CHAPTER 1

INTRODUCTION

1.1 Background

The ever increasing demand for higher bandwidth due to the popularity of the Internet and other bandwidth intensive applications such as remote information access, video-on-demand, video conferencing, on-line banking and multimedia applications has put a major challenge for network engineers to comply. A continuous demand of high capacity networks at low cost has motivated the search for alternatives to traditional electronic networks. Optical networks became the logical choice to meet such demands, owing to huge bandwidths of the order of 25 THz along with very low channel loss upto 0.2 dB/km. In order to explore the huge bandwidth offered by optical fibers, optical wavelength-division multiplexing (WDM) systems have been deployed in many telecommunications networks as backbone link. 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 [Chatterjee 1999]. 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. Basically different optical transport methodologies have been implemented to fulfill the demands of various generations of optical communication technology starting from the first generation to the modern optical networks [Mukherjee 1997].

The first generation optical network architectures consist of several point-to-point links, at which all the incoming traffic into each node from an input fiber is dropped and converted from optics to electronics, and all outgoing traffic is converted back from electronics to optics for transportation to the outgoing fiber. This dropping, conversion and adding of the entire traffic at every node in the network incurs significant overhead in terms of switch complexity, delay and data transmission cost, particularly if the majority of the traffic in the network happens to be a bypass traffic. In order to minimize such complexity, all-optical add-drop devices are used to avoid optical electrical optical conversion and related issues.

Second-generation optical network architectures are based on wavelength add-drop multiplexers (WADM) [Alferness 2000], where traffic can be added and dropped at the WADMs location. WADMs can terminate only selected channels from the fiber and let other wavelengths pass through untouched resolving the issues of unnecessary processing of bypass traffic. In general, the amount of bypass traffic in the network is significantly higher than the amount of traffic that needs to be dropped at a specific node. Hence, by using WADM, we can reduce overall cost of node by dropping only the wavelengths whose final destination is same as the current node, and allowing all other wavelengths to bypass the node. WADMs can serve as a basis for switching, wherein the WADMs is remotely configured to drop any wavelength to any port without manual intervention. We can perform circuit, or point-to point switching in the optical domain with a WADM. The WADMs are mainly used to build optical WDM ring networks which are expected to be deployed mainly in the metropolitan area network.

Third-generation optical network architectures are based on all-optical interconnection devices comprising of *passive router* and *active switch* fabrics [Mukherjee 2000]. There are mainly three types of all-optical transport methodologies, namely, wavelength routing, optical packet switching and optical burst switching.

In wavelength routed WDM networks, end users communicate with one another via all optical WDM channels, which are referred to as lightpaths [Chlamac 1992]. A lightpath is used to support a connection in a wavelength routed WDM network and may span multiple fiber links. In the absence of wavelength converters, a lightpath must occupy the same wavelength on all the fiber links through which it traverses to reach the destination. This property is known as the *wavelength continuity constraint*. Given a set of connections, the problem of setting up lightpaths by routing and assigning a wavelength to each connection is called the routing and wavelength assignment (RWA) problem. Typically, connection requests may be of two types, *static and dynamic*. Wavelength-routed connections are fairly static and they may not be able to accommodate the highly variable and bursty nature of internet traffic in an efficient manner. In order to meet the growing bandwidth demands in a metropolitan or a long-haul environment, transport methodologies supporting fast resource provisioning to handle bursty traffic have become thrust area in the field of optical communication network research. Also, the rapid increase in data traffic in all-optical WDM networks have become attractive to handle diverse traffic demands of the next-generation networks [Bonani 2007][Wason 2009] employing capable of switching at sub-wavelength granularity. Optical burst switching (OBS) and optical packet switching (OPS) have emerged as two such promising methods for transporting traffic directly over a bufferless optical WDM network [Yao 2000][Yao 2001][Yao 2003][Qiao 1999].

Optical packet switching is capable of dynamically allocating network resources with fine packet-level granularity while offering excellent scalability [Yao2001][Mahony 2001][Hunter 2000][Callegeti 1999][Jourdan 2001]. Such networks can be classified into two categories: slotted (synchronous) and unslotted (asynchronous) networks. In a slotted network, all the packets are placed together with the header inside a fixed time slot, which has a longer duration than the packet to provide guard time. In an unslotted network, the packets may or may not have the same size, and the packets arrive and enter the switch without being aligned. Therefore, the packet-by-packet switch action could take place at any point in time leading to contention of different incoming packets for the same outgoing resource. Obviously, unslotted networks offer a larger contention due to unpredictable behavior of packet arriving. On the other hand, unslotted networks are cheaper, easier to build, more robust, and more flexible compared to slotted networks.

A possible near-term alternative to all-optical circuit switching and all-optical packet switching is OBS [Qiao 1999]. In OBS, packets are concatenated into transport units referred to as bursts. The bursts are then switched through the optical core network in an all-optical manner. OBS networks allow for a greater degree of statistical multiplexing and are better suited for handling bursty traffic than optical circuit-switched networks. At the same time, optical burst-switched networks do not have as many technological constraints as all-optical packet-switched networks.

Circuit and packet switching have been used for many years for voice and data communications respectively. However the burst switching [Haselton 1983][Amstutz 1983][Amstutz 1989] has not been exploited extensively in optical network.This switching techniques primarily differs based on whether data will follow *switch cut-through* or *store and forward* mechanism. In circuit switching, a dedicated path between two stations is necessary to establish a data path to transfer the traffic and the call is terminated to release the channels at the end of the call . In packet switching, the data is broken into small packets and transmitted to share the resources by different sources. The individual packets can be individually switched or a virtual circuit can be set up to route the packets. In the first case, the routing decision is done at a packet level while in the later, it is on a virtual channel level. Individual routing may lead to out-of-order message delivery and require proper strategy to arrange the packets at the receiver.

Usually circuit switching is advantageous when we have constant data rate traffic (fixed delays) in the network, like voice traffic; however, it is not suitable under bursty traffic conditions, or when circuits are idle [Hunter 1999]. Packet switching works well with variable-rate traffic, like data traffic, and can achieve higher utilization. Prioritization of data can also be incorporated in packet switching; however, it is difficult to give quality of service (QoS) assurances (best effort service), and packets can have variable delays [Yao 2000].

Circuit Switch involves two way reservation scheme that needs coarse grained control, while packet switching needs a fine grained switching control. OBS is designed to achieve a balance between the coarse-grained circuit switching and the fine-grained packet switching. As such, a burst may be considered as having an intermediate "granularity" as compared to circuit and packet switching. OBS uses one-way reservation schemes with immediate transmission, in which the data burst follows a corresponding packet without waiting for an acknowledgment [Yoo 1999] [Hu 2001] [Turner 1999] [Qiao 2000] [Yoo 1999] [Ramaswami 1998]. Optical burst switching techniques are differentiated on the basis of how and when the bandwidth, are reserved and released. On consequence of such advantages, optical burst switching has attracted much attention to the researchers [Qiao 2000] to understand signaling, control & probing techniques, algorithms and architectures of appropriate switching paradigms.

Table 1 Comparison of Switching Technologies

Switching	Bandwidth Utilization	Latency	Optical Buffering	Overload	Adaptivity
Circuit	Low	High	Not Required	Low	Low
Packet	High	Low	Required	High	High
Optical Burst	High	Low	Required	Low	High

Table 1 summarizes the three different types of transport paradigms used in all-optical networks. From the table, it is obvious to note that optical burst switching has the advantages over both optical circuit switching (or wavelength routed networks) and optical packet switching.

1.2 Contention Resolution Schemes in Optical WDM Network

In optical WDM networks contention occurs when more than one data packet tries to reserve the same wavelength channel on an outgoing link. In electronic network, contention is resolved by buffering the contending packets. In optical WDM network when contention occurs, one of the contending data packets is allowed to reserve the channel, however other data packets are properly handled employing the combination of the popular contention resolution techniques discussed below.

Wavelength domain: This strategy of contention resolution is implemented by means of wavelength conversion, where the burst can be sent on a different wavelength channel to the designated output line [Lee 2003].

Time domain: The contention can also be resolved by utilizing an fiber delay lines (FDL) buffer,where a burst can be delayed until the contending situation is resolved. In contrast to buffers in the electronic domain, FDLs in optical domain provide a fixed delay and maintain the order of the data transmitting through the FDLs [Lee 2003].

Space domain: Space domain contention resolution can be obtained by using deflection routing. In deflection routing, a burst is sent to a different output link of the node and consequently on a different route towards its destination node. Space domain can be exploited differently in case where several fibers are attached to an output line. A burst can also be transmitted on a different fiber of the designated output line without wavelength conversion [Lee 2003] in order to avoid network overload through traffic management policies [Farahmand 2004**].**

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 segmented and dropped [Bonani 1999]. 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 [Vokkarane 2004].

1.3 Motivation

Extensive study have been carried out to design, model and develop different types of all optical nodes that are capable to implement various types of switching, buffering, routing and control operations in order to reduce contention. However research and investigation of guaranteed end-to-end bounds on the total burst loss probability (BLP) on a path [Vokkarane 2004] [Chua 2007] has not been much emphasized, especially in case traffic congestion. Generally the overall performance of a WDM network is estimated by the parameters like throughput, burst loss probability, blocking probability, incoming traffic load distribution, resource utilization and delay etc.

Packet contention resolution has emerged as one of the most important design issue in the OPS/OBS switch design. The conventional methods that mentioned earlier are either used alone or in combined form to implement more sophisticated congestion control techniques. Switch architecture proposed in [Yang 2004] uses all conventional methods to resolve contention. The conventional switch fabric tries to forward the contending packet by using different wavelength, by optical buffering or by deflecting the packet on different output port. Optical buffering has been used in many optical packet switch implementations as proposed by Rostami and Fiems [Rostami 2005] [Fiems 2005]. The output buffering technique involving FDL lines for additional output ports has been proposed in [Mellah 2006], for contention resolution using first in first out (FIFO) queuing model but shows a poor performance for implementation of traffic priority. The packet contention is improved in this technique at the cost of extra FDLs used at the output along with complex switching fabric.

It is observed that the existing buffering implementations require either large amount of FDLs or complex switch architecture for better throughput. It is envisaged that switching hardware cost can be managed by inclusion of flexible delay lines in suitable node architecture to show a better packet contention resolution.

In this thesis we have addressed the issues of traffic congestions by discussing and implementing different contention resolution techniques for optical WDM networks based on OBS and OPS to estimate, analyze and to reduce the losses due to traffic congestion. In traditional OPS networks, packet loss occurs mainly due to the overflow of buffers or unavailability of required wavelength at the output, however in OBS networks losses occur mainly due to contention among multiple bursts. In the literature, congestion has either been understood to be persistent contention losses or the simultaneous loss of large bursts. In such cases different conventional contention resolution techniques are discussed in literatures but still there are scopes to improve the network performance by reducing the traffic contention by incorporating dynamically reconfigurable intelligent node. This thesis proposes some new techniques of contention resolution by using optical buffering employing recirculating fiber delay line, limited or full wavelength convertible switch, deflection routing and also by implementing segmentation burst dropping scheme.

1.4 Objective and Scope of the Thesis

As mentioned in the previous section, the performance of the optical networks is limited due to traffic losses caused by contention. This problem leads to investigate and explore some efficient contention resolution methods to implement on WDM routing node architecture having appropriate switching fabric to realize the required switching schemes. The objectives of the thesis can be summerized as follows:

- To estimate the traffic loss due to contention at optical WDM networks under different switching paradigms.
- To characterize and simulate different contention resolution mechanisms in order to enhance the overall efficiency of the WDM networks.
- To determine the comparative performance analysis between different contention resolution techniques in order to help the network designer to take the better option for contention resolution.

- To simulate and analyze the performance of the modified OBS ring network using dummy node and to find out the effects of different fiber non-idealities on its efficiency.

This thesis work has been concentrated mostly in the area of OBS networks and partially in OPS networks. The scope of the thesis is in the area of networks with advanced contention resolution mechanisms and performance improvement techniques. This thesis opens up research directions in estimation, control, and analysis of contention losses in large scale optical WDM networks and to enhance the overall performance of the network.

1.5 Organization of Thesis

This thesis consists of seven chapters. The present introduction chapter has outlined a brief review of the traffic congestion problems in optical WDM networks and strategies adopted in literature to resolve such contention using different optical switching paradigms. In the rest of thesis, we focus on the classification and performance analysis of different congestion control techniques in OBS and OPS based WDM networks.

Chapter 2 addresses the basic architecture of OBS network and also implement different reservation schemes under different burst scheduling algorithms. The same chapter also briefly describes different contention resolution techniques used in OBS network. Finally a deflection routing based intelligent OBS network has been proposed to handle the incoming traffic dynamically to yield superior blocking probability.

Chapter 3 describes the basics of OPS network and reviews different buffering schemes used in OPS network. We have proposed a network control algorithm under variable loop delay scheme in OPS network for traffic resolution. Thereafter an appropriate mathematical model has been developed to estimate the burst loss probability in the proposed architecture suitable for OBS network. At the later portion of the chapter, a simple node architecture model based on media access control protocol for bursty data traffic of variable time slot duration and data rate has also been proposed to claim packet loss probability. An architectural model with appropriate mathematical model has also been derived to evaluate the performance of the proposed node architecture using synchronous round robin (SRR) protocol.

Chapter 4 discusses the contention resolution in wavelength domain. In this context the basic design aspects and different types of wavelength converters are discussed. An appropriate mathematical model of WDM optical network using wavelength converters has been presented and its performance analysis under Erlang-C traffic has been reported. Blocking Probability analysis of an optical WDM Node in wavelength routed networks (WRON) for three different cases namely no conversion, partial conversion and full conversion have also been addressed.

Chapter 5 reports an architectural model which efficiently reduces the network congestion in an optical burst switching (OBS) ring network without using any conventional contention resolution techniques has been presented. The backbone of the proposed architecture is the use of a dummy node to support the congested nodes by providing a path diversion. The mathematical model predicts a significant reduction in packet dropping probability. In the next section of the same chapter different standard signaling protocols namely just-enough-time (JET) and tell-and-wait (TAW) have also been used to investigate the performance of the proposed architecture. These signaling techniques are evaluated for different data rate under the similar node and channel environment.

In existing contention resolution schemes for optical burst switched networks, when contention between two bursts cannot be resolved through other means, one of the bursts will be dropped in its entirely, even though the overlap between the two bursts may be minimal. For certain applications, which have stringent delay requirements but relaxed packet loss requirements, it may be desirable to lose a few packets from a given burst rather than losing the entire burst.

Chapter 6 discusses a dropping based contention resolution technique called burst segmentation, in which only those packets that overlap with a contending burst will be dropped. In the next section of the same chapter the comparative performance analysis of wavelength conversion and segmentation based dropping method for contention resolution scheme in OBS network has been presented.

Chapter 7 sumarizes the outcome and conclusions of the thesis and presents the scope of the thesis for further research.

CHAPTER 2

SPACE DOMAIN CONTENTION RESOLUTION : DEFLECTION ROUTING

2.1 Introduction

The explosive growth of internet traffic and ever increasing demand of high speed technology are driving the direction of research and development towards the optical networks employing wavelength division multiplexing (WDM) technology [Mukherjee 2000]. In WDM networks, multi-wavelength channels are accessed by the end-user at peak rates. To exploit the huge transmission capacity of such networks, extensive research has been done for developing efficient channel switching technology [Ramaswami 1994] [Chalamtac 1993].

Obviously, the performance of such WDM networks is limited by the quality and functionality of the physical resources used to transport the data traffic from source to destination. This requires a thorough understanding, behavior of the network components and appropriate subsystems used for the routing of multi-wavelengths. This optical traffic routing involves both physical layer signal transport and logical layers containing either electrical switching or optical switching to execute the control optimization of network reliability [Ramamurthy 1998a].

Usually in WDM networks the optical switching and transmission technologies have been increasingly deployed employing transparent optical, purely optical or hybrid components. The main attraction of optical switching is that it enables routing of optical data signals without the need for conversion to electrical signals and, therefore, is independent of data rate and data protocol. The transfer of the switching function from electronics to optics will result in a reduction in the network equipment, an increase in the switching speed, and thus network throughput, and a decrease in the operating power [Ramaswami 1998] [Chu 2002] [Georgios 2003]. Several solutions are currently under research; the common goal for all researchers is the transition to switching systems in which optical technology plays a more central role. The result of such efforts has led to the creation of optical networks, where the optical signal undergoes optical-electrical-optical (O/E/O) conversion at each intermediate node. Two tendencies have emerged for the design and deployment of WDM networks. The first trend attempts to increase transparency in the network in order to remove electronic bottlenecks and manage a large set of heterogeneous signals regardless of protocol formats, modulation, and bit rates. The second trend looks at re-configurability of networks such that bandwidth can be assigned efficiently to end-users in order to accommodate dynamically changing traffic demands. Both trends reflect the vision for future generation networks where optical switching technologies play a fundamental role and bandwidth is promptly available to end-users.

The migration of switching functions from electronics to optics is a critical issue. It is progressively done through several phases. The first deploys wavelength routing (WR), which offers circuit switching services at the granularity level of wavelengths [Chlamtac 1992] [Zang 1999] [Lazzez 2005]. In such circuit switched wavelength routed networks available optical switching technologies involve transparent configurable optical switch fabric to route the traffic efficiently. At an optical circuit switching (OCS) network, once a lightpath is setup, all data carried by one input wavelength will go to a specific output wavelength. Since no O/E/O conversion of data at any intermediate node is needed, multi-hop transparency (in terms of the bit rate, protocol and coding format used) can be achieved. On average, the connection duration should be on the order of minutes or longer as setting up or releasing a connection takes at least a few hundreds of milliseconds. Shorter duration connections needed to accommodate sporadic data transmissions will result in a prohibitively high control overhead. A major difference between OCS and the other approaches is that in OCS, no statistical multiplexing of the client data can be achieved at any intermediate node. More specifically, in the core, bandwidth is allocated by one wavelength at a time, which is a coarse granularity. In practice, however, most of today’s applications only need the sub-wavelength connectivity. In addition, high-bit rate computer communications often involve “bursts” that last only a few seconds or less. In addition, circuit-switching models do not fit well with IP packet switching.

To overcome the above deficiency of the OCS approach, O/E/O conversion can be introduced above an OCS network in the internet protocol (IP) and synchronous optical network (SONET) layers. The electronic switching nodes are used in such an O/E/O approach. Here, statistical multiplexing of the client data at the sub- wavelength granularity is possible with electronic processing and buffering . Since every data unit needs to go through O/E and E/O conversion, this approach is not scalable enough to support hundreds of wavelengths, each working at 40Gbps or beyond (the need for which is anticipated in the near future). In addition, electronic switches are known to suffer from problems such as limited capacity and huge power/space consumption and heat dissipation in addition to requiring expensive O/E/O conversions. Note that, either an optical cross connect or optical add-drop multiplexor may also be used in conjunction with an electronic switch for wavelength granularity traffic that does not need to go through the electronic switch. A hybrid, multi-layer network consisting of such nodes, each consisting of both an electronic switch/router and an optical cross connect, is one way to combine the strength of the optics and electronics, but certainly not the only way to do so, and in fact may not be the ultimate long-term solution.

Since all-optical header processing will not be economically viable in the near future due to the immaturity of high-speed optical logic, the optical packet switching (OPS) approach will likely require each header to go through O/E conversion for processing and E/O conversion for transmission. An important difference from the previous O/E/O approach is that here, the header can potentially be sent at a much slower rate than the data using for instance sub-carrier multiplexing, thereby easing the speed requirement on the O/E/O conversion devices while still maintaining a high data throughput. Nevertheless, OPS is difficult to implement because of its need for a large number of O/E/O conversion devices (one set for each wavelength), header extraction/insertion mechanisms as well as FDLs and packet synchronizers. In the longer term, OPS promises finer switching granularity, providing bandwidth-efficiency, flexibility, and data management [Yao 2000] [Yao 2001] [Sivalingam 2005] [Lazzez 2005] [Dogan 2006]. The achievement of this second phase, however, faces major difficulties since OPS will necessitate the development of a number of component/system technologies that are still in their experimental stage [Yao 2000a] [Yao 2001]. Note that, an optical cross-connect or add-drop multiplexor can also be used in conjunction with the OPS nodes or OBS nodes to be discussed below if/when it is more economic to do so.

The third step undertakes the move toward optical burst switching (OBS) and attempts to minimize the header management at the internal nodes [Qiao 1999] [Turner 1999] [Qiao 2000] [Wei 2000] [Bjornstad 2003] [Vokkarane 2004] [Lazzez 2005] [Dogan 2006] [Du 2006]. OBS is generally considered as an attractive technique for supporting improved switching granularity. Since the transmission unit is a burst, OBS is more efficient than circuit switching when a transmitted data burst does not use a full wavelength.

In the OBS paradigm, only a few control channels (e.g., one per fiber) go through O/E/O conversion .Given that the data is switched all-optically at burst level, data transparency and statistical multiplexing can be achieved concurrently. Since OBS takes advantage of both the huge capacity in fibers for switching/transmission and the sophisticated processing capability of electronics, it is able to achieve cost reduction and leverage the technological advances in both optical and electronic worlds, which makes it a viable technology for the next generation optical internet.

At an OBS node, no synchronization/alignment of bursts is necessary unless the switching fabric operates in a slotted manner. In addition, FDLs and wavelength converters which are optional can help in reducing burst loss [Gauger 2002]. Currently, it is a challenge to implement an OBS switching fabric with hundreds of ports operating at a switching speed which is of the order of nanoseconds. Nevertheless, on-going research work has shown promise [Xiong 2000] [Masetti 2002] [Ramamirtham 2002].

2.2 Optical Switching Techniques

The practical switching techniques that are considered for the deployment of all-optical WDM networks are wavelength routing, optical packet switching and optical burst switching. Wavelength routing technique follows the basic concepts of traditional circuit-switched networks and are usually implemented to enhance the network throughput and to avoid collision [Chlamtac 1992] [Zang 2000] [Lazzez 2005]**.** In a wavelength routed (WR) network, an all-optical wavelength path, called lightpath, can be established between edges of the network. A lightpath is created by dedicating a wavelength channel on every link along the chosen path. After data transfer, the lightpath is released. A WR network is composed of wavelength routers that provide wavelength routing according to the input port and wavelength. In the absence of wavelength converters, a lightpath must occupy the same wavelength on all the fiber links through which it passes. This property is known as the wavelength continuity constraint. Given a set of connections, the problem of setting up lightpaths by routing and assigning a wavelength to each connection is called the routing and wavelength assignment (RWA) problem [Zang 2000] [Pointurier 2006] [Szymanski 2006]. The main objective of a RWA scheme is to set up lightpaths and assign wavelengths in a manner which maximizes the number of connections that are established in the network at any time; thus minimizing the amount of connection blocking [Zang 2000] [Jue 2000] [Pointurier 2006]. The data transmitted in a WR network require no electronic/optical conversion, no buffering, and no processing, at the intermediate nodes. This makes possible of the implementation of wavelength routed networks based on commercially available switching technologies such as opto-mechanical switches, microelectro mechanical system (MEMS) switches, electro-optic switches, and thermo-optic switches [Papadimitriou 2003] [Yano 2005], which unfortunately are still relatively slow. Even as, WR technology constitutes a significant phase towards all-optical networking, it suffers from low bandwidth utilization. In fact, on any fiber link of a wavelength routed network, no wavelength sharing is allowed between two distinct lightpaths. Moreover, wavelength-routed connections are fairly static and may not be able to accommodate the highly variable and bursty nature of Internet traffic in an efficient manner.

2.2.1 Optical Packet Switching

In order to overcome the abovementioned shortcomings of the wavelength routing, a technological breakthrough called optical packet switching emerges in the literature [Yao 2000] [Yao 2001] [Sivalingam 2005] [Hsu 2002] [Lazzez 2005] [Dogan 2006]. In optical packet switching technique data traffic is broken into small packets. An optical packet consists of a data payload and a header. Packets are processed and forwarded hop-by-hop until they reach their destination node. Network resources are dynamically allocated with finer granularity and consequently more efficient bandwidth utilization can be ensured.

Because of store and forward nature of packet switching, optical packets are temporarily buffered at each intermediate node during header processing. An optical packet-switched network should be able to process and forward packets in the optical domain, which makes the network truly transparent. However, as all optical processing is still in the experimental stage, the packet header must be electronically processed. Moreover, due to the lack of optical memory, use of fiber delay lines (FDLs) [Hunter 1998] [Chlamtac 1996] [Chlamtac 2000] [Hsu 2002] [Harai 2006] is currently the most feasible way to implement optical buffers. In an optical packet-switched network, individual photonic switches are combined to form a network. Packets can arrive at the input ports of a network node at different times. Therefore, in packet-switched networks, bit-level synchronization and fast clock recovery are required for packet header recognition and packet delineation.

Optical packet-switched networks can be classified into two categories: synchronous (slotted) and asynchronous (unslotted) networks [Vokkarane 2004] [Yao 2003] [Dogan 2006] . In a synchronous or slotted network, time is slotted, and packets arrive at a core node in synchronized and equally spaced time slots. All packets in a synchronous network have the same size, and the duration of a time slot is equal to the sum of the packet size and the optical header length (plus appropriate guard bands). In an unslotted or asynchronous network, the packets may or may not have the same size, and the packets arrive at a network node at non-synchronized instants. Therefore, the packet-by-packet switch action could take place at any point in time. The impact of contention is often more severe in an unslotted network because the behavior of the packets is more unpredictable and less regulated. However, a slotted network requires synchronization at each switch input, which increases the switch cost and complexity.

As it is presented above, optical packet switching technology constitutes a promising technique for next generation WDM networks that support fast resource provisioning and that handle bursty traffic. However, the deployment of such technology faces major difficulties due to the lack of optical processing and the lack of efficient buffering in the optical domain. Widely speaking, the major problems of optical packet switching include the difficulty of realizing optical packet synchronizer, requirement of optical buffers, and relatively high control overhead resulting from small payloads [Qiao 2000] [Listanti 2000] [Hsu 2002]

2.2.2 Optical Burst Switching

In the literature, a novel approach referred to as optical burst switching (OBS), has been proposed by researchers [Qiao 1999] [Turner 1999] [Qiao 2000] [Wei 2000] [Bjornstad 2003] [Vokkarane 2004] [Lazzez 2005] [Dogan 2006] [DU 2006]. The incentive of this new idea is to keep the advantages of the above presented approaches while eliminating their shortcomings as much as possible. OBS technology provides more efficient bandwidth utilization than wavelength routing technique. At the same time, optical burst-switched networks do not have as many technological constraints as all-optical packet-switched networks. In optical burst-switched networks, a data burst consisting of multiple IP packets is switched through the network all-optically without buffering. Unlike a packet, a burst is a pure payload. Each burst is associated with a control packet recording burst related control information such as burst length and routing information. In this way, the control overhead is alleviated. A control packet is transmitted ahead of the burst in order to establish a path, reserve the needed resources, and configure switches along the burst's route. After a predetermined offset time, the burst is sent optically without waiting for an acknowledgement. The offset time allows for the control packet to be processed and the switch to be set up before the burst arrives at the intermediate node; thus, no electronic or optical buffering is necessary at the intermediate nodes while the control packet is being processed. Thus in this case the bandwidth reservation is a one-way process. The control packet may also specify the duration of the burst in order to let the node know when it may reconfigure its switch for the next arriving burst.

Hence, the OBS paradigm supports dynamic bandwidth allocation and statistical multiplexing of data, which mayensure en efficient network resources utilization. Compared with wavelength routing, data traffic starts transmission without waiting for an acknowledgement and the problem of significant signaling delay may be eliminated. In addition, the separation between a control packet and its burst in both time and wavelength domain can avoid buffering as well as synchronization problem in optical packet switching [Qiao 2000] [Hsu 2002].

Based on the aforementioned discussions, we can visibly observe that optical burst switching has the advantages of both optical circuit switching (and wavelength routed networks) and optical packet switching, while avoiding their shortcomings. According to signaling schemes, there can be various optical burst switching protocols. The most common signaling scheme for reserving resources in OBS networks are just-enough-time (JET), just-in-time (JIT), tell-and-go (TAG), and tell-and-wait (TAW) [Qiao 1999] [Bjornstad 2003] [Hsu 2002]. As JET provides more efficient bandwidth utilization compared to JIT and TAW schemes, and a better QoS compared to TAG protocol, so JET-based optical burst switching scheme is widely viewed as the most promising approach for the deployment of optical burst switched networks [Gauger 2002].

2.3 Contention Resolution

As 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 also there is no optical equivalent of random access memory.

The conventional techniques used to resolve contention for an incoming wavelength signal at the core nodes are discussed below.

2.3.1 Optical Buffering

In OBS networks, optical buffers based on FDLs can be used to delay packets for a fixed amount of time [Chlamtac 1996]. 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 [Hunter 1998]. 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.

2.3.2 Wavelength Conversion

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 can fuether be classified into 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 [Eramo 2003].

2.3.3 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 [Wang 2000].

Basic Concept: A conceptual view of deflection routing is given in fig. 2.1. Both senders *A* and *B* are sending bursts to receiver *E* (denoted their bursts as *b(A, E)* and *b(B, E)*). Before sending bursts, senders *A* and *B* send control packets (denoted as *c(A, E)* and *c(B, E)*) on their out-of band control channels for announcement. Since *c(B, E)* arrives at Node *C* earlier than *c(A, E)*, the output link of Node *C* towards Node *E* is reserved for *b(B, E)*. When *c(A, E)* arrives at node *C*, the link between *C* and *E* is still in use by *b(B, E)*. Node C then checks other output links and selects the idle link between C and D to deflect *b(A, E)*. Node *D* forwards *b(A, E)* via link between *D* and *E* based on its routing table. Since every node performs deflection routing in this manner, the deflected burst arrives at its destination with some extra propagation delay, i.e., traverses several additional nodes than the shortest path. The idle optical links can be considered as fiber delay lines for buffering the blocked bursts. The bursts in the congested part of the network are then distributed to other lessused parts, thus the overall link utilization and network performance can be improved.

The benefits of deflection routing for burst optical networks are discussed below. In traditional burst optical networks, if in an intermediate node along the path a traversing burst fails to reserve the resource (WDM channels), the burst has to be dropped and retransmitted again from the sender. In such a case,

a. A dropped burst wastes the bandwidth on the partially established path. If the burst data has been injected into the network, the network should do the best to forward it to the destination, more than simply drop it. For example when the receiver node is 6 hops away from the sender and the burst is dropped at the 5th hop, it has to be retransmitted and the total hop distance rises to (5 + 6 = 11) hops. If deflection is available, (5 + deflection hop count) is enough, which in most case is less than the total number of hops with the case of retransmission.

b. The delay becomes very large when retransmitting a blocked burst in long-distance links. Different from the traditional concept that mainly concerns about the processing delay in every switching node, the transmission delay becomes dominant value in high-speed and in broad-bandwidth optical networks . For example, the duration of the burst at 10 Gbps is only 0.8 ms for l MB bursts. On the other hand, the transmission delay over a 100 km optical fiber link would be 0.55 ms. If the destination is 7 hops away from the sender and a 1 MB burst is dropped at the 3rd hop, it at least takes (0.55 ms x 3 hops x 2 + 0.55 ms x 4 hops + 0.8 ms= 6.3) ms with one time of retransmission to make the burst totally reach its destination. However, if deflection is performed at the 3rd node, the total transmission time will be (0.55 ms x 3 hops + 0.55 ms x deflection hop count + 0.8 ms). If the deflection hop count is under 7 (in real case the number is actually much smaller), the total transmission delay will be reduced. Accordingly, deflection routing decreases the waste of bandwidth and the retransmission delay by eliminating the probability of burst dropping, yielding performance improvement.

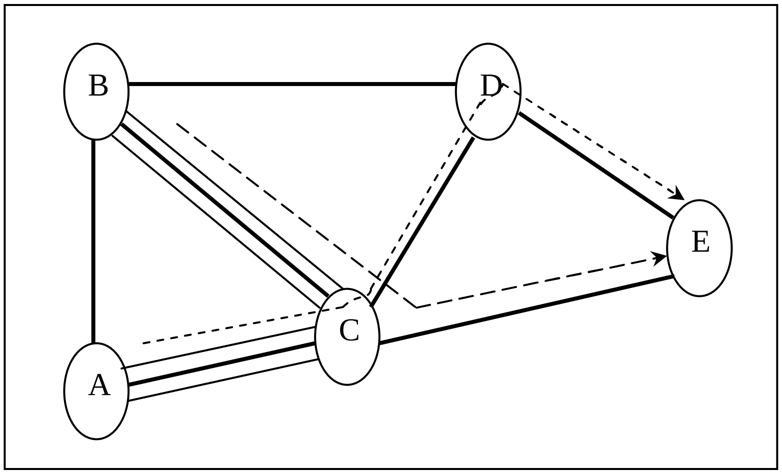


Fig 2.1. A Conceptual View of Deflection Routing for Optical Bursts

Deflection routing also has its disadvantages. For example, normal deflection routing is only efficient when the traffic load of the whole network is relatively low. However, when the traffic load grows, the effect of deflection decreases and eventually induces even higher blocking probability than the case of no deflection. The rapid performance degradation of deflection routing is due to its "indiscriminate" deflection procedure. Deflection routing is based on the assumption that if the default output link is in use, most of other links are idle and available for deflection use. However, when the traffic increases, this assumption begins to break down because the number of idle links for deflection use decreases. Moreover, deflected traffic further lower the network capacity to process newly generated bursts. The blocking probability increases rapidly and the network throughput collapses completely when the load exceeds a certain threshold [Hsu 2002] [Wang 2002].

2.3.4 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 segmented and dropped [Vokkarane 2002]. 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 [Vokkarane 2004].

In this chapter, we focus on the contention resolution in optical burst switching network using deflection routing, however other techniques are discussed the following chapters .

2.4 Motivation and Related Work

The OBS switches can potentially perform traffic grooming in the optical domain using tunable lasers and wavelength cross-connect (all optical) switches. The OBS switches would statistically multiplex traffic from different incoming ports and wavelengths onto a wavelength on an egress port. The statistical multiplexing occurs at the burst level, each burst consisting of numerous packets. There is a possibility that the OBS switches together with the wavelength-division-multiplexing/dense (WDM/DWDM) capability can be produced less expensively than equipment combining ultrahigh capacity core routers, optical switches, and WDM/DWDM. Also, the switching delay for OBS is dropping down to the range of tens or hundreds of nanoseconds, which makes a good case for feasibility of OBS implementation. Although promising, OBS still has implementation challenges, which need to be overcome [Sriram 2003] [Chen 2004]. These challenges include limited optical buffering and optical power and distortion management. The OBS implementation strategy includes both an electronic control processing mechanism for optical burst scheduling and an optical transmission technology utilizing wavelength cross-connects (WXCs or OXCs) together with tunable lasers.

One of the challenging issues in the implementation of burst switching is the resolution of contentions that result from multiple incoming bursts that are directed to the same output port. In an optical burst switch, various techniques designed to resolve contentions include optical buffering, wavelength conversion, and deflection routing [Gauger 2002] [Yoo 2000] [Gauger 2002] [Hsu 2002] [Kim 2002] [Wang 2000] [Li 2002] [Zalesky 2004]. In comparison to other techniques, deflection routing has an advantage as it can work with fiber delay-line (FDL) with limited bufferring capacity. Fiber buffer capacity is often indeed very limited, and a larger amount of it is needed in pure buffering schemes for contention resolution. However, deflection routing can work with limited optical buffering (or even no buffering) because it deflects or reroutes the contending bursts to an output port other than the intended output port. Thus, deflection routing is a very practical approach to resolve contentions, and has been examined through simulations, as well as analysis in [Hsu 2002] [Kim 2002] [Wang 2000] [Li 2002] [Zalesky 2004]. Prior to the emergence of OBS networks, deflection routing was first used as a contention resolution method in optical networks with regular mesh topologies [Borgonovo 1994]. In [Forghieri 1995] and [Bononi 1999], deflection routing is shown to provide much improved performance as compared with hot-potato routing in a network with high-connectivity topology, such as ShuffleNet. Chich et. al. [Chich 2001] have presented a heuristic that enhances unslotted deflection routing to provide similar performance level as slotted routing. In [Castanon 1999], the concept of priority is introduced and output ports are selected based on preassigned port priorities, while considering irregular mesh topologies.

With the emergence of OBS technology, a deflection routing protocol for OBS network was proposed in [Wang 2000] , demonstrating that deflection routing reduces the burst loss and the average delay as compared with the method of data retransmission from the source. Some work about deflection routing is reported in [Hsu 2002] [Kim 2002] [Wang 2000] [Li 2002] . The authors of [Hsu 2002] investigate the performance of deflection routing in OBS networks with prioritized burst types and just-enough-time (JET) scheduling. In [Kim 2002] [Wang 2000], it is demonstrated via simulation studies that the blocking probability improves when deflection routing is used as a means for contention resolution. The authors of [Li 2002] describe how deflection routing can be used in conjunction with the self-routing address scheme. However, these studies do not address the issue of how routing to an alternate path should be done, while considering some performance constraints. Deflection routing approach resolves the congestion by exploiting alternate available paths and utilizes the resources effectively, however if contention is resolved by traditional deflection routing then there is no guarantee that the control packet will be able to reserve all the wavelengths successfully up to the destination on the alternate path, especially in a high traffic load situation. The present chapter proposes a scheme of deflection routing by assigning suitable wavelengths to various routed paths based on respective traffic to be routed.

2.5 Contention Resolution in Deflection Routed Network

Deflection routing is invoked to save the burst of dropping and to redirect the contending burst to the alternate path, which is usually longer than the primary one. However, the problem of insufficient offset time may occur, because the offset time is calculated according to the primary route, which is as a rule the shortest one. It means that control packet needs extra offset time to configure deflection route. The FDL buffer could provide an additional delay to prevent the data burst to arrive in the node before the control packet configures the optical switch in the node and reserves the output channel. Since the optical buffer technology is still immature and has not reached the level of its counterpart electronic buffer considering the possible capacity and the current cost, we propose its limited appliance just for providing an extra offset time to the deflected burst.

This chapter presents a deflection routing based intelligent optical burst switching scheme and investigates its influence on OBS network blocking performance. In section 2.5.1 the deflection routing and JET signaling scheme are presented. The development of the analytical model of the deflected routed OBS network presented in Section 2.5.2. Numerical results are evaluated in section 2.5.3. In section 2.5.4 a modification of the proposed network is done to further improve the blocking probability performance. In section 2.6 we presented some concluding remarks.

2.5.1 Deflection Routing in JET Based OBS Network

The manner in which output wavelengths are reserved for bursts is one of the key features in OBS networks. The common reservation protocols are just-in-time (JIT), just-enough-time (JET) and tail-and-go (TAG). Out of these JET is the most prevailing distributed reservation protocol for OBS networks today because it does not require any kind of optical buffering or data burst delay at each intermediate node. It accomplishes this by letting each control packet to carry the offset time information and make the so called delayed reservation for the corresponding burst, i.e., the reservation starts at the expected arrival time of the burst. The bandwidth is reserved for the burst starting from the burst arrival time until it traverses to the next switch.

Another important feature of JET is that the burst length information is also carried by the control packet, which enables it to make closed-ended reservation. This closed-ended reservation helps the intermediate node to take intelligent decisions as to whether it is possible to make a reservation for a new burst and thus the effective bandwidth utilization can be increased.

The process of bandwidth reservation is performed in one direction, when JET signaling scheme, is used. So, the application of JET signaling scheme does not guarantee the burst delivering on the destination, [Myers 2001]. IP packets arriving in the same ingress node and having common destination are assembled into a huge burst. A header of a burst is sent as a control packet along the separate channel from the burst payload, and after the expiration of the offset time the burst is sent. During the offset time, the burst waits in electronic domain while the control packet reserves switching and transmission resources along the path.

In a conventional electronic router/switch, contention between packets can be resolved by buffering. However, in OBS networks, no or limited buffering is available and thus burst scheduling and contention resolution must be done in a different manner. If wavelength conversion capability is feasible, an incoming burst may be scheduled onto multiple wavelengths at the desired output port. A burst scheduler will choose a proper output wavelength for the burst taking into consideration the existing reservations made on each wavelength, and make a new reservation on the selected channel. Delayed reservation schemes [Qiao 2000], allow multiple setup messages to make future reservations on a given wavelength (provided that these reservations do not overlap in time). The output wavelength is reserved for an amount of time in proportion with the length of the burst.

In JET-based OBS networks, an *offset time* T is necessary between the control packet and data burst [Qiao 2000]. The control packet can employ the *delayed reservation* technique to reserve the bandwidth along the predetermined path. Let (S, D) be the source-destination pair, H be the number of hops between S and D along the predetermined route, and δ be the maximum required processing time for a control packet at each hop. The total delay encountered by control packet is no greater than $\Delta=\delta H$ and therefore the offset time T should be at least Δ. For example, Fig. 2.2.1(a) depicts a sample OBS network and the predefined path between S and D is S-A-B-D, i.e., $H=3$. Let $T=3\delta$, the burst will arrive at D just after the control packet is processed as illustrated in Fig. 2.2.1(b). If the control packet cannot reserve bandwidth at some intermediate hop, say *B*, it may reserve FDL buffer consequently instead of being blocked directly. However, if all FDL resources have been allocated to other bursts, the burst is blocked and the control packet will not be transmitted to *D* (Fig. 2.2.1(c)).

In order to achieve better blocking performance, we may invoke the *deflection routing* at such a congested hop. Unlike the traditional dynamic routing in circuit-switched WDM networks [Fabry-Asztalos 2000][Hsu 2001] where a fixed-alternate or dynamic route is reassigned between (*S*, *D*) pair, the deflection route should be chosen between the congested node *B* and the destination *D* since the control packet has arrived at *B*. Due to the nature of burst transmissions, the network state changes rapidly in OBS networks. As a result, it is hard to perform dynamic calculation of deflection route. To predefine deflection routes between each node pair in a fixed table is a more reasonable solution. In the previous example, the burst is blocked at node *B*. Then the deflection route from *B* to *D* is looked up in the table and the burst is forwarded to the new route *B-C-D*.

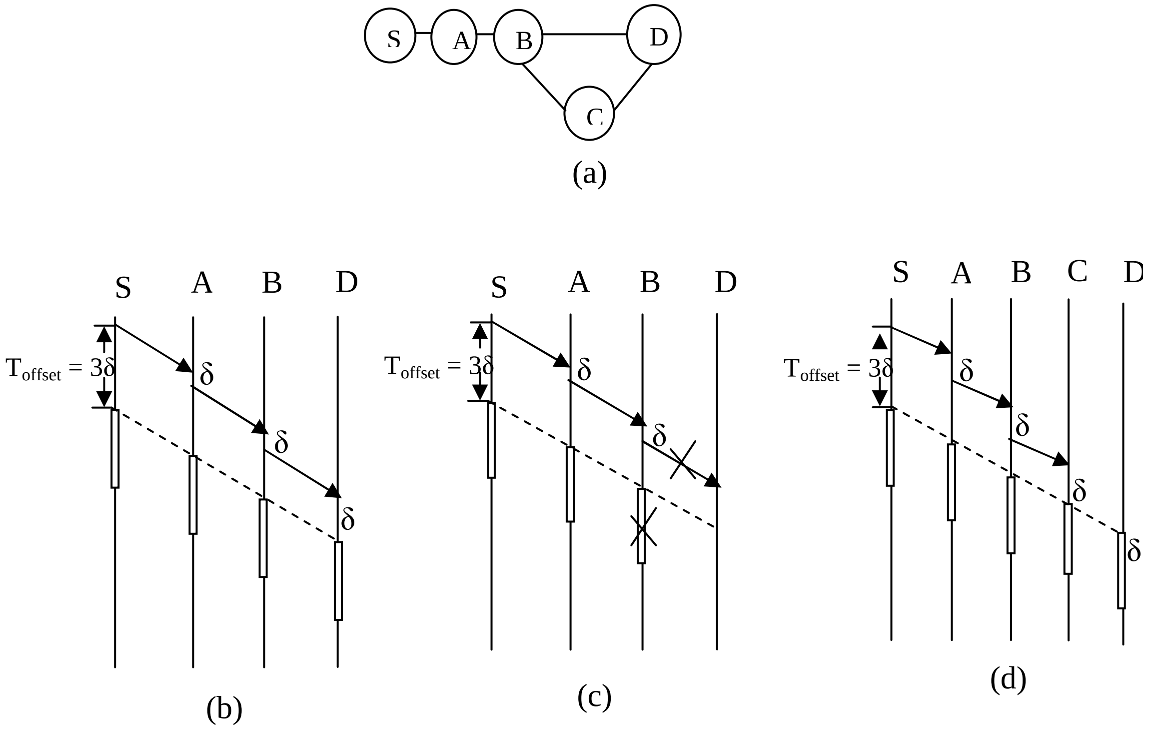


Figure 2.2.1 Possible cases of a burst from *S* to *D*: (a) a sample network, (b) successful transmission on path *S-A-B-D*, (c) FDL reservation failure at *B*, and (d) deflection routing is triggered at *B*

There is a crucial problem when we redirect the burst to the deflection route: *insufficient offset time*. Let h denote the increased number of hops of deflection route. If the initial offset time $T=\delta H$ and $h>0$, the burst will arrive at the destination node *D* earlier than the control packet is completely processed in *D* by δh time units. As shown in Fig. 2.2.1(d), the deflection route *B*-*C*-*D* has one more hop than the original route *B*-*D*, i.e., $h=1$. The burst will reach the destination δ time units before the control packet is processed.

Therefore, the deflection routing will not succeed without enough offset time[. The different possible solutions as follows:

a) Extra offset time

If sufficient offset time is provided, as $T \geq \delta \times (H+h)$, the burst can be successfully redirected to the deflection route. If the offset time is greater than 4δ as shown in fig 2.2.2(a), the burst will arrive at *D* after the control packet is processed. However, it is hard to determine extra offset time in the beginning. Without enough extra offset time, the deflection cannot be completed; with huge extra time, the other bursts may be affected [Yoo 2000a]. Thus, this strategy is lack of flexibility and can not be easily implemented.

b) Delayed-at-previous-hops

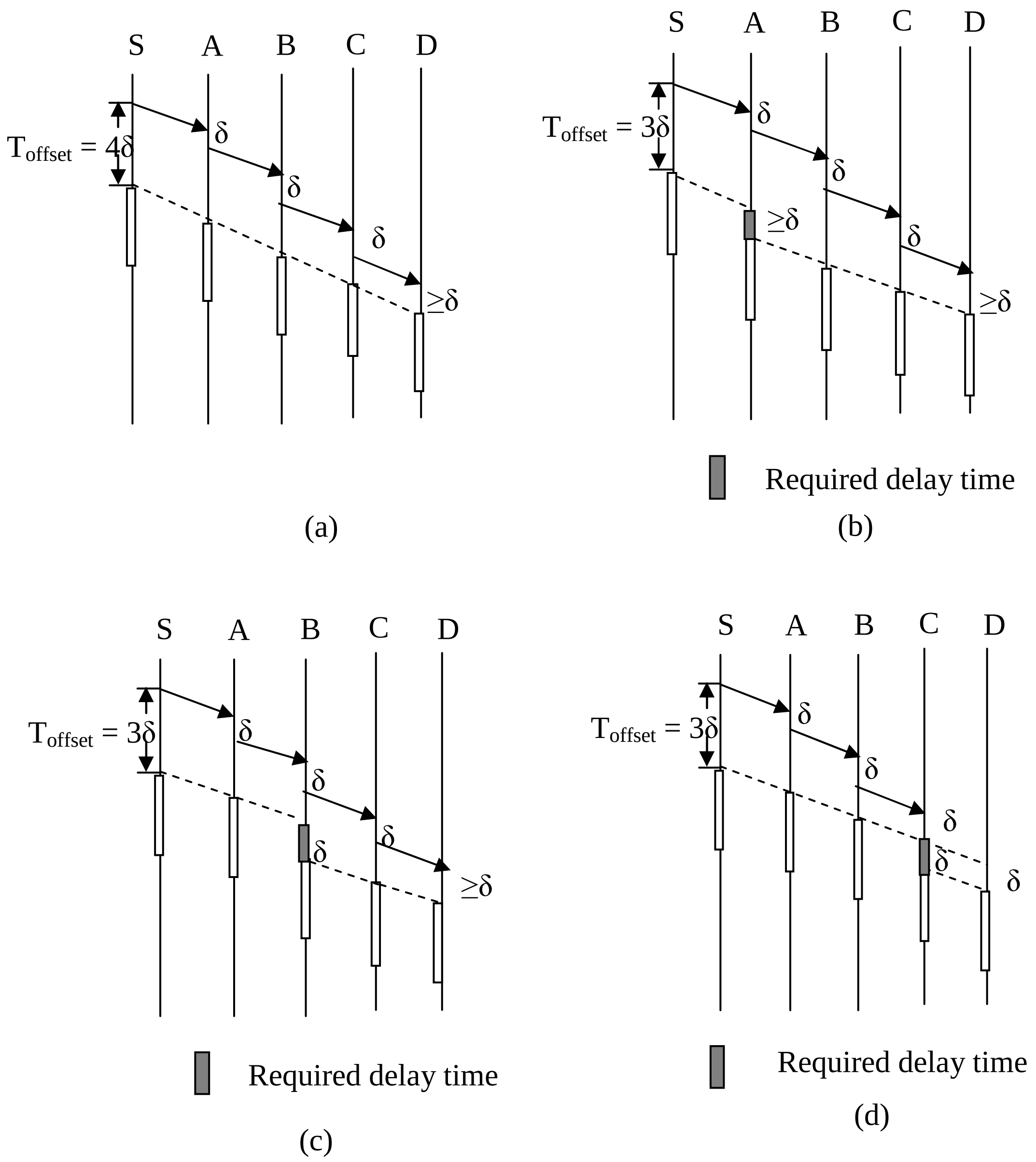
It may happen that the burst has encountered delay before entering the congested node. There will be no problem if total delayed time is greater than $\delta \times h$. Fig. 2.2.2(b) depicts such a situation that the burst has been delayed for more than δ at hop *A*. Nevertheless, this case may not occur each time when deflection routing is required.

c) Delayed-at-congested-node

If the burst does not have sufficient offset time and has not been delayed at previous hops, a buffered delay time $\delta \times h$ is required at the congested hop. In Fig. 2.2.2(c), a delay time of δ is enforced at *B* and the redirection can be performed successfully.

d) Delayed-at-next-hop

Delaying the burst at the next hop of the congested node is also a solution. Because there is at least one hop between the congested node and the destination node, the burst can be transmitted to the next hop where the delay can be performed without any problem. For example, the burst is congested at node *B* and the required delay is issued at its next hop (node *C*) in Fig. 2.2.2(d).



(a) (b)

(c) (d)

Fig. 2.2.2 Approaches for keeping offset time sufficient: (a) extra offset time, (b) delayed-at-previous-hops, (c) delayed-at-congested node, and (d) delayed-at-next hop

2.5.2 Network Architecture and Model Formulation

Deflection routing can be used in case of contention resolution. Here we model an intelligent deflection routed OBS network which is capable to allocate wavelength dynamically. There are *W* available wavelengths on each output link out of these *W* output links *N* are allocated to the deflected bursts only, hoping that its implementation will decrease the possibility of multiple deflection, because this phenomenon may cause higher traffic intensity and network congestion. Number *N* is determined dynamically in compliance with the deflected burst traffic intensity.

In the proposed model we have assumed that the burst lengths are exponentially distributed with mean $1/\mu$, the average number of extra hops for the deflected burst are H, the maximum processing time for the control packet at each hop is τ, the burst arrival at a given output port of an OBS node is a Poisson process with mean rate λ_1 for non-deflected and λ_2 for deflected bursts. The equivalent offered load is $a = \rho_1 + \rho_2$ where non-deflected burst load is $\rho_1 = \lambda_1/\mu$ and the deflected burst traffic load is $\rho_2 = \lambda_2/\mu$.

In order to estimate blocking probability we use a Markovian M/M/c/c queuing model to construct a two-stage model of OBS node [Gross 1974], shown in Fig. 2.3. The first stage represents *N* wavelengths of the output fiber link allocated to the deflected burst only in order to avoid their multiple deflections and to decrease the deflected burst blocking probability. The second stage represents the remaining number of wavelengths *(W-N)* on the output link, shared by both non-deflected and the deflected bursts rejected from stage 1.

The first stage in fig.2.3 represents the M/M/N/N loss model, in which probability p_1 that *N* wavelengths are busy is given by Erlang's loss formula

$$p_1 = \frac{\rho_2^N / N!}{\sum_{i=0}^{N} \rho_2^i / i!} \tag{2.1}$$

where ρ_2 is the traffic load in the first stage. The deflected bursts blocked in the first stage are not discarded, but they are routed to second stage with a mean rate λ_{22} given by

$$\lambda_{22} = \lambda_2 . \frac{\rho_2^N / N!}{\sum_{i=0}^{N} \rho_2^i / i!} \tag{2.2}$$

The second stage represents the multi-dimensional traffic model, since the transmission resources are shared by the bursts with different features. It is assumed that the non-deflected and deflected bursts are arriving according to Poisson process with mean rates λ_1 and λ_{22} respectively.

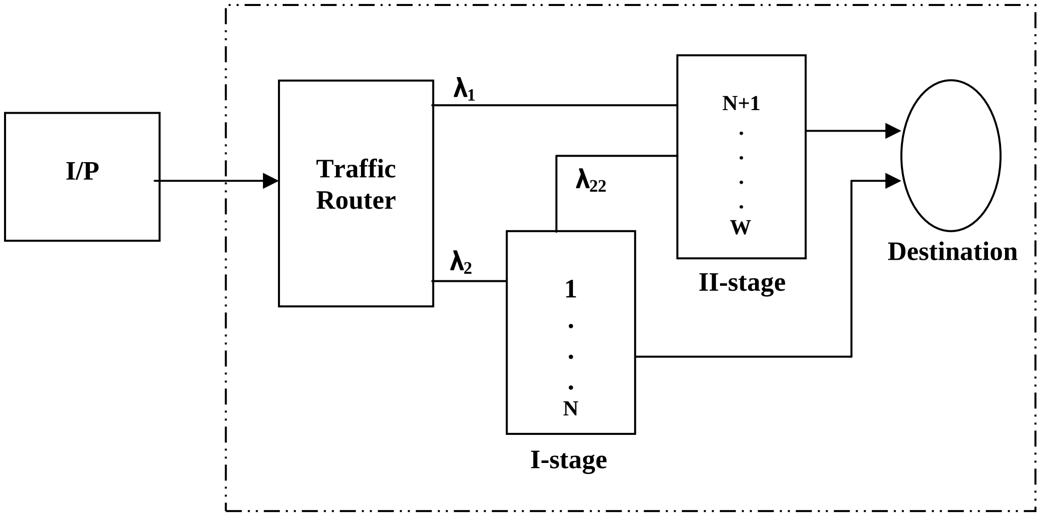


Fig.2.3: Deflection Routed Intelligent OBS network

Let p_{ij} denotes the joint probability that i non-deflected and j deflected bursts exist in the steady state , where $0 \leq i \leq (W\text{-}N)$, $0 \leq j \leq (W\text{-}N)$, $0 \leq (i+j) \leq (W\text{-}N)$. Denoting the individual non-deflected and deflected burst traffic load by $\rho_1 = \lambda_1/\mu$ and $\rho_{22} = \lambda_{22}/\mu$ it can be shown that p_{ij} is equal to

$$p_{ij} = \frac{\rho_1^i}{i!}\frac{\rho_{22}}{j!}[\sum_{i=0}^{(W-N)}\sum_{j=0}^{(W-N-i)}\frac{\rho_1^i}{i!}\frac{\rho_{22}}{j!}]^{-1} \tag{2.3}$$

The blocking probability of the second stage is may be expressed as

$$p_2 = \sum_{i=0}^{(W-N)}\frac{\rho_1^i}{i!}\frac{\rho_{22}^{(W-N-i)}}{(W-N-i)!}[\sum_{i=0}^{(W-N)}\sum_{j=0}^{(W-N-i)}\frac{\rho_1^i}{i!}\frac{\rho_{22}}{j!}]^{-1} \tag{2.4}$$

The overall blocking probability for the two-stage can be written as

$$p = p_{nd} + p_d = \frac{\rho_1^2 p_2}{\rho_2 a} + \frac{\rho_2 p_1 p_2 \rho_{22}}{\rho_2 a} \tag{2.5}$$

Now these equations can be used to simulate the deflected burst blocking probability and overall blocking probability of the proposed network in the MATLAB environment under the appropriate node and traffic assumptions.

2.5.3 Simulations and Results

Simulations have been carried out to investigate the effect of N (the number of wavelengths of the output fiber link allocated to the deflected bursts only) on the overall blocking probability (P) and the deflected burst blocking probability (P_d), by changing a portion of deflected burst traffic in total input traffic load a. The calculations were executed for the several different input values of deflected burst traffic intensity, i.e. for $\rho_2 = 0.3a$, $0.4a$, $0.5a$,$0.6a$ and $0.7a$. The total offered load is normalized with the number of wavelengths ($m = a/W$), and the value m is in the range [0.1,1]. The number of the output link wavelengths is W=64, and N is dynamically changed in the range [0,32]. The numerical results are obtained for the average deflected burst blocking probability P_d, non-deflected burst blocking probability P_{nd} and the overall burst blocking probability P, for different values of ρ_2 and N. Later on comparative study has been done to verify the performance of the proposed OBS network.

Fig 2.4(a) depicts the variation of deflected burst blocking probability for different values of output wavelengths and of incoming traffic to stage 1 i.e, to the deflected path only. It is seen from the fig. that though the traffic to the deflected burst stage is increased but the blocking probability decreased at the same time because the number of output wavelengths are increased. This results implies that when the amount of incoming traffic is high then the performance of the network can be maintained satisfactorily if the number of available wavelengths are increased proportionately. But this will in turn increase the blocking probability of the non deflected path so the extra wavelengths that are allocated dynamically to the deflected burst during the high incoming traffic should be released when the need is over. Fig. 2.4(b) shows the non-deflected blocking probabilities for different values of incoming traffic with different numbers of output wavelengths. The qualititative variation of blocking probabilities with incoming traffic for both the deflected and the nondeflected cases are almost same in nature but only difference is that the amount of blocking suffered is more in non deflected case.

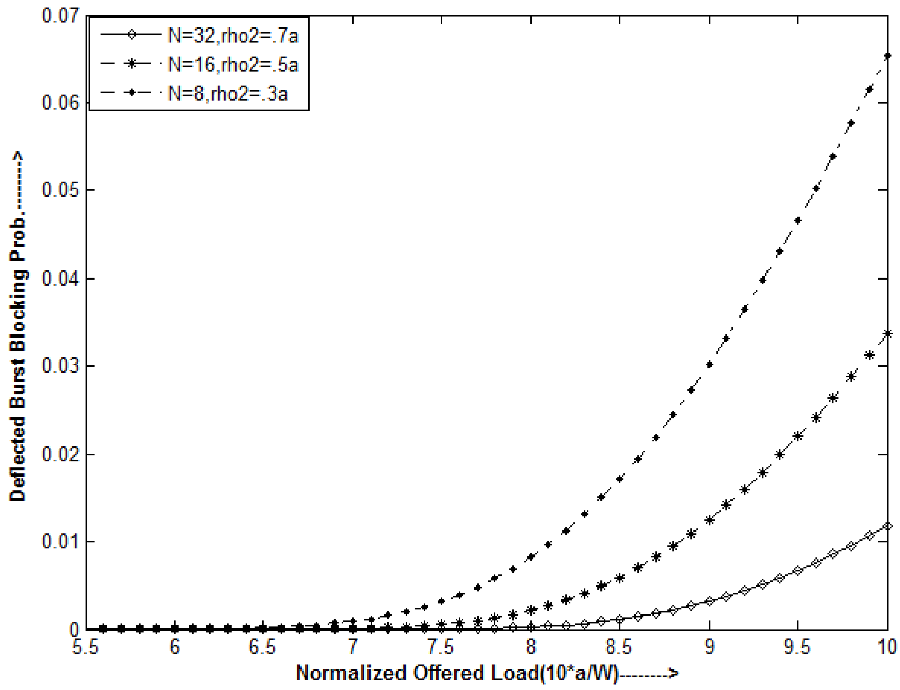


Fig 2.4(a): Deflected Burst Blocking Probability vs Normalized Offered Load

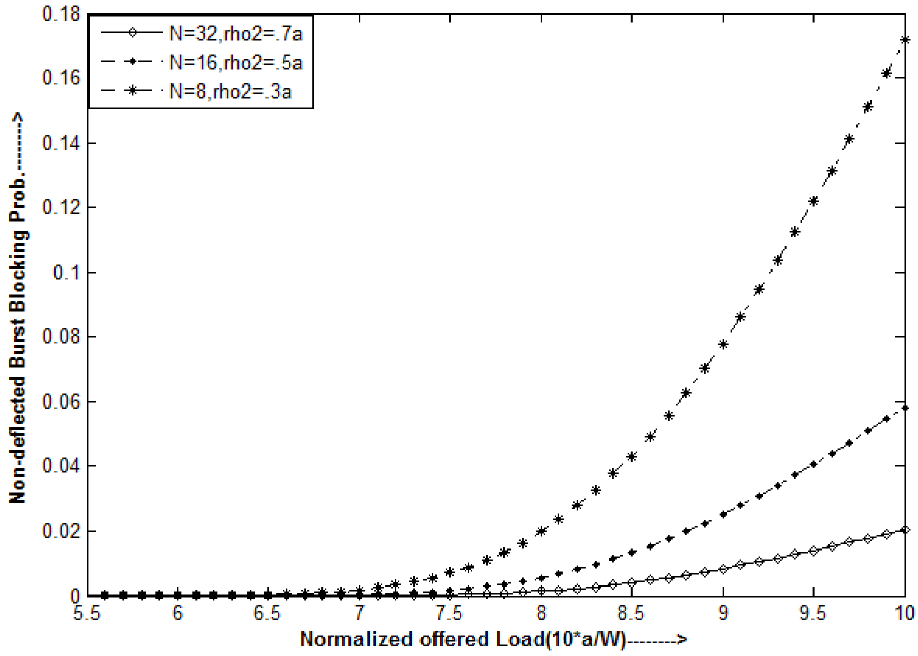


Fig 2.4(b): Non-deflected Burst Blocking Probability vs Normalized Offered Load

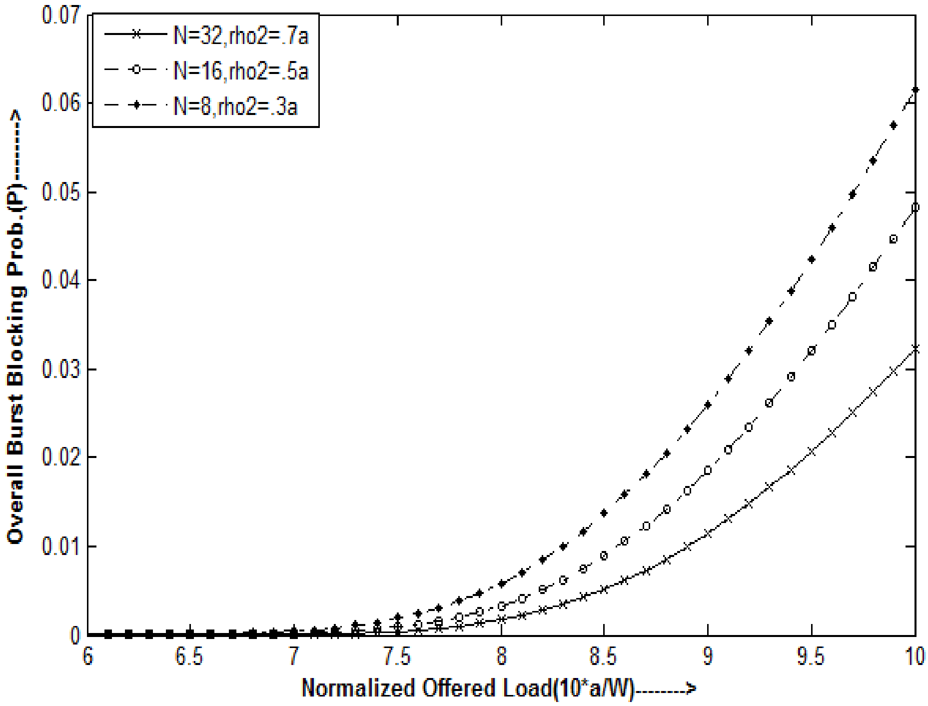


Fig. 2.4(c): Overall blocking probability vs Normalized Offered Load

Fig. 2.4(c) shows the variation of overall blocking probability of the network with offered traffic load. It has been observed from fig. 2.4(c) that the overall blocking probability of the composite system provides the minimum blocking probability. The result obtained in this graph is quite interesting because when we are using the deflection routing with dynamic resource allocation scheme. The performance of the network is improving significantly for all values traffic ρ_2 and the number of wavelengths of the output fiber allocated to the deflected burst only. The comparative curves of burst blocking probabilities P_d and P for high traffic $\rho_2=0.7a$ with $N=0$ and 32, are depicted in fig.2.4(d). It can be seen that P_d and P have been significantly decreased in comparison to the same curves in case when dynamic allocation scheme is not implemented, i.e. when $N=0$. The result reveals that the overall blocking performance of the OBS network can be upgraded if N is adapted to the deflected burst traffic intensity dynamically and intelligently, because the blocking probability of the overall network is greatly influenced by the deflected burst stage.

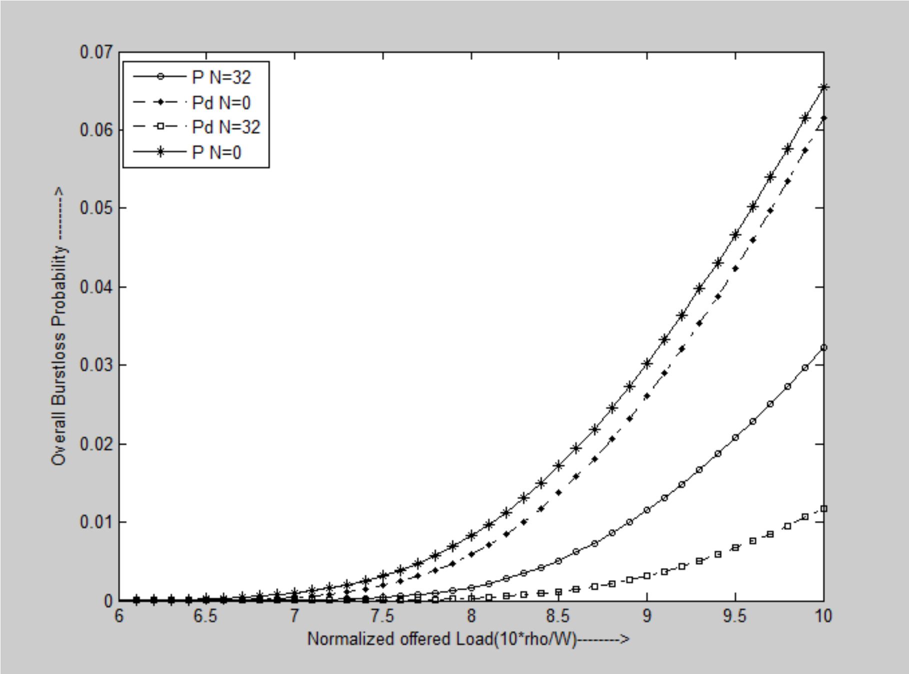


Fig.2.4(d): Comparative Study of Overall Blocking Probability and the Deflected Burst Blocking Probability

Various combinations of ρ_2 and N produce a strings of numerous values of P_d , P_{nd} and P. The obtained results indicate the benefit of the proposed dynamic wavelength allocation technique in the OBS network with deflection routing as contention resolution scheme.

2.5.4 Modification of the Network Architecture and Model

The model proposed in sec 2.5.2 can further be modified by incorporating an additional stage to the deflected bursts as shown in fig 2.5. The first stage represents the FDL buffer that provides an extra offset time for deflected bursts. The second and third stage represent W wavelengths of the output link. The second stage represents N wavelengths on the output fiber link allocated to the deflected bursts only. The third stage represents the remaining number of wavelengths on the output link *(W-N)*, shared by both non-deflected bursts and the deflected bursts rejected fron the second stage.

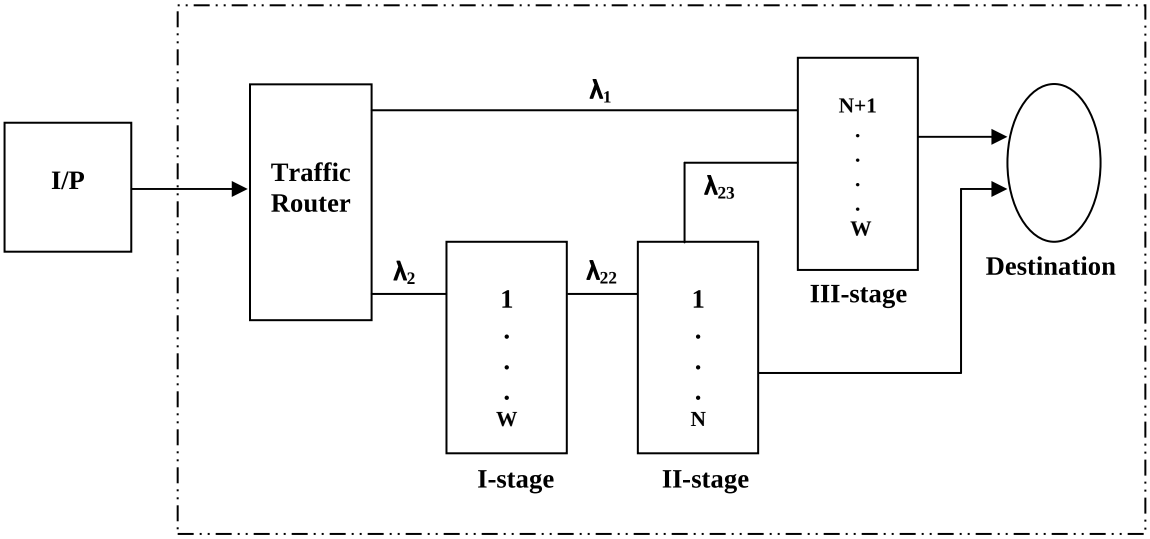


Fig.2.5: Three stage model of OBS network

The first is represented by M/M/W/W model. The blocking probability (P_1) of FDL buffer can be calculated from Erlang's loss formula

$$P_1 = \frac{\rho_2^W / W!}{\sum_{i=0}^{W} \rho_2^i / i!} \tag{2.6}$$

According to Markovian model the departure time distribution and arrival time distribition is identical. So, the departure from the first stage is the Poisson process with mean rate λ_{22} is given by

$$\lambda_{22} = (1 - P_1)\lambda_2 \tag{2.7}$$

The second stage represents the M/M/N/N loss model in which probability (P_2) that N wavelengths are busy is given by Erlang's loss formula. The deflected bursts blocked in the second stage are not discarded, but they are forwarded to the third stage with a mean rate λ_{23} given by,

$$\lambda_{23} = P_2 . \lambda_{22} \tag{2.8}$$

The third stage represents the multi-dimensional trffic model, since the transmission resources are shared by the bursts with different characteristics. It is assumed that the non-deflected and deflected burst arrivals are the Poisson processes with mean rates λ_1 and λ_{23}. If the individual non-deflected and deflected burst traffic load are reprensented by $\rho_1 = \lambda_1/\mu$ and $\rho_{23} = \lambda_{23}/\mu$ then it can be shown that the blocking probability P_3 of the third stage can be expressed as

$$P_3 = \sum_{i=0}^{(W-N)} \frac{\rho_1^i}{i!} \frac{\rho_{23}^{(W-N-i)}}{(W-N-i)!} [\sum_{i=0}^{(W-N)} \sum_{j=0}^{(W-N-i)} \frac{\rho_1^i}{i!} \frac{\rho_{23}}{j!}]^{-1} \tag{2.9}$$

The average burst blocking probability (P) for the three-stage model can be can be written as

$$P = P_{nd} + P_d = \frac{\rho_1^2 P_3 + \rho_2 [P_1 \rho_3 + (1 - P_1) P_2 P_3 \rho_{23}]}{a \rho_3} \tag{2.10}$$

where $a = \rho_1 + \rho_2$ and $\rho_3 = \rho_{1} + \rho_{23}$

2.5.5 Simulations and Result

The analytical results shown in fig 2.6 indicate that the overal burst blocking probability generally decreases as N increases. This is because of the greater part of the total capacity of the output link are utilized by the deflected burst. For instance, the improvement of the overall burst blocking probability value for N=6 is more than one order of magnitude in comparison with N=0 case, for a normalized offered traffic value of 1. Moreover, this burst blocking probability become 3 order lower for the same case at lower offered traffic of value of 0.2. If we compare the overall burst blocking probability for N=0 then it can be shown that there is a significant improvement in the burst blocking probability. For example we can see that for normalized incoming traffic value of 1 the previous model (fig 2.3) gives a blocking probability of almost 0.7 and reduces to almost 0.001 in the modified case (fig 2.5) for N=0 case. This result indicates that the 3 stage modified model provides a superior burst blocking probability.

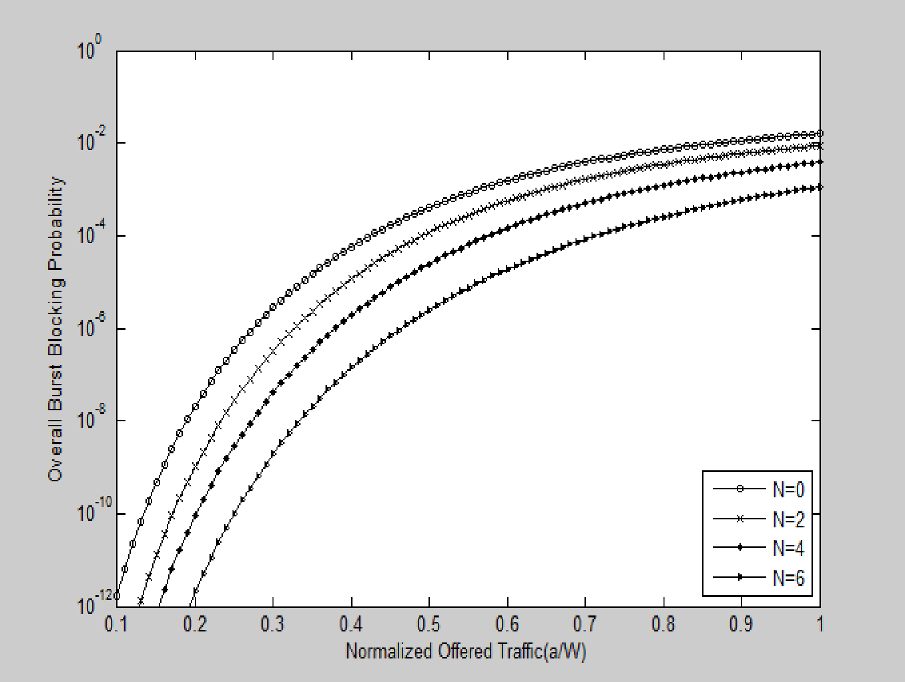


Fig. 2.6 Overall Burst Blocking Probability vs Normalized Offered Traffic for different values of *'N'*

2.6 Conclusion

Contention is a major concern in OBS networks and in this chapter a brief introduction of different contention resolution techniques that are applicable to OBS network are discussed with special emphasis on deflection routing. An analytical approach has also been presented to investigate the performance of a deflected routed OBS network having the capability of allocating variable output wavelength according to the intensity of incoming traffic or with dynamic resource allocating capacity. Mathematical models have also been developed for simulation study. It is observed that the proposed architecture significantly decreases both, overall and the deflected burst blocking probability. The analysis has been extended and modified by including one extra FDL buffer to the deflected bursts to reduce blocking probability. Thus the implementation of the dynamic resource allocation scheme in conjunction with deflection routing in an intelligent OBS network yields a significant improvement on the nodal routing performance. Concerning to the hardware requirements for the implementation of deflection routing needs the limited optical FDL buffer incorporation in OBS network, to provide the deflected burst with the extra offset time. The approach adopted here has been quite simple and involves basic linear model to yield a well acceptable performance.

CHAPTER-3

TIME DOMAIN CONTENTION RESOLUTION: OPTICAL BUFFERING

3.1 Introduction

All optical network has been proposed as a promising candidate for providing high-speed networking [Hui 1990] [Stern 2009] [Diao 1999] because of the huge bandwidth of the optical channels involved. A single fiber offers low attenuation [0.2dB/km] with huge bandwidth and this can be exploited by using a number of independent wavelength channels which is referred to as wavelength division-multiplexing (WDM). Several technologies have been proposed to use WDM in optical networking including broadcast and select, wavelength routing, optical packet switching (OPS), and optical burst switching (OBS)etc [Mukherjee 2001] [Mukherjee 2004]. These technologies have used the circuit switching and packet switching strategies for network traffic streaming and routing, however out of them optical packet switching systems offers a solution for the future all-optical networks to provide large bandwidth utilization, high processing rate, and data transparency [Hui 1990] [Stern 2009]. For each optical packet, the routing information is encoded in the header, which is used by the control unit to transfer the packet to its destined output port. The contention problem exists in all packet-switching systems, when two or more packets are destined to the same switch output at the same time. In this process only one packet can be successfully sent out and other packets have to be buffered for later transmission and causes congestion. The proposed techniques for contention resolution in OPS include optical buffering, wavelength conversion, and deflection routing. For an electrical packet switch, the contending packets can be easily buffered in electrical random access memories (RAMs), however, optical RAM is not yet available with the present day technology . In order to increase the buffer capacity, wavelength conversion has been investigated to implement with the optical buffering. Use of wavelength converters with each fiber delay line (FDL) makes the buffering system capable of carrying a number of packets on different wavelengths at the same time slot [Diao 1999] [Hunter 1998].

The effectiveness of contention resolution greatly influences network performance in terms of probability of packet loss, network utilization, average packet delay, and average source-destination path length.

In this section we describe some promising buffering schemes for this purpose. In the absence of optical RAM, the fiber delay line is currently the medium of choice for optical packet buffering. The simplest FDL packet buffer is made up of a length of fiber, typically several kilometers long, accommodating several packets queued in a first come first serve (FCFS) manner. Usually the length of fiber require to store one packet is inversely proportional to the packet bit rate, high bit rates are advantageous for FDL buffered systems requiring a typical 10m delay line for 100 Gbps system.

A number of node architectures can be employed that provide time domain contention resolution based on FDLs employing various combination of FDLs design, location and connection in the node structure. Optical node architectures are typically modeled after making the equivalent co-relation with the structures commonly used in electrical networks, including input, output, and feedback (recirculation or re-entry) buffering. It is therefore worthwhile to recall this as an electronic approach to model and understand optical nodes.

In a simple packet switched configuration each incoming packet is read into a common memory and then written out to its requested output line when that line is free. The common memory queues the contending packets while they are waiting for transmission on their requested links and using a reconfigurable switch fabric these can be sent out when the node is free.

In OPS node architecture the switch input buffering include, FDLs capable of storing multiple packets at the input ports of the switch and queued them in their respective FDLs to realize an optical buffering. Generally, in input or output buffered systems packet-loss performance improves with the number of buffers employed. Usually a large buffer sizes are difficult to realize in OPS however a new approach to improve contention resolution with a limited number of buffers using feedback delay line architecture have been attempted. In this case, when there is contention between two incoming packet, one of them is directed to one of the outbound links associated with the FDLs. By setting the switch to recalculate the delay required through the FDL, the buffered, packet can keep circulating in side the feedback loop until the outbound link becomes available. This recirculation scheme in effect creates an “endless” delay- in theory. In practice attenuation in the loop and /or noise introduced by amplification with in the loop degrade the quality of the optical signal every time the packet recalculates through the switch fabric. The signal will be mutilated and the packet will have to be dropped after some critical circulation delay.

Another approach involves feedback delay line in the node architecture design with FDLs to realize partially shared buffering (PSB) architecture. This is an output buffering scheme in the sense that there is an optical buffer (called the prime buffer- essentially a set FDLs) for each output line, and in addition there is an output common buffer (FDLs) that is shared among all the outputs. Overflow packets (arriving packets that cannot be accommodated) that would otherwise be blocked are now sent to the shared buffer for temporary storage. Simulation studies in [Diao 1999] demonstrated that the PSB architecture can achieve a higher throughput with out significantly increasing the size of each prime buffer or heavily utilized wavelength converters. It is also found that the increase in packet delay caused by the PSB is very minor and the mean packet delay approaches an upper bound (the mean packet delay of an M/D/1 queue) when the prime buffer size is large enough.

The OPS nodes can be classified into output buffering, shared buffering, recirculation buffering and input buffering depending on the usage of buffers [Hunter 1998] . An output-buffered OPS node consists of a space switch with a buffer on each output port where a packet needs to be output buffered and experiences queuing delay due to contention when more than one packet is destined for the same output port at the same time.

Shared buffering is a form of out buffering, where all output buffers share the same memory space and in optical domain this may be realized by using FDLs that are shared among all output ports. Shared buffered OPS nodes are able to achieve a significantly reduced packet loss performance with much smaller switch sizes and fewer FDLs than their output buffered counterparts [Zhang 2006]. In recirculation buffering, a number of recirculating optical loops from some of the output ports are fed back into the switch input ports. In such buffered nodes contention is resolved by placing all but one packet into the recirculating loops whenever more than one packet simultaneously arrive at the switch input ports destined for the same switch output port as soon as contention clears. Recirculation buffering helps to resolve contention at the expense of optical signal degradation incorporated by the delay units and space switches involved.

Input buffering involves head-of-line (HOL) blocking which occurs when the packet at the head of an input queue cannot be forwarded to its intended output port due to existing contention. The packet has to be stored in the input queue until there is no more contention at the intended output port. As a result, input-buffered OPS nodes suffer from a decreased throughput and increased delay and packet loss and are seldom used in the optical networks.

Typically, optical buffers are implemented by using an array of FDLs of different lengths or SDLs. Using fibers of variable length to store variable-size optical packets is some what tricky since each optical delay line is of fixed length. Once a packet has entered the optical delay line, it can be retrieved only a fixed time period later equal to the propagation delay of the delay line. This constraint poses some limitations on the realization of optical buffers and resource efficiency of optical variable –size packet switching networks [Maier 2008].

3.2 Motivation and Related Work

A rapid increase in the bandwidth requirement for optical network to support high data rate pits the switching speed limit for the supporting electronic technology [Bawab 2002]. Thus, we need a photonic network which can incorporate functions such as the multiplexing, de-multiplexing, switching, and routing in the optical domain substituting the electronic control circuitry. In the recent past aggravated efforts have been made towards bandwidth provisioning in optical domain indicating the intelligence in optical networks. Optical switching improves overall effective utilization of the available bandwidth. A number of research groups have reported various optical sub-wavelength switching approaches, among all OPS approach attracts attention as it is capable of dynamically allocating network resources with fine granularity and excellent scalability.

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

In general, the various OPS node architectures proposed in the literature are varied in terms of switching fabric technology, optical buffer technology and buffer placement in the switch design [Diano 1999] [Corazza 1999]. These switches have been analyzed on the basis of network performance parameters and contention resolution approaches to handle packet conflicts and throughput limitations.

The initial OPS node architecture developed by the European ACTS KEOPS team [Gambini 1998] is designed for slotted OPS network such that each packet exactly in one time slot. The node consists of two stages namely buffering and switching for its operation, where packets are delayed by required amount of time (integral multiple of slot time) using FDLs in order to avoid contention at output ports of the switch. The solution proposed by KEOPS team does not allow packet circulation to deal with packet priority. The WASPNET switch [Hunter 1999] architecture is designed for slotted OPS networks and uses optical buffers (FDLs) to resolve packet contention. The packet can be delayed for a finite amount of time before leaving to the output port in corresponding FDL set. The switch is capable of handling traffic priority by circulating a packet in FDLs, if required.

Optical buffering is widely used in OPS network to overcome the contention problem [Hunter 1998] [Callegati 2000] [Laevens 2003] [Rostami 2005] [Fiems 2005] [Mellah 2006]. The solution proposed by [Fiems 2005] uses two stage optical buffers in which packets received at input are first routed to first stage of FDLs and then again routed to second stage of the FDLs to avoid contention at the output of the first stage. Then analysis proposed there shows a better packet loss ratio as compared to single stage buffers for a limited traffic correlation.

The FDL structure proposed in [Laevens 2003] and [Zhang 2005] assumes the length of the FDLs are multiples of certain granularities and describes the relevance between FDL structure and switch for the offered traffic to resolve contention. The node architecture proposed by Leavens [Laevens 2003] uses dedicated buffering while Zhang assumes a shared buffer FDL structure, for a given number of FDLs, shared buffering performs better than dedicated buffering in terms of packet loss probability as in former case any of the free FDLs can be utilized for any of the output port contention.

It is observed that the existing buffering implementations require either large amount of FDLs or complex switch architecture for better throughput. the switch hardware cost can be better managed by inclusion of flexibility delay lines in suitable node architecture to show a better packet contention resolution. The design can further be modified to allow packet circulation in buffers or FDLs lines. The present chapter focuses on the contention resolution by utilizing fiber delay lines in efficient way in case of optical packet switching (OPS) and the next section describes the estimation of burst loss probability for optical burst switching (OBS) scheme.

3.3 OPS Node Architecture Design and Model

Here we present a concept of architectural model consisting of multiple loop delay to increase the throughput. The simulated behavior of an optical node has been realized by using an $n \times m$ optical switch and recirculating optical delay lines as shown in fig 3.1. This investigation infers the scaling behaviors of the proposed architecture to maintain efficient use of the buffer under Poisson traffic loading. The analysis also reports the traffic handling capacity for the given complexity of the node architectural design.

In wavelength division-multiplexing (WDM) based all optical network system [Hunter 2000] [Develder 2002] [Lin 2007] a packet that cannot be directly sent to the output fiber is sent back to one of the delay lines for recirculation and after being delayed by some specific time, that packet will come out of the delay line to compete for throughput with the newly arriving packets. In case of unsuccessful throughput it gets back into the delay line for the next round trip with additional delays.

In the proposed model a node has been considered with more input channels than output channels and the maximum capacity of this node is decided by the available output channel. It is assumed that arriving packets are destined to their respective destinations based on first come first serve (FCFS) scheduling policy. In this way we can avoid the continuous recirculation of some packet in the delay line. Packets that arrive in the meantime are also sent to delay line. The node includes finite capacity buffer and multiple delay lines arranged in synchronized mode.

The packet switching has its own (unique) issues in optical networks. In an optical packet-switched network, contention occurs due to unavailability of free output wavelength. In electrical packet-switched networks, contention is resolved with the store-and-forward technique, which requires the packets losing the contention to be stored in a memory bank and to be sent out at a later time when the desired output port becomes available. This is possible because of the availability of electronic random-access memory (ERAM).There is no equivalent optical RAM technology; therefore, the optical packet switches need to adopt different approaches for contention resolution. Meanwhile, WDM networks provide one new additional dimension namely wavelength, for contention resolution. There have been studies in literature for utilizing the three dimensions of contention-resolution schemes: wavelength, time, and space.

Here we explore the contention resolution based on time and propose a new scheduling algorithm for prioritizing the packets within the node. The optical buffers basically delay the incoming signal by making it to travel a small distance, so as to provide some time to the processor for serving them in case the service is not available initially. Now this delay can be provided in fixed quanta’s only. This unique feature of optical buffers (unlike their electronic counterpart which ‘store’ a packet) makes it necessary to have a minimum fixed delay once the packet has entered into the fiber delay line (FDL). Traditionally the buffer is implemented such that once the packet has entered into the FDL it suffers the delay and comes out after that time. The packet might be served if necessary arrangements had been made or otherwise dropped. This architecture provides a single chance to server it thus resulting in high packet loss. Ideally the packet should be available at all times at output after having entered the FDL (like equivalent electronic memory) so that it can be served whenever the resources are available. Our new buffer architecture attempts to realize this objective by giving delays in steps of small granularity D (μSec) which allows the packets to be processed if the resource at output is available otherwise reflected back to the FDL for multiple reflections as per the control algorithm.

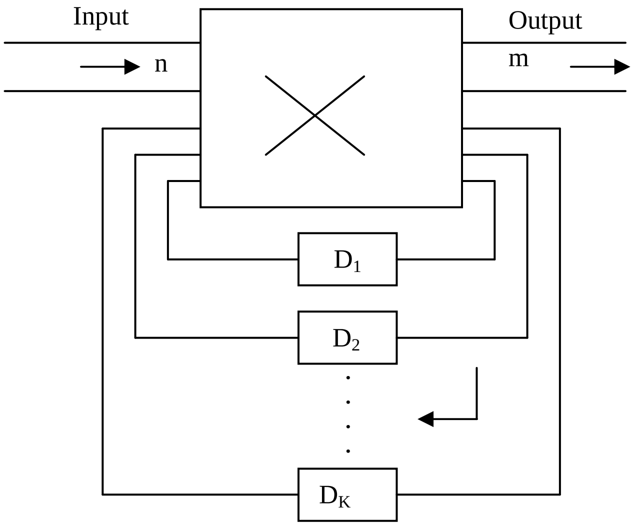


Fig.3.1: Recirculating Delay Line Optical Buffer

It is already assumed that the number of output channels (*m*) is less than the number of input channels (*n*) and therefore the queuing system has a fair chance of packet contention. The buffer works with a first-come first-served (FCFS) scheduling policy and is implemented by means of FDL's with reflection.

In the proposed buffer architecture, when the packet arrives, it will be sent to the output node but if all output nodes are busy then it will be placed back in the first loop of the FDL having a delay of $D_{1,}$ after completion of the delay the packet competes for output port, failing this it will again be reflected back into the second delay of D_2 and so on. The maximum delays that can be provided by using FDL's are assumed to have different values of delay such as a constant, arithmetic or a geometric progressive delay.

The flow chart for the packet servicing algorithm involving multiple delays in the proposed node architecture is presented in fig. 3.2. Obviously as a packet arrives at the node and the server is idle it is served immediately but these are queued if the server is busy. Usually the delays are kept finite by means of the FDL's, due to the limited time resolution related to the granularity and the new packet is going to be delayed at least by an amount of D for one loop circulation. Also it is not possible to make the packet to reflect infinite number of times due to loss of energy at each reflection and hence is limited by accepted SNR.

Thus the packet is dropped after K reflections, which is modeled in terms of acceptable quality q and reflection loss α as a function of $log\ (q\text{-}\alpha)$. Considering the evolution of buffer contents over time, we can identify three important variables viz. order of bursts arrival, the packet inter arrival time (IAT) having Poisson distributed (T_k) and the intermittent time between the kth arrival and the next one.

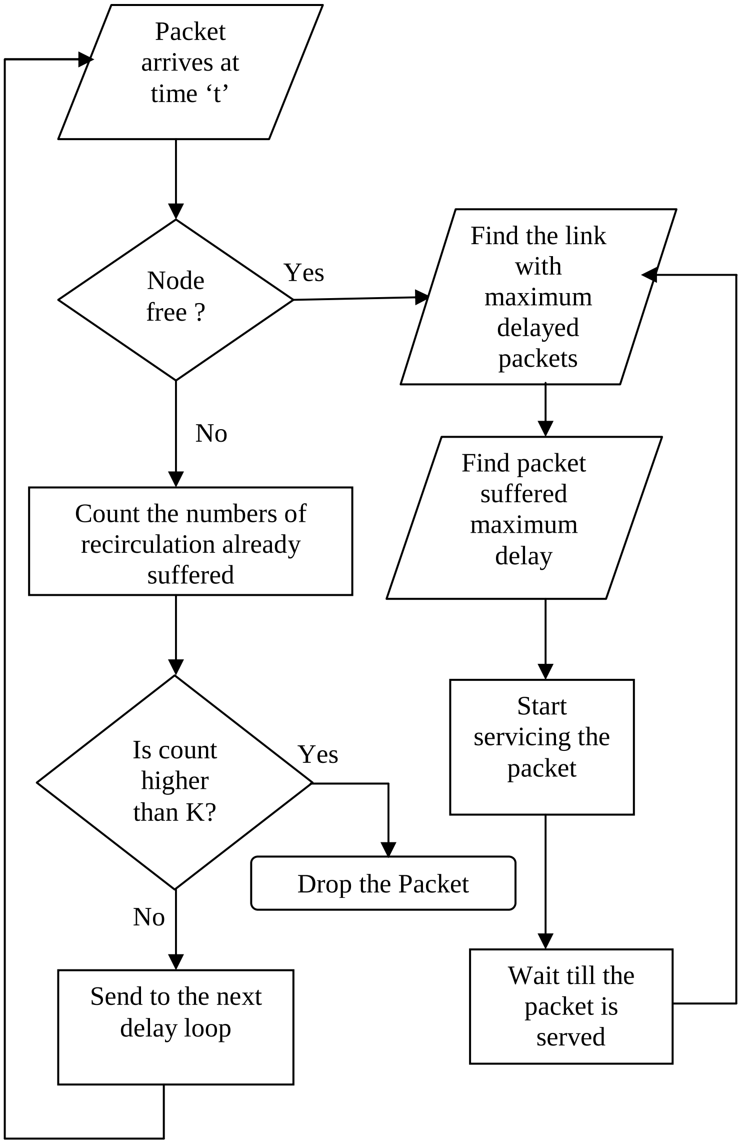


Fig. 3.2: Flow Chart for Node Performance Analysis

This system is modeled for a random input, having an exponential service with N sources, an infinite number of prospective customers and a maximum queue length of L. System probability for jth call is expressed in term of packet arrival rate λ and packet length t_m as:

$$P_j(A) = P_0(A)\frac{A^j}{j!} \quad for \quad 0 \le j \le N \tag{3.1}$$

$$P_j(A) = P_0(A)\frac{A^j}{N!\,N^{j-N}} \quad for \quad N \le j \le N+L \tag{3.2}$$

Where $P_0(A)$ is used to make the sum of P's to unity assuming A as λt_m. Further $P_0(A)$ can be written as:

$$P_0(A) = \left[\sum_{j=0}^{N}\frac{A^j}{j!} + \frac{A^N}{N!}\sum_{j=1}^{L}\frac{A^j}{N^j}\right]^{-1} \tag{3.3}$$

In the proposed algorithm an incoming packet will be blocked if all the servers are busy & queue is full. However the packet will be delayed if the servers are busy but queue is not completely full. The probability that *(N+L)* incoming packet is delayed can be written as

$$P_1 = \sum_{j=N}^{N+L-1} P_j(A) \tag{3.4}$$

Further a packet will be serviced immediately if there are less than *N* packets in the system and the probability of immediate service of packet is expressed as

$$P_{IS} = \sum_{j=0}^{N-1} P_j(A) \tag{3.5}$$

The waiting time distribution for the incoming traffic can be expressed using the standard equation [Allen 1990] as

$$P = P_N(A)\sum_{j=0}^{L-1}\frac{\rho^j}{j!}\int_{Nt/t_m}^{\alpha} x^j e^{-x}\,dx \tag{3.6}$$

This dictates the probability that an arriving packet will be delayed more than t before getting serviced.

In our model this delay is in discrete amount i.e. *D*. After giving delay *D* it is checked whether a server is idle. If not than that packet is given a further delay *D*. This sequence is repeated until the packet has been serviced or it has been a delayed k time which is the maximum number of times it can be sent in FDL. This parameter depends on the loss properties of the fiber because as we send a packet in a FDL it losses some of its power. So in successive repetition its power reduces & there is some minimum power which is necessary in the packet to transmit it.

The model analysis is as follows:

(i) At the first node there are three events that can occur: immediate service, dropping and Delaying. There corresponding probabilities can be calculated from the above mentioned equations.

(ii) At the second node there is only two possibilities servicing or further delaying. Now probability that a packet will get serviced after *D* is equal to 1 minus probability that it will have to wait more than *t* before getting service. Similarly after successive *i* such iteration probability that it will get service is

$$P\text{ (service after k iteration)} = 1 - P(>iD)$$

(iii) At the i_{th} stage probability that this packet will be delayed further is

$$P\text{ (further delay after i iteration)} = P(>iD)$$

(iv) At the last stage i.e. at $i=k$ if it is not getting service than it will be dropped i.e. probability that after going into FDL k times A packet is dropped is

$$P\text{(dropping after k iteration)} = P(>kD)$$

(v) Probability of service after kD delay is

$$P\text{(service after kD delay)} = 1 - P(>kD)$$

Average Delay Analysis

Since in this model a packet can experience delay in discrete amounts or in multiples of *D*. So average delay calculation can be carried out based on weighted average of the delay *D*

$$Average \quad Delay = \frac{\sum_{i=0}^{k} iD[1 - P(> iD)]}{\sum_{i=0}^{k} [1 - P(> iD)]} \tag{3.7}$$

These equations have been used in throughput simulation in the MATLAB environment under the appropriate node and traffic assumptions.

3.3.1 Simulation and Results

Traffic throughput of the offered traffic that gets processed through the node has been estimated under various node design parameter constraints. This traffic has been evaluated using equations (3.2-3.6) for the proposed node operated under traffic resolution algorithm.

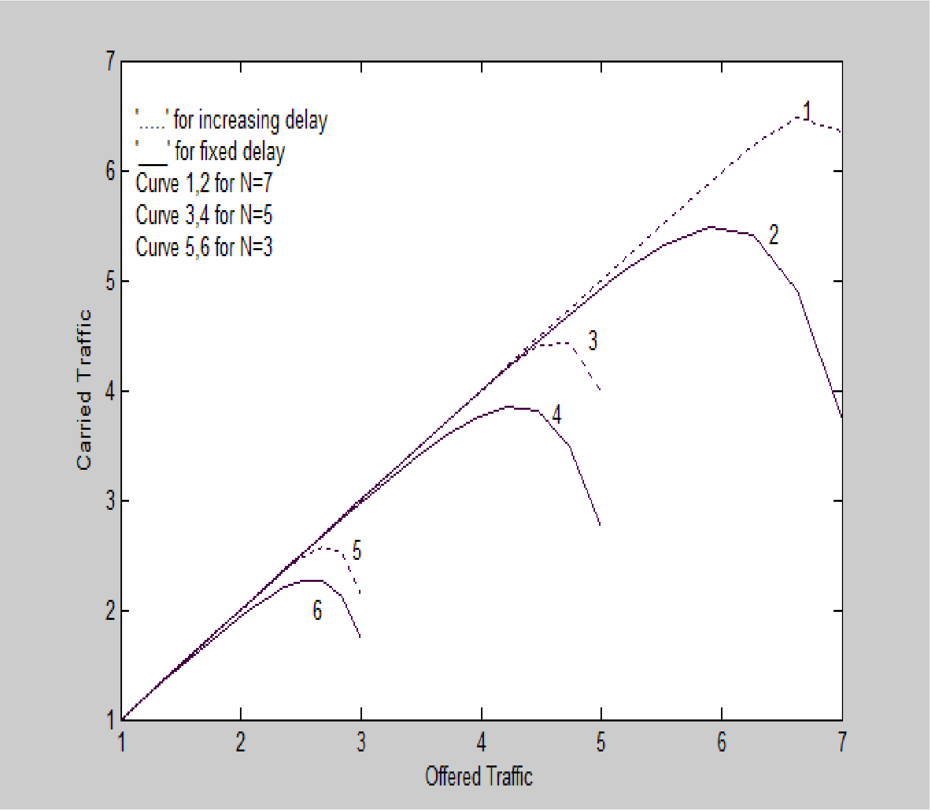


Fig.3.3 Plot of Carried Traffic vs Offered Traffic for different values of 'N'

Fig 3.3 presents the carried traffic corresponding to incoming offered traffic with the variation of number of delay lines (*N*) involved. The simulated curve shows a linear dependence of the carried traffic on the offered traffic only upto a specific input load but beyond that it deteriorates owing to the rise in the blocking probability. Moreover increased incoming traffic results a crowded node forcing to reject the excess traffic. This qualitative behavior is also supported by the simulation curve showing a rejection beyond a critical offered traffic.

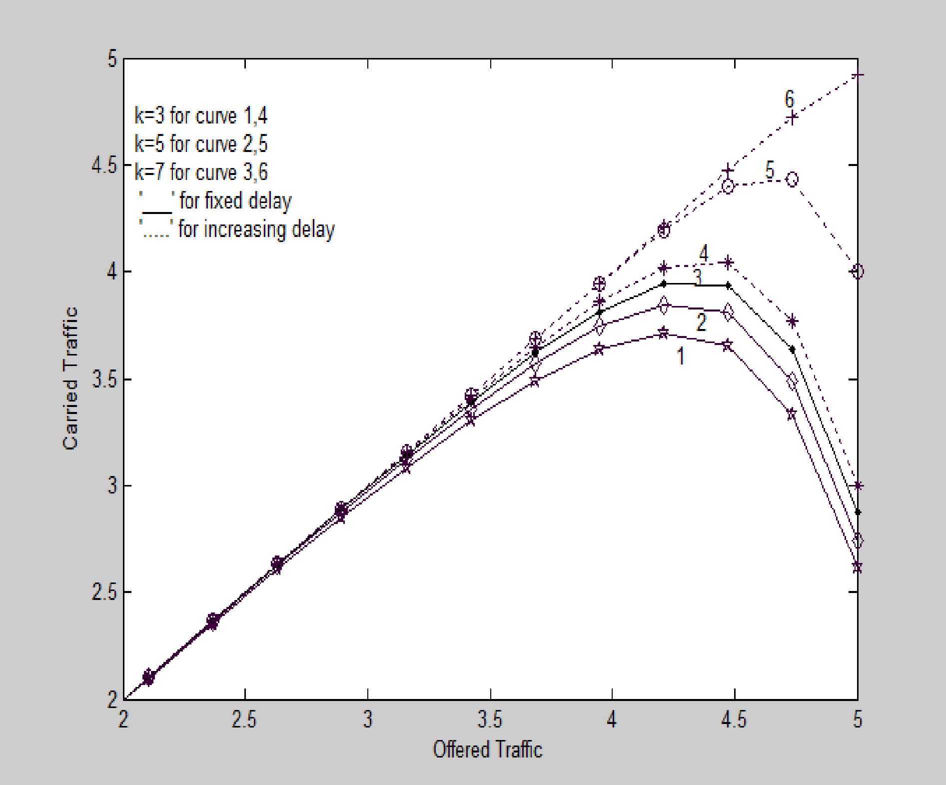


Fig.3.4: Carried traffic vs Offered traffic for different values of 'k'

The fig. 3.4 reveals better throughput is available if the delay is varied for different passes instead of keeping it constant for all passes. Basically if the delay is increased in every recirculation by a certain amount then it requires less number of recirculation comparing the fixed delay case to achieve a same particular amount of delay. As we have already discussed that recirculation of optical signal in the fiber delay line causes attenuation of signal power, insertion of different noises which ultimately affects the throughput of the network so it is better to have less number of recirculation to achieve better output. It may also be inferred from fig. 3.4 that the region of offered traffic for which the throughput is very high or the length of the high throughput region is greater in case of fixed delay network comparing to the variable delay system.

The fig. 3.5 depicts that, as the holding time increases the throughput decreases for all types of delay systems. Holding time corresponds to the processing speed and it increases for slower processing speed. Delay line will provide an amount of delay to the signals which are in the queue of getting served. Fast servicing will provide lesser processing time which in turn reduces the number of recirculation in the delay loop. From fig. 3.5 it is also seen that the spreading of the linear region is greater in case of fixed delay loop comparing to the variable delay loop.

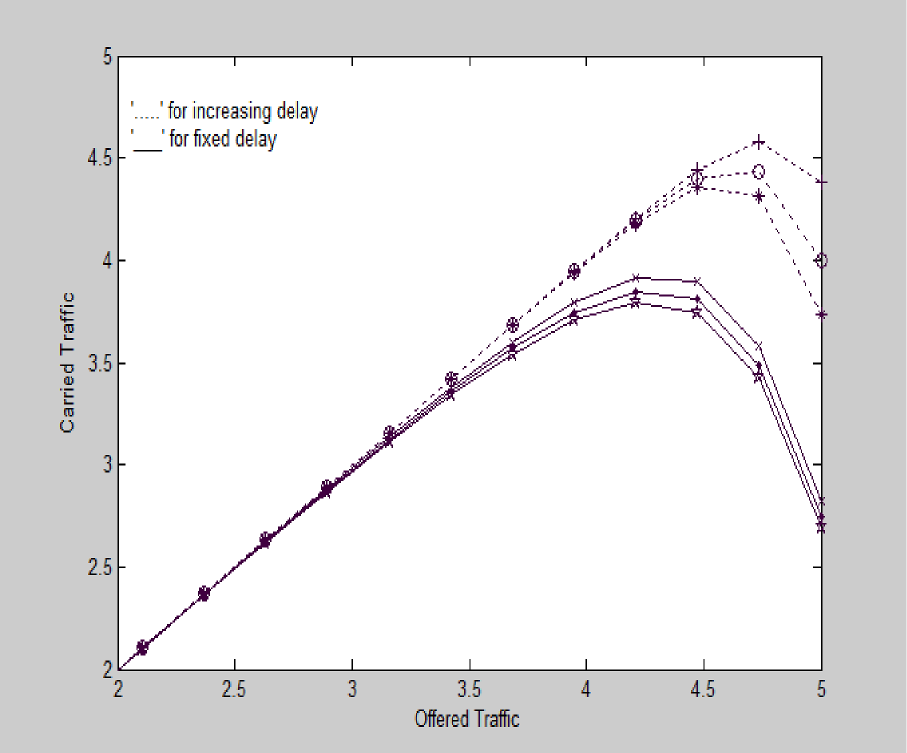


Fig 3.5: Plot of Carried Traffic vs Offered Traffic for different values of holding time

The analysis has been made more general by including a geometrical progressing delay loop in addition to arithmetic progressive and constant delay lines. The corresponding throughputs have been presented in fig 3.6. The fig reveals that the throughput improves as the delay increases which is expected but the increment of throughput will sustain upto a certain value of incoming traffic, after which the output decreases, means the packets which are coming further are being completely rejected.

From fig.3.6 we can also infer that the insertion of more delay in the loop will increase the cost and complexity of the system as well and it is tolerable upto a certain limit. Thus this investigation will help the network designer to take a decision on the possible maximum throughput and the complexity of node architecture design.

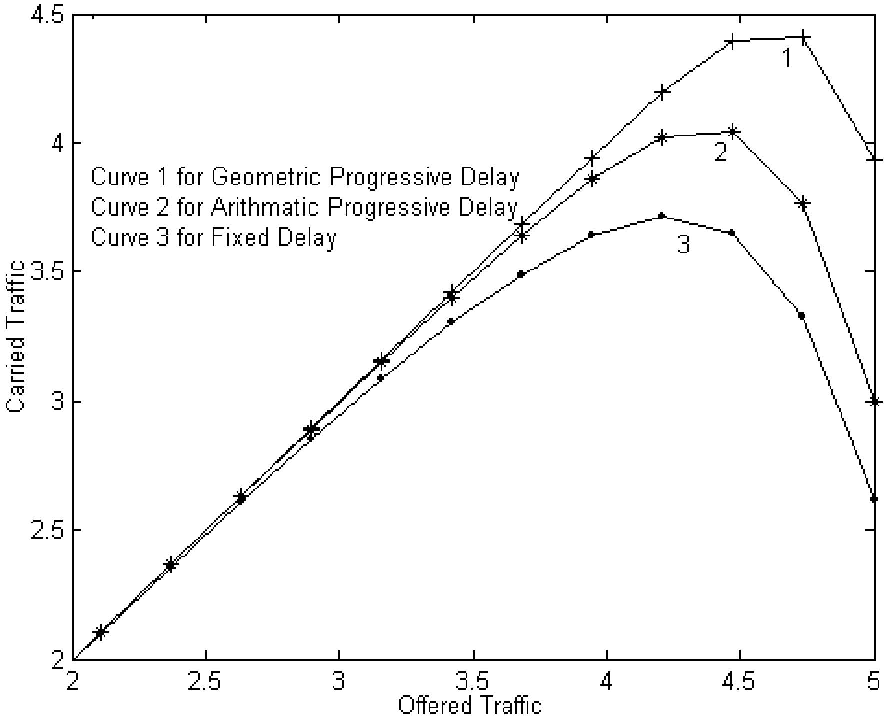


Fig.3.6: Plot of Carried Traffic vs Offered Traffic for different types of delay

3.4 Burst Switching Model and Analysis

In optical burst switching (OBS) networks, the payload is configured in the form of data bursts and kept in the optical domain. Each optical burst has an associated control packet (CP). CP is sent in a separate control channel and processed electronically in order to schedule a pending data burst to an output port [Qiao 1999] The scheduling algorithm may be first-fit (FF), latest available unscheduled channel (LAUC), first-fit with void filling

(FFVF) or latest available unscheduled channel with void filling (LAUC-VF) [Xu 2003]. They differ in bandwidth utilization and computational complexity. Another key characteristic is that OBS uses one-way reservation, i.e., an optical data burst (DB) starts transmission with an offset period after the control packet is sent, without waiting for positive acknowledgement of the end-to-end path setup. Due to the one way reservation mechanism, burst contention resolution is very important to improve network performance. In general, burst loss can be categorized into two types in OBS networks: (a) control packet loss; a control packet may be lost on the route or control packet congestion may occur in the outgoing control channel or inside the control packet processor; (b) congestion occurs in the output port of data channels. Most existing research focus on the second type of loss and assume there is no control packet loss or congestion. To resolve this type of burst loss, three major options can be applied (i) wavelength domain, in which a node with wavelength conversion capability is considered [Ramamirtham 2003] (ii) space domain, in which a contending data burst can be sent along a different route to the destination using deflection routing [Chen 2003] (iii) time domain, in which burst segmentation drops the contending portion of the data burst to improve the bandwidth utilization [Detti 2002] [Vokkarane 2002] [Vokkarane 2003]. Another time domain solution is to use FDLs to delay the arrival of data bursts in order to resolve contention. Here, we focus on using FDLs to resolve burst contention in OBS networks. Although optical buffers are not mandatory in OBS networks, some studies have shown limited FDLs in OBS networks can effectively improve the network performance [Yoo 2000a] [Lu 2004] [Tan 2003] [Xiong 2000]. In [Qiao 1999] [Yoo 2000], FDLs are used to improve the extended offset- time based Quality of service (QoS) scheme. Rather than considering FDL one by one [Xu 2003] partitions FDLs into groups and simplifies the scheduling algorithms [Lu 2004] develop analytical models to evaluate the performance of a single node with FDLs. In [Tan 2003] burst rescheduling is proposed in which a simple nonvoid filling scheduling algorithm is used to achieve performance comparable to the more complex void-filling algorithm. At the same time, FDLs are used to reschedule bursts to resolve burst contentions. However, FDL assignment is limited to bursts which traverse the last hop. In all existing research mentioned above, each node is assumed to have enough FDLs to provide burst contention resolution and there is no contentions in FDLs. Xiong in [Xiong 2000] illustrates another possible node structure with FDLs, but it only shows the impact of the maximum FDL delay on the network performance.

3.4.1 Node with Short FDL Model

We formulate a model to characterize the performance of an optical burst switching architecture employing FDLs; we assume that the destination output port of a given arriving burst is uniformly distributed. Thus, it suffices to model the behavior of a typical output port of the optical switching matrix. Each output port consists of k wavelength channels. Thus, each physical FDL can provide up to k virtual buffers, one corresponding to each wavelength. We shall assume that the total number of virtual buffers is given by $m=kF$. The JET signaling protocol and the LAUC scheduling algorithm are used to schedule DBs for transmission on outgoing wavelength channels [Chaubey 2009] [Dutta 2011].

Bursts are assumed to arrive according to a Poisson process with a mean rate of λ bursts/second. The duration of a DB is an exponentially distributed random variable. We shall further assume that the variable-delay FDLs are employed and are capable of providing any real-valued delay in the range *0 to T*. The base offset time between the BHP and DB is assumed to be constant among all bursts. Under these last two assumptions, the LAUC and LAUC-VF scheduling algorithms are equivalent.

In the regime of short FDLs, i.e., $T \approx 0$, it is more likely for a burst to be blocked, because the waiting time W is greater than T, than for the burst to be blocked because there are not enough available FDLs. Here we will assume that an FDL is always available when it is needed. In this context, an incoming burst arriving at time can enter a wavelength in an FDL if there is at least one wavelength available, and the waiting time of this burst is less than T; otherwise, the burst is blocked. Let λ_i and μ_i , $i \geq 0$, be the burst-generation rate and the burst-service rate, respectively, when the system state is i . If k be the wavelengths available at the output port then for $i<k$ there is no burst loss, since in this case, the incoming DB can always find an idle channel to carry it. However, under the LAUC scheduling algorithm, when all channels are busy, i.e. $i \geq k$, a burst is lost if the earliest available time of all wavelengths is greater than $t+T$. Let us also assume that the burst is lost if the number of service

completions within the time duration *T* is less than *i-k+1*. Let P_{bi} be the burst-loss probability when the system is in state *i*.

Then we have

$$\lambda_i=\lambda(1- P_{bi}). \tag{3.8}$$

Clearly $P_{bi} =0$, for $i<k$. For $i\geq k$, the probability of no loss in state *i*, $(1- P_{bi})$ is equal to the probability that there are at least *(i-k+1)* service completions within time. Thus, we have

$$\begin{aligned} P_{bi} &= 1 - P_r[i-k+1] \\ &= 1 - \int_0^T e^{-k\mu x} k\mu \frac{(k\mu x)^{(i-k)}}{(i-k)!} dx \\ &= 1 - \sum_{j=0}^{i-k} e^{-k\mu T} \frac{(k\mu T)^j}{j!} \end{aligned} \tag{3.9}$$

If we define,

$$\Pi_0 = [1 + \sum_{j=0}^{\alpha} \prod_{i=0}^{j-1} \frac{\lambda_i}{\mu_i - 1}]^{-1} \tag{3.10}$$

$$\Pi_i = \Pi_0 (\prod_{j=0}^{i-1} \frac{\lambda_j}{\mu_j + 1}),\ i \geq 1 \tag{3.11}$$

$$P_{bs} = \sum_{j=k}^{\infty} \Pi_j [1 - \sum_{j=0}^{i-k} e^{-k\mu T} \frac{(k\mu T)^j}{j!}] \tag{3.12}$$

3.4.2 Node with Long FDL Model

In the regime of long FDLs, i.e., *T››0*, it is more likely for a burst to be blocked due to lack of available FDLs than for the burst to be blocked because the waiting time *W* is greater than *T*.

In case of long FDLs, each virtual buffer can provide any delay that might be required in order to schedule an incoming DB. Since there are k wavelength channels and $m=kF$ virtual buffers, the buffer behavior can be approximated by an M/M/k/k+m queuing model. This is precisely the approximate model for FDLs proposed earlier in [Turner 1999] [Yao 2003]. Using the M/M/k/k+m model, the burst-loss probability in the regime of long FDLs is given approximately by

$$P_{bl} = \frac{\dfrac{\rho^{k+m}}{k^{m}}.k!}{\sum_{j=0}^{k-1} \dfrac{r^{j}}{j!} + \sum_{j=k}^{k+m} \dfrac{\rho^{j}}{k^{j-k}.k!}} \tag{3.13}$$

where $r= k\mu T$

Overall burst loss probability is

$$P_b = \sum_{j=k}^{\alpha} \prod_j P_{bj} + \frac{\dfrac{\rho^{k+m}}{k^{m}}.k!}{\sum_{j=0}^{k-1} \dfrac{r^{j}}{j!} + \sum_{j=k}^{k+m} \dfrac{\rho^{j}}{k^{j-k}.k!}} \tag{3.14}$$

3.4.3 Node with Non-ideal FDL

The packets are considered to arrive at the node in Poisson process with an average arrival rate of 'λ' packets per second having average packet duration of 'τ_p' seconds to provide traffic intensity ρ as $\lambda\tau_p$. The blocking probability of a WDM node changes with the processing speed of the node (μ_n), process variable (n), and other node parameters like α which is defined as processing factor for the node which takes into account non-idealities in nodes, fibers and the bandwidth loss caused by different protocols. It may be assumed as unity for an ideal system when node parameters are not affecting the traffic throughput but is always less than one for a real system. The blocking probability increases with node delay

(τ_D). Similarly the blocking increases with the increase in the traffic to cause a lower data throughput, however the throughput improves with the increase in the packet duration owing to enhanced probability of packet processing. We have assumed the process parameter dependence on τ_D as an exponential function as this varies from unity to zero with the delay variation from a negligible value to a large value. So considering all the above factors, the process variable n can be modeled with an exponential dependence on traffic intensity as

$$n = \exp(-(\frac{\tau_D}{\tau_P}) \rho) \tag{3.15}$$

A network is supposed to be transparent to the operating data rate, but the architectural design of the node limits the performance of the node from unity to a model parameter α. The ideality factor can be modeled in terms of bandwidth utilization factor (b), incoming data rate (R) and available bandwidth W by the following expression:

$$\alpha = \exp(- \frac{R}{W.b}) \tag{3.16}$$

The bandwidth utilization factor is well controlled by the burst propagation time (T_{Pro}), reservation mapping time (T_m) and the burst transmission time (τ_p). This can be expressed as: $b = \tau_p/(T_{Pro} + T_m + \tau_p)$. The ratio of average packet duration (τ_p) to average node delay (τ_D) is denoted by variable 'a'.

All the above factors are considered to find out the modified burst loss probability of the FDL's in OBS network.

3.4.4 Simulation and Result

Fig. 3.7 shows the simulation results for burst loss probability vs increasing traffic intensity under different values of available wavelengths (k) at the output port. The curves a & b represents the variation for $k=2$ and 4 respectively when the effect due to different node non-ideality factors are not considered. Curves c & d represents the same variation by considering the non-ideality factors for same k values. The result reveals two interesting facts that if the number of available wavelengths at the output port is increased then burst loss probability increases for both the cases. Secondly, if the different non-ideality factors are considered then the burst lossprobability variation is obtained more accurately for all values of *k*.

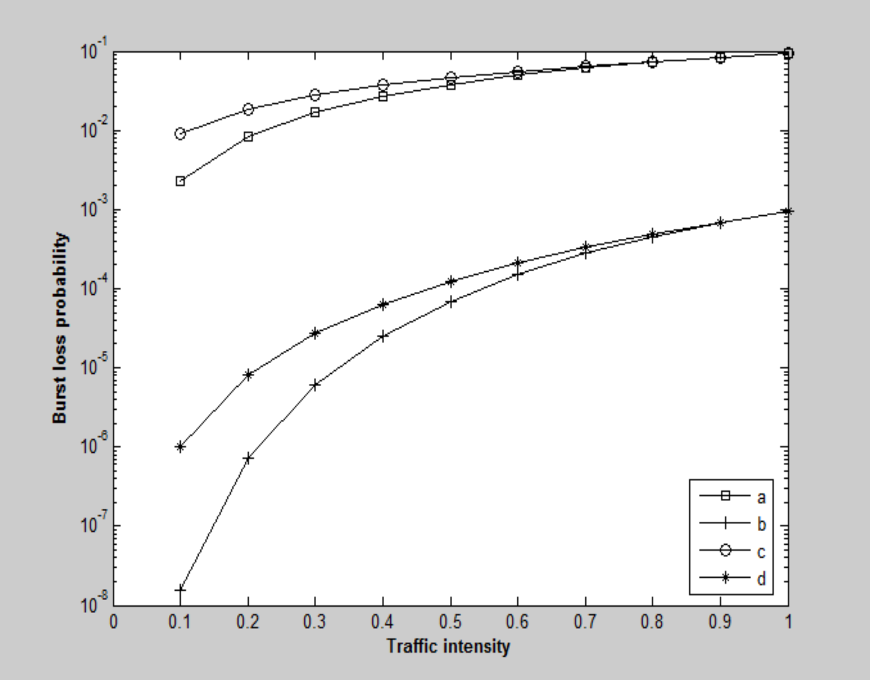


Fig. 3.7: Traffic intensity vs Burst loss Probability comparative plot for both considering(c,d) and not considering(a,b) practical parameters for different values of '*k*'

The burst loss probability is plotted for different values of variable '*a*' in fig. 3.8. We have simulated three cases by varying '*a*' from 0.5 to 1.5 as shown in the fig. It is interesting to note that the simulation curves are qualitatively similar with some quantitative difference due to system parameters difference. It may be inferred that the burst loss probability improves with '*a*' and this result is obvious because as the packet duration increases, the influence of the delay decreases and the processor improves the burst loss probability.

Fig. 3.9 represents the burst lossprobability variation for different values of *k*. The results infer that if the available wavelength at the output port increases the burst loss probability decreases sharply for all possible values of incoming traffic but the burst loss probability changes more sharply with the incoming traffic intensity for higher values of *k*.

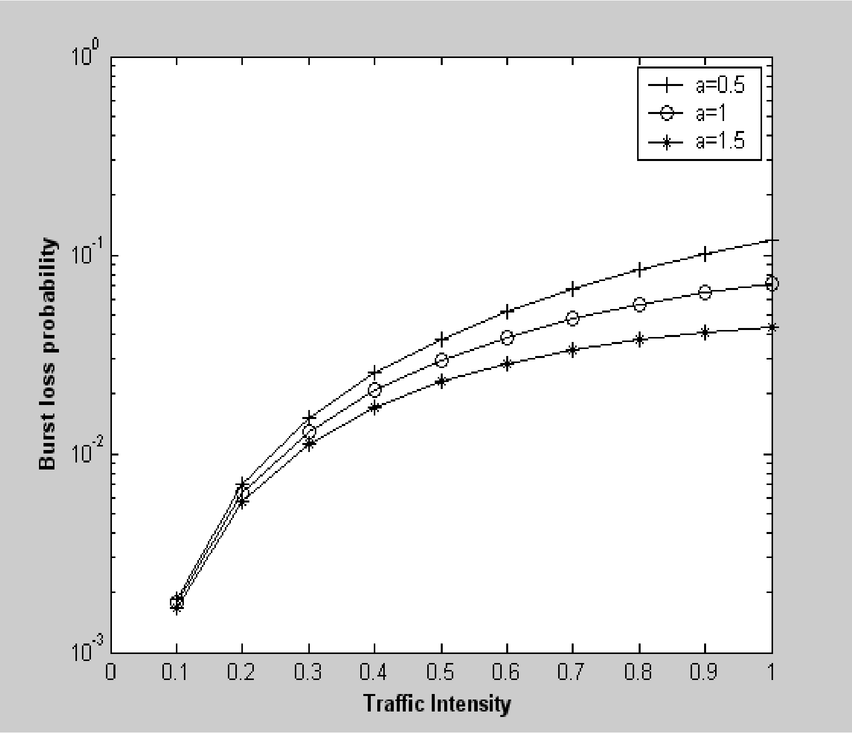


Fig.3.8: Traffic intensity vs Burst loss Probability plot for different values of ‘$a=(\tau_p/\tau_D)$’

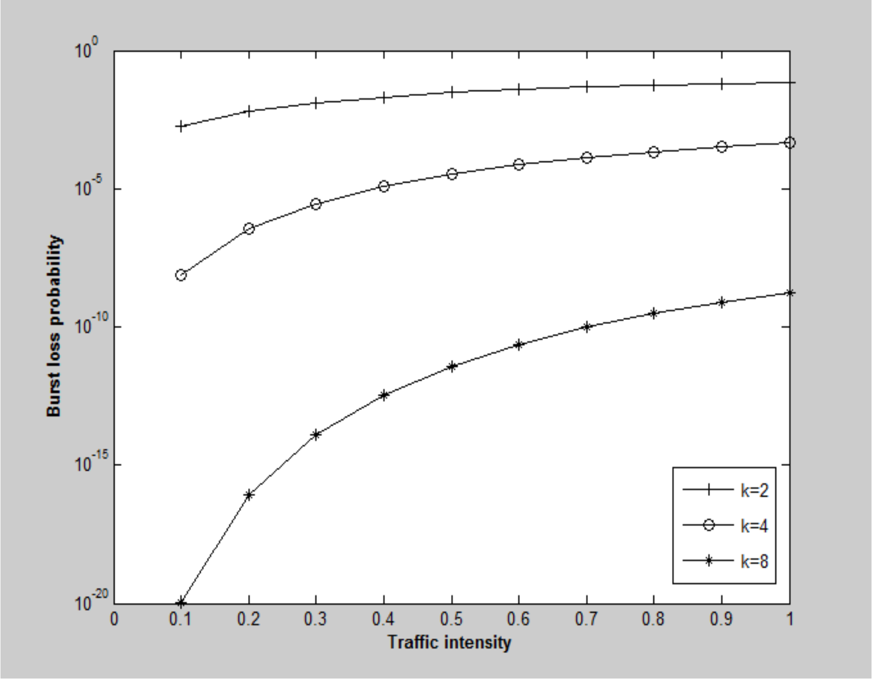


Fig. 3.9: Traffic intensity vs Burst loss Probability plot for different values of ‘*k*’

3.5 Modeling and Performance Analysis of FDL Based Optical WDM Node Architecture using SRR Protocol

In order to enhance the data transport capability and overall throughput of an optical wavelength length division multiplexed (WDM) system, a proper node architecture design is necessary. Limitations in the state-of-the-art optical networking technologies, in particular, the lack of optical random access memory, and the characteristics of the internet traffic, such as variable size packets, packet arrival burstness, non-uniform traffic distribution patterns, and volatile traffic patterns make the transport of internet traffic in WDM rings that perform OPS challenging. A ring is a shared medium for which geographically distributed nodes compete. Thus, a node can disturb the transmissions of other nodes. Moreover, because of ring symmetry, depending on the position in the ring some nodes may get better than-average access opportunities while some others may get worse-than-average access opportunities.

Medium access control (MAC) regulates access to shared media to provide nodes distributed geographically with efficient, fair access opportunities. The MAC function belongs to the data link layer in the traditional network layering models. There are many MAC protocols for packet switching ring networks. These protocols derive from the following media access techniques: token passing, time slotting, buffer insertion, and contention. A brief description of different protocols are given below.

Empty slot contention/collision avoidance (ESCA) [Chlam1995] is the MAC protocol designed for the Pipeline network. ESCA is a slotted ring with destination removal protocol, and it uses slot-synchronization across the channels. Request/Allocation protocol (RAP) [Summe 1997] [Frans 1998] is a contention-free slotted ring protocol designed to regulate access in the MAWSON (Metropolitan area wavelength-switched optical network) network . A source node that wishes to transmit to a particular destination node must request bandwidth from that destination explicitly. Only after an allocation confirmation returns, the source node can transmit.

Carrier sense multiple access with collision avoidance (CSMA/CA) [Shrik 2000b] is the MAC protocol developed for the HORNET (Hybrid opto-electronic ring network) network. There are two versions of CSMA/CA namely, slotted CSMA/CA with multiple slot sizes and unslotted CSMA/CA with back-off. The multitoken interarrival time (MTIT) protocol [Cai 2000] is designed to regulate access in single fibre, multi-channel ring networks consisting of nodes and a node can transmit and receive on all the data channels simultaneously.

In the present discussion a simple node architecture model based on medium access control protocols for bursty data traffic of variable time slot duration and data rate has been proposed to decrease the packet loss probability and to increase the efficiency of an optical WDM system. In this section an architectural model has been developed using synchronous round robin (SRR) protocol. Appropriate mathematical model has been derived to evaluate the performance of the proposed node architecture. It has been observed that the network performance is well controlled through implemented model and the corresponding network design parameters.

3.5.1 Synchronous Round-Robin (SRR) Protocol

Synchronous round robin (SRR) is an almost optimal collision-free access scheme for all-optical packet network based on WDM multi-channel ring topologies providing slotted channels for transmissions to disjoint subsets of destination nodes. Only a channel inspection capability and local status information are required at nodes in order to implement the access protocol.

Designed for networks that follow the tunable transmitter–fixed receiver (TT-FR) configuration, SRR builds on slotted ring with destination removal to provide random, collision-free access to the medium [Salvador 2003]. To achieve almost optimal access, SRR employs a global scheduling that, under heavy load traffic conditions, forces the behavior of the network to that of time division multiplexing access (TDMA) networks with static assignment of slots.

Let N be the number of network nodes and C be the number of wavelength channels. Assuming that N is an integer multiple of C, $D = N / C$ nodes share the same reception channel. Each channel can be divided into D logical partitions, each comprising $N / D = C$ adjacent nodes. The nodes are equally spaced and disposed within each partition in a sequence that reflects their reception channel. That is, the D nodes sharing the i-th reception channel, with $0 \leq i < C$, are in positions $| i + dC |_{N}$, with $0 \leq d < D$. Only the first node of a partition can receive and transmit on the channel associated to that partition; the others node can transmit, but not receive on that channel. Fig. 3.10 illustrates the SRR network topology of an eight-node, four channel ring. Fig. 3.11 illustrates the logical partitioning of channel 0, the reception channel assigned to node 0 and node 4.

As a consequence of ring symmetry, some nodes have better-than-average access to the ring, while some nodes have worse-than-average access to the ring. In other words, when transmitting to a node *j*, a node *i* has priority $|i - j|_N$, whereas 1 is the highest priority and N-1 is the lowest priority.

SRR uses virtual output queuing (VOQ) to avoid head-of-line (HOL) blocking. Each node maintains one queue per each possible destination node. In an arbitrary time slot identified by a label *s*, node *i* schedules for transmission the HOL packet from the queue destined to node $|i+k+1|_N$, where $k = | s |_{N-1}$. If the corresponding queue is empty, the scheduler attempts transmission of the longest queue's HOL packet. If two or more longest queues exist, the scheduler selects the lowest priority queue. In either case, transmission can occur only if the slot is empty.

Synchronous round robin (SRR) is an empty-slot MAC protocol for unidirectional WDM ring network with fixed size time slots and destination stripping. Each node is equipped with one tunable transmitter and one fixed-tuned receiver (TT-FR), where the transmitter is assumed to be tunable across all W wavelengths on a per-slot basis. If $N = C$ each node has its own home wavelength channel for reception. In case of $N > C$, each wavelength is shared by multiple destination nodes.

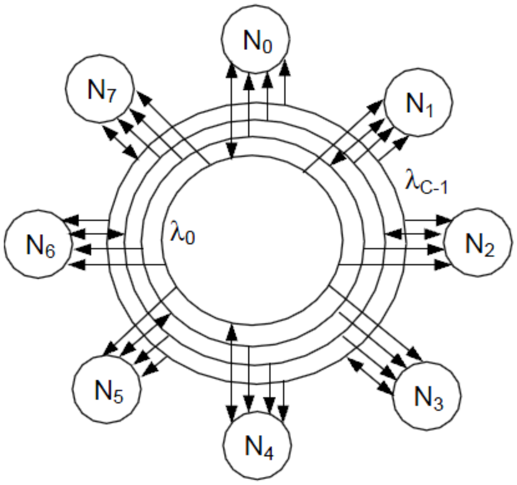


Fig. 3.10: Network Topology

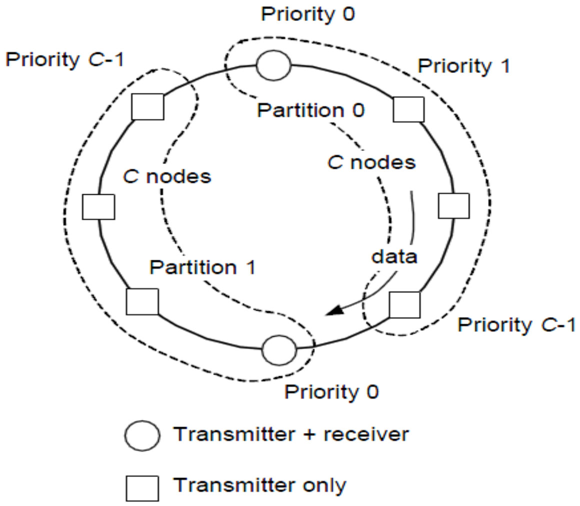


Fig.3.11 Logical Partitioning

For uniform traffic, SRR asymptotically achieves a bandwidth utilization of 100 %. However, presence of unbalanced traffic leads to wasted bandwidth due to nonzero probability that a priori access strategy selects a wavelength channel whose slot is occupied while leaving free slots unused. Posteriori access strategies avoid this drawback, resulting in an improved throughput-delay performance at the expense of an increased complexity. SRR achieves good performance requiring only local information on the backlog of VOQs, which also avoid the well-known head-of-line (HOL) blocking problem. On one hand, owing to destination stripping, slots can be spatially reused raises fairness control problems, particularly under non-uniform traffic. A node to which a large amount of slots is directed generates a large amount of free slots, and nodes immediately downstream are in a favorable position with respect to other nodes.

3.5.2 Model of the Proposed SRR Based Node Architecture

The proposed model for the SRR based node is shown in Fig. 3.12. The node is capable to upload the data traffic of a desired data rate on an available wavelength in a specified time slot to be decided by the used service protocol. In the model the encoder block may encode the tunable sources at a given data rate for the time stack of τ_p on the given wavelength (λ) as decided by the control circuitry. This node may encode data on a specific λ_1 by switching the respective tuned source in a specified time slot in accordance with the control algorithm. This combination may also implement the series data into a parallel data by encoding the incoming bits on λ_1 , λ_2 and λ_3 on alternate timeslots and using the delay lines and optical circulators all the λ_s time slots can be made parallel. Thus provides a scope of variable time stacking and data multiplexing.

In SRR, each node has *N-1* separate first-in / first-out (FIFO), virtual output queues (VOQs), one for each destination. SRR uses a priori access strategy. Specifically, each node cyclically scans the VOQs in a round-robin manner on a per-slot basis, looking for a packet to transmit. If such a deterministically selected VOQ is nonempty, the first (oldest) packet is transmitted provided the current slot was sensed to be empty. If the selected VOQ is empty the transmission of the first packet from the longest queue of remaining VOQs is sent, again provided the current slot is unused. In any case, if transmission in an occupied slot is not possible (because it would cause a channel collision), the next VOQ is selected for the transmission attempt in the subsequent slot according to round-robin scanning of SRR. In doing so, under heavy uniform load conditions when all VOQs are nonempty the SRR scheduling algorithm converges to a round-robin TDMA.

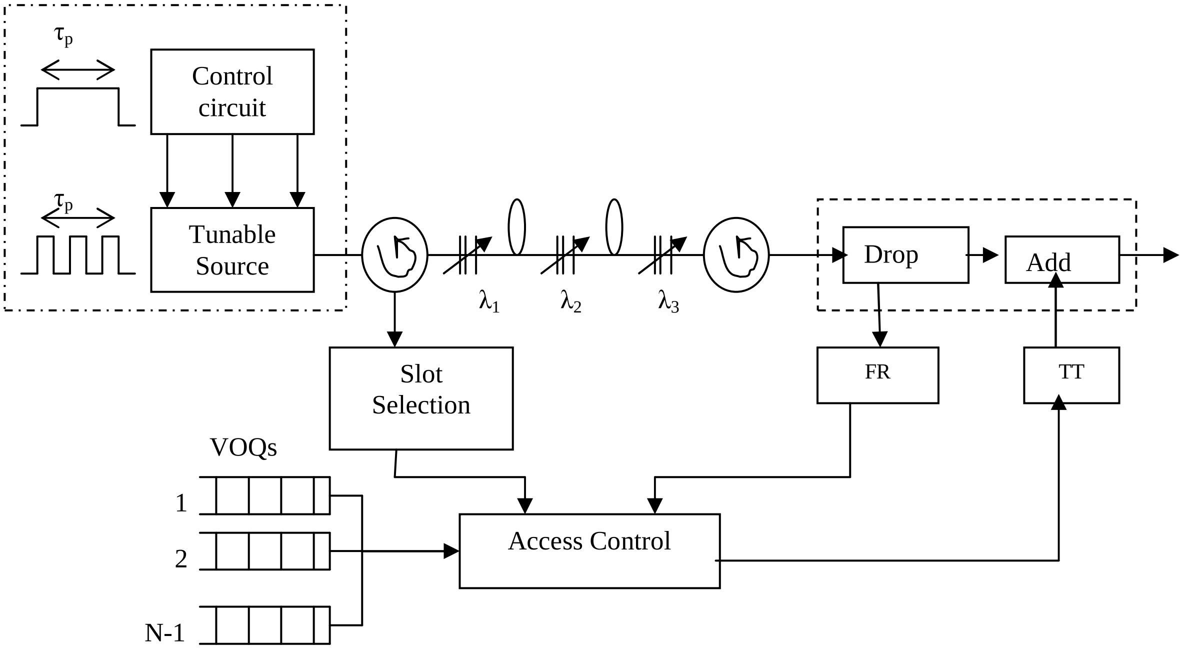


Fig. 3.12: Proposed Node Architecture Model

Obviously the node consisted of different intelligent programmable components such as optical add and drop multiplexer (OPADOM), fixed receiver (FR), tuned transmitter (TT). The cumulative loss, delay and processing time for the node can be modeled on the basis of characteristics of the used components and on the logic decision software and hardware capabilities. Thus the traffic throughput beyond the node may be linearly dependent to the arriving data rate until it is much below the node handling capacity but becomes a complex function of the node, traffic and network parameters. It is envisaged that a node with a maximum capacity C can loose a capacity C_T due to non idealities of the node system and the throughput remains linear for a traffic ρ lesser than the process- able capacity $(C-C_T)$ referred to as communicative capacity (*cc*) of the node. The packets are considered to arrive at the node in Poisson process with an average arrival rate of 'λ' packets per second having average packet duration of 'τ_p' seconds to provide traffic intensity ρ as $\lambda\tau_p$.

The differential throughput with respect to the differential change in arriving traffic $(\frac{dT}{d\rho})$ for a WDM node increases with the processing speed of the node (μ_n). This can be modeled in terms of process variable (n), available capacity of the node ($cc - \rho$) and other node parameters to result in a expression given as:

$$\frac{dT}{d\rho} = \mu_n \alpha n (C - C_T - \rho) \tag{3.17}$$

Here α is defined as processing factor for the node which takes into account non-idealities in nodes, fibers and the bandwidth loss caused by different protocols. It may be assumed as unity for an ideal system when node parameters are not affecting the traffic throughput but is always less than one for a real system. The throughput decreases with node delay (τ_D) as more the delay lesser the number of packets processed. Similarly the blocking increases with the increase in the traffic to cause a lower data throughput, however the throughput improves with the increase in the packet duration owing to enhance probability of packet processing. We have assumed the process parameter dependence on τ_D as an exponential function as this varies from unity to zero with the delay variation from a negligible value to a large value. So considering all the above factors, the process variable n can be modeled with an exponential dependence on traffic intensity as

$$n = \exp(- (\frac{\tau_D}{\tau_P}) \rho) \tag{3.18}$$

From eqns.(3.17) and (3.18), we get

$$\frac{dT}{d\rho} = \mu_n \alpha \exp(-(\frac{\tau_D}{\tau_P}) \rho)(C - C_T - \rho) \tag{3.19}$$

The total throughput (T) at traffic ρ can be evaluated by integrating eqn. (3.19) and can be expressed as :

$$T = \mu_n \alpha \int_0^{\rho'} \exp(-(\frac{\tau_D}{\tau_P})\rho)(C - C_T - \frac{\tau_P}{\tau_D}) d\rho \qquad (3.20)$$

Further simplification of eqn.(3.20) yields the expression for total throughput (T) beyond the processing node:

$$T = \mu_n \alpha \frac{\tau_P}{\tau_D} \{[1 - \exp(-(\frac{\tau_D}{\tau_P})\rho)](C - C_T - \frac{\tau_P}{\tau_D}) + \rho \exp(-(\frac{\tau_D}{\tau_P})\rho)\} \qquad (3.21)$$

Now the above equations can be used in throughput simulation in the MATLAB environment under the appropriate node and traffic assumptions.

3.5.3 Simulations and Results

The simulations are carried out for a general optical network node configuration for a generic traffic with a specific node architecture having a fixed node-processing factor. In the present architecture each of the subsystem can be properly modeled to evaluate the system delay for estimation of node throughput for a given data time slot. Thus we can investigate the influence of time slot duration over data throughput across a node for a given normalized node capacity. Firstly we evaluate these performances in Case 1 and then may proceed to test the node for a given traffic under the provision of varying capacity as discussed in Case 2.

Case 1: The throughput is plotted for different values of the ratio average packet duration to average node delay $(\frac{\tau_P}{\tau_D})$, denoted by variable '*a*,' while keeping the capacity of the system a constant at a normalized unit of communicative capacity (*cc*) as unity. We can simulate four cases by varying '*a*' from 0.2 to 2.0 as shown in Fig. 3.13.

It is interesting to note that the simulation curves are qualitatively similar to the reported results but with some quantitative difference due to system parameters difference. Obviously as the packet duration increases, the influence of the delay decreases and the processor improves the throughput. It may be inferred that the node throughput improves with 'ρ' and thus requires a faster processor and this may be attributed to either the increase of packet duration or to the decrease of the node delay. These curves also reveal that a faster processor maintains a linear relation with the significant incoming traffic range; however this gets truncated to a lower speed or a value and opens a scope for a proper decision for a node designer.

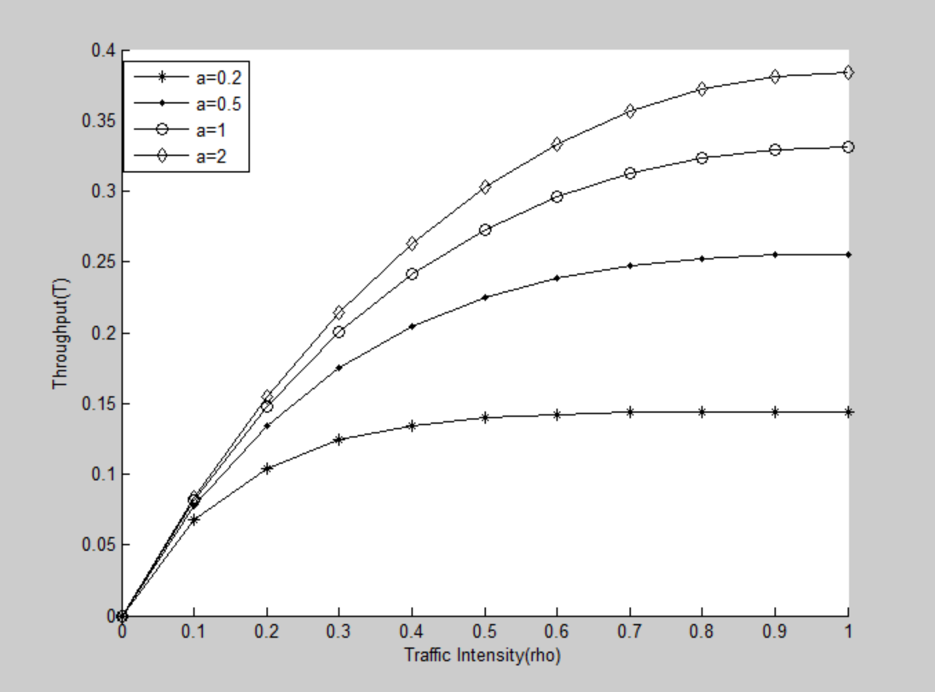


Fig.3.13: Throughput (T) vs Traffic Intensity (ρ) for different values of 'a=(τ_p/ τ_D)'

***Case* 2:** In the second case, the ratio '*a*' is kept a constant and throughput of the node is estimated for different values of available network capacity. In the present situation node performance is visualized for four different communicative capacities by keeping fixed time slot to node delay ratio. Fig. 3.14 shows the simulation results for throughput of the node with respect to increasing traffic under different values of *cc*. The general shape of the curve is as expected for a WDM node and shows a decrement in dynamic slope of the curve as the traffic intensity increases and ultimately saturates beyond a given traffic for a given *cc*.

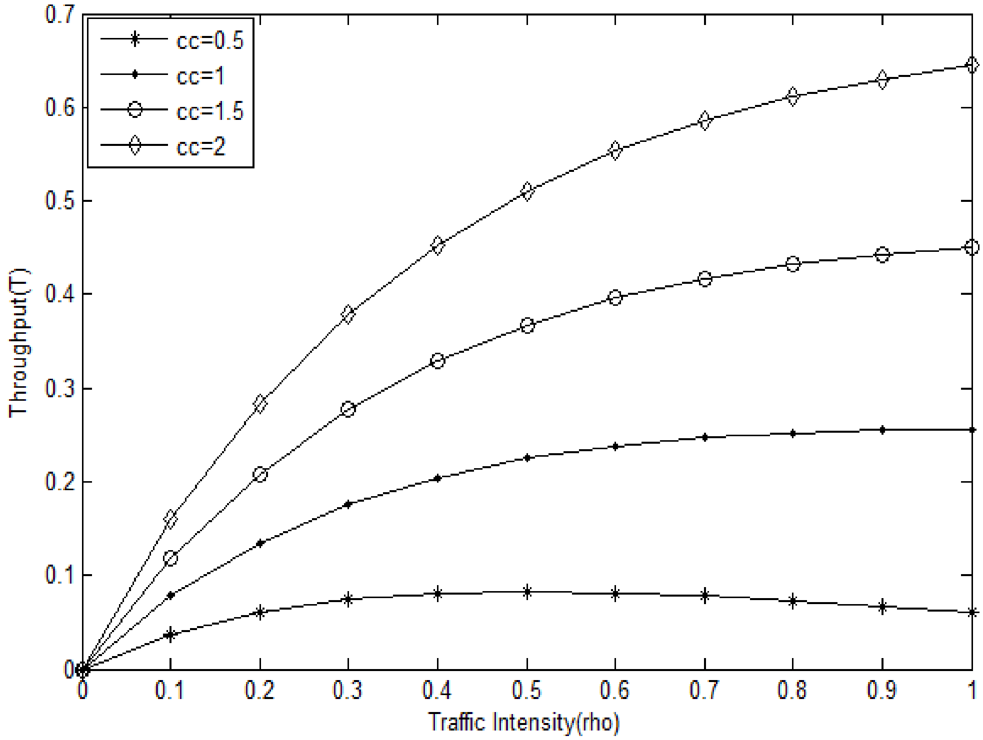


Fig.3.14: Throughput (*T*) vs Traffic intensity (ρ) for different values of ‘*cc*’

It may be noted that for a lower value of '*cc'* the node throughput increment is insignificant and reaches hardly upto 10% of the normalized traffic but this becomes significant upto nearly 65% as the capacity is enhanced to 2.0. Moreover the traffic throughput and traffic intensity relation is maintained for larger traffic range as the '*cc'* of the node is enhanced.

The inferences drawn from the above analysis may be used in traffic grooming and network management through proper resource utilization. The network delay and bandwidth utilization are prime resources to be carefully considered for a proper design.

3.6 Conclusion

Contention is a major problem in optical WDM networks for both switching paradigms like optical packet switching network (OPS) as well as in optical burst switching network (OBS).

In this chapter the possible solution for the problem of contention in packet switched WDM networks using recirculation optical delay lines has been dicsussed. The proposal is based on the priority to the packets which have suffered maximum delay on the link during processing under the proposed contention resolution algorithm.

There after an analytical approach has been proposed to evaluate the performance of an OBS network with FDLs. The analytical model and approximations yield important insights into the delay characteristics of OBS system performance over the entire range of FDL lengths, particularly in the regimes of short and long FDLs. The simulation results reveal that the use of FDLs can significantly reduce the burst-loss probability. An appropriate mathematical expression is also developed to incorporate the impact of different node non-ideality factors on FDL performances. Numerical results suggest that only a small number of unit FDL delays is needed to achieve the performance of the idealized variable-delay FDL.

The discussion has further been extended to investigate the performance of FDL based optical WDM node architecture using SRR protocol. The study is mainly focused on the architectural design and modeling of a WDM node architecture. A simple node architecture model based on media access control protocols for bursty data traffic of variable time slot duration and data rate has been proposed to decrease the packet loss probability. This approach enhances the efficiency of an optical WDM system using synchronous round robin protocol.

CHAPTER 4

WAVELENGTH DOMAIN CONTENTION RESOLUTION: WAVELENGTH CONVERTERS

4.1 Introduction

In Wavelength division multiplexing (WDM) [Brackett 1990] technique multiple independent channels are multiplexed to accommodate dissimilar data formats, including some analog and some digital, within certain limits. Thus, WDM utilizes the huge bandwidth (~50 THz) of a single-mode optical fiber and at the same time maintains the routing capability for respective destinations based on applied routing protocols. The use of wavelengths to route data is referred to as *wavelength routing*, and a network which employs this technique is known as a *wavelength-routed* network [Mukherjee 1997]. Such a wavelength routed network consists of wavelength-routing switches (or routing nodes) which are capable to interconnect different optical fibers to route the network traffic through the assigned light path between source & destination. Some routing nodes (referred to as crossconnects) are attached to access stations where data from several end-users could be multiplexed on to a single fiber. An access station also provides optical-to-electronic (O/E) conversion and *vice versa* to interface the optical network with conventional electronic equipment. A wavelength-routed network which carries data from one access station to another without any intermediate O/E conversion is referred to as an *all-optical* wavelength-routed network. In an all optical network, signals remain in the optical domain from the source to the destination, thereby eliminating the electro-optic bottleneck. While this approach allows information transfer rates to approach those allowed by optical devices, and significantly beyond the rates possible in an electronic network, it also introduces several challenges in the network design. Two popular architectures have been evolved as candidates for all-optical networks [Ramaswami 1993]. An attractive architecture for a local area network (LAN) with a small number of users is the *broadcast-and-select* network. Here, nodes are connected through an passive broadcast star; thus, the signal transmitted by any node is received by all nodes. Since all connections use a single optical hop, routing, management, and control of such connections admit relatively simple solutions. The broadcast-and-select architecture is inadequate for a wide area network (WAN) due to power budget limitations and lack of wavelength reuse. Both of these weaknesses can be remedied by the introduction of suitable wavelength routing algorithms supported by appropriate hardware switches. Such all-optical wavelength-routed networks have been proposed for building large wide-area networks [Bracket 1993]. In order to transfer data from one access station to another, a connection needs to be set up at the optical layer similar to the case in a circuit-switched telephone network. This operation is performed by determining a path (route) in the network connecting the source station to the destination station and by allocating a common free (or idle) wavelength on all of the fiber links in the path. Such an all-optical path is referred to as a *lightpath* or a *clear channel*. The entire bandwidth available on this lightpath is allocated to the connection during its holding time and at that time the corresponding wavelength cannot be allocated to any other connection. When a connection is terminated, the associated lightpath is torn down, and the wavelength becomes idle once again on all of the links along the route and becomes available for further allotment to incoming traffic .

An optical network architecture that appears promising for wide area backbone networks (WANs) is the one based on the concept of wavelength routing. Wavelength routing is a form of circuit switching and it intends to combine the best features of optics and electronics to reroute the desired wavelength beyond the processing node controlled by electronic circuitry. Multicast network has the ability to transmit information from a single source node to multiple destination nodes. Many bandwidth intensive applications, such as worldwide web browsing, video conference, e-commerce, and video-on-demand services, require multicast services for efficiency purposes. Multicast has been extensively studied in the parallel processing and electronic networking community, and has received much attention in the optical networking community recently [Yang 1991] [Yang 1998] [Zhang 2000] [Yang 2000].

Development of WDM networks, require realization and implementation of WDM switching fabrics or switching network which comprises of photonic switches with *N* full-duplex ports.

Each of these ports of such switches can connect to any other without optical-electrical-optical (O/E/O) conversion [Qin 2002] [Ali 2000] [Pankaj 1999] [Tridandapani 1997]. These network switching and traffic managing switches include add-drop multiplexers (ADMs), routers, or cross-connects. These network components meet the requirements of traffic demand for multicast is increasing with many bandwidth-intensive applications [Zhou 2002] [Wang 2002] [Chen 2002]. A connection or a lightpath in a WDM switching network is an ordered pair of ports corresponding to transmission data from source to destination . Multicast communication involves transmitting information from one source port to multiple destination ports, and such a connection are referred as multicast connection. It is required that the optical switches with multicast light-splitting capability should be properly designed. In this chapter some study on multicast communication in WDM switched networks have been carried out to propose a node model based on wavelength conversion techniques.

The blocking performance of such wavelength routing WDM networks with dynamic traffic has received a considerable attention by the researchers [Barry 1996] [Kova 1996] [Birman 1996] [Subramaniam 1996] [Yates 1996] with a good emphasis on the inclusion of wavelength converters. Different degrees of wavelength conversion capabilities [Gerstel 1997] are reported in the literatures. Full wavelength conversion capability implies that any input wavelength may be converted to any other wavelength while the limited wavelength conversion indicates that each input wavelength may be converted to any of a specific set of wavelengths. Realistic wavelength converters demonstrated in laboratories to date are of limited conversion capablity . That is, low degree wavelength conversion is likely to be far easier to realize in practice than higher degree conversion [Gerstel 1997] [Tripathi 2000] [Sharma 2000] [Qin 2002].

A wavelength converter has conversion degree d $(1 \leq d \leq k)$ if an input wavelength can be converted to $d - 1$ different output wavelengths in addition to the input wavelength itself, where *'k'* is the number of fixed tuned optical receiver at each output port. Clearly, $d = 1$ is the case of no conversion, and $d = k$ is the case of full conversion. Obviously all optical full wavelength conversion is particularly difficult to implement [Green 2001], however the limited wavelength conversion is relatively easier to implement.

Although the benefit of using wavelength conversion is obvious since it reduces the blocking probability by eliminating or reducing of the *wavelength continuity constraint,* of for light path establishment. However the introduction of wavelength conversion to WDM switching node architecture will certainly increase its design complexity and cost. Therefore, it is important to establish the precise advantages offered by wavelength converters to improve the network performance. It is also necessary for network designers to determine the degree of wavelength conversion at the design stage for different types of applications, or QoS requirements.

4.2 Motivation and Related Work

A wavelength converter can change the wavelength of a transit circuit from any given incoming wavelength to an required outgoing wavelength. Wavelength convertibility resolve wavelengths conflicts of the lightpaths on a common link to reuse wavelengths thereby improving performance. It minimizes congestion in the links and supports higher loads. Extensive study of load in ring networks is available in [Gerstel 1998] [Gerstel 1997] [Gerstel 1997a] [Gerstel 1998a] [Ramaswami 1997]. Rerouting is much easier in the case of network nodes equipped with wavelength converters and it becomes robust to channel, link and node failures. The lower bound on the number of wavelengths required in a wavelength convertible network is reduced.

A review of the impact of wavelength conversion in WDM networks is presented in [Ramamurthy 1998] [Gerstel 1997a] have explored the maximum traffic load that can be supported , as a function of the amount of wavelength conversion provided in the network under a model where no blocking is allowed . Traffic is characterized by its maximum load L, which is the maximum number of light paths that can be presented on any link at any time. Wavelength conversion is characterized by the conversion degree d; $d=1$, corresponds to fixed; with $d=2$ each wavelength can be converted to two other wavelengths at node ; $d=W$, corresponds to full wavelength conversion, where W denotes the number of wavelengths on each link. For ring networks, a simple greedy approach supports lightpath request sets with load $L \leq [(W+1)/2]$ without wavelength conversion, $L \leq (W-1)$ with limited conversion and $L=W$ for full wavelength conversion in static lightpath establishment. In the dynamic lightpath establishment where light path requests arrive but never get deleted, supports lightpath request sets with load $L \leq [(W+2)/3]$ without wavelength conversion and $L \leq$

$[(W+d)/2]$ with d limited range conversion. In dynamic lightpath establishment with deletion of lightpaths, the load supported is much smaller. It cannot support a load greater than $L \leq [2W/ \log N]$ without conversion, and $\log L+4L \leq W$ *for* $d=3$, which is independent of N, where N is the number of nodes [Gerstel 1997b].

In [Lee 1993], an unconstrained routing algorithm with exhaustive wavelength search over the wavelength set is used to reduce the number of converters. Blocking probability is reduced with the use of wavelength converters, but the time complexity of the algorithm is O (n^4w^2), where n is the number of wavelength routers and w is the number of wavelengths per fiber link. A faster algorithm of time complexity for the same problem is developed in [Banerjee 1996]. In [Barry 1994] Barry et al.,derived a lower bound on the number of switching states in a circuit switched network with wavelength converters. In [Chan1994], each switching node in the network has a limited number of wavelength converters to resolve wavelength conflicts in multihop paths. Wavelength converters cause insignificant reduction in blocking probability at light loads where as at medium loads, the gain is significant. Alternate routing with random wavelength assignment [Hari 1997] with wavelength conversion reduces blocking probability.

Barry et al., [Barry 1996] investigated the impact of wavelength converters using a probabilistic model. Smaller path length, smaller switch size and larger interference length (the expected number of hops shared by two connections which share atleast one hop) reduce blocking probability. They conclude that minimizing the network diameter and employing the minimum hop routing are reasonable heuristics for network without wavelength routers for reducing the blocking probabilities. Path length is a key design parameter for networks without wavelength routers for reducing the blocking probabilities. Path length is a key design parameter for networks without wavelength converters. In order to keep blocking probability low, path length must be kept small since it is less likely to find a free wavelength on all the hops of a path with the increase in the number of hops, i.e., the number of interfering connections on a path tends to increase with the number of hops. Chlamtac et al., [Chalmtac 1996] proposed an efficient algorithm to optimally route lightpaths taking into consideration both the cost of using the wavelength on links and the cost of wavelength conversion.

In [Kovacevic 1996], an approximate analytical model for a static routing circuit switched network of arbitrary topology with and without converters is studied. The results show that benefits of wavelength converters are modest for the ring network while the gains are significant in a large mesh network. The wavelength converters are effective when the network load is low and when the number of wavelength is substantial. In an arbitrary dense WANs , the connectivity and the number of wavelengths are much more important that the availability of the wavelength converters.

Subramaniam et al., [Subramaniam 1996][Subramaniam 1996a] proposed a probabilistic model to estimate the performance of optical networks with sparse wavelength conversion. It has been shown that a small number of converters are sufficient to obtain a certain level of performance or that conversion does not offer a significant advantages. The benefits of conversion are dependent on the network load, the number of available wavelengths and the connectivity of the network. In a dense network, the effect of wavelength converters diminish and in a sparse network, calls do not mix well causing a load correction in successive links. In [Subramaniam 1997] , an attempt is made to study the effect of wavelength conversion under dynamic non-Poisson traffic input. The model predicts that traffic peakedness plays a critical role in determining the blocking performance and the wavelength conversion in insensitive to traffic peakedness over a large range. In [Gerstel 1997c] [Ramaswami 1997], the impact of limited wavelength conversion in WDM ring networks to support higher loads is examined. In [Gerstel 1997d] methods to recover from channel failures, link failures and node failures in a WDM ring network with limited wavelength conversion capabilities at the nodes is presented. Tripathis et al. [Triphathi 1999] have computed the approximate blocking probabilities in wavelength routed all-optical networks with limited range wavelength conversion. Bala et al., [Bala 1997] have examined the benefits of minimal wavelength converters in WDM rings. Wauters et al., [Wauters 1997] observed that there is a reduction blocking probability by partitioning the network with wavelength converters. An efficient algorithm for placement of wavelength converters in arbitrary topologies are developed in [Thiagrajan 1999].

Multifiber solution as an alternative to wavelength conversion is explored in [Jeong 1996]. The analysis is an extension of the work in [Barry 1996] In this approach, the number of fibers to be minimized are more important that the number of wavelengths. It is observed that mesh network has higher utilization than a ring or fully connected network. In [Yates 1996] [Sharma 1998], limited wavelength conversion based on FWM has been investigated. It assumes link load and wavelength independence. The conversion efficiency drops with the increasing range. In [Subramaniam 1998], placement of wavelength converters in a path under uniform and non-uniform loads has been investigated.

4.3 WDM Node Architecture with Wavelength Converter

In the present chapter an appropriate model of WDM optical network using wavelength converters [Barry 1996] has been developed to estimate its traffic servicing performance under Erlang-C traffic model. The particular situation considered here (shown in fig.4.1) can be described like, one access station A requests a session to station B over some path of a mesh network having H hops from A to B on this path. In such networks, each session requires a full wavelength of continuity along the chosen lightpath and in the present analysis and there are F available wavelengths . For simplicity, we assume that A and B are not currently active at the time of the session request (for instance, each station may only contain one light source). Therefore, there are no busy wavelengths on the access or exit fiber and, in particular, a session cannot enter the requested path at node $H + 1$. However, sessions may enter or exit the path at each of the first H intermediate nodes, provided that no two sessions on the same fiber use the same wavelength. Any session which uses at least one of the H fibers on any wavelength is termed an interfering session**.** With wavelength converters at every node, this is a conventional circuit-switched network. In this case, the request between A and B is blocked only if one of the H fibers is full, (a fiber is full when it is supporting F sessions on different wavelengths). Without any wavelength converters, the session must use the same wavelength on each hop of the path. Therefore, a request can be honored on this path only if there exists a free wavelength, i.e., a wavelength which is unused on each of the H fibers. Note that there is the possibility in such networks that requests will be blocked even if all links are supporting less than F sessions. For instance, suppose that $H=F$ and wavelength i is used on hop i only. Then each fiber along this path has only one active session but there is no wavelength available to the request [Barry 1996].

This model intends to follow a wavelength reservation protocol which facilitates reservation of a particular wavelength from the source node itself, thus annulling possibility of wavelength conversion. Though under heavy traffic conditions, it is difficult to always reserve a particular wavelength before packet transmission, this brings in the necessity for wavelength conversion. To cope up with such scenarios when there are no particular wavelength available at all nodes, we have considered a wavelength assignment scheme [Shimizu 2006]. This scheme uses a center wavelength for a long hops connection and edge wavelength for short hops connection, each connection request is assigned to wavelength according to its hop number. Evidently, the noise and delay introduced by multiple channels accumulate to deteriorate the SNR in multiplexed optical networks. Therefore, the objective should be to transfer information over an optical network with minimum number of wavelength conversions. In fact, the network performs satisfactorily below a number of wavelength conversions [Mukherjee 2004] [Dutta 2009]. Further, dispersion, attenuation and cross-talk characteristics of the multiplexed channels ensure that all the channels are not equally efficient. Legal and operational constraints also make the traffic distribution in the channels non-uniform. Even there is a specific band of wavelengths over which the transmission of packets is efficient. Moreover, practical wavelength converters also have few constraints.

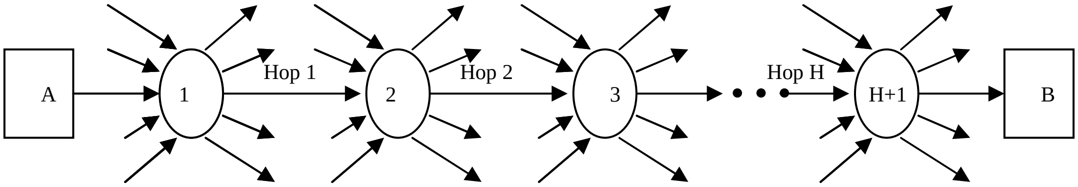


Fig.4.1: An H hop request

4.3.1. Mathematical Model

In order to evaluate the performance of the proposed WDM optical network we need to derive the probabilistic evaluation of the present WDM network contain *M* number of output channels. Erlang C formula is derived from assumption that a queue is used a queue is used to hold all request calls which cannot be immediately assigned a channel. The Erlang C formula is given by

$$P_c[Call\ Delayed\quad] = \frac{\rho^M}{\rho^M + M!(1-\frac{\rho}{M})\sum_{i=0}^{M}\frac{\rho^i}{i!}} \tag{4.1}$$

and the blocking probability is given by

$$P_C = \frac{\rho^M}{\rho^M + M!(1-\frac{\rho}{M})\sum_{i=0}^{M}\frac{\rho^i}{i!}} \times \exp\frac{-(M-\rho)}{\tau_d}t \tag{4.2}$$

where, ρ is the incoming traffic , t is the delay time and τ_d is the average duration of the call. Now let us consider the network with wavelength converters which is shown in fig.4.2. The probability P_c that the session request between Node 1 to Node 3 is given by equation 4.2. As shown in [Barry 1996] a measure of the benefit of wavelength converters can be expressed in terms of the increase in the gain of the network for the same blocking probability.

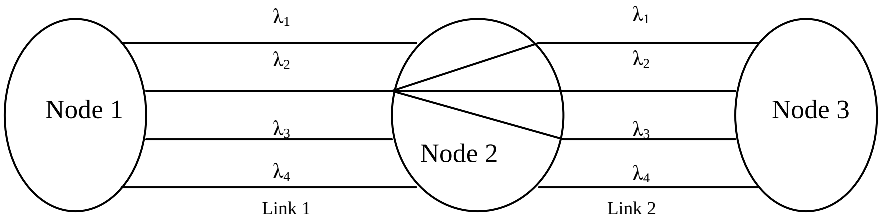


Fig.4.2 Wavelength conversion at node 2

Consider networks with wavelength changers. The probability that the session request is blocked is $P_b^{'}$. Let q be the achievable utilization for a given blocking probability in networks with wavelength converters, H is the number of hops and F is the number of wavelengths, then

$$q = [1-(1-P_b^{'})^{1/H}]^{1/F} \approx (\frac{P_b^{'}}{H})^{1/F} \tag{4.3}$$

where the approximation is valid for small $\frac{P_b^{'}}{H}$

Now consider a network without wavelength changers. In the absence of wavelength changers, if P_b be the probability of blocking and p be the achievable utilization for a given blocking probability in networks without wavelength converters i.e,

$$p = 1-(1-P_b^{1/F})^{1/H} \approx -\frac{1}{H}\ln(1-P_b^{1/F}) \tag{4.4}$$

where the approximation is valid for large H and $P_b^{1/F}$ not too close to one.

As a measure of the benefit of wavelength changers, define the gain $G = q\,/\,p$ as the increase in utilization for the same blocking probability. Setting $P_b = P_b^{'}$ and solving for q/p,

The gain can be written as

$$G = \frac{[1-(1-\frac{\rho^M}{\rho^M + M!(1-\frac{\rho}{M})\sum_{i=0}^{M}\frac{\rho^i}{i!}} \times \exp\frac{-(M-\rho)}{\tau_d}t)^{1/H}]^{1/F}}{1-(1-(\frac{\rho^M}{\rho^M + M!(1-\frac{\rho}{M})\sum_{i=0}^{M}\frac{\rho^i}{i!}} \times \exp\frac{-(M-\rho)}{\tau_d}t)^{1/F})^{1/H}} \tag{4.5}$$

$$G \approx H^{[1-(1/F)]}\frac{(\frac{\rho^M}{\rho^M + M!(1-\frac{\rho}{M})\sum_{i=0}^{M}\frac{\rho^i}{i!}} \times \exp\frac{-(M-\rho)}{\tau_d}t)^{1/F}}{-\ln[1-(\frac{\rho^M}{\rho^M + M!(1-\frac{\rho}{M})\sum_{i=0}^{M}\frac{\rho^i}{i!}} \times \exp\frac{-(M-\rho)}{\tau_d}t)^{1/F}]} \tag{4.6}$$

The gain comes at the cost of increased hardware. These equations have been used in blocking probability and gain calculation for different network parameters in the MATLAB environment under the appropriate node and traffic assumptions.

4.3.2. Simulation and Results

The simulations are carried out for a proposed optical switching configuration for a generic traffic with specific node architecture, having variable traffic routing factor. Here we have analyzed the network performance for various parameters like different incoming traffic rate, different numbers of available output channels and the effect of hop numbers on the network gain. The blocking probability variation of the network for incoming traffic of 3 and 5 Erlang have been shown in fig 4.3 and fig 4.4 respectively. Earlang is a very common traffic measurement parameters in case of communication engineering. The qualitative variation of blocking probability of standard Earlang C traffic model due to change in traffic intensity can be visualized by considering these two cases. If the value of the incoming traffic changes in any case then there will be quantitative variation only.

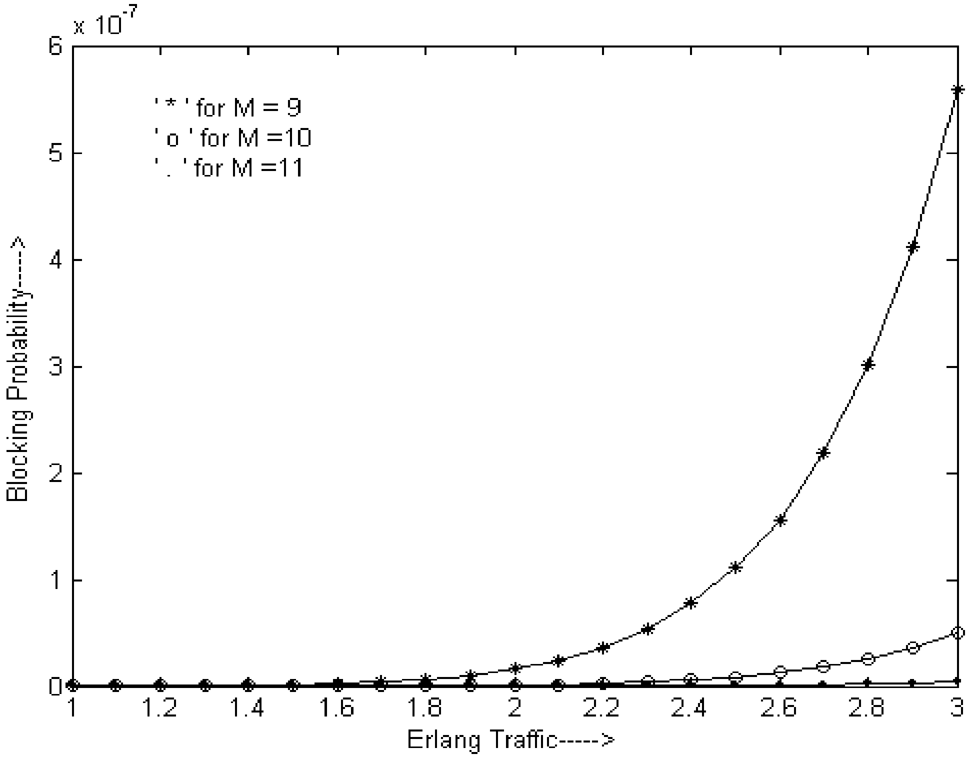


Fig. 4.3: Blocking Probability vs Traffic Arrival Rate for different values of 'M'

Fig. 4.3 reveals that the blocking probability increases with increasing incoming traffic for all values of *M*, and this result is quite obvious because as incoming traffic intensity increases the congestion and blocking probability increases. The change is more prominent for less number of available output channels and this change is almost exponential in nature. But it is interesting to note here that the blocking probability changes almost linearly with the increment of incoming traffic. For example we can consider the network with available output channels equal to 9 where the blocking probability of the network reaches to $5.5 \text{x} 10^{-7}$ and $8 \text{x} 10^{-5}$ for 3 and 5 Erlang of incoming traffic respectively. The same blocking probability changes if the number of available output channels are changed. This result shows that the blocking probability of a network is almost equally dependent on the number of available output channels as on the incoming traffic rate.

Fig. 4.4 shows the same variation of blocking probability with incoming traffic for maximum traffic intensity of 5 Earlang. As we have already mentioned that the qualitative behavior of Erlang C traffic model will remain almost same for different traffic intensity value and the same nature is revealed by fig. 4.4. Only the relative values of blocking probability has changed significantly as the traffic intensity is increased. The important point to note that at low incoming traffic intensity the blocking is very low and almost independent of number of output channels.

Gain is a very important quantity to differentiate the efficiencies between a network with and without wavelength converter. As gain is the ratio of utilization probability with wavelength converter to that of without converter and gain is a measure of the benefit of wavelength changers. Increased gain means network with lesser blocking probability or greater utilization probability and higher efficiency.

Fig. 4.5, 4.6 and 4.7 shows how the gain of the network is dependent on number of the available wavelength per channel and number of hops. Let us first consider gain as a function of the number of hops . Basically each hop contains a wavelength converter so more number of hops means more available wavelength converters.

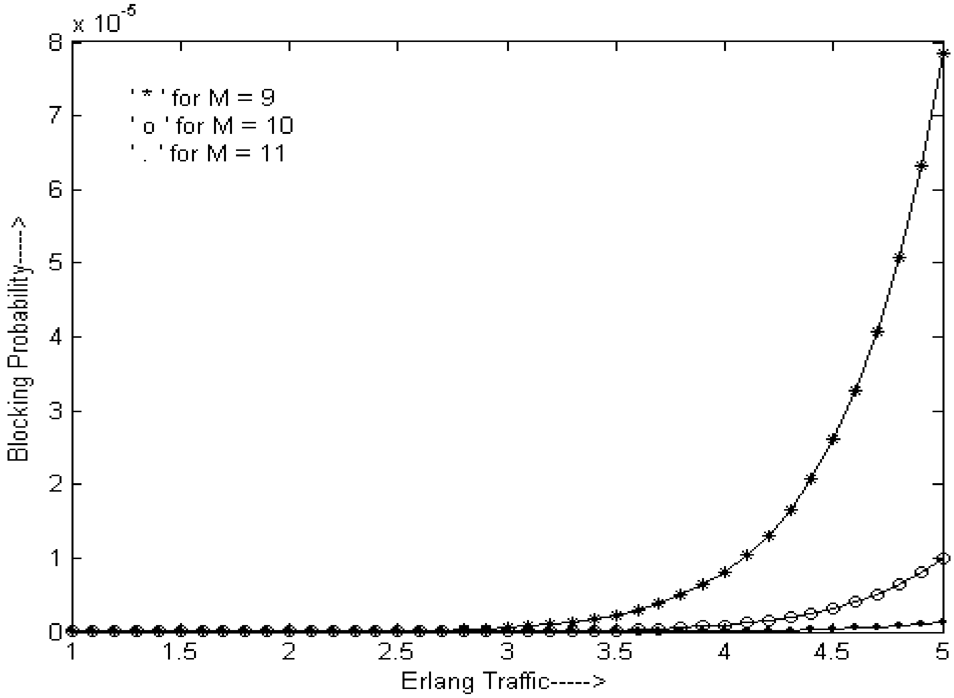


Fig. 4.4 : Blocking Probability vs Traffic Arrival Rate for different values of 'M'

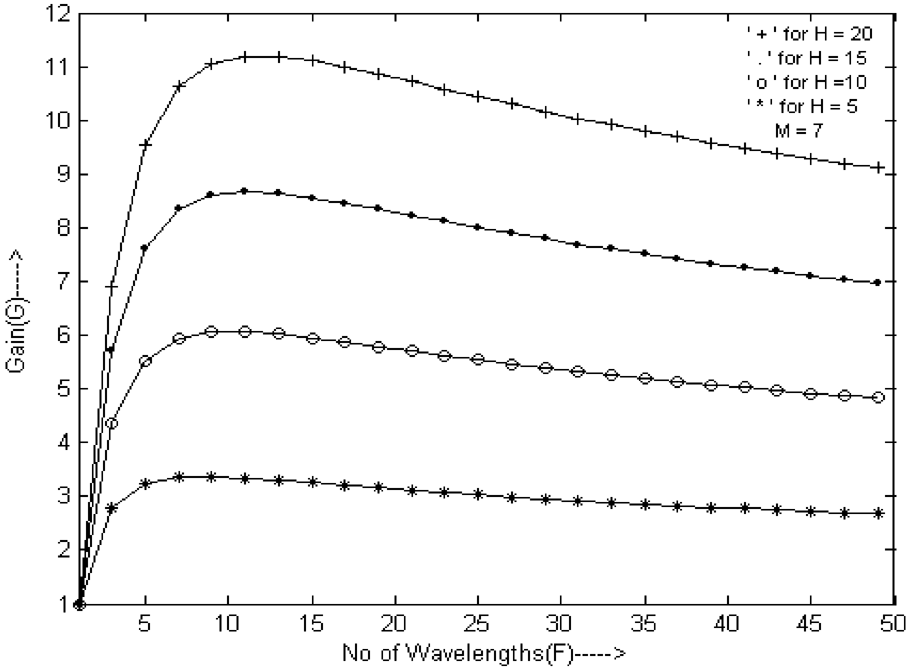


Fig. 4.5: Network Gain vs. number of Wavelengths for different values of 'H'

Notice that for large, the gain is almost linear in the number of hops because blocking probability of a network with wavelength converter is nearly independent of *H* and the blocking probability of a network without wavelength converter is inversely proportional to *H*. Fig. 4.5 depicts that the maximum gain offered by the network is almost equal to 3 , 6 ,9 and 11 for *H* = 5 , 10 ,15 and 20 respectively. This result signifies that the gain increases very sharp at lower value of *H* but at higher values of *H* the change of gain becomes monotonic in nature. The possible reason of this behavior is that at higher value of *H* means there are sufficient amount of converters and the efficiency of the network reaches to maximum achievable value. From this inference the necessity of limited range wavelength conversion instead of full conversion arises.

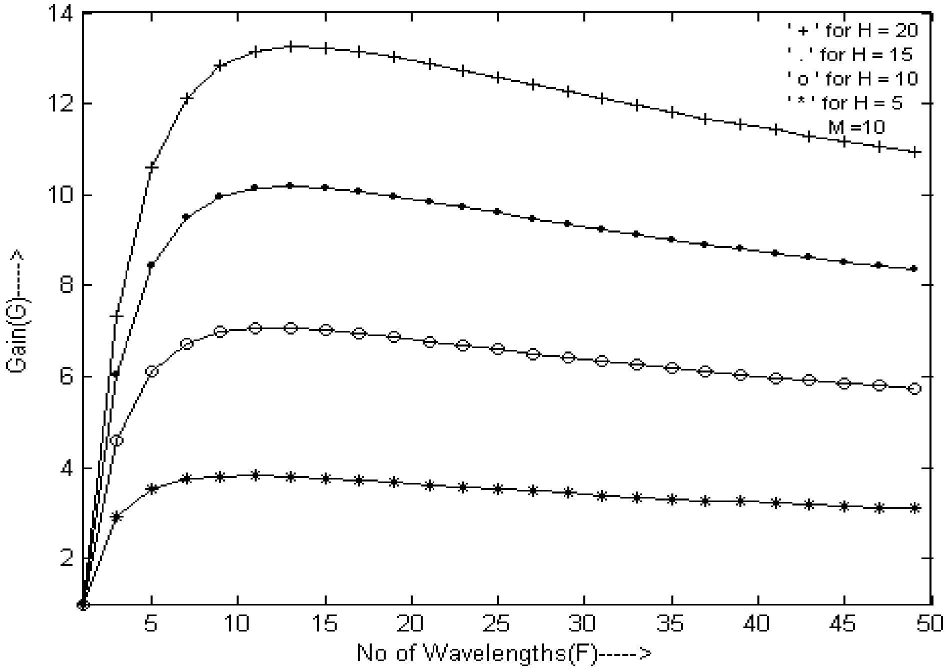


Fig. 4.6: Network Gain vs number of wavelengths for different values of 'H'

Notice that *G* = 1 if either *H* = 1 or *F* = 1 since in either of these cases there is no difference between a system with or without wavelength changers. So, for instance, wavelength changers are useless in two-stage (one hop) switching networks. As *F* increases, the gain increases until *G* peaks somewhere near *F*≈10 (*q* ≈ 0.5) for all cases shown. As can be seen from the figures, the maximum gain is close to *H/2*. After peak, the gain slowly decreases for the simple reason that large trunk groups are more efficient. The convergence is extremely slow since the convergence of p is extremely slow.

It's interesting to note that even for a moderate number of wavelengths, we seem to be operating in a regime where there is diminishing returns for the use of wavelength changers. That is, as we increase the number of wavelengths, the node complexity increases and the benefit of the hardware decreases. Now consider G as a function of the number of hops H. It can be shown that G is never more than $G \leq H^{1-(1/F)}$. Therefore, interestingly, for a two wavelength system, G grows more slowly than n.

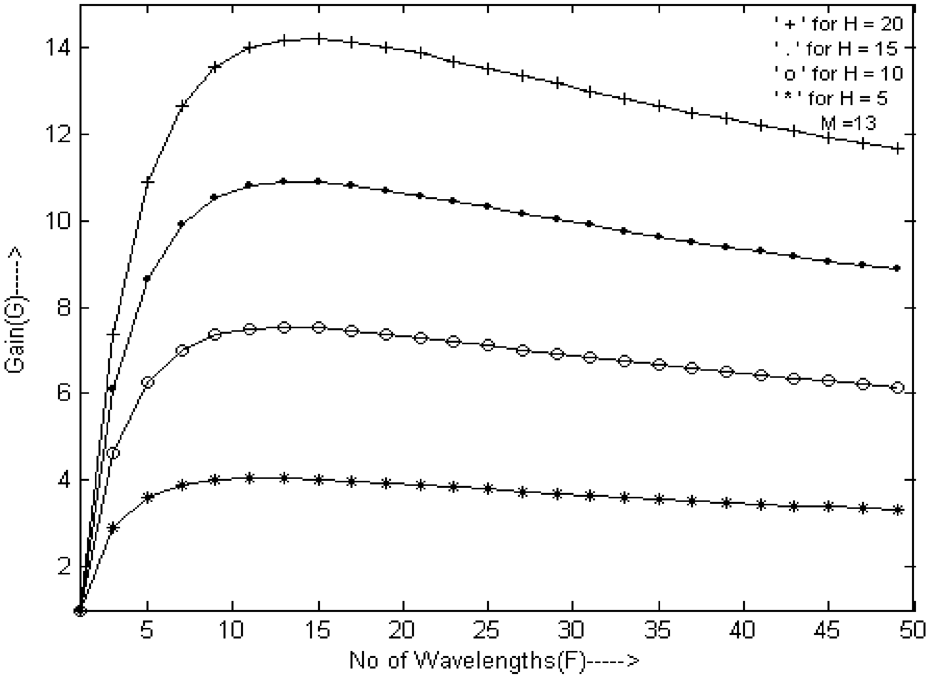


Fig. 4.7: Network Gain vs number of Wavelengths for different values of 'H'

The same observation is true for fig 4.6 and 4.7. It is interesting to note here that for a fixed value of H gain increases linearly with increase of M. For example we can see from fig 4.5, 4.6 and 4.7 that at H=20, G=11 for M=7, G=13 for M=10 and, G=14.5 for M=13. All the observation indicates that the gain of the network depends not only on the number of hops but also on the available output channels. It should also be highlighted here that gain is changing sharply when the number of output channels increases from 7 to 10 but the change not so fast when M increases from 10 to 13. So as the number of output channels increases beyond a certain value the gain becomes almost steady.

In summary, for a moderate to large number of wavelengths, the benefits of wavelength changers increase with the number of hops and decrease with the number of wavelengths. The benefits also increase as the blocking probability decreases; however the effect is small as long as blocking probability is small.

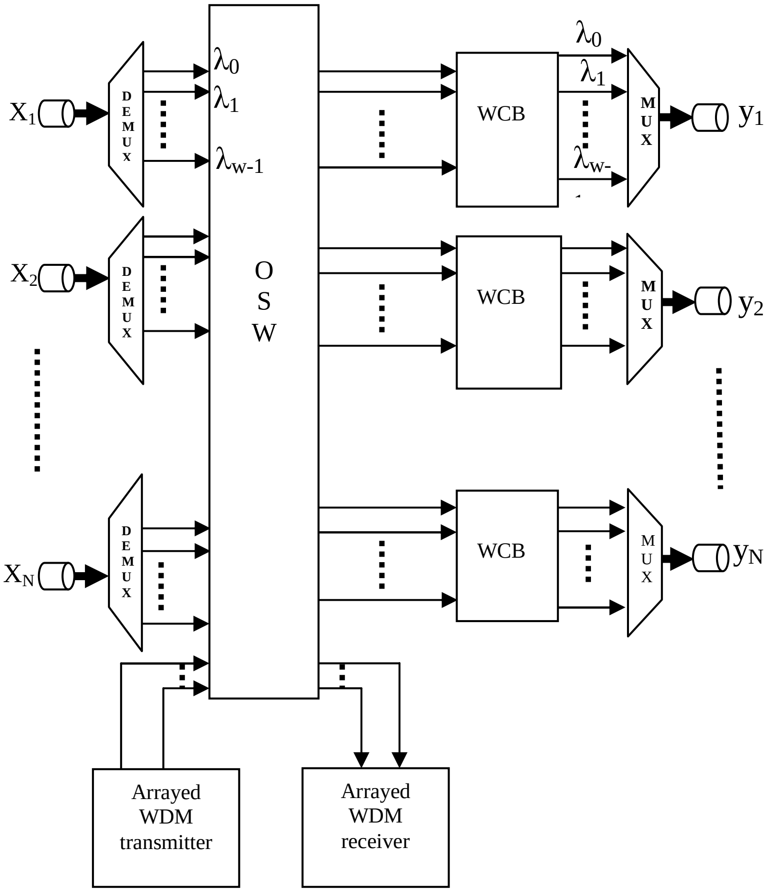
4.4 WDM Node Model with Wavelength Routed Networks

A network with wavelength converters is more flexible and has a smaller blocking probability. In [Kovacevic 1996] [Ramamurthy 1998] [Biman 1996] simple analytical models for blocking probability for the cases of no and full wavelength conversion(WC) has been proposed. The technology for manufacturing the WC has made rapid progress in recent years, the all-optical WC has emerged, but because of the limit of the technology, the cost of WC is expensive, so it directs our interest to use the WC as few as possible. Some researches show that the performance of optical network in which all nodes are equipped with WC can be achieved by equipping WC in some nodes [Subramaniam 1996][Harai 1999].
Previously published simulation and analytical studies [Gao 2003] [Sharma 2000] [Iness 1999] [Lee 1993] mainly focus on the overall blocking of networks with (full or limited) or without wavelength conversion, however, the blocking performance of the individual routing nodes has not been considered. Blocking has to be understood as the fact that an intended connection cannot be established because it needs an optical wavelength which is already being used. Anyway, blocking is due to the already existing traffic. Here we focus on the blocking performance of the node level.

4.4.1 Model for the Analysis of Blocking Probability

The main function of a wavelength router is to transparently switch optical channels from its input fiber to the output fibers. We assume for simplicity that each node has N incoming and N outgoing unidirectional fibers. For the rest of this paper the number of input and output fibers (N) will be considered identical, and the number of wavelengths per fiber (w) will also be considered the same for all the fibers, and so a wavelength router node will have a theoretical maximum capacity $C = N \cdot w$ optical channels or connections.

For the architecture shown in the Figure 4.8 , we suppose that the optical Switch is a $N \cdot w$ by $N \cdot w$ crossbar-like switching fabric and is non-blocking from a space-switching point of view. The realistic wavelength converters, only have the capability of limited wavelength conversion. Moreover, low conversion degree is likely to be far easier to realize in practice than higher degree conversion. Assume that a limited wavelength converter has conversion degree d (for some integer d ,$1 \leq d \leq w$) if an input wavelength can be converted to $d - 1$ different output wavelengths in addition to the input wavelength itself. We refer to these d output wavelengths as the set of available wavelengths of input wavelength λ_i. Apparently, the case of $d = 1$ is the no conversion, and the case of $d = w$ is the full conversion.



DEMUX: Wavelength Demultiplexer

MUX: Wavelength Multiplexer

OSW: Optical Switch

WCB :Wavelength Converter Bank

Fig.4.8: A $N \times N$ Routing Node Structure with W Wavelengths

For a node with limited wavelength conversion of degree three ($d= 3$), incoming wavelength λ_i ($0 \le i \le w-1$) can be converted to outgoing wavelength $\lambda_{(i-1)}$, λ_i and $\lambda_{(i+1)}$. We assume that a wavelengthcan be converted to its adjacent wavelengths on either side of the input wavelength. For example, when $d=3$, incoming wavelength λ_i can be converted to outgoing wavelengths $\lambda_{(i-1)}$, λ_i and $\lambda_{(i+1)}$ i.e. $O_i = \{\lambda_{(i-1)}, \lambda_i, \lambda_{(i+1)}\}$

Now we suppose that the model keep to the following assumptions:

- Point-to-point traffic is considered.
- Requested connections are considered random and uniformly distributed from any input and wavelength to all of the outputs.
- Once a connection is active, the used input wavelength will not be requested anymore.
- The capacity is the same for all the connections in the device. Each call requires a full wavelength.
- Existing calls cannot be reassigned different wavelengths to accommodate the new requests. Calls that cannot be routed in the router are blocked and lost.

Notice that the probability that a wavelength λ is used on an interfering fiber link is not the probability that is used on a requested fiber link i . The former is by definition ρ. To calculate the latter probability ρ_i , notice that because the access link is assumed idle at the time of the request, λ is used in other access fiber links. If λ is not used in a requested access fiber link, then it will be used in other interfering links with probability $(1-1/N)$. Therefore

$$\rho_i = P_r \{\lambda \text{ free in requested fiber link} \mid \lambda \text{ busy in other fiber links}\} = \rho(1-\frac{1}{N}) \qquad (4.7)$$

Let P_b be the blocking probability that a connection request from incoming link (with at least one wavelength available) to outgoing link (with at least one wavelength available) is blocked. Define $P_b^{'}$ be the blocking probability that a connection request from incoming link to outgoing link is blocked, including the cases where there is no free wavelength on incoming or outgoing link. So:

$$\begin{aligned} P_b^{'} &= [\rho_i^w + (1-\rho_i^w)] + (1-\rho_i^w)P_b \\ &= [(\rho(1-\frac{1}{N}))^w + (1-(\rho(1-\frac{1}{N}))^w)\,(\rho(1-\frac{1}{N}))^w] + (1-(\rho(1-\frac{1}{N}))^w)P_b \end{aligned} \tag{4.8}$$

Define P_b and $P_b^{'}$ as internal blocking probability and external blocking probability respectively, we will pay more attention on the internal blocking probability P_b because it can better obtain the effect of wavelength conversion on the node performance. However, to calculate the internal blocking probability, we will first gain the external blocking probability P'_b , and then obtain the internal blocking probability P_b by using the equation (4.8).

Define EV_i to be the event that a connection commencing with incoming wavelength λ_i is blocked. Then the probability $P^{'}_b$ that a connection request from incoming link to outgoing link is blocked is given by:

$$P_b^{'} = P\{{}^{w-1}_{i=0}\bigcap EV_i\} \tag{4.9}$$

We need to consider three cases in the following

No Wavelength Conversion *$d = 1$*

No wavelength conversion is one of the extreme cases for the node model. In the absence of wavelength converters, different wavelengths do not interact with each other, therefore for $i \neq j$ $(0 \leq i\ , j \leq w-1)$, events EV_i and EV_j are independent, and the blocking probability $P_b^{'}$ is the probability that each wavelength is used either on the source link or on the destination link, that is

$$\begin{aligned} P_b^{'} &= P\{EV_0\}.P\{EV_0\}.....P\{EV_0\} = \{\rho(1-\frac{1}{N}) + [1-\rho(1-\frac{1}{N})].\rho(1-\frac{1}{N})\}^w \\ &= \{2\rho(1-\frac{1}{N}) - [\rho(1-\frac{1}{N})]^2\}^w \end{aligned} \tag{4.10}$$

$$P_b = \{\{2\rho(1-\frac{1}{N}) - [\rho(1-\frac{1}{N})]^2\}^w - \{2[\rho(1-\frac{1}{N})]^w - [\rho(1-\frac{1}{N})]^{2w}\}\}/\{1-[\rho(1-\frac{1}{N})]^w\}^2 \tag{4.11}$$

Limited Conversion *2 ≤d ≤w −1*

A connection request commencing on wavelength λ_i is blocked either if input λ_i itself is being used, or if all the available output wavelengths of λ_i (i.e., all wavelength in set O_i)are occupied. Define the event $\bar{\lambda}_i$ is that input wavelength λ_i is being used and let Θ_i be the event that all wavelengths in set O_i are occupied. Accordingly, we can get

$$P_b' = P\{\bigcap_{i=0}^{w-1} EV_i\} = P\{EV_{w-1} \cap (\bigcap_{k=0}^{w-2} EV_k)\} = P\{(\bar{\lambda}_{w-1} \cup \Theta_{w-1}) \cap (\bigcap_{k=0}^{w-2} EV_k)\} \tag{4.12}$$

Note that in the above mathematical induction derivation, we used in the fact that event $\bar{\lambda}_{w-1}$ is independent of both events $\{\bigcap_{i=0}^{w-2} EV_i\}$ and Θ_{w-1}, but dependency exits between events $\{\bigcap_{i=0}^{w-2} EV_i\}$ and Θ_{w-1}, due to the limited wavelength conversion capability.

For $N=20$ and $w=4$ the above equation reduces to the following closed-form expressions

$$P_b = \begin{cases} \dfrac{[14(19\rho/20)^4 - 32(19\rho/20)^5 + 24(19\rho/20)^6 - 8(19\rho/20)^7 + 2(19\rho/20)^8]}{[1-(19\rho/20)^4]^2} & \text{for } d=1 \\[2ex] \dfrac{[8(19\rho/20)^5(1-(19\rho/20))^2]}{[1-(19\rho/20)^4]^2} & \text{for } d=2 \\[2ex] \dfrac{[4(19\rho/20)^6(1-(19\rho/20))^2]}{[1-(19\rho/20)^4]^2} & \text{for } d=3 \end{cases} \tag{4.13}$$

Full Wavelength Conversion *d = w*

Full wavelength conversion is another of the extreme case for the node model. With it, there is no restriction on how wavelengths can be assigned to a connection. A connection request is blocked when all *w* wavelengths on the source link or on the destination link are being used, that is $P_b=0$. Therefore in terms of internal blocking probability, a node with full wavelength conversion capability is always non blocking.

4.4.2 Simulation and Result

The general form of our blocking probability model and two interesting special cases are presented in previous Section. To perform the different simulations, the wavelength routing node has been considered working in the steady-state regime. That the arrivals of connection requests follow a Poisson stochastic process is supposed and that connection holding time is exponentially distributed with unit time is defined ,also we assume that traffic is uniformly distributed across all source-destination pairs, moreover random wavelength assignment algorithms is considered.

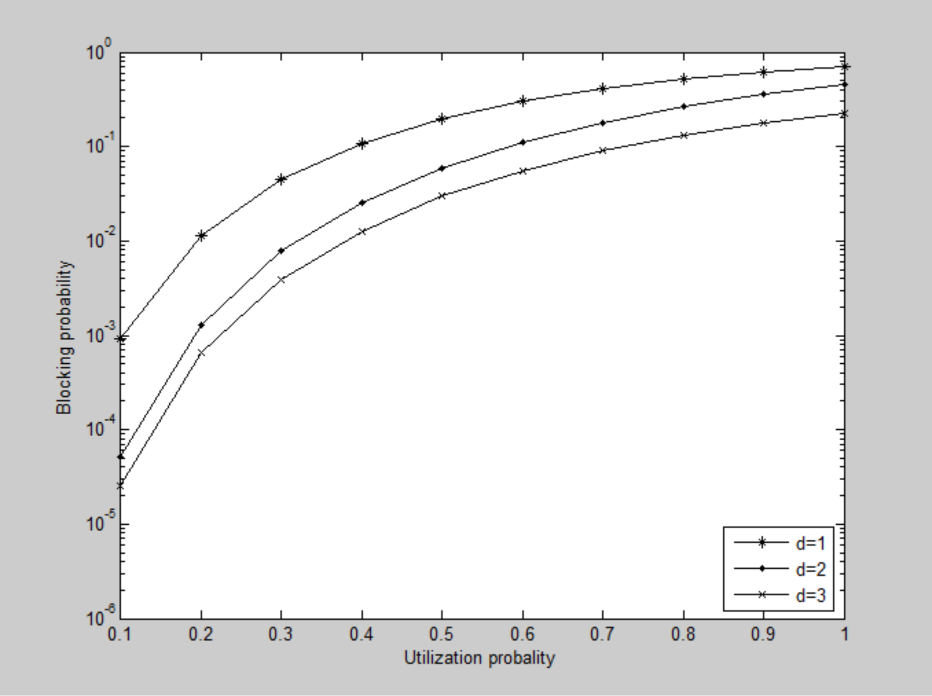


Fig 4.9: Blocking Probability vs Utilization Probability for different degree of conversion

In Fig.4.9 the simulation results for wavelength routing node with 4 wavelengths for the dimension of $N=20$ under different degrees of wavelength conversion is plotted. As conversion degree increases, the wavelength correlations become greater, thus leads to the inaccuracy of the model. Also, as is evident from the plots, with the same value of network utilization, blocking probability reduces as conversion degree increases for a given number of wavelengths w per link.

4.5 Conclusion

In this chapter we have analyzed traffic performance of an Optical WDM network with wavelength converter under Erlang C traffic condition. Traffic parameters like number of output channels, number of wavelengths and number of hops, are considered for the analysis. Performance of the network has shown a significant dependency on the number of output channels and hops. Simulation studies have been performed in due consideration of traffic parameter values used in practical purposes. The analysis presented here is useful to predict the traffic throughput range of an all-optical network with wavelength converter and relevant design parameters.

In the second part of this chapter we have proposed a model in which the degree of wavelength routing node is considered. The simulation results revealed that a significant improvement in the blocking performance of the node can be achieved by using wavelength conversion with small conversion degree (e.g. d = 2,3,4). It may also be inferred that utilization limited wavelength conversion with small conversion degrees is efficient and cost-effective choice. This model presented in this section can be used to the study of performance of all-optical wavelength router.

CHAPTER 5

CONTENTION RESOLUTION IN OBS RING NETWORK

5.1 Introduction

The ever increasing size of data over the internet has lead to an unprecedented rise in the demand for high speed and high capacity networks. This has been the motivation for the development of optical transmission systems based on optical packet switching and the optical burst switching networks [Jue 2005][Qiao 1999].

Optical packet switching (OPS) [Green 1996] promises to provide an efficient and effective solution for carrying the huge volume of traffic in metro area networks (MANs). Usually in OPS the switches are expected to switch in nanoseconds however this strategy reduces the expected speed for O/E/O based conversions and making OPS unrealisable with present day requirements. Nevertheless, with the available technology it is not possible to practically implement OPS in MANs or backbone networks as they need a large number of fiber delay lines (FDLs), sub carrier multiplexing (SCM) header extraction and insertion schemes as well as packet synchronizers and O/E/O conversion devices [Yao 2000a].

Optical burst switching (OBS) [Chen 2004][Yoo 1997][Qiao 1999] is being proposed as an alternate way of implementing OPS in MANs bypassing some of the potential technological bottlenecks of the latter. In OBS each node maintains electronic buffers to store data destined to be delivered to specific nodes. When these data packets are processed, they are first assembled into data bursts. Then a control header containing all the control information corresponding to the data burst is generated and transmitted over the control channel, thereby reserving resources for the upcoming data burst. The data burst is thus transmitted all optically through the reserved resources and finally the received bursts are disassembled at the destination node. In OBS only the control packets moving through the control channel undergo O/E/O conversion which is short in time domain as compared to OPS case and are less prone to the collision .

As the data bursts get transmitted all optically at each intermediate node thus OBS provides higher bandwidth efficiency than OPS networks and can be implemented at the optical layer avoiding high speed electronic switches to control the whole data traffic in the OPS case. So obviously OBS provides an effective all-optical network architecture that is practically possible with present day technology. In recent years, various researchers have proposed OBS implementations in WDM ring networks [Xu 2003] [Fumagalli 2003] [Arakawa 2004][Peng 2009] [Peng 2008]. In [Xu 2003], the authors implemented OBS in WDM ring networks where the network consisted of *N* nodes, and each node had a dedicated home wavelength for transmission. The nodes in the ring were FT-TR (fixed transmitter, tunable receiver) systems. As each node had a dedicated wavelength to transmit, this protocol successfully prevented channel collisions. However the occurrence of destination collision still prevailed as two source nodes might transmit to the same destination node. In such circumstances only one of the randomly selected data burst is received and the rest colliding bursts are dropped and hence lost. As some of the bursts may be lost, so the FT-TR systems are bandwidth inefficient. Moreover, such an OBS implementation in ring networks fails to provide a scalable and bandwidth-efficient solution for MANs since each individual wavelength is dedicated to the burst transmissions of its associated node.

Efficient signaling in a network is an important issue as this influences the network throughput performance considerably. However this signaling issues becomes more critical for optical burst switched networks due to the maintenance of suitable time separation between a data burst and the related control information. The transmission of a pure payload data burst through an optical burst switched network requires the strict follow-up of control information established during signaling step such as burst arrival time, burst length, burst priority, etc. Due to contention problems, a strict respect of the original control information cannot be maintained. Thus, signaling messages must be generated and sent to all remainder nodes on a path each time an unexpected event (e.g., burst dropping, burst segmentation, wavelength conversion, burst buffering, etc.) takes place. If downstream nodes are uninformed of a new situation, then their activities will be based on false information. This may lead to false decisions, particularly during contention, and thereby limits the performance of the network.

There are several variants of burst switching, mainly based on the length of the offset to implement the switching control logic on the OBS node. In the burst switching scheme called tell-and-go (TAG) [Widjaja 1995], the burst is transmitted immediately after the control packet. That is, the offset is only the transmission time of the control packet. This scheme is practical only when the switch configuration time and the switch processing time of a control packet are very short. At the other extreme, the tell and wait (TAW) scheme requires the offset to be at least equal to the time required to receive an acknowledgement from the destination. TAW is equivalent to circuit switching in that it incurs a round-trip delay to set up the transmission, and since the control packet reserves resources, delivery of the burst is guaranteed. Another advantage of TAW is that it eliminates receiver collisions by sending a return acknowledgement for the burst to be accepted. An intermediated burst switching scheme, known as just enough time (JET) [Qiao 1999], selects the offset in a manner that takes into account the processing delays of the control packet at the intermediate switches. JET signaling protocol is commonly considered as the most promising approach for the deployment of optical burst switched networks. While it may provide better bandwidth utilization compared to other schemes, the JET signaling protocol need to be extensively improved towards a JET-like-based optical burst switched network able to support emerging applications with different QoS requirements while offering more efficient bandwidth utilization.

Various burst scheduling algorithms to deal with time complexity and burst loss have been reported in literature. These scheduling algorithms can be categorized as unscheduled channels with void filing or without void filling [Dozer 2001] [Ljolje 2005]. Representative of without void filling algorithms are first fit unscheduled channel (FFUC) [Dozer 2001] [Ljolje 2005] [Xiong 2000][Yoo 2000a]. Latest available unused channel (LAUC) [Yoo 2000] and that of void filling algorithms are: first fit unscheduled channel with void filling (FFUC-VF) [Ljolje 2005], latest available unused channel with void filling (LAUC-VF) [Yang 2001] [Xu 2003] and minimum end void (Min-EV) [Xu 2003].

5.2 Motivation and Related Work

Xu et al. [Xu 2002] proposed an OBS ring architecture consisting of N OBS nodes connected by optical fibers, with $N+1$ wavelengths. The ring can be a metropolitan area network (MAN) serving as the backbone that interconnects a number of access networks . Each of the OBS nodes has a fixed transmitter, set to one of the N wavelengths called the home wavelength, and a tunable receiver so that it can receive bursts along the transmission wavelengths of the other nodes. In addition, each of the OBS nodes is equipped with a secondary pair of a fixed transmitter and a fixed receiver, set to the separate control wavelength, in order to communicate control information along the ring.

The data waiting for transmission is organized into queues according to their destination. The transmit queues are served in a round-robin fashion. In this OBS ring architecture, it is possible for two OBS nodes to send bursts, overlapping in time, toward the same destination. Consequently, these bursts will contend for the tunable receiver of the destination node and one of them will have to be dropped. Xu et al. [Xu 2002] proposed various access protocols to alleviate burst contention problem and analyzed their performance in terms of throughput, packet delay, throughput fairness and delay fairness.

Vishwas et al. [Puttasubbappa 2004], extended these access protocols to the case where different types of traffic such as HDTV, SAN data and best effort data is transported over the ring. Traffic classes like real-time variable bit rate (class 1), variable bit rate with no stringent end-to-end delay constraints (class 2) and best effort traffic (class 3) have been used for simulations. The access protocols serve to minimize burst contention in the OBS ring. In destination-reservation free protocol, the nodes transmit bursts without making any reservations at the receiver node. Hence, there is no guaranteed acceptance of transmitted bursts. Tokens are used to resolve receiver collisions for class 1 bursts in token protocol. All the nodes can transmit bursts only if they possess the token to transmit. A request and acknowledgement mechanism is employed in ack protocol for class 1 traffic. Token-token protocol is a collision free protocol for class 1 and class 2 bursts. Nodes use the token mechanism to ensure that the bursts belonging to class1 or class 2 categories are received without receiver conflict. Ack-ack protocol ensures guaranteed reception both for class 1 and class 2 bursts through acknowledgements.

Jong [Jong 2002] proposed several access protocols for multicasting in an OBS Ring network. A new architecture called the light ring has been proposed by Fumagalli and Krishnamoorthy [Fumagalli 2003] with multi-token protocol to prevent contention among bursts. Each node can transmit on any of the wavelengths as long as it has the token associated with that particular wavelength. Several burst assembly and transmission (BAT) strategies which deal with simultaneous assembly and scheduling of bursts are proposed. Packets from different flows can be assembled into the same burst so as to achieve lower latency of real-time packets. Bouabdallah et al. [Bouabdallah 2003] proposed a collision avoidance MAC protocol for a metropolitan bus-based optical access network. Analytical models were developed to calculate the mean access delay of each node in such a shared-medium system. Fairness issues were also investigated.

A distributed OBS metro ring architecture, designated light ring, was reported in [Fumagalli 2003]. The light ring multi-token media access control (MAC) protocol is designed to reserve bandwidth to ensure the bandwidth-efficient and loss-free transmission of data bursts. Several burst assembly and transmission (BAT) strategies capable of simultaneously assembling and scheduling bursts have been proposed. The OPADM architecture uses the same burst to transmit packets intended for different egress nodes by transmitting the burst with a high-level data link control (HDLC) encoding for each packet in the burst and uses MPLS tags for each packet’s destination. This approach ensures a lower latency in transmitting data bursts. Receiver collision problems can be resolved by allowing each OPADM node to equip with one fixed-tuned receiver and one fixed-tuned transmitter for each data wavelength. However, this architecture has the drawback of increasing the overall cost of the network. Furthermore, in optical ring, every burst must go through O/E and E/O conversion at each of the intermediate nodes. Therefore, optical ring is not sufficiently scalable to support hundreds of wavelengths since it requires more O/E/O conversion devices (i.e. one set for each wavelength) [Qiao 1999].

In the OBS ring network of tunable transmitter, fixed receiver (TT-FR) systems in [Arakawa 2004][Yutaka 2004], nodes were capable of transmitting on any wavelength but could receive only from the home wavelength. As each node received bursts only from the home wavelength, this implies that there were no destination collisions. To solve the source contention, tokens were used. So only channel collision was to be addressed and a segmentation scheme was used to arbitrate after channel collision. In [Lin 2008] a synchronous method was used to guarantee collision free operation at the expense of lower network throughput.

In all the above mentioned methods it is found that these are mainly reactive mechanisms and require extra hardware and /or software components at each core-node that increases the cost, complexity and scalability issues. In this chapter a simple and cost effective solution to resolve contention has been proposed with appropriate node and network architectures. The important feature of the proposed model is the use of dummy node which helps the congested nodes to diverse their traffic through the dummy node and as a result the throughput of the network is increased significantly

5.3 Design of a Modified Optical Burst Switched (OBS) Ring Network

An analytical model of an optical burst switched ring network capable to handle WDM traffic intelligently has been presented here. The efficient node architecture and network operating protocol enhances the data throughput in a congested network. Here we propose a node architecture to ease the traffic congestion in a ring network involving a dummy server connected to backbone of the ring topology to ease the traffic flow into the ring by diverting the packets under the congestion situation. A probabilistic model for the proposed node architecture in case of ring topology has been developed employing packet queuing control to estimate the average number of packets and their waiting time in the buffer for different incoming traffic.

5.3.1 Node Architecture Model

Figure 5.1 shows the OBS-node architecture consisting of N nodes which are appropriately connected to a WDM link. A unidirectional ring network is assumed here, in which data are transferred in the same direction for all destinations. Each WDM link consists of $(W + 1)$ wavelengths, of which W are for data transfer and the remaining one is for transfer of control packets. As a signaling scheme, the just enough time (JET) method [Qiao 1999], which is superior in wavelength use efficiency, is used. In JET, the control packet contains the offset time until the initiation of transmission of the burst signal and the burst signal length. At the relay node, the time of arrival of the burst signal is estimated and the wavelength is reserved only for the time needed for transfer. Each node consists of a fixed wavelength transceiver to transmit and receive the control packets, a variable wavelength transmitter for transmission of data, and a fixed wavelength receiver for receiving data. The scheme of assigning a fixed receiving wavelength is architecture without reception competition, since several burst signals do not arrive simultaneously at a receiver. Each node is connected to several access networks and has a capability to generate burst signals intended for the edge router. A packet arriving at the node from the access network is stored in the buffers (VOQs: Virtual Output Queues) installed at each destination edge router on the basis of the destination information. When the VOQ satisfies the conditions for burst generation, the packet stored in the VOQ is transmitted as a burst signal. As a condition to generate the burst, a method based on the time and length is used [Vokkarane 2002]. When the VOQ reaches a certain length, or otherwise if a certain time is exceeded after the head packet arrives, a burst signal is generated. When the burst signal is transmitted, the control packet is transmitted first using the control wavelength. After a time interval called an offset has elapsed, the burst signal is transmitted [Singh 2004].

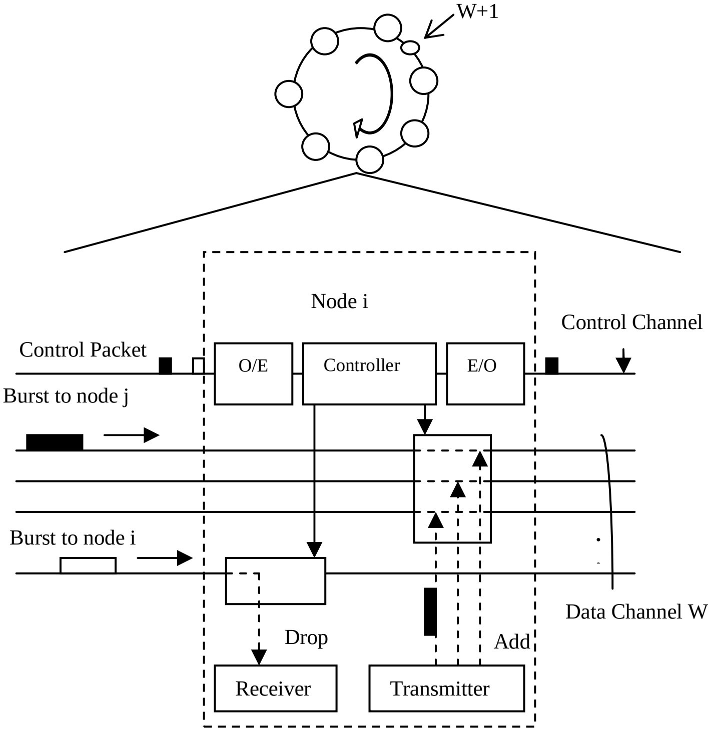


Fig.5.1: OBS ring network and node architecture

5.3.2 Modified OBS Ring Network : Mathematical Model

In the present analysis the OBS ring network is modified for congestion control using a dummy node as shown in fig. 5.2. In this modified ring network dummy node is connected to the n number of nodes in the network, where *n* =5 in this case. Dummy node is physically connected to all the *n* nodes by a two ways connection. It is also connected to one extra node by one way link, as packets from from *N5* can go to *N6*. Every time when there is congestion, the congested node sends a request asking the services of the dummy node. Now, the dummy gets logically connected to the node and starts serving till the timeout. The dummy timeout is calculated in such a manner, that, no packet is being lost [Dutta 2012].

At any instance of time, we assume that *n* nodes are in the state of congestion, and all have made a call to dummy to reduce their queue size, so to reduce congestion. The total time taken by a node to completely fill its queue size is given by the following equation:

$$t_1 = \frac{B}{[\lambda(t) - \mu]} \tag{5.1}$$

The service rate of the system (the particular node and the dummy) is equal to twice the service rate of that particular node, assuming the service rate of the dummy to be same as that of that particular node. The time taken by the dummy node to reduce its queue length to $B[1-\xi(a)]$ is given by equation (5.2).

$$t_i = \frac{\xi(a)B}{[2\mu - \lambda(t)]} \tag{5.2}$$

Here $\xi(a)$ is the processing factor taken which signifies the fractional part of the queue to be cleared.

The total time taken by the dummy node to serve the *n* congested nodes is distributed in such a way that it is equal to the time taken by the particular node to fill its queue to its threshold value. As a result, till the time queue gets completely filled for the particular node, the dummy node has taken one complete full cycle to return to serve that particular node *n* and this can be computed by measuring the summations of all the t_i resulting into t_1 value as shown in eqn. (5.3)

$$t_1 = \sum_{i=0}^{n} t_i = \frac{n\xi(a)B}{[2\mu - \lambda(t)]} \tag{5.3}$$

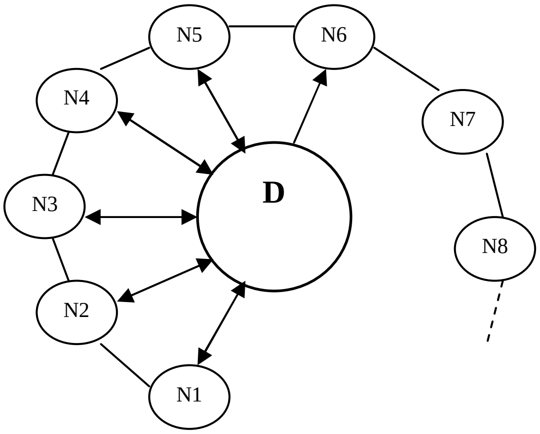


Fig.5.2: Modified Ring Network Using Dummy Node

Instantanous traffic intensity *a(t)* can be expressed by the following expression

$$a(t) = \frac{\lambda(t)}{\mu} \tag{5.4}$$

Using equations (5.3) and (5.4), we get a relation of '*n*' congested nodes with the traffic intensity.

$$n = \frac{2 - a(t)}{\xi(a)[a(t) - 1]} \tag{5.5}$$

Now, this equation can be used to find the maximum number of '*n*' congested nodes which a dummy can handle for the particular value of traffic intensity *a(t)* and *ξ(a)*. Each node is having a buffer (queue) of length *B* packets, i.e., *B* packets can be stacked in a buffer. We have assumed that packet length is same for all packets and of equal buffer length. The mean arrival rate and mean service rate of each node is same. Congestion is uniform in the part of the network where the dummy node is serving. Dummy node does not need a buffer to store because the stacked packets would be lost after dummy timeout. Packet arrival rate is in Poisson process with an average arrival rate λ packet per second and a constant service time μ . We have assumed the propagation delay from one node to the other as negligible and the loss of packet to be zero while the call is being made from the node to the dummy. Let '*a*' be the traffic intensity at the time of congestion, at a particular section of the proposed network .We have assumed $1>a>0$ for the proposed network. The control circuitry [CC] of the network will decide the number of congested nodes to which dummy can be connected. We apply single server model to the node not being served by the dummy. In this case, the server is the node itself and queue is the node buffer. We apply two server models to the node being served by the dummy. In this case, as shown in Figure 5.2, node *N2* and *P* are two servers. Node *N1* forwards a packet only if the node *N2* or dummy *P* is ready to accommodate. The last location in the buffer of *N2*, which has named as 'flag packet' indicates if node *N2* is ready to accommodate or not. If the buffer of *N2* is full, the flag packet acts as a red signal to a node *N1* indicating not to send any packet to *N2*. And if the buffer of *N2* has a single space to accommodate, then Flag Packet acts as a green signal to *N1* asking to send a packet.

Case I: Let *n* be the number of congested nodes which a dummy can handle, $\lambda(t)$ be the mean arrival packet rate ,μ be the mean service rate ,*B* be the buffer length (packets) and B_{th} be the threshold buffer length(packets).Traffic intensity '*a*' be defined as λ/μ.

Consider the probability that a packet is dropped at a node being served by the dummy is calculated by using $[M / M / 2 : FCFS|B|\alpha]$ model

$$P_D = (\frac{a^B}{2^{B-1}}) P_0 \tag{5.6}$$

P_0=Probability that the buffer is empty and can be expressed by the following expression:

$$P_0 = [1 + a + \frac{a^2\{1 - (\frac{a}{2})^{B-1}\}}{2(1 - \frac{a}{2})}]^{-1}; where \quad a \neq 2 \tag{5.7}$$

$$N_P = a^3 \left[\frac{[1-(B-1)(\frac{a}{2})^{B-2} + (B-2)(\frac{a}{2})^{B-1}]P_0}{4(1-\frac{a}{2})^2} \right] \tag{5.8}$$

Where, N_P =Average number of packets in a buffer

$$\tau_P = \frac{N_P}{[\lambda(1-P_D)]} \tag{5.9}$$

τ_P = Average waiting time of packets in a buffer

Case-II: Now, considering the case when the dummy node is not used to serve the congested node. In that case, the probability that packet is dropped at node which is not being served is calculated by using $[M/M/1: FCFS|B|\alpha]$ model

$$P_D = a^3.P_0 \tag{5.10}$$

Where $P_0 = \frac{(1-a)}{(1-a^{B+1})}; where \quad a \neq 1$ (5.11)

$$N = (\frac{a}{1-a}) - \frac{[(B+1)a^{B+1}]}{[1-a^{B+1}]} \tag{5.12}$$

Where N= Average number of packets in buffer

$$\tau = \frac{N - a(1-P_D)}{\lambda(1-P_D)} \tag{5.13}$$

Thus, the average number of packets in a buffer at any instant is,

$$N_{pt} = \{[a^3 \frac{[1-(B-1)(\frac{a}{2})^{B-2} + (B-2)(\frac{a}{2})^{B-1}]P_0}{4n(1-\frac{a}{2})^2}] + [(\frac{a}{1-a}) - \frac{[(B+1)a^{B+1}]}{[1-a^{B+1}]}]\frac{(n-1)}{n}\} \qquad (5.14)$$

Average waiting time of packets in a buffer is given by,

$$\tau_{pt} = \{\frac{N_P}{[\lambda(1-P_D)]n} + \frac{N-a(1-P_D)}{\lambda(1-P_D)}\frac{(n-1)}{n}\} \qquad (5.15)$$

The above equation are used to evaluate the performance of the proposed network. N_{pt} gives the average number of packets in a buffer and equation (5.15) gives the average waiting time after employing dummy node. MATLAB simulation tools have used for this purpose .

5.4 Network Performance Evaluation Under Reservation Protocols

Signaling is a critical aspect that can significantly affect the performance of a network. For OBS networks, signaling is even more important, since the core is (usually) bufferless and any contention for resources during signaling can lead to data loss. In this section, we aim to find out the performance of the proposed network by considering all design parameters before opting for a particular signaling technique.

a. Just-Enough-Time (JET)

In JET method A reservation request is sent in a separate control packet on a different channel while the actual transmission of the data burst is delayed by a certain offset. This basic offset enables the intermediate nodes to process control information and prepare themselves for accommodating the data burst that will arrive there shortly. Figure 5.3(a) illustrates the JET signaling technique. As shown, a source node first sends a burst header packet (BHP) on a control channel toward the destination node. The BHP is processed at each subsequent node in order to establish an all-optical data path for the corresponding data burst. If the reservation is successful, the switch will be configured prior to the burst's arrival. Meanwhile, the burst waits at the source in the electronic domain. After a predetermined offset time, the burst is sent optically on the chosen wavelength [Li 2004] [Jueand 2005]. The offset time is calculated based on the number of hops from source to destination, and the switching time of a core node. If at any intermediate node, the reservation is unsuccessful, the burst will be dropped. The unique feature of JET when compared to other one-way signaling mechanisms is delayed reservation and implicit release. The information necessary to be maintained for each channel of each output port of every switch for JET comprises of the starting and the finishing times of all scheduled bursts, which makes the system rather complex. On the other hand, JET is able to detect situations where no transmission conflict occurs, although the start time of a new burst may be earlier than the finishing time of an already accepted burst, i.e. a burst can be transmitted in between two already reserved bursts. Hence, bursts can be accepted with a higher probability in JET.

b. Tell-and-Wait (TAW)

In the TAW approach, the data burst must be delayed at each node in order to allow time for the burst header to be processed and for the switch to be configured, instead of pre-determining this duration at the source and incorporating the delay in the offset time. Figure 5.3(b) illustrates the TAW signaling technique. In TAW, the “SETUP” BHP is sent along the burst’s route to collect channel availability information at every node along the path. At the destination, a channel assignment algorithm is executed, and the reservation period on each link is determined based on the earliest available channel times of all the intermediate nodes. A “CONFIRM” BHP is sent in the reverse direction (from destination to source), which reserves the channel for the requested duration at each intermediate node. At any node along the path, if the required channel is already occupied, a “RELEASE” BHP is sent to the destination to release the previously reserved resources. If the “CONFIRM” packet reaches the source successfully, then the burst is sent into the core network.

If we compare TAW and JET, the disadvantage of TAW is the round-trip setup time, i.e., the time taken to set up the channel; however in TAW the data loss is very low [Dutta 2012a]. Therefore TAW is good for loss-sensitive traffic. On the other hand, in JET, the data loss is high, but the end-to-end delay is less than TAW. In TAW, it takes three times the one-way propagation delay from source to destination for the burst to reach destination, whereas in the case of JET, the delay is just the sum of one one-way propagation delay and an offset time. There is no signaling technique that offers the flexibility in both delay and loss tolerance values.

A network node is supposed to be transparent to the operating data rate, but the architectural design of the node limits the performance efficiency. The bandwidth utilization factor for a given signaling protocol is well controlled by the burst propagation time (T_{Pro}), reservation mapping time (T_m) and the burst transmission time (τ_p). The non ideality factor (σ) can be modeled in terms of bandwidth utilization factor (b), incoming data rate (R) in Mbps available band width (W) by the following expression:

$$\sigma = e^{(-\frac{R}{bW})} \tag{5.16}$$

Hence the expression for carried traffic can be modified and written as

$$C_T = \mu\sigma \frac{\tau_P}{\tau_D}\{[1 - e^{(-\frac{\tau_D}{\tau_P}a)}](C - \frac{\tau_P}{\tau_D}) + ae^{(-\frac{\tau_D}{\tau_P}a)}\} \tag{5.17}$$

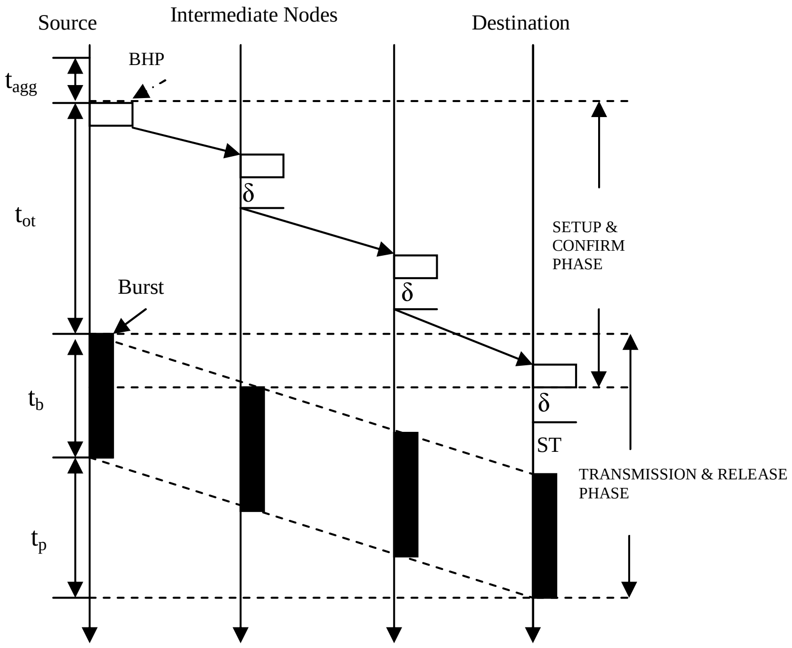


Fig. 5.3(a): JET Signaling Technique

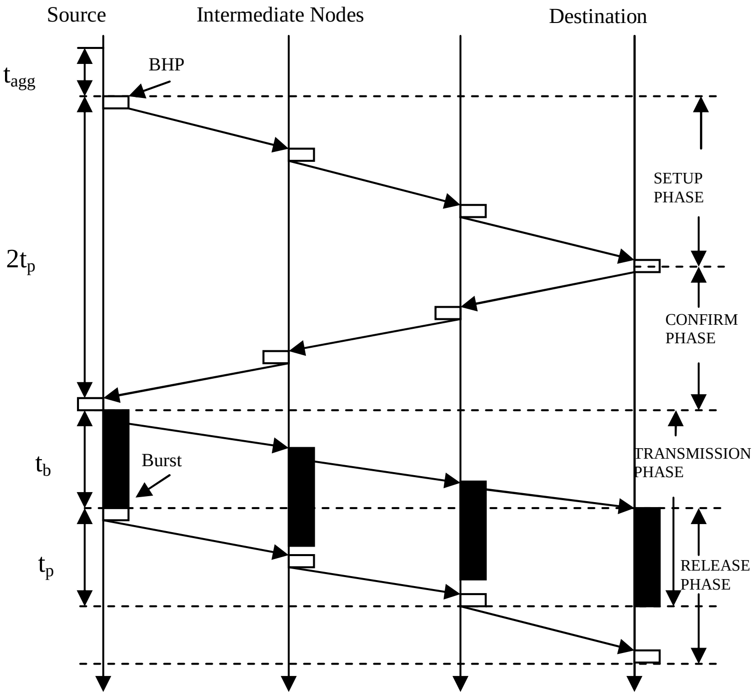


Fig. 5.3(b):TAW Signaling Technique

5.5 Simulations and Results

Average number packets in a buffer and average waiting time of packets in a buffer for the proposed modified ring network, employing different values of *B* vs packet arrival rate has been investigated with MATLAB. In fig.5.4 the comparative performance analysis of optical burst switching ring network with and without employing dummy node have been shown for *B*=20. *B* represents the length of a buffer in terms of number of packets it can accommodate. For a particular value of *B* the nature of the curves of both networks are qualitative similar but in case of modified ring network (with dummy node) as the path from source to destination is deflected so this network will accommodate larger no of packets in its buffer for a given packet arrival rate. For example if we consider the packet arrival rate of 240 packets per unit time then the network with dummy node can accommodate 5 no packets in its buffer where as the normal ring network can provide only 4 packet. As a result of this increased buffering capability of modified ring network the packet dropping probability decreases significantly and correspondingly throughput of the network increases.

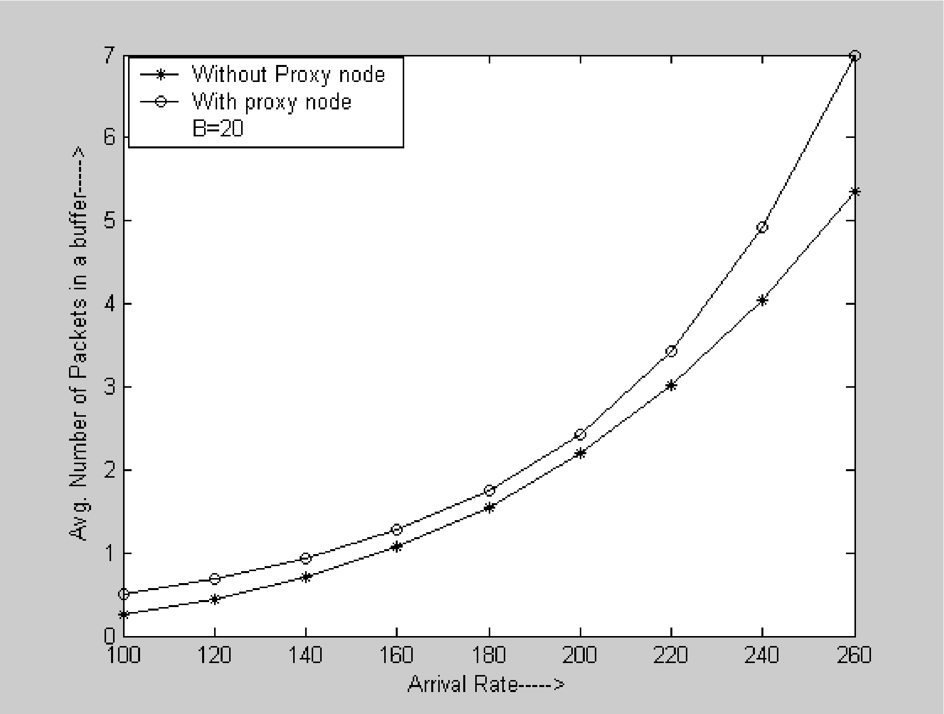


Fig.5.4 :Average no of Packets in a Buffer vs Arrival rate for B=20

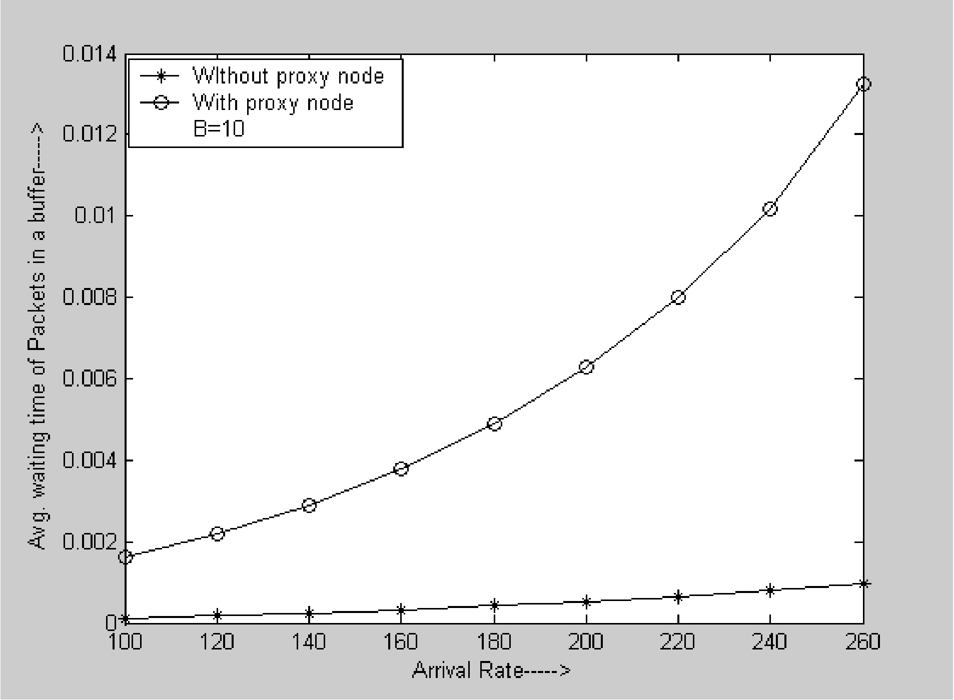


Fig.5.5 (a):Average Waiting Time of a Packet in a Buffer vs Arrival rate for B=10

In fig. 5.5(a) and 5.5(b) the average waiting time in buffer for both types of networks has been depicted for *B=10* and *B=20* respectively. The graph shows that the average waiting time increases for the network with dummy node and for longer buffer length as well. The result is quite obvious because if the dummy node connected between the source and the destination node then the packet has to travel a longer distance so the waiting time will also increase. For example we can see that the average time is less than 0.001µsec for packet arrival rate of 240 packets per unit time for ring network without dummy node but same value increase to 0.01 µsec for the ring network with dummy node. The waiting time value increases significantly for both types of networks when *B=20* This result is quite interesting in network application because without adding any costly and complex additional hardware the incoming packets could be retained in the buffer for longer time thus the packet blocking probability or packet loss probability will be decreased significantly.

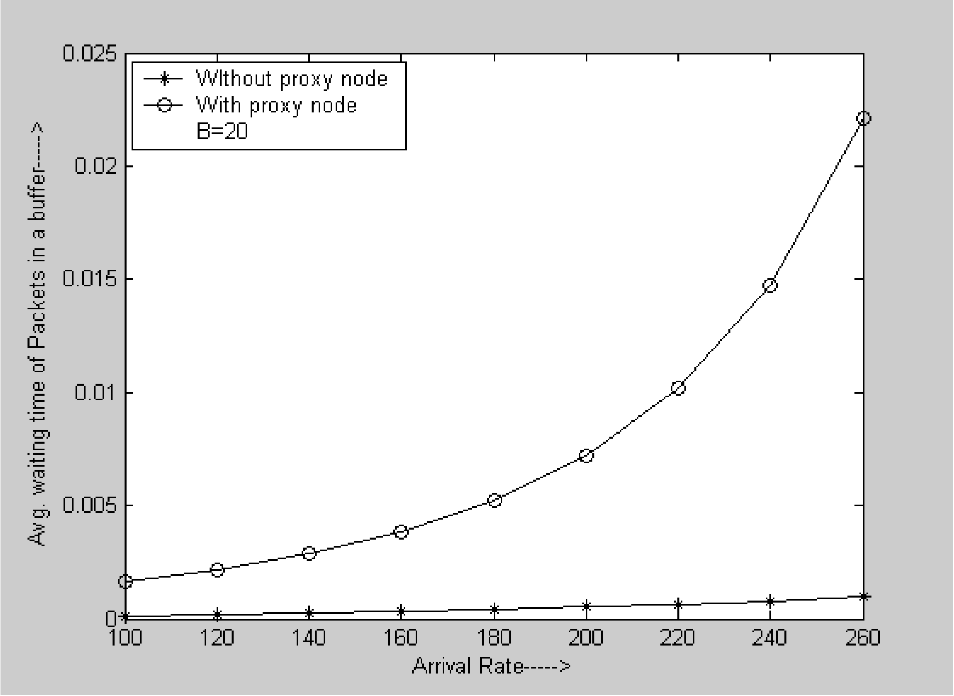


Fig.5.5 (b):Average Waiting Time of a Packet in a Buffer vs Arrival rate for B=20

Fig. 5.6 depict the characteristics of the proposed modified OBS ring network for different values of *B*. Fig 5.6 shows that the average waiting time of a packet in buffer is almost independent of the packet arrival rate upto a certain value of the incoming packet rate after that the waiting time varies with B. At low traffic arrival rate the use of the buffer is negligibly small so the average waiting time is independent of buffer size. But as packet arrival rate is increased beyond a certain value then role of buffer becomes significant. A buffer with long length can accommodate a packet for longer times. So the length of the buffer becomes important factor for high packet arrival rate or high speed network.

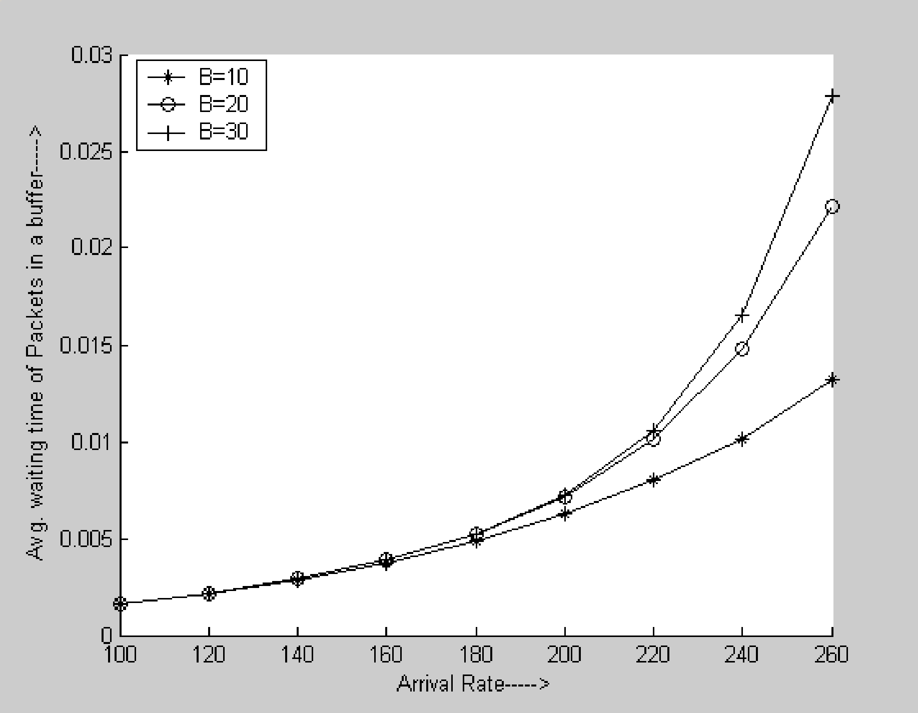


Fig. 5.6 :Average Waiting Time of a Packet in a Buffer vs Arrival Rate for different values of 'B'

The amount of carried traffic equation (eqn. 5.17) is used to evaluate the performance of a given signaling technique by choosing appropriate bandwidth utilization and data rates. Evidently the channel bandwidth has a significant impact on the network control and transmission performance as is implicit from the derived expression. Obviously the network seems to be robust against channel noise, dispersion and other channel or node non-linearity at a lower traffic but faces performance degradation and excessive delay. These constraints needs a larger channel capacity, faster node processor, efficient bandwidth utilization and appropriate signaling technique. In the present analysis JET and TAW signaling techniques have been attempted to investigate their feasibility in network traffic management. The developed model is equally applicable to any other reliable signaling protocols by appropriately considering the involved node parameter and channel utilization factor. The amount of carried traffic for a JET signaling technique has been evaluated with respect to the increasing traffic intensity for a given *R*.

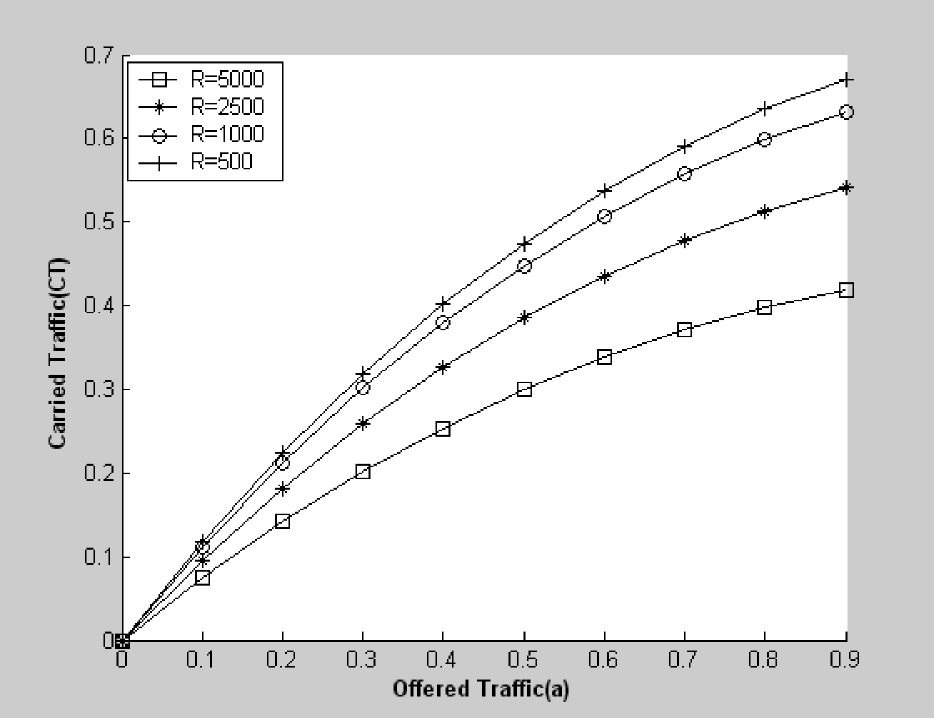


Fig 5.7(a): Carried Traffic (C_T) vs Offered Traffic(a) of JET Signaling Technique for Different Data Rates (*R*)

Fig. 5.7(a) presents simulation results for a network with bandwidth of 20 GHz and at different incoming data rates (*R*) in the units of Mbps. The curve corresponding to 500 Mbps data rate shows a significant larger amount of carried traffic as compare to the case for a higher data rate of 5000 Mbps and this may be attributed to the system capacity limitation. The linear nature of the curve is also sensitive to the data rate and gives a larger range and slope at lower traffic speed but reverses the tendency for a higher data rate. Similar amount of carried traffic analysis for TAW signaling technique has been presented in fig. 5.7(b). This signaling technique is evaluated for different data rate under the similar node and channel environment. These curves are qualitatively similar to that of the curves obtained in case of JET but with a quantitative higher value because of superior bandwidth utilization in the latter case. The analysis presents a superiority of TAW protocol over JET protocol in terms of traffic loss sensitivity. Evidently the model can be used to simulate the performance of different protocols by estimating the node parameters. In a realistic high speed WDM network accumulated channel noise and node non-linearity causes bandwidth limitation, time jitter and synchronization problem to influence the processing decisions and node parameters.

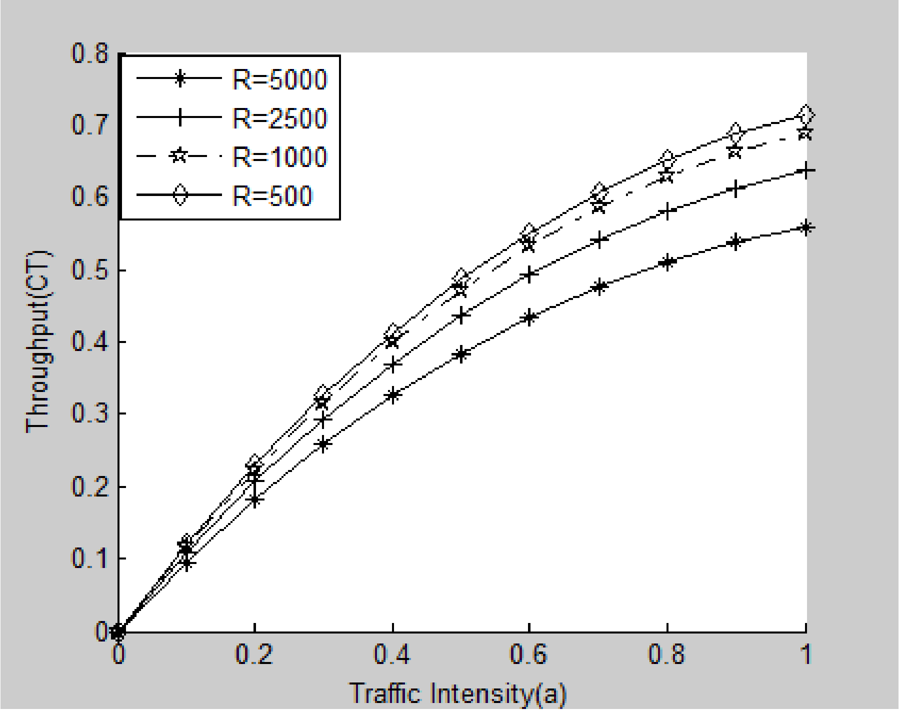


Fig 5.7(b): Carried Traffic (C_T) vs Offered Traffic(a) of TAW Signaling Technique for different data rates(R)

5.6 Conclusion

This chapter addresses the problem of network congestion in an optical burst switching ring network when the packet arrival rate is more than that the service rate of the node. To resolve the problem we have proposed a modified ring topology with adaptive service provisioning to cater varying traffic demands. The chapter reports a brief introduction of OBS ring network involved in contention resolution followed by an analytical model of a ring network which is modified with dummy node and capable handling contention in OBS network.

Appropriate mathematical model is also developed to calculate average waiting time and average number of packets in a buffer for different packet arrival rate. The model has further been extended to evaluate the impact of different standard signaling protocols like JET and TAW on the throughput performance of proposed network. Simulations are performed for different network parameters like buffer length, bandwidth utilization factor and data rate etc to evaluate the network performance. It is shown that proposed model significantly improves the average waiting time of an incoming burst which in turn reduces the burst dropping probability. It has also been observed that channel bandwidth has a significant impact on the network transmission performance as is implicit from the derived expression. The proposed model can also be used to simulate the performance behavior of different signaling protocols by estimating corresponding network parameters.

CHAPTER 6

CONTENTION RESOLUTION : SEGMENTATION BASED DROPPING

6.1 Introduction

The amount of enhanced raw bandwidth on fiber optic links through wavelength division multiplexing (WDM) has provided a cost-effective solution to IP traffic over all-optical transport layer. This transport method must be able to handle asynchronous bursty traffic by quickly provisioning resources with the minimum use of optical buffers. Optical burst switching (OBS) is one such method for transporting such traffic directly over a bufferless optical core network [Qiao 1999].

In an optical burst switched network, bursts of data consisting of multiple packets are switched through all-optical network. A control message is transmitted ahead of the burst in order to configure the switches along the burst's route. The data burst follows the header after some offset time without waiting for an acknowledgment for the connection establishment. The offset time allows for the header to be processed at each node while the burst is buffered electronically at the source; thus, no fiber delay lines are necessary at the intermediate nodes to delay the burst while the header is being processed. The control message may also specify the duration of the burst in order to let a node know when it may reconfigure its switch for the next burst, a technique known as just enough time (JET).

A major concern in optical burst switched networks is contention, which occurs when multiple bursts contend for the same link. Contention in an optical burst switched network is particularly aggravated by the highly variable burst sizes and the long burst durations. Furthermore, since bursts are switched in a cut-through mode rather than a store-and-forward mode, optical burst-switched networks generally have very limited buffering capabilities. Existing contention resolution schemes for photonic packet networks are conventionally based on deflection routing and buffering techniques, however some additional schemes are also implemented in order to combat high contention situations and to improve network utilization.

In [Yoo 2000], an offset scheme was proposed for isolating classes of bursts, such that low priority bursts do not cause contention losses for high-priority bursts. In such resolution schemes sometimes fixed and variable fiber delay line buffers are also utilized to further reduce the blocking. Some proposals presented by the researchers in the literature [Yoo 2000a] [Turner 1999] also reduces the contention by utilizing additional capacity in the form of multiple wavelengths using wavelength conversion capacity. While such optical wavelength conversion has been demonstrated in laboratory environments, the technology is not yet mature, and the range of possible conversions is somewhat limited [Turner 1999] .

Most of the current literature deals with approaches to minimize burst losses rather than packet losses. In existing contention resolution schemes for optical burst switched networks, when contention between two bursts cannot be resolved through other means, one of the bursts will be dropped in its entirety, even though the overlap between the two bursts may be minimal. For certain applications, which have stringent delay requirements but relaxed packet loss requirements, it may be desirable to lose a few packets from a given burst rather than losing the entire burst.

To overcome some of the practical limitations of optical burst switching, we introduce the concept of burst segmentation in this chapter. The burst is divided into basic transport units called segments. Each of these segments may consist of a single packet or multiple packets, and the segments define the possible partitioning points of a burst when the burst is in the optical network. All segments in a burst are initially transmitted as a single burst unit. However, when contention occurs, only those segments of a given burst which overlap with segments of another burst will be dropped, [Vokkarane 2001] and the remaining segments will be scheduled. In this way the bandwidth utilization efficiency increases significantly.

6.2 Burst Segmentation

In a burst segmentation, the burst is divided into basic transport units called segments consisting of a variable number of packets. Each segment consists of a segment header containing fields for synchronization bits, error correction information, source and destination information, and the length of the segment in the case of variable length segments followed by a payload which may carry any type of data, such as IP packets or ATM cells. The fragment structure of burst segmentation is presented in (fig.6.1).

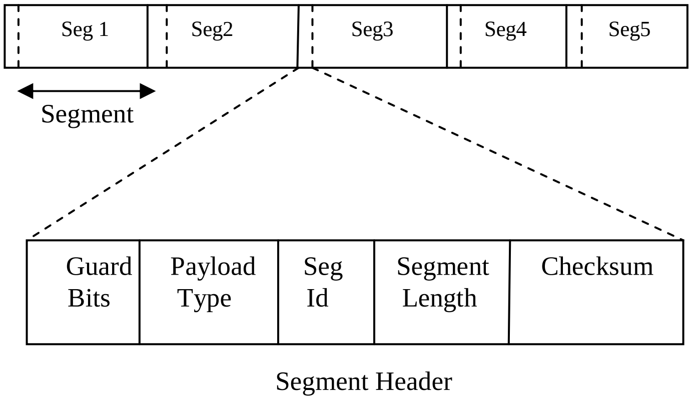


Fig 6.1: Segments Header Details

The choice of the segment length becomes a key system parameter. The segment can be either fixed or variable in length. If segments are fixed in length, synchronization at the receiver becomes easier; however, variable-length segments may be able to accommodate variable-length packets in a more efficient manner. The size of the segment also offers a tradeoff between the loss per contention and the amount of overhead per burst. Longer segments will result in a greater amount of data loss when segments are dropped during contention; however, longer segments will also result in less overhead per segment, as the ratio of the segment header length to the segment payload length will be lower.

Another issue in burst segmentation is the decision of which burst segments to drop when a contention occurs between two bursts. When contention occurs, only those segments of a given burst which overlap with segments of another burst will be dropped, as shown in fig. 6.2. If switching time is non-negligible, then additional segments may be lost when the output port is switched from one burst to another. There are 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. If downstream nodes are unaware of a burst's truncation, then it is possible that the previously truncated tail segments will contend with other bursts, even though these tail segments have already been dropped at a previous node. These contentions may result in unnecessary packet loss.

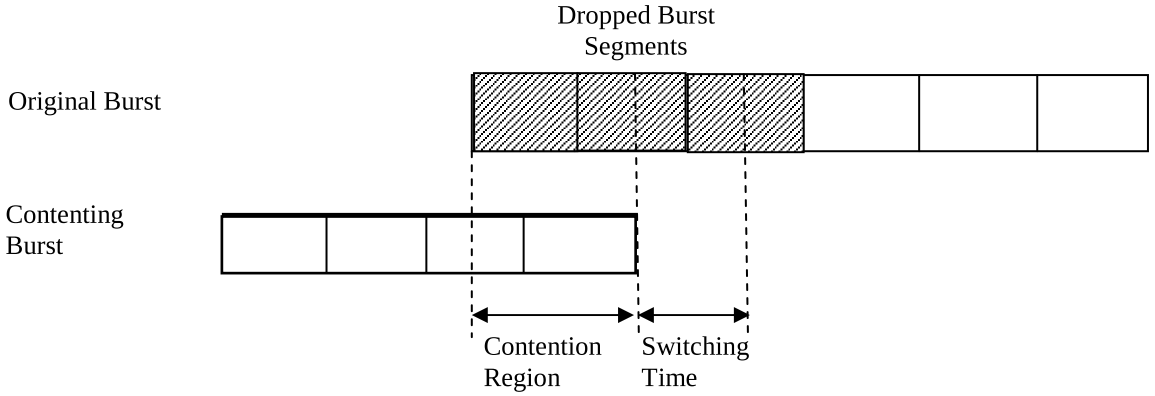


Fig 6.2: Selective Segment Dropping for Two Contending Bursts

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. A simple solution is to have the truncating node generate and send out a trailing control message to indicate when the truncated burst ends. In this policy, the offset between the trailer packet and the end of the truncated burst is similar to the offset between the header and the start of the burst.

In a head-dropping policy, the head segments of the contending burst will be dropped. A head-dropping policy will result in a greater likelihood that packets will arrive at their destination out of order. Also, the control message of the contending burst would need to be modified and delayed. The advantage of head-dropping is that it ensures that, once a burst arrives at a node without encountering contention, then the burst is guaranteed to complete its traversal of the node without preemption by later bursts [Vokkarane 2001].

In addition these there are a number of additional issues and challenges which arise when implementing burst segmentation in practical systems. Some of important issues like switching time, segmentation boundary detection and trailer creation are discussed here in brief to understand the functionality and proposed modeling of JET based OBS modes.

6.2.1 Switching Time

Since the system does not implement buffering or any other delay mechanism, the switching time is a direct measure of the number of packets lost during reconfiguring the switch due to contention. This implies that a slower switching time results in higher packet loss. While deciding which burst to segment, we consider the remaining length of the original burst, taking the switching time into account. By including switching time in burst length comparisons, we can achieve the optimal output burst lengths for a given switching time [Vokkarane 2002].

6.2.2 Segment Boundary Detection

In the optical network, segment boundaries of the burst are transparent to the intermediate nodes that switch the burst segments all-optically. At the network edge nodes, the burst is received and processed electronically. Since the burst is made up of many segments, the receiving node must be able to detect the start of each segment and identify whether or not the segment is intact. If each segment consists of an Ethernet frame, detection and synchronization can be performed using the preamble field in the Ethernet frame header, while errors and incomplete frames can be detected by using the CRC field in the Ethernet frame [Vokkarane 2001].

6.3 Motivation and Related Work

Optical burst-switching (OBS) [Qiao 1999] [Qiao 2001] [Tumer 1999] is one of the promising optical switching paradigms which have been proposed in order to efficiently use the raw bandwidth available at the optical (WDM) layer. OBS takes into consideration the limitation of the existing all-optical technology in terms of processing power limitation, the lack of efficient buffering techniques, and the limited number of wavelengths. [Chan 1998]. In OBS networks, the ingress nodes generate control packets that are sent into the network an offset time ahead of macro-packets. The macro-packets named data bursts (DB) are made up of various upper layers' packets (e.g. IP packets, ATM cells, Frame Relay frame). The control packets configure the fabric switch of the core nodes and reserve the necessary network resources to accommodate the upcoming data bursts. For various reasons the control packet may fail to reserve the full/part of the resources needed to establish an all-optical transmission path for its corresponding DB. Consequently the burst is blocked and discarded in an intermediate node. In order to reduce the burst loss probability, many approaches were considered based on different techniques, such as the use of deflection routing to resolve contention presented by Hsu et al. [Hsu 2002] and Kim et al. [Kim 2002]. Other promising techniques for partial burst dropping (that reduces the packet loss probability) were introduced, based on the concept of burst segmentation. optical composite burst switching (OCBS) proposed by Detti et al. [Detti 2002], suggests that if all the resources are occupied at the time of the burst arrival, then only the initial part of the burst is dropped. The final part of the burst is transmitted once the needed recourses become available.

Similarly, based on the concept of burst segmentation another technique was proposed by Vokkarane et al. [Vokkarane 2002] to reduce the packet loss probability. In this technique designed upon just- enough-time (JET) architecture [Too 1997], the data burst is broken into multiple segments that consist of a single packet or multiple packets. Combined with deflection routing, the authors showed that their approach performed better than the "entire-burst-dropping" policy used by the standard OBS.

In optical burst switching (OBS) network, traffic contention can be resolved in time (optical buffering), wavelength (wavelength conversion), and space domains (deflection routing). Deflection routing [Kim 2002] is an efficient technique to reduce burst in optical burst switched networks. The first three techniques, however, require additional resources in the network and/or nodes. In case, additional resources are not available, or are scarce, it is beneficial to resolve contention using the burst dropping scheme [Haridos 2002] [Sarwar 2008]. To improve bandwidth utilization and efficiency, segmentation method was proposed in order to pass packets as many as possible using the fragmented resources. In this chapter initially a brief discussion of segmentation based dropping scheme has been presented followed by mathematical model to determine the blocking probability of an OBS network using the above mentioned dropping scheme in sec 6.4. In the next section of this chapter a comparative performance analysis between wavelength conversion and segmentation based dropping schemes has been presented . Appropriate mathematical models have been developed to calculate blocking probability and call connection probability for both the techniques (details discussion of wavelength conversion based contention resolution scheme has been presented ch.4) . Performance of the contention resolution techniques have been evaluated in terms of call connection probability vs incoming traffic for different set of network parameters.

6.4 Design and Modeling of JET Based OBS Nodes

In this section, we discuss some analytical models, described in the literature, to model the burst blocking probability of OBS core nodes. Results of burst blocking probability for different analytical models are also presented. The following assumptions are made for modeling the core node. For a given output port at a core node, the burst arrival process is Poisson with mean rate λ. The burst lengths are distributed with mean $1/\mu$. Let N_O represents the number of output links and each output link contains W_O data wavelength channels. If the wavelength conversion is available, n is a multiplication of the number of output links and the number of data channels in an output link, that is $n=N_O W_O$.

6.4.1 Blocking Probabilities

Let we assume that for a given output port at a switch the burst arrival process follows a Poisson process, the number of wavelengths used at each output port is n. and if we have only one priority class and the remaining offset time is equal for each burst at any switch then the JET based OBS systems can be modeled as M/M/n/n loss system [Vu 2002]. In such systems either a burst is accepted or rejected completely. The burst blocking probability of OBS core node can be obtained by using the Erlang loss formula [Dolzer 2001] as follows:

$$P_{JET} = \frac{A^n / n!}{\sum_{k=0}^{n} A^k / k!} \tag{6.1}$$

where A is the accumulated traffic of n channels, i.e, $n\rho$. In this model, Erlang loss formula assumes the infinite number of input channels. However, an OBS JET node has a limited number of input channels ($N_E W_E$) thus, the behavior of JET core node can be modeled and evaluated as M/M/n/n/$N_E W_E$ queuing model [Kleinrock 1975]. This analytical model is expected to represent the real JET core node more accurately and corresponding expression for $P_{JET(\text{Finite Input Channels})}$ can be written as:

$$P_{JET(Finite\quad Input\quad Channels)} = \frac{\begin{pmatrix} N_E W_E \\ n \end{pmatrix} . (\frac{\lambda}{\mu})^n}{\sum_{i=0}^{n} \begin{pmatrix} N_E W_E \\ i \end{pmatrix} . (\frac{\lambda}{\mu})^i}, \qquad N_E W_E \geq n \tag{6.2}$$

The JET segmentation-based dropping core nodes are modeled as M/G/∞ to calculate the packet loss probability [Neuts 2002], where n are real channels out of infinity output wavelength channels, while remaining being the pseudo channels. When a burst arrives at core node it is assigned to a real channel. If all the real channels are busy, the newly arrived burst is assigned to a pseudo channel. As soon as a burst has finished its transmission in a real channel, and that becomes available to service another burst, the remaining part of the burst from pseudo channel can be transmitted over that real channel. In this model, the number of input channels is assumed to be infinity. The packet loss probability is given by,

$$P_{JETseg} = \frac{\sum_{i=1}^{\alpha} i.A^{n+i} \frac{e^{-A}}{(n+i)!}}{A} \tag{6.3}$$

If we consider the limited number of input channels to the core node of JET segmentation-based OBS, it can be modeled as M/G/∞/$N_E W_E$. The packet loss probability is given by,

$$P_{JETseg(Finite\ \ Input\ \ Channels)} = \sum_{k=n+1}^{N_E W_E} \left(\frac{k-n}{n} \frac{N_E W_E!}{k!.(N_E W_E - k)!} \frac{(\frac{\lambda}{\mu})^k}{(1+\frac{\lambda}{\mu})^{N_E W_E}} \right) \tag{6.4}$$

Now these equations can be used to evaluate the performance of an OBS network employing burst segmentation based dropping technique as contention resolution scheme. The performance of the OBS network is usually measured in terms of blocking probability under the appropriate node and traffic assumptions. In the present analysis eqns (6.1)-(6.4) have been used to estimate the blocking probability. The equations have been simulated in MATLAB in the following subsections.

6.4.2 Simulation and Results

Eqn. no 6.1-6.4 have been used to carry out the simulations to evaluate the performance of the segmentation based dropping scheme for different network parameters. Blocking probability as a function of offered load has been presented in Fig. 6.3, which reveals that JET segmentation-based burst dropping systems perform superior to JET systems.

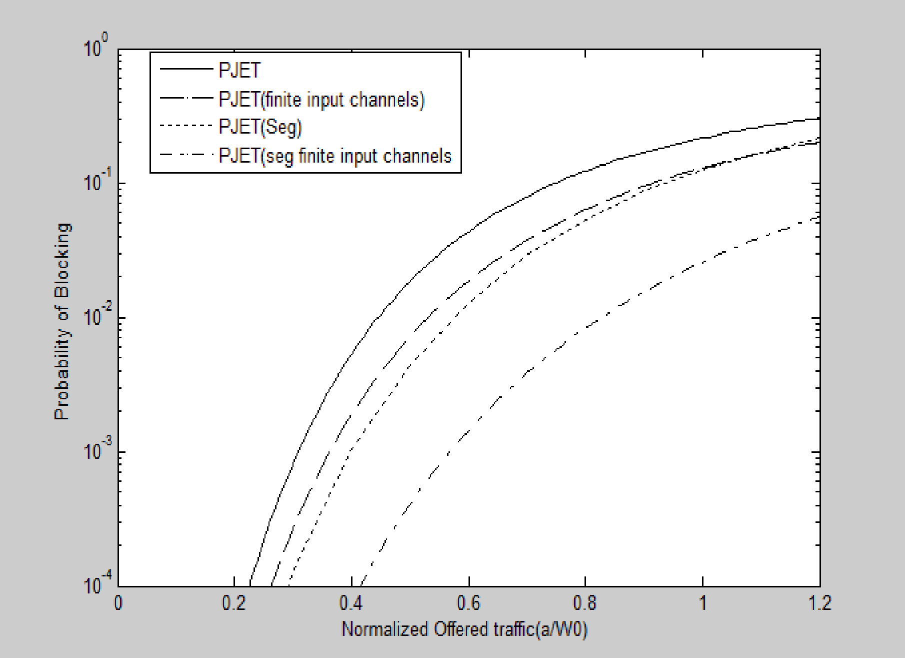


Fig: 6.3 Blocking probability vs Normalized offered load

For example we can see that upto almost normalized offered traffic value of 0.3 the JET segmentation based dropping scheme provides negligible blocking probability. The qualitative nature of blocking probability curves for all four systems are alomost similar but with a quantitive difference. Hence JET segementation based dropping scheme with finite input is the better dropping technique among the four discussed.

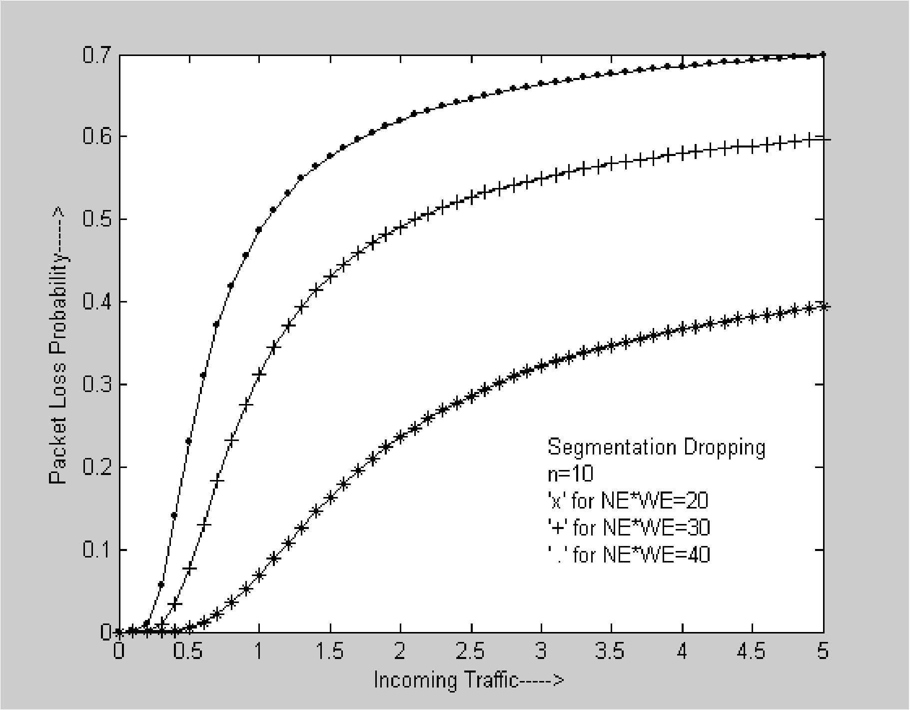


Fig 6.4: Packet Loss Probability vs Incoming Traffic keeping fixed output channels for segmentation dropping

We have analyzed the performance of segmentation dropping scheme for different values of input channels keeping the number of output channels constant as shown in the fig 6.4. The plot of packet loss probability verses incoming traffic shows that as the numbers of input channels are increasing the amount of packet accumulation is also increasing which results a huge number of bursts formation in the network. More number of bursts in a network will obviously increase the contention probability and this fact can be observed from the simulation result as is depicted in fig 6.4. Let us assume that the number of input channels are 30 and if the number of output channels are less than input channels (here 10) then obviously there is congestion in the network. Here that congestion has been tried to resolve by using segmentation dropping approach. Fig 6.4 shows that burst loss probability is almost same for low incoming traffic for any number of input channels. This result is expected because at low incoming traffic intensity probability of congestion is very less and application of any contention resolution is mere necessary. But as the incoming traffic intensity is increasing effect due to congestion is more prominent.

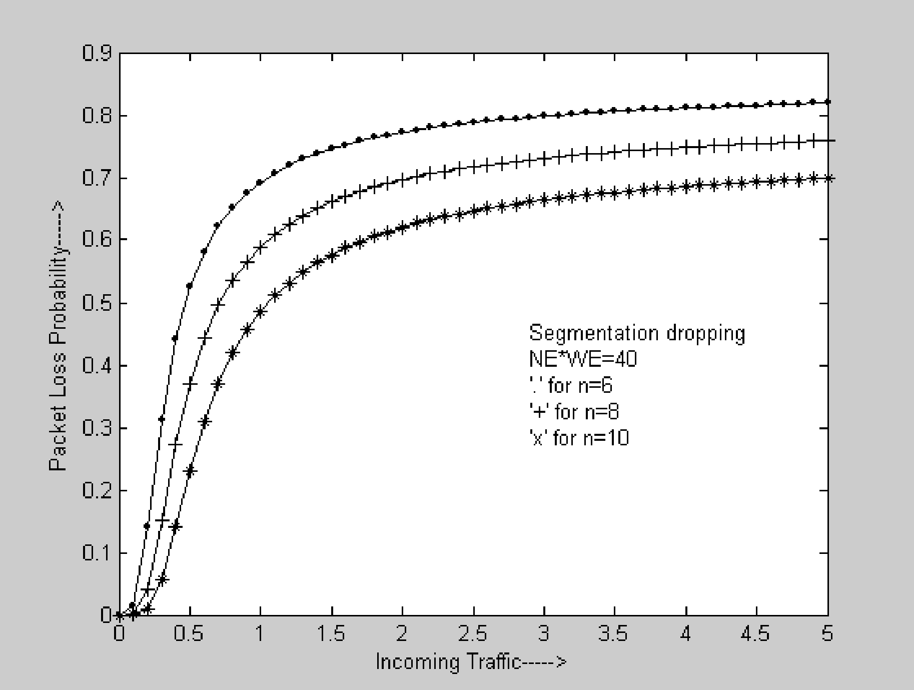


Fig 6.5: Packet Loss Probability vs Incoming Traffic keeping fixed input channels for segmentation dropping

Fig 6.5 represents the burst loss probability for fixed input channels but different output channels. In the previous figure we have shown the variation of blocking probability as a function of input channels but in this fig blocking probability has been presented as a function of output channels. It is interesting to note that the simulation curves are qualitatively similar but with some quantitative difference due to system parameters difference. Obviously as the number of output channels decreases, the influence of congestion is more which increases the blocking probability. It may be inferred that the node blocking probability improves with ‘*n*’ and thus requires more number of output channels to get better network performance.

6.5 Contention Resolution in Optical Burst Switching (OBS) Network

In Optical Burst switching (OBS) networks, the bandwidth reservation is a one way process in which a burst starts its transmission without waiting for the reservation acknowledgment and for this it requires OBS nodes to resolve possible contention.

The currently used contention resolution schemes can be classified into the following domains:

- The space domain, such as deflection routing.
- The time domain, such as buffering with fiber delay line (FDL).
- The wavelength domain, such as wavelength conversion.
- The burst domain, such as segmentation dropping.

Although these schemes perform well, but they have inherent problems such as; that deflection routing makes setting the time lag between a burst header packet and the corresponding data burst i.e. offset time at the edge node a hard problem because the exact transmission path of the burst is not known, and the scheme usually sets the offset time under the worst case; that fiber delay line technology will increase data latency and also introduce complexity for the network, and is not mature enough to be used in network engineering at present; that optical burst segmentation is not easy to carry out in the physical layer nowadays; and that the control scheme increases the complexity of implementation too much. Full wavelength conversion is the most efficient way to solve the burst contention problem, full wavelength converters are expensive and complex devices at present. So there should be a comparative analysis depending on the critical issues of different contention resolution techniques.

In this section a deterministic algorithm for wavelength conversion in an all optical network (AON) has been presented. Necessary mathematical analysis for computing the call connection probability of an all optical network using wavelength conversion (details of wave length conversion has been presented in ch.4) has been provided in the subsequent section. The analysis has further been extended to find-out the call connection probability of the network under the environment of segmentation based dropping. Finally a comparative analysis between wavelength conversion and segmentation based dropping scheme has been presented.

6.5.1 Wavelength Conversion Based Contention Resolution

Consider an optical network with nodes, L links and W wavelengths available. At any time each wavelength $(\lambda_1, \lambda_2, \ldots\ldots, \lambda_w)$ will be busy in any link with probability ρ_i $(i=1,2,\ldots..,W)$, then the probability that the wavelength λ_i is free in any link is $1- \rho_i$. Now assume a network configuration with a constraint on the maximum number of allowed wavelength converters let sat C $(0\leq C\leq L)$ to make a upper limit of the permitted wavelength conversions . The call blocking analysis for such networks are performed for the two following cases.

Case 1: Any one link in the path is completely blocked because all wavelengths are busy in that link

Suppose a call has to be made from Node *1* to Node *N*. when no wavelength conversion is allowed in the network. In this case the call will be blocked on any wavelength λ_i if the wavelength is busy in any one link in the path. Thus, the call blocking probability on any one wavelength λ_i is given by,

P_i = P (λ_i is busy in L links) +P (λ_i is busy in L-1 links) +P (λ_i is busy in L-2 links) +……+P (λ_i is busy in 1 links) (6.5)

Here ring network is considered so the number of nodes N is related to the number of links L as L=N-1. Now, the wavelength λ_i can be busy in k out of L links in ${}^{L}C_{K}$ ways. So, the probability that λ_i is busy in k out of L links is given by

$$P_i = P(\lambda_i \text{ is busy in k links and free in L-k links})$$

$$= {}^{L}C_{k}(\rho_i)^{k}(1-\rho_i)^{L-k} \tag{6.6}$$

Using (6.6) the (6.5) is modifies to

$$\begin{aligned} P_i &= {}^{L}C_{L}(\rho_i)^{L} + {}^{L}C_{L-1}(\rho_i)^{L-1}(1-\rho_i)^{1} + {}^{L}C_{L-2}(\rho_i)^{L-2}(1-\rho_i)^{2} + \ldots\ldots + {}^{L}C_{1}(\rho_i)(1-\rho_i)^{L-1} \\ &= \sum_{k=1}^{L} {}^{L}C_{K}(\rho_i)^{k}(1-\rho_i)^{L-k} \end{aligned} \tag{6.7}$$

Thus the total call blocking probability for all the W wavelengths is given by

$$P_B = (P_1)(P_2)(P_3)........(P_W) = \prod_{i=1}^{W} P_i \tag{6.8}$$

So the total call connection probability is given by

$$P_c = 1 - \prod_{i=1}^{W} P_i \tag{6.9}$$

So the probability that one or more links out of *L* links are blocked is given by
*PB*1 = *P*(1 link is blocked)+*P*(2 links are blocked)+*P*(3 links are blocked) +· · ·+*P*(*L* links are blocked) = *PB*,1+*PB*,2+*PB*,3+. . . *PB*, *L*.

$$PB\,1 = \sum {}^{L}C_i\,(P_B)^i\,(1 - P_B)^{L-i} \tag{6.10}$$

Case 2: All the links are individually free, but a wavelength is busy in more than C links in the network, thereby necessitating more than C wavelength conversions

Let us take case 2. In this case the call is blocked if a wavelength is busy in more than *C* links. Now a wavelength can be busy in *k* out of *L* links in ${}^{L}C_k$ ways. So, the probability that a wavelength is busy in *k* links is given by

$$P_i = {}^{L}C_K\,(\rho_i)^K\,(1 - \rho_i)^{L-K} \tag{6.11}$$

The probability that a call will be blocked on wavelength λ*i* is given by
Pi = *P* (λ*i* is busy in *C*+1 links) +*P* (λ*i* is busy in *C*+2 links) + · · · +*P*(λ*i* is busy in *L* links)

$$P_i = \sum_{K=C+1}^{L} {}^{L}C_K\,(\rho_i)^K\,(1 - \rho_i)^{L-K} \tag{6.12}$$

So, the probability that a call will be blocked on all the wavelengths is given by
*PB*2 = *P* (the call is blocked on λ1) ×*P* (the call is blocked on λ2) × · · · ×*P* (the call is blocked on λ_W),

$$PB2 = \prod_{i=1}^{W} P_i \tag{6.13}$$

Hence the total call blocking probability in the case of a network with a wavelength conversion constraint is given by

$$PB = PB1 + PB2 - PB1 \times PB2 \tag{6.14}$$

So the call connection probability is

$$PC = 1 - PB \tag{6.15}$$

This expression provides the overall call connection probability in a network.

6.5.2. Segmentation Based Dropping for Contention Resolution

If we consider that there are limited number of input channels to the of JET segmentation-based OBS network then the segmentation based dropping probability can be modeled as M/G/∞/$N_E W_E$ system [Neuts 2002]. The packet loss probability is given by

$$P = \sum_{k=n-1}^{N_E W_E} \left(\frac{k-n}{n} \frac{N_E W_E!}{k!(N_E W_E - k)!} \frac{(\frac{\lambda}{\mu})^k}{(1+\frac{\lambda}{\mu})^{N_E W_E}} \right) ; N_E W_E \geq n \tag{6.16}$$

Here the burst arrival process is Poisson with mean rate λ. The burst lengths are distributed with mean $1/\mu$. Let L represents the number of output links and each output link contains W data wavelength channels, n is the multiplication of the number of output links and the number of data channels in an output link, that is n=LW. $N_E W_E$ is the number of input channels. In this case

$$PB1 = \sum {}^{L}C_i (P_B)^i (1 - P_B)^{L-i} \tag{6.17}$$

$$PB2 = \sum_{k=n+1} \left(\frac{k-n}{k}\right)\left(\frac{N_E W_E)C_k}{(1+\rho)^{N_E W_E}} \rho^k\right) \tag{6.18}$$

The net blocking probability remains the same as before, which is

$$PB = PB1 + PB2 - PB1xPB2 \tag{6.19}$$

This equation simply is a union of the 2 call blocking probabilities obtained due to 2 different factors.

The Call connection probability is given by:

$$PC = 1 - PB \tag{6.20}$$

The above equations are used to find out the call connection probability for optical burst switching network using wavelength conversion and segmentation burst dropping scheme.

6.5.3 Simulation and Results

Equation (6.15) has been used to find out the call connection probability in a WDM network based on the wavelength conversion scheme. We have plotted the call connection probability against traffic density for different number of wavelength multiplexed in each link. Further the graphs also reveal the effect of the number of wavelength converters on the network performance.

Fig. 6.6 plots the call connection probability for the given number of links (*L*) between the source and the destination equal to 5 and the number of wavelengths multiplexed in each link (*W*) is 4. It is evident that the call connection probability falls quickly with increasing traffic density in the system without wavelength converters (*C=0*) as compared to the links having wavelength converters. This result is greatly influenced by inclusion of WCs. As for example call connection probability of the network without WC reaches to zero earlier than the networks with WCs. So the improvement of the network performance is achievable by using optimum number of WCs. Now if we compare the performance for different number of WCs then we can see that the performance is improving as is expected but at the same time cost and complexity is also increasing. So instead of going for full wavelength conversion, network designer can go for partial wavelength conversion. Use of partial conversion will provide significant improvement of the node performance with lesser cost and complexity.

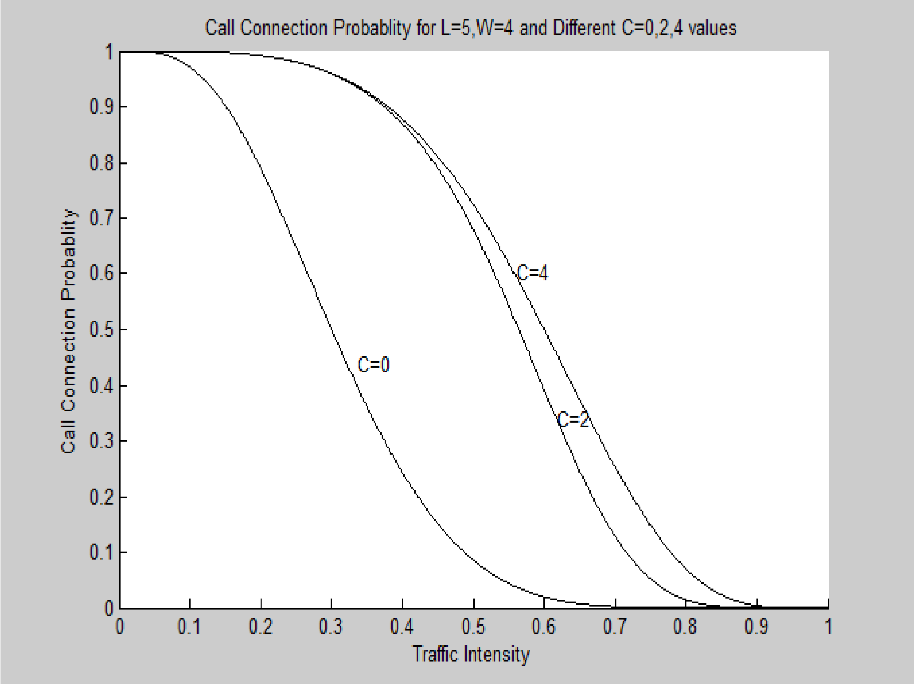


Fig. 6.6 Call Connection Probability vs Traffic Intensity for L=5 and W=4

The similar study is extended in fig. 6.7 by increasing the number of links from 5 to 10. Obviously the call connection probability will be lesser compared to the case reported in fig. 6.6. It is to be observed in fig. 6.6 that nearly 75% traffic intensity yields nearly 95% call connection probability for C=4. Fig. 6.7 shows that 95% call connection probability for traffic intensity of nearly 40% for the same *C*. Even this probability is satisfactory for 10 links.

In fig. 6.8 the performance of the network has been investigated for increased value of *W(W=6)*, i.e, the number of different wavelength multiplexed in the WDM system. As per the basic concepts of wavelength division multiplexing the network performance should be increased if more number of wavelength can be multiplexed simultaneously. This basic theory is verified in this figure.

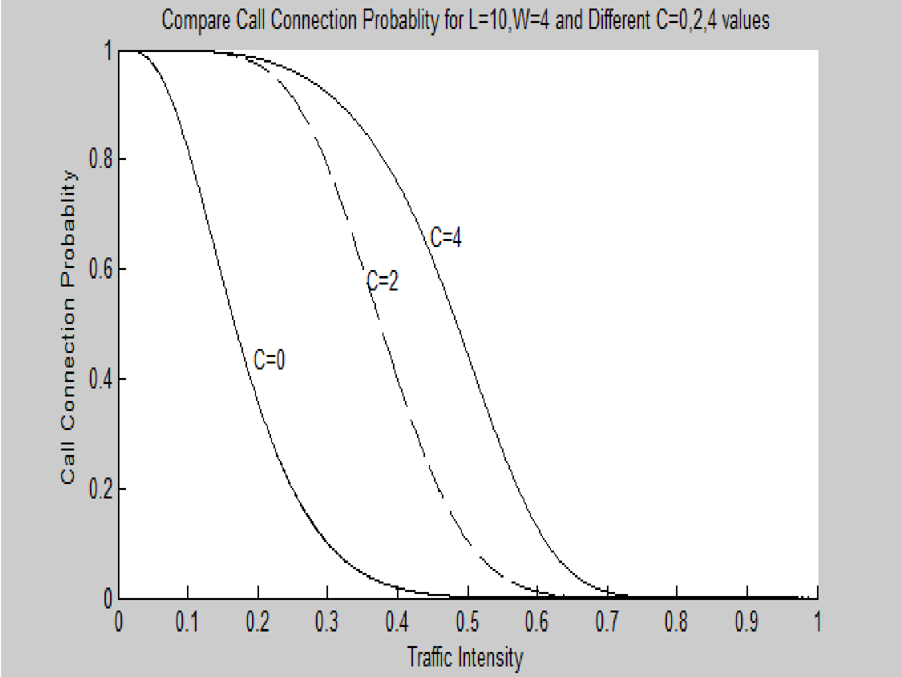


Fig 6.7 Call Connection Probability vs Traffic Intensity for L=10 and W=4

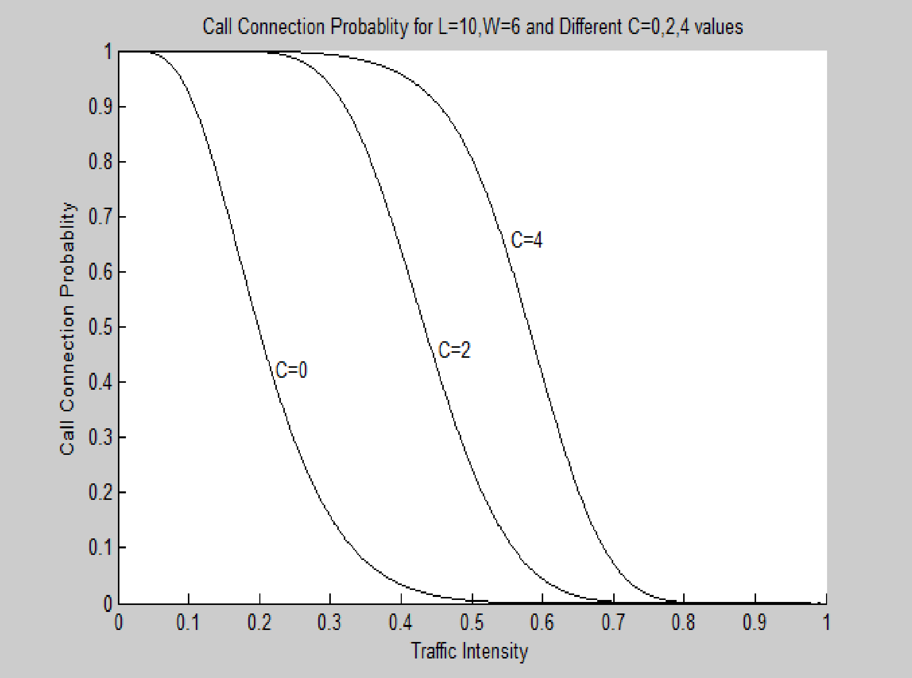


Fig: 6.8 Call Connection Probability vs Traffic Intensity for L=10 and W=6

As compared to fig 6.7 it is noticed that the call connection probability is improving significantly for all values of WCs. Off-course better result is available for higher number of WCs. It is interesting to note that for all the case whether changing the number of WCs or *W* or *L* the qualitative nature of the graphs remain same with a quantitative difference. It can be inferred that these network parameter will not change the basic operation mechanism of the network but only changes the relative performance.

We have extended the proposed algorithm to find out the performance of an optical network using segmentation based dropping scheme. Necessary changes are made in the mathematical model to incorporate the properties of segmentation dropping. Eqn. 6.20 gives the call connection probability for the proposed scheme.

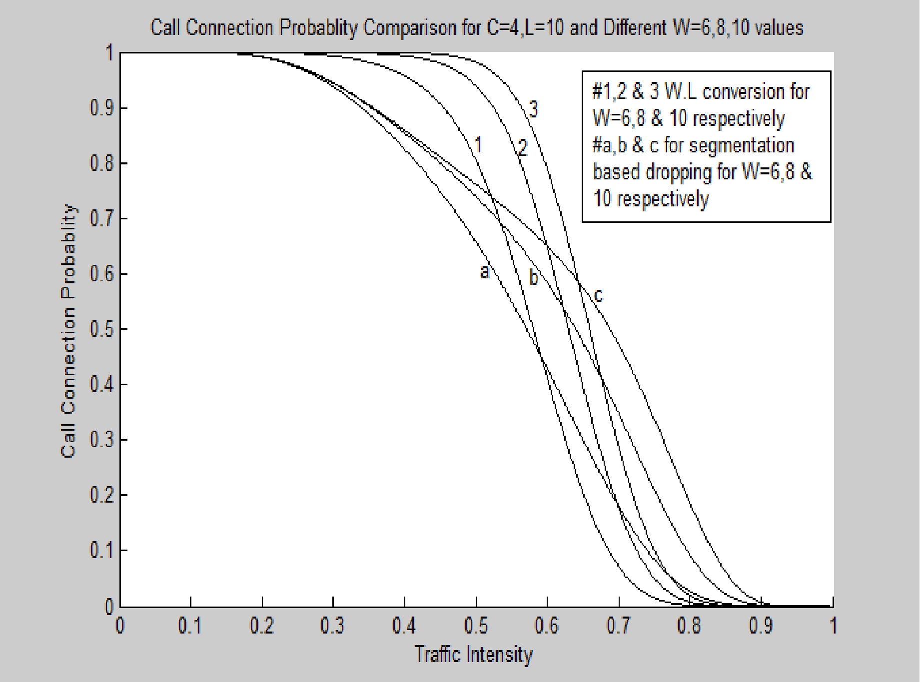


Fig. 6.9 Comparative Call Connection Probability vs Traffic Intensity for wavelength routed & segmentation dropping network for C=4 and L=10

Fig. 6.9 gives the comparative performance analysis of the of an optical network employing wavelength conversion and segmentation based dropping scheme respectively keeping all other network parameters unchanged. This analysis will help the network designer to take right decision regarding the type of contention resolution to be used for a given set of network parameters to get optimum performance in terms of call connection probability. As in case of segmentation based dropping scheme no wavelength converters are used so the varying parameters are *L* and *W*. In this figure the value of *C* is 4, *L* is10 and W as 6,8,9 have been taken. The result suggests that the network with WCs will provide better call connection probability for lesser incoming traffic at all values of *W*, but as the incoming traffic rate increases, segmentation dropping scheme performs better . It is necessary to note here that the performance of the network will changes significantly with the number of wavelength converters used.

Fig 6.10 depicts the call connection probability for *C=2*. This figure shows that for *C=2* for all values of *W* the segmentation based dropping scheme will give better result. This result highlights that the call connection probability changes significantly in case of wavelength converted network for decreasing the number of wavelength converters. Actually even if a few portion of the burst is dropped in segmentation process still this process can provide better result than partially wavelength converter. It should be noted here that if the degree of wavelength conversion increases and approaches towards the full conversion then that should be best possible contention resolution scheme but it is very difficult to implement.

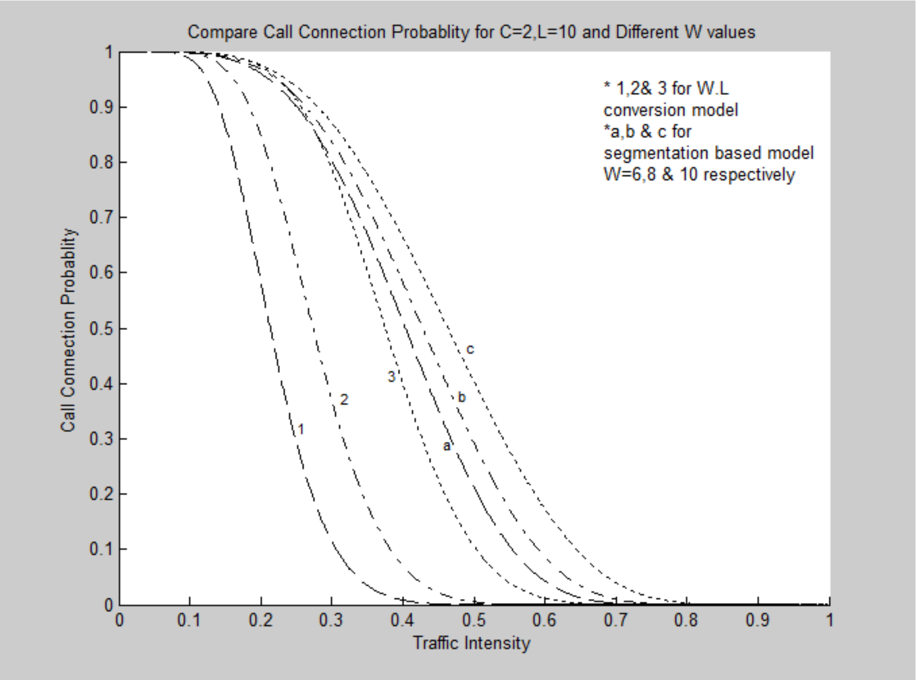


Fig 6.10 Comparative Call Connection Probability vs Traffic Intensity for wavelength routed & segmentation dropping schemens

6.6 Conclusion

A major concern in optical burst switched networks is contention, which occurs when multiple bursts contend for the same link. Contention in an optical burst switched network is particularly aggravated by the highly variable burst sizes and the long burst durations. Furthermore, since bursts are switched in a cut-through mode rather than a store-and-forward mode, optical burst-switched networks generally have very limited buffering capabilities. While existing contention resolution schemes for photonic packet networks, such as deflection and buffering, may be utilized in optical burst switched networks, additional schemes may also be necessary in order to combat high contention rates and to achieve high network utilization.

In this chapter a dropping based contention resolution scheme has been discussed. The basic mechanism behind this technique has been described along with the appropriate mathematical model to evaluate the overall blocking probability and to understand insight information of network operation. In the next section of this chapter a comparative analysis between wavelength conversion and segmentation based dropping scheme has been presented. The comparison is done in terms of call connection probability for the case of OBS network.

Finally the result and discussion section shows the variation of call connection probability vs incoming traffic intensity for various network parameters like number of input to output links, number of wavelength converters used, available wavelengths etc. Results obtained from this discussion provides an idea to the network designer about type of contention resolution scheme that should be useful for given set of network parameter values. Qualitative studies have been performed in due consideration of segmentation dropping and wavelength conversion scheme.

CHAPTER 7

CONCLUSIONS

This thesis addresses different contention resolution techniques in wavelength routed optical WDM networks to enhance its performance. The performance improvement has been measured in terms of blocking probability, throughput, resource utilization, average waiting time, burst loss probability, call connection probability etc. Unavailability of optical RAM to support very high speed of optical data transmission, especially in case of optical packet switching and optical burst switching networks, data congestions become a major challenge for researchers and network developer. Consequence upon this extensive research, efforts are put in this field and various methods are proposed in the literature to combat with this ever increasing network congestion problem. The proper employment of contention resolution schemes is still a big challenge for the researchers. In this thesis efforts have been made to develop few architectural models to use the available standard contention resolution schemes to realize some new node architecture, routing algorithm and protocols to achieve better contention resolution.

This chapter summarizes the major contributions made and also point out some possible future extension of the proposed methodology.

There are mainly four different types of contention resolution schemes available for an optical network. The space domain method is called deflection routing, in time domain network congestion can be controlled by employing fiber delay line while the wavelength domain counterpart is known as wavelength conversion. However if packet or burst dropping is unavoidable due to heavy congestion in network then instead of dropping the entire packet or burst only a segment of the burst is dropped to obtain minimum loss to realize a segmentation based dropping scheme. The last one is basically a dropping based contention resolution scheme. In this thesis different types of congestion control techniques are studied elaborately towards their congestion control capability with a view to develop proper mathematical model and corresponding simulations to establish qualitative and quantitative observations of congestion resolution.

In Ch.2 an intelligent deflection routed OBS network has been proposed to allocate wavelength dynamically. In the proposed model *N* of *W* wavelengths on each output link are allocated to the deflected bursts to decrease the possibility of multiple deflection. This phenomenon may cause higher traffic intensity and network congestion. Number *N* is determined dynamically in compliance with the deflected burst traffic intensity. In order to evaluate the impact of the dynamic allocation scheme on the OBS node performance, an analytical model for an OBS node with deflection routing scheme has been developed to estimate the average burst blocking probability. Mathematical equations have also been developed to characterize the behavior of the proposed node architecture and the results are validated with proper simulations. It is shown that the proposed model significantly decreases both, overall burst blocking probability and the deflected burst blocking probability. The proposed model has further been modified by incorporating an additional stage to the deflected bursts. This additional stage represents the FDL buffer to provide an extra offset time for the deflected burst that in turn decreases the burst blocking probability significantly. For example it can be seen that at normalized incoming traffic value equal to 1 the previous model gives a blocking probability of almost 0.7 which reduces to almost 0.001 in the modified case for N=0 as reported in fig 2.6. Hence the implementation of the dynamic resource allocation scheme in conjunction with deflection routing in an intelligent OBS network yields significant improvement on the nodal performance.

Several approaches have been proposed to manage the optical traffic through WDM network involving optical circuit switching, optical packet switching or optical burst switching with appropriate routing algorithms. WDM technology along with optical packet switching has changed the static usage of WDM network into an intelligent optical network capable of efficient routing and switching. However one of the key problems in application of packet switching in optical domain is the handling of packet contentions. In Ch.3 an attempt to explore the contention resolution in time domain approach has been made and an architectural model consisting of multiple loop delay to increase the throughput is proposed. In the proposed model a node has been considered with more input channels than output channels and the maximum capacity of this node is decided by the available output channel. It is assumed that arriving packets are destined to their respective destinations based on first come first serve (FCFS) scheduling policy, packets that arrive in the meantime are also sent to delay line. The node includes finite capacity buffer and multiple delay lines arranged in synchronized mode. Here we have assumed that the network is time slotted and the packets arrive at the interconnect at the beginning of time slots, and the duration of an optical packet is one time slot. Under these assumptions, the interconnect operates in a synchronized manner. The advantage of such a synchronized scheme is that it has better resource utilization than non synchronized schemes. The traffic is unicast, i.e., each packet is destined to only one output fiber. The performance of the algorithm has been evaluated using MATLAB simulation to establish a better contention resolution using a varied delay lines at the nodes.

In the next section of the same chapter an analytical approach has been used to evaluate the performance of an optical burst switched (OBS) network involving FDLs. The analytical model and suitable approximations yield important insights into the delay characteristics of OBS system operations over the entire range of FDL lengths, particularly in the regimes of short and long FDLs. The simulation result reveals that the use of FDLs can significantly reduce the burst-loss probability. An appropriate mathematical model is also developed to incorporate the impact of different node non-ideality factors on FDL performances. The discussion has further been extended to investigate the performance of fiber delay line based optical WDM node architecture using an almost optimal collision-free media access control protocol known as synchronous round robin (SRR) protocol. An appropriate node architecture model based on media access control protocols for bursty data traffic of variable time slot duration and data rate has been proposed. Mathematical expressions are developed to find-out the throughput performance of the proposed architecture. The results are validated with proper simulations.

In Ch.4 wavelength converters are used to reduce the contention in an WDM network. In the first part of the chapter we have analyzed traffic performance of an optical WDM network with wavelength converter under Erlang C traffic condition. Traffic parameters like number of output channels, number of wavelengths and number of hops, are considered. Performance of the network has shown large dependency on the number of output channels and hops. The analysis presented here is useful to predict the traffic throughput range of an all-optical network with wavelength converter and relevant design parameters. In the second part of the chapter, we have proposed a model in which the degree of wavelength routing node is considered. Simulation result shows that a significant improvement in the blocking performance of the node can be achieved by using wavelength conversion with small conversion degree (e.g. d = 2,3,4) as depicted in fig.4.9. These curves suggest that for no conversion case, the blocking may go upto 0.1 where as for d=2 & 3 the value drops to 0.001 and 0.0005 respectively for same utilization probability of 1. Moreover we see that utilization limited wavelength conversion with small conversion degrees and using small number of fiber link ports with big number of wavelength per link in a node is more effective choice. This model presented in this section can be used to the study of performance of all-optical wavelength router.

In Ch.5 we have suggested an architecture which efficiently reduces the network congestion in an optical burst switching (OBS) ring network without using any conventional contention resolution techniques. The backbone of our architecture is the use of a dummy node which helps the congested nodes to diverse their traffic through it. In this process, it decrease the packet dropping probability, hence increasing the throughput. A logical modification of the existing ring topologies for improved throughput and less network congestion can be achieved by using dummy node. In the present investigation an attempt has been made to model the proposed modified topologies providing a scope for better traffic utilization. Appropriate mathematical model is developed in due course to calculate average waiting time and average number of packets in a buffer for different packet arrival rate. The mathematical model has been verified by varying traffic conditions. The simulation results shows that the use of dummy node in an OBS ring network has significantly increases the average waiting time of an incoming burst and buffering capacity as well, which in turn reduces the burst dropping probability.

In the next section of the same chapter we have further extended the study to investigate the performance of the network under different standard signaling protocols namely Just-Enough-Time (JET) and Tell-And-Wait (TAW). These signaling techniques are evaluated for different data rate under the similar node and channel environment. It has also been observed from the analysis that channel bandwidth has a significant impact on the network control and transmission performance as is implicit from the derived expressions. The curves corresponding to TAW as depicted in fig. 5.7(b) are qualitatively similar to that of the curves obtained in case of JET as depicted in fig. 5.7(a) but with a quantitative higher value because of better bandwidth utilization in the latter case. For example it is observed that for same data rate (R=500 Mbps) and offered traffic (0.9) the amount carried traffic is only 40% in case of JET where as this improves beyond 50% for the case of TAW switching technique. The analysis conferms a superiority of TAW protocol over JET protocol in terms of traffic loss sensitivity. Evidently the model can be used to simulate the performance of different protocols by estimating the node parameters. In a realistic high speed WDM network accumulated channel noise and node non-linearity causes bandwidth limitation, time jitter and synchronization problem to influence the processing decisions and node parameters.

In existing contention resolution schemes for optical burst switched networks, when contention between two bursts cannot be resolved through other means, one of the bursts will be dropped in its entirety, even though the overlap between the two bursts may be minimal. For certain applications, which have stringent delay requirements but relaxed packet loss requirements, it may be desirable to lose a few packets from a given burst rather than losing the entire burst. In Ch.6 we have discussed a dropping based contention resolution technique called burst segmentation, in which only those packets that overlap with a contending burst will be dropped. Mathamatical model has been developed to findout the blocking probability for JET and JET_{seg}. It is concluded from the simulation result that JET_{seg} offers almost 25% better blocking probability performance than normal JET (fig. 6.3). In the consecutive section of the same chapter attempt has been made to compare the contention resolution efficiency of wavelength conversion and segmentation based dropping scheme in case of OBS network. Qualitative studies have been performed in due consideration of segmentation dropping and wavelength conversion scheme. Results obtained from this discussion shows that for partial wavelength conversion with less number of wavelength converters show poorer performance in comparison to segmentation dropping scheme(fig. 6.10). This conclusion provides an idea to the network designer about type of contention resolution scheme that should be useful for given set of network parameter values.

Future Scopes

Areas for future work include developing an analytical model for an OBS network with burst segmentation. Introducing the wavelength dimension and buffering into the simulation model will provide more options for contention resolution. Another area for future work is the investigation of combined segmentation/ deflection schemes in which deflection is performed before segmentation when a contention occurs. The segment dropping and deflection policies can also be implemented with priorities. Priorities would be based on a burst's tolerance for segmentation, deflection, and loss. Design of efficient scheduling algorithms and analyzing the guarantees provided by the scheduler is another challenging issue in OBS networks. Since the one-way reservation mechanism used in OBS networks can be fairly modeled with advanced reservation systems, guarantees in terms of the number of bursts serviced per unit time would be of great use in delivering guaranteed throughput of bursts at the core nodes. So far most of the literature on the design and analysis of scheduling algorithms tried to improve only the time complexity but not the throughput of the algorithms which is also an important measure to ensure a guaranteed loss rate.

[Acampora 1992]A. S. Acampora and I. A. Shah, "Multihop lightwave networks: A comparison of store-and-forward and hot-potato routing", IEEE Transactions on Communications, vol 40(6), pp.1082–1090, June 1992.

[Alferness 2000] R.C. Alferness, H. Kogelnik, and T.H. Wood, “The evolution of optical systems: Optics everywhere,” Bell Labs Technical Journal, vol. 5, no. 1, Jan-March 2000.

[Ali 2000] M. Ali and J. S. Deogun, “Cost-effective implementation of multicasting in wavelength-routed networks,” J. Lightwave Technol., vol. 18, pp. 1628–1638, Dec. 2000.

[Allen 1990] Arnold O. Allen ,”Probability, Statistics, and Queueing Theory with Computer Science Applications,” Academic Press INC, USA 1990.

[Alvaro 2009] Alvaro L. Barradas and Maria do Carmo R. Medeiros, “Edge-Node Deployed Routing Strategies for Load Balancing in Optical Burst Switched Networks”, ETRI Journal, Volume 31, Number 1, February 2009.

[Amstutz 1983] S. Amstutz, “Burst switching - an introduction,” IEEE Communications Magazine, vol. 21, pp. 36–42, November 1983.

[Amstutz 1989] S. Amstutz, “Burst switching - an update,” IEEE Communications Magazine, vol. 21, pp. 50–57, September 1989.

[Arakawa 2004] Y. Arakawa, N. Yamanaka, and I. Sasase, "Performance of optical burst switched WDM ring network with TTFR system", in 1st IFIP Optical Networks & Technologies Conf. (OpNeTec),Pisa, Italy, pp. 95–102, Oct. 2004.

[Bala 1997] K.Bala, E.Bouillet and G.Ellinas, "Benefits of Minimal Wavelength Interchange in WDM Rings," in Proc. of the OFC, 97,pp. 120-121, 1997.

[Banerjee 1996] S.Banerjee and C.Chen, " Design of Wavelength-Routed Optical Networks for Circuit Switched Traffic," in Proc. of GLOBECOM, 96, (London), pp. 306-310, 1996.

[Barry 1994] R.A.Barry and P.A.Humblet, " On the Number of Wavelengths and Switches in All-Optical Networks," IEEE Transaction on Communications, vol. 42, pp. 868-880, Feb-April 1994.

[Barry 1996] R. A. Barry and P. A. Humblet, “Models of blocking probability in all optical networks with and without wavelength changers,” IEEE J. Select. Areas Commun., vol. 14, pp. 858–867, Jun. 1996.

[Bawab 2002] El-Bawab T.S.Shin J.D. " Optical Packet Switching in Core Networks : Between Vision and Reality", IEEE Communications Magazine 40,(9), pp.60-65, 2002.

[Birman 1996] A. Birman, “Computing approximate blocking probabilities for a class of all-optical networks,” IEEE J. Select. Areas Commun., vol. 14, pp. 852– 857, June 1996.

[Bonani 2007] Bonani, L.H. Barbosa, F.R.Moschim, "Optical Packet/Burst Switching Node Architecture with WDM Hierarchical Issues", Microwave and Optoelectronics Conference, IMOC 2007, SBMO/IEEE MTTT-S International, pp. 351-355, 2007.

[Bononi 1999] A. Bononi, G. A. Castanon, and O. K. Tonguz, “Analysis of Hot-Potato Optical Networks with Wavelength Conversion”, IEEE Journal of Lightwave Technology, vol.17, no. 4, pp. 525-534, April 1999.

[Borgonovo 1994] F. Borgonovo, L. Fratta, and J. A. Bannister, “On the design of optical deflection- routing networks,” in PROC. IEEE INFOCOM, vol. 1, Toronto, ON, Canada, Mar. 1994, pp. 120–129, 1994.

[Bouabdallah 2003] N. Bouabdallah, A. L. Beylot, and G. Pujolle, "Collision avoidance and fairness issues in metropolitan bus-based optical access networks", Technical Report, Paris University, 2003.

[Bracket 1993] C. A. Brackett et al., “A scalable multi-wavelength multihop optical network: A proposal for research on all-optical networks,” J. Lightwave Technol., vol. 11, pp. 736–753, May/June 1993.

[Brackett 1990] C. A. Brackett, “Dense wavelength division multiplexing networks: Principles and applications,” IEEE J. Select. Areas Commun., vol. 8, pp. 948–964, Aug. 1990.

[Callegati 1999] F. Callegati, A. C. Cankaya, Y. Xiong, and M. Vandenhoute, “Design issues of optical IP routers for Internet backbone applications,” IEEE Communications Magazine, vol. 37, pp. 124–128, December 1999.

[Callegati 2000] F.Callegati, "Optical Buffers for Variable Length Packets", IEEE Communications Letters, Vol 4, no. 9, pp. 292-294, Sept. 2000.

[Castanon 1999]G. Castanon, L. Tancevski, and L. Tamil, "Routing in all-optical packet switched irregular mesh networks", In Proceedings, IEEE Globecom, pp. 1017–1022, December 1999.

[Chatterjee 1999] S. Chatterjee and S. Pawlowski, “All-optical networks,” Communications of the ACM, vol. 42, no. 6, pp. 74–83, June 1999.

[Chaubey 2009] V K Chaubey and Kiran Divakar, (2009) “ Modeling and simulation of WDM optical networks under traffic control protocols “ Optical Fiber Technology, Vol.15, pp. 95-99, 1999.

[Chen 2002] B. Chen and J. Wang, “Efficient routing and wavelength assignment for multicast in WDM networks,” IEEE J. Select. Areas Commun., vol. 20, pp. 97–109, Jan. 2002.

[Chen 2003] Y. Chen, H. Wu, D. Xu, and C. Qiao, "Performance analysis of optical burst switched node with deflection routing," in Proceedings of IEEE ICC 2003, 2ed, pp. 1355-1359, 2003.

[Chen 2004] Y. Chen, C. Qiao, and X. Yu, “Optical burst switching: A new area in optical networking research,” IEEE Netw. Mag., vol. 18, no. 3, pp. 16–23, May/Jun. 2004.

[Chen 2004] Y.Chen, C.Qiao, and X.Yu, “Optical Burst Switching: A New Area in Optical Networking Research,” IEEE Network, vol. 18, 2004, pp.16-23, 2004.

[Chich 2001] T. Chich, J. Cohen, and P. Fraigniaud, “Unslotted deflection routing: A practical and efficient protocol for multihop optical networks,” IEEE/ACM Trans. Netw., vol. 9, pp. 47–59, Feb. 2001.

[Chlamatac 1996] I. Chlamtac, A. Fumagalli, L. G. Kazovsky, and et al., “CORD: Contention resolution by delay lines,” IEEE Journal on Selected Areas in Communications, vol. 14, no. 5, pp. 1014–1029, June 1996.

[Chlamtac 1992] I. Chlamtac, A. Ganz, and G. Karmi, “Lightpath communications: An approach to high bandwidth optical WANs,” IEEE Transactions on Communications, vol. 40, no. 7, pp. 1171–1182, 1992.

[Chlamtac 1993] I. Chlamtac, A. Ganz and G. Karmi, “Lightnets: Topologies for high-speed optical networks,” IEEE/OSA J. Lightwave Tech., vol 11, pp 951-961, May/June 1993.

[Chlamtac 1995] I. Chlamtac, A. Fumagalli, L. G. Kazovsky, and P. T. Poggiolini, "A Contention/Collision Free WDM Ring Network for Multi Gigabit Packet Switched Communication", In Journal of High Speed Networks, Vol. 4, No. 2, pp. 201-219, 1995.

[Chlamtac 1996] Imrich Chlamtac, A.Farago and T.Zhang," Lightpath (Wavelength) Routing in Large WDM Networks," IEEE Journal on Slected Areas in Communications, vol. 14, pp. 909-913, June 1996.

[Chlamtac 1999] G. Castanon, L. Tancevski, and L. Tamil, “Routing in all-optical packet switched irregular mesh networks,” in Proc. IEEE GLOBECOM, Rio de Janeiro, Brazil, pp. 1017–1022, Dec. 1999.

[Chlamtac 2000] I. Chlamtac, A. Fumagalli, and C.-J. Suh, “Multibuffer delay line architectures for efficient contention resolution in optical switching nodes,” IEEE Transactions on Communications, vol. 48, no. 12, pp. 2089–2098, December 2000.

[Chu 2002] P. B. Chu, S.-S. Lee, and S. Park, “MEMS: The path to large optical cross-connects,” IEEE Commun. Mag., pp. 80–87, Mar. 2002.

[Chua 2007] K. C. Chua, M. Guruswamy, Y. Liu, and M. H. Phung, "Quality of Service in Optical Burst Switched Network", Springer, New York, USA, 2007.

[Corazza 1999] F.C.G Corazza and C.Raffaelli, "An Optical Packet Switch with a Multi-Stage Buffer for IP Traffic", Optical Networking, A.Banoni (Ed), Springer, pp.300-311,1999.

[Detti 2002] A. Detti, V. Eramo, and M. Listanti, "Performance evaluation of a new technique for IP support in a WDM optical network: optical composite burst switching (OCBS)," Journal of Lightwave Technology, vol. 20, no. 2, pp. 154-165, 2002.

[Develder 2002] C. Develder, M. Pickavet, and P. Demeester, "Assessment of Packet Loss for an Optical Packet Router with Recirculating Buffer," Proc. Conf. Optical Network Design and Modeling, pp. 247- 261, 2002.

[Diano 1999] J. Diao and P. Chu. "Analysis of partially shared buffering for WDM optical packet switching", IEEE/OSA J. Lightwave Technol., 17(12), pp.2461–2469, 1999.

[Dogan 2006] K. Dogan and N. Akar, "A Performance Study of Limited Range Partial Wavelength Conversion for Asynchronous Optical Packet/Burst Switching", in proceedings, IEEE 202 International Conference on Communications 2006 (ICC'06) , Istanbul, Turkey, Vol. 6, pp. 2544-2549, June 2006.

[Dozer 2001] K. Dozer, C. Gauger, J .Spath, and S. Bodamer, "Evaluation of Reservation Mechanisms for Optical Burst Switching," AEU International Journal of Electonics and Communications, vol. 55(1), pp. 2017- 2022, January 2001.

[DU 2006] Ping DU and Shunji ABE, "Burst Assembly Method with Traffic Shaping for the Optical Burst Switching Network", in Proceedings, IEEE Global Telecommunications Conference 2006 (GLOBECOM 2006), San Francisco, CA, USA, November-December 2006.

[Dutta 2009] Dutta.M.K, Chaubey .V.K, : Optical Network Traffic Control Algorithm under Variable Loop Delay: A Simulation Approach, Int. J. Communications, Network and System Sciences, 7,pp. 651-655,(2009).

[Dutta 2011] M. K. Dutta , V.K. Chaubey, "Modeling and performance analysis of optical WDM node architecture using SRR protocol", Optik vol. 123, pp.1971– 1974, 2012

[Dutta 2012] M.K.Dutta, V.K.Chaubey, “Modeling and Characterization of Modified Optical Burst Switching (OBS) Ring Network Using Proxy Node”, International Journal on Advanced Science Engineering Information Technology Vol. 2 No. 1, ISSN: 2088-5334, pp. 75-79, 2012.

[Dutta 2012a] M.K.Dutta and V.K.Chaubey, “Performance Analysis of Modified Optical Burst Switching (OBS) Ring Network Using Dummy Node”, Optik vol. 123 , pp.1847–1851, 2012.

[Eramo 2003] V. Eramo, M. Listanti, and P. Pacifici, “A comparison study on the wavelength converters number needed in synchronous and asynchronous all-optical switching architectures,” IEEE/OSA Journal of Lightwave Technology, vol. 21, no. 2, pp. 340–355, February 2003.

[Fabry-Asztalos 2000] T. Fabry-Asztalos, N. Bhide, and K. M. Sivalingam, “Adaptive Weight Functions for Shortest Path Routing Algorithms for Multi-Wavelength Optical WDM Networks,” IEEE ICC 2000, pp. 1330 -1334, 2000.

[Farahmand 2004] F. Farahmand, Q. Zhand, J. P. Jue, “A Feedback-Based Contention Avoidance Mechanism for Optical Burst Switching Networks”, 2004.

[Fiems 2005] D.Fiems, K. Laevens, and H.bruneel, " Performance Analysis of an All-Optical Packet Buffer", IEEE Conference of Optical Design and Modeling, pp. 221-226, February 2005.

[Forghieri 1995] F. Forghieri, A. Bononi, and P. R. Prucnal, “Analysis and comparison of hot-potato and single-buffer deflection routing in very high bit rate optical mesh networks,” IEEE Trans. Commun., vol. 43, no. 1, pp. 88–98, Jan. 1995.

[Frans 1998] J. Fransson, M. Johansson, M. Roughan, L. Andrew, and M. A. Summerfield: Design of a Medium Access Control Protocol for a WDMA/TDMA Photonic Ring Network. In Procs. of IEEE Global Telecommunications Conference (GLOBECOM'98), pp.307-312, Sydney, Australia, November 8-12, 1998.

[Fugumagalli 2003] Fumagalli, A. Krishnamoorthy, P, "A Low-Latency and Bandwidth-Efficient Distributed Optical Burst Switching Architecture for Metro Ring", in Proc. of ICC, vol. 2, pp. 1340 – 1344, May 2003.

[Fumagalli 2003] A. Fumagalli and P. Krishnamoorthy, "A low-latency and bandwidth-efficient distributed optical burst switching architecture for metro ring", In Proceedings of IEEE ICC, volume 2, pp. 1340–1344, 2003.

[Gambini 1998] Gambini P., Renaud M., Guillemot C. et al., "Transparent Optical Packet Switching: Network Architecture and Demonstrators in KEOPS Project", IEEE Journal on Selected Areas in Communications 16, (7), pp.1245-1259, 1998.

[Gao 2003] S. X. Gao, et al., "An optimization model for placement of wavelength converters to minimize blocking probability in WDM networks", Journal of Lightwave Technology 21 (3) pp.684-694, 2003.

[Gauger 2001] Dolzer, K., Gauger, C., "On burst assembly in optical burst switching networks – a performance evaluation of Just-Enough-Time", Information Theory Conf., vol.4, pp. 149–160, 2001.

[Gauger 2002] C. Gauger, “Contention resolution in optical burst switching networks,” In advanced infrastructures for photonic networks: WG 2 Intermediate Rep., [Online]. Available:http://www.ikr.uni-stuttgart.de/Content/Publications/ Archive/Ga_COST266WG2_34 734.ps.gz, 2002.

[Gauger 2002] C. Gauger, “Performance of converter pools for contention resolution in optical burst switching,” in Proc. SPIE Optical Netw. Commun. Conf. (OptiComm 2002), Boston, MA, pp. 109–117, Jul. 2002.

[George 2004] George N. Rouskas, Lisong Xu, “Chapter 1: Optical Packet Switching“, in Book Optical WDM Networks: Past Lessons and Path Ahead, Kluwer, Massachusetts, 2004.

[Georgios 2003] Georgios I. Papadimitriou, Chrisoula Papazoglou, and Andreas S. Pomportsis, " Optical Switching: Switch Fabrics, Techniques, and Architectures ", IEEE Journal of Lightwave Technology, Vol. 21, No. 2, February 2003.

[Gerstel 1997] O.Gerstel, P.Lin and G.H.Sasaki, " A New Angle on Wavelength Assignment in WDM Rings: Minimize System Cost, Not Number of Wavelengths., " in Proc. of IEEE INFOCOM, 98, (San Franscisco, CA, USA), Apr. 1998.

[Gerstel 1997a] O. Gerstel, R. Ramaswami, and G. Sasaki, “Fault-tolerant multi-wavelength optical networks with limited wavelength conversion,” in Proc. IEEE INFOCOM’97, vol. 2, pp. 507–515, Apr. 1997.

[Gerstel 1997b] O.Gerstel, R.ramaswami and G.H.Sasaki, "Benefits of Limited Wavelength Conversion in WDM Ring Networks," in Proc. of the OFC,97, Apr. 1997.

[Gerstel 1998c] O.Gerstel , R.Ramaswami and G.H.Sasaki, "Cost effective Traffic Grooming in WDM Rings.," in Proc. of IEEE INFOCOM, 98, (San Franscisco, CA, USA), Apr. 1998.

[Green 1996] P. Green, "Optical Networking Update", IEEE J. Select. Areas in Commun., vol. 14, pp. 764-779, June 1996.

[Green 2001] P. Green, “Progress in optical networking,” IEEE Commun. Mag., pp. 54–61, Jan. 2001.

[Harai 1997] H.harai, M.Murata and H.Miyahara, " Performance of Alternate Routing Methods in All-Optical Networks," in Proc of the IEEE Infocom , vol. 97, (Tokyo, Japan), 1997.

[Harai 1999] Harai H., et al., "Heuristic algorithm for allocation of wavelength convertible nodes and routing coordination in all-optical networks", Journal of Lightwave Technology, vol. 17 (4), pp.535 -545, 1999.

[Harao 2006] Hiroaki Harai, Motoshi Suzuki and Takeshi Ozeki, “Buffer Management for Shared Feedback Buffer-Type Optical Packet Switches”, in proceedings, IEEE International Conference on Communications 2006 (ICC’06) , Istanbul, Turkey, Vol. 6, pp. 2474-2480, June 2006.

[Haridos 2002] Haridos, K., Vokkarance, V., Jue, J. P, “Threshold-based burst assembly policies for QoS support in optical burst-switched networks”. Opticomm, pp. 125–136, 2002.

[Haselton 1983] E. Haselton, “A PCM frame switching concept leading to burst switching network architecture,” IEEE Communications Magazine, vol. 21, pp. 13–19, June 1983.

[Hsu 2001] C. F. Hsu, T. L. Liu, and N. F. Huang, “Performance of Adaptive Routing Strategies in Wavelength-Routed Networks,” IEEE IPCCC, pp. 163 -170, 2001.

[Hsu 2002] C. Hsu, T. Liu, and N. Huang, “Performance analysis of deflection routing in optical burstswitched networks,” in Proceedings, IEEE Infocom, vol. 1, pp. 66–73, , 2002.

[Hsu 2002] C.F. Hsu, T.-L. Liu, and F.-F. Huang, “Performance analysis of deflection routing in optical burst-switched networks,” in Proc. IEEE INFOCOM, vol. 1, New York, pp. 66–73, Jun. 2002.

[Hsu 2002] Ching-Fang Hsu, Te-Lung Liu, and Nen-Fu Huang. “On the deflectionbrouting in QoS supported in WDM Optical burst-switched Networks”, IEEE International Conference on Communications, vol. 5, pp. 2786-2790, 2002.

[Hui 1990] J. Y. Hui “Switching and Traffic Theory for Integrated Broadband Networks.” Norwell, MA: Kluwer Academic 1990.

[Hunter 1998] D. K. Hunter, M. C. Chia, and I. Andonovic, “Buffering in optical packet switches,” IEEE/OSA Journal of Lightwave Technology, vol. 16, no. 12, pp. 2081–2094, December 1998.

[Hunter 1998] D.K.Hunter, M.C.Chia, and I.Andonovic, "Buffering in Optical Packet Switches", Journal of Lightwave Technology, vol. 16, no 12, pp. 2081-2094, December 1998.

[Hunter 1999] D. K. Hunter et al., “WASPNET: A wavelength switched packet network,” IEEE Communications Magazine, pp. 120–29, March 1999.

[Hunter 2000] D. K. Hunter and I. Andronovic, “Approaches to optical Internet packet switching,” IEEE Communications Magazine, vol. 38, pp. 116–122, September 2000.

[Hunter 2006] Zhang T., Lu K., Jue J. P. “Shared Fiber Delay Line Buffers in Asynchronous Optical Packet Switches”, IEEE Journal on Selected Areas in Communications 24, 4 (Apr.), pp. 118–127, 2006.

[Iness 1999] J. Iness and B. Mukherjee, "Sparse wavelength conversion in wavelength-routed WDM optical networks", Photonic Network Communications 11, vol. 11, pp. 183-205, (1999).

[Jason 2005] Jason P. Jue, Vinod M, Vokkarane,"Optical Burst Switched Network" Springer, NewYork , NY 10013, USA, 2005.

[Jong 2002] J. Jong, "Multicast access protocols in an optical burst switched wdm ring network. Master's thesis", NC State University, 2002.

[Jourdan 2001] A. Jourdan, D. Chiaroni, E. Dotaro, G. J. Eilenberger, F. Masetti, and M. Renaud, "The perspective of optical packet switching in IP dominant backbone and metropolitan networks," IEEE Communications Magazine, vol. 39, pp. 136–141, March 2001.

[Jue 2000] J. Jue et al., "An adaptive routing algorithm for wavelength routed optical networks with a distributed control scheme," in Proceedings of the Ninth International Conference on Computer Communications and Networks, Las Vegas, Nevada, USA, pp. 192–197, October 2000.

[Jue 2002]J.P. Jue. "An algorithm for loopless deflection in photonic packet-switched networks", In Proceedings, IEEE International Conference on Communications (ICC), April 2002.

[Jue 2005] J.P.Jue and V.M.Vokkarane, "Optical Burst Switched Networks", Springer, 2005.

[Kim 2002] S. Kim, N. Kim, and M. Kang, "Contention resolution for optical burst switching networks using alternative routing," in Proc. IEEE ICC, vol.5, New York, pp. 2678–2681, Apr./May 2002.

[Kim 2002] Sungchang Kim, Namook Kim, and Minhon Kang. "Contention resolution for optical burst switching networks using alternative routing", IEEE International Conference on Communications, vol. 5, pp. 2678-268,2002.

[Kleinrock 1975] Kleinrock, L. Queuing Systems, Theory. Vol. 1. New York: Wiley Interscience 1975.

[Kovacevic 1996] M. Kovaˇcevi´c and A. Acampora, “Benefits of wavelength translation in all-optical clear-channel networks,” IEEE J. Select. Areas Commun., vol. 14, pp. 868–879, June 1996.

[Kovacevic 1996] Milan Kovacevic and A. Acampora, " Benefits of Wavelength Translation in All-Optical Clear Channel Networks," IEEE Journal on Slected Areas in Communications, vol.14, pp. 868-880, June 1996.

[Laevens 2003] K.Laevens and H. Bruneel, " Analysis of Single Wavelength Optical Buffer", in Proceedings IEEE INFOCOM 2000, vol.3 , SanFransisco, CA,USA, pp. 2262-2267, March 2003.

[Lazzez 2005] Amor Lazzez, Noureddine Boudriga, M.S. Obaidat, “Optical Switching Techniques In WDM Optical Networks”, in Book “Handbook of Computer Networks”, Volume I, Editor-in-Chief, Hossein Bidgoli, August 2005.

[Lee 1993] K.C.Lee and V.O.K.Li, " A Wavelength-Convertible Optical Network," IEEE Journal of Lightwave Technology, vol. 11, pp. 962-970, May-June 1993.

[Lee 2003] S. Lee, K. Sriram, H. Kim, J. Song, “Contention-based Limited Deflection Routing in OBS Networks” in proceedings of Globecom 2003, pages 2633-2637.

[Li 2002] C. Y. Li et al., “Deflection routing in slotted self-routing networks with arbitrary topology,” in Proc. IEEE ICC, vol. 5, New York, pp. 2781–2785, Apr./May 2002.

[Li 2004] J.Li and C.Qiao, “Recent Progress in Scheduling Algorithms in Optical Burst-Switched Netwroks,” OSA Journal of Optical Networking, Vol.3, pp. 229-241, 2004.

[Lin 2007] W.Lin , R.S.Wolff and B.Mumey, “A Markov-Based Reservation Algorithm for Wavelength Assignment in All-Optical Networks,” Journal of Lightwave Technology, vol.25, No.7 ,pp. 1676-1683, July 2007.

[Lin 2008] H.T. Lin and W.-R. Chang, "CORNet: an OBS metro ring network with QoS support and fairness control", Comput. Netw., vol. 52, pp. 2045–2064, 2008.

[Lisong 2003] Lisong Xu, Harry G. Perros, George N. Rouskas, "A Simulation Study of Optical Burst Switching and Access Protocols for WDM Ring Networks", Computer Networks, pp.143-160, 2003.

[Lu 2004] X. Lu and B. L. Mark, "Performance modeling of optical-burst switching with fiber delay lines," IEEE Transactions on Communications, vol. 52, no. 12, pp. 2175-2183, 2004.

[M.Ljolje 2005] M. Ljolje, Robert Inkret, and Branko Mikac, " A Comparative Analysis of Data Scheduling Algorithms in Optical Burst Switching Networks," In Proceeding of Optical Network Design and Modeling, pp 493- 500, 2005.

[Mahony 2001] M. J. O'Mahony, D. Simeonidou, D. K. Hunter, and A. Tzanakaki, "The application of optical packet switching in future communication networks," IEEE Communications Magazine, vol. 39, pp. 128–135, March 2001.

[Maier 2008] Martin Maier, "Optical Switching Networks" Cambridge University Press 2008, New York.

[Masetti 2002] F. Masetti et.al., "Design and Implementation of a Multi-Terabit Optical Burst/Packet Router prototype," in OFC Postdeadline Papers, pp. FD11–FD13, 2002.

[MCNCRDI 2003] "JumpStart JIT Signaling Definition, Revision 1.17," Tech. Rep., MCNCRDI ANR and North Carolina State Univ, Raleigh, NC, [Online]. Available: http://jumpstart.anr.mcnc.org/Docs/03_05_12/SignalingDefinition. pdf, 2003.

[Mei 2009] Li-Mei Peng and Young-Chon Kim, "Investigation of the Design of MAC Protocols for TT-TR-Based WDM Burst-Switched Ring Networks", J. Opt. Commun. Netw. , vol. 1, no. 2, July 2009.

[Mellaah 2006] H.Mellah and F.M.Abbou, " Cntention Resolution in Slotted WDM Optical Packet Switching Networks Using Cascaded Auxilary Switch", IEE Proceedings of Communications, vol. 153, no.2, pp. 205-206, April 2006.

[Mukherjee 1997] B. Mukherjee, "Optical Communications Networks", McGraw-Hill, New York, 1997.

[Mukherjee 2000] B.Mukherjee, “WDM optical communication networks: Progress and challenges,” IEEE Journal on Selected Areas in Communications, vol. 18, no. 10, pp. 1810-1823, Oct. 2000.

[Mukherjee 2001] B.Mukherjee, "WDM Optical Communication Networks: Progress and Challenges", IEEE Journal on Selected Areas in Communications, vol. 18,no.10,pp.1810-1824, October 2000.

[Mukherjee 2004] A. Mukherjee, S.P. Singh, V.K. Chaubey, “Wavelength conversion algorithm in an intelligent WDM network”, Opt. Commun. 230, pp. 59–65, 2004.

[Mukherjee 2004] A. Mukherjee, S.P.Singh and V.K.chaubey, " Wavelength Conversion Algorithm in an Intelligent WDM Network", Optics Commujnications 230, pp. 59-65, 2004.

[Myers 2001] A. Myers and P. Bayvel, “Performance of the just-enough-time (JET) scheme for optical burst switching,” in Proc. of London Communications Symposium (LCS2001), pp. 163–166, Sept. 2001.

[Neuts 2002] Neuts, M. Rosberg, Z., Vy, H.L.White , J.,Zukerman , M., "Performance Analysis of optical composite burst switching", IEEE Communication Letters 6 ,(8) , pp. 346-348, 2002.

[Neuts 2002] Neuts, M., Rosberg, Z., Vu, H. L., White, J., Zukerman. M, " Performance analysis of optical composite burst switching", IEEE Communications Letters vol. 6 (8), pp. 346–348 , 2002.

[O.Gerstel 1997d] O.Gerstel and S.Kutten, " Dynamic Wavelength Allocation in WDM Ring Networks," in Proc. of IEEE INFOCOM, 97, (Tokyo, Japan),Apr 1997.

[Pankaj1999] R. K. Pankaj, “Wavelength requirement for multicasting in all-optical networks,” IEEE/ACM Trans. Networking, vol. 7, pp. 414–424, Jun. 1999.

[Peng 2005] L. M. Peng, K. M. Yoo, and Y. C. Kim, "Design and performance evaluation of token based MAC protocols in WDM burst switched ring networks", in 2nd Int. Conf. Distributed Computing and Internet Technologies, Bhubaneswar, India, pp. 21–26, Dec. 2005.

[Peng 2008] L. M. Peng, K. M. Yoo, and Y. C. Kim, "Design and performance comparison of multiple- token based MAC protocols for optical burst switched ring networks", Photonic Network Commun., vol. 15, pp. 213–225, 2008.

[Pointurier 2006] Y. Pointurier, M. Brandt-Pearce, T. Deng, and S. Subramaniam, “Fair QoS-Aware Adaptive Routing and Wavelength Assignment in All-Optical Networks ”, In proceedings, IEEE International Conference on Communications 2006 (ICC’06) , Istanbul, Turkey, Vol. 6, pp. 2433-2438, June 2006.

[Puttasubbappa 2004] V. S. Puttasubbappa and H. G. Perros "Access protocols to support different service classes in an optical burst switching ring", In Networking 2004, Athens, May 2004.

[Qiao 1999] C. Qiao and M. Yoo, “Optical burst switching (OBS) - a new paradigm for an optical Internet,” Journal of High Speed Networks, vol. 8, no. 1, pp. 69–84, January 1999.

[Qiao 2000] C. Qiao, “Labeled optical burst switching for IP-over-WDM integration,” IEEE Communications Magazine, vol. 38, no. 9, pp. 104–114, September 2000.

[Qiao 2000a] C. Qiao and M. Yoo, “Choices, features and issues in optical burst switching,” Optical Networks Magazine, vol. 1, no. 2, pp. 36–44, 2000.

[Qiao 2001] C.Qiao and .DIxit, “Optical Burst Switching for Service Differentiation in the next –Generation Optical Internet, IEEEComm. Magazine, pp. 98-104, Feb.2001.

[Qin 2002] X. Qin and Y. Yang, “A cost-effective construction for WDM multicast switching networks,” in Proc. of IEEE International Conference on Communications (ICC) 2002, pp. 2902-2906, New York, NY, April 2002.

[Ramamirtham 2003] J. Ramamirtham, J. Turner, and J. Friedman, "Design of wavelength converting switches for optical burst switching," IEEE Journal on Selected Areas in Communications, vol. 21, no. 7, pp. 1122-1132, 2003.

[Ramamurthy 1998] B.Ramamurthy and B.Mukherjee, "Wavelength Conversion in WDM Networking," IEEE Journal on Selected Areas in Communications, vol. 16,pp.909-912, Sept. 1998.

[Ramaswami 1993] R. Ramaswami 1999, “Multiwavelength networks for computer communications,” IEEE Commun. Mag., vol. 31, pp. 78–88, Feb. 1993.

[Ramaswami 1994] R. Ramaswami and K. Sivarajan, “Optimal routing and wavelength assignment in all-optical networks,” Proceedings of the IEEE INFOCOM, pp. 970-983, 1994.

[Ramaswami 1997] R.Ramaswami and G.H.Sasaki, " Multiwavelength Optical Networks with Limited Wavelength Conversion," in Proc. of IEEE INFOCOM, 97, (Tokyo, Japan),Apr 1997.

[Ramaswami 1998].R R. Ramaswami and K.N.Sivarajan, "Optical Networks: A Practical Perspective", Morgan Kaufmann Publishers, 1998.

[Ramaswami 2002] R. Ramaswami and K.N. Sivarajan. “Optical Networks.A Practical Perspective”, 2nd Ed. Morgan Kaufmann Publishers, Inc., San Francisco, 2002.

[Rammamirth 2002] J. Ramamirtham and J. Turner, “Design of Wavelength Converting Switches for Optical Burst Switching,” in Proceedings of INFOCOMM, 2002, vol. 1, pp. 362–370.

[Rostami 2005] A.Rostami and S.S.Chakraborty, "On Performance of Optical Buffers with Fixed Length Packets", Proceedings of 2nd IFIP WOCN Conference, DUbai,pp. 1570-1572, March 2005

[Salvador 2003] M. R. Salvador, “Mac Protocols for Optical Packet-Switched WDM Rings”, Centre for Telematics and Information Technology (CTIT), University of Twente, 2003.

[Sarwar 2008] S.Sarwar , S.Aleksic and K.Aziz, “ Optical burst switched(OBS) system with segmentation-based dropping,” Electrotechnik & Informationtechnik, vol. 125, no.7-8, 2008.

[Sharma 1998] V.Sharmaand E.A.Varvarigos, " Limited Wavelength Conversion in All-Optical WDM Mesh Networks," in Proc. of IEEE INFOCOM, 98, (San Fransisco, CA), Apr. 1998.

[Sharma 2000] V. Sharma and E. A. Varvarigos, "An analysis of limited wavelength translation in regular all-optical WDM networks", Journal of Lightwave Technology 18, vol. 12, pp. 606 -1619, 2000.

[Sharma 2000] V. Sharma and E. A. Varvarigos, “An analysis of limited wavelength translation in regular all-optical WDM networks,” J. Lightwave Technol., vol. 18, pp. 1606–1619, Dec. 2000.

[Shimizu 2006] Sho Shimizu, Yutaka Arakawa, Naoaki Yamanaka, "A wavelength assignment scheme for WDM Networks with Limited Range Wavelength Converters", IEE ICC, 2006.

[Sing 2004] S.P. Singh, A. Mukkherjee, V.K. Chaubey, “Wavelength conversion algorithm in an intelligent optical network from a multi layered approach”, J. Opt. Network. (OSA), vol. 3 ,pp.354–362, 2004.

[Sivalingam 2005] Krishna M.Sivalingam et al., “Emerging Optical Network Technologies - Architectures, Protocols and Performance”, Springer, 1st, ISBN 0-387-22582-X, vol. 196, 2005.

[Sriram 2003] K. Sriram, D. Griffith, S. Lee, and N. Golmie, “Optical burst switching: Benefits and challenges,” in Proc. 1st Int. Workshop Optical Burst Switching (WOBS), Conjunction With OptiComm, Dallas, TX, Oct. 16, pp. 1–12, 2003.

[Steinar 2003] Steinar Bjornstad et al. “Optical burst and packet switching: Node and network design, contention resolution and Quality of Service - Results from the study in COST 266", In Proceedings of 7th International Conference on Telecommunications (ConTEL 2003), Zagreb, Croatia, June 2003.

[Stern 2009] Thomas E. Stern, Georgios Ellinas ,Krishna Bala, “Multiwavelength Optical Networks, Second Edition Architectures, Design, and Control”, Cambridge University Press, New Delhi, 2009.

[Subramaniam 1997] S.Subramaniam, A.K.Somani, M.Azizoglu," A Performance Model for Wavelength Conversion with Non-Poisson Traffic," in Proc. of IEEE INFOCOM, 97, (Tokyo, Japan),Apr 1997.

[Subramaniam 1996] S. Subramaniam, M. Azizoglu, and A. K. Somani, “All-optical networks with sparse wavelength conversion,” IEEE/ACM Trans. Networking, vol. 4, pp. 544–557, Aug. 1996.

[Subramaniam 1996a ch2] S.Subramaniam , M.Azizoglu and A.K.Somani, "Connectivity and Sparse Wavelength Conversion in Wavelength-Routing Networks," in Proc. of IEEE INFOCOM, 96, Apr. 1996.

[Subramaniam 1998] S.Subramaniam, M.Azizoglu and A.K.Somani, "On the Optimal Palcemet of Wavelength Converters in Wavelength Routed Networks," in Proc. of IEEE INFOCOM, 98, (San Fransisco, CA), Apr. 1998.

[Summe 1997] M.A. Summerfield, "MAWSON: A Metropolitan Area Wavelength Switched Optical Network", In Procs. of 3rd Asia Pacific Conference on Communications (APCC '97), Vol. 1, pp. 327-331, Sydney, Australia, December 7-10, 1997.

[Sungchang 2002] Sungchang Kim, Namook Kim, Minho Kang, "Contention Resolution for Optical Burst Switching NetworksUsing Alternative Routing", Proceedings IEEE, ICC 2002, New York, NY, April-May 2002.

[Szymanski 2006] Andrzej Szymański, Artur Lasoń, Jacek Rząsa, and Andrzej Jajszczyk, “Route Management Strategies for Grade of Service Differentiation in Optical Networks”, in proceedings, IEEE International Conference on Communications 2006 (ICC’06) , Istanbul, Turkey, June 2006, Vol. 6, pp. 2453-2458.

[Tan 2003] S. Tan, G. Mohan, and K. Chua, "Burst rescheduling with wavelength and last-hop FDL reassignment in WDM optical burst switching networks," in Proceedings of IEEE ICC 2003, 2ed, pp. 1448-1452, 2003.

[Thiagarajan 1999] S.Thiagarajan and A.K.Somani," An Efficient Algorithm for Optimal Wavelength Converter Placement on Wavelength-Routed Networks with Arbitrary Topologies," in Proc. of IEEE INFOCOM, 99, (New York, U.S.A) Mar. 1999.

[Thomas 2000] Thomas G. Robertazzi, “Computer Networks and Systems Queueing Theory and Performance Evaluation”, Third Edition, Springer, 2000.

[Tridandapani 1997] S. B. Tridandapani and B. Mukherjee, “Channel sharing in multi-hop WDM lightwave networks: Realization and performance of multicast traffic,” IEEE J. Select. Areas Commun., vol. 15, pp. 488–500, Apr. 1997.

[Tripathi 1999] T.Tripathi and K.Sivarajan, " Computing Approxiamte Blocking Probabilities in Wavelength Routed All-Optical Networks with Limited Range Wavelength Conversion in Proc. of the IEEE INFOCOM, 99,. (New York, U.S.A), Mar. 1999.

[Tripathi 2000] T. Tripathi and K. N. Sivarajan, “Computing approximate blocking probabilities in wavelength routed all-optical networks with limitedrange wavelength conversion,” IEEE J. Select. Areas Commun., vol. 18, pp. 2123–2129, Oct. 2000.

[Turner 1999] J.S. Turner, “Terabit burst switching,” Journal of High Speed Networks, vol. 8, no. 1,pp. 3–16, January 1999.

[Vincent 1998] Vincent W. S. Chan, Katherine L. Hall, Eytan Modiano, and Kristin A. Rauschenbach. “Architectures and Technologies for High-Speed Optical Data Networks”, Journal of lightwave Technology, vol. 16, NO. 12, December 1998.

[Vokkarane 2001] M.V.Vokkarane, "Burst Segmentation: A New approach to reduce packet loss in optical burst switched networks", M.E.Thesis, University of Texas at Dallas,2001

[Vokkarane 2001] V. Vokkarane, J. Jue, and S. Sitaraman, “Burst Segmentation: An Approach For Reducing 2001 Packet Loss In Optical Burst Switched Networks,” UTD Technical Report UTDCS-20-01, September 2001.

[Vokkarane 2002] V. M. Vokkarane, J. P. Jue, and S. Sitaraman, “Burst segmentation: An approach for reducing packet loss in optical burst switched networks,” in Proceedings of IEEE ICC, pp. 2673–2677, April/May 2002.

[Vokkarane 2003] V. M. Vokkarane and J. P. Jue, "Prioritized burst segmentation and composite burst-assembly techniques for QoS support in optical burst switched networks," IEEE Journal on Selected Areas in Communications, vol. 21, no. 7, pp. 1198-1209, 2003.

[Vokkarane 2004] V.M. Vokkarane and J. P. Jue, Optical Burst Switched Networks. Springer, New York, USA,2004.

[Vokkarane 2004a] V. M. Vokkarane, “Design and analysis of architectures and protocols for optical burstswitched networks”, Ph.D dissertation, the university of Texas at Dallas, August 2004.

[Vu 2002] H. Vu and M. Zukerman, “Blocking probability for priority classes in optical burst switching networks,” IEEE Communications Letters, vol. 6, no. 5, pp. 214–216, May 2002.

[Wang 2000] X. Wang, H. Morikawa, and T. Aoyama, “Burst optical deflection routing protocol for wavelength routing WDM networks,” in Proc. SPIE/IEEE OptiComm, Dallas, TX, USA, pp. 257–266, 2000.

[Wang 2002] Xi Wang, Hiroyuki Morikawa, Tomonori Aoyama “Burst optical deflection routing protocol for wavelength routing WDM networks,” Opt. Netw. Mag., pp. 12–19, Nov./Dec. 2002.

[Wang 2002] Y. Wang and Y. Yang, “Multicasting in a class of multicast-capable WDM networks,” J. Lightwave Technol., vol. 20, pp. 350–359, March 2002.

[Wason 2009] A.Wason, R.S.Kaler, "Routing & wavelength assignment in wavelength routed all optical WDM networks", Optik 121 (2010), pp. 1478-1486, 2009.

[Wauters 1997] N.Wauters, W.V.Parys, B.V.Caenegem and P.Demeester, " Reduction of Wavelength Blocking Through Partitioning with Wavelength Converters," in Proc of the OFC, 97, pp. 122-123, 1997.

[Wei 2000] J. Y. Wei and R. I. McFarland, “Just-In-Time Signaling for WDM Optical Burst Switching Networks,” IEEE Journal of Lightwave Technology, Vol. 18, No. 12, pp. 2019-2031, December 2000.

[White 2002] “Optical phased array technology for high-speed switching,” White Paper, http://www.chiaro.com/pdf/ CHI100_OPA_1.pdf, 2002.

[Widjaja 1995] I. Widjaja, " Performance analysis of burst admission control protocols", IEEE Proceeding of Communications, 142: 7-14, February 1995

[Xiong 2000] Y. Xiong, M. Vandenhoute, and H. Cankaya, “Control architecture in optical burst-switched WDM networks,” IEEE Journal on Selected Areas in Communications, vol. 18, pp. 1838–1851, October 2000.

[Xu 2001] L. Xu, H.G. Perros, and G. Rouskas, “Techniques for optical packet switching and optical burst switching,” IEEE Communications Magazine, vol. 39, no. 1, pp. 136– 142, January 2001.

[Xu 2002] L. Xu, H. G. Perros, and G. Rouskas, "A simulation study of optical burst switching and access protocols for ring networks", In Proceedings of Networking, Pisa, Italy, May 2002.

[Xu 2003] J. Xu, Chunming Qiao, Jikai Li, and Guang Xu, “Efficient Channel Scheduling Algorithms in Optical Burst Switching Networks,” In Proceeding of IEEE INFOCOM, vol. 3, pp. 2268-2278, 2003.

[Xu 2003] J. Xu, C. Qiao, J. Li, and G. Xu, "Efficient channel scheduling algorithms in optical burst switched networks," in Proceedings of IEEE INFOCOM 2003, 3ed, pp. 2268-2278, 2003.

[Yang 1991] Y. Yang and G.M. Masson, “Nonblocking broadcast switching networks,” IEEE Trans. Comput., vol. 40, no. 9, pp. 1005-1015, Sept. 1991.

[Yang 1998] Y. Yang and J. Wang, “On blocking probability of multicast networks,” IEEE Trans. Commun., vol. 46, no. 7, pp. 957-968, July 1998.

[Yang 2000] Y. Yang, J. Wang, and C. Qiao, “Nonblocking WDM multicast switching networks,” IEEE Trans. Parallel and Distrib. Syst., vol. 11, pp. 1274– 1287, Dec. 2000.

[Yang 2001] M. Yang, S. Q. Zheng, and D. Verchere, “A QoS Supporting Scheduling Algorithm for Optical Burst Switching DWDM Networks,” In Proceeding of GLOBECOM 01, pp. 86-91, 2001.

[Yang 2004] H.Yang , H.Junqiang, P.Zhong, X.Fei and S.J.B. Yoo, " An Asynchronous, Variable Length Two-Stage Packet Switch Fabric Architecture with Look-Ahead and Load Balance Scheduling Schemes for Optical Label Switching Networks", in Proc. IEEE GLOBECOM (III Cat. No. 04CH37615), Piscataway, NJ, Vol. 3, pp. 1828-1834, 2004.

[Yano 2005] Yano M. et al., “Optical MEMS for photonic switching-compact and stable optical crossconnect switches for simple, fast, and flexible wavelength applications in recent photonic networks”, Selected Topics in Quantum Electronics, IEEE Journal of Volume 11, Issue 2, pp.383 – 394, March-April 2005.

[Yao 2000] S. Yao, B. Mukherjee, and S. Dixit, “Advances in photonic packet switching: An overview,” IEEE Communications Magazine, vol. 38, no. 2, pp. 84–94, February 2000.

[Yao 2000a] S. Yao, B. Mukherjee, S.J.B. Yoo, and S. Dixit, "All-optical packet-switched networks: A study of contention resolution schemes in an irregular mesh network with variable-sized packets", In Proceedings, SPIE OptiComm, pages 235–246, October 2000.

[Yao 2001] S. Yao, S. J. B. Yoo, B. Mukherjee, and S. Dixit, “All-optical packet switching for metropolitan area networks: Opportunities and challenges,” in IEEE Communications Magazine, vol. 39, pp. 142–148, March 2001.

[Yao 2001] Yao S et al., “All-optical packet switching for metropolitan area networks: Opportunities and challenges”, IEEE Communications Magazine, Vol. 39, No. 3, pp. 42-148, 2001.

[Yao 2003] S. Yao, B. Mukherjee, S. J. B. Yoo, and S. Dixit, “A unified study of contention resolution schemes in optical packet-switched networks,” in IEEE/OSA Journal of Lightwave Technology, pp. 1-31, March 2003.

[Yates 1996] J. Yates, J. Lacey, D. Everitt, and M. Summerfield, “Limited-range wavelength translation in all-optical networks,” in Proc. IEEE INFOCOM’96, vol. 3, pp. 954–961, Mar. 1996.

[Yates 1996] J.Jates, J.Lacey, D.Everitt and M.Summerfield, " Limited Wavelength Conversion in All-Optical Networks," in Proc. of IEEE INFOCOM, 96, (San Fransisco, CA), pp. 954-961, Apr. 1996.

[Yoo 1997] M. Yoo and C. Qiao, "Just-Enough-Time (JET): A High Speed Protocol for Bursty Traffic in Optical Networks", in Proc. IEEE/LEOS Conf. Tech. Global Info. Infrastructure, pp. 26–27, Aug. 1997.

[Yoo 1999] M. Yoo and C. Qiao, “A novel switching paradigm for buffer-less WDM networks,” IEEE Communications Magazine, vol.184, pp. 177-179, 1999.

[Yoo 1999a] M. Yoo and C. Qiao, “Supporting multiple classes of service in IP over WDM networks,” in Proceedings, IEEE Globecom, pp. 1023–1027, December 1999.

[Yoo 2000] M. Yoo, C. Qiao, and S. Dixit, “A comparative study of contention resolution policies in optical burst switched WDM networks,” in Proc. SPIE Int. Conf. Terabit Optical Networking: Architecture, Control, Manage, Issues, vol. 4213, Boston, MA, pp. 124–135, Nov. 2000.

[Yoo 2000a] M. Yoo, C. Qiao, and S. Dixit, "QoS performance of optical burst switching in IP-over-WDM networks," IEEE Journal on Selected Arears in Communications, vol. 18, no. 10, pp. 2062-2071, Oct. 2000.

[Yu 2002] Yu X, Chen Y, Qiao C. “Study of traffic statistics of assembled burst traffic in optical burst-switched networks”. Proc OptiComm, pp. 149–159, July–Aug 2002.

[Zalesky 2004] A. Zalesky, H. L. Vu, Z. Rosberg, E. Wong, and M. Zukerman, “Modeling and performance evaluation of optical burst switched networks with deflection routing and wavelength reservation,” in Proc. IEEE INFOCOM, vol. 3, Hong Kong, China, pp. 1864–1871, Mar. 2004.

[Zang 2000] H. Zang et al., “A Review of Routing and Wavelength Assignment approaches for Wavelength- Routed Optical WDM Networks,” Optical Networks Mag., pp.47-60, January 2000.

[Zhang 2000] X. Zhang, J. Y. Wei, and C. Qiao, “Constrained multicast routing in WDM networks with sparse light splitting,” J. Ligthwave Technol., vol. 18, pp. 1917–1927, Dec. 2000.

[Zhang 2004] T. Zhang, K. Lu, and J. P. Jue, “Differentiated contention resolution for QoS in photonic packet-switched networks,” in Proc. IEEE ICC, Pairs, France, pp. 1599–1603, Jun. 2004.

[Zhang 2005] T.Zhang, K.Lu and J.P.Jue, " An Anlytical Model for Shared Fiber Delay Line Buffers in Asynchronous Optical Packet and Burst Switches", in Proc. ICC'05, pp. 1636-1640, May 2005.

[Zhou 2002] C. Zhou and Y. Yang, “Wide-sense non blocking multicast in a class of regular optical WDM networks,” IEEE Trans. Commun., vol. 50, no. 1, pp. 126-134, Jan. 2002.

LIST OF PUBLICATIONS

1. **M.K.Dutta** and V.K.Chaubey, "Priority Based Wavelength Routed WDM Networks: A Queueing Theory Approach", International Journal of Recent Trends in Engineering, Vol. 1, No. 3, May 2009.
2. **M.K.Dutta** and V.K.Chaubey, "Optical Network Traffic Control Algorithm under Variable Loop Delay: A Simulation Approach", Int. J. Communications, Network and System Sciences, vol. 7, pp.651-655,2009.
3. **M.K.Dutta** and V.K.Chaubey, "Performance Analysis of All-Optical WDM Network with Wavelength Converter Using Erlang C Traffic Model", Communications in Computer and Information Science, Springer Publication, Volume 70, pp.238-244, 2010.
4. **M.K.Dutta** and V.K.Chaubey, "Design and Simulation of Intelligent Optical WDM Switching Node: Based on Erlang Traffic Model", Int. J. Communications, Network and System Sciences,vol. 3, pp. 563-368, 2010.
5. **M.K.Dutta** and V.K.Chaubey, "Performance Analysis of Deflection Routing & Segmentation Based Dropping in Optical Burst Switched Network", Presented in 10th International Conference on Fiber Optics & Photonics, PHOTONICS 2010 at IIT Guwahati.
6. **M.K.Dutta** and V.K.Chaubey, "Design and Performance Analysis of Deflection Routing Based Intelligent Optical Burst Switched (OBS) Network", Presented in IEEE sponsored International Conference on Device & Communication, ICDeCom-11, Feb 2011 at BIT Mesra, available online at http://ieeexplore.ieee.org
7. **M.K.Dutta** and V.K.Chaubey, "Development and Performance Analysis of Optical WDM Node Architecture Using SRR Protocol", Optik vol. 123, pp.1971– 1974, 2012.
8. **M.K.Dutta** and V.K.Chaubey , "Study and Performance Analysis of Wavelength Conversion Method and Segmentation Based Dropping Method as Contention

Resolution Scheme in Optical Burst Switching Network”, Published in Procedia Engineering, , Elsevier vol. 30, pp. 1089 – 1096, 2012.

9. **M.K.Dutta** and V.K.Chaubey, “Modeling and Characterization of Modified Optical Burst Switching (OBS) Ring Network Using Proxy Node”, Presented in ICASEIT 2011,12-13 Dec,2011 University Kebangsaan Malaysia and published in International Journal on Advanced Science, Engineering and Information Technology (IJASEIT), Vol. 2, no. 1, pp.75-79, ISSN: 2088-5334, 2012.

10. **M.K.Dutta** and V.K.Chaubey, “Modeling and Performance Analysis of Optical Packet Switching Network Using Fiber Delay Lines”, Presented in IEEE Annual conference, INDICON 2011, 16-18 Dec, BITS-Hyderabad, available at : http://ieeexplore.ieee.org/xpl/mostRecentIssue.jsp?punumber=6132476.

11. **M.K.Dutta** and V.K.Chaubey, “Design and Performance Analysis of Optical WDM Ring Network Using Proxy Node Strategy”, Presented in IEEE Annual conference, INDICON 2011, 16-18 Dec, BITS-Hyderabad, available at : http://ieeexplore.ieee.org/xpl/mostRecentIssue.jsp?punumber=6132476.

12. **M.K.Dutta** and V.K.Chaubey, “Performance Analysis of Modified Optical Burst Switching (OBS) Ring Network Using Dummy Node”, Optik vol. 123 , pp.1847– 1851, 2012.

13 Vinay Chamola, **M.K.Dutta**, V.K.Chaubey, "Effect of Non linearities in Contention resolution using Fiber delay lines", Presented in IEEE co-sponsored ICCICT 2012, Sardar Patel Institute of Technology, Mumbai, Oct 19-21, 2012.

14. **M.K.Dutta**,V.K.Chaubey,"Contention Resolution in Optical Burst Switching (OBS) Network : A Time Domain Approach", has been accepted in the International Conference on Fiber Optics and Photonics to be held during 09-12, December 2012 in IIT Madras, Chennai, India.

Publications not related to the thesis

1. **M.K.Dutta** , B.S.N. Karthik, S.Renikidi and V.K.Chaubey, “Stimulated Raman Scattering Induced Power Penalty Analysis For Optical WDM Network”, Presented in IEEE sponsored International Conference on Device & Communication, ICDeCom-11, Feb 2011 at BIT Mesra, available available online at http://ieeexplore.ieee.org.

2. .**M.K.Dutta**,Vinay Chamola ,Ajinkya Rajandekar, V.K.Chaubey, “Modeling and Characterization of Multi-Rate Direct Sequence CDMA System Using Dynamic Resource Allocation Scheme”, Presented in IEEE WIAD 2012, King’s College London, UK from25-27 June, 2012. Available at *ieeexplore.ieee.org/iel5/6287113/6296540/06296569.pdf.*

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