

**PERFORMANCE ANALYSES OF OPTICAL BURST SWITCHING  
FOR HIGH SPEED NETWORKS**

*A THESIS*

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**Doctor of Philosophy**

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## **Certificate**

This is to certify that the thesis entitled “**Performance Analyses of Optical Burst Switching for High-Speed Networks**” being submitted by Mr. Amit Kumar Garg, to the School of Electronics and Communication Engineering, Thapar Institute of Engineering and Technology, Thapar University, Patiala, Punjab for the award of Doctor of Philosophy in Electronics and Communication Engineering, is a bona-fide research work carried out by him under the supervision and guidance of the undersigned. His thesis has reached the standard of fulfilling of requirements of the regulations related to degree.

The contents in this thesis have not been in part or full submitted to any other university for award of any degree or diploma.

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## **Abstract**

The field of networking has experienced growth at a tremendous rate over the last decade. The popularity of the Internet is soaring as more people gain an increased awareness of the vast amounts of information available at the click of a button. This growing demand is leading to many new opportunities in networking, as people demand faster and better applications and services, such as World Wide Web browsing, video-on-demand and interactive television. The rapid expansion of the Internet and the ever-increasing demand for multimedia information are severely testing the limits of our current computer and telecommunication networks. There is an immediate need for the development of new high-capacity networks that are capable of supporting these growing bandwidth requirements. We need to be able to scale current networks to support the increasing volumes of information. Optical networks are a logical choice to meet the future communication demands, with optical fiber links offering huge bandwidth.

Thus, optical burst switching (OBS) is considered as a suitable transport methodology for the realization of optical core networks due to the balance it offers between coarse-grained optical circuit switching (OCS) and fine-grained optical packet switching (OPS). OBS avoids the use of optical buffering and optical processing logic unlike in OPS but still achieves switching in optical domain. It improves the utilization of the fiber compared to OCS because of statistical multiplexing of bursts on different wavelengths.

Although, optical burst switching appears to offer advantages over optical circuit switching and optical packet switching, several issues need to be considered before optical burst switching can be deployed in transport networks. In particular, these issues include; network architectures problems in terms of lower blocking probability, reservations techniques for efficient utilization of bandwidth as well as network resources; burst dropping and contention resolution schemes supporting quality of service, which need to be investigated further.

Keeping in view the above mentioned aspects, the objectives of the research were formulated which are listed as follows:

1. To study and analyze various optical burst switching architectural alternatives in terms of the burst handling techniques and with the possible use of fiber delay-line for buffering and contention resolution.
2. To study and compare various reservation schemes for efficient network utilization and bandwidth in optical burst switched networks.
3. To analyze and compare the different burst segmentation policies with the standard dropping policies.
4. To investigate, analyze and compare the performance of various contention resolution policies and control schemes for optical burst switched network, in order to reduce packet/burst loss, while supporting quality of service.

An efficient OBS network architecture incorporating small fiber delay line (FDL), adaptive burst assembly as well as dynamic route selection techniques, has been proposed for improving system's performance, in terms of lower blocking probability and higher throughput. The simple closed-form expressions are derived for the burst loss probability of both classless and prioritized traffic. Also, in order to have reduction in electronic switching processing time, delay associated with FDL usage in the above architecture, another efficient congestion-free OBS network architecture utilizing a short-prior-confirmation-packet and optical label processing with just enough time (JET) signaling, has been presented. The proposed architectures make exemplary use of the advantages of all-optical technology by meticulously delegating switch planning and contention avoidance for control processing.

The quality of service (QoS) oriented reservation schemes have been investigated in order to enhance bandwidth and channel utilization in OBS networks. An adaptive reservation scheme based on a multi-service OBS edge node with synchronized bandwidth reservation mechanism has been proposed. The proposed scheme provides a flexible and efficient platform for convergence of packet-based and circuit-based network traffic based on OBS capabilities. In order to have better channel utilization, higher throughput and lower blocking probability, we have investigated an efficient reservation scheme in which data burst are scheduled in batches. To obtain better fairness control and bandwidth utilization, we have presented another efficient reservation scheme in which

each edge router finds a suitable route to the destination edge router autonomously by using feedback and prior information packets. It is shown that by leveraging statistical multiplexing, re-configuration cost is minimized and thus bandwidth utilization is enhanced.

To minimize the burst drop rate in OBS network, an efficient burst dropping policy based on even selection of burst (BDPES) has been proposed. Also, suitable burst assembly and congestion control mechanisms have been used in the proposed policy in order to provide differentiated service for supporting the quality of service (QoS) requirements. In order to obtain better results in terms of bandwidth utilization, lower burst loss rate etc, flexible and enhancing bandwidth utilization, burst dropping technique based on packet count number (PCN) has been presented for contention resolution. The results obtained show that the proposed dropping scheme reduces packet loss rate (PLR) and makes bandwidth utilization more efficient and flexible than existing schemes.

Contention, which may occur when two or more bursts compete for the same wavelength on the same link, is a critical issue. Thus, we have proposed possible better solutions to reduce blocking probability due to contention. Through hybrid contention resolution techniques such as WConv, delay and deflect; WConv, deflect and delay and Prioritized delay, deflect and delay, it is shown that both contention and the burst loss rate have been minimized. In order to have proportional differentiated services, lower packet loss etc, an efficient scheme based on adaptive wavelength selection and burst assignment, which supports better proportional differentiated services with lower packet loss in the buffer-less OBS networks, has been developed. Further, to have both contention resolution and congestion control for reducing burst loss in OBS network, we have investigated an integrated contention resolution and control scheme. Finally, to achieve improvements in terms of wavelength utilization and wavelength efficiency, an efficient scheme based on resource reservation and adaptive network flow routing has been investigated. It has been observed in the achieved results that the proposed schemes reduces burst loss in the network significantly, provides congestion control, support differentiated services and also improves wavelength utilization and efficiency as compared to the conventional schemes.

Thus, the investigations carried out in thesis, result in the performance oriented efficient optical burst switching for high speed networks in terms of handling bursty traffic efficiently, cost effectiveness, enhancing bandwidth and channel utilization, efficient burst dropping scheme for handling contention, congestion control and contention resolution techniques supporting QoS. The results reported in the thesis have been published in the form of eleven papers in the refereed international journals as per the list enclosed.

### **List of Publications**

The thesis includes following research papers:

1. Amit Kumar Garg, R S Kaler, “Comparison Analysis of Optical Burst Switched Network Architectures”, *Optik - International Journal for Light and Electron Optics, Elsevier Science*, vol. 121, No. 15, pp. 1412-1417, September 2010.
2. Amit Kumar Garg, R S Kaler, “A Novel Optical Burst Switching Architecture for High Speed Networks”, *Chinese Optics Letters (Journal of Optical Society of America)*, vol.6, no.11, pp.807-811, November 10, 2008.
3. Amit Kumar Garg, R S Kaler, “An adaptive reservation scheme for optical network”, *Optik - International Journal for Light and Electron Optics, Elsevier Science*, In Press, Corrected Proof, Available online 3 July 2010.
4. Amit Kumar Garg, R S Kaler, “An Efficient Scheme for Optimizing Channel Utilization in OBS Networks”, *Optik - International Journal for Light and Electron Optics, Elsevier Science*, vol. 121, no. 9, pp.793-799, May 2010.
5. Amit Kumar Garg, R S Kaler, “Enhancing Bandwidth Utilization and QoS in Optical Burst Switched High-Speed Network”, *International Journal of Microwaves, Optoelectronics and Electromagnetic Applications*, vol. 7, no. 2, pp.91-100, December 2008.

6. Amit Kumar Garg, R S Kaler, “Burst Dropping Policies in Optical Burst Switched Network”, *Optik - International Journal for Light and Electron Optics, Elsevier Science*, In Press, Corrected Proof, Available online 23 May 2009.
7. Amit Kumar Garg, R S Kaler, “A new flexible and enhancing bandwidth utilization burst dropping technique for an OBS network”, *Optik - International Journal for Light and Electron Optics, Elsevier Science*, In Press, Corrected Proof, Available online 31 May 2010.
8. Amit Kumar Garg, R S Kaler, “Hybrid Contention Resolution Schemes for Optical Burst Switched High-Speed Networks”, *International Journal of Interconnection Networks (JOIN), World-SciNet*, vol.10, no.1/2, pp. 121–132, March/June 2009.
9. Amit Kumar Garg, R S Kaler, “A Novel Technique to Resolve Burst Contention in OBS Networks”, *International Journal of Electronics (Taylor & Francis)*, vol.97, no.3, pp.295–308, March 2010.
10. Amit Kumar Garg, R S Kaler, “Integrated Contention Resolution & Control Algorithm (ICRCA) for Optical Burst Switched Networks”, *International Journal of Fiber and Integrated Optics, Taylor and Francis*, vol.28, no.5, pp. 366–375, September 2009.
11. Amit Kumar Garg, R S Kaler, “Performance Analysis of an Integrated Scheme in Optical Burst Switched High-Speed Networks”, *Chinese Optics Letters (Journal of Optical Society of America)*, vol.6, no.4, pp.244-247, April 10, 2008.

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## List of Acronyms

WDM	:	Wavelength Division Multiplexing
DWDM	:	Dense Wavelength Division Multiplexing
ATM	:	Asynchronous Transfer Mode
O/E	:	Optical-Electronic
FDL	:	Fiber Delay Lines
WADM	:	Wavelength Add-Drop Multiplexer
RWA	:	Routing and Wavelength Assignment
SLE	:	Static Lightpath Establishment
DLE	:	Dynamic Lightpath Establishment
OCS	:	Optical Circuit Switching
OPS	:	Optical Packet Switching
OBS	:	Optical Burst Switching
CP	:	Control Packet
AT	:	Assembly Time
ITU-T	:	International Telecommunication Union-Telecommunication
ABT	:	ATM Block Transfer
OXC	:	Optical Cross Connect
SCU	:	Switch Control Unit
RM	:	Routing Module
BA	:	Burst Assembler
WR-OBS	:	Wavelength-Routed Optical Burst Switching
WRONS	:	Wavelength-Routed Optical Networks
MPLS	:	Multi-Protocol Label Switching
BHP	:	Burst Header Packet
FEC	:	Forward Equivalent Class

LOBS	:	Labeled Optical Burst Switching
FCFS	:	First-Come-First-Served
PQ	:	Priority Queuing
RR	:	Round Robin
WRR	:	Weighted Round Robin
CBQ	:	Class Based Queuing
WTP	:	Waiting Time Priority
TAW	:	Tell-And-Wait
TAG	:	Tell-And-Go
JIT	:	Just-In-Time
JET	:	Just-Enough-Time
SIR	:	Source Initiated Reservation
DIR	:	Destination Initiated Reservation
FFUC	:	First Fit Unscheduled Channel
LAUC	:	Horizon or Latest Available Unscheduled Channel
FFUC-VF	:	First Fit Unscheduled Channel with Void Filling
LAUC-VF	:	Latest Available Unscheduled Channel with Void Filling
LAUT	:	Latest Available Unscheduled Time
MVUC	:	Minimizing Voids Unscheduled Channel
Min-SV	:	Minimum Starting Void
LAW	:	Look-Ahead Window
RAM	:	Random-Access Memory
HOL	:	Head-Of-Line
MEMS	:	Micro-Electro-Mechanical Systems
SOA	:	Semiconductor Optical Amplifier
SOBS	:	Slotted OBS
QoS	:	Quality of Service

LOBS	:	Labeled Optical Burst Switching
SDH	:	Synchronous Digital Hierarchy
DWR-OBS	:	Dynamic Wavelength-Routed Optical Burst Switched Network
FCFS	:	First-Come, First-Served
ACK	:	Acknowledgement
OCBS	:	Optical Composite Burst Switching
BJIT	:	Balanced Just-In-Time Scheme
PRED	:	Prioritized Random-Early Discard
WTP	:	Waited-Time-Priority
SNR	:	Signal-To-Noise Ratio
BER	:	Bit Error Rate
MBL	:	Minimum Burst Length
OCC	:	Orthogonal Optical Codes
OSPF	:	Open Shortest Path Flow
BAR	:	Burst Arrival Rate
EW	:	Economy of Wavelength
CoS	:	Class of Service
PAU	:	Packet Assembler Unit
DCU	:	Data Channel Unit
CU	:	Control Unit
HCL	:	Hop Count Level
LSP	:	Label-Switched Paths
SPCP	:	Short- Prior-Confirmation-Packet
PSBHC	:	Prioritized Scheduling Based on Hop-Counts
LP	:	Latest Arrival Drop Policy
LCR	:	Look-ahead Window Contention Resolution
SBP	:	Shortest Burst Drop Policy

SP	:	Segmentation Drop Policy
ABA	:	Adaptive Burst Assembly Algorithm
NSFNET	:	National Science Foundation Network
BDPES	:	Burst Dropping Policy with Even Selection of Burst
DB	:	Data Burst
DS	:	Data Segment
FCRB	:	Flow Control and Reservation Bits
PLB	:	Packet Loss Probability
ICRCA	:	Integrated Contention Resolution & Control Algorithm
WConv	:	Wavelength Conversion
MRT	:	Minimum Residual Time
PNT	:	Provided Network Time
NBA	:	New Burst Assignment
AWS	:	Adaptive Wavelength Selection
EPFR	:	Equal Proportion Multi-path Flow Routing
HLFR	:	Hop-Length Multi-path Flow Routing

## List of Symbols

$B_{\min}$	: Minimum Burst Length
$B_{\max}$	: Maximum Burst Length
$T$	: Timer Value
$P_{TB}$	: Transit Burst of Priority
$\rho$	: System Utilization
$\beta$	: Average Burst Loss Probability
$\pi$	: Steady State Probability
$c$	: Relative Traffic Intensity of Class
$w(i, j)$	: Link Weighted Function
$\rho(i, j)$	: Offered Load on the Link
$d_{\max}$	: Maximum Physical Distance
$\lambda_a$	: Maximum Value of the Auto-Correlation
$\lambda_c$	: Maximum Value of Cross-Correlation
$T_d$	: Offset Delay
$N_a$	: Attempt Number
$T_{OPL}$	: Optical Label Processing Time
$T_C$	: Chip-Period
$k$	: Number of Wavelengths
$\eta_{NUE}$	: Network Utilization Efficiency
$EW$	: Economy of Wavelength

$G$	: Graph
$T_{prop}$	: Propagation Time
$C_{reconfiguration}$	: Re-Configuration Bandwidth Cost
$T_{release}$	: Release Time
$N_F$	: Number of Received Feedback Packets
$\alpha$	: Traffic Bias
$N_{PI}$	: Number of Prior-Information Packets
$E[L]$	: Mean Loss Rate
$t_{sa}$	: Scheduled Data Burst With Arrival Time
$t_{ca}$	: Contending Data Burst With Arrival Time
$t_{max-burst}$	: Maximum Size of the Burst
$C_p(t)$	: Candidate Wavelength
$\tau$	: Monitoring Timescale
$t_{max}^{offset}$	: Extra Offset Time
$F_I$	: Fairness Index
$r$	: Transmission Rate per Flow

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# CHAPTER I

## INTRODUCTION AND MOTIVATION

### 1.1 Introduction

The ever-increasing demand for Internet and multimedia information are severely testing the limits of our current computer and telecommunication networks. There is an immediate need for the development of new high capacity networks that are capable of supporting these growing bandwidth requirements. Also, we need to be able to scale current networks in order to support the increasing volumes of information.

Thus, the optical networks are a logical choice to meet the growing communication demands, with optical fiber links offering huge bandwidths on the order of 25 THz. In order to meet these growing needs, optical wavelength division multiplexing (WDM) communication systems have been deployed in many telecommunications backbone networks. In WDM networks, channels are created by dividing the bandwidth into a number of wavelength or frequency bands, each of which can be accessed by the end-user at peak electronic rates [1]. In order to efficiently utilize this bandwidth, we need to design efficient transport architectures and protocols based on state-of-the-art optical device technology.

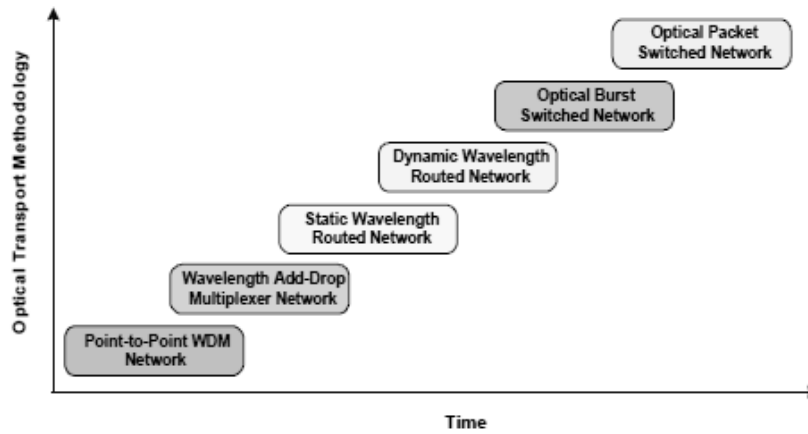
### 1.2 Evolution of Optical Networks

The following figure (1.1) shows the evolution of the different optical transport methodologies [1-2].

The first generation optical transport architecture consists of point-to-point WDM links. This is made up of several nodes interconnected by point-to-point links. The traffic arriving at each node undergoes conversion from optical to electronic domain and is processed electronically before being converted back into optical domain. Such type of electronic processing and switching incurs considerable overhead if most of the traffic is bypass traffic and thus, the need for all-optical switching arises.

The second generation optical network architecture consists of wavelength add-drop multiplexers (WADMs) where traffic can be added or dropped at each WADM node [3-4]. As the amount of bypass network traffic is usually high, WADMs help to reduce the overall cost by selectively dropping and adding traffic on some wavelengths and thus bypassing the traffic on the other wavelengths untouched.

The third generation optical network architectures are based on a mesh network of multi-wavelength fibers interconnected by all-optical interconnection devices such as passive star couplers, passive routers and active switches.



**Figure 1.1: Evolution of optical networks [2]**

There are three switching paradigms that have been proposed for use in WDM all-optical networks, namely optical circuit switching (OCS), optical packet switching (OPS) and optical burst switching (OBS). In OCS an end-to-end all optical path is established between source and destination for the complete session to avoid opto-electronic conversion at the intermediate nodes. In the futuristic OPS, packet buffering and processing capabilities are assumed at the intermediate nodes. The third switching paradigm OBS proposed to overcome the limitations of both circuit switching and packet switching is aimed at mainly supporting the next-generation optical Internet [5]. The benefit of OBS over conventional circuit-switching is that there is no need to dedicate a wavelength for the entire session between a source and destination. Moreover, OBS is more viable than packet switching as the data burst does not need to be buffered or processed at the intermediate nodes.

### **1.3 Optical Circuit Switching**

In OCS networks, dedicated WDM channels or lightpaths are established between a source and destination pair. A lightpath is carried over a wavelength on each intermediate link and switched to another link at each intermediate node along a physical route. Such

wavelength routed networks consist of wavelength cross connects (WXC) interconnected by point-to-point fiber links. The end user (end node) is connected to a WXC via a fiber link. The end node along with its WXC is collectively called as a node. Each node has transmitters and receivers (either tunable or fixed) for sending and receiving data on the lightpaths [6]. A lightpath must use the same wavelength on all the links in the route. This is known as wavelength continuity constraint. However, if wavelength converters are present, the lightpath may be converted from one wavelength to another at an intermediate node. A wavelength can also be used by multiple lightpaths as long as they do not have any common links along the route. This allows spatial reuse of wavelengths in different parts of the network and this property is called wavelength reuse. The wavelength reuse in OCS networks makes them scalable and cost efficient [6]. A lightpath setup involves various phases such as topology and resource discovery, routing and wavelength assignment, signaling and resource reservation. Keeping track of network state information is the main goal of topology and resource discovery task. The network state information includes information about the physical network topology and the status of network links. For wavelength routed networks, information regarding the availability of wavelengths on a particular link in the network is very essential.

One of the core issues in wavelength routed networks is determining routes and assigning wavelength for lightpaths, known as routing and wavelength assignment problem. The lightpaths may be setup in a static or dynamic manner. When the set of connections is known beforehand, the problem of setting up lightpaths is known as static lightpath establishment problem and the goal is to achieve this while minimizing the network resources consumed such as number of wavelengths or fibers used in the network. In dynamic lightpath establishment, the lightpaths are setup in a dynamic way as the connection requests arrive in an online fashion. The objective in this case is to minimize the connection blocking and thus maximize the number of connections established in the network at any time. The literature is available which deals with the solution of lightpath establishment problems for static and dynamic connection requests [6]. One of the main disadvantages of OCS is that setting up a lightpath for long durations causes inefficient utilization of the resources particularly for bursty Internet traffic. A lightpath established once may remain so for days, weeks or months during which there might not be enough traffic to utilize the bandwidth. To avoid such wastage of bandwidth,

it is desired that optical networks have the capability of switching Internet Protocol (IP) packets directly and thus the concept of OPS has come into existence.

#### **1.4 Optical Packet Switching**

An OPS is another switching paradigm, which allows packet switching and routing in optical domain without conversion to electronics at each node [7]. An OPS node has switching fabric which is capable of reconfiguration on a packet-by-packet basis. An optical packet is sent along with its header without any prior path being setup into the network. At a core node, the packet is optically buffered using fiber delay lines (FDLs), while the header undergoes optical to electronic conversion and is processed electronically. 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 is sent. The practical limitation of OPS network is fast switching times while optical switches based on micro-electro-mechanical systems offering switching times of the order of 1 to 10ms. Though semiconductor optical amplifier based switches have considerably lower switching times (around 1ns), they are quite expensive and the switch architecture uses optical couplers which results in higher power losses. Since network resources are not reserved in advance in OPS, some optical packets may contend for the same output port resulting in packet losses. Lack of proper optical buffering technology aggravates the contention problem in OPS networks compared to the traditional electronic packet switching networks, where the electronic buffer technology is very mature. Optical buffering is realized through the use of FDLs which can hold an optical packet for a variable amount of time by implementing multiple delay lines in stages or in parallel [8-9]. The size of optical buffers is severely limited by physical space limitations. In order to delay an optical packet for 5 $\mu$ s, a kilometer length of optical fiber is required. Because of this limitation of optical buffers, an OPS node may not be suitable for handling high loads or bursty traffic. Another solution to the contention problem is to route the contending packets to a different output port other than the intended one. This technique is known as deflection routing. Deflection routing may cause looping and out of order delivery of packets and it requires further research to tackle these limitations [10-11]. Another issue in OPS is synchronization. In OPS networks with fixed length packets, synchronization of packets is required at the switch input port to reduce contention. Though this is difficult to implement, some synchronization techniques have been implemented [12-13].

To avoid the use of optical buffering and optical processing logic, OBS paradigm is studied [14]. OBS is considered as a popular switching paradigm for the realization of all-optical switching due to the balance it offers between coarse-grained OCS and fine-grained OPS.

### **1.5 Optical Burst Switching**

An OBS network has three components: an ingress node, an egress node and a network of core nodes. In OBS network, various types of client data from the access network are aggregated at an ingress node (an edge node) into a single data burst which is transmitted in optical domain. Packets destined to the same egress node (destination edge node) and requiring the same level of service are aggregated into a burst at the burst assembly queue. To avoid buffering and processing of data burst at intermediate nodes called core nodes, a control packet also called burst header packet (BHP), with the information on the length and arrival time of the data burst is sent in advance. The BHPs are transmitted on a dedicated control wavelength, while the data bursts are sent after some time on separate wavelengths. The time lag between a BHP and the corresponding data burst is called offset time which is set sufficient to enable the processing of BHP at the core nodes. Once a burst reaches the egress node, it is disassembled into packets which are routed through the access network. Generally, it is assumed that buffering of data is allowed only at the edge nodes since the technology for optical buffers is immature. The protocol for wavelength reservation in which the wavelength is reserved for the data burst only for its duration and the availability of resources is not acknowledged in any way is known as just-enough-time (JET) protocol [1]. When a data burst arrives at the core node and finds all the wavelengths busy at that time, it is simply dropped. Such losses are termed as contention losses which mainly occur due to the simultaneous arrival of bursts exceeding the number of available wavelengths at that instant. The handling of contention losses is a unique problem to buffer-less OBS networks and it cannot be handled in the same way as congestion in traditional networks (occurs due to the overflow of a queue) for the simple reason that these losses are temporary in nature. OBS combines the advantages of both OCS and OPS while overcoming their shortcomings.

The brief comparison of the three switching paradigms based on various factors is as follow:

### 1. Bandwidth utilization

Link utilization is lowest in OCS networks. A lightpath is setup over dedicated wavelengths from the source to destination node. Hence this lightpath cannot be used by the traffic on other paths, even when the load is low. OCS networks cannot accommodate highly variable or bursty network traffic. But OPS and OBS networks allow traffic between source and destination to share link bandwidth.

### 2. Setup latency

OBS networks use one way signaling schemes for reserving resources on the path before data transfer. Setup latency is very low in such networks, unlike OCS networks where dedicated signaling messages are exchanged between source and destination nodes to setup and tear down lightpaths [15].

### 3. Switching speed

As discussed earlier in Section 1.4, OPS networks require very high switching speed to switch optical packets to different output ports. On the other hand, switching speed required is low in OCS networks. Lightpaths are usually setup for longer durations and therefore the OCS switches have ample time for dynamic switch configuration. In the case of OBS networks, medium switching speed is sufficient due to the larger size of optical bursts compared to optical packets.

### 4. Processing complexity

In OPS networks, as the switching entity is an optical packet, the processing complexity is very high. The header has to be extracted from each packet and processed electronically. In OCS networks, as the lightpaths are set up for a longer duration, the complexity is relatively low when compared to OPS and OBS networks. Because of the larger granularity of bursts which are made up of several IP packets, the processing complexity of OBS falls in between that of OCS and OPS.

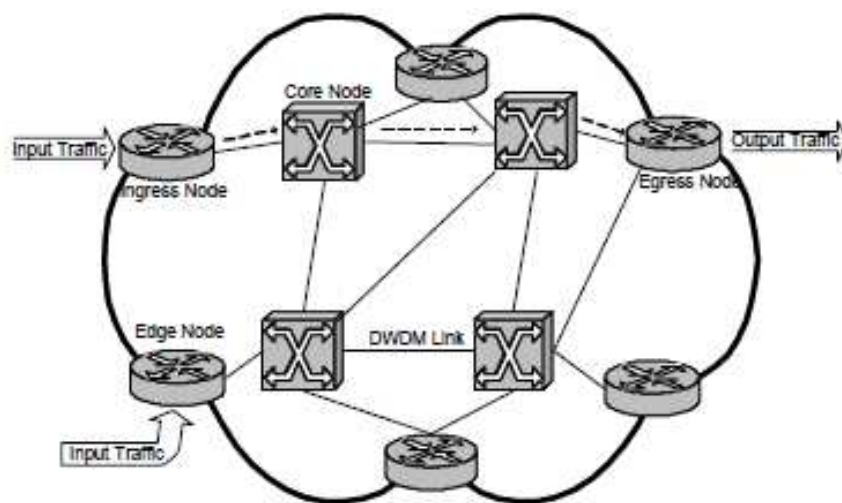
### 5. Traffic adaptivity

An OCS network is not adaptive to variable bursty traffic due to the high setup latency and the use of coarse-grained wavelength switching. But OPS and OBS

networks are capable of handling bursty traffic as they support statistical multiplexing.

### 1.5.1 OBS Network Architecture

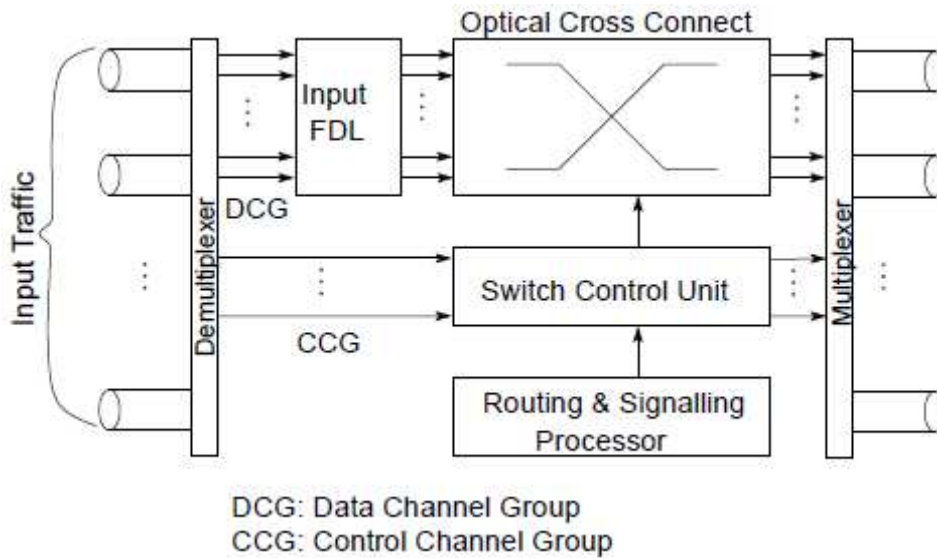
Figure 1.2 gives a block diagram that shows the functionalities of different nodes in an OBS network. There are primarily two types of nodes in an OBS network: edge nodes (ingress and egress nodes) and core nodes. The ingress node collects the IP packets from the access network into bursts and is also responsible for the generation of control packets which setup the path to the egress node. The main functions of an ingress node are: burst assembly, routing and wavelength assignment, signaling, generation of the BHP, and determination of the offset time. The core nodes are responsible for switching the data bursts all optically from one input port to another based on the information provided by the BHP. The core nodes are also responsible for resolving the contention among multiple bursts. The egress node disassembles the burst into IP packets and forwards them to the IP access network.



**Figure 1.2: OBS network architecture [1]**

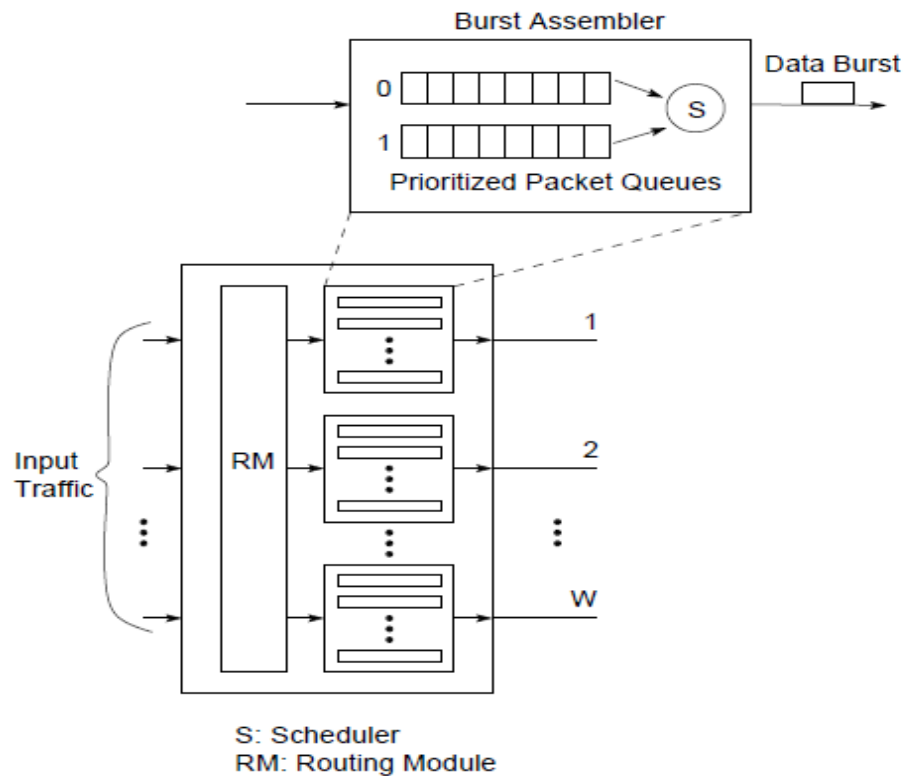
Figure 1.3 shows the architecture of an OBS core node. It consists of a switch control unit (SCU) and an optical cross connect (OXC). The SCU configures the OXC and maintains the forwarding tables. When the SCU receives a BHP, it consults the routing and signaling processors to identify the output port based on the destination. If the output port is available at the time of data burst arrival, the SCU configures the OXC to let the

burst pass through. In case the port is unavailable, SCU configures the OXC based on the contention resolution policy implemented. In case the data burst arrives at the OXC before the BHP the data burst is simply dropped. This problem is known as early burst arrival problem which might happen due to insufficient offset time for bursts at some nodes. The SCU has many important responsibilities which include, burst header interpretation, burst scheduling, contention resolution, forwarding table lookup, switching matrix control, header rewrite and wavelength conversion control.



**Figure 1.3: OBS core node architecture [2]**

Figure 1.4 depicts the architecture of an OBS ingress node. An ingress node comprises of a burst assembler, a routing module, and a scheduler. The ingress nodes have electronic buffers for the burst assembly and scheduling. Each burst assembler module generates bursts from packets destined towards the same egress node. There may be separate packet queues in the burst assembler for each class of traffic. Based on the destination address, the routing module forwards each packet to the corresponding burst assembler module. Different burst assembly mechanisms like burst size threshold based, timer based or a combination of both can be used to aggregate IP packets into bursts. Once the burst is assembled, the burst header packet (BHP) carrying the information about the burst is sent to the egress node. The scheduler module is responsible for scheduling the bursts on the outgoing links. At an egress node, a burst disassembler module which is composed of electronic buffers, disassembles the burst into constituent IP packets.



**Figure 1.4: OBS Edge node architecture [1]**

### 1.5.2 Burst Assembly

Burst assembly is the process of assembling incoming data from higher layers at the ingress node of the OBS network. The most important factor in burst assembly is the trigger criterion which determines when to release a burst. This criterion controls the characteristics of burst traffic into the OBS network. The most popular burst assembly techniques use either a timer or burst size threshold or both.

In time-based assembly, a burst is generated and sent into the network at periodic time intervals [16]. It gives uniform gaps between successive bursts from the same ingress node. In time-based assembly, burst length depends on the load.

In size-based assembly, fixed sized bursts are generated at non-periodic time intervals. In case packets have QoS restrictions, such as delay constraints, time-based assembly is a good choice.

A combination of both time and size-based assembly is proposed in [17] called min-burst-length-max-assembly-period where a burst is generated when a minimum burst length is reached or when the maximum assembly period is reached, whichever happens

first. This scheme provides the best of both methods and is more flexible. There are a few other burst assembly schemes that adapt the assembly parameters according to the traffic parameters [17-20].

A major problem in burst assembly is how to choose the appropriate timer and threshold values for creating a burst in order to minimize the packet loss probability in an OBS network. The selection of such an optimal threshold (or timer) value is still under investigation. If the threshold is too low, the bursts become very short and more bursts will be generated in the network. The higher number of bursts leads to a higher number of contentions, but the average number of packets lost per contention is less. Also, there will be increased pressure on the control plane to process the control packets of each data burst in a quick and efficient manner. If the switch reconfiguration time is non-negligible, shorter bursts will lead to lower network utilization due to the high switching time overhead for each switched (scheduled) burst. On the other hand, if the threshold is too high, then bursts will be long, which will reduce the total number of bursts injected into the network. Hence, the number of contention in the network reduces compared to the case of having shorter burst, but the average number of packets lost per contention will increase. Thus, there exists a tradeoff between the number of contentions and the average number of packets lost per contention. Hence, the performance of an OBS network can be improved if the incoming packets are assembled into bursts of optimal length. The same criterion is also true in a timer-based assembly mechanism.

In [21-25], the authors consider a number of issues regarding burst assembly techniques. In [21], for example, a prediction-based assembly technique was proposed, in which the threshold value (or the timer value) of the next burst is predicted ahead of time based on the incoming traffic rate. Using the predicted burst length, the burst header packet (BHP) can be sent into the core network before the actual creation of the burst, allowing early resource reservation in the OBS core; thereby, reducing the burst assembly delay. In [22-25], the authors study the impact of burst assembly on long range dependency of the input packetized traffic.

### **1.5.3 Routing and Wavelength Assignment (RWA)**

Routing and wavelength assignment is the fundamental control problem in WDM wavelength routed networks. In WDM wavelength routed optical networks, lightpaths need to be established before any communication takes place between the nodes. In order

to establish a lightpath between two nodes, two decisions have to be made. The first is the selection of the path from the source node to the destination node and the second is the selection of wavelength to be assigned to the path.

Many problems in wavelength routed networks have RWA as a sub problem. Depending on the traffic in the network, the RWA problem is classified into static and dynamic. In case of static traffic demand, the connection requests are known in advance. The traffic demand may be provided in terms of source-destination pairs. The objective is to assign routes and wavelengths so as to maximize the number of demands satisfied. In dynamic traffic demand, the connection requests arrive and depart randomly. The established lightpaths will remain only for a finite time. Since the traffic is dynamic, the network has no knowledge of future connection requests. Because of this, the dynamic RWA algorithms perform poorly when compared to the static RWA algorithms [26-29]. A dynamic RWA algorithm processes the connection requests strictly in the order of connection arrival time, whereas a static RWA algorithm processes the connection requests in the order decided by some heuristic.

#### **1.5.4 Reservation Schemes**

Optical Burst switching schemes differ based on how and when the network resources like bandwidth, are reserved and released. Optical burst switching is an adaptation of burst switching technique in asynchronous transfer mode (ATM) networks, known as ATM block transfer (ABT) [30]. There are two versions of ABT: ABT with delayed transmission and ABT with immediate transmission.

In case of an immediate reservation scheme, an output wavelength is reserved for a data burst immediately after the arrival of the corresponding control burst; if a wavelength cannot be reserved at that time, then the setup message is rejected and the corresponding burst is dropped [31]. In a delayed reservation scheme, the control burst (CB) and the data burst (DB) are separated in time by an offset value in order to accommodate the processing of the CB. An output wavelength is reserved for a burst just before the arrival of the first bit of the burst. If, upon arrival of the setup message, it is determined that no wavelength can be reserved at the appropriate time, then the setup message is rejected and the corresponding burst is dropped [31]. These two techniques have been adopted in OBS. Depending on bandwidth reservation, offset time and control

management, three schemes for OBS implementation have been proposed: Tell-and-go (TAG) [31], Just-in-time (JIT) [32-33] and Just-enough-time (JET) [34].

### 1. Tell-And-Go (TAG)

This is an immediate reservation scheme. In TAG, the CB is transmitted on a control channel followed by a DB, which is transmitted on a data channel with zero or negligible offset. The CB reserves the wavelength and buffer (FDL) at each intermediate node along the path for the DB. When the DB reaches an intermediate node, it is buffered using the reserved FDL until the CB processing is finished. Then the DB is transmitted along the reserved channel. If no wavelength is available for reservation, the burst is dropped and a negative acknowledgement (NAK) is sent to the source. The source node sends another CB after transmitting the DB for releasing the reserved wavelengths along the path. Here, the burst size is not fixed in advance. FDLs are expensive and they can only buffer data optically for a very short time. Optical buffering is the main drawback of this scheme. Furthermore, if the “release” CB which is sent to release the reserved bandwidth along the path is lost, then these wavelengths will not be released and this creates bandwidth wastage .

### 2. Just-In-Time (JIT)

This scheme also comes under immediate reservation. Here, an output wavelength is reserved for the upcoming burst as soon as the CB processing is finished. The source transmits the DB after an offset time which is greater than the total CB processing time. If the wavelength is not available, the burst is dropped. The difference between JIT and TAG is that the buffering of the DB at each node is eliminated by inserting a time gap between the CB and the DB. Since the bandwidth is reserved immediately after the CB processing, the wavelength will be idle from the time the reservation is made till the first bit of the DB arrives at the node. This is because of the offset between the CB and the DB. Since the offset value decreases as the CB gets closer to the destination, the idle time also decreases. An in-band-terminator is placed at the end of each burst which is used by each node to release the reserved wavelength after transmitting the DB [32,35].

### 3. Just-Enough-Time (JET)

This is a delayed reservation scheme. Here, the size of the burst is decided before the CB is transmitted by the source. The offset between CB and DB is also calculated based on

the hop count between the source and destination. At each node, if bandwidth is available, the CB reserves wavelength for the upcoming burst for a fixed duration of time. The reservation is made from the time when the first bit of DB reaches the node till the last bit of DB is transmitted to the output port. This eliminates the wavelength idle time which is the main difference between JET and JIT. Since the wavelength is reserved for a fixed duration, there is no need for explicit signal for releasing the reserved wavelength along the path. Since there is no wastage of bandwidth in this scheme, the network utilization for this scheme is higher than with the other schemes. But, this scheme involves complex scheduling when compared to other schemes.

TAG and JIT schemes are significantly simpler than JET since they do not involve complex scheduling or void-filling algorithms. On the other hand, previous studies have shown that JET performs better than either JIT or TAG in terms of burst loss probability [31, 34].

### **1.5.5 Channel Scheduling**

When a burst arrives at a node, it must be scheduled on an appropriate wavelength on the outgoing link. The main objective in this type of scheduling is to minimize “gaps”, where a gap is the idle time between two bursts which are transmitted over the same wavelength. One of the most popular scheduling algorithms is the latest available unscheduled channel (LAUC) scheduling algorithm [14]. This algorithm maintains the starting and ending times of each scheduled burst on every channel. It also maintains the latest available unscheduled time on each wavelength and when a new burst arrives it is scheduled on a wavelength such that the gap is minimal. Simplicity and ease of implementation are the main advantages of the LAUC scheduling algorithm as the scheduler needs to remember only one value, the unscheduled time, for each data wavelength. Since, LAUC scheduling algorithm only keeps track of a single state for each wavelength (latest time at which a wavelength is scheduled to be used), it cannot utilize the voids created by previously scheduled bursts. Therefore, LAUC scheduling algorithm can cause excessive burst losses when the variation in the offset time between the BHPs and the bursts is large. On the other hand the void filling version of this algorithm, latest available unscheduled channel-void filling (LAUC-VF) scheduling algorithm proposed in [30], keeps track of all the voids (gaps) on the wavelengths and tries to schedule a burst in one of the voids whenever possible. LAUC-VF scheduling algorithm is more complex than the LAUC scheduling

algorithm as it has to maintain extra state information of the available voids for each data channel. More details about the LAUC-VF scheduling algorithm can be found in [14]. Since the LAUC-VF scheduling algorithm can use the voids created by previously scheduled bursts, its link utilization is higher than that of the LAUC scheduling algorithm. However, it takes much longer to schedule a burst.

### **1.5.6 Contention Resolution**

As optical burst switched (OBS) networks provide connection-less transport, the bursts may contend with one another at the intermediate nodes. Burst loss due to contention is a major source of concern in OBS networks. Such contention losses which are temporary in nature, can degrade the performance at the higher layers. Contention among two bursts occurs due to the overlap of two bursts (in time) arriving simultaneously on two different links or wavelengths and requesting the same wavelength at a given time. In electronic packet switching networks, contention is handled by buffering. However optical buffers are difficult to implement and there is no optical equivalent of random access memory. When multiple bursts contend for a wavelength at an intermediate node, all but one of the contending bursts is dropped. In OBS, when two or more bursts contend for the same wavelength and for the same time duration, only one of them is allotted the bandwidth. The following is the briefly discussion about the main techniques used to resolve contention for a wavelength at the OBS core nodes.

#### **1. Optical Buffering**

In OBS networks, optical buffers based on FDLs can be used to delay packets for a fixed amount of time [36]. Optical buffers are either single stage, which have only one block of FDLs, or multistage which have several blocks of FDLs cascaded together, where each block consists of a set of parallel FDLs. Optical buffers can be broadly classified into feed-forward, feedback and hybrid architectures [37]. If a FDL connects the output port of a switching element at one stage to the input port of another switching element at the next stage it is called feed-forward architecture. In feedback architecture, the FDL connects the output port of a switching element at one stage to the input port of a switching element at the previous or current stage. A hybrid architecture combines both feed-forward and feedback architectures.

## 2. Wavelength Conversion

If two bursts contend for the same wavelength at a core node, they can be sent on different wavelengths to resolve the contention. Wavelength conversion is the process of converting the bursts on one wavelength in an incoming link to a different wavelength in the outgoing link. This helps to improve wavelength reuse in which the wavelength can be spatially reused to carry different connections on different fiber links in the network. Wavelength conversion is of four types: full wavelength conversion, limited conversion, fixed conversion, and partial wavelength conversion. In full conversion, any incoming wavelength can be shifted to any outgoing wavelength, while in limited conversion, not all incoming channels can be connected to all outgoing channels. In fixed conversion, each incoming channel may be connected to one or more predetermined channels only. In partial wavelength conversion, different nodes in the network can have different levels of wavelength conversion capability [38].

## 3. Deflection Routing

This is a technique of deflecting the bursts onto alternate paths towards the destination in case of contention for a wavelength at a core node [39]. Deflection routing has many disadvantages. It is by nature suboptimal, since it only considers the congestion of the current switch, not the state of links in the forward path. The implementation of deflection routing requires changing the offset time of a burst along the path which is impossible without the use of FDLs. Since deflection routing is done by each individual node without cooperation from the rest of the network, it can lead to routing loops which are very dangerous. Further, deflection routing was found to cause network instability causing a sudden drop in the network throughput [40].

## 4. Burst Segmentation

In burst segmentation, a portion of the burst which overlaps with another burst is segmented instead of dropping the entire burst. When two bursts contend for the same wavelength, either the head of the contending burst, or the tail of the other burst is dropped. In such case, one or a combination of the following three major options for contention resolution can be applied in addition to the option of dropping the unsuccessful bursts is segmented and dropped [30]. Therefore segmentation can be classified into head dropping or tail dropping. The remaining segment of the burst is

transmitted successfully to the destination thereby increasing the packet delivery ratio. A combination of both segmentation and deflection routing has also been proposed for contention resolution [41].

### **1.5.7 Quality-of-Service**

Quality-of-Service (QoS) in the Internet is critical due to service requirements needed by different applications. Hence, an important issue in OBS networks is supporting QoS. Quality-of-service schemes can be implemented in conjunction with existing contention resolution mechanisms and scheduling algorithms. Such schemes can be based on providing loss, delay, or bandwidth constraints or differentiation. Thus, two important objectives in any QoS model are to ensure fairness and maintain high utilization. QoS schemes are classified as relative and absolute methods.

In the relative QoS model, the performance of each class is defined relative to other classes. In such methods, there is no upper bound guarantee on the high priority-class loss probability. Several schemes have been developed to support the relative QoS model. For example, in offset-based QoS, extra offset is given to data bursts with higher priority resulting them to have relatively lower overall blocking probability. This scheme, known as prioritized JET, is proposed in [42] and its limitations are discussed in [43].

The absolute QoS (or quantitative QoS), on the other hand, provides a bound guarantee for the desired traffic metric such as loss probability of different classes. Typically, real time applications with delay and bandwidth constraints, such as multimedia, require such hard guarantee. An early example of bounded QoS is proposed in [44]. In this scheme a two-way lightpath reservation, along with a centralized scheduling technique, is proposed to provide bounded blocking probabilities. Other examples of absolute QoS schemes include early dropping and wavelength grouping schemes proposed in [45-46].

## **1.6 Motivation**

With the rapid growth of the Internet and the rapid evolution of Dense Wavelength Division Multiplexing (DWDM) technique, optical fiber seems to be the perfect carrier for future high-speed networks. In a DWDM system, each fiber carries multiple communication channels, with each channel operating on a different wavelength. Such an optical transmission system has a potential capacity to provide over 50 Tbps bandwidth

on a single fiber. Current networks typically consist of four layers: IP layer for carrying applications and services, ATM (asynchronous transfer mode) layer for traffic engineering, SONET/SDH layer for transport and DWDM for capacity. When the data stream arrives at a switching point, the optical signal of data is converted into electronic form and the processing and forwarding are done in the electronic domain. This is known as an Optical-Electronic (O/E) conversion. When the electronic signal of data is passed to the output port, it is again converted and modulated onto the fiber as an optical signal (Electronic-Optical). Such a switching point is said to perform O/E/O conversion. In such a network, all communications are limited by the electronic processing capabilities of the system. Although hardware-based high-speed electronic IP routers with capacity up to a few hundred gigabits per second are available now, there is still a serious mismatch between the transmission capacity of WDM fibers and the switching capacity of electronic IP routers. With IP traffic as the dominant traffic in the networks, the traditional layered network architecture is no longer adapted to the evolution of the Internet. In the multi-layered architecture, each layer may limit the scalability of the entire network, as well as adding the cost of the entire network. As the capabilities of both routers and OXC (optical cross-connects) grow rapidly, the high data rates of optical transport suggest bypassing the SONET/SDH and ATM layers and moving their necessary functions to other layers. This results in a simpler, more cost-efficient network that can transport very large volumes of traffic. IP over WDM is considered as a promising solution for the next generation network since it has no intermediate layer so that it can void the functionality redundancy of the ATM and SONET/SDH layers.

There are still some difficulties in realizing all optical networks, such as the optical RAM are ongoing research now and some technologies and standards have to be designed. So the processing of IP packets in the optical domain is still not practical yet and the optical router control system is implemented electronically. In optical transport networks, the control messages are processed electronically and the data are propagated in the high-speed transparent data channels. To realize an IP-over-DWDM architecture, several approaches, such as Wavelength Routing (WR), Optical Packet Switching (OPS) and Optical Burst Switching (OBS) have been proposed. Of all these approaches, optical burst switching (OBS) achieves a good balance between the coarse-gained wavelength routing and fine-gained optical packet switching, thereby combining others' benefits while avoiding their shortcomings.

Although, in literature, there are many proposals for OBS architectures, reservation schemes, burst dropping schemes and contention resolution, still there are limited efforts to provide guaranteed end-to-end bounds, reduced blocking probability, efficient utilization of bandwidth and network resources etc. Also, most of the literature in analysis of contention resolution mechanisms limits to a single path.

Thus, in this thesis, we have studied and presented the performance of various proposed schemes for OBS in terms of efficient network architectures alternatives, reservation schemes supporting QoS, efficient burst dropping techniques, better congestion control and resolution schemes. The results obtained show that our proposed schemes for OBS, exhibit better performance metrics such as low burst (packet) loss probabilities, high throughput and reliability, cost-effectiveness and lower delays when compared to conventional techniques proposed in the literature.

### **1.7 Objectives of Thesis**

Considering above mentioned challenges for optical burst switching, objectives of the research were formulated which are listed as follows:

1. To study and analyze various optical burst switching architectural alternatives in terms of the burst handling techniques and with the possible use of fiber delay-line for buffering and contention resolution.
2. To study and compare various reservation schemes for efficient network utilization and bandwidth in optical burst switched networks.
3. To analyze and compare the different burst segmentation policies with the standard dropping policies.
4. To investigate, analyze and compare the performance of various contention resolution policies and control schemes for optical burst switched network, in order to reduce packet/burst loss, while supporting quality of service.

### **1.8 Contribution of Thesis**

In the thesis, we have analyzed and presented possible solutions to several critical issues affecting optical burst switching performance, such as burst loss probability, quality of service, burst assembly, bandwidth utilization, burst dropping and contention. Our main contributions to this thesis are as follows:

To have reduced blocking probability, better throughput, efficient burst aggregation and simplicity, performance oriented OBS network's architecture alternatives has been presented and compared with conventional architectures. An efficient OBS network architecture employing small fiber delay line (FDL) in conjunction with adaptive burst assembly and dynamic route selection technique has been proposed to improve system performance. Also, in order to have lower switching processing time and delay associated with FDL usage, in the above architecture, another efficient congestion-free OBS network architecture utilizing a short- prior-confirmation-packet (SPCP) and optical label processing with Just-enough-time (JET) signaling has been presented. The results obtained have indicated that the proposed OBS architectures reduce the simultaneous contention in the core network and make the traffic smoother and hence improve the performance in terms of burst loss rate and throughput.

Next, to enhance bandwidth and channel utilization in optical burst switched (OBS) networks, efficient quality of service (QoS) oriented reservation schemes has been investigated. An adaptive reservation scheme for high-speed optical transport networks has been proposed, which provides a flexible and efficient platform for convergence of packet-based and circuit-based network traffic based on OBS capabilities. Also, to have better channel utilization, throughput etc, we have investigated another efficient scheme in which data burst are scheduled in batches. The heuristic interval scheduling algorithm is utilized to obtain the maximum number of non-overlapping bursts. Further, to address the problem of fairness control between short and long distance packets, we have analyzed and presented another efficient reservation scheme in which each edge router finds a suitable route to the destination edge router autonomously by using feedback and prior-information packets. The results achieved show that with the proposed reservation schemes, the packet delay is kept within the constraint for each traffic flow and the performance metrics such as burst loss rate, network utilization, throughput and fairness are remarkably improved. By leveraging statistical multiplexing, re-configuration is minimized and bandwidth utilization is enhanced.

The effective and flexible burst dropping techniques/policies have been presented to achieve lower burst dropping rate. In the proposed burst dropping scheme based on even selection of burst (BDPES), the dropped segments are evenly distributed between the contending bursts to achieve some kind of fairness between traffic flows and to minimize

the number of short data bursts. Further, by analyzing various contention scenarios, it is observed that the conventional burst dropping schemes are not able to utilize available bandwidth efficiently. Thus, we have investigated another efficient burst dropping scheme to use bandwidth efficiently. In the proposed scheme, any segment based on packet count number (PCN) in either a scheduled burst or a contending burst can be dropped to resolve contention. The results achieved confirm that the proposed burst dropping schemes performs better in terms of burst (packet) loss rate, bandwidth utilization and flexibility as compared to traditional dropping schemes.

Finally, we have analyzed and presented possible solutions to the contention losses in OBS networks. Through hybrid contention resolution techniques such as (a) wavelength conversion, delay and deflect (b) wavelength conversion, deflect and delay (c) Prioritized delay, deflect and delay policy, it is shown that both contention and the burst loss rate have been minimized. Also, to resolve burst contention in OBS networks, an efficient integrated scheme has been developed based on adaptive wavelength selection and burst assignment, which supports proportional differentiated services in buffer-less OBS networks. Further, to have both contention resolution and congestion control for reducing burst loss in the network, we have investigated integrated contention resolution and control scheme for optical burst switched networks. Also, based on resource-reservation and adaptive network flow routing, an efficient scheme to alleviate resource contention in optical burst switching network, is proposed. Through simulations, it has been demonstrated that the proposed schemes reduce burst loss in the network significantly and improves wavelength utilization and efficiency as compared to the static flow routing schemes

In general, all the above proposed schemes (techniques) provide better solutions to many of the critical issues faced by optical burst switching, thereby making OBS more practical and efficient for high speed networks.

## **1.9 Thesis Organization**

The organization of the thesis is as follows:

Chapter I presents the evolution of optical networks, compares optical switching paradigms and specifically covers the detailed description of optical burst switching.

Also, it includes the basic concepts in optical networks, problem formulation, objectives and major contributions of the thesis.

Chapter II covers the comprehensive literature survey of optical burst switching related to network architectures, reservation and scheduling schemes, burst dropping techniques, contention resolution and congestion control schemes.

Chapter III presents and compares the performance of proposed optical burst switching network architecture alternatives for handling bursty traffic efficiently, reducing burst blocking probability etc to the other already described architectures in the literature.

Chapter IV discusses various quality of service (QoS) oriented, wavelength reservation techniques supporting efficient bandwidth as well as network utilization. Also, it covers the comparison of proposed and conventional reservation schemes.

Chapter V presents efficient burst dropping techniques to reduce burst (packet) loss due to contention in optical burst switched networks. Also, it compares our proposed techniques with those for previously known burst dropping schemes.

Chapter VI covers the proposed efficient and flexible contention (congestion) resolution techniques. It also presents the comparison of proposed techniques with traditional ones in terms of performance metrics such as burst loss rate and QoS.

Finally, the conclusions drawn, recommendations and suggestions for the future scope of the work are given in chapter VII.

## CHAPTER II

### LITERATURE SURVEY

In this chapter, we have discussed the comprehensive literature review of various performance related issues of optical burst switching (OBS). In section 2.1, various OBS architecture alternatives has been described , which also covers the efficient the burst handling and fiber delay-line techniques for buffering and contention resolution. In section 2.2, several reservation schemes for efficient network utilization and bandwidth in optical burst switched networks are discussed. In section 2.3, different burst dropping techniques are studied and described. Finally, in section 2.4, we described the performance of various contention resolution policies and control schemes in terms of quality of service, burst loss rate etc.

#### **2.1 Optical Burst Switched Network Architectures Alternatives**

The architectures based on optical burst switching (OBS) comprises of edge nodes (ingress and egress nodes) and core nodes. The ingress node collects the IP packets from the access network into bursts and is also responsible for the generation of control packets which setup the path to the egress node. The core nodes are responsible for switching the data bursts all optically from one input port to another based on the information provided by the BHP. The various types of OBS architecture alternatives are described in the literature.

*A. Birman* [47] described that wavelength routed networks are not equivalent to electronic circuit switched networks because circuits in a circuit switching network are indistinguishable whereas wavelengths are not because of the continuity constraint that a lightpath take the same wavelength on all links. For this reason, wavelength routed networks suffer higher blocking probabilities than circuit switched networks.

*J. M. Yates et al.* [48] presented networks where wavelength conversion is provided by exploiting four wave mixing (FWM) in semiconductor optical amplifiers (SOAs). Such wavelength converters are limited, meaning that they degrade the signal by an amount which depends on the difference between input and output wavelengths. Thus they do not have absolute freedom to convert from any input to any output wavelength.

Also, *J. M. Yates et al.* [48] introduced the notion of a cost incurred in traversing a cross-connect and a budget for lightpaths from any given point to a given destination.

Using this framework, they showed that limited wavelength conversion networks can give blocking performance close to that of networks with ideal converters.

C. *Qiao* [49] proposed labeled optical burst switched networks (LOBS) as another architecture alternative. These networks try to reconcile the need for serving packetized traffic and the present technological limitation of optics such as RAM, buffering and synchronization. LOBS architecture is viewed as a natural extension of the multi-protocol label switching (MPLS) framework for OBS. In this architecture the MPLS functionality serves as an integration layer between IP and the WDM. A LOBS architecture provides path provisioning, traffic and resource engineering, network survivability and several other features related to the MPLS framework. In LOBS node architecture, incoming bursts can be locally disassembled and again assembled and reinserted into the network. MPLS messages are used to control burst switching, bandwidth reservation and mainly serve to reduce the complexities associated with defining and maintaining a separate optical (burst switching) layer. Additionally, [49] also suggests that from LOBS-based networks, migration and inter-networking with optical packet switching will be easier.

R. *Dutta and G.N. Rouskas* [50] introduced a survey of virtual topology design algorithms for wavelength routed optical networks. A limited set of lightpaths is established between pairs of nodes in the semi-static wavelength routed optical networks (WRONs), which allow embedding a virtual topology in the physical topology. The benefit of this architecture is that the virtual topology can be reconfigured, for instance, to adapt to traffic changes or to react to network failures, but it has the drawback that some traffic may require conversion to the electronic domain at intermediate nodes.

In dynamic WRONs as introduced by *H. Zang et al.* [51], the lightpaths between any two network nodes are established and released on demand on real time. In this scenario, traffic is always transmitted from source to destination without electronic conversion at intermediate nodes. Although, WRONs are relatively easy to build and manage, they do not fully solve the problem of efficient support of traffic services and optimization of optical network resources.

I. *Chlamtac et al.* [52] introduced re-circulating buffer as one of several possible optical packet buffer architectures. Architecture consists of a number of fiber delay lines (FDLs) of varying lengths. Each length is usually a multiple of the packet size. The FDLs may be arranged in parallel or in series, allowing a large number of flexible delays to be

selected by routing the packet through the correct path in the switch. Re-circulating buffers suffer from the fact that at each recirculation the attenuation of the packet in the fiber must be reversed by amplification, which introduces Amplifier Spontaneous Emission (ASE) noise. Traveling type buffers are inflexible since only a finite number of delay times can be synthesized with a finite number of FDLs. Hence photonic buffering remains a significant problem which lags behind the logical and temporal capabilities of electronic memories.

*M. Düser et al.* [53] and *I. de Miguel et al.* [54] proposed wavelength-routed optical burst-switched networks (WR-OBS) as another promising architectures for the transmission of packets with guaranteed maximum end-to-end delays. These are hybrid architectures using dynamic WRONs and OBS networks and are based on the acknowledged establishment of dynamic lightpaths for the transmission of bursts.

One of the common features of the architectures alternatives proposed above is that none of them can transport efficiently different traffic types and services while making efficient use of optical network resources and bandwidth.

*Chunshen Xin et al.* [55] presented hybrid OBS/OCS network architectures which aim at isolating traffic classes and providing differentiated transport services to client layers. Thus, they partition network resources completely and classify traffic flows at the electro/optical interface of the edge router for OBS or OCS transport. Since these approaches assume that traffic is already highly aggregated at the E/O interface and qualifies at least for wavelength granularity, they are not applicable for transport of smaller burst data streams at the edge of metro networks.

The approach proposed by *E. Van Breusegem et al.* [56] aims at balancing network utilization by inserting specially marked IP packets in gaps otherwise dedicated lightpaths. This approach does not consider optical switching and requires network state information of the IP and the WDM layers.

Dynamic Wavelength-Routed Optical Burst Switched Network Architecture (DWR-OBS) was proposed in 2003 by *A. Zapata and P. Bayvel* [57]. It is a compromise between the TAG-OBS and TAW-OBS, as it proposes a node whose function is to act as a reservation request broker to the network. DWR-OBS elects one node in the network to evaluate the resource reservation requests from the edge nodes. This node, called Central

Node then issues back acknowledgment or rejection to the requesting nodes, thus managing all the network resources. Analysis performed in [57] shows that this architecture can cope up to 115 nodes, thus making it suitable for medium size networks. This limitation rises because of the computational load posed on the central node, which must process all the requests from all the nodes. Another limitation of this network is the burst assembly time, which must be long enough as to allow the request to travel from the ingress node to the central node and back.

*P. Bayvel et al.* [58], considered DWR–OBS in an arbitrary type-II OBS network, one whose burst assembly times go from 2.5  $\mu$ s to 25 ms, although it is not explained why OBS networks should be classified according to burst assembly times. One of the common criticisms about this architecture is that a single point of decision is vulnerability for the network operation and that the collapse of such a node (or its connecting links) would render ineffective the whole network for a period of time until a new Central Node becomes active.

*Mohamed Mostafa et al.* [59] proposed new hybrid architecture for optical burst switching networks to support connection-oriented applications. Although efficient in terms of reducing the burst loss probability as well as improving the overall network performance, it provides a limited degree of quality of service (QoS).

*Christoph M. Gauger et al.* [60] developed an optical burst transport network (OBTN) which is optimized towards effective contention resolution to provide an overall very low burst-loss probability while minimizing transit traffic and reducing node sizes. *Y.-L. Hsueh et al.* [61] proposed a new optical burst transport (OBT) architecture to bridge the architectural mismatch between a circuit-based physical transport and the carried bursty packet streams. OBT is based on burst-mode transmission between senders and receivers on a WDM ring topology and does not require complex electronic processing.

*H. Kong and C. Philips* [62] presented a pre-booking mechanism, derived from the DWR–OBS architecture. Authors claim that for a 90 ms end-to-end delay with a  $10^{-4}$  bit loss tolerance, the pre-booking mechanism yields approximately twice traffic as much as with the DWR–OBS.

*Jaedon Kim et al.* [63] proposed a sub-lambda traffic-grooming scheme on wavelength division multiplexing ring networks, named optical burst transport. The network protocol and architecture are designed to support dynamic bandwidth allocation, which is more reasonable for bursty data traffic.

*Farid Farahmand et al.* [64] proposed a new multi-layered architecture for supporting optical burst switching (OBS) in an optical core network. The architecture takes into account both the control plane as well as the data plane. The architecture describes the functionality and the primary protocols that are required at each layer and it explains how the layers interact with each other. Separate the control plane functionalities and protocols from those of the data plane. Such separation appears natural since the control information is transmitted out-of-band in OBS networks. However, the OBS architecture described here is general enough such that it is capable of supporting most types of higher-layer traffic. Thus, as a data transport system, the OBS network architecture implements the lower three layers, namely, physical, data link and network layer. This approach offers high flexibility but limited processing capacity (a few tens of gigabits per second). In this architecture, transmitting control packets (CPs) free of contention and in a highly reliable manner is also very critical, since any error or loss of CPs results in higher data burst loss.

*Nuno M. Garcia et al.* [65] presented new architectural approach to Optical Burst Switching networks which features a common control channel and a node locally maintained network model. The common control channel allows for a fast and efficient broadcast of the network control packets, which in turn are used by every node to update its local network model. The local network model allows efficient network resource planning as each node is aware of the reservation status intentions for the resources on each node.

*Sébastien Rumley et al.* [66] addressed the problem of controlling the performance of optical burst switching (OBS) networks in presence of non-stationary traffic demands. They proposed a joint burst admission control and forwarding mechanism that operates in core nodes. This mechanism dynamically adapts its behavior according to the feedback messages received from other nodes. By not forwarding certain bursts not complying with given requirements, an admission control is implicitly made. Moreover, by forwarding bursts to appropriately selected nodes, traffic balancing is achieved. The advantageous

effects of the proposed mechanism can additionally be amplified by granting extra offset time to the burst. The major advantage of proposed approach consists in the fact that OBS core nodes do not require the full knowledge of the topology anymore at initialization.

## **2.2 Reservation Schemes for Efficient Network Utilization and Bandwidth in OBS**

Optical burst switching (OBS) reservation schemes differ based on how and when the network resources like bandwidth, are reserved and released. There are two types of reservation schemes called as immediate reservation and delayed reservation scheme. In case of an immediate reservation scheme, an output wavelength is reserved for a data burst immediately after the arrival of the corresponding control burst. In a delayed reservation scheme, the control burst (CB) and the data burst (DB) are separated in time by an offset value in order to accommodate the processing of the CB. Depending on bandwidth reservation, offset time and control management; three schemes for OBS implementation have been proposed: Tell-And-Go (TAG), Just-In-Time and Just-Enough-Time (JET).

*J.Y.Wei et al.* [32] proposed another wavelength reservation scheme known as Just-In-Time (JIT) for OBS, in which the data burst is buffered at the edge node where electronic memory is cheap and abundant, rather than at the intermediate switching nodes where optical delay lines are expensive and limited. A source node sends a SETUP message to reserve wavelength before data transmission and a RELEASE message to release wavelength after data transmission. An intermediate switching node will attempt to reserve wavelength immediately when receiving a SETUP message and release wavelength on receiving a RELEASE message. However, it results in worse wavelength utilization due to the fact that the bandwidth holding time is bigger than the burst transmission time.

Also, *M.Yoo et al.* [42] proposed a wavelength reservation scheme known as Just-Enough-Time (JET) for OBS, in which the ingress node waits for a long offset time before it starts to transmit the data burst. The initial offset time is set to be larger than the total processing time of the burst header packet (BHP) along its path. (The calculation of initial offset time is based on the product of number of hops between the source and the destination with per-hop burst header processing time). If at any intermediate node, the reservation is unsuccessful, the burst will be dropped.

*A.Detti et al.* [67] proposed a wavelength reservation scheme known as Tell-And-Go (TAG) for OBS, in which a source node sends out a control packet to inform a burst's arrival. The source node then immediately sends out a data burst. In order to allow time for the processing of the control message and the configuring of the switch at each node, the burst may need to be buffered at each node. In TAG, there is no acknowledgment of the path setup and the control packets are sent on a separate channel.

*J. Li et al.* [68] described the working of one-way reservation protocol such as JET in OBS networks. In JET, a BHP reserves an output channel for a period of time equal to the burst length, starting at the expected burst arrival time, which can be determined based on the offset time value and the amount of processing time the BHP has encountered at the node up to this point in time. If the reservation is successful, the BHP adjusts the offset time for the next hop and is forwarded to the next hop; otherwise, the burst is blocked and will be discarded if there is no fiber delay lines (FDLs).

*S. Junghans et al.* [69] have described JET as RFD (reserve a fixed-duration) algorithm. This implies that the arrival time of the burst at the node and the duration of the transmission is well known at the node. The channel is reserved exactly for the time; the burst really needs the transmission link, but not longer and not earlier. This unique feature of JET is typically called delayed reservation (DR).

Comparing with JIT, the BHP in JET contains the information of the offset time and the burst length. So the wavelength at each intermediate node will be reserved at the start of the data burst and will be released at the end of the data burst (the capacity is reserved from the time when the burst data reaches the switch, not when the control packet arrives). This means the intervening link time can be allocated to some other transmission, improving utilization. This is known as "delayed reservation". Also, the control packet contains the duration of the data burst so that the switch knows when the capacity will be free again and know teardown message is required. Hence, JET has reduced the setup and teardown costs in comparison to circuit switching and TAG and is therefore much better suited to statistically multiplex short timescale switching. A detailed discussion for the JET protocol, together with a simulation-based performance evaluation for networks which retransmit lost bursts can be found in [70].

*M.Yoo et al.* [71] proposed a new optical burst switching protocol for supporting quality of service. They showed that their scheme reduces the burst dropping probability

by several orders of magnitude for high priority bursts at the expense of reducing the blocking probability slightly for low priority bursts, in a two class system. They also found that the overall blocking probability is unchanged when compared to a classless system. Also, they extended their work to analyze multiple classes and systems with fiber delay line (FDL) buffers in [42] where they applied M/M/k/k and M/M/k/D models to provide upper and lower bounds on the burst blocking probability for each class. They found that significant isolation can be achieved for the highest priority class, at the expense of the lower classes. This scheme obviously introduces extra delays for high priority classes which may be at odds with low delay requirements of some services.

*J.Turner et al.* [72] developed a burst switching technique known as “Horizon scheduling”, which is simpler than JET. This is because the state information in JET consists of the start and end times of each burst already allocated to a wavelength, whereas the Horizon scheme maintains only the current scheduling horizon for each channel, i.e. the latest time at which the channel is being used by a burst. Beyond the horizon is where the channel is guaranteed to be free and bursts may only be allocated there in this scheme. For this reason, it achieves lower utilization than JET, but it is much simpler to implement and so may be more attractive in eventual commercial implementations. *K.Dolzer et al.* [15] have discussed an overview of the Horizon, JET and JIT protocols, which shows that JET outperforming Horizon which outperforms JIT in terms of blocking probability. They also introduce an analysis of the blocking probability for a 2-class system which follows quality of service (QoS) scheme as proposed in [42] and extends their analysis. *K.Dolzer et al.* compared their analytical predictions with simulation outcomes and the lower bounds obtained by *M.Yoo et al.* [42]. They showed that their method provides good agreement with simulation and slightly overestimates the blocking probability.

Whilst JET, Horizon and JIT provide signaling protocols, it remains for each switch to decide to which wavelength an outgoing burst should actually be assigned. This is known as wavelength assignment or wavelength scheduling. The algorithms for wavelength scheduling were not discussed until *Y.Xiong et al.* [14] outlined several algorithms. They described a possible architecture for an optical burst switch, similar in design to existing packet switches and also proposed a system design for the control packet processor at the switch. They also described first a simple first-fit (FF) algorithm which does a round-robin search of available wavelengths and assigns the first found; a

latest available unscheduled channel (LAUC) algorithm which is essentially the same as the Horizon algorithm [72] and assigns the burst to the channel which has the latest horizon time (to use the smallest gaps first so that later arrivals which need larger slots are not blocked); and the latest available unused channel with void filling algorithm (LAUC-VF) which exploits knowledge of all burst start and end times to place bursts in gaps between other bursts when it can. Using a self-similar traffic model based on Fractional Gaussian Noise, they simulated their algorithms and found that LAUC-VF performs best, followed by LAUC and FF, in terms of burst loss ratio.

The LAUC-VF algorithm has since been extended in various ways, for instance *M.Yang et al.* [73] give a modification to LAUC-VF for hardware implementation and extend the algorithm such that control packets are queued separately according to service class, with the highest priority queue served first (according to the LAUC-VF discipline) and subsequent queues served in descending priority order until all control packets in all queues are exhausted. In this way, the high priority bursts are given the best pick of available wavelengths and are more likely to be accepted, at the expense of the lower priority bursts. This is a simple idea and produces more than an order of magnitude reduction in the blocking probability of high priority bursts, again at the expense of a worsening in the blocking probability for the lowest priority class. Their system is also slotted and the simulation was performed on essentially a ring of core nodes, with each core node (switch) connected to one source as well as its neighboring core nodes.

*X.Wang et al.* [74] described a highly novel algorithm in which each switch monitors its success rate when sending on each wavelength to each destination and preferentially transmits on the wavelength which succeeds the most when transmitting to that destination. The switches learn from statistical data collected and use a simple update procedure to update the preference given to each wavelength at each observation step. For low traffic intensity this was shown by simulation to provide up to two orders of magnitude of benefit in blocking probability over random wavelength assignment, however this benefit is all but lost for traffic intensities above 0.25. Furthermore, they did not compare their algorithm with LAUC or LAUC-VF, which both perform much better than the random wavelength assignment algorithm. Therefore this idea, which is unique, does not appear to perform well enough to compete with other proposed algorithms.

*J. Xu et al.* [75] presented efficient burst scheduling algorithms in optical burst-switched networks using geometric techniques. They show that Horizon scheduling provides fast wavelength scheduling. However, it can cause excessive burst discard since it can not utilize the voids created by previously scheduled bursts. LAUC-VF (Latest Available Unused Channel with Void Filling) can produce efficient channel schedules but it takes  $O(m)$  time to schedule a burst, which is too slow to be practical. The Min-SV (Minimum Starting Void) algorithm can produce the same wavelength schedule as LAUC-VF and its complexity is  $O(\log m)$  where  $m$  is the number of voids per channel. This is a significant improvement over LAUC-VF. However, Min-SV still requires  $10 \log(m)$  memory accesses for each burst request. It is not unusual that a system will have to keep track of 100 K to a million voids. This means that Min-SV takes up to a few microseconds to schedule a single burst, which is still too slow to meet the stringent burst scheduling requirement.

*I. Ogushi et al.* [76] proposed a parallel reservation protocol in order to improve unfairness of the burst loss probability among bursts with different numbers of hops. The parallel reservation protocol is based on backward reservation in which wavelengths along a transmission path are reserved with an ACK-type control message. It is seen that a burst transmission of the parallel reservation protocol is performed with two-way reservation and this results in larger burst transmission delay than the burst transmission based on one-way reservation.

For the delayed reservation in the OBS, a hop-by-hop priority-increasing scheme was proposed by *B. C. Kim et al.* [77]. In this method, the burst with a small number of remaining hops is given an extra offset time using FDLs. With this method, the loss probability of a burst with a small number of remaining hops decreases. However, this method is not effective due to the cost of FDLs.

*L. Yang et al.* [78] proposed a probabilistic preemption method for realizing service differentiation in the immediate reservation. In this method, a high priority burst can preempt a low priority burst based on the probabilistic parameter, resulting in a lower burst loss probability of high-priority burst than that of low-priority one.

The probabilistic preemption scheme allows multiple preemptions for a burst transmission; however, multiple preemption makes an overall burst-loss probability large as described by *T. Tachibana et al.* [79].

*B. Zhou et al.* [80] proposed a balanced just-in-time scheme (BJIT) and a prioritized random-early discard (PRED) scheme for improving unfairness in the immediate reservation. In BJIT, as a burst is transmitted from one hop to the next, this scheme gradually increases the number of wavelengths available for the burst. When BJIT is well tuned for reducing unfairness, however, the resulting overall burst loss probability increases. On the other hand, PRED is based on proactive burst dropping with a discarding probability that decreases as the burst hop number increases. This scheme discards a newly incoming burst according to probabilistic parameters at the source network access station. However, it is difficult to determine the optimal parameters a priori.

*Jing Teng et al.* [81] presented a detailed analysis of the JIT, JET and Horizon wavelength reservation schemes for optical burst switched (OBS) networks. They develop accurate models for an OBS node operating under the JET, JIT, and Horizon wavelength reservation schemes. The analytical models assume Poisson arrivals, but are valid for arbitrary burst length distributions and arbitrary offset length distributions. The models also account for the processing time of setup messages and the optical switch configuration times and thus, are very general.

One important finding of their work is that, under reasonable assumptions regarding current and future capabilities of optical switch and electronic (hardware) processing technologies, the performance in terms of burst drop probability of the (significantly simpler) JIT reservation scheme is very similar to that of the more complex JET or Horizon schemes. For network scenarios where JET or Horizon outperforms JIT, they introduce enhanced JIT (JIT<sup>+</sup>), a new reservation scheme which retains the simplicity of JIT but exhibits a performance behavior close to JET and Horizon. Another contribution made possible by their analysis is the characterization of the regions of network operation in which a more complex reservation scheme reduces to a simpler one (i.e., when JET reduces to Horizon, Horizon to JIT<sup>+</sup>, or JIT<sup>+</sup> to JIT).

*Z. F. Syahid et al.* [82] developed a simulation of JET and JIT protocols and evaluate their performances under very high bandwidth demands of bursty Internet traffic conditions. Their results identify that the performance of JET is better than JIT, under varying offset length and number of channel.

### 2.3 Burst Dropping Policy/Scheme in Optical Burst Switched Networks

In OBS networks, the contention is resolved either by dropping one of the contending bursts or more efficiently by dropping from one of the contending bursts only the parts that overlap with the other bursts. In both situations, only one data source will suffer the data loss in favor to the other. The policy for selecting which bursts to drop is referred to as the burst dropping policy. A dropping algorithm is utilized in conjunction with a scheduling algorithm to protect high priority bursts while reducing the overall burst loss rate.

*M. Yoo et al.* [42] introduced a prioritized offset scheme to provide quality of service (QoS) in a buffer-less OBS network. In this scheme, higher priority bursts are given a larger offset time with respect to lower priority bursts. By providing higher offset, the probability of reserving the resources for higher priority bursts is increased, while in turn the loss of higher priority bursts is decreased.

*Y. Chen et al.* [83] proposed an active packet dropping policy based on quality of service (QoS). The proposed policy intervenes before congestion occurs, as the selective dropping of data burst (DBs) is initiated according to the data traffic profile to guarantee that the higher priority classes have higher chances to make successful reservations. However, this scheme suffers from a major disadvantage that there is an absence of feedback from the core nodes to the edge nodes and thus traffic volume of different classes cannot be controlled. Furthermore, isolation between different traffic classes is not guaranteed. If the offered traffic load of a low-priority class is significantly augmented, which increases the overall burst loss probability; burst loss probabilities of all classes are increased. Therefore, an additional traffic control mechanism is required.

*V. Vokkarane et al.* [84] proposed a prioritized routing and burst segmentation for quality of service (QoS) in optical burst-switched networks. In segmentation-based scheme, each data burst is divided into several independent segments. If data bursts (DBs) contend for the same network resources, the contention is resolved by discarding or deflecting some segments of one of the contending bursts. The remaining part of the burst (truncated burst) will then be forwarded to the downstream nodes where it will experience more shortening, be dropped or be delivered to the egress node. Unfortunately, this scheme is implemented at the cost of increasing the size of the control packets, since the burst control packet (BCP) should at least contain the segment number, the burst length

and the routing information. Furthermore, the implementation of burst segmentation strategies is faced by some challenges and practical issues such as segment delineation, data-burst size, etc.

*P. Fan et al.* [85] proposed offset-based QoS scheme which adds an extra offset time to the basic offset between BCP and its corresponding DB. The additional offset time called QoS offset is to compensate for the processing time of the BCP. The duration of such a QoS offset is varied, depending on the priority of the service class. This offset-based QoS scheme is proposed for just enough time (JET), whereby higher priority classes have a larger offset. With this scheme, if a low-priority DB with no additional QoS offset time and a higher priority DB with a QoS offset try to make a reservation of the network resources, then, the DB with the larger offset will be able to reserve resources in advance and before the low-priority DB. This results in a lower burst loss probability of high priority classes than that of lower priority classes. Although the offset-based QoS scheme does provide an acceptable service differentiation, it is faced with some challenges that cannot be ignored. For example, DBs of high-priority classes suffer longer waiting time (delay) than the data bursts of low-priority classes. Furthermore, the scheme is non-preemptive i.e., as long as low priority DBs can block optical paths, no complete isolation is achieved. Yet, starvation of low-priority classes is possible if the offered traffic load of high priority bursts is high and not controlled. *V. M. Vokkarane et al.* [30] proposed a segmentation drop policy (SEG) with the assumption that each transmitted data burst consists of individual independent segments such as slots. Therefore, if contention occurs, only the segments of the lower priority burst involved in the contention are removed. Although the QoS-enabled segmentation algorithm appears to be straightforward, the hardware implementation suffers from multiple issues. For example, due to segments being dropped and packets can arrive out of order. Also, the authors in [30] described two approaches for dropping burst segments when contention occurs between bursts. The first approach is to drop the tail of the first burst and the second approach is to drop the head of the contending burst. A significant advantage of dropping the tail segments of bursts rather than the head segments is that there is a better chance of in-sequence delivery of packets at the destination, assuming that dropped packets are retransmitted at a later time. One issue that arises when the tail of a burst is dropped is that the header for the burst, which may be forwarded before the segmentation occurs, will still contain the original burst length; therefore, downstream nodes may not

know that the burst has been truncated. This may result in unnecessary packet loss. If a tail-dropping policy is strictly maintained throughout the network, then the tail of the truncated burst will always have lower priority, and will never preempt segments of any other burst. However for the case in which tail dropping is not strictly maintained, some action must be taken to avoid unnecessary packet losses.

*F. Farahmand et al.* [86-87] considered the various dropping schemes supporting QoS. The following is the detailed description of different drop policies.

Latest arrival drop policy (LDP) searches for an available unscheduled channel (as in LAUC-VF) and if no such channel is found, the latest incoming data burst will be discarded. Although the processing speed of BHPs in the LDP scheme is attractive, the main disadvantage of this technique is that it has relatively poor performance with respect to data loss when no buffers are utilized. Inherently, LDP is not capable of differentiating packets with different priority types.

Look-ahead contention resolution (LCR) policy takes advantage of the separation between the data bursts and the burst header packets. By receiving BHPs one offset time prior to their corresponding data bursts, it is possible to construct a look-ahead window with a size of appropriate time units (slots). Such a collective view of multiple BHPs results in more efficient decisions with regard to which incoming bursts should be discarded or reserved. The LCR mechanism offers absolute as well as proportional class isolation. In absolute class isolation the possibility of a high-priority burst being blocked by any lower priority burst is eliminated. On the other hand, in proportional class isolation the dropping criteria will be based on the relative length and priority level of data bursts. In such a scheme, it is possible that between a short duration high priority burst and a long duration low priority burst, the one with higher priority will be discarded. Clearly, in terms of complexity, minimal additional steps are required to enable service differentiation in LCR. An important issue pertaining to the performance of the LCR is its fairness. LCR is more likely to favor longer bursts and drop short bursts.

In shortest drop policy (SDP) scheme, each incoming burst slot is checked and upon detecting contention, the lower priority burst with the shortest duration and latest arrival time are preferentially be dropped. This allows BHPs to be processed and transmitted soon after they are received. One drawback of such a policy is its potential over-reserving of resources, since some earlier reservations may be eliminated later. In terms of

supporting class differentiation, SDP supports unlimited number of priority levels and requires no extra offset assignments for bursts with higher service requirements. It also guarantees complete class isolation. In addition, SDP offers proportional differentiation.

*Tachibana et al.* [88] introduced an approach in which low-priority bursts are intentionally dropped under certain conditions in order to reduce loss for high-priority bursts. The scheme provides a proportional reduction rather than a complete elimination of high-priority burst losses due to contention with low-priority bursts. A limitation of the scheme is that it can result in the unnecessary dropping of low-priority bursts. *L. Yang et al.* [78] proposed a probabilistic preemptive scheme for providing service differentiation in terms of burst blocking probability in OBS networks. In this scheme, high-priority class traffic is assigned a preemptive probability. Thus, high-priority bursts can preempt low priority bursts in a probabilistic manner. The authors claim that by changing the preemptive probability, an OBS node can adjust the ratio of burst blocking probability between different traffic classes, while the overall blocking probability is not affected.

*Q. Zhang et al.* [89,46] proposed an absolute QoS model that provides a worst-case loss probability for the guaranteed traffic. Two mechanisms for providing loss guarantees at OBS core nodes are an early dropping mechanism, which probabilistically drops the non-guaranteed traffic and a wavelength grouping mechanism, which provisions necessary wavelengths for the guaranteed traffic are proposed. It is shown that integrating these two mechanisms outperforms other schemes in providing loss guarantees, as well as reducing the loss experienced by the non-guaranteed traffic.

To have a better deal with a dynamic environment, a possible solution to provide a desired loss is to use a congestion control method by adjusting the burst sending rate or intentionally dropping burst at the edge nodes: e.g. the flow rates are adjusted according to some feedback information to control loss rate on per flow basis, as presented by *F. Farahmand et al.* [90].

*Zhang et al.* [91] introduced a retransmission scheme in which the bursts in the contention are dropped selectively according to the drop policy adopted in core nodes and retransmitted by edge nodes. The most representative drop policy is the Time-based Drop Policy (TDP), in which the contending burst, i.e., the burst arriving at the core node later, will be dropped in the contention.

A. *Abid et al.* [92] proposed a staged reservation scheme (SRS) based dropping policy in order to increase the throughput of the core-nodes and also to overcome some of the limitations introduced by the burst segmentation concept. By adopting SRS dropping policy, if a contention is anticipated in the core-nodes, the resources allocation process will not be aborted. Conversely, the burst control packet (BCP) is updated according to the resources that the core-node can provide. Hence, only the overlapping segments are dropped at the arrival time, allowing part of the data burst (DB) to be transmitted. Thus, the contention is resolved at the BCPs level rather than at the DBs level.

*Kim et al.* [93] proposed a retransmission-count based drop policy (RCDP). In RCDP, when the contention occurred, retransmission count (RC) of the original and that of the contending burst will be read out and compared with each other and the burst with the lower RC will be dropped and retransmitted. In OBS networks with retransmission, too many retransmission attempts will ruin the network performance, so the retransmission count should be limited.

*Peng et al.* [94] introduced a drop policy based on hop number, in which the burst with larger total hop number is given the higher priority in the contention and that with smaller total hop number is dropped and retransmitted. The theoretical analyses and simulation results show that the drop policy improves the network performance effectively.

## **2.4 Contention Resolution and Control Schemes for OBS Networks**

Burst loss occurs primarily due to the contention of bursts in buffer-less core nodes. In literature, some approaches have been extensively studied to resolve the burst contention problem in OBS, such as wavelength conversion, optical buffering etc. However, when there is no unscheduled channel, the contention cannot be resolved by any one of the above techniques, some of the bursts must be dropped.

In optical burst switching (OBS), contention and burst loss can be reduced by implementing contention resolution techniques. There are different types of contention resolution techniques, such as time deflection (using buffering) [95], space deflection (using deflection routing) [96], wavelength conversion (using wavelength converters) [97] and soft contention resolution (using different contention resolution algorithms) [14,

30]. Using buffering approach introduced by *C. Gauger* [95] for contention resolution in the OBS core switches may not be viable, since the hardware complexity and high cost of such devices make them less attractive and limits their practicality. Space deflection proposed by *X. Wang et al.* [96] results in inefficient routing and potentially a high number of collisions. Furthermore, it results in high end-to-end delay and possible packet reordering, neither of which may be acceptable for many applications.

Similarly, wavelength conversion proposed by *S. Yao et al.* [97] on output ports is a very efficient approach for resolving contention and adds an additional dimension (in addition to time and space) to contention resolution. However, optical wavelength conversion has been demonstrated in laboratory environments, the technology is not yet mature and the range of possible conversions is somewhat limited. Also, two well-defined soft contention resolution algorithms have been proposed and studied. One is based on dropping the latest arrival as proposed by *Y. Xiong et al.* [14] and the other is based on dropping only the portions of the burst involved in contention (known as segmentation) as described by *V. Vokkarane et al.* [30].

*S. Yao et al.* [98] presented a unified study of contention-resolution schemes in optical packet-switched networks. They described that buffering capabilities can be granted to an OBS network to mitigate the congestion. In OBS, buffering is achieved either by storing the traffic at edge nodes in electronic memories (flow smoothing) or at core nodes by the mean of Fiber Delay Lines (FDL) working as optical buffers. By using wavelength converters at the FDL entrance the buffer capacity is automatically multiplied by the number of available wavelength [98]. Thus, only a small number of FDLs might be required. The application of FDLs gives good results in the presence of transient contention but will have no effect when permanent congestion is experienced. However, FDL buffering adds a lot of complexity to OBS, whose main advantage relies precisely in its simplified architecture and operation, when comparing to optical packet switching (OPS). Also, the authors indicated that both deflection routing and buffering lead to an unordered reception of the burst. *M. Yoo et al.* [42] introduced an offset scheme for isolating classes of bursts, such that low-priority bursts do not cause contention losses for high-priority bursts; fixed and variable fiber delay line buffers were also utilized to further reduce blocking. *C.-F. Hsu et al.* [40] presented a method to solve transient congestion states in OBS networks by using deflection routing. In this method, rather than

dropping a burst which failed to get a reservation on a particular link, the burst is sent on an alternative output link.

Also, *S. Gjessin* [99] proposed a hot potato deflection scheme in which an arbitrary link is picked to forward the contenting burst. However, the main difficulty with proposed approaches is caused by the problem of insufficient offset-time. Namely, a burst, when deflected, might have insufficient offset to reach its destination due to the difference in the length of the primary and alternative path. This problem can be solved either by restricting the deflection to the paths with the same length as the primary one or by providing additional offset to the bursts at edge nodes.

*G. Thodime et al.* [100] proposed a dynamic congestion-based load balanced routing in optical burst-switched networks. In this scheme, contention avoidance is achieved by dynamically varying the data burst flows at the source to match the latest status of the network and its available resources. In the proposed scheme, this is achieved by re-routing of some of the traffic from heavily loaded paths to under-utilized paths. A similar approach has also been introduced by *J. Li et al.* [101] where the authors consider balancing the data burst traffic between predefined alternative paths. Also, *H. Wen et al.* [102] proposed a global load-balancing contention resolution scheme and examined its performance for both dynamic and static traffic.

Further, *S. Y. Wang et al.* [103] introduced a transmission control packet (TCP) like congestion avoidance mechanism to regulate the burst transmission rate. In this approach, the ingress edge nodes receive TCP ACK packets from egress edge nodes, calculate the most congested links and reroute their traffic accordingly. *X. Huang et al.* [104] proposed burst cloning as an effective way to reduce data burst loss. The basic mechanism in burst cloning is to replicate a burst at appropriate nodes and send duplicated copies of the burst through the network simultaneously. *F. Farahmand et al.* [90] proposed a feedback based OBS network in which using explicit feedback signaling to each source, the required data burst flow rate going to congested links is controlled. It is observed that the major concern with having feedback-based proactive contention resolution schemes is additional signaling overhead and signals processing. Hence, it is critical to design signaling protocols which are simple to implement and require minimum overhead.

*W. Liao and C. H. Loi* [105] described that in OBS networks, a relative quality of service (QoS) is provided by maintaining the number of wavelengths occupied by each

class of bursts. In this scheme, each class of service has a preset usage ratio of available bandwidth. The incoming bursts which are under-utilizing their share can preempt data bursts violating their assigned share. Similarly, absolute QoS schemes including early dropping and wavelength grouping schemes are proposed by *Q. Zhang et al.* [89, 46]. In the former, bursts of lower priority class are probabilistically dropped in order to guarantee the loss probability of higher priority class traffic. In the wavelength grouping scheme, the traffic is classified into different groups and a label is assigned to each group. A minimum number of wavelengths can be provisioned for each group.

Also, traffic engineering (TE) methods have been described to balance the flows over the network and both linear (as proposed by *J. Zhang et al.* [106]) and nonlinear (as proposed by *M. Klinkowski et al.* [107]) optimization methods have been developed for that purpose. The TE approaches presented allow solving permanent contention by a proactive exploration of the knowledge of average traffic rates.

To further avoid congestion and in particular in cases of network overload, congestion avoidance control (CAC) schemes can be applied. Such schemes aim at limiting the amount of traffic sent to prevent the network from blocking. CAC schemes can be based on the analysis of the incoming flow as introduced by *A. Lazzez and N. Boudriga* [108] or can take their decision based on feedback received from other nodes as suggested by *F. Farahmand et al.* [109].

## CHAPTER III

### OPTICAL BURST SWITCHING NETWORK ARCHITECTURES

#### Publications from Chapter

1. Amit Kumar Garg, R S Kaler, "Comparison Analysis of Optical Burst Switched Network Architectures", **International Journal for Light and Electron Optics, Elsevier Science**, vol. 121, No. 15, pp. 1412-1417, September 2010.
2. Amit Kumar Garg, R S Kaler, "A Novel Optical Burst Switching Architecture for High Speed Networks", **Chinese Optics Letters (Journal of Optical Society of America)**, vol.6, no.11, pp.807-811, November 10, 2008.

In this chapter, we have investigated the first research objective i.e. to study and analyze various optical burst switching architectural alternatives in terms of the burst handling techniques and with the possible use of fiber delay-line for buffering and contention resolution. The chapter is divided into two sections. In the first section, an efficient OBS network's architecture has been presented. The proposed architecture incorporates small fiber delay line (FDL), efficient burst assembly as well as dynamic route selection techniques, for improving OBS system's performance, in terms of lower blocking probability and higher throughput. Also, to enhance the performance of the proposed architecture in terms of performance metrics such as lower switching processing time, queuing delay, better wavelength utilization, cost effectiveness etc, as an alternative, another performance oriented congestion free OBS network architecture based on optical label processing, has been investigated in the second section. Further, the performance of the proposed OBS architectures has been analyzed and compared with the conventional architectures.

#### **3.1 Comparison Analysis of Optical Burst Switched Network Architecture**

In this section, efficient network architecture for optical burst switching has been presented. To improve the system performance, the proposed architecture incorporates small fiber delay line and efficient burst assembly as well as dynamic route selection techniques. A queuing model is used to predict the system behavior for both classless and prioritized traffic. Simple closed-form expressions are derived for the burst loss probability of both classless and prioritized traffic. The simulation results show that the

proposed OBS architecture provides lower blocking probability and higher throughput for prioritized traffic classes as compared to the other traffic classes (in reference to earlier known results).

### 3.1.1 Proposed Efficient Optical Burst Switched Network Architecture

The proposed architecture comprises of classless & prioritized traffic models, efficient burst assembly and dynamic route calculation techniques. The following are some of the assumptions that have been made in the proposed architecture.

1. Assume, an output queuing  $N \times N$  optical burst switch architecture, with  $k$  wavelengths in each port. Each of the input port has  $f$  FDL for storing the bursts. The maximum delay offered by the FDL is  $\tau$  seconds.
2. The full range wavelength conversion capability has been considered i.e. an incoming burst can be directed from any wavelength in the input port to any of the output port.
3. A Just-Enough-Time (JET) signaling protocol has been considered.
4. The Latest Available Unscheduled Channel (LAUC) scheduling algorithm is considered for the classless traffic while the Latest Available Void Channel (LAVC) scheduling algorithm is considered used for the prioritized traffic.
5. The arrival of the optical bursts arrive is considered to be a Poisson process with a total intensity of  $\lambda$  bursts per second on each port. The burst lengths are exponentially distributed with an average length of  $1/\mu$  seconds. The burst destinations are uniformly distributed. The system utilization is considered to be 
$$\rho = \frac{\lambda}{\mu} .$$
6. At first, all of the bursts will contend for the wavelength in the destined output port. If a burst is blocked, it will try to reserve one of the available FDL in the input port. The burst is blocked if there is no FDL available or the FDL cannot provide enough delay. The first-in-first-out (FIFO) service discipline has been assumed for each of the output port.
7. The base offset time has been ignored, since it is common for all the bursts.

#### 3.1.1.1 Classless & Prioritized Traffic Models

In order to study the system behavior, only one output port has been considered by assuming output queuing switch architecture with a uniform traffic distribution. Since the

fiber link contains  $k$  wavelengths, each output port is considered as a  $k$ -server queuing system. Under the assumption of Poisson burst arrivals and exponential burst duration, each output port can be modeled as a  $M/M/K$  queue. In the case of an electronic switch, a packet occupies the buffer space until it is served. As a result, the buffer space capacity is independent of the duration that a packet can stay in the buffer and a conventional  $k$ -server queuing model is sufficient. The maximum number of packets that can be held by the system equals the number of packet buffers. An incoming packet will be dropped whenever there is no buffer space to hold this packet. In the case of an optical buffer, it is assumed that the maximum delay provided by a fiber delay line is  $\tau$  seconds and each FDL can hold multiple bursts. As per the assumption of an exponential distribution for the burst duration, the number of bursts contained in the fiber delay line is actually being unbounded. In addition to the above, the state of the system has been taken to be the number of bursts in the system.

#### (A) Classless Traffic Model

The classless traffic model has been derived as follow:

1. When the system is in state  $i$ ,  $\lambda_i$  and  $\mu_i$  ( $i \geq 0$ ) are considered to be the burst generation rate and the burst service rate, respectively.
2. For the classless traffic,  $\mu_i = \min[i, k]\mu$ , since there are  $k$  wavelengths available in the output port. For  $i < k$ , there is no burst loss, since the incoming data burst can find an idle channel to carry it. Thus  $\lambda_i = \lambda$  for  $i < k$ .
3. When the system is in state  $i$ ,  $\beta_i$  is the burst loss probability. Thus,  $\lambda_i = \lambda(1 - \beta_i)$  and  $\beta_i = 0$  for  $i < k$ .
4. For  $i \geq k$ , the probability of no loss in state  $i$ ,  $(1 - \beta_i)$  is equal to the probability such that there are at least  $i - k + 1$  service completions within time  $\tau$ , given as:

$$1 - \beta_i = \int_0^{\tau} e^{-k\mu x} \frac{k\mu(k\mu x)^{i-k}}{(i-k)!} dx$$

5. After specifying  $\lambda_i$  and  $\mu_i$ , the steady state probabilities  $\pi_i$  are obtained (the system is in state  $i$ ,  $i \geq 0$ ) as:  $\pi_j = \pi_0 \prod_{i=0}^{j-1} \frac{\lambda}{\mu} + 1$ ;  $j \geq 1$
6. The average burst loss probability is calculated as:  $\beta = \sum_{j=k}^{\infty} \pi_j \beta_j$
7. It is observed that all of the above equations depend on the model parameters only and also there are no iterations involved in the computation. Therefore, a simple closed-form expression has been derived for the system performance measure.

## (B) Prioritized Traffic Model

The prioritized traffic model has been derived as follow:

1. A system with  $n$  classes, labeled as  $0,1,\dots,n-1$ , in increasing order of priority, has been considered. Let  $\rho$  denote the overall traffic intensity and  $\rho_i$  denote the traffic intensity of class  $i$  traffic. Similarly, let  $\beta$  denote the overall burst loss probability and  $\beta_i$  denote the burst loss probability of class  $i$  traffic. By using the conservation

relation, we get  $\beta = \sum_{i=0}^{n-1} c_i \beta_i$ . The relative traffic intensity of class  $i$  is  $c_i = \rho_i / \rho$ .

2. A burst is discarded if it's expected waiting time is longer than  $\tau$ , the maximum delay that can provided by the FDL.
3. The burst loss probability derived for single-class traffic is given by:  $\beta = \text{Burst}_{FDL}(k, \rho, f, \tau)$ , where  $k$  is the number of wavelength in each fiber,  $f$  is the number of FDL in an optical buffer,  $\tau$  is the maximum delay provided by an FDL and  $\rho$  is the traffic intensity (It is also assumed that there are  $n$  traffic classes numbered from 0 to  $n-1$ , where class  $n-1$  represents the highest priority traffic).
4. The traffic intensity of class  $i$  traffic is taken as  $\rho_i$ . Also, it is observed that the class  $n-1$  traffic source is completely isolated from the lower priority traffic classes. Thus, its burst loss probability is given as:  $\beta_{n-1} = \text{Burst}_{FDL}(k, \rho_{n-1}, f, \tau)$ .

5. For the class  $j$  traffic, the burst loss probability is affected by the incoming class  $j$  to class  $n-1$  traffic sources

6. By using conservation relation, the average burst loss probability for class  $j$  to class  $n-1$  traffic sources is equal to  $\sum_{i=j}^{n-1} c_i^j \beta_i$ , where  $c_i^j$  is the portion of traffic that comes

from class  $i$  source, given as:  $c_i^j = \rho_i / \sum_{l=j}^{n-1} \rho_l$ .

7. Using above relations, the burst loss probability for class  $j$  traffic,  $0 \leq j \leq n-2$ , is given as:

$$\beta_j = \frac{1}{c_j^j} \left\{ \text{Burst}_{FDL}(k, \sum_{i=j}^{n-1} \rho_i, f, \tau) - \sum_{i=j+1}^{n-1} c_i^j \beta_i \right\}$$

8. Thus, all of the above equations provide an iterative technique for approximating the burst loss probabilities for all traffic classes in prioritized optical burst switching.

### 3.1.1.2 Dynamic Burst Assembly

All incoming packets will be forwarded to the corresponding queue according to their destinations. Also, it is assumed that the ingress node has one dedicated burst assembly queue for each egress node. When the queue size reaches a threshold or the waiting time of the packets in the queue reaches a threshold, the packets in this queue are sent out as a

burst. In this section, a dynamic burst assembly algorithm has been proposed (as it can dynamically change the value of Assembly Time (AT) of any queue at every ingress node (e.g.  $AT_{queue}$ ) according to the length of burst recently sent). The brief functioning of the proposed algorithm is as follows:

1. It is assumed that the network uses a static routing algorithm. For the link between two node  $i$  and node  $j$ , a set  $Q_{ij}$  is defined, which contains all  $q_{sd}$  iff the bursts assembled from  $q_{sd}$  use the link from node  $i$  to node  $j$ . Then, for any  $Q_{ij}$ , the inequality based on the link capacity is given as:

$$\sum_{q_{sd} \in Q_{ij}} \frac{ABL_{q_{sd}}}{AT_s} \leq C \times BW \quad (3.1)$$

( $ABL_{q_{sd}}$ : average burst length of queue  $q_{sd}$ ;  $C$ : number of wavelengths on this link;  $BW$ : bandwidth of one channel).

2. Using inequality in equation (3.1), the constraints on assembly time (assuming that every ingress node uses the same AT.) are obtained as:

$$\frac{\sum_{q_{sd} \in Q_{ij}} ABL_{q_{sd}}}{C \times BW} \leq AT_s \leq \min_f (RTO - RTT) \quad (3.2)$$

(RTO: retransmit timeout value; RTT: the round trip time value;  $\min_f (RTO - RTT)$ : minimum value of  $(RTO - RTT)$  over all TCP flows from  $s$  to  $d$ ).

3. Since  $ABL_{q_{sd}}$  changes with the value of  $AT_s$ , it is difficult to obtain the accurate lower bound of  $AT_s$ . Thus, the following equation (3.3) has been used (similar to the equation for RTT calculation [11]):

$$ABL_q = \Phi \times ABL_q + \Psi \times SABL_q \quad (3.3)$$

( $SABL_q$ : sampled average burst length;  $ABL_q$ : smoothed average burst length;  $\Phi, \Psi$ : positive weights ( $\Phi + \Psi = 1$ )).

4. Given a queue  $q_{sd}$ , it is assumed that the network uses a single path to route each flow, in the extreme case, the assembled burst traffic from  $q_{sd}$  occupies all the output bandwidth. Thus, similar to the rationale behind equation (3.2), the following constraints exist:

$$\frac{ABL_{q_{sd}}}{C \times BW} \leq AT_{q_{sd}} \leq \min_f (RTO - RTT) \quad (3.4)$$

5. Similarly, assembly time ( $AT_{q_{sd}}$ ) of queue  $q_{sd}$ , is given as:

$$AT_{q_{sd}} = \beta \times \frac{ABL_{q_{sd}}}{C \times BW} \quad (3.5)$$

( $\beta \geq 1$ : assembly factor)

6. Using equations (3.1) to (3.5), the following result is obtained:

$$\beta = \frac{BW \times C}{ABL_{q_{sd}} / AT_{q_{sd}}} \cong |Q_{ij}| \quad (|Q_{ij}|: \text{size of } Q_{ij}) \quad (3.6)$$

7. Thus, it is clear from equation (3.6) that  $\beta$  is the average number of the assembly queues that are sharing the link. The data bursts that are too small are not sent in order to reduce the overhead; i.e., bursts are sent out as soon as possible and certainly before the first packet in the burst misses its deadline.

Thus, in the proposed algorithm, a control packet is generated when either a burst exceeds a minimum burst length (MBL) or the assembly times out, whichever comes first. The two parameters namely maximum assembly period (MAT) and MBL can be set such that the minimum burst length is smaller than the average burst length (obtained using equation (3.3)) and also the maximum assembly time is approximately  $\min_f (RTO - RTT)$  (as in equation (3.2)).

### 3.1.1.3 Dynamic Route Calculation

The dynamic route calculation is based on many different metrics such as the physical distance, number of hops, congestion information and link utilization. The routes are recomputed every  $\tau$  units of time. The selection of weight function  $w(i, j)$  is based either on a single metric or a combination of metrics. In order to have minimum delay, the weight function based on congestion as well as physical distance is given as:

$$w(i, j) = \rho(i, j) + d(i, j) / d_{\max} \quad (3.7)$$

( $d(i, j)$ : physical distance of the link  $(i, j)$ ;  $d_{\max}$ : maximum physical distance of any link in the network).

Through simulation, it is observed that the distance-based metric equation (3.7), results in better performance in terms of delay, since minimal link distances are selected in a path, thereby reducing the propagation delay. Thus, in this section equation (3.7) has been considered to have reduced propagation delay in the proposed OBS architecture.

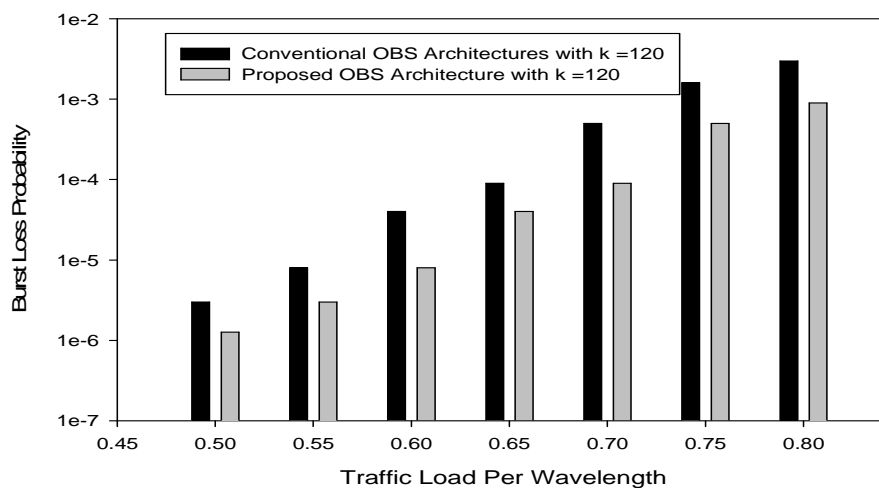
### 3.1.2 Simulation details

In the simulation, a NSFNET (National Science Foundation Network) topology with 12 nodes has been considered [110]. It is assumed that each single fiber link is bidirectional and has the same number of wavelengths. Each link is operating at 2.5Gbps. Each node in

the network routes, generates and receives traffic. The data bursts are not retransmitted. The bit errors in the transmission are ignored. The size of the electrical buffers in the edge nodes is infinite. The simulation experiments are run for a sufficiently long time. Some of the parameters used in the simulation are: average burst length ( $90\mu\text{sec}$ ); control burst processing time ( $2.5\mu\text{sec}$ ); switching time ( $12\mu\text{sec}$ ); propagation delay on a link ( $0.2\text{milliseconds}$ ); assembly factor (12); assembly time ( $0.02\text{sec}$ ); confidence interval (95%).

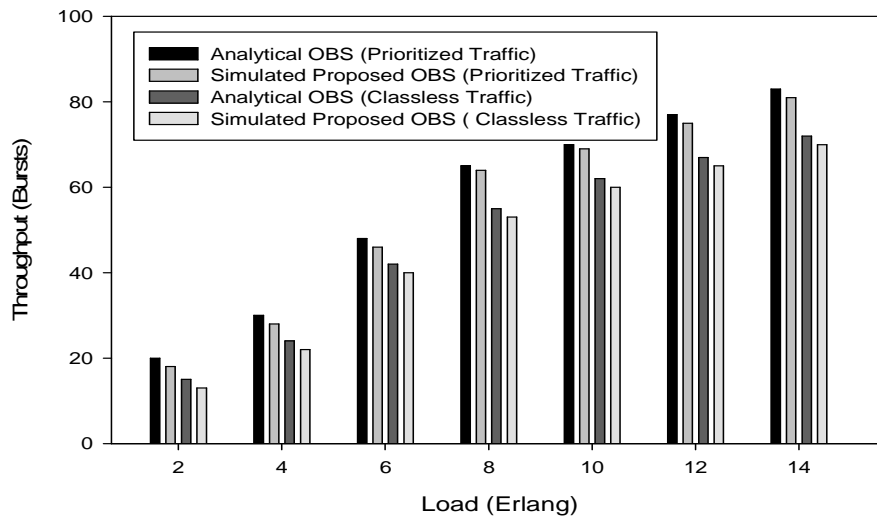
### 3.1.3 Results and Discussions

Figure (3.1) compares the burst loss probability performance of conventional and the proposed OBS architecture. It is observed that better reduction in burst loss probability has been achieved with proposed OBS architecture as compared to conventional architecture.



**Figure 3.1: Burst-loss probability Vs traffic load**

Also, figure (3.2) shows that with the usage of dynamic burst assembly as well as route selection technique, the simulated proposed OBS network architecture provides an accurate fit in terms of throughput with analytical traffic model for prioritized traffic classes and lower bounds for the other traffic classes that are more closed than earlier known results.



**Figure 3.2: Throughput Vs load**

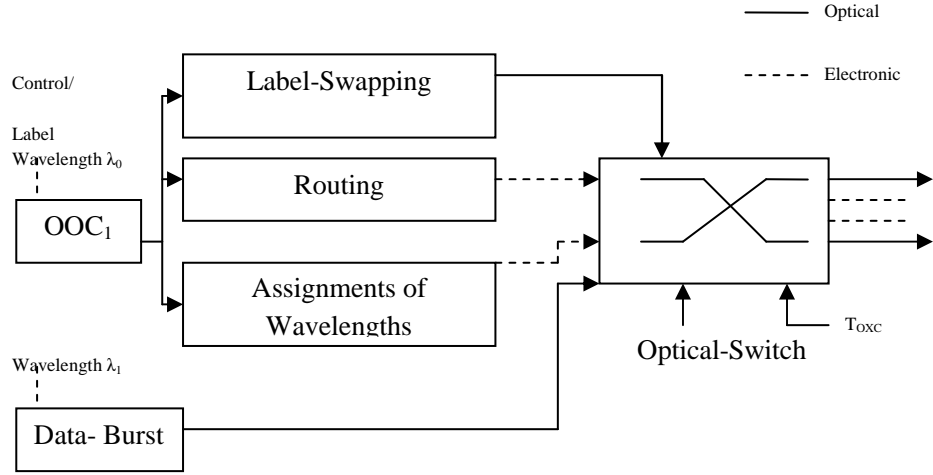
### 3.2 Proposed Congestion Free OBS Network Architecture

In this section, in order to achieve further improvements in the above architecture, in terms of reduction in electronic switching processing time, decrease in delay associated with FDL usage, another efficient congestion-free OBS network architecture, utilizing a short- prior-confirmation-packet (SPCP) and optical label processing with JET signaling has been presented. In the proposed architecture, to avoid burst losses, first, a Short-Prior-Confirmation-Packet (SPCP) is sent over the control channel that simulates the events that the actual packet experiences. Once a SPCP detects a drop at any of the intermediate nodes, the actual packet is not sent but the process is repeated. The orthogonal optical codes (OCC), which are codified only in intensity, have been used. The results achieved have indicated that a decrease in burst loss probability, cost-effectiveness and a gain in processing time are obtained when optical label processing is used as compared to electronic processing.

#### 3.2.1 Proposed OBS Network Architecture based on Optical Label Processing

It is known that the average burst length is strongly related to the performance of the OBS control channel, thus, in the proposed architecture, optical code labels and optical processing has been used with JET signaling at the OBS control channel. The internal architecture of optical burst switching node has been described in the figure (3.3). The

optical processing consists of optical-correlation of the OOC labels that arrive in the OBS node. Each bit is divided up into  $n$  time periods, called as chips. The total number of illuminated chips in the code is called as the weight  $w$ . The encoder of each transmitter represents each bit 1 by sending the code sequence; however, a bit 0 is not encoded and is represented by using all-zero sequence. The set of OOC sequences is characterized by the parameters such as length ( $L$ ), total number of illuminated chips in the sequence ( $w$ ) and maximum values of the auto-correlation and cross-correlation ( $\lambda_a, \lambda_c$ ), respectively.



**Figure 3.3: Internal architecture of optical burst switching node**

By considering  $x$  and  $y$  as two sequences in an OOC, the auto-correlation and cross-correlation are given as follows:

$$\sum_{l=0}^{L-1} x_l x_{l+\tau} = \begin{cases} w, & \text{for } \tau = 0 \\ \leq \lambda_a, & \text{for } 1 \leq \tau \leq L-1 \end{cases} \quad (3.8)$$

$$\sum_{l=0}^{L-1} x_l y_{l+\tau} \leq \lambda_c, \text{ for } 0 \leq \tau \leq L-1 \quad (3.9)$$

( $\tau$  : relative delay between two sequences  $x_l$  and  $y_l$  )

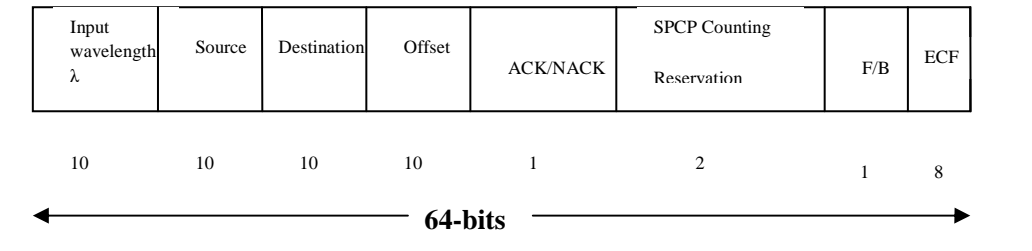
By using, the numbers of sequences in OOC families with same weight, correlation restrictions given by equations (3.8) and (3.9), the possible lengths are given as follows:

$$L \geq L_{\min} = [C.w.(w-1)+1] \quad (3.10)$$

( $C$  : number of sequences in the OOC family with same weight)

### 3.2.1.1 Scheduling with SPCP

In the proposed architecture, before sending the data slot, the switching contentions along the path are checked by a SPCP (i.e. a control message instead of the OBS Burst Header). The SPCP travel in the control channel carrying information to prepare the optical path for the data burst switching. The SPCP, in contrast to the burst header, will return back with the outcome of the reservation attempt. To make this possible, an offset is used longer than the round trip time. In the event of a negative outcome, the data slot will not be emitted. So, only the queues that received a positive SPCP will emit one slot to be switched according to the already prepared schedules in each node. The SPCPs are not owned by the payload slots that triggered their launch, but are used by first in the relevant queues. Thus, the FIFO order is always preserved, despite the existence of negative SPCPs. The different queues are maintained per destination. In the proposed mechanism, source routing is employed and the knowledge about each route also includes the round trip distance measured in slots. The entry port of each node includes a synchronizer, which by means of variable delay lines aligns the boundaries of the incoming slots in all input ports and wavelengths. A small guard-band of a few tens of  $ns$  provides a safety margin. In the control channel, the synchronized transmission occurs in fixed size slots (i.e. control slots) of the same size as of the data slots. Each of the control slots accommodate a large number of SPCP, the format of which is shown in figure (3.4).



**Figure 3.4: SPCP format**

(F/B----Forward or Backward SP-CP direction; ECF---Error Correction Field)

Also, under the assumption that some bits are reserved for future use, the SPCP size reaches 64 bits. Each control slot has a size of 240,000bits and can host more than 3,800 SPCPs, thereby making congestion in the control channel, extremely unlikely. Every node acts as source node for its local traffic and in parallel as a switch for the rest of the traffic.

As a source, each node is responsible for the generations of SPCPs to serve its local traffic. The SPCPs are managed per queue, with each queue associated with a destination. The SPCP departs as soon as a payload fitting the slot has been prepared. Once a SPCP with a certain offset delay ( $T_d$ ) value has been launched, the relevant data will depart  $T_d$  slots later under the condition that a SPCP with positive reservation will have returned before. The SPCP will either return at planned time ( $T_d-1$ ) or earlier, albeit with a negative reservation. The SPCP will be launched starting a new count down to the new  $T_d$ . As a core node, each node is responsible for the handling of transit SPCPs and scheduling its future switching actions. As the SPCP enters each core node, the node switch learns that  $T_d$  slots later, a data slot will enter from the same port in the indicated wavelength claiming the indicated output also, implying a request to reserve a targeted future slot in this output port in the same wavelength (unless conversion is supported, in which case, this is to be decided by the scheduler). In contrast with ordinary switches, which are at any time scheduling the next slot, the nodes in this system are given an early warning by the SPCP and thus they program future switching actions many slots later in time, while simultaneously executing current switching actions that were planned some slots earlier in time. When a new SPCP claims an output, any contentions from other SPCPs entering from other input ports are resolved within the present slot time by considering also any previous claims for the same slots that are already marked in the scheduling log. The latter have of course precedence over newer claims and also among SPCPs with same  $T_d$  (higher attempt number ( $N_a$ ) are preferred in the contentions). Also, if  $N_a$  is same, the ones nearer their destination are favored and if this is also equal, random choice is exercised. The SPCPs that could not be accommodated are switched around and returned back without completing their trip to the other end. Returning with a negative reservation, these SPCPs prompt the dispatch of a new SPCP by the source edge node. Thus, no data slot is sent, avoiding losses of data and this is the most important difference as compared to the other OBS systems. Hence, positive reservations are used to cause a departure of data and negative ones to cause the issue of a new SPCP. The round trip time of control slots is larger than that of data slots by the extra time needed in each node for processing. The control is distributed with each node executing the scheduling and thus either accepting or rejecting reservations on the basis of local information. Each of the core switches may employ wavelength converters as

well as fiber delay lines in multiples of the slot size. However, only converters are assumed in this section, although a significant improvement is to be expected by adding delay line buffering.

### 3.2.1.2 Analytical Model

The description of the analytical model is as follows:

1. The network burst intensity has been modeled by queue theory and also the burst loss probability is calculated for both optical and electronic label processing. The optical label processing time ( $T_{OPL}$ ) is given as:

$$T_{OPL} = \frac{1}{(L-1)/T_C} \quad (3.11)$$

2. The chip-period ( $T_C$ ) using bit rate ( $B$ ) is given as  $T_C = 1/BL$  (3.12)

3. By using equation (3.10),  $T_C$  can also be written as:

$$T_C = \frac{1}{B[C.w.(w-1)+1]} \quad (3.13)$$

4. The equations (3.11) to (3.13) indicate that the optical processing time depends on the bit-rate, the number of codes and the code-weight, thus, optical code processing can affect the OBS network traffic characteristics e.g., burst length. The minimum burst length ( $T_{MBL}$ ) that can be transported to the OBS network is given by:

$$T_{MBL} = N[k - k_C]T_P \quad (3.14)$$

( $N$  : number of fibers in the core-router;  $k$  : number of wavelengths that carry the data bursts;  $k_C$  : number of wavelengths for control)

5. In order to evaluate, the OBS network performance as a function of time processing and burst length, the performance metrics such as network utilization efficiency ( $\eta_{NUE}$ ) and economy of wavelength (EW) are given by:

$$\eta_{NUE} (\%) = \frac{T_{Burst}}{T_{Burst} + T_P} \times 100 \quad (3.15)$$

$$EW(\%) = \frac{W_{Electronic} - W_{Optical}}{W_{Electronic}} \times 100 \quad (3.16)$$

( $T_{Burst}$  : burst-length;  $W_{Electronic}$  and  $W_{Optical}$  : numbers of wavelengths utilized for electronic and optical label processing, respectively)

6. The traffic intensity ( $\rho$ ) of the queue is given by:

$$\rho = \lambda [T_{Burst} + T_{OXC}] \quad (3.17)$$

( $\lambda$ : Burst-Arrival Rate (BAR) in bursts per seconds;  $T_{OXC}$  : optical cross-connect switch-time)

7. Also, the burst-loss probability based on Erlang-B formula [10] is given by:

$$p_b = \frac{1/k! \cdot r^k}{\sum_{m=0}^k 1/m! \cdot r^m}, \text{ where } r = \rho \cdot k \quad (3.18)$$

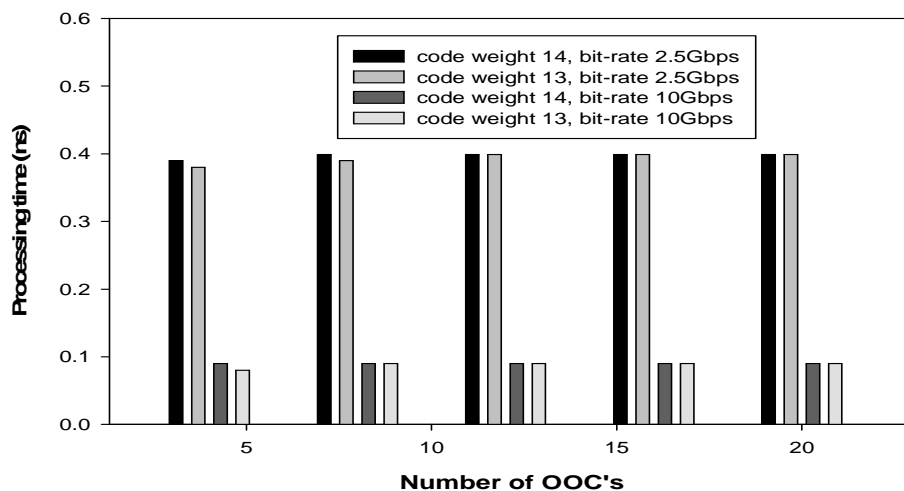
### 3.2.2 Simulation details

The proposed architecture has been evaluated by computer simulation using a 4 x 4 torus network topology [5], where all nodes have one edge interface receiving locally generated traffic and four interfaces to core nodes. The load entering every node is destined with equal probability to each other. The routing is static, determined beforehand using the open shortest path flow (OSPF) algorithm. There are 64 wavelengths at 10Gps for data and one control wavelength at 2.5Gbps in every link of the network. The slot size is 100 $\mu$ s, accommodating 1-Mbit of data with  $T_{OXC} = 1$ ms. The length of links between nodes is 220 km, corresponding to 11 slots (or 1.1ms). Hence, the round-trip times are 2·n·1.1ms, where n is the number of hops. Given that the maximum number of hops in the network is 4, the round-trip can reach 8.8ms at the maximum domain dimension 880km. The full wavelength conversion has been assumed in all nodes (no FDL for delaying data). In order to provide, a realistic pattern for the input traffic of the network, a traffic aggregation unit receiving bursty IP traffic from a large number of sources was simulated, generating 1Mbit payloads. The traffic aggregation unit in each node turns into slots whenever 1Mbit of data are collected or a time-out of 3ms occurs (as described in [111]). The routing is determined beforehand choosing those shortest paths that create a

symmetric distribution of the routes over the links. All nodes produce the same amount of traffic destined to all other nodes with equal probability.

### 3.2.3 Results and Discussions

The results concerning the optical label processing time are shown in figure (3.5), where optical label processing time versus the number of OOC has been illustrated by considering bit rates ( $B$ ) = 2.5 and 10 Gbps and code-weights ( $w$ ) = 13 and 14. It has been observed that low processing times are obtained with optical label processing. The optical label processing time converges approximately to 0.4 and 0.1 ns for bit rates of 2.5 and 10 Gbps respectively, independently of OOC number and code-weight. This occurs because the limitation of optical processing is the bit-period i.e. the reciprocal of the bit-rate and thus, the optical label processing time is very short compared with electronic processing. The optical label processing time also affects the traffic characteristics of OBS network because the burst length accepted to be transported in the OBS network is a function of label time processing.



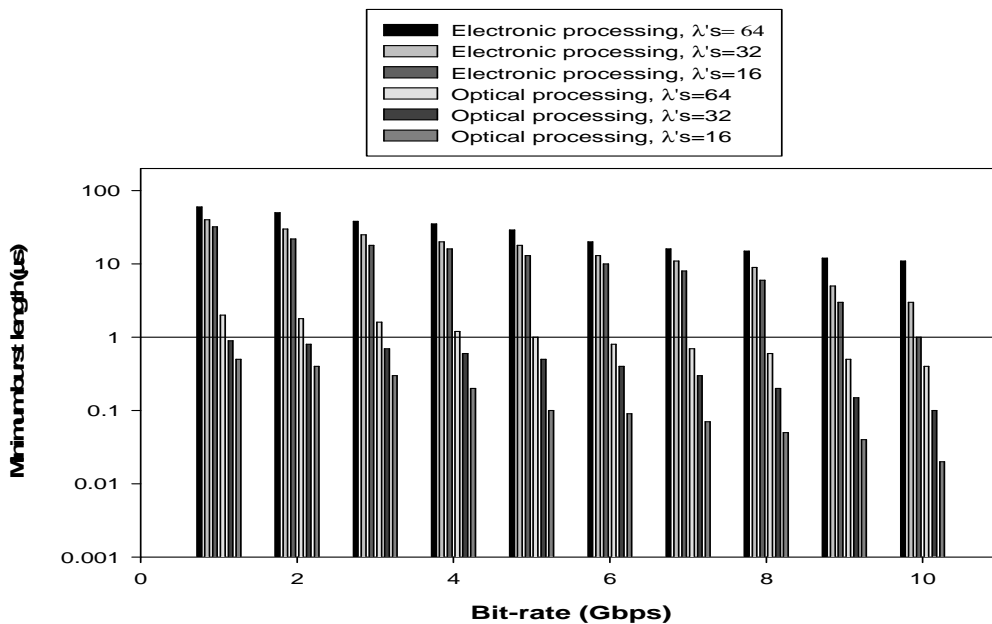
**Figure 3.5: Processing time of optical label processing Vs OOC**

It has been observed in Table 3.1, that for a 10 Gbps bit-rate, the minimum burst length accepted to be transported is 15 ns and 4  $\mu$ s for optical and electronic label processing.

Processing-Time	Minimum Burst-Length	
	(Bit-rates)	
	2.5 Gbps	10 Gbps
Optical (ns)	60	15
Electronic( $\mu$ s)	13	4

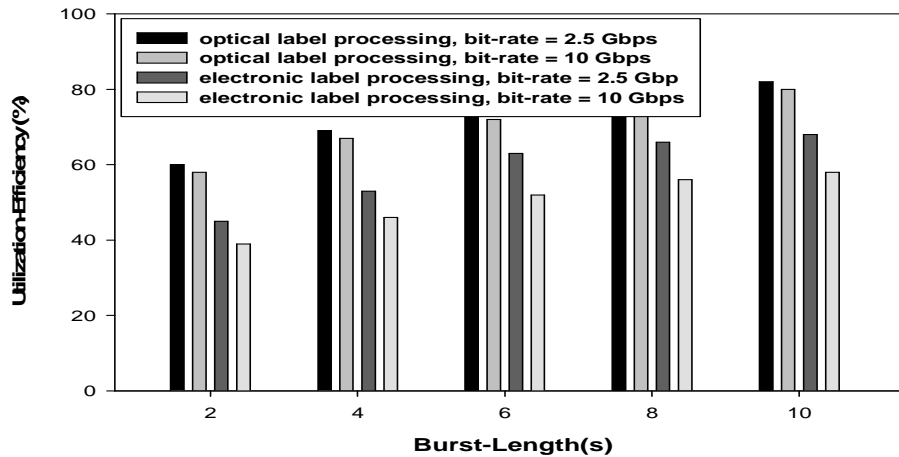
**Table 3.1: Minimum burst length required for electronic and optical label**

For both optical and electronic label processing, the effects of bit rate and number of wavelengths on minimum burst length for transport by an OBS network are shown in the figure (3.6). It has been observed that when optical label processing is utilized, in comparison with electronic processing, the minimum burst length decreases for all number of wavelengths considered. It is also observed that the minimum burst length increases when the number of wavelengths increases and the bit rate decreases. Thus, by using optical label processing, OBS network approaches conventional packet switching granularity and thus network utilization has been increased especially, for small bursts composed by IP traffic.



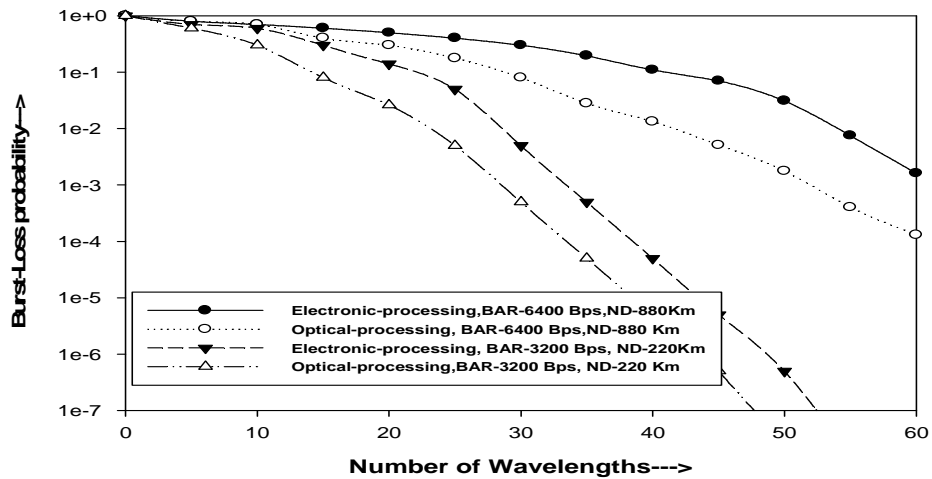
**Figure 3.6: Minimum burst length Vs bit-rate**

From figure (3.7), it is seen that the utilization efficiency for optical label processing is higher than those for electronic processing. However, when the processing time is higher than the burst-length, the utilization efficiency of electronic label processing decreases whereas the utilization efficiency of optical processing is practically the same for different bit-rates. These results have been obtained by considering the burst loss probability equal to zero. This is an effective solution for adjusting the burst length.



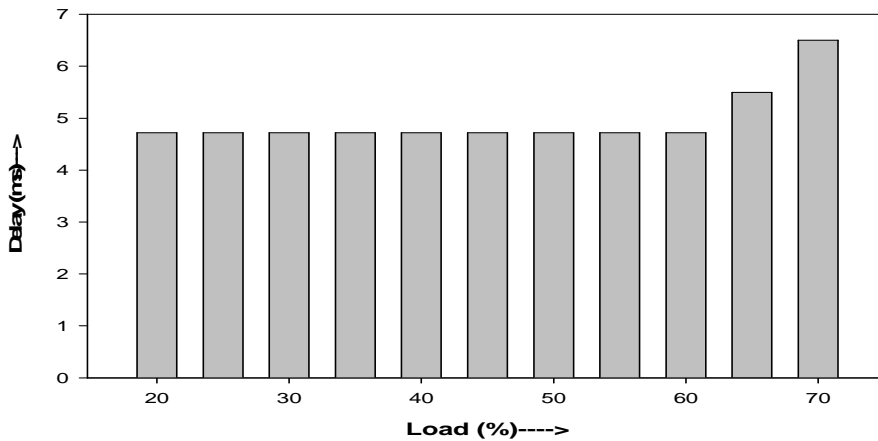
**Figure 3.7: Utilization-efficiency Vs the burst-length**

Figure (3.8) shows that the burst loss probability for optical label processing is lower than electronic processing at same traffic-load (0.6 Erlang). Using electronic label processing, a burst-loss probability of  $1 \times 10^{-3}$  (approx.) is obtained for 33 and 60 wavelengths (with BAR = 3200 and 6400 Bps) whereas 30 and 53 wavelengths are required for optical label processing. This shows an improvement in wavelengths usage of OBS network, which in turn increases the network utilization gain (efficiency). For the burst loss probability of  $1 \times 10^{-3}$  (approx.), there is an economy of wavelength (EW) equal to 9 and 12 % at BAR of 3200 and 6400 Bps, respectively.



**Figure 3.8: Burst-loss probability Vs number of wavelengths**

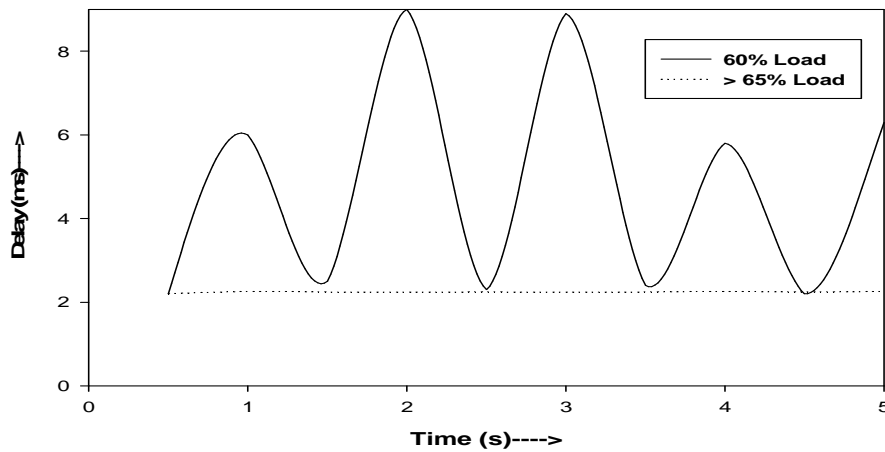
Figure (3.9) shows the average queuing delay over all destinations versus the total offered load expressed as a percentage of the total output capacity of each node. At low loads, the queuing delay remains essentially near the round trip time, since each burst departs with the return of the almost always positive, SPCP.



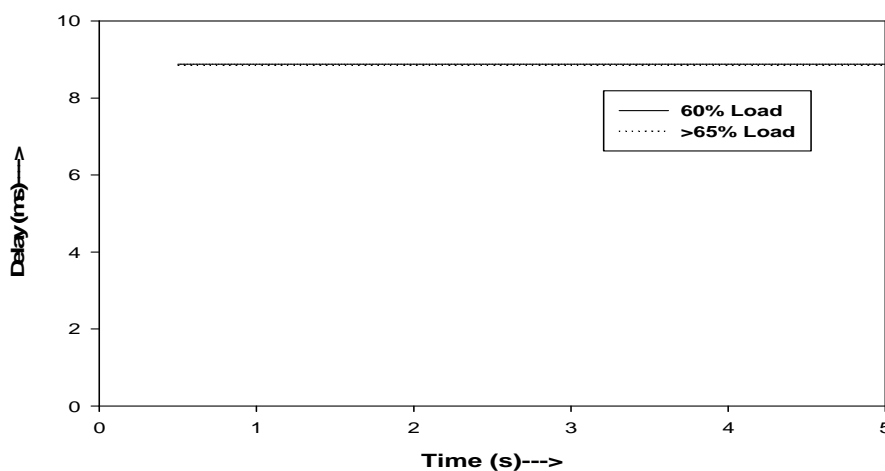
**Figure 3.9: Average queuing delay Vs load**

In the following figures (3.10) and (3.11), the queuing delay for payloads destined to 1-hop and 4-hop destinations, is shown for two different systems load values i.e. for 60% and greater than 65%. For the 60% load, both 1-hop and 4-hops queues show delay that

slightly deviates from the respective round-trip times. For the load up to 65%, most of the SPCPs return with a positive acknowledgement, thereby making the queuing delay close to the round trip time, since each burst departs as soon as the relevant SPCP returns back. As the load increases beyond 65%, the congestion is first mirrored in 1-hop queue, since the relevant SPCPs are addressing future slots that are already being reserved by the higher-hop length queues. As a result, although, the 1-hop queue experiences the congestion even for 65% load, but the delay of the 4-hop queue remains intact regardless of the increasing load in the system (the delays for 4-hop destinations coincide for the load values 60% and greater than 65%, as shown in the figure (3.11)).

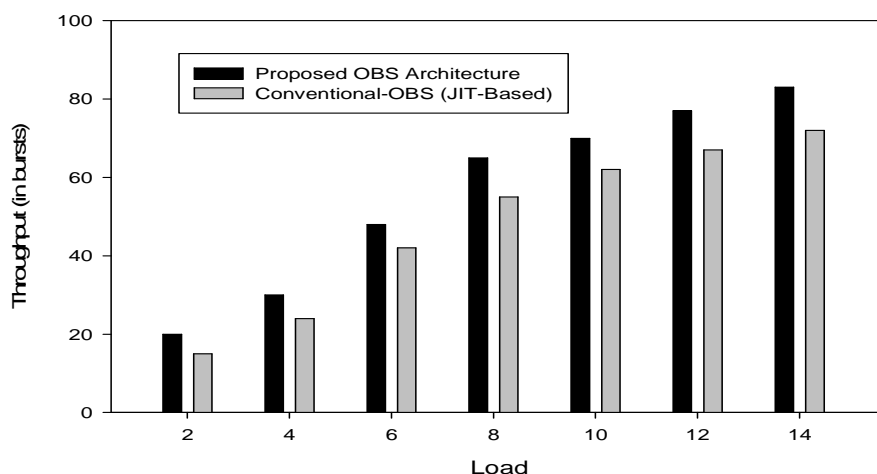


**Figure 3.10: Queuing-delay for 1-hop destination**



**Figure 3.11: Queuing-delay for 4-hop destinations**

Also, it has been observed in the figure (3.12), that the throughput value of proposed OBS architecture is better than conventional OBS architecture. Thus, this is attributed as throughput gain to the fact that proposed OBS architecture can use bandwidth more efficiently.



**Figure 3.12: Throughput Vs load**

### 3.3 Conclusion

In this chapter, we have proposed and presented efficient OBS network's architectures as an alternative, in order to improve network utilization, lower burst blocking probability, cost-effectiveness and to overcome some limitations of conventional OBS architectures. Based on the properties of optical burst flows and bandwidths provisioning in the networks, an efficient OBS network architecture utilizing adaptive burst assembly, small fiber delay line along with dynamic route selection technique, has been investigated. It has been observed through the simulation results that the proposed architecture can reduce the simultaneous contention in the core network, make the traffic smoother and thus improve the system performance in terms of burst loss rate and throughput. Simple closed-form expressions are derived for the burst loss probability of both classless and prioritized traffic. The results obtained show that the simulated proposed OBS network architecture provides an accurate fit with analytical traffic models for prioritized traffic classes and lower bounds for the other traffic classes that are tighter as compared to the earlier known results.

Further, in order to have reduction in electronic switching processing time, delay associated with FDL usage in the above architecture, another efficient congestion-free OBS network architecture utilizing a short- prior-confirmation-packet and optical label processing with JET signaling, has been presented. In comparison to conventional architecture based on electronic switching processing, the proposed architecture provides reduced switching processing time, lower burst loss probability and better network utilization. The proposed architecture incorporates a selective throttling of traffic according to the specific congestion conditions along each route, allowing a graceful release of traffic from the periphery buffers. This is in contrast to the conventional OBS where the network is burdened at times of congestion with repeated retransmissions, further aggravating the problem. Thus, the system makes exemplary use of the advantages of all-optical technology by meticulously delegating switch planning and contention avoidance for control processing, thereby, sidestepping the lack of cheap optical buffering.

Thus, based upon the results achieved above, it is concluded that the proposed architectures, in comparison to conventional architectures, can be considered as cost-effective and efficient OBS network architectures for high speed telecommunication applications.

## CHAPTER IV

### RESERVATION SCHEMES FOR EFFICIENT NETWORK UTILIZATION AND BANDWIDTH IN OBS NETWORKS

#### Publications from Chapter

1. Amit Kumar Garg, R S Kaler, "An adaptive reservation scheme for optical network", **Optik - International Journal for Light and Electron Optics, Elsevier Science**, In Press, Corrected Proof, Available online 3 July 2010.
2. Amit Kumar Garg, R S Kaler, "An Efficient Scheme for Optimizing Channel Utilization in OBS Networks", **Optik - International Journal for Light and Electron Optics, Elsevier Science**, vol. 121, no. 9, pp.793-799, May 2010.
3. Amit Kumar Garg, R S Kaler, "Enhancing Bandwidth Utilization and QoS in Optical Burst Switched High-Speed Network", **International Journal of Microwaves, Optoelectronics and Electromagnetic Applications**, vol. 7, no. 2, pp.91-100, December 2008.

In this chapter, we have investigated the second research objective i.e. to study and compare various reservation schemes for efficient network utilization and bandwidth in optical burst switched (OBS) networks. The chapter is divided into three sections. In the first section, an adaptive reservation scheme based on a multi-service OBS edge node with synchronized bandwidth reservation mechanism has been proposed. The proposed scheme enables network nodes to dynamically reserve the bandwidth needed for active data burst flows. In order to have better channel utilization, higher throughput and lower blocking probability, in comparison to above proposed scheme, in the second section, we have investigated an efficient reservation scheme in which data burst are scheduled in batches. In the proposed scheme, the heuristic interval scheduling algorithm is utilized to obtain the maximum number of non-overlapping bursts. Further, to obtain better fairness control and bandwidth utilization as compared to the above proposed reservation schemes, in the third section, we have presented another efficient reservation scheme in which each edge router finds a suitable route to the destination edge router autonomously by using feedback and prior information packets. This results in decrease of average resource usage for the dropped packets (i.e. the resource wastage) in the network. Also, the performance of proposed reservation schemes has been compared with some existing reservation schemes.

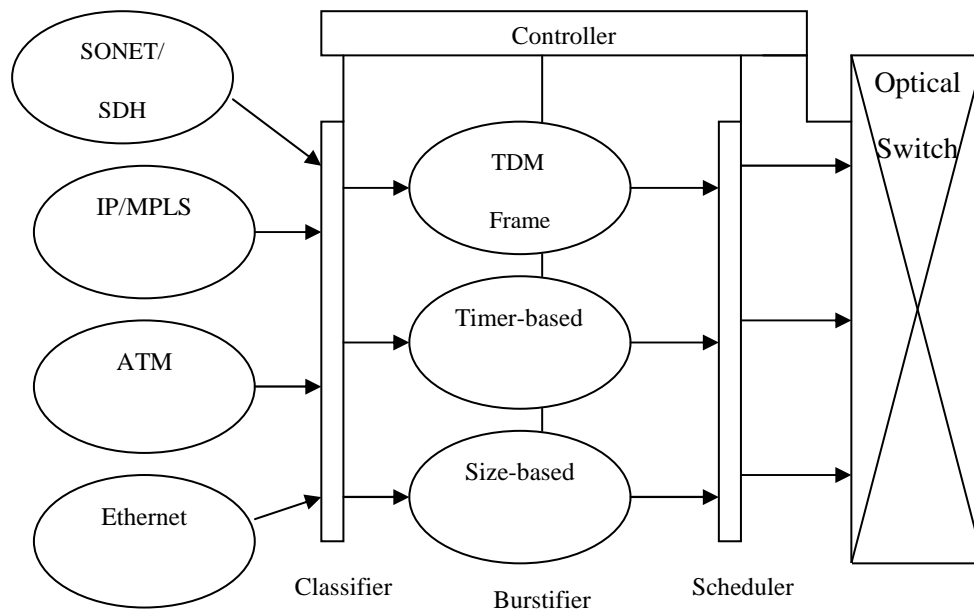
## **4.1 Adaptive Reservation Scheme for Optical Network**

In this section, an adaptive reservation scheme based on a multi-service OBS edge node with synchronized bandwidth reservation mechanism has been proposed, which enables network transport nodes to dynamically reserve bandwidth required for the active data burst flows. The simulation results show that with the proposed scheme, the packet delay obtained is within the constraint for each traffic flow and also the performance metrics such as burst loss rate, throughput are remarkably improved.

### **4.1.1 Proposed Reservation Scheme**

In the proposed reservation scheme, multi-service OBS edge nodes and OBS core nodes are interconnected by wavelength division multiplexed (WDM) fibers (containing wavelength channels). The bandwidth of each wavelength is organized into a series of frames, each of which is sub-divided into fixed length time slots. The structure of the proposed multi-service OBS edge node is shown in the figure (4.1). The node aggregates a diversity of data traffic from emerging real-time services to legacy data-transfer services and also from asynchronous transmissions to synchronous transmissions. The aggregated traffic is then translated into appropriate optical bursts for transmission through the OBS core nodes. The multiservice OBS edge node consists of a traffic classifier, a multiclass burst assembler, a scheduler and an optical switch. The data packets (such as IP packets, ATM cells, SONET/SDH frames and Ethernet packets) are injected into the classifier at the ingress multiservice OBS edge node. The classifier sorts and forwards the incoming data packets into corresponding burstifiers for aggregation on the basis of the traffic, destination, loss and delay specifications. The data packets are placed in the burstifier queue where they are assembled into bursts according to the multiclass burst assembly algorithm. After that, the bursts are scheduled for transmission in the scheduler over the switch fabric. A control packet precedes each burst by an offset time. Once assembled at the ingress node, an optical burst is able to travel any distance via core nodes before it arrives at an egress node, where the optical burst is disassembled and the data packets are forwarded to the client networks. The core node consists of a switch controller and an optical switch. The switch controller creates and maintains a forwarding and reservation table and is also responsible for configuring the optical switch. When the switch controller receives a control packet, it identifies the intended destination and searches the forwarding and reservation table in order to find the intended output port. If the output

port is available when the data burst arrives, the switch controller configures the optical switch and allows the data burst to pass from incoming time-slots to the output port while satisfying the QoS requirement of each data burst flow. Since switching is done in a slot-by-slot manner, all incoming slots in different input ports are aligned with the local time-slot before entering the switching network. This alignment is performed by using optical input synchronizers [112-113].



**Figure 4.1: Architecture of a multi-service OBS edge node**

The multiclass burst assembler of the multiservice OBS edge node aggregates various types of data packets into optical bursts. In aggregating data packets, it takes into account the QoS classification of each packet, such as packet loss rate, delay constraints and transmission efficiency. The multiclass burst assembler consists of time division multiplexed (TDM) frame, timer-based and size-based burstifiers. After receiving a data packet, the multiclass burst assembler checks the traffic type, attributes of the data packet and forwards it to an appropriate burstifier. Once a burst is created by the burstifier, then its corresponding scheduler (according to its burst assembly method) sent the burst to the output port. The packet loss probability can be reduced by using scheduling methods, which actually cooperate with the proposed reservation mechanism performed at core nodes. The TDM frame burstifier supports burst-framing and transmission of TDM frames arriving from legacy SONET/SDH client networks. One or more TDM frames can be encapsulated by using a framing device capable of mapping SONET/SDH frames into slotted burst payloads. The slotted burst in the burstifier queue is scheduled for

transmission in a round-robin order. Consequently, the TDM frame burstifier periodically generates slotted bursts aligned with a slot boundary. The number of incoming TDM frames determines the allocated number of slots, which is expected to be constant on each successive time slot for a long period. By co-operating with this TDM frame burstifier, the core nodes (using the proposed reservation mechanism) are able to reserve slots for the periodic TDM burst flows. The timer-based burstifier is able to guarantee the delay bound of multimedia packets. The packets from the classifier output are queued and fitted into slotted bursts after aggregation in keeping packet delay tolerance. If the size of buffered packets is smaller than the queue size, an arriving packet is admitted; otherwise it is lost. The size-based burstifier fills up a slot with packets to improve the transmission efficiency without considering the delay bound. It utilizes the slot size as a parameter to determine the number of packets to be assembled in a slotted burst. At the time slot boundary, the numbers of slots, which are filled up with packets, are sent. If no slot is filled up with packets at a time slot boundary, the scheduler does not send any burst. In the TDM frame burstifier, the amount of burst emission on each successive time frame/slot is deterministic. The delay of a TDM frame in finding a certain number of TDM frames ahead of it, under the first-come-first-served (FCFS) queuing discipline, is therefore bounded. However, in the timer-based and size-based burstifiers, the exact number of packets that are sent in a burst is random at each successive time frame/slot and depends on the number of waiting packets. If there is a positive probability that the waiting packets receive service within a time frame/slot, the delay of a packet is arbitrarily large, despite the fact that the packet arrives at a burstifier queue with a finite number of packets ahead of it. In these burstifiers, more slots are allocated to one burst where the demand is higher, so that the longer the queue is in terms of the number of packets, the more the packets are served through burst emission. The processing time to generate a burst at each burstifier queue is assumed to be a constant. With the round-robin scheduler, the cycle time to run around all queues in a round robin method is taken as  $T$ . Therefore, in each burstifier queue, the time axis is divided equally into successive frames/slots of length  $T$ . A burst is assembled during the cycle time  $T$  and then the scheduler determines whether to send the assembled burst at the slot boundary. The packets arrive at the multiservice OBS edge node from the access networks. It is assumed that the packets arrive at each burstifier queue according to a homogeneous Poisson process with rate  $\lambda$ . If there are fewer than  $K$  packets present, an arriving packet is

admitted; otherwise, it is lost. A packet admitted during  $(0, T)$  is removed at one of the epochs  $kT$  ( $k \geq 1$ ). If, it is admitted at the time  $T - u$  ( $0 < u < T$ ), its delay is the sum of  $u$  and  $(k - 1)T$ . At the end of a time interval  $T$ , the burstifier queue will contain  $j$  ( $1 \leq j \leq K$ ) packets. The  $i$  packets ( $0 \leq i \leq j$ ) are transmitted out of the buffered  $j$  packets. The remaining  $j - i$  packets remain in the burstifier queue and are considered for transmission in the subsequent slot (with the size-based burstifier, if there is  $N$  or more packets at the end of a time-slot,  $N$  packets are transmitted through a burst; otherwise, the packets will remain in the burstifier queue). It is assumed that  $p(i, j)$  is the probability that  $i$  of the  $j$  packets are sent on first cum first service (FCFS) basis. The quantity  $\{p(i, j)\}$  has to satisfy the following:

$$\sum_{i=0}^j p(i, j) = 1 \quad (4.1)$$

$$\begin{cases} p(N, j) = 1, \text{ for } N \leq j \leq K \\ p(i, j) = 0, \text{ elsewhere} \end{cases} \quad (4.2)$$

In this section, an efficient synchronized bandwidth reservation mechanism (SRM) has been proposed (as shown in figure (4.2)), which enables dynamic establishment of adjustable rate channels while satisfying QoS constraints and bandwidth flexibility through the high speed transport networks. The OBS core nodes support differentiated services. Upon receiving control packets with periodicity, the core node examines the ingress/egress address pair of the burst, determines an outgoing port and also a slot for the burst to be sent to a next node. At first, the core node checks whether there has been a reserved slot on a reserved outgoing wavelength channel for the arriving burst. If the core node finds a reserved slot for the arriving burst, it sends the burst through the reserved slot. If there is no reserved slot, the core node tries to find an available slot among unreserved outgoing slots. When an available outgoing wavelength channel and a slot are determined, the burst is sent via the internal switch fabric to the outgoing channel and then to the slot. If neither an available outgoing wavelength channel nor a slot is found for burst transmission, the core node tries to use the internal fiber delay line (FDL) buffer to delay the burst transmission. If the FDL buffer is full, the burst is dropped. After the burst is successfully sent, the core node records in its arrival record table, the ingress/egress address of the burst, the outgoing wavelength channel and the slot number, required to

send the burst. By checking the transmission records of the arrival-record table, the SRM scheduler knows the slot numbers used to transmit bursts corresponding to a specific ingress/egress address pair. Thus, it recognizes the periodicity of the used slot numbers. A repetition counter is used to judge the periodicity of burst transmission from an ingress node to an egress node. Once the periodicity of burst transmission is determined, the SRM scheduler knows that a certain ingress node requests a bandwidth reservation for its periodic burst flow, so it performs a slot reservation on the upcoming frames for the duration recorded in a certain max-reservation counter. In conventional reservation methods, reservations are either made or denied end-to-end. The proposed mechanism allows a partial reservation, in which some links have resource reservation for a particular burst flow while others do not have.

On links without reservation, bursts are carried on a best-effort basis and the SRM request continues on the downstream towards the egress node. When a core node recognizes that a newly arriving burst flow is trying to reserve a time-slot that was reserved by another flow, it optionally sends a notification message to inform the corresponding ingress node that its bursts have been blocked. A loss counter is used to find the periodicity of lost bursts with the same ingress/egress address. Upon receiving the blocking notification message from the core node, the ingress node reads the blocking notification message and recognizes the loss of bursts that it has sent.

The working of the proposed synchronized bandwidth reservation mechanism (SRM) is as follows:

1. Receive a Burst
2. Read its ingress/egress address
3. If either the reserved slot or outgoing slot for Burst is available
  - Then
    - Forward the Burst through the outgoing slot
    - Lookup the matched entry in the arrival-record table
  - Else
    - Drop or Buffer the Burst
  - Go to 2
4. If either the matched entry or match-counter reaches a preset value
  - Then
    - Reserve the slot number for the ingress/egress address for a preset value

Else

Add an entry with the slot number and ingress/egress address

Increase the counter by 1

5. Go to 1

Although the above proposed mechanism does not mandate the use of FDL, its QoS performance can be significantly improved even with limited FDL to resolve contention for bandwidth among multiple bursts.

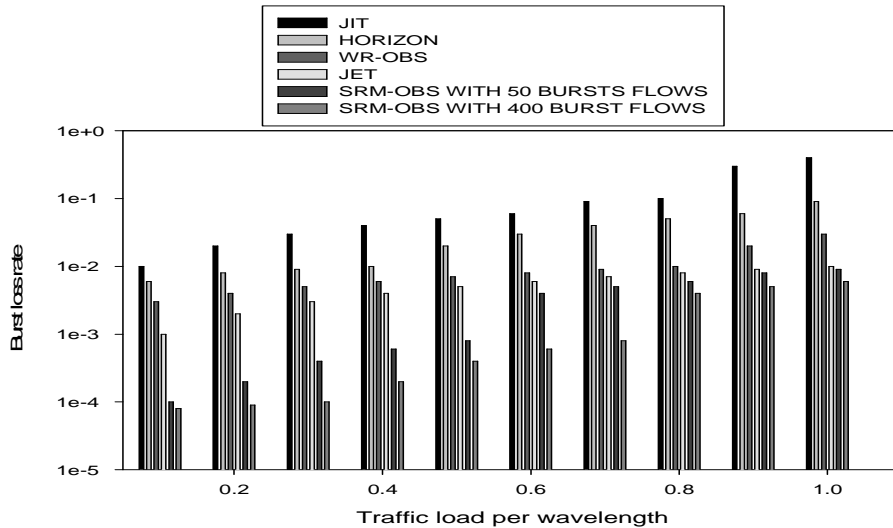
When burst collision occurs because there is no available outgoing slot, the core node can try to allocate the blocked burst in later outgoing slots by using FDL, which store one or more bursts and delay transmission. Once SRM mechanism is performed with FDL, the priority of the burst buffered in the FDL is set lower than that of non-buffered bursts. In this way, it prevents the loss of non-buffered bursts due to competition with buffered bursts.

#### **4.1.2 Simulation Details**

In the simulation, it is considered that the nodes are connected by WDM links with multiple wavelength channels carrying bursts. The node is capable of wavelength conversion and the transmission rate of each wavelength is 10 Gbps. The wavelength is organized into a series of frames, each of which is sub-divided into fixed length time slots (0.175 ms). Each time slot contains about 156 kb of data in one burst. It is assumed that bursts generated by a size-based burstifier of the multi-class burst assembler arrive at a node according to a Poisson process per time slot. It is also assumed that one frame consists of 6 slots and for a burst flow, bursts are periodically transmitted every 6 slots.

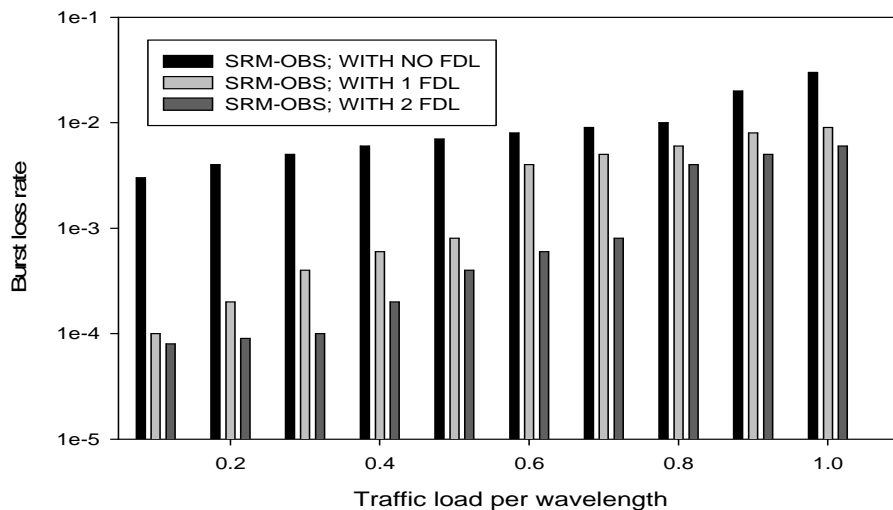
#### **4.1.3 Results and Discussions**

It is observed in the figure (4.2) that better burst loss rate has been achieved with the proposed scheme. As the flow length increases from 50 bursts to 400 bursts in the proposed mechanism, the burst loss rate greatly decreases. At the beginning of a newly arriving burst flow, the bursts comprising the flow experience burst collision for the slot reservations. Once core nodes recognize the periodicity of bursts and execute the SRM mechanism for the subsequent bursts flow, the subsequent bursts do not suffer blocking. Consequently, the overall burst loss rate of long lived burst flows is relatively lower than that of short lived burst flows.



**Figure 4.2: Burst loss rate Vs offered load with various flow lengths**

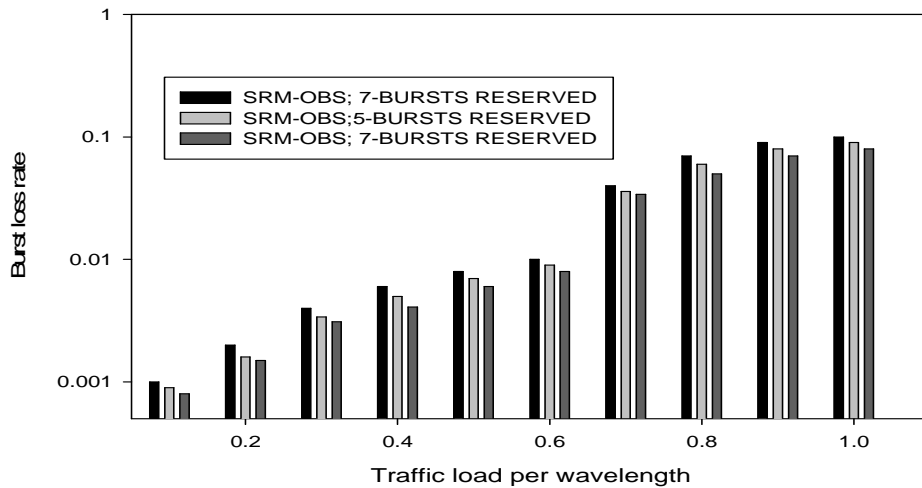
Figure (4.3) shows the burst loss rate of the SRM mechanism with various values of FDL. With the FDL, the burst loss rate is decreased dramatically. While it is certainly possible to improve burst loss rate by allowing bursts to use more than two FDL buffers, but that possibility is not considered here because it is costly and difficult to implement.



**Figure 4.3: Burst loss rate Vs offered load with various numbers of FDL**

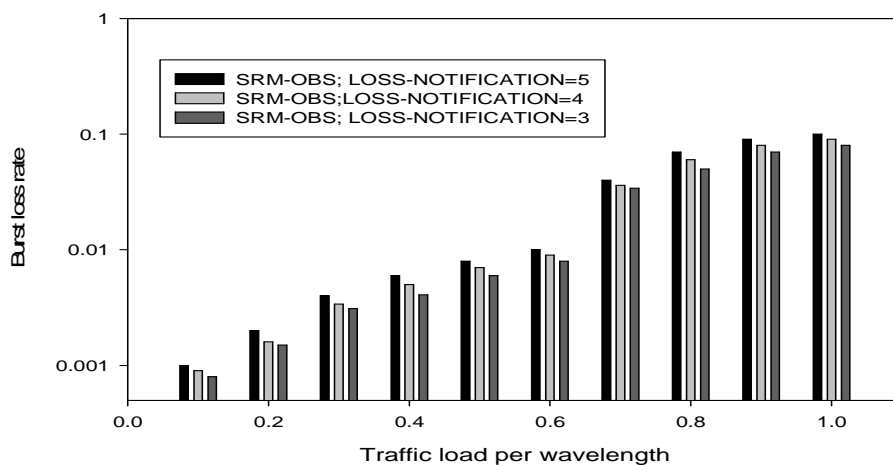
In order to distinguish the effects of the maximum reservation counter, the flow length is set to 100 bursts and its burst loss rate has been investigated (as shown in figure (4.4)). As the number of reserved slots increases, the burst loss rate increases. Although a burst

flow has finished, the reserved slots for the burst flow cannot be used for other bursts. Therefore, if the maximum reservation counter is set to a large value for short lived burst flows, it will waste the channel resources. When a core node recognizes that a newly arriving burst flow is trying to reserve a time-slot reserved by another flow, it sends a notification message to the corresponding ingress node (a loss counter is used to find the periodicity of lost bursts with the same ingress/egress address).



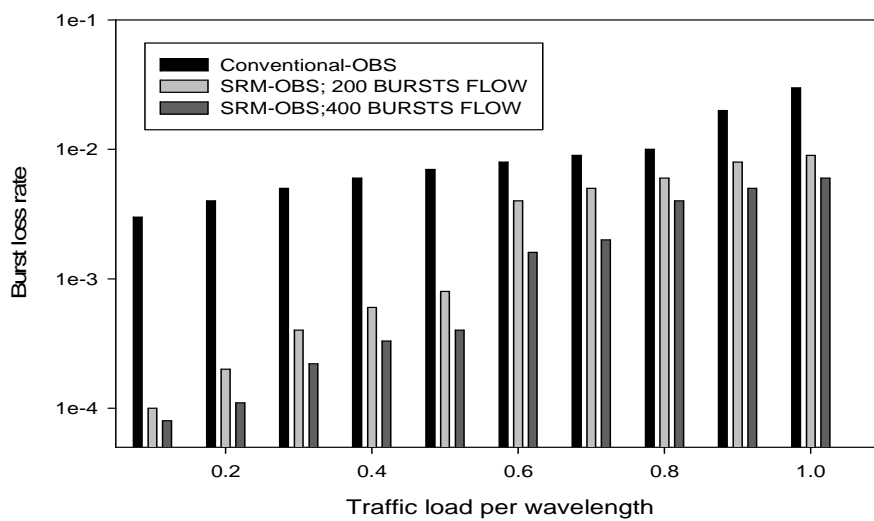
**Figure 4.4: Burst loss rate Vs offered load with various reservation counter values**

As shown in figure (4.5), the lower the loss counter set, fewer bursts are lost because the loss notification is quickly sent to the ingress node. However, if the loss counter value is set too low, this induces core nodes to generate more notification messages in response to the loss of non-periodic single bursts.



**Figure 4.5: Burst loss rate Vs offered load with various loss counter values**

The SRM mechanism improves the burst loss rate by more than one order of magnitude in the region of low offered loads in comparison with the burst loss rate with conventional ones (as shown in figure (4.6)). In the proposed SRM mechanism, once the SRM scheduler recognizes the periodicity of the slotted burst, it reserves slots for the subsequent bursts. Therefore, if the length of burst flow increases more than 400 bursts, the overall burst loss rate decreases. On the other hand, if the flow length decreases by one slot, the burst loss rate of the SRM mechanism is close to that of the conventional reservation schemes.



**Figure 4.6: Overall blocking probability**

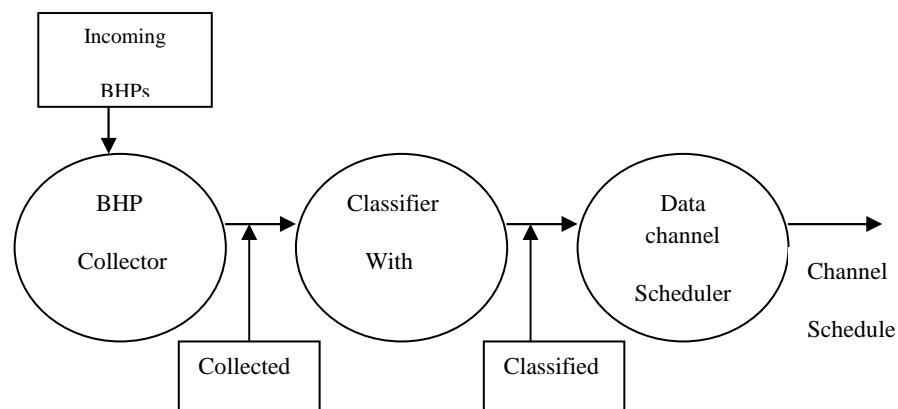
## 4.2 Optimizing Channel Utilization in OBS Networks

In comparison to the scheme proposed in section 4.1, to have better channel utilization, higher throughput and lower blocking probability, in this section, we have investigated an efficient reservation scheme in which data burst are scheduled in batches. In the proposed approach, a burst is represented by an interval of time. The process of scheduling a number of bursts, thus, turns to be a process of fitting a set of the corresponding time intervals on a channel time line that represents a channel-time resource. By doing so, the scheduling process can be formulated as a combinatorial optimization problem. Then, graph theory is applied to schedule as many non-overlapping intervals as possible onto the channel time line. The results obtained show that the proposed scheme gives better

performance in terms of burst loss probability, channel utilization, fairness-control and throughput as compared to existing schemes.

#### 4.2.1 Proposed Reservation scheme for Optimizing Channel Utilization

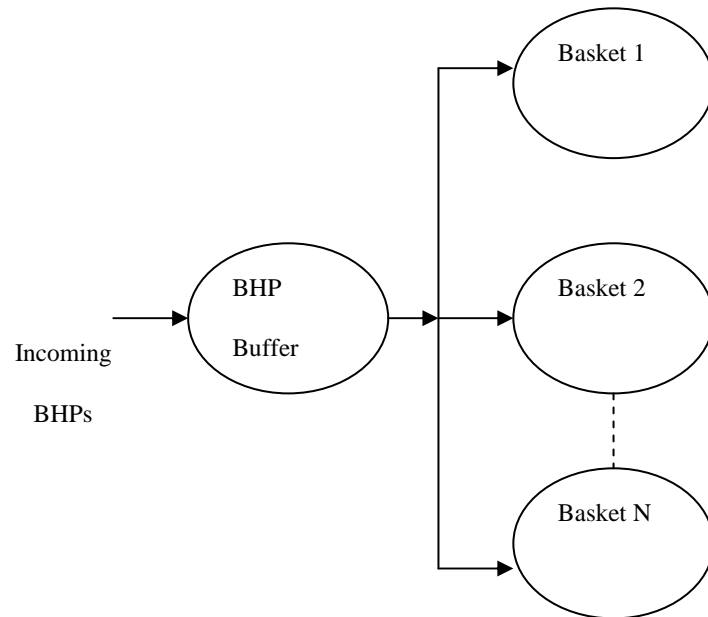
In the proposed scheme, a channel is represented by a time line (as shown in figure (4.7)). The proposed scheme partitions this channel time line into small time windows where a channel scheduling decision takes place on a per window basis. Only those data bursts (DBs) that intend to utilize channel during a certain channel window, not the others, are scheduled together. A burst header packet (BHP), in this scheme, thus serves as a DB agent in requesting channel resources for a particular channel window. The proposed scheme comprises of: BHP collector (batcher) module, a classifier with channel assignment module and a channel scheduler, as illustrated in figure (4.7). The following is the brief working of the system model as shown in figure (4.7).



**Figure 4.7: System model**

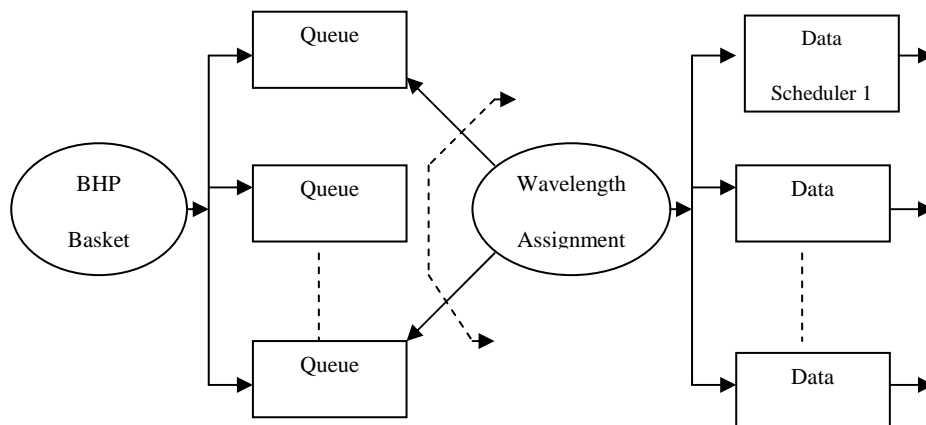
In order to be eligible for scheduling in a certain time window, a BHP must arrive prior to the closing time of this window. The BHP collector (batcher) scrutinizes the BHPs, by looking at their DBs arrival times and durations to determine the channel window in which the DBs are to be transmitted. The BHP batcher then puts the BHP in an appropriate basket as shown in figure (4.8). Each basket represents each channel time window (i.e. it is a one-to-one mapping between a channel time window and a basket.). For each basket, BHPs are sorted (e.g. by their data burst arrival times). This results in assisting BHP classification and channel assignment for multiple-channel scheduling systems. Once the closing time of each channel window is reached, the corresponding

basket is removed from the BHP grouper and no other BHPs are eligible for scheduling consideration in that window.



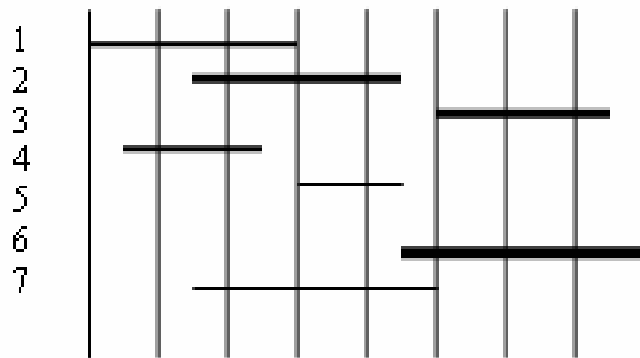
**Figure 4.8: BHP collector (batcher)**

The classifier with channel assignment module is depicted in figure (4.9). It performs channel (or wavelength) allocation and service differentiation. The service differentiation is provided, for examples, by employing a priority scheme (a weighted round robin discipline). After being grouped, the BHPs are classified into classes and are placed in the queues. In case of a single class, there is only a single queue. The channel (wavelength) assignment module then passes BHPs to the channel schedulers.

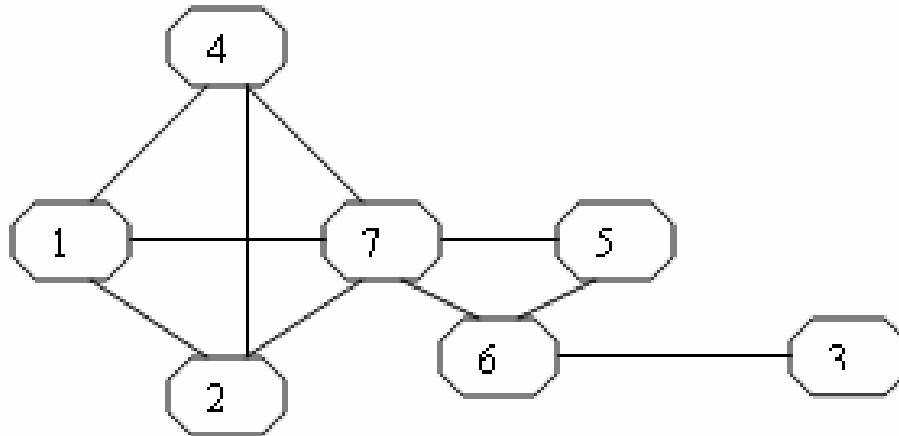


**Figure 4.9: Classifier with channel assignment**

The channel scheduler module schedules BHPs (based on a specification of the start and end times of their corresponding DBs). It maximizes the number of BHPs that are to be scheduled in the channel time window. For a set of BHPs/DBs, the scheduler first establishes interval representation profile (as shown in figure (4.10)). The figure shows seven DBs with various start times and durations. Once the interval representation profile is created, it is transformed to an interval graph. Figure (4.11) depicts the interval graph for the example of figure (4.10). Each vertex in the graph represents a burst. There exists an edge to connect two vertices if and only if, their corresponding bursts are overlapped otherwise, there is no edge between these vertices. For example, DBs 1 and 2 are overlapped, thus, there is an edge connecting vertices 1 and 2 in the figure (4.11). On the other hand, there is no edge between vertices 4 and 5 (as these DBs do not overlap). Based on the interval graph, the channel scheduler applies an appropriate scheduling algorithm to obtain the set of maximum number of non-overlapping intervals. In the given example, there are two possible sets of maximum non-overlapping DBs. The first set is {3, 4 and 5} and the other set is {1, 3 and 4}. The channel scheduler chooses either of the set depending on the criteria deployed in the scheduling algorithm.



**Figure 4.10: Interval representation**



**Figure 4.11: Interval Graph**

#### **4.2.1.1 Scheduling System Operation**

As mentioned above, the channel time is partitioned into a sequence of equal time windows. During each window, a core node keeps collecting BHPs arriving over the control channel. To be eligible for being scheduled in this time window, the BHP arrives before its closing time. Typically, the window closing time is well before of the actual channel time during which DBs is transmitted (taking into consideration other processing times such as scheduling time). The sequence of processes as seen by a core node for a single channel scheduling window is as follows:

1. Burst header packets are batched.
2. Classification with channel assignment takes place.
3. Once the data channel and a class of service are identified, BHPs are scheduled and a set of new BHPs are forwarded to the downstream.
4. Finally, when DBs arrive, they are forwarded according to the schedule plan.

In the proposed scheme, heuristic interval scheduling algorithm has been carried out by the channel scheduler to schedule DBs onto a channel. The basic function of this algorithm is to create an interval graph out of the set of DBs delivered by the classification and channel assignment module. The channel scheduler then uses this graph to obtain the maximum number of bursts that can be scheduled. To achieve this, the

scheduler leverages the unique properties of an interval graph in order to find a clique of maximum size in the graph i.e. maximum stable set of the graph. A clique in an undirected graph  $G = (V, E)$  is a subset  $V' \subseteq V$  of vertices, each pair of which is connected by an edge in  $E$ . The clique problem is an optimization problem of finding a clique of maximum size in graph. The Maximum Clique Problem (MCP) is a hard combinatorial problem, classified as NP-Complete [114-116]. The objective of this algorithm is to find a clique of maximum size in graph using a verification and elimination method. If the algorithm gives an output then it is the maximum size clique in that given graph, but it is not possible to provide an upper bound for the time it takes. Thus, this algorithm is heuristic in nature (heuristic interval scheduling algorithm has been used to find a clique of maximum size in graph). In a graph of size  $N$ , there are exactly  ${}^N C_K$  sub-graphs of size  $K$ . So, the total number of sub-graphs in graph  $G$  is given as:

$$G = \sum_{K=1}^N {}^N C_K = 2^N \quad (4.3)$$

It is seen that equation (4.3) is exponential in nature. So, verifying all of the sub-graphs will take a long time, because number of verifications required is not a polynomial in  $N$ . For decreasing the time required, some of the verifications are avoided. The proposed algorithm uses the following important properties of the clique.

1. Every graph contains at least one clique.
2. In a clique of size  $M$ , all the vertices have the degree  $M-1$ .
3. If the maximum size of any vertex is  $M$ , there doesn't exist a clique of Size  $> M+1$ .
4. If there is a clique of size  $K$ , there are cliques of any Size  $< K$  in the same graph.
5. Conversely, if there is no clique of Size  $K$ , there will not be a clique of Size  $> K$ .

The number of vertices in the clique is known as the size ( $N$ ) of the clique. There are three procedures known as FINDCLIQUE, SELECT and ISCLIQUE which are used in the proposed algorithm. The output will be the maximum clique. The following is the brief description of the proposed algorithm. The different steps of the FINDCLIQUE module are summarized as follows:

1. It finds the maximum degree  $m$ , sets  $lb$  to 0,  $ub$  to  $m$  and  $(lb + ub)/2$  to  $mid$
2. Check whether there is a clique of size  $mid+1$ 
  - (a) If it is there, no need to verify the sub-graphs of size  $\leq mid$  and hence sets  $lb$  to  $mid+1$
  - (b) If not there, then there is no need to consider the sub-graphs with size  $> mid$  (set  $ub$  to  $mid-1$ ).
3. If  $lb \leq ub$ , sets  $(lb + ub)/2$  to  $mid$  and repeats (step 2)
4. The clique, which is found just before when  $lb$  becomes  $> ub$  is the clique of maximum size in the given graph  $G$ .
5. Print the size and vertices in that clique.

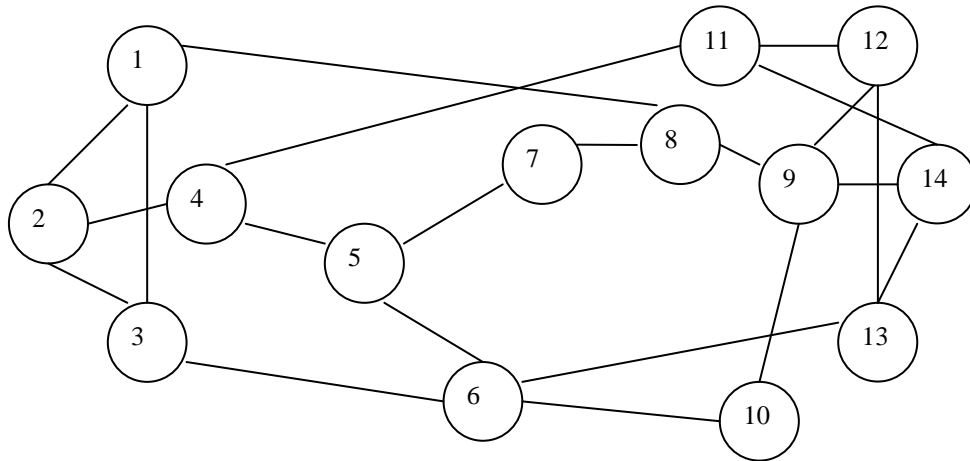
The checking of the existence of the clique of size  $mid + 1$  (step 2) is made by the SELECT module. This module finds the different combinations of the selected vertices and calls the module ISCLIQUE for checking whether that combination of the vertices form a clique or not. If the degree of every vertex, in the induced sub-graph by that combination is equal to  $mid$ , ISCLIQUE returns TRUE.

It is observed that the module FINDCLIQUE works similar to that of binary search. For maximum degree  $M$ , the time complexity of the algorithm FINDCLIQUE is  $O(\log_2(M))$ , which is polynomial. If the size of the sub-graph to be verified is  $K$ , the time complexity of the module ISCLIQUE is  $O(K^2)$ , which is again polynomial. The module SELECT is based on combinations. In worst case, all the  ${}^N C_K$  combinations may have to be verified. But whenever a clique is found, the algorithm will return, neglecting the remaining combinations. So, the average time complexity of the proposed algorithm is practically polynomial.

#### **4.2.2 Simulation details**

The performance of the proposed scheme has been evaluated using NS-2 simulator on the NSF 14-Nodes network (as shown in figure (4.12)). It is assumed that each node is composed of both an edge router and a core router. Each link has some data channel and one control channel and the transmission rate on each channel is 10 Gbps. At each edge router, the aggregate packet arrival process is superimposed by independent ON/OFF source (ON and OFF periods are exponentially distributed and the minimum length of ON period is 1 and that of OFF period is 0). The length of bursts is a fixed value of 15000 bytes. The scheduling time window is considered as 200 $\mu$ s. The following are some of the

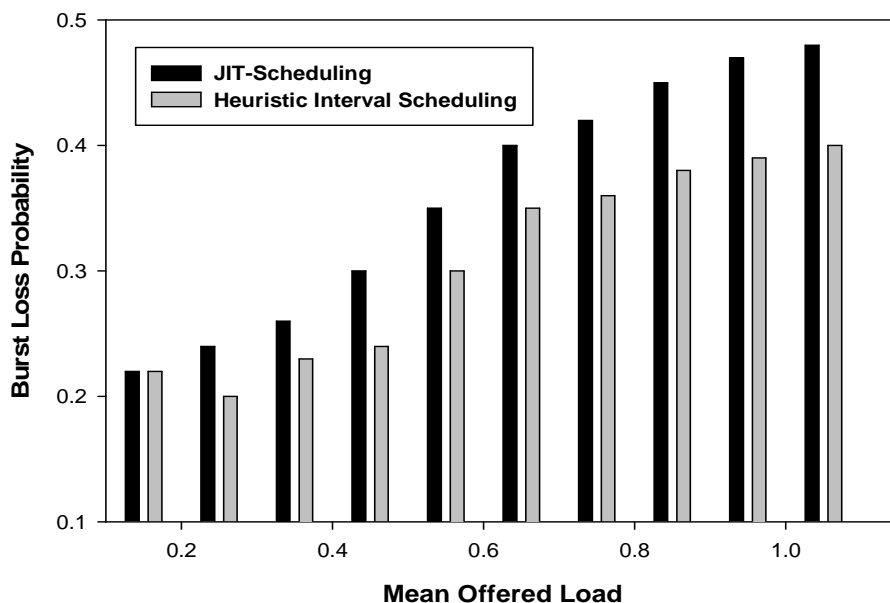
parameters used in the simulation. Wavelengths (10 per fiber), control burst processing time (4  $\mu$ sec), switching time (12  $\mu$ sec) and propagation delay on a link (0.8 milliseconds).



**Figure 4.12: NSFNET (14 nodes)**

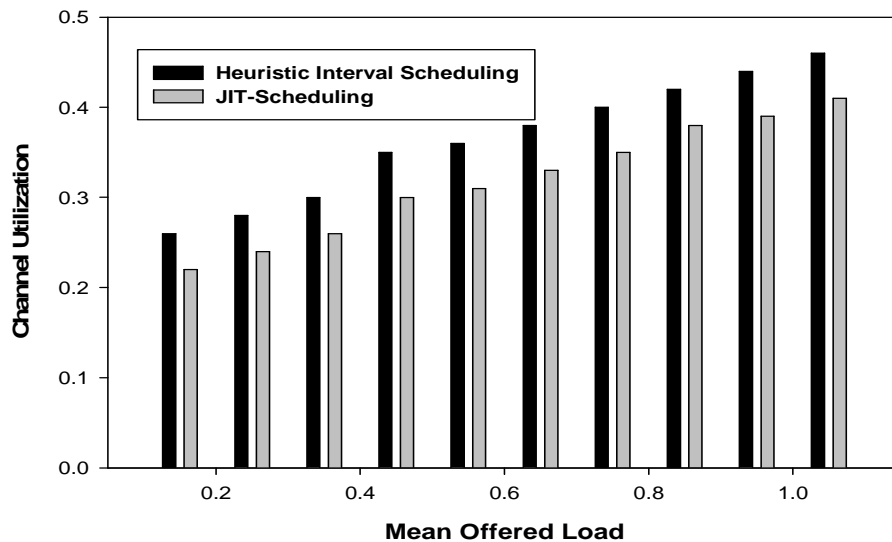
### 4.2.3 Results and discussions

The simulated results (as shown in figure (4.13)) show that the proposed scheme outperforms the conventional scheme over the entire range of the mean offered load. The gain increases slightly with load. The improvement in burst loss probability is achieved with the proposed scheme, particularly in the full load to overload region.



**Figure 4.13: Burst loss probability Vs burst length**

It is also observed (as shown in figure (4.14)) that with the proposed scheme better results are obtained in terms of channel utilization. The improvement is observed over the entire range of mean offered load (0.1 to 0.8). An improvement of the proposed scheduling over the conventional JIT scheduling is shown, specifically at high loads (0.8 to 1.2).



**Figure 4.14: Channel utilization; exponential inter-arrival time and burst length**

### 4.3 Enhancing Bandwidth Utilization and QoS in High Speed Networks

In order to obtain better fairness control and bandwidth utilization, lower blocking probability, as compared to the above proposed reservation schemes (in sections 4.1 and 4.2), in this section, we have presented an efficient reservation scheme that reduces the probability of burst contention by controlling the route at an edge router without contention resolution scheme at a core router and thus, enhances the bandwidth utilization in OBS networks. Also, this section has been focused on the number of resources a packet uses in the network to lower the overall resource usage and loss probability. The simulation results indicate that the proposed scheme improves throughput and quality of service (QoS). By using statistical multiplexing in the proposed scheme, re-configuration is minimized and thus bandwidth utilization is enhanced. The blocking probability of the proposed scheme is also significantly reduced as compared with the traditional OBS schemes.

### 4.3.1 Proposed Reservation Scheme

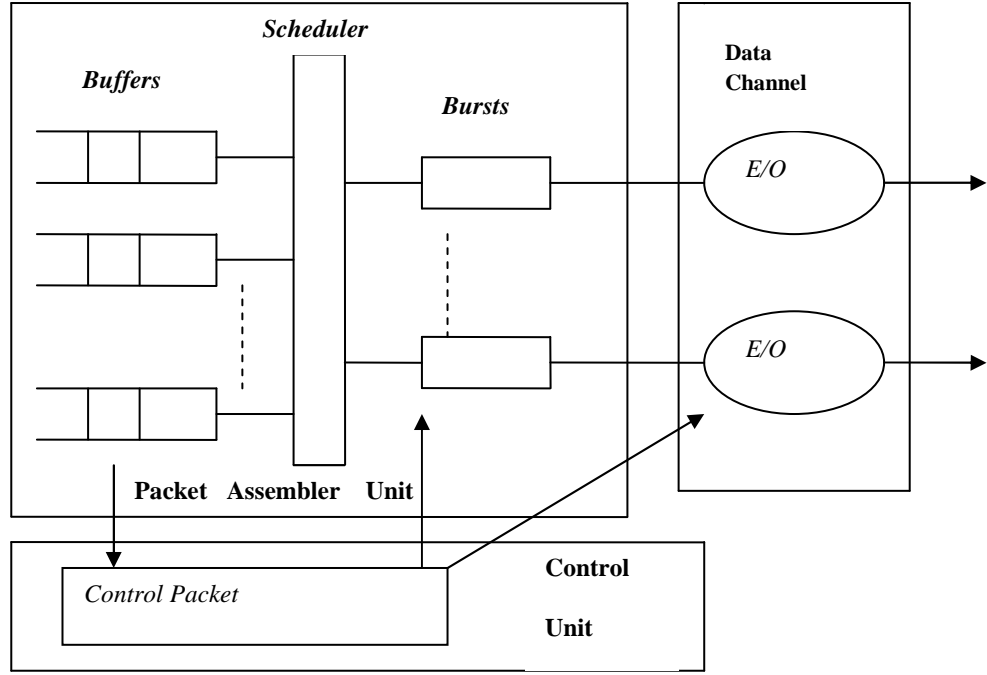
It is already known that the main components of OBS edge router are: Packet Assembler Unit, Data Channel Unit and Control Unit (as shown in figure (4.15)).

1. Packet Assembler Unit (PAU): It collects the input packets and places them in certain burst boxes to form bursts. The incoming buffer acts as an assembler for data flows. The scheduler also makes burst request to control unit to initiate a control information packet. The statistical multiplexing is used to increase utilization of bursts or data channels.
2. Data Channel Unit (DCU): It is the abstraction for a potential wavelength channel to transmit a burst. There are two states for a data channel. In the reservation state, resources such as wavelength, transceiver and OXC ports are assigned to the data channel and hence a wavelength channel is setup. After the burst is transmitted, the wavelength channel is torn down and the resources are released. In the release state, the data channel just waits for new reservation command from control unit.
3. Control Unit (CU): The control unit takes care of the control packet. The control packet includes enough information for burst routing, offset time (on which the burst will arrive) and burst length.

For a data channel to transmit a burst, the four parts compose a reservation of a data channel i.e the time for a reservation state is at least:

$$T_{\text{reservation (Min)}} = T_{\text{setup}} + T_{\text{burst}} + T_{\text{prop}} + T_{\text{teardown}} \quad (4.4)$$

The time such as  $T_{\text{reservation}}$  and  $T_{\text{teardown}}$  are for physical actions in order to setup and to teardown the wavelength channel after receiving the allocation or de-allocation request from the control unit. The time  $T_{\text{prop}}$  is the propagation time that the burst takes to pass the channel.  $T_{\text{burst}}$  is the transmission time for the burst at the full speed of the wavelength channel. The three parts except for the  $T_{\text{burst}}$  are cost incurred by re-configuration. If re-configuration takes place frequently, these parts accumulate a considerable part and lessen the bandwidth utilization.



**Figure 4.15: Components of OBS edge router**

Therefore, statistical multiplexing is used to reduce the effect of re-configuration (in which case the time for setup and teardown is zero and even  $T_{prop}$  is excluded in computing the minimum  $T_{reservation}$ ). The re-configuration bandwidth cost ( $C_{reconfiguration}$ ) and bandwidth utilization ( $U$ ) can be defined as:

$$C_{reconfiguration} = \frac{T_{reservation} - T_{burst}}{T_{reservation}} \quad (4.5)$$

$$U = \frac{T_{burst}}{T_{reservation}} \quad (4.6)$$

By using equations (4.5) and (4.6), it implies that

$$C_{reconfiguration} = 1 - U \quad (4.7)$$

As the burst data is transmitted after the release of the resource reservation occupied by the previous burst, thus, an average end-to-end delay for a burst is:

$$\bar{T}_{delay} = \bar{T}_{reservation} + \bar{T}_{release} \quad (4.8)$$

( $T_{release}$  : release time or idle time for a data channel)

In equation (4.8), the average is made over all of the used data channels. Again, in the case of statistical multiplexing of flows sharing same routing, re-configuration is avoided and delay is identical to all these flows.

#### 4.3.1.1 Prioritized Scheduling

In the proposed scheme, prioritized scheduling based on hop-counts is used, which considers several parameters, such as the packet's time in the network, the application's real-time demand, the number of resources used in the network and the numbers of resources left to use on its path in the network. The JET scheme experiences increasing blocking probability for each hop performed (i.e. resource used). This has the undesirable effect of wasting resources and increasing the network's overall loss probability. It is observed that the proposed scheme not only utilizes the network resources effectively, but also treats the packets fairly. Each edge router keeps the information of all routes to each destination edge router. The priority is set for each route. The source edge router receives a feedback packet after sending a burst. When a burst is forwarded successfully, the destination edge router sends back the feedback packet that indicates the success of the transmission, whereas when a burst is discarded at an immediate core router, the core router sends back the feedback packet that indicates the failure of the transmission. Each route has two values i.e. priority  $P$  ( $0 \leq P \leq 1$ ) and  $N_F$  (number of received feedback packets). The default value of  $P$  and  $N_F$  is 1. On receiving feedback packets, edge routers update  $P$  and  $N_F$  by using the formulas as follows:

$$\text{Success: } P = \frac{P \times N_F + 1}{N_F + 1}, N_F = N_F + 1 \quad (4.9)$$

$$\text{Failure: } P = \frac{P \times N_F}{N_F + 1}; N_F = N_F + 1 \quad (4.10)$$

The route has a high probability of the success, when the priority  $P$  is close to 1. When the priority  $P$  is close to 0, the route has a high probability of the failure. In order to improve the performance; the source edge router sends not only a burst but also some prior information packets on the control channel. The prior information packets are forwarded on several routes, except the route used for the transmission of a burst. By

sending these packets, an edge router searches whether the transmission of a burst is succeeded or failed on the route, except the route used for the transmission of the burst. The transmission of these packets enables an edge router to find a suitable route without sending a burst payload and also the number of discarded burst is reduced.

#### 4.3.1.2 Bandwidth Reservation

Also, in the proposed scheme, two classes of services such as real-time and non-real-time have been considered. The bursts in the real-time class have a strict bound on delay and jitter, thus requiring a guaranteed low blocking probability. On the other hand, the bursts in the non-real-time class tolerate delay but require reliable delivery which is accomplished by buffering and retransmissions. In this section, it has been assumed that no buffers are used in the optical layer, which is highly desirable in all-optical networks. However, buffering is used in the electrical layer for control packets in OBS nodes. The control packet contains the information about its corresponding burst and is electronically processed by the ingress node (as well as at all the subsequent nodes along the path to the destination user). Therefore, the control packets are not transported transparently in an OBS network. It is thus, feasible to buffer the control packets in the electrical layer at the OBS nodes. The two queues are added in JET protocol i.e.  $q_0$  for *class 0* control packets and  $q_1$  for *class 1* control packets. The size of  $q_0$  and  $q_1$  is limited by the memory resource in the OBS node. A time window ( $\Delta t$ ) is also associated with these two queues. The control packets exist in a particular time window  $[t_1, t_1 + \Delta t]$ , if the control packet arrives in that interval. All incoming control packets in the particular window are buffered and are kept in the corresponding queues. There is an offset time between the control packet and its corresponding burst. The proposed bandwidth reservation scheme shows that *class 1* is always scheduled before *class 0* in time window ( $\Delta t$ ) which indicates that *class 1* has more priority than *class 0* in reserving the available bandwidth. The brief description of the proposed bandwidth reservation scheme (at a single node) is shown below:

## Begin

Buffer all the control packets in *time – window*  $\Delta t$  to the corresponding queues

For each control packet  $c_j$  in  $q_1$

If resources are available for  $c_j$

Reserve bandwidth for  $c_j$

Else

Block  $c_j$

End For

For each control packet  $c_j$  in  $q_0$

If resources are available for  $c_j$

Reserve bandwidth for  $c_j$

Else

Block  $c_j$

End For

## End

### 4.3.2 Simulations details

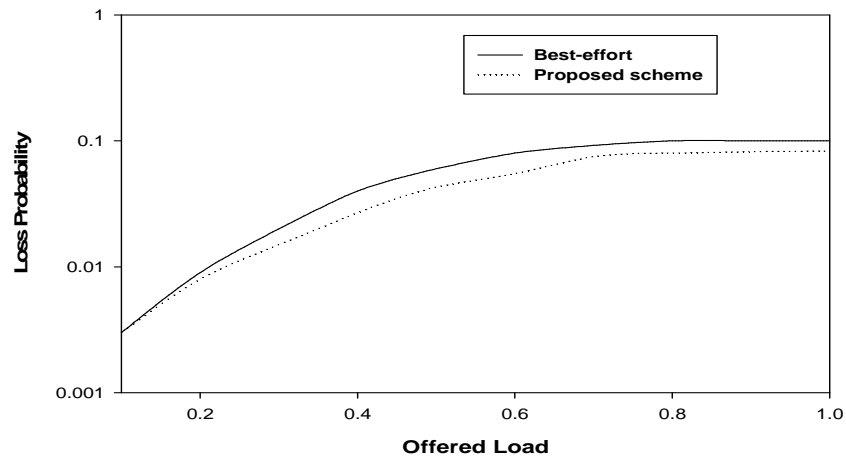
A bidirectional link has been assumed which consists of two unidirectional fibers in opposite directions. Each fiber has 4 data channels at 1 Gb/s transmission capacity. In order to get more realistic results, the long range dependent traffic model is employed. In this traffic model, traffic that arrives at each node pair in the network is the aggregation of multiple IP flows. Each IP flow is an ON/OFF process with Pareto distributed ON and OFF times. The packet length is set to be 100 bytes. There is no wavelength converter and optical buffer in all core routers. The offered load ratio of *class 1* to *class 0* be set at 1 : 9 .

$\frac{\rho}{\alpha}$  is considered as ratio of the offered load to the other traffic ( $\alpha$  : traffic bias). The following are some of the parameters used in the simulation. Wavelengths (12 per fiber), average burst length (100  $\mu$ sec), control burst processing time (2 $\mu$ sec), switching time (12  $\mu$ sec), propagation delay on a link (0.6 milliseconds).

### 4.3.3 Results and discussions

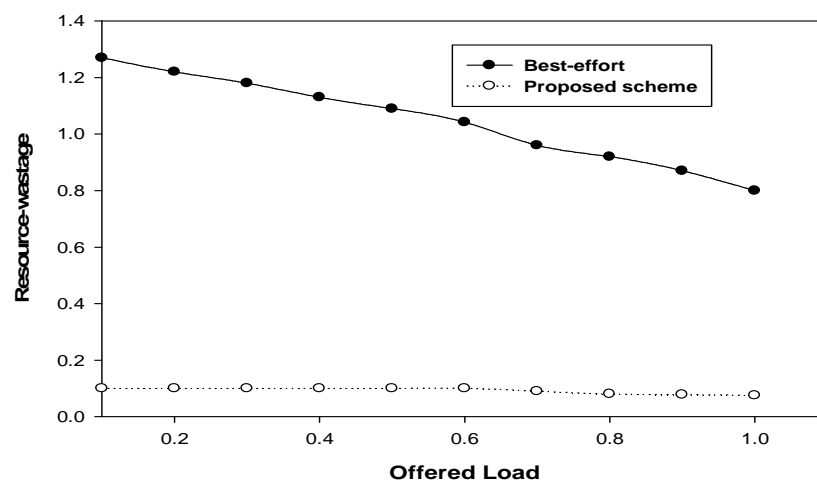
Figure (4.16) shows that network based on the proposed scheme performs better than the best effort network for increasing load. This is because a best effort network drops a packet that has performed several hops in the network with the same probability as a new packet. Such a long distance packet on its path have blocked other packets from being served by the

switch and the thus, the resource utilization is lower in best effort network as compared to the proposed scheme. Also, by differentiating the packets according to their hop count level (HCL), the proposed scheme avoids this effect and hence, increases the throughput.



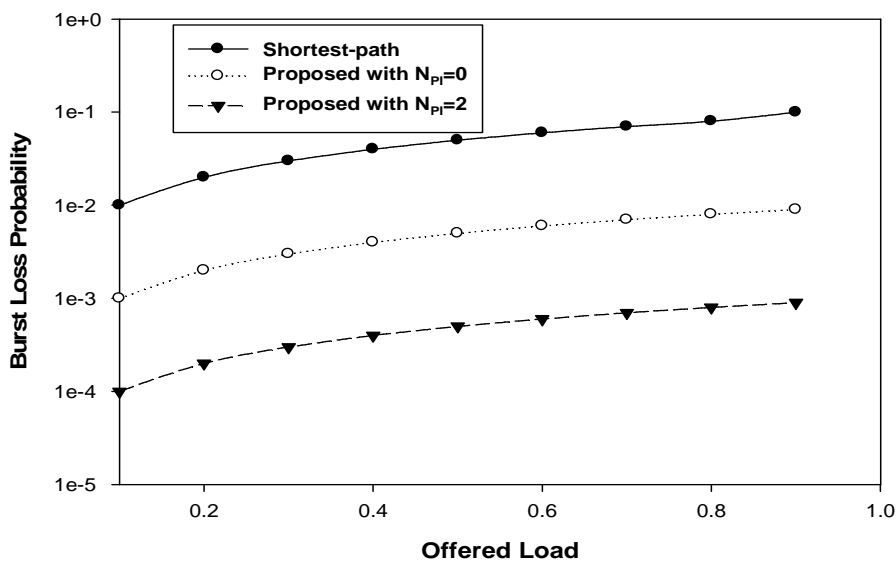
**Figure 4.16: Total loss probability (Proposed Scheme Vs best-effort)**

The average resource usage for dropped packets (i.e. the resource wastage) according to the above reasoning is found to be lower in proposed scheme, as shown in figure (4.17). The resource waste will decrease for an increasing load. This is explained by knowing that the resource wastage is the average number of resources a packet uses before it's dropped (i.e. average number of hops performed before being dropped). When the load increases the average number of hops decreases before the packet is dropped, thus lowering the resource wastage.



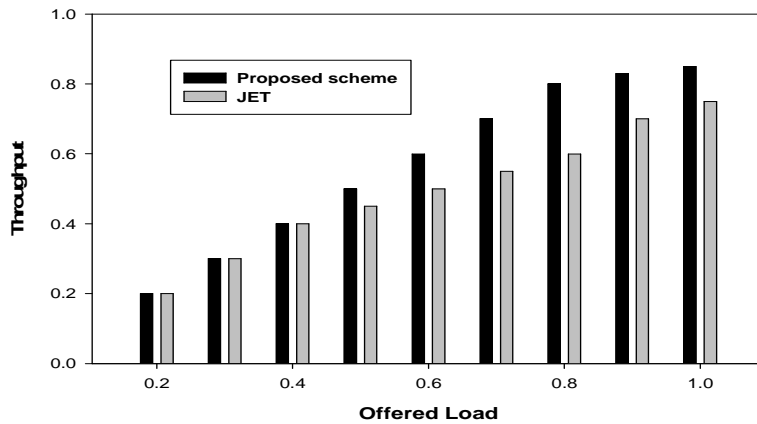
**Figure 4.17: Resource wastage (Proposed Scheme Vs best-effort)**

It is shown in figure (4.18) that the proposed scheme offers lower burst loss probability than the conventional scheme. This is because in the proposed scheme, due to prior information at each edge router, the traffic is not concentrated on particular link. It is observed that the proposed scheme with number of prior information packets ( $N_{PI} = 2$ ) offers lower burst loss probability than that with number of prior information packets ( $N_{PI} = 0$ ). This is because the transmission of prior information packets enables edge routers to get more information and thus, the number of discarded bursts is reduced in this process.



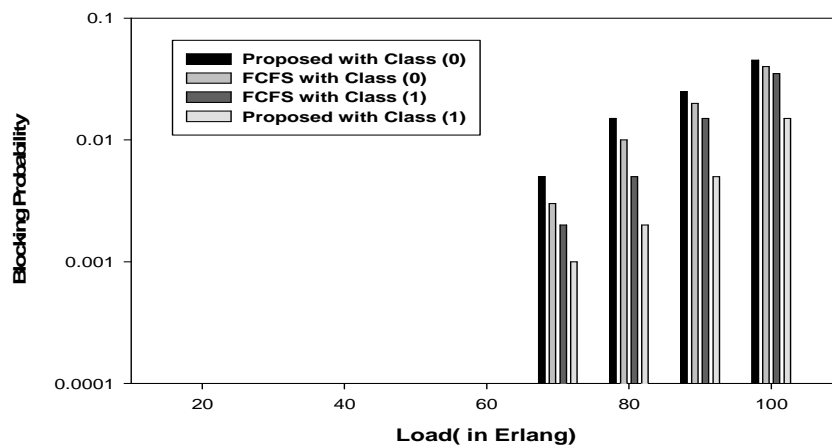
**Figure 4.18: Burst loss probability Vs offered load**

It is observed that the conventional JET scheme exhibits the lowest throughput due to the path length priority effect. In contrast, the proposed scheme (as shown in figure (4.19)) exhibits the best performance in terms of throughput. Therefore, the proposed scheme indicates that a burst traversed more hops complete its transmission more successfully.

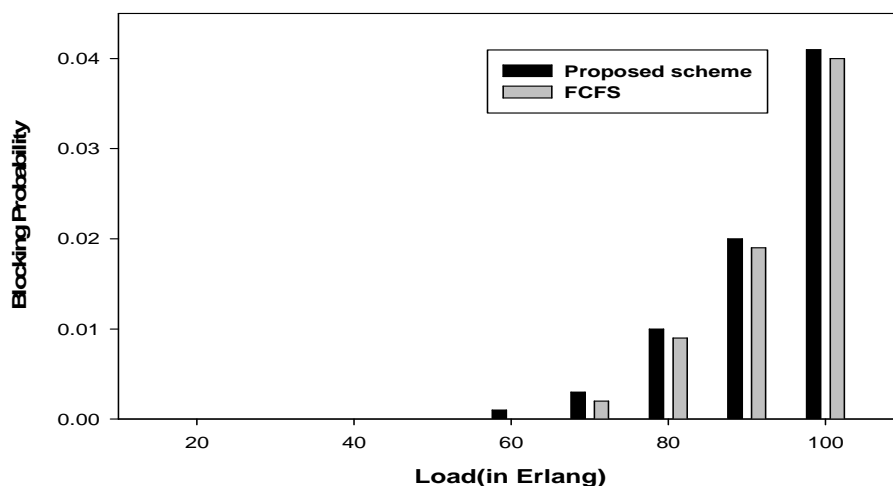


**Figure 4.19: Throughput Vs offered load**

Figure (4.20) shows that *class 1* traffic has better performance with the proposed scheme, especially when the load of the network is greater than 70. Moreover, because *class 1* traffic consumes more bandwidth, it also degrades the performance of class 0 traffic. However, figure (4.21) shows that the total blocking probability in the network is almost the same, which indicates that proposed scheme does not degrade the blocking probability of the network.



**Figure 4.20: Comparison of performance of different traffic**



**Figure 4.21: Burst loss probability Vs FCFS (Time window = 0.5s, Offset time = 0.25s)**

#### 4.4 Conclusion

In this chapter, new quality of service (QoS) oriented reservation schemes has been investigated for enhancing the bandwidth and network utilization in optical burst switched (OBS) networks. An adaptive reservation scheme based on a multi-service OBS edge node with synchronized bandwidth reservation mechanism has been proposed. The proposed scheme enables network nodes to dynamically reserve the bandwidth needed for active data burst flows. It provides a flexible platform for the convergence of packet and circuit based network traffic on the OBS capabilities. The proposed scheme provides QoS guarantee and flexible bandwidth management over the high speed transport networks without any complex signaling or offset-based reservation. By comparing the proposed scheme with other conventional existing schemes, it is observed that better burst loss probability has been achieved with the proposed mechanism. The proposed scheme provides efficient delivery of various types of network traffic, while satisfying QoS constraints.

In order to have better channel utilization, higher throughput and lower blocking probability, in comparison to above proposed scheme, an efficient reservation scheme is investigated. In the proposed scheme, data burst are scheduled in batches. The problem of DB scheduling is mapped to a combinatorial optimization problem of scheduling DB time intervals on a channel time line. The heuristic interval scheduling algorithm is

utilized to obtain the maximum number of non-overlapping bursts. The performance comparison of proposed scheme with existing schemes has been performed. The obtained results show that the proposed scheme is better in terms of burst loss probability and channel utilization.

Further, to obtain better fairness control and bandwidth utilization as compared to the above proposed reservation schemes; another efficient reservation scheme has been presented in which each edge router finds a suitable route to the destination edge router autonomously by using feedback and prior information packets. The simulation results show that the proposed scheme performs better in terms of burst loss probability and resource wastage than a best-effort network. The throughput is thus increased and the network resources are used more effectively. This is especially true for high loads. The proposed scheme also performs admission control. Only new packets that don't block already admissible packets are allowed into the core network. The obtained results have proved that the real time applications which are denoted by class 1 traffic have a better performance using the proposed scheme than with FCFS scheme. Also, the proposed scheme can avoid the path length priority effect and enhance the throughput in multiple hop network environments. Also, by using statistical multiplexing, re-configuration is minimized and thus, the bandwidth utilization is enhanced.

## CHAPTER V

### COMPARISON BETWEEN BURST DROPPING TECHNIQUES

#### Publications from Chapter

1. Amit Kumar Garg, R S Kaler, “Burst Dropping Policies in Optical Burst Switched Network”, **Optik - International Journal for Light and Electron Optics, Elsevier Science**, In Press, Corrected Proof, Available online 23 May 2009.
2. Amit Kumar Garg, R S Kaler, “A new flexible and enhancing bandwidth utilization burst dropping technique for an OBS network”, **Optik - International Journal for Light and Electron Optics, Elsevier Science**, In Press, Corrected Proof, Available online 31 May 2010.

In this chapter, we have investigated the third research objective i.e. to analyze and compare the different burst segmentation policies with the standard dropping policies. The chapter is divided into two sections. In the first section, an efficient burst dropping policy based on even selection of burst (BDPES) has been proposed. Also, an adaptive burst assembly and congestion control mechanisms have been used in the proposed policy in order to provide differentiated service for supporting the quality of service (QoS) requirements. In order to achieve further improvements in the proposed burst dropping policy such as better utilization of bandwidth, lower burst loss rate etc, another efficient, flexible and enhancing bandwidth utilization, burst dropping technique for an OBS network has been presented in the second section. The performance of proposed burst dropping policy/technique has been analyzed and compared with the conventional schemes (such as drop, delay, deflect) in terms of overall all burst drop rate.

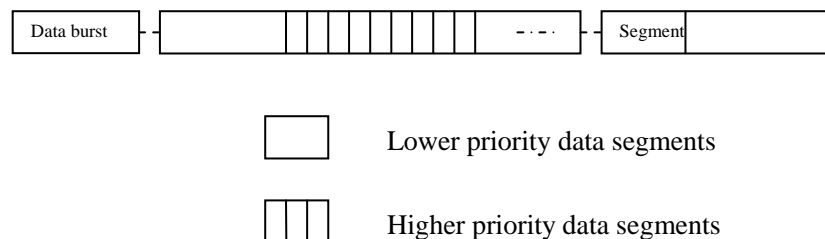
#### 5.1 Burst Dropping Policies in Optical Burst Switched Network

Optical burst switching (OBS) is a competitive switching technology to support the next generation optical Internet. However, due to their one-way resource reservation mechanism, OBS networks experience high bursts (thus packets) loss rate. In OBS networks, the contention is resolved either by dropping one of the contending bursts or more efficiently by dropping only the parts from one of the contending bursts that overlap with the other bursts. In both situations, only one data source will suffer the data loss in favor to the other. In this section, an efficient burst dropping policy based on even selection of burst (BDPES) has been proposed to provide differentiated services. In the

proposed burst dropping policy, the dropped segments are selected evenly from both of the contending bursts and also in proposed policy; the truncated bursts are guaranteed to be larger than the minimum burst length allowed by the network. Furthermore, the proposed policy is enhanced via a flow control mechanism. The simulation results show that the proposed policy is better than existing burst dropping policies in terms of lower burst (packets) loss rate.

### 5.1.1 Proposed Burst Dropping Policy

In the proposed policy, the QoS requirements of the upper layer packets are defined based on their classes. The packets of the same class and destination are assembled into the same data segment, which are labeled with a priority number, accordingly. In the proposed policy, an adaptive burst assembly algorithm has been used to assemble the data segments into data bursts such that the lower priority data segments envelop the higher priority data segments (as shown in the figure (5.1)). In order to achieve high link utilization, the data burst transmission time i.e. burst length/channel speed, has been considered to be larger than the switch fabric configuration time. Earlier, the length of the data burst was entirely overlooked by the resource allocation schemes based on the burst segmentation, since no policy related to the size of the truncated burst during the burst segmentation process in the core nodes was implemented. Also, there was no fairness in allocating the network resources to the contending data burst i.e. all the segments were simply discarded from only one burst to resolve the contention, which increased the likelihood of having bursts shorter than the minimum burst length (MBL). Thus, the better solution is to select the segments to be dropped, evenly, from both of the contending data bursts. Also, the truncated burst are monitored at the core nodes and guaranteed to be larger than the MBL in order to avoid congestion in the control channels.



**Figure 5.1: Burst envelope format**

The following are some of the assumptions that have been made in the proposed BDPES policy.

1. SB: Scheduled data burst with arrival time  $t_{sa}$  and leaving time  $t_{sl}$
2. CB: Contending data burst with arrival time  $t_{ca}$  and leaving time  $t_{cl}$
3. TB: Truncated data burst
4. X,Y: Number of segments in SB and CB respectively
5. DSL: Data segment with length
6. SBL: Scheduled data burst length i.e.  $SBL = t_{sl} - t_{sa} = X * DSL$
7. CBL: Contending data burst length i.e.  $CBL = t_{cl} - t_{ca} = Y * DSL$
8. EDS: Expected number of segments to be dropped from each data burst in case of contention i.e.  $EDS = \lceil t_{ca} - t_{sl} \rceil / 2DSL$
9. TS: Time of switching
10. Offset time condition:  $t_{Offset} \geq t_{max-burst}$  ( $t_{max-burst}$  : maximum burst size)
11. Maximum burst size (upper bound):  $t_{max-burst} \leq t_{propagation} \cdot \alpha / N$   
( $t_{propagation}$  : propagation delay;  $\alpha$  : the ratio of FDL delay to the propagation delay;  $N$  : number of nodes)
12. The delay ratio ( $\alpha$ ) affects the increment of End-to-End (ETE) delay (ETE delay increment from FDL can be reduced by lowering the delay ratio ( $\alpha$ )).

The proposed BDPES policy is based on the four main events such as contention-detection, truncated-burst, resource-allocation and service differentiation. The brief description of the proposed policy is as follows:

1. Check contention-detection // if the condition is true//  
     If  $((t_{ca} - t_{sl}) < TS)$   
     Then  $EDS = \lceil t_{ca} - t_{sl} \rceil / 2DSL$
2. Check truncated burst length // if the condition is true//  
     If  $((SBL - TB < MBL) \mid \mid (CBL - TB < MBL))$   
     Then  
         If  $(CBL < SBL)$  Then  
             Drop CB //Contending data burst is the smallest: dropped//  
             Else  
             Drop SB // Scheduled data burst is the smallest: dropped//

```

        End If
    Else
        Resource-allocation
3. Perform resource-allocation
    I=0 // initialize counter//
    DO
        {
            If (I % 2 = 0) Then  $t_{ca} = t_{ca} + DSL$ 
            Else
                 $t_{sl} = t_{sl} - DSL$ 
            End If
            I++
        }
    WHILE (( $t_{ca} - t_{sl}$ ) < TS)

```

### 5.1.1.1 Proposed Adaptive Burst Assembly Algorithm

To have service differentiation, both of the edge and core nodes co-operate with each other by using the proposed adaptive burst assembly (ABA) algorithm in the edge nodes and BD PES in the core nodes. In proposed adaptive burst assembly algorithm, a small amount of traffic has been stored at the edge router and the output traffic is determined by the amount of stored traffic.

The following are the assumptions made in proposed adaptive burst assembly algorithm:

1. The preset maximum tolerant value for the edge buffering delay is taken as  $T_{\max}^{edge}$ .
2. At the initial phase of assembly, the arriving packets are stored at the edge node until the timer exceeds  $T_{\max}^{edge}$ . Then, edge router sends traffic out at an average rate in the timescale  $[0, T_{\max}^{edge}]$ .
3. At time  $t$ , the rate of the output traffic is set to the average rate as  $[t, t + T_{\max}^{edge}]$ .
4. When the bursts are sent out periodically, the burst size is set to the average number of packets arriving during assembly period  $T_b$ .
5. It is assumed that each edge router has  $M$  queues to sort the arriving packet. Also, the timer and the length of the queue  $Q[i]$  are considered as  $T_i$  and  $L[i]$ .
6. The threshold for generating a burst is taken as  $L_{th}[i]$ . Thus, when the value of the queue length  $L[i]$  is smaller than  $L_{th}[i]$ , all of the packets in  $Q[i]$  will be assembled into a burst. Otherwise, a burst is generated with the length of  $L_{th}[i]$  and all other packets are left in  $Q[i]$ .
7. The threshold  $L_{th}[i]$  has been calculated by the following equation:

$$L_{th}[i] = \begin{cases} (1 + \alpha) \times \overline{L_k}[i], & \text{where } \overline{L_k}[i] \geq L[i]/\beta \\ (1 + \alpha) \times L[i]/\beta, & \text{where } \overline{L_k}[i] < L[i]/\beta \end{cases}$$

( $\overline{L_k}[i]$ ): mean length of the recent  $k$  bursts of  $Q[i]$ ;  $\alpha$ : parameter of the redundancy degree for the prediction of the arriving burst size;  $\beta$  is defined as:  $\beta = T_{\max}^{edge} / T_b$  )

The brief description of proposed adaptive burst assembly (ABA) algorithm is as follows:

### Begin

When a packet with a length of  $b$  arrive at  $Q[i]$

If ( $Q[i]$  is empty)

Start Timer  $T[i]$ ;  $L[i] = b$

Else

Push packet into  $Q[i]$ ,

$L[i] = L[i] + b$

End if

When  $T[i] = b$

If ( $L[i] > L_{th}[i]$ )

$L_b = L_{th}[i]$

$L[i] = L[i] - L_{th}[i]$

$T[i] = 0$

Restart timer  $T[i]$

Else

$L_b = L[i]$ ;  $L[i] = 0$

$T[i] = 0$

Stop timer  $T[i]$

End if

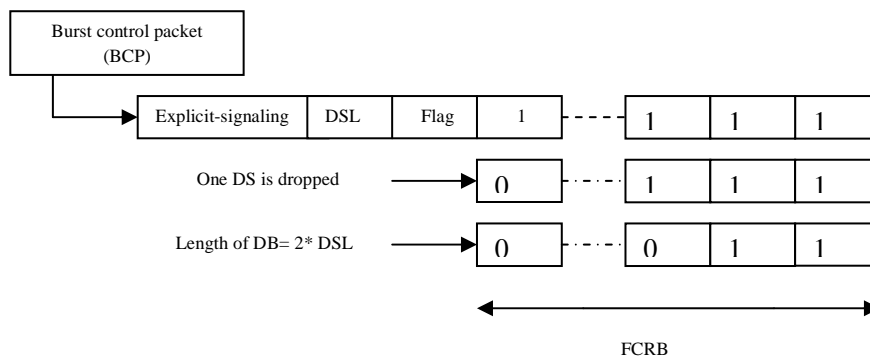
Generate a burst with length  $L_b$  and send it into the OBS network

### End

#### 5.1.1.2 Flow Control

In order to implement the proposed policy (BDPES) effectively, it is seen that neither dividing each data burst into data segments (DSs) nor representing each DSs control information in the burst control packet (BCP) is feasible and sufficient (traditionally done). Thus, in this section, the length of each segment (ranging from one to several packets) is selected, in accordance with minimum and maximum length requirements for efficiency. Additionally, the length of each DS is explicitly reflected in the BCP.

Therefore, a suitable BCP format is proposed. The proposed BCP format provides constant transmission overhead and makes the BCP scalable to higher speeds, as it uses the flow control and reservation bits (FCRB) as the segments length indicator, instead of flags [117]. In the proposed burst control format (as shown in figure (5.2)), an explicit signaling in the backward direction has been used. The bits of FCRB are used to indicate explicitly the amount of data sent and arrived. In the backward direction, explicit signaling notifies the egress node that congestion procedures have to be initiated, wherever applicable for the traffic in the same direction as of the sent bursts. It indicates the number of the dropped segments and also the sent burst that has encountered congested resources. The ingress node then lower the number of data segments sent in each data burst (DB) to be equal to the number of data segments that are allowed through the network to the intended destination. Then, the number of data segments is augmented progressively based on either the maximum size of the data burst reaches or the FCRB field congestion report.



**Figure 5.2: Burst control packet format**

### 5.1.2 Analytical Model

1. In this section, a queuing model  $M/G/\infty$  has been used to evaluate the performance of the proposed BDPES policy.
2. With no buffering, the proposed policy has been modeled as  $M/G/\infty$  queue system with infinity of imaginary servers besides the available  $n$  servers (i.e. number of wavelengths).
3. By considering, the number of busy servers equal to  $(n + k)$ , the following two cases arises:

- (a)  $k \leq 0$ ; no contention (number of busy server  $\leq n$ )
- (b)  $k > 0$ ; all the  $n$  servers are busy and there are  $k$  imaginary active servers for  $k$  upcoming DBs to be switched.

4. For the case (b), there are  $k$  DBs lost for every  $n$  data-segments transmitted.
5. As soon as the contention is resolved, the contending burst is moved from the imaginary server to be served by an original server. Thus, the packet loss probability  $P(PLB)$  is given as:

$$P(PLB) = TL^{-1} \sum_{k=1}^{\infty} i.P(n+k) \quad (5.1)$$

( $TL^{-1}$ : traffic load;  $P(n+k)$ : probability that  $(n+k)$  servers are busy)

6. Since the number of busy servers in M/G/ $\infty$  model has a Poisson distribution [15], Thus the probability  $P(n+k)$  is given as follows:

$$P(n+k) = TL^{n+k} e^{-TL} / (n+k)! , k = 1,2,3,4,\dots \quad (5.2)$$

7. The Erlang-B formula has been used to obtain the burst loss probability:

$$P(k, TL) = \frac{TL^k / k!}{\sum_0^k TL^m / m!} \quad (5.3)$$

( $TL$ : traffic load ;  $k$ : number of wavelengths available at each output port)

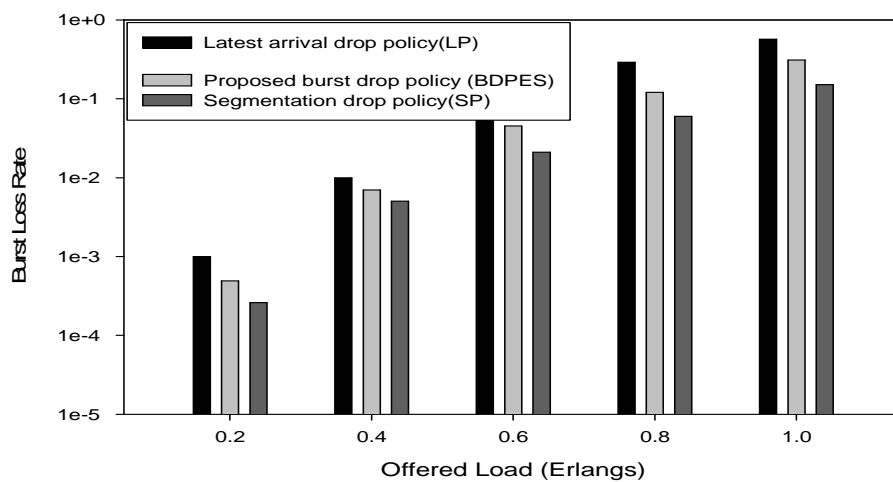
### 5.1.3 Simulation details

The simulation has been performed on the 12-node NSF network. The paths between all of the source-destination pairs are calculated using Dijkstra's shortest path algorithm. The packets are arrived at the ingress nodes following Poisson distribution with rate  $\lambda$  and are assembled into bursts. Each of the burst is composed of 5 segments and each segment is composed of 10 packets. The packet size is exponentially distributed with average size of 10000 bits. The links rates used are 10Gbps. There are no wavelength converters and optical-buffers at the core nodes. The offsets between BHPs and their associated data bursts are fixed. Only two traffic classes are assumed with the same traffic load. First

class with Priority-1 is the higher priority whereas Priority-0 is for the second class, which is the lower priority. The burst loss rate (BLR) is used as a performance metric in the simulation (burst loss rate is the percentage of burst that are sent by the source but never received by the destination).

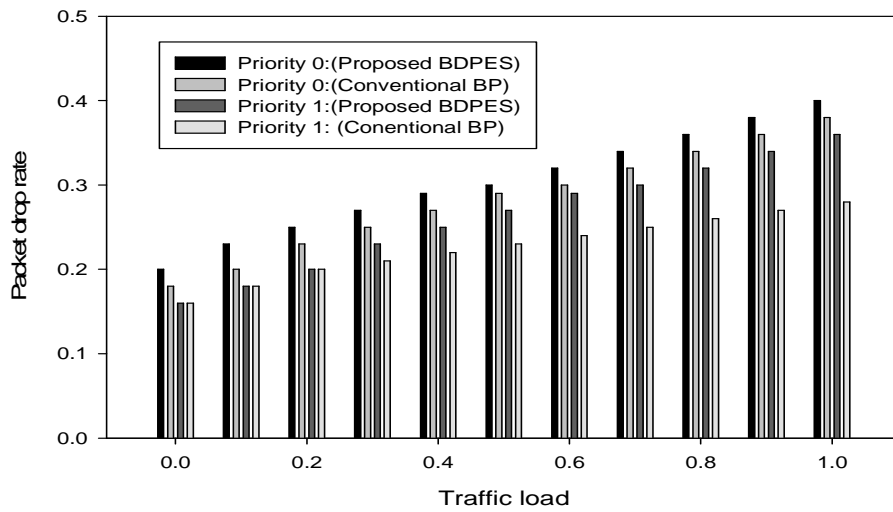
#### 5.1.4 Results and Discussion

Figure (5.3) shows the overall performance of proposed policy in terms of BLR, as compared to the segmentation drop policy (SP) and latest arrival drop policy (LP) policy. As expected, SP and LP provide the upper and lower bounds on performance, respectively. On an average, the proposed policy performs better than LP.

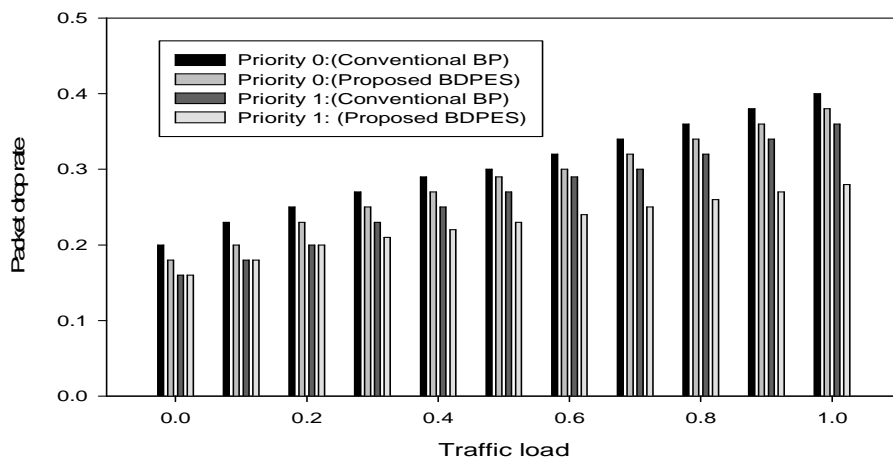


**Figure 5.3: Overall burst loss rate performance using different burst drop schemes**

At first, the simulation has been performed without the use of congestion control mechanism (as shown in figure (5.4)). Afterwards, the proposed congestion control mechanism (only backward signaling) has been used and the corresponding result is shown in figure (5.5). Through simulation results, it has been observed that the lower priority data segments experience more dropping rate. The higher priority data segments are given a higher quality of service and the reduction on the dropping rate is achieved particularly, by using proposed congestion control mechanism.

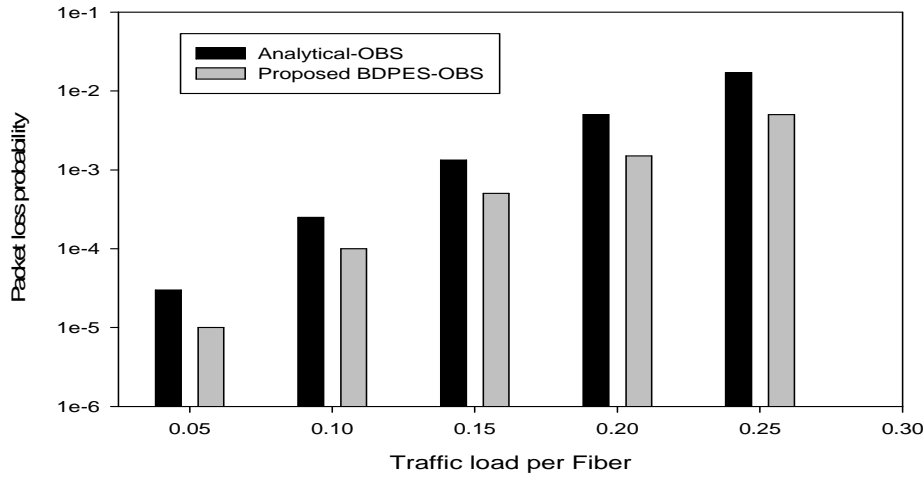


**Figure 5.4: Packet drop rate Vs traffic load (without congestion control)**



**Figure 5.5: Packet drop rate Vs traffic load (with proposed congestion control)**

Figure (5.6) shows that the comparable results in terms of packet loss probability have been achieved in both analytical and proposed policy (further improvement is expected, if the proposed policy is designed to support deflection routing with fiber delay lines or with wavelength conversion capabilities).



**Figure 5.6: Packet loss probability Vs normalized traffic load**

## 5.2 Flexible and Enhancing Bandwidth Utilization Burst Dropping Technique

By analyzing different contention scenarios, it is noticed that the burst dropping policy (as proposed in section 5.1) as well as current dropping schemes e.g. tail dropping and head dropping, are not sufficient to use the available bandwidth efficiently. To address this problem, in this section, efficient, flexible and enhancing bandwidth utilization, burst dropping technique has been investigated for contention resolution in optical burst switched networks. In the proposed scheme, any segment based on packet count number (PCN) in either a scheduled burst or a contending burst are dropped to resolve contention. The simulation results show that the proposed dropping technique performs better than existing burst dropping techniques in terms of packet loss rate (without wavelength converters) and thus utilizes the available bandwidth efficiently.

### 5.2.1 Proposed Burst Dropping Technique

In conventional burst dropping techniques, specifically, tail dropping and head dropping, sometimes, a segment with more packets might be dropped while a segment with fewer packets are scheduled and delivered to the next node. This deteriorates the performance of the system in terms of packet loss rate. However, in the proposed burst dropping technique, segments of either scheduled bursts or contending bursts are dropped whenever contention occurs. In order to determine whether to truncate the contending burst or scheduled burst, a performance metric called as packet count number (PCN) has been used. Whenever contention occurs, there is a need to calculate the PCN of both

truncating the scheduled burst and that of truncating the contending burst, respectively. By comparing the two PCNs, the burst with less value of PCN is truncated. The truncated data bursts are guaranteed to be larger than the minimum burst-length allowed by the network.

It is observed that whenever contention occurs between an arriving burst (contending burst) and some scheduled bursts on a channel, one of the following states (S) occurs (the switching time has been ignored in this section):

1. The head of the contending burst overlaps with the tail of a scheduled burst and the remaining part falls in an open void (S1).
2. The head of the contending burst overlaps with the tail of a scheduled burst and the remaining part falls in a closed void (S2).
3. The tail of the contending burst overlaps with the head of a scheduled burst (S3).
4. The two ends of the contending burst overlap with two scheduled bursts (S4).
5. The middle part of the contending burst overlaps with a scheduled burst (S5).
6. The contending burst overlaps with multiple scheduled bursts (S6).

In the proposed technique, a small amount of traffic has been stored at the edge router and the output traffic is determined by the amount of stored traffic. The brief description of the proposed technique is summarized as follows:

1. Whenever, a new burst arrives at an intermediate node, the scheduling algorithm first try to find a channel without contention. Thus, it tries to find channels closed void first and then tries to find channels with open void.
2. If there are multiple closed void or open void channels available, it will choose the channel on which the minimal start void (the void before the arriving burst after it is scheduled) is minimal.
3. If no voids available, contention happens:
  - Find S2 (first), S3, S1, S4 &S5 (last)
  - Else
  - Drop the arriving burst

4. Calculate the PCNs of the scheduled bursts and that of the contending burst on every candidate channel in order to determine which channel to choose when there are multiple channels available.
5. Channel whose PCN is the minimum among all the candidate channels, is chosen as the channel to be scheduled.
6. Reserve the bandwidth for the arriving burst (based on selection)

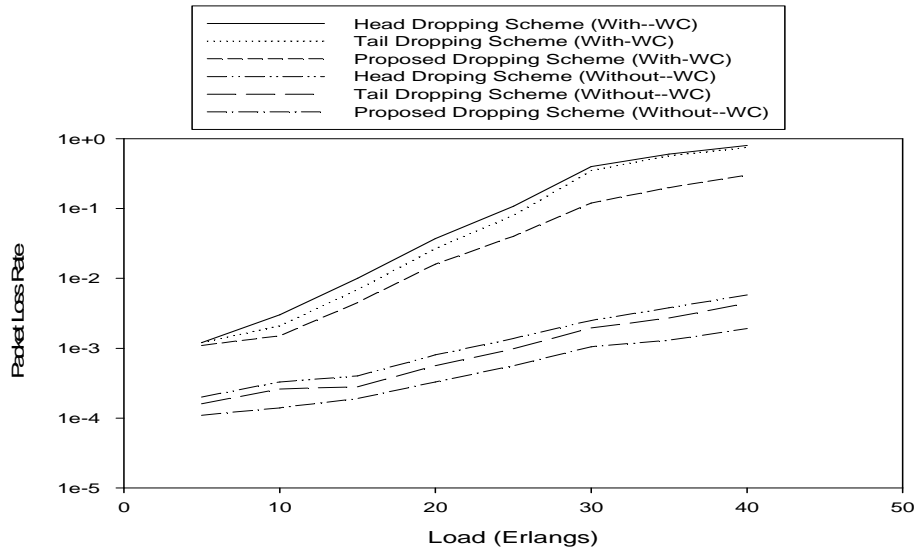
### **5.2.2 Simulation details**

The following are some of the parameters that have been considered in the simulation.

The network topology used is composed of 10 nodes i.e. four edge nodes, two core-nodes and four destination nodes. The edge nodes collect traffic from legacy networks and generate optical bursts. There are 8 wavelengths at each link. The paths between all of the source-destination pairs are calculated using Dijkstra's shortest path algorithm. The packets arrive at ingress nodes following Poisson distribution with arrival rate  $\lambda$ . The packet size is exponentially distributed with average size of 15000 bits. The transmission rate is 10Gbps. There are no buffers at the core nodes.

### **5.2.3 Results and Discussion**

Figure (5.7) plots the packet loss rate versus offered load for reference network with and without wavelength converters at every node. It is seen that when the load is light, the performances of the dropping techniques look similar with wavelength converters, because contentions are not likely happen with light load. However, if the load get heavier, the heavier the load is, the better the proposed dropping scheme performs compared to conventional techniques (specifically, tail and head dropping techniques) while there is not much difference between tail and head dropping. Also, it is observed that even when the load is light, proposed dropping technique out-performs tail dropping and head dropping because there are no wavelength converters (WC) and there are much more chance for contentions to happen even with light load.



**Figure 5.7: Packet loss rate versus load for different burst dropping schemes**

### 5.3 Conclusion

In this chapter, performance of proposed burst dropping policy and technique has been investigated. It is known that the size of the data bursts has a direct impact on the bandwidth utilization and burst loss probability, therefore, flexible and effective burst dropping policy and technique have been developed and compared with the existing techniques in terms of overall all burst drop rate. The dropped segments are evenly distributed between the contending bursts in the proposed BDPES policy for achieving fairness between traffic flows and to minimize the number of short data bursts. Also, the proposed policy enables the core nodes to monitor and manage the size (length) of the data bursts traveling within the network. The proposed scheme is practical and its implementation does not lead to any compromises on one of the main motivational reasons behind the emergence of the OBS paradigm, which is the simplicity. Additionally, a burst control format is proposed to provide flow and congestion control capabilities in the optical domain. With this format, the length of the data burst and data segments, the number of the dropped segments and the forwarded segments using only a limited number of bits (flow control and reservation bits) can be shown. The simulation results show that the proposed policy supports service differentiation with moderate complexity.

To achieve further improvements in the proposed burst dropping policy (discussed above) such as better utilization of bandwidth, lower burst loss rate etc, another efficient, flexible and enhancing bandwidth utilization, burst dropping technique for an OBS

network has been proposed. In the proposed scheme, any segment based on packet count numbers (PCNs) in either a scheduled burst or a contending burst is dropped to resolve contention. It is seen that at low load, the performances of the dropping schemes looks similar with wavelength converters, because contentions are not likely happen at lighter load. However, if the load get heavier, the heavier the load is, the better the proposed dropping scheme performs compared to tail and head dropping techniques while there are not so much difference between tail dropping and head dropping. It is also observed that even when the load is light, proposed dropping technique out-performs tail and head dropping because there are no wavelength converters and there are much more chance for contentions to happen even with light load.

Thus the simulation results achieved above confirm that the proposed burst dropping policy/technique performs better in terms of packet loss rate and flexibility as compared to existing burst dropping schemes.

**CHAPTER VI**  
**CONTENTION RESOLUTION AND CONTROL SCHEMES**  
**FOR OBS NETWORKS**

**Publications from Chapter**

1. Amit Kumar Garg, R S Kaler, “Hybrid Contention Resolution Schemes for Optical Burst Switched High-Speed Networks”, **International Journal of Interconnection Networks (WorldSciNet)**, vol.10, no.1/2, pp. 121–132, March-June 2009.
2. Amit Kumar Garg, R S Kaler, “A Novel Technique to Resolve Burst Contention in OBS Networks”, **International Journal of Electronics (Taylor & Francis)**, vol.97, no.3, pp.295–308, March 2010.
3. Amit Kumar Garg, R S Kaler, “Integrated Contention Resolution & Control Algorithm (ICRCA) for Optical Burst Switched Networks”, **International Journal of Fiber and Integrated Optics (Taylor and Francis)**, vol.28, no.5, pp. 366–375, September 2009.
4. Amit Kumar Garg, R S Kaler, “Performance Analysis of an Integrated Scheme in Optical Burst Switched High-Speed Networks”, **Chinese Optics Letters (Journal of Optical Society of America)**, vol.6, no.4, pp.244-247, April 10, 2008.

In this chapter, we have investigated the fourth research objective i.e. to investigate, analyze and compare the performance of various contention resolution policies and control schemes for optical burst switched (OBS) network, in order to reduce packet (burst) loss, while supporting quality of service. In the first section, to reduce the burst loss rate, hybrid contention resolution schemes based on delay, deflect and wavelength-conversion, have been investigated. In order to improve the scheme, proposed above, in terms of proportional differentiated services, lower packet loss etc, in the second section, an efficient scheme based on adaptive wavelength selection and burst assignment, which supports better proportional differentiated services with lower packet loss in the buffer-less OBS networks, has been developed. Further, to have both contention resolution and congestion control for reducing burst loss in optical burst switched networks, in the third section, we have investigated an integrated contention resolution and control scheme. Finally, to improve the schemes proposed above in terms of wavelength utilization and wavelength efficiency, in the fourth section, an efficient scheme based on resource

reservation and adaptive network flow routing has been presented. The performance of the proposed schemes has also been compared with the existing described schemes.

## **6.1 Contention Resolution Schemes**

In this section, the basic and hybrid contention resolution schemes have been compared with respect to burst loss rate. The results achieved show that proposed hybrid schemes particularly, prioritized delay, deflect and delay provides the lower burst loss rate as compared to existing schemes. It is also observed that a significant differentiation with regard to burst loss has been achieved, when burst priorities are considered.

### **6.1.1 Proposed Hybrid Schemes**

The traditional contention resolution policies are based on drop policy, delay policy and deflect policy. The drop policy discards the contending burst. In the delay policy, the contending burst is delayed by a fiber delay line (FDL) during a bounded time. If during this period time the original burst still occupies the initial port, the contending burst is then dropped. The deflect policy deflects the contending burst to an available alternative port. If there is no available port, then the burst is dropped. In this section, following basic schemes, further assumptions are considered as below (acronyms in parentheses):

- (a) Wavelength Conversion without limitations regarding number of converters or tuning range (WConv).
- (b) Deflection Routing selecting an alternative available output interface in each node in the order of shortest path length (Deflect).
- (c) Buffering uses a shared feedback fiber delay line buffer with a single FDL employing WDM (Delay).

#### **6.1.1.1 Contention Resolution Policies Proposition**

In this section, the following are the three different combinations (based on wavelength conversion, optical delaying and deflection routing) that have been considered for ordering the contention resolution policies.

1. WConv, Delay and Deflect policy
2. WConv, Deflect and Delay policy

### 3. Prioritized Delay, Deflect and Delay Policy

The various situations and choices that arise during burst selection are summarized in Table 6.1. Also, it is considered that when the bursts have the same priority, their lengths are compared and the shorter one is discarded.

<b>Situation</b>	<b>Original Burst Priority</b>	<b>Contending Burst Priority</b>	<b>Longer Burst</b>	<b>Chosen Burst</b>
1	H	H	Contending	Contending
2	H	L	Contending	Original
3	L	H	Contending	Contending
4	L	L	Contending	Contending
5	H	H	Original	Original
6	H	L	Original	Original
7	L	H	Original	Contending
8	L	L	Original	Original

\*H-High, \*L-Low

**Table 6.1: Contention resolution situations between two bursts**

Further, the differentiated service technique is improved in order to optimize the resource usage by using the parameters such as minimum residual time (MRT) and the provided network time (PNT) (for making the selection among two contending bursts). It is assumed that MRT<sub>c</sub> is the contending burst minimum residual time and MRT<sub>o</sub> is the

original burst minimum residual time. For the last situation, as shown in Table 6.2, the choice of the burst selection is made by using the length parameter.

Condition	Chosen Burst
If (( MRT <sub>o</sub> <PNT) & (MRT <sub>c</sub> < PNT) & (MRT <sub>o</sub> < MRT <sub>c</sub> ))	Original
If (( MRT <sub>o</sub> <PNT) & (MRT <sub>c</sub> >PNT))	Original
If (( MRT <sub>o</sub> <PNT) & (MRT <sub>c</sub> < PNT) & (MRT <sub>o</sub> > MRT <sub>c</sub> ))	Contending
If (( MRT <sub>o</sub> >PNT) & (MRT <sub>c</sub> <PNT))	Contending
If (( MRT <sub>o</sub> <PNT) & (MRT <sub>c</sub> < PNT) & (MRT <sub>o</sub> = MRT <sub>c</sub> ))	No decision

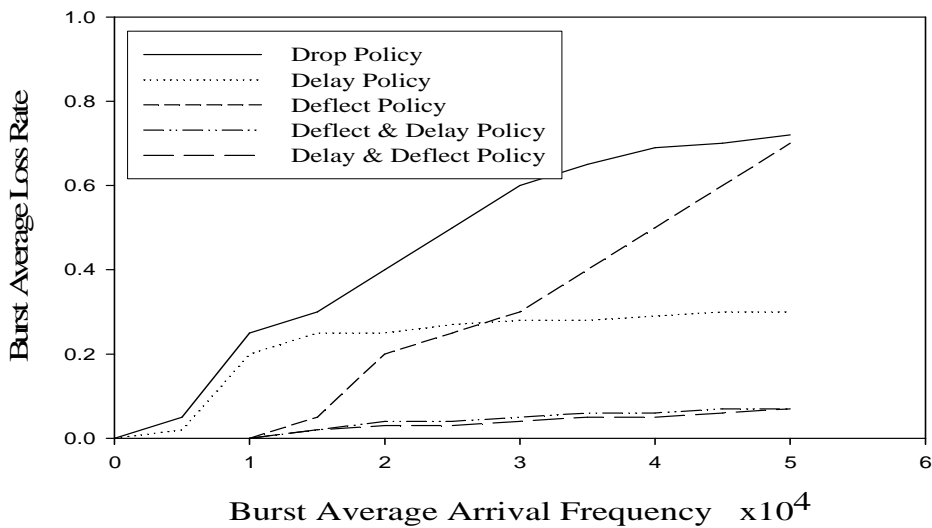
**Table 6.2: Determination of the chosen burst**

### 6.1.2 Simulation details

In order to evaluate the performance of the proposed hybrid contention resolution schemes, the network used in the simulation is NSFNET with 14 nodes. The following are the assumptions that have been made for the simulation. Each fiber has the same number of wavelengths. The burst generation is performed using a Poisson distribution. The burst length is exponentially distributed. The wavelength is randomly assigned by the sender for each burst. The control bursts are transmitted through separate control channels (control burst is never blocked due to unavailability of control wavelength). The network traffic is evenly distributed. The following parameters are considered for the simulation .Wavelengths (11 per fiber), average burst length (100 μsec), control burst processing time (3 μsec), switching time (11 μsec), propagation delay on a link = 0.8 milliseconds).

### 6.1.3 Results and discussions

It is observed in figure (6.1) that the delay and the deflect policies are more efficient than the drop policy. Also, for the burst with lower values of average arrival frequency, the deflect policy has better performance than the delay policy. However, for the burst with higher values of average arrival frequency values, the delay policy has better performance than the deflect policy.

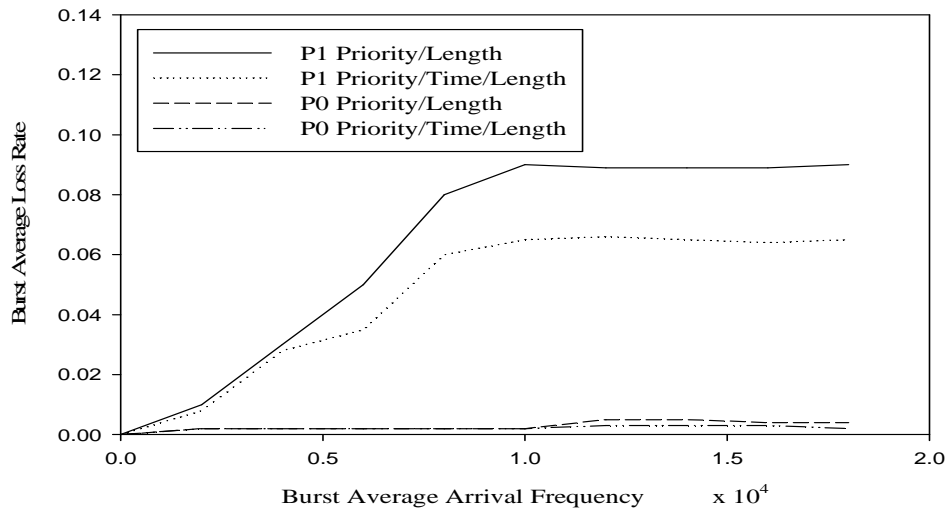


**Figure 6.1: Burst average loss rate Vs burst average arrival frequency (FDL = 5  $\mu$ s)**

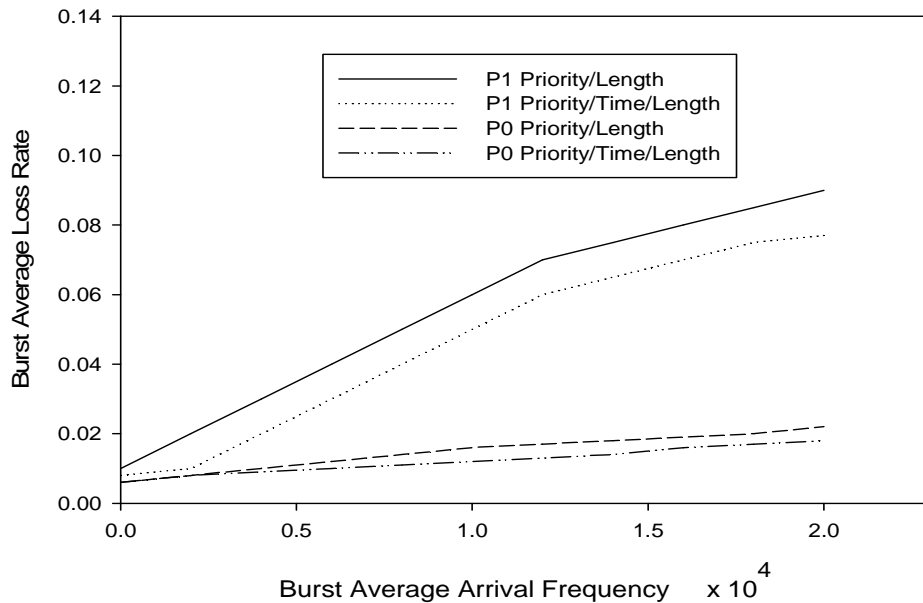
Further, several simulation have been made in order to study the performance of the following three different prioritized policies, supporting QoS. Also, the following are the different fractions of traffic in terms of high priority (P0) and low priority (P1) that have been considered for the policies such as (WConv, prioritized delay and deflect policy), (WConv, prioritized deflect and delay policy) and (Prioritized delay, deflect and delay policy)

1. The fraction in which 25% of the traffic is high priority and 75% of the traffic is low priority (25%, 75%).
2. The fraction in which there is an equal amount of high priority and low priority traffic (50%, 50%).
3. The fraction in which 75% of the traffic is high priority and 25% of the traffic is low priority (75%, 25%).

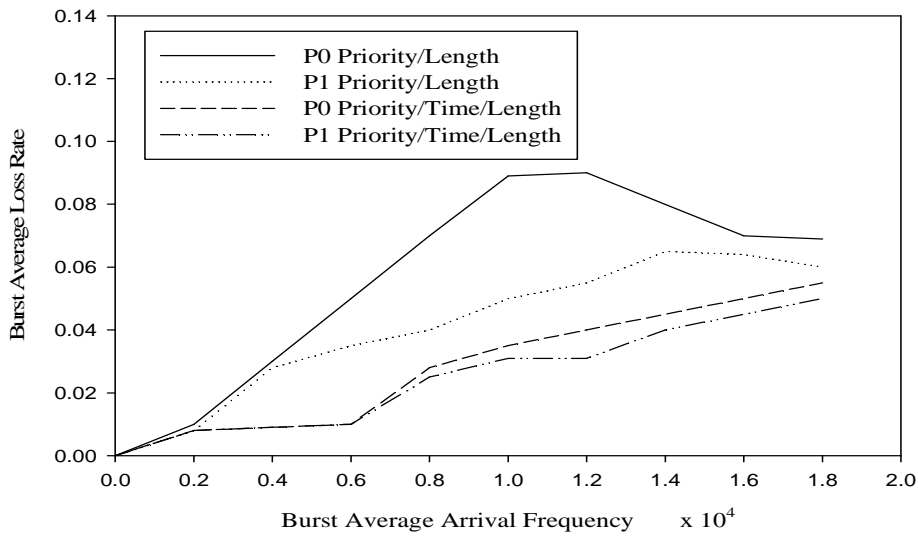
Using WConv, prioritized delay and deflect policy, it has been observed in the figures (6.2) and (6.3) that the loss of high priority bursts is lower than that of low priority bursts. Further, in the figure (6.4), it has been observed that the loss of low priority bursts is lower than that of high priority bursts; however, the gap between losses is less than as compared to the above results.



**Figure 6.2: WConv prioritized delay and deflect policy (P0, P1) = (25%, 75%)**

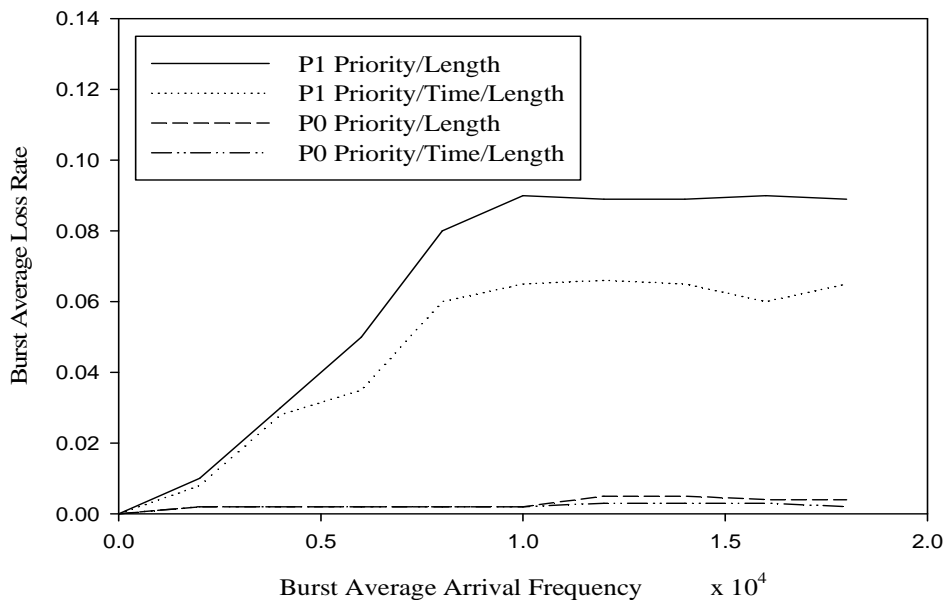


**Figure 6.3: WConv, prioritized delay and deflect policy (P0, P1) = (50%, 50%)**

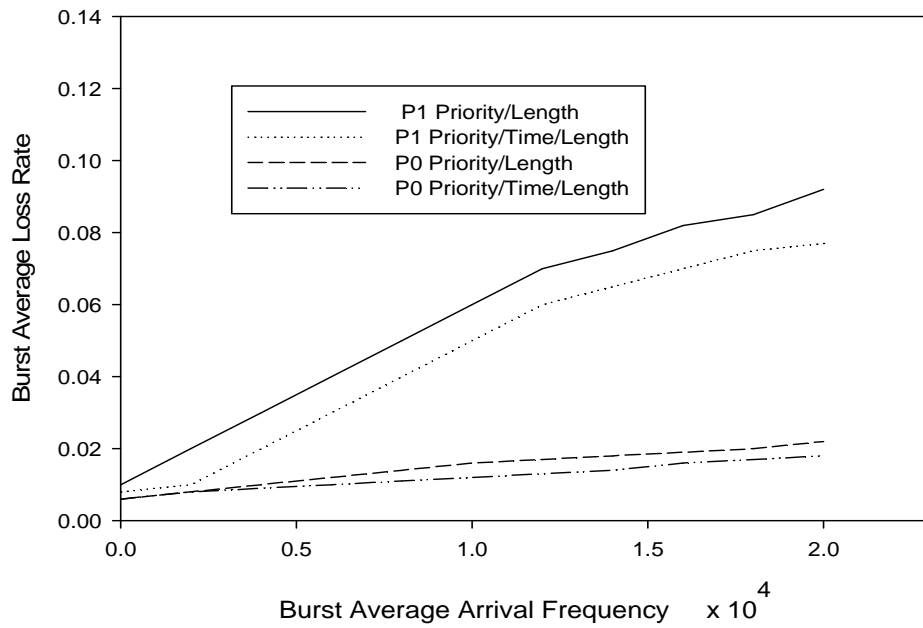


**Figure 6.4: WConv, prioritized delay and deflect policy (P0, P1) = (75%, 25%)**

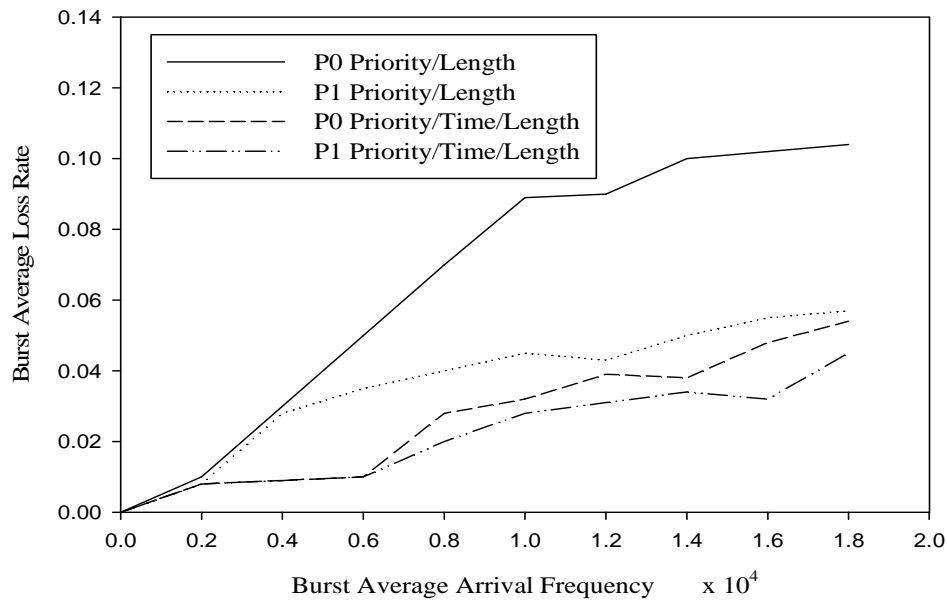
The observations made in terms of high priority burst loss reduction in the figures (6.2), (6.3) and (6.4) are also verified in the following figures (6.5), (6.6) and (6.7) based on WConv, prioritized deflect and delay policy.



**Figure 6.5: WConv, prioritized deflect and delay policy (P0, P1) = (25%, 75%)**

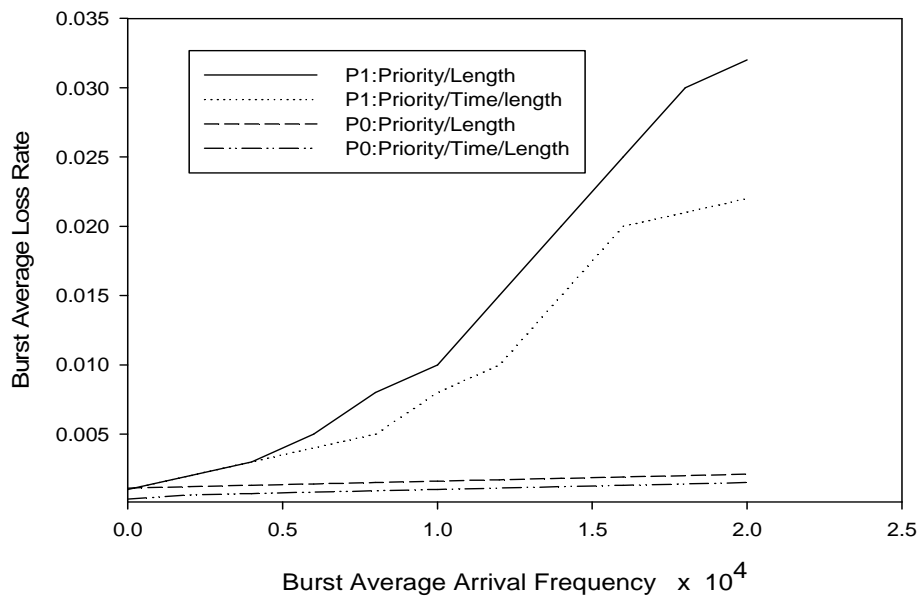


**Figure 6.6: WConv, prioritized deflect and delay policy (P0, P1) = (50%, 50%)**

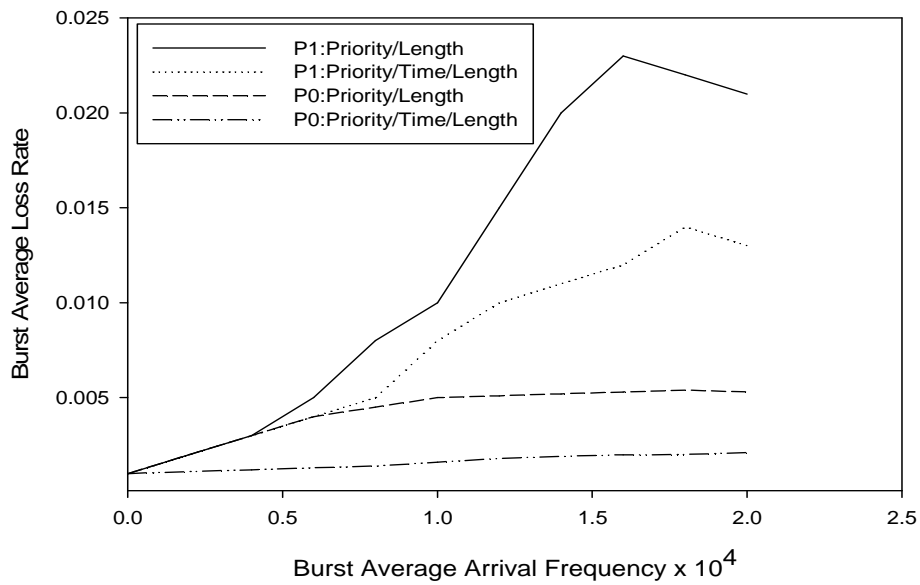


**Figure 6.7: WConv, prioritized deflect and delay policy (P0, P1) = (75%, 25%)**

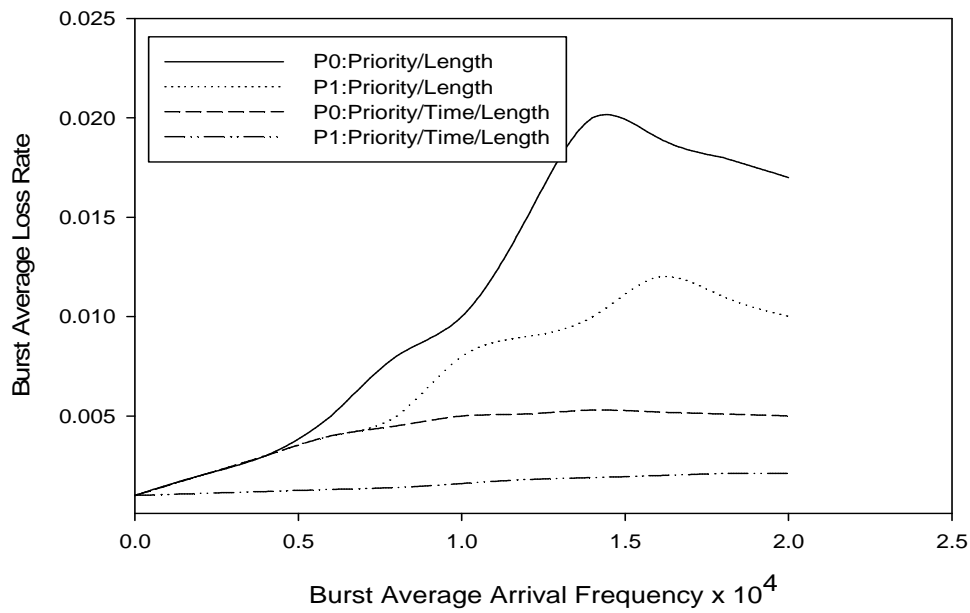
Finally, by using Prioritized delay, deflect and delay policy, the results obtained in figures (6.8), (6.9) and (6.10) are similar to those found in above policies. Also, it has been observed that Prioritized delay, deflect and delay policy has better performance as compared to above two policies. This is because; this policy offers an additional delay for the contention resolution before dropping the burst.



**Figure 6.8: Prioritized delay, deflect and delay policy (P0, P1) = (25%, 75%)**



**Figure 6.9: Prioritized delay, deflect and delay policy (P0, P1) = (50%, 50%)**



**Figure 6.10: Prioritized delay, deflect and delay policy (P0, P1) = (75%, 25%)**

## 6.2 An Efficient Technique to Resolve Burst Contention

To obtain further improvements with the policies proposed above (in section 6.1) in terms of proportional differentiated services, lower packet loss etc, in the second section, an efficient burst contention resolution technique based on adaptive wavelength selection and burst assignment for optical burst switched (OBS) networks, has been proposed. The proposed scheme provides proportional differentiated services in buffer-less OBS networks by dynamically assigning more and longer periods of wavelengths to higher priority classes. In addition to this, burst head packets (BHPs) are buffered electrically so that the fiber delay lines are unnecessary at the core nodes. As a result, BHP of a lower priority class is buffered at the core router when it doesn't find an available wavelength. It has an opportunity to reschedule its burst to the wavelengths that have been assigned to higher priority classes but have not yet been reserved. The proposed scheme not only provides proportional differentiated services but also achieves lower average dropping probability without any preemption or segmentation mechanisms. Compared with existing approaches, the proposed scheme does not need to generate any special packets and needs to maintain only a few parameters at the core nodes. It has been observed that the proposed scheme exhibits simple implementation and improved burst dropping performance in comparison to traditional schemes.

### 6.2.1 Proposed Resolution Scheme

The proposed scheme is based on combination of adaptive wavelength selection (AWS) and burst assignment. Compared with general wavelength continuity based scheme, it is seen that the AWS scheme not only adjusts the wavelength numbers dynamically when the traffic load changes, but also utilizes the wavelengths more efficiently (because the wavelengths are shared among different classes). In addition to this, the proposed scheme is integrated with efficient burst assignment scheme, in which bursts of the lower priority class are processed after a delay to ensure that bursts of the higher priority class have a higher probability of wavelength reservation. In burst assignment scheme, burst head packets (BHPs) are buffered electrically such that the fiber delay lines are unnecessary at the core nodes. Thus, in the proposed scheme, a BHP of a lower priority class is buffered at the core router when it doesn't find an available wavelength. It has an opportunity to reschedule its burst to the wavelengths that have been assigned to higher priority classes but have not yet been reserved. The proposed scheme not only provides proportional differentiated services but also achieves lower average dropping probability without any preemption or segmentation mechanisms. The following are the assumptions that have been made in this section. It is assumed that  $k$  data wavelengths are available for each output link in an OBS node with full wavelength conversion. Latest available unused channel with void filling (LAUC-VF) algorithm has been used at the core nodes due to its high efficiency and simple implementation. In a classless OBS network, there is no constraint on the wavelength searching range. The proposed scheme not only assigns different constraints for different class services in the wavelength searching range but also assigns a candidate wavelength set for each class. For an incoming burst, the core node schedules it to be sent only on one of the candidate wavelengths of its class. The void between two scheduled data bursts on one wavelength is unused wavelength capacity. If a wavelength is occupied exclusively by one class, these voids are wasted despite, bursts of other classes arriving during these periods. To improve wavelength utilization and minimizing the burst dropping probability, different classes have been used to share each wavelength. In addition to this, to maximize wavelength utilization, the highest class is assigned with the whole wavelength set whereas the lower classes are assigned with different subsets. In the proposed scheme,  $C_p(t)$  has been considered as the candidate wavelength set of  $class_p$  at time  $t$ . Also,  $Q$ -burst arrivals are used to represent the monitoring timescale  $\tau$ . A first in first out (FIFO) is used to record the status of the

recent Q-bursts. The depth of the FIFO is M-bits and its width is 2N bits (N is the number of classes). In the proposed scheme, electronic buffer is used. The proposed scheme divides BHPs into two types such as Type- I and Type-II. The Type-I has higher priority over Type-II. The bursts of both types have the same offset time. The BHPs of Type-I bursts are processed as they arrive and BHPs of Type-II bursts are processed after they have been queued for  $t_{wait}$ . A Type-I burst refers to each incoming burst, which is scheduled in accordance with the adaptive wavelength assignment scheme. A Type-I burst is scheduled to be sent only on a wavelength within the candidate wavelength set of its class. If it is scheduled, its BHP is processed normally and sent to the next hop. If it is not scheduled when its BHP arrives and also if it's residual offset time is shorter than a threshold (the minimum time for the remaining route), then it is dropped immediately. If its residual time is longer than the threshold, it is regarded as a Type-II burst, whose BHP is to be queued for  $t_{wait}$  before it is sent on a wavelength within its rescheduling wavelength set. In addition to the candidate wavelength set  $b_i(t)$  for  $class_i$ , a rescheduling candidate wavelength  $b_i^r(t)$  set has been assigned. The rescheduling wavelength set has been assigned with the whole wavelength set when the candidate wavelength is not empty. The rescheduling wavelength set is dynamically adjusted. The bursts are dropped if no suitable wavelength in  $b_i^r(t)$  is found. In order to prevent the end-to-end delay from becoming too large, a parameter  $N_r$  ( $N_r \leq N_{max}$ ) has been considered which indicates the maximum number of times for a BHP to be queued during transmission. When the number of times a BHP has been queued reaches  $N_r$ , the burst are dropped immediately if it can not find a suitable wavelength in its candidate wavelength set. The required extra offset time is thus limited to the expression such as:  $t_{max}^{offset} = t_{wait} \times N_r$ .

The following are the assumptions and notations used in the proposed scheme.

1. The number of candidate wavelengths be  $b_i = k$ , for  $i = 1, \dots, N$
2.  $NA_{i-bursts}$  : Number of arriving burst of  $class_i$
3.  $(N+i)^{th}$  bit equals '1' indicates that a burst of  $class_i$  arrives, whereas  $i^{th}$  bit equals '1' indicates that a burst of  $class_i$  is dropped.
4.  $ND_{i-bursts}$  : Number of dropped burst of  $class_i$
5. SR: Service Differentiation
6. BLR: Burst Loss rate

The brief working of the proposed scheme is as follows:

### Begin

When a burst of  $class_i$  arrives

Use LAUC-VF algorithm to schedule burst,

If (schedule succeeds)

Forward it to next hop

$NA_{i-bursts} ++$

Create a new entry with the  $(N+i)^{th}$  bit set 1

Else

Discard burst

$ND_{i-bursts} ++$

$NA_{i-bursts} ++$

Create a new entry with both  $i^{th}$  and  $(N+i)^{th}$  bit, set 1

End if

Push the new entry into the FIFO and pop the oldest entry

For  $i = 1$  to  $N$

$$NA_{i-bursts} = NA_{i-bursts} - B_{oldentry}^{N+i},$$

$$ND_{i-bursts} = ND_{i-bursts} - B_{oldentry}^{N+i}$$

$$BLR_i = \frac{ND_{i-bursts}}{NA_{i-bursts}}$$

If  $BLR_i / BLR_1 > SR_i / SR_1$

If  $(b_i < k)b_i = b_i + 1$

Else If  $BLR_i / BLR_1 < SR_i / SR_1$

If  $(b_i > 0)b_i = b_i - 1$

End If

### End

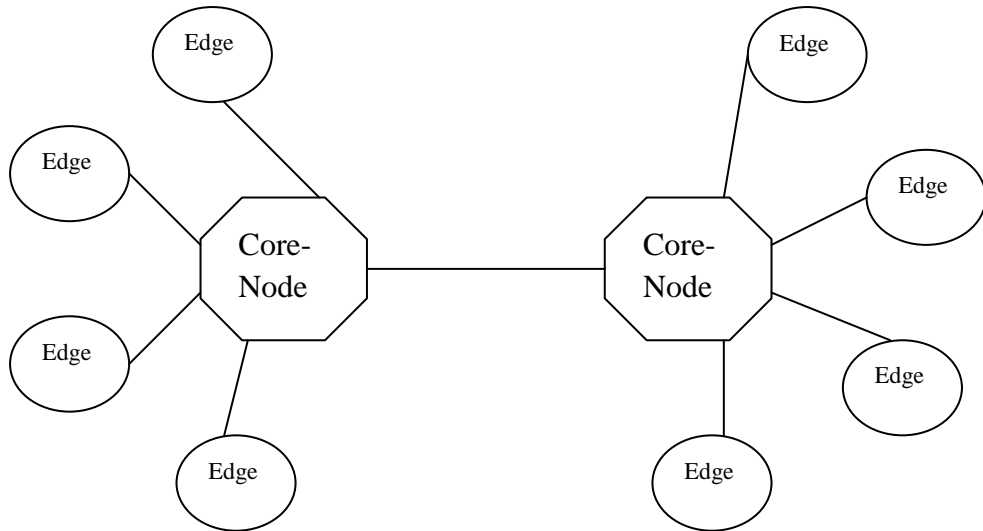
In the proposed scheme, the status of only the recent Q-bursts is recorded, so the oldest entry is deleted when a new burst arrives. The variables such as  $ND_{i-bursts}$  and  $NA_{i-bursts}$ , which records the information of the oldest entry are also updated. When  $BLR_i$  is too high (or low),  $b_i$  is increased (or decreased) in order to decrease (or increase)  $BLR_i$  and also to maintain the ratio  $BLR_i / BLR_1$ . If there is no candidate wavelength ( $b_i = 0$ ) for the arriving burst, the core node drops the burst, immediately. In addition to this, if  $t_{wait}$  is not considered in the proposed scheme, the BHP residual offset time is less than the processing time of the BHP for its remaining route after it has been buffered at intermediate nodes. In this situation, the corresponding data burst (DB) is dropped by the core node because the BHP is not processed before the arrival of DB.

When  $t_{wait}$  is close to zero, the whole system performance deteriorates because there is not enough time for processing BHP of Type-I. On the other hand, a large  $t_{wait}$  causes large extra offset time and also large end-to-end delay. Therefore,  $t_{wait}$  has been included in the extra offset time. The significant advantage of proposed scheme is that there is no basic requirement on the number of wavelengths. It works well even when there is only one wavelength. Thus, the proposed scheme improves wavelength utilization and minimizes the burst contention or burst dropping probability.

### 6.2.2 Simulation details

The following are some of assumptions and parameters that have been considered for the simulation.

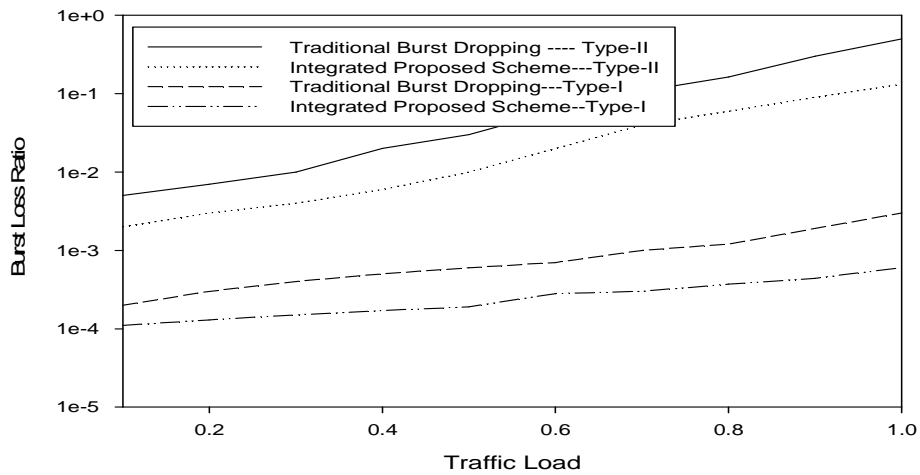
The network topology, as shown in figure (6.11) consists of 10 nodes (eight edge nodes and two core nodes). The bursts are generated at each edge node (with average burst size of 80 Kbytes). All bursts are assumed to have the same initial offset time. The wavelength channels are operating at 2.5 Gbps with average link length of 800 km. Full wavelength conversion is considered at the OBS nodes. Each link is bidirectional comprising two unidirectional fibers in opposite directions. Also, each fiber is assumed to carry eight data wavelengths and one control wavelength. The reservation scheme is based on the Just Enough Time (JET) reservation protocol. The bursts arrive randomly according to Poisson process, with exponentially distributed duration with a mean of  $20\mu s$  (the arrival rate used here is the mean numbers of bursts generated per node, per mean burst duration). The control processing time is assumed to be  $2\mu s$ . The shortest path first routing method is used to establish a route between each pair of edge nodes (with maximum hop distance of 10). Confidence interval (95%).



**Figure 6.11: Star-topology (eight edge nodes and two core nodes)**

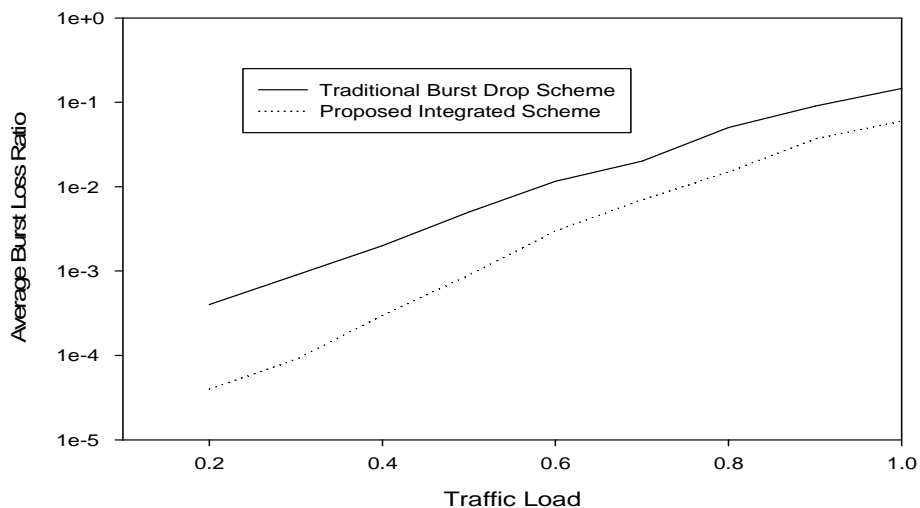
### 6.2.3 Results and discussions

Figure (6.12) compares the burst loss performance of the traditional burst dropping scheme and the proposed integrated scheme. It has been already observed in conventional schemes that the burst loss ratio increases when the traffic load increases. However, the result in figure (6.12) shows that the proposed integrated scheme has better burst loss performance as compared to traditional schemes because the proposed integrated scheme does not waste wavelengths. In figure (6.12), it is seen that the burst loss ratio of the proposed integrated scheme is lower than that of the traditional scheme when the traffic load changes from 0.2 to 0.6. This is because the BHP of a lower priority class (Type-II) in the proposed integrated scheme is buffered at the core node when it does not find an available wavelength and thus, it has an opportunity to reschedule its burst to the wavelengths that have been assigned to higher priority class (Type-I) but have not yet been reserved.

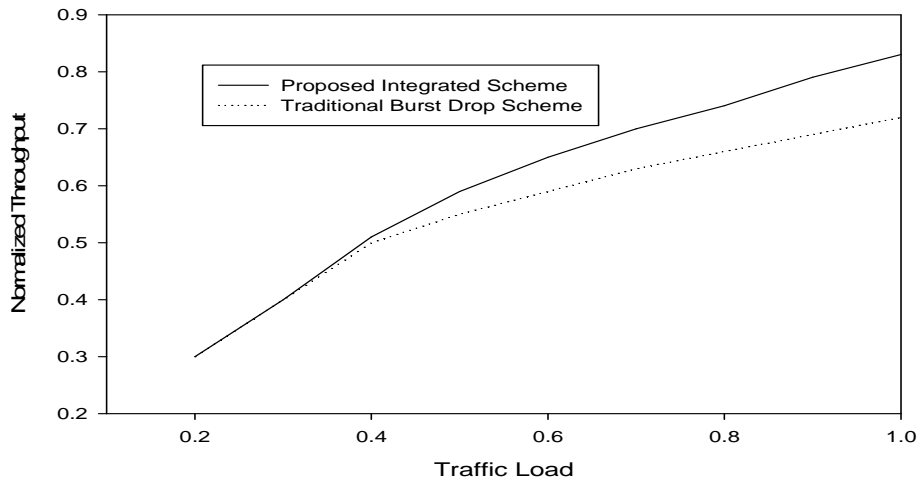


**Figure 6.12: Burst loss ratio Vs traffic load**

Figures (6.13) and (6.14); illustrate the average burst loss ratio and normalized throughput at each link (normalized throughput = throughput/link capacity). The burst loss ratio differs because each of the burst does not have the same size. Thus, the normalized throughput has been used to evaluate the network performance. The proposed scheme has the highest normalized throughput and the lowest average burst loss ratio (as shown in figures (6.13) and (6.14)) whereas the traditional scheme has the lowest normalized throughput as well as the highest loss ratio at all load levels.

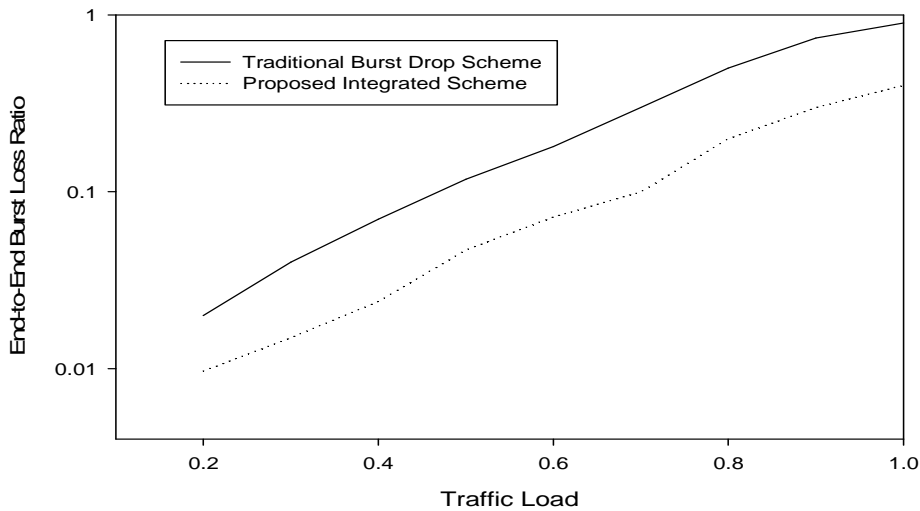


**Figure 6.13: Average burst loss ratio Vs traffic load**



**Figure 6.14: Normalized throughput Vs traffic load**

Figure (6.15) compares the average end-to-end burst loss ratio. The proposed integrated scheme has not only the best hop performance but also having the best end-to-end burst loss performance (the lower priority bursts have larger queuing delay than do the higher priority bursts). The simulation results show that although the proposed scheme improves the burst loss performance at the expense of increasing extra offset time, yet the increase of end-to-end delay is very small (at most hundreds of microseconds) and is negligible for real time applications.



**Figure 6.15: End-to-end burst loss ratio Vs traffic load**

### 6.3 Contention Resolution and Control Scheme for Optical Burst Switched Networks

In order to overcome the limitations of the proposed schemes in section 6.1 and 6.2, in this section, we have investigated an effective scheme based on integration of contention resolution and control algorithm (ICRCA). The simulation results have shown that the proposed scheme behaves well in practice and responds quickly to any change in the network status, while improving the overall network performance. Also, it is seen that the proposed scheme not only provides significantly better burst loss performance as compared to conventional ones, but is also void of any packet re-orderings problems.

#### 6.3.1 Proposed Integrated Scheme

The following are the basic constituents of the proposed scheme.

- A. Contention resolution and control
- B. Traffic control
- C. Fairness

The assumptions that have been used in the proposed scheme are as follows:

1. TFA: Traffic load adjustment
2. FBACK\_CLPKT: Feedback control packet
3. TXR: Transmission rate
4.  $TFA_i$  : Transmission flow increment
5.  $THL$  : Threshold traffic load
6.  $C_c$  : Capacity of channel
7.  $C_\lambda$  : Number of wavelength channels carried by a link
8.  $RTT$  : Round trip delay
9. FWD\_CLPKT: Forward control packet
10. CPBD, CPTL & CPTTH: Contented packet (blocking delay, traffic loss & threshold traffic load)
11. OPTL, OPBD: Original packet (traffic loss, blocking delay)
12. ABD: Average blocking delay

13. FDL\_cnt: Fiber delay line counter
14. RFDL\_num & RFDL\_ur: Real FDL (number & utilization)
15. MFDL\_ur: Maximum fiber utilization
16.  $s[i]$ : Sequence number

#### A. Contention resolution and control

##### *Ingress Edge node (IEN)*

Receive FBACK\_CLPKT

Adjust Traffic load (TFA)

Upon receiving the traffic load adjustment request on link (p, q) at time  $t_1$  ( $TFA_{p,q}^{t_1}$ ) the edge node K, do the following actions:

- (i) If  $TFA_{p,q}^{t_1} = 0$ , continue transmitting at the current rate
- (ii) If  $TFA_{p,q}^{t_1} < 0$ , increase the transmission rate of all (s, d) flows where (p, q)  $\in$  TFA (s, d), according to the increment function *iff* :
  1. The most congested link on TFA (s, d) was (p, q) and  $TXR_{s,d} + TFA_t \leq TXR_{j,k} (1 - TFA_{j,k})$  where (j, k) is the next most congested link on TFA (s, d)
  2.  $THL_{p,q} + TFA_t < THL_{predefined} \times (C_C \cdot C_\lambda)$
- (iii) If  $TFA_{p,q}^{t_1} > 0$ , check the value and time of the FBACK\_CLPKT,  $TFA_{p,q}^{t_0}$  and  $t_0$ 
  1. If  $TFA_{p,q}^{t_0} < TFA_{p,q}^{t_1}$  and  $t_1 < 2.RTT + t_0$   
Then ignore the incoming  $TFA_{p,q}^{t_1}$
  2. If  $TFA_{p,q}^{t_0} > TFA_{p,q}^{t_1}$  and  $t_1 < 2.RTT + t_0$   
Then decrease the transmission rate by  $TFA_{p,q}^{t_1} - TFA_{p,q}^{t_0}$
  3. If  $t_1 > 2.RTT + t_0$   
Then reduce the transmission rate of all (s, d) flows to  $TLI_{s,d} = TL_{p,q} [1 - TFA_{p,q}^{t_1}]$   
(where (p, q)  $\in$  TFA (s, d))

Send FWD\_CLPKT

Modify upcoming traffic

##### *Core Node (CN)*

Receive control packet of the contended packets

Read (CPBD, CPTL & CPTTH)

Identify (OPTL, OPBD)

Initialize  $t_1$ -state = 0

```

If FDL_free = True % available FDL
    FDL_cnt:= FDL_cnt + 1
    t1-state: = t1-state+ 1
    Update (OPBD, ABD)
    Compute (RFDL_num; RFDL_ur)
    Identify (R_CN)
If t1= t1-state% t1 is reached
If RFDL_ur > MFDL_ur
    Generate FBACK_CLPKT
    If forward receive state = True
        Delay FBACK_CLPKT
    Else
        Send FBACK_CLPKT
        Delete packets with Max (CPTL-OPTL) & (RFDL_num < R_CN* ABD)
        Privilege packets with (OPTL ≥ THL)
    End if
End if
End if
End if
Else
Delete contended packets
Update OPTL
End if

```

### ***Egress Edge node (EEN)***

Do reordering action

1. The detection of reordering is performed at the destination, looking at the sequence number  $s[i]$  of each packet, where  $i$  numbers the arriving packet order at destination. This sequence number is set at the source node (following a consecutive integer sequence).
2. In turns, the destination node maintains a counter  $s'[i]$ , which identifies the sequence number of the following expected packet.
3. Under normal conditions,  $s'[i]$  is equivalent to the sequence number of the last received in order packet plus 1.
4. When packet  $i$  arrives, the packet is considered as reordered whether  $s[i] < s'[i]$ . Conversely, whether  $s'[i] > s[i]$ , the packet is considered in order and  $s'[i+1] = s[i] + 1$ .

5. The reordering ratio quantifies (given a certain data stream) the ratio of reordered packets. This figure is easily obtained as the number of reordered packets divided by the number of received packets. (it provides information about the minimal storage (i.e., buffer size) at the receiver, which is needed to restore packet order at destination).

Generate contention requests statistic

Add statistic (FBACK\_CLPKT & FWD\_CLPKT)

Send update information (if request is received)

## B. Traffic control

### 1. Core nodes

- (i) The network load is checked for fixed intervals.
- (ii) If network load is higher than threshold, congestion message is transmitted to data burst sender nodes.
- (iii) If network load is less than threshold, available message is transmitted to data burst sender nodes.

### 2. Edge nodes

- (i) If the congestion message arrives at the node, the generation rate of the incoming traffic decreases by one step.
- (ii) If the available message arrives at the node, the generation rate of the incoming traffic increases by one step.

### 3. Time-window

- (i) The set of flow proportions are periodically evaluated at the end of each measurement time window.
- (ii) If congestion occurs in the paths between the source-destination pair, the flow proportions will be adjusted based on the traffic statistics measured in previous time windows.
- (iii) If none of the paths between the source-destination pair becomes congested, the set of flow proportions will remain the same as that of the nearest previous time window.
- (iv) The time-window-based mechanism is based on the assumption that traffic conditions are predictable (Since bursts in OBS networks are assembled from IP flows, the congestion situation in the network is expected to be predictable).

## C. Fairness

1. Fairness is considered as an important issue in any contention avoidance network with feedback. A widely adopted criterion to define fairness is known as maximum fairness criterion. In this scheme, the traffic flows from different edge nodes with the same priority have an equal share of the congested link.
2. The term  $C_c \cdot C_\lambda / |N|$  is quantified by a fairness index ( $F_f$ ) defined as follow:

$$F_f [TF] = \frac{(\sum TF_i)^2}{|N|(\sum TF_i^2)}$$

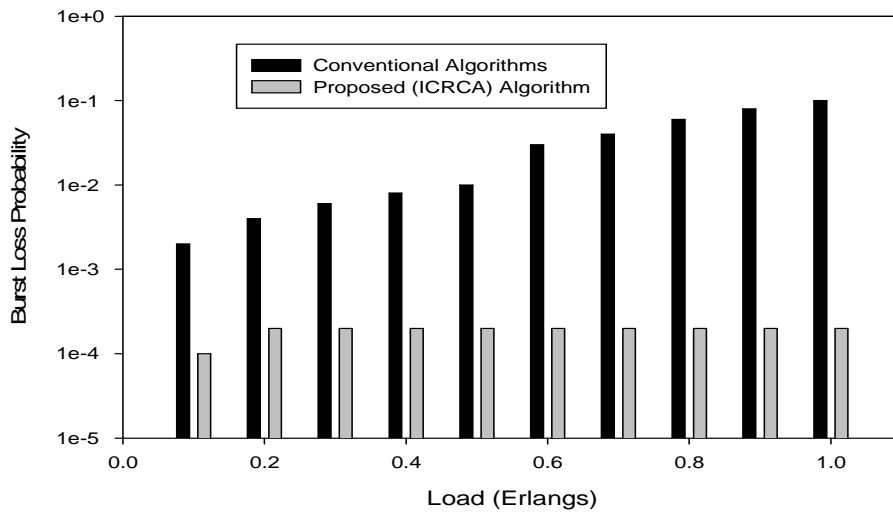
( $|N|$ : number of concurrent flows into the congested link;  $TF_i$ : sending traffic flow of the  $i^{th}$  flow at equilibrium;  $F_i$ : between 0 and 1;  $F_i : 1$  indicates perfect fairness)

### 6.3.2 Simulation details

The following are some of the assumptions and parameters that have been considered to perform the simulation. The simulation has been performed on the 12-node NSF network. All the nodes have the function of both edge and core node, depending on which pair of node is selected to be the source (ingress edge node) and the destination (egress edge node). There are no fiber delay lines and wavelength converters in the network. The reservation scheme is based on the Just-Enough-Time (JET) reservation protocol. The source and destination of each traffic flow are uniformly selected among the nodes. The data bursts are not retransmitted. The bit errors are ignored in the transmission. The size of the electrical buffers in the edge nodes is infinite. Wavelengths (8 per fiber), control burst processing time (4  $\mu$ sec), threshold load (0.8), propagation delay on a link (0.8 milliseconds), switching time (12  $\mu$ sec).

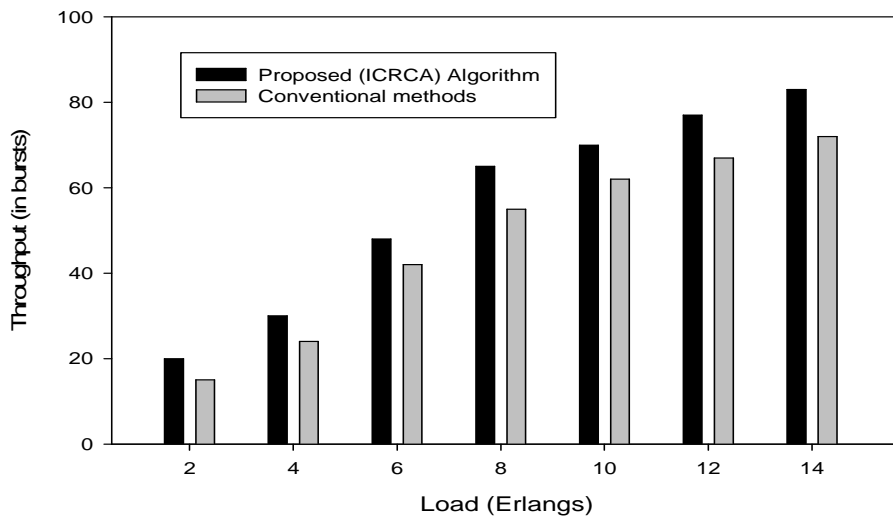
### 6.3.3 Results and discussions

It is seen in figure (6.16) that the data burst loss of the proposed algorithm is lower than one of the conventional ones. In the conventional methods, the higher the network load becomes, the higher the burst loss probability becomes. This occurs because an excessive number of bursts are generated and transmitted into the OBS network when the traffic generation is momentarily high. On the other hand, the burst loss probability is almost identical for any network load in the proposed algorithm, regardless of the load. The proposed algorithm moderates a change of the network load by activating the traffic control policy. Thus, it is possible to control the burst loss probability regardless of a change of the network load in the proposed method.



**Figure 6.16: Burst loss probability Vs load**

Also, it has been observed in figure (6.17) that the throughput value of proposed algorithm is higher than the conventional methods. This is considered as throughput gains to the fact that the proposed scheme uses bandwidth more efficiently.



**Figure 6.17: Throughput Vs load**

## **6.4 Contention Resolution Based on Resource Reservation and Adaptive Network flow Routing**

To improve the schemes proposed above (in sections 6.1 to 6.3) in terms of wavelength utilization as well as wavelength efficiency, in this section, an efficient scheme based on resource reservation and adaptive network flow routing has been presented. The proposed scheme reduces the overall burst loss in the network and also at the same time avoid the packet out-of-sequence arrival problem. Its performance is compared with that of contention resolution schemes based on conventional routing. The simulation results show that the proposed scheme provides lower burst loss in comparison to the basic equal proportion (EPFR) and hop length based traffic flow routing (HLFR) schemes.

### **6.4.1 Proposed Scheme**

The proposed scheme is based on the JET protocol, but it also introduces some mechanism to ensure quality of service (QoS). The ingress node checks all the different optical paths taking into account network topology and load statistics information. The resulting routing information is sent in the control packet. Then, intermediate nodes only need to check the temporal availability for the correct switching configuration to the next hop suggested by the ingress node. The arriving traffic flows are assigned to multiple link disjoint paths between each source and destination (SD) pair based on a set of flow proportions computed adaptively. Once the assignment for a new flow is made, the flow is transmitted using the same path until its departure and is not shifted between different paths in different time windows. Based on the measured quality at the end of each time window as well as the hop length factors of the paths, the set of assigned flow proportions for the paths between SD pair is adjusted accordingly and applied to route new incoming flows in the next time window. Also, the burst assembly time threshold for each path is varied to further enhance the burst loss performance. The proposed scheme provides better QoS, as controlled loops are made by using the previously reserved resources. In contrast to JET, resources are not released just after data burst (DB) transmission but are preventively reserved. If there are no available resources at the next hop node, a loop is created by sending the burst back to the preceding node (where resources have been pre-reserved) and forwarding it again. The uncontrolled loops and the computation problems associated with rerouting are the drawbacks of conventional routing mechanisms which are avoided with the proposed scheme. Due to its flow based nature, the proposed scheme

is free from the problem of packet reordering. The flow routing is performed in a weighted round-robin manner. Whenever a new traffic flow arrives, based on the path selection sequence, a path is chosen to route the flow and the path selection sequence repeats in cycles. The flow based routing algorithm has to maintain the mapping information between the flow and its assigned path. This helps in improving the routing stability and thus, reduces the traffic fluctuations in the network [7-10]. Therefore, the overall network performance has been improved. In case, when two bursts with different priority content the same path, a distributed wavelength assignment algorithm for burst optical networks called as the priority based wavelength assignment algorithm, is used to resolve the contention. The resource contention is resolved in the wavelength domain. With this algorithm, each node assigns wavelengths based on the wavelength priority information learned from its wavelength utilization history in a distributed manner. As the learning process progresses, nodes in the same part of the network tend to assign different wavelengths to avoid contentions, meanwhile, the same wavelengths are spatial reused in the different parts of the network. Each sender node  $x$  keeps a wavelength priority database for every destination node  $y$ . For each wavelength  $w$ , a pair of information,  $P(x, y, w)$  and  $N(x, y, w)$  are recorded, where  $P(x, y, w)$  shows the priority function and  $N(x, y, w)$  shows the number of access times to wavelength  $w$ . The priority of the wavelength is determined by the value of the priority function  $P(x, y, w)$ , i.e., a wavelength with the largest priority function value has the highest priority. The number of access times  $N(x, y, w)$  is used to determine the modification value for updating the wavelength priority. The wavelength priority is calculated by the following iterative formula.

1. When a burst with wavelength  $w$  is successfully delivered,  $P(x, y, w)$  and  $N(x, y, w)$  are updated as:

$$P(x, y, w) = \{P(x, y, w) * N(x, y, w) + 1\} / \{N(x, y, w) + 1\} ;$$

$$N(x, y, w) = N(x, y, w) + 1 \quad (6.1)$$

2. When a burst with wavelength  $w$  is not successfully delivered,  $P(x, y, w)$  and  $N(x, y, w)$  are updated as:

$$P(x, y, w) = \{P(x, y, w) * N(x, y, w)\} / \{N(x, y, w) + 1\} ;$$

$$N(x, y, w) = N(x, y, w) + 1 \quad (6.2)$$

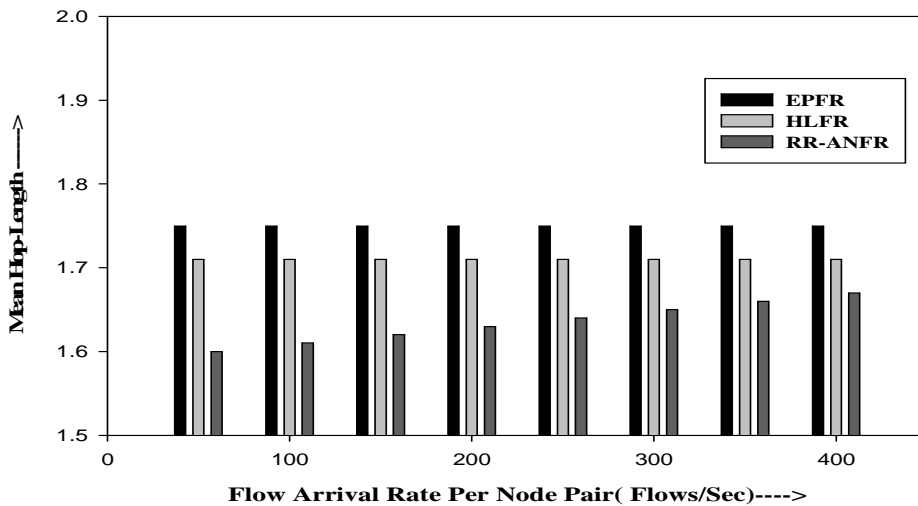
The value  $P(x, y, w)$  approaches to the successful transmission probability as  $N(x, y, w)$  increases under steady state. In non-steady state, however, adaptation becomes difficult as  $N(x, y, w)$  increases, since adaptation speed decreases as  $N(x, y, w)$  increases (an upper limit to  $N(x, y, w)$  is necessary to maintain constant updating of  $P(x, y, w)$  in order to accommodate dynamic change of burst traffic).

#### **6.4.2 Simulation details**

The burst loss probability, mean hop-length, wavelength utilization and wavelength efficiency are used as the performance metrics. The burst loss probability is measured as the fraction of bursts dropped. The mean hop-length is measured as the average number of hops traversed by bursts. The average wavelength (channel) utilization is the percentage of a single wavelength that has been utilized to successfully deliver data bursts. The average wavelength efficiency is the percentage of the average offered load per wavelength that has been successfully contributed to the average wavelength utilization (the average wavelength efficiency shows the successful transmission rate). The proposed scheme has been compared with two flow routing schemes i.e. the equal proportion multi-path flow routing (EPFR) and the hop length based multi-path flow routing (HLFR). For EPFR, traffic flows that arrive at a SD pair are distributed evenly among the multiple paths between the SD pairs. For HLFR, flows are routed to a path with a probability inversely proportional to the hop length of the path. A bidirectional link consists of two unidirectional fibers in opposite direction. Each fiber has four data channels at 1 Gb/s transmission capacity. The data channel scheduling algorithm employed here is the latest available unscheduled channel with void filling. The long range dependent traffic model is employed (traffic that arrives at each node pair in the network is the aggregation of multiple IP flows). Each IP flow is an ON/OFF process with Pareto distributed ON and OFF times. During each ON period, a Pareto distributed number of packets, with mean  $N$  and Pareto shape parameter  $\beta$ , are generated at the peak rate ( $p$ ) packets/sec. The OFF times are also Pareto distributed with mean  $X$  and  $\gamma$ . The set of values used for the simulations are:  $N$  (5),  $\beta$  (1.2),  $X$  ( $46000\mu s$ ),  $\gamma$  (1.3), wavelengths (16) and  $p$  (600). The packet length is set to be 100 bytes. The transmission rate per flow is fixed at 30kb/s. The range of  $P(x, y, w)$  is set to be in between 0 and 1. The limit of  $N(x, y, w)$  is fixed at 10.

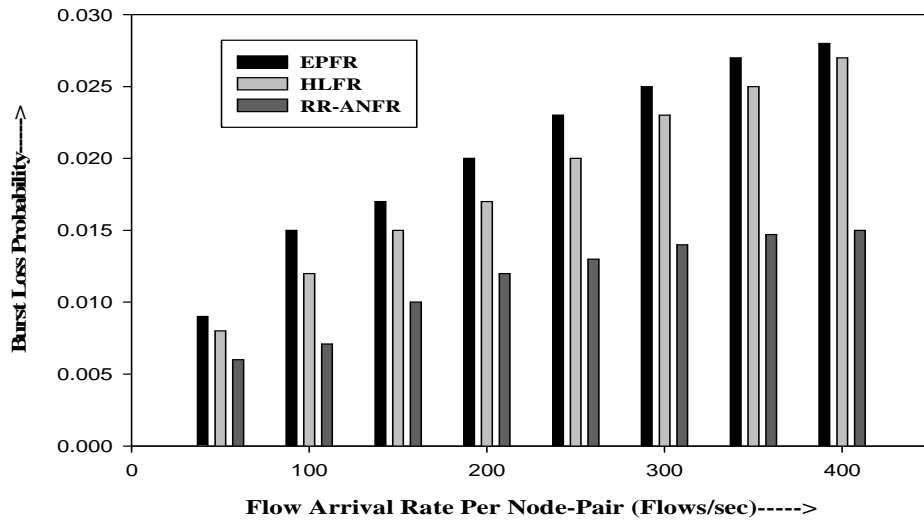
### 6.4.3 Results and discussions

The figure (6.18) shows the mean hop length traversed by a burst with varying traffic load per node pair for various routing schemes. The mean hop length reflects the delay, initial offset time and control burst signaling overhead in the network. Using figure (6.18), it is observed that RR-ANFR achieves a shorter mean hop length over EPFR and HLFRR. The reason is that both EPFR and HLFRR treat all the paths in a fixed manner. The flows are routed through different paths based on the initial flow proportion assignment throughout. Therefore, on the average, bursts traverse longer paths more often than RR-ANFR since the routing does not adapt to the varying traffic conditions in the network. It is also observed that the mean hop length for RR-ANFR increases when the traffic load increases. The proposed scheme tends to give more flow proportions to the longer paths when traffic load increases.



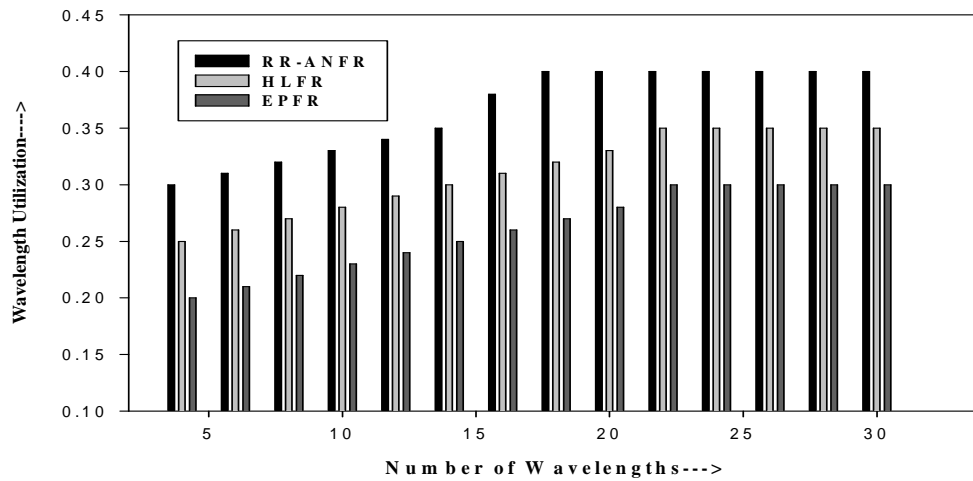
**Figure 6.18: Mean hop length Vs traffic load**

The figure (6.19) shows the burst loss probability of various flow routing approaches with varying traffic load per node pair (traffic load is expressed as the mean flow arrival rate (FAR) per node pair in the network). It is observed that RR-ANFR performs much better than EPFR and HLFRR in terms of overall burst loss rate. Although, both EPFR and HLFRR distribute traffic flows across multiple paths, they perform worse because they fail to keep track of the varying traffic situations in the network.

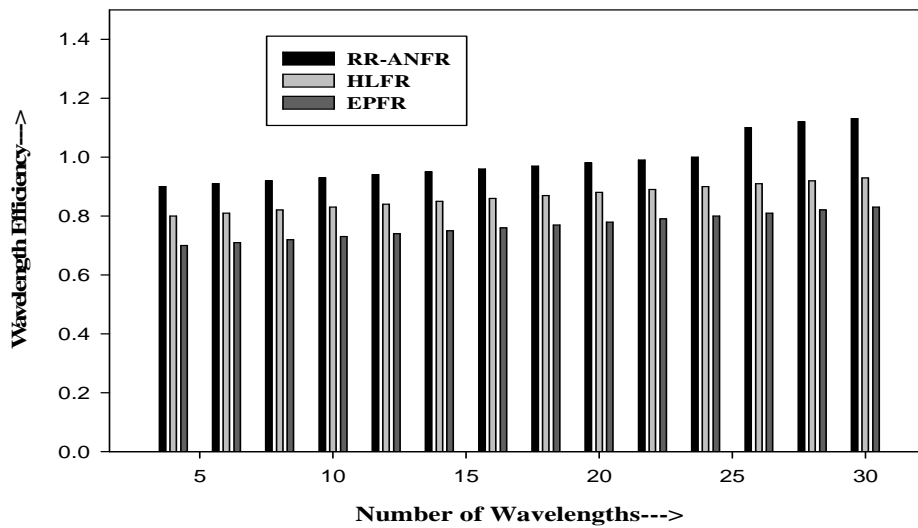


**Figure 6.19: Burst loss rate performance of various flow routing schemes**

The results obtained show that RR-ANFR improves the wavelength utilization and the wavelength efficiency (as shown in the figures (6.20) and (6.21)) in comparison to EPFR and HLF R.



**Figure 6.20: Wavelength utilization**



**Figure 6.21: Wavelength efficiency**

## 6.5 Conclusion

In this chapter, to reduce burst loss due to resource contentions for optical burst switched networks, efficient contention resolution and control schemes have been investigated and are also compared with the conventional schemes. Hybrid contention resolution schemes for OBS networks are developed. Through hybrid contention resolution schemes (such as WConv, delay and deflect, WConv, deflect and delay and Prioritized delay, deflect and delay policy), it is shown that both contention and the burst loss rate have been minimized. Also, different mechanisms have been shown for handling prioritized data traffic which combines prioritized optical delaying with prioritized deflection routing in order to offer differentiated services at the optical layer. The prioritized contention resolution policies provides QoS with 100% class isolation without requiring any additional offset times. The combination of FDL buffers with deflection routing yields lower losses than wavelength conversion with deflection routing in most of the cases, however at the cost of additional buffer. The simulation results show that the hybrid techniques specifically, Prioritized delay, deflect and delay policy reduces the burst average loss rate effectively, as compared to existing techniques. Also, the significant differentiation with respect to burst loss has been achieved.

In order to improve the scheme proposed above, in terms of proportional differentiated services, lower packet loss rate, throughput etc, an efficient scheme based on adaptive wavelength selection and burst assignment, which supports better

proportional differentiated services with lower packet loss in the buffer-less OBS networks has been proposed. The simulation results achieved show that the proposed scheme has better performance in terms of burst loss ratio and throughput. Through simulation, it has been found that when the BHP waiting time period ( $T_{wait}$ ) and the maximum number of times for a BHP to be queued ( $N_r$ ) exceed the predefined value, the performance is improved smoothly. These results prevent the end-to-end delay from becoming too large. In addition to this, the proposed scheme does not need any complex burst segmentation or wavelength preemption support, so it is especially suitable for OBS networks because of its simple implementation. Compared with the existing approaches, the proposed scheme does not need to generate any special packets and needs to maintain only a few parameters at core nodes. Thus, the burst droppings are avoided and the wavelength utilization is improved. Moreover, it provides controllable and predictable proportional differentiated services for different classes. The results obtained show that although the proposed scheme improves the burst loss performance at the expense of increasing extra offset time, the increase of end-to-end delay is very small (at most hundreds of microseconds) and is negligible for real time applications.

To have both contention resolution and control for reducing burst loss in the network, another efficient scheme has been developed. The attractiveness of proposed algorithm (ICRCA) lies in the preservation of packet ordering while reducing the overall burst loss in the network. The performance of the proposed scheme is expected to improve when it is implemented with data burst spreading or intentional data burst dropping on adjacent nodes when a downstream link is subject to congestion. The traffic control scheme ensures congestion recovery in the network by dropping excessive loads and also supports fairness between bursts. For the proposed scheme to be effective, it is ensured that, at the edge router of the network, burst does not enter the network at a rate higher than that the network handles. The simulation results show that proposed scheme successfully prevents overload while it is able to achieve not only fairness but also optimized performance for next generation networks.

Finally, in order to overcome the limitations of the above proposed schemes i.e. to alleviate resource contentions more effectively, an efficient integrated scheme based on resource reservation and adaptive network flow routing for optical burst switched network, has been developed. The proposed approach offers a significant advantage in comparison to conventional routing. In it, the previous node has already reserved the

resources when it has transmitted the burst, so no new paths are required to be calculated. This allows computational resources to be saved and thus, it reduces the number of signaling messages to be conveyed over the network. This simplifies OBS network control. It has been observed in the results that the proposed scheme reduces burst loss in the network significantly and improves wavelength utilization and efficiency as compared to the conventional static flow routing schemes such as EPFR (the equal proportion multi-path flow routing) and HLFRR (the hop-length based multi-path flow routing).

## CHAPTER VII

### CONCLUSIONS, RECOMMENDATIONS AND FUTURE SCOPE

In this chapter we list the conclusions, recommendations and future scope of the research.

#### 7.1 Conclusions

OBS is considered to be one of the possible ways to implement the WDM technology in core of the Internet in future. It avoids the problem of under-utilization of resources in circuit switching and does not require buffers and optical logic processing like packet switching. It is usually assumed that the core OBS network is buffer-less because the main purpose of separating the control and data planes in OBS is to avoid costly optical buffering. Due to the lack of buffers and online reservation system of OBS, even if there is wavelength conversion capability, bursts are dropped whenever the number of them simultaneously arriving at a core node exceeds the number of available wavelengths at that time. These burst losses due to contention for wavelengths are termed as contention losses. These are very serious hindrances to the deployment of OBS networks. With increasing online applications, most of the Internet traffic contains multimedia and real-time traffic. So, loss of bursts which causes simultaneous loss of several packets has a severe impact on many applications at the higher layers.

In this thesis, we addressed the various performance related issues arising in the deployment of OBS networks such as network architectures problems in terms of burst handling, wavelength reservations techniques for efficient utilization of bandwidth as well as network resources, burst dropping and contention resolution schemes, in order to reduce congestion and burst loss at the higher layers to support various networking applications such as with large data requests and sensitive to path delay.

The following are the conclusions based on the results achieved in the individual chapters of the thesis.

1. Considering the problems related to existing OBS network architectures, we have presented efficient OBS network's architecture alternatives in order to increase network utilization, reduction in blocking probability etc. Based on the properties of optical burst flows and bandwidths provisioning in the networks, an efficient OBS

network architecture utilizing adaptive burst assembly, small fiber delay line (FDL) along with dynamic route selection, has been investigated. The results obtained show that the proposed OBS architecture provides better throughput and decrease in blocking probability in comparison to conventional ones. The simulated proposed OBS network architecture provides an accurate fit with analytical traffic models for prioritized traffic classes and lower bounds for the other traffic classes.

Also, to have reduction, in electronic switching processing time, delay associated with FDL usage, in the above architecture, another efficient congestion-free OBS network architecture utilizing a short- prior-confirmation-packet (SPCP) and optical label processing with JET signaling has been presented. By using optical label processing, proposed network architecture approaches conventional packet switching granularity and thus network utilization is increased especially for small bursts composed of IP traffic. It has been observed that for a 10Gbps bit-rate, the minimum burst length accepted to be transported is 15ns and 4 $\mu$ s for optical and electronic label processing. Using electronic label processing, a burst-loss probability of  $1 \times 10^{-3}$  (approx.) is obtained for 33 and 60 wavelengths (BAR = 3200 and 6400 Bps) whereas 30 and 53 wavelengths are required for optical label processing. This shows an improvement in wavelengths usage of OBS network, which in turn increases the network utilization gain (efficiency). It is also observed that at low loads, the queuing delay remains essentially near the round trip time, since each burst departs with the return of the almost always positive, SPCP. For loads up to 65%, most SPCP return with a positive acknowledgement, hence the queuing delay is close to the round trip time since each burst departs as soon as the relevant SPCP returns back. Although the 1-hop queue experience the congestion even for 65% load, the delay of the 4-hop queue remains intact regardless of the increasing load in the system. It has been observed that the throughput value of proposed OBS architecture is higher than traditional architectures. Hence, this is attributed as throughput gain to the fact that proposed OBS architecture uses bandwidth more efficiently.

2. We have also analyzed and presented the quality of service (QoS) oriented, efficient reservation schemes in order to enhance bandwidth and channel utilization in optical burst switched (OBS) networks. An adaptive scheme based on a multi-service OBS edge node with synchronized bandwidth reservation mechanism has been

investigated. The proposed scheme enables network transport nodes to dynamically reserve bandwidth needed for active data burst flows. As the flow length increases from 50 bursts to 400 bursts in the proposed scheme, the burst loss rate decreases. A loss counter is used to find the periodicity of lost bursts with the same ingress/egress address. The lower the loss counter set, fewer bursts are lost because the loss notification is quickly sent to the ingress node. In the proposed scheme, once the scheduler recognizes the periodicity of the slotted burst, it reserves slots for the subsequent bursts. Therefore, if the length of burst flow increases more than 400 bursts, the overall burst loss rate will be decreased greatly.

In order to have better channel utilization, throughput etc, we have investigated another efficient scheme in which data burst are scheduled in batches. The problem of data burst scheduling is mapped to a combinatorial optimization problem of scheduling data burst time intervals on a channel time line. The heuristic interval scheduling algorithm is utilized to obtain the maximum number of non-overlapping bursts. The results show that the proposed scheduling outperforms the JIT scheduling over the entire range of the mean offered load. An improvement in burst loss probability has been seen specifically at high loads, i.e. from 0.8 to 1.2.

In addition to above, to address the problem of fairness control between short and long distance packets, we have analyzed and presented another efficient reservation scheme in which each edge router finds a suitable route to the destination edge router autonomously by using feedback and prior-information packets. The proposed scheme based network performs better than the best-effort network for increasing load. This is because a best-effort network drops a packet that has performed several hops in the network with the same probability as a new packet. Such a long distance packet may on its path have blocked other packets from being served by the switch and the resources will thus be wasted. By differentiating the packets according to their hop count level, the proposed scheme avoids this effect and increases the throughput. This results decrease in average resource usage for dropped packets (i.e. the resource waste) in the network. The proposed scheme offers lower burst loss probability in comparison to conventional schemes. This is because in the proposed scheme, due to prior-information at each edge router, the traffic is not concentrated on particular link. The traditional JET based scheme exhibits the lowest throughput due to the path

length priority effect. In contrast, the proposed scheme exhibits the best performance in terms of throughput. Therefore, this scheme provides that a burst traversed more hops can complete its transmission more successfully. The results obtained show that with the proposed scheme, the packet delay is kept within the constraint for each traffic-flow and the performance metrics such as burst loss rate, throughput and fairness are remarkably improved.

3. It has been observed that the size of the data bursts have a direct impact on the OBS control channels, bandwidth utilization and also results in burst dropping. Therefore, we have presented effective and flexible burst dropping techniques/policies. In the proposed burst dropping scheme based on even selection of burst (BDPES), the dropped segments are evenly distributed between the contending bursts to achieve some kind of fairness between traffic flows and to minimize the number of short data bursts. It has been observed that the lower priority data segments experience more dropping rate. The higher priority data segments are given a higher quality of service and the reduction on the dropping rate is achieved particularly by using congestion control mechanism.

Also, by analyzing different contention schemes, it is noticed that the current burst dropping schemes e.g. tail dropping and head dropping, can not use bandwidth efficiently. To address this problem, we have investigated another efficient burst dropping scheme to use bandwidth efficiently. In the proposed scheme, any segment based on packet count number (PCN) in either a scheduled burst or a contending burst can be dropped to resolve contention. It is seen that at low load, the performances of the dropping schemes look similar with wavelength converters, because contentions are not likely to happen at lighter load. However, if the load gets heavier, the heavier the load is, the better the proposed dropping scheme performs compared to tail dropping and head dropping while there are not much difference between tail dropping and head dropping. It is also observed that even when the load is light, the proposed dropping scheme out-performs tail dropping and head dropping because there are no wavelength converters and there are much more chance for contentions to happen even with light load. Results achieved confirm that the proposed burst dropping scheme performs better in terms of packet loss rate and flexibility as compared to existing burst dropping schemes.

4. Also, we have analyzed and described possible solutions to address the problem of contention losses in OBS networks. Through hybrid contention resolution techniques; WConv, Delay and Deflect, WConv, Deflect and Delay and Prioritized Delay, Deflect and Delay Policy, it is shown that both contention and the burst loss rate have been minimized. The prioritized contention resolution policies can provide QoS with 100% class isolation without requiring any additional offset times. The results show that the hybrid techniques specifically, Prioritized Delay, Deflect and Delay Policy can effectively reduce the burst average loss rate compared to existing techniques; and also the significant differentiation with respect to burst loss has been achieved.

To resolve burst contention (burst dropping) in OBS networks, an efficient integrated scheme has been developed based on adaptive wavelength selection (AWS) and burst assignment, which can efficiently support proportional differentiated services in buffer-less OBS networks. The results show that when the traffic load changes from 0.2 to 0.6, the proposed scheme has better burst loss performance as compared to traditional schemes because it does not waste wavelengths. This is because the burst head packet (BHP) of a lower priority class (Type-II) in the proposed scheme will be buffered at the core node when it cannot find an available wavelength and has an opportunity to reschedule its burst to the wavelengths that have been assigned to higher priority class (Type-I) but have not yet been reserved. Results show that although the proposed scheme improves the burst loss performance at the expense of increasing extra offset time, the increase of end-to-end delay is very small (at most hundreds of microseconds) and would be negligible for real time applications. For different traffic loads, the depicted simulation and analytical results show that the analytical model is in good agreement with the simulation results.

In order to have both contention resolution and congestion control for reducing burst loss in the network, we have investigated integrated contention resolution and control (ICRCA) scheme for optical burst switched networks. In the conventional methods, the higher the network load becomes, the higher the burst loss probability becomes. This occurs because an excessive number of bursts are generated and transmitted into the OBS network when the traffic generation is momentarily high. On the other hand, the burst loss probability is almost identical for any network load in

the proposed algorithm regardless of the load. The proposed scheme can moderate a change of the network load by activating the traffic control policy. Thus, it is possible to control the burst loss probability regardless of a change of the network load in the proposed scheme.

To alleviate resource contention, we have presented another efficient scheme based on resource-reservation and adaptive network flow routing (RR-ANFR). The proposed scheme tends to give more flow proportions to the longer paths when traffic load increases. The performance of RR-ANFR is better as compared to equal proportion multi-path flow routing (EPFR) and hop-length based multi-path flow routing (HLFR). Although, both EPFR and (HLFR) distribute traffic flows across multiple paths, they perform worse because they fail to keep track of the varying traffic situations in the network.

## **7.2 Recommendations**

The following are some of the possible recommendations based on the individual chapters in the thesis.

1. The proposed architectures are shown to be feasible alternative architectures for OBS, with a support for highly effective QoS provisioning and routing management. Thus, they can be used for the backbone of future large-scale networks. The results achieved have shown that proposed OBS network architectures in comparison to existing architectures perform better in terms of lower blocking probability and higher resource utilization. The strong points of the proposed architectures are: compatibility with packet switching at the network edge, simplicity, cost-effectiveness, efficiency and flexibility of allocating different bandwidth granularities, depending on the application needs.
2. The results have shown that the proposed reservations schemes are the best, because they not only reduce the burst loss, but also control the edge buffering delay. The proposed schemes are able to reduce the burst loss, especially at low traffic loads at the expense of a small initial delay. The proposed reservation mechanisms with added complexity have shown decrease in burst loss probability compared to existing reservations like JIT, Horizon. However, the proposed schemes with additional complexity yields better results only if the offset is varying. Also, the access to the

wavelengths reservation mechanism is controlled by admission control. This allows in realizing a very simple but effective solution for the improvement of unfairness and QoS differentiation.

3. It is observed that the proposed burst dropping schemes perform better than the standard dropping schemes and offer the best performance at high loads because the standard dropping schemes which incorporate deflection tend to perform better at low loads, while deflection is not as effective at high loads. The proposed burst dropping schemes are suitable for transmitting packets which have higher delay tolerance, higher loss tolerance, strict loss and delay constraints. Also, the proposed schemes are easily scalable in order to support multiple priorities in an all-optical burst-switched network. In order to further reduce the packet loss, the proposed schemes can be employed in conjunction with all-optical wavelength conversion and buffering through fiber delay lines.
4. The proposed contention resolution schemes provide network stability by controlling the traffic flow without combining with existing dynamic contention resolution schemes, whenever the network needs to recover from instability. The unnecessary packet dropping is avoided by regulating the transmission of bursts, thus resulting in a much reduced packet drop rate. The proposed schemes as compared to existing contention resolution schemes provide flexibility during channel reservation based on the type of data to be transmitted and hence are more convenient in performance evaluation of optical burst switching (OBS) technique because they can be easily modified according to various network topology and architecture. Thus, the proposed schemes provide flexible solution suitable for handling the varying traffic demands of the next-generation optical network.

#### **7.4 Future Scope**

The following are some of the possible areas of future work.

The proposed architectures can be employed in conjunction with all-optical wavelength conversion in order to have better reduction in packet loss. In OBS networks, an additional delay is involved for the prioritized traffic which is equal to the propagation time between source to destination. Future work includes assessing the effect of increased delays, in order to minimize burst losses due to contention, on multimedia applications involving delay constrained traffic. Also, the proposed burst assembly framework can be

extended to handle variable-sized packets. Composite burst assembly is also very important when the core network supports both multicast and unicast application. In this situation, the edge has to differentiate the arriving packets based on their destination egress nodes, their quality of service class and also based on whether they are multicast or unicast applications.

Also, the possible areas of future work are to analyze the end-to-end delay for the proposed reservation schemes, to evaluate the performance in the case of more than two packet classes and to investigate reservation techniques to support delay-based QoS. With optimal offset time with the proposed scheme, it may be possible to provide minimal loss while also guaranteeing end-to-end delay. The performance of proposed schemes with wavelength conversion in a multi-wavelength system can also be analyzed to improve channel utilization and for monitoring the delay trade-off. Also, the performance can be improved by developing accurate analytical loss and delay model for proposed reservation schemes.

An efficient burst dropping schemes have been investigated for contention resolution. The proposed schemes perform better than the standard dropping policy and offer the best performance at high loads. An area for future work is the investigation of proposed schemes with deflection schemes in which deflection is performed before segmentation whenever contention occurs. Also, we considered only one alternate output port for contention resolution. The schemes which consider multiple alternate output ports and in which the selection criteria is based on load and shortest path may also be considered. The proposed schemes can also be implemented with priorities. Priorities would be based on a burst's tolerance for segmentation, deflection and loss. To effectively evaluate the quality of service offered by various priority schemes, a retransmission scheme for dropped packets could be implemented in order to measure end-to-end delay. A reasonable approach would be to implement a TCP layer on top of the optical burst-switched layer. In such an implementation, it would also be useful to evaluate how TCP layer congestion control schemes react to and interact with various contention resolution schemes.

The proposed contention resolution and control schemes would be extended to include limited buffering. Also, it is desirable to investigate whether proposed schemes tend to favor longer and drop shorter bursts or, on average, treat all bursts similarly.

Furthermore, we intend to use our proposed schemes under hardware simulation test-bed to get much deeper insight into the performance. Another desirable study would be to examine the proposed framework such that it should provide better service differentiation and QoS. Another area of future work is to look at burst overlapping at the edge node and find a correlation between the burst rate reduction request and the overlapping factor. Distributed multi-path routing possibly with QoS constraints, will be studied. Since multi-path routing introduces the problem of out-of-order burst arrival. Also, mathematical analysis will be performed to determine the end-to-end bounds on the loss rate and delay by considering the effect of different parameters such as burst length and offset time.

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