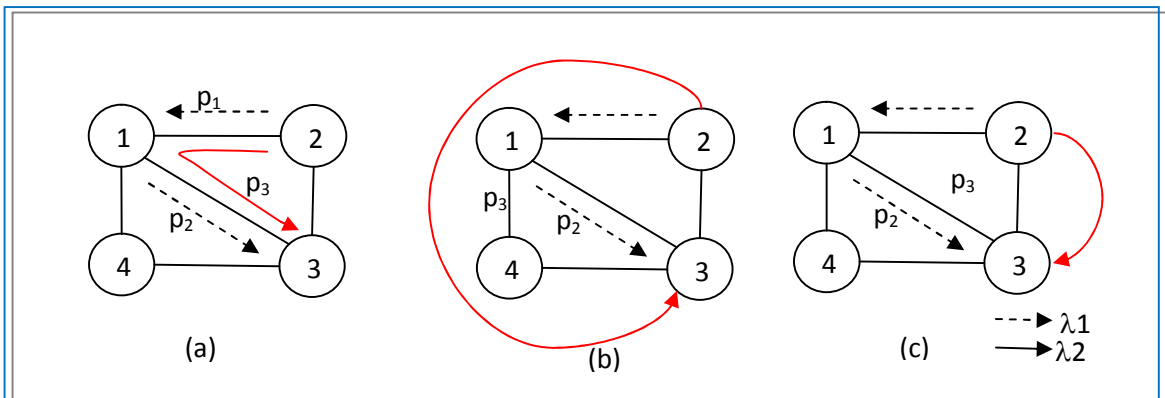


Figure 3.3: Possible destination and routes for  $P_3$



For the given possibilities we have six different cases to route the lightpath  $p_3$  from node 2  $\rightarrow$  node 3 with scheduling it in to two possible intervals, which are given below:

Case 1: node 2  $\rightarrow$  node 1  $\rightarrow$  node 3 with start time  $m=3$

Case 2: node 2  $\rightarrow$  node 1  $\rightarrow$  node 3 with start time  $m=4$

Case 3: node 2  $\rightarrow$  node 1  $\rightarrow$  node 4  $\rightarrow$  node 3 with start time  $m=3$

Case 4: node 2  $\rightarrow$  node 1  $\rightarrow$  node 4  $\rightarrow$  node 3 with start time  $m=4$

Case 5: node 2  $\rightarrow$  node 3 with start time  $m=3$

Case 6: node 2  $\rightarrow$  node 3 with start time  $m=4$

Now for the given cases we can count number of active nodes and number of active links as shown in the table 3.2 and 3.3.

**Table 3.2: Illustrative Example**

Intervals	m=1		m=2		m=3		m=4		m=5	
Case #	Active nodes	Active Links	Active nodes	Active Links	Active nodes	Active Links	Active nodes	Active Links	Active nodes	Active Links
<b>Case 1</b>	0	0	2	1	3	2	3	2	0	0
<b>Case 2</b>	0	0	2	1	3	2	3	2	3	2
<b>Case 3</b>	0	0	2	1	4	4	4	4	0	0
<b>Case 4</b>	0	0	2	1	3	2	4	4	4	3
<b>Case 5</b>	0	0	2	1	3	3	3	3	0	0
<b>Case 6</b>	0	0	2	1	3	2	3	3	2	1

Table 3.3: Number of active nodes and links for each case

	Number of Active Nodes	Number of active Links
<b>Case 1</b>	8	5
<b>Case 2</b>	11	7
<b>Case 3</b>	10	9
<b>Case 4</b>	13	10
<b>Case 5</b>	8	7
<b>Case 6</b>	10	7

For an example, in demand  $p_3$  two possible destinations are node 3 and node 4. Now for demand  $p_3$ , if we select the node 3 as destination other than node 4 then it allows node 4 to remain in low power state. Node 3 is already in use by other two demands  $p_1$  and  $p_2$ . Also the route  $2 \rightarrow 1 \rightarrow 3$  is selected for demand  $p_2$ , rather than shorter route  $2 \rightarrow 3$ . The reason behind this is links  $2 \rightarrow 1$  and  $1 \rightarrow 3$  are already in use by other demands  $p_1$  and  $p_2$ . This means that optical amplifiers on link  $2 \rightarrow 3$  can remain in low power state. In scheduling  $p_1$  and  $p_2$  start during interval  $m=3$  and  $m=2$  rather than intervals  $m=1$  and  $m=2$ . This allows  $p_1$  and  $p_2$  to remain active for the entire duration of demand  $p_3$ . This shows that the network components will be active for minimum amount of time which leads to less energy consumption. As shown in table 3.3 the number of active links and number of active nodes are minimum for case 1, which uses our proposed routing scheme for RWA.

# Chapter 4

## EXPERIMENTATION AND RESULTS

In this chapter we present experimental results, obtained using our proposed ILP formulations. The ILP is able to generate optimal results for practical sized problems. Our ILP formulation considers all possible paths between source node and destination node in order to give optimal results.

### 4.1.Simulation Parameters

To perform experiments for our proposed ILP formulations, we considered three well known topologies ranging in size from 11 nodes to 24 nodes. This includes the standard NSFNET [24] and COST-239 [24] topologies as shown in Figure 4.1 – 4.3. In our experimentation we have considered the network size ranging from 11-24 nodes as we are addressing the network which supports large volume of data transmission with relatively high speed like data-center networks and grid applications. We have performed experiments considering 10, 20, 40 and 80 lightpaths. The simulation was run 5 times for each specified demand size and specified network topology. We have considered number of factors for demand set such as length of the links, the number of available destination nodes and the distribution of demands. The results obtained from the simulations, correspond to average values (rounded to the nearest integer) over different experiment runs. The simulation was carried out with IBM ILOG CPLEX 12.6.2 [30].

For each given network topology, we have tested our proposed approach with different sized demand sets and different demand time correlations  $\delta$  as defined in [29].

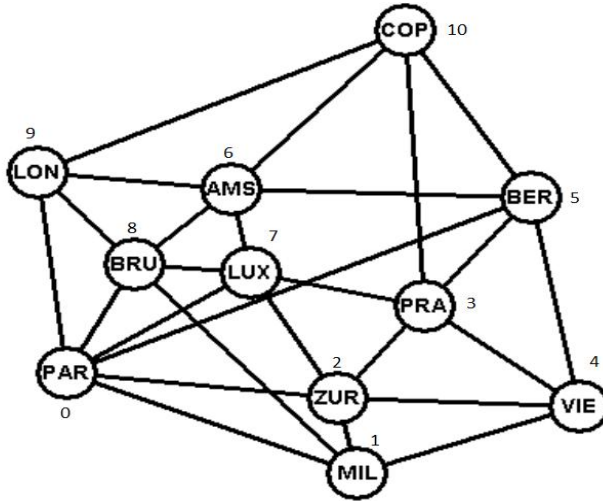


Figure 4.1: Topology 11-node network: 24 links (COST-239)

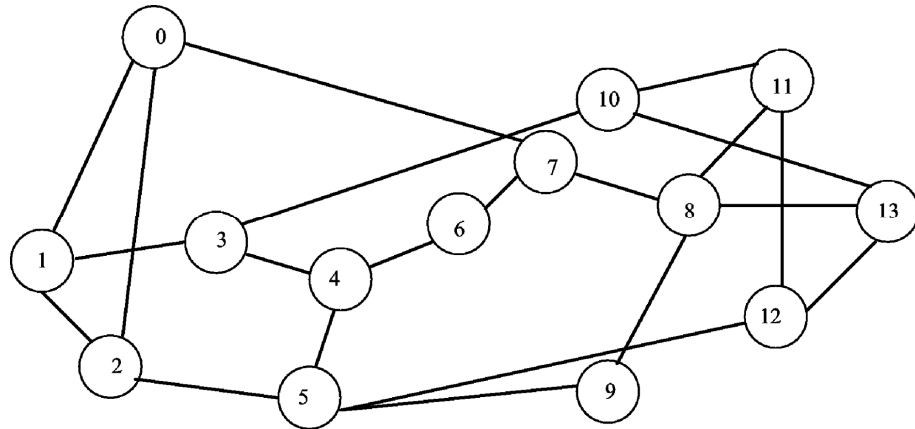


Figure 4.2: Topology 14-node network: 21 links (NSFNET)

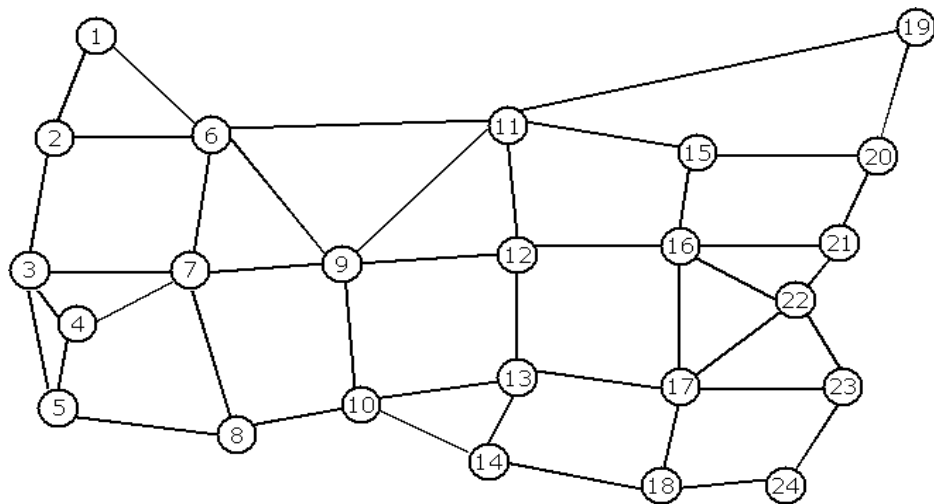


Figure 4.3: Topology 24-node network: 43 links

The demand time correlation  $\delta$  determines the overlapping between different demands. If  $\delta=0$ , it means that the demands do not overlap in time, so RWA can be done for each demand separately.

## **4.2. Comparison of energy consumption for ILP formulations**

It has been already shown that energy aware *anycast* routing under the fixed window traffic demand allocation, where demand start time and end times are specified beforehand, can lead to energy savings compared to both energy- unaware *anycast* and energy aware *unicast* approaches [24]. In this thesis, we investigate how much *additional* improvements can be achieved using *sliding* scheduled lightpath demand allocation, even over previous best performing model.

In this section we present the simulation results for joint scheduling and routing of scheduled lightpath demands in optical grid networks. The results reported in this section are average results based on at least five simulation runs.

For the simulations we have considered four distinct scenarios:

- a) Energy aware *anycast* sliding scheduled traffic model (*EA-anycast-SSLD*): This is our proposed approach, where the ILP selects the best possible destination node and start time for each demand, and then performs RWA.
- b) Energy aware *anycast* fixed window traffic model (*EA-anycast-FW*): In this case the ILP is free to choose a suitable destination node, but the start time of each demand is fixed.

- c) Energy aware *unicast* sliding scheduled traffic model (*EA-unicast-SSLD*): In this case the destination node is specified beforehand, but the ILP can select suitable start time for each demand.
- d) Energy aware *unicast* fixed window traffic model (*EA-unicast-FW*): In this case both the destination node and start time of demand are fixed and the ILP only performs the RWA for each demand.

Figure 4.4 shows the results for 11-node topology (COST-239), with 16 channels per fiber and demand set sizes of 10, 20 and 40. The Y-axis shows the normalized energy minimization for each case with respect to worst case scenario and X-axis shows the number of demands. In 11-node topology we have normalized the energy consumption values with respect to the energy consumption for *EA-unicast-FW* for 40 number of lightpath demands. It is clearly seen from the graph that the proposed approach (*EA-anycast-SSLD*) performs best irrespective of the number of demands. The *EA-unicast-SSLD* performs better compared to *EA-unicast-FW*, and *EA-unicast-FW* has the worst performance. The *EA-anycast-SSLD* shows improvement about 13% over *EA-anycast-FW*, 24% over *EA-unicast-SSLD*, 32% over *EA-unicast-FW* for the 10 lightpath case. For 20 lightpath demands *EA-anycast-SSLD* shows improvement about 11% over *EA-anycast-FW*, 38% over *EA-unicast-SSLD*, 46% over *EA-unicast-FW*. The *EA-anycast-SSLD* shows improvement about 7% over *EA-anycast-FW*, 40% over *EA-unicast-SSLD*, 46% over *EA-unicast-FW* for the 40 lightpath case. It is also notable from the graph that as the number of demands increase the energy consumption also increases.

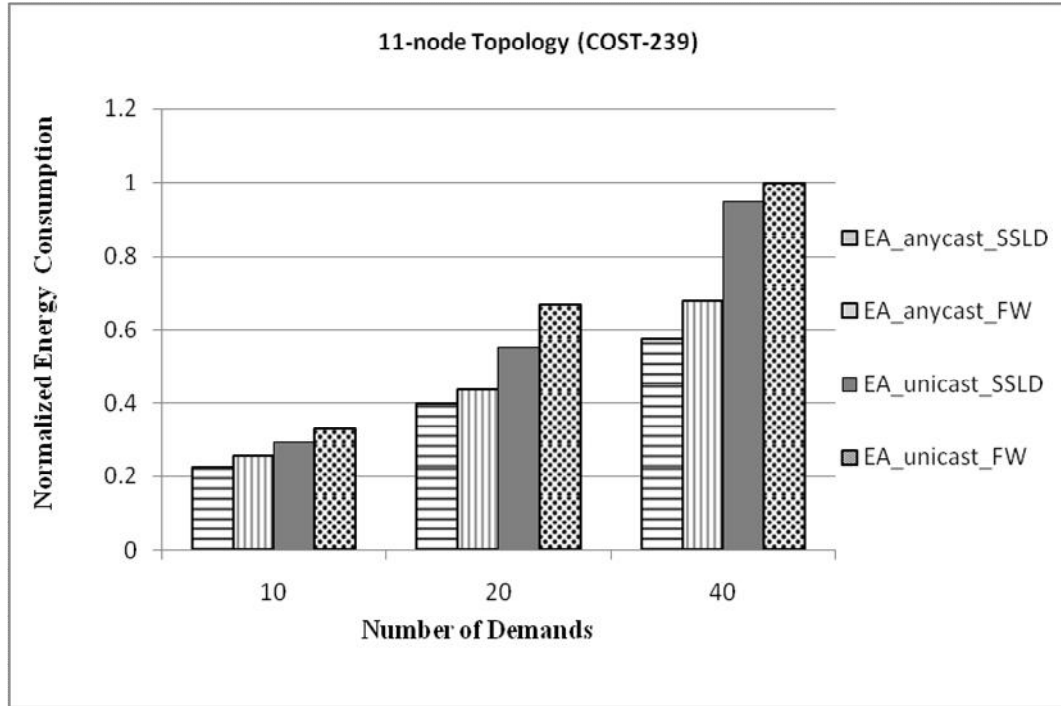


Figure 4.4: Comparison of Energy Consumption for 11-node Topology

As we see in Figure 4.4, the gap between *anycast* approach and *unicast* approach is large compared to the gap between fixed window models and sliding scheduled models, which indicates that selection of the destination node is a more important factor in determining overall energy consumption compared to the start time. As expected, the overall trend shows an increase in energy consumption with increase in number of demands, since more network components such as switches, routers and amplifiers will be required to turn on.



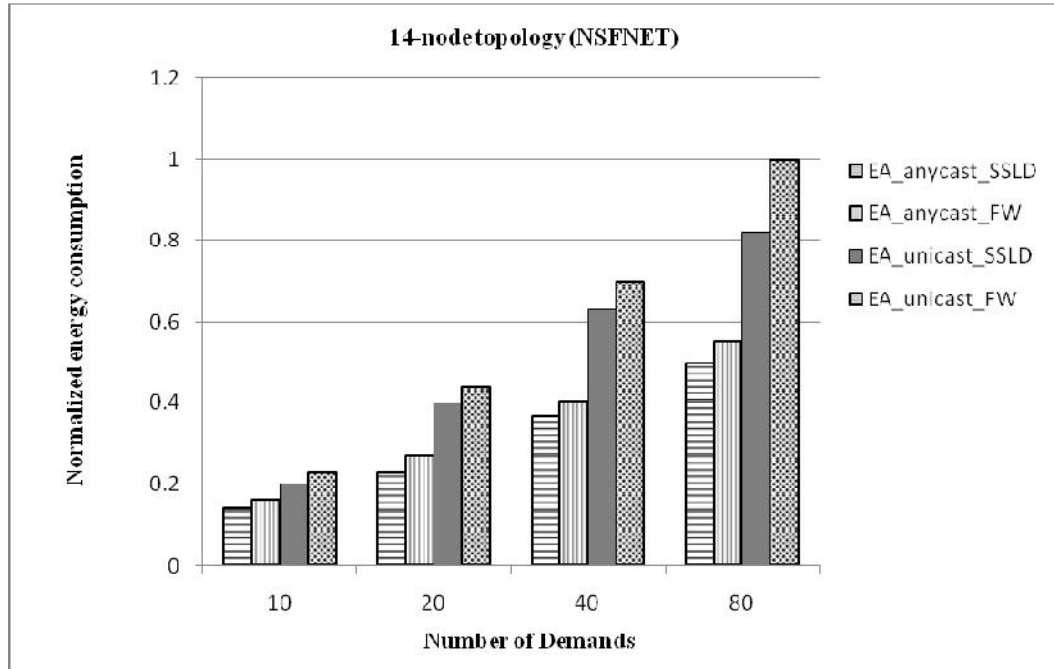


Figure 4.5: Comparison of Energy Consumption for 14-node Topology

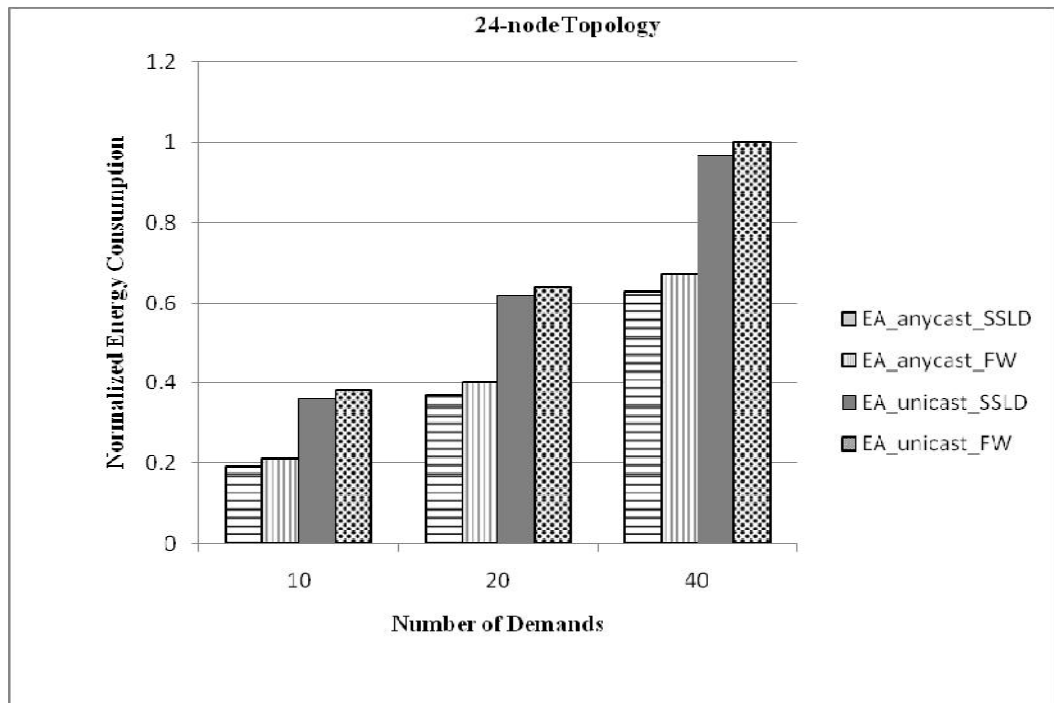


Figure 4.6: Comparison of Energy Consumption for 24-node Topology

In Figures 4.5 and 4.6, the comparison of energy consumption for 14-node topology with 21 links (NSFNET) and 24-node with 43 links is illustrated. For 14-node topology, we have performed experiments with 10, 20, 40 and 80 lightpath demands. For 24 node topology, the experiments were performed on 10, 20 and 40 lightpath demands.

For both networks, the proposed sliding scheduled traffic demands allocation model outperforms other approaches. The energy consumption also increases as the number of demands increase for both the topologies. The average improvement over the next best approach (*EA\_anycast\_FW*) is 13%, 11% and 7% for with 10, 20 and 40 demands respectively.

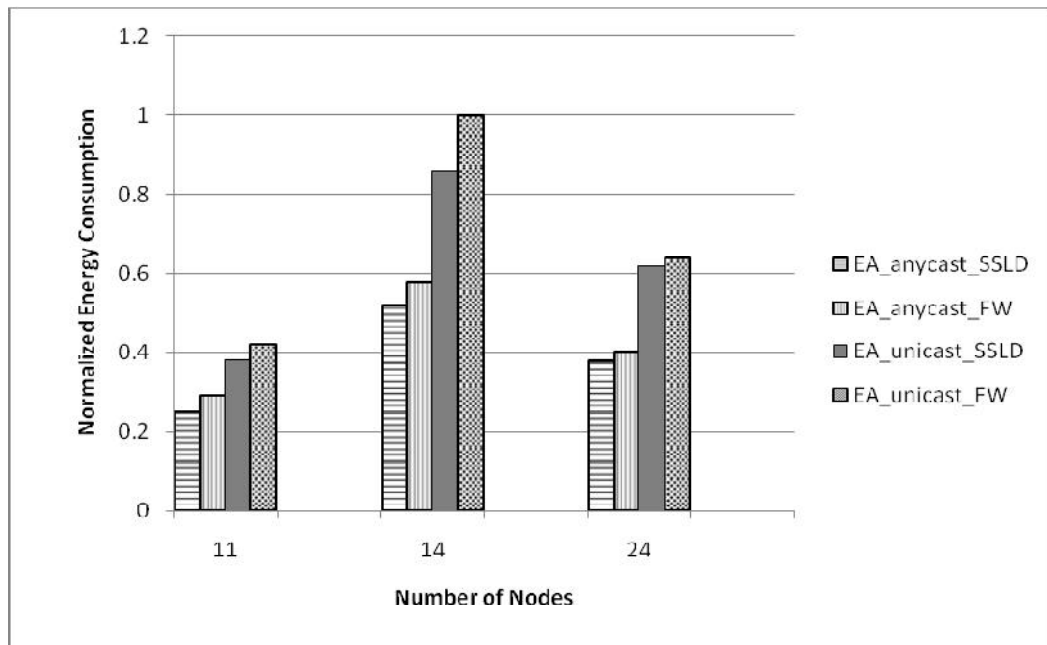


Figure 4.7: Comparison of Energy Consumption for different networks

We next consider results for different networks with the same number of demands as illustrated in Figure 4.7. The graph illustrates that the energy consumption is more in the case of 14-node topology compared to 11-node topology for all the approaches, but the energy consumption for 24-node topology is less compared to 14-node topology although

24-node topology includes more nodes and links compared to 14-node topology. This can be due to a number of factors, such as the length of the links, the number of available destination nodes, and the distribution of the demands.

In Figure 4.8 we show the relative improvement obtained using the EA-*anycast*-SSLD over other schemes. EA-*anycast*-SSLD shows 12% improvement on 11-node topology, 11% improvement on 14-node topology and 7% improvement on 24-node topology comparing to next best technique EA-*anycast*-FW.

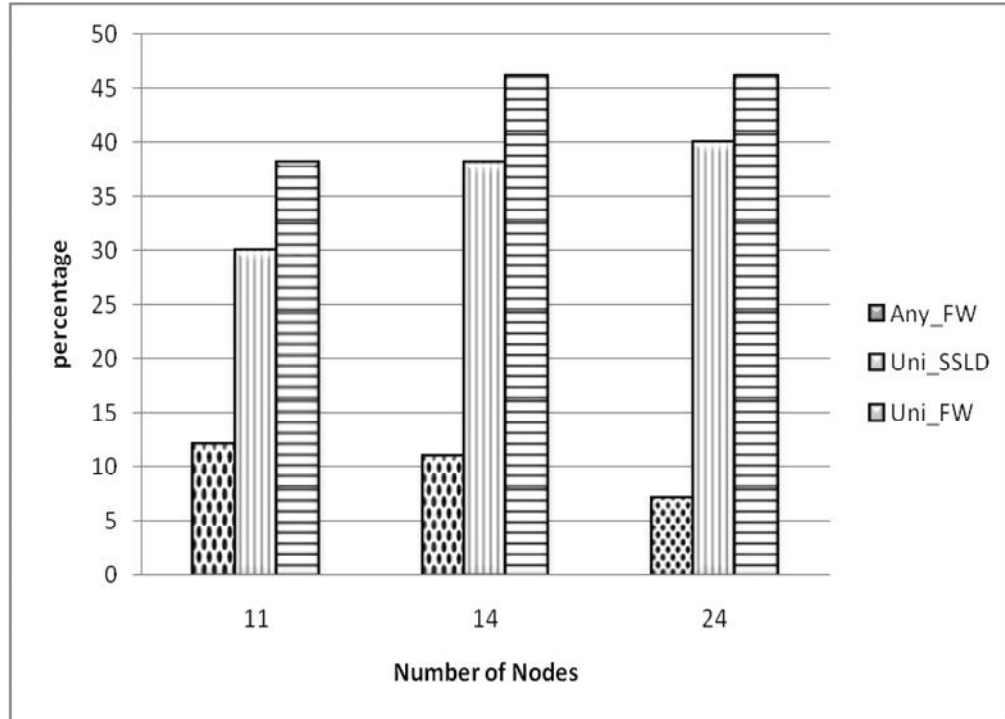


Figure 4.8: Improvement by EA\_anycast\_SSLD in %

The simulation results show a big improvement by EA-*anycast*-SSLD over EA-*unicast*-SSLD and EA-*unicast*-FW. EA-*anycast*-SSLD performs 30% better on 11-node topology, 38% better on 14-node topology and 40% better on 24-node topology compared to EA-*unicast*-SSLD. EA-*anycast*-SSLD performs 38% better on 11-node

topology and 46% better on 14-node and 24-node topologies compared to EA-unicast-FW.

### 4.3. Comparison of solution times

We next consider the comparison of execution times of our proposed approach with the other approaches. The simulation results show that *fixed window* traffic allocation requires significantly less time compared to sliding scheduled demand allocation. The reason is that the additional flexibility in demand start time leads to an increase in the number of integer variables, which results in a much larger search space.

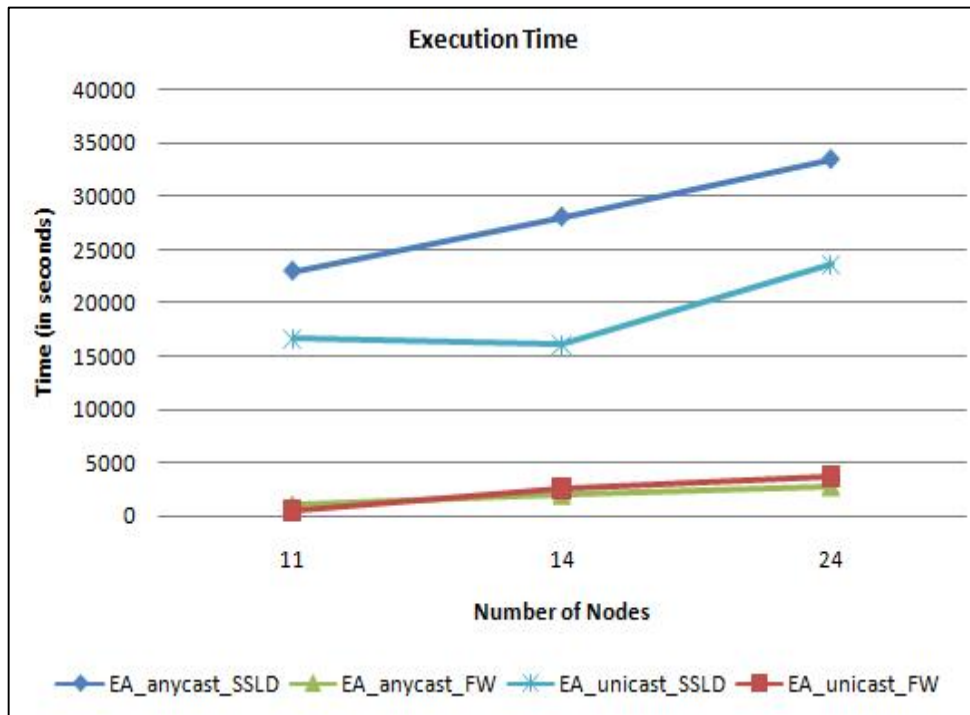


Figure 4.9: Comparison of Execution time

The graph in Figure 4.9 shows that the execution time increases with number of nodes, increases as expected.

The EA-*anycast*-SSLD shows linear steady growth in execution time with increase in number of nodes. EA-*unicast*-SSLD performs slightly faster compared to EA-*anycast*-SSLD. The two fixed window approaches, EA-*anycast\_FW* and EA-*unicast\_FW* perform the best and are significantly faster than the other approaches.

# Chapter 5

## CONCLUSION AND FUTURE WORK

### 5.1. Conclusion

In this thesis, we have presented a new approach for energy aware RWA, which jointly schedules demands (in time) and performs routing of sliding scheduled lightpath demands in optical grid networks with exploiting the flexibility of *anycast* principle. We propose an approach which implements comprehensive energy-aware resource allocation for optical grid networks which is able to consider power consumption over a wide variety of network components [24]. We have considered both *anycast* principle and sliding scheduled demand allocation model in order to minimize the overall energy consumption of the network. To the best of our knowledge no optimal ILP formulation exists for sliding scheduled lightpath demands with the objective of energy minimization for optical grid networks. The objective of this thesis was to minimize the overall energy consumption through minimizing number of active network components. Our approach minimizes the number of active network components by routing the lightpath to already active nodes and links instead of turning on new network elements.

We have compared our results with previous best technique using fixed window demand allocation model. We have performed experimentation on different standard topologies like NSFNET and COST-239. The simulation results demonstrate that the proposed approach can significantly lower energy consumption, even compared to previous energy-aware routing for lightpaths with pre-specified start and end times.

## 5.2.Future Work

In sliding scheduled lightpath demand allocation and fixed window demand allocation, once the transmission of a demand is started, it does not terminate until the entire data has been transported. In practical applications it may not be the case that the continuous data transmission is compulsory. Instead it may be possible to divide the total data into small chunks, which are sent separately. The full amount of data transfer should still be completed within the specified time range. This type of traffic model is known as non-continuous sliding scheduled traffic model, in which a demand can be decomposed into more than one component.

The non-continuous sliding scheduled model adds more flexibility to our proposed sliding scheduled approach. One possible direction for future work is to develop an energy-aware RWA for the non-continuous sliding scheduled traffic model.

Our simulation results show that the execution time of the proposed approach increases significantly as the number of nodes and links increase and also with the increase of number of demands. Therefore, it would be useful to develop fast heuristic algorithms to solve the same problem. The possibility of several meta-heuristics such as genetic algorithm, tabu search or simulated annealing can be explored in order to get faster results. The optimal solutions obtained from our approach can be used as a benchmark for evaluating heuristic solutions for small networks.

## REFERENCES/BIBLIOGRAPHY

- [1] <http://www.internetlivestats.com/internet-users/>[retrieved on date:14-oct-15]
- [2] <http://optics.org/news/3/10/43> [retrieved on date:14-oct-15]
- [3] Bandyopadhyay S. (2007). *Dissemination of Information in Optical Networks: From Technology to Algorithms*. Springer Science & Business Media.
- [4] Wikipedia: Optical networking Wikipedia, the free encyclopedia [Online accessed 23-April-2015].
- [5] <http://optics.org/news/3/10/43>[retrieved on date:14-oct-15]
- [6] Chen Y., "Resource Allocation for Periodic Traffic Demands in WDM Networks" (2013). Electronic Theses and Dissertations. Paper 4918.
- [7] [https://en.wikipedia.org/wiki/Optical\\_networking](https://en.wikipedia.org/wiki/Optical_networking) [retrieved on date:22-oct-15]
- [8] [https://commons.wikimedia.org/wiki/File:Optical\\_fiber\\_cable.jpg](https://commons.wikimedia.org/wiki/File:Optical_fiber_cable.jpg)[retrieved on date: 22-oct-15]
- [9] <https://commons.wikimedia.org/wiki/File:RefractionReflextion.svg> [retrieved on date:22-oct-15]
- [10] <http://www.e-sciencecity.org/EN/communication-centre/image-bank.html> [retrieved on date:22-oct-15]
- [11] <http://www.gridpp.ac.uk/datagrid.jpg> [retrieved on date:22-oct-15]
- [12] <http://www.transmode.com/en/technologies/wdm-the-transmode-way/wdm-the-transmode-way-html/2-wdm-networking-technologies> [retrieved on date:22-oct-15]
- [13] [https://en.wikipedia.org/wiki/Optical\\_fiber](https://en.wikipedia.org/wiki/Optical_fiber) [retrieved on date: 26-oct-15]
- [14] [https://en.wikipedia.org/wiki/Total\\_internal\\_reflection](https://en.wikipedia.org/wiki/Total_internal_reflection) [retrieved on date: 26-oct-15]



- [15] [https://en.wikipedia.org/wiki/Worldwide\\_LHC\\_Computing\\_Grid](https://en.wikipedia.org/wiki/Worldwide_LHC_Computing_Grid) [retrieved on date: 26-oct-15]
- [16] [https://en.wikipedia.org/wiki/Grid\\_computing](https://en.wikipedia.org/wiki/Grid_computing) [retrieved on date: 26-oct-15]
- [17] <http://www.extremetech.com/computing/187258-43tbps-over-a-single-fiber-worlds-fastest-network-would-let-you-download-a-movie-in-0-2-milliseconds> [retrieved on date: 30-oct-15]
- [18] <http://www.transmode.com/en/technologies/wdm-the-transmode-way/wdm-the-transmode-way-html/2-wdm-networking-technologies> [retrieved on date: 30-oct-15]
- [19] Habib M., Chris D., Brigitte J., and Massimo T. "Dimensioning resilient optical grid/cloud networks." *Communication Infrastructures for Cloud Computing* (2013): 73.
- [20] Buysse J., Cavdar C., De Leenheer M., Dhoedt B., & Davelder C. (2011, November). Improving energy efficiency in optical cloud networks by exploiting anycast routing. In *Asia Communications and Photonics Conference and Exhibition* (p. 83100X). Optical Society of America.
- [21] Coiro, A., Listanti M., Valenti A., & Matera, F. (2011). Reducing power consumption in wavelength routed networks by selective switch off of optical links. *Selected Topics in Quantum Electronics, IEEE Journal of*, 17(2), 428-436.
- [22] Tafani D., Kantarci B., Mouftah H. T., McArdle C., & Barry, L. P. (2012, December). Distributed management of energy-efficient lightpaths for computational grids. In *Global Communications Conference (GLOBECOM), 2012 IEEE* (pp. 2924-2929). IEEE.

- [23] Chen Y., & Jaekel A. (2013, June). Energy optimization in optical grids through anycasting. In *Communications (ICC), 2013 IEEE International Conference on* (pp. 3835-3839). IEEE.
- [24] Chen Y., Jaekel A., & Li K. (2014, June). Energy efficient anycast routing for scheduled lightpath demands in optical grids. In *Communications (QBSC), 2014 27th Biennial Symposium on* (pp. 10-13). IEEE.
- [25] Orgerie A. C., Assuncao M. D. D., & Lefevre L. (2014). A survey on techniques for improving the energy efficiency of large-scale distributed systems. *ACM Computing Surveys (CSUR)*, 46(4), 47.
- [26] <https://www.techopedia.com/definition> [retrieved on date: 26-oct-15]
- [27] Konda V. R., & Chow T. Y. (2001). Algorithm for traffic grooming in optical networks to minimize the number of transceivers. In *High Performance Switching and Routing, 2001 IEEE Workshop on* (pp. 218-221). IEEE.
- [28] Shen G., & Tucker R. S. (2009). Energy-minimized design for IP over WDM networks. *Optical Communications and Networking, IEEE/OSA Journal of*, 1(1), 176-186.
- [29] Kuri J., Puech N., Gagnaire M., Dotaro E., & Douville R. (2003). Routing and wavelength assignment of scheduled lightpath demands. *Selected Areas in Communications, IEEE Journal on*, 21(8), 1231-1240.
- [30] [ftp://public.dhe.ibm.com/software/websphere/ilog/docs/optimization/cplex/ps\\_usrman/cplex.pdf](ftp://public.dhe.ibm.com/software/websphere/ilog/docs/optimization/cplex/ps_usrman/cplex.pdf) [retrieved on date: 26-oct-15]
- [31] Pickavet M., Vereecken W., Demeyer S., Audenaert P., Vermeulen B., Develder, C., & Demeester, P. (2008, December). Worldwide energy needs for ICT: The rise of

- power-aware networking. In *Advanced Networks and Telecommunication Systems, 2008. ANTS'08. 2nd International Symposium on* (pp. 1-3). IEEE.
- [32] Musumeci F., Tornatore M., & Pattavina A. (2012). A power consumption analysis for IP-over-WDM core network architectures. *Journal of Optical Communications and Networking*, 4(2), 108-117.
- [33] Shaikh A., Buysse J., Jaumard B., & Develder C. (2011). Anycast routing for survivable optical grids: scalable solution methods and the impact of relocation. *Journal of Optical Communications and Networking*, 3(9), 767-779.
- [34] Chen Y., & Jaekel A. (2012). Energy aware resource allocation based on demand bandwidth and duration. *Procedia Computer Science*, 10, 998-1003.
- [35] Develder C., Dhoedt B., Mukherjee B., & Demeester P. (2009). On dimensioning optical grids and the impact of scheduling. *Photonic Network Communications*, 17(3), 255-265.
- [36] Chlamtac I., Ganz A., & Karmi G. (1993). Lightnets: Topologies for high-speed optical networks. *Lightwave Technology, Journal of*, 11(5), 951-961.
- [37] Wang Y., Wu M. Y., Jin Y., Guo W., Sun W., & Hu W. (2007). Joint scheduling for optical grid applications. *Journal of Optical Networking*, 6(3), 304-318.
- [38] Yetginer E. & Rouskas G. N. (2009, November). Power efficient traffic grooming in optical WDM networks. In *Global Telecommunications Conference, 2009. GLOBECOM 2009. IEEE* (pp. 1-6). IEEE.
- [39] Hasan M. M., Farahmand F., Jue J. P. & Rodrigues J. J. (2013). A study of energy-aware traffic grooming in optical networks: Static and dynamic cases. *Systems Journal, IEEE*, 7(1), 161-173.

- [40] Manousakis K., Angeletou A., & Varvarigos E. (2013). Energy efficient RWA strategies for WDM optical networks. *Optical Communications and Networking, IEEE/OSA Journal of*, 5(4), 338-348.
- [41] Idzikowski F., Orłowski S., Raack C., Woesner H., & Wolisz A. (2010, February). Saving energy in IP-over-WDM networks by switching off line cards in low-demand scenarios. In *Optical Network Design and Modeling (ONDM), 2010 14th Conference on* (pp. 1-6). IEEE.
- [42] Bathula B. G., & Elmirghani J. M. (2009, April). Green networks: Energy efficient design for optical networks. In *Wireless and Optical Communications Networks, 2009. WOCN'09. IFIP International Conference on* (pp. 1-5). IEEE.
- [43] Lui Y., Shen G., & Shao W. (2013). Design for energy-efficient IP over WDM networks with joint lightpath bypass and router-card sleeping strategies. *Journal of Optical Communications and Networking*, 5(11), 1122-1138.
- [44] Buysse J., Georgakilas K., Tzanakaki A., De Leenheer M., Dhoedt B., & Develder C. (2013). Energy-efficient resource-provisioning algorithms for optical clouds. *Journal of Optical Communications and Networking*, 5(3), 226-239.
- [45] Silvestri A., Valenti A., Pompei S., Matera F., & Cianfrani A. (2009). Wavelength path optimization in optical transport networks for energy saving. In *2009 11th International Conference on Transparent Optical Networks*.
- [46] Pagnan P., & Schiano M. (2009, September). A  $\lambda$  switched photonic network for the new transport backbone of Telecom Italia. In *Int. Conf. on Photonics in Switching* (pp. 15-19).

- [47] Chiaraviglio L., Mellia M., & Neri F. (2009, June). Reducing power consumption in backbone networks. In *Communications, 2009. ICC'09. IEEE International Conference on* (pp. 1-6). IEEE.
- [48] Tucker R. S., Parthiban R., Baliga J., Hinton K., Ayre R. W., & Sorin W. V. (2009). Evolution of WDM optical IP networks: A cost and energy perspective. *Journal of Lightwave Technology*, 27(3), 243-252.
- [49] Baliga J., Ayre R., Sorin W. V., Hinton K., & Tucker R. S. (2008, February). Energy consumption in access networks. In *Optical Fiber Communication Conference* (p. OThT6). Optical Society of America.
- [50] Chabarek J., Sommers J., Barford P., Egan C., Tsang D. & Wright S. (2008, April). Power awareness in network design and routing. In *INFOCOM 2008. The 27th Conference on Computer Communications. IEEE*. IEEE.
- [51] Murakami M., & Oda K. (2009, June). Power consumption analysis of optical cross-connect equipment for future large capacity optical networks. In *Transparent Optical Networks, 2009. ICTON'09. 11th International Conference on* (pp. 1-4). IEEE.
- [52] Yannuzzi M., Quagliotti M., Maier G., Marín-Tordera E., Masip-Bruin X., Sánchez-López S. & Tamiri G. (2009, February). Performance of translucent optical networks under dynamic traffic and uncertain physical-layer information. In *Optical Network Design and Modeling, 2009. ONDM 2009. International Conference on* (pp. 1-6). IEEE.

## VITA AUCTORIS

NAME: Darshil Rami

PLACE OF BIRTH: Ahmadabad, India

YEAR OF BIRTH: 1991

EDUCATION: JS High School, Ahmadabad, India, 2009  
Gujarat Technological University , India, 2013  
University of Windsor, M.Sc., Windsor, ON, 2016