Design and Development of Performance Enhancement Techniques in Optical WDM Networks

THESIS

Submitted in partial fulfillment
of the requirements for the degree of
DOCTOR OF PHILOSOPHY

by

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Under the Supervision of
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October 2013

CERTIFICATE

This is to certify that the thesis entitled "**Design and Development of Performance Enhancement Techniques in Optical WDM Networks**" submitted by **Mr. Virendra Singh Shekhawat** ID No. **2004PHXF414P** for award of Ph.D. degree of the Institute embodies the original work done by him under my supervision.

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Dedicated

To God

for gifting me with the best
Parents, Teachers & Friends
one can have…

ACKNOWLEDGEMENTS

This thesis resulted in part out of years of research that has been done. During this period, I have met several people who have made a significant contribution in assorted ways to the research and the completion of this thesis and who deserve special mention. I am glad to take the opportunity to convey my gratitude to them in my humble acknowledgement.

In the first place, thanks are due to Prof. B N Jain, Vice-chancellor and Prof. G. Raghurama, Director, Pilani campus for the constant support and concern. I would like to gratefully acknowledge Prof. S K Verma, Dean, ARD for the support.

I deem it a great pleasure to express my gratitude whole-heartedly to Prof. V K Chaubey, Professor, Electrical & Electronics Engineering for his valuable advice, suggestions and guidance from the very early stages of this research. Besides providing me unflinching encouragement and support in various ways, he has also allowed me the freedom to experiment with my innovation which has in a major proportion enhanced and nourished my intellectual growth.

I am greatly indebted to Prof. R P Khare, Prof. Sudeept Mohan, Dean, Admissions, Prof. J. P. Misra, Unit Chief, IPC Unit, Prof. Sundar Balasubramaniam, Dean Academics & Resource Planning, Prof. Navneet Goyal, HoD, Computer Science & Information Systems, for their guidance, constructive comments, and motivation. I thank them for their willingness to share their knowledge with me, which was very fruitful in shaping my ideas and research. I acknowledge their promptness in providing me with all the equipment to facilitate the research. Collective and individual acknowledgements are due to all my colleagues who have directly or indirectly helped me in my work.

A special word of appreciation is owed to Prof. Rahul Banerjee, Unit Chief, SDETU for providing the necessary aid, support and facilities on several occasions.

Words fail me to express my gratitude to my parents and wife who deserve a special mention for their support and prayers. Without their care and love, this thesis would not have been possible. Many thanks are due to my fellow researchers Dinesh Tyagi, Manoj Dutta and all my other friends who were always ready to lend a hand. I would also like to thank my friend

Heramb Mishra for his continuous support and guidance. I thank everybody who was important to the successful realization of this thesis, as well as express my apology that I could not mention personally one by one. Finally, I would like to thank God for always guiding me.

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ABSTRACT

Optical network is a promising solution for satisfying the huge bandwidth and low latency requirement for emerging bandwidth intensive applications. Moreover, Wavelength Division Multiplexing (WDM) technology exploits the opto-electronic bandwidth mismatch. Since the emergence of the Internet, there has been a huge change in the kind of applications which are running over the Internet with varying QoS (Quality of Service) requirements. This needs improvement in the network performance to meet the ever growing traffic requirement & QoS. The WDM network's layered architecture has three layers; physical layer, network control & management layer and application layer. According to a cross layer design principle, network performance improvement solutions at each layer influence each other. In other words, the impact on network performance due to limitations at physical layer can be minimized by providing solutions at control & management layer and vice versa. This thesis focuses on the relationship between above mentioned layers & as also on providing solutions for network performance enhancement at physical and network control & management layer. The performance parameters considered in the present work are network throughput, call connection probability, resource utilization, traffic load distribution, and delay.

Among the physical layer solutions, a modified dual ring network topology with additional alternate links is proposed which logically divides the network into regions based on traffic statistics. The analytical model justifies the improvement in traffic handling capability of such networks by considering traffic priority as well. Similarly, the impact of WDM node architecture on the overall network performance is analysed with the help of an analytical model. The node architecture considered here is configurable to handle packet switching as well as circuit switching. It can also optically bypass the wavelengths for which the node is not the destination. This functionality reduces the processing overhead at the node. The node's performance is theoretically analysed by considering it as a part of ring and star topology. The throughput of an Optical Packet Switched (OPS) node can degrade due to lack of good packet conflict resolution mechanism. A packet conflict resolution algorithm based on circular Fiber Delay Lines (FDLs) is proposed to improve the packet conflict handling capability of a synchronous OPS node.

Through the node and network architecture level solutions, the network performance enhancement can be achieved only up-to a certain level. The network control & management layer solutions are proposed in this thesis for further enhancement of the network performance. The Routing and Wavelength Assignment (RWA) algorithms play a significant role to achieve better network performance. This thesis proposes five such algorithms; Weight based Edge Disjoint Path (WEDP), Wavelength Intersection Cardinality (WIC), Least Count First (LCF), Least Recently Used First (LRUF) and multipath routing. The aim behind developing these algorithms is to minimize the wavelength requirement and maximize the number of light-path requests to be handled by the network. The WEDP-RWA proposes hybrid link weight (i.e. static and dynamic link parameters) calculation method while WIC-RWA algorithm chooses the routing path on the basis of common wavelength availability on the route. The LCF and LRUF algorithms are proposed for wavelength mesh graph based RWA. These two algorithms improve the traffic handling capability of the network and also the call connection ratio compared to a Fixed Order (FO) based wavelength searching algorithm by reducing the average number of wavelength scans to satisfy the incoming light-path requests. The proposed multipath routing algorithm explores the possibility of sending the data over multiple edge-disjoint paths to meet the delay and bandwidth requirements of network applications. Moreover, it also improves the bandwidth utilization and does the traffic distribution across the network. Further, among the network control layer solutions, wavelength reservation protocols enhance the overall network performance beyond the RWA algorithms. The three commonly used wavelength reservation protocols are; Source Initiated Reservation (SIR), Destination Initiated Reservation (DIR) and Intermediate-node Initiated Reservation (IIR). The performance of these reservation protocols is measured in terms of channel over-reservation and vulnerable time or race condition. The IIR reservation protocol gives trade-off between these two performance parameters. This thesis proposes three modified versions of IIR protocols; Aggressive-IIR (AIIR), IIR_SIR and IIR_DIR. The AIIR reduces the race condition chances compared to IIR by dividing end to end path into multiple segments and by blocking all free probed wavelengths in each segment. The IIR_SIR reduces the over-reservation compared to SIR while IIR_DIR reduces the vulnerable time as compared to DIR protocol. The IIR_DIR protocol performs better than IIR_SIR in terms of call blocking probability for a given number of wavelengths per link. This concludes that the impact of over-reservation on call blocking is more significant as compared to blocking due to vulnerable time.

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ADM	Add Drop Multiplexer
AIIR	Aggressive Intermediate Initiated Reservation
ATM	Asynchronous Transfer Mode
BRP	Backward Reservation Protocol
CDM	Code Division Multiplexing
DIR	Destination Initiated Reservation
DLE	Dynamic Light-path Establishment
DPN	Demand and Priority Number
EDP	Edge Disjoint Path
FCFS	First Come First Serve
FDLs	Fiber Delay Lines
FRP	Forward Reservation Protocol
GMPLS	Generalized Multi Protocol Label Switching
GOS	Grade of Service
GSF	Grooming Switch Fabric
IIR	Intermediate-node Initiated Reservation
ILP	Integer Linear Programming
IP	Internet Protocol
LAN	Local Area Network
LCF	Least Count First
LCP	Least Congested Path
LRFU	Least Recently First Used
MAN	Metropolitan Area Network

MEDP	Maximum Quantity of Edge Disjoint Path
OBS	Optical Burst Switching
OCS	Optical Circuit Switching
OEO	Optical Electronic Optical
OPADOM	Optical Add Drop Multiplexer
OPS	Optical Packet Switching
OXC	Optical Cross Connect
QoS	Quality of Service
ROADM	Reconfigurable Optical Add Drop Multiplexer
RWA	Routing and Wavelength Assignment
SDH	Synchronous Digital Hierarchy
SIR	Source Initiated Reservation
SLE	Static Light-path Establishment
SONET	Synchronous Optical Networks
TDM	Time Division Multiplexing
TOS	Type of Service
TWSR	Time Wavelength Space Routers
WADOM	Wavelength Add Drop Multiplexer
WAN	Wide Area Network
WDM	Wavelength Division Multiplexing
WEDP	Weight based Edge Disjoint Path
WIC	Wavelength Intersection Cardinality
WRS	Wavelength Routed Switch
WSXC	Wavelength Selective Cross Connect

CHAPTER 1

INTRODUCTION

1.1 Background

Optical fiber has been recognized as the best candidate among the transmission media for telecommunication and data networks. It provides transmission facilities in the form of light waves which have various advantages over electronic transmission channels. It provides huge bandwidth (e.g. 50 Terabits), low signal attenuation (0.2 dB/km), immunity to electromagnetic interference, low signal distortion, low power requirement, no crosstalk, and high electric resistance. Also, in modern light-wave communication systems, switching can be done in optical, or electrical, or hybrid and its granularity level can be packet, or circuit, or in the form of a burst (i.e. group of packets). The most established deployments of optical light-wave link so far are based on Optical-Electronic-Optical (OEO) switches, which operate at OC-192 (i.e. 10 Gbps) rate. However, inside the OEO switch each input channel is de-multiplexed into capacity of 51.84 Mbps (i.e. electrical level transmission). As the optical light-wave transmission systems became popular, various network standards were developed including Synchronous Optical Networks (SONET) in the United States and Synchronous Digital Hierarchy (SDH) standard in Europe [Cavendish 2002] [Ramaswami 2001].

Backbone optical networks have also evolved to include various network topologies utilizing intelligent network elements to implement all optical control-plane to realize Generalized Multiprotocol Label Switching (GMPLS), fiber to the home/premises, Metropolitan Area Network (MAN). These evolutions have initiated an extensive research and development activity to explore, realize and develop innovative products like [Goswami 2011] [Fawaz 2004]. Research and development in the field of optical circuit switched, packet switched and burst switched networks has led to some new applications of wavelength on demand, virtual private optical networks and bandwidth trading. These innovations have revolutionized the global telecommunication scenario by increasing the data traffic rate at a lower cost to the end users [Callegati 2000] [Yao 2000].

The maximum rate at which an end user can access the network is limited by the electronic speed to a few Gbps. Hence, optical communication networks are designed such that they tap opto-electronic bandwidth mismatch and simultaneously utilize the huge bandwidth of optical fiber. This can be achieved by Wavelength Division Multiplexing (WDM), or Time Division Multiplexing (TDM) or Code Division Multiplexing (CDM). WDM is a more favourable technology for practical optical networks because it allows the end user to access the network using appropriate switching and routing equipment suitable for optical circuit switching. Further, switching technology is fine grained from connection level to burst level to the packet level. Hence, the job of the optical node becomes more and more challenging because traditional wavelength switching is a bottleneck for packet switching [Chlamtac 1996] [Mukherjee 1996].

Optical networks enabled with WDM support tremendous bandwidth with low latency and better Quality of Service (QoS). Advances in optical WDM networks in the last decade have made it possible to increase the number of channels per fiber strand to 300 and more. The tremendous growth in the number of Internet users, huge traffic demand and QoS requirements of emerging network applications (e.g. teleconferencing, audio/video content dissemination, video on demand and online distributed gaming) provides a big scope for the network research community [Ramaswami 1995a] [Zang 2000] .

The performance of light-wave networks are broadly analysed by the important characteristics of the physical topology, functionality of the link, node and control algorithms for assigning, routing, multiplexing and provisioning of connections. An efficient physical topology and hardware node architecture provides many alternate paths for traffic routing, increased network capacity, potential survivability and adaptability to dynamic traffic load [Ramamurthy 1998a]. However, the capacity of the physical topology can be enhanced many-fold by implementing control algorithms, switching and multiplexing functionality, logical network overlays and optical channel assignment protocols. Obviously, a node with a high degree of controllability under the supervision of control algorithms improves the resource utilization and satisfies the QoS requirements. Extensive research has been carried out to design, model and develop different types of optical nodes capable of implementing various types of switching, buffering, routing and control operations [Mukherjee 1996] [Gambini 1998] [Ramaswami 2002]. Thus, the development of evolving optical networking field and its supporting technology needs a thorough understanding of related subsystems and methodology required to model, design, analyse, and simulate them.

Network topology design and its configuration influence the traffic handling capability significantly. In particular, adding traffic grooming functionality in a ring topology reduces traffic fluctuation to quite an extent. Similarly dual ring architecture provides more robustness, fault tolerance and reliability. At control layer, the Routing and Wavelength Assignment (RWA) problem is the key to achieve overall network performance for wavelength routed optical WDM networks. The ideal goal of an RWA algorithm is to establish the maximum number of light-paths under the constraint of wavelength channel availability in the links. Once the routing path is identified, signalling or resource reservation protocols are used to reserve wavelength channels to setup light-paths. The Integer Linear Programming (ILP) based RWA solution enhances the time complexity with the increase in the number of nodes and channels per link [Banerjee 1996]. Thus, heuristic approaches are preferred to get near optimal solutions for the better time complexity [Shen 2001] [Shiva Kumar 2002] [Zang 2000]. Distributed resource reservation protocols have been given more attention over centralized resource reservation protocols due to better scalability [Mei 1997] [Yuan 1999] [Ahmad 2004]. The various signalling protocols reported in the literature are different in terms of vulnerable time and resource reservation strategies [Ramaswami 1995b] [Ramaswami 1997] [Zheng 2001].

In general, the overall network performance is measured through the parameters like throughput, end to end delay, delay-jitter, reliability, blocking probability, traffic load distribution, resource utilization and survivability etc.

1.2 Objective and Scope of the Thesis

The optical network architecture follows a layered architecture such that each layer has its own role in order to achieve end to end communication under required performance parameters. Broadly, it is categorized into three layers; physical layer, network control & management layer and application layer. Physical layer functionalities specify network architecture and node related attributes like traffic grooming, wavelength conversion capability, wavelength switching, buffering, data encoding at various wavelengths, Optical Cross Connects (OXCs), Add Drop Multiplexers (ADM), packet contention handling, logical and architectural modification in topology to incorporate better traffic handling [Mukherjee 2004] [Singh 2004]. The network control and management layer functionalities cover dynamic traffic routing protocols, wavelength assignment protocols, signalling and channel reservation protocols. Finally, the application layer deals with application specific functionalities like differentiated services, bandwidth economics, failure-recovery model and service level agreements etc.

According to a cross-layer design principle the knowledge of lower layer helps to design upper layer solutions with improved performance. More precisely, without a significant knowledge of device capabilities and limitations, developing a network control & management system may be un-realizable. Similarly, a new device development is not useful without knowing the functionality of the system. Hence, a suitable device modelling becomes an important aspect to conduct the performance analysis to understand the desired functionality and capability. The node architecture influences the traffic routing and channel assignment algorithms. For example, a limited support (e.g. no wavelength conversion, wavelength add-drop capability etc.) for traffic handling at a node can be compensated at the control level by better routing and wavelength assignment algorithms/protocols. Also, control level solutions can be designed such that they can benefit from node capability and improve the network performance further. Hence, in this thesis an attempt has been made to explore the possibility of cross layer design for performance enhancement in the optical WDM network.

This thesis comprises of seven chapters. The next section describes the chapter wise organization of the rest of the thesis.

1.3 Organization of the Thesis

The rest of the thesis is organized into six chapters followed by a list of publications.

Chapter 2: Network Topology and Performance Analysis

This chapter deals with the role of network topology in achieving overall network performance and provides solutions through configuration changes to handle traffic efficiently. Architectural and logical configuration changes can be made such that it improves the traffic handling capability with better survivability, fault tolerance and traffic engineering functionality. One such proposed solution provides alternate paths in a WDM dual ring backbone network to improve the traffic handling capability of the network. These alternate paths give flexibility to service providers to route the traffic at the nodes through least congested routes. A mathematical model has been developed to analyse the performance of such networks under different traffic intensity in different regions of the network. The model also incorporates traffic priority option to handle different types of traffic with different QoS requirements. The analysis reports the performance of a network comprised of nodes with wavelength conversion and without conversion as well.

Chapter 3: WDM Node Architecture and Performance Analysis

This chapter signifies the role of network node to achieve overall network performance. The WDM node architecture varies in terms of hardware components used to design it. The commonly used components are like Wavelength Add Drop Multiplexers (WADM), switching fabric, Fiber Delay Lines (FDL), wavelength encoder/decoder, input/output ports, and waveguides. Further these nodes can be distinguished through their switching granularity, routing, traffic handling, wavelength conversion and conflict resolving capabilities. The growth of optical WDM network due to huge bandwidth demand need optical nodes/routers to support bandwidth intensive application’s QoS demands. As bandwidth granularity becomes finer, optical nodes need to tune to handle more wavelength channels. The performance of WDM node architecture is analysed with the help of a probabilistic model for ring and star network topologies.

Chapter 4: Contention Resolution in OPS WDM Networks

This chapter deals with the well known problem of packet contention for optical nodes. Among three types of solutions (i.e. deflection routing, wavelength conversion and fiber delay line) FDL based solutions are more popular. A circular FDL based packet conflict algorithm for synchronous Optical Packet Switching (OPS) node is designed by us and analysed with a mathematical model using the Erlang C traffic model. Simulation results are also presented in support of the proposed mathematical model. This solution supports packet circulation in FDLs to improve the throughput.

Chapter 5: Adaptive RWA Algorithms for WDM Networks

This chapter focuses on the support provided by network control and management layer to enhance overall network performance. The node performance is usually limited due to existing hardware technology limitations. Hence further performance enhancement can be achieved through better Routing and Wavelength Assignment (RWA) algorithms. The RWA algorithms must be designed such that they utilize the underlying network infrastructure efficiently. Since adaptive routing algorithms have the better traffic handling capability hence the focus is on adaptive solutions. The four adaptive single path RWA heuristic algorithms and one edge disjoint multipath algorithm proposed by us are described in this chapter. The first of these algorithms is named as Weighted Edge Disjoint Path (WEDP) routing algorithm. This algorithm combines the path based and link based approach to solve RWA for wavelength routed networks. The second algorithm uses Wavelength Intersection Cardinality (WIC) based link weight method to establish the light-path connections. The next two algorithms are designed for dynamic light-path assignment using a wavelength mesh graph approach. These two algorithms are named as Least Count First (LCF) and Least Recently Used First (LRUF). The last algorithm in this chapter explores the possibility of multipath routing in wavelength routed WDM networks. It chooses multiple link-disjoint paths to transmit the data and improves reliability by providing fault tolerance as well as delay constraint.

Chapter 6: Distributed Wavelength Reservation Protocols

This chapter analyses the distributed wavelength reservation protocols and their role in overall network performance. Three popular protocols which are in this category are the

Source Initiated Reservation (SIR), Destination Initiated Reservation (DIR) and Intermediate node Initiated Reservation (IIR). Three modified versions of IIR protocols named as AIIR (Aggressive Intermediate-node Initiation Reservation), IIR_SIR (IIR_Source Initiated Reservation) and IIR_DIR (IIR_Destination Initiated Reservation) developed by us are explained with comparative performance analysis. The AIIR protocol probes wavelength in forward direction and blocks all the free wavelengths in all the links of each of the segments in backward direction. Finally, the sender chooses one of the blocked wavelengths for reservation. On the other hand, IIR_SIR reserves the wavelengths in forward direction during the probing process itself. The IIR_DIR protocol extends IIR protocol with multiple attempts for the wavelength reservation.

Chapter 7: Conclusion

This chapter summarizes the work and provides some directions for future work.

CHAPTER 2

NETWORK TOPOLOGY AND PERFORMANCE ANALYSIS

2.1 Introduction

Today most of the Wide Area Networks (WAN) and Metropolitan Area Networks (MAN) use preferably multi-ring topology in optical networks relying on the well established principles of self healing and multi failure protection capability. Since the emergence of Wavelength Division Multiplexing (WDM) technology, these optical rings have been upgraded to WDM for meeting the increased traffic demands. These rings are interconnected using Optical Cross Connects (OXCs) in such a way that it provides a large geographical coverage [Wang 2002] [Farahmand 2002] and transparent data communication to eliminate the bottlenecks of electronic processing at intermediate nodes. Usually ring networks employ wavelength switching mechanisms and, hence, face limited bandwidth utilization under traffic fluctuation. Therefore traffic grooming techniques has been employed to resolve this issue [Zhu 2003] [Hu 2002]. Traffic grooming allows multiplexing of two or more low data rate streams into a single higher data rate channel to exploit the available optical channel bandwidth [Hu 2004] [Dutta 2002]. Ring networks under various architectural and logical ring configurations have been designed and analysed to improve the traffic handling capability, survivability, and fault tolerance [Herjog 2004] [Sen 2005] [Funabiki 2010] [Ramaswami 1995a]. The modified ring network architecture presented by [Sen 2005] with different traffic intensity zones in an optical multi ring network topology is found to be interesting for further study. The analysis of such modified networks can help to improve the network performance. In the present work the ring topology has been modified to provide alternate paths to the traffic and a model has been proposed to estimate the call connection probability and traffic delay. Further, the analysis has been extended to observe the priority based traffic handling in the network for a better grade of service.

In this chapter the influence of topological configuration on the network performance enhancement is presented. The WDM optical ring network topology for improved performance analysis is considered in the present chapter. The status of research and motivation of the work is presented in section 2.2. Section 2.3 describes the architectural design of the proposed modified ring topology and its mathematical model to investigate the network performance through simulation. The results are compared with the traditional dual ring architecture. The next section highlights the importance of the proposed work and provides a comprehensive literature review.

2.2 Related Work and Motivation

The WDM optical ring networks employ pre-configured optical light-paths to communicate with the network at an increasingly higher data rate. An all-optical path can be formed using different wavelengths available in the connecting links employing wavelength converters and supportive switching algorithms at the respective nodes in a wavelength convertible network [Ramamurthy 1998a] [Ramaswami 1994] [Mukherjee 2000]. These WDM networks perform more efficiently through proper placements of wavelength converters at intermediate nodes but also face a challenge of reliability and high cost of full range wavelength converters [Harissh 2003] [Singh 2004] [Frey 2001]. In another approach, the light-path is established by enforcing the wavelength continuity constraint in the network. These networks employ some efficient traffic control and management techniques, either in a centralized or in a distributed way to support the network functionality [Ramaswami 1997] [Mukherjee 2004]. In the centralized scenario, the central node has to process and allocate the wavelength resources and faces the scalability and the survivability problem [Lu 2005]. On the contrary, in the distributed approach, the network control is distributed among different nodes and eliminates the processing congestion as well as reducing the risk of complete network failure due to single node failure [Feng 2005]. Light-path based WDM networks through distributed control are based on periodic information exchange between neighbouring nodes to support traffic routing via updated traffic forwarding information. However, due to convergence and propagation delays, these updates may not be well suited for sustained high traffic and bursty traffic. Thus these situations need to be handled in different ways.

However, in high-speed WDM ring networks placement of an add-drop multiplexer at each node allows certain wavelengths to optically bypass the node without being electronically terminated. This reduces the overall cost in case of properly assigned channels under appropriate traffic grooming algorithms. To achieve this, various wavelength routing algorithms and optimization techniques for a WDM ring has been proposed in the literature [Bouabdallah 2007] [Narvaez 2000] [Ghafouri-Shiraj 2001]. It has been observed that the control level solutions for network performance optimization can give better results if underlying network infrastructure is tuned accordingly. In other words, lower layer solutions like wavelength conversion capability, traffic grooming, topology configuration etc. greatly influence the higher layer solutions for traffic handling using routing and channel assignment algorithms. So network architecture and configuration solutions need to be deployed for better traffic handling capability in WAN optical WDM networks. The various solutions have been devised and implemented to cater to the traffic handling problem with required QoS.

In this regard the node aggregation approach suggested by [Funabiki 2010] describes the improvement in the traffic handling capability of WDM ring networks. This approach reduces the number of Local Area Networks (LAN) connection points in the Metropolitan Area Networks. This further reduces the requirement of costly hardware at the nodes i.e. transmitters/receivers. But for higher traffic demands it increases the traffic load at aggregated nodes which needs to be addressed separately.

The probabilistic model based on blocking probability is widely used by researchers to analyse the performance of all optical networks. Such a model has been developed by [Barry 1996] for all optical networks with and without wavelength converters considering the effects of path length, switch size and interface length (i.e. number of hops shared by two sessions) on blocking probability.

The above mentioned investigations have mainly concentrated on optimizing the number of usable wavelengths and the cost in terms of fibers and electronic terminal equipments (i.e. transmitters/receivers) but it is envisaged that an architectural/configuration change in the WDM ring design leads to improvement in the network performance with better handling of traffic fluctuation.

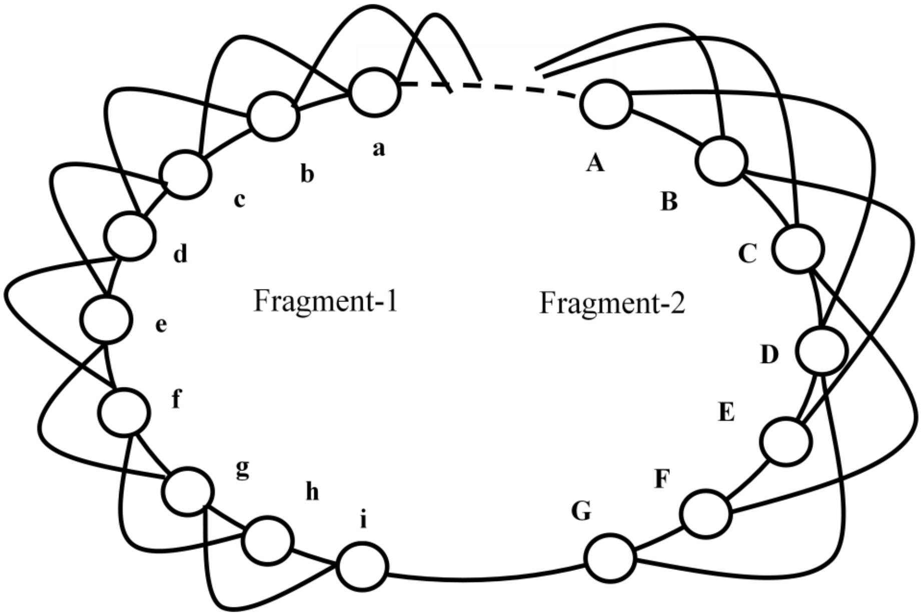

Figure 2.1 Modified Ring Network with Different Traffic Intensity Zone

A modified backbone ring network architecture proposed by [Sen 2005] shows the impact of the network configuration in the overall network performance. The proposed model suggests, splitting the conventional ring topology into various fragments as per local traffic demands. A ring network with two such fragments i.e. fragments 1 and 2 is shown in Fig. 2.1 [Sen 2005]. Each of the nodes of the fragment 1 is connected to the adjacent nodes as well as the next adjacent node, i.e. node g is connected to node h, node f, node i and node e. This layout can be adopted in the regions of networks having higher traffic demands. Further, the wavelength conversion capability can be added to either alternate nodes or all the nodes in the network for traffic handling. In fragment 2, each of the nodes is connected to the adjacent node as well as the node which is lying two nodes ahead of the node considered, i.e., node A is connected to node B and node D, node B is connected to node C and node E and so on. Thus, the entire network is assumed to be made up of a number of such fragments (each corresponding to a region of different traffic density), connected adjacent to each other.

Each network fragment provides alternate paths based on traffic demand pattern for the traffic routing. The nodes lie in a high traffic demand region have been provided with more alternate traffic routing paths as compared to the lower traffic demand region in the network. The model also considered the suitability of the wavelength conversion capability of the nodes to estimate the call connection probability for the modified ring along with the bidirectional dual ring. The mathematical model also caters the traffic fluctuations by keeping one wavelength reserved for meeting the additional traffic demands.

The literature review reveals that the detailed analysis of such modified networks for evaluating the traffic handling capability of the nodes under different traffic conditions has not been emphasized so far. In this chapter an attempt has been made to analyse such modified ring networks. A mathematical model has been developed to evaluate call blocking probability and traffic handling capability for such modified ring network architectures. The network performance is analysed by estimating the blocking probability and average delay as the data traverses from the source to the destination node. The model also caters the traffic priority.

The next section describes the proposed node architecture and its mathematical model to evaluate delay and call blocking probability.

2.3 Network Traffic Model for Call Connection and Delay Analysis[1]

In the present analysis, the conventional ring topology is modified to provide alternate paths to the traffic, and thereby, reducing the number of hops for data transmission under an appropriate routing algorithm. The modified ring architecture as shown in Fig. 2.2 illustrates the node connection architecture and is compared with the traditional dual ring topology as shown in Fig. 2.3.

In the proposed architecture, each node is connected to an alternate node with an assumption that the data flow is unidirectional. At each node data can move from a node to the next node under the transmission algorithm with a specified probability. Traffic arrival at any node is modelled as a Poisson process with an exponentially distributed service time at each of the nodes.

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[1] This work has been published in: Design and Characterization of a Modified WDM Ring Network - An Analytical Approach", Optik- International Journal for Light and Electron Optics, Elsevier, Vol. 123, No. 12, pp. 1103-1107, June 2012

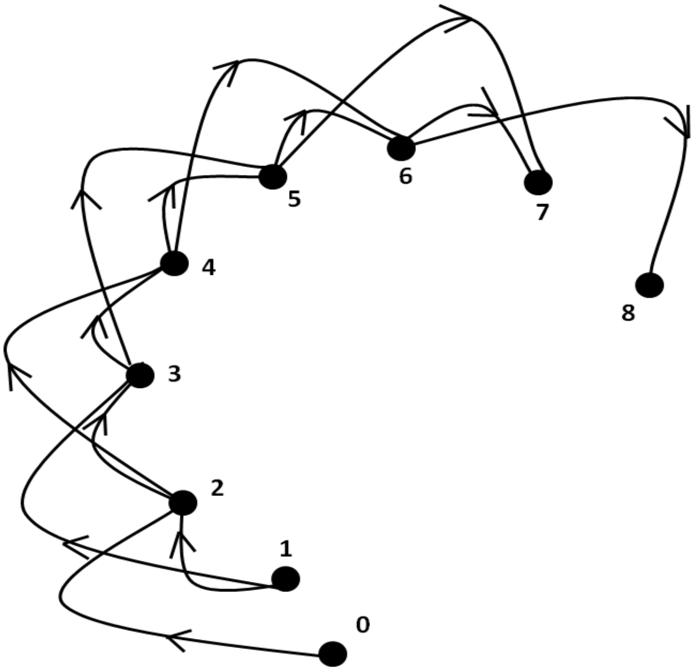

Figure 2.2 Modified Ring Network Topology

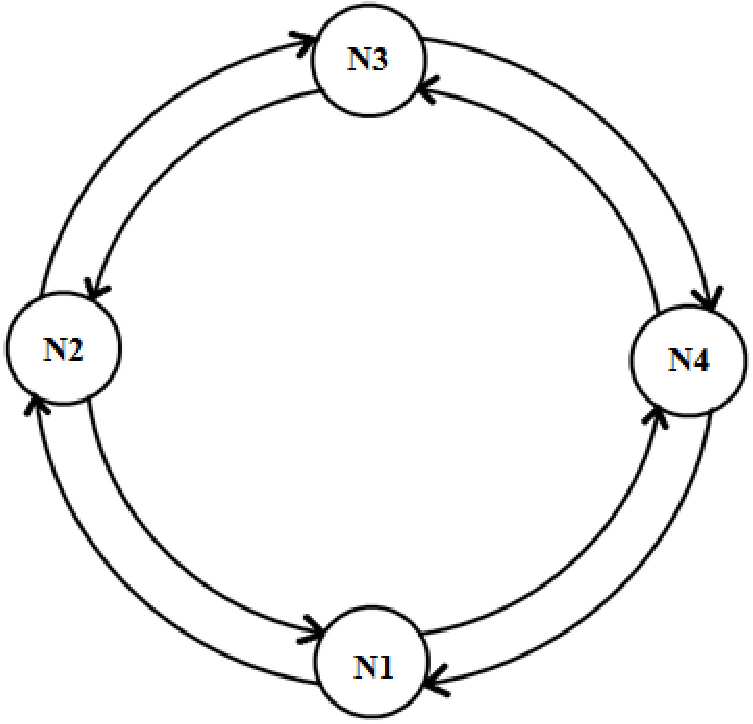

Figure 2.3 Conventional Dual Ring Network Topology

It is assumed that these rates are independent to be state of the system and other existing nodes. The traffic arrival rate and the node processing rates are λ_i and μ_i respectively. The traffic ρ_i for the ith node is given as λ_i/μ_i.

These nodes include buffers of size m to enhance the capacity and C_i is the number of servers for processing. Now the probability $r_{i,j}$ that a call after being serviced at node i will go to node j can be given as:

$$r_{i,j} = \begin{cases} p_0 & j = i+1 \\ 1-p_0 & j = i+2 \\ 0 & elsewhere \end{cases} \tag{2.1}$$

This gives:

$$\sum_{i=0}^{n} (\lambda_i \, r_{i,j}) = \sum_{i=0}^{n} (\mu_i \, \rho_i r_{i,j})$$

Further the above equation can be written as:

$$\lambda_i = \lambda_{i-1} r_{i-1,j} + \lambda_{i-2} r_{i-2,j} \tag{2.2}$$

Since summation of all probabilities should be one and $n_1 + n_2 + \dots\dots\dots + n_k = N$, we can write the probability of number of calls at node 1, 2 … k are $n_1, n_2, \dots n_k$ respectively, given as:

$$p_{n_1 n_2, \dots\dots\dots n_k} = (1-\rho_1)\rho_1^{n_1}(1-\rho_2)\rho_2^{n_2} \dots\dots (1-\rho_k)\rho_k^{n_k} \tag{2.3}$$

Here ρ_k is assumed as traffic at kth node.

The routing matrix for this node configuration can be written as:

$$\begin{bmatrix} 0 & p_0 & 1-p_0 & 0 & 0 & 0 \\ 0 & 0 & p_0 & 1-p_0 & 0 & 0 \\ . & . & . & . & . & . \\ . & . & . & . & . & . \\ 0 & 0 & 0 & 0 & 0 & p_0 \end{bmatrix} \tag{2.4}$$

Now, we need to find the marginal probability for each node, $p_i(n)$ i.e., the probability that n numbers of call requests are present at a particular node irrespective of the number of call requests present at the other nodes of the system.

This can be written as:

$$p_i(n) = \sum_{n_1=0}^{m} \sum_{n_2=0}^{m} \cdots \sum_{n_{(i-1)}=0}^{m} \quad \sum_{n_{(i+1)}=0}^{m} \cdots \sum_{n_k=0}^{m} p_{n_1,n_2,\ldots\ldots,n_{(i-1)},n,n_{(i+1)},\ldots\ldots,n_k} \tag{2.5}$$

The effective arrival rate at each node (ignore the local node call) can now be written as:

$$\lambda_i = \sum_{n=0}^{m-1} \lambda_i(n) p_i\,(n) \tag{2.6}$$

Thus, the numbers of calls (L) present at a particular node i can be expressed as:

$$L = \sum_{n=0}^{m} n p_i(n) \tag{2.7}$$

The average delay W_i at node i can be expressed as:

$$W_i = \frac{L}{\lambda_i} = \frac{\sum_{n=0}^{m} n p_i(n)}{\sum_{n=0}^{m-1} \lambda_i(n) p_i(n)} \tag{2.8}$$

The calculation is based upon First Come First Serve (FCFS) basis. In the priority base service system, the service is provided on the basis of priority irrespective of arrival pattern. The traffic with higher priority is selected for the service ahead of the traffic with lower priority without preemption. Calls at each node are categorized into two priority classes by assigning an appropriate number. The usual convention is the smaller the number, the higher the priority. Suppose λ_1 is a mean rate of arrival for first priority and λ_2 is the mean rate of arrival for second priority and thus provides an overall arrival as ($\lambda_1+\lambda_2$). Considering these notations and assumptions, a system of steady-state balance equations for the proposed network can be established. The P_{mnr} is the probability with m units of priority 1 (r=1) and n units of priority 2 (r=2) in the steady state of the system. The ordering of service doesn't affect the probability of idleness. The percentage of time the system is busy is ρ, the percentage of time it is busy with a type r customer becomes ${}^{\rho\lambda_r}/_{\lambda}$ so that:

$$\sum_{m=1}^{\infty} \sum_{n=0}^{\infty} p_{mn1} = \frac{\lambda_1}{\mu} \tag{2.9.a}$$

and

$$\sum_{m=0}^{\infty} \sum_{n=1}^{\infty} p_{mn2} = \frac{\lambda_2}{\mu} \tag{2.9.b}$$

Using the principles of queuing theory we can represent the probability of number of call requests of higher priority at a node as given below:

$$P(n) = (1-\rho)\left(\frac{\lambda_1}{\mu}\right)^n + \frac{\lambda_2}{\lambda_1}\left(\frac{\lambda_1}{\mu}\right)^n \left[1 - \frac{(\lambda_1/\mu)^n}{(1+\lambda_1/\mu)^{n+1}}\right] \qquad (2.10)$$

Where μ , is the common service rate for both of the calls and ρ is given as $(\lambda_1 + \lambda_2)/\mu$. Now the average number of call requests present in a particular node at any instant becomes:

$$L = \sum_{n=0}^{m} np(n)$$

We have taken the limits of summation from 0 to m for L and 0 to m-1 for λ (ignoring node's own traffic), where m is the number of buffers on that particular node. This gives the average delay at a given node as:

$$W = \frac{L}{\lambda} = \frac{\sum_{n=0}^{m} np(n)}{\sum_{n=0}^{m-1} \lambda(n)p(n)} \qquad (2.11)$$

We can further investigate the network performance by considering different service rate for the two priority calls and then estimate the probability of number of calls of higher priority at a node.

This can be given as:

$$P(n) = (1-\rho)\left(\frac{\lambda_1}{\mu_1}\right)^n + \frac{\lambda_2}{\lambda_1+\mu_2-\mu_1}\left[\left(\frac{\lambda_1}{\mu_1}\right)^n - \frac{\mu_1{\lambda_1}^n}{(\lambda_1+\mu_2)^{n+1}}\right] \qquad (2.12)$$

Here λ_1 and λ_2 represent the arrival rate of the 1st and 2nd priority calls respectively. Similarly, μ_1 and μ_2 represent the service rate of the 1st and 2nd priority calls respectively. The total traffic ρ is given as:

$$\rho = \frac{\lambda_1}{\mu_1} + \frac{\lambda_2}{\mu_2}\,.$$

The average delay at a given node can be calculated by Eq. (2.11) using Eq. (2.12). It is evident from the derived expressions that the network performance parameters can be numerically computed for the given traffic in a conventional ring topology and in a modified one with varied node architecture. Node capability can be extended by variable buffer size or by changing the processing rate. Network call-blocking probabilities under the influence of diverse number of buffers at each node and delay performance either with or without priority have been investigated in the succeeding sections using the derived analytical model.

2.3.1 Network Performance Analysis

Network performance parameters e.g., blocking probability, delay, buffer utilization and influence of priority in traffic grooming becomes important parameters to be evaluated for the better system design and simulation. The blocking probability is estimated for the conventional dual ring and the proposed modified ring with the given traffic arrival rate and service rate of the processing nodes using Eqs. (2.3) and (2.4). The simulation study also included buffers at nodes to justify the appropriate number of buffers for a given call blocking probability. The call blocking probability of modified ring for four different service rates along with the conventional ring having a service rate of 2 normalized units is shown in Fig. 2.4. It is observed from the graph that the modified ring has more blocking probability as compared to the conventional ring for a slow processor but it quickly clears the call requests with the higher processor speed and the buffer capacity at the nodes. This can be attributed to higher data arrival at the node of modified ring. The blocking probability of the network decreases with the increase in the processing rate of the node processor. Also, the increased capacity of buffers at the node reduces the call blocking probability significantly for the modified ring.

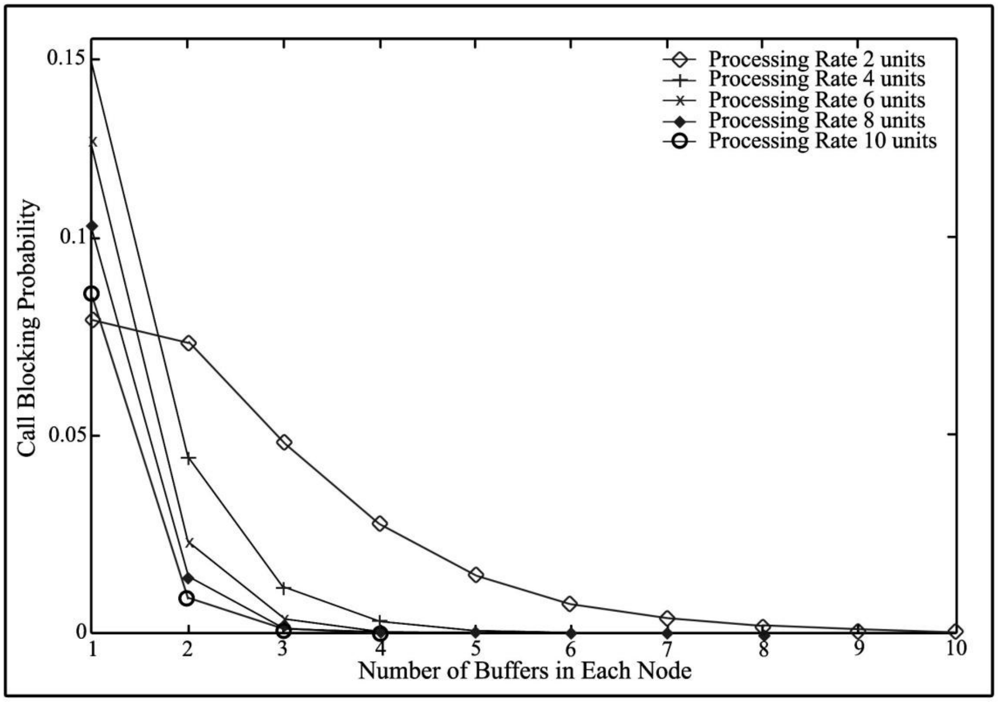

Figure 2.4 Call Blocking Probability for Different Service Rates

In high speed networks, delay simulation is also important and this has been estimated for the data traversing from node 1 to node 5 for the traditional ring and also for the proposed modified ring. The results have been plotted in Fig. 2.5a and Fig. 2.5b for both the cases.

This simulation has been carried out for unit data arrival rate and processing rate varying from 2 units to 10 units in step of 2. Network simulation towards delay estimation of the traditional ring network shows an increase in the delay with the increase in the number of buffers at the node, however this increase is less pronounced for faster processor as shown in the Fig. 2.5a with the least slope. This analysis is useful to decide the buffer size of the node for a given processor speed. It is interesting to note that the modified ring also shows the similar qualitative graphs but with a lower value of the corresponding delay as depicted in the Fig. 2.5b. It is observed from the graph, that the influence of the node processing rate, on the delay is not very significant up to three buffers however; it becomes significant beyond four buffers. This observation can be used to decide the amount of allowed delay in the network.

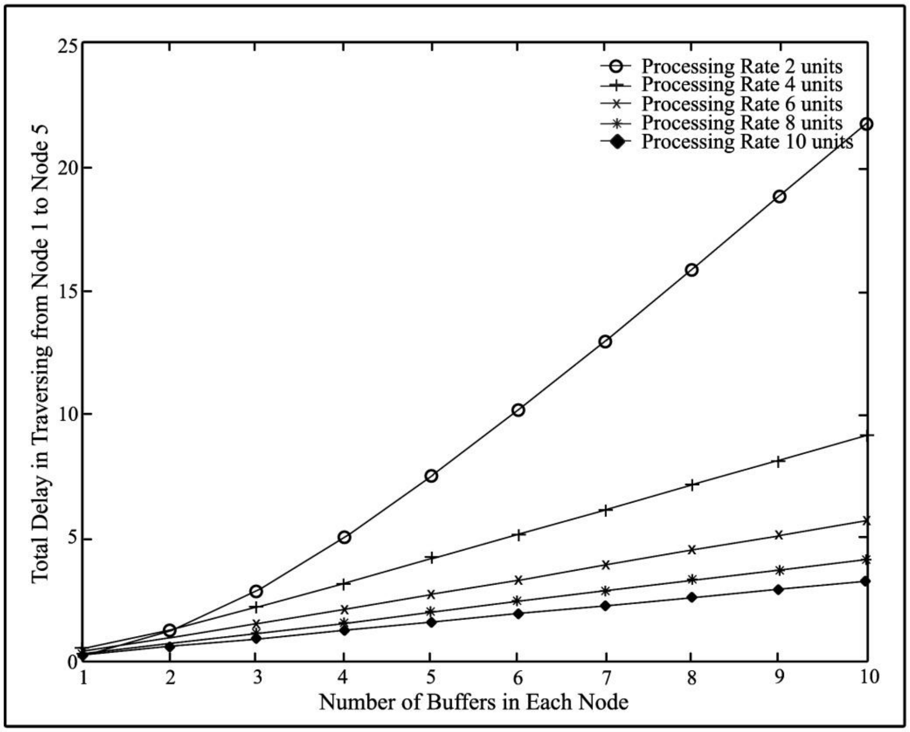

Figure 2.5a Delay Analysis of a Conventional Ring

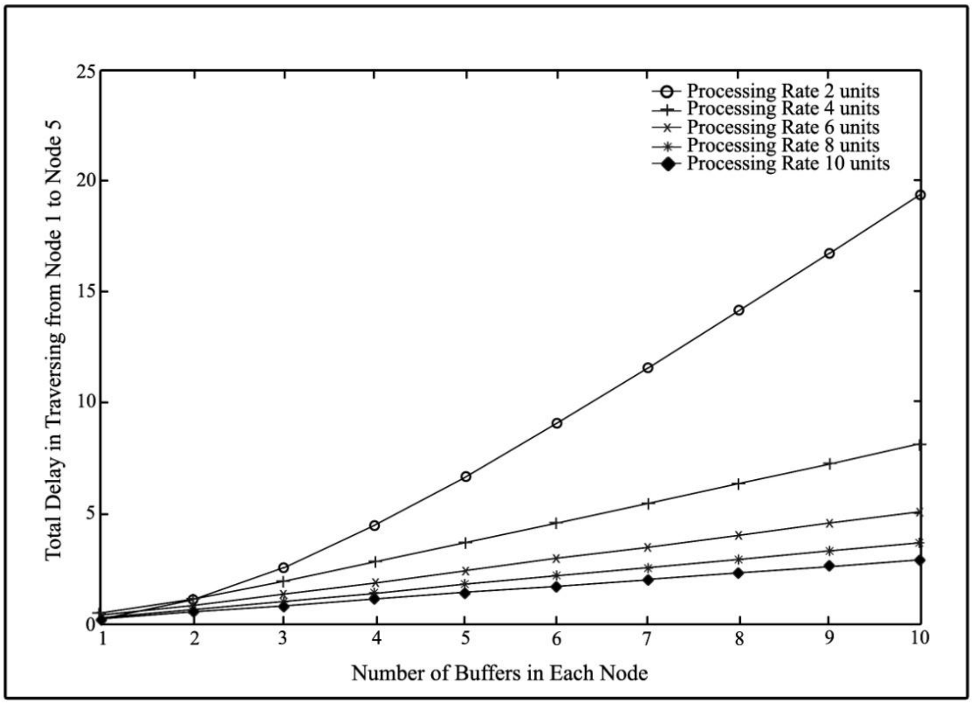

Figure 2.5b Delay Analysis of a Modified Ring

Sometimes the call congestion control algorithm needs a variable control over the buffer capacity or the priority implementation level of the data traffic type based on delay or processing priorities. This analysis can be carried out for a general case using Eqs. (2.11) and (2.12). In the present analysis, we have assumed two priority levels (i.e. high and low) for the incoming traffic. The higher priority data is processed with different processing rates to implement the priority scheme. Delay analysis of the data reaching at the node with different arrival rates with two different priority levels have been presented as a function of the buffers. The simulation results are reported in Fig. 2.6a. The curve indicates that the addition of buffers will not simply add to the delay in a linear way unlike the case of a network without considering the traffic priority. This case shows a decrement in the delay slope with the increment in the numbers of buffers. It is observed that, beyond a certain number of buffers the incremental change in delay becomes insignificant and ultimately saturates to a maximum delay value. This decrease in the incremental change of the delay with the addition of the buffers can be attributed as an improved effective processing of the traffic under the priority scheme.

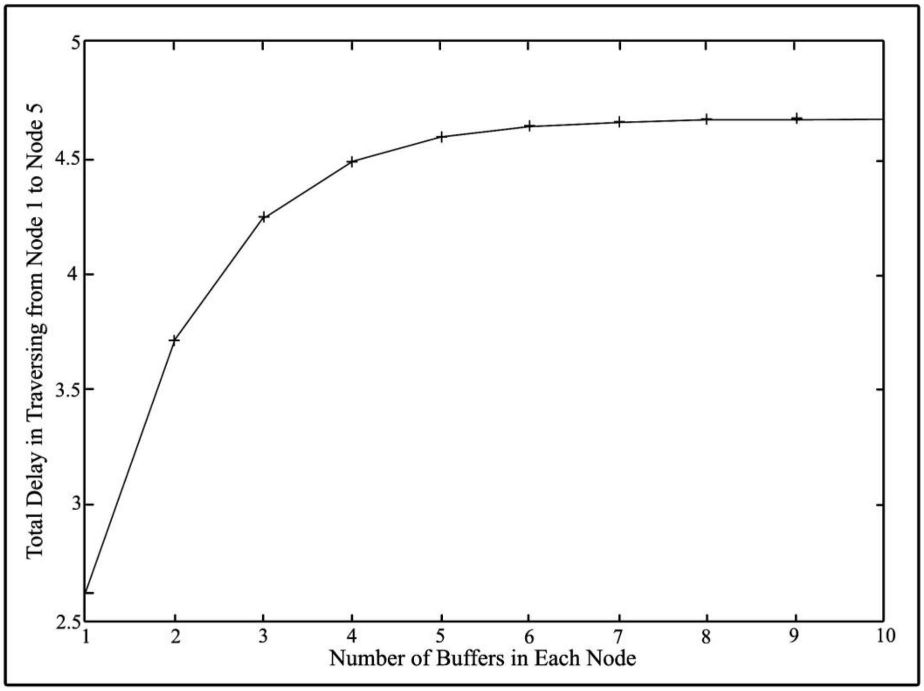

Figure 2.6a Delay Analysis for High (1 unit) and Low (2 unit) Priority of Traffic

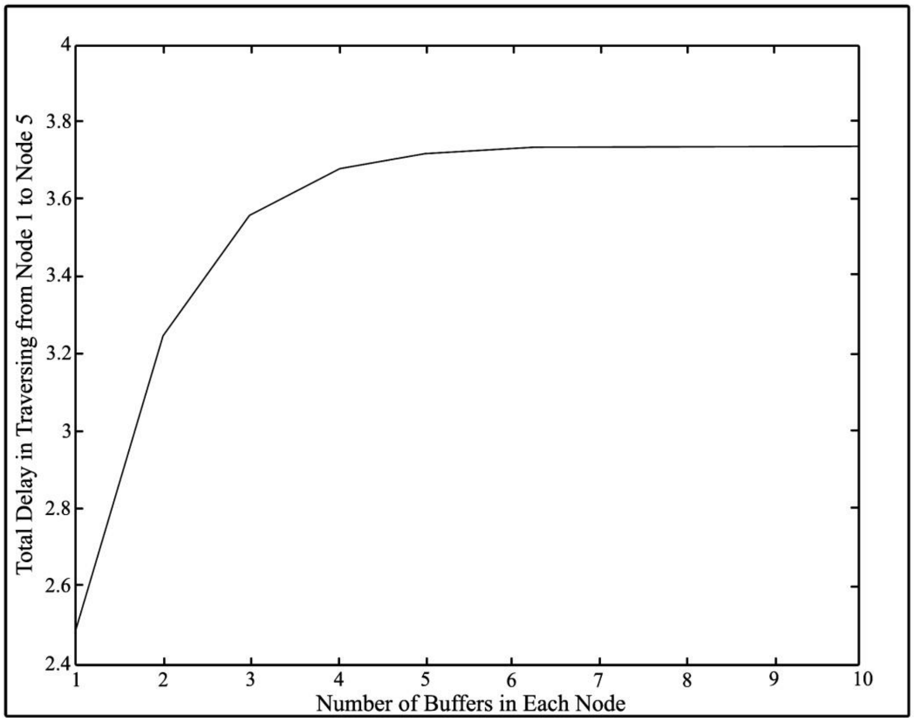

Figure 2.6b Delay Analysis for High (2 unit) and Low (1 unit) Priority of Traffic

The Fig. 2.6b depicts the delay analysis for the case, if the arrival rate of higher priority data is doubled as compared to the arrival rate of the low priority data for the same source destination separation. A similar qualitative behaviour is observed but with a lower delay because in this case a larger portion of the traffic is processed quickly. It is inferred that the delay reduction at the node can be achieved by managing the processing speed for the different priority traffic to achieve the optimum performance.

Thus the presented model equations can be used to understand the nodal delay in a WDM network employing buffers for traffic engineering and network management. Of course the analysis seems to be simple for a smaller network but it becomes more computationally complex for a larger network. At present to feel the physical insight of the network behaviour, the call handling capability has been considered.

2.4 Results and Conclusion

This chapter describes the concept of involving the design and implementation of a modified ring topology based on the statistical data, which gives an estimate of the regional traffic demands having provisions to adapt traffic fluctuations. The influence of network architecture and configuration on the network performance enhancement has been studied and analysed with an analytical model. For this a backbone ring network has been modified by connecting the alternate nodes in regions identified statistically as areas of high traffic density. A mathematical model is presented for the modified ring network having node storage capability by adding reasonable amount of buffers. The developed model is used to investigate network characteristics to emphasize the improvement in blocking probability and average delay from a particular node to another node using buffers. The network performance of the modified ring is well emphasized with the numerical simulation results. The delay performance of the network is also calculated for the nodes having different processing speed under the different traffic priority consideration. A significant improvement in the node delay is observed under the priority scheme especially for modified ring topology. In conclusion, we can sum up that the modified topology has its own advantages of implementation and usage in establishing the improved WDM network.

Further, network performance is constrained with node capability in terms of wavelength add drop-multiplexer, buffering capability, switching granularity and other configuration parameters. The next chapter describes the influence of node architecture on network performance.

CHAPTER 3

WDM NODE ARCHITECTURE AND PERFORMANCE ANALYSIS

3.1 Introduction

Optical node architectures are categorized on the basis of the switching domain (i.e. electronic and optical) and switching granularity (i.e. wavelength, packet and burst). Optical networks were not all-optical in the early stage of their development because of optical-electronic-optical conversion involved in switching nodes. Which means at every switching node optical signals are converted to electrical form, buffered electronically and again converted back into optical signals before forwarding to the next node in the path [Papadimitriou 2003]. This conversion process affects the network speed significantly. As the network capacity increases after the employment of Wavelength Division Multiplexing (WDM), electronic switching becomes a bottleneck and is unable to keep up with optical speed [Mukherjee 1996] [Chlamtac 1996]. These high speed switching requirements can be met by developing all-optical switching capabilities. The migration from electronic to optical switching increases the switching speed and reduces the overall network operating cost. Thus switching in optical domain has become much more efficient as compared to an electronic switching [Ramaswami 2002]. In addition to cater the higher data rate (i.e. 40 Gbps or beyond) optical switching should satisfy the service provisioning requirements as well. The main challenges in optical switching are bit level processing and optical data buffering. Hence in packet switched networks electronic processing of the header is the only practical solution [Yao 2000]. This requires modification in existing optical node architectures such that it manages the huge traffic to ensure the QoS requirements [Xiaohui 2011].

In general switching granularity performance depends upon the network type (i.e. backbone, Internet, ATM etc.). However wavelength based switching in Optical Circuit Switched (OCS) networks guarantees the end to end traffic transport owing the prior established light-path from source to destination. Such types of networks are appropriate for backbone networks which cover a large geographical area. In these networks active light-paths are maintained for longer time duration. However, the end to end delay for connection establishment and wavelength level granularity makes circuit switching to less suitable for packet switched networks e.g. Internet [Wen 2005]. The OCS technology is not appropriate to deal with the bursty nature of traffic since it lacks flexibility and overhead of bandwidth reservation for each connection even for a small duration [Papadimitriou 2003]. The growth and uses of Internet indicate the need for traffic switching at packet level [Corazza 1999] and this switching paradigm is known as Optical Packet Switching (OPS).

After OPS another promising switching paradigm introduced in optical domain is Optical Burst Switching (OBS) which fits between OCS and OPS with respect to switching granularity. In OBS, packets are aggregated at edge nodes of the network on the basis of some common feature (e.g. destination basis) and sent as a collection of packets called a burst in the network towards the destination. Once the burst reaches the destination, it gets disassembled into individual packets and is delivered accordingly [Turner 2000] [Xu 2001] [Rajabi 2010].

Today’s network requirement is to integrate heterogeneous networks through a generalized framework called as Generalized Multiprotocol Label Switching (GMPLS) which can support wavelength, packet and burst switching as per QoS requirements. This requires support at the architectural level of the node as well as at the control plane level through which node functionality can be dynamically configured on demand for the requested service. Thus network node architecture requires a dynamic reconfigurable switching fabric to sustain the demand of resource allocation to support traffic fluctuation and scalability [Pattavina 2005] [Rouskas 2004]. The node architecture capable to support different network protocols enhances the data transport capability in a WDM network. Similarly, the node can be integrated with intelligence to support distributed and online traffic control for a better network management through efficient routing and traffic forwarding protocols [Bonani 2007]. This implies that the node’s hardware should be reconfigurable through the control circuitry to handle the switching granularity (i.e. wavelength, packet, and burst) at different data rates.

This chapter emphasizes on the influence of the node architecture design onto network performance. The node architecture parameters considered here are switching operation at different granularity with desired data rate and service provisioning requirements. The optical node architecture [Chaubey 2007] used for the present analysis has been described in the section 3.3. The described node architecture is used to develop a mathematical model to investigate the network performance of a ring and a star topology. The next section highlights the related work done by various research groups and the motivation for proposed work.

3.2 Related Work and Motivation

The traditional node architecture comprising of the Wavelength Routed Switch (WRS) and Wavelength Selective Cross Connect (WSXC) is shown in Fig. 3.1. In this node, signals are de-multiplexed into individual wavelengths at each of the input port and then send to different reconfigurable space switch.

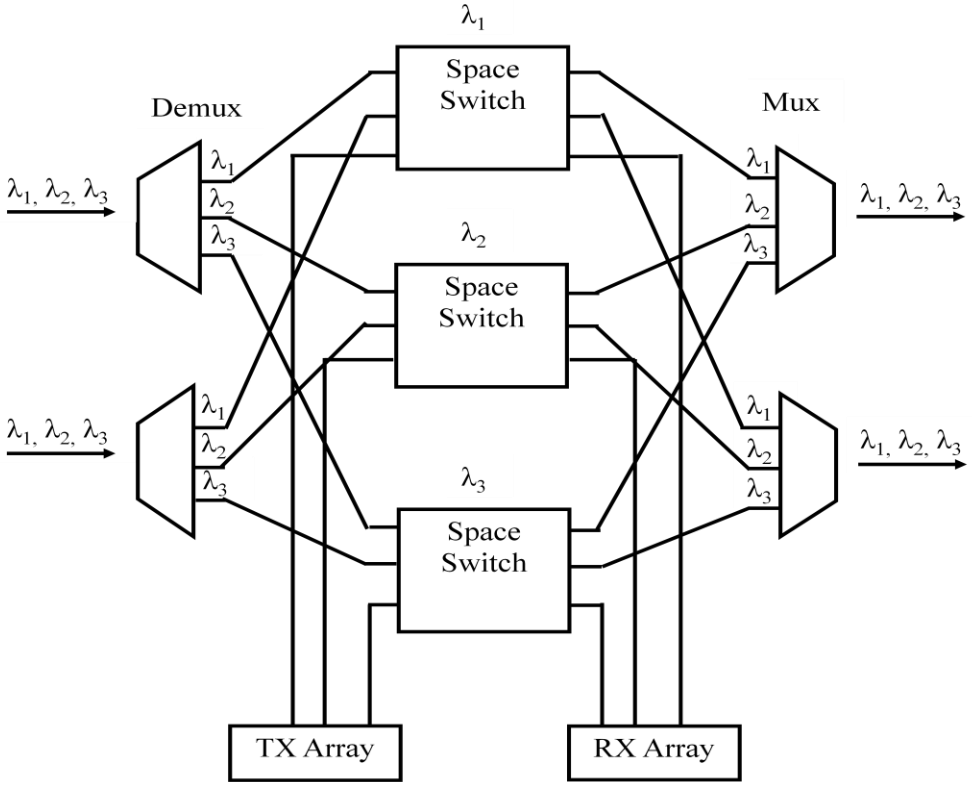

Figure 3.1 Wavelength Routed Node Architecture

Space switch routes these signals to the output port such that no two signals can reach to same output port on the same wavelength. Each signal is grouped on different wavelengths at each output port before reaching to output port [Jue 1999] [Hunter 1999]. These nodes are not scalable with respect to the addition of new wavelengths and also do not support for OPS/OBS technology.

A scalable node architecture developed in [Jue 1999] can add more wavelengths without additional space switch by incorporating wavelength insensitive components in the architecture. However, the node performance degrades by adding wavelength insensitive components because a wavelength entering to a given input port cannot be individually routed to different output ports. So there is a trade-off between scalability and flexibility.

As optical technology becomes mature in high speed optical and networking, the significant changes in node architecture have been proposed in the last two decades [Pattavina 2005] [Yao 2000]. Optical node design can be broadly classified into seven categories: opto-mechanical, thermo-optical, liquid crystal, micro-electrical mechanical, acousto-optic, bubble and electro-optical. Among the various switch performance parameters; scalability, configurability, buffering capability, crosstalk, insertion loss and switching speed are mostly considered [Dugan 2001] [Papadimitriou 2003]. The first commercially available optical switch was based on opto-mechanical technology in which switching function was performed by mechanical means like mirrors, prisms and directional couplers. The switching speed offered by mechanical switches is limited to few milliseconds, which is still slow for optical switching purpose. Scalability and long term reliability are other limitations of these mechanical switches [Papadimitriou 2003].

The development in packet switched networks is started by providing low cost solutions for wavelength scalability with higher throughput to support switching high speed. The node architecture by European ACTS KEOPS [Gambini 1998] team and the WASPNET node [Hunter 1999] is among the first few nodes proposed for OPS networks. The traffic prioritization is handled using optical buffering by [Hunter 1999], that ensures the lesser loss and delay for high priority traffic. The OPS node architecture and its packet contention problems are discussed in chapter 4. The optical node becomes more and more intelligent with the inclusion of add/drop multiplexers, wavelength converters, and control circuitry [Mukherjee 2004] [Srinivasan 2002]. The node architecture proposed by [Lazzez 2007] supports optical packet and burst switching with QoS support using switching fabric unit, waiting unit, control unit and input/output processing units. In such architectural design control unit provides the information about wavelength, buffering units and I/O port availability to implement routing protocols.

However electronic switching speed limits the scalability of multi-hop wavelength routed networks, while optical packet switching is constrained due to lack of effective optical buffer implementation and conflict resolution techniques at nodes. Thus a solution with improved wavelength utilization can give a better network performance. Wavelength is accessed in such type of nodes on the Time Division Multiplexing (TDM) basis in cyclic manner [Huang 2000] [Gumaste 2007]. The node architecture proposed by Huang et al., divides each of the wavelengths into fixed time slots and routes the traffic in the dimension of time, wavelength and space. These types of routers are called as Time Wavelength Space Routers (TWSRs). Similarly the node architecture given by Gumaste et al., supports multiple connections based on a time sharing over a single wavelength without any need of switch reconfiguration. This node architecture is based on the concept of light-trail which is analogous to wavelength bus [Gumaste 2004] [Gumaste 2003]. Nodes within light-trail can communicate each other without any switching requirement. The node comprises of Reconfigurable Optical Add Drop Multiplexer (ROADM) to receive composite wavelength signal.

The performance of optical circuit switched network critically depends on the active and passive circuit components used at the nodes. In such networks each subscriber is assigned a separate wavelength channel working at a minimum loss and crosstalk. However, the performance of packet switched optical networks are characterized by the strategy involved in handling the packet blocking either through utilizing buffers or wavelength conversion [Srinivasan 2002]. The network node architecture requires a dynamic reconfigurable switching fabric to sustain with resource allocation demands and provisioning requirement to support different traffic rates and scalability. Thus it is essential for a network developer to optimize the network performance for the least crosstalk, minimum delay and best throughput applicable for most of the network topologies. Optical packet switching [Diano 1999] combined with WDM technology has changed the static usage of WDM network into an intelligent optical network capable of an efficient routing and switching. The need for fixed or variable packet length with full optical synchronization has added a new feature in such network nodes to support the data traffic [Gambini 1998].

An architectural study and analysis of such intelligent nodes has been less emphasized in the recent past and thus requires an attention to model a proper optical node. Node architecture for such networks involves multiple delay lines, output queuing, wavelength encoding and control blocks. The performance modelling and analysis of a node to handle high data rate becomes tedious and time complex with the increase in number of wavelengths. A novel method for achieving such intelligent routing at a fast speed is attained by mapping the optical network onto the reserved signaling channels and updating the node status table to implement the routing algorithm for better traffic handling [Banerjee 1996]. This proper online update may lead to implement the decision by activating the wavelength converters to maintain the light-path even in the case of single channel availability between the source and destination. This may provide a simpler way to achieve an optimal path between a source and destination without going for time complex recursive algorithms to find all possible path combinations. On the other side, large number of nodes with wavelength converters degrades the multiplexed WDM signal to be acceptable for a given QoS [Ramamurthy 1998b].

The node architecture proposed by [Chaubey 2007] is modelled as a network processor to read the information from the packet header to implement the required algorithm using standard queuing concepts. The node supports packet stacking with different time slots which helps to convert serial data into parallel and vice versa. This node architecture allows the network provisioning at higher data rates. The node can also be used to optimize the path on the basis of applied algorithms to process the data traffic. The simulations have been carried out for a mesh network topology to analyse the performance of the node. The simulation results presented in the paper show that the node supports huge data transmission up to a significant data rate and provides an improvement in call connection probability. Such mathematical model of a WDM node helps to simulate realistic networks for performance analysis. Further, it helps to design and configure the networks as per current traffic demands and QoS requirements. The online algorithms help to adapt the network nodes as per current network conditions.

This node architecture and its model are found to be promising, hence we extend it to analyse the performance of the other two popular network topologies i.e. ring and star. The next section describes the node architecture in detail with the corresponding model. The subsequent sections of this chapter report the node's performance evaluation for the ring and star network topology.

3.3 Node Architecture Model

Optical network performance can be improved by pre-configuring the switching elements based on control signals derived from traffic control algorithms. Such control algorithms help to determine data transmission feasibility over the path on the first node itself. If such transmission is not possible, then the signal is to be blocked at the initial node itself. This in turn saves a lot of time and resources, especially in the case where the signals get blocked after traversing first few links of the path. Such kind of blocking can be avoided or reduced, by using a dedicated wavelength for communicating the status of the channels originating from the other nodes. This wavelength is usually separate from the main set of wavelengths. The node architecture model considered here is capable of routing the signal over different wavelengths in the various links such that the path with minimum propagation loss, delay and crosstalk is chosen. The wavelength routed networks exploit the wavelength resources but sometimes the allocated wavelength/bandwidth is not fully utilized due to stochastic arrival of insufficient traffic data at the node. Thus, the node should be compatible with wavelength bandwidth partitioning into fixed length or dynamic length of time slots and thereby changing the granularity of bandwidth allocation to time slots instead of entire wavelength.

An architectural design of an optical node having routing and conversion capability has been presented here. The node architecture design depicted in Fig. 3.2 is proposed by [Chaubey 2007]. It includes the relevant functional blocks required to implement the optical packet stacking on the assigned wavelength channel. Wavelength allocation status is regularly updated through the control channel for the efficient use of wavelengths in accordance with adopted algorithm. The incoming traffic at a node is kept in a specified time slot of an assigned wavelength through the control operation of the tuned transmitter involving control signals, Grooming Switch Fabric (GSF) and Optical Add and Drop Multiplexer (OPADOM). The OPADOM allows bypassing of the optical channels, if required; and drops only the wavelengths which carry the traffic to the destined node. The incoming data is uploaded on a specific transmitter at W_i, if the same is on for a time slot duration τ_p. The incoming serial data on the node to be processed is uploaded on the tunable laser operating at different frequencies (wavelengths) (e.g. W_1, W_2, and W_3) for consecutive time slots of duration τ_p. The output data becomes a time slotted data on different channels in series which can be converted into the parallel time slot by using of embedded grating, delay line, and circulator. For example, W_1 slot have to be delayed by $2*\tau_p$ to make it in the same time slot as of W_3 after being circulated toward OPADOM.

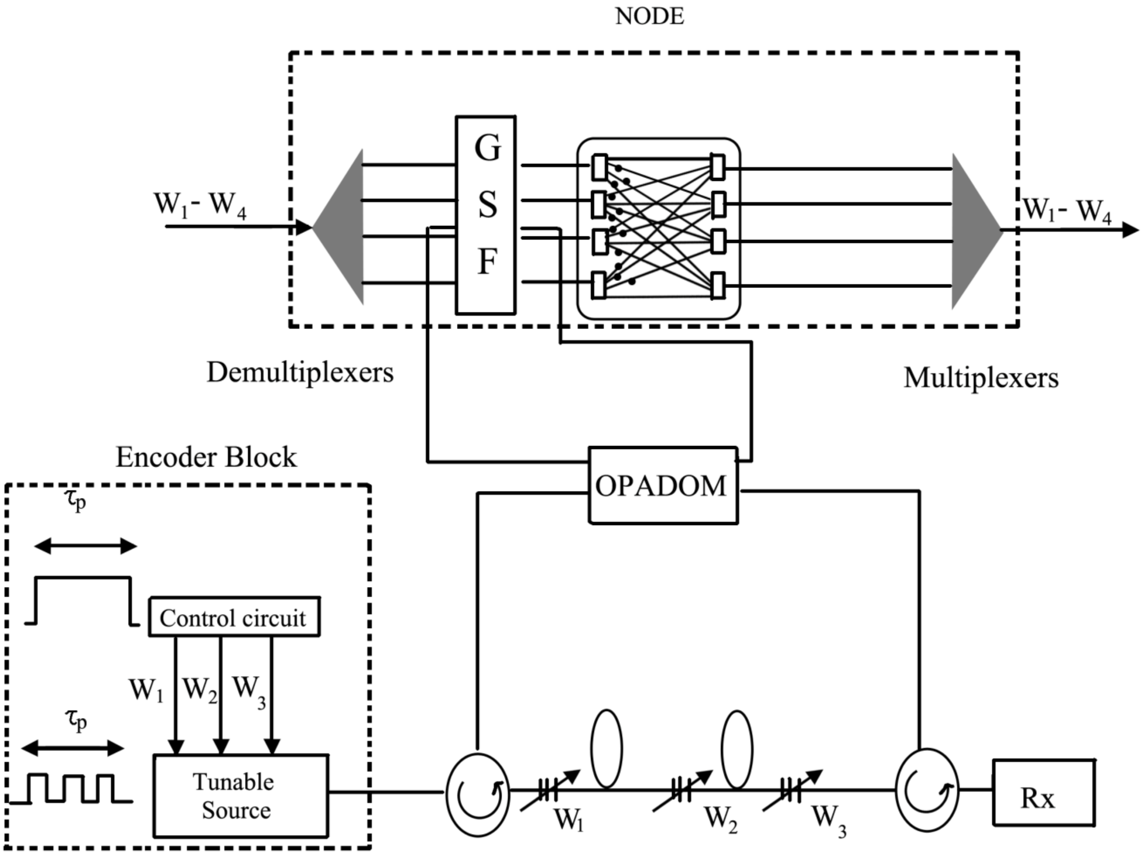

Figure 3.2 WDM Node Architecture

The cumulative loss and delay can be modelled for a given number of wavelengths on the basis of grating parameter, coupler, and delay characteristics.

The estimation of the routing time requires the determination of the time taken up in the different stages of switching, comparison and loading to and from the memory. The proper routing decision requires an estimation of the switching time. The model assumes the Poisson distribution process for traffic arrival. The node architecture performance analysis is carried out on the basis of large sets of packets. The node reads the header information or scans the entire wavelength to decide whether to convert or to download the packet at the node using GSF. The node can upload data on a given wavelength by switching to the respective source for a given time slot duration (τ_p) through the encoder block as shown in Fig. 3.2. The model assumes the node performance in an ideal situation; however the non-linearity of the subcomponent and jitter of the encoding block limits the performance by incorporating some additional delay. These node components can be modelled as delay components with some random noise adder. This in turn governs the value of data processing time (μ) and the total number of packets that can be processed by the router. The effective traffic (ρ) at the node depends on the channel capacity (C), packet arrival rate (λ), processing time (μ) and the number of nodes (n) in the network involved.

This traffic (ρ) is expressed as:

$$\rho = n\lambda / C\mu \qquad (3.1)$$

This traffic equation is used to evaluate the performance of the node architecture in the WDM network.

The performance analysis of mesh topology is carried out by [Chaubey 2007] for the above mentioned node architecture. The traffic distribution for a WDM node of a mesh topology is shown in the Fig. 3.3. The figure shows the number of packets delivered at a node is equal to the number of packets routed at each of the nodes. Similarly, in the equilibrium state, the number of outgoing packets from a node is equal to the number of arriving packets at that node from its adjacent nodes. Thus, the total number of data packets arriving at a node would become $\lambda\times(1+1/m)$. Here m is the fraction of the packets generated from the node itself.

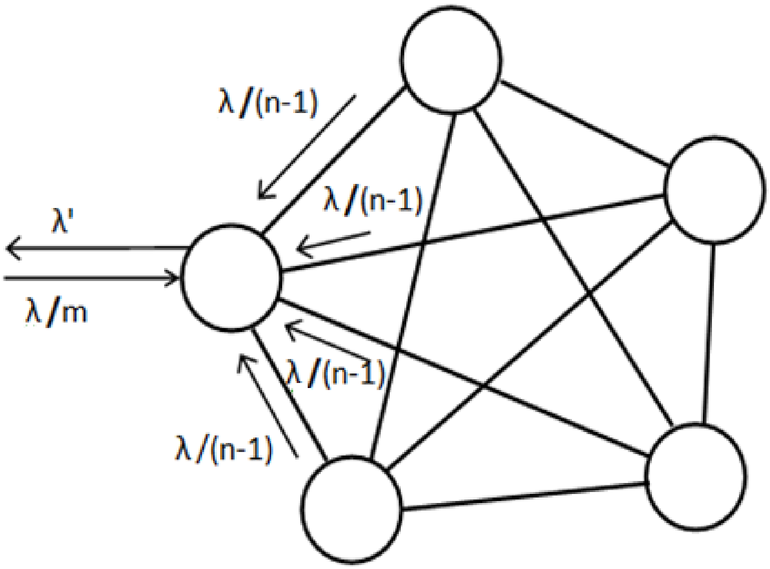

Figure 3.3 Traffic Distribution of a Mesh Topology

The dropping probability of incoming packets at the node for ‘w’ wavelengths per link is given by the following equation:

$$P = \rho^{w+1}(1-\rho)/(1-\rho^{w+2}) \qquad (3.2)$$

This gives the probability of a packet to be served by the router at any node as $(1-P)$. Hence the effective service rate for the entire network is given by the following equation:

$$\lambda' = \lambda\{1 - [\rho^{W+1}(1-\rho)/(1-\rho^{W+2})]\}/m \qquad (3.3)$$

This formulation is used to calculate the call connection probability and the mesh node performance with different traffic rates. The simulation results infer that the network performance is limited by the number of wavelengths and the number of nodes in the network. The performance values are sensitive to the switching and processing delay parameters and can be modified for the optimized design.

In this chapter the above mentioned node architecture is considered as a part of ring and star network topologies. The performance of the node architecture is evaluated for the ring and star topology with the help of an analytical model and the findings have been discussed in the following sections.

3.3.1 Performance Analysis with Ring Topology[2]

The router or node is considered as a single server model for the simulation purpose, which allows ‘w’ waiting slots for each of the channels and serves the request on the basis of First Come First Serve (FCFS). The traffic arrives at a node according to Poisson distribution and competes for the service with independent, identically distributed service times. Thus the queuing system model provides service to the incoming request if the processor is free otherwise it is queued. The congestion model can be described using Kendall’s notation [Schwartz 2004] showing ‘M’ as distribution of inter arrival and service times of calls for a single server serving through a finite number of wavelengths ‘w’ to a large number of connection request population. The notation in the present case can be expressed as:

$(M|M|1)/(FCFS|w+1|\infty)$

The data packet arrival rate at each node from its adjacent nodes is assumed as λ and the node’s own contribution is assumed as 1/m (m is an integer) fraction of the incoming traffic. This gives a total traffic rate as $n\lambda/m$ for a network having ‘n’ nodes. The performance of a network can be evaluated on the basis of its ability to process the arriving packets efficiently. This can be represented by the traffic parameter ρ, given as $n\lambda/m\mu$. Assuming the number of wavelengths on each link is ‘w’ which provides the total number of ‘w’ buffering slots on each of the links.

Now, the dropping probability of incoming packets for a ring topology can be written as:

$$P_{ring} = \rho^{w+1}(1-\rho)/(1-\rho^{w+2}) \qquad (3.4)$$

The probability that an incoming packet at any node to be served by a router is given as:

$$P_{Service} = 1 - P_{ring} \qquad (3.5)$$

At each node, every wavelength can be thought of as a server and μ' is the time to transmit a data packet between two nodes over a link. Therefore, the effective service rate for the entire network is:

$$\lambda' = \lambda\{1 - [\rho^{w+1}(1-\rho)/(1-\rho^{w+2})]\}/m \qquad (3.6)$$

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[2] This work has been published in: WDM Network Topologies - A Probabilistic Model, International Conference on Advanced Computing and Communications, ADCOM 2007, pp. 733 – 737, December 2007

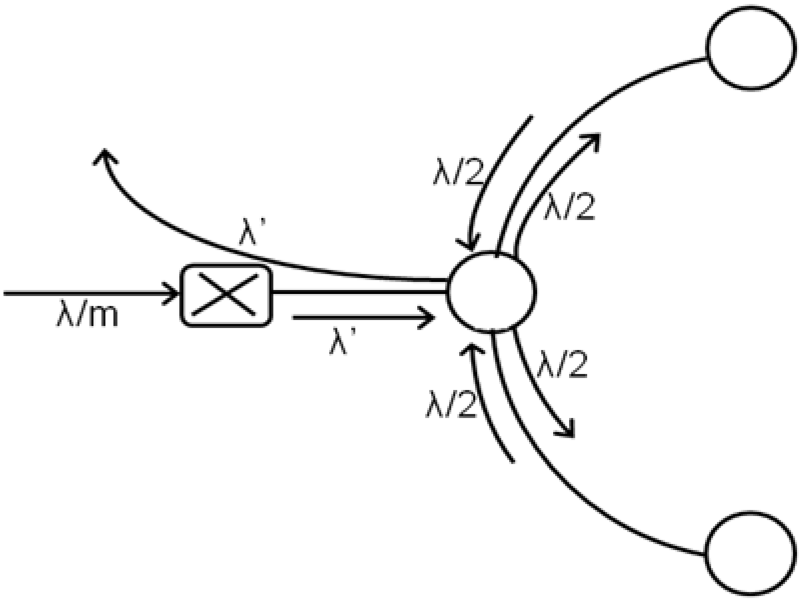

Figure 3.4 Traffic Distribution of a Ring Topology

For the traffic congestion model, the performance parameter ρ´ becomes λ/μ´. Thus the total number of data packets arriving at a node would become λ×(1+1/m), which is illustrated in Fig. 3.4. The figure shows the number of packets delivered at a node is equal to the number of packets routed at each node and similarly the number of outgoing packets from a node is equal to the number of packets arriving at a node from its adjacent nodes.

The probability (P) that at-least one wavelength is free on a link is given as:

$$P = \sum_{k=0}^{w-1} (\rho^k / k!) P_0 \qquad (3.7)$$

Hence for the entire ring network, the probability that at-least one wavelength is free on all 'n/2' links for routing is given as:

$$P_{2ring} = \{\sum_{k=0}^{w-1} (\rho^k / k!) P_0\}^{n/2} \text{, for n being even} \qquad (3.8)$$

and

$$P_{2ring} = \{\sum_{k=0}^{w-1} (\rho^k / k!) P_0\}^{(n-1)/2} \text{, for n being odd} \qquad (3.9)$$

The total call connection probability for the ring is given as:

$$P_{net-ring} = (1 - P_{ring}) P_{2ring} \qquad (3.10)$$

This makes $P_{net-ring}$ for a ring with an even number of nodes as:

$$\{1 - [\rho^{w+1}(1-\rho)/(1-\rho^{w+2})]\} \times \{\sum(\rho^k/k!)P_0\}^{n/2} \tag{3.11}$$

and $P_{\text{net-ring}}$ for a ring with odd number of nodes is given as:

$$\{1 - [\rho^{w+1}(1-\rho)/(1-\rho^{w+2})]\} \times \{\sum_{k=0}^{w-1}(\rho^k/k!)P_0\}^{(n-1)/2} \tag{3.12}$$

Here P_0 is given as:

$$P_0 = \left[1 + \frac{\rho'^{w}\left(1-\left\{\frac{\rho'}{w!}\right\}^{w+1}\right)}{\left(1-\frac{\rho'}{w}\right)w! + \sum_{k=0}^{w-1}\frac{\rho'^{k}}{k!}}\right]^{-1} \tag{3.13}$$

These equations are used to evaluate the call connection probability and the blocking probability of the router for a given number of nodes and link parameters.

The call connection probability is calculated using Eq. (3.11) for a ring topology of 20 nodes having a link length of 20 km and working at the service rates μ and μ´ as 10^7 and 10^4 respectively. The results are plotted in Fig. 3.5 where the graph shows the call connection probability of the entire ring network for different number of available wavelengths. It is observed that the data packets supported in the channel significantly depend on the number of available wavelengths and therefore provides a scope for choosing the optimized data rate for a given connection probability.

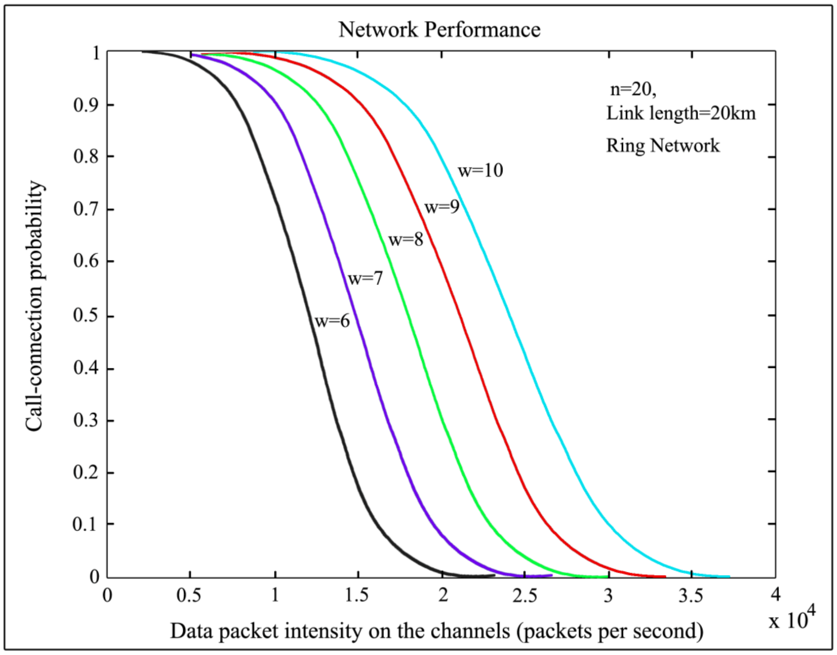

Figure 3.5 Call Connection Probability of a Ring Topology

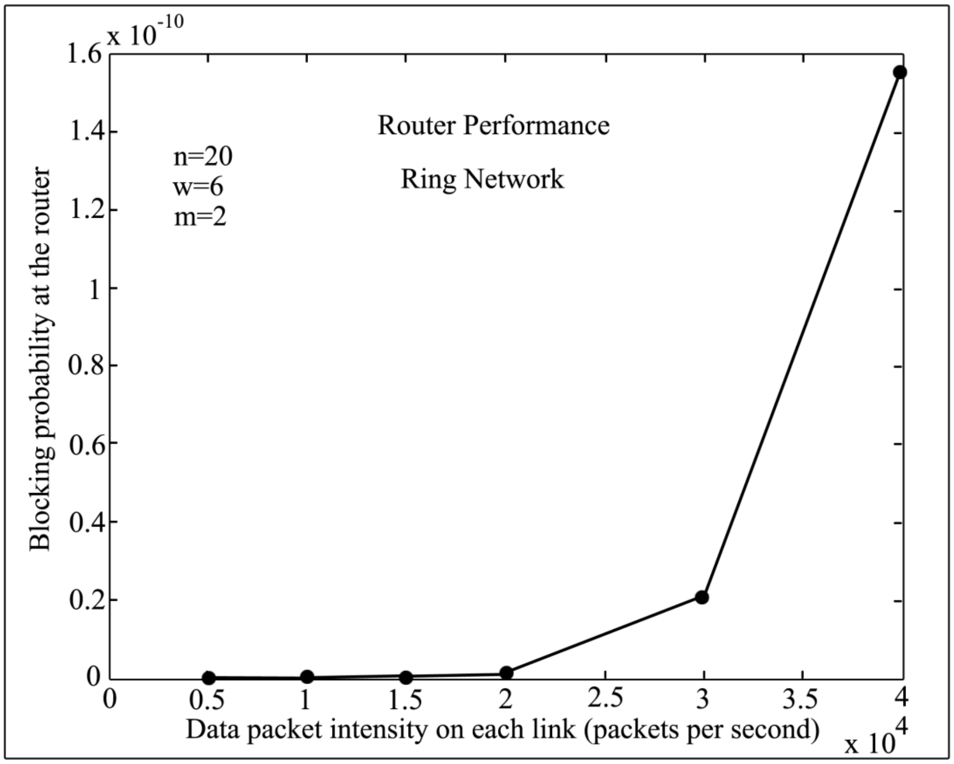

Figure 3.6 Router Performance of a Ring Topology

The blocking probability at the router having six wavelengths on each link for a ring topology of 20 nodes is plotted in Fig. 3.6. The node (i.e. router) demonstrates an impressive performance, as it is capable of routing large number of data packets in the network. The blocking probability is very low up to a significant data rate (i.e. $2\text{x}10^4$ pkts/sec) on each link. Thus the router is capable of taking correct routing decision for a large number of data packets and the connection is only limited by the number of such virtual circuits that can be formed with the given network parameters.

3.3.2 Performance Analysis with Star Topology

In order to evaluate the performance of a star topology similar kind of analytical expressions has been derived. The star topology consists of ‘n’ edge nodes connected via a central hub is shown in Fig. 3.7. The packet arrival rate at each edge node is assumed as λ and service rate is defined as μ. The number of wavelengths on each link is assumed as ‘w’, which provides the ‘w’ buffering slots on each of the links.

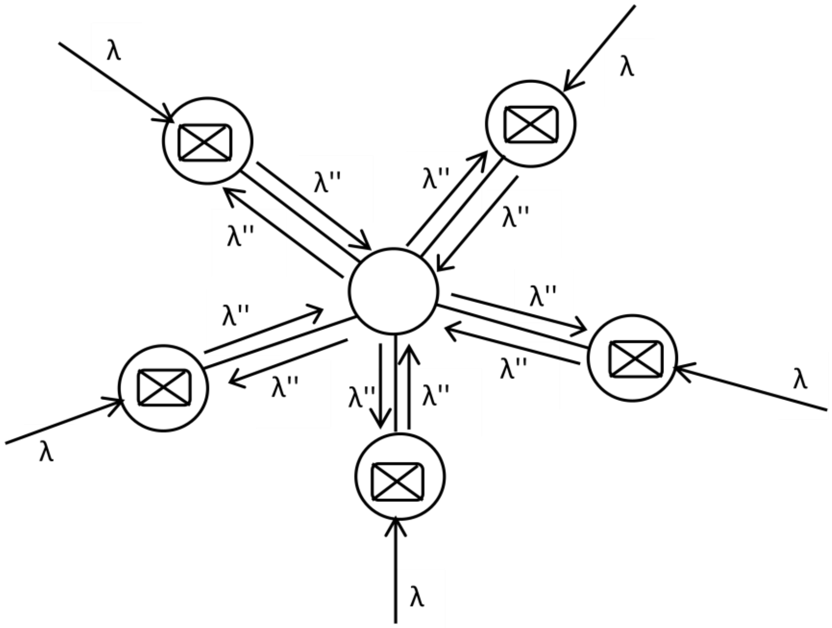

Figure 3.7 Traffic Distribution of a Star Topology

The blocking probability for the star is given as:

$$P_{star} = \left(\frac{n\lambda}{\mu}\right)^{w+1}\left[1-\left(\frac{n\lambda}{\mu}\right)\right]\Big/\left[1-\left(\frac{n\lambda}{\mu}\right)^{w+2}\right] \tag{3.14}$$

The probability that a packet arrives at any edge node will be serviced by a node is 1-P_{star}. This makes the effective number of data packets being routed at each node as λ× (1-P_{star}) and is marked as λ'' in the Fig. 3.7.

The traffic parameter ρ for the star topology can be written as:

$$\rho = 2\lambda \times (1 - P_{star})/\mu'$$

Here μ', represents the effective time to transmit the data packets.

The probability that at-least one wavelength is free on all the links is given as:

$$P_{2star} = [\textstyle\sum_{k=0}^{w-1}(\rho^k/k!)P_0]^2 \tag{3.15}$$

The net probability for the star topology can be written as:

$$P_{net-star} = (1 - P_{star}) \times P_{2star} \tag{3.16}$$

The graphs for the performance evaluation of a star topology node and the call connection probability are shown in Fig. 3.8 and Fig. 3.9 respectively. The superior performance of the router has been observed here also. The routing behaviour implies that the router can be suitable for taking routing decisions for Gigabit networks.

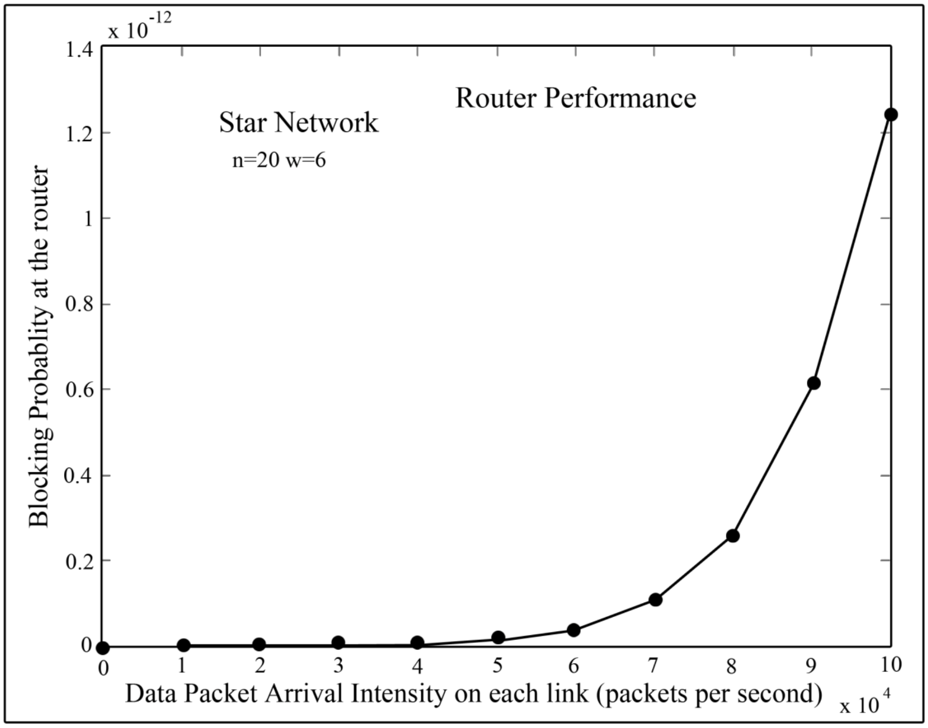

Figure 3.8 Router Performance of a Star Network

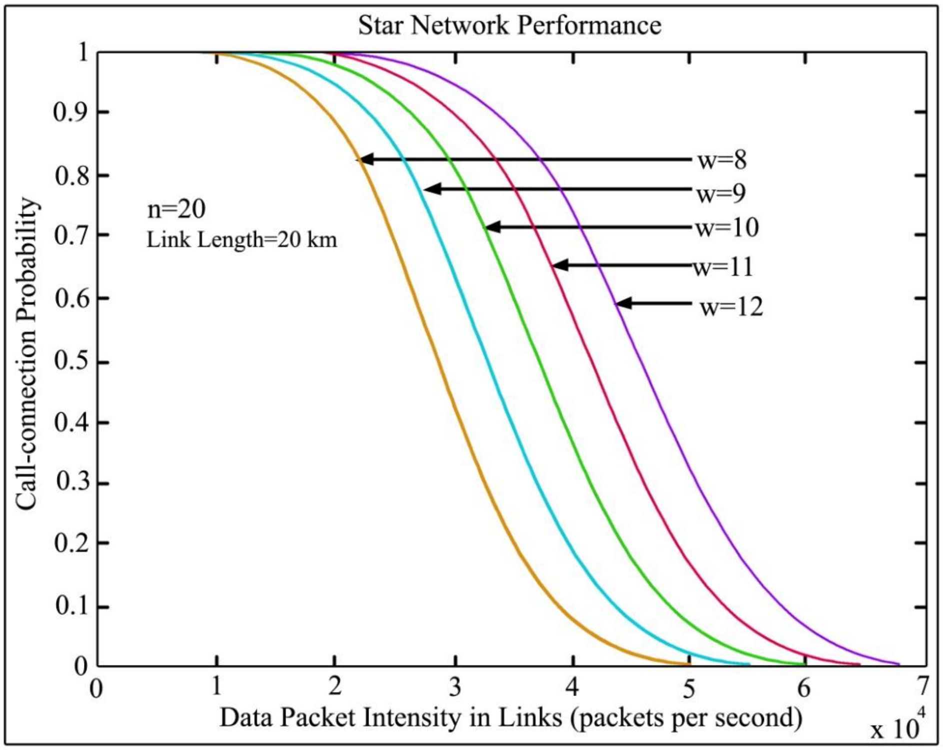

Figure 3.9 Call Connection Probability of a Star Network

The router performance for a star network having 20 nodes and 6 wavelengths per link has been evaluated and the results are shown in Fig. 3.8. It is inferred from the graph that the blocking probability is insignificant for data packet intensity up to a critical rate (i.e. $8x10^4$ pkts/sec) and increases exponentially for a given network parameters beyond this. The performance of the star network having 20 nodes and link length of 20 km is presented in Fig. 3.9 for the different number of wavelengths per link. These curves are qualitatively similar to the case of a ring topology but with a quantitative difference. The graphs confirm that the router performance is high for a comparatively large number of wavelength usages per link. The proper design makes the router to capable for high speed routing in a network.

3.4 Results and Conclusion

The node architecture described in this chapter suits to both wavelength-routed networks as well as packet switched networks. The OPADOM are used to reduce the number of ADM required at each node which eventually reduces the cost and size of the WDM node. The node's pre-configuration capability reduces the switching time for each incoming packet and enables to handle high data rate promisingly. The node handles the packets asynchronously as well as synchronously. An analytical model is developed to evaluate the performance of the node architecture. The call blocking probability is measured for ring and star network topology in a WDM optical network for different data arrival rates. The proposed node architecture is found to be very efficient in making the routing decision up to a significant data rate (i.e. $2x10^4$ pkts/sec) for a ring topology. The connection probability of a WDM routed network is solely limited by the network parameters like the number of wavelengths; the routing capability of the router, link delay and traffic intensity. The router can achieve a processing capability of as many as 10^7 to 10^8 data packets per second for the star topology, which is further governed by the design of the chip and speed of the processor. The results obtained with a star and ring topology are quantitatively quite similar to the results reported by [Chaubey 2007] for mesh topology analysis.

The rapid development in the field of integrated circuit design further provides a promising ground for exploring the possible development of high speed router based on the proposed model. This chapter dealt with the role of node architecture design in WDM network performance analysis and it is achieved through proper mathematical modelling. It is observed that node design flexibility and its configurable feature can improve the network performance beyond its switching capability.

Moreover, the implementation of better RWA algorithms at control plane can further improve the network performance by taking the maximum advantage of hardware capability of the nodes. The chapter 5 describes the RWA algorithms in WDM networks.

CHAPTER 4

CONTENTION RESOLUTION IN OPS WDM NETWORKS

4.1 Introduction

Wavelength routed networks, in which light-paths are setup prior to the data transfer on specific wavelengths, have been the focus of researchers in the last decade [Mukherjee 2000] [Mukherjee 2004]. The current research is more focused towards enabling bandwidth provisioning in the optical domain, which provides fine grained switching capability compared to wavelength routed networks [Awduche 2001] [Chaubey 2007]. In addition, optical packet switching offers high speed, data rate/format transparency, better bandwidth utilization and configurability which are some of the important characteristics required in future networks supporting different forms of data [Yao 2000] [Papadimitriou 2003]. Optical Packet Switching (OPS) allows switching and routing in optical domain without converting the data into the electronic domain at each node. An optical packet is sent along with its header without any prior path being setup on the network. At a core node, the data packet is optically buffered using Fiber Delay Lines (FDLs), while the header undergoes optical to electronic conversion and is processed electrically. Based on the header information, a switch is configured for transmitting the optical packet from input port to the output port and this connection is released immediately after the packet has been sent. Practical deployment of OPS networks demands for fast switching times. The optical switches based on micro-electro-mechanical systems offer switching times of the order of 1 ms to 10 ms. Though semiconductor optical amplifier based switches have considerably reduced the switching time up to few nanoseconds but they are quite expensive and use of optical couplers to design them result in higher power losses [Blumenthal 1994]. The OPS switch architecture can be classified in two categories; one is slotted or synchronous and second is un-slotted or asynchronous. In general, slotted OPS networks work only with fixed sized packets whereas un-slotted OPS networks can also handle variable sized packets.

Since network resources are not reserved in advance in OPS, some optical packets may contend for the same output port at the same time for the same wavelength resulting in packet losses. Contention can be resolved by exploiting the time, wavelength, and space dimensions or any combination thereof [Hunter 1998]. More precisely, contention in OPS nodes can be resolved by using buffering (time dimension), wavelength conversion (wavelength dimension), and/or deflection routing (space dimension). The contention problem is more challenging and complex in OPS networks as compared to the traditional electronic packet switching networks due to the non availability of the optical Random Access Memory (RAM). Optical RAM can be realized by using FDLs, which can hold an optical packet for a fixed amount of time based on the length of FDL. The packet can hold for a variable amount of time by implementing multiple delay lines in stages or in parallel [Gambini 1998]. The size of optical buffers is severely limited by physical space limitations. In order to delay an optical packet for 5μs, a kilometer of optical fiber is required. Because of this limitation of optical buffers, an OPS node may be very inefficient in handling high loads or bursty traffic. Another solution for the packet contention problem is deflection routing, where contending packets are routed via alternate possible paths to the output port. Deflection routing may cause looping and out of order delivery of packets, which needs to be handled separately [Forghieri 1995]. The wavelength conversion based solution resolve the contention by shifting optical packets on another free available wavelength. The performance of optical wavelength converters strongly depends on the combination of input and output wavelengths and required convertibility [Danielsen 1998] [Kamal 2004]. The comprehensive literature review carried out for various packet contention resolution techniques in OPS networks is presented in section 4.2. The subsequent sections of this chapter describe the proposed node architecture for slotted OPS network with FDL circulation based contention resolution technique.

4.2 Related Work and Motivation

A rapid increase in the bandwidth requirement for optical networks to support high data rate faces the switching speed limit of the supporting electronic technology [El-Bawab

2002]. Thus, we need a photonic network which can incorporate functions such as the multiplexing, de-multiplexing, switching, and routing in the optical domain by substituting the electronic control circuitry. In the recent past aggravated efforts have been made towards bandwidth provisioning in the optical domain which incorporates the intelligence in optical networks. Optical switching improves overall effective utilization of the available bandwidth. The OPS approach attracts more to the researchers, as it is capable of dynamically allocating network resources with fine granularity and excellent scalability [Diano 1999] [Corazza 1999].

The node architecture requires significant modifications for shifting the switching granularity from message level to the packet level. In general, an OPS node has multiple inputs and output ports and consists of an input interface, switching matrix, buffer, output interface, and an electronic control unit. The input interface is mainly responsible for extracting the optical packet header and forwards it to the switch control unit for processing. The switch control unit processes the header information, determines an appropriate output port and wavelength for the packet, and forward it to the switch fabric to route the packet towards the destination. The switch may need to buffer the packet and/or may convert to a new wavelength for the routing purpose. The switch controller also determines a new header for the packet, and forwards it to the output interface. When the packet arrives at the output interface, the new header is attached, and the packet is forwarded on the outgoing fiber link to the next node along the path.

Optical packet switched networks are categorized as synchronous and asynchronous networks. In the synchronous OPS networks, packets are of fixed length and needs to be aligned with respect to their slot boundaries before entering to the switching matrix. In general, the various OPS node architectures proposed are diverse in terms of switching fabric technology, optical buffer technology and placement of the buffer in the switch. Further, these switches can be analysed on the basis of contention resolution approaches used to handle packet conflicts.

The first OPS node architecture developed by the European ACTS KEOPS team [Gambini 1998] is designed for slotted OPS network such that each packet fits exactly in one time slot. The node consists of two stages namely buffering and switching for its operation. Packets are delayed by the required amount of time (i.e. integral multiple of slot time) using FDLs in order to avoid contention at output ports of the switch. However, the solution proposed by KEOPS team does not allow packet circulation to deal with the packet priority. The header of Internet protocol (i.e. IPv4 and IPv6) contains ToS (Type of Service) field to distinguish the packets and treats them accordingly. Thus, IP traffic carried by the OPS network with such kind of nodes can’t process the traffic with priority. The WASPNET switch [Hunter 1999] architecture is also designed for slotted OPS networks and uses optical buffers (FDLs) to resolve packet contention. The packet can be delayed for a finite amount of time before leaving to the output port in the corresponding FDL set. This switch is capable of handling the traffic with priority by circulating a packet in FDLs, if required.

In the recent past, asynchronous OPS networks have been received much attention due to the growth of IP network supporting packets of variable length [Tancevski 2000]. An asynchronous OPS node becomes a natural choice to carry IP traffic as packets can be received by the OPS node at any instance of time without the need of packet alignment. More specifically, if optical packets can be received by OPS nodes at any instant of time without requiring packet alignment but packet switching is aligned with respect to the time slot, then the OPS network operation is called asynchronous and the internal operation of the switching node is called synchronous. An OPS node using an asynchronous input interface and a synchronous switching matrix is proposed and investigated in [Pattavina 2005a] with slot duration equal to the 40 byte packet transmission time i.e. equal to the minimum IP packet length. The larger packet size is allowed in the switch by using multiple time slots in sequence to receive the packet at the input.

The complexity of the slotted OPS switching nodes increases due to the requirement of synchronization stage and packet alignment process. Asynchronous switches are more suitable to carry IP traffic while synchronous switches are good for Asynchronous Transfer Mode (ATM) cells. Obviously, asynchronous OPS is more vulnerable for packet contention compared to synchronous because of unequal length of packets. More packet contention leads to throughput degradation. So there is a tradeoff between throughput and switch architecture complexity. Synchronous optical switching fabrics, much like their electronic counterparts, are easier to build and operate; hence synchronous OPS networks have received more attention from the research community.

The packet contention resolution is one of the most important design issues for the OPS switch design. The conventional methods used so far are based on, optical buffering, wavelength conversion and deflection routing. These methods are either used alone or in combined form to implement more sophisticated techniques. For example, a switch architecture proposed in [Yang 2004] uses all three methods in sequence to resolve the packet contention. The switch fabric tries to forward the contending packet by using different wavelength, by optical buffering or by forwarding the packet on different output port. The wavelength conversion in pure form is the simplest method to resolve contention. In this method one of the contending packets is forwarded to the output port over the alternate wavelength. Usually, this method is a superior option as it does not introduce a delay in the data path and also avoid packet re-sequencing. On the other hand number of converters and placement of these converters in the network is an NP complete problem [Mukherjee 2004] [Danielsen 1998].

The deflection routing [Pattavina 2005b] exploits the space dimension to resolve packet contention but it introduces delays in the data path and requires packet re-sequencing as packets may arrive out of order at the destination. Deflection routing also increases load on the network unless the packets are deflected uniformly to all the neighbouring nodes to avoid contention. This requires better deflection routing algorithms which can distribute the packets uniformly [Baresi 2003]. Optical buffering is a fundamental technique which has been widely used in many optical packet switch implementations to overcome the packet contention problem [Hunter 1998] [Callegati 2000] [Laevens 2003] [Rostami 2005] [Fiems 2005] [Mellah 2006]. When more than one packet is competing for same output port, at the same wavelength, at the same time; one of the contending packets is forwarded to the desired output port and others are sent to buffers. The solutions proposed by various researchers varies on the concepts involved like the placement of buffers, number of buffers used, complexity of the node architecture, buffer granularity, feed forward buffering and feed backward buffering etc.

The solution proposed in [Fiems 2005] uses two stage optical buffers in which packets received at input are first routed to the first stage of FDLs and then again routed to the second stage of the FDLs to avoid contention at the output of the first stage. The analysis presented there shows a better packet loss ratio as compared to single stage buffers for a limited traffic correlation.

An output buffering technique for contention resolution has been proposed by [Mellah 2006], in which FDLs are used to provide additional output ports to handle packet contention resolution. This technique uses the First In First Out (FIFO) queuing model hence the traffic prioritization is not considered here. The packet contention is improved in this technique at the cost of extra FDLs used at the output along with additional complex switching fabric.

The FDL structure proposed in [Laevens 2003] and [Zhang 2005] assumes the lengths of the fiber delay lines as multiples of certain granularities. These two papers also describe the relation between the FDL structures and switch architecture for the offered traffic to resolve packet contention. The node architecture proposed by Leavens uses dedicated buffering while Zhang assumes a shared buffer FDL structure. For a given number of FDLs, shared buffering performs better than dedicated buffering in terms of packet loss probability as in the former case the free FDLs can be utilized for any of the output port contention.

It is observed that the existing buffering implementations require either large amount of FDLs or complex switch architecture for better throughput. The switch hardware cost can be better managed by inclusion of flexible delay lines in suitable node architecture to show a better packet contention resolution. This design can further be modified to allow packet circulation in buffers or FDLs. The present chapter focuses on the contention resolution problem in OPS networks and proposes a suitable switch architecture that utilizes the delay lines in an efficient manner and provides support for handling traffic prioritization by enabling the packet circulation in FDLs. Such kind of feed backward FDL structure also improves the packet loss ratio as compared to the feed forward case. The next section describes the proposed node architecture and the suitable packet contention resolution algorithm for it.

4.3 Node Architecture and Contention Resolution Algorithm[3]

The proposed node architecture consists of k fixed length FDLs as shown in Fig. 4.1 labelled as f_1, f_2….f_k each having a delay length equal to the packet transmission time to achieve synchronization. Conflicted packets are circulated in the FDLs causing delay in multiples of T and makes nT time unit delay after n times of circulation. In case of contention for a particular output port 'm', one packet is transmitted to the desired output port and remaining packets are diverted to the fixed sized free FDLs as per the proposed algorithm. Additional output ports are connected to the switch through FDLs as shown in Fig. 4.1. The appropriate fiber delay lines are chosen through the feedback control mechanism to resolve the packet contention. For example, if two packets (i.e. packet-1 and packet-2) are competing for same output port 'm', at time t_0, packet-1 can be sent to the desired output port and the packet-2 is sent to one of the free fiber delay line at time t_1, as decided by the FDL control system. The packet-2 emerges from the delay line at time t_2; simultaneously, packet-1 is transmitted successfully at time t_2 from output port m. Hence the port 'm' is free to send packet-2 at time t_3. Let us say, at time t_3 if a new packet (i.e. packet-3) also competes for the output port 'm', then packet-2 and packet-3 are in contention having delay time T (i.e. packet's transmission delay) and 0 respectively. At this point of time packet-3 is sent to one of the free FDLs and packet-2 will be directed towards the desired output port.

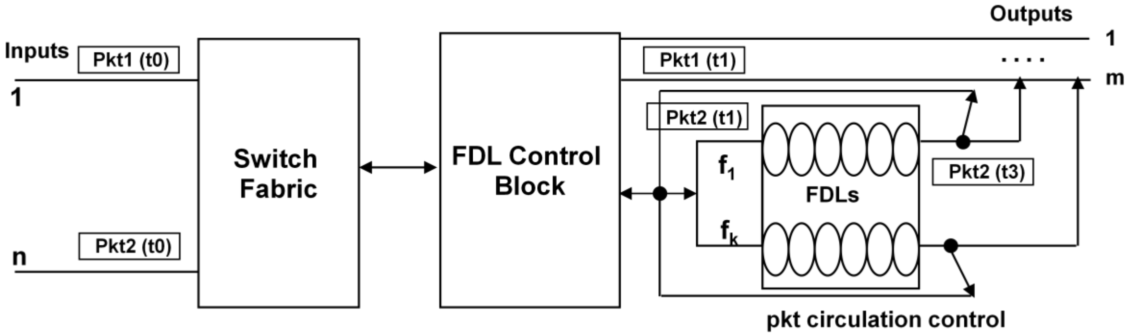

Figure 4.1 Packet Switch Node Architecture

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[3] This work has been published in: Virendra Singh Shekhawat, Dinesh Kumar Tyagi, V K Chaubey, "A Novel Packet Switch Node Architecture for Contention Resolution in Synchronous Optical Packet Switched Networks", International Journal on Communications, Network and System Sciences, Vol.2, No. 6, pp. 562-568, September 2009

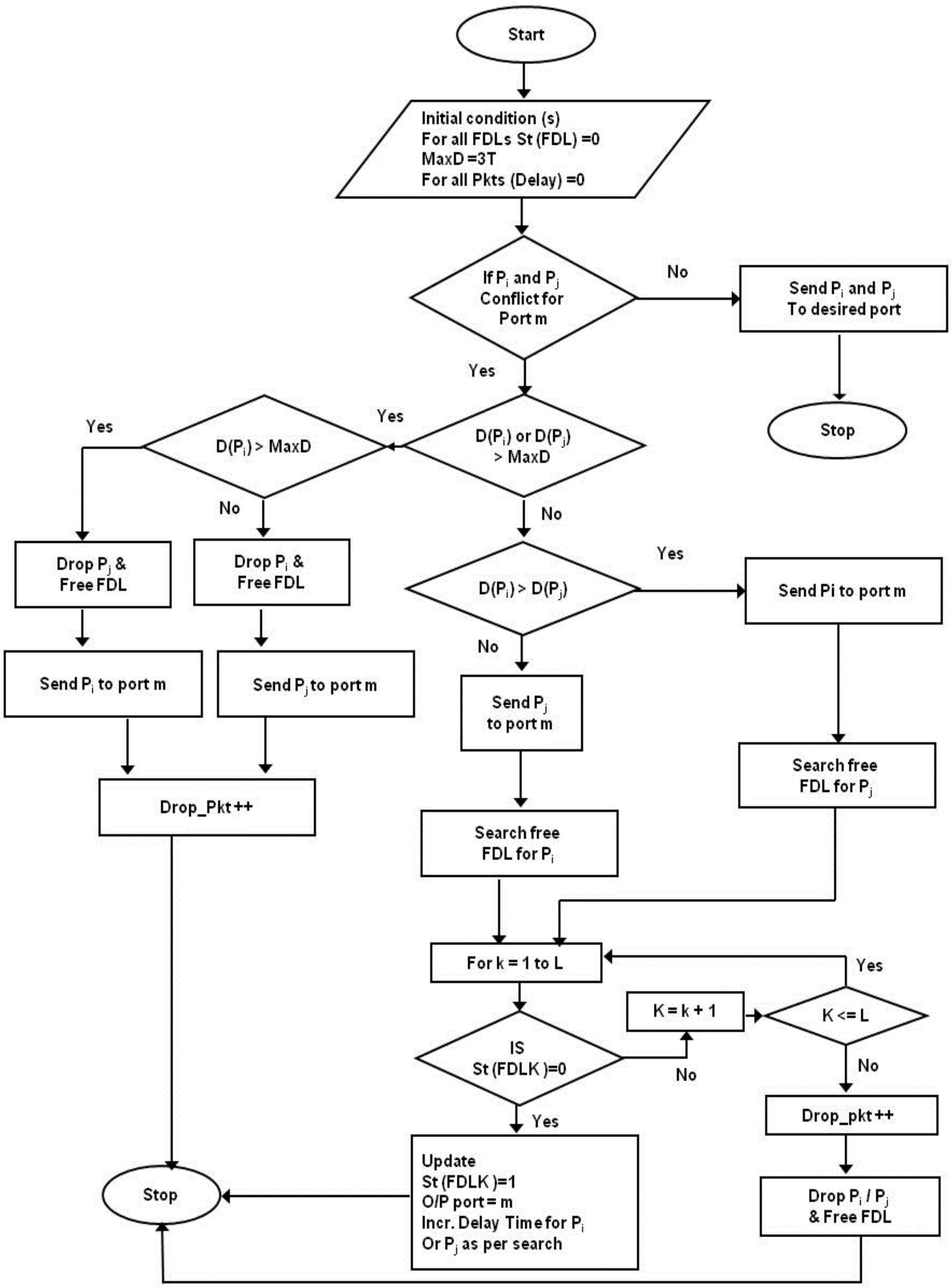

Figure 4.2 Flow Chart for Contention Resolution Algorithm

Here:

MaxD = Maximum delay for the packet

St(FDL_k) = Status of FDL_k (0 for free and 1 for busy)

D(Pi) = Delay for the i^{th} packet

Drop_pkt = Drop packet count

Here the scheduling algorithm based on delay time is developed to forward the packets in the appropriate direction. The packets can be delayed in the FDL control block for the desired amount of time by circulating it in FDL structure. The maximum possible delay time can be decided based on the signal to noise ratio received at the output port which depends upon the number of circulations and fiber characteristics. Eventually, this constraint limits the number of maximum possible circulation for a given packet within the FDL structure.

The overall performance of the system is improved as circulation frequency is increased; this compensates the additional cost involved in the switch. The description of the proposed algorithm is illustrated with the help of a flow chart as shown in Fig. 4.2. A control structure maintained inside the control block of the switch, keeps track of the status of the each delay line (i.e. 0 for free and 1 for busy), contended output port and delay time (i.e. how long the packet is delayed).

A mathematical model has been developed to analyse the internal behaviour of the proposed switch architecture. The model involves auxiliary FDLs to resolve the packet contention and it is based on Erlang C data traffic model having a data arrival rate and packet transmission time as λ and $1/\mu$ respectively.

Let's assume S sources are sending optical packet traffic destined for an output fiber F of the switch. Let the on and off periods of each source be exponentially distributed with common means $1/\sigma$ and $1/\tau$, respectively. The mean offered load (ρ) to the system with W wavelength channels per fiber is given as:

$$\rho = \frac{S\tau}{W(\sigma+\tau)} \tag{4.1}$$

A switch with M inputs and N outputs can be modelled as an M/M/N/N queue. The probability that the packet has to wait for d unit of time for service (i.e. packet blocking probability) is given by the following Erlang C formula:

$$P(d > 0) = \frac{W\rho^{W}/W!(W-\rho)}{\sum_{i=0}^{W-1}\left[\frac{\rho^{i}}{i!}+\frac{W\rho^{W}}{W!(W-\rho)}\right]} \tag{4.2}$$

In the proposed switch architecture, if the destined output port of the packet is not free, it can be sent to one of the free FDL for a fixed amount of delay (i.e. equal to the packet transmission time). Assuming that the total number of delay lines is D, which gives the total number of outputs L = W + D. So this can be modelled as M/M/L/L queue. Now the packet delay probability can be modified as shown below:

$$P'(d > 0) = \frac{L\rho^L / L!(L-\rho)}{\sum_{i=0}^{L-1}\left[\frac{\rho^i}{i!} + \frac{L\rho^L}{L!(L-\rho)}\right]} \tag{4.3}$$

Now the probability for a number of packets delayed by more than t seconds can be calculated by multiplying the probability of a number of packets delayed by time t=0 seconds with the negative exponential of tμ(L-ρ).

$$P(d > t) = P'(d > 0) \times e^{-t\mu(L-\rho)} \tag{4.4}$$

By using Eq. (4.4) we can calculate the packet blocking probability for a given amount of delay time t seconds. For example for t=1ms, the above expression gives the probability of number of packets that will be delayed by more than 1ms.

4.4 Performance Analysis of Proposed Switch Architecture

The proposed switch architecture has been characterized for its packet delay performance and blocking probability under the influence of varying numbers of fiber delay lines. The performance of the proposed switch architecture having eight wavelength channels has been evaluated and compared with the conventional switch architecture (i.e. without FDLs).

4.4.1 Packet Delay Analysis

The packet delay probability for a switch comprised of multiple delay lines is computed using Eq. (4.4) and the corresponding results are presented in Fig. 4.3 at traffic rate of 5 Erlang. It has been observed that the packet delay probability decreases with the inclusion of FDLs and becomes quite insignificant for 4 FDLs in the present analysis. Also, it has been inferred that the delay probability decreases further for a given FDL structure by increasing the packet delay time (i.e. number of circulations allowed in the FDLs). It depicts that the effect of increasing the number of FDLs on packet delay probability is more significant as compared to delay the packets by circulating in the FDLs.

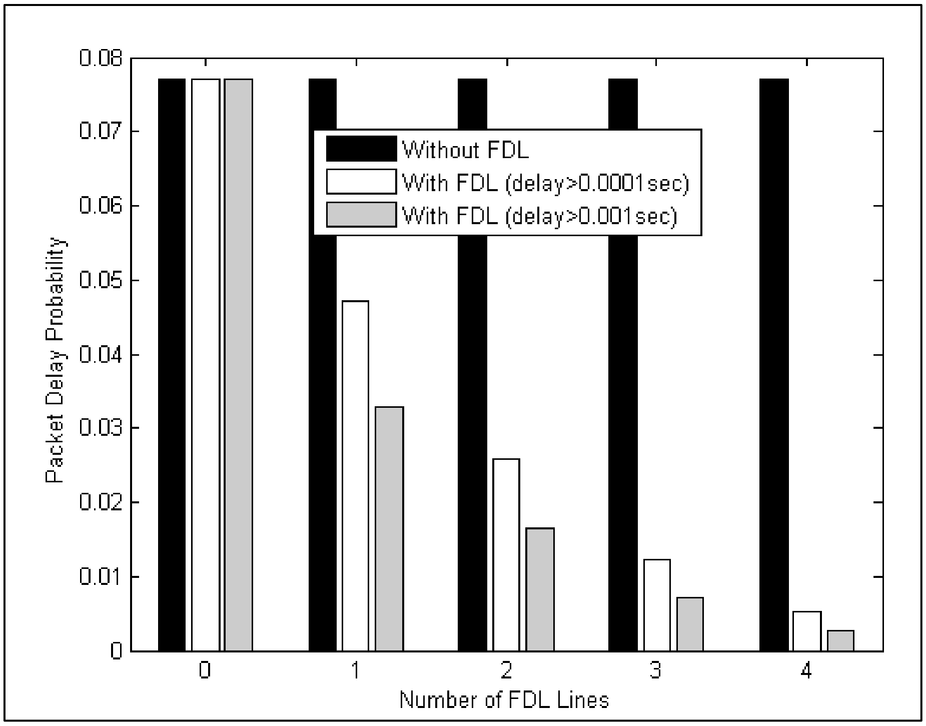

Figure 4.3 Packet Delay Probability for FDLs as a Function of Delay Time

The influence of traffic load on the delay probability of the proposed switch architecture also has been computed using the developed mathematical model and the results are depicted in Fig. 4.4, for the case of packet delay time to packet hold time ratio as unity. It has been observed that the packet delay probability is not a linear function of traffic intensity and increases rapidly with the rise in traffic at the lower traffic range however this slope gradient reduces at the high traffic range in the case of a normal switch without FDLs.

In the case of proposed switch architecture with a single FDL, the qualitative behaviour of the delay probability is found to be similar but with a quantitative difference with a lower numerical value. It is further observed that the inclusion of more FDLs in the switch makes the delay probability to further reduce but not with a significant difference. It is interesting to note that, though the numerical delay for a given load is lower for the FDLs in the switch, yet the gradient of the delay is slightly higher. This behaviour reveals that in the case of FDLs the traffic fluctuation may cause more variation in the delay probability as compared to a switch without FDLs. The packet delay analysis for different time delay to packet hold time ratio is obvious to appreciate the physical operation of the switch. The variation of packet delay probability, for the case of packet delay time to packet hold time ratio as 10 is shown in Fig. 4.5. As we increase the delay time, the packet delay probability decreases significantly due to more circulations in the delay lines, which finds a better probability for the packet to be processed. The curves in Fig. 4.5 are qualitatively similar to the curves in the Fig. 4.4 but with a significant numerical difference.

The effect of delay time on packet delay probability with different number of FDLs has also been investigated and the results are shown in Fig. 4.6. The packet delay probability decreases with the increase in the delay time in the switch and this tendency is maintained for the more FDLs in the switch as well. However, it may be noted that the slope of the curve is more in the case of more FDLs which shows a reduction in the packet delay probability with a slight increment in delay time.

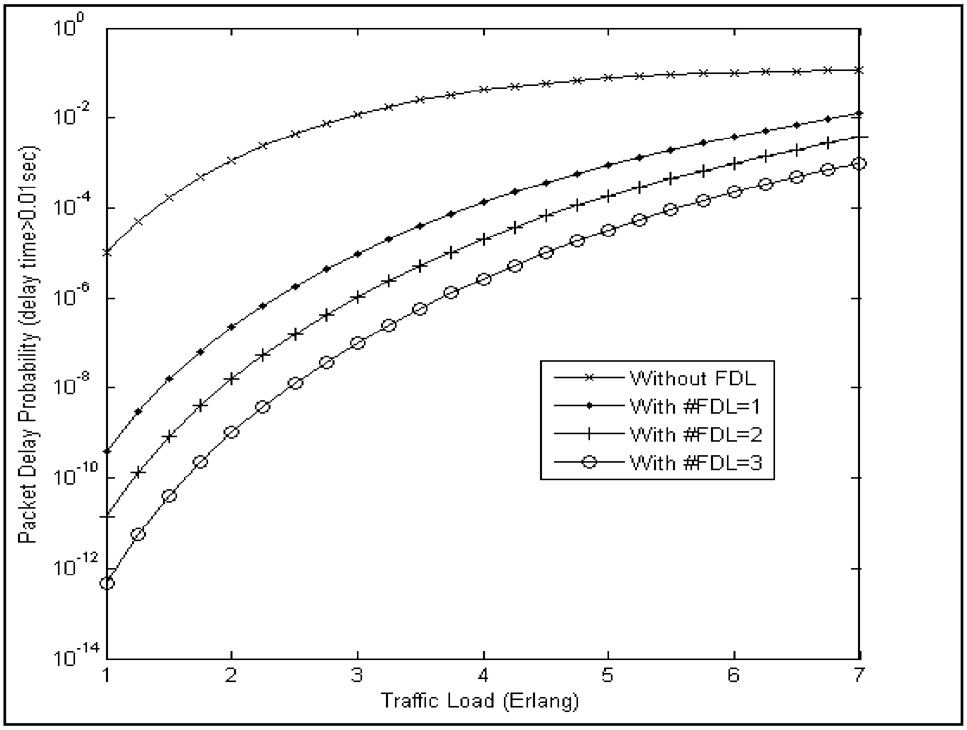

Figure 4.4 Packet Delay Probability with Traffic Load (Delay Time > 0.01 Sec)

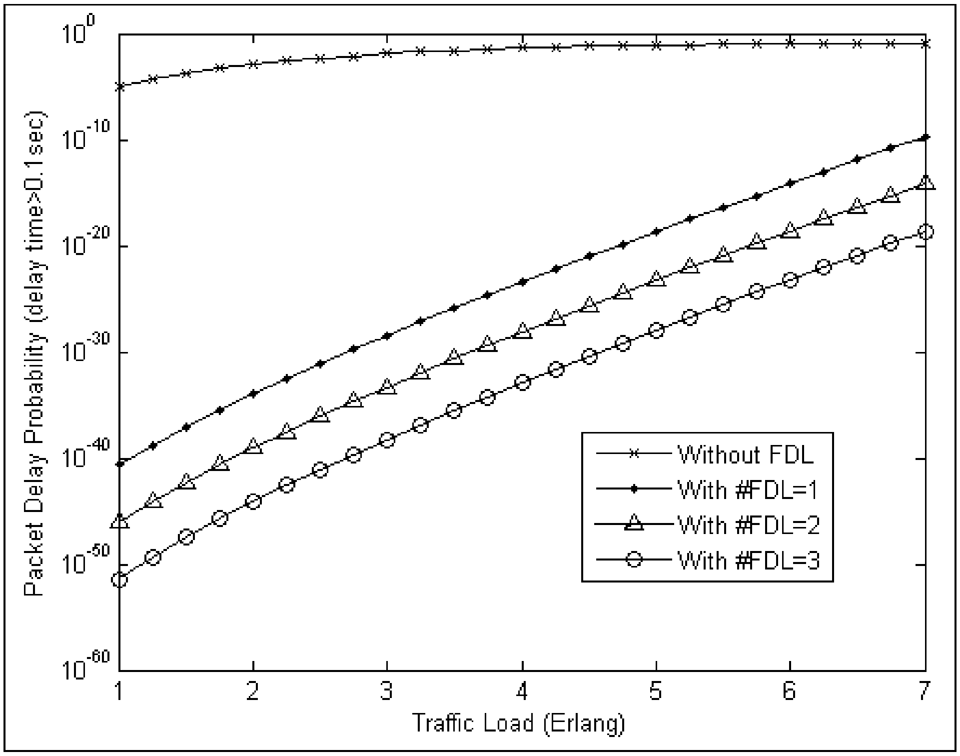

Figure 4.5 Packet Delay Probability with Traffic Load (Delay Time > 0.1 Sec)

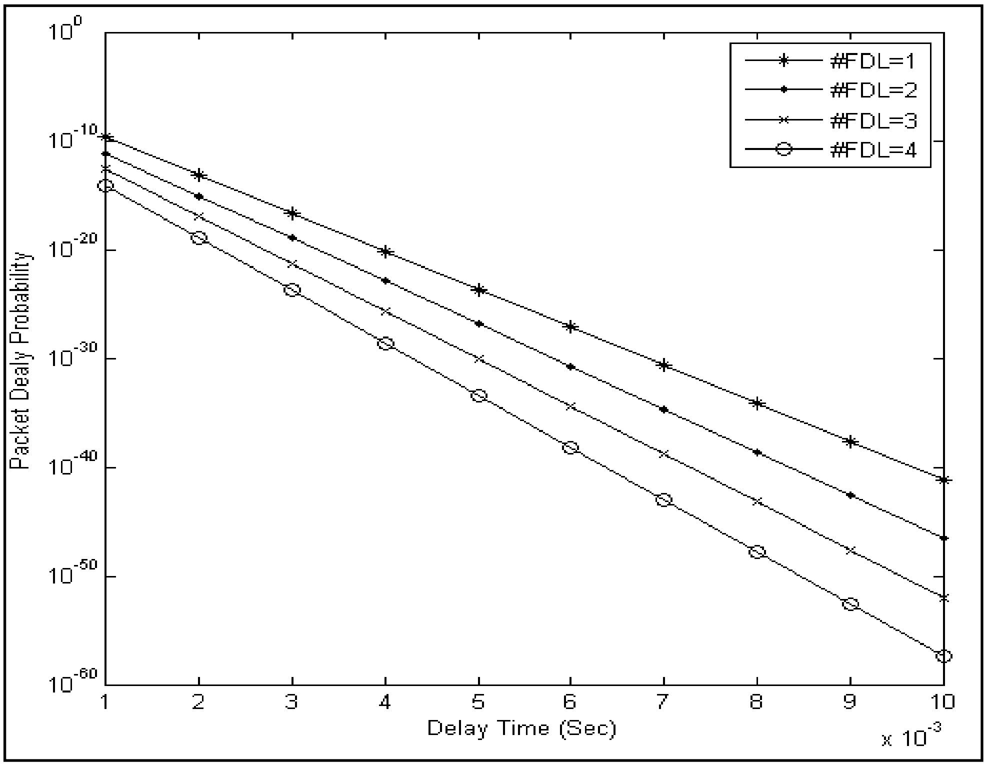

Figure 4.6 Packet Delay Probability as a Function of Delay Time

4.4.2 Throughput Analysis

The proposed switch architecture has been simulated to evaluate the node throughput employing 5 output ports with the number of FDLs vary from 1 to 4. The random size request sets are generated and repeated 10 times for each random value. The number of circulations for each packet also varies from 0 to 3 in the simulation. The throughput results are presented in Fig. 4.7 for 4 different values of FDLs. It has been inferred from the graphs that the throughput is almost equal at lower traffic rates (i.e. 10 to 20 requests per second) for different number of delay lines in the switch. This may be attributed to the easy availability of the output ports for the lower incoming packet rate. However, at moderate traffic rates (i.e. 40 to 70 requests per second) the availability of free output ports decreases due to packet contentions and thereby reduces the throughput for lesser number of FDLs in the switch. The simulation results also support the expected results by showing a remarkable dropout in the throughput in the case of one FDL as compared to the four FDLs. The results also indicate that the throughput difference decreases at higher traffic rates (i.e. 80 to 100 requests per second) and show a consistent value irrespective of the number of FDLs. This shows a limited packet handling capacity of the FDLs.

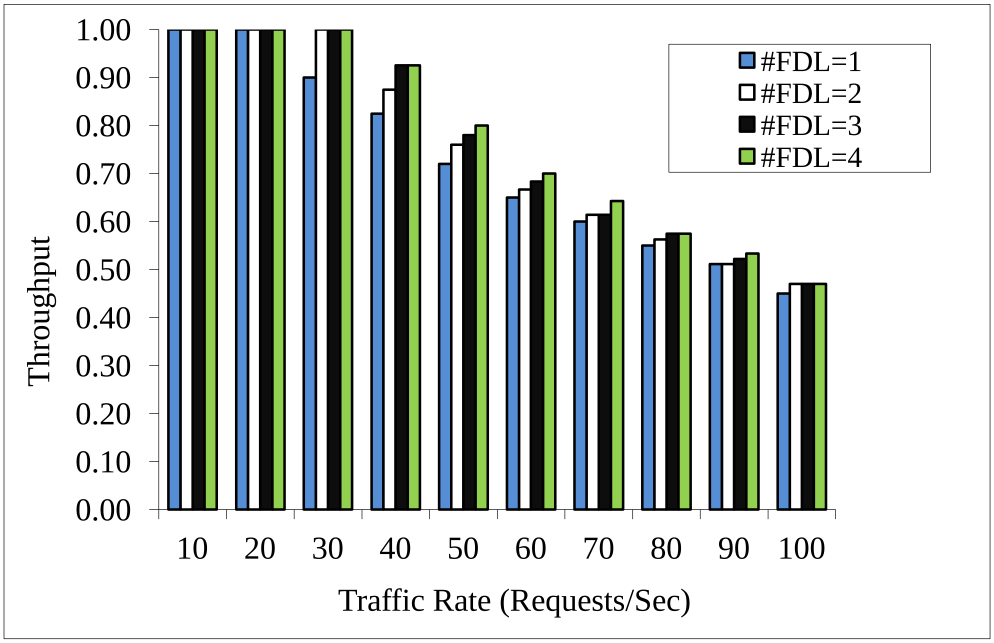

Figure 4.7 Node Throughput for Different Number of FDLs

It has been observed that the FDLs are beneficial up to certain traffic rate beyond that switch performance is controlled by the input-output ports.

The switching behaviour of the incoming traffic involving three delay lines with different number of packet circulations in the FDLs has also been investigated. The simulation results for the case of 0, 1, 2 and 3 circulation loops for the packets have been presented in Fig. 4.8. It is obvious to note that the results for without packet circulation show the minimum throughput as compared to the other cases. These results also infer that the throughput is improved significantly in case of circulating packets even for once at a moderate traffic rate. However, these improvements are insignificant at higher traffic rates due to the constraints of the number of input-output ports.

The simulation analysis confirms that the size of the switch (i.e. number of input-output ports), limits the throughput and makes it nearly constant after a certain traffic rate. However, this traffic limit can be increased by using additional delay lines in the switch. The data handling capacity of the switch can be further improved by circulating the packets in fiber delay lines which increases the probability for availability of the desired output port. The number of circulation is a notion of packet delay time and can be limited by the maximum delay time allowed in the network.

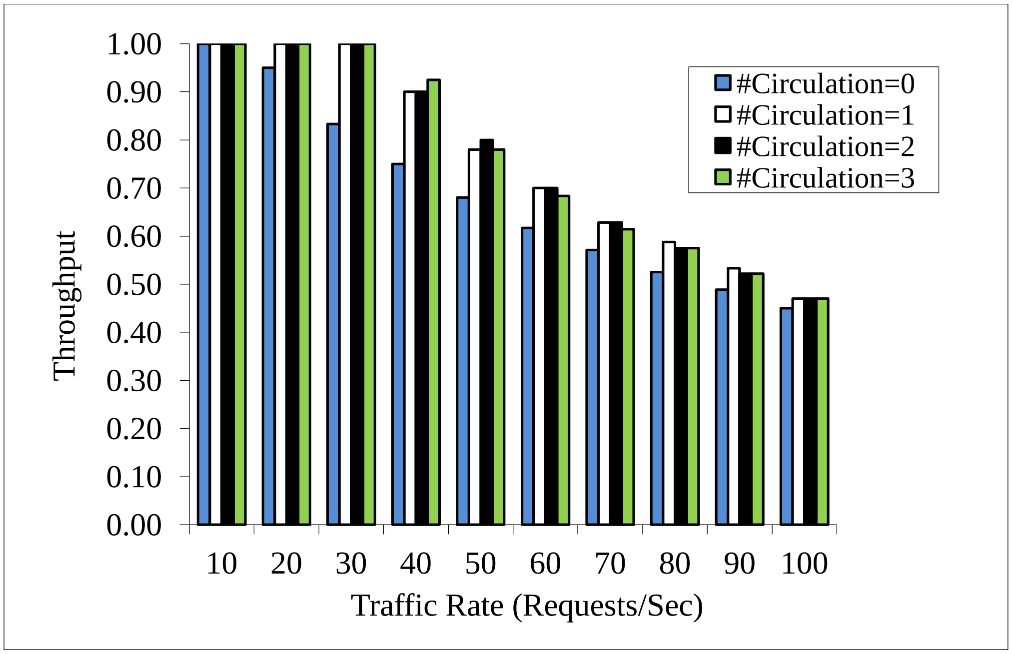

Figure 4.8 Node Throughput for Different Number of Packet Circulations

4.5 Results and Conclusion

The suitable node architecture is proposed in this chapter to resolve the packet contention problem for the synchronous OPS node. The proposed node architecture and the packet contention resolution algorithm have been discussed with the help of a mathematical model. A shared buffer feed backward contention resolution technique is used to simulate the node performance. The model gives a more generic solution for the packet conflict problem at the switching node using FDLs under proposed control algorithm. The model is compared for feed backward and without feed backward FDL structure to report a significant improvement in the packet loss ratio with the former approach. Packet circulation in delay lines is the key feature of the proposed method that improves the connection probability up to a significant traffic rate. Model proves a better FDL utilization through packet circulation. A useful observation has been made out that the maximum number of FDLs and the circulations have a significant impact on throughput for a given switch. Moreover, the traffic priority is handled by controlling the number of circulating loops for the desired quality of service required. Performance analysis of the proposed FDL structure for asynchronous OPS node can be done as future work.

The chapters 2, 3 and 4 focus on the physical level solutions for achieving network performance and shows influence of node architecture and topological configuration of overall network performance. The next two chapters deal with control level solutions and analyse the role of RWA algorithms and signalling protocols for further enhancement in network performance.

CHAPTER 5

ADAPTIVE RWA ALGORITHMS FOR WDM NETWORKS

5.1 Introduction

In order to meet the traffic demand of existing and forthcoming communication applications, wavelength routed optical networks are considered to be a viable solution for next generation wide-area backbone networks. Wavelength routed optical networks are being deployed mainly as backbone networks for large geographical area e.g. for nationwide [Ramaswami 1995b]. In a wavelength routed WDM network, end users communicate via all-optical WDM channels, known as light-paths. The light-path provides a circuit switched interconnection between two nodes which are located far from each other [Mukherjee 2004]. In an N node network, each node pair can’t connect to each other by an optical light-path because of the limited number of wavelength availability on fiber links and constraint on number of optical transceivers at nodes. Moreover, with the increase in the network size, the gap between the number of possible light-paths and the light-paths which could be established practically also increases. Once the light-paths have been identified, we need to route the traffic through such light-paths and assign a wavelength to each of one. This is referred as the Routing and Wavelength Assignment (RWA) problem [Zang 2000] in optical WDM networks.

The objective of the RWA problem’s solution is to establish the maximum number of light-paths under the constraint of wavelength channel availability in the optical fiber. There is no such algorithm available which can give an optimal solution of the RWA problem in the polynomial time complexity. Thus RWA problem becomes an NP complete [Banerjee 1996]. A number of heuristics have been proposed by researchers to obtain good solutions [Shen 2001] [Shiva Kumar 2002] [Keqin 2008]. The RWA problem comprises of two sub problems; one is Routing and the other is Wavelength Assignment [Chlamtac 1996]. These two sub problems can be solved in either way; first routes are selected and then the wavelengths are searched or first wavelengths are searched and then routes are selected [Zang 2000]. Alternatively, routes and wavelengths search can be considered jointly [Birman 1995] to implement RWA. In order to establish a light-path between a source destination node pair, a same wavelength is assigned to all the intermediate links then the light-path is called as wavelength continuous. This common wavelength constraint is defined as a wavelength continuity constraint. Usually, wavelength routed networks follows wavelength continuity constraint but it can be relaxed by using wavelength conversion functionality either in full or partial way at few nodes in the network [Singh 2004]. However, the huge cost and complexity of a wavelength convertible node makes this approach less attractive for network design.

The important routing algorithms considered in the literature so far are named as; fixed routing, fixed-alternate routing and adaptive routing algorithms [Zang 2000]. In the fixed routing, only one pre-calculated route is selected either on the basis of shortest distance or on the basis of least hop count. Once a connection request arrives for a node pair, the free wavelength availability is searched on the pre-calculated fixed route. In the case of fixed-alternate routing, two or more routes are pre-calculated for each node pair [Wason 2010]. When a new connection request arrives, the free wavelength availability is searched on the routes one by one in a fixed order. The wavelength searching process is stopped, once a route satisfies the connection request or all the routes are searched. If a common free wavelength is not found on any of the pre-calculated path then the request is treated to block. These two algorithms are simple and run time complexity for both is of O(1). Obviously, fixed-alternate routing gives better call connection probability than fixed routing due to availability of alternate choice(s) in former one for establishing light-path [Ramamurthy 1998c]. Both of the algorithms do not capture network status information at run time as both are static by nature. So there is a need of such algorithms which can dynamically select the routes by incorporating current network status in route the selection process; like wavelength availability on each of the links in real time. The class of such algorithms is called as adaptive routing algorithms [Dharma 2004]. In adaptive routing, the route between source destination node pair is selected dynamically at run time. It may be possible that for a given source destination node pair two different routes are selected at different course of time due to changes in the network status.

The Least Congested Path (LCP) routing [Li 2002] [Chan 1994] is also a form of adaptive routing algorithms where the least congested route is selected to process a connection request. Congestion is measured in terms of the free wavelengths availability on the path [Bhinde 2001]. Usually, a path with large number of free wavelengths is treated least congested as compared to a path with less number of free wavelengths. Wavelength availability on each link of the path is defined as link weight or link cost and it varies with light-path establishment and termination. In general, the adaptive routing approach gives a better call connection probability.

Evidently routing algorithms for wavelength routed WDM networks provides one best path based on desired link/path metric to send data from source to destination node as explained above. Though, some algorithms first calculate a set of candidate paths (e.g. alternate path and exhaustive routing algorithms) and use one best path to transfer the data. The current commercial optical transmission bandwidth available in the single channel is not sufficient for extremely high bandwidth requirement applications like emerging media and scientific applications [Chen 2009]. Hence to meet the bandwidth requirements of such applications, one channel is not sufficient. Also, some mission critical applications need a backup path for protection or restoration. Thus a single path routing needs to be modified to a multipath routing to provide the desired bandwidth [Wei 2008] [Lin 2006]. Most of the routing protocols deployed in the Internet rely on the single path for traffic forwarding between each source-destination node pair. However, sometimes multiple paths are calculated to select a single best path [Heand 2008]. Nowadays the traffic engineering requirements demand for online adaptive traffic management with online bandwidth provisioning to meet the QoS requirements for bandwidth sensitive applications like live video streaming, video conferencing, online gaming, teleconferencing and voice over IP [Kandula 2005]. The multipath routing algorithms can be used to satisfy such QoS requirements for these applications without adding much to the existing infrastructure. The multipath routing also reduces the backup path requirement for high performance applications leading to superior network performance.

The section 5.2 provides a comprehensive literature review of RWA algorithms.

5.2. Related Work and Motivation

This section provides the literature review and motivation for single path and multipath routing algorithms.

5.2.1 Single Path Routing

Optical fiber networks has been rapidly gaining acceptance as a means to handle the tremendous increase in the bandwidth requirement of telecommunication and data networks. In a wavelength-routed WDM network, end users communicate via all-optical WDM channels, known as light-paths established through an RWA [Sang 2000] [Choi 2000]. The number of free wavelengths available on fiber links limits the number of end-to-end connections and physical constraints such as wavelength channel spacing in a fiber, capability of optical transceivers, and bandwidth granularity [Asuman 2003]. Moreover, a light-path with the wavelength continuity constraint leads to inefficient utilization of wavelength channels and results in higher blocking probability [ShivaKumar 2002] [Mohan 2000]. The wavelength continuous paths preferred over wavelength non-continuous paths due to the simplicity and lower cost of WDM node without wavelength conversion capability. Hence the performance of RWA solution for a network differs in terms of; whether wavelength conversion support is there or not, and also whether the support is partial or full [Mukherjee 2004] [Singh 2004].

The RWA solution also depends upon the connection requests or traffic demand types which can be categorized as static, incremental and dynamic [Choi 2000]. In the case of static traffic demand, connection requests known in advance, and then the RWA problem becomes to assign routes and wavelengths to all the requests such that the minimum number of wavelengths and fiber links are used. If the number of wavelengths is fixed for a given number of connection requests then the problem becomes, to satisfy maximum possible connection requests with the given number of wavelengths. Such type of RWA problem is called as Static Light-path Establishment (SLE) problem [Nina 2006]. In the case of dynamic and incremental traffic demand, connection requests arrive sequentially one by one, a light-path is setup for each incoming request as it arrives. Each of such established light-paths have to be released after a finite amount of time; moreover the connection holding time for each of the individual requests may be different. Unlike dynamic traffic, the connection holding time for the incremental traffic is infinite which means once a connection is established it will be maintained forever. The objective for the incremental and dynamic traffic cases is to assign routes and wavelengths to each of the connection requests such that it minimizes the number of connections blocked or maximize the number of connections established. This RWA problem is called Dynamic Light-path Establishment (DLE) problem. The SLE problem can be solved by mixed Integer Linear Programming (ILP) method, which is computationally NP-complete [Ramaswami 1995b] [Barpanda 2010]. On the other hand the DLE is more difficult to solve since the request sequence is not known in advance, and therefore heuristic methods are preferred generally [Keqin 2008]. To make the problem more tractable, RWA problem can be partitioned into two sub problems, first is routing and second is wavelength assignment. These two sub problems can be solved in any order. Heuristic methods are available for both of them. Unlike the SLE problem, any solution for the DLE must be computationally simple, as the requests need to be processed online.

Meanwhile RWA algorithms assume either centralized or distributed control for selecting routes and wavelengths [Murthy 2002]. In the centralized control system, a central controller keeps track of the status of the network and is accountable for the establishment and termination of all light-paths. Whereas in distributed control system each node has partial information about the network status. Whenever a light-path needs to be established between a node pair under a distributed control, the first task is to send appropriate control signals to select the route and a wavelength. After this, appropriate control signals are sent to configure the switches in the selected path. Similarly the control signals are required to be sent after completion of the data transfer to release the resources on the path. Centralized schemes are better for smaller size networks while the distributed schemes are scalable to large networks and work better for them.

Three broad categories are found in the literature for routing sub problem: fixed routing, fixed-alternate routing and adaptive routing. Among these, fixed routing is the least complex while adaptive routing is superior to all in performance. Fixed-alternate routing is a tradeoff between complexity and performance. Fixed and fixed-alternate routing (i.e. offline routing) is static in nature, which means routes are predefined and do not change with network status. Adaptive routing has got more attention by researchers as it captures the dynamics of network during run time and also called as online routing.

The heuristic algorithm proposed by [Zhang 2002] for solving the dynamic RWA problem considers the shortest path routing algorithm in a distributed manner. The algorithm creates an auxiliary graph for solving routing as well as wavelength assignment sub-problem. This algorithm considers the cost of wavelength and wavelength convertor to find the link weight. Each node has a full wavelength conversion capability in shared mode which makes node cost high. The static RWA algorithm proposed by [Manohar 2002] uses a Bounded Greedy Approach (BGA) to find the Edge Disjoint Paths (EDPs). A greedy EDP algorithm is developed to solve RWA problem with lesser complexity as compared to the standard ILP based solutions. The wavelengths are assigned to the selected paths using graph colouring algorithm. The algorithm proposed by Manohar et al., randomly selects the request from the request set. Use of EDPs reduces the number of unique wavelength requirement to setup the given number of light-paths as compared to standard solutions but still the bandwidth utilization is not efficient.

The static RWA algorithm developed by [Choo 2006] is based on the maximum flow to get the maximum quantity of EDPs. The algorithm uses a lookup table to store the maximum number of EDPs calculated for all possible connections for establishing a light-path for each of the connection request to reduce the time complexity. This solution is good for the situation where network topology changes rarely. However, for a network with dynamic topology, the lookup table needs to be regularly updated to incorporate the topology changes. This algorithm reduces the wavelength requirement for repeated connection requests compared to the other EDP based static RWA algorithms. The algorithm proposed by [Kim 2003] called as LTB_RWA is based on the Disjoint Path-set Selection Protocol (DPSP). This algorithm also creates a Lookup Table like in [Choo 2006], which has possible EDPs for each DPSP request of the request set. In obtaining the Lookup Table, the weight matrix is also maintained to reflect the contribution of each edge. The routes are determined in order, by the weight matrix for the given request set.

The static RWA solution proposed by [Manohar 2002] and Choo [2006] are based on maximum EDPs and both solutions tried to minimize the number of wavelengths required to setup the given light-path connections. Similarly the solution proposed by [Yoon 2006] for static RWA also finds the maximum EDPs for each request. Unlike the BGA for EDP algorithm, the request order is determined according to the length of EDPs and its degree in path conflict graph. The path conflict graph determines the degree of conflict of each of the EDP which indicates the number of links shared by other routes from the EDPs. This algorithm outperforms the BGA for EDP algorithm in terms of number of wavelength requirement. The maximum EDP based heuristic solutions found in the literature to solve RWA problem selects a path from a set of candidate paths, which has a common wavelength available on all the links of it. Similarly, the conventional RWA algorithms based on fixed-routing, shortest path routing and fixed alternate routing also works.

Another class of heuristic methods for solving RWA problem works on link by link basis which selects the route based on the current status of the network. In this approach, each link has been assigned a cost or weight, based on some network parameters like number of free wavelengths, the ratio of the free wavelength count to total wavelengths, link speed, link delay and node degree etc. The parameters which decide the link weight are broadly of two types, one is static and other is dynamic. The parameters like node degree and link speed usually are static for a given network topology until topology changes. The change in network topology is not so frequent and therefore these parameters are considered as static. While the parameters like free wavelength count and the ratio of free wavelengths of total wavelengths is changing as the light-paths are assigned and released. Thus the change in link weight is reflected in path selection for incoming connection requests. Similarly, the network status information can be incorporated into conventional RWA algorithms which use a path based approach. The various link weight based RWA heuristic algorithms have been proposed to capture the network status. [Mokhtar 1998] [Li 1999] [Bhinde 2000] [Dharma 2004]

The dynamic RWA algorithms proposed by [Mokhtar 1998] adaptively chooses the path for a connection request which arrives randomly. This algorithm does not use any predefined path. The path has been selected either adaptively or sequentially at the time of the connection request arrives. The common heuristics proposed in the literature for searching a wavelength to setup a light-path are named as most utilized first, least utilized first, random, fixed and exhaustive search. These heuristics require wavelength usage information either globally or locally. This needs appropriate control messages to be exchanged between the nodes to keep up to date information about the network state.

Two dynamic routing heuristics are discussed by [Li 1999] based on the congestion status of the path and neighbour-hood link. In the path congestion based algorithm connection requests are sent towards the destination node over multiple paths in parallel. At the destination node a route with maximum number of free wavelengths is selected for light-path setup which represents the least congested path. This algorithm suffers with large setup delay and the control overhead. It also causes a conflict in case of multiple nodes trying to setup light-paths simultaneously. In another variant of this approach, only a few links are scanned for each of the probable path to predict the wavelength availability on the entire path. Here the blocking rate largely depends upon the number of links scanned for the path selection. This reduces the setup delay and control overhead by compromising with the blocking performance. In both of the approaches, if more than one wavelength is free then one of the existing wavelength assignment algorithms is used.

In [Bhinde 2000a] and [Bhinde 2000b], WDM aware link weight functions are proposed to claim a superior performance of these weight functions over conventional weight functions (e.g. hop count, free available wavelengths). The weight functions considered are of the combination of hop count, available wavelengths, and total wavelengths. The reported results show a better performance with the combination of weight functions as compared to be used in their pure form. In [Dharma 2004], A distributive routing algorithm has been proposed by [Dharma 2004], selects the route on a link by link basis in spite of choosing a route from predefined candidate routes. Unlike other link based approach, this algorithm selects a link on the basis of dynamic functions defined as link preferred functions. The functions choose the next preferred link in the path based on parameters like congestion, shortest path, blocking probability and free wavelength count. The key factor for the better performance of this algorithm is the frequent update of network information like blocking probability and free wavelength count of the links at each node. Too many options for selecting the next preferred link in the route contribute significant delay to setup a light-path.

In [Zhou 2005], a compact bitmap representation of the link state information is presented and the wavelength availability status on the link is represented using logical binary values. Each of the links having N wavelengths has associated with a N bit vector such that the corresponding bit position in the vector represents the status of the corresponding wavelength on the respective link. Here a bit value zero in the vector indicates corresponding wavelength as blocked and a bit value one indicates that the wavelength is free. The same approach has been extended for multi-fiber channels as well. This approach reduces the amount of data to maintain the network status information. Further, bitwise computations take less time to check the availability of the wavelengths on the path even across the multiple fibers. For routing purpose, the path with the highest number of free wavelengths is selected. In the case of multiple paths having the equal wavelength availability count, the path with least hop count is preferred for routing. This representation is not scalable with the increase in the number of fibers as well as a number of wavelengths per link.

The link state based Estimated Congestion Routing (ECR) algorithm introduced in [Mewanou 2006] calculates the congestion on each of the links of all the candidate paths selected using modified Yen’s K-shortest path algorithm. The function defined to measure the congestion level of a link is inversely proportional to the number of idle wavelengths on the link. Unlike the algorithms proposed by [Li 1999], the ECR algorithm performance does not depend on the number of links scanned in the candidate path. The other algorithm proposed by [Mewanou 2006] finds K most congested links of each of the candidate paths and then chooses a path with the maximum number of continuous free wavelengths in the K most congested links from each of the paths. This algorithm reduces the number of blocked requests by selecting a wavelength continuous path. The time complexity of this algorithm is more than the algorithm FPLC-k proposed by [Li 1999] because of its complicated computational process for computing K most congested links corresponding to each of the paths.

The advantage of heuristic approaches for adaptive RWA algorithms is to reduce the time complexity and to get near to optimal solution. As we know that the objective of RWA problem’s solution is to minimize the required number of wavelengths to setup the given number of connection requests or minimize the blocked request count. The common heuristic approaches used so far for RWA are categorized as a path based approaches and link based approaches. Among the path based approaches, the EDP based approach is found to be the most popular technique as compared to the normal edge sharing paths. This can be attributed to the reduction of total number of wavelengths required to establish the given number of connection requests. Another commonly used approach selects the best path based on the least congestion among the K shortest paths. Usually the congestion of the path is computed by summing up the congestion of each of the links in the path. Link congestion is defined by various parameters like degree of left and right nodes of the link, free wavelength count, link cost etc. Unlike EDP based solutions, the K-shortest path based algorithms give guarantee of the best shortest path selection. The common performance metrics usually investigated in a WDM networks are named as the required number of wavelengths, blocking probability, throughput, connection setup delay, time complexity, fairness, network load, and number of fiber resources.

5.2.2 Multipath Routing

There are two different categories of applications, one with low latency (e.g. interactive video applications) and another with high bandwidth requirement (e.g. scientific and engineering applications). Single path routing becomes a performance bottleneck for such kind of applications. The existing solutions (e.g. TOS field in the IPv4 protocol header) for delay sensitive traffic are not sufficient to improve their performance. Similarly, bandwidth intensive applications need special treatment as compared to other traditional low bandwidth applications. It has been observed that the large size networks have a better availability of link disjoint multiple paths between node pairs and these can be exploited by using modified routing protocols/algorithms through forward the traffic on multiple routes. The incoming data at source node can be distributed among various available paths in such a way that each path carries a small chunk of it. The granularity of the data division is decided on the basis of the application requirements. Some of the common data division criteria are called as the packet basis; destination host basis; flow basis and IP prefix basis division. The applications with huge bandwidth demand require multipath routing to satisfy their needs. A multipath light-path provisioning mechanism is proposed by [Chen 2009] to minimize the end to end delay for data transmission.

Unlike single path routing, the multipath routing reduces the end to end delay and also does the load balancing to control the congestion in the network [Paganini 2006] [Javed 2009]. A multipath routing algorithm is proposed by [Banner 2007] minimizes the network congestion by using approximation algorithms. Moreover the connection setup delay observed in a multipath routing is lower than the single path routing due to multiple parallel reservations initiated for multipath routing. In single path reservation process, the connection setup time becomes larger in the case of multiple retries [Cidon 1999]. Single path adaptive routing algorithms [Bhinde 2001] [Dharma 2004] [Lin 2008] do the load balancing and avoid the congested links for traffic forwarding. These algorithms offer a large reaction time as it shifts the traffic gradually from the highly congested region of the network to the least congested region of the network. Further, in a path failure situation, multipath routing can manage the data transfer via other available alternate paths. This provides the built in fault tolerance capability in the multipath routing which lacks in the single path routing.

Multipath routing techniques are common in wireless Ad hoc networks [Das 2000] and wireless sensor networks [Dulman 2003]. Mobility of the nodes causes a big challenge to the path stability and this needs the distribution of larger data chunks into smaller data chunks to transmit over multiple paths. This reduces the end to end delay for each path. The number of multiple paths is dynamically decided on the basis of the probability of the path stability.

Apart from above mentioned positive aspects of multipath routing, there are some overheads involved. In the case of multipath routing, the control overhead increases due to the requirement of additional information exchange to find multiple paths availability status. Similarly, data plane overhead also increases due to the additional memory requirement to keep the information for multiple routes. Over the above these multipath routers also need more processing power to process the additional data. The performance of a multipath routing algorithm largely depends upon the number of parallel paths explored, number of parallel paths used, path selection criterion and bandwidth distribution among the paths. In general, data arrives out of order at the destination node via multiple paths because of the fact that each path offers different delay. Thus, out of order data arrival requires a larger buffer size and introduces more delay. This degrades the quality of video streaming services. A scheduling algorithm proposed by [Chen 2004] segments and multiplexes the video over multiple paths such that end host can assemble the data and play back in quick time. This algorithm is implemented at the source node on the basis of path length by reducing setup delay accordingly.

The path selection criterion can be tuned to constraint the delay difference among multiple paths to relax the memory requirement. A differential delay technique proposed by [Pandhi 2010] constraints the delay difference between longest and shortest path and reports the effect of bandwidth distribution process among various paths under multipath routing algorithm. The proposed even and uneven bandwidth distribution techniques have been applied for link utilization and connection establishment to show a superiority of the latter over the former. Similar kind of differential delay minimization approach has been investigated by [Ahuja 2004] for virtually connected Ethernet or SONET (Synchronous Optical Network) systems.

Obviously, multipath routing is an alternative to survivable routing where multiple paths are assigned to a session (i.e. connection requests to data transfer) such that the probability of session failure becomes minimal. Edge disjoint paths are always a better choice to add as an alternate path to a session because of the fact that failure of one path due to one or multiple link failure will not affect the other paths. Hence the less number of paths will be sufficient to ensure the session survivability. The availability of link disjoint paths increases with the average nodal degree and the size of the network. The time complexity to find link disjoint paths is crucial for a multipath routing. A link penalty based multipath routing algorithm for survivability is proposed by [Shin 2004] which eliminates the requirement of link disjoint paths with comparable performance. The penalty assigned to each of the links reflects to the failure probability of the link. The link failure probability is used to calculate the path failure probability. In other words, the link penalty controls the sharing of the link across multiple paths i.e. more sharing increases the failure probability. The paths are added to a session until the failure probability of the respective session reaches up to a desired value. The algorithm's performance depends upon the link penalty assignment parameters. Similarly a multipath based reliable service provisioning for high capacity backbone mesh network is proposed by [Rai 2007] uses average or effective multipath bandwidth metric for accommodating connections to ensure the reliability requirements.

Hence multiple paths availability between the sender and receiver reduces the data transfer time and thereby improves the network resources utilization. It is envisaged that the consideration of edge disjoint multiple paths in a multi-wavelength network further improves network performance significantly. The literature review suggests that a few attempts have been made so far on multipath routing in WDM networks [Chen 2009]. In this chapter an attempt is made to explore the possibility of multipath routing in WDM networks. The proposed methodology to implement multipath data transmission and simulation study in a WDM network is discussed in the section 5.6.

There are five RWA algorithms that have been proposed and explained in detail in the rest of this chapter. These algorithms are:

- Weight based Edge Disjoint Path RWA algorithm (WEDP-RWA)
- Wavelength Intersection Cardinality Routing and Wavelength Assignment (WIC-RWA)
- Least Count First (LCF)
- Least Recently Used First (LRUF)
- Multipath Routing Algorithm

The WEDP-RWA algorithm is explained in section 5.3. In this algorithm, each link of the network is associated with two types of weight i.e., static and dynamic. The best path selection criterion is chosen in the proposed algorithm on the basis of the static and dynamic link weight. It has been observed through a literature survey that this combination of link weight has not been used so far. The WIC-RWA algorithm proposed by us for solving the dynamic RWA problem has been explained in section 5.4. A wavelength intersection cardinality based link weight allocation scheme ensures the wavelength continuous path selection among the available K-shortest paths between each source destination node pair. Two light-path assignment heuristics for RWA problem, LCF and LRFU are proposed for dynamic light-path assignment in section 5.5. These heuristics are coined in such a way that they reduce the time complexity of light-path assignment process for WDM networks. The section 5.6 describes simulation and analysis of multipath routing in wavelength routed WDM networks.

5.3 WEDP-RWA Algorithm[4]

This algorithm employs an edge disjoint path approach for solving a static RWA problem. Unlike other EDP based algorithms mentioned in the previous section, the proposed algorithm defines a criterion for selecting a suitable path among available EDPs between the given source destination pair. In a conventional EDP based algorithm, paths are scanned either according to the hop count order (i.e. minimum to maximum) or randomly to check the common wavelength availability to setup a light-path request. It is observed that the incorporation of the current wavelength load on each link with topological characteristics (i.e. node degree) shows improvement in the wavelength utilization. In other words, it does a kind of load balancing among the available wavelengths.

5.3.1 Problem Formulation of WEDP-RWA Algorithm

Let G (V, E) denote a graph that models the network, where V is the vertex set and E is the edge set. The request set R is a set of pairs $\{(s_1,d_1), (s_2,d_2), \ldots\ldots..(s_k,d_k)\}$, where s_i, d_i Є V, i =1,….m. Here 'm' represents the total number of connection requests. The s_i and d_i denotes source and destination nodes respectively. When a request arrives at source node s_i for a destination node d_i, a wavelength 'W' and path has to be selected to assign a light-path. The connection requests which are sharing the same physical links, required to be assigned different wavelengths to setup wavelength continuous paths. This constraint increases the count for the number of wavelengths to be required to setup a given number of light-paths. The use of EDPs can reduce the requirement of different wavelengths. The optimal number of required wavelengths is given by, the total number of connection requests divided by the cardinality of the edge cut set between source and destination. The maximum quantity of edge disjoint paths algorithm has been used to find the all possible

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[4] This work has been published in: Virendra Singh Shekhawat, Dinesh Kumar Tyagi, V K Chaubey, "Weight Based Edge Disjoint Path Routing and Wavelength Assignment (WEDP-RWA) Algorithm for WDM Networks", IEEE Region 10 Colloquium and the Third ICIIS, Kharagpur, India, pp.1-5, December 2008

EDPs between each pair of source destination node. Further, weight is assigned to each edge of all the EDPs for all possible node pairs in the network. The link weight calculation and assignment method is explained in the subsequent section.

5.3.2 Link Weight Assignment Method

The new link weight assignment method for each edge of the network is devised such that it includes both static and dynamic parameters of the network. As the name implies, static weight of the each link in a given network topology is fixed and depends on the arrangement of the edges and vertices in the network topology. The static weight for each edge is equal to the sum of in-degree and out-degree of the two vertices which form the edge. The more static weight of an edge indicates that the edge is likely to participate in the large number of EDPs for various source destination pairs. An edge with larger values of static weight should be given less priority to be included in the path to satisfy the incoming source destination pair request. On the other side, the dynamic weight for each edge is calculated on the basis of the percentage of wavelengths currently occupied or busy on the edge. More the number of wavelengths are occupied on an edge at a given point of time; the dynamic weight for that edge is assigned in such a way that the probability of choosing that particular edge in the path for incoming request becomes less. Whenever a new connection request arrives at any source node, the appropriate path is selected from the pre-calculated set of EDPs on the basis of above mentioned link weight strategy.

The path selection algorithm first finds the path with the least dynamic weight. In the case of multiple paths having the least dynamic weight, the tie is broken by selecting the path with the least static weight to get the best path. After selecting the best path as explained above, the First Fit (FF) wavelength assignment algorithm is used to assign a wavelength to the selected path to satisfy the connection request.

5.3.3 Link Weight Calculation And Wavelength Allocation Method

The static weight of an i^{th} edge is given as follows:

$\text{Staticweight\_Edge}_i = \text{Indegree\_Edge}_i + \text{Outdegree\_Edge}_{i.}$

The static weight of the path is given by summing up the static weight of each edge included in the path as given below.

Staticweight_Path = ∑ (Staticweight_Edge$_i$).

The dynamic weight of each edge is given by number of wavelengths currently used on that edge. The summation of individual edge’s dynamic weight of a path gives the dynamic weight of the path.

Dynamicweight_path = ∑ (Dynamicweight_Edge$_i$).

The FindBestPath(s, d) first selects the available EDPs (pre-computed in the table) to find a list of paths with least dynamic weight and then selects the best path with least static weight from the list. Algorithm for FindBestPath(s,d) is as follows:

```
FindBestPath(s,d)
{
     PathSet=getEDP(s,d) and dyn, st=9999
     /*Large value is represented as infinity*/
     /*EDPs are pre-computed using EDP_Table(G) and fetched from
     the table */
     path = PathSet.getfirstpath()
     While (Path != NULL)
     {
          If(path.Dynamic_weight ≤ dyn)
               {
                    Add path to Dynresult
                    dyn = path.Dynamic_weight
               }
          path = PathSet.getnextpath()
     }
path = Dynresult.getfirstpath()

While (path!= NULL)
  {
     if(path.Static_weight ≤ st)
     {
          Add path to result
```

```
            st = path.St_weight
      }
            path = PathSet.getnextpath()
  }
Return result.getfirstpath()
}
```

The wavelength allocation algorithm is given as follows:

```
Begin
EDP_Table(G)
while (the same G)
do
      Retrieve a new R    /* Find a request */
      W = 0              /* Wavelength Initialization */
      while (R != NULL)
      do
            W = W + 1
            if (FindBestPath(s,d)!= NULL)
                  Assign P(sj, dj, W)
                  R = R – (sj, dj)
            end if
      end while
end while

End
```

5.3.4 Case Study Example

Let’s take a random network topology as shown in Fig. 5.1 and the sample connection request set is as follows: { (1,8), (1,7), (4,6), (3,7), (1,7), (3,7) }.

First we will find the list of EDPs for each connection request. The request node pair (1,8) has two paths; 1→3→9→8 and 1→2→4→6→8. Next request node pair (1,7) has two paths; 1→3→9→8→7 and 1→2→4→5→7. The request node pair (4,6) has two paths; 4→6, 4→5→6 and finally the request node pair (3,7) has three paths; 3→9→8→7, 3→4→6→7, 3→2→4→5→7. The static weight is calculated for each of these EDPs using in-degree and out-degree of each of the links, and listed in the Table 5.1. Initially, all the wavelengths are free so the dynamic weight for all the edges becomes zero and it changes as wavelengths are allocated for each node pair from the request set. Requests are considered in First Cum First Serve (FCFS) to setup the light-paths. For request node pair (1,8), since both of the candidate paths have least dynamic weight hence path-1 is selected as its static weight is the least. After satisfying this request, the dynamic weight for each of the edges included in path-1 becomes one. The path-4 is selected for the next request node pair (1,7) due to its minimum dynamic weight between two available candidate paths. For the request node pair (4,6), path-5 is selected as its dynamic weight is the least. For the request node pair (3,7), path-8 is used due to minimum dynamic weight among three possible paths.

Similarly, for the next two request node pairs (1,7) and (3,7), the path-3 and path-9 are selected respectively. This path allocation process requires only two unique wavelengths for the given request set. If the wavelength allocation is performed on the same request set according to the MEDP algorithm [Choo 2006], then it requires three unique wavelengths. The path selection process for the proposed algorithm ensures proper traffic distribution and avoids the most congested edges in the network to be chosen for data transfer.

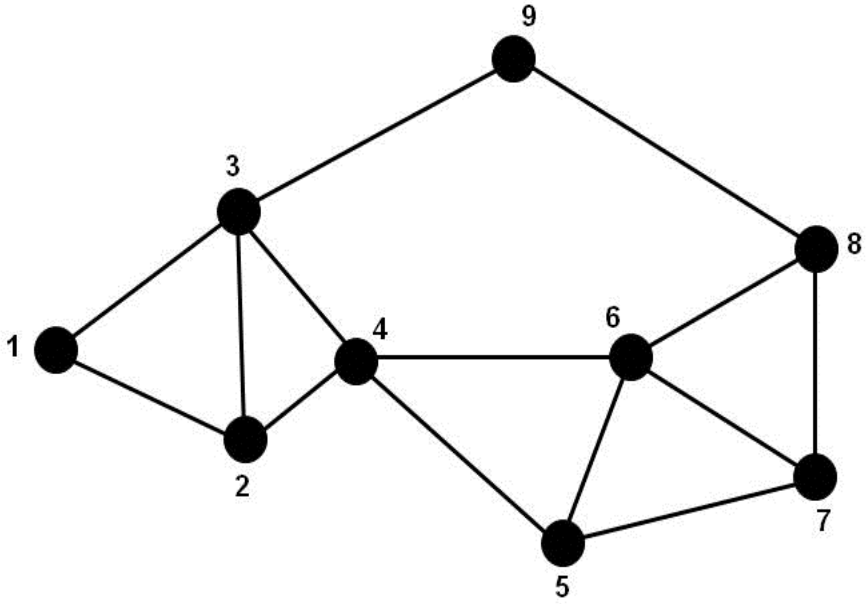

Figure 5.1 Random Network Topology

Path No.	Path	Node Pair	Static Weight
1	1→3→9→8	1,8	11
2	1→2→4→6→8	1,8	19
3	1→3→9→8→7	1,7	15
4	1→2→4→5→7	1,7	17
5	4→6	4,6	6
6	4→5→6	4,6	10
7	3→9→8→7	3,7	11
8	3→4→6→7	3,7	17
9	3→2→4→5→7	3,7	19

Table 5.1 Static Weight Allocation for EDPs

5.3.5 Simulation and Analysis

The proposed algorithm is simulated with the help of a C language program. The program generates a random network topology for a given number of nodes N. The randomness of the topology is controlled by varying the Pe (i.e. probability of edge existence between any node pairs) and Pl (i.e. probability of request). Random request set for getting various source destination node pairs is generated by incorporating Mc (i.e. multiplicity of the single request) through simulation program. Simulation runs for one thousand iterations for each combination of N, Pe, Pl and Mc. The number of wavelengths needed for the request set for proposed algorithm along with MEDP algorithm is shown in Table 5.2.

It has been observed that in most of the cases, the proposed scheme outperforms the MEDP algorithm. The proposed algorithm performs better for higher values of Mc and for N. In particular, for a network of 20 nodes, one can see a significant and consistent improvement over the MEDP algorithm in terms of the number of wavelengths needed to setup a light-path. However, MEDP performs almost similar to the proposed one for a small size network.

A new link weight heuristic scheme is devised to select the best path from a list of pre-calculated candidate paths between source destination node pair. These pre-calculated candidate paths are chosen as EDPs. The two fold link weight (i.e. static and dynamic) assigned to each edge of the network captures the static and dynamic properties of the network. The path selection algorithm is tested to solve the static RWA problem.

N	**Pe**	**Pl**	**Mc=1**		**Mc=4**		**Mc=7**		**Mc=10**		**Mc=13**	
			MEDP	**WEDP (New)**	**MEDP**	**WEDP (New)**	**MEDP**	**WEDP (New)**	**MEDP**	**WEDP (New)**	**MEDP**	**WEDP (New)**
5	0.2	0.6	4.018	4.018	9.159	9.159	21.627	22.354	33.545	33.545	47.369	47.969
	0.2	0.8	6.411	6.411	16.958	16.958	29.030	28.792	42.626	42.815	61.123	60.773
	0.2	1.0	4.806	5.001	20.358	20.969	30.960	32.319	58.614	57.030	67.250	65.001
	0.4	0.6	2.208	2.208	6.813	7.000	20.215	20.398	23.119	22.762	26.034	27.097
	0.4	0.8	3.191	3.395	13.502	13.430	24.735	25.101	30.525	31.193	50.852	52.655
	0.4	1.0	4.770	4.770	19.108	19.660	24.148	24.144	44.750	45.275	61.184	59.108
10	0.2	0.6	10.392	10.433	42.090	42.076	65.688	64.984	99.921	98.750	108.174	110.01
	0.2	0.8	11.383	11.504	55.900	56.956	77.117	78.286	153.439	151.096	155.355	155.25
	0.2	1.0	17.607	17.677	64.538	64.640	112.62	115.51	178.192	179.59	228.375	230.55
	0.4	0.6	4.903	4.880	17.717	17.717	33.141	34.248	45.320	45.551	60.521	61.741
	0.4	0.8	8.125	8.430	28.448	29.487	46.302	46.731	57.781	57.967	90.996	93.174
	0.4	1.0	11.499	10.868	36.070	36.759	67.503	68.902	86.672	83.201	134.284	135.91
15	0.2	0.6	16.296	16.328	60.912	60.432	94.521	94.004	166.716	165.767	192.293	192.64
	0.2	0.8	20.909	20.825	91.846	90.860	140.31	139.14	201.506	200.837	298.288	295.81
	0.2	1.0	26.186	25.605	118.27	117.63	195.64	194.58	248.575	243.006	357.276	355.17
	0.4	0.6	7.765	7.988	27.050	27.021	44.817	44.781	65.356	65.950	90.068	90.001
	0.4	0.8	10.342	10.553	39.781	39.916	70.344	70.501	104.813	105.040	122.755	123.97
	0.4	1.0	13.969	14.245	55.400	54.863	93.285	93.935	126.928	129.285	166.342	166.35
20	0.2	0.6	22.056	21.991	85.194	83.893	144.22	143.22	207.231	205.789	254.483	251.72
	0.2	0.8	28.992	28.735	114.88	113.41	207.51	204.82	283.940	281.290	370.495	364.44
	0.2	1.0	36.117	35.485	140.90	138.22	256.82	254.13	365.944	359.942	474.539	464.67
	0.4	0.6	8.883	8.787	33.434	33.202	56.438	56.06	79.379	79.067	106.618	106.04
	0.4	0.8	13.248	13.267	51.594	51.261	86.498	86.263	126.725	126.699	158.691	157.89
	0.4	1.0	17.397	17.364	66.916	65.984	116.52	115.58	167.165	164.593	217.617	214.52

Table 5.2 Number of Wavelengths Comparison for MEDP and WEDP

A similar approach can be used to solve dynamic RWA problem as well. The proposed algorithm results are compared with MEDP algorithm developed by [Choo 2006]. The results reveal that, the proposed algorithm requires a lesser number of wavelengths to establish the light-paths as compared to the MEDP algorithm for the network having 20 nodes and higher values of multiplicity factor (i.e. Mc=10 and Mc=13). The comprehensive simulations support the proposed algorithm for better utilization of available wavelengths, especially when more requests arrive for the same set of node pairs within a given network. The order of run time complexity of both the algorithms is same, as there is no significant contribution in the run time complexity of the proposed algorithm due to static and dynamic weight calculation for each path.

5.4 WIC-RWA Algorithm[5]

The optimal route selection and wavelength assignment is a key aspect in wavelength routed WDM optical network. Literature review suggests that the heuristic approaches are always superior with respect to conventional approaches in real time scenario. Furthermore, heuristic algorithms basically give tradeoff between performance and complexity. In general, the traffic forwarding decision under adaptive routing algorithms is a function of the number of free channels on the links. This doesn't ensure the common wavelength availability on the entire path. The WIC-RWA algorithm presents a novel approach for taking traffic forwarding decision by ensuring the wavelength continuity constraint between the source destination node pair. The path selection algorithm developed here establishes the light-path with less computational overhead and gives better throughput. The proposed algorithm is compared with a conventional adaptive routing algorithm through simulation. Observations reveal that the new algorithm performs better by dipping Average Blocking Time of the Network (ABTN). In particular, it outperforms at higher traffic rates with a limited number of channels per link.

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[5] This work has been published in: Virendra Singh Shekhawat, Ohmkar K, V K Chaubey, "A Wavelength Intersection Cardinality Based Routing and Wavelength Assignment Algorithm in Optical WDM Networks", ICCCS'11, Rourkela, Odisha, India, pp. 110-113, February 2011

5.4.1 Wavelength Intersection Cardinality

The performance of an RWA algorithm largely depends upon the route selection criterion between source and destination node pair. Dynamic route selection schemes always give better connection probability than the fixed shortest path routing. A link can be expressed in a path as a set of free wavelengths. The wavelength intersection cardinality of a particular route is the intersection set of free wavelengths on all the links between the source destination pair. Most of the algorithms target the free available wavelengths on each of the links to assign a weight factor; it may be possible that the selected wavelengths in a particular link might not be available on other links in the path. Wavelength intersection cardinality is coined in order to overcome from this situation.

A link having large number of free wavelengths gets more weight, subsequently, the probability of including that link in the path increases. The weight functions which are calculated based on this concept gives no guarantee of the availability of the common free wavelength throughout the path. Ultimately, the connection request has to be blocked during the wavelength reservation process. If the wavelength continuity constraint is satisfied at the time of finding the path then such kind of call blocking can be avoided. The WIC based RWA algorithm combines the routing and wavelength assignment in a single thread to ensure the continuity constraint.

5.4.2 WIC-RWA Algorithm Description

```
Input: Graph G (V, E)
Here $V = \{v_1, v_2, ..…….v_n\}$ and $E = \{e_1, e_2,…..e_m\}$
Output: Wavelength continuity path for a request $r_q$ between $v_i$ to $v_j$, if available. Otherwise the request is blocked.

1. Initialization:  $TotalBlkTime_i$ = 0, ABTN = 0, $MsgQueue_i$ [len] and $BlkQueue_i$ [len]
Where i = 1 to n
```

/* K-shortest paths calculated for all possible destination nodes in the network. Connection requests at each node follow a Poisson process at each node. */

```
2. For each request $r_q \in MsgQueue_i$ at vertex $v_i$ for destination vertex $v_j$. Where $i, j = 1$ to $n$ and $i \neq j$. $q$ = total number of requests at node $v_i$
        2. a) WIC for each of K paths identified is calculated
              between vertex $v_i$ and $v_j$
        2. b) If any path available with WIC>0
/* A path with minimum positive value of WIC is chosen and $TotalBlkTime_i$ is updated as follows: */
      $TotalBlkTime_i = TotalBlkTime_i + CurrentReq\_BlkTime$
      else
      Add request in BlkQueue at vertex $v_i$
3. Repeat step-2 until $MsgQueue_i != \phi$ at node $v_i$
   or until $BlkQueue_i != \phi$
4. $ABTN = \sum(TotalBlkTime_i)/TotalRequests$      (where i = 1 to n)
5. Stop
```

Abbreviation for terms used in this algorithm:

$MsgQueue_i$ [len]: Request Message queue of length len at node N_i

$BlkQueue_i$ [len]: Blocked Message queue of length len at node N_i

$TotalBlkTime_i$: Total blocked time of the requests at node N_i

CurrentReq_BlkTime: Current request blocked time

ABTN: Average Blocking Time of the Network

5.4.3 Case Study Example

Let us consider a network topology consisting of 8 nodes and 12 links as shown in the Fig. 5.2. Assuming each of the links having 9 wavelengths and are numbered from 0 to 8. The numbers displayed on each of the links in the Figure 5.2 indicates free wavelengths on the link. Suppose there is a request for a connection from node P to Q. Consider the k-shortest path algorithm with k=3, the first three shortest paths are as follows: i) P→O→N→Q, ii) P→R→S→Q and iii) P→T→M→Q. Path P→R→S→Q with length of three hops having maximum number of free wavelengths i.e. 9.

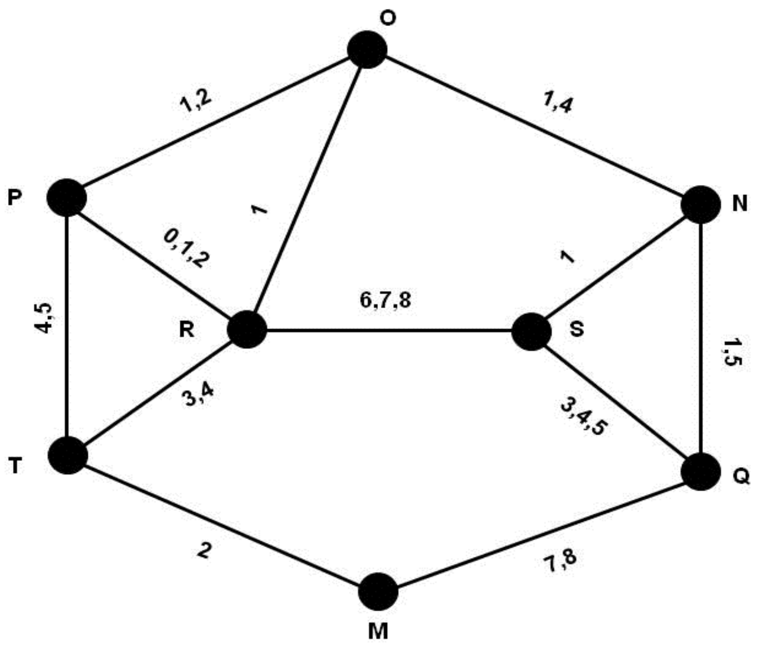

Figure 5.2 Network Topology for Case Study

So as per the link weight criterion based on free available wavelengths the path ii) will be selected for the data transfer. This light-path will not be established due to non-availability of common free wavelength on the path. But as per proposed algorithm the path P→O→N→Q will be chosen with a Wavelength Intersection Cardinality as one (one common free wavelength available on all the links of the path). So the wavelength reservation process can be started by reserving wavelength number one. It gives better performance as a wavelength continuity constraint was preserved at the time of route selection.

5.4.4 Simulation Model and Performance Analysis

A two phase simulation process is developed to test the proposed algorithm. In the first phase a random network topology is generated and first three shortest paths are calculated for each of the possible node pair. The second phase focuses on the communication between the nodes for agreeing upon a route and a wavelength. A main thread which keeps looking for requests between any node pair selects a route and a wavelength as per the proposed algorithm. Each of the nodes in the network maintains two message queues, one to keep list of requests and other to keep the blocked requests. It is assumed that the simulation is run until all the requests are processed. Each of the nodes will be simulated by its own randomly generated thread. The connection requests are generated from a node to other nodes in the network with equal probability. The requests arrive at each of the nodes as per the Poisson distribution process. The connection holding times are distributed negative exponentially with mean 1/μ for a traffic load ρ of the network.

The time difference between request arrival time and request serviced time gives the blocking time duration for a given request at a given node. The ratio of total blocking time and total number of requests generated for that node gives the Average Blocking Time (ABT) for that node. The sum of these ABTs divided by the total number of nodes, gives the Average Blocking Time for the Network (ABTN). The proposed WIC-RWA algorithm gives 4% to 10% lower ABTN value as compared to the traditional routing algorithm which uses free wavelength based link weight for the traffic rate range from 80 to 160 requests per minute. The simulation has been carried out to find ABTN at the different traffic rates for both the approaches and the results are shown in Fig. 5.3. The number of wavelengths per link is assumed as eight. Initially at lower traffic rate both the algorithms show almost equal value of ABTN, this implies that at lower traffic rate (i.e. less than 50 requests per minute) most of the wavelengths are free.

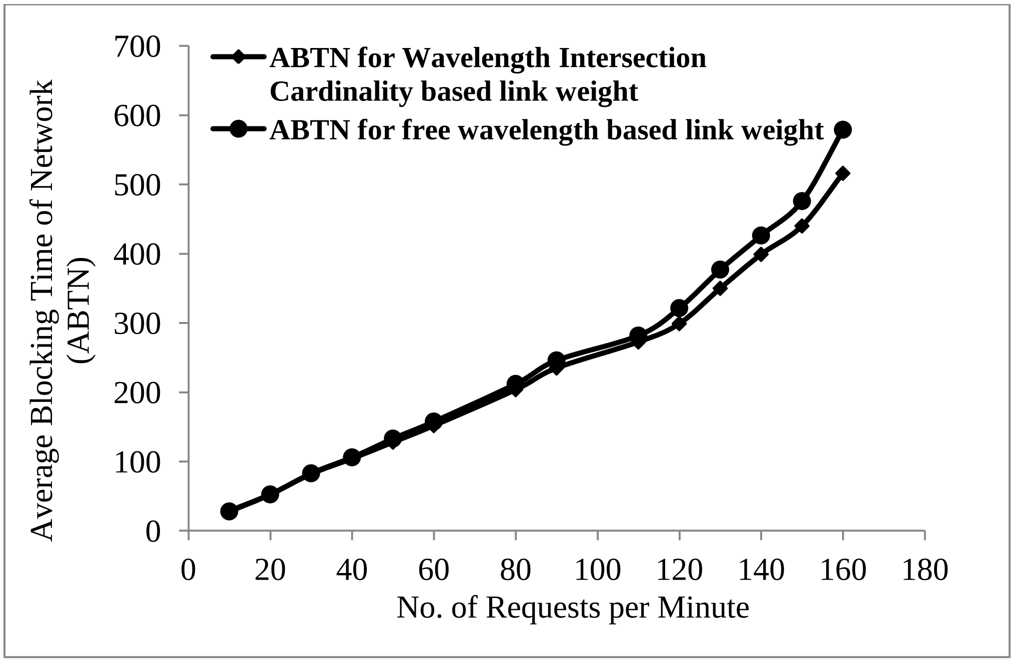

Figure 5.3 Traffic Load vs. Average Blocking Time of Network

So the probability of the finding of common free wavelengths is high and it also confirms a better performance for the free wavelength based link weight. It is also observed that the wavelength cardinality based algorithm causes to decrease the ABTN with the increase in the incoming traffic rate. The increase in the traffic rate reduces the wavelength availability on the links and lowers the probability of finding a common free wavelength for any node pairs. The proposed algorithm is advantageous here due to the path selection procedure for the given connection request. The algorithm selects the path having a minimum positive value of the WIC. On the other side, the regular link weight (i.e. free wavelength based link weight) based routing algorithm selects the path which has the maximum number of free wavelengths. Moreover, as the traffic rate increases (i.e. 150 and more request per minute) the increased gap between the two curves indicates that the proposed algorithm is scalable and works better even at higher traffic rate.

The variation in the ABTN with respect to the number of wavelength channels on a link has also been simulated. The Fig. 5.4 shows the change in the ABTN with respect to number of wavelengths per link for 50 requests per minute per node. It is observed that, as the number of wavelengths per link increased, the ABTN value gets reduced for both the algorithms. Once the number of wavelengths per link increases from 6 to 10 the ABTN value for WIC based algorithm decreases more than the regular link weight based routing algorithm. This confirms that the resource utilization is better for wavelength intersection cardinality based algorithm than the regular link weight based routing algorithm. However, it is evident from the analysis that the improvement is not very significant at the larger number of wavelengths per link. This implies that the better resource availability makes the performance comparable for both of the algorithms. This analysis can be used to optimize the available resources to ensure the minimum blocking probability.

The investigation focuses on the routing scheme that inherits the wavelength continuity constraint which is usually missing in the regular link weight based RWA algorithms. Simulation results confirm the influence of path selection method on the call blocking probability, by reducing average blocking time of the network.

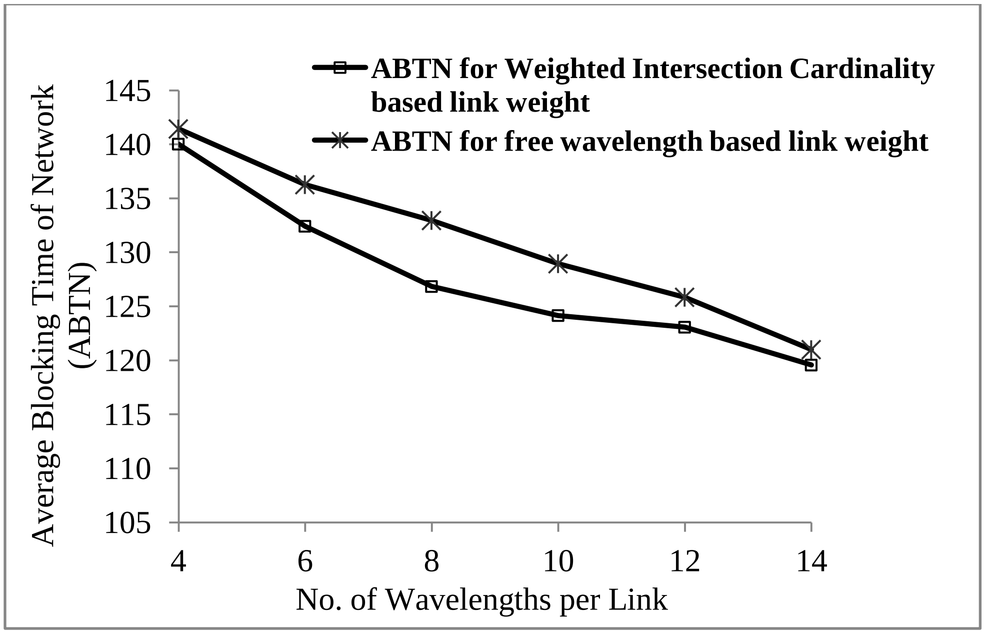

Figure 5.4 Wavelengths per Link vs. Average Blocking Time of Network

The objective of the WIC based algorithm is to select the route for the current request to ensure the resource availability for the incoming requests. The proposed algorithm chooses a path such that the number of common free wavelengths is the least on the path. This approach combines routing and wavelength assignment together which simplifies the wavelength reservation process. This approach can also be extended for multi-fiber link networks.

5.5 LCF and LRUF Light-path Assignment RWA Algorithms[6]

A network topology having N nodes with W wavelengths per link can be visualized as a W layered wavelength mesh graph between the given source and destination node pair. The RWA problem can be formulated such that it finds at-least one wavelength mesh graph which satisfies the connection request between a source destination node pair. One of such attempt has been made by [Shen 2001] to solve RWA problem. The heuristic RWA algorithms proposed by [Shen 2001] follows an exhaustive approach to search a shortest path among all possible paths and assign the best available path on the cost of

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[6] This work has been published in:Virendra Singh Shekhawat, Amrit Kumar Saini, V K Chaubey, “Efficient Heuristic Algorithms for Routing and Wavelength Assignment in Optical WDM Networks”, IUP Journal of Telecommunications, Vol. 4, No. 3, pp. 31-43, August 2012

time complexity. The modified versions of this algorithm are designed in this section. The proposed algorithms reduce the time complexity by enabling the wavelength search order based on dynamic functions.

Instead of using Fixed Order (FO) search, a dynamic ordering of wavelength mesh graphs has been proposed. Since one of the drawbacks of fixed ordering algorithm is that the light-path requests tend to be assigned as a cluster into first few wavelength mesh graphs. The subsequent light-path requests have to be assigned to next remaining wavelength mesh graphs but for that it scans from the start. This increases the delay in the light-path allocation process. Hence a mechanism can be devised in which the wavelength mesh graphs can be arranged dynamically from high to low probability of their availability. This reduces the average scanning time overhead and hence more requests can be entertained in the given amount of time. This also improves the resource utilization which leads to better throughput. The next section describes the proposed RWA heuristics in detail.

5.5.1 LCF and LRUF Algorithm Formulations

This algorithm has been proposed to be used for the wavelength continuity constraint based optical WDM networks to establish a light-path between given source and destination node pair. A mesh network of N nodes and L links having total W wavelengths on each of the links can be considered as a W layered graph between any two node’s pair as shown in the Fig. 5.5.

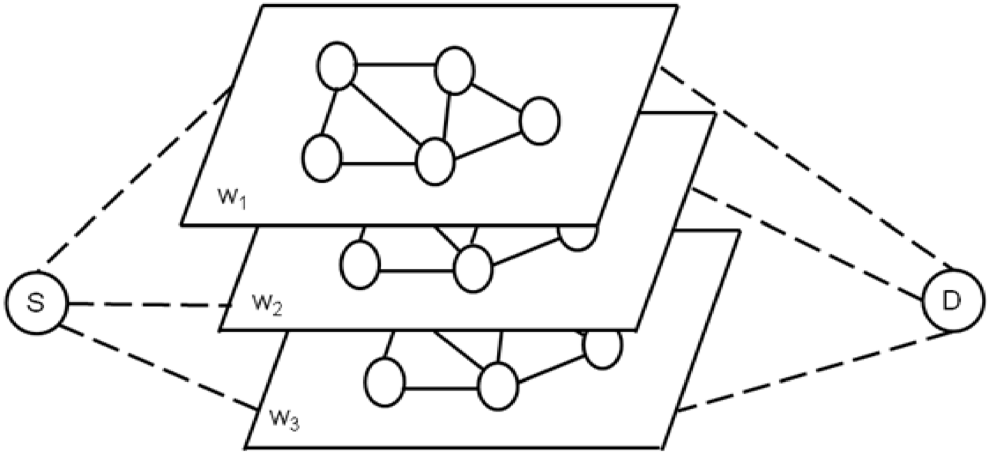

Figure 5.5 WDM Network as a Layered Graph

This is also called as wavelength mesh graphs where each edge in the graph represents a wavelength. The number of edges in such graphs can be found by the product of L and W. At any moment a connected edge indicates the presence of that wavelength while unconnected edge shows that the wavelength is busy in the data transmission. Hence for each new light-path established on a certain wavelength, the edges corresponding to it are removed from the wavelength mesh graph to indicate the unavailability of this wavelength at that moment. Similarly, once a light-path terminates; the edges corresponding to it are restored in the wavelength mesh graph to indicate their availability for next light-path request.

Given a new light-path request between a source and destination node pair, our approach is to first find those wavelengths mesh graphs where a route can be established between the requested node pair. If at least one such graph exists, the light-path can be established otherwise the light-path request is treated as blocked. On the other hand, if more than one such graph exists then a dynamic ordering technique is used for choosing one best feasible light-path out of them. The motivation behind the proposed techniques is to enable the wavelength mesh graph probing process to select the light-path in the order from most likely to the least likely path availability.

5.5.1.1 Least Count First (LCF) Algorithm

This heuristic approach is based on the simple frequency count method. Whenever a new light-path request is satisfied, the corresponding edges of the respective wavelength mesh graph are removed and the corresponding wavelength frequency count is incremented. Similarly, when a light-path terminates, the corresponding edges are added to the respective wavelength mesh graph and then the wavelength frequency count gets decremented. For a new light-path request between a source destination node pair, the wavelength mesh graphs are probed in the increasing order of wavelength frequency count. The probing process continues until a wavelength mesh graph found to connect the source and destination node. A shortest path between these two nodes is calculated in this wavelength mesh graph to establish the light-path on the corresponding wavelength. This process will be repeated for subsequent requests as well. This approach reduces the run time complexity of the light-path establishment by arranging the wavelengths in a favourable order of availability. The complete logical process of algorithm is explained by a flow chart shown in Fig. 5.6.

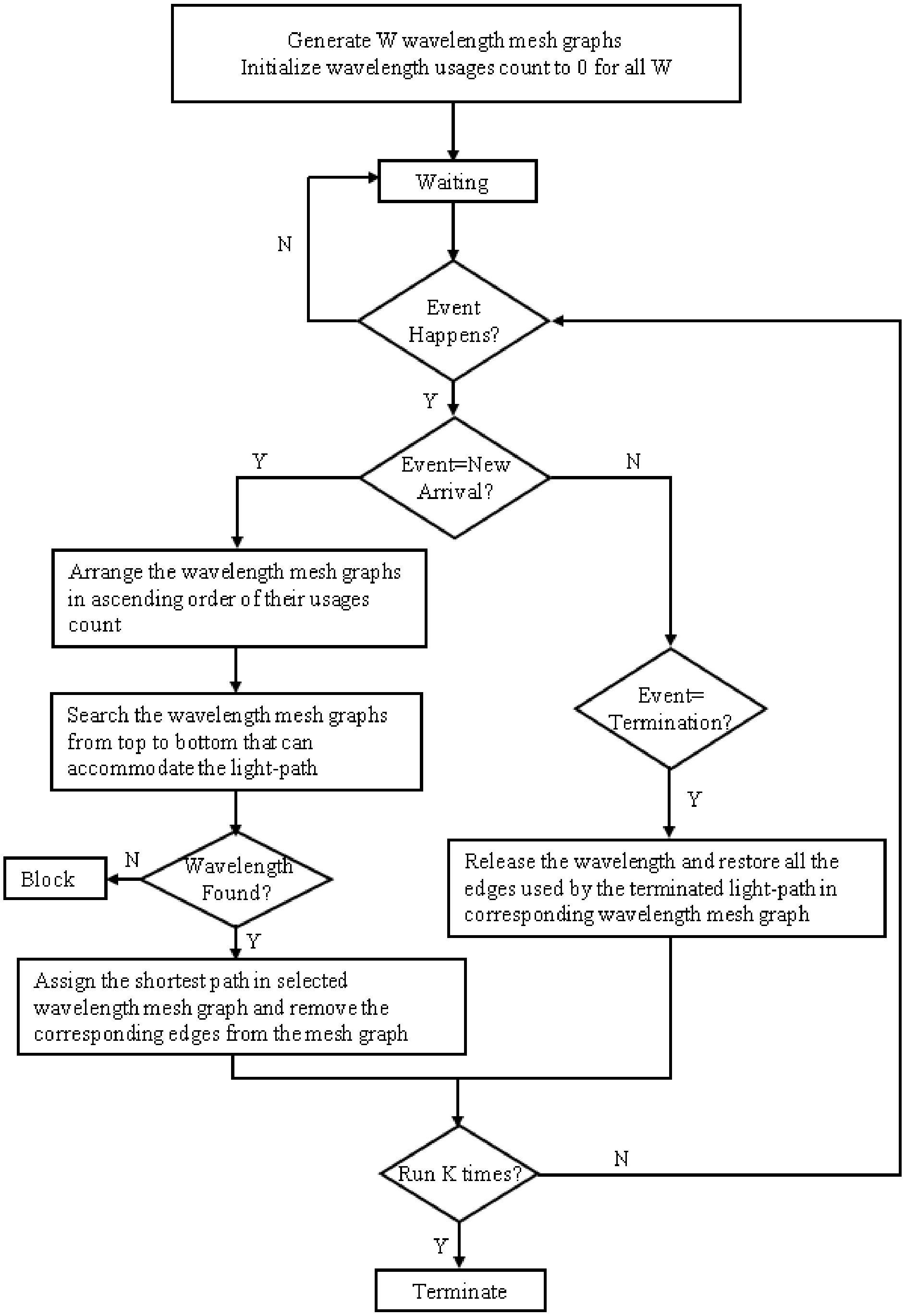

Figure 5.6 Flow Chart of LCF Algorithm

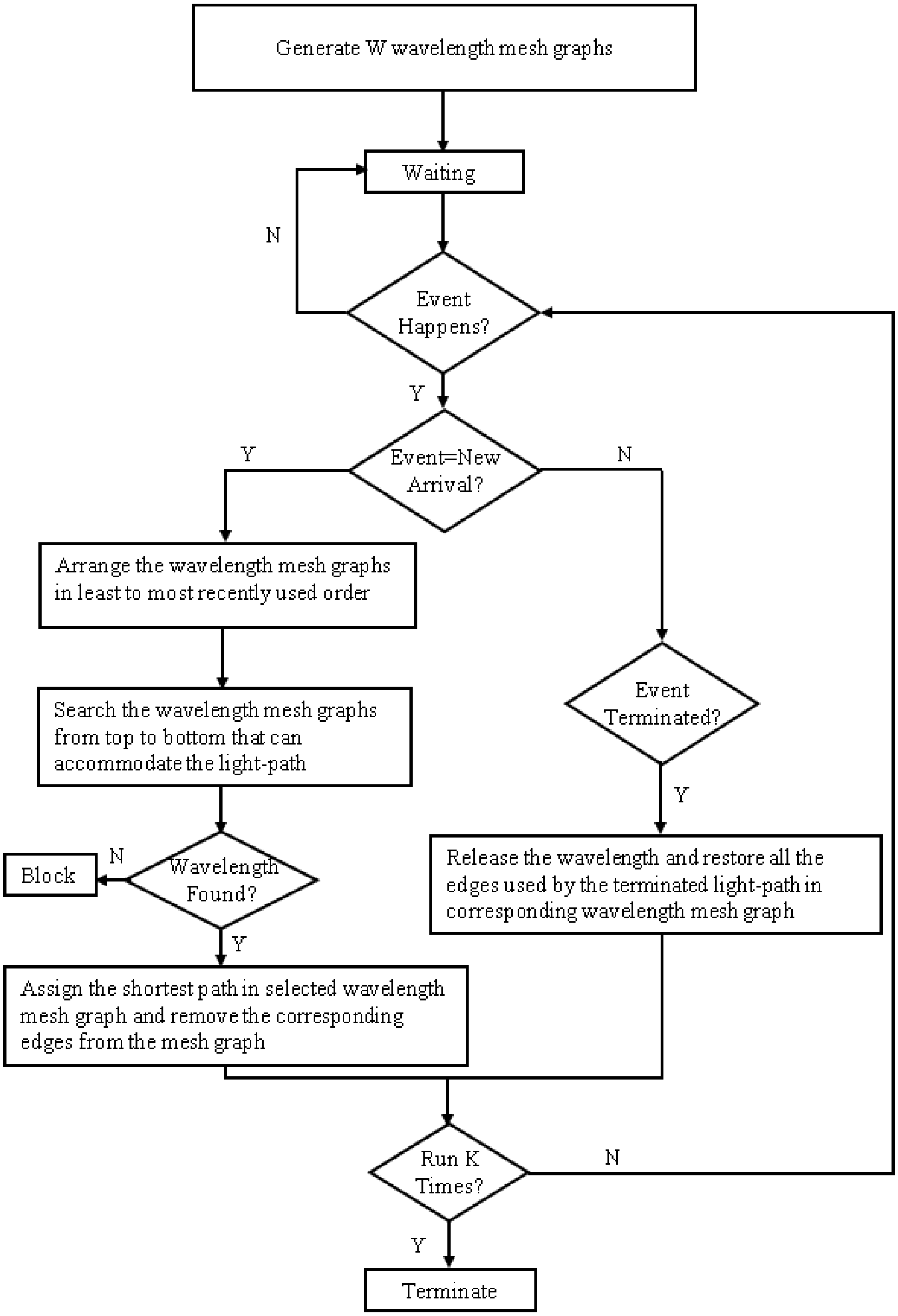

Figure 5.7 Flow Chart of LRUF Algorithm

5.5.1.2 Least Recently Used First (LRUF) Algorithm

The LRUF algorithm is a popular algorithm used for page replacement in a virtual memory system and as a block replacement algorithm in the cache memory system. In this algorithm the wavelength mesh graphs have been scanned in the order from the least recently to most recently use to serve a new light-path request. If a path is found on any wavelength mesh graph then corresponding edges are removed from the mesh graph and keep this mesh graph at the bottom of the list. Remaining mesh graphs lying below the currently selected are moved up by one position.

The wavelength mesh graph ordering is updated for every new light-path establishment. Once a light-path terminates, the corresponding edges are restored to the wavelength mesh graph without making any change in wavelength mesh graph probe order list. The complete logical process of algorithm is explained using a flow chart as shown in Fig. 5.7

5.5.2 Simulation and Performance Analysis

The performance of the LCF, LRUF and FO algorithms has been simulated on NSFNET topology shown in Fig. 5.8. The simulation has been carried out by assuming 16 and 32 wavelengths on each link of the network. In the simulation model each of the nodes in the network is capable to generate light-path request to a random destination node. The average inter-arrival time between successive requests has been varied in the range from 10 ms to 50 ms with a holding time varies between 1 to 10 seconds. There are 100 sample runs performed in simulation to compute the number of processed requests for each of the inter-arrival time values. The requests for which light-path is not available is treated as blocked requests and removed from the network. There are three metrics considered for the comparative performance analysis i.e. total number of requests handled by the network in a given time, the number of requests satisfied and average number of scanned wavelength mesh graphs to satisfy the requests. The Fig. 5.9 and 5.10 show the total number of requests handled by the network for FO, LCF and LRUF algorithms having maximum 16 wavelengths on each link of the network. The graphs show the variation in the number of requests handled with respect to the average inter-arrival time of requests. It is observed from the charts that LCF and LRUF algorithms are performing superior over FO algorithm.

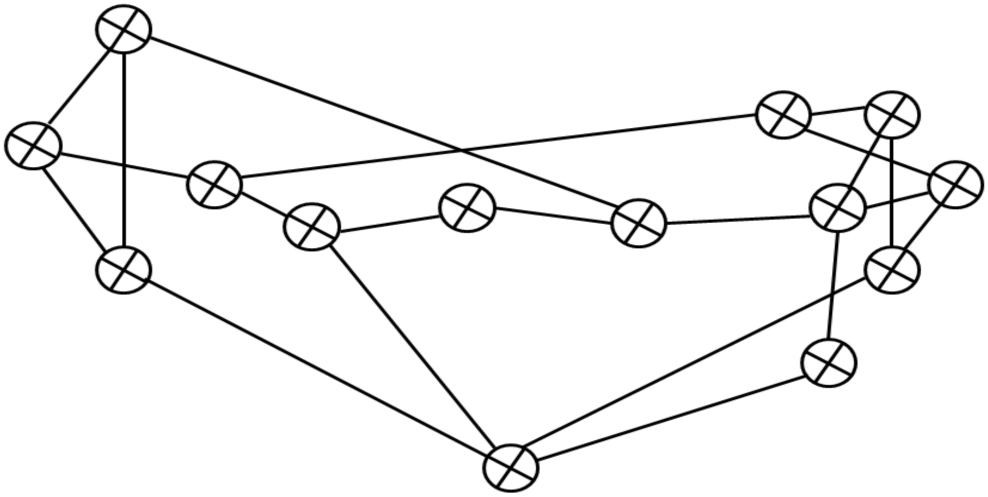

Figure 5.8 NSFNET Topology

The total number of connection requests handled by LCF and LRUF are significantly higher than that served by the FO algorithm in the present case. In particular, the difference in requests handled by LCF and LRUF with respect to FO is more promising at higher traffic rates (i.e. lower inter-arrival time) compared to low traffic rates and is further enhanced for larger number of wavelengths on the link. The number of requests handled at higher traffic rates by LCF is around 48% more than FO for 32 wavelengths per link however at lower traffic rates it becomes around 32% as shown in Fig. 5.10. Similarly LRUF also outperforms FO in terms of request handing capability by around 45% and 27% for higher traffic and lower traffic rates respectively. Further, it can be observed from the graph shown in Fig. 5.9 and Fig. 5.10 that, the traffic handling capability of the proposed algorithms becomes almost three times with respect to the FO algorithm when the number of wavelengths per link increases from 16 to 32. This indicates that the proposed algorithms are showing better resource utilization compared to existing one. The simulation results reveal that the LCF overshoot LRUF in terms of traffic handling capability in the range of 1% to 10% in both the cases. Further, there is no significant performance variation observed between them with respect to number of wavelengths per link. This implies the consistency between them.

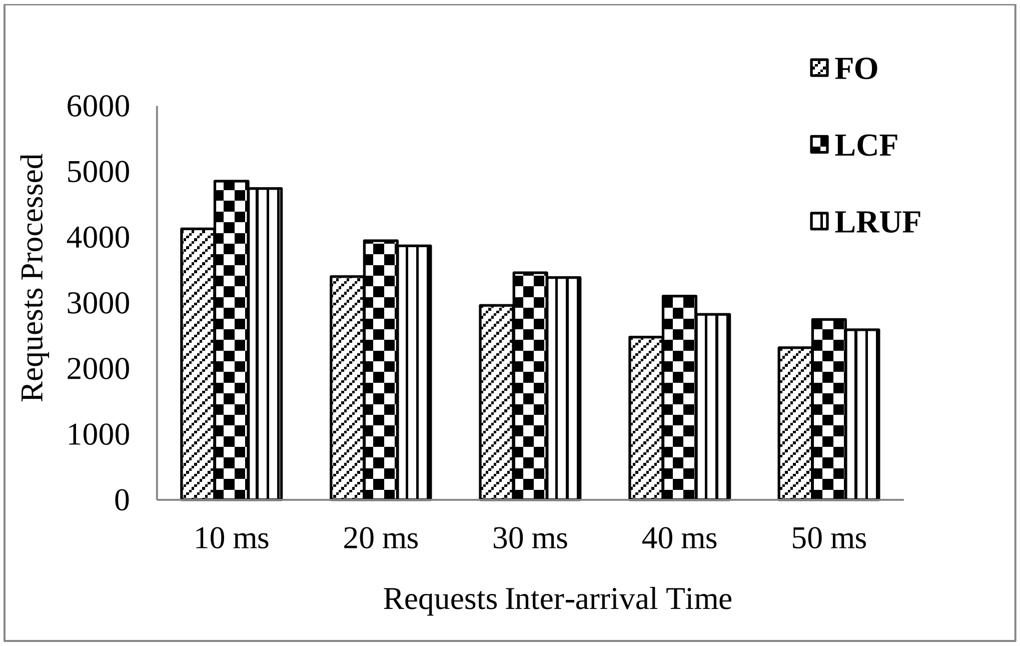

Figure 5.9 Total Requests Handled by the Network for W=16

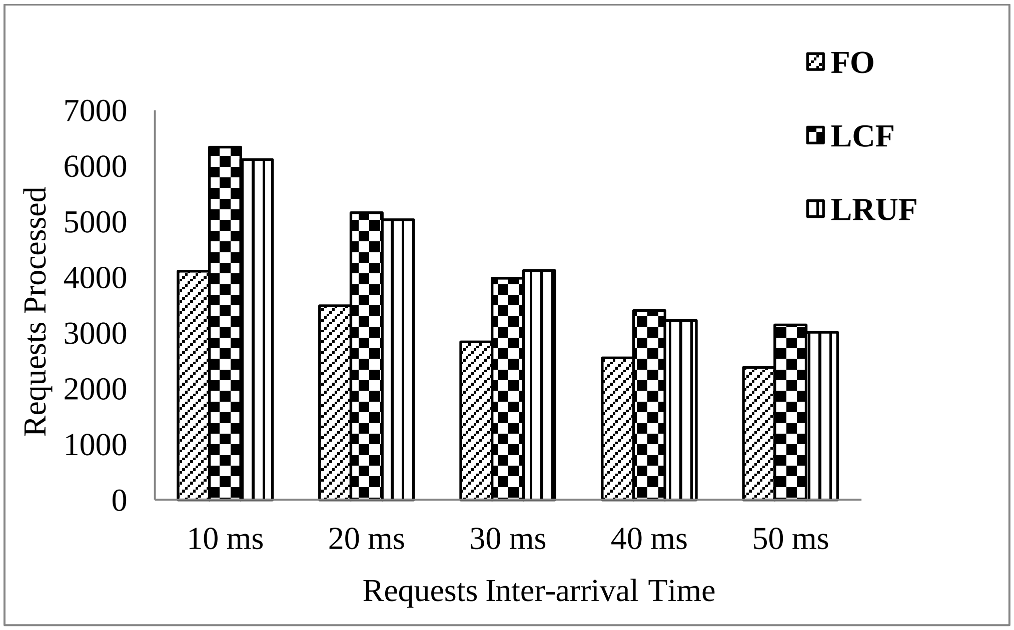

Figure 5.10 Total Requests Handled by the Network for W=32

The performance of algorithms with respect to number of connection requests satisfied is presented in Figs. 5.11 and 5.12 for 16 and 32 wavelengths per link respectively. The graphs indicate the superiority of proposed algorithms over the existing one in terms of better call connection probability. The percentage improvement observed in the traffic handling capability for LCF and LRUF over FO is not reflected in the same amount of ratio as connection probability in the case of 16 wavelengths per link. It reduces from around 15% to 8%, at higher traffic rates. The pattern is more or less same at the higher traffic rate as well with slight improvement of 2% to 3%, however for the 32 wavelengths per link the percentage gain for traffic handling capability is exactly reflected in the number of requests satisfied. This implies that, in the case of a limited number of resources, the influence of an RWA algorithm on connection request probability becomes less significant as compared to better resource availability. Here one can analyse from the simulation results that the amount of the gain received by LCF and LRUF in traffic handling capability for 32 wavelengths per link is reflected in the same ratio for the number of requests satisfied at all traffic rates simulated by us.

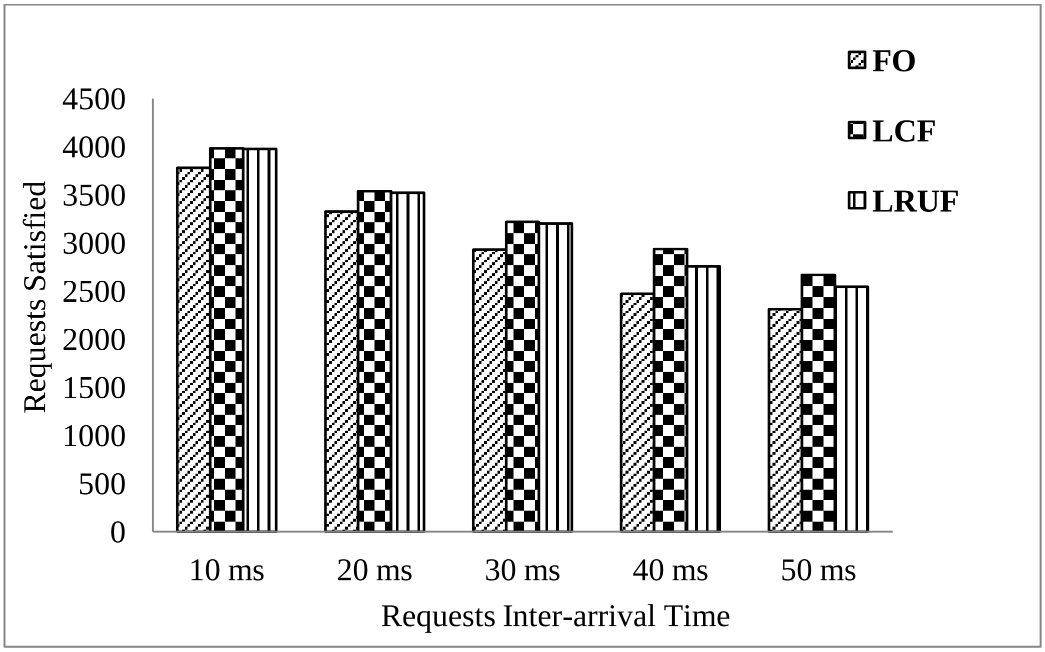

Figure 5.11 Total Requests Satisfied by the Network for W=16

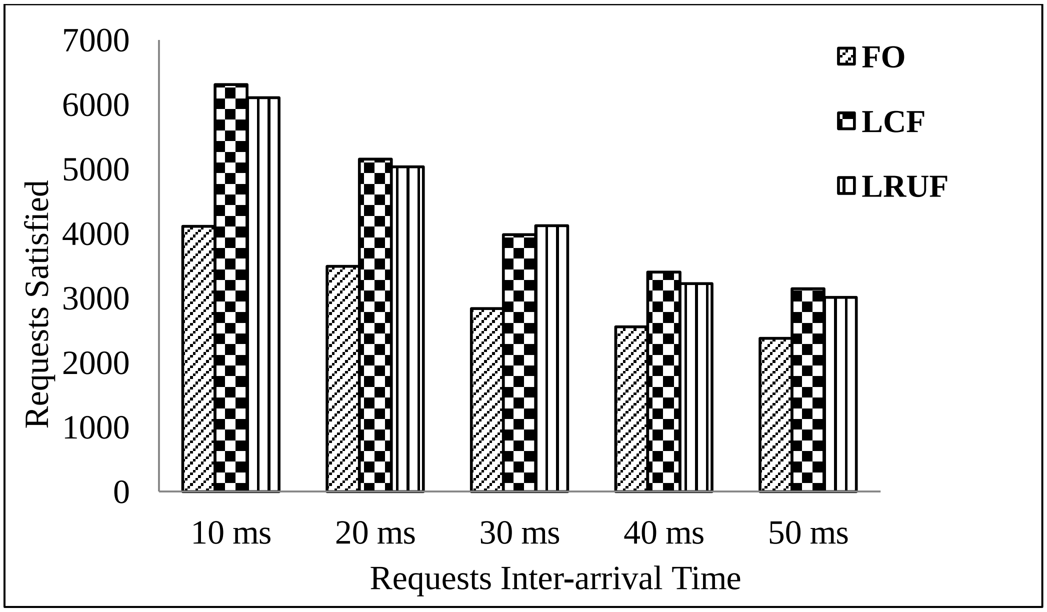

Figure 5.12 Total Requests Satisfied by the Network for W=32

The average number of wavelengths scanned per request is shown in Figs. 5.13 and 5.14 for 16 and 32 wavelengths per link respectively. It is increasing with traffic rate for all three algorithms. The LCF and LRUF outperform the FO algorithm at all traffic rates for both 16 and 32 wavelengths per link. The average number of wavelength scans for FO is almost consistent with the number of wavelengths per link while for the LCF and LRUF it varies significantly. Number of wavelength scans is decreasing for these two proposed algorithms with the number of wavelengths per link. The difference between FO and proposed algorithms is more significant at the lower traffic rates compared to the higher ones. For example, in Fig. 5.13 the average number of wavelength scans for LCF is 26% lesser than the FO at 10 ms inter arrival time whereas at 50 ms inter arrival time it is 54% lesser than from it. Similar kind of observations is inferred for LRUF and FO. Further, LCF outperforms LRUF with a margin of 2% to 10% for 16 wavelengths per link while for 32 wavelengths per link this becomes in the range of 4% to 18%. The improvement in average number of wavelength scans per request reduces the time required to setup a light-path; this enables more incoming request processing in a given amount of time which gives scope for the more light-paths to be established in the network.

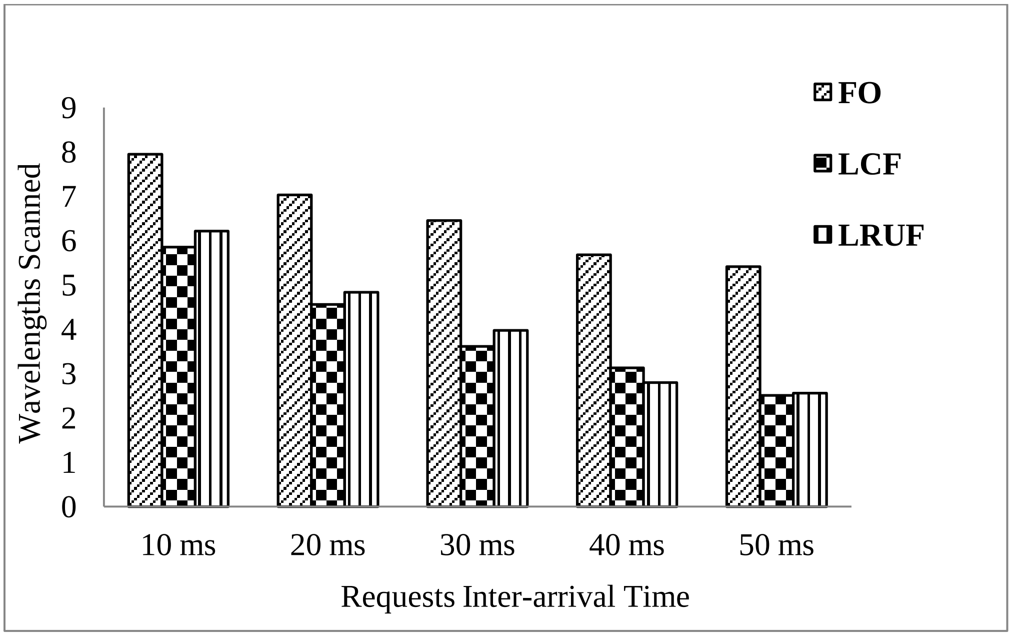

Figure 5.13 Average Number of Wavelengths Scanned for W=16

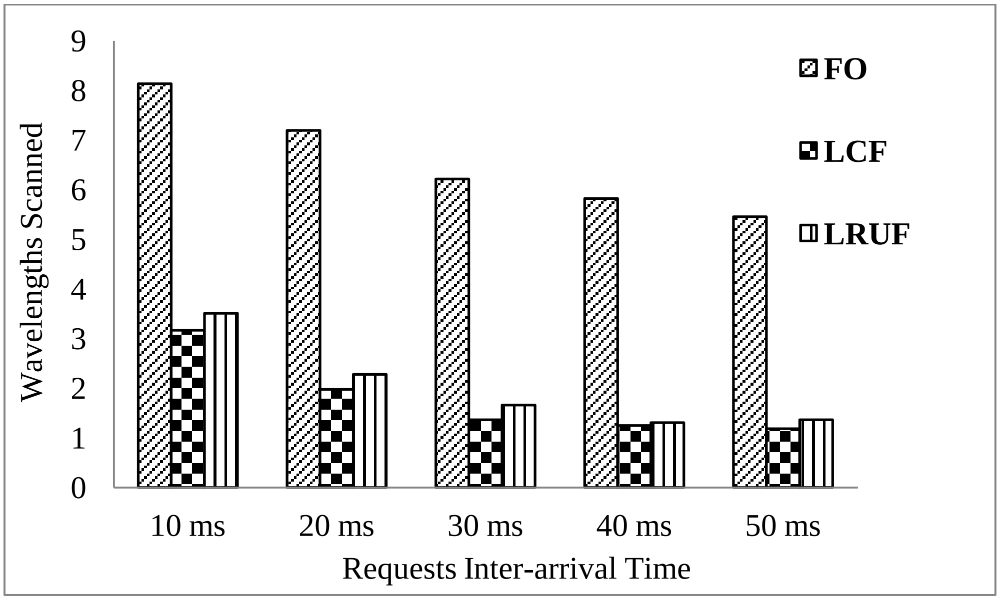

Figure 5.14 Average Number of Wavelengths Scanned for W=32

The RWA algorithms explained here are based on the wavelength mesh graph representation of an optical WDM network. The LCF algorithm searches the wavelength mesh graphs in the order of least to most used order while the LRUF searches in the order of least to most recently used.

The proposed RWA algorithms are compared with FO which searches the wavelengths in some predefined fixed order. The performance of these three algorithms is analysed with simulation using three metrics i.e. total number of requests entertained by the network, requests satisfied and average wavelength mesh graph scans per request. Results reveal that the LCF and LRUF outperform the FO significantly, while LCF and LRUF performance is almost comparable with LCF as a slight upper hand. One important observation highlighted through this work is that the better RWA algorithm's performance can be visualized comprehensively only with sufficient number of resources.

5.6 Multipath Data Transmission Approach[7]

A light-path is required to transfer the data from source to destination node in wavelength routed WDM networks. The proposed multipath routing algorithm explores the available path diversity in the network and finds multiple edge disjoint paths under a given constraint for each connection request arrives at the source. The multiple edge disjoint paths give better connection availability due to the fact that the failure probability for each of the paths is independent from each other. Further, it does the proper traffic distribution across the network. Once the paths are discovered, control messages are sent from the source node to the destination node to initiate the wavelength reservation process. A backward reservation protocol is used to reserve the appropriate wavelengths on the discovered paths. The sender node divides the data to be sent in several segments according to the number of paths discovered and assigns a sequence number to each of them for the ease of reassembly at the receiver node. Evidently, for three EDPs the sender divides data into three segments with sequence numbers 0, 1, and 2 to send through three

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[7] This work has been published in: Virendra Singh Shekhawat, Sirish Kumar, V K Chaubey, “A Novel Multi-path Data Transmission Algorithm for Wavelength Routed Optical WDM Networks", ICETECT 2011, Kanyakumari, India, IEEE, pp. 994-997, March 2011

reserved paths as per control information. An adaptive weight function associated with each link of the network aids to find least congested EDPs which improve the connection probability as compared to the simple hop count or distance based path selection method.

5.6.1 Illustrative Example for Multipath Data Transmission

Let us consider, node A receives a connection request for data transfer to the destination node K in the network topology shown in Fig. 5.15. The three edge disjoint paths available between A and K are A→E→L→K, A→F→I→J→K and A→C→D→G→K. Thus node A sends three control messages towards node K to collect the wavelength availability status on each of the paths. Once node K receives the control messages; it processes the messages and does the destination initiated wavelength reservation. If the wavelength reservation process becomes successful on the three paths then node A divides the received data into three segments and sends each of them through three independent paths by assigning sequence numbers 0, 1, 2 respectively.

The source node A doesn't wait for all three light-paths to be established, hence as soon as the first light-path is established between node A and K, the first segment with sequence number 0 is sent by node A. During the transmission of the first segment; if the second light-path is established, the second segment is sent through the second path and when the third light-path is established, the last segment is sent.

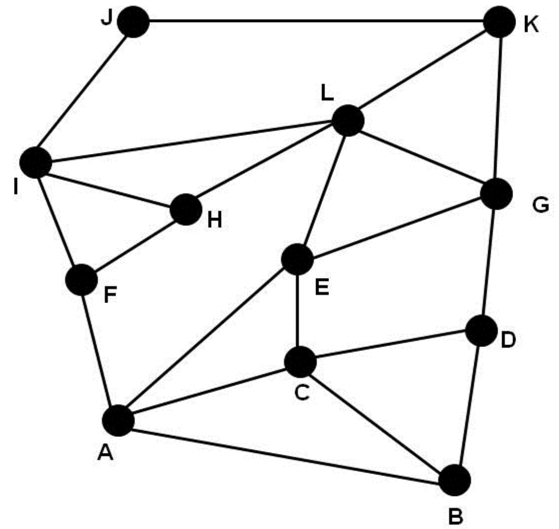

Figure 5.15 Mesh Network Topology

If out of the three paths only two of them could establish then the three fragments will be sent through the two paths and if only single path is established then all the three fragments are sent over that path. The multi-path data transfer algorithm is shown through a flow diagram in Fig. 5.16.

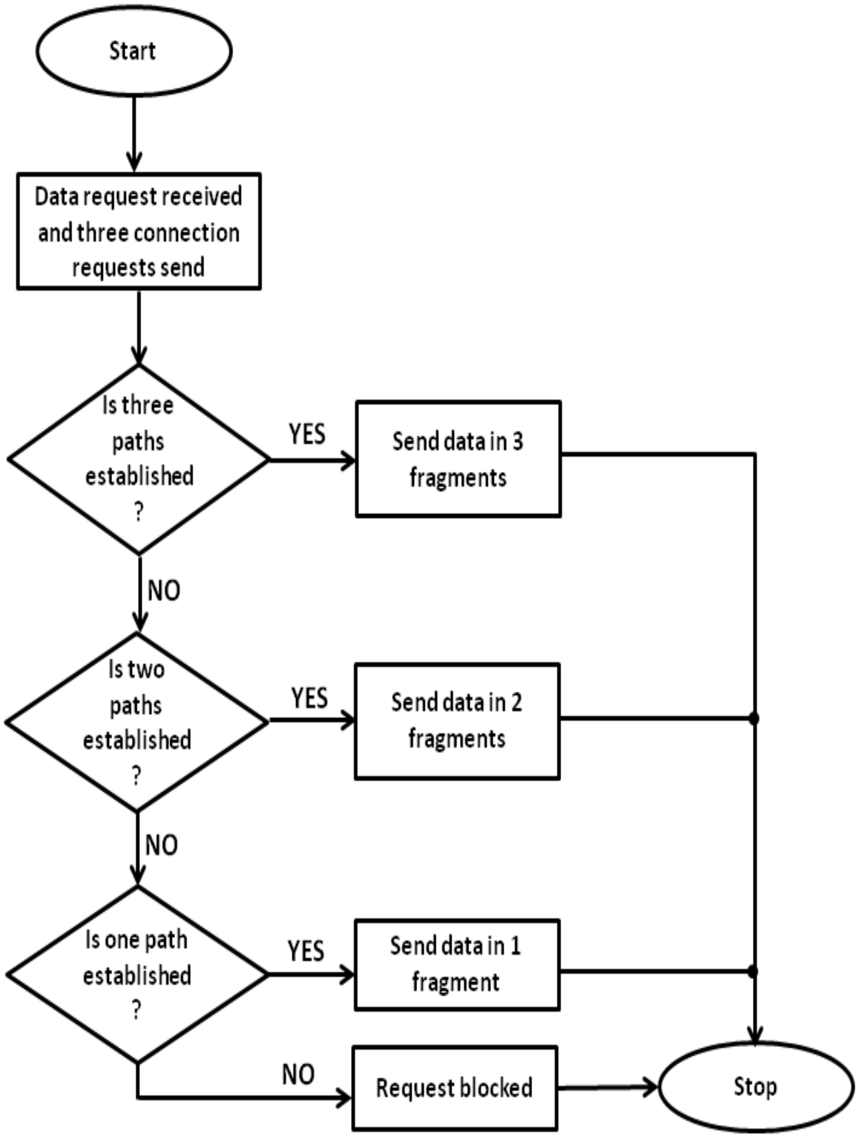

Figure 5.16 Data Flow Diagram for Three Edge-Disjoint Paths

5.6.2 Adaptive Link Weight Function

In general the routing algorithm performance is governed by the link weight metrics and the weight factor associated to each of them. Adaptive or dynamic link weight based algorithms always give better call connection probability compared to static weight based algorithms. Various adaptive link weight techniques proposed in recent past allocate weight metrics based on free wavelengths available on the links and give an estimation of free available wavelengths in the selected path [Dharma 2004] [Bhinde 2001] [Li 2002] [Miliotis 2003]. This estimation becomes incorrect when wavelength availability status changes frequently as there is always a significant amount of latency between information gathering and wavelength allocation. The estimation errors become more critical for the bottleneck links. The metric, nodal degree (i.e. count of neighbouring nodes) can be used to identify the bottleneck links in the network. The link with a higher nodal degree becomes bottleneck for the routes passing through it and therefore a lesser weight would be assigned to such a link. Consider the network shown in Fig. 5.17 for data transmission between node 1 and 11. The one of the shortest paths seems to be 1→5→8→11 with three hops. However, the link between the nodes 5 and 8 becomes bottleneck for most of the paths originating from nodes 2, 3, 4, 9, 10, and 12 which requires manipulation in the weight factor to avoid the bottleneck link.

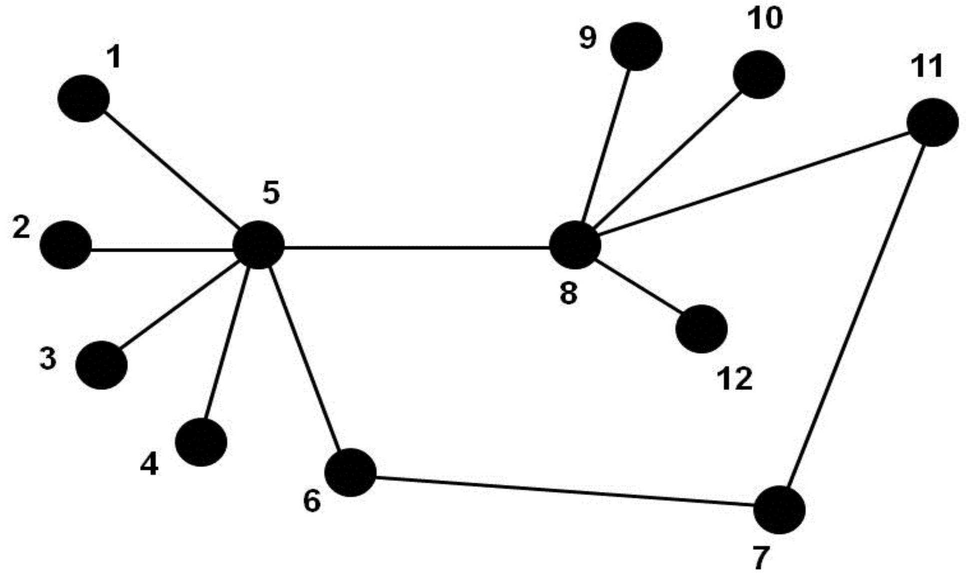

Figure 5.17 Network Topology

The path 1→5→6→7→11 with four hops is better as compared to the former as it is not passing through the bottleneck link between node 5 and node 8. The choice of the sum of the degree of the nodes adjacent to the link is trivial to decide the weight of the link to the network performance. The link weight assignment based on the number of wavelength channels is very common for the WDM networks which directly reflect the congestion level of the link. Here, the link weight is defined as a combination of these two metric with an appropriate weight-age to each of them. Thus the function which is used to determine the link weight (W) dynamically on the basis of degree of nodes (D), and congestion level (B) is as follows:

$$W = t \times D + (1 - t) \times B \qquad [0 \leq t \leq 1] \qquad (5.1)$$

The parameter ‘t’, decides the contribution of metric D and B for the link weight assignment. Obviously, when the link weight is governed only by the degree of the node, the value of ‘t’ becomes unity and it becomes zero for the case when only the congestion level is considered for the link weight. The value of B defined in [Chunxian 2007] depends upon the congestion level (B) which indirectly tells about the number of free channels on the link as shown in the Table 5.3. Congestion level depends on a parameter ‘R’, which is defined as the ratio of the number of free wavelengths on the link to the total number of wavelengths on the link.

Congestion level (B)	**Wavelength Ratio R (free/total)**
7	$R < 0.2$
5	$0.2 \leq R < 0.4$
3	$0.4 \leq R < 0.6$
1	$0.6 \leq R < 0.8$
0.2	$R \geq 0.8$

Table 5.3 Congestion Level Measurement

5.6.3 Simulation and Performance Analysis

Network performance is simulated based on transition diagram depicted in Fig. 5.16 network topology of 1000 nodes. The average degree of the node has been assumed as 10 for the present simulation. Each of the links in the network has been assigned a weight based on an adaptive method to compute the paths for routing. The network is simulated for single path and multipath data transmission to estimate the blocking probability. The network is analysed using 4 wavelengths per link with different weight factors by varying the parameter 't'. The results are presented here for t=0.2 to show the request responses for multiple path availability due to better link utilization. The graph presented in Fig. 5.18 and 5.19 present the selectivity response for incoming requests and shows the domination of multipath transmission over single path transmission for lower traffic rates. It is obvious because of the fact that, at low traffic rates network is the least congested and hence provides better resource availability for multiple paths. However, this availability decreases with the increase in traffic rate. It is also inferred from the curves that the responses to the three path selection tend to decrease beyond a rate of 600 requests per second.

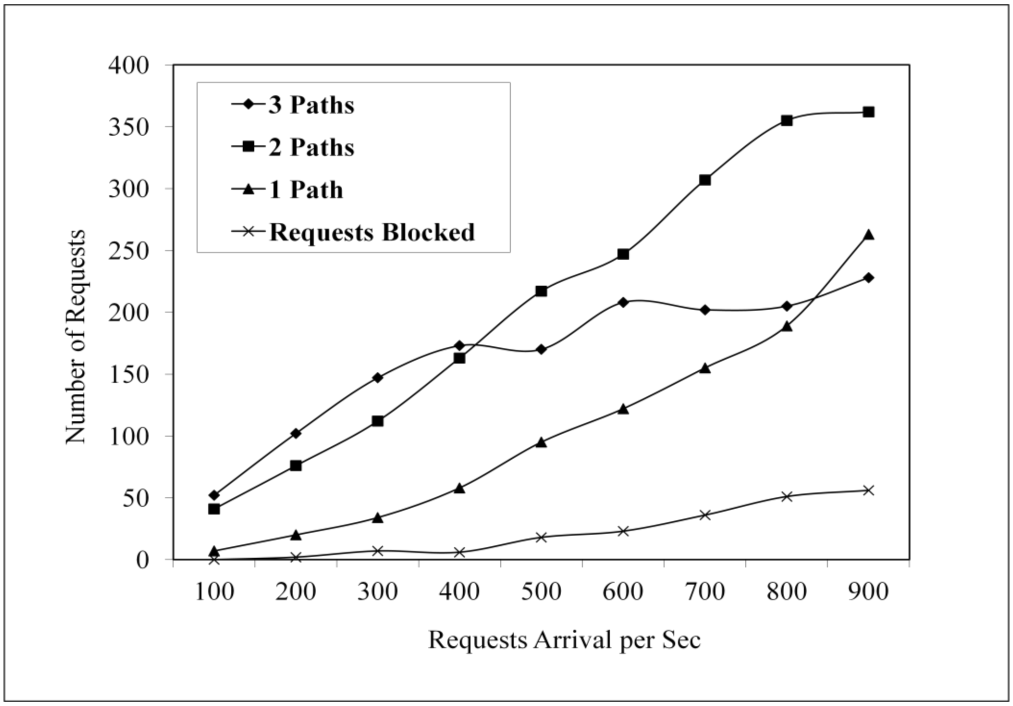

Figure 5.18 Multipath Data Transmission with Maximum Three Paths

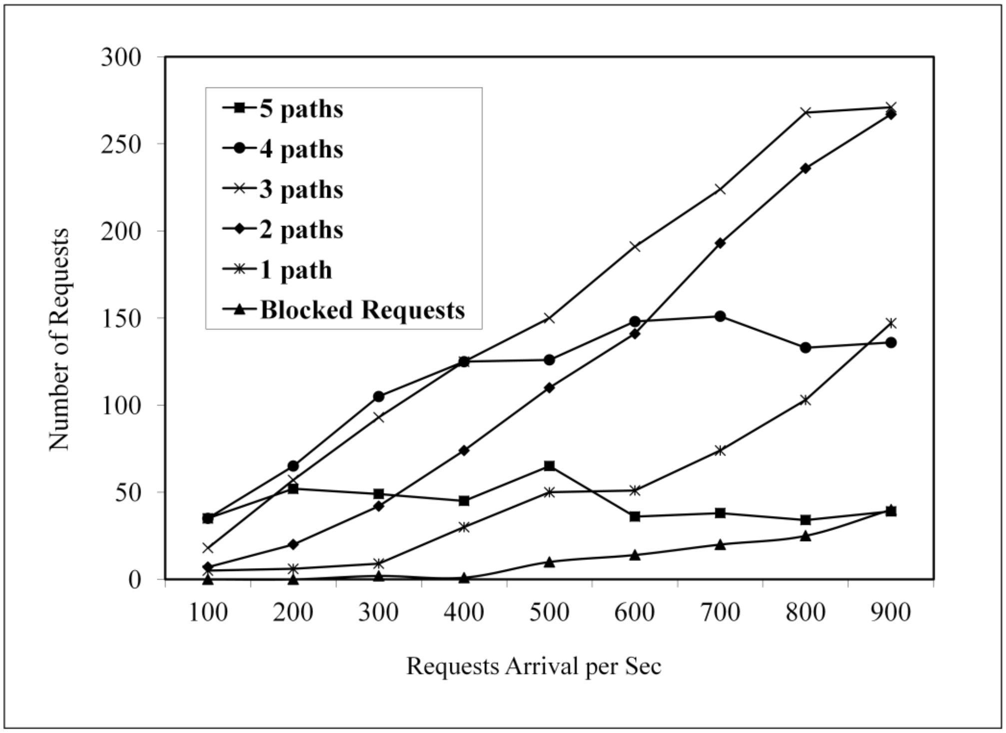

Figure 5.19 Multipath Data Transmission with Maximum Five Paths

This decreases further below that requests satisfied with the single path beyond the request rate of 800 per second. The Fig. 5.19 shows the comparison of blocking probability for multiple path selection up-to maximum five paths. It is observed that the single path selection finds high blocking probability (i.e. attributed with lesser number of requests satisfied using a single path) as compared to multipath transmission case. It is further inferred that, the data transmission with the multiple paths reduces the blocking probability, by maintaining the least variation in the blocking rate with the increase in request arrival rate. The standard deviation for the link utilization shown in the Fig. 5.20 with t=0.0 and t=0.2 measures the load balancing quantitatively in the network.

It is observed from the graph that the standard deviation is lower in the case where the static weight of the link is taken into consideration for route selection. The best load balancing is observed at t=0.2 after running simulations with different values of t. The average path length observed for t=0.2 and t=0.0 are 4.127 and 4.058 hops respectively. This indicates the deviation from the least congested path is not significant even with the consideration of static weight for the links. The effect of the number of wavelengths per link on the selection of the multiple paths is shown in Fig. 5.21.

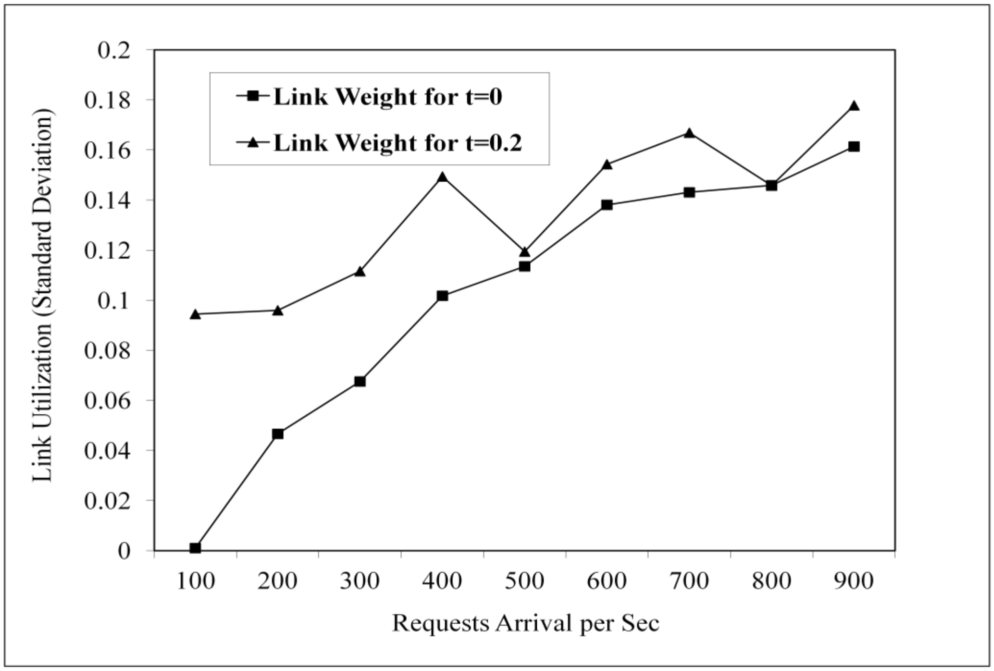

Figure 5.20 Standard Deviation of Link Utilization vs. Traffic Load

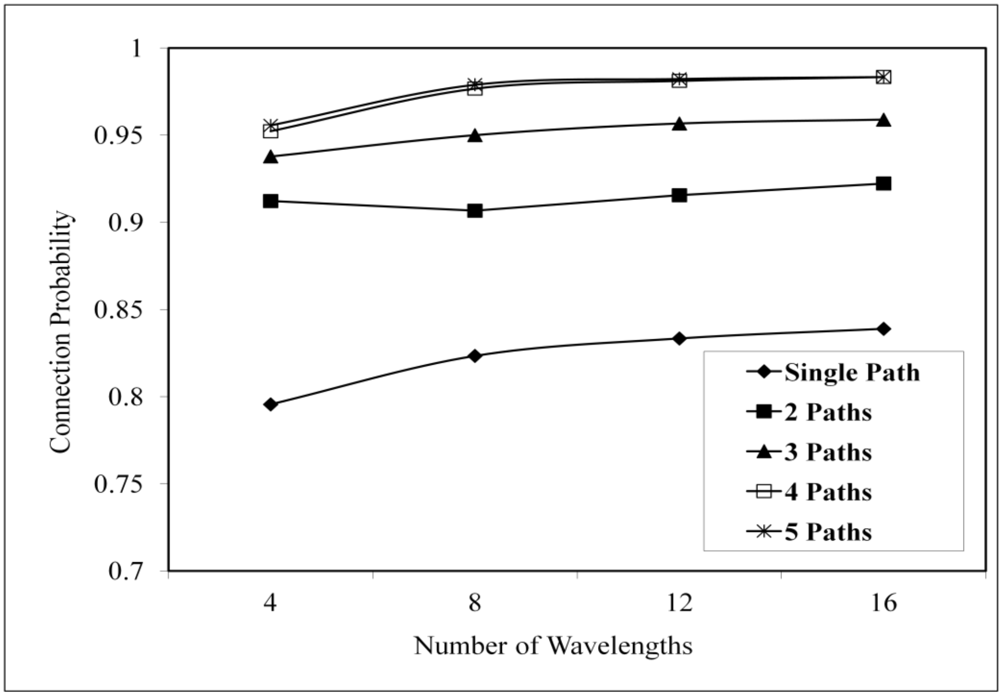

Figure 5.21 Connection Probability vs. Wavelengths per Link

The connection probability increases and gradually saturate with the increase in the number of wavelengths per link. The connection probability for multiple paths is significantly higher than the single path. It is noted that, even for two paths selection provides a better connection probability than the single path. This gives a good indication to favour a multiple path transmission over single path transmission.

Multipath selection algorithms have an edge over a single path algorithm showing a better connection probability for the former. It is inferred that the blocking probability decreased by allowing the data transfer on multiple edge disjoint paths in the case of failure of the single selected path. The simulations show that the simultaneous wavelength reservation on multiple edge-disjoint paths reduces the effect of vulnerable time which effectively improves the connection probability. The work reports the simulation results of the traffic handling capability of a WDM network using the combination of adaptive and static link weight based routing algorithm and establishes the choice for the optimum number of path selection for the desired quality of service.

5.7 Results and Conclusion

In this chapter heuristics approaches has been discussed to solve RWA problem for wavelength routed optical WDM networks. Five adaptive RWA algorithms have been proposed using link or path based heuristics. Adaptive RWA algorithm's performance is governed by the various metrics based on the traffic load, network topology, hop count and traffic flow between node pairs. There is always a challenging task to get an optimal solution within the required time complexity due to real time constraints, scalability and resource availability at routing nodes. Hence heuristic methods are preferred in this chapter to get near optimal or a better solution.

A modified link weight heuristic named as Weight based Edge Disjoint Path RWA (WEDP) is defined to select the best path from a list of pre calculated EDP candidate paths between source destination node pair. The two fold link weight (i.e. static and dynamic) assigned to each edge of the network which captures the static and dynamic properties of the network and improves the wavelength requirement for the given network. Since the wavelength continuity constraint is not guaranteed in the link weight based algorithms.

Hence the RWA algorithm can be modified such that the wavelength continuity can be insured at the time of route selection itself by assigning a weight to a link based on common wavelength availability on the entire path. Such algorithms, which combine the routing and wavelength assignment, give better results in terms of call connection probability over the traditional link weight based algorithms.

Similarly, RWA problem can be solved by visualizing the WDM network as a number of wavelength mesh graphs corresponding to each of the wavelength in the network. Further the network performance is influenced by the scan order of these mesh graphs for incoming connection requests. This influence has been studied and analysed with the help of three heuristic algorithms called LCF, LRUF and FO. In general, LCF outperforms the other two in terms of network’s traffic handling capability and the number of successful established connection requests.

Multiple path selection based on edge disjoint property also adds reliability to the network. A multipath routing algorithm for WDM networks has been proposed to show the superiority over the single path routing. The observation from simulation analysis shows the effectiveness of this approach for traffic routing in WDM networks in terms of reliability and connection probability. The present investigation is based on the predetermined multiple paths, however this leaves a scope for further investigation for path establishment using adaptive path selection algorithms.

CHAPTER 6

DISTRIBUTED WAVELENGTH RESERVATION PROTOCOLS

6.1 Introduction

One of the challenges involved in designing all optical routed WDM networks is to develop efficient routing algorithms and protocols for establishing light-paths. The routing algorithms select routes and wavelengths to utilize available network resources effectively by establishing the maximum possible number of light-paths. In order to setup a light-path, signalling protocols are required to exchange control information among nodes to reserve wavelength along the selected route for maximum bandwidth utilization [Ramaswami 1995b] [Ramaswami 1997] [Zheng 2001]. The signalling and resource reservation protocols are categorized based on whether the resources are reserved on each link in parallel or reserved on a link by link basis from source to destination node [Ramaswami 1996]. The link by link or hop by hop signalling strategy can further be differentiated by the fact that whether the resources are reserved in a forward direction from source to destination node or in backward direction from destination to source node [Ahmad 2004]. The signalling mechanism can be controlled either centrally or in a distributed manner. In centralized control each request is processed by a central controller at one node, which selects a path and assigns a wavelength to establish a light-path. Under the distributed control, the source node sends a reservation packet towards the destination node. This packet is processed by each node along the path and an appropriate wavelength is reserved based on the protocol implemented. Hence distributed approach requires more complex signalling protocols for coordination among the involved nodes. Centralized control becomes unfeasible for large size networks because control and status information exchange between the central controller and processing nodes takes a long time, hence distributed control approaches are more popular [Mei 1997] [Yuan 1999] [Feng 2003]. Moreover, the performance of distributed and centralized reservation schemes depends upon traffic patterns and reservation time. It gives an improved performance in terms of blocking probability for the latter case [Shen 2002]. To cope up with the rapid growth of optical networks, distributed control is becoming increasingly important and is being standardized within the Generalized Multi-Protocol Label Switching (GMPLS) framework. Among distributed wavelength reservation protocols or acknowledgement based protocols like Source Initiation Reservation (SIR) protocols, Destination Initiation Reservation (DIR) protocols and Intermediate-node Initiation Reservation (IIR) protocols [Yuan 1999] have been extensively used. The comprehensive review of various distributed protocols developed in the past few years is explained in the next section. Subsequent sections of this chapter present the details of the proposed work.

6.2 Related Work and Motivation

We need to make use of reservation mechanisms to establish and tear down light-paths in wavelength routed networks by configuring the switches in the nodes. There are two basic approaches to select wavelengths to establish a light-path. One approach is to setup a wavelength continuous light-path and other is to setup a wavelength non-continuous light-path [Mei 1997] [Yuan 1999]. The wavelengths are reserved using either centralized or distributed control schemes. The centralized schemes are simple and work better for static traffic while the distributed schemes are scalable and reliable, and work better for dynamic traffic in large networks [Sichani 2005] [Ramaswami 1997]. In general, the distributed mechanisms are grouped in three categories based on the wavelength reservation initiator node, which can be a source node, a destination node or any intermediate node in the path. The protocols in which wavelength reservation process is initiated by source node are called Source Initiated Reservation (SIR) protocols or Forward Reservation Protocols (FRP). Similarly, the group of protocols in which wavelength reservation process is initiated by destination node is called Backward Reservation Protocols (BRP) or Destination Initiation Reservation (DIR) protocols. The third group of protocols, in which the wavelength reservation process can be initiated by any of the intermediate node, is called an Intermediate-node Initiation Reservation (IIR) protocols.

6.2.1 Source Initiated Reservation (SIR) Protocol

In the basic SIR protocol, once the route or path is decided for a connection request by the source node then it initiates wavelength reservation by sending a RESV packet towards the destination node. At the source node, all the free available wavelengths status is changed from IDLE to RESERVE and is treated as candidate wavelengths to setup the light-path. This RESV packet is forwarded to the next link in the path along with the candidate wavelength information. When an intermediate node receives this RESV packet, it checks the status of these candidate wavelengths on the outgoing link, and only reserve the intersection set of candidate wavelengths and free wavelengths available on the outgoing link. This intersection set now becomes the new set of candidate wavelengths and the information is carried by the RESV to the next node towards the destination node. In this process, if an intermediate node receives an empty candidate set then this node sends a Negative Acknowledgement (NACK) towards the source node to notify the connection failure. Each of the nodes which receives a NACK, changes the status of reserved wavelengths belonging to it from RESERVE to IDLE on its outgoing link. After receiving the NACK, the source node drops the RESV packet and tries again after some time to establish the connection. In case, a nonempty set of candidate wavelengths is received by the destination node; one of the wavelengths is selected to establish the light-path and a positive acknowledgement (ACK) is sent towards the source node. On the way to the source node, ACK releases all the wavelengths reserved for this connection on each intermediate link of the path except the wavelength which has been selected by the destination node. The ACK received at the source node gives confirmation of connection establishment on the wavelength selected by the destination node. After that the source node starts transferring the data on the successfully reserved wavelength. Once the data is transferred, the source node sends a release (REL) packet to tear down the connection. Moreover, if a reservation request cannot progress at any intermediate node then either the request can be dropped immediately by sending a NACK towards source node or it can wait for a specified amount of time to free the desired wavelength. The waiting time can be defined in reservation request itself. This scheme reduces the connection setup time as well as the blocking of the request. The complete functionality process is shown in Fig. 6.1.

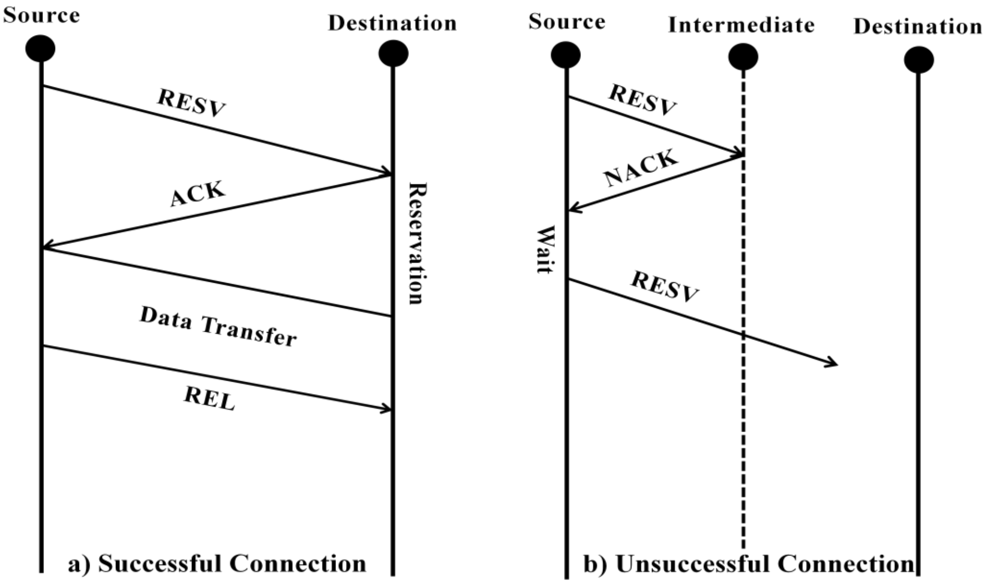

Figure 6.1 Source Initiated Reservation Process

The basic SIR protocol reserves wavelengths in parallel which increases the chances of connection establishment with the minimum setup delay. This, however, on the other hand also increases the blocking of future connections, particularly under heavy traffic load due to over-reservation of bandwidth resources.

The modified version of the SIR protocol in which source node chooses only one wavelength out of all free available wavelengths at a time to avoid wavelength over-reservation. In this process, all free available wavelengths are to be tried one by one until the connection is established. This process reduces the future connection blocking however the connection setup time in this case increases owing to multiple attempts are required to reserve the wavelength. Moreover, the order in which the connection requests are tried on different wavelengths is also critical. This scheme has been implemented in GMPLS [Berger 2003] framework with a protocol named as CR-LDP.

In spite of reserving maximum possible wavelengths along the path, few of them can be reserved on the basis of traffic pattern or load in the network. Such type of variation of SIR is explained in [Saha 2000b] and named as Selective-N approach. A priority based algorithm is proposed by [Pong 2002] to decide N wavelengths out of all possible free wavelengths. This algorithm assigns a priority to each of the wavelengths at each node for each destination node based on the frequency of usages of the wavelength for that particular destination node. The wavelength which is used maximum number of times at source node S, to setup the connection with a destination node D is assigned the highest priority and will get the first chance to be selected for next connection request between S and D. Each node maintains a wavelength priority database which becomes huge and complex as the network size increases.

In case of parallel reservation (i.e. basic SIR protocol or Selective-N) many wavelengths are dropped in the middle of the path due to unavailability. In this situation many wavelengths are reserved only in a few links of the path unnecessarily until the completion of the connection setup phase. These wavelengths can be released immediately after discontinuity is observed by tracking them and this reduces the inherent wastage of bandwidth in the forward reservation schemes. One of such attempt has been made by [Saha 2000b] to release the wavelengths which are reserved in the previous link but are not available free in the immediate link of the current node. Implementation of such protocol requires the exchange of additional control messages between consecutive nodes.

The SIR protocol can also be implemented using parallel signalling as explained in [Ramaswami 1996] [Shen 2004] in place of hop by hop or link by link signalling shown by [Saha 2000b] and [Yuan 1999]. Parallel signalling performs better only when each of the network nodes has the global network topology information (e.g. resource availability, routing table). Here the source node simultaneously sends REQ packet to each node in the path. After that each node sends the RESV packet back to the source node. Once a source node receives RESV from all of the nodes involved in the path, it starts sending the data. If a node doesn't find any free wavelength on its immediate link, a NACK packet is sent towards the source node to indicate the connection failure. In this case source node sends REL packet to each of the nodes in the path to release all the wavelengths reserved earlier. The same REL packet is sent by the source node after successful data transfer to release the resources from the nodes involved in the connection. In parallel resource reservation scheme, the connection setup time as well as connection tear down time reduces significantly as compared to the hop by hop reservation process. This also reduces the probability of resource contention as compared to the hop by hop reservation. The negative side of parallel reservation schemes is the processing of control packets which consumes more computing resources.

6.2.2 Destination Initiated Reservation (DIR) Protocol

The other popular acknowledgement based distributed reservation protocol in which destination node initiates the wavelength reservation is called DIR or BRP [Sichani 2005] [Mei 1997] [Zheng 2001]. In this reservation scheme, the source node sends a PROB control packet towards the destination. The PROB collects the wavelength usage information on each intermediate link along the path. Unlike the SIR protocol, in DIR no wavelengths are reserved during this phase. Once the PROB packet reaches to the destination node with the candidate list of wavelengths which are free along the entire path; the destination node chooses one of the wavelengths from the candidate list. After choosing a wavelength, destination node sends a control packet RESV towards source node to reserve it on all the links along the path. If the reservation is successful then the source node starts transmitting the data along with encapsulating control packet ACK (to inform the destination node about the successful reservation) over the reserved wavelength otherwise destination node tries to reserve another wavelength (if any) from the available set [Saha 2000a]. The destination node tries till either successful reservation happens or free wavelength set is exhausted. If an intermediate node finds that the desired wavelength for reservation is not available free on the immediate link then it sends a control packet NACK towards the source node to inform about reservation failure. Simultaneously, it also sends a control packet FAIL to destination node to inform about the reservation failure. In case of either free wavelength set is exhausted or initially an empty set of wavelength is received by the destination node (i.e. no wavelength continuous path), the connection request is assumed to be blocked.

Moreover, after successful data transmission a control packet REL is sent by the source node towards the destination node to release the reserved wavelength on the path. The Fig. 6.2 shows the functional process of the basic DIR protocol.

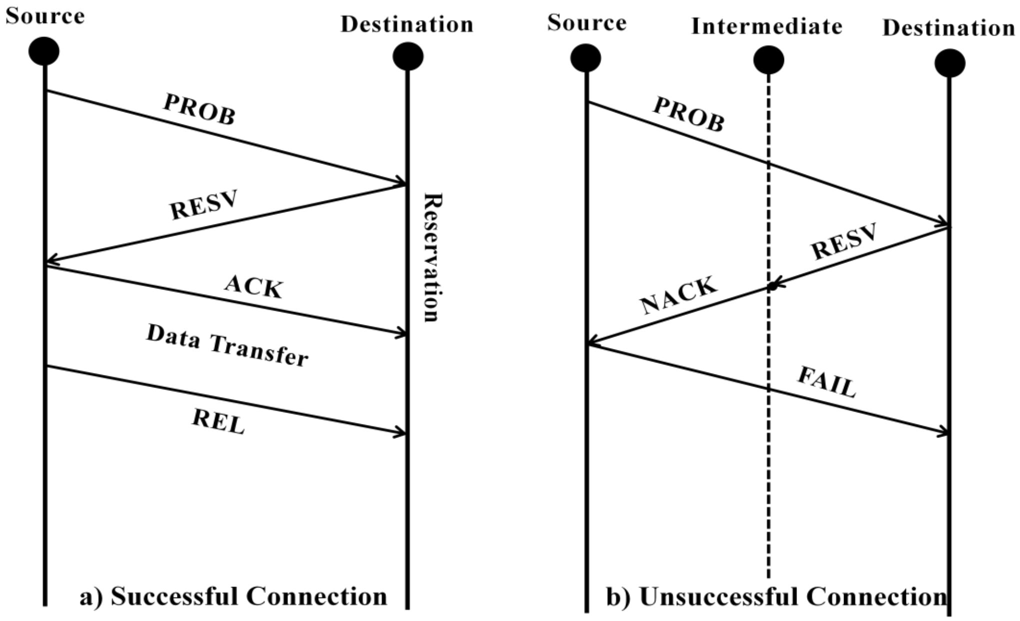

Figure 6.2 Destination Initiation Reservation Process

In the above mentioned backward reservation scheme, the destination node doesn’t lock all the free wavelengths identified by the PROB packet and initiate a reservation process by choosing one wavelength at a time until the reservation process is successful. This allows other connection requests to reserve the rest of the available wavelengths. That means more number of attempts are to be made for a successful wavelength reservation and this leads to larger latency. This conservation approach degrades the system performance drastically.

To avoid the latency and performance degradation, reservation can be started with all free available wavelengths identified during PROB instead of a single wavelength. This aggressive reservation approach reduces the chances of other requests to reserve any of these wavelengths. In case of more wavelengths are reserved by the current connection request, one wavelength is used to transfer the data while others are released immediately. Obviously, this improves the performance and reduces the connection setup delay but it is at the cost of over-reservation of wavelengths. This over-reservation can be minimized if a wavelength is released immediately at the time of wavelength discontinuity is observed at any intermediate node [Yuan 1999]. In other words, partially reserved paths should be released immediately to reduce the effect of multiple initiated reservations. The drawback of this implementation is that, it requires more control bandwidth to transfer the additional control signals for releasing wavelengths on partially reserved paths.

The above two approaches (i.e. conservative and aggressive reservation) are on two extreme points on the performance scale, since conservative scheme completely eliminates the over-reservation while the aggressive scheme has the maximum possible over-reservation. An intermediate approach has been discovered by the [Sichani 2003] which decides the amount of over-reservation on the basis of the current network status. The proposed Progressive Reservation Protocol (PRP) by Sichani et al., defines the interval time between two successive RES packets to be sent by the destination node on the basis of current network load. The time interval becomes larger for lightly loaded networks. The network load is inversely proportional to the size of the wavelength set received from the PROB packet. In other words, more free available wavelengths indicate lesser load on the network; hence the time interval between two successive RES packets should be large. The blocking probability observed using PRP is more than the conservative DIR but it less than the aggressive DIR. The time complexity and the control overhead are the two probable challenges in the PRP.

It has been observed that there will be a significant performance improvement in blocking rate in spite of resource over-reservation, if multiple wavelengths are tried in backward reservation protocols [e.g. Aggressive DIR and PRP]. The multiple reservation protocols discussed so far do not tell the order in which the wavelengths should be tried. The intelligent DIR protocol proposed by [Saha 2010] gives a history based solution to decide the order of the wavelength for retry. According to it, each node keeps the recent usage of wavelength history in the memory. The protocol has selected the least recently released wavelength, because the chances of the least recently released wavelength to be occupied again by any other connection request are less. The intelligent DIR protocol is a combination of SIR and DIR. In this protocol, the source node first tries to reserve the least recently released wavelength and if this selective SIR fails then it tries to reserve the wavelength through the standard DIR protocol. The history mechanism used to order the wavelengths, reduces the connection setup time as compared to the other variation of DIR protocol. Moreover, it also reduces the over-reservation as compared to the other variation of SIR and DIR protocols. The performance improvement of the intelligent DIR protocol is achieved at the cost of additional information maintained about the wavelength usage at each of the nodes and the control overhead to implement the proposed feature.

Unlike the forward reservation approaches, the backward reservation schemes are suffering from outdated state information problem because there is a significant time gap exists between the information gathered about the unoccupied wavelengths and the wavelength locking. This results in terms of the increase in blocking probability. To avoid the request blocking due to outdated state information, some parallel reservation schemes are proposed by [Liu 2007]. The proposed schemes do the wavelength searching and wavelength reservation in parallel. Moreover, to avoid the adverse effect of parallel reservation (i.e. blocking due to over-reservation and high control overhead), the parallelism is restricted in terms of the number of requests sent by the source to setup a connection and number of wavelengths to be reserved. Among the multiple options received by the source node, one of them is to be selected to transfer the data and remaining reservations should be immediately released to reduce the blocking. The heuristics proposed for MPPR (Multi Path Parallel Reservation) method are as named as Single-path Single Reservation, Single-path Double Reservation, Alternate path Single Reservation, Alternate path Double Reservation and Alternate path Four Reservation.

In general, the performance of the distributed reservation protocol depends upon the parameters like the amount of over-reservation of resources, connection setup delay, bandwidth utilization, vulnerable time, control overhead, complexity, wavelength selection algorithms, routing algorithms, traffic pattern and the node architecture. The influence of the node architecture design for the implementation of different wavelength reservation protocols has been investigated by [Chaubey 2009]. An analytical model has been devised to analyse the node performance under different traffic conditions for different network topologies. The performance of the network node under two basic reservation protocols (i.e. SIR, DIR) has been evaluated to show their qualitative proximity with the existing results. These protocols are evaluated based on their bandwidth utilization factor.

It has been observed through literature review that IIR based wavelength reservation protocols become more effective in terms of reducing call blocking due to vulnerable time as compared to SIR and DIR protocols. The IIR based protocols perform better than other protocols (i.e. SIR and DIR) on the cost of control overhead. The next section describes the IIR based protocols in detail along with some protocols proposed by us.

6.3 Intermediate-node Initiated Reservation (IIR) Protocol

In general, backward reservation based protocols outperform over forward reservation based protocols in terms of bandwidth utilization and blocking performance. Moreover, better bandwidth utilization in backward reservation schemes is not only in terms of the number of wavelengths reserved for each connection but also the amount of extra time it reserved before actual data transfer. On the other side the major issue with BRPs is the outdated state information which leads to the wavelength contention problem. The problem occurs when a connection request attempts to reserve the probed wavelength and it is no longer available or in the case of two or more requests are trying to reserve the same wavelength. The effect of outdated state information becomes more prominent for the longer paths as compared to the shorter paths due to the time gap observed (i.e. vulnerable time) between the wavelength probing process and its reservation.

There are various solutions proposed by the research community in the last decade (discussed in section 6.2) to overcome from the outdated information problem. One of the major attempts that have been made in this direction is to allow wavelength reservation initiation by an intermediate node in the path. A class of protocols proposed in [Lu 2003] is called as IIR, which partitions the complete path between source to destination node into multiple segments and segment boundary node (i.e. last node of the segment) initiates the wavelength reservation process independently in any of such segments. When a connection request arrives at source node it sends a control packet PROB towards the destination to collect the segment wise common free wavelengths information. Once the PROB reaches to the last node of a segment it selects one wavelength from the list received by PROB and sends a control packet RESV towards the first node of the segment to reserve the wavelength. The PROB is forwarded to the next node in the path. When the PROB reaches at the destination node it completes the wavelength reservation process in the last segment by choosing one wavelength and sends a positive acknowledgement ACK to the source node to ensure a successful connection. Now the source node starts sending the data and once the data transfer is completed, a control packet REL is sent towards the destination to release the reserved wavelength. If the reservation process fails in any segment due to unavailability of common free wavelength then the last node of each of the segments sends a negative acknowledgement NACK to the source node to indicate the connection failure. Finally, the source node sent a REL packet to release the reserved wavelengths in other segments along the path [Ahmad 2004].

A backward reservation protocol has been proposed by [Pezoulas 2003] supports the wavelength conversion and uses the concept of path segments. Nodes equipped with the wavelength converter initiates the wavelength reservation process in each of the segments as shown in Fig. 6.3. The protocol performance depends upon the way wavelengths are selected at each segment along the path.

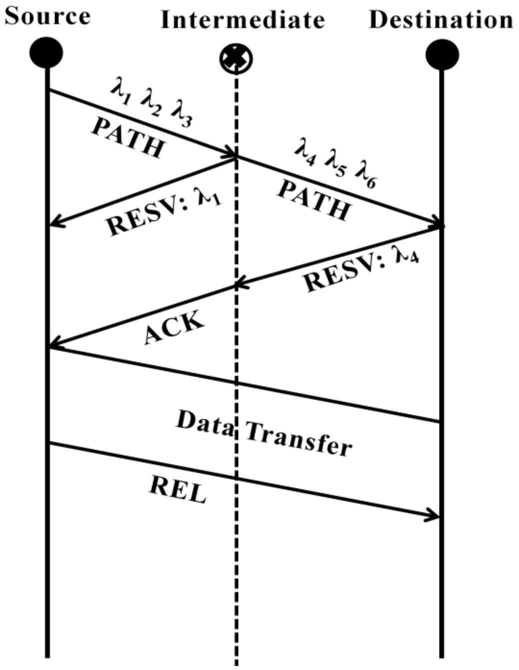

Figure 6.3 Intermediate-node Initiated Reservation Protocol

In First-Fit (i.e. first wavelength in the list of wavelengths available in the segment) wavelength selection algorithm, wavelength to be reserved is decided at each segment boundary during the probing phase itself and only that wavelength information is passed to the next segment. Once a destination node receives this information it initiates the wavelength reservation by sending a RESV packet towards source node. If wavelength reservation fails in any of the segment due to unavailability of the selected wavelength then the request becomes blocked. In this case there is no possibility of retry as only one wavelength information per segment is passed from each segment. If the wavelength selection decision is made at the destination node in place of each of the segments and the complete wavelength availability information is passed to the destination then the destination node has a chance to make multiple attempts to reserve the wavelength. This algorithm is called as the First-Available algorithm. The control packet size becomes large for First-Available algorithm as compared to the First-Fit algorithm. Since both algorithms do not reduce the vulnerable time as compared to that of a standard DIR protocol thus blocking due to race condition (i.e. two or more requests trying to reserve same wavelength) is still significant.

6.3.1 Aggressive-IIR (AIIR) Protocol[8]

The intermediate-node initiation based reservation class of protocols reduces the connection blocking due to a race condition. In IIR protocol, the end to end path is assumed to be segmented and wavelength conversion is allowed at each of the segment boundary nodes which can initiate reservation independently. The IIR protocol reserves the free wavelength in a segment once the connection request reaches to the last node of the segment. In the probing phase, the information about the availability of free wavelengths in a segment is collected by sending a PATH control message. Once the PATH control message reaches to the end of the segment; the last node of the segment reserves a wavelength which is free throughout the segment. In the case of a race condition, the node tries to reserve another free available wavelength in the segment. The connection setup time increases significantly with the multiple attempts hence all the

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[8] This work has been published in: Virendra Singh Shekhawat, Mahesh Lagadapati, Dinesh Tyagi, and V K Chaubey, "A Novel Aggressive Intermediate-node Initiated Reservation (AIIR) Protocol for Wave length Routed Optical WDM Networks", IJRTE Vol. 3, No. 1, pp. 126-128, 2010

common free available wavelengths in the segment which are identified during the probing phase can be reserved simultaneously. This eliminates the multiple attempts completely. This variant of IIR minimizes the chances of race condition within a segment and hence improves the connection probability. The proposed variant of IIR is named as Aggressive-IIR protocol because of its aggressive approach to reserve a wavelength. The new protocol has been investigated to decide the optimal number of segments between the source and destination node through simulations. The subsequent sections explain the working of the protocol in detail with simulation results.

6.3.1.1 Working Principle of AIIR Protocol

The principle of the protocol is described in terms of the control messages exchanged between the nodes to establish a light-path between a source destination node pair. The steps are as follows:

1. PATH message: In first step source node sends the message for collecting information about the availability of free wavelengths.

2. BLOCK (BLK) message: This message is sent from the last node of a segment in the backward direction (towards the first node of the segment) after receiving the PATH message. It blocks all the common free wavelengths available identified in the first step.

3. RESERVE (RESV) message: This message is sent from by the first node of a segment in the forward direction (towards the last node of the segment) after receiving the BLOCK message. It selects one common blocked wavelength to reserve on the segment and releases rest of the blocked wavelengths in the segment.

4. NOTIFY message: This message is sent from the destination node in the backward direction after receiving the PATH message. It notifies the source node about the completion of the wavelength reservation process.

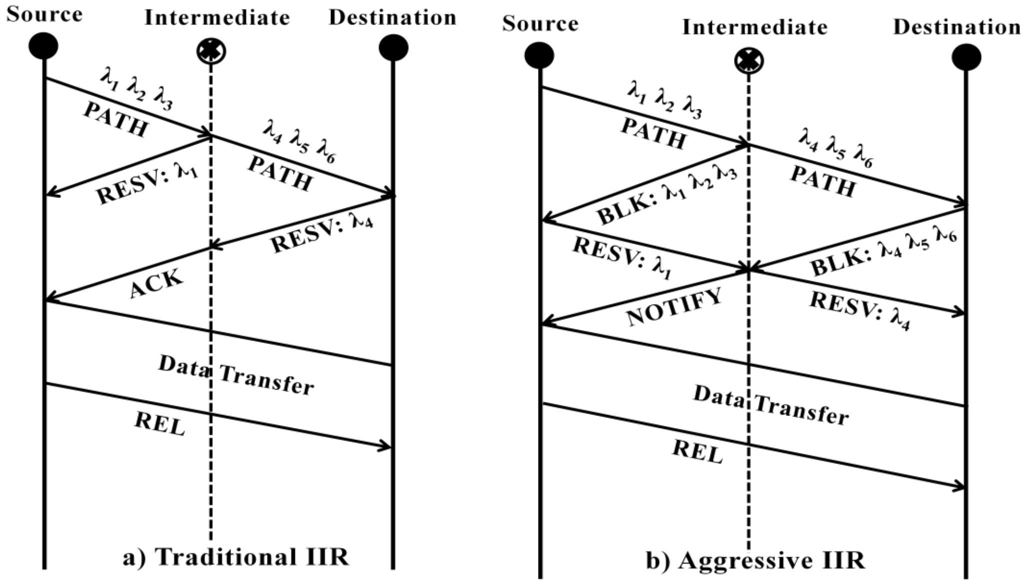
5. FAIL message: This message is sent from the last node of the segment in the backward direction to intimate about the connection failure in the case of unavailability of common free wavelength in any of the segments.

6. RELEASE (REL) message: This message is sent from the source node to all the nodes in the path to release the wavelength allocated for the data transfer. It is sent in the case of either data transfer is completed or wavelength couldn’t be reserved.

The Fig. 6.4 shows the control messages exchanged among the nodes in the case of successful connection establishment for IIR and AIIR protocols.

6.3.1.2 Performance Analysis with Ring Topology

A ring network topology having N nodes is simulated to test the performance of AIIR protocol and compared with the DIR and SIR protocols. Each node initiates the traffic by sending a connection request of length N. Each node is treated as a process and have a message queue associated with it for inter process communication. If a node wants to communicate with another node, it just needs to connect to the message queue associated with that node and push a message in that queue. A node can only send messages to either its right neighbour or to the left neighbour. If a wavelength required for connection is not available at intermediate nodes, it sends a failure message ‘FAIL’ to the source node.



a) Traditional IIR

b) Aggressive IIR

Figure 6.4 Successful Connection Establishment for IIR and AIIR Protocols

Protocol	**Connection Probability (%)**	**Delay per Connection (Sec)**
SIR	18.55	7.6
DIR	21.42	15.4
AIIR(segment length = 4)	55.55	17.9
AIIR(segment length = 2)	20.13	15.4
AIIR(segment length = 7)	20.34	17.2

Table 6.1 Ring Topology of 15 Nodes

Protocol	**Connection Probability (%)**	**Delay per Connection (Sec)**
SIR	20.32	6.7
DIR	25.67	20.1
AIIR(segment length = 4)	42.23	24.3
AIIR(segment length = 5)	45.23	27.9
AIIR(segment length = 2)	19.12	18.3
AIIR(segment length = 10)	18.34	20.3

Table 6.2 Ring Topology of 20 Nodes

Protocol	**Connection Probability (%)**	**Delay per Connection (Sec)**
SIR	17.7	9.2
DIR	15.3	24.3
AIIR(segment length = 5)	48.23	22.4
AIIR(segment length = 6)	50.23	21.3
AIIR(segment length = 2)	12.34	17.5
AIIR(segment length = 10)	17.23	22.8

Table 6.3 Ring Topology of 25 Nodes

Protocol	Connection Probability (%)	Delay per Connection (Sec)
SIR	18.55	11.2
DIR	11.23	15.4
AIIR(segment length =5)	44.23	30.12
AIIR(segment length=6)	42.11	29.84
AIIR(segment length=2)	20.13	21.23
AIIR(segment length=10)	20.34	17.2

Table 6.4 Ring Topology of 30 Nodes

The inter arrival time of each connection is assumed as 8 seconds and data transfer time for each connection is assumed as 2 seconds. The simulation is carried out for a ring topology of 15, 20, 25, and 30 nodes and the corresponding results are presented in Table 6.1, Table 6.2, Table 6.3 and Table 6.4 respectively.

The protocols are compared based on two metrics called as connection probability and average delay per connection for different size of ring network. Delay per connection metric indicates the control overhead as it is caused due to the queuing up of messages at each node. The AIIR protocol uses the concept of segments to setup a light-path for a connection request. Unlike SIR protocol, which reserves common free available wavelengths on the entire path between a source destination node pair, AIIR protocol blocks common free available wavelengths only within a segment. The AIIR protocol restricts the wavelength over-reservation to a segment, thus blocking the connections due to over-reservation of resources is reduced. Unlike DIR protocol, which allocates the wavelength after the request reaches the destination and reserves one wavelength at a time, AIIR protocol blocks all the free wavelengths available in that segment and reserves the one of the blocked wavelength, which in turn reduces the chances of race condition. Similarly in traditional IIR [Lu 2003] only one wavelength is selected to reserve, which is commonly available on all the nodes in the segment.

Protocol	Resource Over-Reservation	Race Condition	Control Overhead	Connection Setup Delay
SIR	High	No	Low	Low
DIR	Low	Yes (High)	High	Medium
IIR	Medium	Yes (Medium)	Medium	High
AIIR	Medium	Yes (Very Low)	Medium	High

Table 6.5 Performance Comparison of Reservation Protocols

This also can lead to race conditions (i.e. wavelength contention) even though the chances are comparatively lesser than the DIR protocol. This new modified IIR (i.e. AIIR) reduces the chances of wavelength contention with the marginal overhead of resource reservation. A comparative analysis of various reservation protocols is shown in Table 6.5. Simulation results reveal that the successful connection establishment rate for AIIR protocol is high as compared to its counterparts SIR, DIR and traditional IIR protocols. The AIIR protocol gives a better success rate as compared to SIR and DIR protocols, when the end to end path is divided into segments such that the segment length is almost equal to the total number of segments in the path.

The performance degrades drastically when the segment size is either too small (closer to SIR) or too big (closer to DIR). The overall results show that the SIR protocol requires less connection setup delay as it requires only two types of control messages one for reserving wavelengths and another for releasing wavelengths. The resource over-reservation (compared to DIR and IIR) and control overhead in AIIR protocol is compensated by a reduction in wavelength contention which reflects through the better connection probability as compared to existing protocols. The next subsection describes two hybrid versions of IIR protocol.

6.3.2 IIR_SIR and IIR_DIR Wavelength Reservation Protocols

The intermediate node initiated wavelength reservation protocol gives better call connection performance as compared to SIR and DIR protocols but with the cost of connection setup delay. The AIIR protocol shows an improvement over the traditional IIR. The AIIR protocol probes the wavelengths in forward direction and blocks all the available wavelengths in backward direction and then finally sender chooses one of the wavelengths (if at-least one wavelength is identified free during probing as well as at blocking time) to reserve. This process happens simultaneously in each of the segments of the selected path. A connection request will be blocked in AIIR protocol, if the wavelengths are found free during probing but at the time of blocking all of them have been reserved by some other nodes. This can further be improved by reserving the free wavelengths during probing time itself similar to SIR protocol. This new protocol is named as IIR_SIR. In this protocol the resource over-reservation problem is lesser as compared to SIR protocol but more than AIIR protocol. The resource over-reservation can further be minimized by using a traditional IIR protocol with multiple reservation attempts in case of failure of the first attempt. This modified IIR protocol is named as IIR_DIR. It uses the DIR protocol in each segment with multiple reservation attempts. The working principle of these two protocols is explained in subsequent subsections.

6.3.2.1 IIR_SIR Wavelength Reservation Protocol

1. PROBE-RES packet: This packet is sent from the source node to the last node of the segment. It probes and reserves the free available wavelengths on all the links on a segment. Partially reserved wavelengths are released immediately.

2. ACK packet: This packet is sent from the last node of the segment to the source node. It confirms the reservation of a wavelength to the source.

3. REL packet: This packet is sent from the first node of a segment to the last node of the segment. It releases the additional reserved wavelengths (if any) in the segment.

4. NACK packet: This packet is sent from the last node of the segment to the source node. It is sent to indicate the failure of wavelength reservation process.

The source start transmitting the data once it receives ACK from all the segments otherwise request treated as blocked.

6.3.2.2 IIR_DIR Wavelength Reservation Protocol

1. PROBE packet: This packet is sent from the source node to the last node of the segment. It probes the free wavelengths availability on the segment.

2. RES packet: This packet is sent from the last node of the segment to the first node of the segment. It reserves one of the freely available wavelengths identified during probe phase. This packet is sent until a wavelength is not reserved or free wavelength list is not exhausted in the segment.

3. ACK packet: This packet is sent from the first node of the segment to the source node. It confirms the wavelength reservation in a segment.

4. NACK packet: This packet is sent from the first node of the segment to the source node. It is sent in the case of unsuccessful wavelength reservation.

5. REL packet: This packet is sent from the first node of the segment to the last node of the segment. It is sent either on observing any NACK packet traversing towards source node or data transfer is completed, to release the reserved wavelength in any of the segments.

A light-path is assumed to be established successfully; once a source node receives ACK from all segments of the path otherwise request is treated as failed.

6.3.2.3 Simulation and Performance Analysis

A network simulation is carried out to compare the SIR, DIR, IIR_SIR and IIR_DIR protocols. The NSFNET network topology shown in Fig. 6.5 is used to simulate proposed wavelength reservation protocols. In the case of IIR_SIR and IIR_DIR protocols, numbers of segments are assumed as two to simplify the proceedings. Light-path requests are assumed to be generated dynamically in a random fashion at different rates and routed using Dijkstra’s shortest path algorithm. A successfully established light-path holds the wavelength for a specified amount of time on the path and then releases the reserved wavelength.

A light-path request is assumed blocked, in case of resource unavailability. The parameters considered for performance analysis are blocking rate and connection request setup delay. The blocking rate measured with different request rates for holding time of 2 seconds at 4 and 8 wavelength channels per link and the results are plotted in Fig. 6.6 and 6.7 respectively. The blocking rate for SIR and DIR protocols at different traffic rates is observed to be almost equal with a margin of 1% to 4%. Between the SIR and DIR protocols, DIR performs better which indicates that the blocking due to over-reservation of resources dominates over blocking due to outdated information. As traffic rate increases, the performance difference reduces between them (i.e. SIR and DIR) to indicate that the blocking due to outdated information becomes more significant at higher traffic rates. It can be observed from both the figs (i.e. Fig. 6.6 and 6.7) that, at lower traffic rates all protocols have almost similar behaviour in terms of blocking rate but with the increase in traffic rate, the blocking rate reduces for IIR based protocols compared to SIR and DIR protocols.

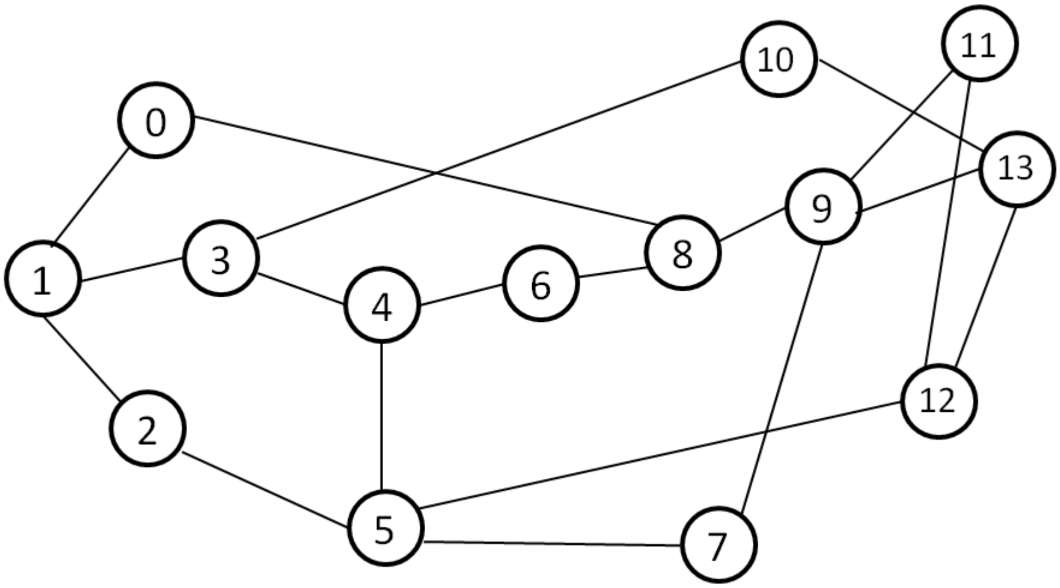


Figure 6.5 NSFNET Topology used for Simulation

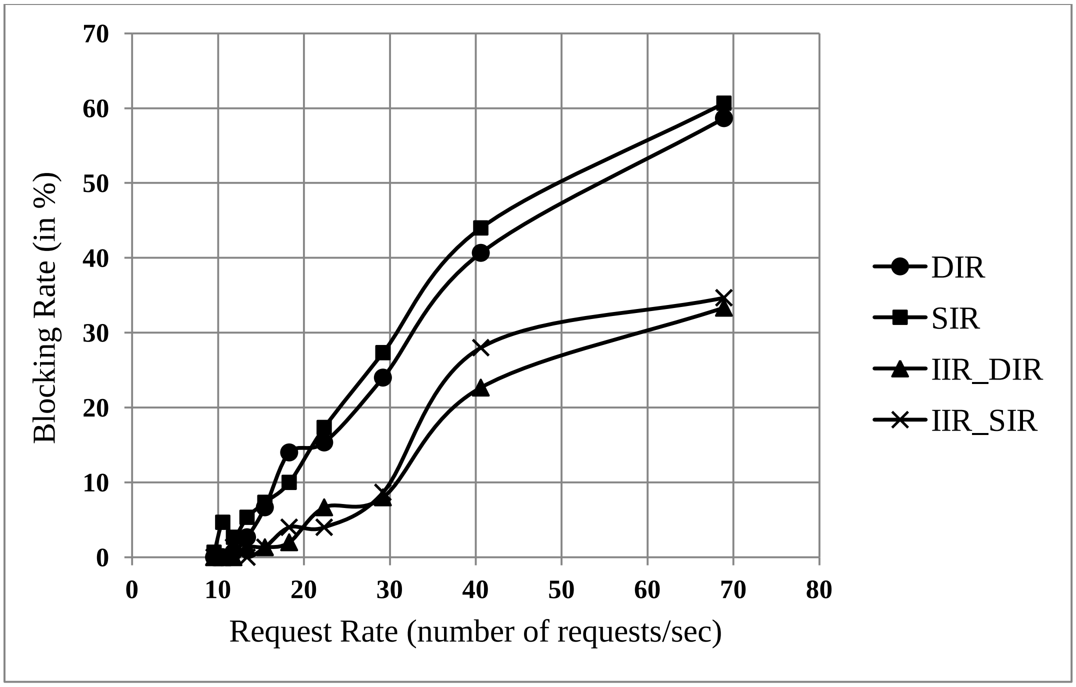


Figure 6.6 Blocking Rate for 4 Wavelengths per Link

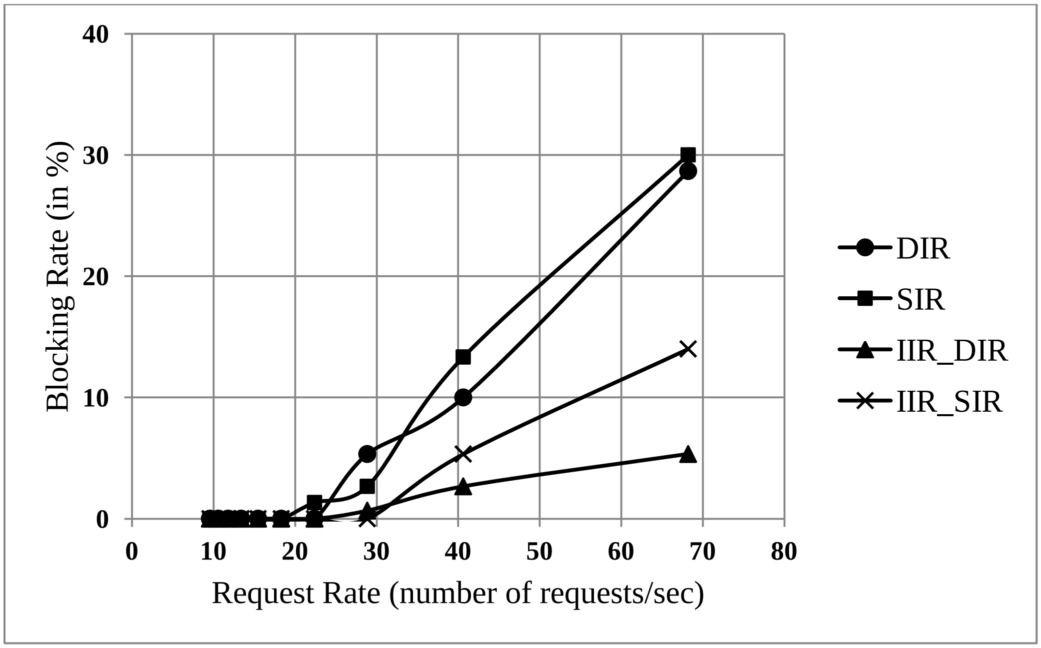


Figure 6.7 Blocking Rate for 8 Wavelengths per Link

For example at 70 requests per second (Fig. 6.6) the blocking rate difference is about 25%. The IIR_DIR protocol performs better than that of IIR_SIR. Again the blocking rate difference between IIR_SIR and IIR_DIR protocols shows that the impact of resource over-reservation on blocking is more than the outdated information at lower traffic rates. At higher traffic rates this impact is almost same as indicated in Fig. 6.6. The effect of an increase in wavelength channels per link is visualized (Fig. 6.7) in terms of overall reduction of 50% in blocking rate for all protocols. The obvious reason for this is the better resource availability in the latter case. The only significant difference between the two graphs is the variation in blocking rate between IIR_SIR and IIR_DIR protocols, which is more in the presence of additional wavelengths. Hence IIR_DIR protocol performs better than IIR_SIR protocol with a large number of wavelength channels per link.

The average connection setup delay measurement for these protocols is shown in Table 6.6. The connection setup delay is defined as the time difference observed between the connection request arrival time and the light-path setup time. The SIR protocol reserves the wavelength during the probing phase itself hence it has least connection setup delay. The connection setup delay becomes high for IIR based protocols due to more control overhead of these protocols.

Reservation Protocol	**Average Connection Setup Delay per request (μs)**
DIR	4.70
SIR	4.49
IIR_DIR	5.57
IIR_SIR	5.53

Table 6.6 Average Connection Setup Delay Comparison

The variation observed in connection setup delay between IIR_SIR and IIR_DIR protocols is marginal. The higher value of connection setup delay is termed as an overhead but still IIR based protocols (i.e. IIR_SIR and IIR_DIR) performs better than SIR and DIR protocols because of the better resource utilization as compared to the SIR protocol and less vulnerable time as compared to the DIR protocol.

6.4 Results and Conclusion

This chapter focuses on wavelength reservation protocols and their relative performance in WDM networks. The three new protocols based on the intermediate node initiated reservation method named as AIIR, IIR_SIR, IIR_DIR. The AIIR protocol reserves all wavelengths which are found free during probing in each of the segments, while IIR_SIR protocol follows the SIR approach on a segment basis. The IIR_DIR protocol uses a DIR based approach for wavelength reservation on a segment basis. The IIR_DIR protocol also supports multiple attempts to reserve a wavelength in a segment. These protocols are compared to the traditional protocols like SIR, DIR and IIR. The blocking rate of IIR based protocols is lower as compared to the SIR and DIR protocols on the cost of control overhead. The control overhead reflects in terms of higher connection setup delay. The higher value of connection setup delay is compensated by better resource utilization. Among the IIR protocol variations, AIIR and IIR_DIR gives better results by further reducing the amount of wavelength over-reservation and reservation time significantly. The IIR_SIR and AIIR protocols reduce the blocking due to outdated information or race conditions while as IIR_DIR protocol reduces the blocking due to over-reservation of wavelengths.

The channel reservation protocols in WDM networks assist routing protocols to improve the resource utilization and throughput. Hence, better channel reservation protocols also improve overall network performance.

CHAPTER 7

CONCLUSIONS AND FUTURE DIRECTIONS

The thesis proposes some performance enhancement techniques in wavelength routed optical WDM networks at the physical layer and at network control & management layer. The performance enhancement is achieved in terms of throughput, reliability, end-to-end delay, blocking probability, traffic load distribution and resource utilization. This is achieved by using a new node architecture design, modified network topology, routing and wavelength assignment algorithms and wavelength reservation protocols. The analysis carried out in thesis can help to understand the influence of various network parameters on overall network performance. This further helps to design and configure the network as per traffic demands and QoS requirements. In the current scope of work, physical and network control & management layers functionalities have been explored.

Physical layer performance improvement is achieved by providing solutions for network topology configurations and node architecture. The ring topology is considered in the analysis. A variant of dual ring topology is proposed based on the statistical data that gives an estimate of the regional traffic demands with provisions to adapt dynamically to varying traffic demands. This solution suggests additional alternate links between nodes based on traffic density. These additional links provide alternate paths to carry the traffic at the nodes with high traffic demands. This modified ring topology gives significant improvement in terms of call connection probability traditional dual ring configurations.

At the topology level, the network performance gain is constrained from node architecture capability hence further improvement can be governed through node level modification as per requirement. The node architecture described in chapter 3 is suitable for circuit switching as well as for packet switching through packet stacking at different time slots. Thus bandwidth utilization becomes better for bursty traffic. The OPADOM allows dropping a wavelength at the node or bypassing it optically as per requirement. Hence node is capable of processing more traffic due to less switching overhead. The node's performance analysis is carried out using an analytical model considering it as a part of ring and star topology. The call connection probability with different traffic rates is evaluated for network topologies and it is observed that this depends upon the number of available wavelengths, traffic rate, link delay and processing capability of the node. Thus, the proposed model is beneficial to design and configure a node with required parameters as per performance requirement. Further, one of the most critical problems of optical packet switched node i.e. packet conflict resolution, is addressed in chapter 4. A modified FDL based solution is proposed for the packet contention problem in synchronous OPS network. The proposed solution relies on variable delay across shared FDLs with looping capability. The results reveal the importance of the proposed method over traditional FDL solution (i.e. without looping) and thereby providing better network throughput.

The performance improvement solutions attempted to node and topology design show the influence of physical parameters on overall network performance. Conversely the network performance is restricted due to node architecture limitations. Thus the further performance enhancement is achieved by providing solutions at control & management layer using RWA and channel assignment protocols. There are five such algorithms that are proposed and described in chapter 5. A weight based route selection algorithm (i.e. WEDP-RWA) for selecting a route among pre-calculated EDPs gives better wavelength utilization over existing EDP based approach. In particular, this new algorithm performs marginally better for a mesh topology having 15 or more nodes with request multiplicity value ranges from 1 to 13 as shown in Table 5.2. The link weight calculation based on static and dynamic parameters of network avoids bottleneck links to be selected in the route. Similarly an algorithm (i.e. WIC-RWA) ensuring the wavelength continuity constraint at the time of route selection has also been proposed. This outperforms traditional link weight based adaptive algorithms by reducing average blocking time of the connection requests. An exhaustive simulation carried out for this confirms its superiority over the traditional free wavelength based link weight RWA algorithms at higher traffic rates. In particular, the WIC-RWA algorithm gives 4% to 10% lower ABTN value compared to traditional routing algorithm which uses free wavelength based link weight in the traffic rate range from 80 to 160 requests per minute for eight wavelengths per link. Further WIC-RWA gives low average blocking time for 6 to 12 wavelengths per link. Next two algorithms exploit the wavelength mesh graph approach for solving RWA problem. There are two new wavelength search heuristics proposed; one is LCF and another is LRUF. These heuristics are coined to reduce the number of wavelength search operation (i.e. wavelength scans) to establish the light-path. The reduction in wavelength scans increases the traffic handling capacity of the network. The LCF and LRUF are compared with an existing FO algorithm. Simulation results prove the superiority of LCF and LRUF over FO and significant improvement is observed for 32 wavelengths per link. The LCF traffic handling capacity is observed to be 32% to 48% more than FO for 32 wavelengths per link. Moreover LCF overshoots LRUF in the range of 1% to 10 % for the same number of wavelengths. The last section of chapter 5 explores the scope for multipath routing in wavelength routed WDM networks. It reduces the end to end delay as well as meets the bandwidth requirement of bandwidth intensive applications. The simulation is carried out for a mesh network of 1000 nodes to show the multipath routing dominance over a single path routing with control overhead to manage multiple paths. The probability of multiple path availability is observed to be more at lower traffic rates. The link utilization graph (Fig. 5.20) indicates improvement in terms of load balancing and bandwidth utilization.

The performance of RWA algorithms is closely associated with wavelength reservation algorithms/protocols. Hence chapter 6 focuses on wavelength reservation methods to show their influence to further improve the network performance. The SIR protocol's performance is limited by resource over-reservation and DIR protocol's performance is constrained due to vulnerable time duration/race condition. The IIR protocol reduces both of the constraints. Thus to further improve performance three new modified versions of IIR protocols are proposed namely AIIR, IIR_SIR and IIR_DIR. The AIIR reduces the race condition chances better than IIR by dividing end to end path into multiple segments and blocking all free probed wavelengths in each segment. The other two protocols (i.e. IIR_SIR and IIR_DIR) also give better connection probability compared to SIR and DIR. Moreover SIR_DIR outperforms by providing trade-off between race condition and channel over-reservation compare to others.

The entire research work carried out for the completion of this thesis assumes communication links as single fiber links. As an extension of this work the single fiber link constraint can be relaxed to multiple fiber links. Similarly, the topology modification of a ring network for dividing into multi traffic zone areas can be extended from ring architecture to star and mesh architecture as well. In the current work, the control layer solutions are assumed to be independent of the application layer. Moreover, application layer solutions for performance enhancement are not in the current scope of the thesis and hence can be explored as an extension to this work. Thus, research can be carried to tune the network control & management layer functions such that an application can choose the control layer functionality according to its QoS requirements.

Among the three switching technologies (i.e. circuit, packet and burst), optical packet switching perform better than others, provided that optical memory availability ensured at reasonable cost. Currently optical buffers have been observed through fiber delay lines. The optical memory at WDM nodes will also ease the IP over WDM network integration. Currently a multilayer approach is used to carry IP traffic over WDM networks. This multilayer approach (i.e. IP over ATM over SONET) introduces extra cost as well as delay. Hence, there is a scope of work to improve the performance for IP over WDM integration such that IP traffic can be carried over WDM networks with less delay overhead and cost implications.

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