DISSERTATION

WAVELENGTH CONVERTER ALLOCATION AND RANGING FOR MULTI-FIBER SHARE-PER-LINK SWITCHES IN SLOTTED/UNSLOTTED ALL-OPTICAL NETWORKS

Submitted by

Abdulgader A. Habiballa

Department of Electrical and Computer Engineering

In partial fulfillment of the requirements

for the Degree of Doctor of Philosophy

Colorado State University

Fort Collins, Colorado

Fall 2005

COLORADO STATE UNIVERSITY

August 17, 2005

WE HEREBY RECOMMEND THAT THE DISSERTATION PREPARED UNDER OUR SUPERVISION BY ABDULGADER A. HABIBALLA ENTITLED WAVELENGTH CONVERTER ALLOCATION AND RANGING FOR MULTI-FIBER SHARE-PER-LINK SWITCHES IN SLOTTED/UNSLOTTED ALL-OPTICAL NETWORKS BE ACCEPTED AS FULFILLING IN PART REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY.

Committee on Graduate Work

Y. K. Malaiya

M. M. Siddiqui

Adviser

Department Head

ABSTRACT OF DISSERTATION

WAVELENGTH CONVERTER ALLOCATION AND RANGING FOR MULTI-FIBER SHARE-PER-LINK SWITCHES IN SLOTTED/UNSLOTTED ALL-OPTICAL NETWORKS

The end-to-end performance for circuit switched all-optical networks in multi-fiber multi-hop environments is modeled and evaluated with and without wavelength conversion. The increase in performance in wavelength routing DWDM network due to wavelength conversion at each node with different degrees of wavelength conversion is considered. Models relating parameters such as hop count, number of fibers, number of wavelengths in each fiber, and degree of conversion to end-to-end performance are developed. This work also examines different wavelength converter sharing architectures and their effects on performance when the hops along the path between source-distention pair have different loads. It also examines the performance issues for share-per-link wavelength convertible switch (WCS) using different Conversion Resources Allocation Algorithms (CRAA). We propose and evaluate three different CRAA algorithms, Narrow Search Algorithm (NSA), Inclusive Search Algorithm (ISA), and Optimized Inclusive Search Algorithm (OISA), for dynamically allocating conversion resources.

As a second major topic of this research, the effects of different wavelength conversion ranging configurations on the performance of Wavelength Division Multiplexing (WDM) optical switches are investigated. *Any-to-Any*, *Any-to-Range*,

Range-to-Any, and *Range-to-Range* conversion ranging configurations are considered. These mechanisms provide important design alternatives for optical switches due to technological limitations in the implementation of full range wavelength conversion in an all-optical wavelength converter device. Limited-range wavelength converter (LRWC) is a more economical and practical solution for WDM based optical networks. Differences among the input and output side ranging mechanisms and their effects on conversion resource sharing, and consequently on performance, are investigated. *Any-to-Range* ranging configuration is the most efficient mechanism and it operates comparably to *Any-to-Any*. The obtained results help in determining the most efficient ranging configuration for all-optical crossconnect.

Finally, we study the synchronous optical packet-switched (OPS) networks with limited number of converters that are shared between all wavelengths on specific output link (Share-per-Link WCS). The end-to-end performance of such networks, which service symmetric/asymmetric traffics at each node along the path between the source and destination, is modeled. The effects of employing multiple fibers on the network performance and how that affects the needed conversion resources are studied in detail. The multi-fiber synchronous photonic share-per-link packet switch model is used as the basic switch element on which the linear end-to-end network model is built. Different performance aspects and tradeoffs, which are used to grasp the quantitative performance differences when using multiple fibers and the adaptation of limited wavelength conversion, are investigated.

Abdulgader A. Habiballa
Department of Electrical and Computer Engineering
Colorado State University
Fort Collins, Colorado 80523
Fall 2005

ACKNOWLEDGEMENTS

First and for most, I thank GOD, THE ALMIGHTY ALLAH, whom I owe every breath I put into this work to. I am eternally indebted to his grace and compassion for upbringing an orphan of both parents this far. I am grateful for all the bounties HE blessed me with, regardless of my shortcomings.

Everlasting appreciations go to my late stepmother Aishah Belal and my late adopting father Abdulrazzaq Al-Nemari who showed me how normal people can be larger than life. To them I say, "It breaks my heart that I wasn't able to give back and that I lost you both while I was pursuing my Ph.D. studies in the United States."

I would like to express my gratitude to my kids, Kholood, Abdulrazzaq, Reem, Ryan, Jumanah, Ghaith, and my wife Ghada for giving me reasons to go on and defining my existence. They made my life worth living. I hope my son Abdulrazzaq gets the virtue behind this accomplishment and understands that giving up is not an option. To him I say "If you believe in yourself and have dedication, pride and never quit, you'll be a winner. The price of victory is high but so are the rewards."

Particular thanks go to my sisters Hajer, Zaynab, Khadijah, and my brother Bader Al-Judhei for extraordinarily supporting me. Many thanks go to my "Country and its Citizens" for granting me the chance to do my college and graduate studies abroad. To them I say, "I still have you to give back and test my worthiness."

Last but not least, words of gratitude to my advisor Professor Anura Jayasumana who has been a great deal of support in every aspect and helped me make this accomplishment possible. Words may not express my gratitude thereto.

Abdulgader
August 17, 2005

DEDICATION

to my late stepmother Aishah Belal, my late adopting father Abdulrazzaq Al-Nemari, my kids, and the Faithful....

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Chapter 1

INTRODUCTION

For the Internet to scale and accommodate the exponentially growing traffic, we must scale all dimensions of the optical core, which provides bit-rate transparency; that is, the fabric will switch data independently of the signal format or bit rate, routing and wavelength assignment process, and how it integrates with upper layers. This scaling should take into account the ability of the optical network elements to handle traffic efficiently without degrading the utilization performance. The optical nature of the backbone, network core, poses a challenge in the required mechanisms. This challenge is being tackled in many different levels and frameworks depending on the level of traffic grooming or on traffic aggregation technology adopted. As a result, researchers have developed various high-speed, reliable, and affordable optical infrastructure components and supporting resources. These network devices and complementary resources, such as wavelength conversion elements, continue to be investigated. Optical cross connects, optical add-drop multiplexers, and wavelength converters, all perform distinct functions necessary for the successful implementation of optical networks. For efficient utilization of network resources, proper configuration of these resources is required to handle the huge traffic aggregated to the core. This configuration can be achieved through dynamic provisioning of resources by implementing efficient resource reservation schemes. Such schemes require a comprehensive understanding of the interrelated issues of traffic nature, performance behavior of network resources, and basic network parameters.

As bandwidth requirements increase by orders of magnitude, the most pressing issue is how to manage and control large optical networks. Seeking increasing agility in the dense wavelength division multiplexing (DWDM) based optical core pushes the way for more intelligent core devises able to be managed by intelligent transport services that will allow clients such as IP routers to interconnect using optical interfaces. A number of newly proposed optical crossconnect (OXC) architectures have demonstrated controllability and manageability potentials in order to add more intelligence to the optical core and increase scalability and configuration flexibility. One of the goals of this research is to study such OXC architectures in terms of their scalability, complexity, and different performance aspects. The investigation of their operational limitations is approached by introducing analytical models that describe their behavior as far as their performance goes with respect to different network parameters and operational conditions for both wavelength routing and optical packet-switching networks. These models are assessed in terms of their performance and overall complexity to determine the tradeoffs of integrating these switches with the optical control plane. Another goal for this research is developing algorithms to mange switch resource efficiently. Mechanisms to manage switch resources will lead the way for proposing architectures for integrating these algorithms with the optical control plane. The optical network control plane is responsible for provisioning and maintaining connections and managing network resources. Provisioning of resources require algorithms for resource allocation, and signaling mechanisms to request and establish connectivity within the network along a chosen route. For these reasons, the first part of this research presents an analytical model for conversion resource allocation algorithms, which can be used to study network behavior without excessive computational complexity. Analytical results are useful to verify the need for such schemes. We can achieve better utilization of network resources by modeling and studying the behavior of these algorithms. Optimally assigning paths to connection requests is subject to the availability of complementary network resources. The optimization of related algorithms can be particularly important to the complex optical control plane hierarchy. We present three dynamic Conversion Resources Allocation Algorithm (CRAAs) that improve the utilization of the optical links. The proposed CRAAs in this work are: (1) Inclusive Search Algorithm, ISA (2) Narrow Search Algorithm, NSA and (3) Optimized Inclusive Search Algorithm, OISA. We consider these algorithms where various performance attributes, such as utilization performance and blocking probability, directly influence the cost function of switching. The aim is to optimize the allocation of scarce wavelength conversion resource using different CRAA algorithm scenarios that change the behavior of the traffic blocking models in the share-per-link WCS. This work is presented in details in chapter 4.

The second part of the dissertation involves the use of different ranging mechanisms of wavelength converters. These ranging mechanisms would have important roles in managing conversion resource efficiently. This work, which is presented in chapter 5, investigates issues associated with Limited-Range Wavelength Converter (LRWC) in the presence of conversion resource sharing. It considers the effects of employing different conversion ranging architectures that fall under partial wavelength conversion category, within a WDM optical switch. These ranging mechanisms are identified as an important design criterion due to technological limitation in the implementation of full range wavelength conversion in an all-optical wavelength convertible device. The adopted conversion ranging schemes consider different cases where an incoming wavelength can be converted to a pre-specified range of outgoing wavelengths. The differences between the input and output side ranging mechanisms and their effects on conversion resource sharing and consequently performance are also explored. We will analyze the impact of using different architectures for wavelength conversion to mitigate the cost penalty. The implementation of our proposed *Any-to-Range* ranging architecture in all-optical wavelength converters would be compared to the *Any-to-Any*, in terms of performance, to obtain an efficient solution. The issues of connection flexibility due to a reduction in connection permutation of the all-optical switch are explored. The concept of output side ranging and its advantages with respect to resource sharing are studied in details. Simulation results for full conversion, *Any-to-Any* case, are provided for comparison. These simulation results are important to demonstrate that the performance improvement obtained by full range wavelength conversion can be achieved by using the proposed fractionally ranged LRWC, limited-range wavelength converters. The throughput improvement due to the use of LRWC in the presence of conversion sharing, which is tightly coupled with the ranging mechanism, is contrasted to the mechanism of widening the conversion range.

The third part of this research, presented in chapters 6 and 7, involves the investigation of optical packet-switched networks OPS, which are realized to run the IP layer traffic over the optical (WDM) layer. The multiple concurrently incoming packets cause contentions when two or more of them are contend for the same output port. The contention can happen both in the input side at the receiver or in the output side when packets destined to another network node. It is important to study the mechanisms in which these types of contention are resolved in order to enhance the performance of the network. The method in which contention is resolved has a significant effect on network performance. Wavelength conversion is considered to be one of the most effective mechanisms to tackle the packet contention problem in the optical packet-switched networks. The wavelength conversion devices are expensive elements, thus number of converters could be considered an important cost parameter in OPS network design. Sharing limited number of conversion devices is an effective paradigm in the cost reduction of the OPS network design process. In this research work, we study the synchronous OPS networks with limited number of converters that are shared between all wavelengths on specific output link (Share-per-Link WCS). We investigate an end-to-end contention wavelength resolution in the presence of multiple fibers, which contributes in resolving, or at least minimizing, packet contention problem. Wavelength conversion contention resolution schemes, key determinants of packet-loss performance in optical packet-switching networks, are explored in details.

Our work presented in chapters 6 and 7 discusses the node architecture within the context of optical packet-switched networks which employ wavelength conversion. The scope of this work also includes the development of performance models for multi-fiber share-per-link OPS network which operates in a slotted mode and services symmetric/asymmetric traffics. The models and results presented in this work investigate different packet-switched networks with a small range of wavelength conversion capability and contrast them to networks equipped with full wavelength conversion. One of the purposes for this study is to analyze the effect of load variation among the incoming/outgoing links of the synchronous optical packet-switched network. The effect of load variation on the performance of the network is studied. The study explores different performance aspects and tradeoffs to have an insight into performance differences when using multiple fibers and limited wavelength conversion.

Chapter 2 presents detailed introductions to relevant topics and reviews related literatures. Research problem statements, goals, and modeling methodologies are presented in chapter 3. Chapter 4 presents the performance of multi-fiber optical networks and the dynamic allocation of conversion resource in shared-per-link WCS. Chapter 5 presents simulation-based performance evaluation of shared limited-range wavelength conversion schemes in optical WDM networks. The performance analysis of synchronous WDM share-per-link multi-fiber packet-switched networks is provided in chapter 6. Chapter 7 presents performance analysis of the synchronous WDM share-per-link multi-fiber packet-Sswitched networks under asymmetric traffic condition. Chapter 8 presents the network simulation related issues. Finally, chapter 9 provides the conclusions.

Chapter 2

WAVELENGTH ROUTING/PACKET SWITCHING WDM NETWORKS

2.1 Introduction

This chapter introduces and reviews a number of research works that have been previously done in areas that are tightly related to the research work in hand. It exposes the latest advancement and possible research work needed to enhance and refine what has been already accomplished in terms of performance and interoperability of the optical domain. This chapter reviews work done in six different areas that are considered in this research work. These areas include:

- Fiber requirement in multi-fiber WDM networks and its effects on the efficiency of optical control plane to allocate networks resources.
- Optical switch architectures and performance issues related to their ability to employ different degrees of wavelength conversion option.
- Wavelength convertible optical networks in terms of number of wavelength converters needed in all-optical bufferless switching architectures.
- Optimization of wavelength conversion resources allocation and selection algorithms on wavelength conversion gain in WDM optical networks
- Path setting contention in wavelength routed optical networks under different wavelength conversion scenarios and different network architectures.

- Shared-per-link multi-fiber synchronous optical packet switch architecture and its network implementations.

2.2 IP Routing Optical Networks

IP routing continues to receive much attention from the research and vendor communities. Its primary function, forwarding packets between networks, still keeps pace with the demands of the exponentially growing end user population. It also keeps accommodating attachment of gigabit data link technologies such as ATM, Sonet, Gigabit Ethernet, and WDM. As network providers introduce new services supporting multicast, QoS, voice, and security, IP routing will be called upon to analyze additional packet information at gigabit rates to determine how each packet should be handled. Performing these new functions while maintaining parity with the advances in available bandwidth presents an interesting challenge for the forwarding capabilities of IP routers and how the predominantly IP traffic is handled within the lower levels of the network, downward to the physical layer.

For the Internet to scale and accommodate the exponentially growing IP based traffic, we must scale all dimensions of the IP routing process and how it integrates with the physical layer. This scaling should take into account the ability of the different layers of the network to handle the IP based traffic efficiently without degrading the expected utilization performance at lower levels of the network.

2.2.1 Dense Wavelength Division Multiplexing (DWDM)

Dense wavelength division multiplexing (DWDM) is a technology that combines multiple optical signals so that they can be amplified as a group and transported over a single fiber to increase capacity. Each signal carried at the same time on its own separate light wavelength. In effect, one fiber is transformed into multiple virtual fibers. Using DWDM, up to 64 (and theoretically more) separate wavelengths or channels of data can be multiplexed into a light stream transmitted on a single optical fiber. Because DWDM is capable of supporting massive growth in bandwidth demands, this subsection addresses the importance of scalable DWDM systems in enabling service providers to accommodate consumer demand for ever increasing amounts of bandwidth. DWDM is a crucial component of optical networks that allows the transmission of different types of data over the optical layer. A number of considerations should be involved when deploying a DWDM based system. The migration and provisioning strategies of prospect huge capacity, the required adaptation of a comprehensive network management tool, which is essential for provisioning, performance monitoring, fault identification and isolation, and remedial action, are some of the areas that require more research. The capacity of optical networks will grow as advances in related technologies continue to press forward. The interesting development is that DWDM is going beyond data transportation and becoming a basis for optical networking that employs wavelength routing and provisioning. Switching these wavelengths at the optical layer by the introduction of wavelength routing protocol allows these wavelength based light paths to traverse the network.

2.2.2 DWDM System Functions

DWDM involves a number of physical-layer functions. Figure 2.1 shows a DWDM link system, which has four channels and each channel occupies a wavelength, performing the following main functions:

- Generating the signal using a solid-state laser source/transmitter.
- Multiplexing the wavelength to combine signals, at the transmitting side of the fiber. A multiplexer takes individually-encoded multiple wavelengths and combines them into a single optical fiber.

- Transmitting the optical signals over fiber.

- Amplifying and boosting wavelengths without electrical conversion to compensate for the inherent loss, which can be minimized by controlling variables such as channel spacing, wavelength tolerance, and laser power levels, associated with multiplexing and demultiplexing.

- Demultiplexing and separating out the received signals at the receiving end, the incoming signal is demultiplexed into the original individually-encoded multiple wavelengths using a demultiplexer.

- Receiving the demultiplexed signals by a photo-detector.

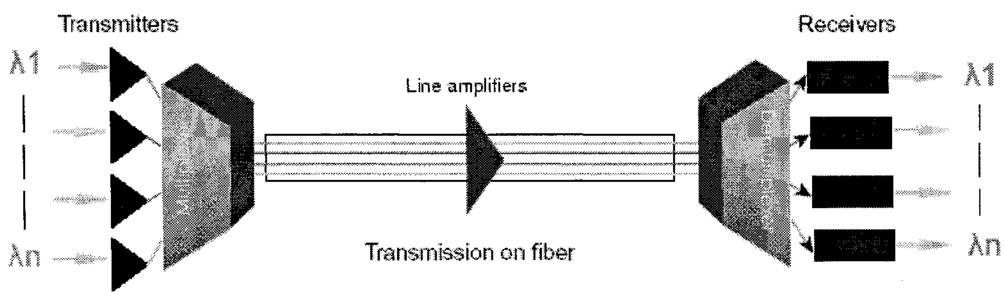

Figure 2.1: DWDM Link Interfaces

2.2.3 The Challenges of Today's Telecommunications Network

The explosion in demand for network bandwidth is largely due to the growth in data traffic, specifically Internet Protocol (IP). At the same time that network traffic volume is increasing, the nature of the traffic itself is becoming more complex. Traffic carried on a backbone can originate as circuit based (TDM voice and fax), packet based (IP), or cell based (ATM and Frame Relay). Another problem for carriers is the challenge of deploying and integrating diverse technologies in one physical infrastructure. Customer demands and competitive pressures mandate that carriers offer diverse services and deploy them over the optical network. DWDM provides service providers an answer to that demand.

Despite the fact that these formats, IP, ATM, and SONET/SDH, provide unique bandwidth management capabilities, all three can be transported over the optical layer using DWDM. This unifying capability allows flexibility to respond to customer demands over one network. A platform that is able to unify and interface with these technologies and position the carrier with the ability to integrate current and next generation technologies is critical [21].

SONET, Time Division Multiplexing (TDM), multiplexes both synchronous and asynchronous signals, which have to be converted from electrical to optical or from optical to electrical and back to optical before being multiplexed, to a single higher bit rate wavelength over fiber for transmission where as WDM multiplexes multiple optical wavelengths over a single fiber which means that a number of non-interfering optical signals to be transmitted simultaneously over a single fiber, with each optical signal carried at a different wavelength. The early versions of DWDM technology transmitted around 625,000 phone calls over a single where as the present day version can carry about 25 million phone calls. This difference clearly distinguishes DWDM over SONET. Each of the multiple wavelengths that can be transmitted simultaneously in a fiber can be transferred in 10Gbits/ (OC-192). Currently, a fiber can accommodate about 64 wavelengths with a speed that reaches 640 Gbps. Laboratory trials have accomplished a capacity of 170 wavelengths with speed of 1.7 Tbps both in C and L bands [28].

2.2.4 Capacity Expansion and Flexibility of DWDM

One way to alleviate exhaustion of fibers is to lay more fibers. For those networks where the cost of laying new fiber is minimal, this will prove the most

Optical-Carrier-n	Speed
OC-768	40Gbps
OC-192	10Gbps
OC-96	5Gbps
OC-48	2.5Gbps
OC-24	1.25Gbps
OC-12	622Mbps

Band	Descriptor	Wavelength range(nanometer)
O-Band	Original	1260 to1360
E-Band	Extended	1360 to 1460
S-Band	Short	1460 to 1530
C-Band	Conventional	1530 to 1565
L-Band	Long	1565 to 1625
U-Band	Ultra-long	1625 to 1675

Figure 2.2: Transmission speed and different wavelength bands in optical fiber

economical solution. However, laying new fiber will not necessarily enable networks to provide new services or utilize the bandwidth management capability of a unifying optical layer.

The other choice is dense wavelength division multiplexing (DWDM), which increases the capacity of embedded fiber by first assigning incoming optical signals to specific frequencies (wavelength, lambda) within a designated frequency band and then multiplexing the resulting signals out onto one fiber.

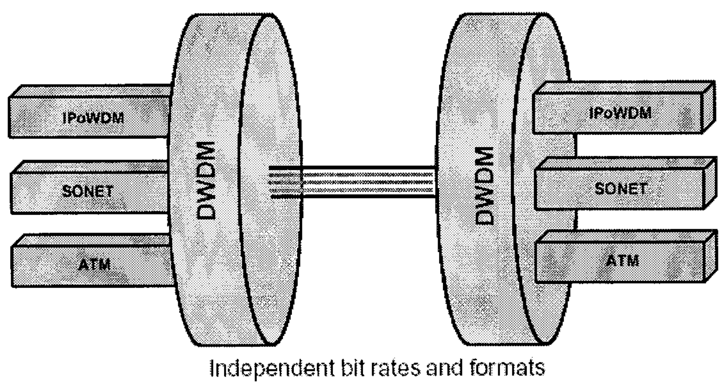

Figure 2.3: Bit rate and format independency

As shown in Figure 2.3, DWDM systems are bit rate and format independent and can accept any combination of interface rates on the same fiber at the same time [23]. Because the optical layer carries signals without any additional multiplexing, carriers can quickly introduce ATM or IP without deploying an overlay network. An important benefit of optical networking is that it enables any type of cargo to be carried on the highway [21, 28].

2.2.5 Related Research Literature

In single-fiber networks, each wavelength on one link can support one single lightpath or connection between hops. If there is another lightpath using the same wavelength, both connections cannot share that link. However, in multi-fiber networks, lightpaths using the same wavelength can share common links due to the multiplicity of wavelength in the multi-fiber system. One of the ways to conquer the wavelength continuity constraint, multiple fibers on each link in WDM networks can be employed. In such networks, each link consists of multiple fibers, and each fiber has the same set of wavelengths. A wavelength that cannot continue on the next hop on the same fiber can be switched to different fiber using an optical cross-connect, in case that wavelength is available. Multiple fibers networks have the same effect as the limited wavelength conversion and the degree of such equivalent conversion would be studied in this research. Since the cost of a multi-fiber network is likely to be higher than a single-fiber networking, as far as the required optical equipments go, the design goal is to achieve high network performance. An important question in multi-fiber networks is to decide on the count of fibers per link that are required to guarantee network performance that is similar to a network with full-range wavelength converters at every node. The fiber requirement may depend on many factors, e.g., the network topology, traffic patterns, the number of wavelengths per fiber, and the routing algorithm employed in the network. Number of research work has considered the Fiber requirements for wavelength routed networks.

The work done in [10] has analyzed Fiber requirements for numerous network topologies both without and with link failure restoration, considering different optical cross-connect (OXC) configurations and terminal functionalities. The aim of this work was to analyzes and minimize wavelength requirement, the number of wavelengths on each fiber, which was allowed to be as large as necessary to satisfy the traffic demand. This paper discussed the multi-fiber requirement in the scope of network planning that is determined by physical topology, fiber availability, and the actual and forecasted traffic demand. It showed that a large number of wavelengths in a single fiber may be justified if the initially deployed excess capacity is accessible for future traffic growth. The study stressed potential benefit of wavelength conversion within the wavelength routing nodes, or optical cross-connects (OXC's) and how these benefits diminish for active lightpath allocation. This work stressed the need for multiple fibers in terms of network resiliency to link failures.

The study in [62] considered the fiber requirement under dynamic traffic in different topologies with alternate path routing (APR). An analytical model was developed to evaluate the blocking performance of such networks. The analytical and simulation results showed that the number of required fibers per link to provide high network performance is slightly higher in the APR than the fixed-path routing (FPR). It also showed that the number of required fibers to offer high network performance depends on the routing scheme employed by the multi-fiber wavelength-routed network. For example, the alternate routing algorithm required more fiber than the fixed path routing algorithm. The study in [62] utilized the blocking probability model that was developed in [61, 57].

The papers considered in this section have studied the multi-fiber requirements in the sense of link resiliency to multiple path failures, network topology, traffic patterns, the number of wavelengths per fiber, and the routing algorithm employed in the network. They did not consider the need for multi-fibers in the presence of alternative network resources such as wavelength conversion. The tradeoffs of using multiple fibers and use of different wavelength conversion capable OXCs will be considered in this research work.

2.3 Optical Switch Architectures

In general, the point to point links between optical switches consist of bundles of optical fibers. An optical switch can choose to switch any possible subset of the optical bundle as a single unit. All the data traffic in such unit on the incoming interface is switched to a corresponding type/size of unit on the outgoing interface.

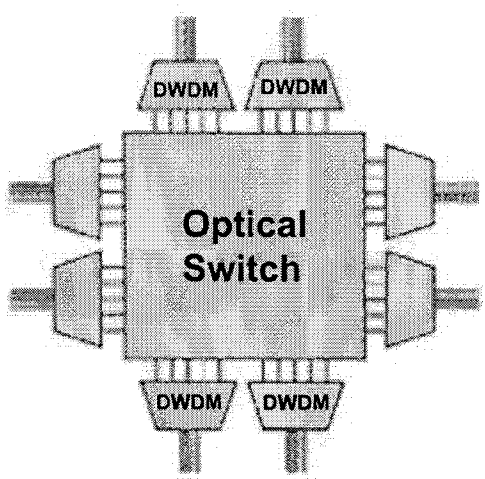

Figure 2.4: Multi-link Optical Switch

The most obvious and basic quantity to switch is an entire fiber. All of the data that arrives on a single fiber is switched to be transmitted out to another fiber. Within a single fiber, the available bandwidth can be divided up by frequency into wavelengths (also known as lambdas). An optical switch could switch all of the data in wavelength A on the incoming fiber to wavelength B on the outgoing fiber. A restriction of some optical switches (e.g., MEMS) is that they are incapable of wavelength conversion, in which case B must be the same as A.

Waveband switching is a generalization of lambda switching. If a fiber's bandwidth is divided by frequency, wavelengths are grouped together as a band and switch the band using a single port. This has potential benefits in reducing the number of paths in place, which saves on signaling and switching hardware. The process of switching a waveband can be viewed as a path tunnel that switches each of the payload wavelength paths in the same way. The introduction of such technology helps the concept of traffic grooming in optical networks. IP layer traffic grooming is used to reduce the traffic load in the optical layer where IP routers are used to aggregate multiple traffic-flows onto a single wavelength which enhances the performance of the network by reducing the number of wavelengths. It can also be implemented in the optical layer by grouping lightpaths into a waveband and wavebands into a fiber. Multi-granular OXCs are used to switch traffic at different levels of granularity each using a single port, fiber, waveband or wavelength levels. These multi-granular OXCs offer small-scale modularity, cross-talk and complexity reduction.

2.3.1 Related Research Literature

Due to the current costs of the optical network components, ways are being sought to maximize the benefits of optical networks while minimizing costs. Wavelength conversion has been studied as a way to improve efficiency in all-optical networks. A network utilizing wavelength conversion can minimize the number of wavelengths it employs, reducing the complexity and cost.

The work in [55, 56] showed that few converters provided and shared by the incoming circuits in the share-per-node or the share-per-link wavelength-convertible switch can improve the efficiency. A heuristic algorithm for dynamic routing is used to reduce the number of converters. Performance gain in call blocking probability and the reduction of the number of converters are also studied. The main contribution of this paper is the proposition of two wavelength-convertible switches that conserve converters by sharing the conversion circuits. These proposed switch architectures are shared-per-node and shared-per-link wavelength convertible switches. The simulation results of this work showed that the performance gain of using wavelength converters in terms of blocking probability and fairness is higher due to the reduction in wavelength conflicts.

The performances of two kinds of OXC (optical cross connect): share-per-link OXC and share-per-node OXC, are compared in [98]. A heuristic algorithm is proposed to decide how many wavelength converters are equipped in the share-per-node OXC. Through unequally distributing the wavelength converters in different links of the share-per-link OXC, the performance of share-per-link OXC is studied, by simulation in three networks. The results showed that it is better than that of share-per-link OXC whose wavelength converters are equally distributed in each link.

The work in [56] studied a wavelength-convertible switch architecture and routing algorithm for circuit switched wavelength division multiplexing optical networks. Wavelength converters were used to resolve wavelength conflicts. These converters were not dedicated to individual channels, but are shared by the channels of a node or those of an outbound link in the share-per-node or the share-per-link wavelength-convertible switch, respectively. It was found that converters can improve the network performance, such as the blocking probability and fairness. This work involved a simulation model that characterized the performance of the involved switches. To facilitate routing a new connection, the original network was transformed to an auxiliary graph on which polynomial-time algorithm was used. The simulation results are obtained for the ARPA2 network.

In [59], the study discussed the optimal allocation of wavelength converters in shared-per-link structure in WDM networks. The authors considered the following two cases: (1) Allocating wavelength converters at outgoing links of the node such that the total amount of traffic getting through the system was maximized given the total number of converters available in the system,. (2) Allocating wavelength converters properly at the outgoing links of the node such that the total amount of traffic getting through the system was maximized given the number of converters available at each node in the system. An optimization algorithm was proposed to solve case (1), and a heuristic algorithm is developed to find an approximate solution for case (2). They used computer simulations to evaluate performance of the proposed allocation method. Simulations were carried out on both the NFSNET and randomly generated networks.

Most of the reviewed work also preformed a performance comparison between shared-per-link switch and shared-per-node switch architectures. Most of these papers had relied on simulation models and did not introduce analytical models that study the behavior of such switches within a network. The fact that these studies lacked analytical models for the proposed architectures weakened their findings. Our present research work involves constructing analytical models for these switch architectures under symmetric and asymmetric traffic. It also attempts to analyze and compare the performance of these architectures for different networks and consider the different parameters involved in these models.

2.4 Wavelength Converter Requirement in Optical Networks

Multiple concurrently incoming packets cause contentions when two or more of them contend for the same output port. It is important to study the mechanism in which these types of contention are resolved in order to enhance the performance of the network.

2.4.1 Optical Contention Resolution

There are three domains in WDM networks to resolve contention. Contention-resolution schemes are wavelength, space, and time resolution, more technically termed as wavelength conversion, path (space) deflection, and optical delay-lines respectively.

2.4.1.1 Deflection Routing

Deflection routing is a complement to wavelength conversion for handling interface/port contention resolution. Deflection routing is achieved by deflecting the contending packet into a different route causing the packet to traverse a longer path but not dropped due to contention. In other words, when a node accepts a connection setup, it will set a path towards its destination on the shortest path available without queuing. This scheme has the lowest cost because it shifts the burden of resolving contention to the whole network control. It also removes the need for the expensive infrastructure investment of optical buffering, by reducing the need for optical amplifiers, signal regeneration hardware, and calibrated delay lines. The disadvantage of this scheme is that it lowers network throughput. To prevent this scheme from causing network congestion due to wandering packets for a long time in the packet switched optical network, time-to-live (TTL, or maximum number of hops) can be used.

2.4.1.2 Optical Delay-Lines

Optical delay-lines contention mechanism sends the contending packet to a local fiber delay line and makes it re-circulate back into an input port of the same node at which point, routing will be re-attempted again. This mechanism introduces an extra negligible delay to the packet. Due to the fact that packet might not be aligned or that the packets' lengths are not the same, the length of the delay line might not be standardized. This creates a chance for tradeoff between the contention resolution efficiency and the minimum optical latency.

2.4.2 Wavelength Conversion

Wavelength converters are necessary to increase the system efficiency. Optical wavelength conversion is a critical optical networking component that will allow routing to be achieved entirely within the optical domain. This technology will complement optical switching, by providing additional functionality within high-speed core networks. Wavelength conversion based optical networks behave better than networks with no wavelength conversion. In wavelength routed networks using wavelength conversion, a call is accepted if on all the links on its route there is at least one free wavelength, whereas no-conversion networks accepts a call on a route if there exists at least one wavelength free on all the links of that route. This behavior is known as the wavelength continuity constraint. This means a call can be blocked even if there are free wavelengths on all the links due to the lack of wavelength conversion devices. Having wavelength conversion is beneficial in that it decreases the blocking probability. However, the implementation of all-optical full wavelength conversion is quite difficult due to technological limitations.

2.4.2.1 Techniques for Wavelength Conversion

Wavelength converters should operate at high speed, be cascadable, consume low power, and achieved at low costs. The output wavelength should be speedily tunable over a wide wavelength range to complement the task of wavelength routing. Nowadays, wavelength conversion is frequently achieved electro-optically, which consists of a detector followed by an electrical regenerator, and a laser, that retransmits the incoming signal on a new wavelength. The electro-optic wavelength conversion suffers delays due to the E/O/E conversion whereas the all-optical wavelength conversion allows the optical signal to remain in the optical domain throughout the conversion process. The electro-optical wavelength conversion device imposes a significant limitation on the transparency of the network.

2.4.2.2 All-Optical Wavelength Conversion

Having conversion performed completely in the optical domain provides a speed benefit due to the elimination of O/E/O [27]. Laser modulation is time consuming and hinders a system's ability to be rapidly reconfigured in the event of optical channel corruption. Work is underway to move the wavelength conversion process to the optical domain in an effort to simplify network design and management [67]. All-optical wavelength conversion reduces the wavelength contention issue in photonic switching. Optical switching is wavelength dependent; therefore, only one stream can be transmitted on any given wavelength throughout the network segment at a given time [52]. All-optical wavelength converters are key devices for future WDM networks to eliminate wavelength blocking in the core optical cross-connects (OXCs). They are adopted to simplify traffic allocation and network management in the optical layer. A major benefit of all-optical converters is their ability to support a variety of optical signal wavelengths and formats and, therefore, a high degree of transparency. Several types of all-optical wavelength converters have been proposed in recent literature. A number of these proposed mechanisms, such as cross-gain modulation, cross-phase modulation, and four-wave mixing, will be explained in section 5.1.1 of this dissertation.

2.4.2.3 Wavelength-Converter Design

There are a number of design elements that are important for wavelength converters in order to complement its original function of converting an input side wavelength onto a different output wavelength among the wavelengths in the system. An ideal wavelength converter has a number of characteristics:

- transparency to bit rates and signal formats
- fast setup time of output wavelength
- conversion to both shorter and longer wavelengths
- moderate input power levels
- insensitivity to input signal polarization
- low-chirp output signal with high extinction ratio and large signal-to-noise ratio
- simple implementation

These characteristics are critical for the implementation of the future all-optical WDM networks and are considered very important elements for research.

2.4.3 Related Research Literature

There is a significant debate in progress about the degree of conversion needed in WDM optical network. WDM networks make very effective utilization of the fiber bandwidth and offer flexible interconnections for wavelength routing. In high capacity, dynamic WDM networks, blocking due to wavelength contention can he reduced by wavelength conversion.

The study in [94] reviews various wavelength conversion techniques, discusses the advantages and shortcomings of each technique, and addresses their implications for transparent networks. It shows that electronic wavelength conversion is an obstacle in realizing a transparent WDM network. Among numerous wavelength conversion techniques reported to date, only few techniques offer strict transparency. Optoelectronic conversion (O/ E/O) techniques achieve limited transparency. The majority of all-optical wavelength conversion techniques also offer limited transparency but they have a potential advantage over the opto-electronic counterpart in realizing lower packaging costs and crosstalk when multiple wavelength array configurations are considered. Wavelength conversion by difference-frequency generation offers a full range of transparency while adding no excess noise to the signal.

The work in [63] investigates the need for translating the wavelength of a signal within an optical network and the comparison of the performance of the wavelength path (WP) and virtual wavelength path (VWP) approaches. An analysis of the algorithms allowing VWP and WP schemes is reported. Their performances are compared in terms of the number of ports of each network node. A wavelength rearrangement algorithm is proposed which allows the performance of VWP scheme to be reached, with a greatly reduced total number of wavelength converters with respect to that corresponding to VWP.

In [13], the study described the need for wavelength conversion in an all-optical transport network. It focused on the comparison of wavelength paths (WP) and virtual wavelength paths (VWP) in terms of non-hierarchical all-optical networks with blocking and with waiting queues. The author studied a system where the requests for a free wavelength path arrives randomly and assumed to be based on Poisson distribution. The results showed that the VWP with waiting queue can significantly improve the traffic performance of the network. It also showed that VWP has a larger routing freedom than WP in non-hierarchical transport system with blocking and in non-hierarchical transport system with waiting queues.

The work in [74, 73] proposes optical wavelength division multiplexed (WDM) networks with limited wavelength conversion that can efficiently support lightpaths (connections) between nodes. It proposes ring networks with a fixed wavelength conversion capability within the nodes that can support all lightpath requests. It also proposes ring networks with selective pair-wise wavelength conversion capability within the nodes that can support all lightpath requests. Moreover, it proposes a star network with fixed wavelength conversion capability at its hub node that can support all lightpath requests. It extends its results to tree networks and networks with arbitrary topologies.

The study in [87] is an attempt to study the impact of wavelength converters in WDM wavelength routed all-optical networks. A new heuristic approach for placement of wavelength converters to reduce blocking probabilities is explored. Multihop virtual topology is designed to minimize the number and overall cost of converters. Blocking probabilities for static lightpath establishment (SLE) and dynamic lightpath establishment (DLE) are analyzed. In the case of SLE, arranging lightpaths in ascending order of their path length reduces blocking probability. Wavelength converters placed at nodes with high nodal degree further reduces the blocking probabilities.

The work in [93] examined the performance improvements offered by wavelength converters in WDM networks which have different number of wavelengths on different links. They showed that wavelength converters can provide significant performance improvements in networks with differing numbers of wavelengths on each link than in networks with the same number of wavelengths on each link. However, these performance improvements depended on the number of wavelengths on each link, the offered loads and the wavelength assignment scheme used. The paper offered an analytical model which described blocking behavior.

The work in [78] studied the impact of wavelength conversion capability on wavelength routing WDM networks with fixed shortest-path routing. The authors proposed a method for implementing wavelength routing in a WDM network with partial wavelength conversion capability. The light-path traffic loads on different node pairs were bidirectional, independent and identically distributed. They assumed that light-path requests for each node-pair are generated from identical Poisson processes and have independent holding times having unity mean exponential distributions. They also assumed that the shortest-path between the node pair is always used for light-path routing. Simulation results showed that such partial wavelength conversion networks provide a performance in between that of wavelength continuous networks and those with full conversion capability.

The papers considered in this section have studied the wavelength conversion requirements in the WDM optical networks. They did not consider the degree of conversion required and the savings in conversion resources in the presence of alternative network resources such as the use multi-fibers in optical links. The tradeoffs of using multiple fibers and use of different wavelength conversion capable OXCs will be considered in this research work.

2.5 Optimizing Wavelength Conversion Resources Allocation on Wavelength Routing Networks

Wavelength routed optical networks employ lightpath switching functions of OADMs and OXCs. Wavelength-routing enables the reuse of wavelengths in different parts of transparent optical networks to overcome some of the limits of a finite number of available wavelengths. They may optionally use tunable transmitters and receivers to provide routing within a larger-scale network. Wavelength routed optical networks provide the ability to optically add and remove wavelengths from the network with multiplexing/demultiplexing. The implementation of optical cross connects further expands the network's ability to optically pass information between networks. Wavelength routed optical networks can be either circuit switched or packet switched, depending upon the configuration of the OADMs, OXCs, and whether the optical transceivers are wavelength-agile or not.

2.5.1 Optical Network Control Plane

The optical network control plane is responsible for provisioning and maintaining connections and managing network resources. Provisioning of connections requires algorithms for route selection, and signaling mechanisms to request and establish connectivity within the network along a chosen route. Once a connection is successfully established, it needs to be maintained subject to service level agreements. Knowledge of a network's topology (inventory and connectivity) and the available resources are fundamental to the operation of the network. Ideally, the topology and network resources should be auto-discovered, requiring mechanisms and algorithms for neighbor and end-system discovery, and for advertising this information throughout the network. In addition, efficient utilization of network resources requires that an inventory of the currently available network resources be maintained.

Migration towards all-optical networks will begin with the core backbone network elements and expand to the edge devices. Edge devices will be required to perform electronic-optical conversion to convert the electrical signaling data into optical for backbone transport. These optical gateways will need to interface between many protocols and the optical layer. DWDM optical network layer now promises intelligent transport services that will allow clients such as IP routers to interconnect using optical interfaces. As bandwidth requirements increase by orders of magnitude, the most pressing issue is how to manage and control large optical networks. To address the critical issue of control, GMPLS based control intelligence is being adopted for use within optical networks through the use of a standard signaling interface, User-Network-Interface, between client and optical networks. UNI enables clients to establish optical connections dynamically using signaling procedures compatible with GMPLS signaling, as shown in Figure 2.5. This, along with intelligence within the optical network, will allow provisioning to

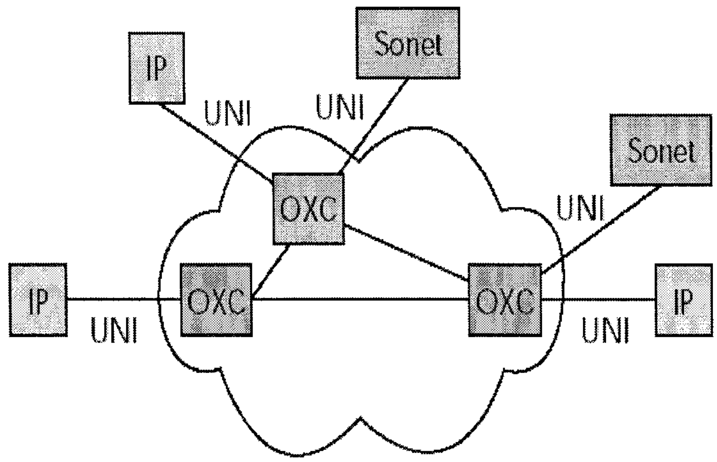

Figure 2.5: UNI Use in Controlling and Managing the Optical Core

occur within seconds. In addition to signaling, the UNI specification includes two other aspects to simplify management of these complex networks. The first is a neighbor discovery mechanism that will permit equipment on both ends of a fiber link to identify each other. Neighbor discovery will allow management systems to build interconnection maps automatically.

2.5.2 Related Research Literature

In WDM networks it is desired that a wavelength can be routed without electrical conversions. Wavelength converters improve the blocking performance, but there is a mix of results in the literature on the amount of this performance enhancement especially when the routing and wavelength assignment problem is considered.

The work in [75] considers routing connections in a reconfigurable optical network using WDM. Each connection between a pair of nodes in the network is assigned a path through the network and a wavelength on that path, such that connections whose paths share a common link in the network are assigned different wavelengths. The authors derive an upper bound on the carried traffic of connections (or equivalently, a lower bound on the blocking probability) for any routing and wavelength assignment (RWA) algorithm in such a network. The bound scales with the number of wavelengths and is achieved asymptotically (when a large number of wavelengths is available) by a fixed RWA algorithm. The bound can be used as a metric against which the performance of different RWA algorithms are compared for networks of moderate size. The authors illustrate this by comparing the performance of a simple shortest-path RWA (SP-RWA) algorithm via simulation relative to the bound. They also derive a similar bound for optical networks using dynamic wavelength converters and compare the two cases. Finally, they quantify the amount of wavelength reuse achievable in large networks using the SP-RWA via simulation as a function of the number of wavelengths, number of edges, and number of nodes for randomly constructed networks. They also quantify the difference in wavelength reuse between two different optical node architectures.

The objective of the study in [71] is to consider an optical network which employs wavelength-routing cross-connects that enable the establishment of wavelength division multiplexed (WDM) connections between node pairs. In such a network, when there is no wavelength conversion, a connection is constrained to be on the same wavelength channel along its route. Alternate routing can improve the blocking performance of such a network by providing multiple possible paths between node pairs. The study shows that wavelength conversion can improve the blocking performance of such a network by allowing a connection to use different wavelengths along its route. This work proposes an approximate analytical model that incorporates alternate routing and sparse wavelength conversion. It demonstrated that alternate routing generally provides significant benefits, and that it is important to design alternate routes between node pairs in an optimized fashion to exploit the connectivity of the network topology.

The work in [51] uses two metrics to quantify the wavelength conversion gain: the reduction in blocking probability and the increase in maximum utilization, compared to a network without converters. It studies the effects of wavelength routing and selection algorithms on these measures for mesh networks. It uses the overflow model to analyze the blocking probability for wavelength-selective (WS) mesh networks using the first-fit wavelength assignment algorithm. It also proposes a dynamic routing and wavelength selection algorithm, the least-loaded routing (LLR) algorithm, which jointly selects the least-loaded route-wavelength pair. In networks, both with and without wavelength converters, the LLR algorithm achieves much better blocking performance compared to the fixed shortest path routing algorithm. The LLR produces larger wavelength conversion gains. However, these large gains are not realized in sufficiently wide utilization regions and are diminished with the increased number of fibers.

The work in [9] considers the problem of routing and assignment of wavelength (RAW) in wavelength-routed optical networks. Given a set of requests for all-optical connections (or lightpaths), the problem is to find wavelength-continuous routes from the source nodes to their respective destination nodes. Since the number of wavelengths available per link is limited, lightpaths cannot be established between every source-destination node pairs. Moreover, a common wavelength might not be available on all the segments of a chosen route. Thus, routing and wavelength assignment are to be considered for the best possible performance. Several heuristic algorithms have already been proposed for the RAW problem, however, most of these algorithms are based on the traditional model of circuit-switched networks where the routing and wavelength assignment steps are decoupled. A new RAW scheme was developed which unifies the routing and wavelength assignment sub-problems. This unified approach is found to yield significantly better solutions to the RAW problem than the earlier ones. This paper also introduces an analytical model for predicting the average number of lightpath requests for a given physical network.

In the process of route computation using different routing and wavelength assignment algorithms, these algorithms calculate all possible routes with sufficient available bandwidth and other supplementary network resources such as wavelength conversion online. This means that the control plane architecture responsible for routing and wavelength assignment consists of multiple blocks for calculating the availability of different resources upon request. The interaction of these different control blocks and the simultaneous optimization of different network resources assignment algorithms depending on their availability outcomes the optimal path placement in multiple connections optical networks. The issue of optimizing different resources allocation algorithms, such as wavelength conversion resources, can be particularly important for wavelength routing. These issues were not considered in these research works and it is our intention to study and propose different resources allocation algorithms and study their effects on network performance.

2.6 Connection Request Blocking in Wavelength Routed Networks

Optical networks are composed of various enabling technologies, merged in harmony to produce high-speed, reliable, and affordable communications backbones. The benefits of all-optical networks are vast, yet the technologies necessary to render this dream a reality are complex. Advancements in semiconductor research, networking concepts, optical processing techniques, and switching implementations continue to be investigated.

2.6.1 Optical Infrastructure Components

In an effort to realize all-optical networks and photonic switching, researchers have developed various optical infrastructure components to perform various tasks similar to those performed by existing electrical network elements. Optical cross connects, optical add-drop multiplexers, and optical gateways all perform distinct functions necessary for the successful implementation of an all-optical network.

2.6.1.1 All-Optical Switches

The present and future all-optical switches are categorized under four different classes. The all optical switch categories are the following:

- Optical add/drop multiplexers (OADMs)
- Optical cross-connects (OXC)
- Optical burst switch (OBS)
- Optical packet switches (OPS)

2.6.1.2 Optical Cross Connects (OXC)

Cross-connecting in the optical layer is emerging as WDM technology matures. In an optical network, the wavelength paths will need to be managed. The OXC performs the following functions:

- multiplexing and demultiplexing
- space switching
- possibly, wavelength conversion (WC).
  This allows for cross-connection of the optical signals between incoming and outgoing wavelengths as shown in figure 2.6.

For all-optical switching, the evolution of OXCs stemmed from advances in micro-electromechanical systems (MEMS). MEMS is a technology that enables the control of miniature mechanical devices such as very small mirrors. In OXCs,

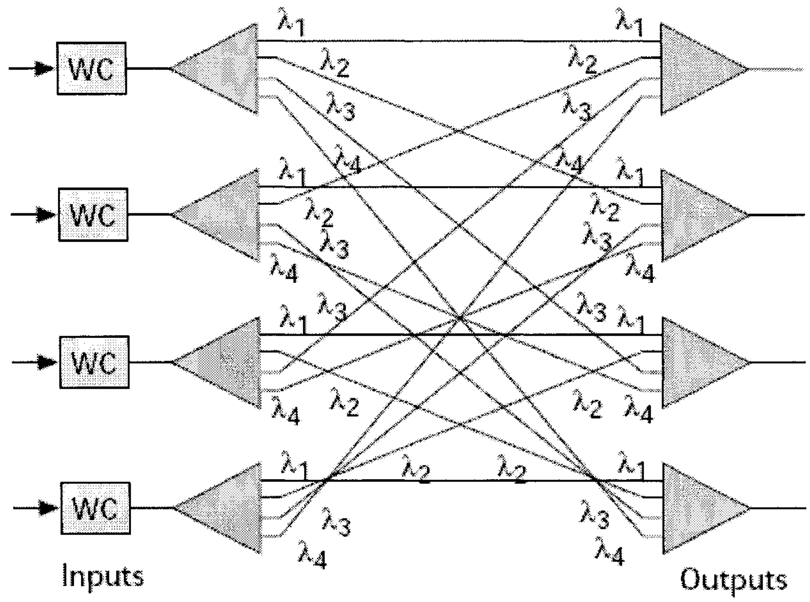

Figure 2.6: OXC Structure

MEMS mirrors are used to reflect the optical signal from one input to the chosen output. Three-dimensional optical cross connects utilize three-dimensional mirror matrices to connect any input to any output and reduce cost by utilizing fewer mirrors [42]. Figure 2.7 depicts the two-dimensional OXC structure. While the OXC's success and popularity depends, in part, on the availability, cost, and performance of future terabit IP router platforms, it remains attractive because it can provide certain useful functions:

- More efficient forwarding of traffic aggregates: IP edge routers will aggregate and multiplex IP traffic streams onto a single lambda, enabling more efficient switching in the network core than more granular operations at the electronic IP layer. This efficiency contributes to network scalability and lower costs.
- Optical bypass: Transit traffic arriving at a provider's point of presence (POP) can be switched at the optical layer rather than demultiplexed into

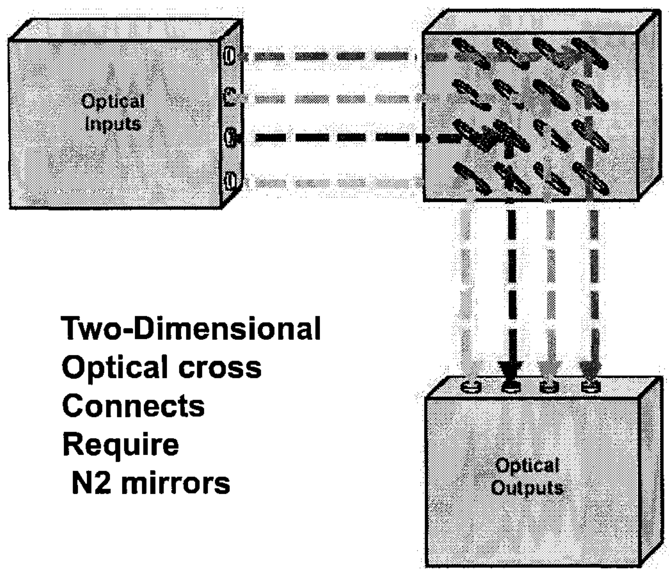

Figure 2.7: Two-Dimensional OXC MEMS Structure

packets and processed at the IP layer. Expensive electronic IP router resources can be allocated for serving customer traffic originating or terminating at the POP rather than traffic that is just passing through.

- Optical-layer reconfigurability: By distributing topological awareness and signaling intelligence on the OXC, we can efficiently configure optical network resource pool to provision services or react to failures.

2.6.1.3 Optical Add-Drop Multiplexers (OADM)

Optical Add-Drop Multiplexers (OADM) are responsible for adding or removing individual signals (wavelengths) at individual points along the optical transport channel. OADMs function fully in the optical domain without performing an O/E/O conversion. OADMs operate as peripherals to the OXCs. Figure 2.8 shows how Add-Drop Multiplexers function.

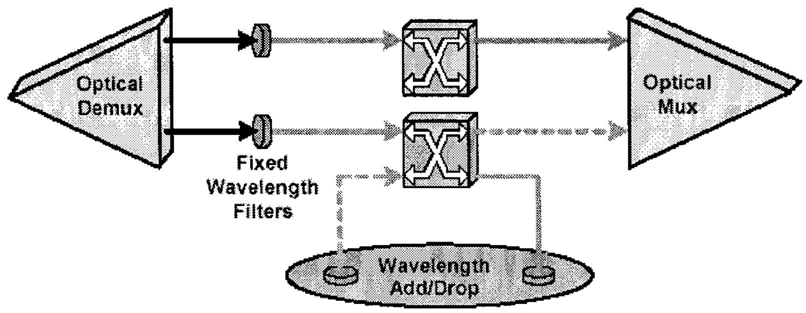

Figure 2.8: Add-Drop Multiplexers

2.6.2 Related Research Literature

It is necessary to have a generalized network model that allows the study of blocking performance of optical networks. The following research works explore different methods for different wavelength conversion settings for optical networks to study the blocking performance.

The authors of [14] studied a class of all-optical networks using wavelength division multiplexing and wavelength routing in which a connection between a pair of nodes in the network is assigned a path and a wavelength on that path. Using a generalized reduced load approximation scheme the authors calculated the blocking probabilities for the optical network model for two routing schemes: fixed routing and least loaded routing

The work in [11, 12] introduced a traffic model for circuit switched all-optical networks (AONs) which is used to calculate the blocking probability along a path for networks with and without wavelength changers. The performance gain when using full wavelength conversion is calculated as the ratio between wavelength-routed network performance when full wavelength conversion capability is available and without. It investigates the effects of path length, switch size, and interference length (the expected number of hops shared by two sessions which share at least one hop) on blocking probability and the ability of wavelength changers to improve performance. It also showed that the network diameter has more effects on wavelength-routed network performance than the switch size. The probabilistic model for a wavelength-routed network correctly predicts unobvious qualitative behavior, demonstrated in simulations, in previous works.

The study in [82] considered the effects of topological connectivity and wavelength conversion in circuit-switched all-optical wavelength-routing networks. An approximate blocking analysis of such network is performed. It proposed an improved framework for the analysis of networks with arbitrary topology. It introduced a simple model for networks with a variable number of converters and analyzes the effect of wavelength converter density on blocking probability. Then, it applied this framework to two sparse network topologies, the ring and the mesh-torus, and obtains the blocking performance. The results show that, in most cases, only a fraction of the network nodes need to be equipped with wavelength conversion capability for good performance.

The study in [50] developed a model for evaluating the blocking probability of various connection management protocols for wavelength-routed optical networks with dynamic lightpath establishment. The model characterizes both blocking due to insufficient resources and blocking due to multiple interfering connection requests. Then, the analytical model is used to compare two connection management schemes, one which utilizes source-initiated reservation, and another which utilizes destination-initiated reservation.

The work in [39] considers the call connection probability in an all-optical network using wavelength division multiplexing (WDM), which depends on the number of WDM wavelengths and on the network capability for wavelength conversion at network nodes as an extension to [11]. The analysis, based on the assumption that wavelengths on different links are used independently, slightly underestimates call connection probability. This is because in a real network the wavelengths used on consecutive links tend to be positively associated. New closed-form expressions for call connection probability were derived which reflect these dependencies. These expressions are combined in a converter availability model to study the impact of wavelength conversion on call connection probability and the tradeoff between network wavelength conversion capability and the number of WDM wavelengths.

The study in [99] considers a class of circuit-switched wavelength routing networks with and without wavelength converters, and presents the first part of a new analytical framework to accurately and efficiently evaluate the blocking performance of such networks. The model allows non-uniform traffic, it accounts for the correlation among the loads at all links in a path, and it can be used when the location of converters is fixed but arbitrary. It presents a Markov process that captures the behavior of a path in terms of wavelength use. It also obtains an approximate Markov process which has a closed-form solution that can be efficiently computed for short paths. Then, it develops an iterative algorithm to analyze approximately arbitrarily long paths. The algorithm decomposes a path into shorter segments which are then studied in isolation using the corresponding approximate Markov process. The individual solutions are appropriately combined to obtain a solution for the original path. Finally, it demonstrates how the analytical techniques can be used to gain insight into the problem of converter placement in wavelength routing networks.

The study work in [72] examines the various facets of the wavelength-conversion technology from its realization using current OE devices, to its incorporation in a wavelength routed network design, to its effect on efficient routing and management algorithms, to a measurement of its potential benefits under various network conditions. This study highlights systems challenges and performance issues which need to be addressed in order to incorporate wavelength conversion effectively. A review/survey of the enabling technologies, design methods, and analytical models used in wavelength-convertible networks is provided.

A single-Fiber wavelength-routed network is wavelength-routed network using WDM as a multiplexing technology that employs one fiber connected at every pair of nodes. These discussed studies have considered the single-fiber wavelength-routed network extensively and did consider the multi-fiber case. Different probabilistic models dealing with performance issues of single-fiber wavelength-routed network that uses simple OXC architectures were presented in these studies. These models study the effect of various wavelength-routed network parameters such as number of wavelengths used, size of the optical switches, the average length of the optical paths, availability of wavelength converters, etc., on the blocking probability and utilization of the network. They were, also, short in producing analytical models for different conversion sharing OXC architectures. In this research work, we intend to propose models for different networks using conversion sharing OXC architectures and then compare their results with the multi-fiber wavelength routed network. We will also consider different conversion resources allocation algorithms and try to optimize their execution to enhance the optical control plane.

2.7 Multi-Fiber Synchronous Optical Packet Switch Network

Multi-fiber synchronous optical packet switch promises large cost reductions for transporting IP services. Various protocols (such as GMPLS) can be used to map IP directly over WDM with less hardware [70]. Transporting IP over a true optical network means that some of this functionality will be achieved in layer 1, e.g. network protection. Figure 2.9 shows some of the possible protocol mappings of IP into a WDM network. The protocol stacks that maps the classical IP over ATM over SONET/SDH is the most commonly deployed today.

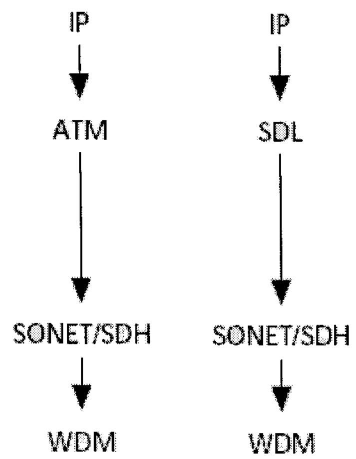

Figure 2.9: Possible Protocol Mappings of IP into a WDM

2.7.1 Optical Packet Switching

Due to the fact that data traffic is steadily exceeding the telephony traffic, the existing circuit-switched networks will need to be upgraded to support packet switched data networks. Optical packet switching seems to be a strong contender due to the high speed, data format transparency and configurability it offers. The absence of optical memory is a major difference between the design of an optical packet network and an electronic packet network. A realistic optical packet-switching technology is not available today and from the economy point of view, networking companies seem to doubt its feasibility in the short foreseeable future. As far as the research community, there seem to be many ongoing researches in this area but most research in all-optical networks is confined to circuit switching [22].

2.7.1.1 Optical Packet Header Retrieval

The realization of optical packet switch networks requires that the problems such as contention, signaling and local and global synchronization be resolved.

One major problem in all-optical packet-switched networks is that of signaling. A receiving node must be able to retrieve header information from the incoming WDM-multiplexed packets on the fly for processing. A header error causes packets to be misrouted and the processing technology of the header is very important in the optical network to be able to route the packet correctly. Three options for header extraction and processing are explained in the following subsections.

2.7.1.2 Subcarrier Multiplexing (SCM)

Subcarrier multiplexing technology can transport header information with the payload using relatively inexpensive electronics. A low-bandwidth header is placed on an electrical subcarrier above the base band frequencies occupied by the packet payload, and both are transmitted in the same time slot. The header can impose a power penalty on the payload through inter-modulation distortion, and a compromise must be made to ensure appropriate header detection sensitivity and minimal payload penalty. Header removal is also difficult since the SCM header passes through the photonic switching matrix with the payload.

2.7.1.3 Transmit the Header and Payload on Separate Wavelengths

Transmitting the header on a separate wavelength offers a simple method of extracting the header. Each node on the path requires delay compensation to realign the header and payload. An additional laser is necessary to update the packet header introducing an extra cost and complexity in header extraction implementation. This method could suffer from crosstalk since the payload and header are transmitted in parallel in the same link.

2.7.1.4 Transmit the Header before the Payload Serially

The third option is to transmit the header before the payload serially. This scheme facilitates header extraction/insertion and eliminates the penalty due to header and payload interaction, but it will be at the expense of bandwidth utilization. The header is usually at a lower bit rate and it is removed by gating an optical switch at the appropriate time.

2.7.2 Synchronous and Asynchronous Optical Packet Switch Networks

Synchronization at the packet time-slot level is a very critical aspect of all-optical packet switch networks. In synchronous packet switch networks, all packets have the same length, and an alignment mechanism is deployed to align all packets entering a switch for synchronization. This calls for some form of global slot alignment. The alignment process improves the contention-resolution efficiency. Clock recovery has to be implemented on a packet-by-packet basis since in adjacent time-slots a node may be looking at packets coming from different transmitters. The packet synchronizers used for packet alignment requires additional cost in terms of hardware and constraints the network by imposing a condition of equal packet lengths.

These cost limitation due to the implementation of packet synchronizer is absent from the asynchronous packets witched network. This type of networks allows packets of arbitrary lengths and does not require a complex clocking mechanism. However, the network's contention-resolution efficiency can be lower than the synchronous packet switch system.

2.7.3 Related Research Literature

The work presented in [31] introduced an analytical model which enabled the performance evaluation of a bufferless optical packet switch equipped with limited-range wavelength converters when an optimum scheduling algorithm is adopted. The model concentrates on the optimum scheduling problem in slotted bufferless packet-switching architectures equipped with wavelength conversion. The optimum scheduling algorithm is introduced as an algorithm that minimizes the number of packets lost at each time slot. In their study, they showed that the problem of finding the optimum scheduling architectures does not have a trivial solution.

The study in [33] compares selected optical packet switching architectures that use a wavelength conversion technique to solve the packet contention problem. The architectures considered in this study are equipped with shared and limited-range wavelength converters. The study focuses on two architectures: the shared per node (SPN) and the shared per output fiber (SPOF) architectures. In order to compare these two architectures, analytical and simulation models were developed that allowed to evaluate the number of LRWCs needed as a function of the main system and traffic parameters. Their results showed that the SPOF and SPN architectures allowed for greater saving in terms of number of wavelength converters needed. The performance of the SPC, SPOF and SPN architectures in this study were evaluated when the First Available Algorithm was adopted. The algorithm showed that SPOF and SPN architectures could have been further improved if an optimized scheduling of arriving packets was performed. These results call for further investigation into this scheduling algorithm for the SPOF and SPN architectures. The authors evaluated the performance issues and the need to determine in which way the packets will actually be scheduled in order to obtain the optimum performance.

The objective of the study in [32] was to investigate the performances of packet-switching architectures working in a synchronous and asynchronous way. In such architectures, the packet contention was resolved using wavelength conversion. The author investigated the amount of saving in the number of converters that could be allowed in both the synchronous and asynchronous architectures and compared the obtained results. The study showed that when a packet loss probability is fixed, the synchronous case saved greater number of converters than the asynchronous case. The results also showed that the asynchronous switch required more expensive switching matrix. Their analysis was performed under both unicast and multicast traffic scenarios. In the multicast traffic case, the results showed that the SPN architecture operates in a synchronous and the asynchronous switches indifferently and it allows a little saving of wavelength converters.

The research work in [79] considered a slotted WDM packet switch with limited-range wavelength converters using simulation models with various types of data traffic. Results showed that the slotted WDM packet switch with a small range of wavelength conversion capability can achieve a performance close to that of a switch with the full range of wavelength conversion capability. These results were obtained by means of simulations. The results showed that wavelength conversion can lead to significant performance improvement of the WDM packet switch and that a threshold of wavelength conversion exists for the performance improvement of the switch.

The objective of [18] was to present a detailed analytical traffic model for all-optical WDM photonic packet switch network and the requirements for buffer size and link dimensions. This study showed that due to the topology, packets may generate traffic bottlenecks produced by a tendency of the routing scheme to send packets with different destinations through preferred paths. This effect increases the traffic load and, hence, the probability of blocking at output links of specific routers in the network and, therefore, a large buffer depth or an increment in the number of fibers per link was required. The model presented in the paper assumed non-correlated traffic and, therefore, gives a lower bound characterization for the number of delay lines required in all-optical routers. It represented the queuing behavior of the traffic in terms of a minimum number of parameters. But they did not study the impact of correlated traffic on the queuing performance of the routers, and the network growth produced in providing protection and restoration resources in the network. It is noticeable that this work has not added much to the work presented in [25].

The work in [15] studied the performance of packet switch networks. It showed that when the active nodes are provided with a number of optical receivers/transmitters equal to the number of wavelengths, routing without buffers in conjunction with full wavelength conversion becomes an interesting option to solve contentions in packet switching networks. They analytically compared three implementations of the access function: (1) local arrivals are centrally managed with tunable transmitters, (2) local arrivals are centrally managed with fixed transmitters, and (3) local arrivals are evenly split among fixed, independently managed transmitters. Their analysis showed that the simpler access scheme (3), gives better throughput/delay results at high loads than the centrally managed schemes. It also showed that delay-line optical buffers are much more effective way of solving contentions than using wavelength conversion. This result might not be accurate due to their employment of deflection routing. They stated the fact that optical buffers increase the accumulation of intra-band crosstalk and amplifies spontaneous emission noise, while wavelength conversion can provide noise suppression and signal reshaping and accordingly, they suggested that optical packet switch networks with a small number of wavelengths may use optical buffers instead of wavelength conversion.

The work in [25] is an analytical traffic model for a photonic WDM packet switch block and the requirements for buffer size. Three different switch architectures were considered, each of them representing different complexities in terms of component count and requirements for components. The first switch block used a physical buffer per outlet resulting in as many internal wavelengths in the switch as there were wavelengths in the network. The second switch block had one physical buffer completely shared among all outlets. The third configuration physically shared a number of buffers among all outlets. Due to the difference in the number of needed wavelengths, the tuneability requirements for wavelength converters differed. The presented architectures were compared in terms of space-switch sizes, the complexity of the involved optical devices including wavelength converters, and the ability of the architectures to scale with the number of wavelength channels. Regarding the component count of the space-switch, the complexity was highest for configuration with one buffer per outlet while configuration with one physically shared buffer shows the best performance. It was shown that the number of fiber delay-lines can be significantly reduced by the use of tunable optical wavelength converters, thereby exploiting the wavelength domain to solve contention of optical packets. The authors also analyzed the physical buffer structure with special attention to the possibility that several outlets share the same physical buffer. They concluded that when a buffer is physically shared among outlets, it requires many wavelengths internally in the switch block whereas, architectures with buffers dedicated to each outlet require a smaller number of wavelengths to achieve similar performance.

The research work in [24] presented a traffic analysis of optical packet switch design. Special consideration was given to the complexity of the optical buffering and the overall switch block structure in general. Wavelength converters were used to improve the traffic performance of the switch blocks for both random and bursty traffic. Furthermore, the traffic performance of switch blocks with add-drop switches has been assessed in a Shuffle network showing the advantage of having converters at the inlets. Finally, the aspect of synchronization was discussed through a proposal to operate the packet switch block asynchronously. The emphasis of this work was on the ways to reduce the switch complexity related to optical buffering and optical synchronization. The scenarios considered in the traffic studies included both simple interconnection networks as well as networks where the switch nodes require add-drop functionality like Shuffle networks. The results also suggested that optical packet alignment at switch inlets may be avoided. The anthers claimed that asynchronously operated optical packet switch blocks suffer a high packet loss ratio, but use of wavelength converters reduced the impairment significantly and accordingly, the complex optical packet alignment units could be avoided.

The work in [29] analyzed an architecture for optical packet switch in which the wavelength converters were shared per input line (SPIL). The architecture's performance was evaluated by means of an analytical model and compared with those of an optical packet switch architecture in which the wavelength converters are shared per output line (SPOL).

The objective of the study in [34] was to propose an optical packet switching architecture in which wavelength converters were needed to solve output packet contentions. The authors evaluated the performances of the proposed architecture when control algorithms with different complexity were adopted. Under a unicast traffic scenario the obtained performances were compared to the ones of the architectures in which the wavelength converters are shared per node. The architecture with sharing-per-node needed fewer wavelength converters than the proposed architecture. According to the authors, the complexity was due to the flexibility provided to the arriving packets in accessing the shared-per-node converters bank.

The work in [68] introduced a new model for synchronous bufferless optical packet switch network employing full wavelength conversion. The authors presented a non-uniform traffic arrival model where looping should not occur, which meant that packets should not be re-routed to the same fiber they originally arrived from. They showed that the Poisson arrival model could be used to approximate the Binomial arrival model.

The papers considered in this section did not consider the presence of multi-fiber in the slotted optical packet switch and its effect in reducing the required number of wavelength converters in the switch. These discussed studies have considered the single-fiber network extensively and did not consider the multi-fiber case. They also have not quantified their results within a network to generalize their findings into the network environment. The tradeoffs of using multiple fibers and use of different wavelength conversion in the synchronous share-per-link optical packet switch will be considered in this research work. The use of such switch and its behavior within a network would be explored.

Chapter 3

RESEARCH PROBLEM STATEMENT

3.1 Introduction and Research Goals

Greatly simplified versions of real-life networks have to be considered in order to be able to build an analytical model. A good model can produce results within an acceptable range even with simplified assumptions. A modeling methodology that just tries to model the real network in every detail is inappropriate and not realistic. Obviously, the model must be simple enough to achieve the identified goals, while representing a fair representation of behavior of the real network. The goals of this study are to model and examine various OXC switching architectures with respect to network performance.

Using Wavelength Convertible Switches (WCSs) in the multi-fiber wavelength routed network enhances the flexibility of bandwidth allocation by increasing the agility of wavelengths in DWDM optical networks. The employment of various types of WCSs, such as Share-per-node OXC and Share-per-link OXC improves the utilization of wavelength conversion resources and enhances the overall performance of optical networks. This enhancement is due to the efficiency in resource sharing introduced by the implementation of these architectures in wavelength routed networks. Using the conventional circuit-switched networks (Wavelength-Routed network), where a connection (light-path) between source-destination pair has to be established on the top of the WDM multiplexing technology before data transmission start, for short-connection duration packet-switched traffic will result in ineffective use of the enormous bandwidth provided by such technology. This problem is not an issue for applications that require long connection duration in the core where a point-to-point dedicated connection is required.

Optical packet-switching (OPS), which allows fast allocation of wavelengths in an on demand overcomes the inherent poor utilization of the WDM bandwidth in wavelength-routed network when serving short-connection-duration packet-switched traffic. OPS suffers from packets contention problem that arises when two or more of the incoming packets on the same wavelength intend to leave the switch through the same output port, which results in packet loss and poor network performance. The contention could be cleared by shifting all but one of the contending packets to one of the unused wavelengths on the requested output. The wavelength conversion of the contending packets takes place by utilizing wavelength converters. Using wavelength conversion (WC) at OPS reduces the packets loss due to contention.

In this research work, we also identify the tradeoffs involved in using Wavelength Convertible Switches, in both wavelength routed networks and optical packet switching networks, and describe the goals and objectives of our research accordingly. This research work proposes mechanisms and solutions for integrating different switch architectures into both kinds of networks in the presence of multiple fibers. These solutions are then analytically modeled and evaluated to verify feasibility in terms of their effects on network performance.

For the Internet to scale and accommodate the exponentially growing traffic, we must scale the performance of the different components in the optical core that provides bit-rate transparency. Bit transparency refers to the fact that the fabric will switch data independently of the signal format or bit rate, routing and wavelength assignment process, and how it integrates with upper layers. This scaling should take into account the ability of the optical network elements to handle traffic efficiently without degrading the utilization performance.

As bandwidth requirements increase by orders of magnitude, the most pressing issue is how to manage and control large optical networks. DWDM based optical core pushes the way for more intelligent core devises able to be managed by intelligent transport services that will allow clients such as IP routers to interconnect using optical interfaces. A number of newly proposed OXC architectures have demonstrated controllability and manageability potentials in order to add more intelligence to the optical core and increase scalability and configuration flexibility.

The main goal of this research is to study such OXC architectures in terms of their scalability, complexity, and different performance aspects. The investigation of their operational limitations is approached by introducing analytical models that describe their behavior and performance with respect to different network parameters and operational conditions, wavelength routing and optical packet switching. Different network architectural scenarios, which require different parameter configurations depending on the switch architecture, were analyzed using analytical models. In this context, the cost effectiveness, in terms of equivalent wavelength counts required, of employing multi-fiber links in wavelength conversion resource sharing switch architecture, share-per-link wavelength convertible switch, is studied. The employment of multi-fiber link, when the total number of wavelengths in the link is equal to the number of wavelength in the single fiber setting, introduces operational flexibilities in term of reusing the existing range receiver/transmitter components instead of redesigning such transceivers just to accommodate more wavelengths on the single fiber link. Another reason for considering multi-fiber networks is the fact that such networks would be more flexible in handling wavelength connection requests due to the use of similar sets of wavelengths in every fiber in the link. This means that connection requests asking for similar wavelength can still be served resulting in a higher switching element utilization and accordingly better blocking performance. So the effects of adding more fiber in a link, relative to adding more wavelengths in a single fiber link network, is investigated in this research work.

Another goal for this research is developing algorithms to mange the switch resources efficiently. Mechanisms to manage switch resources will lead the way for proposing architectures for integrating these algorithms with the optical control plane. The optical network control plane is responsible for provisioning and maintaining connections and managing network resources. Provisioning of resources require algorithms for resources allocation, and signaling mechanisms to request and establish connectivity within the network along a chosen route. Different operational scenarios resulting for the employment of different resource allocation algorithms are assessed in terms of their performance and computational complexity to determine the tradeoffs of integrating such algorithms with the optical control plane.

The proposal of new ranging mechanisms of wavelength converters, a major design element of the optical switch, is one of the important goals of this dissertation. These ranging mechanisms would have important roles in managing conversion resources efficiently. This work will explore the differences between the input/output side ranging mechanisms and their effects on conversion resources sharing and consequently performance. It will analyze the impact of using different architectures for wavelength conversion to mitigate the cost penalty.

3.2 Research Objectives

The significance of this work is in the wide scope of interrelated ideas that span the areas of optical switch architecture, resources management, control mechanisms, and optical system integration. Much concentration is paid for share-per-link wavelength convertible switch networks within both the wavelength routing and optical packet-switching frameworks. The objectives of this research include performance studies of different operational scenarios of different switch architectures, the proposal of different wavelength conversion resource algorithms, examination of operational tradeoffs due to the implementation of multi-fiber link networks, the proposal of new ranging mechanisms of wavelength converters and the exploration of the differences between the input/output side ranging mechanisms and their effects on conversion resources sharing performance. The following are some of the general research objectives:

- Model/evaluate the wavelength/packet contention in terms of blocking/packet loss performance for wavelength routing/optical packet-switching networks.

  The current technology of wavelength division multiplexing (WDM) allows multiple traffic streams to be multiplexed efficiently into a single fiber. While introducing wavelength converters to improve network performance, it is often of interest to know the benefits offered by conversion resources used in terms of blocking/packet loss probability. It is necessary to have a generalized network model that allows the study of blocking/packet loss performance of optical networks.

  Previous work has considered single-fiber networks extensively, but have not considered the multi-fiber case in detail. Different probabilistic models dealing with performance issues of single-fiber networks that use simple OXC architectures were presented in these studies. These models studied the effects of various network parameters such as number of wavelengths used, size of the optical switches, the average length of the optical paths, availability of wavelength converters, etc., on the blocking/packet loss probability and throughput of the network. These studies lacked the consideration of multi-fiber networks. They were, also, short in producing analytical models for different conversion sharing OXC architectures. In this research work, we will propose models for different networks using conversion sharing OXC architectures and then compare their results with the multi-fiber network.

In optical packet switching networks sense, this research involves modeling the behavior of such networks under both the symmetric and asymmetric traffic conditions. It will focus on share-per-link multi-fiber packet switch based networks and explore different performance aspects and tradeoffs to grasp the quantitative performance differences when using multiple fibers and limited wavelength conversion. The proposed models help accomplish operational comparisons in terms of network performance.

- Evaluate/compare the enhancement of performance of multi-fiber vs. single-fiber link networks, when same total number of wavelength are used, under both wavelength routing and optical packet-switching network frameworks

  An important problem in multi-fiber WDM networks is the tradeoffs between using multiple fibers and other network resources while guaranteeing high network performance. A cost effectiveness evaluation is conducted in terms of the number of wavelengths requires in a single fiber link network to result in a similar performance to the multi-fiber setting. The fiber requirement may depend on many factors, e.g., the network topology, traffic patterns, the number of wavelengths per fiber, and network architecture. A number of research works have considered the fiber requirement for different optical network settings. They have studied the multi-fiber requirements in the sense of link resiliency to multiple path failures, network topology, traffic patterns, number of wavelengths per fiber, and routing algorithm employed in the network. They did not consider the need for multi-fibers in the presence of alternative network resources such as wavelength conversion. The tradeoffs of using multiple fibers with different wavelength conversion capable OXCs are considered in this research work.

- Evaluate wavelength converter requirement in optical networks to meet performance criteria, under both wavelength routing and optical packet-switching network frameworks

  There is a significant debate in progress about the degree of conversion needed in WDM optical network. WDM networks make a very effective utilization of the fiber bandwidth and offer flexible interconnections for wavelength routing as well as for optical packet switching. In dynamic WDM networks, blocking due to wavelength contention can be reduced by wavelength conversion. Wavelength conversion addresses a number of key issues in WDM networks including transparency, interoperability, and network capacity.

  Previous work have studied the wavelength conversion requirements in the WDM optical networks. They did not consider the degree of conversion required and the savings in conversion resources in the presence of alternative network resources such as the use multi-fibers in optical links. The tradeoffs between using multi-fiber networks and networks with different wavelength conversion capable OXCs are considered in this research work.

- Model and evaluate of different wavelength resource sharing optical switch architectures

  Due to the existence of wide variations of optical network components and network architectures, ways are being sought to adopt cost effective devices and architectures to maximize the performance of optical networks. Wavelength conversion has been studied as a way to improve efficiency in optical networks. A network utilizing wavelength conversion can minimize the number of wavelengths it employs, reducing the complexity and cost.

Previous work has not modeled the architectures of dedicated, share-per-node, share-per-link wavelength convertible switches. The fact that these studies lacked analytical models for the proposed architectures weakened their findings. These findings were results of simulation models that were not studied and verified analytically. Our research work involves constructing analytical models for different network architectures employing such switches under asymmetric traffic conditions. It will also attempt to analyze and compare the performance of these architectures for different networks and consider different parameters involved in these models.

- Propose, model, and evaluate different wavelength conversion recourse allocation algorithms for share-per-link switch architecture

  The new generation of optical transport equipment will allow fast provisioning and reallocation of network resources. For this purpose, dynamic resources allocation will be implemented through the introduction of protocols and functions similar to those currently available on router equipment. In WDM networks, it is desired that a wavelength/optical packet be routed without electrical conversions. Wavelength converters improve the blocking/optical packet loss performance, but there is a mix of results in the literature on the amount of this performance enhancement. The process of route computation, using different routing and wavelength assignment algorithms, requires the calculation of all possible routes with sufficient available bandwidth and the online reservation of supplementary network resources, such as wavelength conversion. This means that the control plane architecture consists of multiple blocks for calculating the availability of different resources upon request. The interaction of these different control blocks and the simultaneous optimization of different network resources assignment algorithms results in the optimal path placement in multiple connections optical networks. The issues of optimizing different resource allocation algorithms, such as wavelength conversion resources, can be particularly important for wavelength routing. These issues have not been considered in detail in previous research works and it is the intention of this study to propose different resources allocation algorithms and analyze their effects on network performance.

The new generation of optical transport equipment will allow fast provisioning and reallocation of network resources. For this purpose, dynamic resources allocation will be implemented through the introduction of protocols and functions similar to those currently available on router equipment. In order to assess the impact of networks resources allocation mechanisms, it is required to develop a model capable of describing the functionality and performance of the resources allocation capabilities of the underlying optical control plane technology. So, the goals of this study also include modeling different proposed wavelength-conversion-allocation algorithms and study them comparatively to have a vision of how the next generation optical network control plane should be architected and integrated with the already established control plane functions.

- Propose and evaluate new shared limited range wavelength conversion schemes in optical WDM networks

  A significant cost penalty can be incurred if wavelength converter (WC) is not utilized in an efficient manner. One of the objectives of this research is to show how one could significantly mitigate this penalty by allowing limited range WC, using a small subset of wavelengths as the range, complemented with the ability to share these resources. Range tunable transmitters and receivers are cheaper and simpler to construct than fully ranged ones. Our aim is to determine the range configuration that is most practical for tunable all-optical devices in the presence of WC resources sharing. Accordingly, a number wavelength converter ranging architectures are proposed and evaluated in this study to effect of such mechanisms on the performance of the optical switch. The cost of conversion not only depends on the number of converters in the network, but also on the architectural complexity introduced within the optical switch. This study examines how WC is related to efficient utilization of an optical channel.

3.3 Main Research Topics

After laying out the general research objectives, the main research topics, according to their order in the following chapters, are introduced in this section. The main results of this work is presented in this thesis as follows:

- Performance of Multi-fiber Optical Networks and the Allocation of Resources in Shared-per-Link WCS (Chapter 4)
- Simulation Based Performance Evaluation of Shared Limited Range Wavelength Conversion Schemes in Optical WDM Networks (Chapter 5)
- Performance Analysis of Synchronous WDM Share-per-link Multi-fiber Packet-Switched Networks under Symmetric Traffic Condition (Chapter 6)
- Performance Analysis of Synchronous WDM Share-per-link Multi-fiber Packet-Switched Networks under Asymmetric Traffic Condition (Chapter 7)

The following sub-section will give a brief introduction of goals concerning each chapter.

3.3.1 Performance of Multi-fiber Optical Networks and the Allocation of Resources in Shared-per-Link WCS

There are many facets of the routing and wavelength assignment problem in optical networks that require investigation. These include route computations for individual connections, topology information discovery and distribution, resource status information distribution, and reachability information. In this research work, new conversion resources allocation schemes are developed to enhance RWA sub-problem. These proposed conversion resources allocation algorithms will complement the RWA tasks in the optical control plane. They are to be optimized in order to minimize the execution time of conversion resources allocation that is needed for establishing an optical path upon request. Analytical models are presented for conversion resources allocation algorithms, which can be used to study network behavior without excessive computational complexity. Analytical results are useful to verify the need for such schemes.

These proposed resource allocation algorithms have to work, in a cooperative manner, with RWA algorithms. We can achieve better utilization of network resources by modeling and studying the behavior of these algorithms. Optimally assigning paths to connection requests is subject to the availability of complementary network resources. The optimization of related algorithms can be particularly important to the complex optical control plane hierarchy. Topology discovery and resource status and allocation are areas that require more understanding due to its relation to route computation. The optimized system should reduce the complexity of controlling and managing network resources. Some of the issues that must be faced in the process of understanding the degree of integration required for different resources managing modules are:

- Outlining the dimension of the network and network elements

- Evaluating the impact of different node architectures

In order to complement the use of adaptive routing and increase the performance of the routing scheme, the control should adopt a scheme to dynamically assign conversion resource to traffic request on demand. Dynamic Conversion Resources Allocation Algorithms (CRAA), based on the parameters declared by the control plane, play fundamental roles in Routing and Wavelength Allocation problem, RWA, by accommodating connection requests with the required conversion resources in case of the original requested wavelengths are exhausted. The complexity of the Wavelength Allocation, WA, depends on the wavelength conversion capability of network nodes.

We present three CRAAs that improve the utilization of the optical links. The proposed CRAAs in this work are: (1) Inclusive Search Algorithm, ISA (2) Narrow Search Algorithm, NSA and (3) Optimized Inclusive Search Algorithm, OISA. We consider these algorithms where various performance attributes, such as utilization performance and blocking probability, directly influence the cost function of switching. The aim is to optimize the allocation of scarce wavelength conversion resources using different CRAA algorithm scenarios that change the behavior of traffic blocking models in share-per-link WCS. Connection requests are assumed to arrive randomly according to a Poisson process and exponential holding time. There is no queuing of connection requests: once a connection request is rejected, it is not considered for a later setup.

The improvements of key performance metrics such as end-to-end blocking performance and throughput in wavelength routing networks employing multi-fiber multi-hop configurations under different wavelength conversion scenarios are investigated. A detailed presentation of this topic follows in Chapter 4.

3.3.2 Simulation Based Performance Evaluation of Shared Limited Range Wavelength Conversion Schemes in Optical WDM Networks

Optical switches, used to aggregate data through optical backbone networks, must exhibit high efficiency and cost effectiveness. Wavelength Converter (WC) [27], optical switches, routers, and add/drop multiplexers, represent very important resources that are essential for exploiting the capacity of optical networks. WCs are used to eliminate the severity of "wavelength continuity constraint" [84], and improve wavelength agility for dynamic reallocation of optical channels, which in turn enhances the scalability of the network to match the demand for bandwidth. The proper use of converters decreases the number of necessary wavelengths to achieve a given throughput in an optical network. The tuneability of a WC further enhances utilization and flexibility of the network. Since the number of available wavelengths and converters are limited, and they also affect the complexity of the switch, performance models for different WC ranging architectural configurations help to achieve optimal cost and performance, while maintaining efficiency.

This work, which is presented in Chapter 5, investigates issues associated with limited-range wavelength converter (LRWC) in the presence of conversion resources sharing. This study considers the effects of employing different conversion ranging architectures that fall under partial wavelength conversion category, within a WDM optical switch. These ranging mechanisms are identified as an important design criterion due to technological limitation in the implementation of full range wavelength conversion in an all-optical wavelength convertible device. Optical networks employing wavelength ranging mechanism will be more efficiently implemented than networks that have no constraints on conversion. The adopted conversion ranging scheme consider different cases where an incoming wavelength can be converted to a pre-specified range of outgoing ones. The differences between input/output side ranging mechanisms and their effects on conversion resources sharing and consequently performance are also explored.

Previous work has shown that LRWC can offer performance comparable to Full-RWC in all-optical networks, [73, 90]. However, the concept of conversion resource sharing in conjunction with different wavelength range configurations has not been explored. In this study, we perform a simulation based analysis of different LRWC configurations that implement conversion resources sharing. This study focuses on maximizing the efficiency associated with converters and maintaining an appropriate level of performance by quantifying the penalty, in terms of call blocking, for mismanaging the WC resources. In this work, wavelength converters can be categorized into two types: (1) full-range wavelength converters, which can convert an incoming wavelength to any outgoing wavelength, and (2) limited-range wavelength converters (LRWC), which can convert an incoming wavelength to a subset of the full wavelength set.

In [73, 90], analysis of all-optical networks does not consider WC sharing or the architectural differences in defining the conversion range. Converters sharing, [44, 4, 5], has led the way for a new generation of wavelength routers. The different types of WCS architectures have introduced different WC sharing schemes in order to minimize the cost and maintain efficiency [4, 5, 92]. Notably, our study allows the observation of the interactive behavior of LRWC with conversion sharing and the tradeoff scenarios that could result in less hardware complexity and higher utilization.

The implementation of our proposed *Any-to-Range* ranging architecture in all-optical wavelength converters would be compared to the performance of *Any-to-Any* control algorithms to obtain an efficient solution. The issues of connection flexibility due to a reduction in connection permutation of the all-optical switch will be explored. The concept of output side ranging and its advantages with respect to resources sharing will be studied in details. Simulation results for the full conversion, *Any-to-Any* case, will be provided for comparison. These simulation results are important to demonstrate that the performance improvement obtained by full range wavelength conversion can be achieved by using the proposed fractionally ranged LRWC. The throughput improvement due to the use of LRWC in the presence of conversion sharing, which is tightly coupled with the ranging mechanism, is contrasted to the mechanism of widening the conversion range.

3.3.3 Performance Analysis of Synchronous WDM Share-per-link Multifiber Packet-Switched Networks under Symmetric Traffic Condition

The next-generation high-speed networks are based on two main functional layers: the Internet protocol (IP) layer and the optical WDM layer. The increasing need for bandwidth efficiency and scalability has introduced optical packet switching (OPS) as a prospective solution. OPS networks are realized to help run the IP layer over the optical (WDM) layer and to provide transparency to data protocol and format. Contention resolution schemes are key determinants of packet-loss performance in optical packet switching networks. Optical packets, which are statistically distributed in time, can be either destined to the node or need to be switched to output channels. Multiple concurrently incoming packets cause contentions when two or more of them are contend for the same output port. The contention can happen both in the input side, at the receiver, or in the output side, when packets destined to another network node. The method in which contention is resolved has a significant effect on network performance.

Wavelength conversion is considered to be one of the most effective mechanisms to tackle the packet contention problem in the optical packet switch networks. Wavelength conversion devices are expensive elements, [7], thus number of converters could be considered the most effective cost parameter in OPS design. Sharing limited number of conversion devices is an effective paradigm in the cost reduction of the OPS design process. Previous research works suffered the lack of a quantitative insight that characterizes the performance of multi-fiber optical packet switch networks.

Our work presented in Chapters 6 discusses the node architecture with the context of optical packet switch network, which employs wavelength conversion. The scope of this work will also include the development of performance models for multi-fiber share-per-link OPS network which operates in a slotted mode and services symmetric traffic. The models and results presented in this work investigate different packet switch networks with a small range of wavelength conversion capability and contrast them to networks equipped with full wavelength conversion. In this research work, we investigate an end-to-end network in the presence of multiple fibers, which contribute in resolving, or at least minimizing, packet contention problem.

3.3.4 Performance Analysis of Synchronous WDM Share-per-link Multi-fiber Packet Switch Networks under Asymmetric Traffic Conditions

Realistically, optical packet-switching nodes within the optical core can not have identical offered load among all the incoming links. This is due to the dynamic nature of the optical traffic. A more realistic scenario is that the incoming traffic offered load varies, in most cases, among the incoming links. This introduces the asymmetric traffic conditions. In Chapter 6, the optical packet-switched networks under the symmetric traffic condition were considered, where as Chapters 7 discusses the node architecture of multi-fiber optical packet-switched network under the asymmetric traffic conditions, which employs wavelength conversion. Performance models for multi-fiber share-per-link OPS network which operates in a slotted mode and services asymmetric traffic are developed and evaluated. In this work, we investigate the differences between the symmetric and the asymmetric traffic condition on the behavior of the end-to-end network in the presence of multiple fibers. The load variation among the incoming links on each of the switching node on the performance of the network is analyzed for the synchronous optical packet switch networks. The effects of load variation on the performance behavior of the network are studied by introducing a method to measure such load variation among incoming links.

Chapter 4

PERFORMANCE OF MULTI-FIBER OPTICAL NETWORKS AND RESOURCES ALLOCATION IN SHARED-PER-LINK WCS

4.1 Introduction

Although the trend in WDM systems is toward larger number of wavelengths transmitted over a single fiber, the maximum number of wavelengths is ultimately limited by technological constraints, such as the optical amplifier's (EDFA) operational bandwidth, nonlinear limitations in WDM transmission, and the possible exhaustion of C-band. Packing channels much more closely together introduces dense WDM (DWDM). The EDFA amplifies wavelengths in the region of 1530-1560 nm that is commonly referred to as the C-band. There exists a bound on channel spacing, minimum frequency separation between two different signals multiplexed, in the C-band window. Even thought the number of channels that can be packed into one fiber is huge, such packing, fine channel spacing, introduces more physical limitation such as higher levels of crosstalk between channels. Further more, the expansion of the number of wavelengths in single-fiber system requires redesigning the transceiver (Transmitter/Receiver) incurring high cost to accommodate the new wavelengths and resulting in a limited flexibility as far as the switch architecture is concerned.

Even in the core, where today more than enough resources are available and where there is still an extensive amount of dark fibers waiting to be lit, networks employing multiple fibers, using multiple wavelengths on each link, will need to be modeled and compared to networks that are equipped with conversion option to better understand the tradeoffs involved in using such network. Additional efforts in this area are needed to further improve the performance of such networks. Several aspects concerning the architectural designs and control algorithms of OXCs will be considered in the contexts of shared-conversion-resources based switches.

In multiple fibers networks, to establish a multiple hop lightpath, the originating node sends a create request to the destination. Nodes in the path forward the request and process it by configuring their optical cross-connect. Once constructed, the new lightpath transparently bypasses the intermediate routers allowing the path to carry arbitrary traffic. The wavelength of the lightpath may be converted at intermediate nodes if conversion is available. Since wavelengths and fibers are finite, a lightpath is not always established between each source and destination OXCs.

It has been demonstrated in previous research efforts that wavelength translation, conversion, can significantly improve the performance of a large network. These research efforts did not consider the use of different shared-wavelength-convertible switches analytically in heterogeneous traffic cases, where every node along the path has different offered load. This work will propose a number of analytical models for different wavelength-conversion-resources sharing switch architectures under the heterogeneous traffic condition. The conservation of wavelength converters while maintaining performance close to that of a network with abundant of converters or abundant of fibers will be closely studied. Several research works have indicated that converters and the use of multiple fibers can improve the network performance, such as the blocking probability and fairness, considerably. But the lack of analytical models of the switch architectures that share conversion resources in these research works has left their work incomplete in terms of explaining their findings. For example, we will attempt to explain why the network diameter significantly affects wavelength-routed network performance. These probabilistic models for shared wavelength-conversion-resources architectures will be used to predict the unobvious qualitative behavior demonstrated in previous works.

A wavelength channel, whose transmission rate is fixed, is dedicated to a lightpath. This dedication leads to inefficient channel utilization when the amount of traffic between two nodes is much less than the transmission rate of the lightpath. When multi-hop routing is used, edge OXCs may forward incoming traffic from two lightpaths into one lightpath if equipped with electronic grooming technique. The goal is to maximize network throughput. For a given number of total wavelengths, the employment of multiple fibers should maximize network throughput, which is defined as the sum of the bandwidths provided to all pairs of source and destination nodes, and offer more performance flexibility than single-fiber networks. The proposed models for multi-fiber networks complemented with different levels of wavelength conversion are used in our research work to study network throughput performance. The multi-fiber networks that use shared-conversion-resources architectures were not analytically modeled in past literatures that treat multi-hop networks. Since the bandwidth needed by each pair of source and destination nodes changes dynamically depending on the cross traffic in the intermediate nodes, the proposed models in our research work should consider the heterogeneous traffic case.

The other part of this research is modeling a network that employs a share-per-link switch architecture with different resources allocation algorithms. Routing and wavelength assignment, RWA, is intended to efficiently manage WDM network resource utilization (wavelengths, nodal switching/conversion capabilities) in order to optimize various performance criteria such as network throughput, blocking probabilities, etc. Many different constraints serve to complicate this process, examples being wavelength-continuity requirements, wavelength conversion limitations, etc. Currently, however, no standardized RWA algorithms exist. Many authors have proposed optimization schemes to formulate the RWA problem, with the objective of minimizing various cost functions (e.g., wavelengths, blocking probabilities, delays, etc), but they did not take into account the management of complementary network resources.

The control plane is responsible for provisioning and maintaining connections and managing network resources. Provisioning of network resources requires algorithms for resources allocation, and signaling mechanisms to request and establish connectivity within the network along a chosen route. Knowledge of a network's topology and the available resources are fundamental to the operation of the network. Ideally, the topology and network resources should be auto-discovered and assigned, requiring mechanisms and algorithms for discovery, and for advertising this information throughout the network. In addition, efficient utilization of network resources requires that an inventory of the currently available network resources such as conversion resources be maintained. The integrated optical network control plane is to be implemented using the efficient modules performing different sets of operations that include:

- Resource Discovery by protocols like Interior Gateway Protocol
- Network State (Topology, resource availability data) information exchange
- Path computation for deciding the route for explicit routing
- Route management which performs activities like path relocation, maintenance, placement and resources distribution

As each connection request is presented to an optical network, a route is calculated through the network from source to destination, typically using RWA algorithms. We can recognize a problem that was not addressed earlier. This problem is in the integration of network resources allocation mechanisms that complement the routing and wavelength assignment algorithms and their optimization in time, which has a big effect on performance of the optical networks. Different measures of network performance can be optimized by adjusting how these algorithms interact with the mechanisms employed for assigning other network resources such as wavelength converters.

Wavelength conversion allows the translation of the incoming wavelength to a different outgoing wavelength in order to improve efficiency and reduce the frequency of blocking events[27, 90]. Wavelength convertible switches (WCS), optical switches (OSW) employing wavelength converters (WC) [27, 92], offer flexible lightpath switching, contention resolution, network interoperability as well as transparency of the optical layer [66, 92]. Important functions of WCSs are that they allow optical networks to be reconfigurable on a wavelength-by-wavelength basis to match changing traffic demands and to restore the network in case of failures [76, 88]. The major categories of WCS are reviewed next.

The *dedicated WCS*, shown in figure 4.1, offers a wavelength converter for each outgoing wavelength allowing any incoming wavelength to be switched at desired wavelength to the desired link [56]. The dedicated WCS is the least cost efficient and most flexible architecture. More cost effective architectures use different converter sharing mechanisms [48, 72].

Share-per-link WCS offers each outgoing link a dedicated collection of converters that can only be used by channels on that specific link as shown in figure 4.2 [56]. The use of different CRAAs for share-per-link WCS depicts different performance parameters.

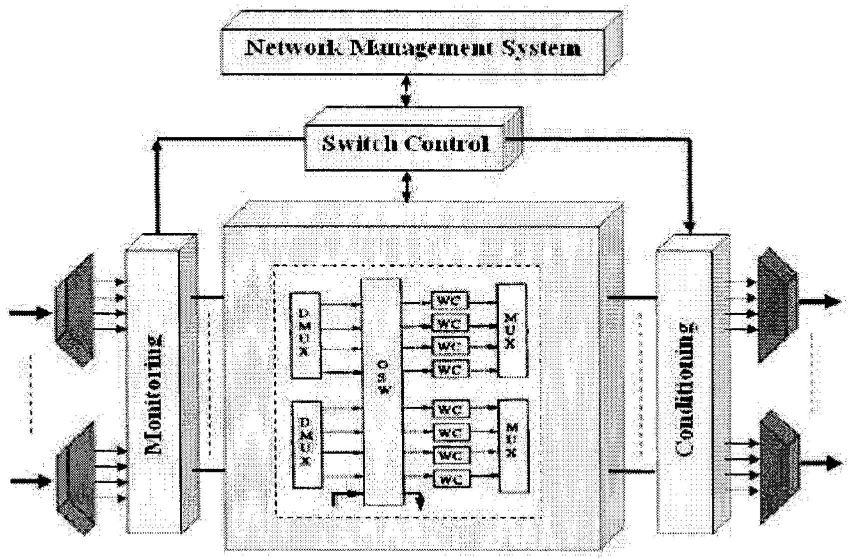

Figure 4.1: The dedicated wavelength-convertible switch [56]

Share-per-node WCS offers all outgoing links a shared collection of converters that can be used by any channel on any link as shown in figure 4.3 [56]. For increased performance and reduced hardware cost, wavelength routing protocols are responsible for better conservation of conversion resources where converters are not dedicated to individual channels or outgoing links.

In all of these switch architectures, sharing efficiency of wavelength converters is inversely related to the hardware complexity of the optical switch. Next, we investigate the single-route end-to-end blocking probabilities using these switch architectures in the multi-fiber multi-hop networks.

The future success of optical networks depends on the ability to efficiently accommodate integrated traffic by allocating available resources in the most efficient manner. It is evident that the conversion resources allocation policy plays a key role in determining the overall system capacity, i.e., the maximum load that the system can carry with a given set of resources. To establish an end-to-end light path in a wavelength-routed optical network, a route between the source-

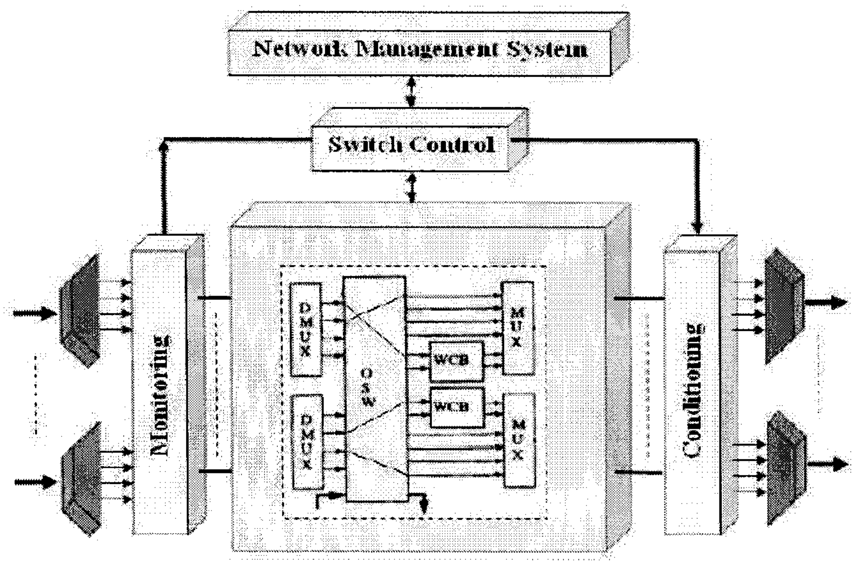

Figure 4.2: Share-per-link wavelength-convertible switch[56]

destination pair is established with appropriate wavelengths allocated on the links along the path, and de-allocated after some holding time corresponding the time of transmission. If the traffic in the wavelength-routed network is dynamic, then connection requests for establishing lightpaths arrive randomly to the network over time, which implies that these resources must be efficiently assigned and utilized on demand. When a connection request arrives, the control plane is accountable for finding a route and a wavelength for the lightpath, and for reserving the required network resources. The purpose of CRAA is to allocate converters among requests in such a way that maximizes channel utilization.

Share-per-link WCS offers each outgoing link a dedicated collection of converters that can only be used by channels on its corresponding incoming links as shown in figure 4.2 [4, 5, 56]. The figure shows a single plane switch, where each incoming fiber is associated with an outgoing fiber, where as all the corresponding incoming fibers are associated with an outgoing fiber in the multi-plane switch. This correspondence is determined by the nodal degree of the WCS. Different wavelengths

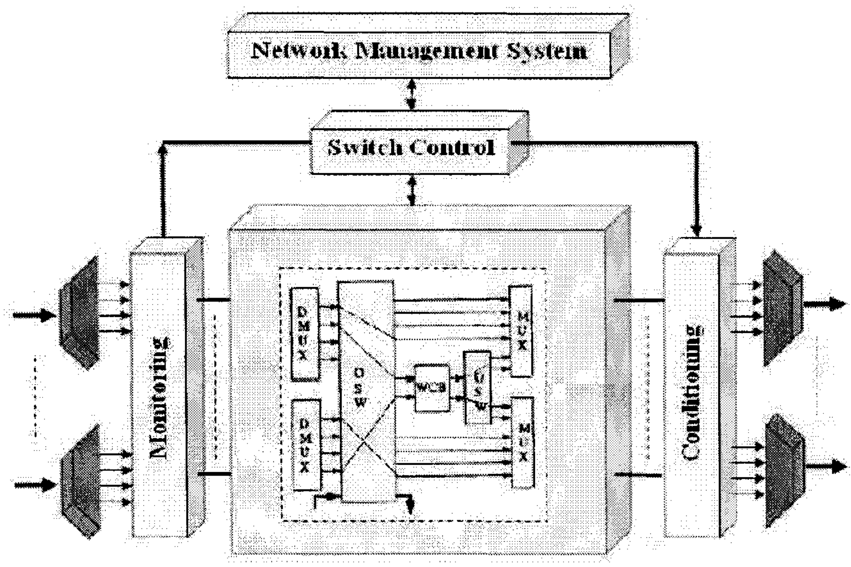

Figure 4.3: Share-per-node wavelength-convertible switch[56]

could be used along each of the hops in a lightpath. The CRAA that is adopted by the control plane affects the blocking performance and the network architecture. One source of connection blocking is insufficient network resources. A poor conversion resources allocation is a factor that could lead to poor network performance due to a higher rate of blocked traffic. These CRAAs are analyzed for the share-per-link WCS and it is shown that a WCS with shared contention resolution resources are the best candidates to reduce hardware volume and cost of all-optical networks. It is shown that switches with a bank of completely shared wavelength converters, WCs, require a fraction of WCs compared to switch architectures that use a WC per wavelength.

The end-to-end performance for circuit switched all-optical networks in multi-fiber multi-hop environments is modeled and evaluated with and without wavelength conversion. The increase in performance in the wavelength routing DWDM network due to wavelength conversion at each node, and different degrees of wavelength conversion is considered. This work also examines different wavelength converter sharing architectures and their effects on performance when the hops along the path between source-distention pair have different loads. It also examines the performance issues for share-per-link wavelength convertible switch (WCS) using different Conversion Resources Allocation Algorithms (CRAA). We propose and evaluate three different CRAA algorithms, Narrow Search Algorithm (NSA), Inclusive Search Algorithm (ISA), and Optimized Inclusive Search Algorithm (OISA), for dynamically allocating conversion resources.

4.2 Fiber Requirement in Multi-Fiber WDM Networks

Wavelength converters are likely to remain expensive in the near future. Using multiple fibers on each link in WDM networks is an alternate resolution to overcome the wavelength continuity constraint. In multi-fiber networks, each link consists of multiple fibers, and each fiber holds data stream on multiple wavelength channels. A wavelength that can not continue on the subsequent hop on the same fiber can be switched to another fiber using an optical cross-connect (OXC) in case the requested wavelength is available on one of the other outgoing fibers that distained to the same next hop. Thus, multiple fibers in WDM networks have the same effect as the limited wavelength conversion. Since the cost of a multi-fiber network is higher than a single-fiber network due to more amplifiers and multiplexer/demultiplexer in the system, the goal of a multi-fiber network is to attain high network performance with the minimum number of fibers per link between hops. An important problem in multi-fiber networks is to decide on the count of fibers per link that are required to guarantee comparable network performance to a network with full-range wavelength converters at every node. This fiber requirement depends on many factors, such as the traffic patterns, the number of wavelengths per fiber, and resources allocation schemes adapted.

4.3 Network Model

The network model in this study consists of a number of access stations attached to a group of wavelength routing optical nodes. Each access station has at least one optical transmitter and one optical receiver as well as optoelectronic interface to the user(s). The physical topology of the WDM optical networks consists of wavelength routing nodes, interconnected by point-to-point fiber links in a linear topology. In single-fiber networks, each wavelength on one link can support one lightpath at the most. Lightpaths using the same wavelength cannot share any link. However, in multi-fiber networks, lightpaths using the same wavelength can share common links, as long as they can be accommodated on different fibers. Wavelengths are assigned to the transmitters and receivers creating several independent channels all of which are multiplexed onto the optical fiber defining the logical connectivity among the nodes. In this architecture, the use of wavelength multiplexers provide the advantage of higher aggregate system capacity due to the reuse of wavelengths and support a large number of users, even with a limited number of wavelengths. A lightpath consists of a path through the network between nodes and a wavelength on each of these links in the path. Each lightpath may be used to carry a circuit switched data independent of other lightpaths in the fiber. Call requests arrive according to a Poisson process with a rate that depends on the source-destination pair. If the request can be satisfied, an optical circuit is established between the source and destination for the duration of the call. Call holding times are exponentially distributed. If a node in the path employs wavelength converters, it can switch an incoming wavelength to an arbitrary outgoing wavelength. When there are converters at all nodes, the situation is identical to that in classical circuit-switching networks. If no wavelength converters are employed in the path, a call can only be established if the same wavelength is free on all the links used by the call. If a call cannot be established due to lack of wavelengths, the call is blocked. On the other hand, if a call can be accommodated, one of the wavelengths that are available on the links used by the call is randomly assigned to it. Thus, we only consider the random wavelength assignment policy. It is usually not feasible to establish lightpaths on a single wavelength between every pair of nodes due to physical constraints on the number of wavelengths limited number and tunability of the optical receivers at each node and lightwave dispersions that limit the physical length of the lightpath.

4.4 Blocking Probability for Paths without Wavelength Conversion with Heterogeneous Loads

Consider a network with multiple fibers in each hop as shown in figure 4.4, where node S requests a path session to destination node D over a DWDM optical network. We assume that every call requests a capacity of a full wavelength bandwidth. Any particular fiber along the path has the same set of wavelengths and no two sessions on the same fiber use the same wavelength according to the wavelength continuity constraint. An optical path is set from source to destination by reserving the particular wavelength in all intermediate hops.

In this section, we consider the networks without wavelength conversions, presented in [5]. A request is blocked when no common unused wavelength is available in all the hops. We also assume different offered loads ρ_i for each hop along the path between source-destination pair.

The analytical model for a single-fiber multi-hop environment under the assumption of having different offered loads ρ_i, where i is the index of the node, for each hop along the path between source-distention pair approximates the blocking probability along a path by

$$P = (1 - \prod_{i=1}^{H}(1 - \rho_i))^W \tag{4.1}$$

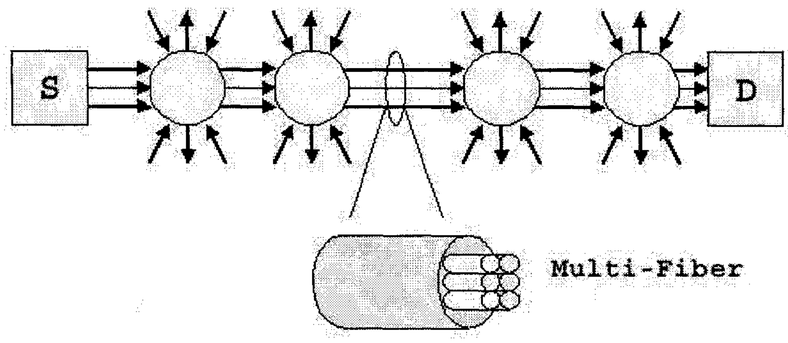

Figure 4.4: A multi-fiber multi-hop environment

where H denotes the number of hops along a path, W the number of wavelengths per fiber, $\rho_i = \frac{\lambda_i}{\mu_i}$ is the probability that a wavelength is used on a hop, λ_i is the arrival rate per wavelength, and μ_i is the service rate per wavelength. ρ_i is also a measure of the load per wavelength. The blocking probability P is the probability that each wavelength is used on at least one of the intermediate hops H. Any particular fiber along the path has the same set of wavelengths and no two sessions on the same fiber use the same wavelength.

For a network with multi-fibers for each hop as shown in figure 4.4, any particular link along the path has the same number of fibers F and the same set of wavelengths in each fiber. All requests will be accommodated if two or more, depending on F, sessions request the same wavelength due to availability of resources in other fibers. This overcomes the crosstalk problem introduced due to packing a large number of wavelengths, wavelength fine spacing in the C-band, in a single fiber by using multiple version of the same wavelength set in each fiber. The blocking probability P for multi-fiber multi-hop network is the probability that each wavelength in every fiber is used on at least one of the intermediate hops, H. The availability, A, along the path in the case of multi-fiber no conversion hop is shown in figure 4.5.

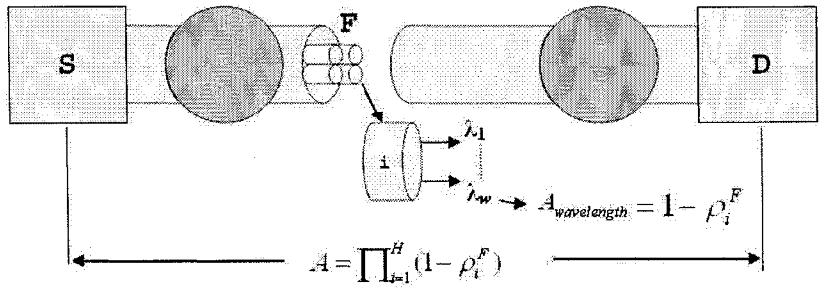

Figure 4.5: End-to-end multi-fiber link

P is thus given by

$$P = \left[1 - \prod_{i=1}^{H}(1 - \rho_i^F)\right]^w \tag{4.2}$$

We compare multi-fiber case with a single fiber network with the same number of wavelengths ($W = F \cdot w$). Thus for the single fiber network, the blocking probability along the path is

$$P = \left[1 - \prod_{i=1}^{H}(1 - \rho_i)\right]^W \tag{4.3}$$

The end-to-end throughput, given a blocking probability of P with respect to a certain source-destination load G in a network is given by

$$U = (1 - P) \cdot G \tag{4.4}$$

The change in the blocking probability P due to the load of the connection under consideration, G, is neglected. This is due to the fact that the total capacity of the link used in optical fiber is typically significantly higher than the load generated by a single source-destination pair.

The throughput gain in the case of the multi-fiber multi-hop network without the conversion option, with respect to the single fiber situation, increases appreciably due to lower blocking probability and higher throughput. This gain is a significant improvement that reflects on the end-to-end path blocking probability and the overall network performance, when the total number of wavelengths is equal in both cases:

$$Gain = \frac{1 - \left[1 - \prod_{i=1}^{H}(1 - \rho_i^F)\right]^w}{1 - \left[1 - \prod_{i=1}^{H}(1 - \rho_i)\right]^W} \tag{4.5}$$

where w is the number of wavelengths available on each fiber in multi-fiber case and W is the total number of wavelengths available in a hop in the single fiber case. The gain in the achievable throughput comes at the cost of adding multiple fibers between nodes with similar sets of wavelengths in each fiber. It increases as the blocking probability of a given path decreases.

4.5 Blocking Probability for Paths with Wavelength Conversion with Heterogeneous Loads

In this section, we model the performance of networks with different wavelength conversion schemes as well as the different wavelength conversion sharing mechanisms, presented in [5]. C denotes the number of wavelength converters in the wavelength converter banks. The total number of wavelengths available on all fibers in a hop is W, $W = w \cdot F$, and $C = W \cdot DC$, where DC is a fraction that represents the number of converters with respect to W. The probability that zero converters are busy P_{0_i}, where i is the index of the switching node along the path, and the probability of all converters are busy P_{C_i} in the single-fiber case , cite33, are derived from $M/M/C/C$ model as follows:

$$P_{0_i} = \frac{1}{1 + \sum_{k=1}^{C}(\frac{1}{k!}) \cdot (\frac{W!}{(W-k)!}) \cdot \rho_i^{2 \cdot k}} \tag{4.6}$$

$$P_{C_i} = \frac{1}{C!} \cdot \frac{W!}{(W-C)!} \cdot \rho_i^{2 \cdot C} \cdot P_{0_i}$$

$$P_{C_i} = \frac{W!}{C! \cdot (W-C)!} \cdot \frac{\rho_i^{2 \cdot C}}{1 + \sum_{k=1}^{C}(\frac{1}{k!}) \cdot (\frac{W!}{(W-k)!}) \cdot \rho_i^{2 \cdot k}} \tag{4.7}$$

This mean that this system can be represented by M/M/C/C, Erlang B, model where there are C servers, converters, and C customers, requests, that can be in the system. Since in such a model, a conversion request is either accepted or rejected in its entirety, P_{C_i} depends on the number of converters C, the number of incoming wavelengths, and the load per wavelength ρ_i.

Considering the case of a single-fiber with partial conversion, no blocking occurs when the original requested wavelength is available in each hop, or in case it is not available and at least one wavelength converter in the conversion bank is free and at least one other wavelength is free. The availability of a wavelength along the path that traverses H hops is shown in figure 4.6 and given by:

$$A = \prod_{i=1}^{H} \left[(1-\rho_i) + \rho_i \cdot (1-P_{C_i}) \cdot (1-\rho_i^{W-1})\right] \tag{4.8}$$

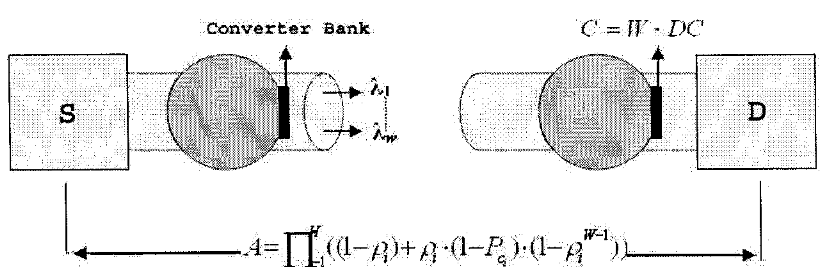

Figure 4.6: End-to-end availability for a single fiber hop with conversion

In this case the blocking probability is given by:

$$P = \left(1 - \prod_{i=1}^{H} \left[(1-\rho_i) + \rho_i \cdot (1-P_{C_i}) \cdot (1-\rho_i^{W-1})\right]\right)^{w} \tag{4.9}$$

In the model for share-per-node conversion bank, the request rate for a converter is the arrival rate per wavelength λ given that the same wavelength is busy in all output fibers (an event with probability of ρ_i^F). So, a conversion request rate due to a single wavelength is obtained by $(\rho_i^F \cdot \lambda_i)$. Consequently, the transient rate from state i *(i converters are busy)* to state *i+1* is $((W-i-1) \cdot \rho_i^F \cdot \lambda)$. The probability that zero converters are busy P_0 and the probability that all converters are busy P_C are derived from $M/M/C/C$ model shown in figure 4.7 to predict the behavior of the conversion bank.

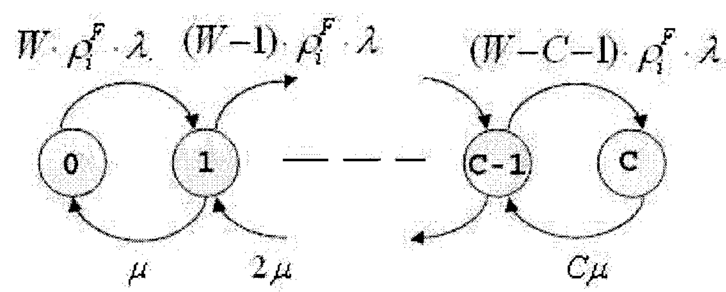

Figure 4.7: $M/M/C/C$ model for share-per-node conversion bank

$$P_{0_i} = \frac{1}{1 + \sum_{k=1}^{C} (\frac{1}{k!}) \cdot (\frac{W!}{(W-k)!}) \cdot \rho_i^{k \cdot F + k}} \tag{4.10}$$

$$P_{C_i} = \frac{1}{C!} \cdot \frac{W!}{(W-C)!} \cdot \rho_i^{C \cdot F + C} \cdot P_{0_i}$$

$$P_{C_i} = \frac{W!}{C! \cdot (W-C)!} \cdot \frac{\rho_i^{CF+C}}{1 + \sum_{k=1}^{C} (\frac{1}{k!}) \cdot (\frac{W!}{(W-k)!}) \cdot \rho_i^{kF+k}} \tag{4.11}$$

The avilability of a wavelength , A, along the path in the case of multi-fiber hop with share-per-node conversion is shown in figure 4.8.

The blocking probability obtained for the limited wavelength conversion case employing share-per-node WCS is thus given by.

$$P = \left(1 - \prod_{i=1}^{H} \left[(1 - \rho_i^F) + \rho_i^F \cdot (1 - P_{C_i}) \cdot (1 - \rho_i^{W-F})\right]\right)^w \tag{4.12}$$

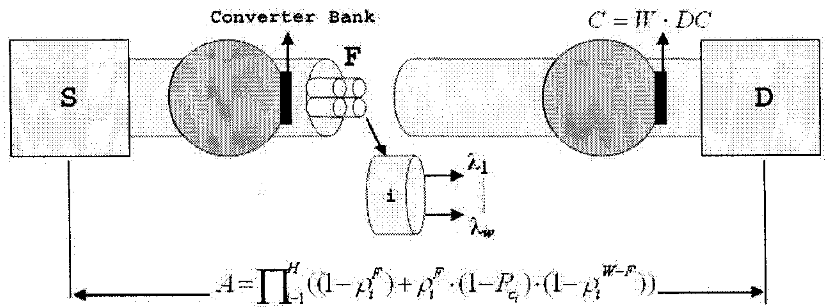

Figure 4.8: End-to-end availability for multi-fiber multi-hop with share-per-node

When full-range wavelength conversion is considered by employing dedicated WCS, the blocking probability for the multi-fiber multi-hop converges with the blocking probability of the single fiber full conversion case as shown next.

$$P = \left(1 - \prod_{i=1}^{H}(1 - \rho_i^W)\right)^w \tag{4.13}$$

It is note worthy that for a fully loaded network and a given number of wavelengths, full conversion does not improve performance significantly. This fact will also be demonstrated in the result section.

The achievable throughput gain obtained in this case comes at the cost of adding wavelength conversion. The throughput gain in the case of the dedicated WCS (multi-fiber with full conversion option) with respect to the multi-fiber with no conversion option increases appreciably due to the improvement in blocking performance resulted from using full wavelength conversion. This gain improves the end-to-end path blocking probability and the overall network performance significantly as shown in equation 16.

$$Gain = \frac{1 - \left[1 - \prod_{i=1}^{H}(1 - \rho_i^W)\right]^w}{1 - \left[1 - \prod_{i=1}^{H}(1 - \rho_i^F)\right]^w} \tag{4.14}$$

4.6 Algorithms and Analytical Models for Share-per-link WCS

In order to allocate appropriate resources to a connection, we need to develop an appropriate algorithm to specify its allocation behavior in terms of known parameters. Based on the system configuration, where every node employs a share-per-link WCS, we present here three different algorithms for conversion resource allocation. Only the connection setup is treated, but it is assumed that after the service time is expired, each circuit is disconnected (released) and the connectivity database is updated. These different algorithms are constructed in a way that describes the use of the limited conversion resources (using constraints and decision variables) to achieve a certain measure of optimization (objective).

We focus particularly in developing algorithms that make intelligent choices in allocating conversion resources based on relevant feedback information from the control plane, which aids the dynamic routing and channel allocation process in a tightly coupled manner as shown in figure 4.9. This intelligent resources

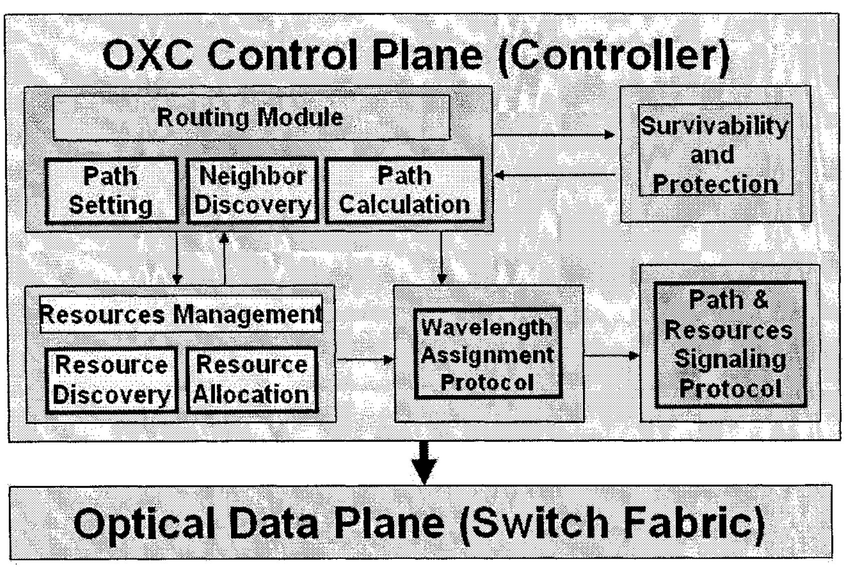

Figure 4.9: Switch control architecture

allocation and management enhances provisioning of network resources, scalability, controllability, and allows optical channels to be manipulated efficiently.

A key component of this evolution is ensuring "a best network utilization performance" requirements for different types of resources allocation algorithms. Essential to the notion of throughput performance is the efficient allocation of network resources such that network performance requirements are maintained. Performance parameters using different CRAAs under the assumption of having different offered loads ($\rho_i, i = 1, 2, ..H$) in the hops along the path between source-distention pair are considered.

A request is blocked when any hop in the path is supporting W different sessions or when the requested wavelength is already in use and the conversion resources are not available in any hop along the path in a network. The unavailability of conversion resources could be a result of a poor resources allocation technique.

The previous studies had indicated that throughput decreases and the blocking probability increases when the number of hops, H, increases and the number of wavelengths in the fiber, w, decreases [4, 5, 12]. In the following subsections, we model different CRAA schemes for share-per-link WCS.

4.6.1 Narrow Search Algorithm (NSA)

Narrow Search Algorithm, NSA, is developed with hardware complexity of the WCS in mind. It searches for a free converter in the conversion bank that belongs to the corresponding outgoing fiber in the share-per-link WCS. The following is the general description of NSA:

Step 1: Detect the connection request and check for the desired output wavelength in all outgoing fibers considering the final destination. In case the desired channel is not available in any fiber, go to Step 2, otherwise go to Step 4. The probabilities associated with these transitions are shown in figure 4.10. For example the probability the desired channel is not available in any fiber is ρ^F.

Step 2: Check for a free converter in the conversion bank that belongs to the corresponding outgoing fiber i. In case a converter is available, go to Step 3, otherwise go to Step 5.

Step 3: Check for any other wavelength in the outgoing fiber to use the available converter with. In case a wavelength is available, go to Step 4, otherwise go to Step 5.

Step 4: Forward the connection request, go back to step 1.

Step 5: Drop the connection request, go back to step 1.

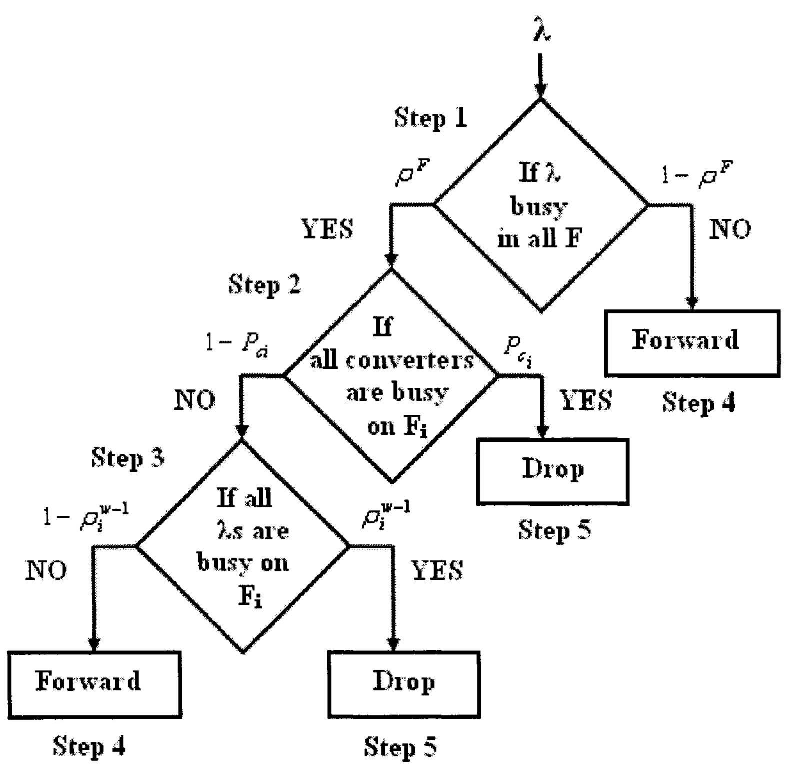

Figure 4.10: Narrow Search Algorithm, NSA

In the model for share-per-link conversion bank employing NSA algorithm, the request for a converter is the arrival rate per wavelength λ given that the same wavelength on hop i is busy in all output fibers, an event with probability of ρ_i^F.

So, a conversion request rate due to a single wavelength is obtained by $(\rho_i^F \cdot \lambda)$ as shown in figure 4.10, where ρ_i is the probability of the requested wavelength being busy, w is the number of wavelengths per fiber, F is the number of fibers, P_c is the probability of a converter bank being busy, and λ_j is the arrival rate for the wavelength j. Consequently, the transient rate from state j *(j converters are busy)* to state *j+1* is $((w-j) \cdot \rho_i^F \cdot \lambda)$. The probability of all converters are busy P_c is derived from $M/M/C/C$ model shown in figure 4.12 to predict the behavior of the conversion bank. P_{0_i} and P_{C_i} for the multi-fiber multi-hop case with limited wavelength conversion employing share-per link WCS are derived as follows:

$$P_{0_i} = \frac{1}{1 + \sum_{k=1}^{c} (\frac{1}{k!}) \cdot (\frac{w!}{(w-k)!}) \cdot \rho_i^{k \cdot F + k}} \tag{4.15}$$

$$P_{C_i} = \frac{1}{c!} \cdot \frac{w!}{(w-c)!} \cdot \rho_i^{c \cdot F + c} \cdot P_{0_i}$$

$$P_{C_i} = \frac{w!}{c! \cdot (w-c)!} \cdot \frac{\rho_i^{cF+c}}{1 + \sum_{k=1}^{c} (\frac{1}{k!}) \cdot (\frac{w!}{(w-k)!}) \cdot \rho_i^{kF+k}} \tag{4.16}$$

The avilability, A, along the path is shown in figure 4.11. The lower case c denotes

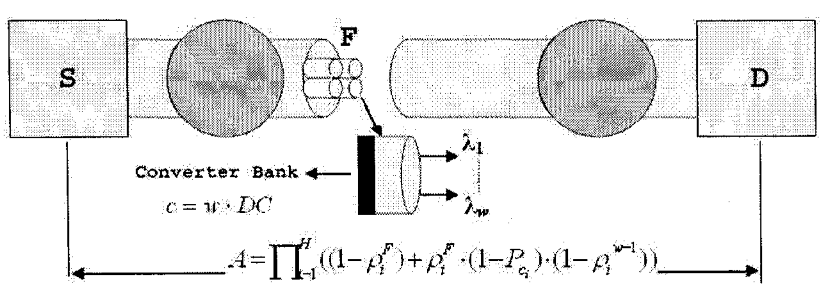

Figure 4.11: End-to-end availability for multi-fiber hop with share-per-link conversion

the number of converters with respect to the total number of wavelengths available on each fiber w, where $w = \frac{W}{F}$ and $c = (w \cdot DC)$. The following expression shows the blocking probability for a switch employing NSA conversion resources algorithms.

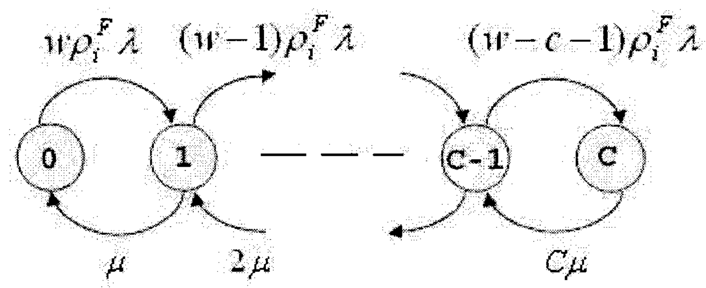

Figure 4.12: *M/M/C/C* model for share-per-link conversion bank using NSA

$$P = \left(1 - \prod_{i=1}^{H} \left[(1-\rho_i^F) + \rho_i^F \cdot (1-P_{c_i}) \cdot (1-\rho_i^{w-1})\right]\right)^w \quad (4.17)$$

The lower case c donates to the number of converters with respect to the total number of wavelengths available on each fiber w.

4.6.2 Inclusive Search Algorithm (ISA)

Inclusive Search Algorithm, ISA, searches for a free converter in any outgoing fiber that is destined to the desired destination. It exhaustively searches for a converter in all banks. The following is the general description of ISA:

Step 1: Detect the connection request and check for the desired output wavelength in all outgoing fibers considering the final destination. In case the desired channel is not available in any fiber, go to Step 2, otherwise go to Step 7. The probabilities associated with these transitions are shown in Figure 4.13. For example the probability of the desired channel is not available in any fiber is ρ^F.

Step 2: Check for a free converter in the conversion bank that belongs to the corresponding outgoing fiber i. In case a converter is available, go to Step 3, otherwise go to Step 4.

Step 3: Check for any free wavelength in the outgoing fiber that the available converter belongs to. In case a wavelength is available, go to Step 7, otherwise go to Step 4.

Step 4: Check for a free converter in a different conversion bank that belongs to a different outgoing fiber K, *where* $K = 1..F and K \neq i$ considering the final destination. In case a converter is available, go to Step 5, otherwise goes to Step 6.

Step 5: Check for any free wavelength in the outgoing fiber K that the converter belongs to. In case a wavelength is available, go to Step 7, otherwise go to Step 6.

Step 6: Check for a conversion bank that was not considered before. In case of availability, go to Step 4, otherwise go to Step 8.

Step 7: Forward connection request, go back to step 1.

Step 8: Drop the connection request, go back to step 1.

The worst case scenario for this algorithm, shown in figure 4.13, is that it checks all the conversion banks that belong to the output fibers leading to the desired destination in search of free resources. This excessive search process puts a burden on the control plane as far as the processing time goes. The probability of all converters are busy P_c is derived from $M/M/C/C$ model showen in figure 4.14 to predict the behavior of the conversion bank. P_{0_i} and P_{C_i} for share-per-link WCS employing ISA conversion resources algorithm are derived as follows:

$$P_{0_i} = \frac{1}{1 + \sum_{k=1}^{c}(\frac{1}{k!}) \cdot (\frac{w!}{(w-k)!}) \cdot \rho_i^{k \cdot F+k} \cdot \sum_{j=0}^{F-1}(P_{c_i}^j)^k} \tag{4.18}$$

$$P_{C_i} = \frac{1}{c!} \cdot \frac{w!}{(w-c)!} \cdot \rho_i^{c \cdot F+c} \cdot P_{0_i} \cdot \sum_{j=0}^{F-1}(P_{c_i}^j)^c$$

$$P_{C_i} = \left[\frac{w!}{c! \cdot (w-c)!} \cdot \frac{\rho_i^{cF+c} \cdot \sum_{j=0}^{n-1}((P_{c_i}^j)^k)}{1 + \sum_{k=1}^{c}(\frac{1}{k!}) \cdot (\frac{w!}{(w-k)!}) \cdot \rho_i^{kF+k} \cdot \sum_{j=0}^{n-1}((P_{c_i}^j)^k)}\right] \tag{4.19}$$

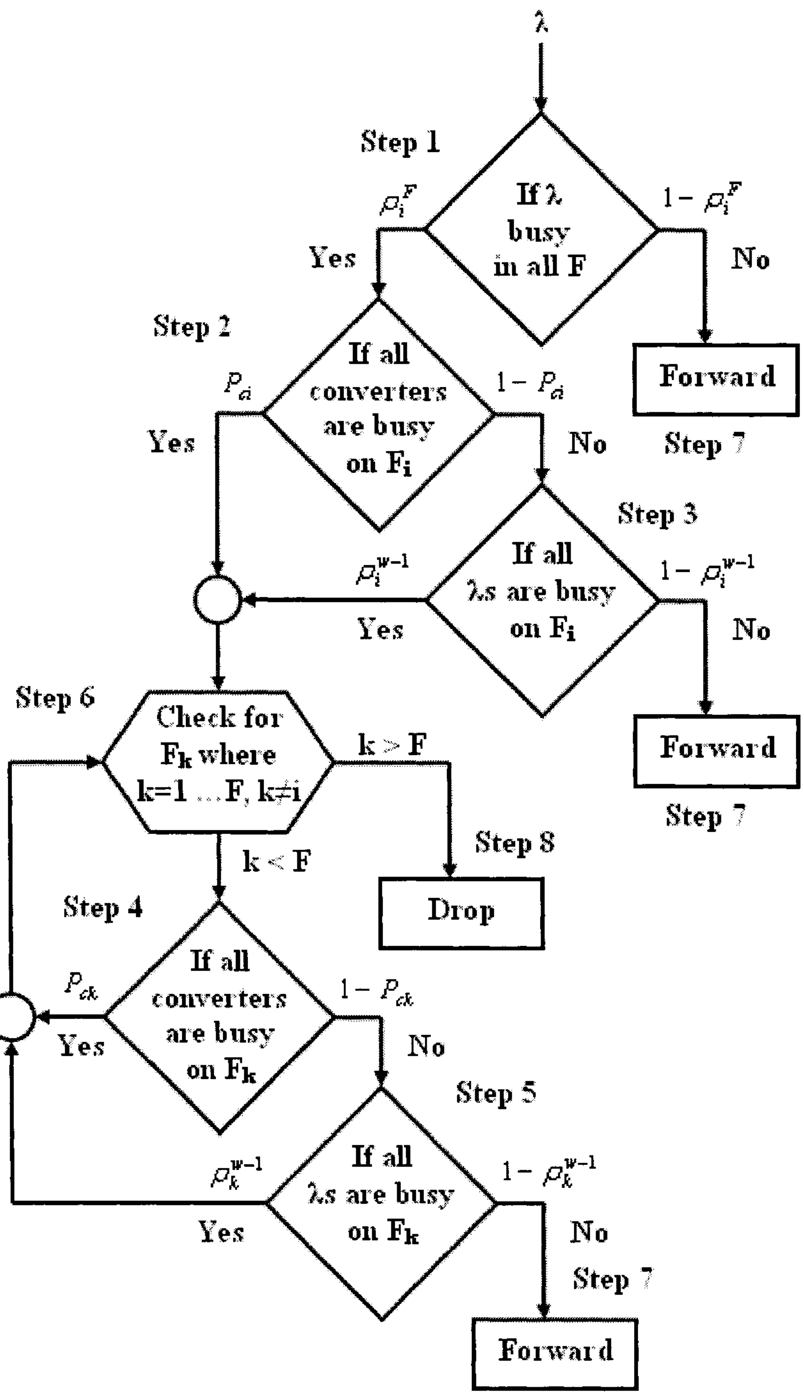

Figure 4.13: Inclusive Search Algorithm, ISA

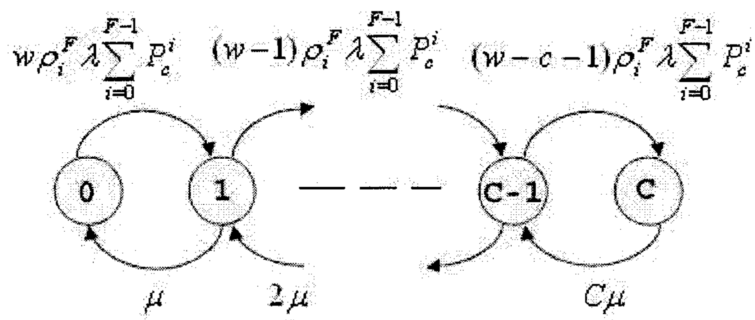

Figure 4.14: $M/M/C/C$ model for share-per-link conversion bank using ISA

4.6.3 Optimized Inclusive Search Algorithm (OISA)

To optimize the processing time required by ISA, the previous algorithm is altered to control the number of time the algorithm loops back (n), instead of F in ISA case. The control plane switches the incoming wavelength to the desired outgoing wavelength under the following conditions. If the original requested wavelength is not available in any outgoing fiber, the request will be forwarded to the conversion bank that belongs to the corresponding outgoing fiber. If there is not a free converter in the conversion bank or there is not a free wavelength available on the outgoing fiber, then the request will be directed to a different conversion bank and droped after checking a pre-specified number (n) of conversion banks. This limitation on the number of banks tested for free conversion resources will minimize the exhaustive nature of the ISA search and results in a comparable throughput performance as explained the result section.

The probability of all converters are busy P_c is derived from $M/M/C/C$ model showen in figure 4.15 to predict the behavior of the conversion bank. P_{0_i} and P_{C_i} for share-per-link WCS employing OISA conversion resources algorithm are derived

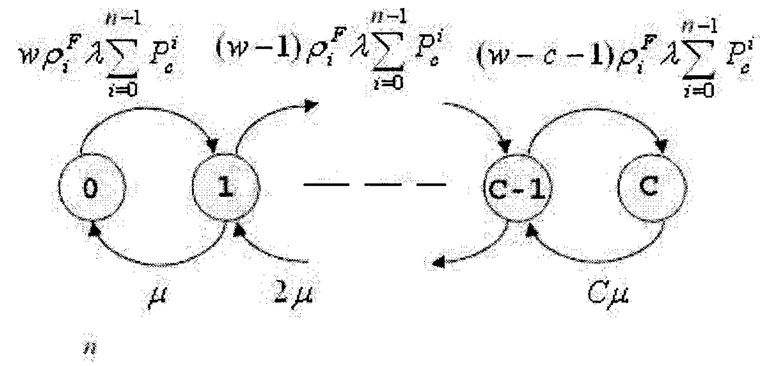

Figure 4.15: $M/M/C/C$ model for share-per-link conversion bank using OISA

as follows:

$$P_{0_i} = \frac{1}{1 + \sum_{k=1}^{c}(\frac{1}{k!}) \cdot (\frac{w!}{(w-k)!}) \cdot \rho_i^{k \cdot F+k} \cdot \sum_{j=0}^{n-1}(P_{c_i}^j)^k} \tag{4.20}$$

$$P_{C_i} = \frac{1}{c!} \cdot \frac{w!}{(w-c)!} \cdot \rho_i^{c \cdot F+c} \cdot P_{0_i} \cdot \sum_{j=0}^{n-1}(P_{c_i}^j)^c$$

$$P_{C_i} = \Big[\frac{w!}{c! \cdot (w-c)!} \cdot \frac{\rho_i^{cF+c} \cdot \sum_{j=0}^{n-1}((P_{c_i}^j)^k)}{1 + \sum_{k=1}^{c}(\frac{1}{k!}) \cdot (\frac{w!}{(w-k)!}) \cdot \rho_i^{kF+k} \cdot \sum_{j=0}^{n-1}((P_{c_i}^j)^k)}\Big] \tag{4.21}$$

The following expression shows the blocking probability for share-per-link WCS employing ISA and OISA conversion resources algorithms, where the value P_c is different depending on the proposed model for each algorithm.

$$P = \Big(1 - \prod_{i=1}^{H}\big[(1-\rho_i^F) + \rho_i^F \cdot (1 - P_{c_i}^n) \cdot (1 - \rho_i^{w-1})\big]\Big) \tag{4.22}$$

where n denotes the number of fibers F in the case of ISA or the number of conversion banks wanted to be checked in the case of OISA.

The throughput gain in the case of share-per-link WCS employing ISA with respect to the case of similar WCS using NSA increases appreciably due to less blocking probability and higher throughput. This gain is considered an improvement that reflects on the end-to-end path blocking probability and overall network performance when the total number of wavelength converters is equal in both cases:

$$Gain = \frac{Throughput_{ISA}}{Throughput_{NSA}} \tag{4.23}$$

The gain in the achievable throughput comes at the cost of high algorithm time complexity that requires higher processing load to achieve better allocation rate than NSA for a similar set of wavelength converters in each fiber.

4.7 Results for Paths without Wavelength Conversion with Heterogeneous Loads

In this section, we discuss the performance improvements in the multi-fiber environment over the single-fiber multi-hop case considering all network parameters in the absence of wavelength conversion. In figure 4.16, the source-destination (stream) throughput with respect to G, which is significantly less than the capacity of the link, is plotted as a function of the number of wavelengths in the multi-fiber case for different path lengths (intermediate hops) for $\rho_i = 0.7$. This means that the input offered load for the various node along the path, background load ρ_i, is typically significantly higher than the load generated by a single source-destination pair, so the change in blocking probability due to the offered load of the end-to-end small stream G is negligible. It shows that throughput decreases when the number of hops, H, increases and the number of wavelengths in the fiber, w, decreases. The stream throughput always increases along with the number of wavelengths, which can provide additional network capacity to handle the traffic. The Stream Throughput improvement due to the use of multi-fiber in a network with a diameter of 5-hops is considerable with respect to the performance of the single-fiber no conversion case. In the multi-fiber case, we have more freedom with the network diameter as apposed to the single fiber case due to the improvement

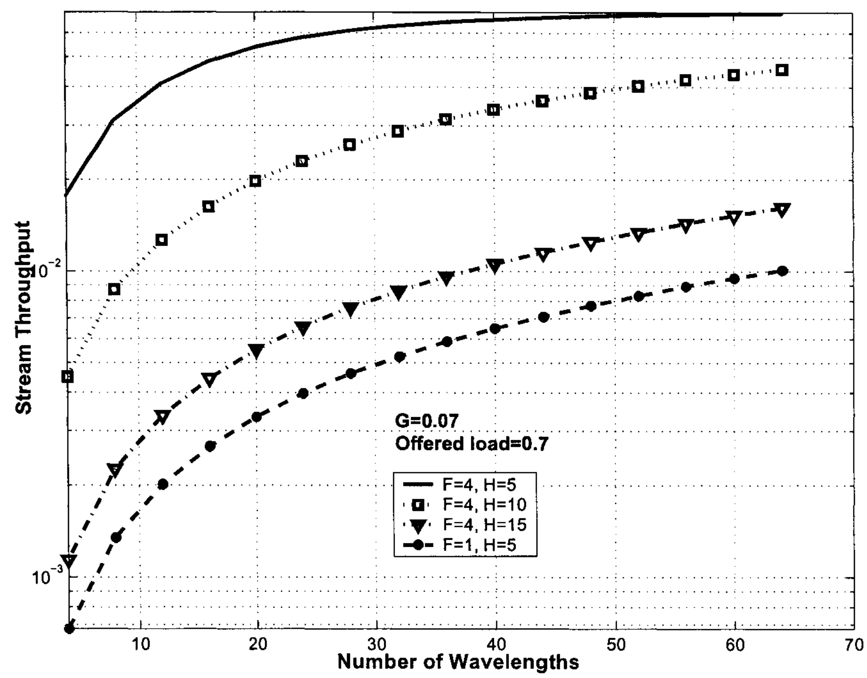

Figure 4.16: Stream Throughput vs. number of wavelengths

in the throughput resulting from the ability to accommodate multiple requests for the same wavelength in different fibers in the same hop. Using multiple fibers compensate for the throughput degradation caused by the number of hops that a path traverses. The figure shows a considerable improvement in throughput for similar network parameters, where the number of wavelengths is divided among multiple fibers used in links between nodes.

In figure 4.17, blocking probability is plotted as a function of offered load for the multi-fiber case with 4 fibers and 4 wavelengths per fiber for different path lengths (intermediate hops). An example of a 5-hop network diameter shows a dramatic improvement of blocking performance in the multi-fiber case compared to the single-fiber case. It should be noted that the increase of the number of wavelengths in the fiber will further improve the optical path blocking probability, which in turn improves the stream throughput performance of the network and

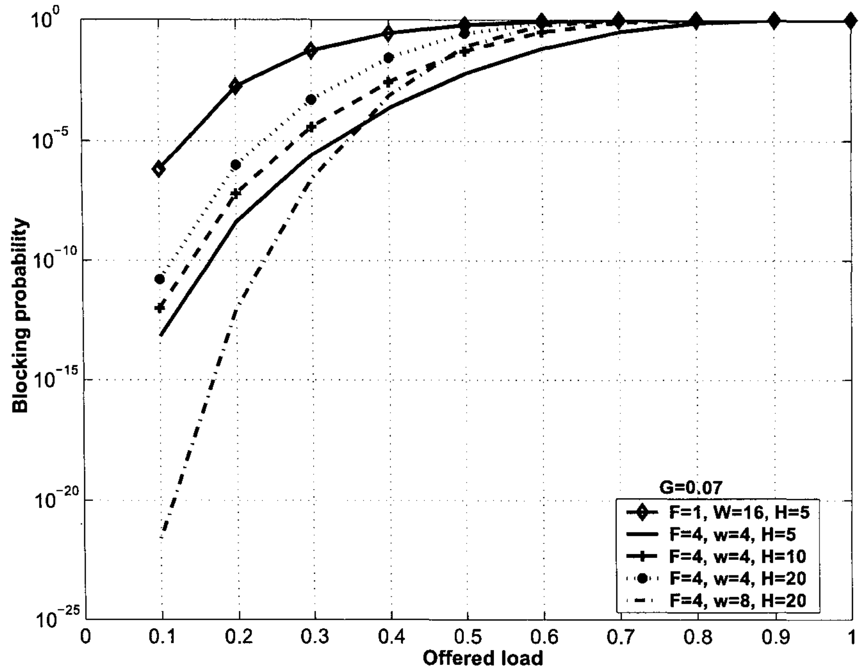

Figure 4.17: Blocking probability vs. offered load

increases the possible reach of the network by increasing the deployable network diameter.

In figure 4.18, stream throughput is plotted as a function of offered load in the multi-fiber multi-hop case for different networks with different parameters. Using a network with parameters w=4, H=20, and F=4 as a reference, we notice that the increase of the number of wavelengths w will increases the stream throughput. It is also noticed that the decrease of the number of hops, H, that a path traverses increases the stream throughput significantly at the cost of network diameter and network reach, which is not practical for the ever growing optical domain. The network with parameters $w=4$, $H=20$, and $F=8$ confirms the main objective of this study. It shows that the increase of the number of fibers, F, in links deployed between nodes have the dominating effect in improving the stream throughput performance, reducing the path blocking probability, and increasing the network

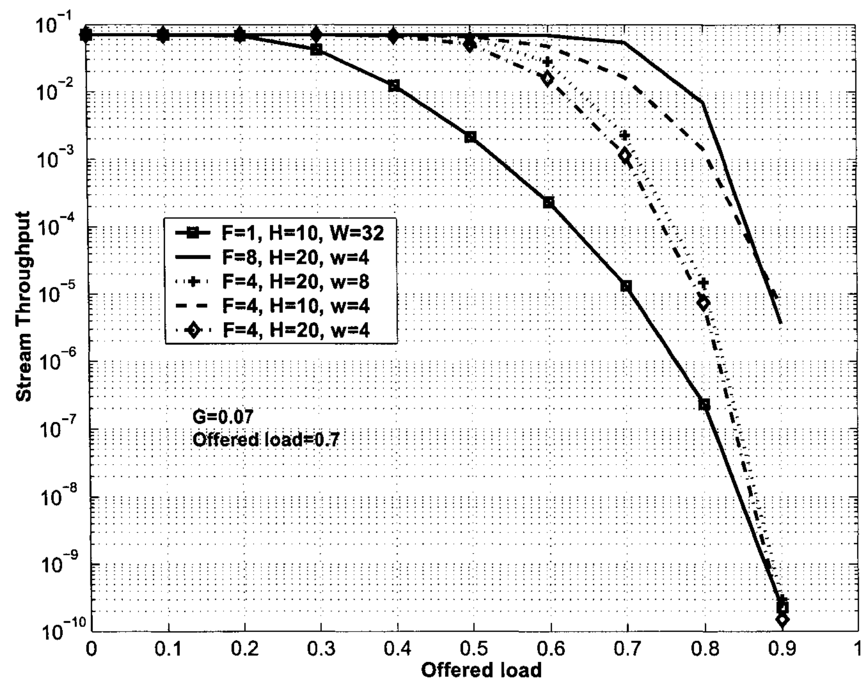

Figure 4.18: Stream Throughput vs. offered load for different networks

reach by increasing the diameter. The figure also shows that the increase of offered load reinforces the negative effect of network diameter on the stream throughput performance and consequently the end-to-end blocking probability.

As a measure of the benefit of multi-fiber multi-hop environment, the gain was defined as the increase in achievable throughput with respect to the single fiber case. Figure 4.19 shows that the multi-fiber system offers better performance in large networks due to significantly higher gain with reference to single fiber system given that other network parameters are fixed. It also shows a tremendous gain, that comes at the cost of adding more fibers between nodes, when the offered load increases. It is economically more feasible to use single-fiber link where the expected offered load is low due to the fact that the increase in the number of fibers would not increase the stream throughput performance. This means that

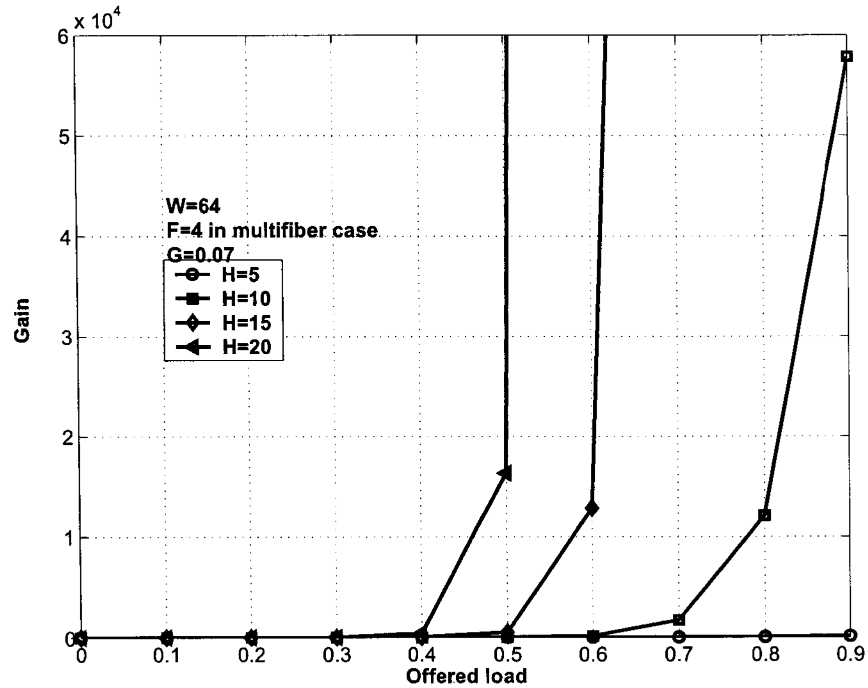

Figure 4.19: Gain vs. offered load

the blocking probability would be a comparable quantitatively when the expected offered load is low.

4.8 Results for Paths with Wavelength Conversion option with Heterogeneous Loads

In this section, we discuss results showing the performance improvements in the multi-fiber environment with various wavelength conversion options considering all network parameters. In figure 4.20, the stream throughput is plotted as a function of the number of wavelengths in the multi-fiber case with 50% conversion for different WCS architectures and a single path network of 20 hops. The stream

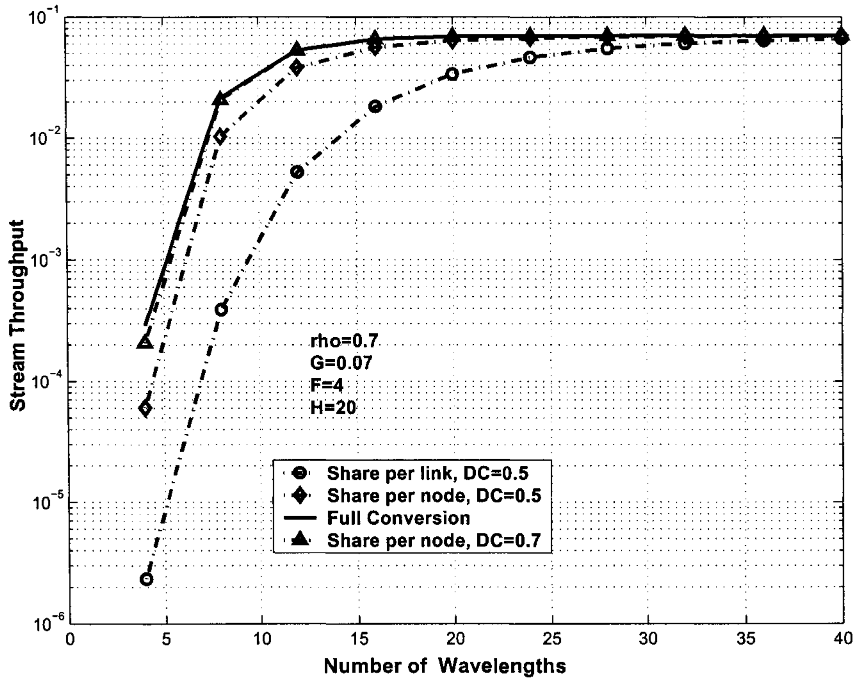

Figure 4.20: Stream Throughput vs. number of wavelength

throughput improvement due to the use of wavelength conversion depends on the degree of conversion. The use of wavelength conversion increases the degree of freedom to increase network diameter due to the improvement in stream throughput resulting from the ability to minimize wavelength contention. It is noted that a degree of 70% conversion resulted in performance that is very comparable quantitatively to full-range conversion in the share-per node WCS case. This indicates that the increase of conversion range at higher wavelength count does not result in a significantly higher performance. It also shows that smaller degree of conversion can yield the same performance as full-range wavelength conversion due to low network throughput where some wavelength converters remain unused.

As a measure of the benefit of wavelength conversion in multi-fiber multi-hop environment, the gain was defined as the increase in achievable throughput with respect to the full-range conversion case. Figure 4.21 shows better gain performance at higher rates of offered load when using switches that employs wavelength converter with sharing mechanism. It is more economically feasible to use WCSs with

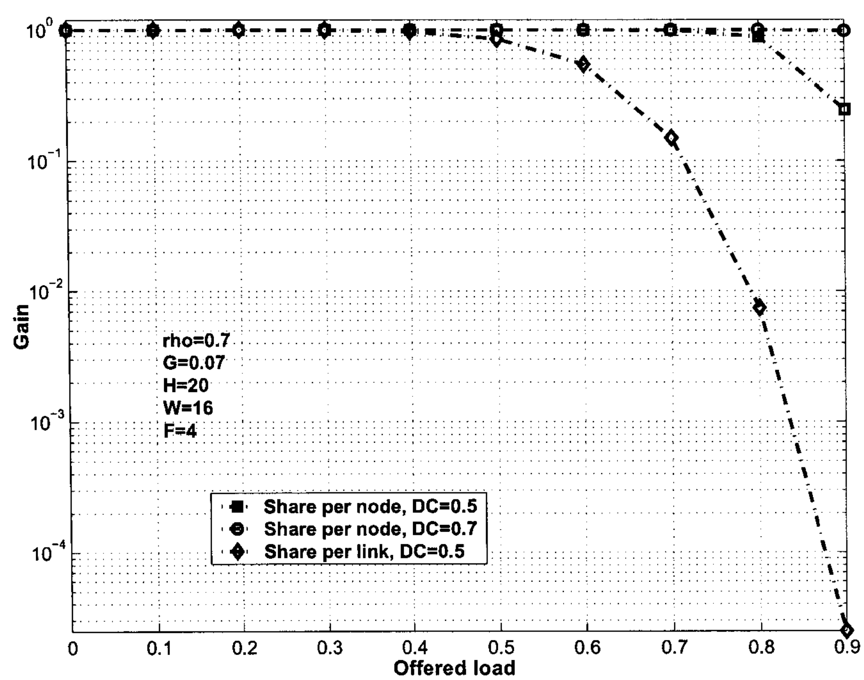

Figure 4.21: Gain vs. offered load

conversion sharing and lower hardware complexity to reduce wavelength blocking probabilities and obtain better throughput gain. Results also prove that share-per-node is the most efficient and its performance reaches that of full-range conversion at 70% wavelength conversion. This means that the blocking probability would be comparable quantitatively to full-range conversion due to the optimized use of conversion resources.

In figure 4.22, The end-to-end stream throughput for a source-destination pair is plotted as a function of conversion percentage (DC). As expected, the stream

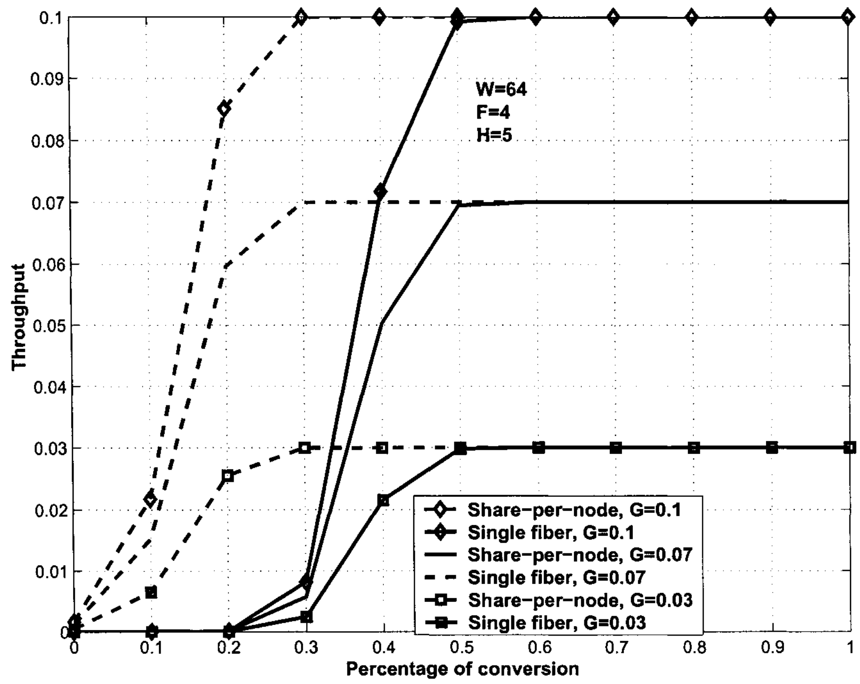

Figure 4.22: Stream Throughput vs. Percentage of conversion

throughput increases as the number of converters increases. However, after an initial steep increase, the curves generally tend to flatten as the number of converters increases. This behavior is consistent with the results of earlier observations.

4.9 Results for Share-per-link Optimization

In this section, we discuss the performance results in share-per-link WCS architecture based multi-fiber multi-hop networks, which employ different CRAAs. The offered load for all hops are assumed to be equal ($\rho_i = \rho$). In figure 4.23, the source-destination blocking probability is plotted as a function of number of wavelengths for three proposed conversion resources algorithms for a 10-fiber 10-hop network. It shows that the use of different CRAAs for share-per-link WCS depicts

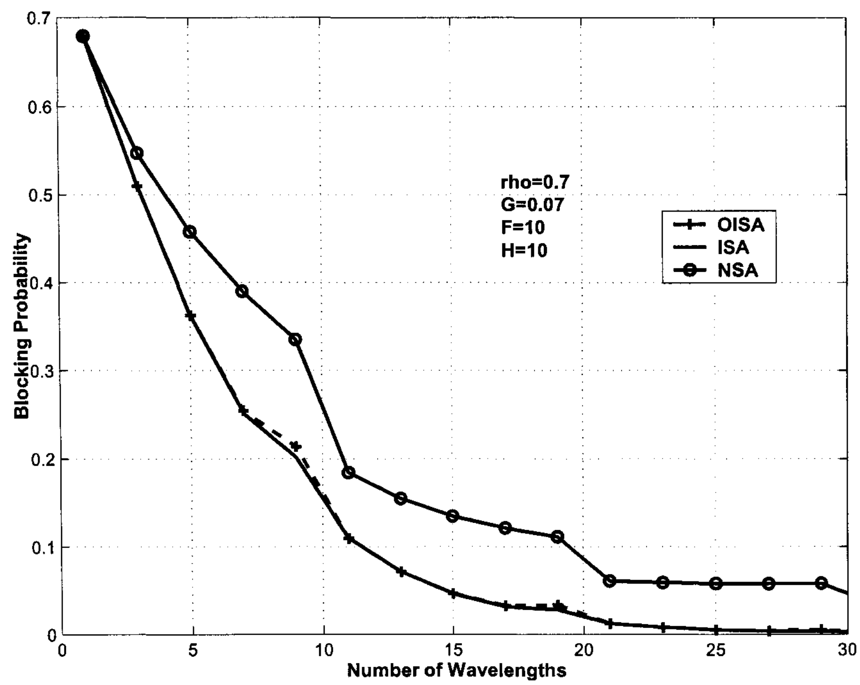

Figure 4.23: Blocking probability vs. number of wavelengths

different performance behaviors. It also shows that blocking probability decreases considerably with the increase of number of wavelengths in the fiber due to better accommodation of connection requests, and reduced frequency of blocking events regardless of the type of CRAA used to allocate conversion resources. Throughput always increases along with the number of wavelengths, which provide additional network capacity to handle higher traffic volume. ISA, which is computationally complex due to the exhaustive nature of the search algorithm for free converters, offers the best blocking performance compared to NSA and OISA. In this case, OISA tested two conversion banks (n) compared to 10 conversion banks in ISA and one conversion bank in NSA. OISA offered a very comparable performance to ISA and required less processing time due to lower algorithm complexity. The uneven changes in this graph and the next one are due to adding additional converters to conversion banks. These irregularities are explained in figure 4.26.

In figure 4.24, the source-destination throughput with respect to G, which is equal to 10 percent of the local hop load ρ, is plotted as a function of the number of wavelengths for a path length=10 (intermediate hops) for $\rho = 0.7$. It shows that

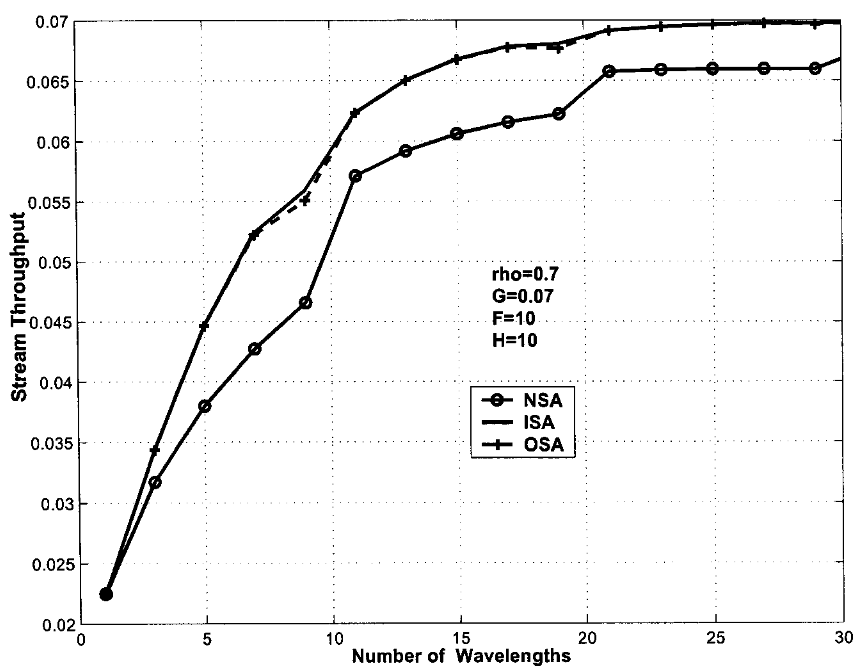

Figure 4.24: Throughput vs. number of wavelengths

throughput increases considerably with the increase of number of wavelengths in the fiber, which is consistent with observation made for the previous figure. The optimized allocation of scarce wavelength conversion resources offered by OISA for share-per-link WCS presented an equivalent performance to a system that employs ISA. The optimized version of ISA is used to moderate the high processing load on the control plane, which in turn uses CRAA in determining better solution for the RWA problem in a tightly coupled manner. The optimization target is to maximize the volume of traffic traversing a link without adding additional burden on the control plane.

In figure 4.25, the blocking probability is plotted as a function of the width of share-per-link conversion banks with respect to the number of wavelengths on each fiber for the proposed algorithms. It shows that ISA is more responsive to the increase of converters in each bank. For a system with parameter described in the figure, it shows that ISA approaches very low blocking region when the number of converters in the conversion banks at 30% of the number of wavelengths in each fiber, w. This improvement offered by OISA leads to a reduction in the required number of converters in conversion banks, cost, in addition to the improvement in allocation algorithm processing time.

In figure 4.26, the gain increase obtained by using ISA and OISA with respect to the gain obtained by using NSA is plotted as a function of number of wavelengths. ISA and OISA offer an improvement in the gain at lower count of wavelengths. The region with lower counts of wavelengths is characterized by higher blocking probability due to a higher susceptivity for traffic request contentions. ISA and OISA show a higher rate of sensitivity to region with higher susceptivity for blocking. The gains for ISA and OISA tend to taper down due to the abundance of available resources at higher counts of wavelengths, which make the gain performance comparable for all algorithms, but the advantages obtained by ISA and OISA in terms of algorithm processing time and the reduction in the width of conversion banks remain significant. At the peak of every spike, a new

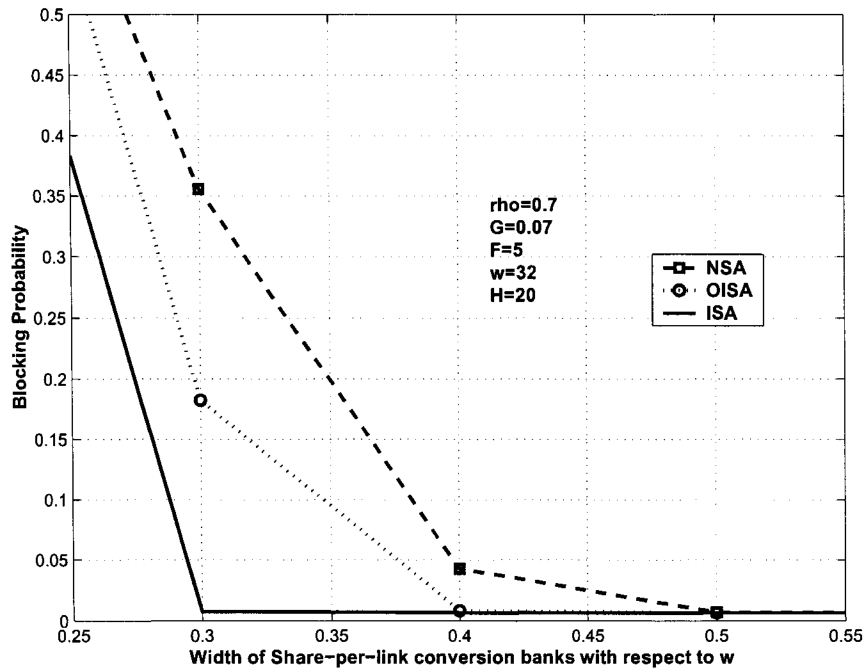

Figure 4.25: Blocking probability vs. width of Share-per-link conversion bank with respect to w

converter is added to the conversion banks. The effect of adding new converters is consistent with the previous observation, where added resources tend to diminish the gain obtained by ISA and OISA. At a certain point, where the increase of wavelengths requires more conversion resources, the use of ISA and OISA produces a positive gain once more. A sample spike for a fixed converter count is explained in details in figure 4.28.

In figure 4.27, the blocking probability is plotted as a function of number of hops, *H*. This figure shows that NSA, ISA, and OISA are scalable with hop count. The scalability of these algorithms emphasizes the positive effects of conversion resources allocation algorithms, CRAAs, in extending network reach, network diameter, by reducing the blocking of the system and increasing the throughput performance.

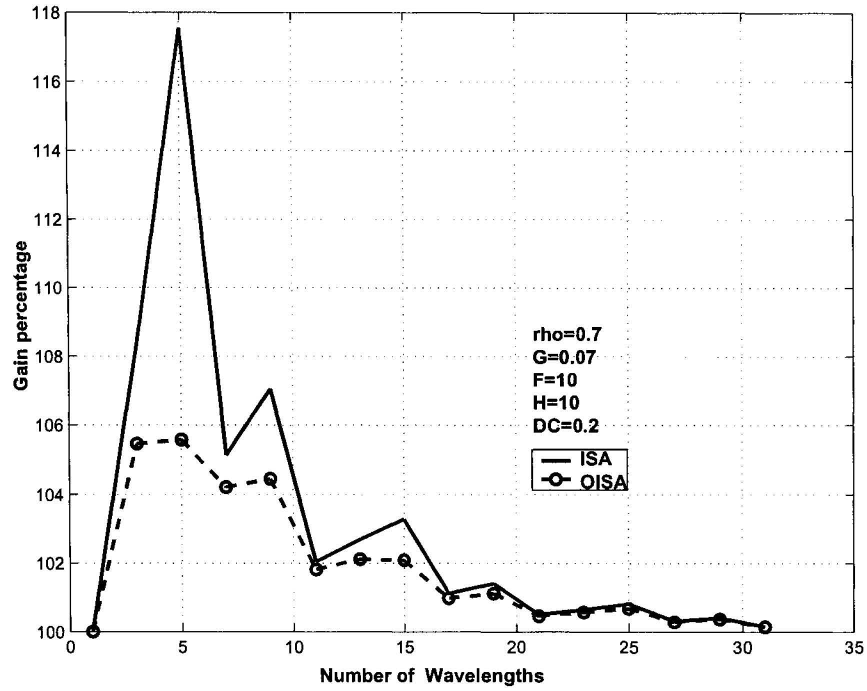

Figure 4.26: Gain percentage vs. number of wavelengths

In figure 4.28, the gain increase obtained by using OISA with respect to the gain obtained by using NSA is plotted as a function of number of wavelengths on each fiber for different hop counts. For a network with $F = 10$ and $c = 3$, OISA offers an increase in the gain at higher hop counts, which emphasizes the scalability of conversion resources allocation algorithms. At a certain wavelength count, the gain diminishes due to the abundance of wavelength and conversion resources, which results in a comparable performance, gain wise.

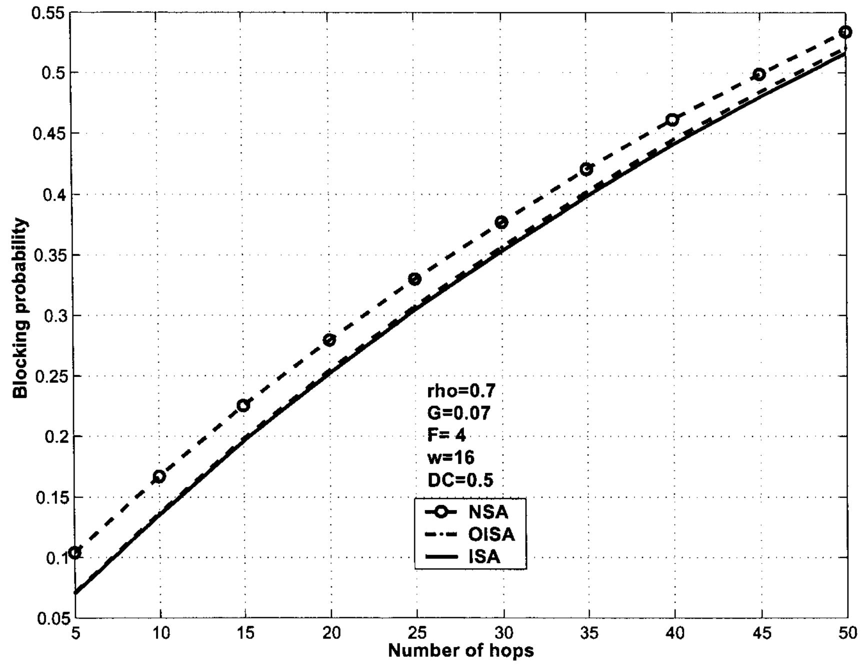

Figure 4.27: Blocking probability vs. number of hops

4.10 Chapter Summary

In this research work, the trade-offs involving the use of multi-fiber multi-hop networks such as the number of fibers, number of wavelengths, conversion options, and the different switch configurations were studied in terms of key performance metrics such as end-to-end blocking and throughput.

The study shows that the use of multiple fibers in multi-hop networks reduces the end-to-end blocking probability by reusing the same set of wavelengths in multiple fibers and by increasing the availability of the end-to-end paths. The use of multiple fibers compensate for the throughput degradation caused by the increase in hop count that a path traverses. It also adds more flexibility in increasing network reach (diameter) without effecting throughput significantly. It helps reduce the cross-talk problem resulting from having a large number of channels in a single fiber using DWDM fine spacing techniques; it helps to overcome the capacity

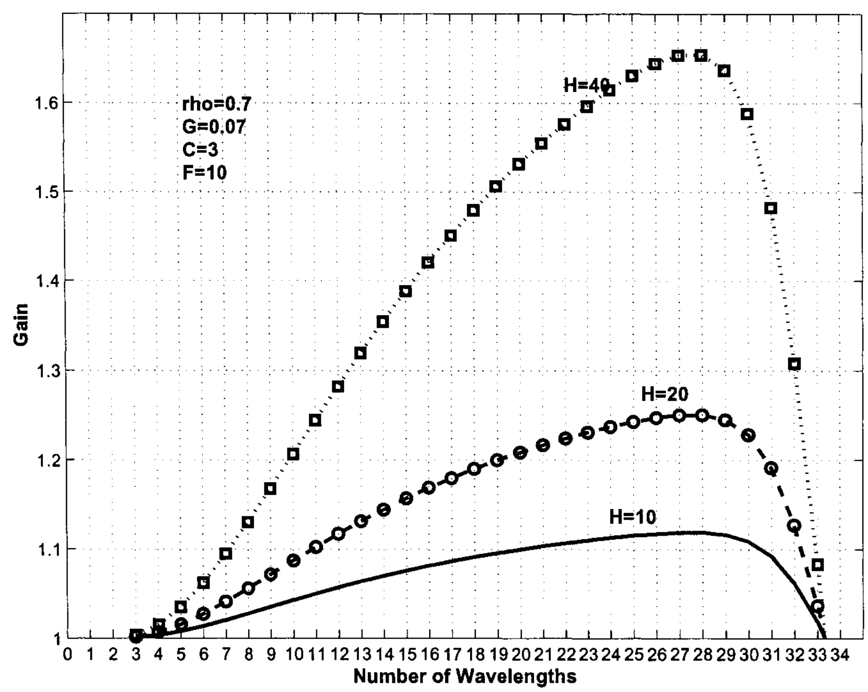

Figure 4.28: Gain vs. number of wavelengths

exhaustion problem in C-band window by offering the same set of wavelengths on multiple fibers.

The use of wavelength conversion increases the improvement in throughput resulting from the ability to minimize wavelength contention. Wavelength conversion may possibly improve the performance of the network by resolving the wavelength contention problem, but it incurs increased cost, hardware complexity, and space requirements implying potential trade-offs between the performance and the number of wavelength converters needed. The cost of using wavelength conversion could be adjusted by employing conversion resources sharing schemes. Results show that share-per-node WCS is the most efficient. It provides a sufficient and decent performance compared to full wavelength case. Considering more intelligent CRAAs that dynamically accommodate more conversion request for share-per-link WCS will improve the overall performance at the expense of control algorithm complexity.

NSA, ISA, and OISA resources allocation algorithms are introduced to attain an efficient usage of conversion resources. It is demonstrated that these algorithms realize not only efficient usage of the resources but also robustness to the traffic change. It is demonstrated that ISA, which is characterized by a high algorithm time complexity, presents the best performance from the viewpoint of efficient usage of resources, but requires higher processing load to achieve better allocation rate than NSA.

Since these resources allocation algorithms will be used by network control functions, it necessitates that the complexity of these algorithms be kept low while still taking into account the characteristics and the desired throughput performance. To reduce the complexity of implementation of ISA due to the exhaustive nature of the search algorithm for free converters, a simpler algorithm was proposed. OISA is used to moderate the high processing load on the control plane, which in turn uses CRAA in determining an optimal solution for the RWA problem in a tightly coupled manner. The control algorithm utilizes a mechanism to optimally assign both the wavelength converters and the needed channel to transport data over light in the optical domain.

The improvement offered by OISA leads to a reduction in the required number of converters in conversion banks, cost, in addition to the improvement in allocation algorithm processing time. The fact that these algorithms are scalable with the hop count, emphasizes the positive effects of conversion resources allocation algorithms, CRAAs, in extending network reach, network diameter, by reducing the blocking of the system and increasing the throughput performance. Improved ISA, OISA, efficiently reduces the hardware (infrastructure) costs by requiring fewer wavelength converters and optimizes the processing time, which in turn increases the efficiency of sharing conversion resources. The proposed algorithms also increase the throughput of the optical network, thus increasing overall throughput of the optical domain.

Chapter 5

SIMULATION-BASED PERFORMANCE EVALUATION OF SHARED LIMITED RANGE WAVELENGTH CONVERSION SCHEMES IN OPTICAL WDM NETWORKS

5.1 Introduction

The proper use of converters in optical networks decreases the number of necessary wavelengths to achieve a given throughput. The tuneability of a wavelength converter further enhances utilization and flexibility of the network. Since the number of available wavelengths and converters are limited resources, and they also affect the complexity of the switches, models for different WC ranging configurations help to achieve optimal cost and performance, while maintaining efficiency. Based on their conversion capability, wavelength converters can be categorized into two types: (1) full-range wavelength converters (FRWC), which can convert an incoming wavelength to any outgoing wavelength, and (2) limited-range wavelength converters (LRWC), which can convert an incoming wavelength to a subset of the full wavelength set. Optical networks with limited range wavelength conversion (LRWC) are less costly to implement than networks that have no constraints on conversion.

Converters sharing has led the way for a new generation of wavelength routers, called wavelength convertible switches or WCSs. The different types of WCS architectures have introduced different WC sharing mechanisms in order to minimize the cost and maintain efficiency. Notably, our study considers the combined behavior of LRWC with conversion resource sharing and the tradeoff scenarios that could result in less hardware complexity and higher utilization. In this work, we perform a simulation based analysis of different LRWC configurations that implement conversion resource sharing. It focuses on maximizing the efficiency associated with converters and maintaining an appropriate level of performance by quantifying the penalty, in terms of call blocking, for mismanaging the WC resources.

5.1.1 All-Optical Wavelength Converters

Conventional optoelectronic conversion, using O/E/O line cards that incorporate tunable lasers for their outputs, incurs a high delay. All information in the form of phase, frequency, and analog amplitude of the optical signal is lost, which in turn adversely affects transparency, during the conversion process. Ideally, the conversion process should be independent of bit rate or signal format, require little power, require fast setup time of output wavelength, not degrade the signal, tunable in its ability of conversion to both shorter and longer wavelengths and simple in its implementation. Knowing that the optoelectronic converters provide only limited digital transparency and deploying multiple converters in a WDM cross-connect requires complex packaging to avoid cross talk among channels, which leads to increased costs, makes all-optical conversion architecture more attractive.

All-optical WC [81] is of increasing interest for future all-optical telecommunication networks. The conversion within each node could be accomplished all-optically, which is quite difficult due to technological limitations, but the recent advancement in all-optical WC technology makes it possible to convert the input wavelength to different output wavelength if those are within different limited ranges. In these all-optical devices [91], the conversion efficiency is a function of the input and output wavelengths, leading to limited conversion ranging capabilities. All-optical WC promises better response, simplicity, and transparency to the signal format whereas optoelectronic converters are inherently dependent on input transmission format and bit rate, so a change in data rate requires changing the converter, [27]. The tuning range, in such architecture, is determined at the time of fabrication. All-Optical wavelength conversion eliminates the electronic bottleneck and delivers scalability, and flexibility and can be further categorized into the following categories:

a) Wavelength conversion using wave-mixing that arises from a nonlinear optical response of a medium when more than one wavelength is present. It results in the generation of another wavelength whose intensity is proportional to the product of the interacting wavelength intensities. It also can be used in simultaneous conversion of a set of input wavelengths to another set of output wavelengths.

b) Wavelength conversion using cross modulation techniques, known as optical-gating wavelength conversion, utilize active semiconductor optical devices. The transmitters and receivers for all-optical wavelength converters are tunable [60].

Following are some of the all-optical conversion techniques based on the pervious two categories:

- Four Wave Mixing, [49], is made possible by nonlinear effects between two closely spaced wavelengths, that produce conjugate outputs from both initial wavelengths. Cross-phase modulation converters use the input signal to modulate the phase of a second wavelength. This effect can be used to convert an input signal at a specific wavelength to an exact copy of the signal at a different wavelength. This technique provides modulation-format independence and high bit-rate capabilities. The conversion efficiency from pump energy to signal energy of this technique is not very high and it decreases with increasing conversion span.

- Good results have been obtained with parametric conversion in periodically poled lithium-niobate waveguides [17]. It is a very fast conversion method relying on interaction between a signal and high-power pump beam inside the nonlinear crystal. Single or multi-channel WC is achieved in the optical chip. The WC chip is protocol independent and currently supports 10 Gbit/s, 40 Gbit/s, and the future extension to 160 Gbit/s high-speed network applications. The operation of this type covers the entire C-band.

- Difference frequency generation (DFG) is a consequence of a second-order nonlinear interaction of a medium with two optical wavelengths: a pump wavelength and a signal wavelength. This technique offers a full range of transparency without adding excess noise to the signal, and spectrum inversion capabilities, but it suffers from low efficiency.

- A semiconductor optical amplifier (SOA) [89], can be used to improve a signal that has weakened. The nonlinear phenomena in semiconductor optical amplifiers have been widely utilized for WC and optical switching. A continuous signal at the desired output wavelength is modulated by the gain variation so that it carries the same information as the original input signal. It outputs a new wavelength that has same modulation as input wavelength. The operation of a wavelength converter using SOA in cross-phase modulation (XPM) mode is based on the fact that the refractive index of the SOA is dependent on the carrier density in its active region. An incoming signal that depletes the carrier density will modulate the refractive index and thereby result in phase modulation of a continuous wave signal coupled into the converter. The wavelength can be engineered to vary within a very large range between 1300 and 1600 nm.

- In the single-mode semiconductor lasers, the lasing-mode intensity of the medium is modulated by input signal light through gain saturation. The output signal obtained is inverted compared to the input signal. This gain suppression mechanism has been employed in a distributed Bragg reflector (DBR) laser to convert signals at 10-Gb/s.

As shown in the result section, all-optical LRWC, even though it does not eliminate the severity of wavelength continuity problem completely, decreases blocking probability, enhances the performance to levels close to full wavelength conversion, reduces the cost in term of implementation and control, and increases NxN switch scalability. It also lowers power consumption, and operates at speeds important for telecommunication.

5.2 WC Ranging Architectures

This study examines how WC is related to efficient utilization of an optical channel. The cost of conversion not only depends on the number of converters in the network, but also on the architectural complexity introduced within the optical switch as shown in figure 5.1. A significant cost penalty due to architectural complexity can be incurred if WC is not maintained in an efficient manner. However, we show how one could significantly mitigate this penalty by allowing limited range WC, using a small subset of wavelengths as the range, complemented with the ability to share these resources. Range tunable transmitters and receivers are cheaper and simpler to construct than fully ranged ones. Our aim is to determine the range configuration that is most practical for tunable all-optical devices in the presence of WC resources sharing.

We define a measure of WC called the conversion range. If a network node has a conversion range d then a wavelength may be converted to any one of a predefined set of d wavelengths. The cost of all-optical devices, packaged in a way that both transmitter and receiver are in the same chip, is a function of the complexity in ranging both the transmitters and receivers. The different ranging mechanisms

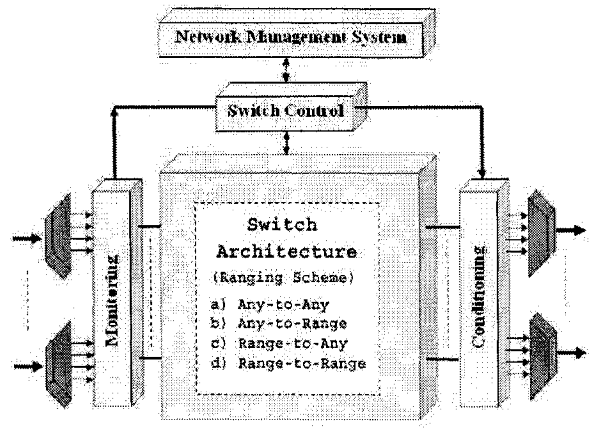

Figure 5.1: LRWC based optical switch

explained in this study affect the switch input/output port connection permutation. The simulation analyzes the performance of the different switch architectural configurations in terms of impact of these ranging mechanisms, which determine the connection permutations, on conversion resources sharing and efficiency. For an NxN switch, a set of N connections in which each input port is connected to exactly one output port is called a connection permutation between the switch input ports and the output ports. From the simulation results, we realize that the permutation connection between the switch input ports and the output ports are defined by the ranging mechanism adopted in the all-optical switch. These connection permutations can be abstracted by converter ranging mechanisms to quantify the performance of an all-optical switch element. In a non-blocking switching element such as the one employing *Any-to-Any* ranging scheme, all connections in any permutation assignment can be realized without any conflicts. The goal is to examine and analyze these ranging schemes in more detail to identify the most practical one in terms of their blocking performance. The ranging architectures, shown in figure 5.2, simulated in this study have LRWC in the following categories.

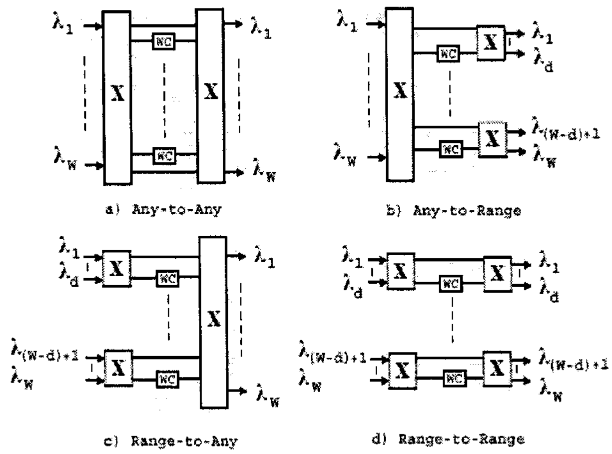

Figure 5.2: LRWC ranging architectures, *a) Any-to-Any*, *b) Any-to-Range*, *c) Range-to-Any*, *d) Range-to-Range*

- The *Any-to-Any* device shown in figure 5.2(a) can convert any incoming input wavelength in the full set $\Lambda_i = \{\lambda_1, \lambda_2, ..., \lambda_W\}$ to any outgoing one in the full set $\Lambda_o = \{\lambda_1, \lambda_2, ..., \lambda_W\}$, corresponding to full range conversion. This device, however, is not very cost efficient since the entire wavelength converters may not be required all the time. The conversion device based on this architecture can not fall under all-optical category due to technology limitations. Even in optoelectronic converters, wider range tunable transmitters are more difficult to build and accordingly more expensive. The connection permutation of the *Any-to-Any* device is the highest, which explains why it eliminates the wavelength continuity constraint, but the technical limitation and control implementation cost associated with this type of devices make them less desirable in the all-optical switches.

- *Any-to-Range*: This conversion device, shown in figure 5.2(b), can convert any incoming wavelength in the full set $\Lambda_i = \{\lambda_1, \lambda_2, ..., \lambda_W\}$, to a subset of outgoing wavelengths $\Lambda_{o_k} = \left\{\lambda_{(k-1)d+1}, \lambda_{(k-1)d+2}, ..., \lambda_{kd}\right\}$ for $k = 1, 2, ..., c$, which is a pre-specified range for full non-overlapping coverage of wavelengths defined by $d = W/c$, where W is the total number of wavelengths in the fiber and c is the number of converters shared in the node. This definition of the range d applies to all LRWC ranging architectures through out this study with exception of the full conversion case, *Any-to-Any*, since every converter can convert the incoming signal into the full available output wavelength set. Since it is not cost-effective to equip all the output ports of a switch with conversion capability, this conversion ranging method offers the ability to share the conversion resources for all the incoming wavelengths with respect to a pre-determined output range, which is a subset of the all available wavelengths. It is obvious that the connection permutations of this type is less than the *Any-to-Any* type, but it allows sharing of converters among the various signals in the switch. Simulation analysis shows that switches employing such devices, however, compare favorably with those utilizing converters employing *Any-to-Any* ranging method.

- *Range-to-Any*: This device, shown in figure 5.2(c), behaves in a complementary manner compared to the previous ones. The incoming request is required to use one specific conversion device, k, depending on its wavelength and the range it falls into, $\Lambda_{i_k} = \left\{\lambda_{(k-1)d+1}, \lambda_{(k-1)d+2}, ..., \lambda_{kd}\right\}$ for $k = 1, 2, ..., c$. The output range of this scheme is defined as $\Lambda_o = \{\lambda_1, \lambda_2, ..., \lambda_W\}$, which means that the output of the converter can utilize any wavelength in the full set. The input side ranging mechanism of a converter employed in this switch type defines the degree of sharing of such converter with respect to the input side ports. In other words, limiting the range, of the input side of the converter directly influences the degree of sharing of conversion resources and consequently limiting the performance of the switch. This means that the input side ranging mechanism imposes further limitations on the behavior of the switch in a manner that degrades performance compared to the two previous cases.

- *Range-to-Range*: The range in both sides of the device, shown in figure 5.2(d), are defined by d. The incoming request is required to use one specific conversion device, k, depending on its wavelength and the range it falls into, $\Lambda_{i_k} = \left\{\lambda_{(k-1)d+1}, \lambda_{(k-1)d+2}, ..., \lambda_{kd}\right\}$ for $k = 1, 2, ..., c$. The output range of this scheme is restricted to $\Lambda_{o_k} = \left\{\lambda_{(k-1)d+1}, \lambda_{(k-1)d+2}, ..., \lambda_{kd}\right\}$ for $k = 1, 2, ..., c$, which means that the output of the converter can utilize only the wavelengths within the subset k. This type is ranged and restricted from both sides of the converters leading to the least connection permutations. There is a restricted set of wavelengths in each side of the WC and, therefore, the performance of this type of WCs is much more limited compared to all other types. This type could be considered a viable choice for switches that work in low offered load settings.

5.3 Performance Results

Networks with different conversion ranging architectural definitions and different conversion sharing degrees were simulated considering c, number of shared converters in the conversion bank, W, total number of wavelengths available on a fiber, and d, the range of conversion in the LRWC configurations. If the requested wavelength is not available in any outgoing fiber, the request will be forwarded to one of the shared converters within the pre-specified range d for the given architecture.

The following assumptions are used in our simulation models. 1) The offered traffic is in the form of connection requests for an entire optical channel. These requests arrive at each node according to an independent stationary Poisson process with rate λ. 2) Connection holding time is exponentially distributed with the mean

$1/\mu$. 3) Connection request that cannot be serviced are blocked. 4) The connection requests are uniformly distributed among the wavelengths. For the simulator, a Poisson distribution generator is used for the arrival generation. The *mean inter-arrival time* defines the time between successive packets that arrive at a node. The load of the node is defined as the ratio of the Mean Transmission Time to the Mean Inter-Arrival Time.

The simulator, written in C++ language, implements a discrete event simulation of node. The node configuration parameters are fed to the simulator as inputs. It has the ability to handle different types of node configurations. To get an accurate result from the simulator, the data is not accumulated until the steady state is reached as indicated by the loss probability. The tolerance for testing the steady states is 0.001, i.e., the simulation runs until the loss probability reach a variation of not more than 0.1%.

The simulation emulates the conditions imposed by the ranging architectures on the behavior of each specific switch. Existing requests cannot be reassigned different wavelengths. If the input/output range of the converter is defined as *Any-to-Any*, i.e., $d=W$, the request will be forwarded to any one of the shared output converters. In this case, if there is no free wavelength available on the outgoing *range*, or there is no free converter, then the request is blocked. Both *Any-to-Any* and *Any-to-Range* conversion architectures have the same conversion bank behavior, but they differ in the available output wavelength range that can serve the path setting request. The *Any-to-Range* scheme, which is easily implemented as all-optical devices, has a connection permutations that is the closest to of the *Any-to-Any*. This indicates that the behavior of the conversion bank under this scheme affects the performance metrics in a slightly different manner than the earlier scheme. The resultant performance can be further enhanced by adjusting or managing the conversion resources sharing degree. In the *Range-to-Any* and

Range-to-Range LRWC simulations, the behavior of the conversion bank differs from the previous two cases due to the fact that each request uses just one specific converter that has the incoming wavelength in its range. In this section, we present simulation results for different LRWC ranging schemes.

In Figures 5.3 and 5.4, the blocking is plotted as a function of offered load per wavelength for 4 differently ranged LRWC architectures. We considered 3 different *Any-to-Any* switch sizes, *W=64, 32, 16*, that have similar W/c ratio of 2. The results for this architecture consistently show that switches with higher number of wavelengths, *W*, have better blocking performance given similar W/c ratio. In this full conversion case, the W/c ratio is not considered as the *Shared Conversion Degree, d,* as it is the case in the LRWC cases. Although *Any-to-Any* conversion method, full-wavelength conversion, is desirable because it substantially decreases blocking probability, it is difficult to implement in practice. The graphs also show that at lower offered loads, all 3 cases have similar performances due to the abundance of wavelengths and conversion resources with respect to load serviced. In the same graph, we also considered 3 different *Any-to-Range* switch sizes, *W=64, 32, 16*, that have shared conversion degree *d=2*. The results showed that *Any-to-Range* architecture's performance obtain most of the performance advantages of *Any-to-Any* case at lower architectural complexity and within the technological limitation of the all-optical conversion devices implying that the front ranging mechanism does not degrade performance while maintaining an efficient use of the conversion resources in the switch. This behavior, also, creates an opportunity for network efficiency, which depends on number of converters, and conversion efficiency, which depends on converter architecture, tradeoffs. Figure 5.4 confirms earlier results and shows that *Any-to-Range* closely behaves like the *Any-to-Any* case and superior to the other two cases.

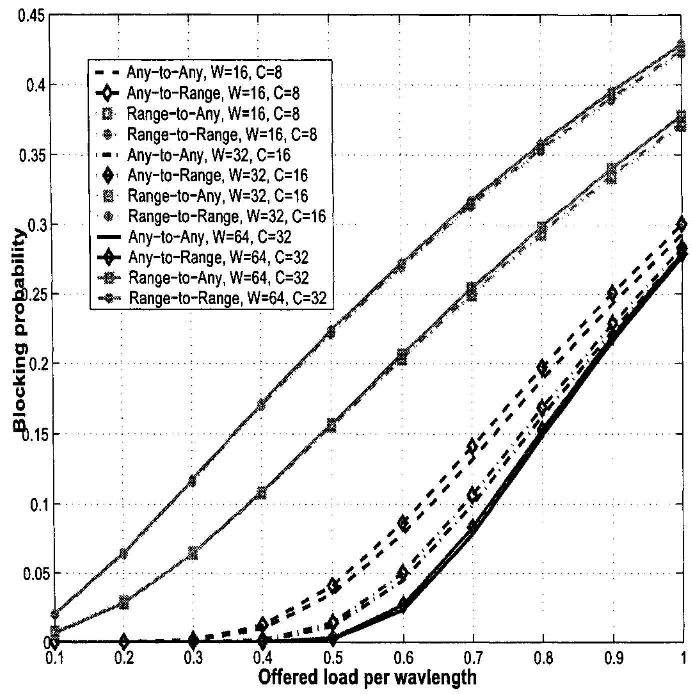

Figure 5.3: Blocking Vs. Offered Load per Wavelength for all conversion ranging schemes in Linear Scale

In a similar fashion, we considered switch sizes of *W=64, 32, 16* and *d=2* for *Range-to-Any* and *Range-to-Range* cases. The blocking performances for these two architectures are considerably worse than *Any-to-Any* and *Any-to-Range* due to the *one converter limitation* imposed, resulting from the input side ranging mechanism, on all incoming requests. This limitation makes the switch behave the same regardless of the size, *W*, implying that the input side ranging scheme can severely degrade performance. The *Range-to-Range* scheme is the least practical due to the fact that its behavior is severely affected by the ranging limitation imposed on both the input and the output sides. These results also confirm that the connection permutation for the *Any-to-Any* and *Any-to-Range* schemes are much greater than that under the other two schemes, which implies that the use of output side ranging scheme's performance is much better than input side ranging schemes. Thus, using backend-ranged converters improves switch performance.

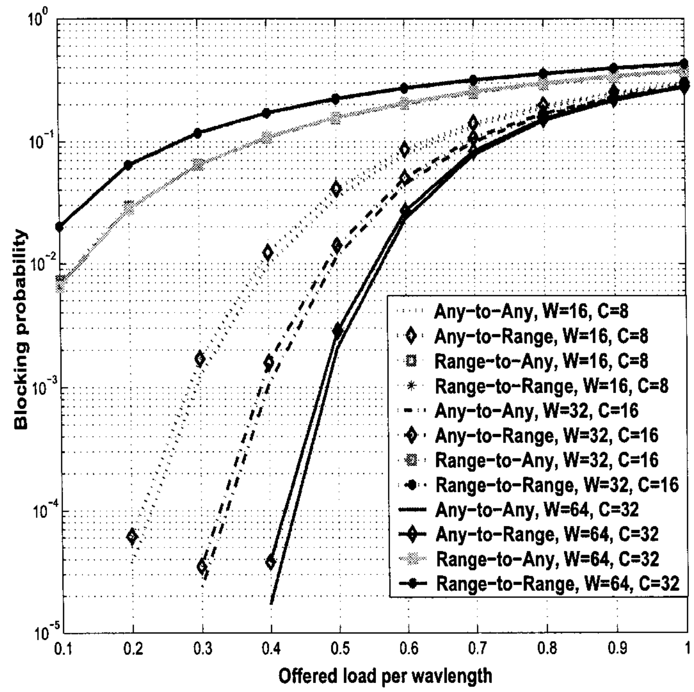

Figure 5.4: Blocking Vs. Offered Load per Wavelength for all conversion ranging schemes in Log Scale

From pervious results, we can expect that *Range-to-Any* and *Range-to-Range* architectures to be less sensitive to the change in number of converters, and accordingly to *d*, due to the already imposed ranging limitation on their input sides. This raises a question about how sensitive the *Any-to-Any* and *Any-to-Range* schemes to the change in number of converters *c* and the conversion range *d*.

In Figures 5.5 and 5.6, for an LRWC with *W=64* and *c=32, 30, 16, 8, 4, and 2*, the blocking of *Any-to-Any* and *Any-to-Range* architectures decreases with converter count, even though the width of the conversion range, *d*, gets smaller. The graphs also show that both *Any-to-Any* and *Any-to-Range* architectures behave comparably in each scenario indicating that *Any-to-Range* ranging scheme is a valid architectural abstraction that provides an equivalent performance behavior to *Any-to-Any* scheme. This reaffirms the preceding results and show that

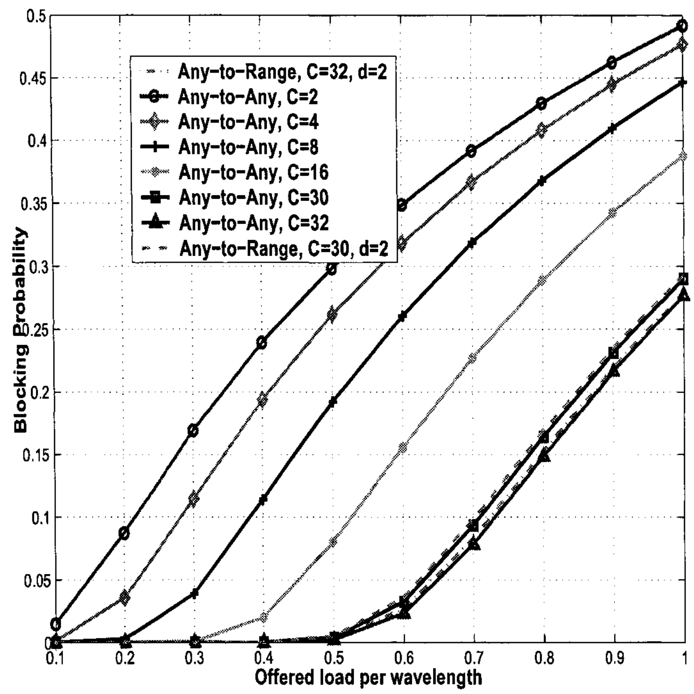

Figure 5.5: Blocking Vs. Offered Load behavior for *Any-to-Range* and the Full range conversion, *Any-to-Any* in Linear Scale

Any-to-Range is the most practical and the most comparable to the Any-to-Any architecture.

According to the relationship between the conversion range d and the number of shared converters, the range of each converter is expected to be less with increased sharing. Accordingly, the *Range-to-Range* architecture suffers the most due to ranging restriction imposed on both sides when the number of shared converters increases resulting in performance degradation. It also can be deduced that these conversion ranging schemes are more responsive to the change in number of shared converters than the change in the conversion range, even though, both are interrelated according to $d{=}W/c$.

For figure 5.7, the simulation was performed with a traffic load of 0.9 for the reason that the efficiency of conversion at higher offered loads is more evident

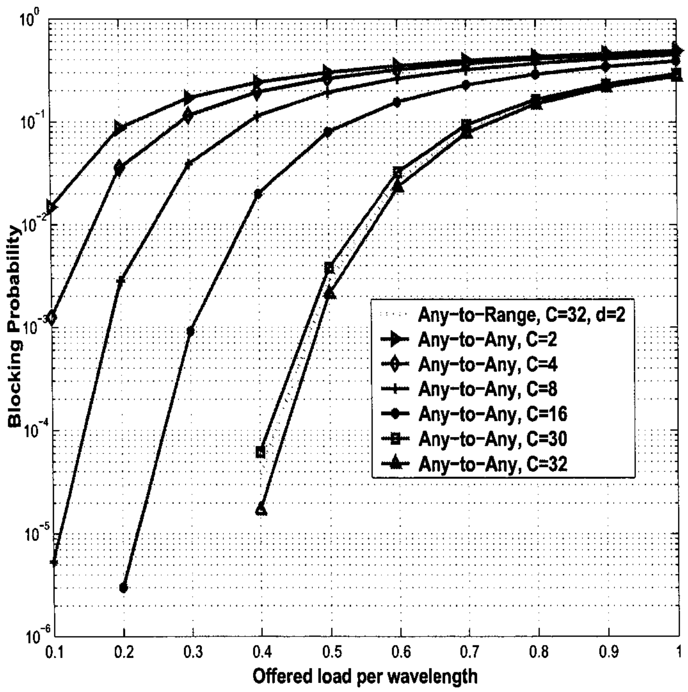

Figure 5.6: Blocking Vs. Offered Load behavior for *Any-to-Range* and the Full range conversion, *Any-to-Any* in Log Scale

than lower offered loads. This graph shows the relationship between the blocking probability of the *Any-to-Any* ranged switch and the ratio of shared converters over the number of wavelength serviced by the switch, c/W, for *W=8, 16, 32, 64, and 128*. The blocking is obtained for a range of shared converters starting from *c=0*, representing the no conversion case, till $c=W/2$. The graph shows that blocking performance improves the more converters are shared, and it also shows that the blocking of larger switches are less due to the increased availability of wavelength resources. The differences in blocking behavior diminishes at higher counts of wavelength indicating that the available resources for the given offered load are sufficient to maintain an efficient utilization of such resources.

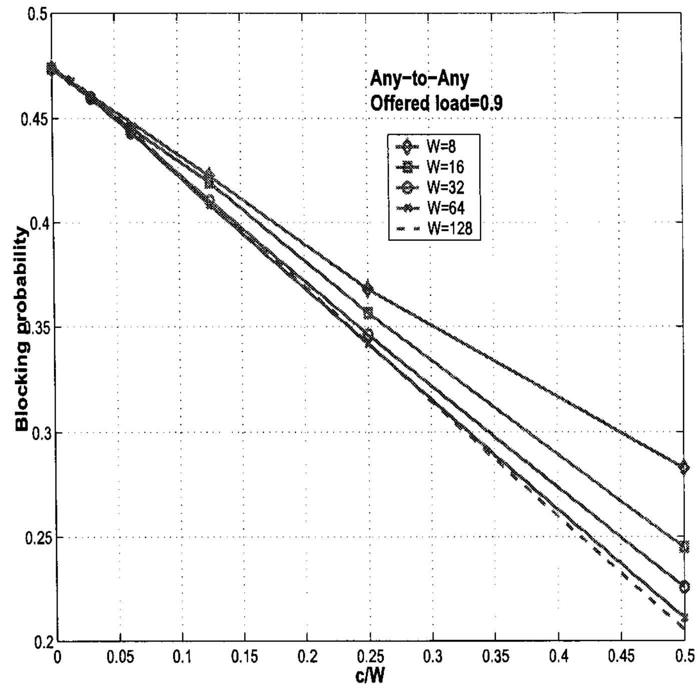

Figure 5.7: Blocking probability Vs. c/W ratio for *Any-to-Any* ranging scheme

Figure 5.8, examines the blocking performance of the *Any-to-Range* switch for the similar settings considered in the previous figure. The resulting set of graphs for the different switch sizes almost match the results of the similar graphs in the figure 5.7 confirming that the *Any-to-Range* ranging scheme is operationally analogous to the *Any-to-Any* scheme even though the connection permutation in both cases are different. This is explained by the degree of sharing utilized in the case of *Any-to-Range.* In this figure, the differences in blocking behavior, also, diminishes at higher counts of wavelength indicating that the available resources for the given offered load are sufficient and comparable to of the *Any-to-Any* scheme.

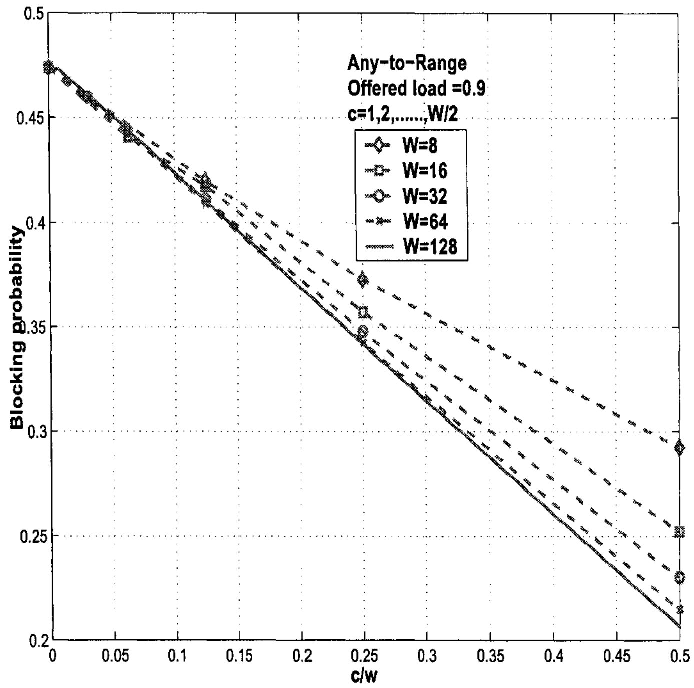

Figure 5.8: Blocking probability Vs. c/W ratio for *Any-to-Range* ranging scheme

Figures 5.9 and 5.10, examine the blocking performance of the *Range-to-Any* and *Range-to-Range* switches respectively for settings similar to the previous two figures. The resulting set of graphs for the different switch sizes in the *Range-to-Any* case showed an interesting behavior that is consistent with our earlier findings. It showed that blocking performance for the different switch sizes behaved almost comparably due to the input side ranging limitation which restricted the input signals to one specific converter. This result confirms that the input side ranging mechanisms are more limiting and consequently degrades the performance of the switch that adopts such ranging scheme. From this we can deduce that the differences in the blocking behavior for the *Any-to-Any* and *Any-to-Range* based switches were a direct result of not restricting the incoming requests to a specific converter, which means that the efficiency of conversion resources sharing is higher when ranging is imposed on the output side of converters rather than the input side.

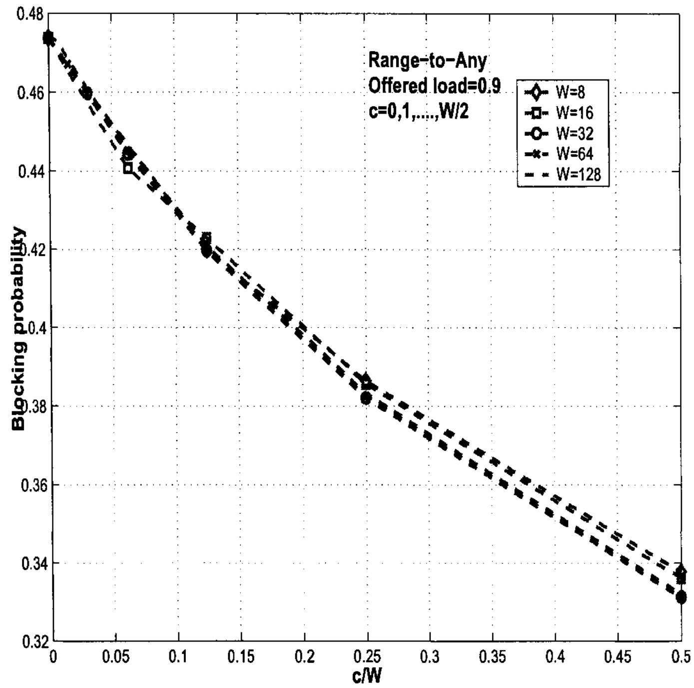

Figure 5.9: Blocking probability Vs. c/W ratio for *Range-to-Any* ranging scheme

In the case of *Range-to-Range* switch, additional interesting behavior is revealed in figure 5.10. The figure shows that blocking performance behavior remains almost constant after *c/W=0.25*. This indicates that the double ranging imposed on both sides of the shared converter limits the benefits gained by adding additional conversion resources after certain *c/W* ratio regardless of the size of the switch. From these result, we can conclude that switches that employ input side ranging methods are less practical than the output side ranging methods due to negative impact they have on the degree of sharing. Sharing resources is much accomplished when the entire set of converters are accessible by the incoming traffic requests. If the traffic request is restricted to a pre-defined set of converters, the sharing efficiency degrades considerably regardless of how these converters are ranged on the output side.

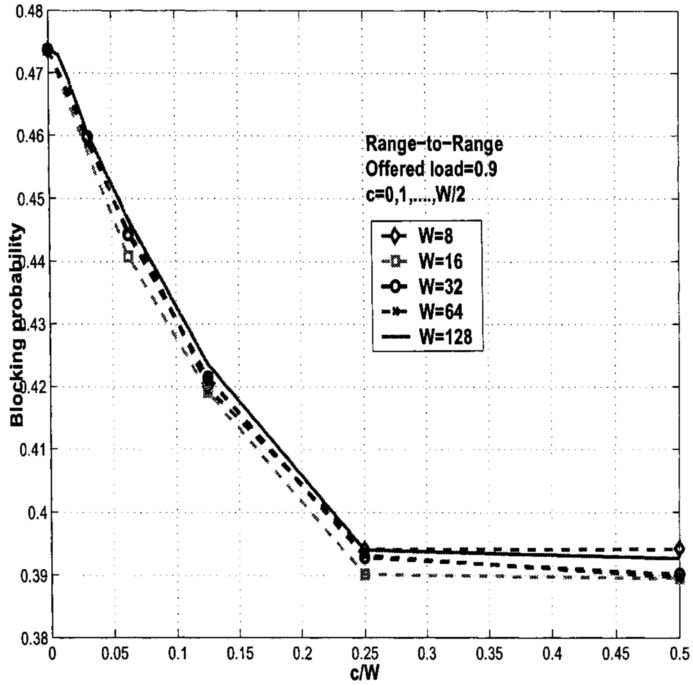

Figure 5.10: Blocking probability Vs. c/W ratio for *Range-to-Range* ranging scheme

Figure 5.11 examines the blocking performance of the all cases with respect to *c/W* ratio for switch sizes of *W=64 and 128.* The graph shows that the performance of the *Any-to-Any* and *Any-to-Range* based switches are almost comparable. The graph also shows that the performance of *Range-to-Any* and *Range-to-Range* switch cases lag considerably behind the previous two output side ranging schemes. This result confirms that *Any-to-Range* method is an operationally analogous alternative to full conversion that could be implemented in the all-optical wavelength converters. It also takes full advantage of resources sharing mechanism, which further improves its efficiency.

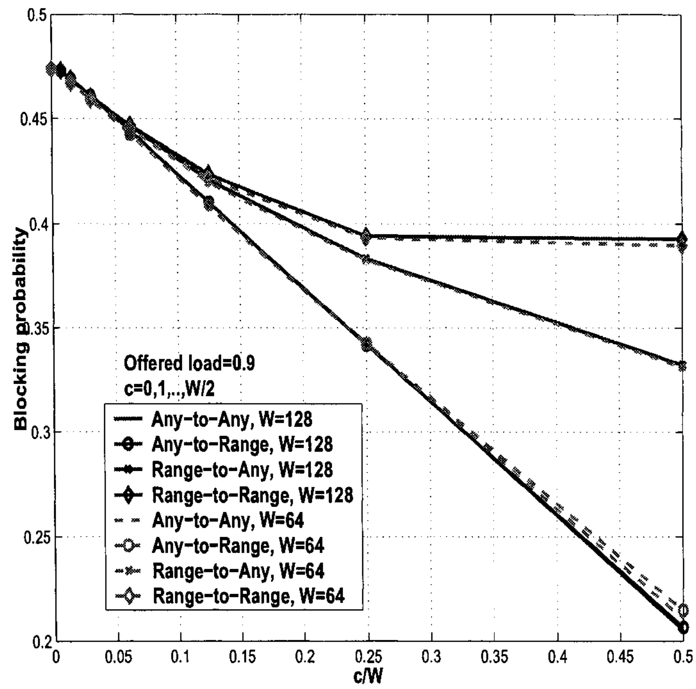

Figure 5.11: Blocking probability Vs. c/W ratio for all LRWC ranging schemes

In figure 5.12, the throughput is plotted as a function of offered load per wavelength for the full conversion case, *Any-to-Any*, and three LRWC switch architectures. For the LRWC switch architectures, we considered 3 different switch sizes, $W=64$, *32*, *16*, that have similar shared conversion degree of $d=2$, where $d=W/c$. The results for this architecture consistently show that switches with higher number of wavelengths, W, have better throughput performance at higher offered loads given similar d. It also shows that switches employing output side ranging methods performs considerably better than the switches that employ input side ranging methods. This result is consistent with results discussed for the various graphs presented in this section.

The offered load versus the gain, which is defined as the ratio of utilization of the *Any-to-Any* architecture versus that of the architecture of interest, shown in figure 5.13, for W=64, c=32 and d=2, confirms that the *Any-to-Range* architec-

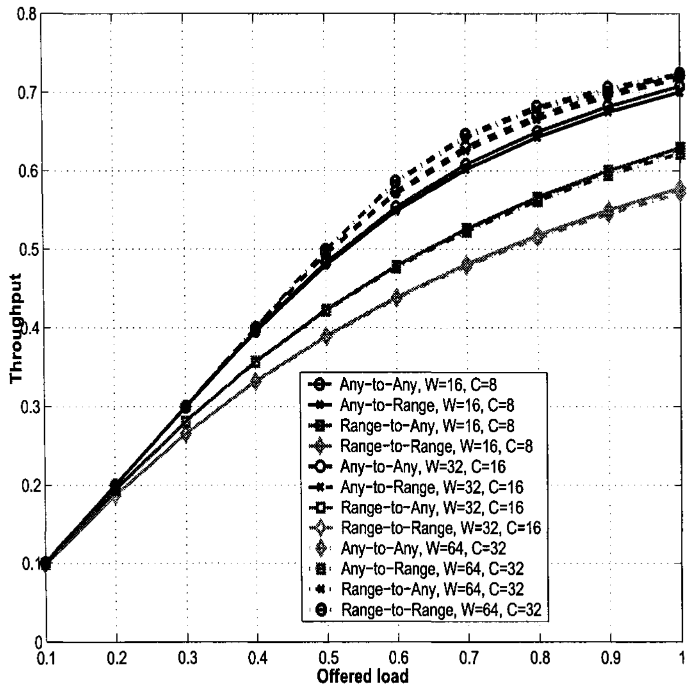

Figure 5.12: Throughput Vs. Offered Load per Wavelength for Full Range Conversion, *Any-to-Any*, and all the LRWC ranging schemes

ture performs in an analogous fashion to the fully ranged *Any-to-Any* method. It also shows that *Range-to-Any* architecture lags in performance due to the input limitation imposed on the incoming traffic where as the *Range-to-Range* method is the poorest due the dual limitation imposed on both sides of the converter as explained earlier. These performance differences are clearer at higher offered loads due to the facts that limited range architectures are more susceptive to lag in utilization performance with higher traffic demand. The differences in these architectures define the practicality of each case with respect to a range of offered loads. This indicates that more limiting architectures, conversion range wise, can be employed in lightly loaded networks increasing the cost efficiency on both the WC hardware and control architecture of the switch. It should be noted that ranging of LRWC architectures can be implemented in an overlapping fashion causing a relative improvement in performance at the expense of control complexity.

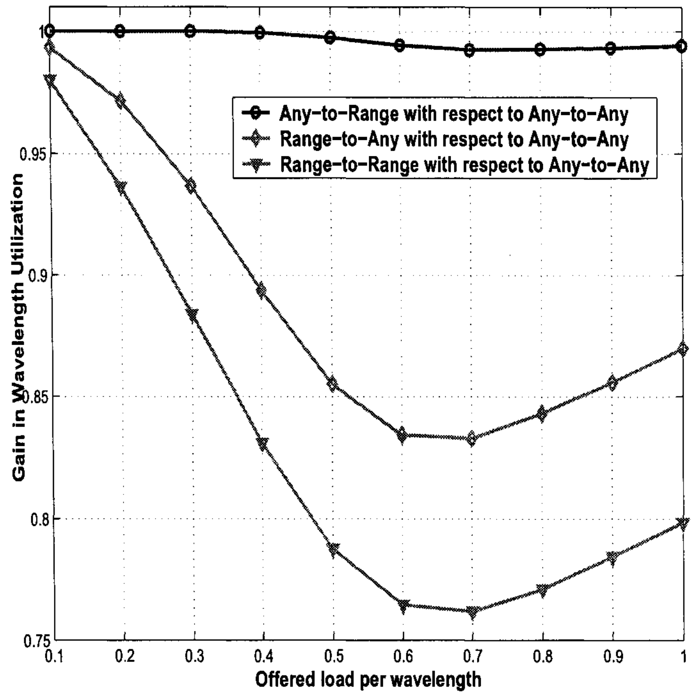

Figure 5.13: Gain in wavelength utilization Vs. Offered Load per Wavelength for all the LRWC ranging schemes with respect to the Full Range Conversion case

5.4 Chapter Summary

This work investigated issues associated with LRWC in the presence of conversion resources sharing. The ranging mechanisms of a wavelength converter are identified as major design criterions of the optical switch, and that it has an important role in managing conversion resources efficiently. This work also explored the differences between the input and output side ranging mechanisms and their effects on conversion resources sharing and consequently performance. It analyzes the impact of using different architectures for wavelength conversion to mitigate the cost penalty. The throughput improvement due to the use of LRWC, in the presence of conversion sharing, depends more on the degree of sharing than the conversion range. The study shows that smaller input-side conversion ranges can approach the same performance as full-range WC at slightly higher degree of sharing. The implementation of *Any-to-Range* architecture in all-optical wavelength converters would be a more efficient and elegant solution, allowing fully integrated optical cross-connect/wavelength conversion boxes. *Any-to-Range* means less complex and less costly hardware than full range conversion, yet it results in acceptable channel utilization. This introduces the issue of cost effectiveness when considering different switching architectures, conversion options, and hop configurations.

The limited range architecture reduces the need for extremely complex *Any-to-Any* control algorithms. Nevertheless, these ranging architectures do give up some flexibility and overall network efficiency. The complexity and the cost of all-optical converters depend on its conversion ranging mechanism. Switches with limited range conversion will be less costly to implement than the ones that employ full ranged converters. The cost of implementing optical layer can be expected to scale roughly in proportion to the number of conversion resources and how the resources are architected.

It is shown that switches with completely shared wavelength converters require a fraction of WCs in comparison to switch architectures that use a wavelength converter per wavelength. This indicates that resources sharing is an important factor in reducing hardware volume and costs of all-optical networks. The sharing efficiency is tightly coupled with the ranging mechanism employed in the switch. Switches that employ output side ranging methods can take full advantage of wavelength conversion resources sharing, whereas these sharing advantages are severely limited in switches that employ input side ranging method.

Chapter 6

PERFORMANCE ANALYSIS OF SYNCHRONOUS WDM SHARE-PER-LINK MULTI-FIBER PACKET-SWITCHED NETWORKS UNDER SYMMETRIC TRAFFIC CONDITION

6.1 Introduction

Using the conventional circuit-switched networks (Wavelength-Routed network), where a connection (light-path) between source-destination pair has to be established on top of the WDM multiplexing technology before data transmission starts, will result in ineffective use of the enormous bandwidth provided by such technology [32]. To overcome this inherent poor utilization of the WDM bandwidth in Wavelength-Routed network, optical packet-switching (OPS), which allows fast allocation of wavelengths in an on demand fashion, is used. OPS suffers from packets contention problem that rises when two or more of the incoming packets on the same wavelength intend to leave the switch through the same output port, which results in packet loss and poor network performance. The contention resolution schemes in optical switches could be time dimensioned [55, 38], space dimensioned [26], or/and frequency dimensioned. Time dimension contention resolution scheme is realized through utilizing fiber delay lines (FDLs). In this scheme, one of the contending packets is forwarded to the desired output port and the remaining packets are forwarded to FDLs where they are delayed for fixed time, during which the contention might have been resolved [46]. Thus the number of FDLs is an important design switch parameter because it has an impact on the switch size and cost [30].

Deflection routing is an example of the space dimension contention resolving technique. In deflection routing scheme, one of the contending packets utilizes the intended output port while the others are deflected to other available output ports, otherwise they are dropped [37]. The effectiveness of this scheme significantly depends on the network topology. The drawback of this approach is that the deflected packet may have to traverse a longer path to reach the destination, which may result in a significant crosstalk noise in the optical signal. Therefore, the network becomes more congested as more deflections take place. This scheme could lead to poor wavelength utilization and low network performance if the deflected packets are dropped after a number of deflections [96].

Wavelength conversion (WC) [27] is an example of frequency dimension contention resolution techniques. In this scheme multiple wavelengths are utilized in order to resolve the contention. The contention could be cleared by shifting all but one of the contending packets to unused wavelengths on the requested output. The wavelength translation of the contending packets takes place by utilizing a wavelength converter. Using wavelength conversion (WC) at OPS reduces the packets loss due the contentions. Furthermore, WC is used to eliminate the severity of *wavelength continuity constraint* [20], and improve wavelength agility for dynamic reallocation of optical channels, which in turn enhances the performance and scalability of the network to match the demand for bandwidth.

The wavelength conversion device is an expensive element, [7], thus number of converters could be considered the most effective cost parameter in OPS design. Sharing limited number of conversion devices is an effective paradigm in the cost reduction of the OPS design process. Previous research works suffered a lack of a quantitative insight that characterizes the performance of the optical packet-switched networks. In this research work, we study the synchronous OPS networks with limited number of converters that are shared between all wavelengths on specific output link (Share-per-Link WCS). This chapter will introduce a model for such networks that services symmetric traffic at each node along the path between the source and destination. We will also explore the effects of employing multiple fibers on the network performance and how that affects the needed conversion resources. The multi-fiber synchronous photonic share-per-link packet-switch model we developed in [35] would be the basic switch element on which we build the multi-hop fixed routing end-to-end network model in this work.

6.2 OPS Analytical Model based on Symmetric Traffic Switch

In this section, we present a performance model, [2, 35, 36], for multi-fiber share-per-link OPS network which operates in a slotted mode. This model is used together with the multi-hop network model presented in Chapter 4 to study the performance of the synchronous multi-fiber share-per-link OPS network. A Symmetric OPS employing share-per-link conversion resource with N inputs, coming from different sources, and destined to N output links, each consisting of F parallel fibers as shown in figure 6.1, is considered as the building block of the OPS networks with fixed routing algorithm that we intend to study in this research. We developed the analytical model of such switch, [2, 35, 36], and the full derivation of this model is presented in Appendix D of this dissertation. The aim is to use such switch model to develop an analytical model for synchronous OPS network with fixed routing algorithm. The Network supports a *WDM* signal with w wavelengths per fiber. A total of $wF=W$ output wavelengths share a conversion bank of c converters. The incoming packets are synchronized at the inputs of every node before they processed. The packet length is assumed to be fixed for one time slot. The

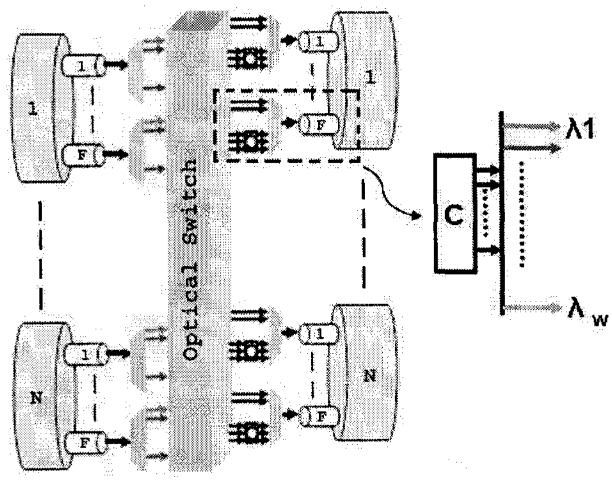

Figure 6.1: Multi-fiber Synchronous OPS Employing Share-per-link Conversion Resources

notations used for the following model is detailed in Appendix D. The topologies of the networks we consider in this chapter are similar to the networks we introduced in chapter 4 but in the synchronous sense.

The number of packet arrivals at an output per wavelength in every node in the path in a given time slot and destined to the output link under consideration follows the binomial distribution for x=$0...NF$, i.e.,

$$P(X_i = x) = \binom{NF}{x} \cdot \left(\frac{\rho}{N}\right)^x \cdot \left(1 - \frac{\rho}{N}\right)^{N \cdot F - x} \tag{6.1}$$

This means that in a given time slot, letting X_i be a random variable representing the number of packets present at an output on λ_i, there are *NF* copies of λ_i at the inputs side of each switch on the path, so the maximum value that could be taken by X_i is *NF*, which happens when all packets arrived at the inputs on λ_i are destined to same wavelength on the output under consideration. The minimum value of X_i is *zero*, which means that there is no arrival on λ_i at the inputs or none of the arrived packets are destined to that specific output link. The probability that a packet arrives at an input in a given time slot is denoted by ρ, which corresponds to the normalized offered load. Packet arrivals per wavelength at different inputs are independent of each other. Also the number of packet arrivals on different wavelengths is *Identically and Independently Distributed*; $\{X_i\}_{i=0}^{w}$ is *iid.*

For a given time slot, if the numbers of arrivals per wavelength, which are destined to the considered output, are more than F packets, contention among them will occur. Per wavelength, F packets out of the contending ones leave the switch directly, one on each fiber. The rest of these packets are forwarded to the conversion bank that belongs to the output port under consideration. In our model in [2, 35, 36], we calculate the packets that can be forwarded to conversion bank from a single wavelength as shown by equation D.5 in Appendix D.

The number of rejected packets, Y_i, from different wavelengths and forwarded to conversion bank is identically independently distributed, *iid.* Let N_Y be a random variable representing the number of *Y's* that need to be considered for conversion resources competition. N_Y could take any value between *zero* to w. When N_Y is equal to *zero*, it means that all arrived packets on all wavelengths can leave the switch without any conversion or none of the arrivals are destined to output port under consideration. If every wavelength on the output had received more than F packets, then N_Y will be equal to w. So the distribution of N_Y for $ny=0\ldots w$ is as follows:

$$P\left(N_Y = n_y\right) = \binom{w}{n_y} \left(\sum_{j=F+1}^{N\cdot F} P(X=j)\right)^{n_y} \cdot \left(\sum_{j=0}^{F} P(X=j)\right)^{w-n_y} \tag{6.2}$$

Conditioned on N_Y, λ_i is available on the output link if the number of arrivals per λ_i is less than F packets per time slot, so these free $\lambda_i s$ need to be considered as available wavelengths that can be used to convert the contending packets to. The number of free λ_i out of the F copies on the output port is calculated in equation D.9 in Appendix D. The number of packets, which can utilize conversion resources and leave the switch, depends on the minimum of the total available wavelengths on all fibers at the output and number of available conversion resources. Since the packet length is fixed, all converters are available at beginning of the time slot. Accordingly, the total number of wavelengths that are available on the output link after all direct packets are assigned to outgoing wavelengths is to be found.

B is defined as a random variable that represents the total number of available wavelengths in the out port and could take any value between *zero* and *F(w-ny)*. B equals to *zero* means every outgoing wavelength has at least F arrivals. In this case, all packets to the conversion bank are lost. In contrast, B equals to *F(w-ny)* when there are n_y wavelengths on the output, each having more than F arrivals, where the remaining *w-ny* wavelengths have *zero* arrivals. To find the available wavelengths on the output link for a given N_Y, the distribution of the total number of free wavelengths on the output link under consideration is given by:

$$P\left(B=\beta | N_Y=n_y\right)=\begin{cases} 0 & n_y=w \\ (d^{\beta}/dz^{\beta})\cdot H_B(z)|_{z=0} & \text{otherwise} \end{cases} \tag{6.3}$$

The moment generating function $H_B(z)$ is calculated in equation D.26 in Appendix D.

The number of packets lost per time slot is equal to the difference between the total number of packets that need conversion and those that left the switch after utilizing converters from the conversion bank. For a given N_Y, the total number of packet that are directed to the conversion bank is equal to the summation of all rejected packets from all busy wavelengths as shown in equation D.29 in Appendix D. So, the maximum number of packets that can compete for conversion resources are *ny(NF-F)* where the minimum is n_y, which means that every wavelength considered in n_y has *F+1* arrivals. Accordingly, we calculate the average numbers of packets forwarded to the conversion bank, *E[T]*, which is equal to:

$$E[T]=\sum_{n_y=0}^{w} P(N_Y=n_y)\cdot(n_y\cdot E[Y]) \tag{6.4}$$

The average number of packets that are forwarded to the conversion bank per wavelength, *E[Y]*, is given by:

$$E[Y] = \sum_{j=1}^{N \cdot F - F} (j \cdot P(Y = j)) \tag{6.5}$$

If total number of $Y_i s$, n_y, is less than the minimum of available converters and free wavelength on the out put, all packets forwarded to the conversion bank will utilize the conversion resource and leave the switch without any loss. Accordingly, the average number of lost packets, *E[d]*, equals to *zero*. On other hand, if n_y is greater than the minimum of available converters and free wavelength on the out put, only the minimum of available converters and free wavelength determine the number of packets that can leave the switch through wavelength converters while the rest will be lost. So, in [2, 35, 36], we calculate the average packets that will utilize the conversion resources and leave the switch *E[A]* as shown in equation D.40 in Appendix D.

Now we can calculate the average number of packets that will be dropped, *E[d]*, as the difference between the average of total forwarded packets to conversion bank, *E[T]*, and the average accepted packets for conversion, *E[A]*:

$$E[d] = E[T] - E[A] \tag{6.6}$$

The average number of packet arrivals per wavelength on the output under consideration is equal to $F \cdot \rho$. So, the total expected arrival to the output link is given by:

$$E[\xi]_{symmetric} = w \cdot F \cdot \rho \tag{6.7}$$

Packet loss takes place when all $\lambda_i s$ are busy on all outgoing F fibers and the total number of packets forwarded to the conversion bank is greater than the minimum number of available converters and free wavelengths on the output. On the other hand, some of the rejected packets from direct connection can be served by utilizing the available wavelengths and leave the switch by getting converted to one of the available channels on the output, if there are available $\lambda_i s$ on the output port under consideration. The blocking probability of the switch, P_b, is then defined as the ratio of expected number of packet lost, *E[d]*, to the total number of arrivals of the output port i.e.:

$$P_b = \frac{E[d]}{E[\xi]_{symmetric}} \tag{6.8}$$

6.3 Network Analytical Model based on Symmetric Traffic Switch

After obtaining the blocking probability for each individual switch on the path, we consider finding the probability of packet loss for end-to-end networks. We examine multi-hop fixed routing networks with a collection of packet-switching optical node connected in series to study the effects of employing multiple fibers and determine the amount of conversion resources needed to obtain best performance. A data packet can be exchanged between any pair of nodes on the path by tuning the source's transmitter to the destination's receiver wavelength if conversion took place. Accordingly, the data packet is extracted from the network at the destination node. According to our assumption of symmetric traffic going through each node, identical number of input/out link, channels and slot structures are used in all hops and network slots are synchronized across the wavelengths in order to form groups of aligned packets propagating within the fiber. The model for a symmetric multi-hop network approximates the packet loss probability along a path with uniformly distributed load on all links entering the intermediate nodes by:

$$P_{Network} = 1 - \left[1 - \frac{E[d]}{E[\xi]_{symmetric}}\right]^H \tag{6.9}$$

where H denotes the number of hops along a path. The packet loss probability for the traffic under consideration assumes identical synchronous packet-switch structure across the network. This means that the model assumes that every node along the path has the same set of input/output links, same number of fibers in each link, same number of wavelength per fiber, same number of conversion resources, and similar input traffic. These conditions describe the symmetric traffic nature of the optical packet-switch in the network.

The achievable end-to-end throughput for a given packet loss probability with respect to a certain source-destination load g in the network is given by:

$$Th_{Network} = g \cdot \left[1 - \frac{E[d]}{E[\xi]_{symmetric}}\right]^{H} \tag{6.10}$$

The change in the packet loss probability $P_{Network}$ due to the load under consideration, g, is neglected, i.e. the offered load of the link is assumed to be a given constant value, not affected by g. This is due to the fact that the total capacity of the link, the optical fibers, is typically significantly higher than the load generated by a single source-destination pair. In the following sections, we explore the analytical and simulation result for such networks in details and discuss the effects of different switch and networks parameters on the over all performance of these networks.

6.4 Result Analysis for Single-Fiber Synchronous Packet-Switched Networks

In this section, we explore further the effects of different parameters on different multi-hop fixed routing synchronous networks. For the results in this chapter, we considered a background traffic with an offered load of $\rho = 0.7$ per wavelength and a certain source-destination stream offered load of g=0.07. The intention is to study the packet loss probability of a multi-hop fixed routing OPS network that consists of a number of nodes H. The end-to-end packet loss probability $P_{Network}$ of the source-destination stream is a function of the single switch packet loss probability P_b presented in equation 6.8. Accordingly the achievable end-to-end throughput with respect to the source-destination offered stream load, *g=0.07*, under consideration is a function of the end-to-end network availability as shown in equation 6.10.

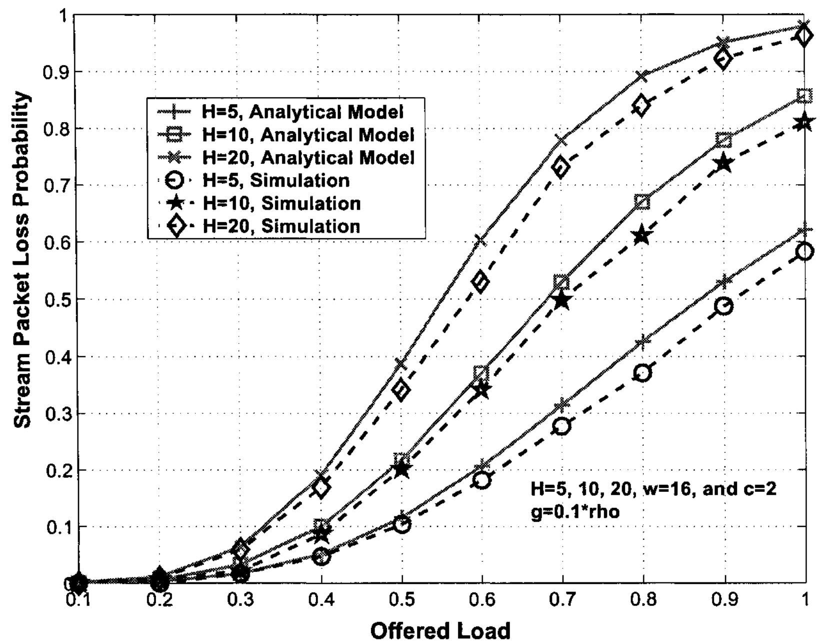

Figure 6.2: Packet Loss Probability vs. Offered Load

In Figure 6.2, the packet loss probability is plotted as a function of offered load for 3 different single fiber networks with diameter of *H=5, 10, 20*, *w=16* per fiber, and *c=2* per out put link. The c/w ratio is constant in this case. It is clear that the packet loss probability increases with load and network diameter, indicating that the network diameter is an important design factor in determining the over all performance of the network. We also notice that the simulation results are lower than results obtained by the analytical model. This is due to the fact that the model considers the links along the path to be equally loaded with a constant ρ, accounting for the packet loss of the observed traffic along the path, where it is not the case in the simulation. The simulation accounts for all the packet loss in the pervious node and accordingly the load in the proceeding links reflects such loss which means that the next node is less loaded resulting in less packet loss in the node and consequently lower end-to-end packet loss probability. This deficiency in the analytical model behavior will be adjusted and rectified when we introduce the asymmetric network model in chapter 7. Table H.1 in the appendix shows the analytical model and simulation data.

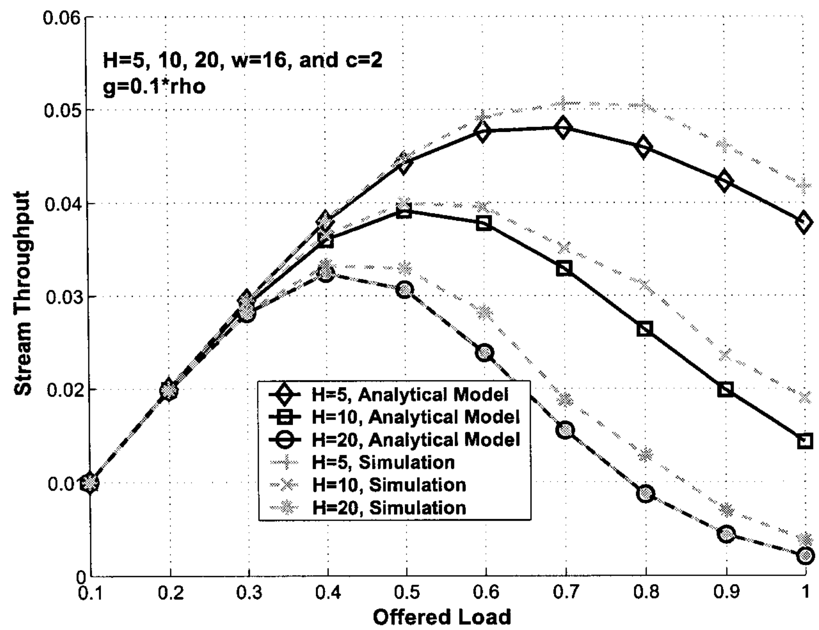

Figure 6.3: Throughput vs. Offered Load for Different Single-Fiber Networks

In Figure 6.3, the stream throughput corresponding to figure 6.2 is plotted as a function of offered load. In this graph, we notice that networks with smaller diameter have higher throughputs. The behavior of the throughput is somehow interesting in the context of this graph. It is noticeable that the throughput tends to increase with the offered load till a certain point and then it start to decline steadily. This behavior is due to the exhaustion of the constant number of wavelength converters used per link. We mentioned earlier that c/w is constant where $c=2$ and $w=16$. This means that the employment of 2 converters per link has a positive effect on the throughput till a certain point where the throughput is maximized. Then, this effect is overwhelmed by the increasing offered load causing the throughput to decline due to the lack of additional converters to deal with the increasing traffic. Similar observation concerning the difference between the results of the analytical model and the simulation as mentioned earlier is applicable to this graph. Table H.2 in the appendix shows the analytical model and simulation data.

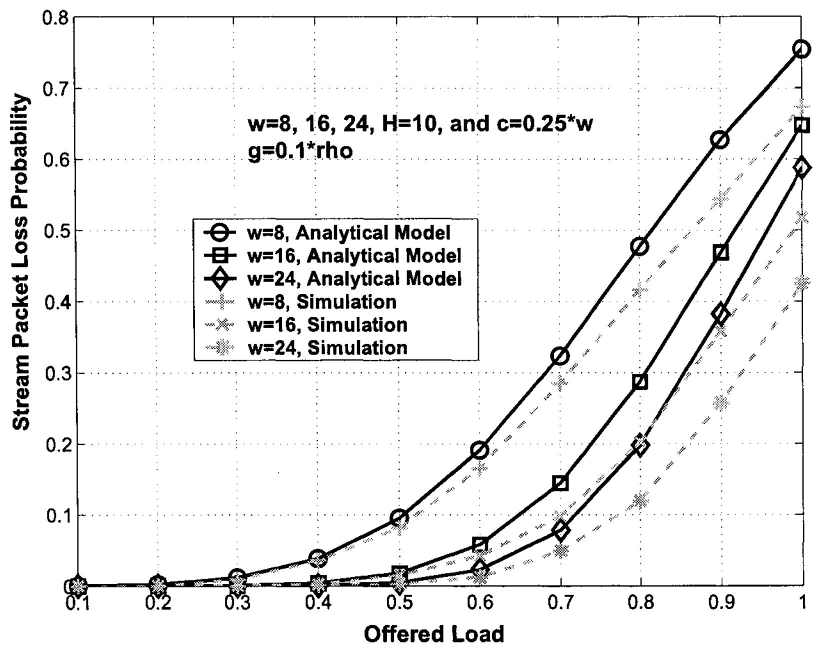

Figure 6.4: Packet Loss Probability vs. Offered load for Networks with *w=8, 16, 24*

In Figure 6.4, the packet loss probability is plotted as a function of offered load for 3 different single fiber link networks with *w=8, 16, 24* per fiber, *H=10*, and *c/w=0.25*. This means that *c* changes with the introduction of more wavelengths. It is clear that the packet loss probability decreases with the introduction of more wavelengths in the network, indicating that count is also an important design factor in determining the over all performance of the network. We notice that even though the total offered load per link is higher in higher count of wavelength, the corresponding packet loss probability is lower than if the network had less wavelengths. This tells us that the increase wavelength count has positive effects on the performance even if it means more traffic competing for the network resources. Table H.3 in the appendix shows the analytical model and simulation data.

In Figure 6.5, the throughput corresponding to figure 6.4 is plotted as a function of offered load. We notice that a conversion ratio of $c/w=0.25$ is not enough to sustain an increase in throughput after a certain point. The throughput increases with the offered load till the effects of available converters are exhausted. This means that $c/w=0.25$ per link has a positive effect on the throughput till a certain point where the throughput is maximized. Then, this effect is overwhelmed by the increasing offered load causing the throughput to decline due to the lack of additional converters to deal with the increasing traffic. In the following part of this chapter, we aim to find a c/w ration that offers best performance. Table H.4 in the appendix shows the analytical model and simulation data.

In the following graphs, we consider the behavior of the analytical model, where it considers all the links on the path from source to destination to have similar offered load ρ. In order to check the consistency of the data obtained by the analytical model with the effects of different parameters, we try to compensate for the traffic dropped at every hop in the simulation with exception to the tagged traffic we try to monitor. This alteration in the simulation would make the simulation to behave similar to the model and allows us to check for the effect of the different parameters of the network and their effects of the performance.

In Figure 6.6, the packet loss probability is plotted as a function of number of converters for 3 different single fiber link networks with $H=5,\ 10,\ 20$, $w=20$, and $\rho = 0.7$ per wavelength. The c/w ratio changes every time a new converter is introduced to these networks. We can see that the packet loss probability of

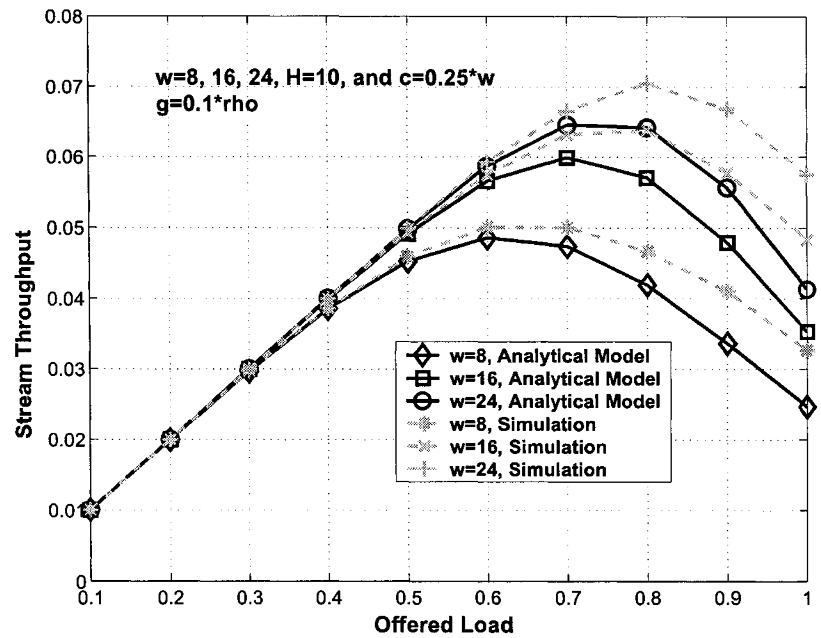

Figure 6.5: Throughput vs. Offered Load for Networks with *w=8, 16, 24*

smaller diameter networks is lower than networks with higher hope count, which is consistent with earlier findings. The interesting observation in this graph is that the packet loss probability flattens at a point where the c/w ratio is around 33% regardless of the diameter of the network. Any addition of converters after the $c/w=0.33$ has no effects. At the ratio of $c/w=0.33$, the network operates equivalently to the full conversion network. This indicates that the amount of performance improvement in packet loss probability due to the introduction of converters is independent of the network diameter, hop count H. The introduction of more converter beyond the $c/w=0.33$ would be considered wastage of important resources indicated by the flat packet loss probability behavior in the graph. With contrast to Figure 6.4, this figure also shows that the effects of introducing more converters are more dramatic with respect to performance than introducing more wavelengths. This is clear due to the steep negative slope of the packet loss prob-

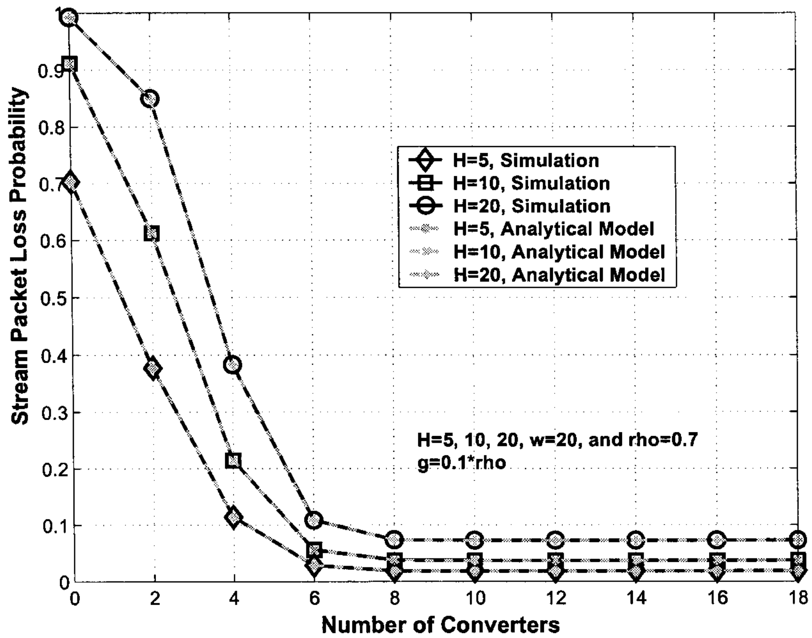

Figure 6.6: Packet Loss Probability vs. Number of Converters for Networks with *H=5, 10, 20*

ability with the introduction of converters. Table H.5 in the appendix shows the analytical model and simulation data for figure 6.6.

In Figure 6.7, the throughput corresponding to figure 6.6 is plotted as a function of number of converters. The behavior of the throughput is consistent with the corresponding packet loss probability behavior. We see that the throughput also flattens at around $c/w=0.33$ indicating that the throughput would not improve due to any introduction of additional converters beyond this point. This explains why the introduction of more converter beyond the $c/w=0.33$ would be considered wastage of resources. For these networks with $w=20$, the full conversion happen when $c=20$. The fact that an equivalent behavior can be obtained at $c/w=0.33$ is a significant result. In later graphs, we will explore the effect of offered load on the c/w and try to relate such parameter to the point where the system behaves as

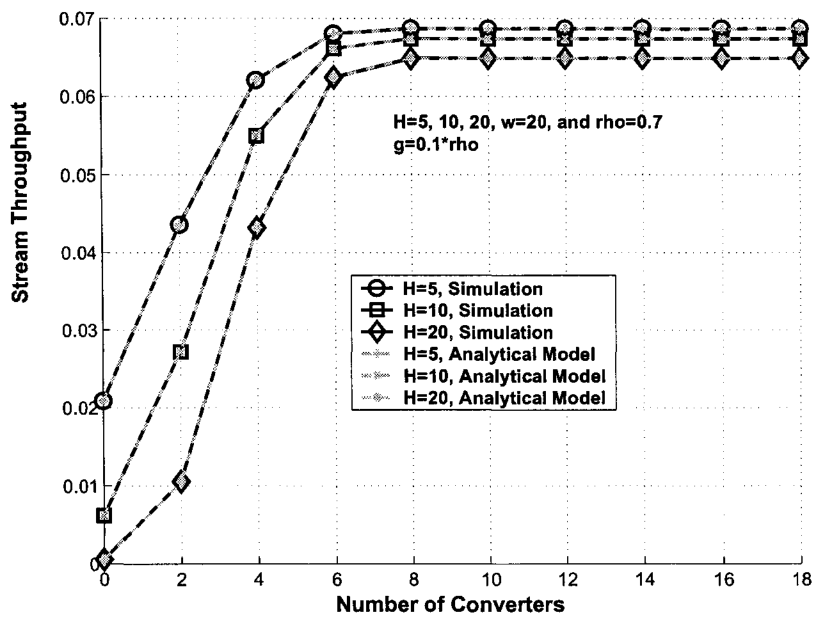

Figure 6.7: Throughput vs. Number of Converters for Networks with *H=5, 10, 20*

a full conversion network. Table H.6 in the appendix shows the analytical model and simulation data for figure 6.7.

6.5 Result Analysis for Multi-Fiber Synchronous Packet-Switched Networks

After this brief exposure to single-fiber networks, we explore both single and multi-fiber networks in order to contrast their performance with respect to switch and network parameters. In Figure 6.8, the packet loss probability is plotted as a function of offered load for 6 different networks with diameter of *H=5, 10, 20*, *W=16* per fiber, and *c=2* per out put link. The *c/W* ratio is constant in this case. The total number of wavelength in the multi-fiber networks is $W = w \cdot F$, where w is the number of wavelength per fiber. It is important to notice that the multi-fiber networks in this figure result in better packet loss probability performance even in lower offered lower even thought the total wavelengths employed in these networks are similar to the single-fiber networks in the same figure. This indicates that dividing the available wavelengths into a multiple of similar sets of wavelengths would reduce the packet loss probability and increases performance.

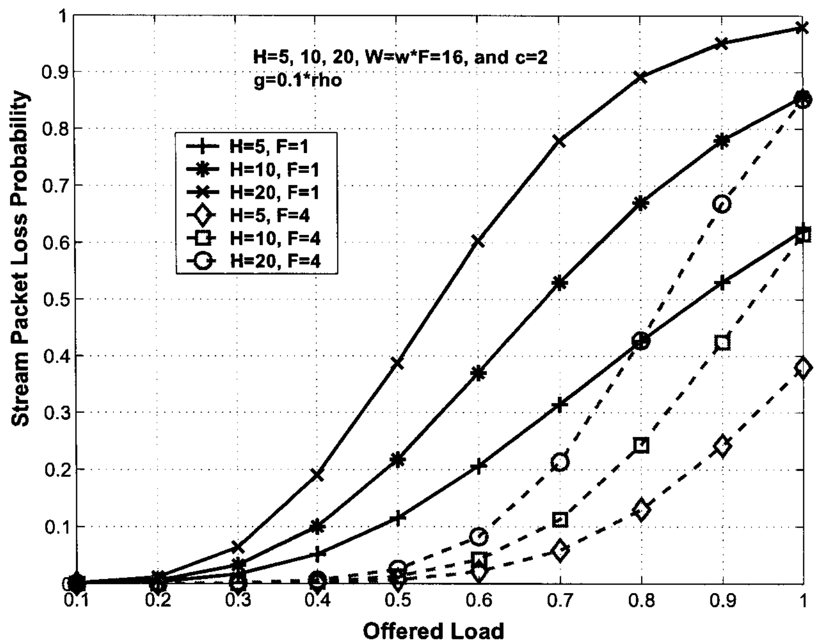

Figure 6.8: Packet Loss Probability vs. Offered Load for Multi-Fiber Networks

In Figure 6.9, the throughput for 6 different networks with diameter of *H=5, 10, 20*, *W=16* per fiber, and *c=2* per out put link is plotted as a function of offered load. In this graph, the total normalized background load is constant for both systems since the total number of wavelength is the same. The OPS network services more packet/slot load with the increase of the fiber count per link. We notice that networks with smaller diameter have higher throughputs. It is noticeable that the throughput is lower in the single fiber network case and it tends to increase with the offered load till a certain point and then it start to decline steadily. This decline seems to be delayed in the case of multi-fiber networks. This behavior is due to the exhaustion of the constant number of wavelength converters effect at higher levels of offered load. The delay in the throughput decline is due to the introduction of multiple fibers. The increasing traffic due to a higher offered load seem to overwhelm the effect of the constant converters less in the case of using multiple fibers than when a single fiber is used in the network. The effect of introducing multiple fibers can be envisioned as an enhancement to the network by making the conversion more effective. It also can be claimed that the employment of such fibers can have an effect of a very limited wavelength conversion.

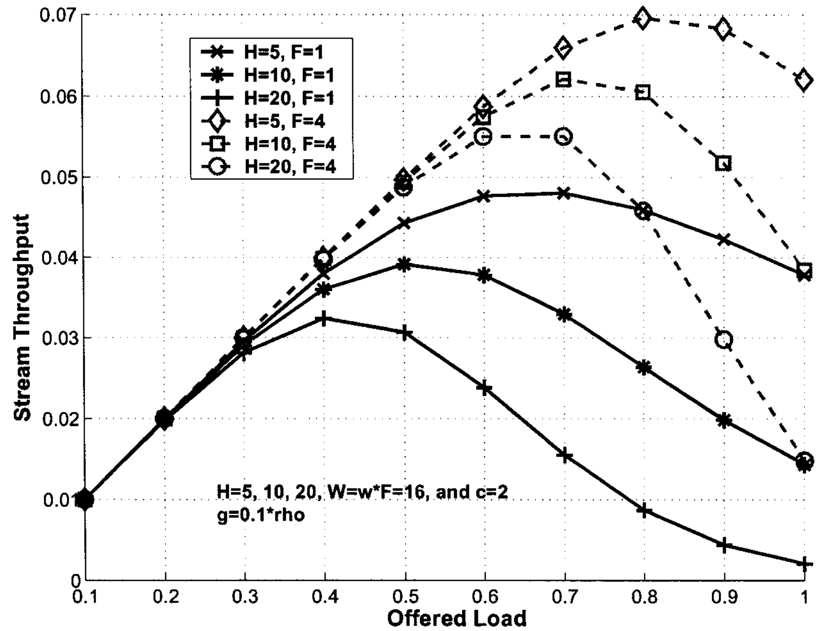

Figure 6.9: Throughput vs. Offered Load for Different Multi-Fiber Networks

In Figure 6.10, the packet loss probability is plotted as a function of offered load for 6 different networks with *w=8, 16, 24* per fiber, *H=10*, and *c/W=0.25*. This means that c changes with the introduction of more wavelengths. It is clear that the packet loss probability decreases more in the multi-fiber networks with the introduction of more wavelengths. We notice that even though the total offered load per link is higher in higher count of wavelength, the corresponding packet loss probability is lower than if the network had less wavelength. This tells us that the increase in wavelength count, more traffic competing for the network resources, has positive effects on the performance, even in the case of employing multiple fibers.

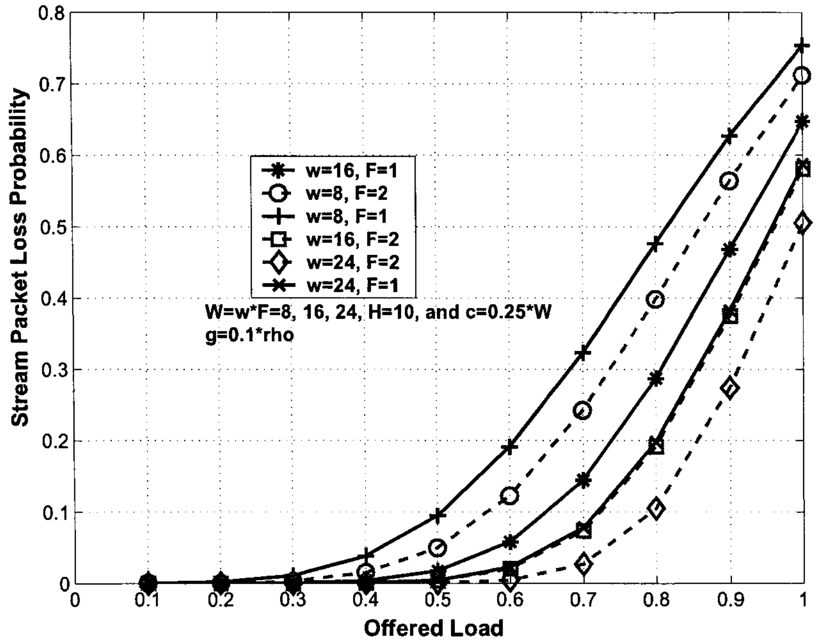

Figure 6.10: Packet Loss Probability vs. Offered load for Multi-Fiber Networks with *w=8, 16, 24*

In Figure 6.11, the throughput corresponding to figure 6.10 is plotted as a function of offered load. We notice that a conversion ratio of $c/W=0.25$ is not enough to sustain an increase in throughput after a certain point even in the multi fiber environment, but is enough to delay the decline in the throughput with comparison to single-fiber based networks. The throughput increases with the offered load till the effects of available converters are exhausted. This means that $c/W=0.25$ per link has a positive effect on the throughput till a certain point where the throughput is maximized.

In Figure 6.12, the packet loss probability is plotted as a function of number of converters for 6 different networks with $H=5,\ 10,\ 20$, $W=20$, and $\rho = 0.7$ per wavelength. The c/W ratio changes every time a new converter is introduced to

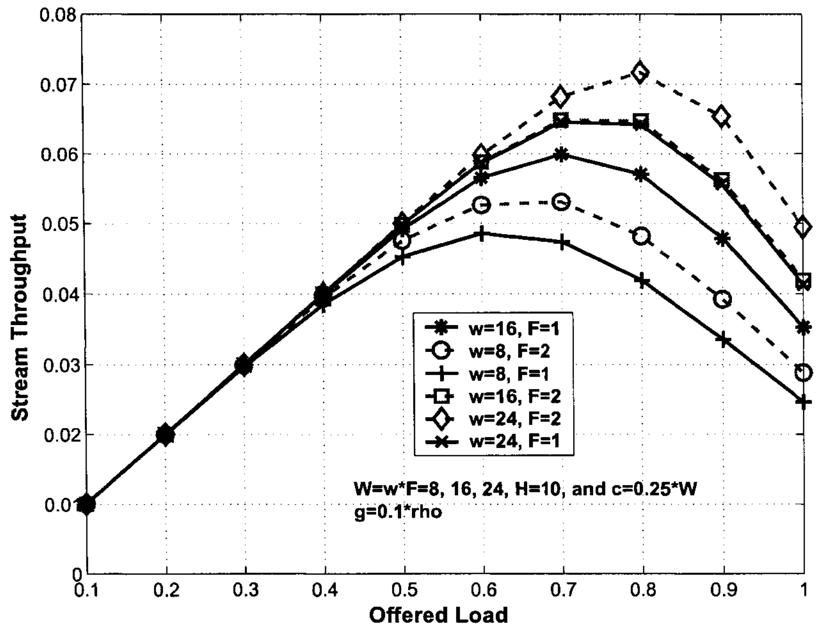

Figure 6.11: Throughput vs. Offered Load for Multi-Fiber Networks with *w=8, 16, 24*

these networks. The packet loss probability flattens at a point where the c/W ratio for multi-fiber networks is less than the 33% established for the single-fiber networks. In this case, this behavior is independent of network diameter. For the multi-fiber networks considered in this graph, we see that the c/W is around 25%. Any addition of converters after the c/W=*0.25* has no effects. At the ratio of c/W=*0.25*, the network operates equivalently to the full conversion network. This ratio would be tested further in the following figures in this section.

In Figure 6.13, the throughput corresponding to figure 6.12 is plotted as a function of number of converters. The behavior of the throughput is consistent with the corresponding packet loss probability behavior. We see that the throughput also flattens at around c/W=*0.25* for multi-fiber networks indicating that the throughput would not improve due to any introduction of additional converters beyond this point given $\rho = 0.7$. In later graphs, we will explore the effect of

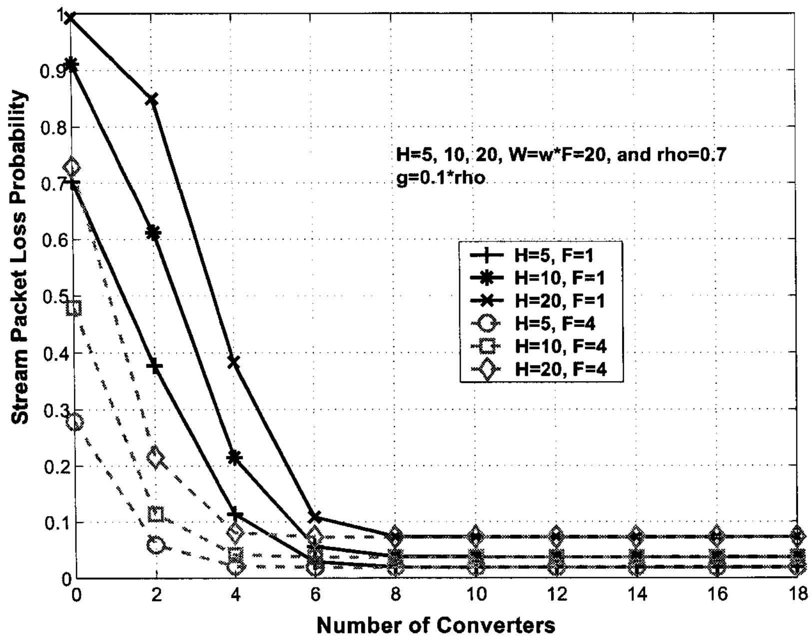

Figure 6.12: Packet Loss Probability vs. Number of Converters for Multi-Fiber Networks with *H=5, 10, 20*

offered load on the c/W in the presence of multiple fibers and try to relate such parameter to the point where the system behaves as a full conversion network.

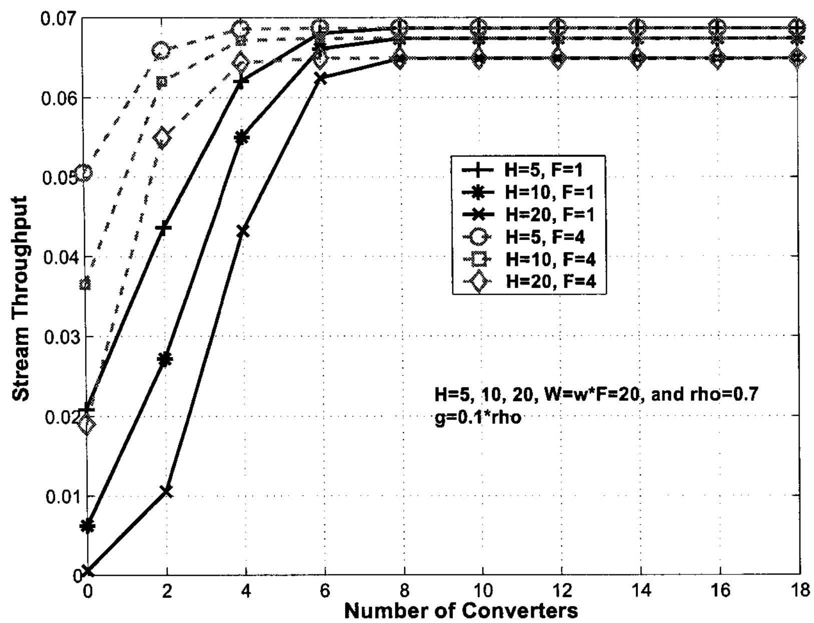

Figure 6.13: Throughput vs. Number of Converters for Multi-Fiber Networks with *H=5, 10, 20*

In Figure 6.14, we investigate the effects of offered load on the packet loss probability in the presence of wavelength converters. The packet loss probability is plotted as a function of number of converters for 3 single-fiber and 3 multi-fiber networks with $\rho = 0.3, 0.6, 0.9$, *H=20*, and *W=64*. The c/W ratio for all networks changes every time a new converter is introduced to these networks. We notice that lightly loaded networks reach the point where the system behaves equivalent to full conversion network earlier than networks with higher offered load. This shows that the needed for converters in a given network is a function of how the network loaded. It can be seen that the single-fiber network with $\rho = 0.3$ reached such point at *c/W=0.10*, where a network with $\rho = 0.6$ reached the same point at *c/W=0.21*. It also can be seen that the multi-fiber network with $\rho = 0.3$ reached such point at *c/W=0.031*, where a network with $\rho = 0.6$ reached the same point at *c/W=0.091*, which represents a significant saving in the converters count comparing to the single-fiber networks. After reaching such point, the introduction of any additional converter would not improve the packet loss probability for both kinds of networks. This indicates that the amount of performance improvement in packet loss probability due to the introduction of converters is dependent on the network load.

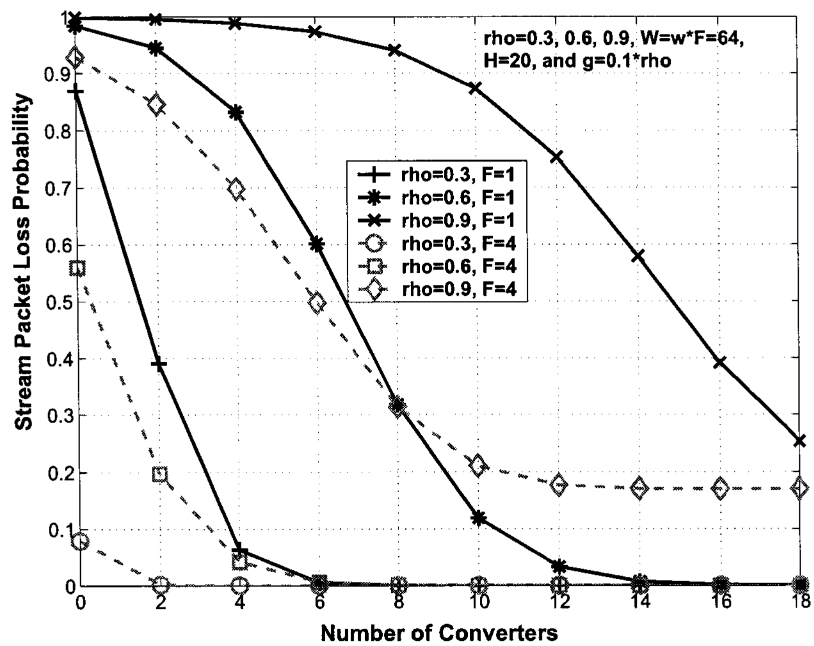

Figure 6.14: Packet Loss Probability vs. Number of Converters for Multi-Fiber Networks with $\rho = 0.3, 0.6, 0.9$

In Figure 6.15, the throughput corresponding to figure 6.14 is plotted as a function of number of converters. The behavior of the throughput is consistent with the corresponding packet loss probability behavior. We see that the throughput for single-fiber networks flattens at around *c/W=0.10* where as the throughput of multi-fiber networks flattens at around *c/W=0.031* when is $\rho = 0.3$ indicating that the throughput would not improve due to any introduction of additional converters beyond this point.

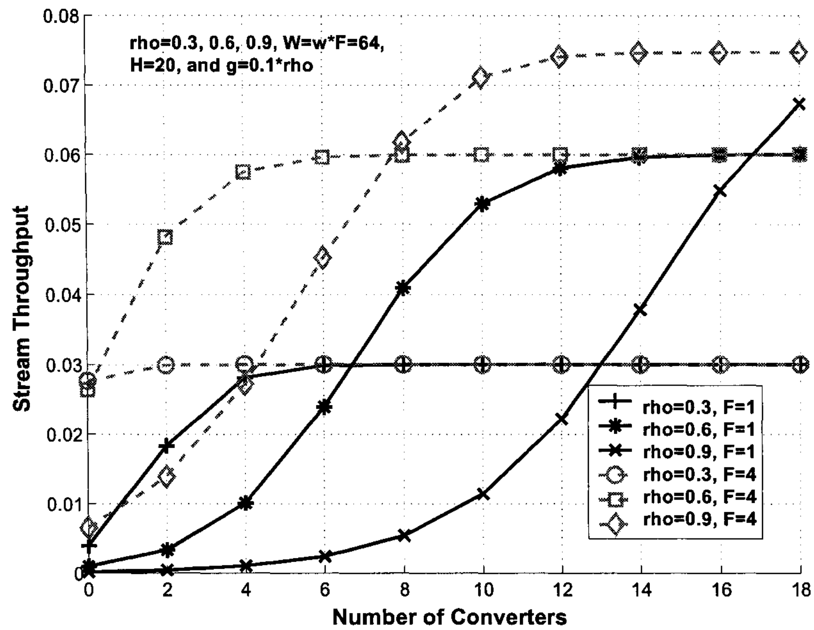

Figure 6.15: Throughput vs. Number of Converters for Multi-Fiber Networks with $\rho = 0.3, 0.6, 0.9$

In Figure 6.16, the packet loss probability is plotted as a function of number of wavelength for 3 single-fiber and 3 multi-fiber networks with *H=5, 10, 20* $\rho = 0.75$, and *c/W=0.5.* The constant *c/W* ratio for all of these networks says that the number of converters increase with the introduction of additional wavelength. We should expect that these networks operate equivalently to full conversion because of the fact that they are beyond the *c/W=0.33* ratio. This notion will be tested further though out this research work. We notice that the introduction of additional wavelength decreases the packet loss probability even though it means the introduction of additional load given $\rho = 0.75$ per wavelength. It is noticeable that the introduction of additional wavelength does not match the effect of adding more converters, which indicates that the effect of increasing the number of wavelengths in the network is less significant comparing to the use of conversion resources. Also, this graph confirms earlier result where it shows the network with lower hop counts have less packet loss probability than networks with higher hop counts.

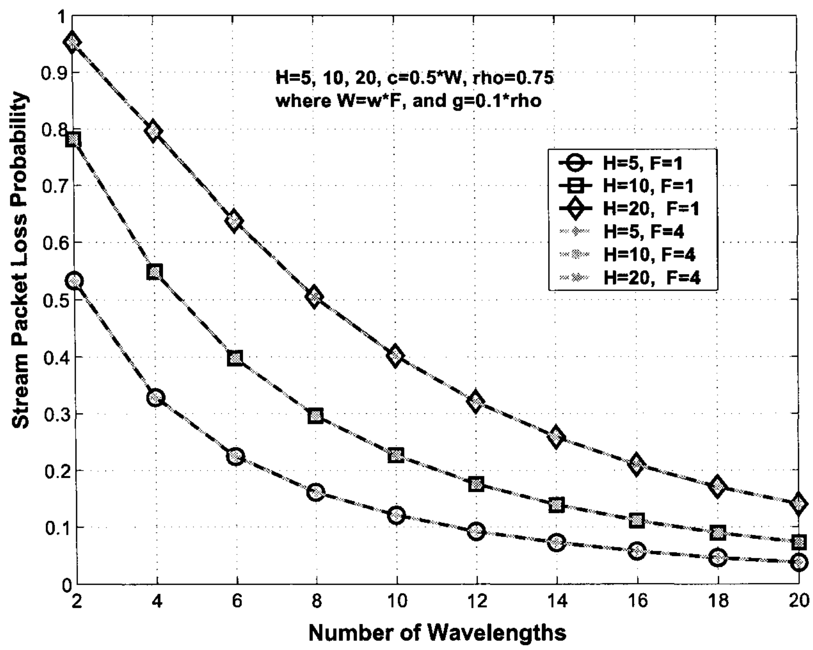

Figure 6.16: Packet Loss Probability vs. Number of wavelengths for Multi-Fiber Networks with *H=5, 10, 20*

In Figure 6.17, the throughput corresponding to figure 6.16 is plotted as a function of number of wavelengths. The behavior of the throughput in this graph is also consistent with the corresponding packet loss probability behavior. Unlike Figures 6.9 and 6.11 where they operate at low c/W ratio, the throughput does not decline due to the fact that the networks considered in this graph are operating equivalently to full conversion networks with c/w higher than 33%.

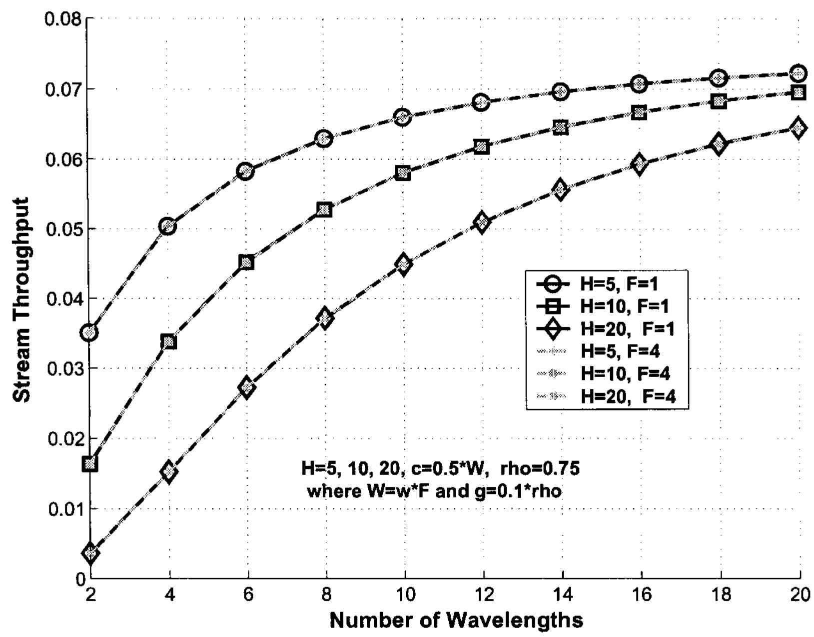

Figure 6.17: Throughput vs. Number of Wavelengths for Multi-Fiber Networks with*H=5, 10, 20*

Considering the prominent effect of offered load in determining the converters count needed in multi-fiber networks to reach the equivalent performance of full wavelength conversion, in the Figures 6.18 and 6.19, the packet loss probability and the throughput are plotted as a function of number of wavelength respectively for 3 single-fiber and 3 multi-fiber networks with c/W*=0.25, 0.5, 0.75* $\rho = 0.8$, and *H=10*. The difference in these networks is in the number of wavelength converters per output link. It is interesting to see that networks operating at c/W ratio higher than 33% have the same performance, which is equivalent to full conversion, where as the network operating at lower that c/W*=0.33* has higher packet loss rate and lower throughput. It does not mater here if the network is single-fiber or multi-fiber. It is noticeable that even the single-fiber network behave as the multi-fiber after the c/W of 33%, which means when a network reaches the region where it behaves as full conversion network, the fact that it uses multiple fibers would not add any significant improvement. The difference in the c/W ratio before the 33% value in multi-fiber networks is considered an advantage in complementing the efficiency of the available conversion and serving higher traffic than single networks. If the offered load was in the lower region as one of the pervious graphs, even the network with low value of c/W ratio would have similar performance as full conversion. This affirms all the pervious analysis and shows that limited conversion of 33% has a similar performance as full conversion at the highest possible offered load in the network indicating that the use of any additional wavelength converters would be considered wastage of resources and increases the cost of the network unnecessarily.

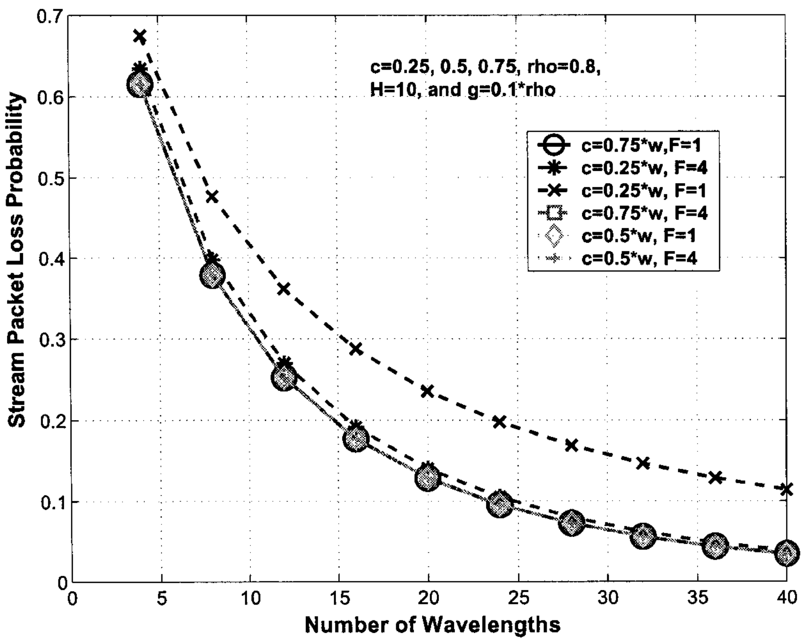

Figure 6.18: Packet Loss Probability vs. Number of wavelengths for Multi-Fiber Networks with *c/w=0.25, 0.5, 0.75*

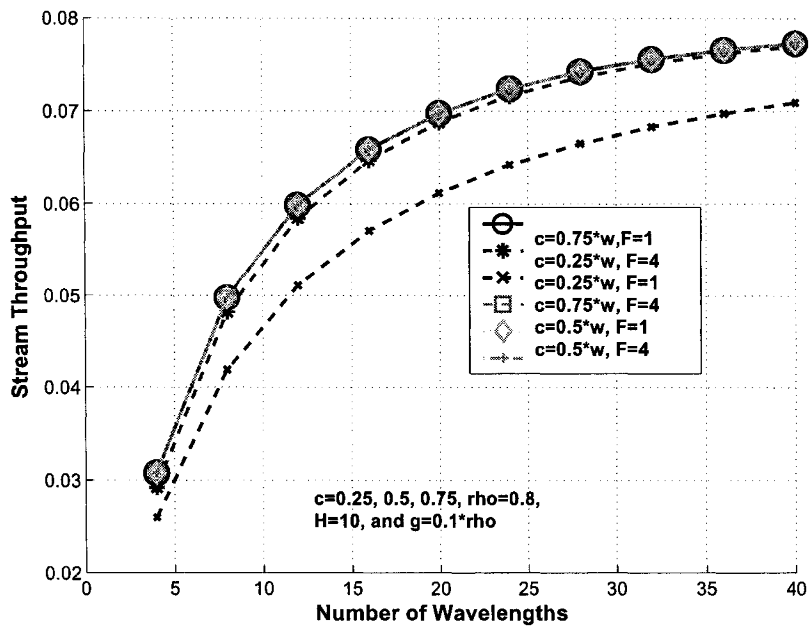

Figure 6.19: Throughput vs. Number of Wavelengths for Multi-Fiber Networks with *c/w=0.25, 0.5, 0.75*

To test the result of the pervious two graphs, in Figures 6.20 and 6.21, the packet loss probability and the throughput are plotted as a function of c/W ratio respectively for 3 single-fiber and 3 multi-fiber networks with *H=5, 10, 15* $\rho = 0.9$, and *w=20*. Since the number of wavelength W in all of these networks is constant, the number of converters changes in order to change the c/W ratio in the graph. The results show that at this particular offered load, the packet loss probability and the corresponding throughput reach the point where they behave as full conversion in different manner between the single fiber networks and the multi-fiber ones. In a single-fiber network, that happens at around c/W*=0.33*, where as for the multi-fiber network, it seems it happens in a lower value of c/W ratio as it shows in both of these figures, c/W*=0.25*. The difference among these lines come from the fact that they have different network diameter, hop count, other than that, they behave in a similar fashion when considering the point where the network is comparable to full conversion system with the difference in the effect of c/W ratio on both the single-fiber networks and the multi-fiber networks. We also confirm that the network diameter has no effects on the point where the network imitate the behavior of full conversion system in the multi-fiber network case. According to this conclusion, we can say for certain that limited conversion of 33% is sufficient for full conversion no matter what the offered load is to accommodate the traffic in a similar manner to full conversion and that any additional wavelength converters would be considered wastage of resources. We also confirm that in the multi-fiber setting, the need of converters is less to reach such point than single-fiber networks.

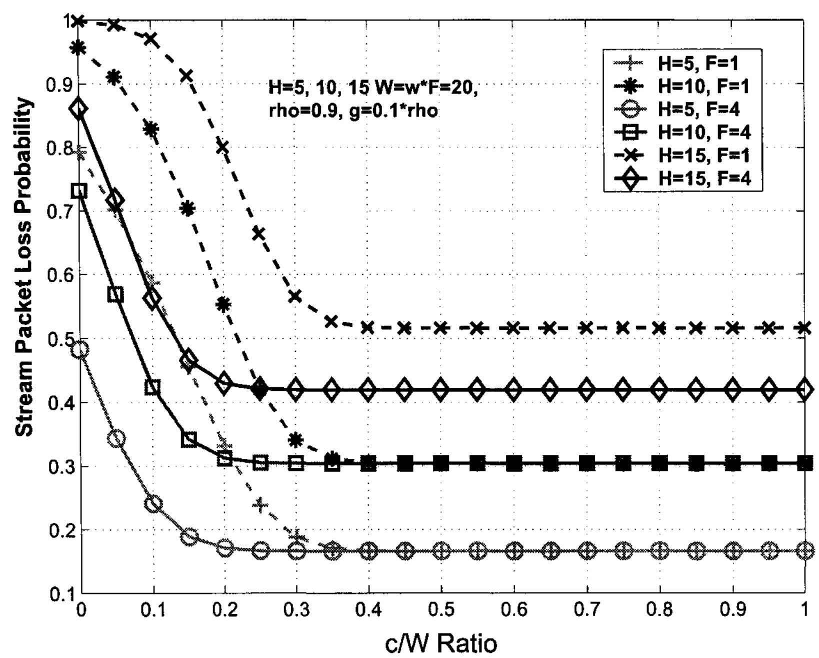

Figure 6.20: Packet Loss Probability vs. c/W Ratio for Multi-Fiber Networks with *H=5, 10, 15*

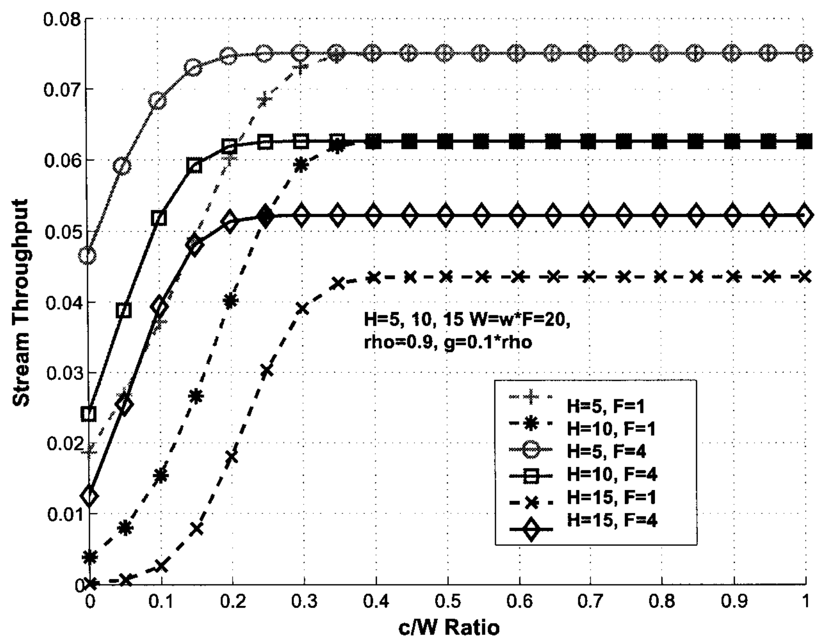

Figure 6.21: Throughput vs. c/W Ratio for Multi-Fiber Networks with *H=5, 10, 15*

In Figures 6.22 and 6.23, the packet loss probability and the throughput are plotted as a function of c/W ratio respectively for 3 single-fiber and 3 multi-fiber networks with $\rho = 0.3, 0.6, 0.9$, *H=20*, and *W=20*. Since the number of wavelength *W* in all of these networks is constant, the number of converters changes in order to change the c/W ratio in the graph. We can see from these graphs that lightly loaded networks reach the point where they behave like networks equipped with full wavelength conversion at lower rates of c/W ratio where as networks with high offered loads reach similar behavior at higher rates of c/W ratio indicating that the offered load play a deterministic role in the appropriate converter count in networks with less traffic volatility. As for network that are characterized as volatile in terms of traffic load, the maximum of $c/W{=}0.33$ is sufficient to exhibit conversion behavior equivalent to full conversion. From these graphs, we also can see that wavelength conversion has prominent effects on multi-fiber systems with lower offered load and less effect on networks with higher offer load. In networks with higher offered loads, the increasing traffic overwhelms the effects of converters, saturate the positive effects of conversion, faster than networks with lower offered loads. This explains why the throughput of the network with $\rho = 0.9$ is lower than the network with $\rho = 0.6$ in both the single and multi-fiber networks cases. In other words, the prominent effect of conversion at $\rho = 0.6$ resulted a better throughput than the network that is highly loaded.

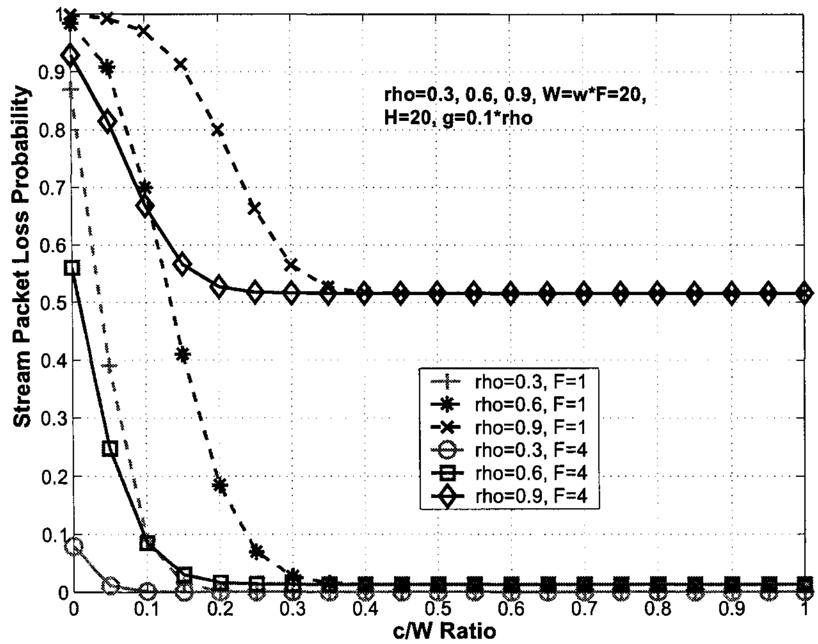

Figure 6.22: Packet Loss Probability vs. c/W Ratio for Multi-Fiber Networks with $\rho = 0.3, 0.6, 0.9$

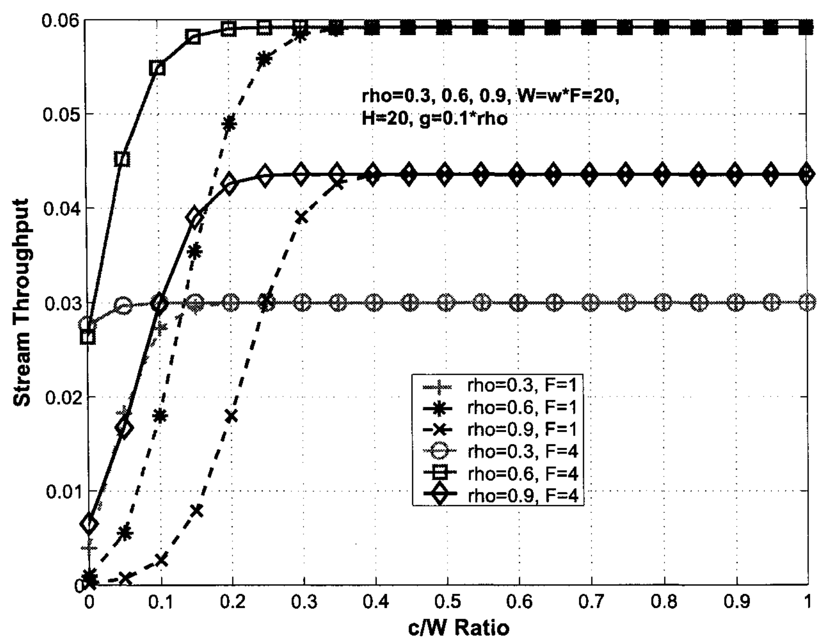

Figure 6.23: Throughput vs. c/W Ratio for Multi-Fiber Networks with $\rho = 0.3, 0.6, 0.9$

In Figures 6.24 and 6.25, the packet loss probability and the throughput are plotted as a function of c/W ratio respectively for 3 single-fiber and 3 multi-fiber networks with *H=5, 10, 20*, $\rho = 1.0$, and *c=2*. In these two graphs, c held constant and W is changed to reflect on the advantages of adding more wavelength after knowing the prominent effects of wavelength conversion in both the single and multi-fiber networks. We notice that both graphs start the x axis with *W=20* and keep decreasing the wavelength count till *W=c*. Interestingly enough, we notice that the packet loss probability decreases and the utilization increases in multi-fiber setting with the decrease of wavelength count. This effect is not hard to explain if we keep in mind that the increase of wavelength count means the increase of the total traffic that traverse the path between the source and destination. But, why is the increase in the throughput if the total traffic traversing the path is less? To answer such question, we should revisit earlier conclusions. We have seen earlier that when the number of converters is fixed in the system, especially at lower c/W

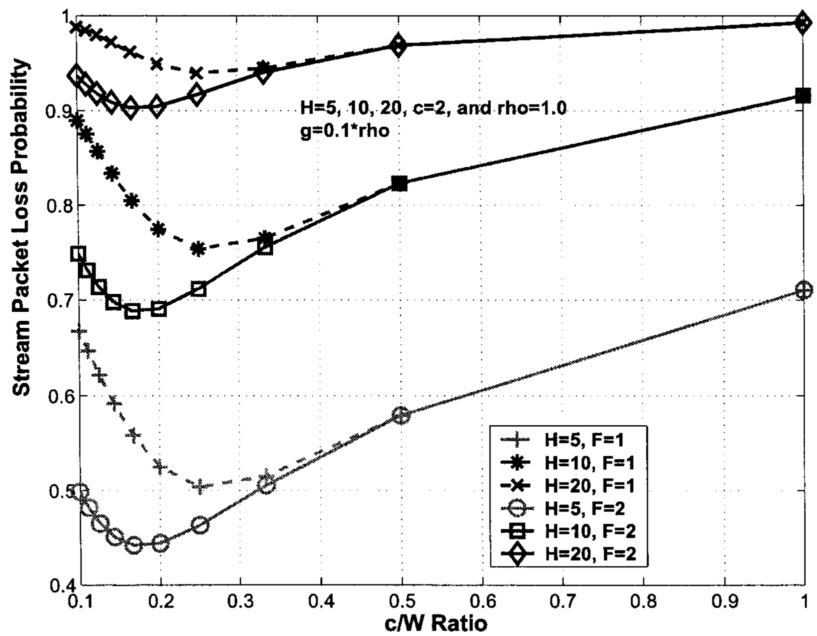

Figure 6.24: Packet Loss Probability vs. c/W Ratio for Multi-Fiber Networks with *H=5, 10,20*

ratios, the increase in the offered load, the total traffic that traverses the path, results in overwhelming the effect of converter and causes the throughput to decline. In these figures, we have a similar situation but in reverse. Considering that the number of converters is constant, when the number of wavelength decreases, the packet loss probability decreases due to the lower total traffic traversing the path, at the same time, the utilization increases due to the increase in the c/W ratio, which means that the converter count has a stronger effect at lower wavelength count. This also means that if we increase the wavelength count beyond the maximum point in throughput, the extra wavelengths added would be considered as wastage in wavelength resources and cause the throughput to degrade. We can see that if we keep adding wavelength to the system, starting from the left side of the graphs, the effects of two converters last till the wavelength count is around *W=17* for single-fiber networks and *W=19* for multi-fiber networks and then any extra introduction of wavelength, more traffic, would cause the system throughput to decline indicating that these extra wavelength are considered wastage because they overwhelm the effect of available conversion and increase packet loss probability. We see that the extra added offered load, through the introduction of more wavelengths, overwhelms the effects of conversion faster in single fiber-setting than the multi-fiber setting. These effects are clearer in networks with lower hop count where a converter count of *c=2* means much.

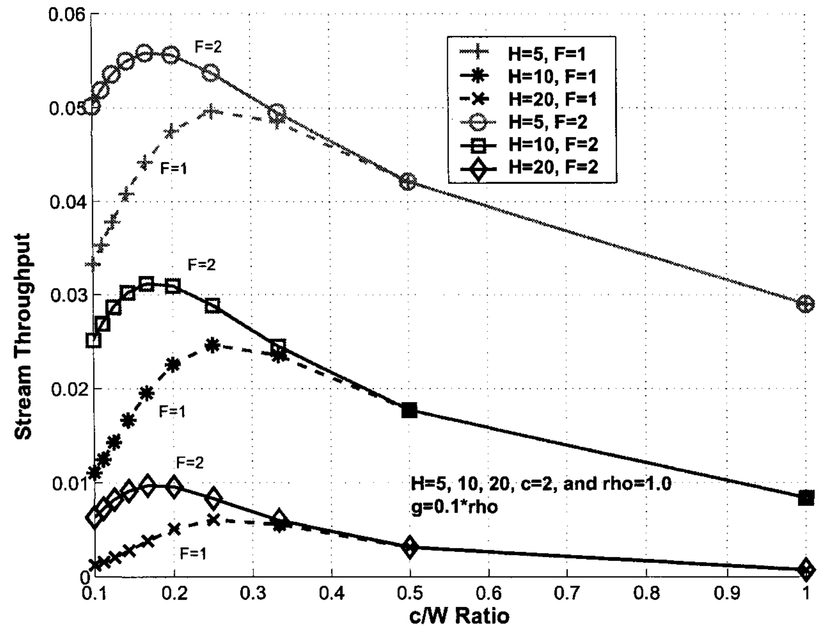

Figure 6.25: Throughput vs. c/W Ratio for Multi-Fiber Networks with $H=5,\ 10,20$

In Figures 6.26 and 6.27, the packet loss probability and the throughput are plotted as a function of network diameter respectively for a number of differently configured networks. We can see that the single-fiber network with $\rho = 0.6$, *w=4*, and *c=0* has the highest packet loss probability and the lowest throughput even though is has a lower offered load. This is because it does not employ wavelength conversion. A similar network with one wavelength converter, $\rho = 0.6$, *w=4*, and *c=1*, has far better performance due to the use of wavelength conversion. This emphasizes the prominent effects of wavelength conversion.

Considering the other two single-fiber networks with $\rho = 0.9$, we see that the network with $\rho = 0.9$, *w=12*, and *c=8* outperforms the network with $\rho = 0.9$, *w=24*, and *c=4* even though the later has more wavelength count. Looking back at the two networks, we see that the earlier operates at c/W around 33%, equivalent to full conversion, where the later operates at c/W of 16.66%. This difference is significant according to our earlier findings and explains why earlier network outperforms the later even though it has less wavelength count. This result also confirms that the effects of adding wavelength converter is more valuable as far as the performance goes than adding more wavelength. Even though the network with $\rho = 0.9$, *w=12*, and *c=8* is highly loaded comparing the $\rho = 0.6$ networks, it's throughput outperforms the $\rho = 0.6$ networks due to its higher c/W ratio.

We can see that the multi-fiber network with $\rho = 0.9$, *W=24*, *F=2*, and *c=4* has lower packet loss probability than the network with $\rho = 0.9$, *w=24*, *F=1*, and *c=4* because the advantages gained by introducing multiple fibers have increased the efficiency of the 4 converters in the earlier network. This confirms that the use of multi-fiber increases the operational efficiency of the wavelength conversion knowing that the c/W is the same for both systems due to the similar total wavelength count.

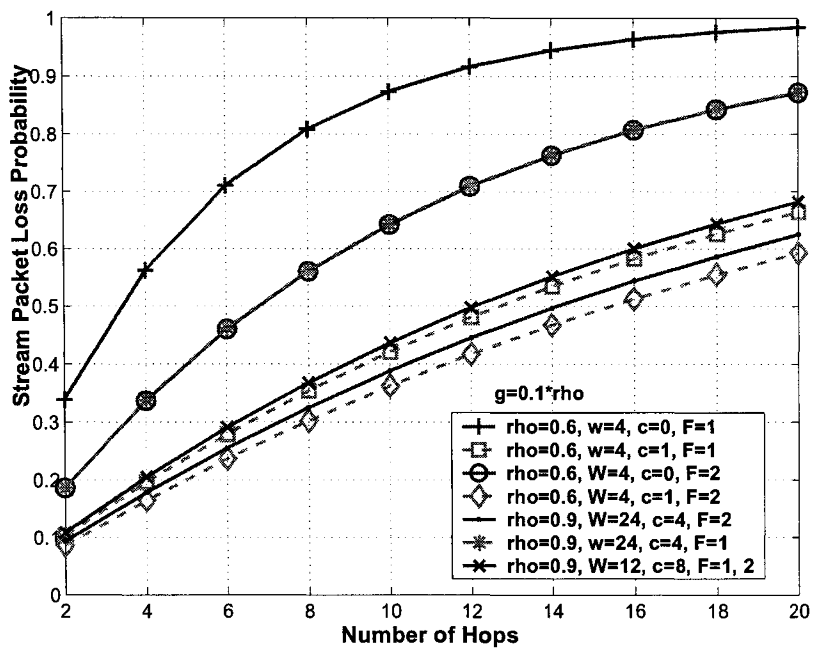

Figure 6.26: Packet Loss Probability vs. Network Diameter for Differently Configured Multi-Fiber networks Networks

If we look into $\rho = 0.9$, *w=12*, *F=1*, *c=8* single fiber network and $\rho = 0.9$, *W=12*, *F=2*, *c=8* multi-fiber network, we see that both behave the same indicating that they operate at c/W ratio higher than 33%. This notion is significant, according to our earlier findings; it sheds more light why the introduction of multiple fibers would not improve the performance if the system operates in the region that is equivalent to full wavelength conversion. We also see that the throughput of networks employing multiple fibers outperforms the throughput of single-fiber networks.

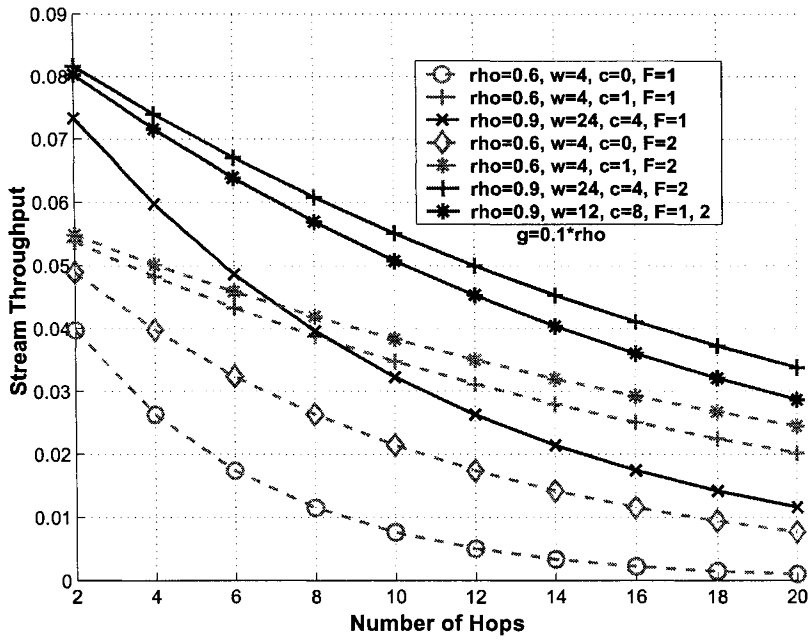

Figure 6.27: Throughput vs. Network Diameter for 4 Differently Configured Multi-Fiber Networks

Finally, we examine the performance gain for multi-fiber networks with different converter count and contrast them to similar single-fiber networks. In Figure 6.28, the performance gain is plotted as a function of offered load for *c=3, 4, 5, 6, 7*, *H=20*, and *W=20* for both kind of networks. Since these two kinds of networks are similar in every parameter except for the introduction of multiple fibers, we can see how the introduction of such fibers changes the performance. The performance of these networks is referenced to a network with full conversion. We can clearly see that the multi-fiber network with *c=6*, which has a *c/W* close to 33% is the closest to full conversion, where as all the other networks exhibit a declining performance with the increase of offered load for reasons explained earlier. It also shows that a single-fiber network with *c=7* come right after the multi-fiber network with *c=6* in terms of gain performance indicating that the introduction of multiple fiber increases the efficiency of the conversion resources even when the total number of wavelength and the total traffic traversing both systems are the same.

This graph shows that limited wavelength conversion with a c/W ratio in the vicinity of 33% is sufficient for these multi-fiber synchronous networks to perform as if they are equipped with full conversion. This means a significant cost reduction and architectural efficiency for the individual switches on the path between the source and destination.

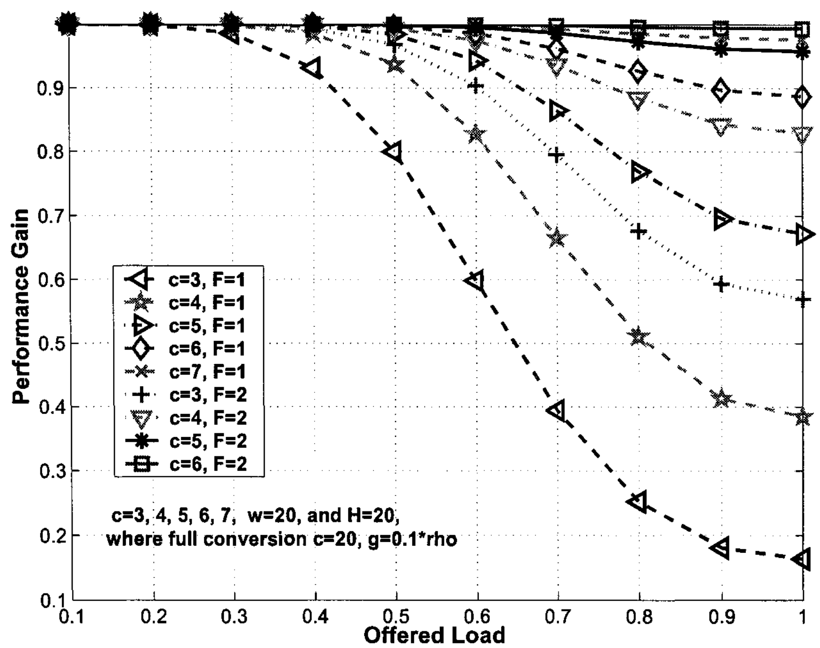

Figure 6.28: Performance Gain vs. Offered Load for Networks with *c=3, 4, 5, 6, 7*

6.6 Tradeoffs Analysis of Packet Switch Network Parameters

In this section, we will explore different performance aspects and tradeoffs related to optical packet-switched networks that employ multi-fiber share-per-link synchronous switch, which supports symmetric traffic. We have established that using multiple fibers enhances the performance of the optical packet switch. We have also established that such use of multi-fiber in the packet switched network would affect the performance in a way similar to a very limited wavelength conversion. It is essential to grasp the quantitative performance differences when using multiple fibers and limited wavelength conversion. Such insight would enable network designer to choose the scenario that fits the need of the specific network according to cost based tradeoffs, if available. Essential to such cost analysis is the operational comparison in terms of network performance. In this section, we examine how the introduction of wavelength converters affects the performance of the network under different offered load scenarios and then we study these effects with different fiber count per link to have an insight on how the fiber count affects the efficiency of wavelength conversion.

In Figure 6.29, the reduction of packet loss probability with the introduction of conversion resources is plotted as a function of number of wavelength converters for 10 single-fiber networks with $\rho = 0.1,.,1.0$, *F=1*, *W=36*, *c=0,., 12* for each network, and *H=10.* For each of these networks, the packet loss probability is obtained every time a converter is introduced. Then, the difference in of packet loss probability is calculated between before introducing a converter and after as shown in Tables 6.1 and 6.2. The aim is to have a feeling on how much each converter changes the packet loss performance. From the graph, we see that in lightly loaded networks, converters have significant effects and the introduction of converters would improve the packet loss performance dramatically, whereas for highly loaded networks, the introduction of converters changes the packet loss probability in an incremental fashion. That means the earlier ones and the very late ones have less effects on the packet loss probability than the ones introduced in the middle. This behavior is due to two different facts. First, the earlier converters are faced with high offered load and their contribution in reducing the packet loss probability is limited accordingly. Second, the lately introduced ones work in the region where the packet loss probability is already low and close to the $c/W=0.33$ region and accordingly, their contribution is also limited to the upper boundary of c/W, which characterizes the region that behaves comparable to full conversion. This gives an important insight on how conversion resources behave under different network offered load scenarios. Moreover, it is noticeable that the packet loss behavior for all considered networks converge at the point where $c=12$, which is around $c/W=0.33$ given $W=36$, which substantiate our finding in this research work.

ρ	C_0	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}	C_{12}
0.1	.28	.02	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
0.2	.49	.12	.02	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
0.3	.64	.30	.09	.02	.00	.00	.00	.00	.00	.00	.00	.00	.00
0.4	.74	.49	.24	.09	.03	.01	.00	.00	.00	.00	.00	.00	.00
0.5	.82	.65	.44	.24	.11	.04	.01	.00	.00	.00	.00	.00	.00
0.6	.87	.77	.61	.43	.26	.14	.06	.03	.01	.00	.00	.00	.00
0.7	.91	.85	.75	.61	.45	.30	.18	.09	.05	.02	.01	.01	.01
0.8	.94	.90	.84	.75	.63	.49	.35	.23	.15	.09	.07	.06	.06
0.9	.96	.93	.89	.84	.76	.66	.55	.43	.33	.26	.22	.21	.20
1.0	.97	.95	.93	.90	.85	.79	.71	.62	.55	.49	.46	.45	.45

Table 6.1: Packet Loss Probability of Different Networks with Different Converter Counts

As we mentioned in earlier observation, the employment of multiple sets of optical fiber increases the efficiency of wavelength conversion devices and therefore enhances the performance of the optical packet switch network. The effects of using multiple fibers on network performance would not be by any means comparable

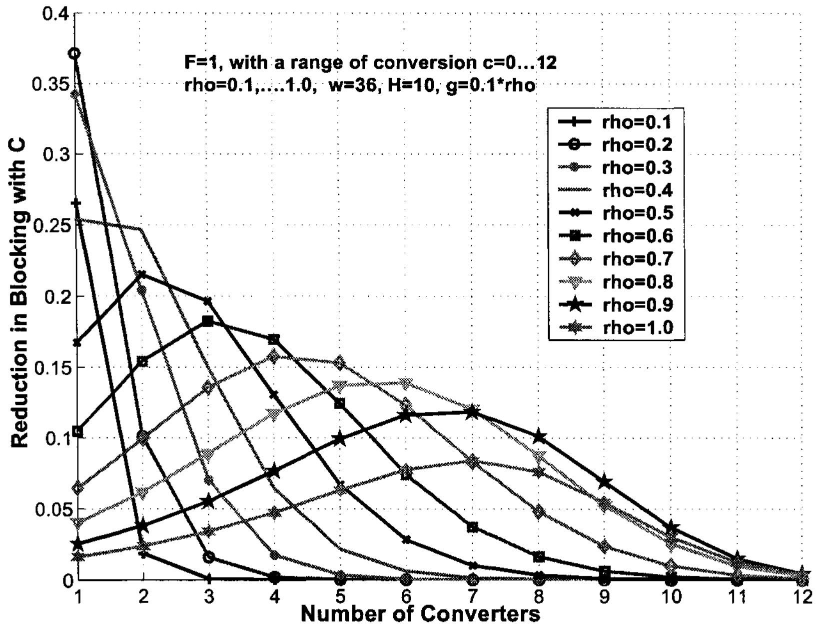

Figure 6.29: Reduction in Packet Loss probability with Conversion Recourses Introduction

to the use of wavelength conversion devices, even though it is considered as comparable to a very limited conversion. In other words, the increase of wavelength count or the increase of fiber count in the absence of wavelength conversion would not be feasible to reach network performance similar to full conversion. So, it is important to study the effects of using multiple fibers in the sense that it is an effective tool to enhance the efficiency of wavelength conversion resources.

In Figure 6.30, the reduction of packet loss probability with the introduction of one converter in the presence of different fiber counts is plotted as a function of offered load for 5 different networks with *F=1, 2, 4, 8, 16*, $W = w \cdot F = 64$, *c=0, 1*, and *H=10*. For example, for the single-fiber network, we run the network without wavelength conversion at a specific offered load and obtain the packet loss probability. Then, we do the same thing with the introduction of one wavelength converter. The difference between these values of packet loss probabilities would constitute the reduction in the packet loss probability with the introduction of one

ΔP_N / ρ	$P_0 - P_1$	$P_1 - P_2$	$P_2 - P_3$	$P_3 - P_4$	$P_4 - P_5$	$P_5 - P_6$
0.1	0.265	0.019	0.001	0.000	0.000	0.000
0.2	0.371	0.101	0.016	0.002	0.000	0.000
0.3	0.342	0.204	0.070	0.017	0.004	0.001
0.4	0.254	0.246	0.150	0.064	0.022	0.006
0.5	0.167	0.215	0.196	0.131	0.067	0.028
0.6	0.105	0.154	0.183	0.170	0.124	0.074
0.7	0.065	0.099	0.136	0.158	0.153	0.123
0.8	0.040	0.062	0.089	0.117	0.137	0.139
0.9	0.025	0.038	0.055	0.077	0.099	0.116
1.0	0.016	0.024	0.034	0.047	0.063	0.078

ΔP_N / ρ	$P_6 - P_7$	$P_7 - P_8$	$P_8 - P_9$	$P_9 - P_{10}$	$P_{10} - P_{11}$	$P_{11} - P_{12}$
0.1	0.000	0.000	0.000	0.000	0.000	0.000
0.2	0.000	0.000	0.000	0.000	0.000	0.000
0.3	0.000	0.000	0.000	0.000	0.000	0.000
0.4	0.001	0.000	0.000	0.000	0.000	0.000
0.5	0.010	0.003	0.001	0.000	0.000	0.000
0.6	0.037	0.016	0.006	0.002	0.001	0.000
0.7	0.083	0.048	0.024	0.010	0.003	0.001
0.8	0.120	0.087	0.053	0.025	0.010	0.003
0.9	0.118	0.101	0.069	0.037	0.015	0.004
1.0	0.084	0.076	0.055	0.030	0.012	0.004

Table 6.2: Reduction in Packet Loss probability with Conversion Recourses Introduction

converter at the specific offered load. We do the same procedure for the offered load, ranged form $\rho = 0.1$ to $\rho = 1.0$, and for the all different networks with *F=1, 2, 4, 8, 16*, keeping in mind that the total number of wavelength in each of these networks is *W=64*. Table 6.3 shows the data obtained by such procedure. The region where the introduction of one wavelength converter is most effective moves with the fiber count F and the offered load ρ. In networks with lower fiber counts, the introduction of conversion at lower offered load is more significant than higher offered load region, where as for networks with higher fiber counts, it is more significant to introduce wavelength conversion to the system at higher offered load regions. This says, for instance, in single-fiber networks, due to the lack of multiple fibers, the introduction of wavelength conversion would have a positive contribution at lower offered load. As for the high offered load region, the packet loss probability

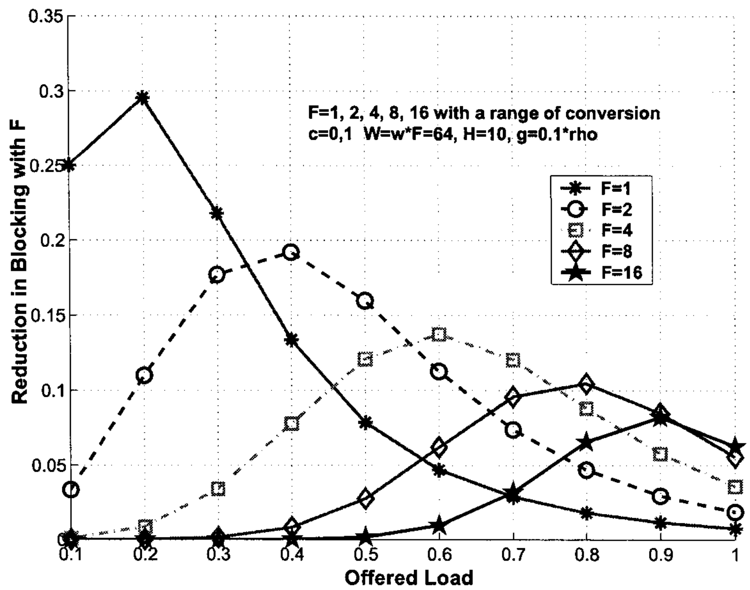

Figure 6.30: Effects of Using Wavelength Conversion in the Presence of Multiple Fibers

would be higher anyhow and such introduction of limited wavelength conversion would not change the performance significantly. As far for multi-fiber networks, the presence and the effects of multiple fibers would deal with the packet contention problem at lower regions of offered loads rather sufficiently, so the introduction of conversion resources would not be so essential. For higher offered load regions, such introduction of conversion resources would have a superior effect on the packet loss performance. This confirms our earlier claim that the use of multiple fibers would increase the efficiency of wavelength conversion.

Next, we examine different network parameters and relate their effects to packet loss performance of the optical packet switch network. The individual switch size along the path between the source and destination is a relevant issue to the over all performance of the optical packet switch network. In Figures 6.31 and 6.32, the packet loss probability and the throughput are plotted as a function of offered load respectively for a number of differently configured networks. In these figures, the switch size is characterized by the number of input/out links N, the

ρ	.1	.2	.3	.4	.5	.6	.7	.8	.9	1
$F = 1$										
P_0	.28	.49	.64	.74	.82	.87	.91	.94	.96	.97
P_1	.03	.19	.42	.61	.74	.83	.88	.92	.95	.96
$P_0 - P_1$	.25	.30	.22	.13	.08	.05	.03	.02	.01	.01
$F = 2$										
P_0	.03	.13	.25	.39	.52	.64	.74	.82	.87	.92
P_1	.00	.02	.08	.20	.37	.53	.67	.77	.85	.90
$P_0 - P_1$	.03	.11	.18	.19	.16	.11	.07	.05	.03	.02
$F = 4$										
P_0	.00	.01	.04	.10	.21	.34	.48	.62	.73	.82
P_1	.00	.00	.01	.03	.09	.20	.36	.53	.67	.79
$P_0 - P_1$	.00	.01	.03	.08	.12	.14	.12	.09	.06	.04
$F = 8$										
P_0	.00	.00	.00	.01	.04	.11	.22	.38	.55	.70
P_1	.00	.00	.00	.00	.01	.04	.13	.27	.46	.65
$P_0 - P_1$	.00	.00	.00	.01	.03	.06	.10	.10	.08	.06
$F = 16$										
P_0	.00	.00	.00	.00	.00	.02	.06	.18	.36	.57
P_1	.00	.00	.00	.00	.00	.01	.03	.11	.28	.51
$P_0 - P_1$	.00	.00	.00	.00	.00	.01	.03	.07	.08	.06

Table 6.3: The reduction of Packet Loss Probability with the Introduction of One Converter in the Presence of Different Fiber Counts

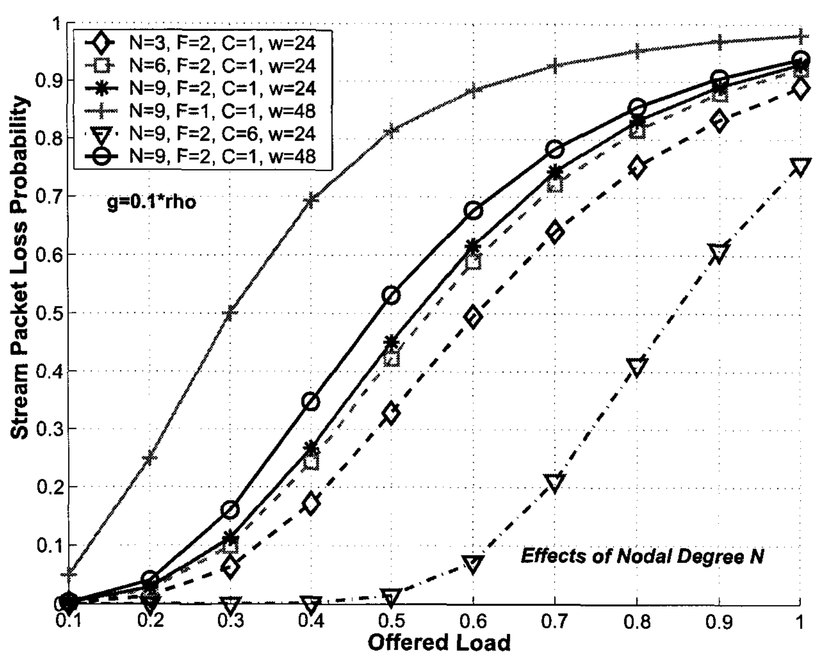

Figure 6.31: Switch Size Effects on Network Packet Loss Probability

number of fibers F in each link, and the number of wavelengths w in each fiber. We see that packet loss probability performance of the network with $N=3$, and $F=2$, $c=1$, and $w=24$ is better than the one with $N=6$, and $F=2$, $c=1$, and $w=24$. This is crude indication that larger switches on the path account for higher packet loss probability due to the larger traffic going through them. To look closer on the effects of N of each individual switch along the path, we consider the network with $N=9$, and $F=2$, $c=6$, and $w=24$ and the network with $N=9$, and $F=2$, $c=1$, and $w=48$. We see that the earlier outperforms all the networks considered in this graph, where as the later underperforms them all. This is because the earlier has less wavelengths per fiber and higher c/W ratio. By comparing these two networks to the earlier two, we can conclude that the effect wavelength conversion is superior to the effect of the switch size, even though the switch size determines the amount of traffic that goes through the network. Moreover, the switch size is a parameter that is not flexible for changes and accordingly is not considered as a tool to enhance the performance along the network. The throughput behavior of all of these networks is not strange to us by now. We see that the throughput declines after a certain point, which reminds us of a similar behavior explained earlier. We notice that the c/W ratio for all of these considered networks well below the 33% range. This fact makes the increasing offered load overcome the effects of the available wavelength converters. This is characterized by the declining throughput region where any remaining wavelengths, which would be able to use wavelength conversion due to the lack of such resources, are considered wasted resources.

6.7 Chapter Summary

In this chapter, we introduced an analytical model for synchronous optical packet-switching networks that employ multi-fiber share-per-link optical switch. Results obtained by the developed performance model for multi-fiber share-per-link

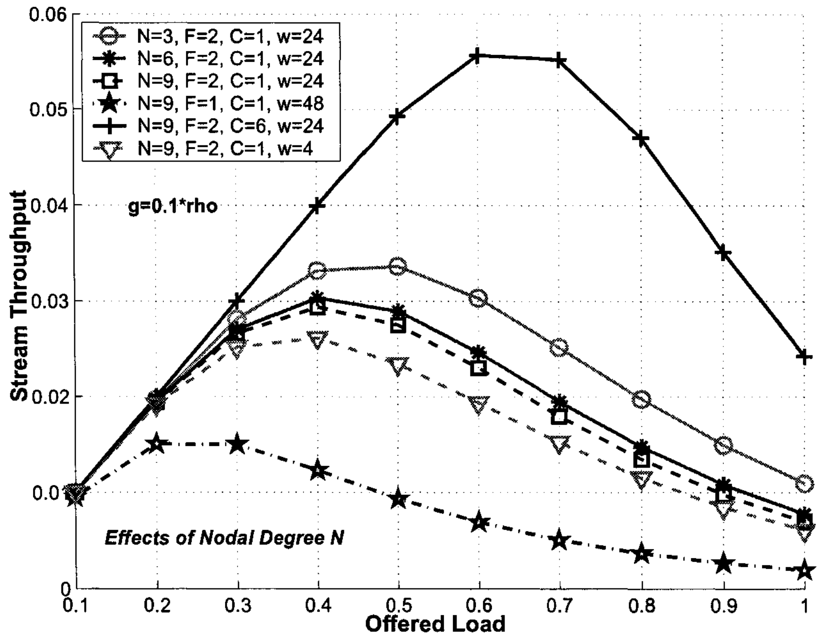

Figure 6.32: Switch Size Effects on Network Throughput

OPS network, which operates in a slotted mode, and the simulation model were analyzed for different network and switch parameters. The results showed that the packet loss probability decreases with the introduction of more wavelengths in the network, indicating that count is an important design factor in determining the over all performance of the network. The increase of wavelength count has positive effects on the performance even if it means more traffic competing for the network resources.

The packet loss probability of smaller diameter networks is lower than networks with higher hope count. The interesting observation is that the packet loss probability flattens at a point where the c/W ratio is around 33% regardless of the diameter of the network and regardless if it is a single-fiber of multi-fiber network. At the ratio of $c/W=0.33$, the network operates equivalently to the full conversion network. This indicates that the amount of performance improvement in packet loss probability due to the introduction of converters is independent of the network diameter, hop count *H*. The introduction of more converter beyond the $c/W{=}0.33$ would be considered wastage of important resources. It does not mater here if the network is single-fiber or multi-fiber, it is noticeable that even the single-fiber network behave as the multi-fiber after the $c/W{=}0.33$, which means that when a network reaches the region where it behaves as full conversion network, the fact that it uses multiple fibers would not add any significant improvement. The difference in the c/W ratio before the 33% in multi-fiber networks is considered an advantage in complementing the efficiency of the available conversion and serving higher traffic than single networks.

The throughput of the multi-hop fixed routing synchronous networks increases with the offered load till the effects of available converters are exhausted if these network operate in the region where c/W is less than 33%, which means that the available converters have a positive effect on the throughput till a certain point where the throughput is maximized. Then, this effect is overwhelmed by the increasing offered load causing the throughput to decline due to the lack of additional converters to deal with the increasing traffic. If the offered load was in the lower region, even the network with low value of c/W ratio would have similar performance as full conversion. The result showed that lightly loaded networks reach the point where the system behaves equivalent to full conversion network earlier than networks with higher offered load. This shows that the needed for converters in a given network is a function of how the network loaded. This indicates that the amount of performance improvement in packet loss probability due to the introduction of converters is dependent on the network load. This shows that limited conversion of 33% has a similar performance as full conversion at the highest possible offered load in the network indicating that the use of any additional wavelength converters would be considered wastage of resources and increases the cost of the network unnecessarily.

The results also showed that the network diameter has no effects on the point where the network imitate the behavior of full conversion system in the multi-fiber network case. According to this conclusion, we can say for certain that limited conversion of 33% is sufficient for full conversion no matter what the offered load is to accommodate the traffic in a similar manner to full conversion. We also confirm that in the multi-fiber setting, the need of converters is less to reach such point than single-fiber networks. Wavelength conversion has prominent effects on multi-fiber systems with lower offered load and less effect on networks with higher offer load. In networks with higher offered loads, the increasing traffic overwhelms the effects of converters, saturate the positive effects of conversion, faster than networks with lower offered loads.

From the results of this chapter, we can see that even though the c/W value that gives a comparable performance to full wavelength conversion network is the same for both single-fiber and multi-fiber networks, wavelength converters are more effective in the case of single-fiber networks than in the case multi-fiber networks. The introduction of conversion into single-fiber networks improves the performance significantly. The employment of multiple-fiber links in the network increases the efficiency of the conversion devices and accordingly the over all performance of the whole network. Earlier introduction of converters change the packet loss probability significantly relative to the ones introduced at later times. The employment of wavelength converters is far superior and more influential on the performance of the optical packet switch networks. In lightly loaded networks, converters have a significant effect and the introduction of converters would improve the packet loss performance dramatically, where as in highly loaded networks, the introduction of converters change the packet loss probability in an incremental fashion. The earlier converters are faced with high offered load and their contribution in reducing the packet loss probability is limited accordingly. The lately introduced ones work in the region where the packet loss probability is already low and close to the $c/W{=}0.33$ region and accordingly, their contribution is also limited to the upper boundary of c/W.

The effects of using multiple fibers on network performance would not be by any means comparable to the use of wavelength conversion devices, even though it is considered as comparable to a very limited conversion. In other words, the increase of wavelength count or the increase of fiber count in the absence of wavelength conversion would not be feasible to reach network performance similar to full conversion. The region where the introduction of one wavelength converter is most effective moves with the fiber count F and the offered load ρ. In networks with lower fiber counts, the introduction of conversion at lower offered load is more significant than higher offered load region, where as for networks with higher fiber counts, it is more significant to introduce wavelength conversion to the system at higher offered load regions. This says, for instance in single-fiber networks, due to the lack of multiple fibers, the introduction of wavelength conversion would have a positive contribution at lower offered load. As for the high offered load region, the packet loss probability would be higher anyhow and such introduction of limited wavelength conversion would not change the performance significantly. As far for multi-fiber networks, the presence and the effects of multiple fibers would deal with the packet contention problem at lower regions of offered loads rather sufficiently, so the introduction of conversion resources would not be so essential.

Chapter 7

PERFORMANCE ANALYSIS OF SYNCHRONOUS WDM SHARE-PER-LINK MULTI-FIBER PACKET-SWITCHED NETWORKS UNDER ASYMMETRIC TRAFFIC CONDITION

7.1 Introduction

In this chapter, we develop a performance model for multi-fiber share-per-link OPS network which operates in a slotted mode and services asymmetric traffic, the offered loads ρ_i applied on each of the N links in the switch nodes along the path are different from each other. One of the purposes for the asymmetric traffic model is to analyze the effect of load variation among the incoming/outgoing links of the synchronous optical packet switch networks. The effect of load variation on the performance behavior of the network is studied by introducing a method to measure such load variation among incoming links. The model that is proposed in this chapter is meant to overcome the earlier deficiency in the model proposed in chapter 6, where switch analytical model for the symmetric traffic considered the links along the path to be equally loaded. This deficiency in the symmetric traffic switch model behavior is to be adjusted and rectified in this chapter by the introduction of asymmetric traffic condition.

The results obtained due to asymmetric traffic condition would facilitate the work of network designer in choosing a scenario that fits the operational network conditions. It is important to consider such factor to adjust network performance according to network requirements. We have seen in chapter 6 that the individual switch parameter of the synchronous optical packet switch and network parameter such as network diameter are important design element and imperative for determining network performance and accordingly would be the basic element in trying to enhance performance. The study of the asymmetric distribution of offered load on the input links of each switch on the path will aid in envisioning a realistic network model.

7.2 Network Analytical Model based on Asymmetric Traffic Switch

In this section, we present a performance model for multi-fiber share-per-link OPS network with fixed routing algorithm which operates in a slotted mode and services asymmetric traffic, which means that the traffic of the input links are not the same as far as the offered load goes. An asymmetric OPS, which wee modeled in [3], employing share-per-link conversion resource with N inputs, coming from different sources, and destined to N outputs links, each consisting of F parallel fibers as shown in figure 6.1, is considered as the building block of the multi-hop networks with fixed routing algorithm that we intend to study in this work. The Network supports a *WDM* signal with w wavelengths per fiber. A total of $wF=W$ output wavelengths share a conversion bank of c converters. The incoming packets are synchronized at the inputs of every node before they processed. The packet length is assumed to be one time slot.

The number of packet arrivals at an output per wavelength i from each input j in every node in the path, at a given time slot, and destined to the output link under consideration follows the binomial distribution for $x=0...F$, i.e.,

$$P(X_{ij} = x) = \binom{F}{x} \cdot \left(\frac{\rho_{ij}}{N}\right)^{x} \cdot \left(1 - \frac{\rho_{ij}}{N}\right)^{F-x} \tag{7.1}$$

This means that in a given time slot, letting X_{ij} be a random variable representing the number of packets present at an output on λ_{ij} from input j, there are F copies of λ_{ij} at the input side of each switch on the path, so the maximum value that could be taken by X_{ij} is F, which happen when all packets arrived at the input on λ_{ij} are destined to same wavelength on the output under consideration. The minimum value of X_{ij} is *zero*, which means that there is no arrival on λ_{ij} at the inputs or none of the arrived packets are destined to that specific output link. The probability that a packet arrives at an input j in a given time slot is denoted by ρ_{ij}, which corresponds to the normalized offered load per wavelength per input. Packet arrivals per wavelength at different inputs are independent of each other. Also the number of packet arrivals on different wavelengths is *Identically and Independently Distributed*; $\{X_{ij}\}_{i=0}^{w}$ is *iid*.

For a given time slot, if the numbers of arrivals per wavelength, which are destined to the considered output, are more than NF packets, contention among them will occur. Per wavelength, F packets out of the contending ones leave the switch directly, one on each fiber. The rest of these packets are forwarded to the conversion bank that belongs to the output port under consideration. In model of asymmetric OPS we present in [3], we obtain the number of packets that can be forwarded to the conversion bank from a single wavelength by equation D.18 in Appendix D.

The number of rejected packets from different wavelengths and forwarded to conversion bank is identically independently distributed, *iid*. Let N_Y be a random variable representing the number of wavelengths received more than F packets, which need to be considered for conversion resources competition. N_Y could take any value between *zero* to W. When N_Y is equal to *zero*, it means that all arrived packets on all wavelengths can leave the switch without any conversion or none of the arrivals are destined to output port under consideration. If every wavelength on the output had received more than F packets, then N_Y will be equal to W. So the distribution of N_Y for $n_y = 0 \ldots W$ is as follows:

$$P\left(N_Y = n_y\right) = \binom{w}{n_y}\left(\sum_{i=F+1}^{N \cdot F} P(X=i)\right)^{n_y} \cdot \left(\sum_{i=0}^{F} P(X=i)\right)^{w-n_y} \tag{7.2}$$

Conditioned on N_Y, λ_i is available on the output link if the number of arrivals per λ_i is less than F packets per time slot, so these free $\lambda_i s$ need to be considered as available wavelengths that can be used to convert the contending packets to. The number of free λ_i out of F copies on the output port is calculated by equation D.22 in Appendix D. The number of packets, which can utilize conversion resources and leave the switch, depends on the minimum of the total available wavelengths on all fibers at the output and number of available conversion resources. Since the packet length is fixed, all converters are available at beginning of the time slot. Accordingly, the total number of wavelengths that are available on the output link after all direct packets are assigned to outgoing wavelengths is to be found.

B is defined as a random variable that represents the total number of available wavelengths in the out port and could take any value between *zero* and *F(w-ny)*. B equals to *zero* means every outgoing wavelength has at least F arrivals. In this case, all packets to the conversion bank are lost. In contrast, B equals to *F(w-ny)* when there are n_y wavelengths on the output, each having more than F arrivals, where the remaining *w-ny* wavelengths have *zero* arrivals. To find the available wavelengths on the output link for a given N_Y, the distribution of the total number of free wavelengths on the output link under consideration is given by:

$$P\left(B = \beta | N_Y = n_y\right) = \begin{cases} 0 & n_y = w \\ (d^{\beta}/dz^{\beta}) \cdot H_B(z)|_{z=0} & \text{otherwise} \end{cases} \tag{7.3}$$

The moment generating function $H_B(z)$ is calculated in equation D.26 in Appendix D.

The number of packets lost per time slot is equal to the difference between the total number of packets that need conversion and those that left the switch after utilizing converters from the conversion bank. For a given N_Y, the total number of packet that are directed to the conversion bank is equal to the summation of all rejected packets from all busy wavelengths as shown in equation D.29 in Appendix D. So, the maximum number of packets that can compete for conversion resources are *ny(NF-F)* where the minimum is n_y, which means that every wavelength considered in n_y has *F+1* arrivals. Accordingly, we calculate the average numbers of packets forwarded to the conversion bank, *E[T]*, which is equal to:

$$E[T] = \sum_{n_y=0}^{w} P(N_Y = n_y) \cdot (n_y \cdot E[Y]) \tag{7.4}$$

The average number of packets that are forwarded to the conversion bank per wavelength, *E[Y]*, is given by:

$$E[Y] = \sum_{j=1}^{N \cdot F - F} (j \cdot P(Y = j)) \tag{7.5}$$

If total number of $Y_i s$, n_y, is less than the minimum of available converters and free wavelength on the out put, all packets forwarded to the conversion bank will utilize the conversion resource and leave the switch without any loss. Accordingly, the average number of lost packets, *E[d]*, equals to *zero*. On other hand, if n_y is greater than the minimum of available converters and free wavelength on the out put, only the minimum of available converters and free wavelength determine the number of packets that can leave the switch through wavelength converters while the rest will be lost. So, in [2, 35, 36], we calculate the average packets that will utilize the conversion resources and leave the switch *E[A]* as shown in equation D.40 in Appendix D.

Now we can calculate the average number of packets that will be dropped, *E[d]*, as the difference between the average of total forwarded packets to conversion bank, *E[T]*, and the average accepted packets for conversion, *E[A]*.

$$E[d] = E[T] - E[A] \tag{7.6}$$

The average number of packet arrivals per wavelength on the output under consideration is equal to $F \cdot \rho_i$. So, the total expected arrival to the output link is given by:

$$E[\xi]_{asymmetric} = \sum_{i=1}^{N} \frac{w \cdot F \cdot \rho_i}{N} \tag{7.7}$$

Packet loss takes place when all $\lambda_i s$ are busy on all outgoing F fibers and the total number of packets forwarded to the conversion bank is greater than the minimum number of available converters and free wavelengths on the output. On the other hand, some of the rejected packets from direct connection can be served by utilizing the available wavelengths and leave the switch by getting converted to one of the available channels on the output, if there are available $\lambda_i s$ on the output port under consideration. The blocking probability of the switch, P_b, is then defined as the ratio of expected number of packet lost, *E[d]*, to the total number of arrivals of the output port i.e.:

$$P_b = E[d] / \sum_{i=1}^{N} \frac{w \cdot F \cdot \rho_i}{N} \tag{7.8}$$

As we mentioned earlier, the model proposed in this chapter deals with asymmetric traffic applied to the input side of the switch. This means that the ρ_i applied to the wavelengths in each of the N links are different from each other. The intention for this model is to study the effect of such load variation among the incoming and outgoing links of the synchronous optical packet-switching network and the ability of such network to tolerate traffic asymmetry, which is caused by the dynamic nature of the traffic in the network. In order to account for such behavior, we introduce a method to measure such load variation factor among the incoming link. The introduction of a new measure α helps in demonstrating how such load variation among the incoming link would affect the performance of the switch and accordingly the whole network. The total normalized load serviced by the switch L is the summation of the offer loads of all input links and shown as follows:

$$L = \sum_{i=1}^{N} \alpha^{i-1} \cdot \gamma \tag{7.9}$$

where α is the load variation measure, between all input links, and γ is the maximum load per input link. It is noticeable that when $\alpha = 1$, all the input links of the synchronous optical packet switch will have the same offered load of γ. This state describes the symmetric traffic condition studied in chapter 6. The offered load of any individual input link is given as follows:

$$\rho_i = \alpha^{i-1} \cdot \gamma \tag{7.10}$$

The network considered in this chapter is consistent with networks considered in Chapters 4 and 6. We examine multi-hop networks with fixed routing algorithm that has a collection of OPS nodes to study the effects of employing multiple fibers and determine the amount of conversion resources needed to obtain best performance. The model for the asymmetric multi-hop network obtains the packet loss probability along a path by:

$$P_{Network} = 1 - \prod_{j=1}^{H} \left[1 - \left(E[d]_j / \sum_{i=1}^{N} \frac{w \cdot F \cdot \rho_{ij}}{N} \right) \right] \tag{7.11}$$

where H denotes the number of hops along a path. We can clearly see that this model accounts for the packet loss probability for all the uniquely configured asymmetric optical packet switches along the path between the source and destination. Each switch can be configured individually and the packet loss in each node would be reflected on the following output link, which in turn results in a more realistic scenario.

7.3 Result Analysis for Asymmetric Packet-Switched Networks

This chapter deals with asymmetric traffic applied to the input side of each switch on the path, which means that the ρ_i applied to the wavelengths in each of the N links are different from each other. The intention is to study the ability of the synchronous optical packet-switching network to tolerate traffic asymmetry. In order to account for such behavior, we introduced, in the pervious section, a method to measure such load variation among the incoming links. The introduction of this measure, α in equation 7.9, helps understanding the effect of such factor in a network setting. For the results in this chapter, the background traffic with an offered load of ρ_i is different for each link and relate to each other according to the total normalized load serviced by the switch L, which is the summation of the offer loads of all input links and shown as 7.9. The source-destination stream offered load of $g = 0.1 \cdot \rho i$. The intention is to study the packet loss probability of a multi-hop fixed routing OPS network that consists of a number of nodes H and the effect of load variation on the behavior of such network.

In Figure 7.1, the packet loss probability is plotted as a function of α factor for 8 different networks with different total offered load L. These networks have a common configuration of *H=20*, *W=F*w=16* and *C=0.* As defined in equation 7.9, the α value for link load variation for a network with *N=3* and *L=1.0* is shown in Table 7.1. Four differently loaded networks of *L=1.0, 1.2, 1.5, 1.8* and *N=3, 4*, where L is the total load per switch along the path, the possible rage of α is tested to have an insight on the effect of such factor. Similar total number of wavelengths W is used for these networks. The network with *L=1.0* and *N=3* shows that it has the lowest packet loss probability when the offered loads on its input links are most varied (lowest α factor value) and has the highest packet loss probability when the offered loads on the input links are equal (the symmetric

α	ρ_1	ρ_2	ρ_3	P_N
0.000	1.000	0.000	0.000	0.000
0.050	0.950	0.048	0.002	0.274
0.101	0.900	0.091	0.009	0.458
0.153	0.850	0.130	0.020	0.586
0.207	0.800	0.166	0.034	0.676
0.264	0.750	0.198	0.052	0.740
0.324	0.700	0.227	0.073	0.786
0.388	0.650	0.252	0.098	0.820
0.457	0.600	0.274	0.126	0.846
0.534	0.550	0.293	0.157	0.864
0.618	0.500	0.309	0.191	0.878
0.713	0.450	0.321	0.229	0.887
0.823	0.400	0.329	0.271	0.893
0.952	0.350	0.333	0.317	0.896
1.000	0.333	0.333	0.333	0.896

Table 7.1: Link Load Variation

traffic scenario). A similar network with $L=1.0$ and $N=4$ shows that it has a lower packet loss probability than the previous network due to the greater freedom it has in varying the offered loads on the input links, which means that it has a greater range of α. The network with $L=1.8$ and $N=3$ shows that it has the highest packet loss probability and the most limited range of α among the tested networks. It also shows that whenever the total load L is closer to the upper limit of such value, $L=3$ for network switching elements with $N=3$, the range of α narrows and the packet loss probability increases. It also means that the variation in the input offered load on the input links would be limited and accordingly its effects on the packet loss probability would diminish.

It is interesting to notice that networks with lightly loaded nodes along the path has a wider range of α, whereas networks with highly loaded nodes along the path have a limited range of α. This means that lightly loaded networks has more freedom with respect to the α factor, where the load variation among the input links can vary more. It is noticeable from the graph that when the

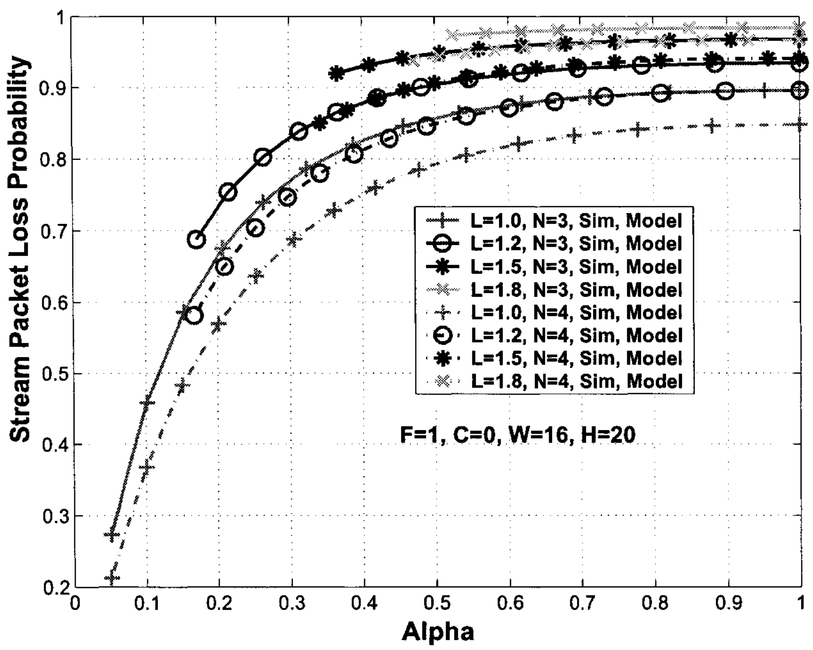

Figure 7.1: Range of α for differently loaded networks.

switching nodes have a higher nodal degree, they would have a wider range for the α factor, if same total load L is considered. From this graph we can say that for highly loaded networks, the limited freedom of the α factor would limit its effect on the performance of the network whereas networks that have lightly loaded switching nodes can benefit more from the change in α factor. When $\alpha = 1$, the resulting packet loss probability behavior is considered as the lower boundary of network performance with respect to this factor. Accordingly, the symmetric traffic switch model introduced in chapter 6 characterized the lower boundary of performance with respect to α factor. From the graph, we notice that the difference of performance for the different values of α is not drastic for highly loaded networks, which indicates that this factor is not that prominent as far as its effects on network performance go unless the network is lightly loaded.

In Figures 7.2 and 7.3, the packet loss probability is plotted as a function of α factor for 8 different single-fiber networks with different wavelength conversion

α	$P_{N_c=0}$	$P_{N_c=1}$	$P_{N_c=2}$	$P_{N_c=3}$	$P_{N_c=4}$	$P_{N_c=5}$	$P_{N_c=6}$
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0501	0.2737	0.0124	0.0003	0.0000	0.0000	0.0000	0.0000
0.1009	0.4584	0.0440	0.0022	0.0001	0.0000	0.0000	0.0000
0.1530	0.5858	0.0871	0.0065	0.0004	0.0000	0.0000	0.0000
0.2071	0.6755	0.1358	0.0134	0.0009	0.0001	0.0000	0.0000
0.2638	0.7397	0.1855	0.0225	0.0019	0.0001	0.0000	0.0000
0.3238	0.7863	0.2334	0.0333	0.0034	0.0003	0.0000	0.0000
0.3880	0.8204	0.2775	0.0451	0.0052	0.0005	0.0000	0.0000
0.4574	0.8456	0.3165	0.0571	0.0072	0.0007	0.0001	0.0000
0.5335	0.8642	0.3498	0.0687	0.0094	0.0010	0.0001	0.0000
0.6180	0.8777	0.3770	0.0790	0.0115	0.0014	0.0002	0.0000
0.7134	0.8871	0.3978	0.0875	0.0133	0.0016	0.0002	0.0000
0.8229	0.8931	0.4118	0.0936	0.0146	0.0019	0.0002	0.0001
0.9516	0.8958	0.4184	0.0965	0.0153	0.0020	0.0002	0.0001
1.0000	0.8960	0.4189	0.0968	0.0154	0.0020	0.0002	0.0001

Table 7.2: Packet Loss Probabilities for Networks with Different Wavelength Conversion Capabilities

capabilities, C=*0, 1, 2, 3, 4, 5, 6, 7*. These networks have a common configuration of $H=20$, $W=F*w=16$, $F=1$, $N=3$, and $L=1.0$. The packet loss probabilities for networks with different wavelength conversion capabilities are shown in Table 7.2 for different values of α factor, link load variation.

We can see from Figures 7.2 and 7.3 that networks with lower count of wavelength converters have higher packet loss probabilities whereas networks with higher counts of wavelength converters have lower packet loss probabilities. It also can be seen that the effect of the α factor is more evident in networks with lower counts of wavelength converters. The fact that wavelength conversion enhances the performance of the network and increases the efficiency of the optical resources limits the effects of changing α factor on performance. The change of the α factor has more effects on the packet loss probability performance when the network has no wavelength conversion capabilities or when it has a low C/W ratio. We also can see that the networks with $C=6$ and $C=7$ have almost similar

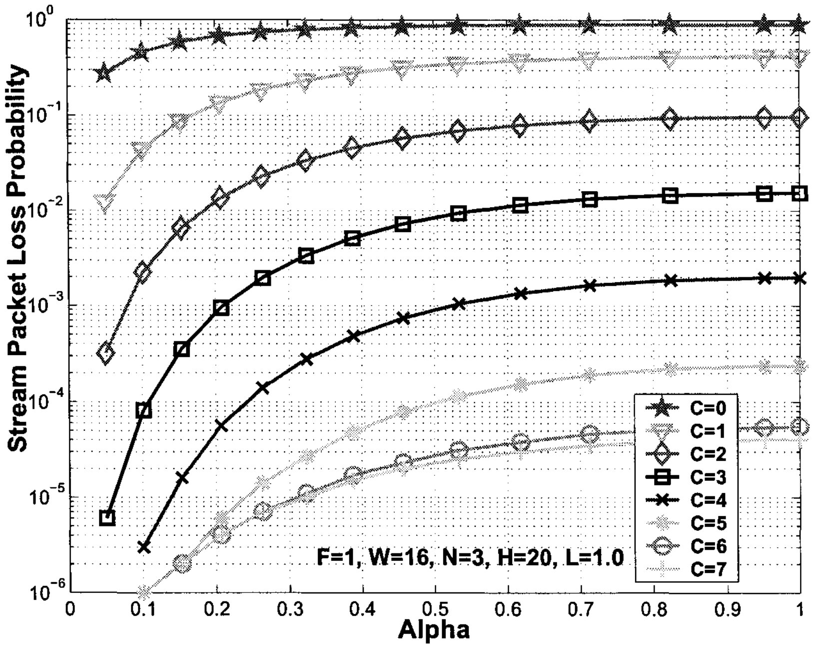

Figure 7.2: Packet Loss Probability vs. α for Networks with Different Wavelength Conversion Capabilities in Log Scale.

packet loss performance due to the fact that these networks operate beyond the *C/W=0.33* region. It is worth noting that the packet loss probability for networks that operate beyond the *C/W=0.33* point do not completely imitate the full conversion packet loss behavior but the difference is within 10^{-1} and 10^{-3} range, which is considered as close as possible to the packet loss behavior of systems with full conversion. Acknowledging such small difference, we consider systems within 10^{-1} and 10^{-3} range as equivalent to full conversion systems.

In Figures 7.4 and 7.5, the packet loss probability is plotted as a function of α factor for 5 different Multi-fiber networks with different wavelength conversion capabilities, *F=1, 2, 4, 8, 16.* These networks have a common configuration of *H=20*, *W=F*w=16*, *C=0*, *N=3*, and *L=1.0.* The packet loss probabilities for different multi-fiber are shown in Table 7.3 for different values of α factor. The

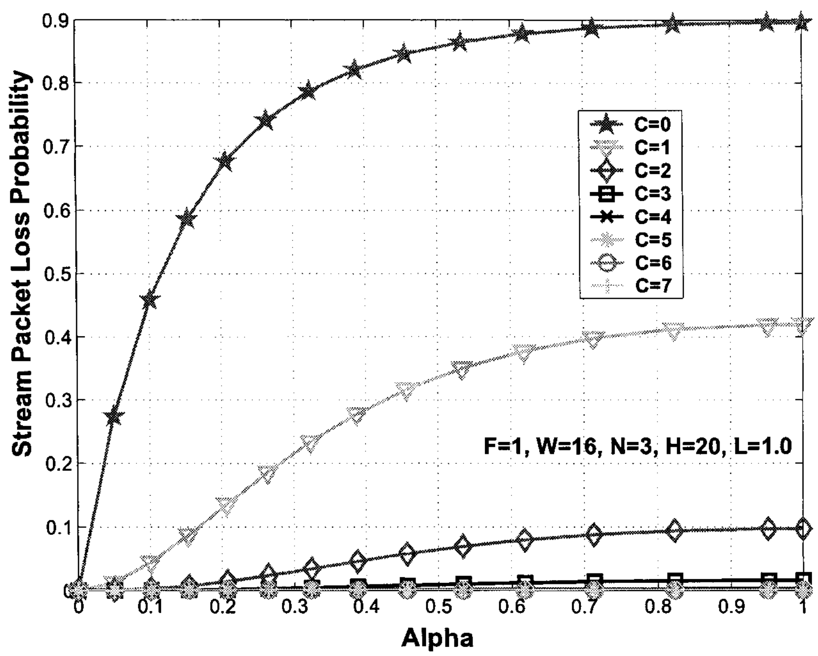

Figure 7.3: Packet Loss Probability vs. α for Networks with Different Wavelength Conversion Capabilities in Linear Scale.

purpose is to explore the effects of such factor on the performance of the multi-fiber networks.

Analogous to conclusion made for the earlier graph, in Figures 7.4 and 7.5, we can see that networks with lower fiber count have higher packet loss probabilities whereas networks with higher counts of fibers have lower packet loss probabilities. It also can be seen that the effect of the α factor is more evident in networks with lower counts of fiber, when the total load is similar. We have seen in Chapter 6 that multi-fiber networks exhibit higher performance due to the flexibility they offer in terms of serving the optical traffic. Such flexibility limits the effects of load variation, α factor. So, like the networks with higher wavelength converter counts, networks with higher fiber counts per link also are less susceptive to be affected by the load variation factor measured by α. We also see that such factor would have drastic effects on systems with lower fiber or wavelength converter counts.

α	$P_{N_{F=1}}$	$P_{N_{F=2}}$	$P_{N_{F=4}}$	$P_{N_{F=8}}$	$P_{N_{F=16}}$
0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
0.050120	0.273652	0.099212	0.012280	0.000229	0.000000
0.100925	0.458380	0.179068	0.024415	0.000594	0.000000
0.153047	0.585847	0.244482	0.036323	0.001071	0.000002
0.207107	0.675525	0.298763	0.047879	0.001637	0.000004
0.263763	0.739694	0.344197	0.058942	0.002267	0.000007
0.323754	0.786263	0.382383	0.069368	0.002937	0.000010
0.387954	0.820422	0.414449	0.079013	0.003619	0.000015
0.457427	0.845627	0.441185	0.087733	0.004286	0.000020
0.533529	0.864196	0.463121	0.095381	0.004910	0.000025
0.618034	0.877683	0.480584	0.101805	0.005461	0.000030
0.713352	0.887104	0.493718	0.106840	0.005911	0.000035
0.822876	0.893061	0.502489	0.110304	0.006229	0.000038
0.951600	0.895803	0.506660	0.111979	0.006385	0.000039
1.000000	0.895991	0.506950	0.112097	0.006396	0.000040

Table 7.3: Packet Loss Probabilities for Different Multi-Fiber Networks

That means that such systems are more susceptive to be affected by load variation. The dynamic nature of the optical traffic tells us that the load variation among links would be also dynamically changing and that the packet loss performance of networks with limited contention resolution resources are to be greatly affected by such dynamic changes in the load variations among the optical links. It is very interesting and worthy to note that when the fiber count is very high, when each fiber has one wavelength given that the total wavelength count is preserved, the network system behaves like a network with full wavelength conversion. More precisely, the packet loss behavior of such system is within 10^{-1} and 10^{-3} range. Such configuration is not practical as explained in the pervious chapter.

In Figure 7.6, the packet loss probability is plotted as a function of C/W ratio for a number of single-fiber networks with different values for α. These networks have a common configuration of H=*20*, $W=F^*w$=*16*, F=*1*, N=*3*, and L=*1.0*. The packet loss probabilities for networks with different wavelength conversion capabilities are shown in Table 7.2 for different values of α factor, link load variation.

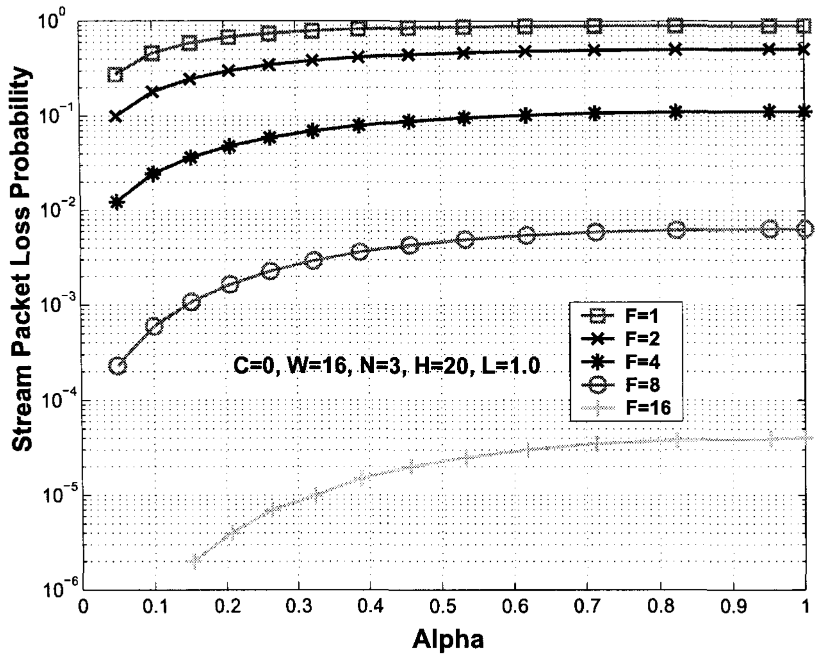

Figure 7.4: Packet Loss Probability vs. α for Different Multi-Fiber Networks in Log Scale.

From this graph, we can see that networks with lower α value, offered loads on input links are greatly varied, tends to have a lower packet loss probabilities confirming the earlier results whereas networks with higher values for α tend to have higher packet loss probabilities. The increase in C/W ration improves the packet loss performance till a point where a network behaves as a network with full conversion, where the packet loss performance is within 10^{-1} and 10^{-3} range of full conversion. Such point is reached with lower counts of wavelength converters for networks that have lower values of α factor whereas networks with higher values of α require more wavelength converters to reach such point. This means that the dynamically changing nature of the optical traffic also affects the efficiency of wavelength conversion.

In Figures 7.7 and 7.8, the packet loss probability is plotted as a function of number of fibers per link along the path for 6 different Multi-fiber networks with

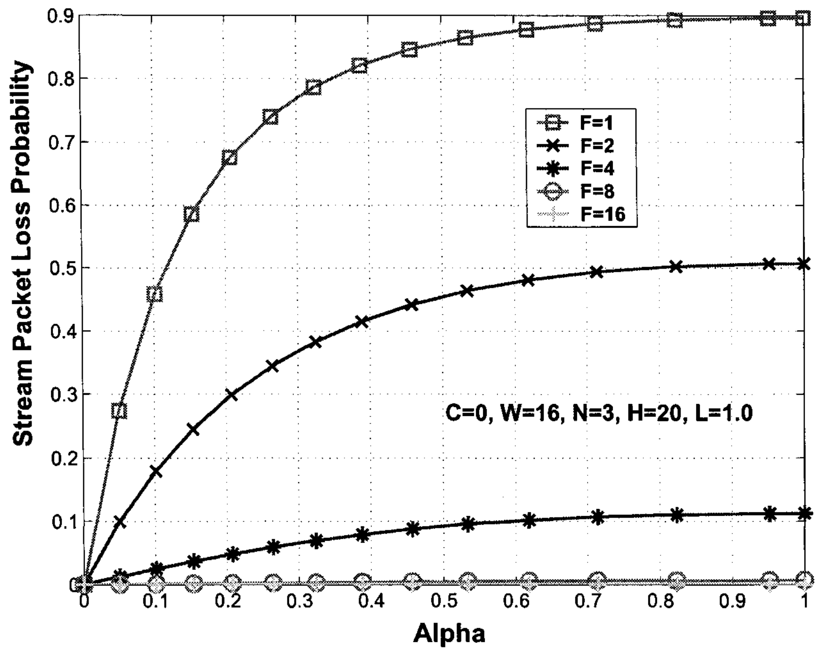

Figure 7.5: Packet Loss Probability vs. α for Different Multi-Fiber Networks in Linear Scale.

different α factor value. These networks have a common configuration of *H=20*, *W=F*w=16*, *C=0*, *N=3*, and *L=1.0*. The packet loss probabilities for different multi-fiber are shown in Table 7.4 for different values of α factor. In these two figures, it can be seen that networks with lower values of α have lower packet loss probabilities than networks with higher values for the α factor. The packet loss probability decreases with the introduction of more fibers into the system. From the linear graph, we can see that the few earlier fibers have more effects on the packet loss probabilities than the ones introduced later. This confirms the conclusion we reached in Chapter 6.

In later figures, we explore the effects of introducing fiber/wavelength converter resources on the packet loss performance of optical packet-switching network. In Figures 7.9 and 7.10, the packet loss probability is plotted as a function of the α factor for 8 different networks. These networks have a common configura-

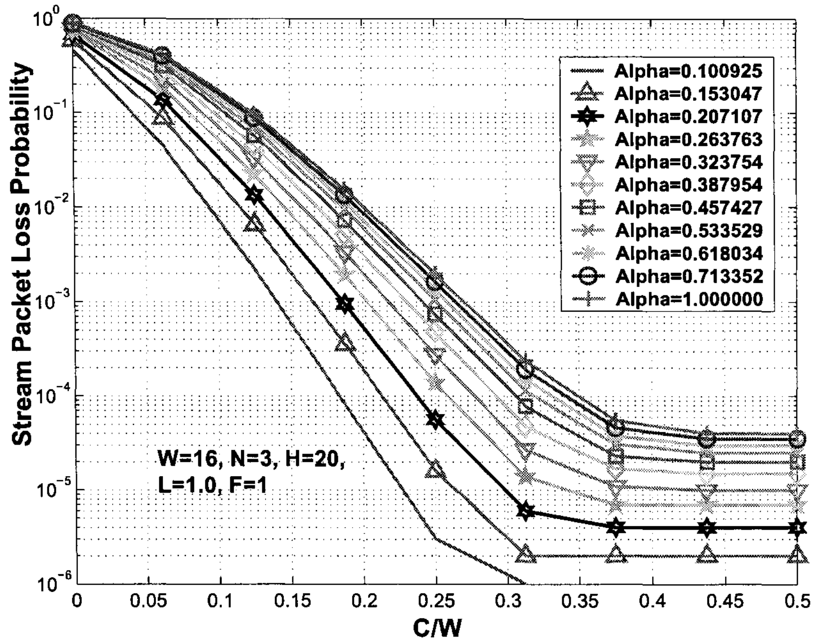

Figure 7.6: Packet Loss Probability vs. C/W ratio for Networks with Different Values of Load Variation Factor α.

tion of *H=20*, *W=F*w=16*, and *N=3*. We tested 4 different networks with *L=1.0, 1.2, 1.5, 1.8* by introducing one wavelength converter or introducing an extra fiber into the network system. The intention is to comparatively study the effects of introducing one wavelength converter and introducing an additional fiber. From the figures, we can clearly see that for all the networks considered, the α factor is not of an importance for highly loaded networks whereas lightly loaded networks' behavior change according to the load variation among the input links. It also shows that the introduction one wavelength converter improves the performance more significantly in lightly loaded networks than the introduction of an extra fiber. This is not the case for highly loaded networks. In highly loaded networks, the performance when adding an extra fiber is almost the same to the effects of introducing a wavelength converter.

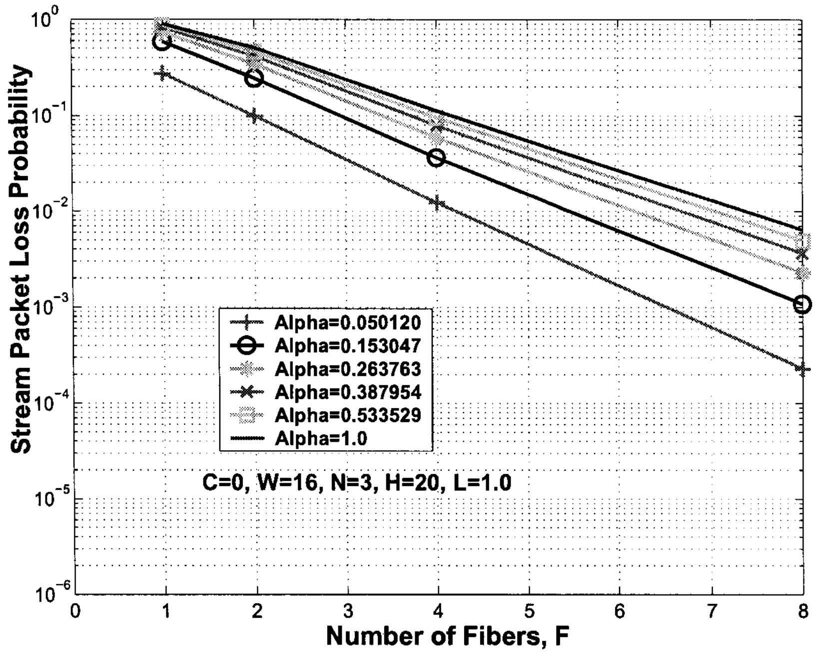

Figure 7.7: Packet Loss Probability vs. Number of Fibers in Log Scale.

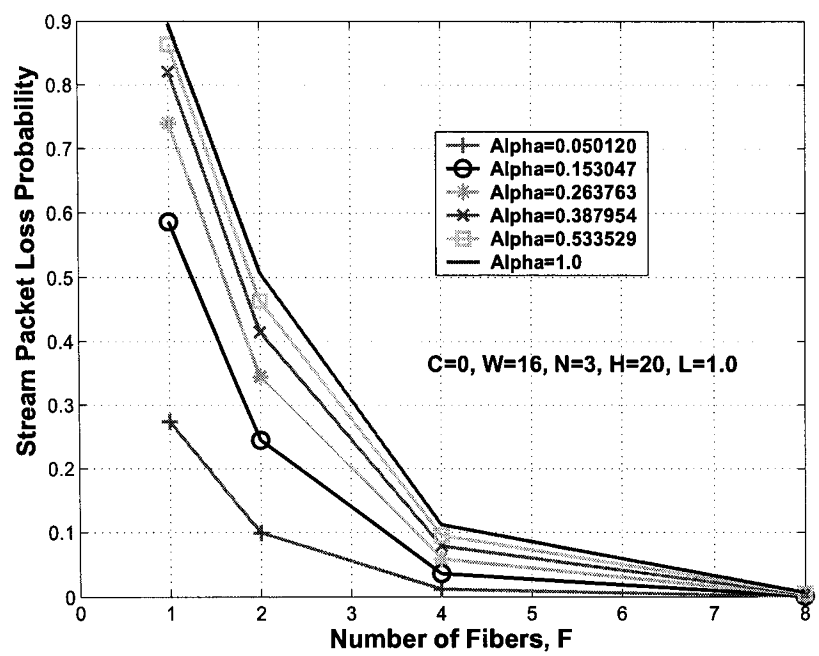

Figure 7.8: Packet Loss Probability vs. Number of Fibers in Linear Scale.

α	$P_{N_{F=1}}$	$P_{N_{F=2}}$	$P_{N_{F=4}}$	$P_{N_{F=8}}$
0.0501	0.2737	0.0992	0.0123	0.0002
0.1530	0.5858	0.2445	0.0363	0.0011
0.2638	0.7397	0.3442	0.0589	0.0023
0.3880	0.8204	0.4144	0.0790	0.0036
0.5335	0.8642	0.4631	0.0954	0.0049
1.0000	0.8960	0.5070	0.1121	0.0064

Table 7.4: Packet Loss Probabilities for Different Multi-Fiber Networks with Different Load Variation Factor (α)

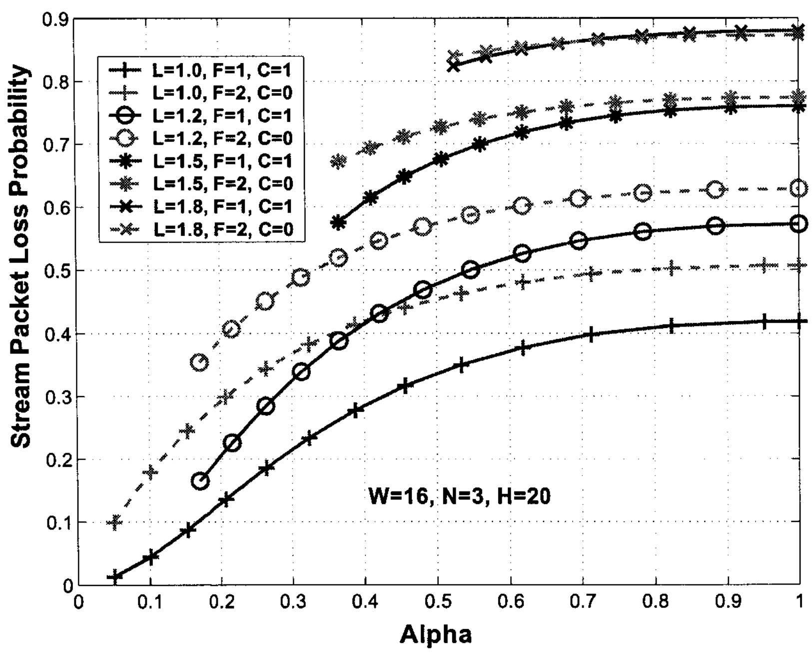

Figure 7.9: Packet Loss Probability vs. α for Differently Configured Networks (Linear Scale).

The earlier result showed that the performance when adding an extra fiber is almost the same as the effects of introducing a wavelength converter in highly loaded networks. This raises a question of which is a better solution when it comes into resolving packet contention in highly loaded networks if both, the introduction of one wavelength converter and the introduction of an extra fiber, would result in a similar performance behaviors? To answer such question and to verify our earlier

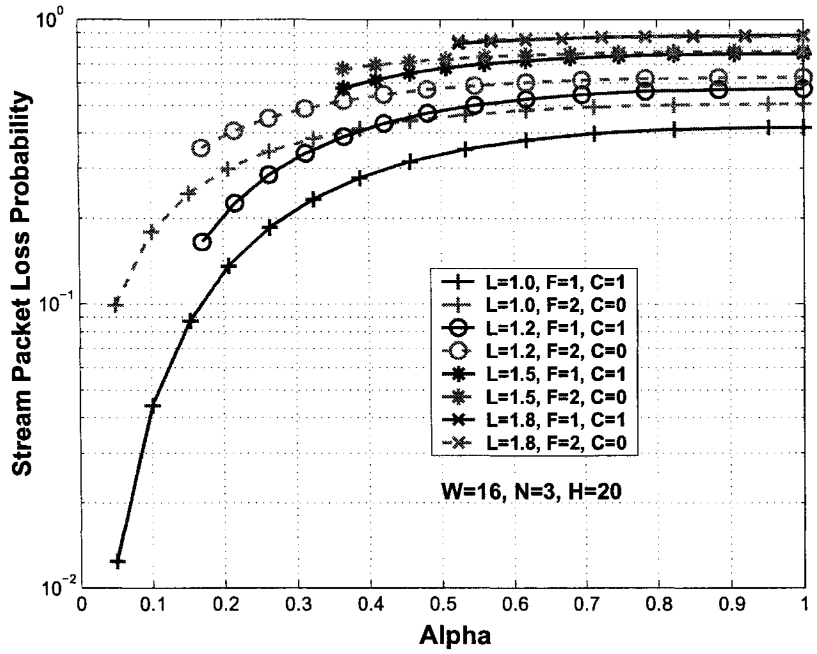

Figure 7.10: Packet Loss Probability vs. α for Differently Configured Networks (Log Scale).

conclusions in Chapter 6, we tested the earlier networks when introducing 3 wavelength converters and adding 3 extra fibers. Figure 7.11 shows that introducing 3 converters results in a far better performance than the introduction of 3 extra fibers both in lightly and highly loaded networks. This confirms that wavelength conversion is more effective in resolving packet contention.

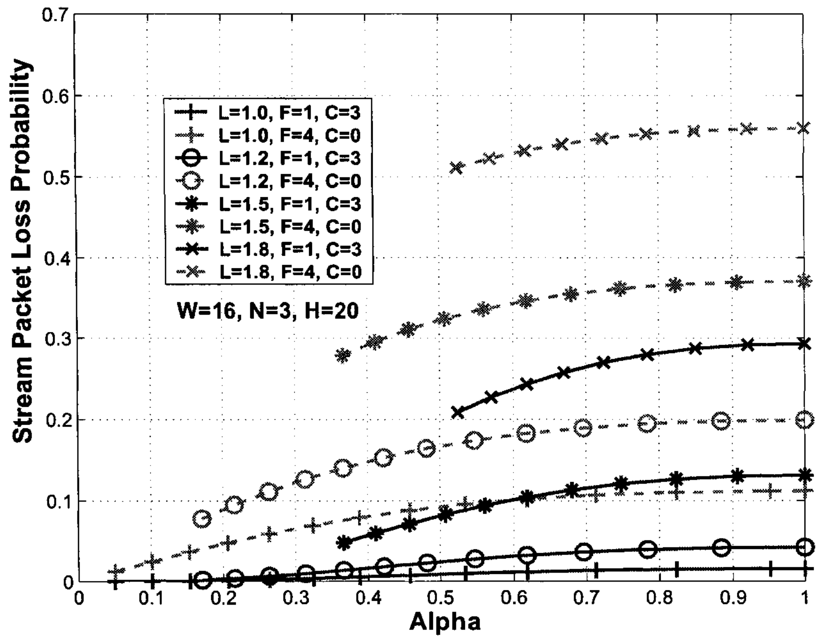

Figure 7.11: Packet Loss Probability vs. α for Networks with Higher Counts of Fibers/Wavelength Converters.

7.4 Chapter Summary

In this section, we have introduced a more realistic scenario for the share-per-link synchronous optical packet-switching networks, where each node along the path serves asymmetric traffic, which means that the ρ_i applied to the wavelengths in each of the N links are different from each other. The asymmetric traffic condition is due to the dynamic traffic nature of the optical core. This realistic scenario raised the question of how this load variation among the input links would affect the performance behavior of the network. In order to account for such behavior, we introduced a method to measure such load variation among the incoming links and accordingly relate such factor to network performance. The introduction of this measure, α in equation 7.9, helped in understanding the effects of such factor in a network setting. It is important to note that the load variation factor is of no use to actively influence the behavior of the network because the factor dynamically changes according to the dynamically changing nature of the network. This means that load variation offers a limited controllability for the purpose of network control. It is still an important factor to study in the sense of its effects on network parameters and resources. We have seen that this dynamically changing load variation factor has a non-negligible effect on wavelength conversion resource. In this study, we referenced such factor (α) to the total load (L) served by each node along the path. Accordingly, we came to a number of important conclusions that help us in envisioning the behavior of the synchronous optical network.

It has been shown that networks with lightly loaded nodes along the path has a wider range of α, whereas networks with highly loaded nodes along the path have a limited range of α. This meant that lightly loaded networks has more freedom with respect to the α factor, where the load variation among the input links can vary more. Networks with switching nodes that have a higher nodal degree would have a wider range for the α factor, if same total load L is considered. When $\alpha = 1$, the resulting packet loss probability behavior is considered as the lower boundary of network performance with respect to this factor. Accordingly, the symmetric traffic switch model introduced in chapter 6 characterized the lower boundary of performance with respect to α factor. The difference of performance for the different values of α is not drastic for highly loaded networks, which indicates that this factor is not that prominent as far as its effects on network performance go unless the network is lightly loaded.

The effect of the α factor is more evident in networks with lower counts of wavelength converters. The fact that wavelength conversion enhances the performance of the network and increases the efficiency of the optical resources limits the effects of changing α factor on performance. The change of the α factor has more effects on the packet loss probability performance when the network has no wavelength conversion capabilities or when it has a low C/W ratio. The effect of the α factor is more evident in networks with lower counts of fiber. This means that networks with higher fiber counts per link are less susceptive to be affected by the load variation factor measured by α. As we mentioned earlier, the dynamic nature of the optical traffic tells us that the load variation among links would be also dynamically changing and that the packet loss performance of networks with limited contention resolution resources are to be greatly affected by such dynamic changes in the load variations among the optical links. The increase in C/W ration improves the packet loss performance till a point where a network behaves as a network with full conversion. Such point is reached with lower counts of wavelength converters for networks that have lower values of α factor whereas networks with higher values of α require more wavelength converters to reach such point. This means that the dynamically changing nature of the optical traffic also affects the efficiency of wavelength conversion.

Chapter 8

NETWORK SIMULATORS

8.1 Introduction

Optical network simulation model is an essential tool that provides a mechanism for studying the dynamic behavior of such networks to characterize system performance. It facilitates researchers with a way to analyze the behavior of optical networks without the expense of building a real one. Optical network simulator is used as a behavior verifying tool by simulating various network configurations and traffic loads, and obtaining statistics such as utilization of network links, call blocking/packet loss and throughput rates. It can be used to answer questions such as: what would be the performance conditions of the networks given a set of operational conditions?; what is the effective way of maximizing network performance?; or is the analytical model successful in representing the behavior of the network? For example, such as with our study, researchers can investigate the effectiveness of various optical resources allocation mechanisms for optical networks and address such issues as mechanisms for fast allocation, performance optimization, and bandwidth utilization. Optical network simulation models do not require as many assumptions as required by analytical models. This leads to a closer emulations to real life network, and accordingly used as a benchmarking tool for such models.

Our research work involves the implementation of a number of different discrete event simulators, which are developed to evaluate the performance of different optical network scenarios considered in different chapters of this dissertation.

These simulators were written in C++ computer language as independent modules, which make them easy to modify and more flexible to test the individual module as stand alone program.

8.2 General Network Simulation Model

The network model in this study consists of a number of access stations attached to a group of optical nodes. Each access station has at least one optical transmitter and one optical receiver as well as optoelectronic interface to the user(s). The physical topology of the WDM optical networks consists of optical nodes, interconnected by point-to-point fiber links in a linear topology. In single-fiber networks, each wavelength on one link can support one lightpath at the most. Lightpaths using the same wavelength cannot share any link. However, in multi-fiber networks, lightpaths using the same wavelength can share common links, as long as they can be accommodated on different fibers. Wavelengths are assigned to the transmitters and receivers creating several independent channels all of which are multiplexed onto the optical fiber defining the logical connectivity among the nodes. In this architecture, the use of wavelength multiplexers provides the advantage of higher aggregate system capacity due to the reuse of wavelengths, even with a limited number of wavelengths. A lightpath consists of a path through the network between nodes and a wavelength on each of these links in the path does not require electronic processing at intermediate nodes. Each lightpath may be used to carry either circuit switched or packet switched data independent of other lightpaths in the fiber. If a call request can be satisfied, an optical circuit is established between the source and destination for the duration of the call. If a node in the path employs wavelength converters, it can switch an incoming wavelength to an arbitrary outgoing wavelength. When there are converters at all nodes, the situation is identical to that in classical circuit-switching networks. If no wavelength converters are employed in the path, a call can only be established if the same wavelength is free on all the links used by the call. If a call cannot be established due to lack of wavelengths, the call is blocked. On the other hand, if a call can be accommodated, one of the wavelengths that are available on the links used by the call is randomly assigned to it. Thus, we only consider the random wavelength assignment policy for the wavelength routing portion of this research. In a reconfigurable switch, signals on any wavelength propagates through an optical switch which outputs them in a specific permutation independent of all other wavelengths; and unlike in a non-reconfigurable switch, this permutation can be set for each wavelength.

To execute such network simulation model, the user creates a network consisting of any number of optical switches interconnected by links that service the required bandwidth as described earlier. Connections between any two hops are predetermined in an input topology file. While a simulation is running, various instantaneous performance data collection measures (counters) can be saved to a file for subsequent analysis. The results for any particular simulation run provides the time and data required to reach a stable state for the given network topology. The output also provides the amount of data required to maintain this stable state. By studying multiple simulation runs and varying the simulation input parameters, one can determine an optimal parameter configuration for the given network.

8.3 Common Simulator Components

The object oriented module that was followed in the implementation of the simulators leads to having common components for these simulators. Therefore, the common component will be described first.

8.3.1 Simulation Events

The activities that have to take place at a certain time on the optical network are defined as events. These events describe the optical network resources status, or packet processing. According to the Event-Type field, events can be classified into two main categories, Packet event or Resources event. In the case of packet events, the Event-Type field is set up at the time of packet generation to 1; on the other hand if the event is a resource event, this field set to 0. The Initial-Time field for a new generated packet is set to the simulation current time where in the case of a resources event, this field is set to 0. The Time-of-Arrival is set to 0 for new generated packets and will be updated while the packet traverses through the optical network by a cumulative value of the transmission and propagation time to the next node. This event field will be set to 0 for the resources event. The Time-to-be-Processed event field is set according to the distribution that describes the packet arrival or according to the resources holding time in case of the resources event. The wavelength field contains the wavelength that needs to be reserved or released in the case of the resources event or that was utilized by the packet on the previous hop. To keep track of packets, Source-Node, Destination-Node, and Current-Node fields are defined in case of packet event. The Current-Node event field is utilized in the case of a resource event to identify the node at which the resources status has to be updated. The events that are generated during the running of the simulation are listed in a timely order. This list is called an event list. Initially the event list is empty and then every generated event is inserted on the list according to the Time-to-be-Processed event field. The header pointer at the top of the list always points to the next event that will be processed and the Tail pointer at the bottom of the list points to the end of the list. If header and tail point to the same memory location, that means there is only one event in the list. When the event, which is pointed to by the header, is picked and processed, one or more of the following events could be generated if this event is a packet event. 1) Resources release event if the packet gets forwarded. 2) New packet event if the event reaches the destination or is dropped at one of the intermediate nodes. 3) Arrival packet event if the event gets forwarded and did not reach the destination. The optical network resources will be affected by processing a resource event. So if the header points to a resource event one of the following actions will be executed to update the network resources status. 1) Release the wavelength, specified by the Wavelength field on the fiber indicated by the Fiber field, and the converter, indicated by the Converter field, if a converter was reserved by the packet event, which generates this release event. 2) Reserve the wavelength specified by the Wavelength field on the fiber indicated by the Fiber field and the converter indicated by the Converter field if the packet event, which generates a release event utilizes a converter.

8.4 Asynchronous Conversion Ranging Optical Network Simulator

The asynchronous conversion ranging optical switch simulator, in chapter 5, is implemented to study the blocking performance of a single optical node deploying different wavelength conversion ranging configurations and sharing schemes. Two different modules, wavelength assignment module and packet generating module, are implemented for different switch ranging architectures. The different conversion ranging architectural definitions and the different conversion sharing degrees were simulated considering c, number of shared converters in the conversion bank, W, total number of wavelengths available on a fiber, and d, the range of conversion in the LRWC configurations. If the requested wavelength is not available in any outgoing fiber, the requests are forwarded to one of the shared converters within the pre-specified range d for the given architecture.

The following assumptions are used in our simulation models:

- The offered traffic is in the form of connection requests for an entire optical channel. These requests arrive at each node according to an independent stationary Poisson process with rate λ.

- Connection holding time is exponentially distributed with the mean $1/\mu$.
- Connection request that cannot be serviced are blocked.
- The connection requests are uniformly distributed among the wavelengths.

For the simulator, a Poisson distribution generator is used for the arrival generation. The Mean Inter-Arrival Time defines the time between successive packets that arrive at a node. The load of the node is defined as the ratio of the Mean Transmission Time to the Mean Inter-Arrival Time.

The simulator simulates the conditions imposed by the ranging architectures on the behavior of each specific switch. Existing requests cannot be reassigned different wavelengths. If the input/output range of the converter is defined as *Any-to-Any*, i.e., $d=W$, the request will be forwarded to any one of the shared output converters. In this case, if there is no free wavelength available on the outgoing *range*, or there is no free converter, then the request is blocked. Both *Any-to-Any* and *Any-to-Range* conversion architectures have the same conversion bank behavior, but they differ in the available output wavelength range that can serve the path setting request. The *Any-to-Range* scheme, which is easily implemented as all-optical devices, has a connection permutations that is the closest to of the *Any-to-Any*. This indicates that the behavior of the conversion bank under this scheme affects the performance metrics in a slightly different manner than the earlier scheme. The resultant performance can be further enhanced by adjusting or managing the conversion resources sharing degree. In the *Range-to-Any* and *Range-to-Range* LRWC simulations, the behavior of the conversion bank differs from the previous two cases due to the fact that each request uses just one specific converter that has the incoming wavelength in its range.

The simulator, written in C++ language, implements a discrete event simulation of the network. Each node configuration parameters along the network are fed to the simulator as inputs. It has the ability to handle different type's node configurations. To get accurate results from the simulator, the data is not accumulated until the steady state is reached as indicated by the loss probability. The tolerance for testing the steady states is 0.001, i.e., the simulation runs until the loss probability reach a variation of not more than 0.1%. The activities that have to take place at a certain time on the optical network are defined as events. These events describe the optical network resources status, or packet processing. The asynchronous conversion ranging optical network simulator is presented in Appendix C. All optical network simulators have a number of basic events implemented into different functions, which are described in the following subsections.

8.4.1 Packet Generating Function

In the packet generating module, the inverse transformation of the uniform random generator is implemented to generate random values that follow exponential distribution to find the time between successive packets' arrival as well as the packet size. When the simulation starts, the individual switch initialization function is called upon. This function initializes parameters such as number of inputs/outputs, number of fibers, number of wavelengths per fiber, number of converters, random generator seeds, inter-arrival time and mean packet size. To start generating traffic on all wavelengths in all inputs and to start building the initial event list, the status of all output wavelengths and all converters is set to the available state by the event handler function, which is fed to the event list processing function to start the network simulation. The header of the initial event list is picked and processed and its Time-to-be-Processed field is captured as the simulation starting time. When a packet event is dropped, a new packet is generated and inserted into the event list according to its Time-to-be-Processed field. Also when a resource event is processed, the node resources status gets updated. The number of packets dropped is accumulated. The point when the variation in the packet loss probability from the previously calculated value is less than 1%, which is considered as a starting point of the steady state of the simulator, the statistical data are cleared and the simulator runs for another 100,000 packet events and the collected statistics in this simulation window are considered as the final results of the simulation.

8.4.2 Topology Construction Function

For this function, an input network topology file is created by user describing general network topology. The input file is read by the simulation and the nodes connectivity topology is constructed by declaring the next node and previous node for every single node in the network. The input topology file includes essential topology information such as the number of fibers, number of wavelengths per fiber and distance between nodes. Distance between nodes is declared to calculate the propagation delay to update the Arrival-Time field of the packet event.

8.4.3 Packet Processing Function

At the beginning of this function, a comparison between packet current node and destination node is carried out to identify the status of the current packet event. Then it updates packet event information. If the next hop for the current packet event is not its final destination, the Arrival-Time, Time-to-be-Processed, and Current-Node fields will be updated and the network resources required to transmit the packet to next hop by this packet event will be reserved. The new event is inserted into the event list according to their Time-to-be-Processed fields and after a pre-specified propagation time, a release event for these resources is generated. On the other hand, if the next hop for the current packet event is the final destination, necessary network resources for delivering the packet are reserved and then a release event for the allocation of resources and as well as a new packet event from the same source on same wavelength are generated. Accordingly, these two new events will be inserted into the event list and the current packet event is deleted.

8.4.4 Resources Release Function

Resources release function is invoked when the header pointer of the event list points to a resource release event. At the beginning of this function, the wavelength, fiber, node number, and the converter number are set to free state and extracted from the event. This means that the status of these resources is updated to Free and the event is removed from the event list.

8.5 Synchronous Optical Packet Switched Network Simulator

A synchronous optical packet switched network with a conversion bank shared-per-output-link is simulated, in Chapters 6 and 7, considering c, number of shared converters in the conversion bank, w, number of wavelengths per fiber, and F parallel fibers per output in each switch in the path. Given the binomial nature of the traffic, if the requested wavelength is not available in any outgoing fiber in the output link, there are more than F packets at the inputs that are destined to λ_i on a time slot, the request will be forwarded to a shared converter bank. If there is not a free converter or if there is a free converter but no free wavelength on the output link, the incoming request will be lost.

The following assumptions are used in the simulation models:

- The offered traffic is in the form of connection requests for an entire optical channel. These requests per wavelength arrive at inputs according to an independent stationary binomial distribution with parameter (NF, ρ). A binomial distribution generator is used for the request arrival generation.
- Connection holding time (packet length) is fixed as one time slot.

- Connection requests that cannot be serviced are lost.

- The connection requests are uniformly distributed among the wavelengths.

The simulator, written in C++ language, implements a discrete event simulation of the network. The nodes configuration parameters are fed to the simulator as inputs. It has the ability to handle different node's performance parameters such as number of fibers per output link F, number of wavelengths per fiber w, and different number of shared converters per output link c. To get an accurate result from the simulator, the data is not accumulated until the steady state is reached as indicated by the loss probability. The tolerance for testing the steady states is 0.001, i.e., and the simulation runs until the loss probability reach a variation of not more than 0.1%.

The synchronous simulator mainly works as the asynchronous version, but the only difference is that the grid data structure in the asynchronous version is not necessary any more since each node in the network operates based on the slotted fashion. During every time slot, each node checks its inputs for packet arrivals and processes those packets. This means that there will be no release event generated in this type of simulation since the packet size is fixed. To free the resources, the resources release function is invoked at the beginning of every time slot. The Synchronous optical packet-switched network simulators (both for symmetric and asymmetric traffic conditions) are presented in Appendixes F and G.

8.6 Simulation Verification and Validation

Simulator verification is the process of determining correctness of the optical network implementation and its result data accuracy. This process addresses the simulation's credibility and applicability for emulating real networks. It focuses on simulation structural integrity and evaluates whether the simulated network conditions have been met. The difference between the verification process and the validation process is that verification determines if the simulation was built right where as validation determines if the right thing was built. The simulation facilitates a way to trace each call/packet to verify correctness. Information like the timestamp of the call, route, details of the links between two nodes, and wavelength in which the call has been established are parameters for simulation tracing. Another mechanism to verify the simulator is to boundary-scan the implemented network settings.

Chapter 9

CONCLUSION

For the Internet to scale and accommodate the exponentially growing traffic, we must scale relevant dimensions of the optical core. This scaling should take into account the ability of the optical network elements to handle traffic efficiently without degrading the performance. The optical nature of the backbone, network core, poses a challenge in the required mechanisms. In this research, we have studied different aspects of the share-per-link wavelength convertible switch networks. These aspects ranged from developing mechanisms for ranging individual converters within a switch, proposing different wavelength resource allocation algorithms, and implantation of such switch architecture in synchronous/ asynchronous network settings.

This chapter sums up some of the results and conclusions of this research endeavor. The study in chapter 4 shows that the use of wavelength conversion increases the improvement in throughput resulting from the ability to minimize wavelength contention. Wavelength conversion may possibly improve the performance of the network by resolving the wavelength contention problem, but it incurs increased cost, hardware complexity, and space requirements implying potential trade-offs between the performance and the number of wavelength converters needed. The cost of using wavelength conversion could be adjusted by employing conversion resources sharing schemes. Results show that share-per-node WCS is the most efficient. It provides a comparable performance to full wavelength conversion case for typical operating range. Considering more intelligent conversion resource allocation algorithms CRAAs that dynamically accommodate more conversion request for share-per-link WCS will improve the overall performance.

Three resources allocation algorithms are introduced namely, Narrow Search Algorithm NSA, Inclusive Search Algorithm ISA, and Optimized Inclusive Search Algorithm OISA, to attain an efficient usage of conversion resources. It is demonstrated that these algorithms realize not only efficient usage of resources but also robustness to the traffic change. It is demonstrated that ISA, which is characterized by a high algorithm time complexity, presents the best performance from the viewpoint of efficient usage of resources, but requires higher processing load to achieve better allocation rate than NSA. Since these resources allocation algorithms will be used by network control functions, it is necessary that the complexity of these algorithms be kept low while still taking into account the characteristics and the desired utilization performance. To reduce the complexity of ISA due to the exhaustive nature of the search algorithm for free converters, a simpler algorithm was proposed. OISA is used to moderate the high processing load on the control plane, which in turn uses CRAA in determining an optimal solution for the RWA problem in a tightly coupled manner. The control algorithm utilizes a mechanism to optimally assign both the wavelength converters and the needed channel to transport data over light in the optical domain.

The improvement offered by OISA leads to a reduction in the required number of converters in conversion banks, cost, in addition to the improvement in allocation algorithm processing time. The fact that these algorithms are scalable with the hop count, emphasizes the positive effects of conversion resources allocation algorithms, CRAAs, in extending network reach, network diameter, by reducing the blocking of the system and increasing the utilization performance. Improved ISA, OISA, efficiently reduces the hardware (infrastructure) costs by requiring fewer wavelength converters and optimizes the processing time, which in turn increases the efficiency of sharing conversion resources. The proposed algorithms also increase the throughput of the optical network, thus increasing overall utilization of the optical domain.

In chapter 5, we investigated issues associated with LRWC in the presence of conversion resource sharing. The ranging mechanisms of a wavelength converter, which are presented in chapter 5, are identified as a major design criterion of the optical switch, which has an important role in managing conversion resources efficiently. The differences between the input and output side ranging mechanisms and their effects on conversion resource sharing, and consequently performance, were explored. The impact of using different architectures for wavelength conversion to mitigate the cost penalty was evaluated. The throughput improvement due to the use of LRWC, in the presence of conversion sharing, depends more on the degree of sharing than the conversion range.

The study shows that switch architectures with smaller input-side conversion ranges can approach the same performance as those using full-range WC at slightly higher degree of sharing. The implementation of *Any-to-Range* configuration in all-optical wavelength converters would be a more efficient and elegant solution, allowing fully integrated optical cross-connect/wavelength conversion boxes. *Any-to-Range* corresponds to less complex and less costly hardware than full range conversion, yet it results in acceptable channel utilization. This introduces the issue of cost effectiveness when considering different switching architectures, conversion options, and hop configurations.

The limited range wavelength configuration reduces the need for extremely complex *Any-to-Any* control algorithms. Nevertheless, these ranging configurations do give up some flexibility and overall network efficiency. The complexity and the cost of all-optical converters depend on its conversion ranging mechanism. It is shown that switches with completely shared wavelength converters require a fraction of WCs in comparison to switch architectures that use a converter per wavelength. The sharing efficiency is tightly coupled with the ranging mechanism employed in the switch. Switches that employ output side ranging methods can take full advantage of wavelength conversion resource sharing, where as these sharing advantages are severely limited in switches that employ input side ranging method.

In chapter 6, we introduced an analytical model for synchronous optical packet switching networks that employ multi-fiber share-per-link optical switch. Results obtained by the developed performance model for multi-fiber share-per-link OPS network, which operates in a slotted mode, and the simulation model were analyzed for different network and switch parameters. The results showed that the packet loss probability decreases with the introduction of more wavelengths into the network, indicating that wavelength count is an important design factor in determining the over all performance of the network.

The packet loss probability of smaller diameter networks is lower than networks with higher hop count. The interesting observation is that the packet loss probability flattens at a point where the c/W ratio is around 33% regardless of the diameter of the network and regardless if it is a single-fiber of multi-fiber network. Any addition of converters after the $c/W=0.33$ has no effects. At the ratio of $c/W=0.33$, the network operates equivalently to the full conversion network. The amount of performance improvement in packet loss probability due to the introduction of converters is independent of the network diameter, hop count H. The introduction of more converter beyond the $c/W=0.33$ would be considered wastage of important resources indicated by the flat packet loss probability behavior. It does not mater if the network is single-fiber or multi-fiber, it is noticeable that even the single-fiber network behaves as the multi-fiber network after the c/W of 33%, which means when a network reaches the region where it behaves as full conversion network, the fact that it uses multiple fibers would not add any significant improvement. The difference in the c/W ratios before the 33%, between multi-fiber networks and single-fiber networks, is considered an advantage in complementing the efficiency of the available conversion and serving higher traffic.

The results also showed that the network diameter has no effects on the point where the network imitate the behavior of full conversion in multi-fiber network case. It can be said for certain that limited conversion of 33% is sufficient, no matter what the offered load is, to accommodate the traffic in a similar manner to full conversion and that any additional wavelength converters would be considered wastage of resources. We also confirm that in multi-fiber setting, the need of converters is less to reach such point, $c/W=0.33$, than single-fiber networks. Wavelength conversion has prominent effects on multi-fiber systems with lower offered load and less effect on networks with higher offer load. In networks with higher offered loads, the increasing traffic overwhelms the effects of converters, saturate the positive effects of conversion, faster than networks with lower offered loads.

Even though the c/W value that gives a comparable performance to full wavelength conversion network is the same for both single-fiber and multi-fiber networks, wavelength converters have a more significant effects in the case of single-fiber networks than multi-fiber networks. The introduction of conversion into single-fiber networks improves the performance significantly. The employment of multi-fiber links in the network increases the efficiency of the conversion devices and accordingly the over all performance of the whole network. The employment of wavelength converters is far superior and more influential on the performance of the optical packet switch networks. In lightly loaded networks, converters have a significant effect and the introduction of converters would improve the packet loss performance dramatically, where as of highly loaded networks, the introduction of such converters change the packet loss probability in an incremental fashion. Converters introduced earlier are faced with high offered load and their contribution in reducing the packet loss probability is limited accordingly. The lately introduced ones work in the region where the packet loss probability is already low and close to the $c/W{=}0.33$ region. Accordingly, their contribution is also limited to the upper boundary of c/W, which characterizes the region that behaves comparable to full conversion.

The effects of using multiple fibers on network performance would not be, by any means, comparable to the use of wavelength conversion devices, even though it is considered as comparable to a very limited conversion. In other words, the increase of wavelength count or the increase of fiber count in the absence of wavelength conversion would not be feasible to reach network performance similar to full conversion. The region where the introduction of one wavelength converter is most effective moves with the fiber count F and the offered load ρ. In networks with lower fiber counts, the introduction of conversion at lower offered load is more significant than higher offered load region, where as for networks with higher fiber counts, it is more significant to introduce wavelength conversion to the system at higher offered load regions. This says, for instance in single-fiber networks, due to the lack of multiple fibers, the introduction of wavelength conversion would have a positive contribution at lower offered load. As for the high offered load region, the packet loss probability would be higher anyhow and such introduction of limited wavelength conversion would not change the performance significantly. As far for multi-fiber networks, the presence and the effects of multiple fibers would deal with the packet contention problem at lower regions of offered loads rather sufficiently, so the introduction of conversion resources would not be so essential.

In chapter 7, we have introduced a more realistic scenario for the share-per-link synchronous optical packet-switching networks, where each node along the path serves heterogeneous traffic, which means that the ρ_i applied to the wavelengths in each of the N links are different from each other. The intention is to study the ability of the synchronous optical packet-switching network to tolerate traffic asymmetry. The asymmetric traffic condition is due to the dynamic traffic nature of the optical core. This realistic scenario raised the question of how this load variation among the input links would affect the performance behavior of the network. In order to account for such behavior, we introduced a method to measure such load variation among the incoming links and accordingly relate such factor to network performance. The introduction of this measure α helped in understanding the effects of such factor in a network setting. It is important to note that the load variation factor changes constantly due to the dynamically changing nature of network traffic. This means that load variation offers no controllability for the purpose of network control. It is still an important factor to study in the sense of its effects on other network parameters and resources. We have seen that this dynamically changing factor has a non-negligible effect on wavelength conversion resource. In this study, we referenced such factor (α) to the total load (L) served by each node along the path. Accordingly, we came to a number of important conclusions that help us in envisioning the behavior of the synchronous optical network.

It has been shown that networks with lightly loaded nodes along the path has a wider range of α, whereas networks with highly loaded nodes along the path have a limited range of α. This meant that lightly loaded networks have more freedom in adjusting performance, where the load variation among the input links can vary more. Networks with switching nodes that have a higher nodal degree would have a wider range for the α factor, if same total load L is considered. When $\alpha = 1$, the resulting packet loss probability behavior is considered as the lower boundary of network performance with respect to this factor. Accordingly, the symmetric traffic switch model introduced in chapter 6 characterized the lower boundary of performance with respect to α factor. The difference of performance for the different values of α is not drastic for highly loaded networks, which indicates that this factor is not that prominent as far as its effects on network performance go unless the network is lightly loaded.

The effect of the α factor is more evident in networks with lower counts of wavelength converters. The fact that wavelength conversion enhances the performance of the network and increases the efficiency of the optical resources limits the effects of the dynamically changing α factor on performance. The dynamic change of the α factor has more effects on the packet loss probability performance when the network has no wavelength conversion capabilities or when it has a low C/W ratio. The effect of the α factor is more evident in networks with lower counts of fiber. This means that networks with higher fiber counts per link are less susceptive to be affected by the load variation factor measured by α. As we mentioned earlier, the dynamic nature of the optical traffic tells us that the load variation among links would be also dynamically changing and that the packet loss performance of networks with limited contention resolution resources are to be greatly affected by such dynamic changes in the load variations among the optical links. The increase in C/W ratio improves the packet loss performance till a point where a network behaves as a network with full conversion. Such point is reached with lower counts of wavelength converters for networks that have lower values of α factor whereas networks with higher values of α require more wavelength converters to reach such point. This means that the dynamically changing nature of the optical traffic also affects the efficiency of wavelength conversion.

Bibliography

[1] N. Akar, and E. Karasan, "Exact Calculation of Blocking Probabilities for Bufferless Optical Burst Switched Links for Bufferless Optical Burst Switched Links," 1st International Conference on Broadband Networks, pp. 110-117, October 2004.

[2] F. A. Al-Zahrani, "Modeling, Performance Analysis, and Survivability Evaluation of Multi-Fiber WDM Optical Networks," Ph.D. Dissertation, Colorado State University, July 2005.

[3] F. A. Al-Zahrani, A. A. Habiballa, A. Fayoumi, and A. P. Jayasumana, "Performance Analysis of the Asymmetric Optical Packet-Switch with Shared-per-Link Wavelength Converters," To be submitted for publication.

[4] F. Al-Zahrani, A. Habiballa, and A. Jayasumana, "Path Blocking Performance in Multi-Fiber Wavelength Routing Networks with and without Wavelength Conversion," Proc. 13th IEEE ICCCN03, pp. 580-583, October 2003.

[5] F. Al-Zahrani, A. Habiballa, and A. Jayasumana, "Performance Merits of Multi-Fiber DWDM Networks Employing Different Shared Wavelength Conversion Resources Architectures," Proc. IEEE region 5 conference, pp. 59-67, April 2004.

[6] F. Al-Zahrani, A. Habiballa, A. Fayoumi, A. Jayasumana "Performance Tradeoffs of Shared Limited Range Wavelength Conversion Schemes in Optical WDM Networks," IEEE/IFIP WOCN05, pp. 18-22, March 2005.

[7] V. Auletta, I. Caragiannis, L. Gargano, C. Kaklamanis, and P. Persiano, "Sparse and Limited Wavelength Conversion in All-optical Tree Networks," Theoretical Computer Science, Vol. 266, No. 1-2, pp. 887-934, 2001.

[8] D. Awduche, and Y. Rekhter, "Multiprotocol Lambda Switching: Combining MPLS Traffic Engineering Control with Optical Cross Connects," IEEE Communications Magazine, March 2001.

[9] S. Banerjee and C. Chen, "Design of Wavelength-Routed Optical Networks for Circuit Switched Traffic," Proc. IEEE Globecom 96, Vol. 1, pp. 306-310, November 1996.

[10] S. Baroni, P. Bayvel, R. Gibbens, and S.K. Korotky, "Analysis and Design of Resilient Multifiber Wavelength-Routed Optical Transport Networks," Journal of Lightwave Technology, Vol. 17, No. 5, pp. 743-758, May 1999.

[11] Barry and P. Humblet, "Models of Blocking Probability in All-Optical Networks with and without Wavelength Changers," Proc. IEEE Infocom'95, Boston, pp. 402-412, April 1995.

[12] R. Barry, and P. Humblet, "Models of Blocking Brobability in All-Optical Networks with and without Wavelength Changers," IEEE Journal on Selected Areas in Communications, Vol. 14, No. 5, pp. 858-867, June 1996.

[13] B. Batageli, "The need for Wavelength Converters in All-optical Transport Network," 10th Mediterranean MELECON 2000, Vol. 1, pp. 277-280, May 2000.

[14] A. Birman, "Computing Approximate Blocking Probabilities for a Class of All Optical Networks," Proc. IEEE Infocom'95, Boston, Vol. 2, pp. 651-658, April 1995.

[15] A. Bononi, G. Castanon, and O. K. Tonguz, "Analysis of Hot-potato Optical Networks with Wavelength Conversion," J. Lightwave Technology, vol. 17, No. 4, pp. 525-534, April 1999.

[16] C. Brackett, "Dense Wavelength Division Multiplexing Networks: Principles and Applications," IEEE J. Select. Areas Communication, vol. 8, No. 6, pp. 948-964, August 1990.

[17] D. Caccioli, A. Paoletti, et al, "Field Demonstration of in-Line All-Optical Wavelength Conversion in a WDM Dispersion Managed 40-Gbit/s Link," IEEE J. Selected Topics in Quantum Electronics, Vol. 10, No. 2, pp. 356-362, March-April 2004.

[18] G. Castanon, "Design-Dimensioning Model for Transparent WDM Packet-Switched Irregular Networks," Journal of Lightwave Technology, Vol. 20, No. 1, pp.1-9, January 2002.

[19] G. Castanon, L. Tancevski, and L. Tamil, "Routing Strategies for the Optimization of Components in All-optical Packet Switched Networks," Eur. Conf. Optical Communications (ECOC '99), Paper P4.1, September 1999.

[20] G. Castanon, L. Tancevski, and L. Tamil, "Optical Packet Switching with Multiple Path Routing," Computer Networks, vol. 32, no. 4, May 2000.

[21] D. Cavendish, "Evolution of Optical Transport Technologies: From SONET/SDH to WDM," IEEE Communications Magazine, Vol. 38, No. 6, pp. 164-172, June 2000.

[22] K. Chan, F. Tong, C. K. Chan, L. K. Chen, and W. Hung, "An All-optical Packet Header Recognition Scheme for Self-Routing Packet Networks," in Proc. Optical Fiber Communication, Paper WO4, p. 284, March 2002.

[23] I. Chlamtac, A. Ganz and G. Karmi, "Lightpath Communications: An Approach to High Bandwidth Optical WAN's," IEEE Transactions on Communications, Vol. 40, No. 7, pp. 1171-1182, July 1992.

[24] S. Danielsen, P. Hansen, and K. Stubkjaer, "Wavelength Conversion in Optical Packet Switching," J. Lightwave Technology vol. 16, No. 12, pp. 2095-2108, December 1998.

[25] S. Danielsen, B. Mikkelsen, C. Jorgensen, T. Durhuus, and K. Stubkjaer, "WDM Packet Switch Architectures and Analysis of the Influence of Tuneable Wavelength Converters on the Performance," J. Lightwave Technology, vol. 15, pp. 219-227, February 1997.

[26] S. Danielsen, C. Joergensen, B. Mikkelsen, and K. Stubbkyaer, "Optical Packet Switched Network Layer without Optical Buffers," IEEE Photonics Technology LetterS, Vol. 10, No. 6, pp. 896-898, June 1998.

[27] J. Elmirghani and H. Mouftah, "All-Optical Wavelength Conversion: Technologies and Applications in DWDM Networks," IEEE Communication Magazine, Vol. 38, No. 3, pp. 86-92, March 2000.

[28] J. Elmirghani, and H. Mouftah, "Technologies and Architectures for Scalable Dynamic Dense WDM Networks," IEEE Communications Magazine, Vol. 38, No. 2. pp. 58-66, February 2000.

[29] V. Eramo, M. Listanti, "Input Wavelength Conversion in Optical Packet Switches," IEEE Communication Letter, Vol. 7, No. 6, pp. 281-283, June 2003.

[30] V. Eramo and M. Listanti, "Packet Loss in a Bufferless Optical WDM Switch Employing Shared Tunable Wavelength Converters," Journal of Lightwave Technology, Vol. 18, No. 12, pp. 1818-1833, December 2000.

[31] V. Eramo, M. Listanti, and M. Donato, "Performance Evaluation of a Bufferless Optical Packet Switch with Limited-range Wavelength Converters," IEEE Photonic Technology Letters, Vol. 16, No. 2, pp. 644-646, February 2004.

[32] V. Eramo, M. Listanti, and P. Pacifici, "A Comparison Study on the Number of Wavelength Converters Needed in Synchronous and Asynchronous All-Optical Switching Architectures," Journal of Lightwave Technology, Vol. 21, No. 2, February 2003.

[33] V. Eramo, M. Listanti, and M. Spaziani, "Dimensioning Models in Optical Packet Switches Equipped with Shared Limited-range Wavelength Converters," IEEE GLOBECOM, Vol. 3, pp. 1735-1741, November-December 2004.

[34] V. Eramo, M. Listanti, and M. Tarola "Advantages of Input Wavelength Conversion in Optical Packet Switches," IEEE GLOBECOM '03, Vol. 5, pp. 2714-2718, December 2003.

[35] A. Fayoumi, F. Al-Zahrani, A. Habiballa, and A. Jayasumana, "Performance Analysis of Multi-Fiber Synchronous Photonic Share-per-link Packet Switches," IEEE LCN '05, November 2005.

[36] A. Fayoumi, F. A. Al-Zahrani, A. A. Habiballa, and A. P. Jayasumana, "Performance Analysis of Multi-Fiber WDM Switches with Shared-per-Link Wavelength Converters," To be submitted for publication.

[37] A. Fayoumi, A. Jayasumana, "Performance Evaluation of an All-optical Shuffle Net using Optical Buffering and Deflection Routing," Photonic Net. Communication, Vol. 6, No. 1, pp. 43-50, July 2003.

[38] A. Fayoumi, A. Jayasumana, "Performance Model of an Optical Switch using Fiber Delay Lines for Resolving Contentions," Proc. IEEE LCN '03, pp. 178-186, October 2003.

[39] M. Frey, and T. Ndousse, "Wavelength Conversion and Call Connection Probability in WDM Networks Communications," IEEE Transactions, Vol. 49, No. 10, pp. 1780-1787, October 2001.

[40] P. Gambini et al., "Transparent Optical Packet Switching: Network Architecture and Demonstrators in the KEOPS Project," IEEE J. Select. Area Communication, Vol. 16, No. 7, pp. 1245-1253, September 1998.

[41] R. Giles, K. Kumaran, D. Mitra, C. Nuzman, and I. Saniee, "Selective Transparency in Resilient Optical Networks," Proceedings MILCOM 2002, vol.1, pp. 72-74, October 2002.

[42] P. Green, "Progress in Optical Networking," IEEE Communications Magazine, Vol. 39, No. 1, pp. 54-61, January 2001.

[43] C. Guillemot et al., "Transparent Optical Packet Switching: The European ACTS KEOPS Project Approach," J. Lightwave Technology., Vol. 16, No. 12, pp. 2117-2134, December 1998.

[44] A. Habiballa, F. Al-Zahrani, and A. Jayasumana, "Wavelength Conversion Resources Allocation Algorithms for Share-per-link Wavelength Convertible Switch," Proc. IEEE Region 5 Conference, pp. 131-139, April 2004.

[45] A. Habiballa, F. Al-Zahrani, A. Fayoumi, and A. Jayasumana, "Performance Tradeoffs of Optical WDM Switches Using Different Shared Limited Range Wavelength Conversion Mechanisms," Submitted for Publication.

[46] D. Hunter, M. Chia, and I. Andonovic, "Buffering in optical packet switches," J. of Lightwave Technology, Vol. 16, No. 12, pp. 2081-2094, December 1998.

[47] E. Iannone, and R. Sabella, "Analysis of Wavelength-Switched High-Density WDM Networks Employing Wavelength Conversion by Four-wave-mixing in Semiconductor Optical Amplifiers," Journal of Lightwave Technology, Vol. 13, No. 7, pp. 1579-1592, July 1995.

[48] J. Iness and B. Mukherjee, "Sparse Wavelength Conversion in Wavelength-Routed WDM Optical Networks," Photon. Network Communication, Vol. 1, pp. 183-205, November 1999.

[49] K. Inoue, T. Hasegawa, K. Oda, and H. Toba, "Multichannel Frequency Conversion Experiment Using Fiber Four-Wave Mixing," Electronics Letter, Vol. 29, No. 19, pp. 1708-1710, September 1993.

[50] J. Jue and G. Xiao, "Analysis of Blocking Probability for Connection Management Schemes in Optical Networks," Proc. IEEE Globecom'01, Vol. 3, pp. 1546-1550, November 2001.

[51] E. Karasan, and E. Ayanoglu, "Effects of Wavelength Routing and Selection Algorithms on Wavelength Conversion Gain in WDM Optical Networks," IEEE/ACM Transactions on Networking, Vol. 6, No. 2, pp. 186-196, April 1998.

[52] M. Kovacevic and A. Acampora, "Benefits of Wavelength Translation in All-optical Clear Channel Networks," IEEE Journal of Selected Areas on Communications/Journal of Lightwave Technology, Vol. 14, No. 5, pp. 868-880, June 1996.

[53] H. Kuwahara, H. Imai, T. Touge, and K. Ohta. "Photonic Networks and Their Forward View," Fujitsu Scientific Technical Journal, Vol. 35, No. 1, July 1999.

[54] J. Lang, V. Sharma, and E. Varvarigos, "An Analysis of Oblivious and Adaptive Routing in Optical Networks With Wavelength Translation," IEEE/ACM Trans. Networking, Vol. 9, No. 4, pp. 503-517, August 2001.

[55] K. Lee, and V. Li, "A Wavelength-Convertible Optical Network," Journal of Lightwave Technology," Vol. 11, No. 5, pp. 962-970, May-June 1993.

[56] K. Lee and V. Li, "Routing and Switching in a Wavelength Convertible Optical Network," Proc. IEEE INFOCOM 93, Vol. 2, pp. 578-585, March-April 1993.

[57] L. Li and A. K. Somani, "Blocking Performance Analysis of Fixed-Paths Least-Congestion Routing in Multifiber WDM Networks," International Journal of Communication Systems, Vol. 15, No. 2-3, pp. 143-159, March-April 2002.

[58] D. Li, and X. Jia, "Allocating Wavelength Converters in Shared-per-link Structure in WDM networks," IEE Proceedings Communications," Vol. 149, No. 3, pp.185-188, June 2002.

[59] D. Li and X. Jia, "Placement of Wavelength Converters in Shared-per-link Structure in WDM Networks," Int. Conf. on Parallel Processing '01, pp. 277-282, September 2001.

[60] T. Lin and G. Sasaki, "Nonblocking WDM Networks with Fixed-Tuned Transmitters and Tunable Receivers," Proc. 37th Annual Allerton Conference on Communication, Control, and Computing, pp. 400-401, 1999.

[61] L. Ling and A. Somani, "A New Analytical Model for Multifiber WDM Networks," Proc. Globecom'99, Rio de Janeiro, Brazil, Vol. 1b, pp. 1007-1011, December 1999.

[62] L. Ling and A. Somani, "Fiber Requirement in Multifiber WDM Networks with Alternate-path Routing," Proc. 8th International Conference Computer Communications and Networks, pp. 338-343, October. 1999.

[63] M. Listanti, M. Berdusco, and R. Sabella, "Optical Path Strategies in WDM All-optical Networks: Minimization of Wavelength Converters in Optical Cross Connects," Global Telecommunications Conference, IEEE, Vol. 1, pp. 583-587, November 1997.

[64] M. Listanti, R. Sabella, and V. Eramo, "Architectural and Technological Issues for Future Optical Internet Networks," IEEE Commun. Mag., Vol. 38, No. 9, pp. 82-92, September 2000.

[65] D. Mitra, C. Nuzman, I. Saniee, and P. Whiting. "Optical Cross-connect with Shared Wavelength Conversion under Dynamic Load," IEEE/OFC Technical Digest, pp. 160-162, March 2002.

[66] B. Mukherjee, "Optical Communication Networks, McGraw-Hill," 1997.

[67] D. Nesset, T. Kelly, and D. Marcenac, "All-Optical Wavelength Conversion Using SOA Nonlinearities," IEEE Communications Magazine, Vol. 36, No. 12, pp. 56-61, December 1998.

[68] H. Overby "Performance Modelling of Synchronous Bufferless OPS Networks," 6th International Conf. on Transparent Optical Networks, 2004, vol.1, pp. 22-28, July 2004.

[69] C. Qiao. "Labeled Optical Burst Switching for IP-over-WDM Integration," IEEE Communications Magazine, Vol.38, No. 9, pp. 104-114, September 2000.

[70] B. Rajagopalan, D. Pendrakis, D. Saha, R. Ramamoorthy, and K. Bala, "IP over Optical Networks: Architectural Aspects," IEEE Communications Magazine, Vol. 38, No. 9, pp. 94-102, September 2000.

[71] R. Ramamurthy, and B. Mukherjee, "Fixed-Alternate Routing and Wavelength Conversion in Wavelength-Routed Optical Networks," Transactions on Networking, IEEE/ACM , Vol. 10, No. 3, pp. 351-367, June 2002.

[72] B. Ramamurthy and B. Mukherjee, "Wavelength Conversion in WDM Networking," IEEE J. Select. Areas Communication, vol. 16, No. 7, pp. 1061-1073, September 1998.

[73] R. Ramaswami and G. Sasaki, "Multiwavelength Optical Networks with Limited Wavelength Conversion," IEEE/ACM Trans. Networking, Vol. 6, No. 6, pp. 744-754, December 1998.

[74] R. Ramaswami, and G. Sasaki, "Multiwavelength Optical Networks with Limited Wavelength Conversion," Proceedings IEEE 16th Annual Joint Conference of the IEEE Computer and Communications Societies, Vol. 2, pp. 489-498, April 1997.

[75] R. Ramaswami and K. Sivarajan, "Routing and Wavelength Assignment in All-optical Networks," IEEE/ACM Trans. on Networking, Vol. 3, No. 5, pp. 489-500, October 1995.

[76] K. Sato et al., "Network Performance and Integrity with Optical Path Layer Technologies," IEEE J. Select. Areas Communication, Vol. 12, pp. 159-171, January 1994.

[77] V. Sharma, and E. Varvarigos, "An Analysis of Limited Wavelength Translation in Regular All-Optical WDM Networks," Journal of Lightwave Technology, Vol. 18, No. 12, pp. 1606-1619, December 2000.

[78] G. Shen, S. Bose, T. Cheng, C. Lu, and T. Chai, "Operation of WDM Networks with Different Wavelength Conversion Capabilities," IEEE Communications Letters, Vol. 4, No. 7, pp. 239-241, July 2000.

[79] G. Shen, S. Bose, T. Cheng, C. Lu, and T. Chai, "Performance Study on a WDM Packet Switch with Limited-range Wavelength Converters," IEEE Communication Letter, Vol. 5, No. 10, pp. 432-434, October 2001.

[80] J. Spth, U. Gremmelmaier, U. Briem, M. Huber, "Architecture and Performance Evaluation of Future Photonic Networks," Proc. 12th International Conference on Computer Communication (ICCC '95), Seoul, pp. 661-666, 1995.

[81] L. Spiekman, U. Koren, M. Chien, B. Miller, J. Wiesenfeld, and J. Perino, "All-Optical Mach-Zehnder, Wavelength Converter with Monolithically Integrated DFB Probe Source," IEEE Photonics Technology Letters, Vol. 9, No. 10, pp. 1349-1351, October 1997.

[82] S. Subramanium, M. Azizoglu, and A. Somani, "Connectivity and Sparse Wavelength Conversion in Wavelength-Routing Networks," Proc. IEEE Infocom'96, San Francisco, Vol. 1, pp. 148-155, March 1996.

[83] N. Torrington-Smith, H. Mouftah, and M. Rahman, "An Evaluation of Optical Switch Architectures Utilizing Wavelength Converters," 2000 Canadian Conference on Electrical and Computer Engineering, Vol.2 , pp. 1008-1013, March 2000.

[84] T. Tripathi and K. Sivarajan, "Computing Approximate Blocking Probabilities in Wavelength Routed All-optical Networks with Limited Range Wavelength Conversion," IEEE J. Select. Areas Communication, Vol. 18, No. 10, pp. 2123-2129, October 2000.

[85] E. Varvarigos and V. Sharma, "The Ready-to-go Virtual Circuit Protocol: A Loss Free protocol for Multigigabit Networks Using FIFO Buffers," IEEE/ACM Trans. Networking, Vol. 5, No. 5, pp. 705-708, October 1997.

[86] M. Veeraraghavan, R. Kari, T. Moors, M. Karol, and R. Grobler, "Architectures and Protocols that Enable New Applications on Optical Networks," IEEE Communications Magazine, Vol. 39, No. 3, pp. 118-127, March 2001.

[87] K. Venugopal, E. Rajan, and P. Kumar, "Performance Analysis of Wavelength Converters in WDM Wavelength Routed Optical Networks," 5th International Conference on High Performance Computing 1998, pp. 239-246, December 1998.

[88] N. Wauters and P. Demeester, "Design of the Optical Path Layer in Multi-Wavelength Cross-connected Networks," IEEE J. Select. Areas Communication, Vol. 14, pp. 881-892, June 1996.

[89] D. Wolfson, P. Hansen, T. Fjelde, A. Kloch, C. Janz, A. Coquelin, I. Guillemot, F. Gaborit, F. Poingt, and M. Renaud, "40Gbit/s All-Optical Wavelength Conversion in an SOA-Based Allactive Mach-Zehnder Interferometer," ECOC'99, pp.170-171, 1999.

[90] G. Xiao and Y. Leung, "Algorithms for Allocating Wavelength Converters in All-optical Networks," IEEE/ACM Trans. Networking, Vol. 7, No. 4, pp. 545-557, August 1999.

[91] L. Xu, L. Oxenlowe, N. Chi, J. Mork, P. Jeppesen, K. Hoppe, and J. Hanberg, "Basic Characterization of Wavelength Conversion at 40 Gb/s Based on Electroabsorption Modulators," Proc. IEEE Lasers and Electro-optics Society 2002 Annual meeting, pp. 111-112, 2002.

[92] J. Yates and M. Rumsewicz, "Wavelength Converters in Dynamically Reconfigurable WDM Networks", IEEE Communications Surveys, Second quarter, pp.2-15, 1999.

[93] J. Yates, M. Rumsewicz and J. Lacey, "Wavelength Conversion in Networks with Differing Link Capacities," IEEE GLOBECOM' 98, Vol. 4, pp. 2315-2320, November 1998.

[94] S. Yoo, "Wavelength Conversion Technologies for WDM Network Applications," Journal of Lightwave Technology, Vol. 14, No. 6, pp. 955-966, June 1996.

[95] X. Yuan, R. Melhem, R. Gupta, Y. Mei, and C. Qiao, "Distributed Control Protocols for Wavelength Reservation and Their Performance Evaluation," Photonic Network Communications, Vol. 1, No. 3, pp. 207-218, 1999.

[96] A. Zalesky, H. Vu, M. Zukerman, Z. Rosberg, and E. Wong, "Evaluation of Limited Wavelength Conversion and Deflection Routing as Methods to Reduce Blocking Probability in Optical Burst Switched Networks," IEEE Int. Conf. on Communication, Vol. 3 , pp. 1543-1547, June 2004.

[97] H. Zang, J. Jue and B. Mukherjee, "A review of Routing and Wavelength Assignment Approaches for Wavelength-Routed Optical WDM Networks," Optical Network Magazine, Vol. 1, pp. 47-63, January 2000.

[98] L. Zhang; and L. Li, "Performance Comparison of Share-per-link and Share-per-node Optical Cross Connect in WDM Networks," Communications, IEEE 2002 International Conference on Circuits and Systems and West Sino Expositions, Vol. 1, pp. 840-844, June-July 2002.

[99] Y. Zhu, G. Rouskas, and H. Perros, "Blocking in Wavelength Routing Networks .I. The Single Path Case," Proceedings of IEEE 18th Annual Joint Conference of the IEEE Computer and Communications Societies, Vol. 1, pp. 321-328, March 1999.

APPENDIX

Appendix A

ANALYTICAL MODEL SOURCE CODE: BLOCKING PROBABILITY OF WAVELENGTH-ROUTED NETWORK

The source code of the analytical model, which is written in Matlab, to evaluate the blocking probability of the wavelength-routed network is shown below.
The blocking probability models for these wavelength-routed network configurations explained in detail in Chapter 4.

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% File name: Blocking-Probability.m
%%
%% Purpose: To calculate the blocking probability of the
%% wavelength-routed network. Three differenet
%% wavelength-routed network are considered:
%% 1. Single-fiber wavelength-routed network
%% 2. Wavelength-routed network with dedicated conversion
%% 3. Multi-fiber share-per-node wavelength-routed network
%%
%% Inputs:
%% DC : Degree of conversion
%% rho: Load per wavelengt
%% G : Source-destination per load
%% H : Number of hops
%% F : Number of fibers
%% W : Total number of wavelengths per hop
%% c : Number of converters
%%
%% Outputs:
%% ps : Single-fiber environment blocking probability
%% Us : Single-fiber environment throughput
%% p0s: Probability of zero converters is busy in the
%% single-fiber case
%% pcs: Probability of all converters are busy in the
```

```
%% single-fiber case
%% pn : Multi-fiber share-per-node environment blocking
%% probability
%% Un : Multi-fiber share-per-node environment throughput
%% p0n: Probability of zero converters is busy in the
%% multi-fiber share-per-node case
%% pcn: Probability of all c converters are busy in the
%% multi-fiber share-per-node case
%% pf : Dedicated conversion environment blocking
%% probability
%% Uf : Dedicated environment throughput
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
clear all;
clc;
ranage=11;
DC=0.7
rho=0:0.1:1;
G=0.07;
H=20;
F=2;
W=16;
c=ceil(DC*W);
pl=zeros(ranage,1);
pf=zeros(ranage,1);
ps=zeros(ranage,1);
pn=zeros(ranage,1);
p0s=zeros(ranage,1);
pcs=zeros(ranage,1);
p0n=zeros(ranage,1);
p0l=zeros(ranage,1)
pcl=zeros(ranage,1);
pcn=zeros(ranage,1);
Us=zeros(ranage,1);
Uf=zeros(ranage,1);
Un=zeros(ranage,1);
Ul=zeros(ranage,1)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% Calculating probability of zero converters is busy%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
sump=0;
for j=1:ranage
for i=1:c
sump=sump+(1/factorial(i))*(factorial(W)/
factorial(W-i))*rho(j)^(2*i);
```

```
end
p0s(j)=1/(1+sump);
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% Calculating probability of c converters are busy%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
for i=1:ranage
pcs(i)=p0s(i)*(1/factorial(c))*(factorial(W)/
factorial(W-c))*rho(i)^(2*c);
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% Calculating blocking probability of single-fiber case %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
for i=1:ranage
ps(i)=(1-((1-rho(i))+rho(i)*(1-pcs(i))*(1-rho(i)^(W-1)))^H)^W;
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% Calculatin throughput of single-fiber case %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
for i=1:ranage
Us(i)=(1-ps(i))*G;
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% Calculating blocking probability of dedicated conversion case%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
for i=1:ranage
pf(i)=(1-(1-rho(i)^(W))^H)^W;
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% Calculating throughput of dedicated conversion case%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
for i=1:ranage
Uf(i)=(1-pf(i))*G;
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%Calculating probability of zero converters is busy%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
sump=0;
for j=1:ranage
for i=1:c
sump=sump+(1/factorial(i))*(factorial(W)/
factorial(W-i))*rho(j)^(i*F+i);
end
p0n(j)=1/(1+sump);
```

```
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% Calculating probability of c converters is busy %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
for i=1:ranage
pcn(i)=p0n(i)*(1/factorial(c))*(factorial(W)/
factorial(W-c))*rho(i)^(c*F+c);
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% Calculating blocking probability of multi-fiber
%% share-per node case
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
for i=1:ranage
pn(i)=(1-((1-rho(i)^F)+(rho(i)^F)*(1-pcn(i))*
(1-rho(i)^(W-F)))^H)^W;
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% Calculating throughput of multi-fiber share-per node case%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
for i=1:ranage
Un(i)=(1-pn(i))*G;
end
```

Appendix B

ANALYTICAL MODEL SOURCE CODE: CONVERSION RESOURCES ALLOCATION ALGORITHMS (CRAA)

The source code of the analytical model, which is written in Matlab, to evaluate the blocking probability of different wavelength conversion resources allocation algorithms for the share-per-link wavelength-routed network is shown below. The blocking probability model for NSA explained in detail in Chapter 4.

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% File name: CRAA.m
%% Purpose: To identify the blocking probabilty of
%% the wavelength-routed network employing share-per-
%% link conversion schme.
%% Inputs:
%% DC : Degree of conversion
%% rho: Load per wavelengt
%% G : Source-destination pair load
%% H : Number of hops
%% F : Number of fibers
%% W : Total number of wavelengths per hop
%% c : Number of converters
%% Outputs:
%% p0 : Probability of zero converters is busy
%% pc : Probability of all c converters are busy in
%% the single-fiber case
%% pb : Blocking probability
%% U : Throughput
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
clear all;
clc;
pc=0:0.001:1;
ranage=101;
pc2=zeros(16,1);
rho=.8;
G=0.07;
```

```
F=10;
w=1:1:32;
DC=0.2;
c=ceil(DC*w);
H=10;
pb=zeros(11,1);
n=input(n = );
s=0;
s1=0;
U=zeros(32,1);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% The following section is the implementation of the
%% Inclusive Search Algorithm (ISA). Numerical iteration
%% method is implemented to calculate pc and p0. First p0
%% is calculated by using initial values for pc, which
%% is set above, then new values for the pc is found.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
for j=1:F-1
s1=s1+pc(1)^ j;
end
s1=s1+pc(1)^0;
for k=1:c(1)
x=(1/factorial(k))*(factorial(w(1))/
factorial(w(1)-k))*rho^(k*F+k)*s1^k;
s=s+x;
end
p0=1/(1+s);
pck=(1/factorial(c(1)))*(factorial(w(1))/
factorial(w(1)-c(1)))*(rho^(c(1)*F+c(1)))*p0*s1^c(1);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% The difference between the pervious value of pc and
%% the new calculated value is considered as the tolerance
%% for this numerical iteration method. This tolerance is
%% calculated in the following code line.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
y1=sign(pc(1)-pck);
for i=1:32
for l=2:1001
s=0;
s1=0;
for j=1:F-1
s1=s1+pc(l)^ j;
end
s1=s1+pc(l)^ 0;
```

```
for k=1:c(i)
x=(1/factorial(k))*(factorial(w(i))/
factorial(w(i)-k))*rho^(k*F+k)*s1^k;
s=s+x;
end
p0=1/(1+s);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% The new values of pc is calcualted%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
pck=(1/factorial(c(i)))*(factorial(w(i))/
factorial(w(i)-c(i)))*(rho^(c(i)*F+c(i)))*p0*s1^c(i);
y=sign(pc(1)-pck);
if ((y~=y1)|(y==0))
pc2(i)=pc(1);
break;
end
y1=y;
end
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% Blocking probability of ISA calculation.%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
for i=1:32
pb(i)=1-((1-rho^ F)+(rho^F)*(1-(pc2(i))^ F)*
(1-rho^((w(i)-1))))^ H;
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% Throughput is calculation%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
for i=1:32
U(i)=(1-pb(i))*G;
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% The following section is the implementation
%% of the Narrow Search Algorithm (NSA).
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
sump=0;
%%%%%%%%%%%%%%%%%%%
%% Calculating p0%
%%%%%%%%%%%%%%%%%%%
for j=1:32
for i=1:c(j)
sump=sump+(1/factorial(i))*(factorial(w(j))/
factorial(w(j)-i))*rho^(i*F+i);
```

```
end
p0(j)=1/(1+sump);
end
for i=1:32
pc(i)=p01(i)*(1/factorial(c(i)))*(factorial(w(i))/
factorial(w(i)-c(i)))*rho^(c(i)*F+c(i));
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% Calculating the blocking probability%
%% for NSA. %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
for i=1:32
pb(i)=1-((1-rho^F)+(rho^F)*(1-pcl(i))*
(1-rho^((w(i)-1))))^H;
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% Calculating the throughput of NSA.%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
for i=1:32
U(i)=(1-pb(i))*G;
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% The following section is an implementation of %
%% Inclusive Search Algorithm (OSA). The Numerical %
%% iteration method that is useed for ISA will be %
%% utilized in this algorithm implementation. %
%% The only difference between the implementation of %
%% the numerical iteration method is taht the of wavelength %
%% conversion bank that will be searched in OSA will be %
%% specified. First p0 is calculated by using initial values%
%% for pc, which is set above, then new values for the %
%% pc is found. %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
s=0;
s1=0;
clear pc2;
clear pck;
clear p0;
for j=1:n
s1=s1+pc(1)^j;
end
s1=s1+pc(1)^0;
for k=1:c(1)
x=(1/factorial(k))*(factorial(w(1))/factorial(w(1)-k))
```

```
*rho^(k*F+k)*s1^k;
s=s+x;
end
p0=1/(1+s);
pck=(1/factorial(c(1)))*(factorial(w(1))/factorial(w(1)-c(1)))
*(rho^(c(1)*F+c(1)))*p0*s1^c(1);
y1=0;
y1=sign(pc(1)-pck);
pc2=zeros(32,1);
for i=1:32
y=0;
for l=2:1001
s=0;
s1=0;
for j=1:n
s1=s1+pc(l)^j;
end
s1=s1+pc(l)^0;
for k=1:c(i)
x=(1/factorial(k))*(factorial(w(i))/factorial(w(i)-k))
*(rho^(k*F+k))*(s1^k);
s=s+x;
end
p0=1/(1+s);
pck=(1/factorial(c(i)))*(factorial(w(i))/factorial(w(i)-c(i)))
*(rho^(c(i)*F+c(i)))*p0*s1^c(i);
y=sign(pc(l)-pck);
if ((y~=y1)|(y==0))
pc2(i)=pc(l);
break;
else
y1=y;
end
end
end
for i=1:32
pb(i)=1-((1-rho^F)+(rho^F)*(1-(pc2(i)^(n)))*
(1-rho^((w(i)-1))))^H;
end
for i=1:32
U(i)=(1-pb(i))*G;
end
```

Appendix C

DIFFERENT WAVELENGTH CONVERSION RANGING SIMULATOR

```
/*--------------------------------------------------------------
--             Different Conversion Ranging Simulator
--
--  This simulator was build as a part of my Ph.D dissertation and
presented in Chapter 5.
--  This simulator is used to evaluate the blocking performance
--  of different conversion ranging. These are Any-to-Any,
--  Any-to-Range, Range-to-Any and Rang-to-Range
--  File name: Sim_Range.cpp
-- Inputs:
--      F: Number of fibers
--      w: Number of wavelengths
--      C: number of converters
--      C_T: Conversion type
--      Lambda: Arrival rate
--      Mu: Service rate
--      d: Degree of conversion
-- Outputs:
--      Pb: Switch blocking probability
----------------------------------------------------------------*/
/*--------------------------------------------------------------
--                       Global variables
-- In this Part of the simulator all global variables that are
-- used in the different functions of the simulator are defined
-- These variables are:
-- Mu: The packets service rate
-- Lambda: The packets arrival rate
-- Last_Time: Holds the last packet arrival time
-- Simulator_end_Time: Holds the simulator end time
-- Simulator_start_Time: Holds the simulator starting time
-- d: The conversion range
-- C: Number of converters
```

```
-- Cflag: Flag to identify all packets that get converted
-- Busy_C : Holds how many converters are busy per iteration
-- Busy_Out: number of busy wavelengths per outputper iteration
-- Seed1: The Initial seed used to generate the packet arrival time
-- Seed2: The Initial seed used to generate the packet length
-- Seed3: Initial seed used by wavelength assignment
-- algorithm to pick
-- one of the free wavelengths
-- Seed 4: The Initial seed that used to by the wavelength
--  assignment to pick one of the free converters
-- Last_Packet: It is used to keep track the number
-- of packets generated
-----------------------------------------------------------------*/
#include "list.h"
double Mu=0.0;
double Lambda=0.0;
__int64 Last_Time=0;
__int64 Simulator_end_Time=0;
__int64 Simulator_start_Time=0;
int d=-1;
int C=-1;
int Cflag=0;
int Busy_C=0;
int Busy_Out=0;
__int64 Seed1=3;
__int64 Seed2=7;
__int64 Seed3=11;
__int64 Seed4=15;
long Last_Packet=0;
int No_of_Input;
__int64 dpc1;
__int64 dpc2;
__int64 dpc1o;
__int64 dpc2o;
/*---------------------------------------------------------------
--                      Random generator module
-- There are two functions in this module. The First one is
-- used to generate the seed that will be use to generate the
-- next random variable. The second function is the actual
-- implementation of the LCG random generator.
-----------------------------------------------------------------*/
/*--------------------------------------------------------
--                          GenerateSeed function
-- Function return type: 64 bit integer
```

```
-- Calld in variables funtion: Seed- 64 bit integer
-- Returned funtion variable : a - 64 bit integer
-----------------------------------------------------*/
__int64 GenerateSeed(__int64 Seed)
{
   __int64 a=0;
   a =(__int64)(labs((16807 * Seed) % (2147483647)));
   return a;
}
/*--------------------------------------------------
--                            Generateu function
-- Function return type: bouble
-- Calld in variables funtion: Seed- 64 bit integer
-- Returned funtion variable : u - double
----------------------------------------------------*/
double Generateu(__int64 Seed)
{
   double u=0.0;
   u = ((double)(Seed) / (double)2147483647);
   return u;
}
/*------------------------------------------------------------
--                     Packet generation module
-- There are two functions in this module. The First function
-- is used to generate the release resources packets.
-- The second function is the used to generate the data
-- packet events.
----------------------------------------------------------*/
/*----------------------------------------------------------
--                            C_packet function
-- Function return type: packet class type
-- Called in variables function: c- packet class type
-- Returned function variable : Current_Packet - packet class type
-- The called function passes the c packet pointer to this function.
-- the C_packet function extract the necessary information from
-- the packet such as Sourcs, wavelength, Fiber, conversion flag,
-- Packet ID, Departure_Time, then it generate a new packet event
-- and set the departure time for this new packet as departure time
-- of the original packet plus the original packet length
---------------------------------------------------------------*/
packet *C_packet(packet *c)
{
   int Intialize_Time=0;
   packet *Current_Packet=NULL;
```

```
   Current_Packet=new packet();
   Current_Packet->Departure_Time=c->Departure_Time+
   (long)c->Packet_Length;
   Current_Packet->Initial_Time=c->Departure_Time;
   Current_Packet->Packet_Length=c->Packet_Length;
   Current_Packet->Lambda=c->Lambda;
   Current_Packet->F=c->F;
   Current_Packet->C_Flag=c->C_Flag;
   Current_Packet->Packet_Type='R';
   Current_Packet->Packet_ID=c->Packet_ID;
   Current_Packet->Prev_Packet=NULL;
   Current_Packet->Next_Packet=NULL;
   return Current_Packet;
}
/*----------------------------------------------------------------
--                         Generate_packet function
-- Function return type: packet class type
-- Returned function variable : Current_Packet - packet class type
-- The called function passes the node information as variable node
-- of type class node1, this variable contains all node infromation
-- such as conversion type number of inputs, number of outputs,
-- wavelengths, number of fibers and some information about the last
-- genearted packet such as time of generation, seed etc.
-- called functions:
-- GenerateSeed: To generate a new interarrival time seed and packet
-- length seed
-- Generateu: To genetrate a uniform random number
----------------------------------------------------------------*/
packet *Generate_packet(node1 *node,int w)
{
   double u=0.0;
   __int64 temp_time=0;
   __int64 x1=0;
   __int64 temp_length=0;
   packet *Current_Packet=NULL;
   Current_Packet=new packet();
   Current_Packet->Packet_Type='D';
   Current_Packet->C_Flag=0;
   Current_Packet->Packet_ID=Last_Packet+1;
   Last_Packet++;
   Current_Packet->Source=99;
   u=Generateu(Seed1);
   Seed1=GenerateSeed(Seed1);
   temp_time=(__int64)((-1.0/Lambda)*log(1-u));
```

```
  x1=Last_Time+temp_time;
  Current_Packet->Initial_Time=x1;
  Current_Packet->Arrival_Time=x1;
  Current_Packet->Departure_Time=x1;
  Last_Time=x1;
  u=0.0;
  u=Generateu(Seed2);
  Seed2=GenerateSeed(Seed2);
  temp_length=(__int64)((-1.0/Mu)*log(1-u));
  Current_Packet->Packet_Length=temp_length;
  Current_Packet->Prev_Packet=NULL;
  Current_Packet->Next_Packet=NULL;
  u=0.0;
  u=Generateu(Seed3);
  Seed3=GenerateSeed(Seed3);
  int y = (int)(u*node->Out_W);
  Current_Packet->Lambda=y;
  Current_Packet->F=0;
  Current_Packet->C_Flag=-1;
  return Current_Packet;
}
/*----------------------------------------------------------------
--                         Releas_Resources function
-- Function return type: packet class type
-- Returned function variable : c-packet class type
-- The called function passes node & packet information
-- event that conatins all the infromtion of the resources
-- need to be updated such as output port which identified
-- by the wavelength number and the fiber fiels in the c event.
-- also this function check the c_flag
-- field of the c pacekt event passed to the fucntion to figure
-- out if there is a conversion resource need to be updated.
-- the function delete the event c from the event list after
-- release all resources researved by the
-- c event and return a new event list header.
---------------------------------------------------------------*/
packet *Releas_Resources(packet *c, node1 *node)
{
  list LIST;
  packet *temp=NULL;
  temp=c;
  node->Out_Port[c->Lambda][c->F]=1;
  if (c->C_Flag!=-1)
  {
```

```
    dpc1=dpc2;
    dpc2=c->Departure_Time;
    node->C[c->C_Flag].C_Status=1;
    Busy_C--;
    node->C[0].Pbusy[Busy_C+1]=node->C[0].Pbusy[Busy_C+1]+
    (dpc2-dpc1);
  }
  dpc1o=dpc2o;
  dpc2o=c->Departure_Time;
  Busy_Out--;
  node->C[1].Pbusy[Busy_Out+1]=node->C[1].Pbusy[Busy_Out+1]+(
  dpc2o-dpc1o);
  c=LIST.Delete_From_List(temp);
  return c;
}
/*------------------------------------------------------------
--                           Blocked_Packet function
-- Function return type: packet class type
-- Called in variables function: c - packet class type,
-- node -node class type Returned function variable
-- : c - packet class type
-- The called function passes the node information as well as
-- the packet event that conatins all the infromtion of the
-- blocked packet this function call Generate packet function
-- to generate a new pacekt using the same wavelength of
--  the dropped one. then it deleted the dropped packet
-- from the event list and insert the new generated packet and
-- return the header of the event list to the called function.
--------------------------------------------------------------*/
packet *Blocked_Packet(packet *c, node1 *node)
{
  list LIST;
  packet *temp;
  temp=NULL;
  node->blocked++;
  node->C[2].Attempt[Busy_C]++;
  temp=Generate_packet(node,c->Lambda);
  c=LIST.Delete_From_List(c);
  c=LIST.Insert_To_List (c,temp);
  return c;
}
/*--------------------------------------------------------------
--                           Any_To_Any
-- Function return type: packet class type
```

```
-- Called in variables function: c - packet class type,
-- node -node class type
-- Returned function variable : c - packet class type
-- This function is called if the conversion option is any-to-any,
-- and used to check for a free converter and wavelength in the
-- case of the original requested wavelength is busy.
----------------------------------------------------------------------*/
packet *Any_To_Any(packet *c, node1 *node)
{
  int c1=-1;
  int w=-1;
  int f=-1;
  int count=0;
  double m=-1.0;
  int y=-1;
  packet *temp=NULL;
  packet *temp1=NULL;
  list LIST;
  int *Free=new int[C];
  for (int i=0;i<C;i++)
    Free[i]=-1;
  do{
    count=0;
    m=Generateu(Seed4);
    Seed4=GenerateSeed(Seed4);
    y=(int)(m*C);
    if ((node->C[y].C_Status==1))
    {
     c1=y;
     break;
    }
    Free[y]=1;
    for(int i=0;i<C;i++)
    {
     count+=Free[i];
    }
     if (count==C)
       break;
   }while (c1==-1);
   delete[] Free;
   int *Free1=new int[node->Out_W];
   for (i=0;i<node->Out_W;i++)
      Free1[i]=-1;
   count=0;
```

```
m=-1.0;
y=-1;
for (int j=0;j<node->Out_F;j++)
{
 for (i=0;i<node->Out_W;i++)
 {
  if (node->Out_Port[i][j]==1)
  {
   Free1[count]=i;
   count++;
  }
 }
}
m=Generateu(Seed3);
Seed3=GenerateSeed(Seed3);
y=(int)(m*count);
w=Free1[y];
f=0;
delete[] Free1;
node->C[0].Attempt[Busy_C]++;
node->C[1].Attempt[Busy_Out]++;
if((c1!=-1)&&(w!=-1)&&(f!=-1))
{
  node->Arrived_Packet++;
  node->Out_Port[w][f]=0;
  node->C[c1].C_Status=0;
  Busy_C++;
  Busy_Out++;
  dpc1=dpc2;
  dpc2=c->Departure_Time;
  dpc1o=dpc2o;
  dpc2o=c->Departure_Time;
  node->C[1].Pbusy[Busy_Out-1]=node->C[1].Pbusy[Busy_Out-1]+
  (dpc2o-dpc1o);
  node->C[0].Pbusy[Busy_C-1]=node->C[0].Pbusy[Busy_C-1]+
  (dpc2-dpc1);
  temp1=Generate_packet(node,c->Lambda);
  c->C_Flag=c1;
  c->Lambda=w;
  c->F=f;
  node->Th[c->Lambda][c->F]+=c->Packet_Length;
  temp=C_packet(c);
  c=LIST.Delete_From_List(c);
  c=LIST.Insert_To_List (c,temp1);
```

```
    c=LIST.Insert_To_List (c,temp);
  }else
  {
    c=Blocked_Packet(c,node);
  }
  return c;
}
/*-----------------------------------------------------------------
--                         Any_To_Range Function
-- Function return type: packet class type
-- Called in variables function: c - packet class type,
-- node -node class type
-- Returned function variable : c - packet class type
-- this fucntion is called if the conversion option is
-- any-to-range, and used
-- to check for a free conveter and wavelength in the case
-- of the original requested wavelength is busy.
-----------------------------------------------------------------*/
packet *Any_To_Range(packet *c, node1 *node)
{
  int c1=-1;
  int w=-1;
  int f=-1;
  packet *temp=NULL;
  packet *temp1=NULL;
  list LIST;
  int count=0;
  double m=1.0;
  int y=0;
  int *Free=new int[C];
  int Fre[256];
  for (int i=0;i<C;i++)
  {
    Free[i]=-1;
  }
  for (i=0;i<node->Out_W;i++)
   Fre[i]=-1;
  for (i=0;i<C;i++)
  {
   if (node->C[i].C_Status==1)
   {
     for (int j=0;j<node->Out_F;j++)
     {
       for (int k=node->C[i].Out_S_Range;k<=node->
```

```
        C[i].Out_E_Range;k++)
        {
          if (node->Out_Port[k][j]==1)
          {
            Free[count]=i;
            count++;
            break;
          }
        }
      }
     }
    }
    if (count>0)
    {
      m=Generateu(Seed4);
      Seed4=GenerateSeed(Seed4);
      y=(int)(m*count);
      c1=Free[y];
      count=0;
      m=-1.0;
      y=-1;
      for (i=0;i<node->Out_F;i++)
      {
        for (int j=node->C[c1].Out_S_Range;j<=node->
        C[c1].Out_E_Range;j++)
        {
          if (node->Out_Port[j][i]==1)
          {
            Fre[count]=j;
            count++;
          }
        }
      }
      if (count>0)
      {
        m=Generateu(Seed3);
        Seed3=GenerateSeed(Seed3);
        y=(int)(m*count);
        w=Fre[y];
        f=0;
      }
    }
    delete[] Free;
    if((c1!=-1)&&(w!=-1)&&(f!=-1))
```

```
  {
    Busy_C++;
    Busy_Out++;
    node->Arrived_Packet++;
    node->Out_Port[w][f]=0;
    node->C[c1].C_Status=0;
    temp1=Generate_packet(node,c->Lambda);
    c->C_Flag=c1;
    c->Lambda=w;
    c->F=f;
    node->Th[c->Lambda][c->F]+=c->Packet_Length;
    temp=C_packet(c);
    c=LIST.Delete_From_List(c);
    c=LIST.Insert_To_List (c,temp1);
    c=LIST.Insert_To_List (c,temp);
  }else
  {
    c=Blocked_Packet(c,node);
  }
  return c;
}
/*----------------------------------------------------------------
--                         Range_To_Any Function
-- Function return type: packet class type
-- Called in variables function: c - packet class type,
-- node -node class type
-- Returned function variable : c - packet class type
-- this fucntion is called if the conversion option is
-- Range_To_Any, and used
-- to check for a free conveter and wavelength in the
-- case of the original requested wavelength is busy.
----------------------------------------------------------------*/
packet *Range_To_Any(packet *c, node1 *node)
{
  int c1=-1;
  int w=-1;
  int f=-1;
  packet *temp=NULL;
  packet *temp1=NULL;
  list LIST;
  int count=0;
  double m=1.0;
  int y=0;
  int *Free=new int[node->Out_W];
```

```
for (int i=0;i<C;i++)
{
  if ((node->C[i].In_S_Range<=c->Lambda)&&(c->Lambda<=node->
  C[i].In_E_Range))
  {
    c1=i;
    break;
  }
}
for (i=0;i<node->Out_W;i++)
{
  Free[i]=-1;
}
if (node->C[c1].C_Status==1)
{
  for (i=0;i<node->Out_F;i++)
  {
    for (int j=0;j<=node->Out_W;j++)
    {
     if (node->Out_Port[j][i]==1)
     {
       Free[count]=j;
       count++;
     }
    }
   }
   if (count>0)
   {
     m=Generateu(Seed3);
     Seed3=GenerateSeed(Seed3);
     y=(int)(m*count);
     w=Free[y];
     f=0;
   }
 }
 delete[] Free;
 if((c1!=-1)&&(w!=-1)&&(f!=-1))
 {
   Busy_C++;
   Busy_Out++;
   node->Arrived_Packet++;
   node->Out_Port[w][f]=0;
   node->C[c1].C_Status=0;
   temp1=Generate_packet(node,c->Lambda);
```

```
    c->C_Flag=c1;
    c->Lambda=w;
    c->F=f;
    node->Th[c->Lambda][c->F]+=c->Packet_Length;
    temp=C_packet(c);
    c=LIST.Delete_From_List(c);
    c=LIST.Insert_To_List (c,temp1);
    c=LIST.Insert_To_List (c,temp);
  }else
  {
    c=Blocked_Packet(c,node);
  }
  return c;
}
/*-----------------------------------------------------------------
--                          Range_To_Range Function
-- Function return type: packet class type
-- Called in variables function: c - packet class type,
-- node -node class type
-- Returned function variable : c - packet class type
-- this fucntion is called if the conversion option is
-- Range_To_Range, and used
-- to check for a free conveter and wavelength in the case
-- of the original requested wavelength is busy.
-------------------------------------------------------------------*/
packet *Range_To_Range(packet *c, node1 *node)
{
  int c1=-1;
  int w=-1;
  int f=-1;
  packet *temp=NULL;
  packet *temp1=NULL;
  list LIST;
  for (int i=0;i<C;i++)
  {
    if ((node->C[i].In_S_Range<=c->Lambda)&&(c->Lambda<=node->
    C[i].In_E_Range))
    {
      c1=i;
      break;
    }
  }
  int count=0;
  double m=1.0;
```

```
int y=0;
int *Free=new int[d];
for (i=0;i<d;i++)
{
  Free[i]=-1;
}
if (node->C[c1].C_Status==1)
{
  for (i=0;i<node->Out_F;i++)
  {
     for (int j=node->C[c1].Out_S_Range;j<=node->
     C[c1].Out_E_Range;j++)
     {
       if (node->Out_Port[j][i]==1)
       {
         Free[count]=j;
         count++;
       }
     }
  }
  if (count>0)
  {
    m=Generateu(Seed3);
    Seed3=GenerateSeed(Seed3);
    y=(int)(m*count);
    w=Free[y];
    f=0;
  }
}
delete[] Free;
if((c1!=-1)&&(w!=-1)&&(f!=-1))
{
  Busy_C++;
  Busy_Out++;
  node->Arrived_Packet++;
  node->Out_Port[w][f]=0;
  node->C[c1].C_Status=0;
  temp1=Generate_packet(node,c->Lambda);
  c->C_Flag=c1;
  c->Lambda=w;
  c->F=f;
  node->Th[c->Lambda][c->F]+=c->Packet_Length;
  temp=C_packet(c);
  c=LIST.Delete_From_List(c);
```

```
    c=LIST.Insert_To_List (c,temp1);
    c=LIST.Insert_To_List (c,temp);
  }else
  {
    c=Blocked_Packet(c,node);
  }
  return c;
}
/*-------------------------------------------------------------------
                        Conversion1 function
-- Function return type: packet class type
-- Called in variables function: c - packet class type,
-- node -node class type
-- Returned function variable : c - packet class type
-- in this function a continuous wavelength for the current
-- packet is checked if the requested wavelength is available
-- on the out put then it reserved increment the number
-- of arrived packet counter change the status of the
-- wavelength to busy and call C_packet function to generate
-- release packet to release the reserved resources.
-- if the requested wavelength is busy it will call one
-- of the conversion option function mentioned
-- above depend on the C_T field in the node, which indicate
-- the conversion  option that adopted by the simulated node.
-------------------------------------------------------------------*/
packet *Conversion1(packet *c, node1 *node)
{
  packet *temp=NULL;
  packet *temp1=NULL;
  list LIST;
  ++node->Pro_Packet;
  if(node->Out_Port[c->Lambda][c->F]==1)
  {
    Busy_Out++;
    dpc1o=dpc2o;
    dpc2o=c->Departure_Time;
    node->C[1].Pbusy[Busy_Out-1]=node->C[1].Pbusy[Busy_Out-1]
    +(dpc2o-dpc1o);
    node->Arrived_Packet++;
    node->Th[c->Lambda][c->F]+=c->Packet_Length;
    node->Out_Port[c->Lambda][c->F]=0;
    c->C_Flag=-1;
    temp=C_packet(c);
    temp1=Generate_packet(node,c->Lambda);
```

```
    c=LIST.Delete_From_List(c);
    c=LIST.Insert_To_List (c,temp1);
    c=LIST.Insert_To_List (c,temp);
  }else if(node->C_T==0)
  {
    c=Any_To_Any(c,node);
  }else if(node->C_T==1)
  {
    c=Any_To_Range(c,node);
  }else if (node->C_T==2)
  {
    c=Range_To_Any(c,node);
  }else if( node->C_T==3)
  {
    c=Range_To_Range(c,node);
  }
  else
  {
    c=Blocked_Packet(c,node);
  }
  return c;
}
/*-------------------------------------------------------------------
                        Packet_Processing function
-- Function return type: packet class type
-- Called in variables function: c - packet class type,
-- node -node class type
-- Returned function variable : c - packet class type
-- depend of the event type if data or release this
--function call either
-- Conversion1 function or Releas_Resources
-------------------------------------------------------------------*/
packet *Packet_Processing(packet *c, node1 *node)
{
  if(c->Packet_Type=='D')
  {
    c=Conversion1 (c,node);
  }
  else if(c->Packet_Type=='R')
  {
    c=Releas_Resources(c,node);
  }
  return c;
}
```

```
/*-----------------------------------------------------------
                        List_Processing function
-- Function return type: packet class type
-- node-node class type Called in variables function: head-packet
-- class type, Returned function variable : NULL
-- This function get the header of the event list and pass it
-- to the packet processing function to be processed. Also this
-- function keep track of  how many packets get processed and
-- calculate the blocking probability
-- if this number reach 1000000 packet event. if the tolerance
-- between the current blocking probability and the pervious
-- from the pervious iteration less 0.0001 the simulator will
-- be ended after the computer memory get cleaned by deleting
-- all the event list.
-------------------------------------------------------------*/
packet *List_Processing(packet *head, node1 *node)
{
   packet *temp;
   temp=NULL;
   temp=head;
   double pb=0;
   double pb1=0;
   double epslon=0.0;
   long Packet_Count=0;
   int exit=-1;
   dpc1=0;
   dpc2=0;
   dpc1=dpc2=temp->Departure_Time;
   dpc1o=0;
   dpc2o=0;
   dpc1o=dpc2o=temp->Departure_Time;
   while (temp->Next_Packet!=NULL)
   {
    if((temp->Packet_Type=='D'))
       Packet_Count++;
    temp=Packet_Processing(temp,node);
    Simulator_end_Time=temp->Departure_Time;
    if ((Packet_Count==1000000)&&(exit==-1))
    {
      pb=(double)(node->blocked)/(double)(node->Pro_Packet);
      epslon=fabs(pb-pb1);
      if (epslon<=0.0001)
      {
        Packet_Count=0;
```

```
        node->blocked=0;
        node->Arrived_Packet=0;
        node->Pro_Packet=0;
        pb1=pb;
        exit=0;
      }else
      {
        Packet_Count=0;
        node->blocked=0;
        node->Arrived_Packet=0;
        node->Pro_Packet=0;
        pb1=pb;
      }
    }
    if(Packet_Count==1000000)
    {
      pb=(double)(node->blocked)/(double)(node->Pro_Packet);
      cout<<endl<<"Blocked "<<node->blocked;
      cout<<endl<<"Arrived "<<node->Arrived_Packet;
      cout<<endl<<"Processed "<<node->Pro_Packet;
      cout<<endl<<"Blocking ="<<pb;
      break;
    }
  }
  while(temp!=NULL)
  {
    head=temp->Next_Packet;
    delete temp;
    temp=head;
  }
  cout.flush();
  return NULL;
}
/*------------------------------------------------------------------
                        Event_Handeler function
-- Function return type: Void
-- Called in variables function: node -node class type
-- Returned function variable : NULL
-- This function generates the initial event list and set up the
-- simulator starting time to the time of the first event will be
-- processed
--------------------------------------------------------------------*/
void Event_Handeler(node1 *node)
{
```

```
  __int64 Simulation_Time=0;
  packet *Event_Head=NULL;
  list LIST;
  packet *c1=NULL;
  for(int j=0;j<node->Out_W;j++)
  {
    c1=Generate_packet(node,j);
    Event_Head=LIST.Insert_To_List(Event_Head,c1);
  }
  Simulator_start_Time=Event_Head->Departure_Time;
  if(Event_Head!=NULL)
     Event_Head=List_Processing(Event_Head,node);
  Simulation_Time=Simulator_end_Time-Simulator_start_Time;
  __int64 sum=0;
  cout<<endl<<"--------------------------------------------";
  cout.flush();
}
/*-----------------------------------------------------------------
                       Node_Intiliaze function
-- Function return type: node class type
-- Called in variables function:
-- Returned function variable : node
-- This function generate the initial all variables of the node
------------------------------------------------------------------*/
node1 *Node_Intiliaze()
{
  node1 *n=new node1();
  int F;
  int w;
  int C_T;
  cout<<"Please Enter the The Arrival rate";
  cin>>Lambda;
  cout<<endl<<"Please Enter the Service rate per wavelength ";
  cin>>Mu;
  cout<<endl<<"Ouput Fibers ";
  cin>>F;
  cout<<endl<<"Number of wavelength per fiber ";
  cin>>w;
  cout<<endl<<"Conversion Type ";
  cin>>C_T;
  cout<<endl<<"No of Converters";
  cin>>C;
  Cflag=C_T;
  n->Out_F=F;
```

```
  n->Out_W=w;
  n->C_T=C_T;
  Lambda=Lambda*n->Out_W;
  cout<<endl<<"Enter d";
  cin>>d;
  n->Out_Port_Initialization(C,d);
  return n;
}
void main()
{
  node1 *node=NULL;
  node=Node_Intiliaze();
  Event_Handeler(node);
}
```

Appendix D

SYMMETRIC/ASYMMETRIC SYNCHRONOUS PACKET SWITCH ANALYTICAL MODEL

N	Number of Inputs/Outputs of the switch
F	Number of fibers per output
w	Number of wavelengths per fiber
C	Number of converters shared per output link
X_i	Random variable representing the number of packets present at an output on λ_i in a slot time where $i = 1, ..., w$
Y_i	Random variable representing the number of packet that are forwarded for conversion from λ_i
N_Y	Random variable representing the number of input wavelengths that compete for conversion
G_i	Random variable that represents number of free λ_i
B	Random variable representing the total number of free wavelengths on the outputs prior to allocating output of converters
$E[d]$	Expected number of packets lost
T	Random variable representing the total number of packets forwarded for conversion
$E[T]$	Average number of packets forwarded to the conversion bank
A	Random variable representing packets utilizing the conversion bank
$E[A]$	Average number of packets that will utilize the conversion resources
$E[\xi]$	The expected number of the total packet arrivals to the output

D.0.1 Symmetric Traffic Model

The analytical model for the symmetric optical packet switch we developed in this section of the appendix is presented in detail in [2, 35, 36].

```
--------------------------------------------------
Probability that there are x arrival on a wavelength
--------------------------------------------------
```

$$P(X_i = x) = \binom{NF}{x} \cdot \left(\frac{\rho}{N}\right)^x \cdot \left(1 - \frac{\rho}{N}\right)^{N \cdot F - x} \tag{D.1}$$

```
--------------------------------------------------
Probability there are y packets forwarded to the
conversion bank from a wavelength
--------------------------------------------------
```

$$P\left(Y_i = y | X_i > F\right) = \frac{P\left(Y_i = y \bigcap X_i > F\right)}{P\left(X_i > F\right)} \tag{D.2}$$

$$P\left(Y_i = y \bigcap X_i > F\right) = P\left(X_i = y + F\right) \tag{D.3}$$

$$P\left(X_i = y + F\right) = \binom{N}{y+F} \cdot \left(\frac{\rho}{N}\right)^{y+F} \cdot \left(1 - \frac{\rho}{N}\right)^{N-y-F} \tag{D.4}$$

$$P\left(Y_i = y | X_i > F\right) = \binom{N}{y+F} \cdot \left(\frac{\rho}{N}\right)^{y+F} \cdot \frac{\left(1 - \frac{\rho}{N}\right)^{N-y-F}}{1 - \sum_{j=0}^{F} P(X_i = j)} \tag{D.5}$$

```
-------------------------------------------------------
The probability that there is ny wavelengths that have
more than F arrivals (number of Y's)
-------------------------------------------------------
```

$$P\left(N_Y = n_y\right) = \binom{w}{n_y} \left(\sum_{j=F+1}^{N \cdot F} P(X = j)\right)^{n_y} \cdot \left(\sum_{j=0}^{F} P(X = j)\right)^{w-n_y} \tag{D.6}$$

```
-------------------------------------------------------
The probability that there is g copies of
a wavelength are free
-------------------------------------------------------
```

$$P\left(Gi = g | X_i \leq F\right) = \frac{P\left(G_i = g \bigcap X_i \leq F\right)}{P\left(X_i \leq F\right)} \tag{D.7}$$

$$P\left(G_i = y \bigcap X_i \leq F\right) = P\left(X_i = F - g\right) \tag{D.8}$$

$$P\left(G_i = g | X_i \leq F\right) = \frac{P\left(X_i = F - g\right)}{\sum_{j=0}^{F} (P(X = j))} \tag{D.9}$$

D.0.2 Asymmetric Traffic Model

The analytical model for the asymmetric optical packet switch we developed in this section of the appendix is presented in detail in [3].

```
----------------------------------------------------
Probability that there are x arrival on a wavelength
----------------------------------------------------
```

$$P(X_{ij} = x) = \binom{F}{x} \cdot \left(\frac{\rho_{ij}}{N}\right)^{x} \cdot \left(1 - \frac{\rho_{ij}}{N}\right)^{F-x} \tag{D.10}$$

$$X_t = \sum_{i=1}^{N} X(i) \tag{D.11}$$

$$H_{X_i}(z) = \sum_{x=0}^{F} (P(X_i = x_i) \cdot z^{x} \tag{D.12}$$

$$H_{X_t}(z) = \left[\sum_{x=0}^{F} (P(X_i = x_i) \cdot z^{x}\right]^{N} \tag{D.13}$$

$$P(X_t = x_t) = \begin{cases} \prod_{i=1}^{N} X_i(0)\ if & x_i = 0 \\ (d^{x_t}/dz^{X_t}) \cdot H_{X_t}(z) & \text{otherwise} \end{cases} \tag{D.14}$$

```
---------------------------------------------------
Probability there are y packets forwarded to the
conversion bank from a wavelength
---------------------------------------------------
```

$$P(Y_i = y | X_t > F) = \frac{P(Y_i = y \bigcap X_t > F)}{P(X_t > F)} \tag{D.15}$$

$$P\left(Y_i = y \bigcap X_t > F\right) = P(X_t = y + F) \tag{D.16}$$

$$P(X_t = y + F) = \binom{NF}{y+F} \cdot \left(\frac{\rho_i}{N}\right)^{y+F} \cdot \left(1 - \frac{\rho_i}{N}\right)^{N-y-F} \tag{D.17}$$

$$P(Y_i = y | X_t > F) = \binom{NF}{y+F} \left(\frac{\rho_i}{N}\right)^{y+F} \left[\frac{\left(1 - \frac{\rho_i}{N}\right)^{N-y-F}}{\left(1 - \sum_{j=0}^{F} P(X_t = j)\right)}\right] \tag{D.18}$$

```
-----------------------------------------------------
The probability that there is ny wavelengths that have
more than F arrivals (number of Y's)
-----------------------------------------------------
```

$$P(N_Y = n_y) = \binom{w}{n_y} \left(\sum_{i=F+1}^{N \cdot F} P(X_t = i)\right)^{n_y} \cdot \left(\sum_{i=0}^{F} P(X_t = i)\right)^{w-n_y} \tag{D.19}$$

```
-----------------------------------------------------
Probability that there are g copies of a wavelength
are free
-----------------------------------------------------
```

$$P\left(Gi = g | X_t \leq F\right) = \frac{P\left(G_i = g \bigcap X_t \leq F\right)}{P\left(X_t \leq F\right)} \tag{D.20}$$

$$P\left(G_i = y \bigcap X_t \leq F\right) = P\left(X_t = F - g\right) \tag{D.21}$$

$$P\left(G_i = g | X_t \leq F\right) = \frac{P\left(X_t = F - g\right)}{\sum_{j=0}^{F}(P(X_t = j))} \tag{D.22}$$

D.0.3 Common Analysis

```
-----------------------------------------------------
Probability that there are beta free wavelengths on
the output
-----------------------------------------------------
```

$$B = \sum_{i=0}^{w}(G_i) \tag{D.23}$$

$$P\left(B = \beta | N_Y = n_y\right) = P(\sum_{i=0}^{w-n_y}(G_i) = \beta) \tag{D.24}$$

$$H_{G_i}(z) = \sum_{g=0}^{F}(P(G_i = g) \cdot z^g \tag{D.25}$$

$$H_B(z)|_{n_y} = \left[\sum_{g=0}^{F}(P(G_i = g) \cdot z^g\right]^{w-n_y} \tag{D.26}$$

$$P\left(B = \beta | N_Y = n_y\right) = \begin{cases} 0 & n_y = w \\ (d^\beta / dz^\beta) \cdot H_B(z)|_{z=0} & \text{otherwise} \end{cases} \tag{D.27}$$

```
-----------------------------------------------------
Blocking probability
-----------------------------------------------------
```

$$P_b = \frac{E[d]}{E[\xi]} \tag{D.28}$$

$$T|_{n_y} = \sum_{i=1}^{n_y}(Y_i) \tag{D.29}$$

```
-----------------------------------------------------
Probability that there are alpha packets forwarded
to the conversion bank
-----------------------------------------------------
```

$$P\left(T=\alpha|N_Y=n_y\right)=P(\sum_{i=1}^{n_y}(Y_i)=\alpha) \tag{D.30}$$

$$H_{Y_i}(z)=\sum_{y=1}^{NF-F}\left(P(Y_i=y)\cdot z^y\right. \tag{D.31}$$

$$H_T(z)|_{n_y}=\left[\sum_{y=1}^{NF-F}\left(P(Y_i=y)\cdot z^y\right.\right]^t \tag{D.32}$$

$$P(T=\alpha|N_Y=n_y)=\frac{d^\alpha}{dz^\alpha}\cdot H_T(z)|_{z=0} \tag{D.33}$$

```
---------------------------------------------------
Expected number of the total number of packets that
are forwarded to the conversion bank
---------------------------------------------------
```

$$E[T|N_Y=n_y]=E[\sum_{i=1}^{n_y}Y_i]=\sum_{i=1}^{n_y}E[Y_i] \tag{D.34}$$

$$E[T|N_Y=n_y]=n_y\cdot E[Y] \tag{D.35}$$

$$E[T]=\sum_{n_y=0}^{w}P(N_Y=n_y)\cdot(n_y\cdot E[Y]) \tag{D.36}$$

```
---------------------------------------------------
Expected number of forwarded packets to the
conversion bank
---------------------------------------------------
```

$$E[Y]=\sum_{j=1}^{N\cdot F-F}\left(j\cdot P(Y=j)\right) \tag{D.37}$$

$$A=\begin{cases}\mathrm{T,if}\ n_y\leq min(C,\beta)\ and\ T\leq min(C,\beta)\\ \\ min(C,\beta),\mathrm{otherwise}\end{cases} \tag{D.38}$$

```
---------------------------------------------------
Expected number of accepted packets by the
conversion bank
---------------------------------------------------
```

$$E[A|_{n_y,\beta}] = \begin{cases} min(C,\beta), \text{ if } min(C,\beta) < n_y \\ \sum_{j=n_y}^{min(C,\beta)} (j \cdot P(T=j)) + min(C,\beta) \cdot \\ (\sum_{j=min(C,\beta)+1}^{n_y(F(n-1))} P(T=j)), \text{ otherwise} \end{cases} \tag{D.39}$$

$$E[A] = \sum_{n_y=1}^{w} (P(N_Y = n_y) \sum_{\beta=0}^{(w-n_y)F} P(B=\beta) \cdot (E[A|N_Y = n_y, B = \beta])) \tag{D.40}$$

$$E[d] = E[T] - E[A] \tag{D.41}$$

$$E[\xi]_{symmetric} = w \cdot F \cdot \rho \tag{D.42}$$

$$E[\xi]_{asymmetric} = \sum_{i=1}^{N} \frac{w \cdot F \cdot \rho_i}{N} \tag{D.43}$$

Conversion bank utilization

$$U = \frac{E[A]}{C} \tag{D.44}$$

Appendix E

SYMMETRIC PACKET SWITCH NETWORK ANALYTICAL MODEL IN MAPLE

The source code of the analytical model, which is written in Maple, to evaluate the blocking probability of the optical packet switch with share-per-link conversion is shown below.

```
#######################################################
## File name: OPS.mws
##
## Purpose: To identify the blocking probabilty of
## the OPS employing share-per-link conversion schme.
##
## Inputs:
## N : Number of inputs/outputd of the switch
## rho: Load per wavelengt
## w : Number of wavelengths per fiber
## F : Number of fibers
## C : Number of converters
## H : Number of hops
##
## Outputs:
## PB1 : Switch blocking probability
#######################################################
############################
# Switch paramters settings
############################
N:=4:rho:=1.0:w:=32:C:=4:F:=3:
#######################################################
# Probability that there are x arrival on a wavelength
#######################################################
X := (x) -> binomial(N*F,x)*(((rho)/N)^x)*((1-((rho)/N))^((N*F)-x)):
#############################################################
# The probability that there is n Ys that will constitute T
#############################################################
NY := (n) -> binomial(w,n)*((sum(X(i),i=(F+1)..N*F))^n)
```

```
*(sum(X(i),i=0..F))^(w-n):
##############################################################
#Probability there are y packets forwarded to the conversion
#bank from a wavelength
###############################################################
Y := (y) -> X(y+F)/(sum(X(i),i=(F+1)..N*F)):
#########################################################
#Expected number of forwarded packets to the conversion
#########################################################
EY:= sum(j*Y(j),j=1..N*F-F):
###############################################################
#Probability that there are g copies of a wavelength are free
###############################################################
G := (g) -> X(F-g)/(sum(X(i),i=0..F)):
##################################################
#G random number probability generating function
##################################################
tmp1:=(sum(G(g)*z^g,g=0..F))^tt:
#################################################################
# Probability that there are beta free wavelengths on the output
#################################################################
B := proc(ny,beta)
if (ny=w) then 0;
elif (beta=0) then (G(0))^(w-ny);
else eval(diff(eval(tmp1,tt=(w-ny)),z$beta)/beta!,z=0):
end if:
end proc:
##############################################################
# Correspondong to those wavelengths that dont contribute to
#Ys considered in formulating T
##############################################################
tmp2:=(sum(Y(y)*z^y,y=1..(N*F-F)))^tt:
#####################################################
# Probability that there are alpha packets forwarded
# to the conversion
#####################################################
T := (t,k) -> eval(diff(eval(tmp2,tt=t),z$k)/k!,z=0):
######################################################
# Expected number of the total number of packets that
# are forwarded to the conversion
######################################################
ET := sum(NY(ny)*(ny*EY),ny=0..w);
#######################################################
#Expected number of accepted packets by the conversion
```

```
#########################################################
EA:=sum(NY(ny)*sum(B(ny,beta)*sum(min(j,min(beta,C))*
T(ny,j),j=ny..ny*(N*F-F)),beta=0...((w-ny)*F)),ny=1..w);
ED1:=ET-EA;
#######################
#Network Packet Loss probability
#######################
PB1:= ED1/(w*F*rho);
Blocking:=1-(1-PB1)^H;
throughput:=(1-Blocking)*0.1*rho;
```

Appendix F

SYMMETRIC PACKET SWITCH NETWORK SIMULATION CODE

```
This Simulation results are presented in Chapter 6.
#include "list.h"
/*-------------------------------------------------------------
--                      Global variables
-- In this Part of the simulator all global variables that are
-- used in the different functions of the simulator are defined
-- These variables are:
-- Slot_Time: Is used to keep track of the numebr of the slots
-- P_Seed: Is used as an initial seed for selecting input
-- W_Seed: Is used as an initial seed for selecting wavelength
-- F_Seed: Is used as an initial seed for selecting fiber
-- C_Seed: Is used as an initial sedd for selecting converters
-------------------------------------------------------------*/

double Load=0;
double Load1=0;
int C=0;
long Slot_Time=1;
long P_Seed=7;
long W_Seed=13;
long C_Seed=21;
long Tag_Seed=33;
int No_of_Nodes=-1;
int Prob_Time=1;
double blocked=0;
double processed=0;
double forwarded=0;
long Pro_Packet[4][100];
long Blocked[4][100];
long Forward[4][100];

/*-------------------------------------------------------------
--                      Random generator module
```

```
-- There are two functions in this module. The First one is
-- used to generate the seed that will be use to generate the
-- next random variable.The second function is the actual
-- implementation of the LCG random generator.
-----------------------------------------------------------------*/
/*-------------------------------------------------------------
--                          GenerateSeed function
-- Function return type: long integer
-- Calld in variables funtion: Seed- long integer
-- Returned funtion variable : a - long integer
-----------------------------------------------------------------*/
long GenerateSeed(long Seed)
{
   long a;
   a =(long)(abs( (16807 * Seed) % (2147483647)));
   return a;
}
/*--------------------------------------------------------------
--                          Generateu function
-- Function return type: bouble
-- Calld in variables funtion: Seed- long integer
-- Returned funtion variable : u - double
-------------------------------------------------------------------*/
double GenerateU(long Seed)
{

   double u=0.0;
   u = ((double)(Seed) / (double)2147483647);
   return u;
}

/*----------------------------------------------------------------
--                          Slot_Initilaze function
-- Function return type: Void
-- Called in variables: n1-node class type
-- Returned function variable : NULL
-- This function is called at the end of every time slot to reset the
-- node resources to the free state.
---------------------------------------------------------------------*/
void Slot_Initilaze(node1 n[])
{
for (int k=0;k<No_of_Nodes;k++)
{
for (int i=0;i<n[k].Output;i++)
```

```
{
n[k].C[i]=C;
for(int j=0;j<n[k].Wo;j++)
n[k].Out_Port[j][i]=1;
}

}

}
/*--------------------------------------------------------------
--                          Any_To_Any function
-- Function return type: packet class type
-- Called in variables: c packet class type,
--                      node node class type
-- Returned function variable : c - packet class type
-- This function is called when a contention between packets
-- occur. A free wavelength and free converter in the conversion
-- bank that associated to the requested output port are sought,
-- if a free wavelength and free converter is found then they
-- assigned to the passed packet. And change the status of
-- these resources to busy. Otherwise this packet as well as
-- all other packets that destined to the same output port in
-- the current time slot dropped.
----------------------------------------------------------------*/
packet *Any_To_Any(packet *c, node1 node[],int Node_No)
{
list LIST;
int C_Counter=0;
int Choosed_Packet=-1;
int Choosed_W=-1;
int count=0;
double u=-1.0;
packet *temp=NULL;
packet *temp1=NULL;
temp=c;
while (c!=NULL)
{
Choosed_Packet=-1;
Choosed_W=-1;
count=0;

temp=c;
u=GenerateU(P_Seed);
P_Seed=GenerateSeed(P_Seed);
```

```
while(temp!=NULL)
{
count++;
temp=temp->After;
}
Choosed_Packet=(int)(u*count);
count=0;
temp=c;
while(count!=Choosed_Packet)
{
if (count!=Choosed_Packet)
temp=temp->After;
count++;
}

int *Free1=new int[node[Node_No].Wo];
for (int i=0;i<node[Node_No].Wo;i++)
Free1[i]=-1;
count=0;
for (i=0;i<node[Node_No].Wo;i++)
{
if (node[Node_No].Out_Port[i][temp->Output]==1)
{
Free1[count]=i;
count++;
}
}
if (count>0)
{
u=GenerateU(W_Seed);
W_Seed=GenerateSeed(W_Seed);
Choosed_W=(int)(u*count);
Choosed_W=Free1[Choosed_W];
delete [] Free1;
}
if((Choosed_W!=-1)&&(node[Node_No].C[temp->Output]>0)&&(temp->
Slot_Time==Slot_Time))
{
if (temp->Output==0)
C_Counter++;
node[Node_No].Out_Port[Choosed_W][temp->Output]=0;
node[Node_No].C[temp->Output]--;
temp->C_Flag=1;
```

```
temp->Out_Lambda=Choosed_W;
temp->Slot_Time+=Prob_Time;
temp->Current_Node=node[temp->Current_Node].Next_Node;
node[Node_No].Forwarded_Packet++;
if (temp==c)
{
c=c->After;
if (c!=NULL)
c->Before=NULL;

}else
{
temp1=temp->Before;
temp1->After=temp->After;
if (temp->After!=NULL)
{
temp1=temp->After;
temp1->Before=temp->Before;
}
}
if (temp->Destination==node[Node_No].Next_Node)
{
Forward[temp->Input][temp->Lambda]++;
if ((temp->Tag==1))
{
forwarded++;

}
temp->Before=NULL;
temp->After=NULL;
delete temp;
}
else
{
temp->Before=NULL;
temp->After=NULL;
Forward[temp->Input][temp->Lambda]++;
if ((temp->Tag==1))
{

node[node[Node_No].Next_Node].h[temp->Out_Lambda]=
LIST.Insert_To_List(node[node[Node_No].Next_Node].h[temp->
Out_Lambda],temp);
}
```

```
else
delete temp;
}

}
else
{
if (c->Before!=NULL)
c=c->Before;
while (c!=NULL)
{
temp=c;
c=c->After;
Blocked[temp->Input][temp->Lambda]++;
if(temp->Tag==1)
{
blocked++;

}
else if(temp->Tag!=1)
node[Node_No].blocked++;
delete temp;
}
node[Node_No].h_c=NULL;

}
node[Node_No].h_c=c;
}
node[Node_No].U_C[C_Counter]++;
return c;
}
/*------------------------------------------------------------
--                           Not_Node_Zero function
-- Function return type: Void
-- Called in variables: n[] node class type
-- c  packet class type
-- No integer
-- Returned function variable : NULL
-- In this function, the requested wavlength on the desired output
-- is checked for the current packet (c) and node No. if the
-- wavelength is free changet its status to busy and check if
-- the packet's desitnation is the next node delete the current
-- packet from the event list, otherwise added it to the eventlist
-- of the next node. If the requested wavelwngth is not available
```

```
-- on the desinted output add this packet to the current node
-- conversion list.
---------------------------------------------------------------*/
void Not_Node_Zero(node1 n[], packet *c, int No)
{
list LIST;
// Check if the current packet has to be processed at this time slot
if (c->Slot_Time==Slot_Time)
{
// Check if the requested wavelength is free
if (n[No].Out_Port[c->Out_Lambda][c->Output]==1)
{
// Set the requested wavelength to busy
n[No].Out_Port[c->Out_Lambda][c->Output]=0;
if (c->Destination==n[No].Next_Node)
{
Forward[c->Input][c->Lambda]++;
if ((c->Tag==1))
{
forwarded++;
}
// if the destination of the current packet is the next node
//delete it from the event list
delete c;
}else
{
// if the destination of the current packet is not the next
//node update the packet slot time field
// update the packet current node and added it to the event
//list of the new current node

c->Slot_Time+=Prob_Time;
c->Current_Node=n[No].Next_Node;
Forward[c->Input][c->Lambda]++;
if ((c->Tag==1))
{

n[n[No].Next_Node].h[c->Out_Lambda]=LIST.Insert_To_List(n[n[No].
Next_Node].h[c->Out_Lambda],c);
}
else
delete c;
}
}else
```

```
{
// if the requested wavelength is busy add the current
//packet to the conversion list of the current node.
n[No].h_c=LIST.Insert_To_List(n[No].h_c,c);

}
}
}
/*------------------------------------------------------------
--                          Eevnt_Handeler function
-- Function return type: Void
-- Called in variables: n-node class type
-- Returned function variable : NULL
-- In this function, all wavelengths are checked if there
-- is an arrival on the wavelength under consideration then
-- randomly select one of the switch outputs as a destination
-- for this arrival. Every time slot this process is repeated.
-- Every 100000 time slot runs the blocking probability is
-- calculated and compared with blocking probability previous
-- value, If the difference is less than 0.001 the simulators
-- will be ended and all statistics collected.
---------------------------------------------------------------*/
void Event_Handeler(node1 n[])
{
packet *Current_Packet=NULL;
list LIST;
double p0=0;
double p1=-9999.0;
    double e=9999;
double u=0.0;
int In=-1;
int Temp_In=-1;
int Out=-1;
int Break_Flag=0;
int ch[100];
int Slot_C=1;
long test_Count=0;
for (int i=0;i<4;i++)
{
for (int k=0;k<n[0].Wi;k++)
{
Pro_Packet[i][k]=0;
Blocked[i][k]=0;
Forward[i][k]=0;
```

```
}
}
for (i=0;i<=No_of_Nodes-1;i++)
{
cout<<endl<<"Node No="<<i;
cout<<endl<<"Input="<<n[i].Input;
cout<<endl<<"Input wavelengths="<<n[i].Wi;
cout<<endl<<"Output="<<n[i].Output;
cout<<endl<<"Outptut wavelength="<<n[i].Wo;
cout<<endl<<"Converters="<<n[i].C;
cout<<endl<<"Load="<<Load;
cout.flush();
}
//++++++++++++++++++++++++++++++++++++++++++++++++++++
// Check if the blocking difference is less than 0.001
//++++++++++++++++++++++++++++++++++++++++++++++++++++
while (e>0.001)
{
for (int No_Nodes=0;No_Nodes<=No_of_Nodes-1;No_Nodes++)
{
for(int i=0;i<n[No_Nodes].Wi;i++)
{
Break_Flag=0;
for (int k=0;k<n[No_Nodes].Input;k++)
ch[k]=k;
while (Break_Flag==0)
{
int IN_Count=0;
for (int k=0;k<n[No_Nodes].Input;k++)
{
if (ch[k]!=-1)
IN_Count++;
}
if (IN_Count>0)
{
u=0.0;
In=-1;
Out=-1;
Temp_In=-1;
u=GenerateU(n[No_Nodes].Input_Seed);
n[No_Nodes].Input_Seed=GenerateSeed(n[No_Nodes].Input_Seed);
Temp_In=(int)(u*IN_Count);
In=ch[Temp_In];
ch[Temp_In]=-1;
```

```
IN_Count=0;
Break_Flag=0;
for (k=0;k<n[No_Nodes].Input;k++)
{
if(ch[k]!=-1)
{
ch[IN_Count]=ch[k];
if(IN_Count!=k)
ch[k]=-1;
IN_Count++;
}
}
//++++++++++++++++++++++++++++++++++++++++++++++++++
// Randomaly select one of the siwtch outputs
// and consider it as the current packet destination
//++++++++++++++++++++++++++++++++++++++++++++++++++
int Tag_Flag=-1;
if ((In==0)&&(No_Nodes!=0)&&(n[No_Nodes].h[i]!=NULL)&&(n[No_Nodes].
h[i]->Slot_Time==Slot_Time))
{
Out=0;
Tag_Flag=1;
}
else
{
u=GenerateU(n[No_Nodes].Output_Seed);
n[No_Nodes].Output_Seed=GenerateSeed(n[No_Nodes].Output_Seed);
Out=(long)(u*n[No_Nodes].Output);
Tag_Flag=-1;
}

u=GenerateU(n[No_Nodes].Seeds[i][In]);
n[No_Nodes].Seeds[i][In]=GenerateSeed(n[No_Nodes].Seeds[i][In]);
if(Out==0)
{
//++++++++++++++++++++++++++++++
// Check if there is an arrival.
//++++++++++++++++++++++++++++++
if((u<=Load)||(Tag_Flag==1))
{
Pro_Packet[In][i]++;
if ((In==0)&&(i==0)&&(No_Nodes==0))
{
test_Count++;
```

```
u=GenerateU(Tag_Seed);
Tag_Seed=GenerateSeed(Tag_Seed);
if (u<=1)
{
Tag_Flag=1;
processed++;
}else
Tag_Flag=-1;
}
Current_Packet=new packet();
Current_Packet->Packet_ID=Slot_Time;
Current_Packet->After=NULL;
Current_Packet->Before=NULL;
Current_Packet->Current_Node=No_Nodes;
Current_Packet->Input=In;
Current_Packet->Lambda=i;
Current_Packet->Slot_Time=Slot_Time;
Current_Packet->Output=Out;
Current_Packet->Out_Lambda=i;
Current_Packet->C_Flag=-1;
Current_Packet->Tag=Tag_Flag;
//+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
// Check if the arrived packet is a taged pakcet and the current
// node is not the first node of the pakcet
// if so add this packet to the event list of the next node
//+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
if ((Current_Packet->Tag==1)&&(No_Nodes!=0))
{
packet *Temp=NULL;
Temp=n[No_Nodes].h[i];
n[No_Nodes].h[i]=n[No_Nodes].h[i]->After;
Temp->After=NULL;
Temp->Before=NULL;
delete Temp;
}
if (Current_Packet->Tag!=1)
n[No_Nodes].Pro_Packet++;
if (Current_Packet->Tag==1)
Current_Packet->Destination=No_of_Nodes;
else
Current_Packet->Destination=n[No_Nodes].Next_Node;
Not_Node_Zero(n,Current_Packet,No_Nodes);
}
}
```

```
}else
Break_Flag=1;
}

for (int j=0;j<n[No_Nodes].Input;j++)
ch[j]=-1;
}
//++++++++++++++++++++++++++++++++++++++++++++++++++++
// Check if there are packets in the conversion list.
// if so call the conversion function
//++++++++++++++++++++++++++++++++++++++++++++++++++++
if ((n[No_Nodes].C_T==0)&&(n[No_Nodes].h_c!=NULL))
n[No_Nodes].h_c=Any_To_Any(n[No_Nodes].h_c,n,No_Nodes);
}
//+++++++++++++++++++++++++++++++++++++++++++++++++++++++
// check how long the simulator run. If the Slot counter
// is equal 100000 calculate the blocking probability and
// comaper it with the previous value.
//++++++++++++++++++++++++++++++++++++++++++++++++++++++++
if (Slot_C==100000)
{
double Ptest=0.0;
cout<<endl<<"Processed= "<<processed;
cout<<endl<<"forwarded= "<<forwarded;
cout<<endl<<"blocked= "<<blocked;
cout<<endl<<"Total="<<blocked+forwarded;
cout<<endl<<"T1="<<test_Count;
test_Count=0;
p0=(double)(blocked)/(double)(processed);
e=fabs(p0-p1);
p1=p0;
cout<<endl<<"P0="<<p0;
cout<<endl<<"-----------------------------";
blocked=0;
processed=0;
forwarded=0;
Slot_C=0;
for (int i=0;i<=No_of_Nodes-1;i++)
{
Ptest=0;
Ptest=(double)n[i].blocked/(double)n[i].Pro_Packet;
cout<<endl<<"Pbtest"<<i<<"= "<<Ptest;
cout.flush();
n[i].blocked=0;
```

```
n[i].Pro_Packet=0;
}
}
Slot_C++;
//++++++++++++++++++++++++++++++++++++++++++++++++++++++
// Initialize the slot counter and call the node initialztion
// function explained above.
//+++++++++++++++++++++++++++++++++++++++++++++++++++++++
Slot_Initilaze(n);
Slot_Time++;
}
cout<<endl<<"Blocking= "<<p0<<endl;
cout<<endl<<Slot_Time;
cout.flush();

}
/*-----------------------------------------------
                    Node_Intiliaze function
-- Function return type: node class type
-- Called in variables function:
-- Returned function variable : n
-- This function create the nodes object and
-- initialize all the nodes' variables
--------------------------------------------------*/
void  Node_Intiliaze(node1 n[])
{

ifstream f("Topology.dat",ios::in);
f>>No_of_Nodes;
double temp=0;
for (int i=0;i<No_of_Nodes;i++)
{
int Input=0;
int Wo=0;
int no=-1;
int next=-1;
f>>no;
f>>next;
f>>Input;
f>>Wo;
f>>C;
f>>Load;
n[i].Node_No=no;
n[i].Next_Node=next;
```

```
    n[i].Input=Input;
n[i].Output=Input;
n[i].Wo=Wo;
n[i].Wi=Wo;
n[i].C_T=0;
n[i].Out_Port_Initialization(C,0);
 }
f.close();

}

void main()
{
ifstream f("Topology.dat",ios::in);
f>>No_of_Nodes;
f.close();
node1 *node=new node1[No_of_Nodes];
Node_Intiliaze(node);
Event_Handeler(node);

}
```

Appendix G

ASYMMETRIC PACKET SWITCH NETWORK SIMULATION CODE

This Simulation results are presented in Chapter 7.

```
#include "list.h"
/*---------------------------------------------------------------
--                        Global variables
-- In this Part of the simulator all global variables that are
-- used in the different functions of the simulator are defined
-- These variables are:
-- Slot_Time: Is used to keep track of the numebr of the slots
-- P_Seed: Is used as an initial seed for selecting input
-- W_Seed: Is used as an initial seed for selecting wavelength
-- F_Seed: Is used as an initial seed for selecting fiber
-- C_Seed: Is used as an initial sedd for selecting converters
---------------------------------------------------------------*/
double Load=0;
double Load1=0;
int C=0;
long Slot_Time=1;
__int64 P_Seed=7;
__int64 W_Seed=13;
__int64 C_Seed=21;
__int64 Tag_Seed=33;
int No_of_Nodes=-1;
int Prob_Time=1;
double blocked=0;
double processed=0;
double forwarded=0;
long Pro_Packet[4][100];
long Blocked[4][100];
long Forward[4][100];

/*--------------------------------------------------------------
--                        Random generator module
```

```
-- There are two functions in this module. The First one is
-- used to generate the seed that will be use to generate the
-- next random variable.The second function is the actual
-- implementation of the LCG random generator.
-----------------------------------------------------------------*/
/*---------------------------------------------------------------
--                           GenerateSeed function
-- Function return type: long integer
-- Calld in variables funtion: Seed- long integer
-- Returned funtion variable : a - long integer
-----------------------------------------------------------------*/
__int64 GenerateSeed(__int64 Seed)
{
   __int64 a;
   a =(__int64)(abs( (16807 * Seed) % (2147483647)));
   return a;
}
/*----------------------------------------------------------------
--                           Generateu function
-- Function return type: bouble
-- Calld in variables funtion: Seed- long integer
-- Returned funtion variable : u - double
-------------------------------------------------------------------*/
double GenerateU(__int64 Seed)
{

   double u=0.0;
   u = ((double)(Seed) / (double)2147483647);
   return u;
}

/*-------------------------------------------------------------------
--                           Slot_Initilaze function
-- Function return type: Void
-- Called in variables: n1-node class type
-- Returned function variable : NULL
-- This function is called at the end of every time slot to reset the
-- node resources to the free state.
---------------------------------------------------------------------*/
void Slot_Initilaze(node1 n[])
{
for (int k=0;k<No_of_Nodes;k++)
{
for (int i=0;i<n[k].Output;i++)
```

```
{
n[k].C[i]=C;
for(int j=0;j<n[k].Wo;j++)
n[k].Out_Port[j][i]=1;
}

}

}

/*------------------------------------------------------------
--                          Any_To_Any function
-- Function return type: packet class type
-- Called in variables: c packet class type,
--                      node node class type
-- Returned function variable : c - packet class type
-- This function is called when a contention between packets
-- occur. A free wavelength and free converter in the conversion
-- bank that associated to the requested output port are sought,
-- if a free wavelength and free converter is found then they
-- assigned to the passed packet. And change the status of
-- these resources to busy. Otherwise this packet as well as
-- all other packets that destined to the same output port in
-- the current time slot dropped.
--------------------------------------------------------------*/
packet *Any_To_Any(packet *c, node1 node[],int Node_No)
{
list LIST;
int C_Counter=0;
int Choosed_Packet=-1;
int Choosed_W=-1;
int count=0;
double u=-1.0;
packet *temp=NULL;
packet *temp1=NULL;
temp=c;
while (c!=NULL)
{
Choosed_Packet=-1;
Choosed_W=-1;
count=0;

temp=c;
u=GenerateU(P_Seed);
```

```
P_Seed=GenerateSeed(P_Seed);

while(temp!=NULL)
{
count++;
temp=temp->After;
}
Choosed_Packet=(int)(u*count);
count=0;
temp=c;
while(count!=Choosed_Packet)
{
if (count!=Choosed_Packet)
temp=temp->After;
count++;
}

int *Free1=new int[node[Node_No].Wo];
for (int i=0;i<node[Node_No].Wo;i++)
Free1[i]=-1;
count=0;
for (i=0;i<node[Node_No].Wo;i++)
{
if (node[Node_No].Out_Port[i][temp->Output]==1)
{
Free1[count]=i;
count++;
}
}
if (count>0)
{
u=GenerateU(W_Seed);
W_Seed=GenerateSeed(W_Seed);
Choosed_W=(int)(u*count);
Choosed_W=Free1[Choosed_W];
delete [] Free1;
}
if((Choosed_W!=-1)&&(node[Node_No].C[temp->Output]>0)&&(temp->
Slot_Time==Slot_Time))
{
if (temp->Output==0)
C_Counter++;
node[Node_No].Out_Port[Choosed_W][temp->Output]=0;
node[Node_No].C[temp->Output]--;
```

```
temp->C_Flag=1;
temp->Out_Lambda=Choosed_W;
temp->Slot_Time+=Prob_Time;
temp->Current_Node=node[temp->Current_Node].Next_Node;
node[Node_No].Forwarded_Packet++;
if (temp==c)
{
c=c->After;
if (c!=NULL)
c->Before=NULL;

}else
{
temp1=temp->Before;
temp1->After=temp->After;
if (temp->After!=NULL)
{
temp1=temp->After;
temp1->Before=temp->Before;
}
}
if (temp->Destination==node[Node_No].Next_Node)
{
Forward[temp->Input][temp->Lambda]++;
if ((temp->Tag==1))
{
forwarded++;

}
temp->Before=NULL;
temp->After=NULL;
delete temp;
}
else
{
temp->Before=NULL;
temp->After=NULL;
Forward[temp->Input][temp->Lambda]++;
if ((temp->Tag==1))
{

node[node[Node_No].Next_Node].h[temp->Out_Lambda]=LIST.
Insert_To_List(node[node[Node_No].Next_Node].h[temp->Out_Lambda],
temp,temp->Input,node);
```

```
}
else
delete temp;
}

}
else
{
if (c->Before!=NULL)
c=c->Before;
while (c!=NULL)
{
temp=c;
c=c->After;
Blocked[temp->Input][temp->Lambda]++;
if(temp->Tag==1)
{
blocked++;

}
else if(temp->Tag!=1)
node[Node_No].blocked++;
delete temp;
}
node[Node_No].h_c=NULL;

}
node[Node_No].h_c=c;
}
node[Node_No].U_C[C_Counter]++;
return c;
}

/*------------------------------------------------------------
--                         Not_Node_Zero function
-- Function return type: Void
-- Called in variables: n[] node class type
-- c  packet class type
-- No integer
-- Returned function variable : NULL
-- In this function, the requested wavlength on the desired output
-- is checked for the current packet (c) and node No. if the
-- wavelength  is free changet its status to busy and check if the
-- packet's desitnationis the next node delete the current packet
```

```
-- from the event list, otherwise added it to the eventlist of
-- the next node. If the requested wavelwngth is not available
-- on the desinted output add this packet to the current node
-- conversion list.
---------------------------------------------------------------*/
void Not_Node_Zero(node1 n[], packet *c, int No)
{
list LIST;
// Check if the current packet has to be processed at this time slot

if (c->Slot_Time==Slot_Time)
{
// Check if the requested wavelength is free
if (n[No].Out_Port[c->Out_Lambda][c->Output]==1)
{
// Set the requested wavelength to busy
n[No].Out_Port[c->Out_Lambda][c->Output]=0;
if ((c->Tag==1))
{
forwarded++;
}
c->Slot_Time+=Prob_Time;
Forward[c->Input][c->Lambda]++;
if (c->Tag!=1)
  c->Destination=n[c->Current_Node].Next_Node;
c->Current_Node=n[No].Next_Node;
if ((c->Destination==No_of_Nodes)&&(c->Tag!=1))
// if the destination of the current packet is the next node
/delete it from the event list

delete c;
else if ((c->Destination==c->Current_Node)&&(c->Tag==1))
delete c;
else
// if the destination of the current packet is not the next node
//update the packet slot time field
// update the packet current node and added it to the event list
//of the new current node

n[n[No].Next_Node].h[c->Out_Lambda]=LIST.
Insert_To_List(n[n[No].Next_Node].h[c->
Out_Lambda],c,c->Input,n);

}else
```

```
{
// if the requested wavelength is busy add the current
//packet to the conversion list of the current node.

n[No].h_c=LIST.Insert_To_List(n[No].h_c,c,c->Input,n);

}
}
}

/*-------------------------------------------------------------
--                        Eevnt_Handeler function
-- Function return type: Void
-- Called in variables: n-node class type
-- Returned function variable : NULL
-- In this function, all wavelengths are checked if there
-- is an arrival on the wavelength under consideration then
-- randomly select one of the switch outputs as a destination
-- for this arrival. Every time slot this process is repeated.
-- Every 100000 time slot runs the blocking probability is
-- calculated and compared with blocking probability previous
-- value, If the difference is less than 0.001 the simulators
-- will be ended and all statistics collected.
--------------------------------------------------------------*/
void Event_Handeler(node1 n[])
{
packet *Current_Packet=NULL;
packet *Temp=NULL;
list LIST;
double p0=0;
double p1=-9999.0;
    double e=9999;
double u=0.0;
int In=-1;
int Temp_In=-1;
int Out=-1;
int Break_Flag=0;
int ch[100];
int Slot_C=1;
long test_Count=0;
for (int i=0;i<4;i++)
{
for (int k=0;k<n[0].Wi;k++)
{
```

```
Pro_Packet[i][k]=0;
Blocked[i][k]=0;
Forward[i][k]=0;
}
}
for (i=0;i<=No_of_Nodes-1;i++)
{
cout<<endl<<"Node No="<<i;
cout<<endl<<"Input="<<n[i].Input;
cout<<endl<<"Input wavelengths="<<n[i].Wi;
cout<<endl<<"Output="<<n[i].Output;
cout<<endl<<"Outptut wavelength="<<n[i].Wo;
cout<<endl<<"Converters="<<n[i].C;
cout<<endl<<"Load="<<Load;
cout.flush();
}
//+++++++++++++++++++++++++++++++++++++++++++++++++++++
// Check if the blocking difference is less than 0.001
//+++++++++++++++++++++++++++++++++++++++++++++++++++++
while (e>0.001)
{
for (int No_Nodes=0;No_Nodes<=No_of_Nodes-1;No_Nodes++)
{
for(int i=0;i<n[No_Nodes].Wi;i++)
{
Break_Flag=0;
for (int k=0;k<n[No_Nodes].Input;k++)
ch[k]=k;
while (Break_Flag==0)
{
int IN_Count=0;
for (int k=0;k<n[No_Nodes].Input;k++)
{
if (ch[k]!=-1)
IN_Count++;
}
if (IN_Count>0)
{
u=0.0;
In=-1;
Out=-1;
Temp_In=-1;
u=GenerateU(n[No_Nodes].Input_Seed);
n[No_Nodes].Input_Seed=GenerateSeed(n[No_Nodes].Input_Seed);
```

```
Temp_In=(int)(u*IN_Count);
In=ch[Temp_In];
ch[Temp_In]=-1;
IN_Count=0;
Break_Flag=0;
for (k=0;k<n[No_Nodes].Input;k++)
{
if(ch[k]!=-1)
{
ch[IN_Count]=ch[k];
if(IN_Count!=k)
ch[k]=-1;
IN_Count++;
}
}
int Tag_Flag=-1;
if ((In==0)&&(No_Nodes!=0)&&(n[No_Nodes].h[i]!=NULL))
{
if((n[No_Nodes].h[i]->Tag==1)&&(n[No_Nodes].h[i]->Slot_Time==Slot_Time))
{
Out=0;
Tag_Flag=1;
}else if(n[No_Nodes].h[i]->Slot_Time==Slot_Time)
{
u=GenerateU(n[No_Nodes].Output_Seed);
n[No_Nodes].Output_Seed=GenerateSeed(n[No_Nodes].Output_Seed);
Out=(long)(u*n[No_Nodes].Output);
if (Out!=0)
{
Temp=n[No_Nodes].h[i];
n[No_Nodes].h[i]=n[No_Nodes].h[i]->After;
if(n[No_Nodes].h[i]!=NULL)
n[No_Nodes].h[i]->Before=NULL;
Temp->After=NULL;
Temp->Before=NULL;
    delete Temp;
}
Tag_Flag=0;
}
}
else if (No_Nodes==0)
{
u=GenerateU(n[No_Nodes].Output_Seed);
n[No_Nodes].Output_Seed=GenerateSeed(n[No_Nodes].Output_Seed);
```

```
Out=(long)(u*n[No_Nodes].Output);
Tag_Flag=-1;
}else if ((In!=0)&&(No_Nodes!=0))
{
u=GenerateU(n[No_Nodes].Output_Seed);
n[No_Nodes].Output_Seed=GenerateSeed(n[No_Nodes].Output_Seed);
Out=(long)(u*n[No_Nodes].Output);
Tag_Flag=-1;
}

if(Out==0)
{
if ((No_Nodes==0)||(In!=0))
{
u=GenerateU(n[No_Nodes].Seeds[i][In]);
n[No_Nodes].Seeds[i][In]=GenerateSeed(n[No_Nodes].Seeds[i][In]);
//++++++++++++++++++++++++++++++
// Check if there is an arrival.
//++++++++++++++++++++++++++++++
if(u<=Load)
{
Pro_Packet[In][i]++;
if ((In==0)&&(i==0)&&(No_Nodes==0))
{
test_Count++;
u=GenerateU(Tag_Seed);
Tag_Seed=GenerateSeed(Tag_Seed);
if (u<=0.1)
{
Tag_Flag=1;
processed++;
}else
Tag_Flag=-1;
}

Current_Packet=new packet();
Current_Packet->Packet_ID=Slot_Time;
Current_Packet->After=NULL;
Current_Packet->Before=NULL;
Current_Packet->Current_Node=No_Nodes;
Current_Packet->Input=In;
Current_Packet->Lambda=i;
Current_Packet->Slot_Time=Slot_Time;
Current_Packet->Output=Out;
```

```
Current_Packet->Out_Lambda=i;
Current_Packet->C_Flag=-1;
Current_Packet->Tag=Tag_Flag;
//+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
// Check if the arrived packet is a taged pakcet and the current
//node is not the first node of the pakcet
// if so add this packet to the event list of the next node
//+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
if (Current_Packet->Tag==1)
Current_Packet->Destination=No_of_Nodes;
else
Current_Packet->Destination=n[No_Nodes].Next_Node;
}
}else
{
Current_Packet=n[No_Nodes].h[i];
n[No_Nodes].h[i]=n[No_Nodes].h[i]->After;
if(n[No_Nodes].h[i]!=NULL)
n[No_Nodes].h[i]->Before=NULL;
Current_Packet->After=NULL;
Current_Packet->Before=NULL;
}
if (Current_Packet!=NULL)
{
Not_Node_Zero(n,Current_Packet,No_Nodes);
Current_Packet=NULL;
}
}
}else
Break_Flag=1;
}

for (int j=0;j<n[No_Nodes].Input;j++)
ch[j]=-1;
}

//++++++++++++++++++++++++++++++++++++++++++++++++++++
// Check if there are packets in the conversion list.
// if so call the conversion function
//++++++++++++++++++++++++++++++++++++++++++++++++++++
if ((n[No_Nodes].C_T==0)&&(n[No_Nodes].h_c!=NULL))
n[No_Nodes].h_c=Any_To_Any(n[No_Nodes].
h_c,n,No_Nodes);
}
```

```
//+++++++++++++++++++++++++++++++++++++++++++++++++++++
// check how long the simulator run. If the Slot counter
// is equal 100000 calculate the blocking probability and
// comaper it with the previous value.
//++++++++++++++++++++++++++++++++++++++++++++++++++++++
if (Slot_C==100000)
{
double Ptest=0.0;
cout<<endl<<"Processed= "<<processed;
cout<<endl<<"forwarded= "<<forwarded;
cout<<endl<<"blocked= "<<blocked;
cout<<endl<<"Total="<<blocked+forwarded;
cout<<endl<<"T1="<<test_Count;
test_Count=0;
p0=(double)(blocked)/(double)(processed);
e=fabs(p0-p1);
p1=p0;
cout<<endl<<"P0="<<p0;
cout<<endl<<"----------------------------";
blocked=0;
processed=0;
forwarded=0;
Slot_C=0;
for (int i=0;i<=No_of_Nodes-1;i++)
{
Ptest=0;
Ptest=(double)n[i].blocked/(double)n[i].Pro_Packet;
cout<<endl<<"Pbtest"<<i<<"= "<<Ptest;
cout.flush();
n[i].blocked=0;
n[i].Pro_Packet=0;
}
}
//++++++++++++++++++++++++++++++++++++++++++++++++++++++++
// Initialize the slot counter and call the node initialztion
// function explained above.
//+++++++++++++++++++++++++++++++++++++++++++++++++++++++++

Slot_C++;
Slot_Initilaze(n);
Slot_Time++;
} //while (e>0.001)
cout<<endl<<"Blocking= "<<p0<<endl;
cout<<endl<<Slot_Time;
```

```
cout.flush();

}

/*------------------------------------------------
                       Node_Intiliaze function
-- Function return type: node class type
-- Called in variables function:
-- Returned function variable : n
-- This function create the nodes object and
-- initialize all the nodes' variables
-------------------------------------------------*/
void  Node_Intiliaze(node1 n[])
{

ifstream f("Topology.dat",ios::in);
f>>No_of_Nodes;
double temp=0;
for (int i=0;i<No_of_Nodes;i++)
{
int Input=0;
int Wo=0;
int no=-1;
int next=-1;
int F=-1;
f>>no;
f>>next;
f>>Input;
f>>F;
f>>Wo;
f>>C;
f>>Load;
n[i].Node_No=no;
n[i].Next_Node=next;
    n[i].Input=Input;
n[i].Output=Input;
n[i].F=F;
n[i].Wo=Wo;
n[i].Wi=Wo;
n[i].C_T=0;
n[i].Out_Port_Initialization(C,0);
 }
 f.close();
 Slot_Initilaze(n);
```

```
}

//-----------------------------------------------------------------
void main()
{
ifstream f("Topology.dat",ios::in);
f>>No_of_Nodes;
f.close();
node1 *node=new node1[No_of_Nodes];
Node_Intiliaze(node);
Event_Handeler(node);

}
```

Appendix H

DATA TABLES

ρ	$H = 5$	$H = 10$	$H = 20$
Analytical Model			
0.1	0.0001478103	0.0002955987	0.0005911100
0.2	0.0029590259	0.0059092960	0.0117836723
0.3	0.0163674851	0.0324670757	0.0638800403
0.4	0.0513217890	0.1000096520	0.1900173735
0.5	0.1151291231	0.2170035311	0.3869165297
0.6	0.2061129554	0.3697433605	0.6027765683
0.7	0.3140747141	0.5295065021	0.7786358685
0.8	0.4257145534	0.6701962258	0.8912294705
0.9	0.5302559679	0.7793405443	0.9513094046
1.0	0.6218502867	0.8570027943	0.9795517992
Simulation			
0.1	0.0000000000	0.0000000000	0.0000000000
0.2	0.0000000000	0.0077519400	0.0088235300
0.3	0.0164779000	0.0210843000	0.0590631000
0.4	0.0469552000	0.0867270000	0.1689920000
0.5	0.1034890000	0.2010710000	0.3412350000
0.6	0.1811590000	0.3409850000	0.5305120000
0.7	0.2768120000	0.4980440000	0.7315020000
0.8	0.3704400000	0.6110290000	0.8395560000
0.9	0.4876400000	0.7384460000	0.9228210000
1	0.5825910000	0.8104480000	0.9623950000

Table H.1: Packet Loss Probability Data for Figure 6.2

ρ	$H = 5$	$H = 10$	$H = 20$
Analytical Model			
0.1	0.0099985219	0.0099970440	0.0099940889
0.2	0.0199408195	0.0198818141	0.0197643266
0.3	0.0295089754	0.0290259877	0.0280835988
0.4	0.0379471284	0.0359996139	0.0323993051
0.5	0.0442435438	0.0391498234	0.0306541735
0.6	0.0476332227	0.0378153984	0.0238334059
0.7	0.0480147700	0.0329345449	0.0154954892
0.8	0.0459428357	0.0263843019	0.0087016424
0.9	0.0422769629	0.0198593510	0.0043821536
1	0.0378149713	0.0142997206	0.0020448201
Simulation			
0.1	0.0100000000	0.0100000000	0.0100000000
0.2	0.0200000000	0.0198449612	0.0198235294
0.3	0.0295056630	0.0293674710	0.0282281070
0.4	0.0381217920	0.0365309200	0.0332403200
0.5	0.0448255500	0.0399464500	0.0329382500
0.6	0.0491304600	0.0395409000	0.0281692800
0.7	0.0506231600	0.0351369200	0.0187948600
0.8	0.0503648000	0.0311176800	0.0128355200
0.9	0.0461124000	0.0235398600	0.0069461100
1	0.0417409000	0.0189552000	0.0037605000

Table H.2: Throughout Data for Figure 6.3

ρ	$H = 5$	$H = 10$	$H = 20$
Analytical Model			
0.1	0.0001079048	0.0000000000	0.0000000000
0.2	0.0020036990	0.0000215398	0.0000000000
0.3	0.0112704958	0.0004543291	0.0000253997
0.4	0.0380628621	0.0037012010	0.0004991928
0.5	0.0949276463	0.0175299552	0.0043739669
0.6	0.1907446858	0.0577732615	0.0224694196
0.7	0.3232768752	0.1445193078	0.0780570954
0.8	0.4765113023	0.2871814315	0.1977197325
0.9	0.6267908008	0.4680958051	0.3819592541
1	0.7538323722	0.6472770815	0.5873649826
Simulation			
0.1	0.0000000000	0.0000000000	0.0000000000
0.2	0.0000000000	0.0000000000	0.0000000000
0.3	0.0092024500	0.0009813540	0.0000000000
0.4	0.0358449000	0.0028880900	0.0015186000
0.5	0.0817166000	0.0148280000	0.0029744200
0.6	0.1651060000	0.0423096000	0.0120240000
0.7	0.2849210000	0.0974745000	0.0490486000
0.8	0.4159760000	0.2025880000	0.1190820000
0.9	0.5438770000	0.3583280000	0.2568780000
1	0.6732030000	0.5165460000	0.4250790000

Table H.3: Packet Loss Probability Data for Figure 6.4

ρ	$H=5$	$H=10$	$H=20$
Analytical Model			
0	0.0208417414	0.0062054026	0.0005501003
2	0.0436002341	0.0271568631	0.0105356459
4	0.0620363757	0.0549787416	0.0431808861
6	0.0680220639	0.0661000168	0.0624173175
8	0.0686759822	0.0673770075	0.0648523020
10	0.0686900426	0.0674045993	0.0649054286
12	0.0686900658	0.0674046448	0.0649055163
14	0.0686900658	0.0674046448	0.0649055163
16	0.0686900658	0.0674046448	0.0649055163
18	0.0686900658	0.0674046448	0.0649055163
Simulation			
0	0.0209043800	0.0061911000	0.0010486000
2	0.0437511000	0.0271119000	0.0110357010
4	0.0620489000	0.0549544000	0.0428866000
6	0.0679573000	0.0661343000	0.0624836000
8	0.0686491000	0.0673356000	0.0648386000
10	0.0686400010	0.0673486000	0.0646287000
12	0.0686402000	0.0673665000	0.0648390000
14	0.0686402000	0.0673665000	0.0648266000
16	0.0686402000	0.0673665000	0.0649413000
18	0.0686402000	0.0673665000	0.0648656000

Table H.6: Throughput Data for Figure 6.7

ρ	$H = 5$	$H = 10$	$H = 20$
Analytical Model			
0.1	0.0099989210	0.0100000000	0.0100000000
0.2	0.0199599260	0.0199995692	0.0200000000
0.3	0.0296618851	0.0299863701	0.0299992380
0.4	0.0384774855	0.0398519520	0.0399800323
0.5	0.0452536177	0.0491235022	0.0497813017
0.6	0.0485553189	0.0565336043	0.0586518348
0.7	0.0473706187	0.0598836485	0.0645360033
0.8	0.0418790958	0.0570254855	0.0641824214
0.9	0.0335888279	0.0478713775	0.0556236671
1	0.0246167628	0.0352722919	0.0412635017
Simulation			
0.1	0.0100000000	0.0100000000	0.0100000000
0.2	0.0200000000	0.0200000000	0.0200000000
0.3	0.0297239000	0.0299705000	0.0300000000
0.4	0.0385662000	0.0398844000	0.0399392000
0.5	0.0459141000	0.0492586000	0.0498512000
0.6	0.0500936000	0.0574614000	0.0592785000
0.7	0.0500555000	0.0631767000	0.0665665000
0.8	0.0467219000	0.0637929000	0.0704734000
0.9	0.0410510000	0.0577504000	0.0668809000
1	0.0326797000	0.0483454000	0.0574921000

Table H.4: Throughout Data for Figure 6.5

ρ	$H = 5$	$H = 10$	$H = 20$
Analytical Model			
0	0.702260837	0.911351391	0.992141424
2	0.3771395125	0.6120448132	0.8494907730
4	0.1137660611	0.2145894056	0.3831301982
6	0.0282562298	0.0557140451	0.1083240353
8	0.0189145407	0.0374713215	0.0735385431
10	0.0187136776	0.0370771534	0.0727795915
12	0.0187133461	0.0370765029	0.0727783387
14	0.0187133461	0.0370765029	0.0727783387
16	0.0187133461	0.0370765029	0.0727783387
18	0.0187133461	0.0370765029	0.0727783387
Simulation			
0	0.7013660000	0.9115550000	0.9850200000
2	0.3749840000	0.6126860000	0.8423467000
4	0.1135870000	0.2149360000	0.3873333300
6	0.0291810000	0.0552233000	0.1073767000
8	0.0192985000	0.0380618000	0.0737330000
10	0.0194257000	0.0378759000	0.0767322000
12	0.0194257000	0.0376214000	0.0737272200
14	0.0194257000	0.0376214000	0.0739047400
16	0.0194257000	0.0376214000	0.0722668000
18	0.0194257000	0.0376214000	0.0733473500

Table H.5: Packet Loss Probability Data for Figure 6.6

ρ	$H = 5$	$H = 10$	$H = 20$
Analytical Model			
0	0.0208417414	0.0062054026	0.0005501003
2	0.0436002341	0.0271568631	0.0105356459
4	0.0620363757	0.0549787416	0.0431808861
6	0.0680220639	0.0661000168	0.0624173175
8	0.0686759822	0.0673770075	0.0648523020
10	0.0686900426	0.0674045993	0.0649054286
12	0.0686900658	0.0674046448	0.0649055163
14	0.0686900658	0.0674046448	0.0649055163
16	0.0686900658	0.0674046448	0.0649055163
18	0.0686900658	0.0674046448	0.0649055163
Simulation			
0	0.0209043800	0.0061911000	0.0010486000
2	0.0437511000	0.0271119000	0.0110357010
4	0.0620489000	0.0549544000	0.0428866000
6	0.0679573000	0.0661343000	0.0624836000
8	0.0686491000	0.0673356000	0.0648386000
10	0.0686400010	0.0673486000	0.0646287000
12	0.0686402000	0.0673665000	0.0648390000
14	0.0686402000	0.0673665000	0.0648266000
16	0.0686402000	0.0673665000	0.0649413000
18	0.0686402000	0.0673665000	0.0648656000

Table H.6: Throughput Data for Figure 6.7