Evaluation of Burst Loss Rate of an Optical Burst Switching Network with Wavelength Conversion Capability

by

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List of Abbreviations

ACK = Acknowledgment
AON = All-Optical Network
APD = Avalanche Photo Diode
ASK = Amplitude Shift Keying
ATM = Asynchronous Transfer Mode
BER = Bit Error Rate
BW = Band Width
CoS = Classes of Service
CR-LDP = Constraint-Based Route Label Distribution Protocol
DPSK = Differential Phase Shift Keying
FDL = Fiber Delay Line
FEC = Forward Equivalent Classes
FSK = Frequency Shift Keying
GMPLS = Generalized Multi Protocol Label Switching
IM/DD = Intensity Modulation / Direct Detection
JET = Just-Enough-Time
JIT = Just-In-Time
LASER = Light Amplification of Stimulated Emission and Radiation
LAUC-VF = Latest Available Unused Channel with Void Filling
LCR = Look-Ahead Window Contention Resolution
LED = Light Emitting Diode
MPLS = Multi Protocol Label Switching
M-UCAST = Multiple Unicasting
OBS = Optical Burst Switching
OBSN = Optical Burst Switched Network
OCDMA = Optical Code Division Multiple Access
O-E-O = Optical-to-Electrical-to-Optical
OFDM = Optical Frequency Division Multiplexing
OOK = On-Off Keying

OPSN = Optical Packet Switched Network
OTDM = Optical Time Division Multiplexing
OXC = Optical Cross-Connect
PPM = Pulse Position Modulation
PSK = Phase Shift Keying
QoS = Quality of Services
QPSK = Quadrature Phase Shift Keying
RSVP-TE = Resource Reservation Protocol with Traffic Engineering
RWA = Routing and Wavelength Allocation
SBS = Stimulated Brillouin Scattering
S-MCAST = Separate Multicasting
SPM = Self-Phase Modulation
SRS = Stimulated Raman Scattering
TS-MCAST = Tree-Shared Multicasting
WDM = Wavelength Division Multiplexing
WRN = Wavelength-Routed Network
WR-OBS = Wavelength-Routed Optical Burst Switching
XPM = Cross-Phase Modulation

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Abstract

An analytical expression for the burst loss rate is proposed on the basis of a one-way protocol in a slotted optical burst-switching network with wavelength conversion capability. In this protocol, a wavelength is reserved (in a core node) for a burst immediately after the arrival of the corresponding control packet. In our analysis, a slotted timing model is used in which the entire time period of a burst is divided; each of divided duration is called slot time. Burst loss rate is related with different network design parameters such as wavelength conversion capability, burst arrival probability, network traffic, number of slots per burst and number of wavelengths. Further, analytical expression for burst loss rate is also extended which shows the relationship of burst loss rates between two different service classes. Each service class has a fixed number of reserved wavelengths. If the transmitted burst of one service class is smaller than the number of reserved wavelengths, the excess reserved wavelengths of that service class are used to carry bursts of the other service class. In this situation, an algorithm is developed to calculate the number of wavelengths for each service classes. The burst loss rates between two service classes is differentiated where one service class has increasing number of reserved wavelengths and the other service class has decreasing number of reserved wavelengths in an OBS network with constant number of wavelengths.

Performance results are evaluated in terms of burst loss rate (BLR) for wavelength conversion capability, burst arrival probability, network traffic, number of slots per burst and number of wavelengths. Results show that system performance improves with the increasing of wavelength conversion capability and number of wavelengths but the system performance degrades with the increasing of burst arrival probability and number of slots per burst or network traffic. The model results are found to be satisfactory agreement with the expected results.

The analytical results of this thesis will find application in design of a WDM system in a slotted optical burst switching network with wavelength conversion capability.

Chapter 1

INTRODUCTION

1.1 Introduction

Communication is the process of transferring information or message like voice, video text, data, picture, etc. from a distance to another distance. Communication is a technique by which two or more entities exchange their information. The function of communication system is to convey the signal from the information source over the transmission medium to the destination [1]. A great interest in communication at the optical frequencies was created with the advent of the laser in 1960, which made available a coherent optical source. In 1966 Kao et al discovered that optical fibers could be used as ideal support for the transmission of light waves. Yet it was not until 1970 that attenuation in fibers decreased from more than 100 dB/Km to over 20 dB/Km thereby making optical fibers a practical proportion for a wide range of uses [2]. It is now recognized that compared to metal conductors or waveguides, optical fibers offer greater information capacity arising from a high carrier frequency and lower material costs. What we are observing today is a kind of communication revolution where information is crated, managed, processed and distributed. This revolution is leading the human society to an integrated global network that will carry the information in the form of video, data and voice channels across national boundaries, transferring the globe into a local network, overcoming time and distance and changing the overall concept of communication, business and style of life [3].

1.2 Advantages of Fiber Optic Communication

Compared to conventional metal wire (copper wire), optical fibers are-

- Less expensive→Several miles of optical cable can be made cheaper than equivalent lengths of copper wire. This saves your provider (cable TV, Internet) and you money.
- Thinner→Optical fibers can be drawn to smaller diameter than copper wire.
- Higher carrying capacity→Because optical fibers are thinner than copper wires, more fibers can be bundled into a given-diameter cable than copper wires. Than allows more phone lines to go over the same cable or more channels to come through the cable into your cables TV box.
- Less signal degradation→The loss of signal in optical fiber is less than in copper wire.
- Light signals→Unlike electrical signals in copper wires, light signals from one fiber do not interfere with those of other fibers in the same cable. This means clearer phone conversations or TV reception.
- Low power→Because signals in optical fibers degrade less; lower-power transmitters can be used instead of the high-voltage electrical transmitters needed for copper wires. Again, this saves your provider and you money.
- Digital signal→Optical fibers are ideally suited for carrying digital information, which is especially useful in computer networks.
- Non-flammable→Because no electricity is passed through optical fibers, there is no fire hazard.
- Lightweight→ An optical cable weighs less than a comparable copper wire cable. Fiber-optic cables take up less space in the ground.
- Flexible→Because fiber optics are so flexible and can transmit and receive light, they are used in many flexible digital cameras for the following purposes:

  - ✓ Medical imaging- in bronchoscopes, endoscopes, laparoscopes.
  - ✓ Mechanical imaging-inspecting mechanical welds in pipes and engines (in airplanes, rockets, space shuttles, cars).
  - ✓ Plumbing-to inspect sewer lines

1.3 Disadvantages of Fiber Optic Communication

- Higher cost.
- Need for more expensive optical transmitters and receivers.
- More difficult and expensive to splice than wires.

Almost all of these disadvantages have been surmounted or bypass in contemporary telecommunication usage and communication systems are now unthinkable without fiber optics.

1.4 Elements of Optical Fiber Communication Link

The principal parts of the optical fiber communication system are the optical transmitter, the fiber and the optical receiver. Additionally optical amplifier, coupler, etc. are associated with it. Each of the parts has limited capabilities with respect to both the intensity and bandwidth of the signals it can handle without distortion. The block diagram of a basic optical communication link is as follows. The key sections are a transmitter consisting of a light source (LED/LASER) and its associated drive circuitry, a cable offering mechanical and environmental protection to the optical fibers contained inside and a receiver consisting of a photo detector plus amplifier and signal restoring circuitry.

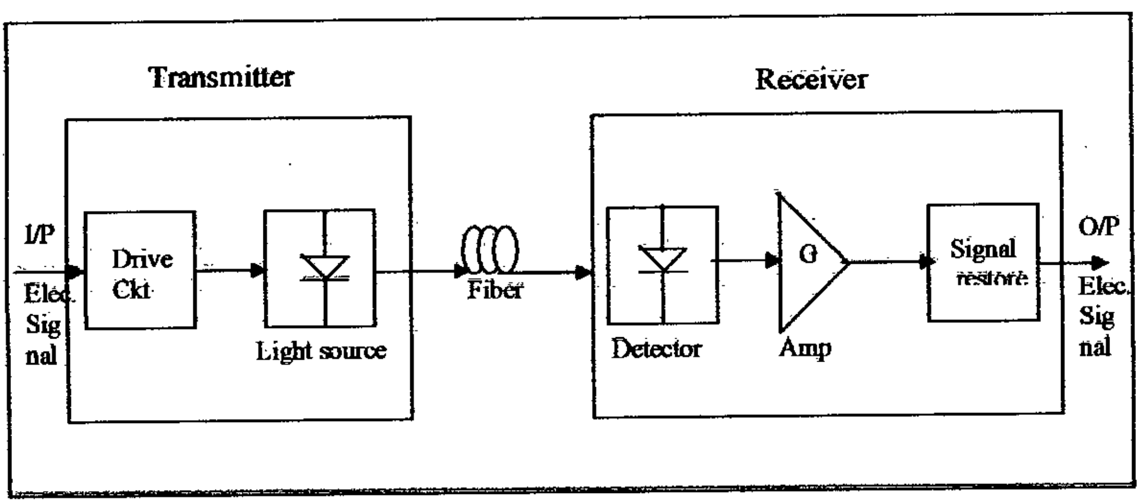

Fig. 1.1: Block diagram of a basic optical fiber link.

Semiconductor light emitting diode (LED) and LASER diodes are suitable transmitter sources for this purpose since their light output can be modulated rapidly by simply varying the bias current. The electronic input signal, either analog or digital, is converted to an optical signal by varying the current flow through the light source. An optical source is a square law device, which means that a variation in device current results in a corresponding change in the optical power. After an optical signal has been launched into the fiber, it will become progressively attenuated and distorted with increasing distance because of scattering, absorption and dispersions. At the receiver the attenuated, distorted and modulated optical power emerging from the fiber end will be detected by a photo detector diode. The photo diode converts the received optical power directly into an electrical signal (photo-current) output. Semiconductor PIN ("P" intrinsic "N") and Avalanche photo diode (APD) are the two types of photo detectors used in fiber optic links. For very low power optical signal APD is normally used since it provides higher receiver sensitivity owing to an inherent internal gain mechanism (avalanche effect). The principal figure of merit for a receiver is the minimum optical power necessary at the desired data rate to attain either a given error probability for digital systems or a specified signal to noise ratio for an analog system. The ability of a receiver to achieve a certain performance level depends on the photo detector type, the effect of noise in the system and the characteristics of the successive amplification stages in the receiver components of optical communication.

1.5 Fiber-Optic Characteristics

Fiber optic characteristics can be classified as linear and nonlinear [4].

1.5.1 Linear characteristics

Linear characteristics include→

A. Attenuation

B. Dispersion in a fiber

(A) Attenuation: Several factor cause attenuation, but it is generally categorized as either intrinsic or extrinsic. Substances inherently present in the fiber cause intrinsic attenuation, where as extrinsic attenuation is caused by external forces such as bending. The attenuation coefficient α is expressed in decibels per kilometer and represents the loss in decibels per kilometer of fiber.

(a) Intrinsic attenuation: Intrinsic attenuation results from materials inherent to the fiber. It is caused by impurities in the glass during the manufacturing process. As precise as manufacturing is, there is no way to eliminate all impurities. When a light signal hits an impurity in the fiber, one of two things occurs. It scatters or it is absorbed. Intrinsic loss can be further categorized by two components:

i) Material absorption

ii) Rayleigh Scattering

(i) Material absorption: Material absorption occurs as a result of the imperfection and impurities in the fiber. The most common impurity is the hydroxyl (OH^-) molecule, which remains as a residue despite stringent manufacturing techniques. The three principle windows of operation include the 850-nm, 1310-nm and 1550-nm wavelength bands. These correspond to wavelength region in which attenuation is low and matched to the capability of a transmitter to generate light efficiently and a receiver to carry out detection. Unlike scattering, absorption can be limited by controlling the amount of impurities during the manufacturing process.

(ii) Rayleigh scattering: As light travels in the core of a fiber, it interacts with the silica molecules in the core. Rayleigh scattering is the result of this elastic collision between the light wave and silica molecules in the fiber. Rayleigh scattering accounts for about 96% of attenuation in optical fiber. If the scattered light maintains an angle that supports forward travel within the core, no attenuation occurs. If the light is scattered at an angle that does not support continued forward travel, however, the light is diverted out of the core and attenuation occurs. Depending on the incident angle, some portion of the light propagates forward and other part deviates out of the propagation path escapes from the fiber core. Some scattered light is reflected back toward the light source.

(b) Extrinsic attenuation: Extrinsic attenuation is caused by two external mechanisms: macro-bending or micro-bending. Both cause a reduction of optical power. If a bend is imposed on an optical fiber, strain is placed on the fiber along the region that is bent. The bending strain affects the refractive index and the critical angle of the light ray in that specific area. As a result, light traveling in the core can refract out, and loss occurs.

(i) Macro-bend: A macro-bend is a large-scale bend that is visible, and the loss is generally reversible after bends corrected. To prevent macro-bends, all optical fiber has a minimum bend radius specification that should not be exceeded. This is a restriction on how much bend a fiber can withstand before experiencing problems in optical performance or mechanical reliability.

(ii) Micro-bend: The second extrinsic cause of attenuation is a micro-bend. Micro bending is caused by imperfections in the cylindrical geometry of fiber during the manufacturing process. Micro bending might be related to temperature, tensile stress or crushing force. Like macro bending, micro bending causes a reduction of optical power in the glass. Micro bending is very localized and bend might not be clearly visible on inspection. With bare fiber, micro bending can be reversible.

(B) Dispersion in a fiber: Dispersion of the transmitted optical signal causes distortion for both digital and analog optical fibers. When considering the major implementation of optical fiber transmission, which involves some form of digital modulation, then dispersion mechanisms within the fiber cause broadening of the transmitted light pulses as they travel along the channel. In order to appreciate the reasons for the different amounts of pulse broadening within the various types of optical fiber, it is necessary to consider the dispersive mechanisms involved. These include material dispersion, waveguide dispersion, and inter-modal dispersion.

(a) Intra-modal dispersion: Intra-modal or chromatic dispersion may occur in all types of optical fiber and results from the finite spectral line-width of the optical source. Since optical sources do not emit just a single frequency but a band of frequencies (in the case of the injection LASER corresponding to only a fraction of a percent of the centre frequency, where as for the LED it is likely to be a significant percentage), then there may be propagation delay differences between the different spectral components of the transmitted signal. This causes broadening of each transmitted mode and hence intra-modal dispersion. The delay differences may be caused by the dispersive properties of the waveguide material (material dispersion) and also guide effects within the fiber structure (waveguide dispersion).

(i) Material dispersion: Pulse broadening due to material dispersion results from the different group velocities of the various spectral components launched in to the fiber from the optical source. It occurs when the phase velocity of a plane wave propagating in the dielectric medium varies nonlinearly with wavelength and a material is said to exhibit material dispersion when the second differential of the refractive index with respect to wavelength is not zero.

(ii) Wave-guide dispersion: The wave guiding of the fiber may also create intra-modal dispersion. This results from the variation in-group velocity with wavelength for a particular mode. Considering the ray theory approach it is equivalent to the angle between the ray and fiber axis varying with wavelength which subsequently leads to a variation in the transmission time for the rays and hence dispersion.

(b) Inter-modal dispersion: Pulse broadening due to inter-modal dispersion results from the propagation delay differences between modes within a multimode fiber. As the different modes which constitute a pulse in a multimode fiber travel along the channel at different group velocities, the pulse width at the output is dependent upon the transmission times of the slowest and fastest mode. Multimode step index fibers exhibit a large amount inter-modal dispersion, which gives the greatest pulse broadening. Under purely single mode operation there is no inter-modal dispersion and therefore pulse broadening is solely due to the intra-modal dispersion mechanism.

1.5.2 Non-linear characteristics

Nonlinear characteristics are influenced by parameters such as bit rates, channel spacing and power level. Nonlinear characteristics include→

- A. Self-phase modulation (SPM)
- B. Cross-phase modulation (XPM)
- C. Four-wave mixing (FWM)
- D. Stimulated Raman scattering (SRS)
- E. Stimulated Brillouin scattering (SBS)

(A) Self-phase modulation: Phase modulation of an optical signal by itself is known as self-phase modulation. SPM is primarily due to self-modulation of the pulses. Generally, SPM occurs in single-wavelength systems. SPM results in phase shift and a nonlinear pulse spread. As the pulse spread, they tend to overlap and are no longer distinguishable by the receiver.

(B) Cross-phase modulation: Cross-phase modulation (XPM) is a nonlinear effect that limits system performance in wavelength-division multiplexed systems.

(C) Four-wave mixing: FWM can be compared to the inter-modulation distortion in standard electrical systems. FWM affects WDM systems and also causes inter-channel cross talk effects for equally spaced WDM channels.

(D) Stimulated Raman scattering: When light propagates through a medium, the photons interact with silica molecules during propagation. The photons also interact with themselves and cause scattering effects, such as stimulated Raman scattering (SRS). This results in a sporadic distribution of energy in a random direction.

(E) Stimulated Brillouin scattering: Stimulated Brillouin scattering (SBS) is due to the acoustic properties of photon interaction with the medium. When light propagates through a medium, the photon interacts with silica molecules during propagation. The photons also interact with themselves and cause scattering effects such as SBS in the reverse direction of propagation along the fiber.

1.6 Modulation, Multiplexing and Detection Schemes

The modulation schemes normally employed for optical transmission are intensity modulation, position modulation and frequency/phase modulation as is used in conventional communication system viz. OOK, PPM, ASK, PSK, FSK, QPSK, DPSK, MSK etc. Each of the modulation schemes has its own merits and demerits on the basis of information capacity and energy efficiency. In the optical fiber communication further the information viz. data, telephone signal, TV signal etc. from multiple users may be transmitted over this system using optical time division multiplexing (OTDM), optical frequency or wavelength division multiplexing (OFDM/WDM) and optical code division multiple access (OCDMA) techniques. The OTDM technique is generally preferred to OFDM technique because of the ease of transmission of error free data and voice information. However OFDM is still a more popular technique than OTDM due to the technological problems arising from building very high-speed laser transmitters required for OTDM. OFDM is efficient as long as long as each user requires the use of the network a large percentage of time. If such is not the case, available bandwidth is being wasted since other users could have transmitted on this bandwidth. Having examined point-to-point links. WDM is more sophisticated system to fully utilize the transmission capacity (BW) of an optical fiber. Since optical sources have relatively narrow spectral widths, this type of transmission makes use of only a very narrow portion of the transmission bandwidth of a fiber. In light wave communication system, two important types of detection of received optical signals in the receiver are used viz. direct detection and heterodyne/coherent detection. In direct detection receiver, the intensity of the received optical signal (field) is directly converted to an electrical signal (current) by a photo detector (photo diodes). It is hence called intensity modulation direct detection (IM/DD) scheme. The term IM stems from two facts as the light intensity (not the amplitude) is modulated linearly with respect to the input signal voltage and that basically no attenuation is paid to the phase to the phase of the carrier. The original spectral spread of the optical carrier is usually much wider than the spread due to modulation. The term DD stems from that the signal is detected directly at the optical stage of the receiver; neither the frequency conversion nor sophisticated signal processing is required. On the other hand, the heterodyne (coherent) scheme became common since 1930. The heterodyne schemes are more sensitive to learn phase noise compared to direct detection (DD). The IM/DD system has great advantages due to simplicity and low cost. On the other hand, some applications of the optical fiber communications exist in which long repeater separation is our concern, an example is the optical fiber communication between islands. In such case, the improvement of the receiver sensitivity by a heterodyne type receiving technique or coherent modulation/demodulation such as PCM-FSK or PCM-PSK may become advantageous, even at the sacrifice of simplicity and low cost. The expectation on the receiver sensitivity improvement is the principal motivation underlying the present effort toward the heterodyne coherent optical fiber communications. On the other hand, it is accepted by all the specialists that the IM/DD system will never retire because heterodyne/coherent systems are and will continue to be rather expensive [30].

1.7 Review of Previous Works

When two or more bursts are destined for the same output port at the same time, contention occurs; there are many contention-resolution schemes that may be used to resolve the contention. The primary contention-resolution schemes are optical buffering (FDL), wavelength conversion, deflection routing and burst segmentation. The performance measures of optical burst switching (OBS) such as steady state system throughput and average blocking probability have been investigated and presented numerically by several authors i.e. in [5-10]. The key design parameters for application of fiber delay line (FDL) buffers for contention resolution in optical burst switching nodes are discussed and studied [11]. Investigations are performed for a Poisson and self-similar traffic model including a study on the impact of traffic characteristics. Dimensioning of feed-forward as well as feedback FDL buffer architectures for OBS networks has been investigated considering two reservation strategies for FDL buffers, PreRes and PostRes. The impact of key design parameters such as FDL delay, buffer architecture, total number of buffer ports as well as assignment of buffer ports to individual FDL's on burst blocking probability has been studied. The authors in [9] introduce a new contention resolution algorithm called Look-ahead window Contention Resolution (LCR) that can support service differentiation. The performance of LCR has been studied in a single core node. The impact of switching overhead and finite processing capacity of the electronic core-node header processors have been shown on the performance of some OBS networks [12-13].

1.8 Objectives of the Thesis

The objectives of this research work are as follows:

- To propose a new analytical expression for burst loss rate on the basis of a one way wave length reservation protocol in a slotted optical burst switching network.

- To investigate the burst loss rate against different network design parameters such as wavelength conversion capability, burst arrival probability, network traffic, number of slots per burst and the number of wavelengths in an optical burst switching network.

- To extend the analytical expression of burst loss rate for two different types of service classes, where each service class has a fixed number of reserved wavelengths.

- To develop an algorithm to calculate the number of wavelengths for each service classes in a slotted optical burst switching network when the number of incoming bursts is not equal to the number of reserved wavelengths.

- To differentiate burst loss rates between two different service classes in an OBS network where the total number of wavelengths is constant.

1.9 Contribution of this Work

In this research work, an analytical expression for the burst loss rate will be derived on the basis of a one-way protocol in a slotted optical burst switching network. In this protocol, a wavelength will be reserved (in a core node) for a burst immediately after the arrival of the corresponding control packet. In our analysis, a slotted timing model will be used in which the entire time period of a burst will be divided, each of divided duration is called slot time. Burst loss rate will be related with different network design parameters such as wavelength conversion capability, burst arrival probability, network traffic, number of slots per burst and number of wavelengths. Further, analytical expression for burst loss rate will also be extended which will show the relationship of burst loss rates between two different service classes. Each service classes will have a fixed number of reserved wavelengths. If the transmitted burst of one service class is smaller than the number of reserved wavelengths, the excess reserved wavelengths of that service class will be used to carry bursts of the other service class. In this situation, an algorithm will be developed to calculate the number of wavelengths for each service classes. A computer simulation will be carried out to verify the analytical results. The burst loss rates between two service classes will be differentiated where one service class will have increasing number of reserved wavelengths and the other service class will have decreasing number of reserved wavelengths in an OBS network with constant number of wavelengths.

Chapter 2

BURST SWITCHING IN OPTICAL COMMUNICATION

2.1 Introduction

The benefits of optical communication systems have been known for quite awhile, but it was not until the invention of wavelength-division multiplexing (WDM) that the potential of fiber was fully realized. Current WDM networks operate over point-to-point links, where optical-to-electrical-to-optical (OEO) conversion is required at each step. All future WDM designs, however, are focused on all-optical networks (AON) where the user data travels entirely in the optical domain. The elimination of OEO conversion in AON allows for unprecedented transmission rates. AON can further be categorized as wavelength-routed networks (WRN), optical burst switched networks (OBSN), or optical packet switched networks (OPSN). Also, each step of the optical evolution begins with a simpler ring design before moving on to the more general mesh topologies. The AON evolution begins with WRN, whose operation consists of setting up circuit connections, called light paths, between the network nodes. The main constraint of WRN, typical of all optical communications, is the limited number of wavelengths per fiber. In a larger WRN, for example, this scarce number of wavelengths makes it impossible to create a full mesh of light paths between all end users. Consequently, for each WRN topology, network architects have to solve the NP-hard problem of routing and wavelength allocation (RWA) of the light paths in order to optimally satisfy the desired user communication. The other challenge of WRN is their quasi-static nature, which prevents them from efficiently supporting constantly changing user traffic. The proposed signaling protocol for WRN is generalized multi protocol label switching (GMPLS). In OPSN, user traffic is carried in optical packets along with in-band control information. The control information is extracted and processed in the electrical domain at each node. This is a desirable architecture because it is a well-known fact that electronic packet switched networks are characterized by high throughput and easy adaptation to congestion or failure. The problem with OPSN, however, is the lack of practical optical buffer

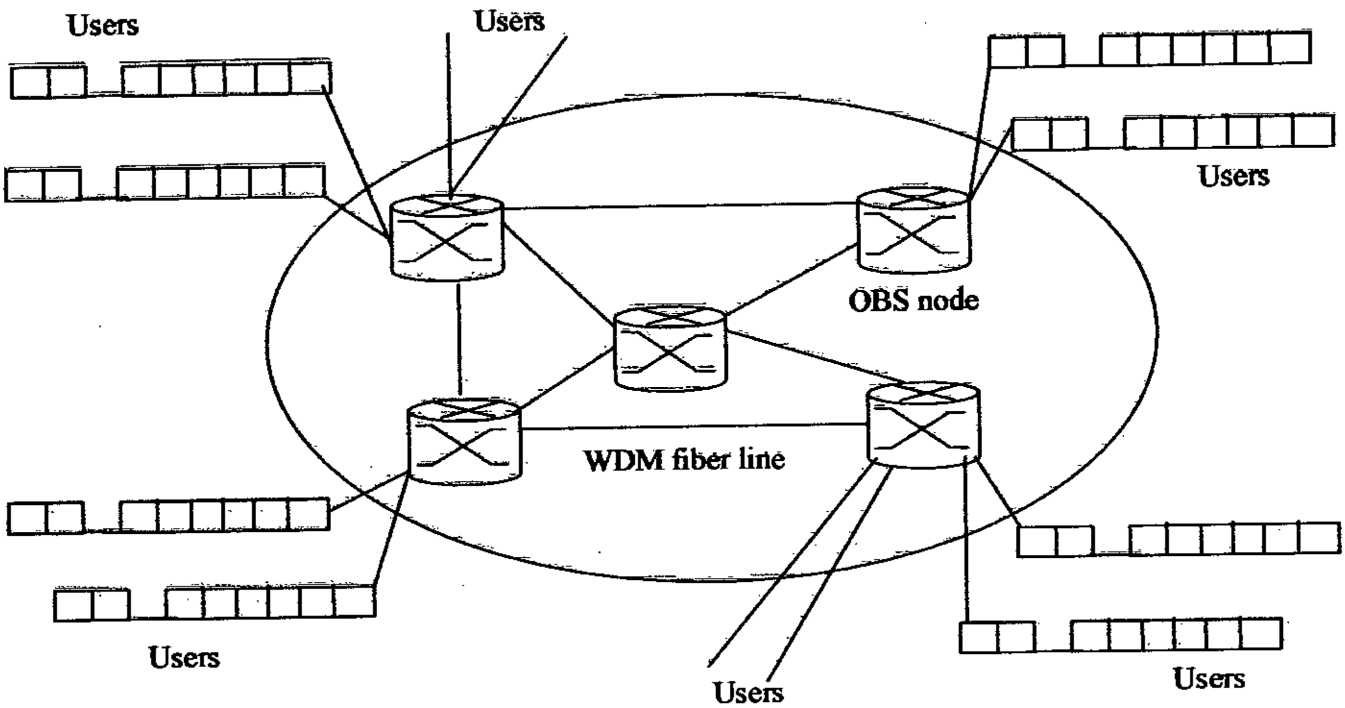

Fig. 2.1: OBS network architecture

The users consist of an electronic router and an OBS interface, while the core OBS nodes require an optical switching matrix, a switch control unit, and routing and signaling processors. Xiong et al. [15] give a detailed architectural design of all of these nodes.

2.2 Burst Aggregation

One of the main functions of an OBS user is to collect upper layer traffic, sort it based on destination addresses, and aggregate it into variable-size bursts. The exact algorithm for creating the bursts can greatly impact the overall network operation because it allows the network designers to control the burst characteristics and therefore shape the burst arrival traffic. The burst assembly algorithm has to consider the following parameters: a preset timer, and maximum and minimum burst lengths. The timer is used by the user in order to determine when exactly to assemble a new burst. The maximum and minimum burst parameters shape the size of the bursts.

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2.3 Connection Setup Mechanisms

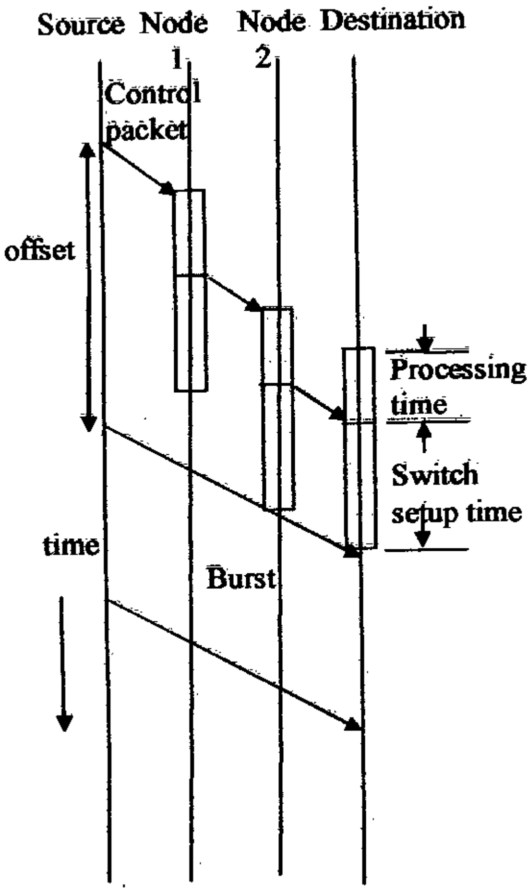
OBS users are also responsible for setting up the connections for each burst. This procedure consists of three main components: signaling, routing, and wavelength allocation. Signaling is used to set up and tear down the connections for the bursts. Routing is used to decide the path of a burst through the OBS network. Wavelength allocation is used to determine on which particular wavelength to transmit the burst.

2.3.1 Signaling for OBS

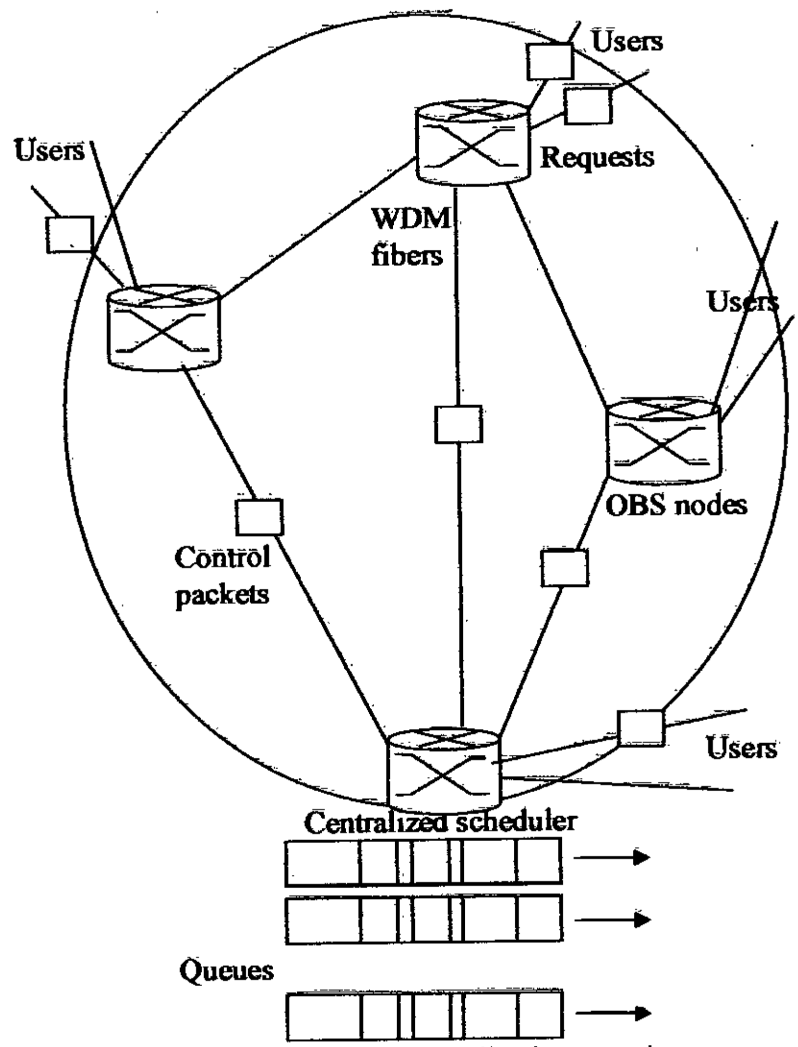
Signaling is an important aspect of OBS architecture. It specifies the protocol by which the OBS nodes communicate connection requests to the network, and its operation determines whether or not the resources are utilized efficiently.

2.3.1.1 Distributed signaling with one-way reservation

Most of the proposed OBS architectures utilize a one-way signaling procedure (Fig. 2.2 a) to set up a burst transmission path through the network. Prior to transmitting a burst, a user transmits a control packet to its ingress OBS node. This control packet contains information about the corresponding burst, and is electronically processed by the ingress OBS node and all the subsequent nodes along the path to the destination user. The control packet is transmitted in an out-of-band control channel, which may be a wavelength dedicated to signaling or a separate electronic control network, such as an IP or asynchronous transfer mode (ATM) network. In either case, the separation of control and data, in both time and physical space, is one of the main advantages of OBS. It facilitates efficient electronic control while allowing for great flexibility in the user data format and rate because the bursts are transmitted entirely over an optical signal and remain transparent throughout the OBS network. The burst itself is transmitted after a delay,



(a) One way reservation



(b) End-to-end centralized reservation

Fig. 2.2: OBS signaling

known as the offset, without waiting for a positive acknowledgment (ACK) that the entire path has been successfully established. Intuitively, the one-way reservation scheme is appropriate because OBS will most likely be implemented in long-haul networks, and therefore it will significantly decrease the time needed for connection establishment [14]. Wei and McFarland [17] analyzed the setup latency of a one-way reservation OBS signaling protocol called Just-In-Time (JIT) and compared it to circuit switching. They concluded that the one-way signaling scheme has a much shorter setup time and better throughput performance. Due to the one-way reservation scheme, burst loss may occur in an OBSN because the control packets may not an OBSN because the control packets may not succeed in reserving resources at some of the intermediate OBS core nodes. In addition, burst loss is possible if the control channel itself suffers from congestion or other failure. Because of these reasons, the burst loss probability is an important performance measure of OBS architecture. Despite the fact that burst loss is possible in OBS, the proposed architectures do not implement retransmission of lost bursts. One reason is the high data rate, which makes it unmanageable to keep copies of all previously transmitted bursts at the OBS edge nodes. Therefore, retransmission of lost bursts in an OBS network is left as a responsibility of the higher-layer protocols. It is also possible that an application may tolerate burst loss, in which case there is no need for retransmissions.

2.3.1.2 Centralized signaling with end-to-end reservation

Contrary to the more common one-way OBS signaling protocols, Dueser and Bayvel [18] propose a centralized connection signaling method, termed wavelength-routed optical burst switching (WR-OBS), which utilizes an end-to-end resource reservation procedure. In this design there is a centralized request server, responsible for resource scheduling of the entire OBS network (Fig. 2.2b). When an OBS ingress node receives a setup request from a user, it sends a control packet to the centralized scheduler, where it is queued up based on the destination address. This centralized server has global knowledge of the state of the OBS switches and wavelength availability along all the fiber links. The responsibility of this central server includes processing incoming control packets, determination of routes to the required destinations, and assignment of available wavelengths along each link. The central server processes the control packet and sends a positive ACK to the OBS user, upon receipt of which the node transmits the burst.

2.3.2 Routing

The routing of a burst through an OBS network can be done on a hop-by-hop basis, as in an IP network, using a fast table lookup algorithm to determine the next hop. Another approach is to use multi protocol label switching (MPLS) [19-21]. The MPLS idea is to assign control packets to forward equivalent classes (FEC) at the OBS users in order to reduce the intermediate routing time to the time it takes to swap the labels. A third approach is to use explicitly pre calculated setup connections, which can be established via Constraint-Based Route Label Distribution Protocol (CR-LDP) or Resource Reservation Protocol with Traffic Engineering (RSVP-TE). Explicit routing is very useful in a constraint-based routed OBS network, where the traffic routes have to meet certain QoS metrics such as delay, hop count, bit error rate (BER), or bandwidth. In addition, in order to deal with node or link failures, OBS routing should also be augmented with fast protection and restoration schemes. Unfortunately, this is a weak point for explicit routing schemes because sometimes the routing tables can become outdated due to the long propagation time until a failure message reaches all of the OBS nodes.

2.3.3 Wavelength allocation: with or without conversion

In an OBS network with no wavelength converters, the entire path from source to destination is constrained to use a single wavelength. The other possibility is an OBS network with a wavelength conversion capability at each OBS node. In this case, if two bursts contend for the same wavelength on the same output port, the OBS node may optically convert one of the signals from an incoming wavelength to a different outgoing wavelength. In addition, the conversion capability at an OBS node can be classified further as full or sparse. In the former case, there is one converter per each wavelength, whereas in the latter case the number of converters is less than the total number of wavelengths. Wavelength conversion is a desirable characteristic in an OBS network as it reduces the burst loss probability. However, it may not necessarily be a practical assumption since all optical converters are still an expensive technology. Another important question with respect to the OBS wavelength allocation scheme is the fairness achieved between the successful transmissions of bursts over long vs. short paths. The fairness issue is inherent to all optical networks, not just OBS networks, and it is due to the fact that it is easier to find free wavelengths along all of the links of a short path than it is for a longer one. Therefore, the proposed all-optical architectures should consider heuristics that try to improve the fairness among the connections with different number of hops. Ogushi et al. [22], for example, proposed a parallel wavelength reservation scheme as a solution to the fairness problem in an OBS network. This scheme achieves better fairness by segmenting the usage of the resources; the longest connections utilize the entire set of wavelengths, while short connections are limited to a subset of the wavelengths.

2.4 Pre-Transmission Offset Time

An OBS user first transmits a control packet and, after an offset time, it transmits the burst. This offset allows the control packet to reserve the needed resources along the transmission path before the burst arrives. Furthermore, the OBS nodes need this offset time to set up their switching fabrics so that the data burst can "cut through" without the need for any buffers. Ideally, the offset estimation should be based on the number of hops between source and destination, and the current level of congestion in the network. Obviously, an incorrect offset estimation would result in data loss because the burst may arrive at an OBS node before the optical cross connect has been completely set up. Therefore, determining this offset is a key design feature of all OBS networks, and its effectiveness is measured in terms of the burst loss probability. There are variations in the OBS literature on how exactly to determine the pre transmission offset time and how to reserve the needed resources at the core OBS nodes. Despite their differences, however, all of the proposed OBS architectures have dynamic operation, which results in high resource utilization and adaptability.

2.4.1 Fixed offsets

The most popular scheme comes from the Just-Enough-Time (JET) OBS protocol by Qiao and Yoo [14], where the offset time is fixed and is equal to the sum of the total processing time at all the intermediate OBS hops plus the switch fabric configuration time of the egress OBS node. The offset estimation requires the precise number of hops from source to destination. This information can be provided by the OBS user or the edge OBS node. The latter case is a more likely scenario, since the edge OBS nodes participate in the routing protocol and therefore may have more precise knowledge of the number of hops for each destination. Also, in this scheme the processing and switch configuration time at each OBS node are assumed to be pretty much the same, but in practice these times may vary from node to node because of possible queuing delays in the control channel.

2.4.2 Statistical offsets

Verma et al. [23] proposed a variable (statistical) offset generation scheme where each OBS user generates transmission tokens, based on a Poisson process with a predetermined rate of arrival. In this scheme, as soon as a burst is assembled, its corresponding control packet is immediately sent into the OBS network, while the burst itself is delayed until it is able to obtain a transmission token. The authors' conclusion was that the variable offset model regulates the average rate at which data bursts are released into the OBSN, which consequently reduces the burst loss probability.

2.4.3 WR-OBS offsets

In the WR-OBS architecture, the offset is calculated as the sum of the time it takes an OBS user to request resources from the centralized scheduler, the computation time of the routing and wavelength allocation algorithm, and the path signaling time. Most OBS time offsetting techniques are based on the assumption that the control packet is sent after the entire burst is assembled. A variation on these techniques is to send the control packet prior to collecting the entire burst from the upper layers. The main advantage of this variation is the reduction in the burst pre transmission delay. However, the exact length of the burst is not included in the corresponding control packet, which may result in an inefficient wavelength occupation scheme.

2.5 Inside the OBS Network

2.5.1 Scheduling of resources: reservation and release

Upon receipt of the control packets sent from the OBS users, the OBS nodes schedule their resources based on the included information. The proposed OBS architectures differ in their resource (wavelength) reservation and release schemes. Baldine et al. [24] classified these schemes based on the amount of time a burst occupies a path inside the switching fabric of an OBS node. In explicit setup, a wavelength is reserved, and the optical cross connect is configured immediately upon processing of the control packet. In estimated setup, the OBS node delays reservation and configuration until the actual burst arrives. The allocated resources can be released after the burst has come through using either explicit release or estimated release. In explicit release, the source sends an explicit trailing control packet to signify the end of a burst transmission. In estimated release, an OBS node knows exactly the end of the burst transmission from the burst length, and therefore can calculate when to release the occupied resources. Based on this classification, the following four possibilities exist: explicit setup/explicit release, explicit setup/estimated release, estimated setup/explicit release, and estimated setup/estimated release. Each of these schemes has advantages and disadvantages. For example, when estimated release is implemented the OBS node knows the exact length of the burst, and thus can release the resources immediately upon burst departure. This results in shorter occupation periods and thus higher network throughput than explicit release. The difficulty, however, is that the estimated schemes are quite complicated, and their performance greatly depends on whether the offset estimates are correct. On the contrary, the explicit setup/explicit release scheme is easier to implement but occupies the-switching fabrics for longer periods than the actual burst transmission, and therefore may result in high burst loss probability. The burst assembly strategy, implemented at the OBS users, also dictates how resources are reserved and released in the OBS network. For example, if the length of the burst is known prior to sending its control packet, the estimated release scheme could be implemented. However, if the control packet is sent before the burst is completely assembled, the OBS nodes have to utilize explicit release.

The next few paragraphs discuss the choice of resource occupation scheme in the various published OBS architectures. In the Jumpstart project, which defines the OBS signaling protocol for the JIT architecture, Baldine et al. [24] considered only the explicit setup/explicit release and explicit setup/estimated release schemes. The other two schemes were disregarded because of their necessity for a scheduler at each node. The Jumpstart signaling protocol, however, is designed to be implemented mostly in hardware and does not use a scheduler. In the JET architecture, Qiao and Yoo [14] utilize the estimated setup/estimated release scheme, where the occupation of the resources is exactly from the burst arrival until the transmission of its last bit. They term this scheme delayed reservation. In their analytical and simulation studies, they confirm the beneficial effects of delayed reservation on the burst loss probability in an OBS network. Intuitively, these results are expected because of JET'S efficient resource occupation scheme. Another OBS resource scheduling scheme, Horizon, is described by Turner [20]. This scheme can be classified as explicit setup/estimated release. In Horizon, the control packets contain both the offset time and burst length; therefore, the scheduler can maintain a deadline (horizon) when each resource will be freed and available for future scheduling. This scheme is categorized as explicit setup because as soon as the control packet arrives at an OBS core node, a wavelength is immediately scheduled for the future burst arrival. In other words, upon processing the control packet, this algorithm schedules the resource with the closest horizon to the time when the corresponding burst would arrive. The Horizon scheme is practical and simple, and its look ahead resource management minimizes the wasteful gap between reservation time and the actual burst arrival. An extension of the Horizon scheme, latest available unused channel with void filling (LAUC-VF) is presented by Xiong et al. [15]. LAUC-VF differs from Horizon in the fact that it keeps track of the latest unwed resources instead of the latest unscheduled resources, which are available just before the arrival time of an oncoming burst. In other words, even if a resource is scheduled it is still considered available because it may be possible to fit a short burst into a time gap before the arrival of a future scheduled burst. Recently, Xu et al. [25] also proposed several algorithms, based on techniques from computational geometry, for scheduling bursts in the JET architecture. In fact, the simulation of one of their algorithms called Min-Sv showed that it can schedule bursts as fast as Horizon but achieves burst loss as low as LAUC-VF.

2.5.2 Limited buffering using fiber delay lines

One of the main design objectives for OBS is to build a buffer less network, where user data travels transparently as an optical signal and cuts through the switches at very high rates. Buffer less transmission is important to OBS because electronic buffers require O-E-O conversion, which slows down transmission, and optical buffers are still quite impractical. In fact, as of today there is no way to store light, so the only possible optical buffering is to delay the signal through very long fiber lines. Some authors have explored the use of fiber delay lines (FDL) because they can potentially improve network throughput and reduce burst loss probability. In the presence of FDL buffers, the OBS reservation and release schemes must be revised. In addition to scheduling the wavelengths at the output ports, the OBS nodes also have to manage the reservation of their available FDL buffers. As described by Gauger [26], there are two different FDL scheduling mechanisms: PreRes and PostRes. Most FDL OBS architectures are based on the PreRes scheme, where the request to reserve an FDL buffer for an oncoming burst is made as soon as the control packet is processed and it is determined that there is no available wavelength on the required output port. Therefore, in the PreRes scheme, the new offset time between the control packet and the burst is increased to the sum of the original offset plus the assigned FDL delay. In the PostRes scheme, the offset time is kept to its original value by delaying both the control packet and its associated burst for a period of time without prior knowledge of whether a resource will be available for the burst upon leaving the FDL buffer.

2.5.3 Variations on burst dropping

Most of the OBS literature specifies that if all the resources are occupied at the moment of a burst arrival, the entire data burst is lost. An interesting OBS variation, designed to reduce the probability of burst losses, was presented by Vokkrane et al. [27]. It is built on the JET architecture and combines burst segmentation with deflection routing. Specifically, in this OBS model, each burst is divided into multiple segments; in the case of resource contention, instead of dropping the entire burst, either the head or tail segment is deflected to an alternate route to the destination. The authors proposed two ways to implement this idea: segment-first or.deflect-first. In the former, the lengths of the currently scheduled burst and the new contending burst are compared; the shorter one is segmented and its tail deflected. In the deflect-first policy, the contending burst is deflected if the alternate port is free. However, if the port is busy, similar to the segment-first policy, the lengths of the currently scheduled and contending bursts are compared and the tail of the shorter one is dropped.

2.6 Classes of Traffic

It is desirable for OBS architecture to support different classes of traffic in the user plane. One reason is that applications such as voice and video cannot tolerate long queuing delays and therefore may need to be given higher priority than regular data traffic. In addition, in order to ensure proper operation, OBS protection and restoration traffic must also be given priority over regular user data. Specifically, in an OBSN, filtering of upper-layer data and assignment of priorities to bursts will occur at the edge of the network during the burst assembly process. Therefore, in order to minimize the end-to-end delay of high-priority traffic, the burst assembly algorithm can vary parameters such as preset timers or maximum/minimum burst sizes. However, selecting the values for these parameters is a difficult task because of the throughput interdependence between the different classes of traffic. Below we describe some of the proposed solutions.

2.6.1 Classes based on extended offsets

In JET, Qiao and Yoo [28] proposed the extended offset scheme, where higher-priority traffic is assigned a longer offset between transmission of its control packet and its corresponding data burst. The authors explained that the burst blocking probability decreases as the offset time increases. One of the main constraints of this scheme is the maximum acceptable upper-layer delay; certain high-priority applications cannot tolerate long pre transmission offsets. The authors, however, believed that the longer pre transmission delays endured by higher-priority traffic is balanced out by lower blocking probability, which in turn reduces the delays caused by retransmissions in the upper layers. In the extended offset scheme, it becomes apparent why it is important to keep the offset to its original value as proposed in the PostRes FDL reservation of an earlier section. In PreRes, the other FDL scheme, the burst is delayed at the FDL buffer but the control packet is immediately sent into the OBS network. This, however, has the undesirable effect of increasing the offset and therefore raising the priority of the burst.

2.6.2 Classes based on priority queues

In the WR-OBS architecture, OBS users maintain CoS by sorting the upper-layer traffic based on destination address and a maximum acceptable delay. That is, each user has C x (N - 1) buffers, where C is the number of classes and (N - 1) is the number of possible user destinations. In this architecture, the burst size for each priority is limited by a preset timer. When the timer pops, a new burst of a particular priority is constructed, and the user immediately sends a request to the centralized scheduler. These requests are placed in C priority queues at the centralized scheduler, where they are processed according to their priority.

2.6.3 Classes based on the optical signal properties and preemption

In Jumpstart, Baldine et al. [24] proposed an OBS CoS scheme which is based on the physical quality of the optical signal such as maximum bandwidth, error rates, signal-to-noise ratio, and spacing between the different wavelengths. In the Jumpstart signaling protocol, these CoS parameters are included in the control packets. A connection is established only if all of these requirements can be met, possibly using a constrained based routing algorithm. In addition to the intrinsic physical quality, Jumpstart implements priorities based on a preemption mechanism, where a lower-priority burst in the process of being transmitted can be preempted by a higher-priority one.

2.7 Multicast

In OBS, as in wavelength routed networks, multicasting is achieved through light splitting, which inherently results in signal losses. Therefore, there is a limit on the number of times the signal can be split and the number of hops it can traverse. In addition, multicasting in all WDM networks is tightly coupled with wavelength allocation and is greatly dependent on the availability of wavelength converters. It is important to note that, however, that the dynamic nature of OBS makes it suitable for optical multicasting because the resources of the multicast tree are reserved on a per burst basis. Jeong et al. [29] reviewed three schemes for multicast sessions: separate multicasting (S-MCAST), multiple unicasting (M-UCAST), and tree-shared multicasting (TS-MCAST). In the first, at the edge of the network, multicast and unicast traffic are collected into separate bursts that travel independent of each other through the OBS network. In the M-UCAST scheme, multicast data is treated as unicast. In other words, a copy of the multicast data is assembled in a burst together with the unicast data for the same OBS destinations. Finally, TS-MCAST is the most sophisticated scheme because it recognizes whether there is a certain degree of membership overlap between multicast sessions in order to share the resources of multicast trees. In Jumpstart, Baldine et al. [24] assumed that there will be only sparse multicast capability in the OBS network. In their model, drawn from multicasting in ATM networks, there are only a few OBS multicast servers that manage all of the multicast sessions. Prior to network operation, each OBS node is assigned one of these multicast servers. Three different ways to build the multicast trees are proposed: source-initiated, leaf-initiated, and hybrid. The latter is chosen for Jumpstart because it allows the greatest flexibility. Once a multicast tree is built, all of its subsequent bursts travel over the same route through the OBS network. Note, however, that no resources are permanently allocated, and each new multicast burst has to send its own control packet prior to transmission.

2.8 OBS Ring Network

So far, we have focused on OBS networks with mesh topology. Xu et al. [30] proposed an OBS ring architecture consisting of N OBS nodes connected by optical fibers, which supports N + 1 wavelength. Each of the OBS nodes has a fixed transmitter, set to one of the N wavelengths, 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. In this architecture it is possible for two OBS nodes to send bursts, overlapping in time, toward the same destination node. Consequently, these bursts will contend for the tunable receiver of the destination node, and one of them will be dropped. Xu et al. [30] proposed various access protocols; they analyze their performance in terms of throughput, packet delay, throughput fairness, and delay fairness.

Chapter 3

PERFORMANCE ANALYSIS

3.1 Introduction

We introduce a mathematical model and our mathematical model depends on the construction of a state diagram that describes the status of an OBS node. We start by some definitions and preliminaries.

3.2 System Architecture

The basic architecture of an OBS network is composed of a set of N interconnected nodes and a set of available wavelengths of cardinality w. An ingress node assembles the Internet protocol packets that are coming from the local access networks and destined to the same egress node, into large bursts. A core node is composed of an optical cross-connect (OXC) fabric and a set of wavelength converters of cardinality $u \in \{0, 1, \ldots, w\}$. Each ingress node sends a control packet before the transmission of the optical burst starts. This control packet contains information about the sender, receiver, and transmission wavelength of the corresponding burst. Its main function is to configure all the core nodes along the path to destination so that the burst travels smoothly in the optical domain without the need to be converted into the electrical domain.

3.3 OBS Protocol

In this thesis work, we focus on a one-way protocol, which is just-in-time (JIT) protocol, for our OBS network. In this protocol, a wavelength is reserved (in a core node) for a burst immediately after the arrival of the corresponding control packet; if a wavelength cannot be reserved at that time, then the control packet is rejected and the corresponding burst is said to be blocked and dropped. Fig. 3.1(a) illustrates the operation of JIT-OBS protocol. Let a control packet C arrives at some OBS core node along the path to the destination. Once the processing of C is complete, a wavelength is immediately reserved for the upcoming burst, and the operation to configure the OXC fabric to switch the burst is initiated. It should be noticed that the optical burst arrives at the OBS node under consideration after an offset time T_{off} from the arrival of the control packet [Fig. 3.1(a)], which takes care of the processing and configuration times of the control packet and OXC fabric, respectively. Thus, the total time T spent from the transmission of the control packet until the end of the optical burst is

$$T = T_c + T_{off} + T_b$$

where T_c and T_b are the control packet and optical burst time durations, respectively.

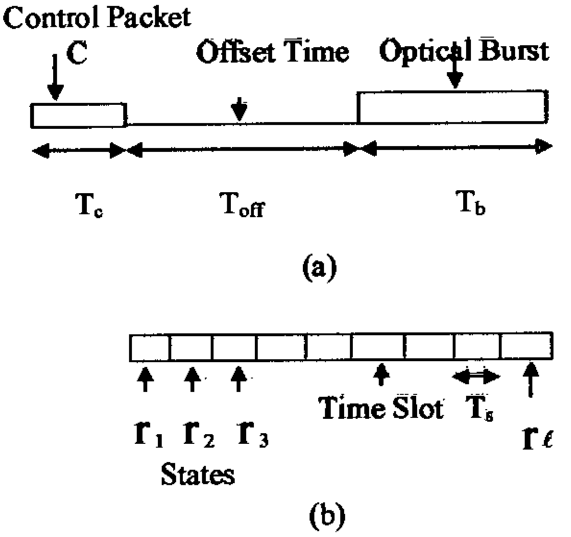


Fig. 3.1: (a) Transmission of an optical burst, (b) Slotted timing diagram.

3.4 Model

In our analysis, we use a slotted timing model [Fig. 3.1(b)] in which we divide the resource reservation time $T_{off} + T_b$ into small time slots, each of duration T_s called slot time. The total number of slots ℓ is calculated as

$$\ell = \frac{T_{off} + T_b}{T_s}$$

Where, we assume, without loss of generality, that ℓ is an integer. In addition, we can assume that T_s is a multiple of the bit duration and will be held fixed. It should be emphasized that during a time slot T_s s, the node would get enough information about the selected wavelength.

Time Slots and Burst Arrivals: We assume that the optical bursts (or control packets) arrive to any OBS node with rate R_b bursts/s. In addition, the arrival process follows a Poisson distribution. Thus, the probability that n bursts arrive to an OBS node during time slot $i \varepsilon \{1, 2, ..., \ell\}$ is given by

$$P_b(n) = e^{-R_b T_s} \frac{(R_b T_s)^n}{n!}, \qquad n \in \{0, 1, 2 \ldots\ldots\ldots\}$$

Furthermore, we assume that the time slot duration T_s is small enough so that $P_b(n) \cong 0$ for every $n \geq 2$. Thus, the last equation can be simplified to

If n = 0

$$P_b(n) = e^{-R_b T_s} \cong 1 - A$$

If n=1

$$P_b(n) = e^{-R_b T_s} R_b T_s \cong A$$

Else

$$P_b(n) = e^{-R_b T_s} \frac{(R_b T_s)^n}{n!} \cong 0$$

where A denotes the probability of a burst arrival within a slot time, also called the user activity. It should be noted that, under fixed bit rate and transmission bandwidth, the probability of a burst arrival A decreases as we increase the burst length ℓ so that their product is fixed. This product $A\ell$, which is a measure to the data traffic, will be called the network traffic k :

$$k = A\ell \quad \text{bursts / burst time.}$$

Initial State and Transition Probabilities: We assume that initially, an OBS node is in state m , called the initial state (Fig. 3.2). If there is an arrival (with probability A), the OBS node will enter the following state r_1 and starts processing the control packet (Fig. 3.2). On the other hand, if there is no arrivals (an event that occurs with probability $1-A$, the OBS node will remain as is.

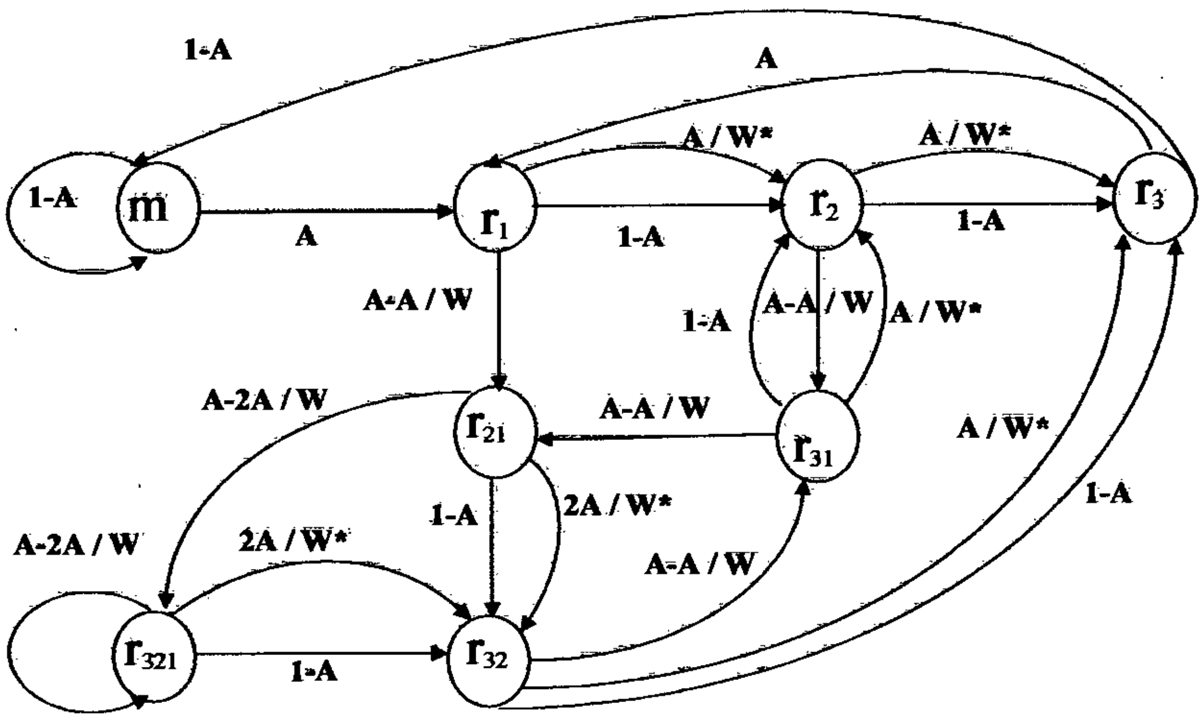


Fig. 3.2: State diagram for an OBS network with $\ell = 3$ and $w \geq \ell$. The stars denote blocking probabilities.

3.5 State Diagram

In the following two sections, we describe the state diagram of our OBS network models. We study here two models depending on the availability of the wavelength converters. In one model, we assume that there is no wavelength conversion in any OBS node. In the other model, however, we assume that there are wavelength conversion capabilities in all OBS nodes. In order to simplify the analysis and have some insight on the problem under consideration, we start by a simplified model and generalize it in a later stage. In any model, we always consider an OBS network with W wavelengths available for transmission of bursts. In addition, we assume that all bursts that arrive to an OBS node are of fixed lengths, as shown in Fig. 3.1. That is, an OBS node needs ℓ time slots to serve any accepted burst arrival. Although this assumption is not easy to achieve, we adopt it here in order to simplify the analysis. In a more realistic scenarios, ℓ can be considered as the average number of time slots.

3.6 OBS Networks with no Wavelength Conversions

In this section, we focus on the case where there is no wavelength conversion in any OBS node. We start our analysis with a simplified model, namely with $\ell = 3$, and generalize it in a later stage.

State Diagram for an OBS Network With $\ell = 3$ and $W \geq \ell$: In this section, we consider an OBS network with $\ell = 3$ and $w \geq \ell$. The state diagram can be constructed as shown in Fig. 3.2. There are four types of states, each labeled by the probability of an OBS node being in the state.

Initial state $\{m\}$: An OBS node is in this state (with probability m) if it is not serving any burst. After staying in the initial state for T_s, one of the two events happens. Either there is an arrival to the node (an event that occurs with probability A) or there are no arrivals. In the first case, the OBS node will enter state r_1 (defined below), whereas in the second case, the node will remain as is.

1-λ states $\{ r_1, r_2, \ldots\ldots r_\ell \}$: An OBS node is in these states if it is using one of the available wavelengths (as identified in the control packet). That is, for $\ell = 3$, if an OBS node is in state m and there is an arrival, it will reserve one of the available wavelengths and enter state r_1 . If it is in state r_1 and there are no arrivals after T_s, it enters state r_2 (corresponding to time slot 2). On the other hand, if it is in state r_1 and there is an arrival that needs to use the same wavelength (an event that occurs with probability) A / w , the burst will be blocked and the node will again enter state r_2. However, if the node is in state r_1 and there is an arrival that needs to use another wavelength (an event that occurs with probability $A(w - 1) / w$, the node will serve both bursts and enters state r_{21} (defined below). The process on these states is the same until being in the last state $r_\ell = r_3$, where after staying for T_s in this state, the node returns back to the initial state if there are no arrivals (where the current burst has already served) or returns to state r_1 if there is a new arrival.

2-λ states $\{ r_{21} , r_{31} , r_{32} \}$: An OBS node is in these states if it is using two of the available wavelengths and is serving two different bursts. That is, the node is in state r_{ij} , $i, j \varepsilon \{1,2,3\}$ and $i > j$, if it is serving slots i and j of the two bursts. For example, if the node is in state r_{21} , then it is serving slot 2 of the first burst and slot 1 of the second burst. After T_s s, if there is an arrival that needs to use one of the reserved wavelengths (an event that occurs with probability $2A / w$, it will be blocked, and the node enters state r_{32} to serve slot 3 of the first burst and slot 2 of the second burst. If the arrival, however, needs to use another wavelength, it will be served, and the node enters state r_{321} to serve slot 3 of the first burst, slot 2 of the second burst, and slot 1 of the new burst.

3-λ state $\{ r_{321} \}$: An OBS node is in this state if it is using three of the available wavelengths and is serving three different bursts (as mentioned above). For example, if the node is in state r_{321} , it is serving slot 3 of the first burst, slot 2 of the second burst, and slot 1 of the third burst. If after T_s s there are no arrivals (an event that occurs with probability 1 − A), then the node enters state r_{32} to serve slot 3 of the second burst and slot 2 of the third burst, where the first burst has already been done. The rest of the state diagram can be easily followed in a similar way.

3.6.1 Mathematical analysis

We start by writing the flow equations of the above state diagram. We should emphasize that each state is labeled by its probability.

$$\begin{aligned}
r_1 &= A(m + r_3) \\
r_2 &= (1 - A + \frac{A}{w})(r_1 + r_{31}) \\
r_3 &= (1 - A + \frac{A}{w})(r_2 + r_{32}) \\
r_{21} &= (A - \frac{A}{w})(r_1 + r_{31}) \\
r_{31} &= (A - \frac{A}{w})(r_2 + r_{32}) \\
r_{32} &= (1 - A + \frac{2A}{w})(r_{21} + r_{321}) \\
r_{321} &= (A - \frac{2A}{w})(r_{321} + r_{21})
\end{aligned} \tag{3.1}$$

It can be shown (using some algebraic manipulations, Appendix-A) that the above equations reduce to

$$r_1 = r_2 = r_3 = \frac{A}{1 - A}.m = \frac{w}{w.\dfrac{1 - A}{A}}.m$$

$$r_{21} = r_{31} = r_{32} = \frac{(w-1)A^2}{[w-(w-1)A](1-A)}.m = \frac{w}{w.\dfrac{1-A}{A}}.\frac{w-1}{w.\dfrac{1-A}{A}+1}.m$$

$$r_{321}=\frac{(w-1)(w-2)A^3}{[w-(w-2)A][w-(w-1)A](1-A)}m=\frac{w}{w.\frac{1-A}{A}}\cdot\frac{w-1}{w.\frac{1-A}{A}+1}\cdot\frac{w-2}{w.\frac{1-A}{A}+2}m \quad (3.2)$$

Imposing the condition that the sum of all probabilities equals to 1

$$m + 3r_1 + 3r_{21} + r_{321} = 1 \quad (3.3)$$

we can obtain the probability that an OBS node is in the initial state m:

$$m=[1+3\frac{w}{w\frac{1-A}{A}}+3\frac{w}{w\frac{1-A}{A}}\cdot\frac{w-1}{w\frac{1-A}{A}+1}+\frac{w}{w\frac{1-A}{A}}\cdot\frac{w-1}{w\frac{1-A}{A}+1}\cdot\frac{w-2}{w\frac{1-A}{A}+2}]^{-1} \quad (3.4)$$

State Diagram for an OBS Network With $\ell = 3$ and $w<\ell$: In this section, we consider an OBS network with $\ell = 3$ and $w<\ell$.

Case 1→w = 2: In this case, state $r_{321}=0$ in (3.1)-(3.3), and the state diagram is the same as that in Fig. 3.2 but when removing state r_{321} and all arrows to or from it.

Case 2→w = 1: In this case, states $r_{21}=r_{31}=r_{32}=r_{321}=0$ in (3.1)-(3.3), and the state diagram is the same as that in Fig. 3.2 but when removing states $r_{21}, r_{31}, r_{32}, r_{321}$ and all arrows to or from them. Of course, (3.4) reduces to

If $w = 2$

$$m=[1+3\frac{w}{w\frac{1-A}{A}}+3\frac{w}{w\frac{1-A}{A}}\cdot\frac{w-1}{w\frac{1-A}{A}+1}]^{-1}$$

If $w = 1$

$$m=[1+3\frac{w}{w\frac{1-A}{A}}]^{-1}$$

Steady-State Blocking Probability: In this section, we calculate the blocking probability in our OBS network. The steady-state blocking probability $P_b(A, \ell, w)$ is defined as the probability that an arrival is being blocked. Referring to Fig. 3.2, it is given by

$$P_b(A,3,w) = r_1 \frac{A}{w} + r_2 \frac{A}{w} + r_{31} \frac{A}{w} + r_{32} \frac{A}{w} + r_{21} \frac{2A}{w} + r_{321} \frac{2A}{w}$$

$$= \frac{A}{w} . 2 (r_1 + 2 r_{21} + r_{321})$$

3.6.2 General model

We consider an OBS network with w wavelengths and fixed length bursts (each of length $\ell \geq 1$ time slots). In addition, we assume that the user activity is A and there are no wavelength converters per any node. Fig. 3.3 shows an n-λ state $r_{i_n, i_{n-1}, i_{n-2}, \ldots, i_2, i_1}$ (where $n \varepsilon \{1,2,3,\ldots\ldots\ldots, \ell \wedge w\}$ and $i_1, i_2, \ldots\ldots i_n \varepsilon \{1,2,3,\ldots\ldots, \ell\}$ with $i_n > i_{n-1} > \ldots\ldots > i_1$. Here, $\ell \wedge w = \min(\ell, w)$. The node in this state is serving slot i_n of the first burst, slot i_{n-1} of the second burst, and so on. Two different scenarios may generate this state.

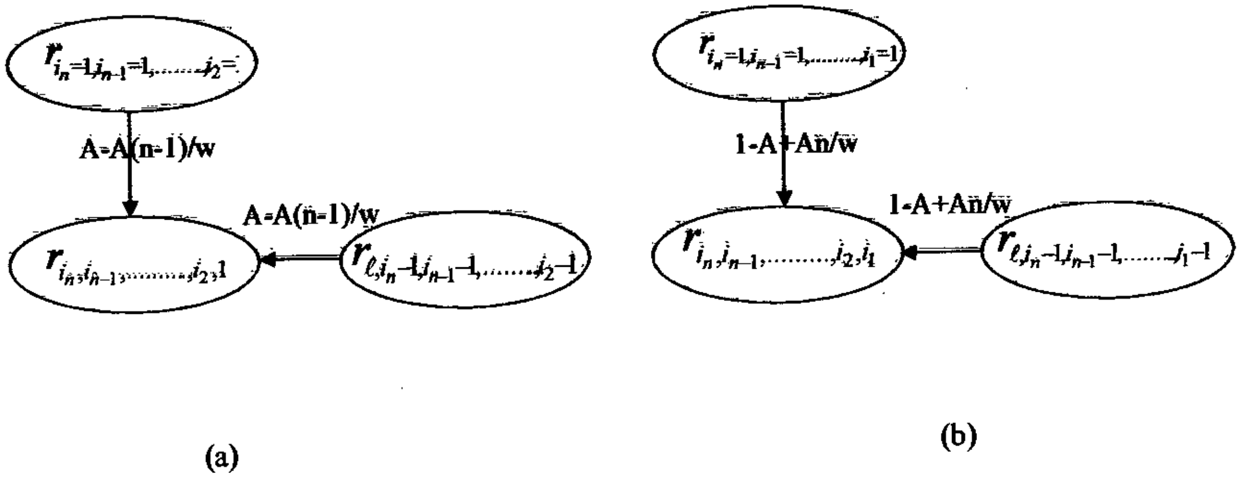


Fig. 3.3: **Generation of an n-λ state: (a) $i_1 = 1$, (b) $i_1 \neq 1$.**

(1) $i_1 = 1$: That is, the above node is serving first slot of a new arrival. The previous states are, thus, either an $(n - 1)$-λ state $r_{i_n-1, i_{n-1}-1, \ldots, i_2-1}$ or an n-λ state $r_{\ell, i_n-1, i_{n-1}-1, \ldots, i_2-1}$ [Fig. 3.3(a)]. The transition probability is given by

$$
\begin{aligned}
P_{n1} &= \Pr\{\text{ a new arrival }\} \times \Pr\{\text{ the arrival selects an unused wavelength }\} \\
&= A\left(1 - \frac{(n-1)}{w}\right) \\
&= A - \frac{(n-1)A}{w}
\end{aligned}
$$

The corresponding flow equation is thus

$$
r_{i_n, i_{n-1}, i_{n-2}, \ldots, i_2, i_1} = \left[A - \frac{(n-1)A}{w}\right] \times \left(r_{i_n-1, i_{n-1}-1, \ldots, i_2-1} + r_{\ell, i_n-1, i_{n-1}-1, \ldots, i_2-1} \right) \quad (3.5)
$$

(2) $i_1 \neq 1$: That is, there is either no new arrival or the new arrival is blocked. The previous states are either an *n-λ* state $r_{i_n-1, i_{n-1}-1, ..., i_1-1}$ or an (*n* + 1)-*λ* state $r_{\ell, i_n-1, i_{n-1}-1, ..., i_1-1}$ [Fig. 3.3(b)]. The transition probability in this case is given by

P_{n2} = Pr { no arrivals } +Pr {a new arrival} x Pr { the arrival selects a used wavelength }

$$= 1 - A + \frac{nA}{w}$$

The corresponding flow equation is thus

$$r_{i_n, i_{n-1}, i_{n-2}, ..., i_2, i_1} = [1 - A + \frac{nA}{w}] \times (r_{i_n-1, i_{n-1}-1, ..., i_1-1} + r_{\ell, i_n-1, i_{n-1}-1, ..., i_1-1}) \qquad (3.6)$$

Solution of the State Equations: The complete set of state equations is described by (3.5) and (3.6) for any. $n \varepsilon \{1, 2, 3, ... , \ell \wedge w\}$ Similar to (3.2), the unique solution occurs when all *n-λ* states are equal. That is, for any $i_1, i_2, ... i_n \varepsilon \{1, 2, 3, ... , \ell\}$ with $i_n > i_{n-1} > .... > i_1$

$$r_{i_n, i_{n-1}, i_{n-2}, ..., i_2, i_1} = e_n$$

where e_n can be determined by substitution in (3.5) and (3.6):

$$e_n = [A - \frac{(n-1)A}{w}](e_{n-1} + e_n)$$

$$\Rightarrow e_n = \frac{A - \frac{A}{w}.(n-1)}{1 - A + \frac{A}{w}.(n-1)} e_{n-1}$$

$$e_n = [1 - A + \frac{nA}{w}](e_n + e_{n+1})$$

$$\Rightarrow e_{n+1} = \frac{A - \frac{A}{w}.n}{1 - A + \frac{A}{w}.n} e_n$$

The similarity of the two equations ensures the consistency of our solution. Performing the induction method on one of the last equations yields

$$e_k = \prod_{i=0}^{k-1} \frac{w-i}{w.\frac{1-A}{A}+i} e_o = \prod_{i=0}^{k-1} \frac{w-i}{w.\frac{1-A}{A}+i} m$$

The value of the initial probability m can be determined by imposing the condition that the sum of all probabilities equals to 1:

$$m + \sum_{n=1}^{\ell \wedge w} \binom{\ell}{n} e_n = 1$$

$$m = \left[1 + \sum_{n=1}^{\ell \wedge w} \binom{\ell}{n} \prod_{i=0}^{n-1} \frac{w-i}{w.\frac{1-A}{A}+i} \right]^{-1}$$

Hence, for any $k \varepsilon \{1,2,3,\ldots\ldots\ldots \ldots, \ell \wedge w\}$

$$e_k = \frac{\prod_{i=0}^{k-1} \frac{w-i}{w.\frac{1-A}{A}+i}}{1 + \sum_{n=1}^{\ell \wedge w} \binom{\ell}{n} \prod_{i=0}^{n-1} \frac{w-i}{w.\frac{1-A}{A}+i}} \qquad (3.7)$$

Steady-State Blocking Probability: The following theorem provides the expressions for blocking probability for the generalized model.

Theorem 1: In an OBS network with w wavelengths and fixed-length bursts (each of length $\ell \geq 1$ time slots), if the user activity is A and there are no wavelength converters per any node, then the steady-state blocking probability is given by

$$P_b(A, \ell, w) = \frac{A}{w} \cdot \frac{(\ell - 1)}{\ell} \cdot \sum_{k=1}^{\ell \wedge w} \binom{\ell}{k} . k . e_k$$

Here, e_k , $k \varepsilon \{1,2,3,\ldots\ldots\ldots \ldots, \ell \wedge w\}$ are given by (3.7).

Proof: The proof of the blocking probability $P_b(A, \ell, w)$ for $w \geq \ell$ can be performed as follows, Consider an *n-λ* state $r_{i_n, i_{n-1}, i_{n-2}, \ldots, i_2, i_1}$ (where $n \varepsilon \{1,2,3,\ldots\ldots\ldots, \ell \wedge w\}$ and $i_1, i_2, \ldots\ldots\ldots i_n \varepsilon \{1,2,3,\ldots\ldots\ldots, \ell\}$ with $i_n > i_{n-1} > \ldots\ldots\ldots > i_1$. The node in this state is serving slot i_n of the first burst, slot i_{n-1} f the second burst, and so on. After T_s s, if there is an arrival that needs to be served, then two blocking cases may arise.

1) If $i_n \neq \ell$, the arrival will be blocked with probability *nA/w*. The blocked node will enter state $r_{i_n+1, i_{n-1}+1, i_{n-2}+1, \ldots, i_1+1}$

2) If $i_n = \ell$, the arrival will be blocked with probability $(n-1)A/w$. The blocked node will enter state $r_{i_{n-1}+1, i_{n-2}+1, \ldots, i_1+1}$. The blocking probability $P_b(A, \ell, w, n)$ for this node is thus

$$P_b(A, \ell, w, n) = e_n . \left[n \frac{A}{w} . \right] . \text{ number of times } (i_n \neq \ell) \text{ occurs in}$$

$$r_{i_n, i_{n-1}, i_{n-2}, \ldots, i_2, i_1} + e_n \left[(n-1) \frac{A}{w} \right] . \text{ Number of times}$$

$$(i_n = \ell) \text{ occurs in } r_{i_n, i_{n-1}, i_{n-2}, \ldots, i_2, i_1}$$

$$= e_n \cdot \frac{A}{w}\left[n\binom{\ell-1}{n} + (n-1)\binom{\ell-1}{n-1} \right]$$

$$= e_n \cdot \frac{A}{w} \cdot \frac{\ell-1}{\ell} \cdot n \cdot \binom{\ell}{n}$$

Thus, the total blocking probability is

$$P_b(A, \ell, w) = \sum_{k=1}^{\ell \wedge w} P_b(A, \ell, w, k)$$

$$= \frac{A}{w} \cdot \frac{(\ell-1)}{\ell} \cdot \sum_{k=1}^{\ell \wedge w} \binom{\ell}{k} \cdot k \cdot e_k$$

3.7 OBS Networks with Wavelength Conversion Capabilities

In this section, we focus on the case where there are some wavelength conversion capabilities in all OBS nodes.

3.7.1 General model

We consider an OBS network with w wavelengths. The set of available wavelengths is denoted by Λ def $= \{ \lambda_1, \lambda_2, \ldots, \lambda_w \}$. In addition, each node in the network is equipped with u wavelength converters, $u \varepsilon \{ 1,2,3,\ldots\ldots\ldots,w \}$ Only u wavelengths of Λ can be converted to any other wavelength in the set; the rest $w - u$ wavelengths cannot be converted. The factor

$$\rho = \frac{u}{w}, \qquad 0 \le \rho \le 1$$

is called the network conversion capability. If $\rho = 0$, then the network has no conversion capability, whereas if $\rho = 1$, then the network has a full conversion capability. It can be assumed that, at any node, all wavelengths are available in a pool. When an arriving burst is to be served with a specific wavelength, this wavelength is removed from the pool until after the service is complete. If another arriving burst is to be served with a wavelength not available in the pool, it will be converted to another one from the pool. This latter wavelength is then removed, and u is decreased by one. Blocking occurs whenever the pool is empty, or a used wavelength is needed while $u = 0$. The state diagram in this case can be described as follows. Consider an n-λ state $r_{i_n,i_{n-1},i_{n-2},\dots,i_2,i_1}$ (where $n\varepsilon\{1,2,3,\dots\dots,\ell\wedge w\}$ and $i_1,i_2,\dots\dots,i_n\varepsilon\{1,2,3,\dots\dots,\ell\}$ with $i_n > i_{n-1} > \dots\dots > i_1$. Three different scenarios may generate this state.

(1) $i_1 = 1$: That is, the above node is serving first slot of a new arrival. The previous states are, thus, either an $(n-1)$-λ state $r_{i_n-1,i_{n-1}-1,\dots,i_2-1}$ or an n-λ state $r_{\ell,i_n-1,i_{n-1}-1,\dots,i_2-1}$. The transition probability is given by

P_{n1} = Pr { a new arrival } x Pr { the arrival selects an unused wavelength or a convertible used wavelength }

$$= A\left(1 - \frac{(n-1)}{w} + \rho\,\frac{n-1}{w}\right)$$

$$= A - (1-\rho)\frac{(n-1)A}{w}$$

The corresponding flow equation is thus

$$r_{i_n,i_{n-1},i_{n-2},\dots,i_2,i_1} = [A-(1-\rho)\frac{(n-1)A}{w}]\times(r_{i_n-1,i_{n-1}-1,\dots,i_2-1}+r_{\ell,i_n-1,i_{n-1}-1,\dots,i_2-1}) \quad (3.8)$$

(2) $i_1 \neq 1$ and ($w \geq \ell$ or $n \neq w$): That is, there is either no new arrival or the new arrival is blocked. The previous states are either an *n*-λ state $r_{i_n-1,i_{n-1}-1,\ldots,i_1-1}$ or an (*n* + 1)-λ state $r_{\ell,i_n-1,i_{n-1}-1,\ldots,i_1-1}$. The transition probability in this case is given by

P_{n2} = Pr { no arrivals } +Pr {a new arrival} x Pr { the arrival selects a nonconvertible used wavelength }

$$= 1 - A + A(1-\rho)\frac{n}{w}$$

$$= 1 - A + (1-\rho)\frac{nA}{w}$$

The corresponding flow equation is thus

$$r_{i_n,i_{n-1},i_{n-2},\ldots,i_2,i_1} = [1 - A + (1-\rho)\frac{nA}{w}] \times (r_{i_n-1,i_{n-1}-1,\ldots,i_1-1} + r_{\ell,i_n-1,i_{n-1}-1,\ldots,i_1-1}) \quad (3.9)$$

(3) $i_1 \neq 1$, $w < \ell$ and $n = w$: That is, there is either no new arrival or the new arrival is blocked. Here the previous state should be a $w-\lambda$ state $r_{i_w-1,i_{w-1}-1,\ldots,i_1-1}$. The transition probability in this case is unity P_{n3}=1, and the corresponding flow equation is thus

$$r_{i_w,i_{w-1},\ldots,i_2,i_1} = r_{i_w-1,i_{w-1}-1,\ldots,i_1-1} \quad (3.10)$$

Solution of the State Equations: The complete set of state equations is described by (3.8)–(3.10) for any $n \varepsilon \{1,2,3,\ldots, \ell \wedge w\}$. Again, the unique solution occurs when all *n*-λ states are equal. That is, for any $i_1, i_2, \ldots i_n \varepsilon \{1,2,3,\ldots, \ell\}$ with $i_n > i_{n-1} > \ldots > i_1$:

$$r_{i_n, i_{n-1}, i_{n-2}, \ldots, i_2, i_1} = e_n$$

where e_n can be determined by a substitution in (3.8)–(3.10):

$$e_n = \frac{A - (1-\rho)(n-1)A/w}{1 - A + (1-\rho)(n-1)A/w} e_{n-1}$$

$$= \frac{w - (1-\rho)(n-1)}{w \cdot \frac{1-A}{A} + (1-\rho)(n-1)} e_{n-1}$$

After some algebraic manipulations (Appendix-B) as were done earlier, we get for any $k \varepsilon \{1,2,3,\ldots\ldots, \ell \wedge w\}$:

$$e_k = \frac{\prod_{i=0}^{k-1} \frac{w - i(1-\rho)}{w \frac{1-A}{A} + i(1-\rho)}}{1 + \sum_{n=1}^{\ell \wedge w} \binom{\ell}{n} \prod_{i=0}^{n-1} \frac{w - i(1-\rho)}{w \frac{1-A}{A} + i(1-\rho)}} \qquad (3.11)$$

Steady-State Blocking Probability: The following theorem provides expressions blocking probability for the generalized model.

Theorem 2: In an OBS network with w wavelengths and fixed-length bursts (each of length $\ell \geq 1$ time slots), if the user activity is A and the conversion capability in any node is ρ, $\rho \varepsilon \{0, 1/w, 2/w, \ldots\ldots, 1\}$, then the blocking probability is given by

$$P_b(A,\ell,w,\rho) = \begin{cases} \frac{A(\ell-1)}{w\ell}(1-\rho)\sum_{k=1}^{\ell\wedge w}\binom{\ell}{k}.k.e_k & \text{If } w \geq \ell \\ \frac{A(\ell-1)}{w\ell}(1-\rho)\sum_{k=1}^{\ell\wedge w}\binom{\ell}{k}.k.e_k + \binom{\ell-1}{w}A.\rho.e_w & \text{If } w < \ell \end{cases} \quad (3.12)$$

Here, e_k , $k\varepsilon\{1,2,3,............,\ell\wedge w\}$ are given by (3.11).

Proof: The proof of the first assertion of blocking probability $P_b(A,\ell,w,\rho)$ is also exactly the same as that of theorem 1. The proof of the second assertion of blocking probability can be performed as follows. Assume that $w < \ell$, and Consider an n-λ state $r_{i_n,i_{n-1},i_{n-2},...,i_2,i_1}$ (where $n\varepsilon\{1,2,3,........,\ell\wedge w\}$ and $i_1,i_2,.......i_n\varepsilon\{1,2,3,.......,\ell\}$ with $i_n > i_{n-1} > .... > i_1$). After T_s s, if there is an arrival that needs to be served, then three blocking cases may arise.

(1) If $i_n = \ell$, the arrival will be blocked with probability $(1-\rho)(n-1)A/w$. The blocked node will enter state $r_{i_{n-1}+1,i_{n-2}+1,....i_1+1}$.

(2) If $i_n \neq \ell$ and $n \neq w$, the arrival will be blocked with probability $(1-\rho)nA/w$. The blocked node will enter state $r_{i_n+1,i_{n-1}+1,i_{n-2}+1,....i_1+1}$.

(3) If $i_n \neq \ell$ and $n = w$, the arrival will be blocked with probability A. The blocked node will enter state $r_{i_n+1,i_{n-1}+1,i_{n-2}+1,....i_1+1}$.

Thus, if $n \neq w$, the blocking probability $P_b(A,\ell,w,\rho,n)$ for this node is given by

$$P_b(A,\ell,w,\rho,n) = \frac{A(\ell-1)}{w\ell}(1-\rho)n\binom{\ell}{n}e_n \quad (3.13)$$

If $n = w$, however, it is given by

$$P_b(A,\ell,w,\rho,w) = e_w .A \text{ .number of times } (i_w \neq \ell) \text{ occurs in } r_{i_w,i_{w-1},i_{w-2},\dots,i_2,i_1} +$$

$$e_w\left[(1-\rho)(w-1)\frac{A}{w}\right]\text{.. number of times } (i_w = \ell) \text{ occurs}$$

$$\text{in } r_{i_w,i_{w-1},i_{w-2},\dots,i_2,i_1}$$

$$= \frac{A}{w}\left[w\binom{\ell-1}{w} + (1-\rho)(w-1)\binom{\ell-1}{w-1}\right]e_w$$

$$= \frac{A}{w}\left[(1-\rho)w\binom{\ell-1}{w} + (1-\rho)(w-1)\binom{\ell-1}{w-1} + \rho w\binom{\ell-1}{w}\right]e_w$$

$$= \frac{A(\ell-1)}{w\ell}(1-\rho)w\binom{\ell}{w}e_w + A\rho\binom{\ell-1}{w}e_w \qquad (3.14)$$

Thus, the total blocking probability in this case is

$$P_b(A,\ell,w,\rho) = \sum_{k=1}^{w} P_b(A,\ell,w,\rho,k)$$

$$= \frac{A(\ell-1)}{w\ell}(1-\rho)\sum_{k=1}^{\ell\wedge w}\binom{\ell}{k}.k.e_k + \binom{\ell-1}{w}A.\rho.e_w \qquad (3.15)$$

We denote the burst arrival probability on an input wavelength in a given time slot as A ($0 \le A \le 1$) and assume that A is independent on burst arrivals in other wavelengths and burst arrivals on in previous time slots. Let A_k ($0 \le A_k \le 1$) be the probability for k ($0 \le k \le w$) arrivals to the output fiber on a given time slot. A_k is then distributed according to a Binomial process $P_A(k/w)$.

$$A_k = P_A(k/w) = \binom{w}{k}(A)^k(1-A)^{w-k} \qquad (3.16)$$

The average number of burst arrivals in a time slot is E[A_k]= Aw. When bursts arrive on the input wavelengths to the switch in a given time slot, the control packets are processed electronically. Based on the desired information extracted from the control packets, the control module decides which wavelengths the bursts are switched to and configure the switch fabric accordingly. If two control packets are to reserve the same wavelength at a given core node for two different bursts, then only one burst will be offered to this wavelength. The other will be blocked and lost (unless there is an available wavelength converter or fiber delay line (FDL)).

If A_k be the probability for k arrivals to the output fiber on a given time slot and blocking probability for k arrivals is $P_b(A,\ell,w,\rho,n)$ then the actual number of bursts arrival will be $(A_k.k)$ and the number of blocked or dropped bursts will be $(A_k.k.P_b(A,\ell,w,\rho,n))$.

So we obtain the average burst loss rate as follows:

$$BLR_{avg} = \frac{1}{Aw}\sum_{k=1}^{\ell\wedge w} A_k.k.P_b(A,\ell,w,\rho,k) \tag{3.17}$$

If $k<w$

$$BLR_{k<w} = \frac{1}{Aw}\sum_{k=1}^{\ell\wedge w} A_k.k.\frac{A(\ell-1)}{w\ell}(1-\rho).k.\binom{\ell}{k}.e_k$$

If $k=w$

$$BLR_{k=w} = \frac{1}{Aw}A_w.w.[\frac{A(\ell-1)}{w\ell}(1-\rho)w\binom{\ell}{w}e_w + A\rho\binom{\ell-1}{w}e_w]$$

The average burst loss rate will be

$$BLR_{avg} = BLR_{k<w} + BLR_{k=w}$$

3.8 BLR Differentiation for Two Service Classes

As illustrated in Fig. 3.5, we consider a slotted burst switch with one input and output fiber, where the fiber provides N wavelengths by using wavelength-division multiplexing. The switch has no buffers for contention resolution, but employs wavelength converters with ρ conversion capability at each output. We assume a uniform traffic pattern, which means that we can restrict our study to consider the burst loss rate on a single output fiber. The effect of the switching time is ignored.

Let the network has d service classes, ranging from service class 0 to service class d-1. Let BLR_i $(0 \leq i \leq d\text{-}1)$ be the burst loss rate for class i traffic at the output fibre, and let S_i be the relative share of class i traffic. The service classes are isolated based on different $BLRs$.

Let A_k $(0 \leq A_k \leq 1)$ be the probability for k $(0 \leq k \leq N)$ arrivals to the output fibre on a given time slot. A_k is then distributed according to a Binomial process $P_A(k/N)$.

$$A_k = P_A(k/N) = \binom{N}{k}(A)^k(1-A)^{N-k} \tag{3.18}$$

The average number of burst arrivals in a time slot is $E[A_k]=AN$.

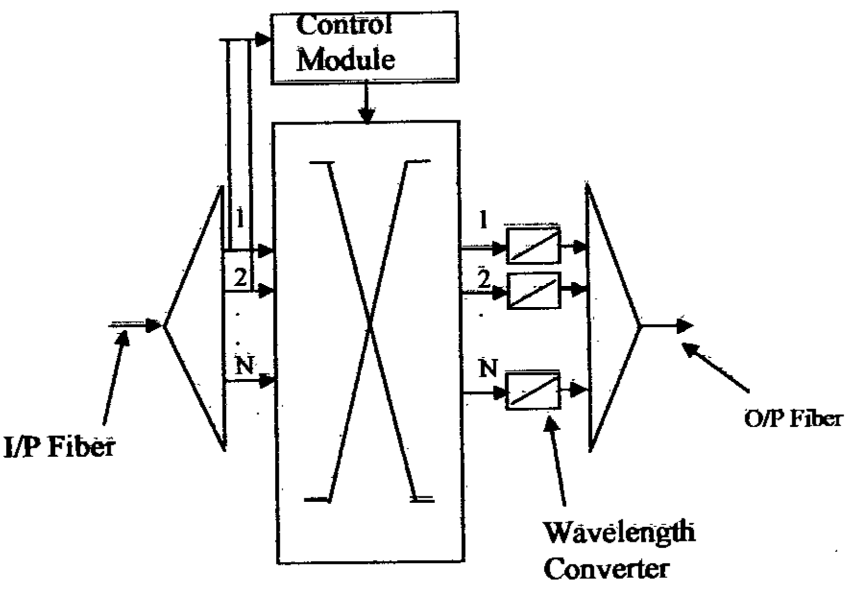


Fig. 3.4: Slotted optical burst switch.

In order to isolate the service classes, we introduce the parameter L_i ($0 \le L_i \le N$), which is the number of wavelengths reserved for class i traffic in the case of contention in a time slot. Let j_i denote the number of class i bursts that arrive in a time slot. If the total number of burst arrival to the output fibre in a time slot is k, we must have $j_0 + j_1 + \ldots\ldots + j_{d-1} = k$. Regarding service class i , if $j_i \le L_i$ then L_i - $j_i(1 - P_b(j_i))$, wavelengths in the considered time slot that are not utilized by the class i bursts are denoted as free wavelengths, where $P_b(j_i)$ denotes the burst blocking probability for j_i number of burst. On the other hand if, $j_i \ge L_i$, there are more bursts than reserved wavelengths available for service class i. In this case, L_i bursts will be transmitted, however, j_i - L_i number of bursts that do not get a wavelength among the L_i reserved wavelengths are denoted as overflow bursts only when the network has full wavelength conversion capability i.e. ρ = 1 and $w \ge \ell$. But the networks with wavelength conversion capability less than 1 will have burst loss greater than the number j_i - L_i.

Overflow bursts will attempt to seize free wavelengths from other service classes, if available, in order to ensure that all wavelengths are utilized. In any case, we do not leave any wavelengths idle when contention occurs. Here we consider d=2 i.e. two different service classes have been considered. Fig. 3.4 illustrates different loss scenarios exemplified for a d=2 service classes case. If we consider the network has full wavelength conversion capability and $w \geq \ell$ .So there will be no loss of bursts if the number of burst arrival of a service class is less than the number of reserved wavelengths of that service class. In case of scenario given in Fig 3.4(a), there is no overflow bursts so there will be no burst loss of any service classes. Scenario shown in Fig. 3.4(b) contains overflow bursts of service class 1 which is J_1-L_1 but service class 0 has free wavelengths L_0 - J_0. So the overflow burst of service class 1 will be transmitted on the free wavelengths of service class 0. Scenario in Fig. 3.4(c) shows that the service class 0 has overflow bursts which will be transmitted by the free wavelengths of service class 1. But if the network doesn't have full wavelength conversion capability and $w \geq \ell$, there may be blocking probability of overflow and normal bursts as a result more bursts will be lost

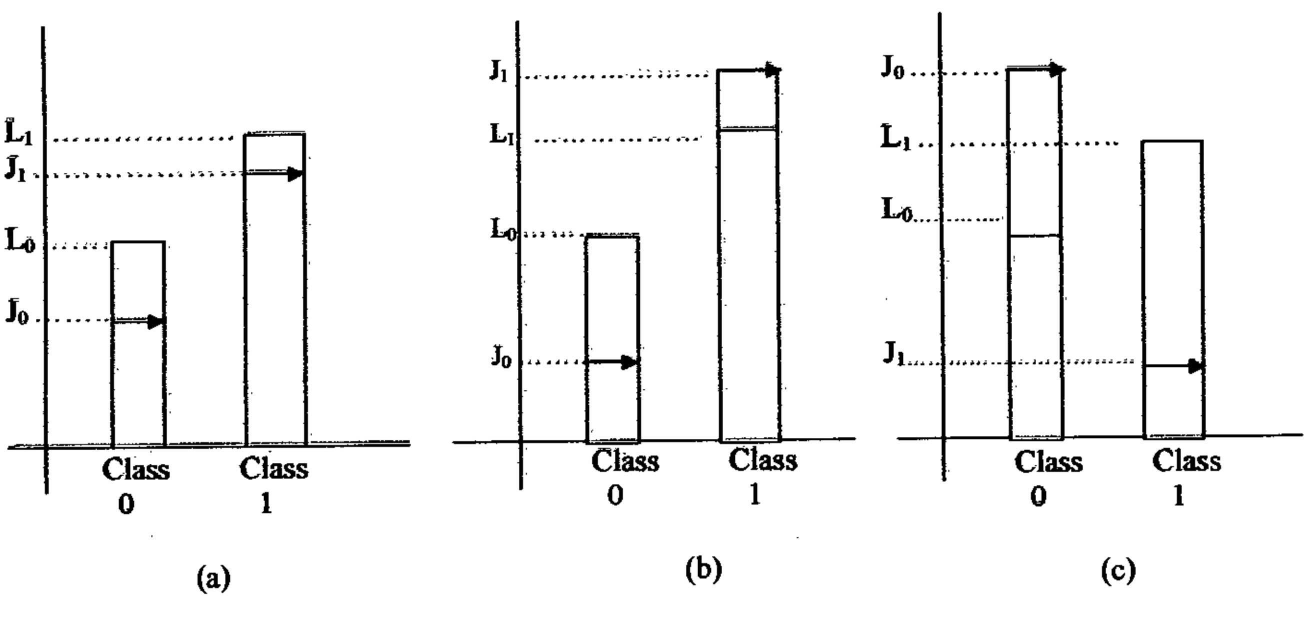


Fig. 3.4: Different scenarios showing overflow bursts (a) no overflow bursts, (b) Class 1 has overflow bursts J_1-L_1 (c) Class 0 has overflow bursts J_0-L_0

So the burst loss rate (BLR_i) for c class i traffic given below in equation (3.19) [31],

$$BLR_i = \frac{1}{ANS_i}\sum_{k=1}^{l\wedge N} A_k \left[\sum_{j_0=0}^{k}\sum_{j_1=0}^{k-j_0} \cdots\cdots \sum_{j_{d-2}=0}^{k-\sum_{v=0}^{d-3} j_v}\left[M\left(j_0,\ldots\ldots,j_{d-2},k-\sum_{v=0}^{d-2} j_v; S_0,S_1,\ldots\ldots,S_{d-1}\right)\times L_{lost}\right]\right] \quad (3.19)$$

Where

$$M\left(j_0,\ldots\ldots,j_{d-2},k-\sum_{v=0}^{d-2} j_v; S_0,S_1,\ldots\ldots,S_{d-1}\right)=\binom{k}{j_0 j_1 \ldots j_{d-2}\, k-\sum_{v=0}^{d-2} j_v} S_0^{j_0} S_1^{j_1} \cdots\cdots S_{d-1}^{j_{d-1}} \quad (3.20)$$

when d=2 then the above two equations are reduced to the form given below:

$$BLR_i = \frac{1}{ANS_i}\sum_{k=1}^{l\wedge N} A_k \left[\sum_{j_0=0}^{k} [M(j_0, k-j_0; S_0, S_1)\times L_{lost}]\right] \quad (3.21)$$

$$M(j_0,k-j_0;S_0,S_1)=\binom{k}{j_0\, k-j_0} S_0^{j_0} S_1^{j_1} = \frac{k!}{(j_0!).(k-j_0)!} S_0^{j_0}.S_1^{j_1} \quad (3.22)$$

where A_k is given in equation (3.18), $M(.)$ is given in equation (3.20) which is the multinomial distribution and L_{lost} is the number of lost bursts for service class i. L_{lost} can be calculated from the following algorithm:

```
IF (j_0 < L_0) THEN DO

   IF (j_1 < L_1)
        L_0_new = L_0 + [L_1 - j_1 (1- P_b(j_1) ]
        L_1_new = L_1 + [L_0 - j_0 (1- P_b(j_0) ]
   ELSE
        L_0_new = L_0
        L_1_new = L_1 + [L_0 - j_0 (1- P_b(j_0) ]
   END
```

ELSE
 	
  IF $(j_1 < L_1)$
    $L_{0\_new} = L_0 + [L_1 - j_1 (1 - P_b(j_1))]$
    $L_{1\_new} = L_1$
  END
 	
END
 	
L_{0_new} = round (L_{0_new})
L_{1_new} = round (L_{1_new})
 	
For Service Class 0
    $L_{lost} = j_0 \cdot P_b(j_0)$
 	
For Service class 1
    $L_{lost} = j_1 \cdot P_b(j_0)$

Here, L_{0_new} and L_{1_new} approximately denote the number of wavelengths for service class 0 and service class 1 respectively.

Let us consider w is the resultant wavelengths for any service class and the number of burst arrival is k for that service class at any instant of time.

For service class 0,	For service class 1,
$w = L_{0\_new}$ $k = j_0$ $P_b(j_0) = P_b(A, \ell, w, \rho, j_0)$	$w = L_{1\_new}$. $k = j_1$ $P_b(j_1) = P_b(A, \ell, w, \rho, j_1)$

So the blocking probability is determined for service class 0 using $w = L_{0\_new}$ and for service class 1 using $w = L_{1\_new}$.

Chapter 4

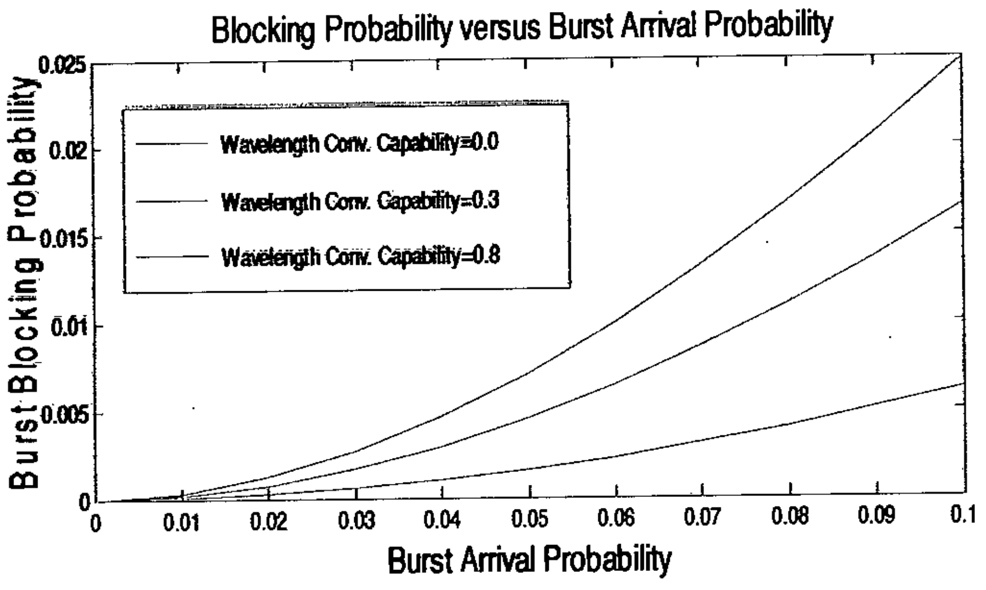
RESULTS AND DISCUSSIONS

4.1 Introduction

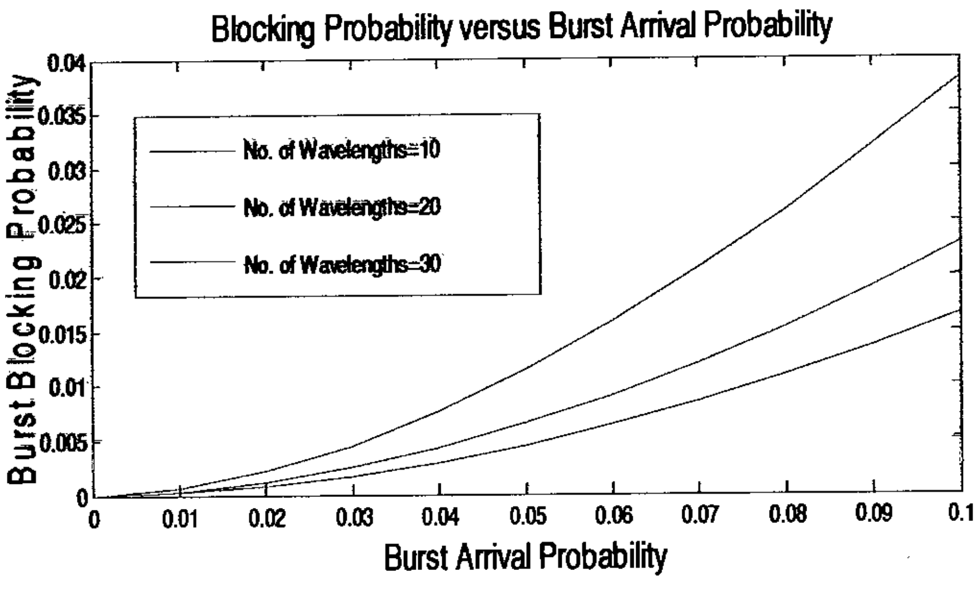
The analytical results presented for average burst loss rate (BLR) have been simulated and simulation results have been discussed in this chapter. The average burst loss rates have been investigated with various network design parameters such as wavelength conversion capability, burst arrival probability, network traffic, number of slots per burst and the number of wavelengths in an slotted optical burst switching network. Also the average burst loss rates for two different classes have been investigated. The effect of several network design parameters on burst blocking probability have also been shown.

4.2 Results and Discussions

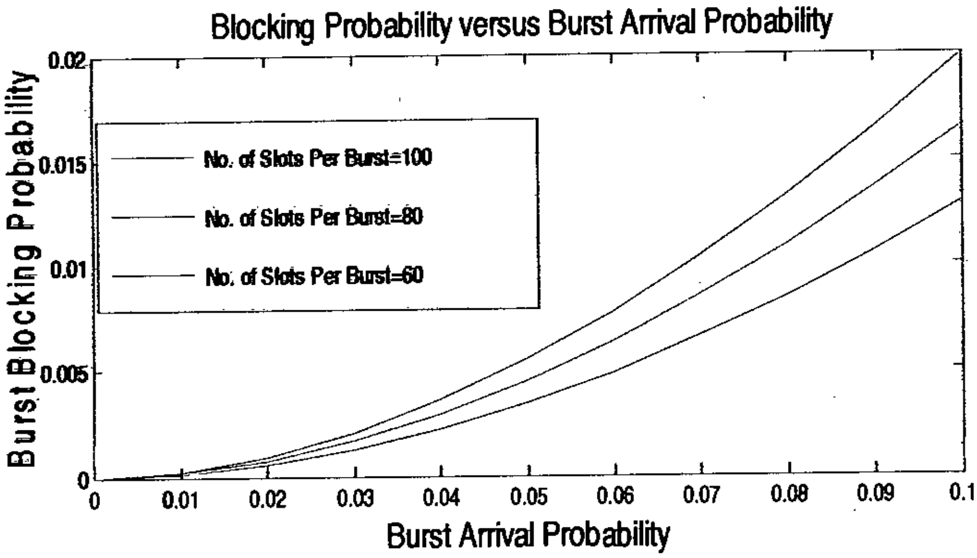
Simplified mathematical model has been proposed for evaluating the performance measure of an OBS-JIT network which is burst loss rate. The effect of several network design parameters on the system performance measure have been investigated and presented numerically. The simulation results that we have got from the derived analytical results of burst loss rate have been shown below. All the simulation results are satisfactorily agreed with the expected results.



Figs. 4.1: Burst blocking probability versus burst arrival probability with different wavelength conversion capabilities. Here number of slots per burst ℓ =100, total number of wavelengths w =30 and $w<\ell$.



Figs. 4.2: Burst blocking probability versus burst arrival probability with different number of wavelength. Here number of slots per burst ℓ =100, wavelength conversion capability ρ= 0.4 and $w<\ell$.



Figs. 4.3: Burst blocking probability versus burst arrival probability with different number of slots per burst. Here total number of wavelengths $w = 20$, wavelength conversion capability $\rho = 0.5$ and $w < \ell$.

The burst blocking probability versus the burst arrival probability has been plotted in the above Figs. (4.1, 4.2 and 4.3). The burst blocking probability increases with the burst arrival probability and this behavior is expected because the greater the probability of the burst arrival the greater will be the blocking probability. Figs. 4.1, 4.2 and 4.3 show the effect of different wavelength conversion capabilities, number of wavelengths and number of slots per burst respectively on the burst blocking probability while the other parameters are constant. The burst blocking probability should decrease with the increasing of wavelength conversion capabilities and number wavelengths and increase with the increasing of the number of slots per burst. The simulation result is satisfactorily agreed with the expected results.

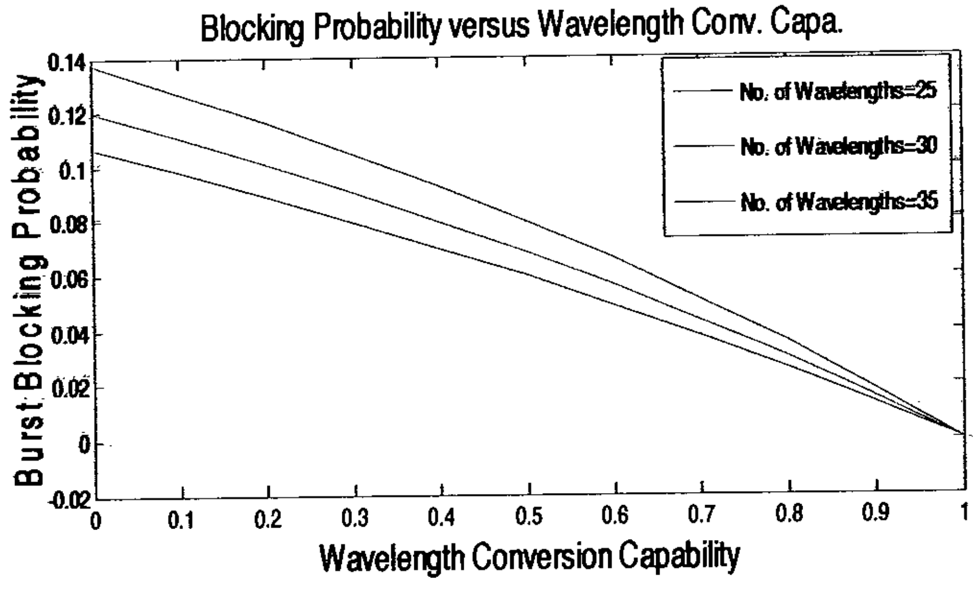


Fig. 4.4: Burst blocking probability versus wavelength conversion capability with different number of wavelengths. Here number of slots per burst ℓ = 20, burst arrival probability A= 0.5 and $w \geq \ell$.

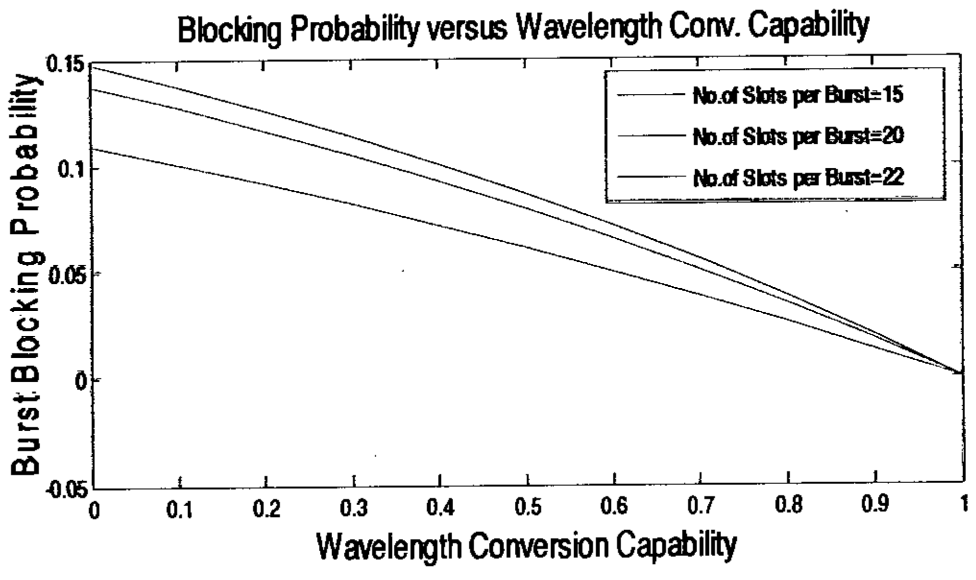


Fig. 4.5: Burst blocking probability versus wavelength conversion capability with different number of slots per burst. Here total number of wavelengths W = 25, burst arrival probability A= 0.5 and $w \geq \ell$.

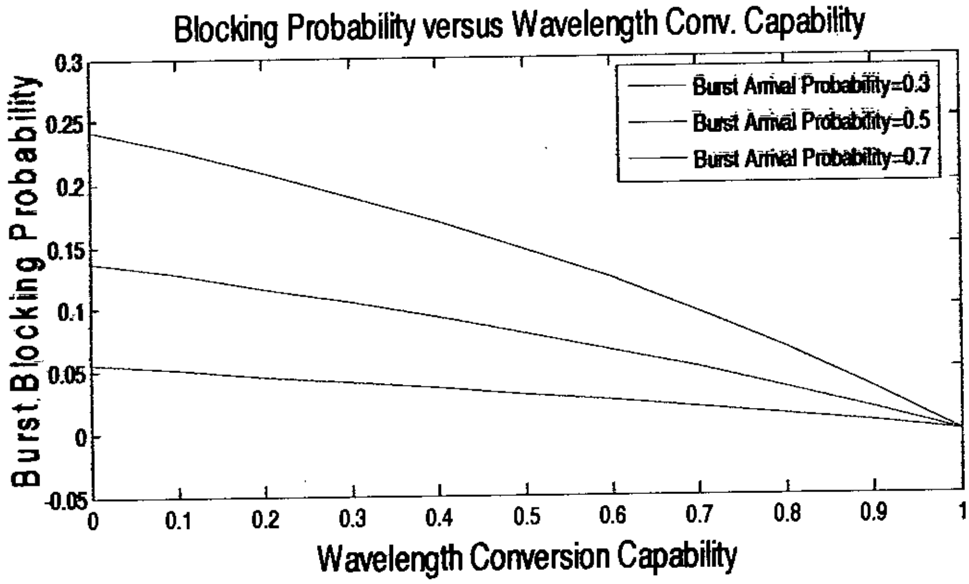


Fig. 4.6: Burst blocking probability versus wavelength conversion capability with different burst arrival probability. Here number of slots per burst $\ell = 20$, total number of wavelengths $w = 25$ and $w \geq \ell$.

The burst blocking probability versus the wavelength conversion capability has been plotted in the above Figs. (4.4, 4.5 and 4.6) with the condition $w \geq \ell$. The burst blocking probability decreases with the wavelength conversion capability and this behavior is expected because the greater the capability of the wavelength conversion the lesser will be the blocking probability. When the network has full wavelength conversion capability then the blocking probability is zero under the condition $w \geq \ell$. Figs. 4.4, 4.5 and 4.6 show the effect of different number of wavelengths, number of slots per burst and burst arrival probability respectively on the burst blocking probability while the other parameters are constant. The burst blocking probability should decrease with the increasing of the number of wavelengths and increase with the increasing of the number of slots per burst and the burst arrival probability. The simulation result is satisfactorily agreed with the expected result.

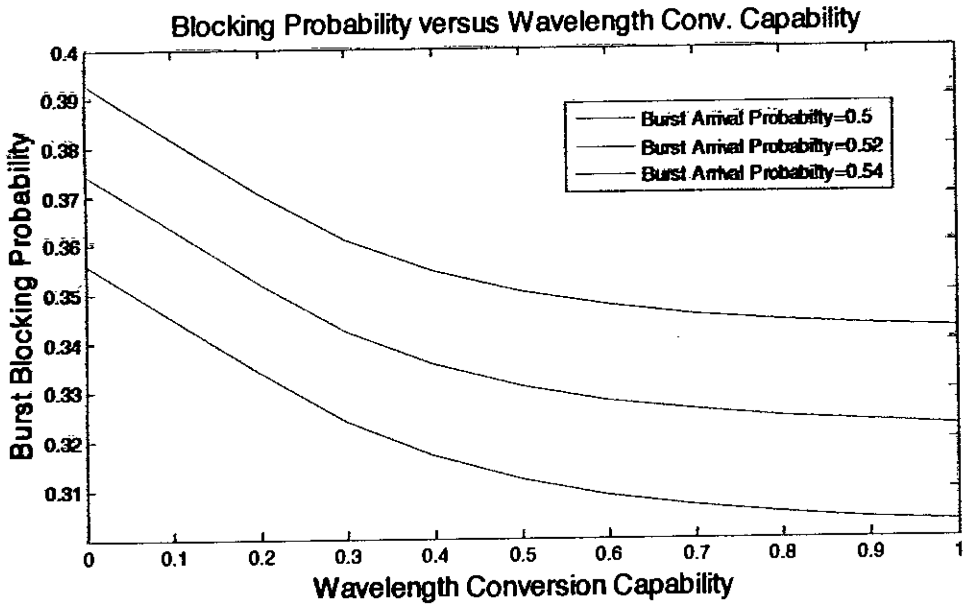


Fig. 4.7: Burst blocking probability versus wavelength conversion capability with different burst arrival probability. Here number of slots per burst ℓ =100, total number of wavelengths w = 20 and $w < \ell$.

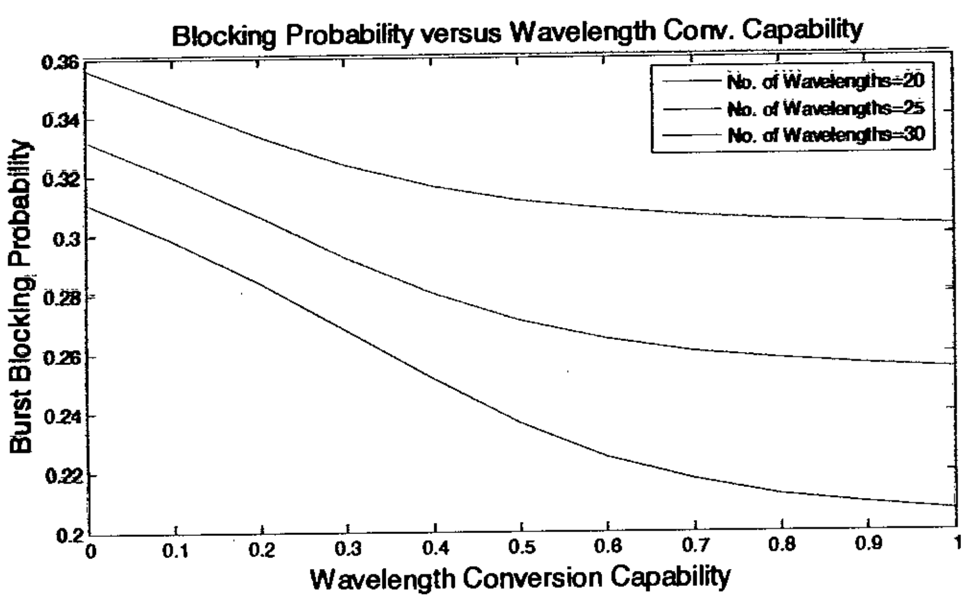


Fig. 4.8: Burst blocking probability versus wavelength conversion capability with different number of wavelengths. Here number of slots per burst ℓ = 100, burst arrival probability A= 0.5 and $w < \ell$.

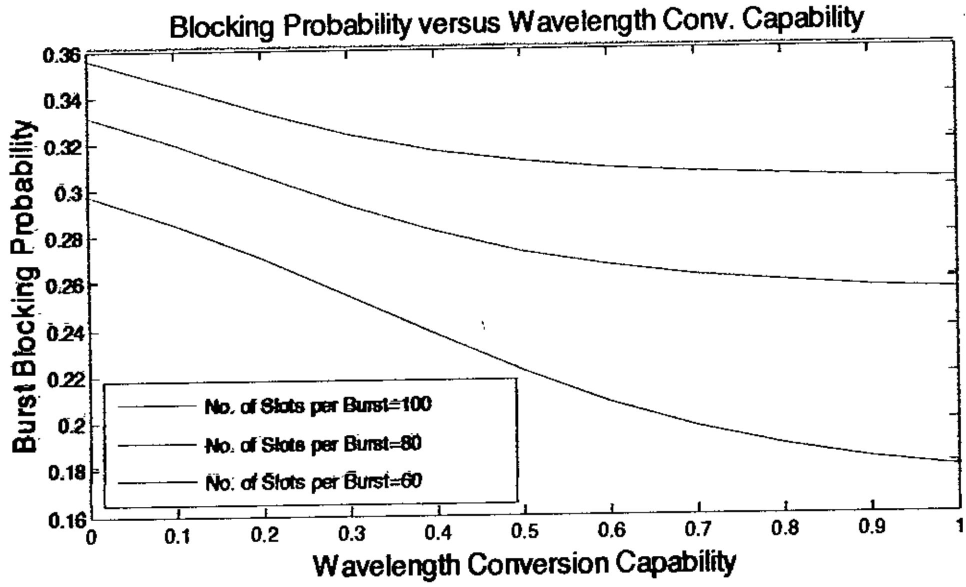


Fig. 4.9: Burst blocking probability versus wavelength conversion capability with different number of slots per burst. Here total number of wavelengths $w = 20$, burst arrival probability A=0.5 and $w < \ell$.

The burst blocking probability versus the wavelength conversion capability has been plotted in the above Figs. (4.7, 4.8 and 4.9) with the condition $w < \ell$. When the network has full wavelength conversion capability then the blocking probability is not zero under the condition $w < \ell$ and this result was expected from the derivation of the analytical expression of the burst blocking probability because the maximum number of slots per burst can be accommodated equals to the number of wavelengths.

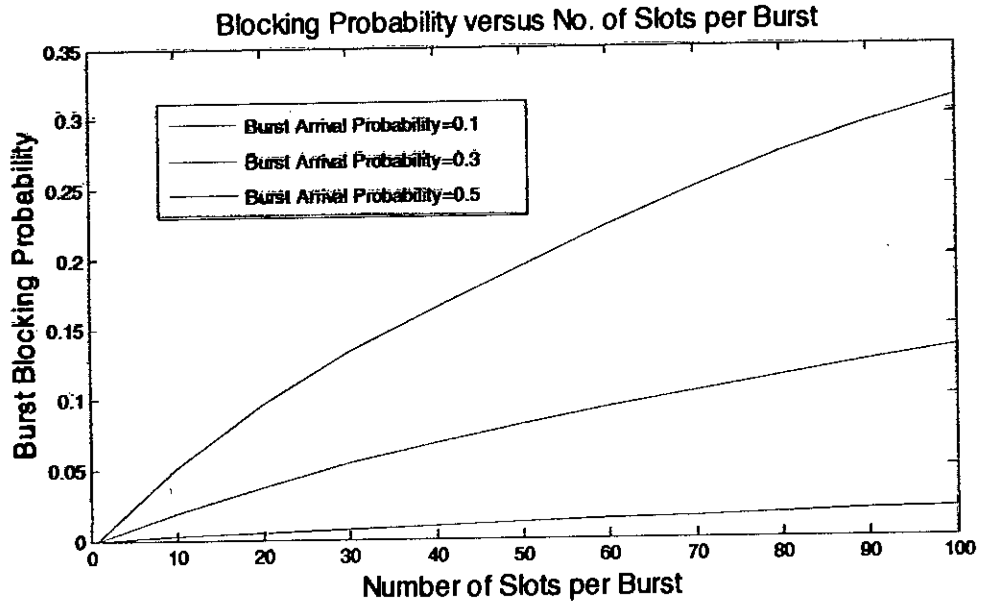


Fig. 4.10: Burst blocking probability versus number of slots per burst with different burst arrival probabilities. Here total number of wavelengths W =20 and wavelength conversion capability ρ=0.5.

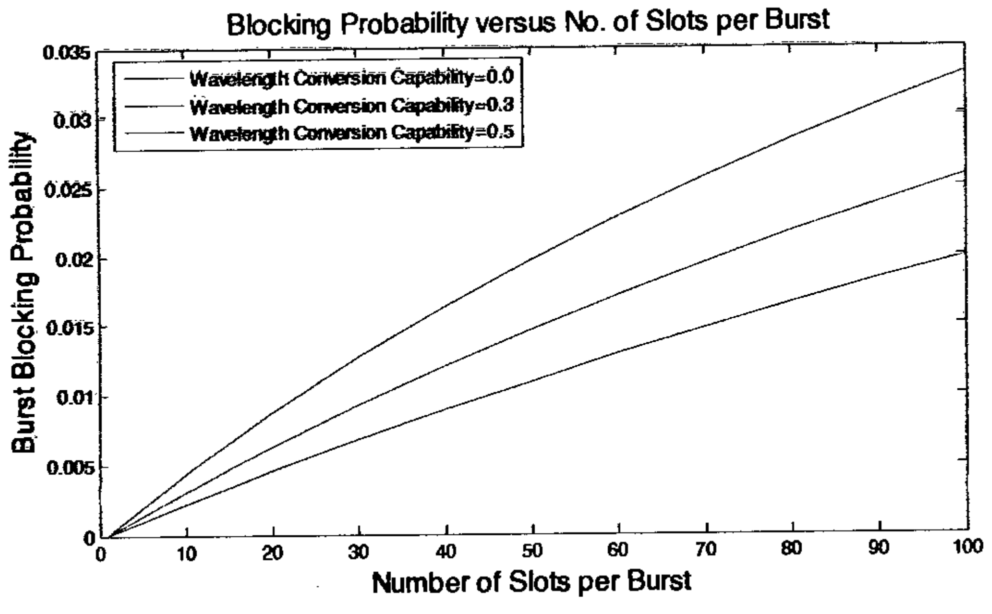


Fig. 4.11: Burst blocking probability versus number of slots per burst with different wavelength conversion capabilities. Here burst arrival probability A =0.1 and total number of wavelengths W =20.

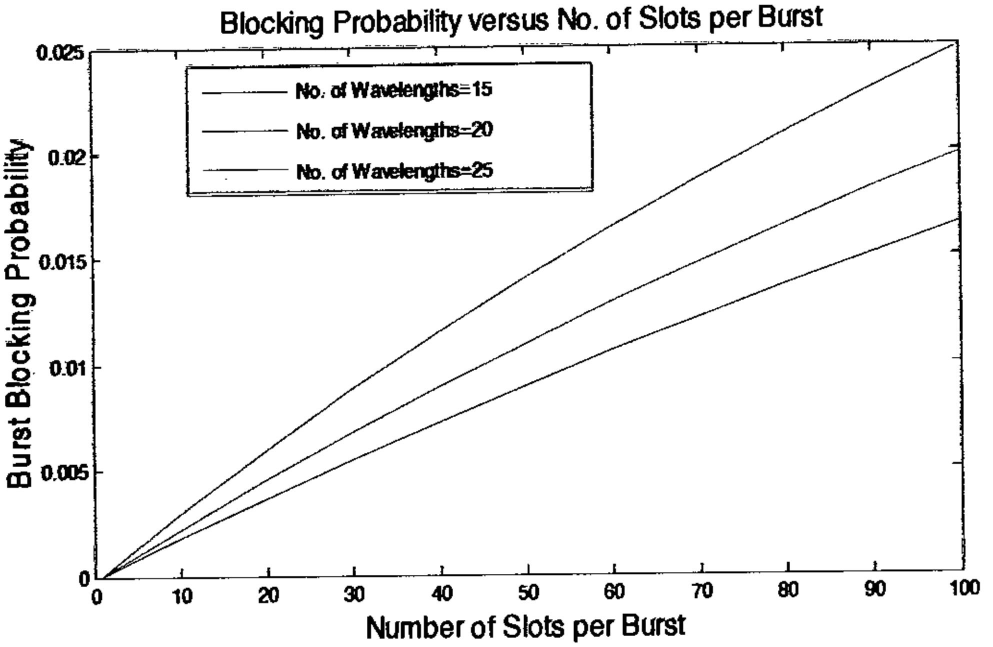


Fig. 4.12: Burst blocking probability versus number of slots per burst with different number of wavelengths. Here burst arrival probability A = 0.1 and wavelength conversion capability ρ=0.5.

The burst blocking probability versus the number of slots per burst has been plotted in the above Figs. (4.10, 4.11 and 4.12). The burst blocking probability increases with the number of slots per burst and this behavior is expected because for constant burst arrival probability network traffic increases with the increasing of the number of slots per burst. Figs. 4.10, 4.11 and 4.12 show the effect of different burst arrival probability, wavelength conversion capability and number of wavelengths respectively on the burst blocking probability while the other parameters are constant. The burst blocking probability should decrease with the increasing of the wavelength conversion capability and the number of wavelengths and increase with the increasing of the burst arrival probability. The simulation result is satisfactorily agreed with the expected result.

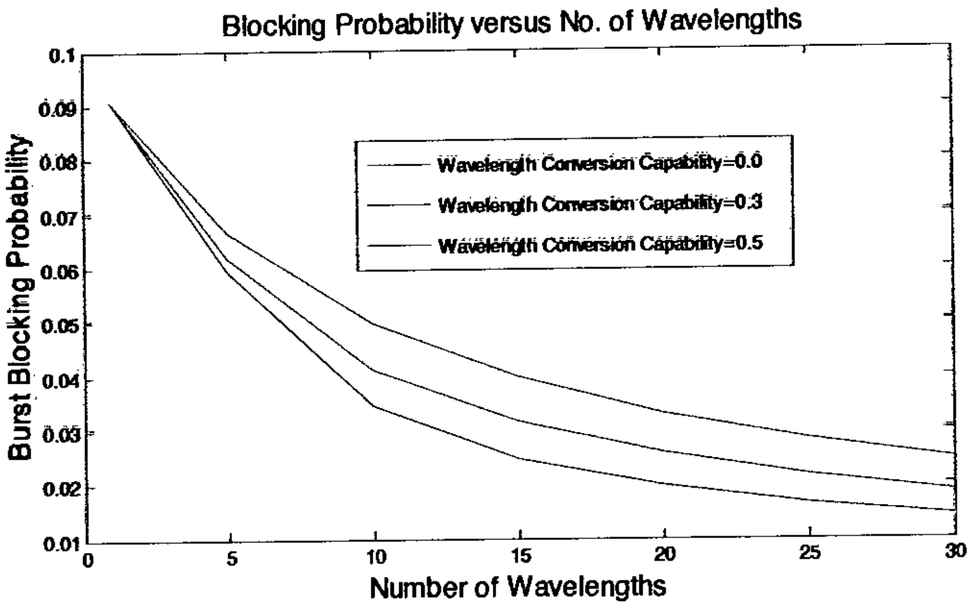


Fig. 4.13: Burst blocking probability versus total number of wavelengths with different wavelength conversion capabilities. Here number of slots per burst ℓ =100, burst arrival probability A= 0.1 and $w < \ell$.

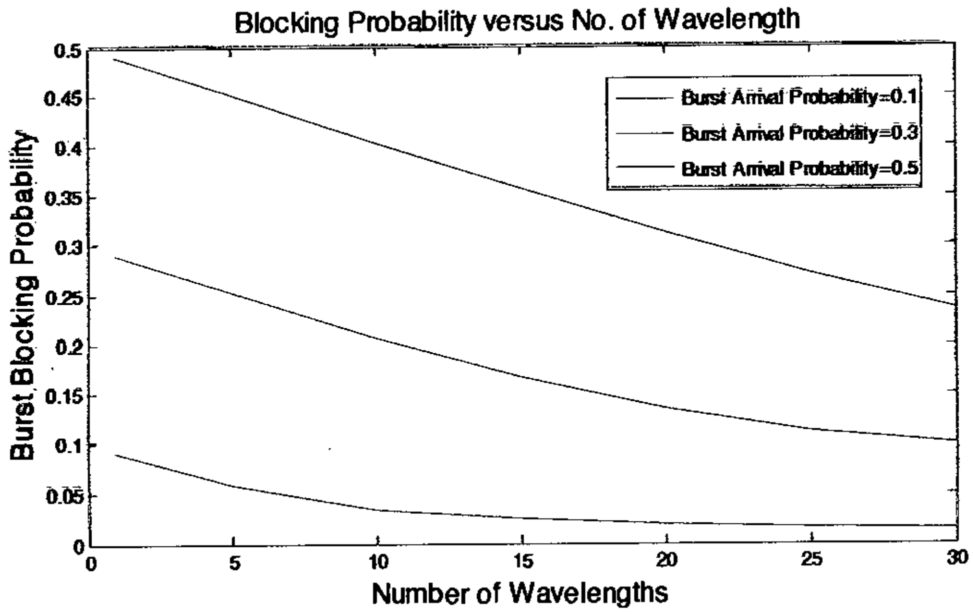


Fig. 4.14: Burst blocking probability versus total number of wavelengths with different burst arrival probabilities. Here wavelength conversion capability ρ=0.5, number of slots per burst ℓ =100 and $w < \ell$.

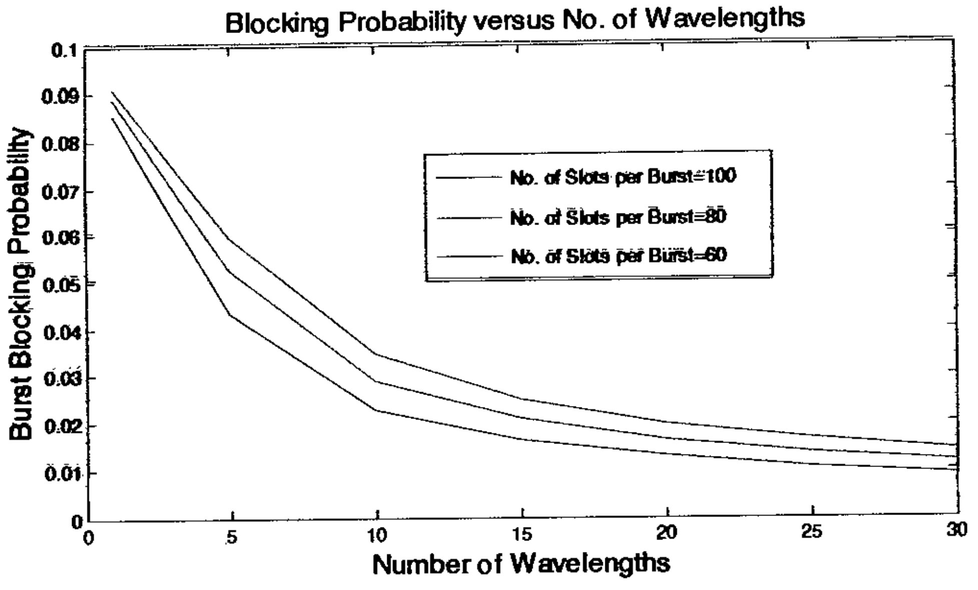


Fig. 4.15: Burst blocking probability versus total number of wavelengths with different number of slots per burst. Here wavelength conversion capability ρ= 0.5, burst arrival probability A= 0.1 and $w < \ell$.

The burst blocking probability versus the number wavelengths has been plotted in the above Figs. (4.13, 4.14 and 4.15). The burst blocking probability decreases with the number of wavelengths and this behavior is expected because with increasing of the number of wavelengths the number of channel will be larger and the large will be the chance to get a free wavelength. Figs. 4.13, 4.14 and 4.15 show the effect of different wavelength conversion capability, burst arrival probability and number of slots per burst respectively on the burst blocking probability while the other parameters are constant. The burst blocking probability should decrease with the increasing of the wavelength conversion capability and increase with the increasing of the burst arrival probability and the number of slots per burst. The simulation result is satisfactorily agreed with the expected result.

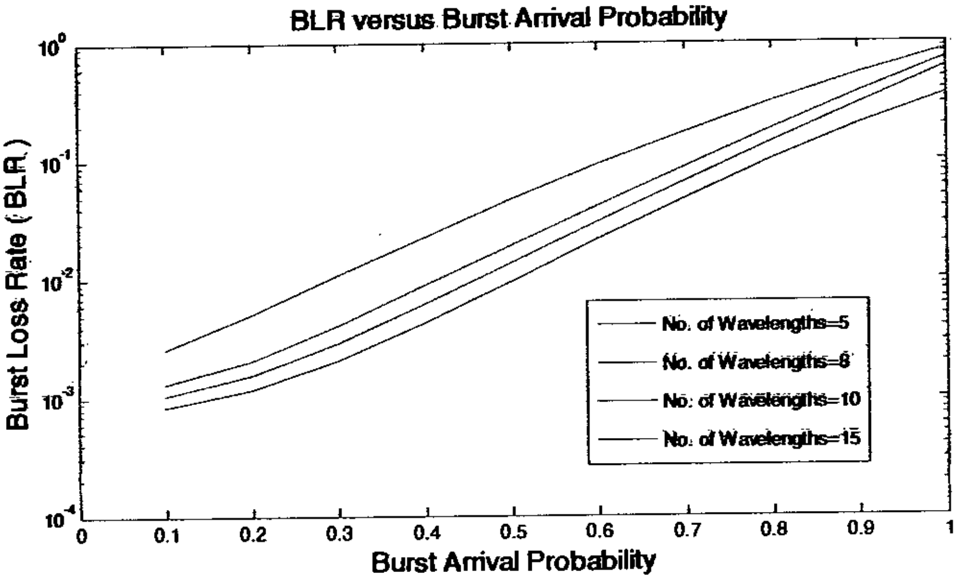


Fig. 4.16: Burst loss rate versus burst arrival probability with different number of wavelengths. Here wavelength conversion capability ρ=0.1, number of slots per burst ℓ=100 and $w < \ell$.

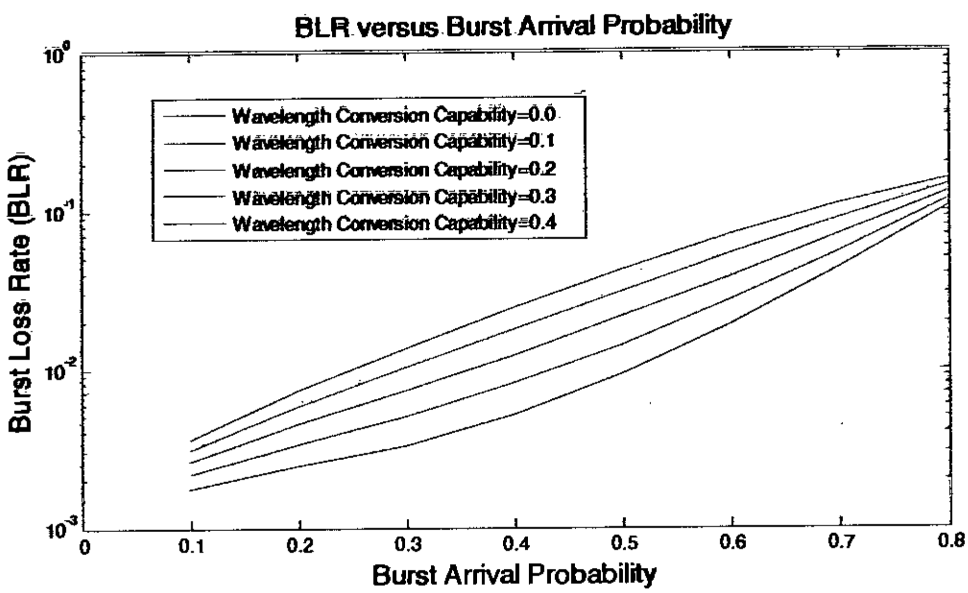


Fig. 4.17: Burst loss rate versus burst arrival probability with different wavelength conversion capabilities. Here total number of wavelengths W = 20, number of slots per burst, $\ell = 100$ and $w < \ell$.

The burst loss rate versus the burst arrival probability has been plotted in the above Figs. (4.16, 4.17). The burst loss rate increases with the burst arrival probability and this behavior is expected because the greater the probability of the burst arrival the greater will be the loss rate. Figs. 4.16 and 4.17 show the effect of different number of wavelengths and wavelength conversion capability respectively on the burst loss rate while the other parameters are constant. The burst loss rate should decrease with the increasing of wavelength conversion capabilities and wavelengths. The simulation results show the desired results.

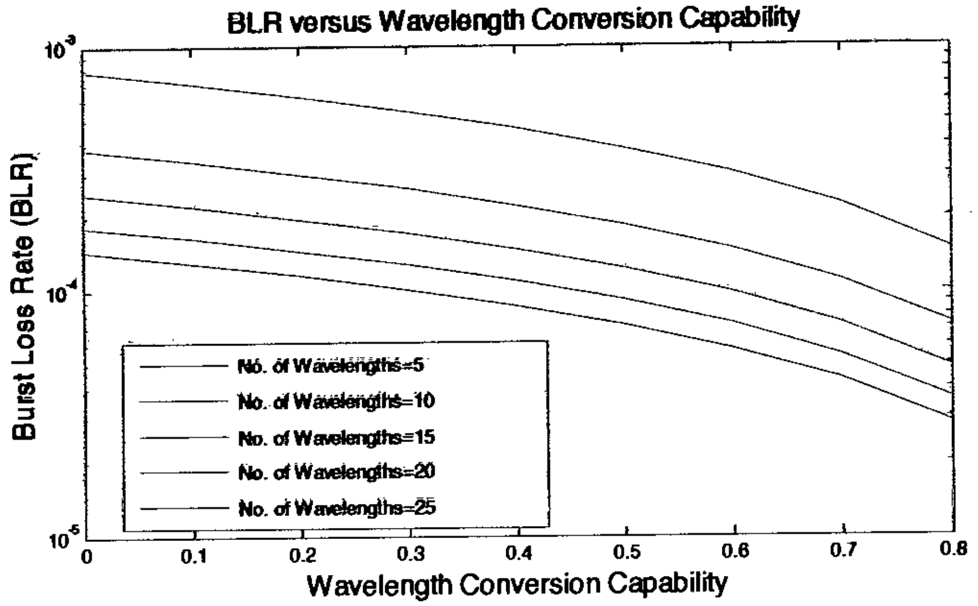


Fig. 4.18: Burst loss rate versus wavelength conversion capability with different number of wavelengths. Here number of slots per burst ℓ =100, burst arrival probability A=0.01 and $w < \ell$.

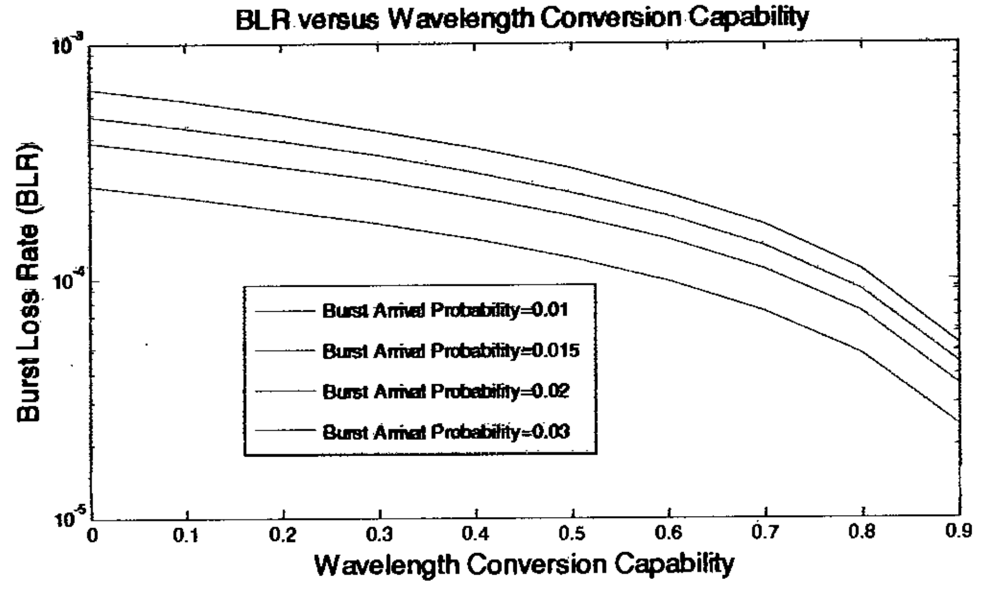


Fig. 4.19: Burst loss rate versus wavelength conversion capability with different burst arrival probabilities. Here number of slots per burst ℓ =100, number of wavelengths w = 15 and $w < \ell$.

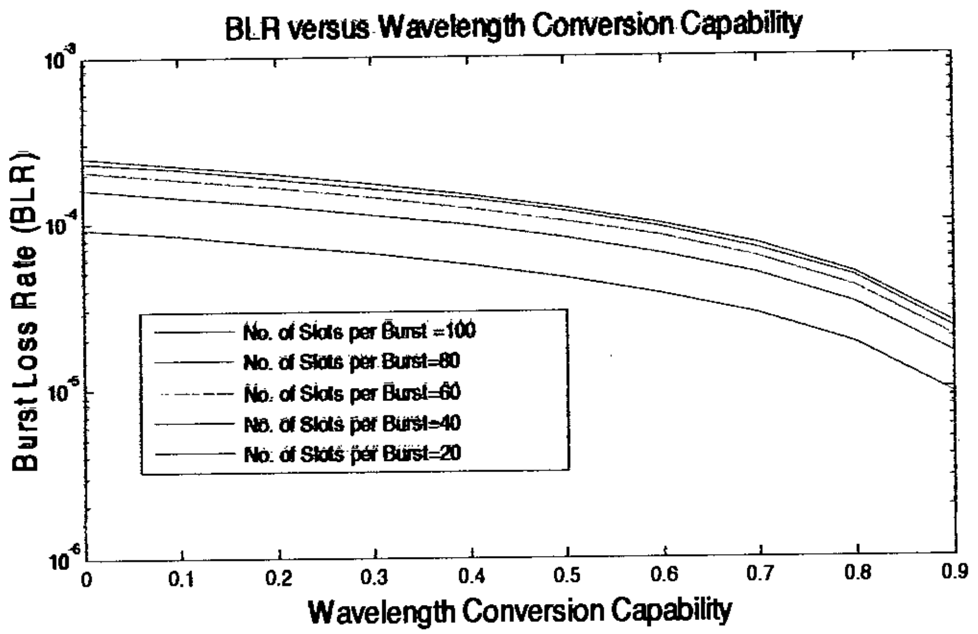


Fig. 4.20: Burst loss rate versus wavelength conversion capability with different number of slots per burst. Here number of wavelengths W =15, burst arrival probability A=0.01 and $w < \ell$.

The burst loss rate versus the wavelength conversion capability has been plotted in the above Figs. (4.18, 4.19 and 4.20) with the condition $w < \ell$. The burst loss rate decreases with the wavelength conversion capability and this behavior is expected because the greater the capability of the wavelength conversion the lesser will be the burst dropping. Figs. 4.18, 4.19 and 4.20 show the effect of different number of wavelengths, burst arrival probability and number of slots per burst respectively on the burst loss rate while the other parameters are constant. The burst loss rate should decrease with the increasing of the number of wavelengths and increase with the increasing of the number of slots per burst and the burst arrival probability. The simulation result is satisfactorily agreed with the expected result.

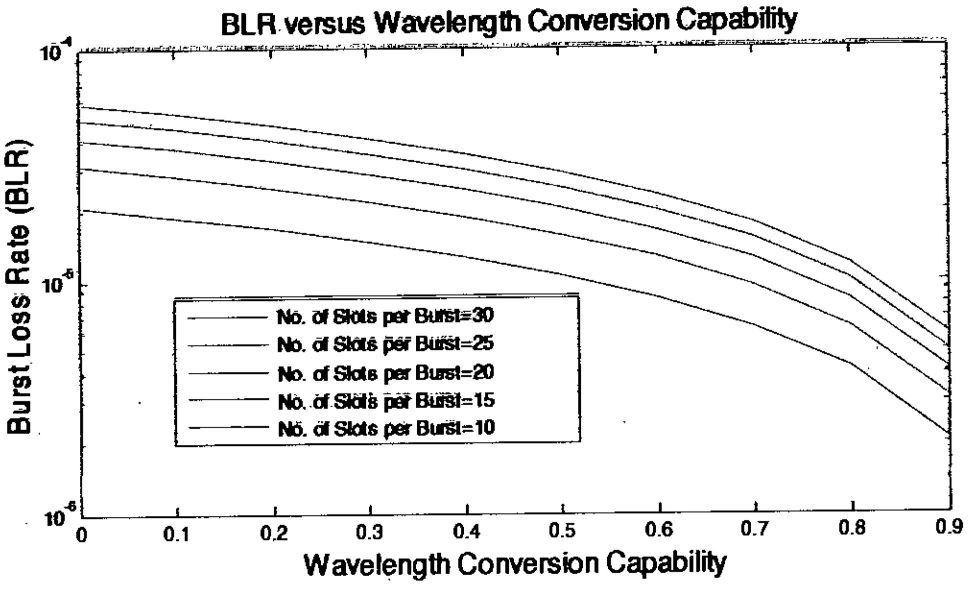


Fig. 4.21: Burst loss rate versus wavelength conversion capability with different number of slots per burst. Here number of wavelengths W =30, burst arrival probability A= 0.01 and $w \geq \ell$.

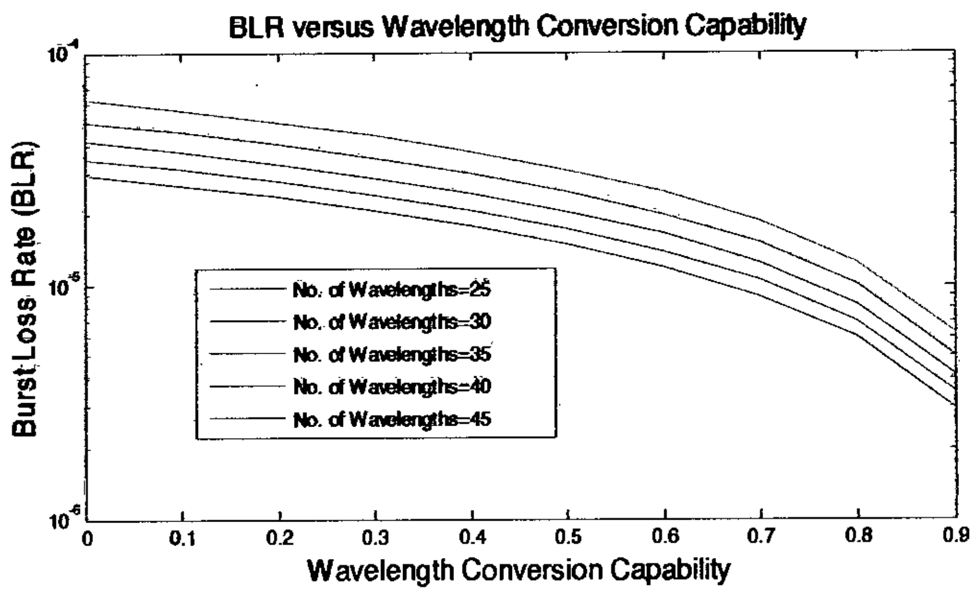


Fig. 4.22: Burst loss rate versus wavelength conversion capability with different number of wavelengths. Here number of slots per burst ℓ =25, burst arrival probability A=0.01 and $w \geq \ell$.

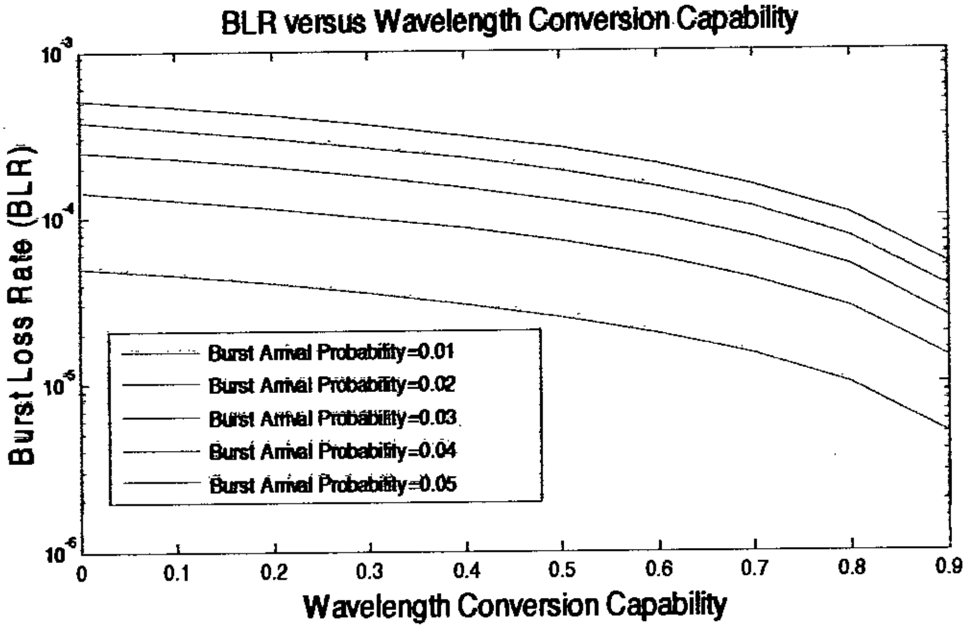


Fig. 4.23: Burst loss rate versus wavelength conversion capability with different burst arrival probabilities. Here number of slots per burst ℓ =25, number of wavelengths W =30 and $w \geq \ell$.

The burst loss rate versus the wavelength conversion capability has been plotted in the above Figs. (4.21, 4.22 and 4.23) under the condition $w \geq \ell$. The burst loss rate decreases under the condition $w \geq \ell$ compared to the condition $w < \ell$ because when the network has full wavelength conversion capability, burst blocking probability with condition $w \geq \ell$ is zero but blocking probability is not zero with the condition $w < \ell$ which is clearly shown in Figs. 4.4 - 4.9.

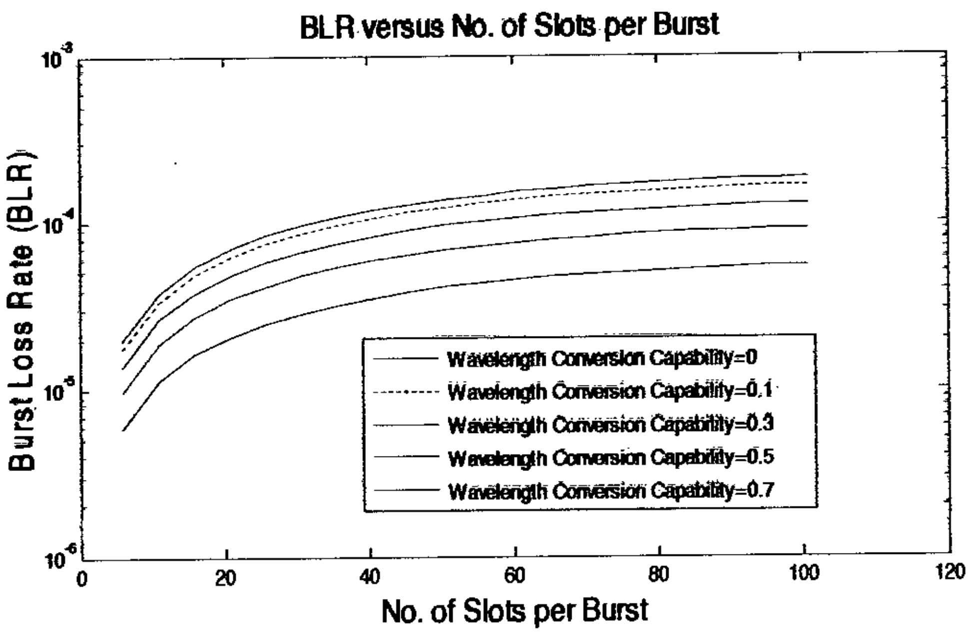


Fig. 4.24: Burst loss rate versus number of slots per burst with different wavelength conversion capabilities. Here burst arrival probability A = 0.01 and number of wavelengths $W = 20$.

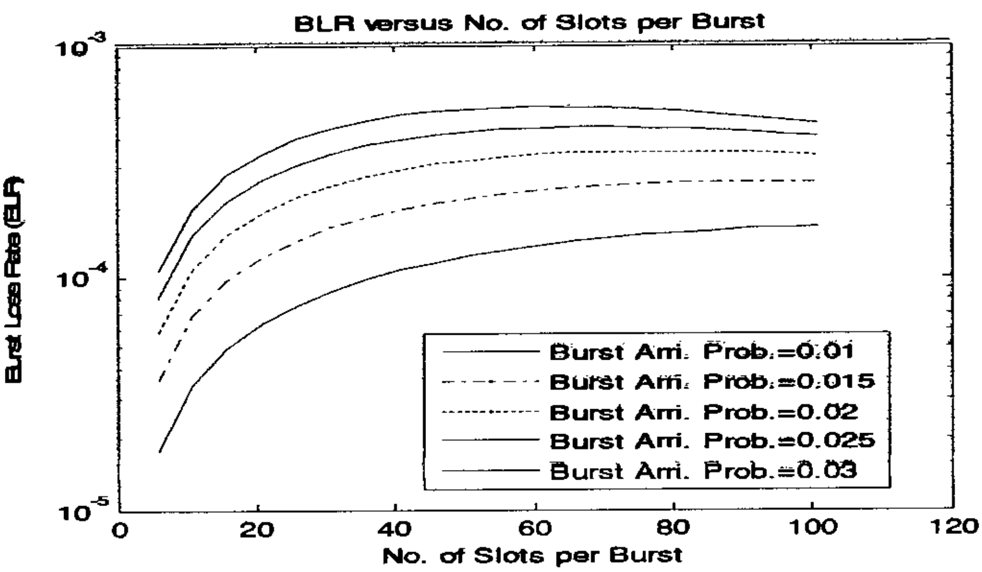


Fig. 4.25: Burst loss rate versus number of slots per burst with different burst arrival probabilities. Here wavelength conversion capabilities $\rho = 0.1$ and number of wavelengths $W = 20$.

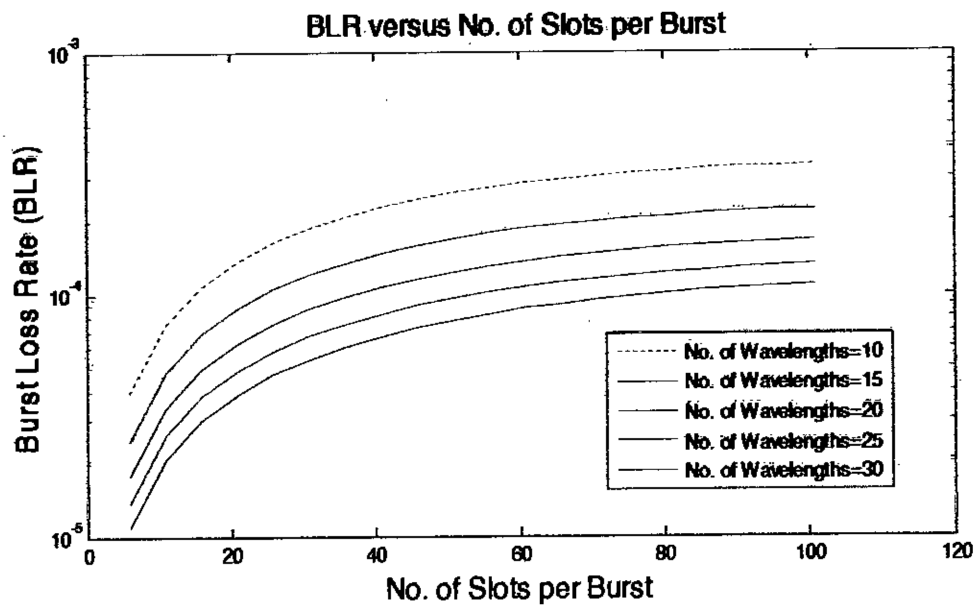


Fig. 4.26: Burst loss rate versus number of slots per burst with different number of wavelengths. Here burst arrival probability A = 0.01 and wavelength conversion capabilities ρ = 0.1.

The burst loss rate versus the number of slots per burst has been plotted in the above Figs. (4.24, 4.25 and 4.26). The burst loss rate increases with the increasing number of slots per burst and this behavior is expected because for constant burst arrival probability network traffic increases with the increasing of the number of slots per burst. Figs. 4.24, 4.25 and 4.26 show the effect of different wavelength conversion capability, burst arrival probability and number of wavelengths respectively on the burst loss rate while the other parameters are constant. The burst loss rate should decrease with the increasing of the wavelength conversion capability and the number of wavelengths and increase with the increasing of the burst arrival probability. The simulation result verifies the desired result.

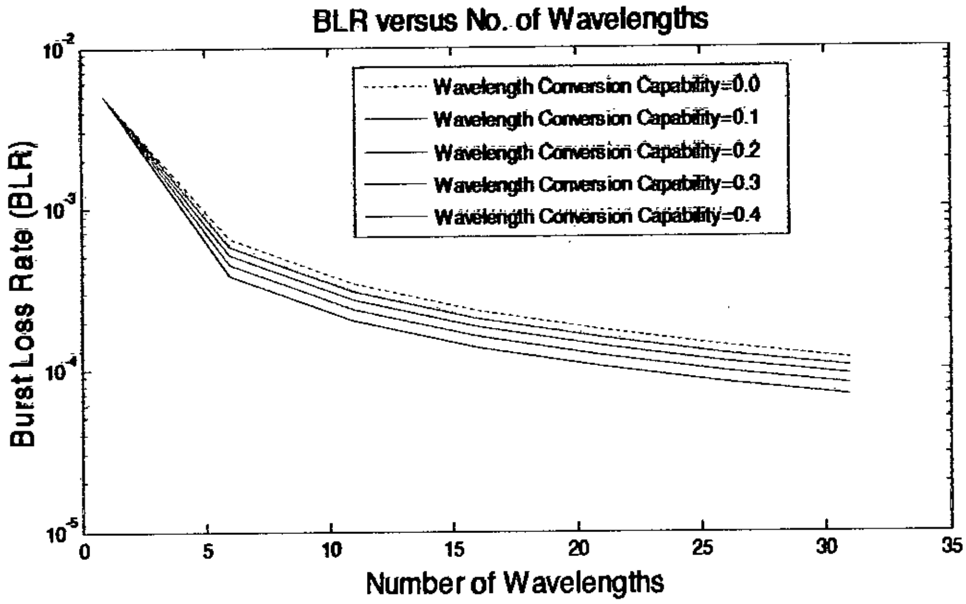


Fig. 4.27: Burst loss rate versus total number of wavelengths with different wavelength conversion capabilities. Here number of slots per burst ℓ =100, burst arrival probability A=0.01 and $w < \ell$.

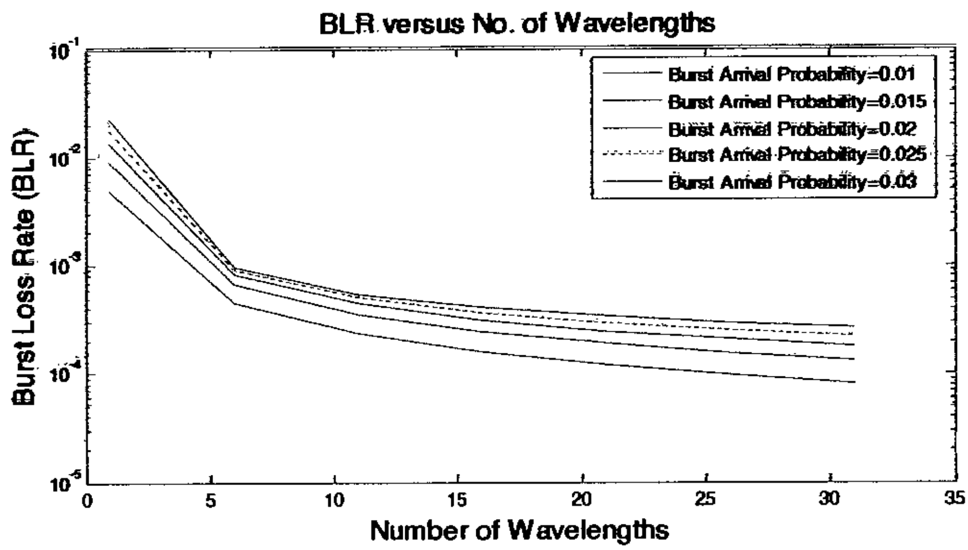


Fig. 4.28: Burst loss rate versus total number of wavelengths with different burst arrival probabilities. Here number of slots per burst ℓ =100, wavelength conversion capability ρ =0.3 and $w < \ell$.

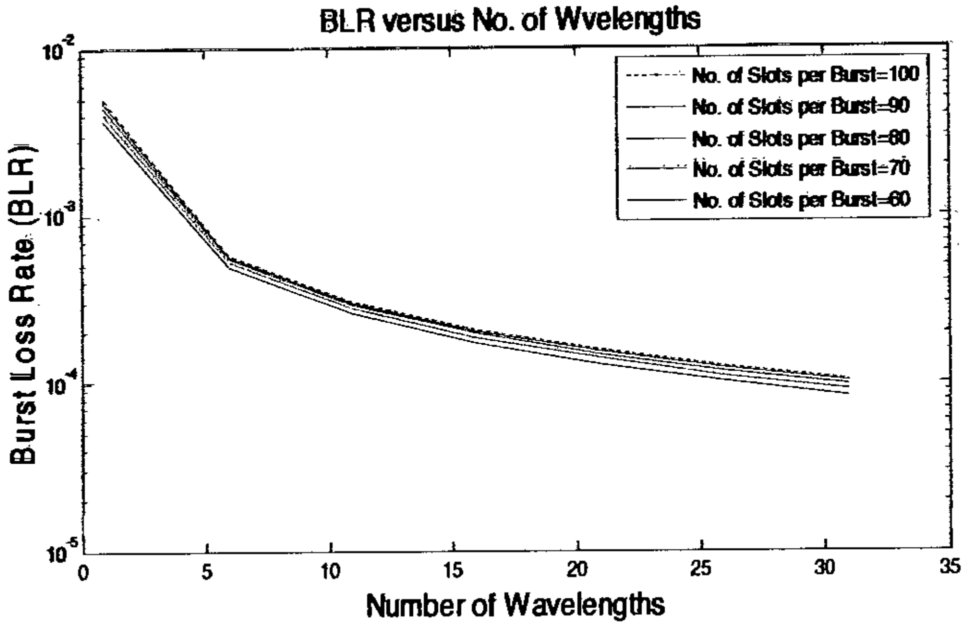


Fig. 4.29: Burst loss rate versus total number of wavelengths with different number of slots per burst. Here burst arrival probabilities A=0.01, wavelength conversion capability ρ =0.1 and $w < \ell$.

The burst loss rate versus the number of wavelengths has been plotted in the above Figs. (4.27, 4.28 and 4.29). The burst loss rate decreases with the increasing number of wavelengths and this behavior is expected because with increasing of the number of wavelengths the number of channel will be larger and the large will be the chance to get a free wavelength. Figs. 4.27, 4.28 and 4.29 show the effect of different wavelength conversion capability, burst arrival probability and number of slots per burst respectively on the burst loss rate while the other parameters are constant. The burst loss rate should decrease with the increasing of the wavelength conversion capability and increase with the increasing of the burst arrival probability and the number of slots per burst. The simulation result in Figs. (4.27, 4.28 and 4.29) shows the expected result.

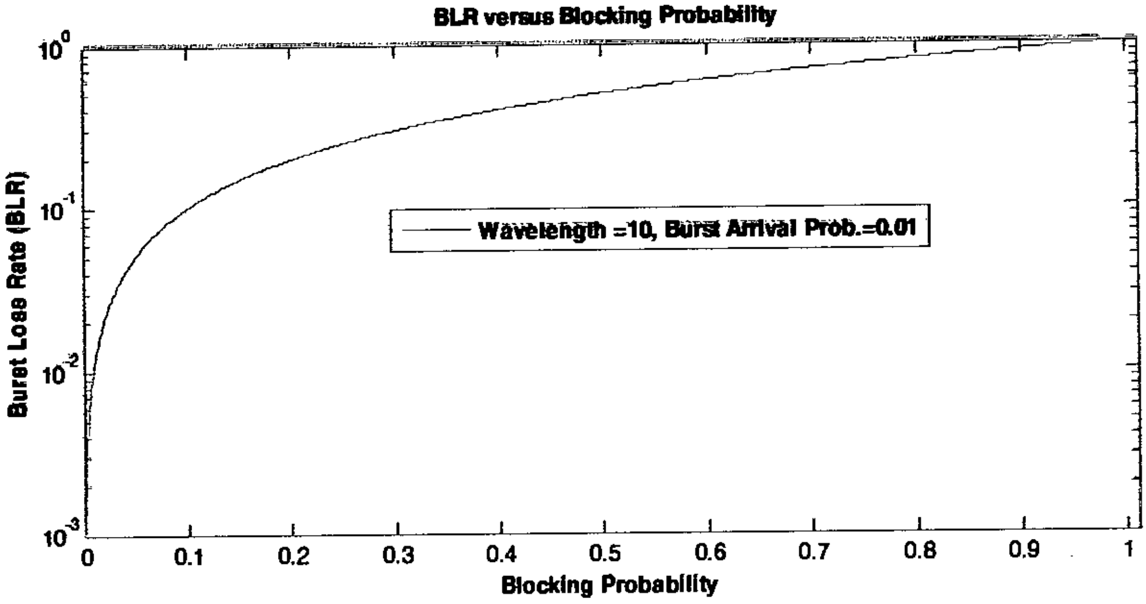


Fig. 4.30: Burst loss rate versus burst blocking probability. Here $w < \ell$.

In Fig. 4.30, burst loss rate has been plotted against the burst blocking probability under the condition $w < \ell$ .The burst loss increases with the increasing of the blocking probability because the higher the blocking probability, the greater number of burst will be dropped. The entire burst should be lost when the blocking probability is one and this result is noticed from the simulation result in Fig. 4.40.

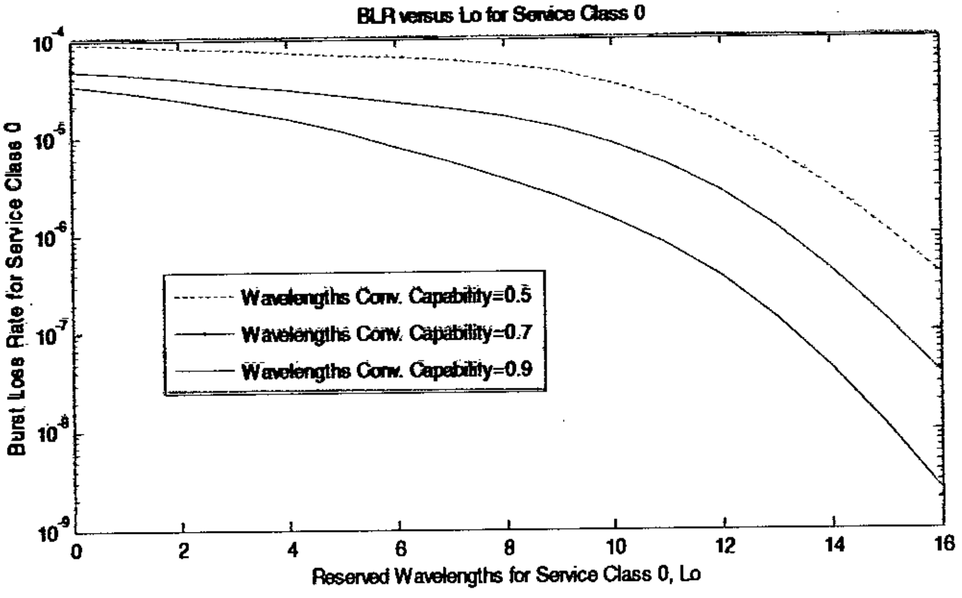


Fig. 4.31: Burst loss rate versus reserved wavelengths of service class 0 with different wavelength conversion capabilities. Here N =16 A=0.5, S_0 =0.4, S_1= 0.6, $L_1 = N - L_0$ and ℓ =100.

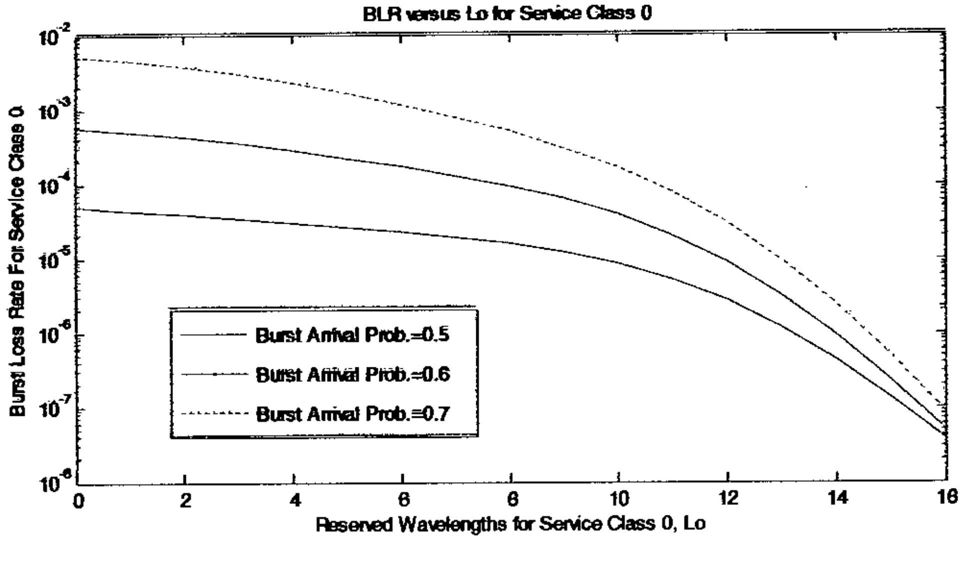


Fig. 4.32: Burst loss rate versus reserved wavelengths of service class 0 with different burst arrival probabilities. Here N=16, ρ =0.7, S_0 =0.4, S_1= 0.6, $L_1 = N - L_0$ and ℓ =100.

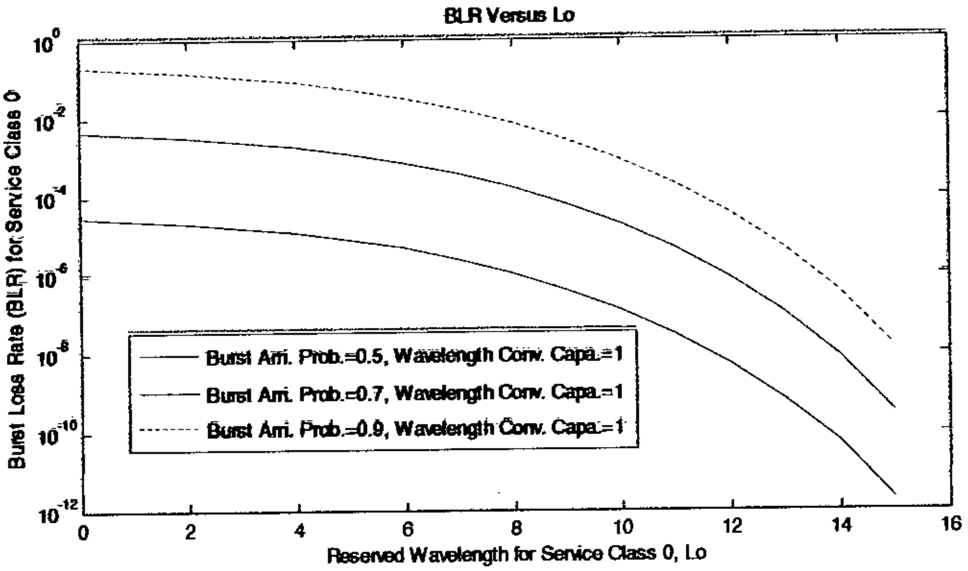


Fig. 4.33: Burst loss rate versus reserved wavelengths of service class 0 with different burst arrival probabilities and full wavelength conversion capability. Here N =16, S_0 =0.4, S_1 = 0.6, L_1 = N - L_0 and ℓ =100.

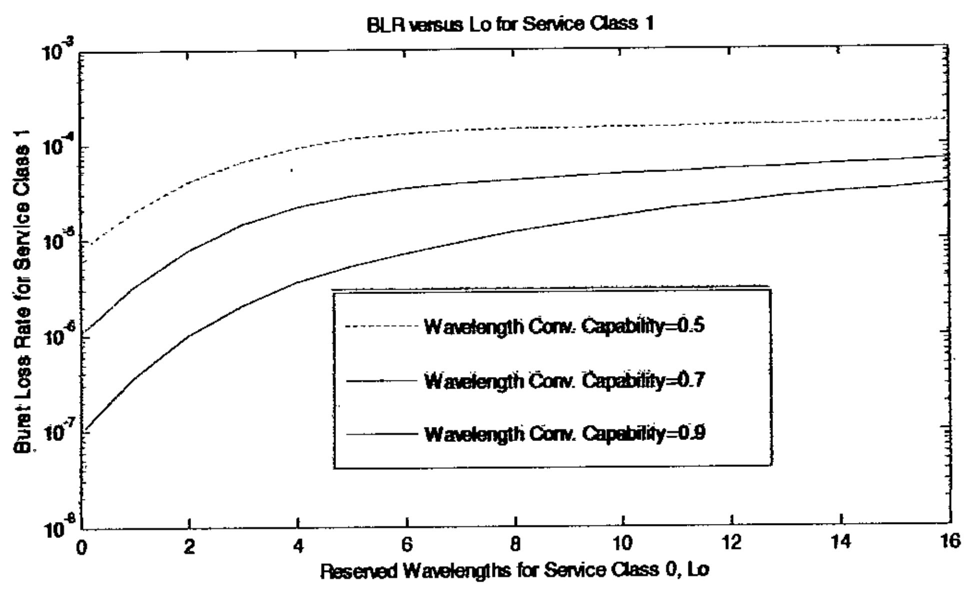


Fig. 4.34: Burst loss rate of service class 1 versus reserved wavelengths of service class 0 with different wavelength conversion capabilities. Here N =16, A=0.5, S_0 =0.4, S_1 = 0.6, L_1 = N - L_0 and ℓ =100.

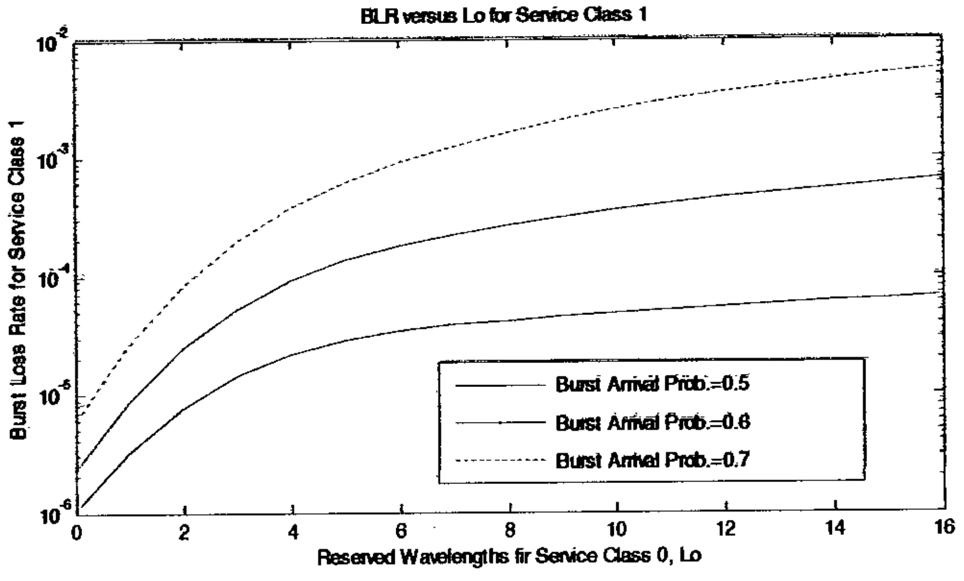


Fig. 4.35: Burst loss rate of service class 1 versus reserved wavelengths of service class 0 with different burst arrival probabilities. Here N =16, ρ =0.7, S_0 =0.4, S_1= 0.6, $L_1 = N - L_0$ and ℓ =100.

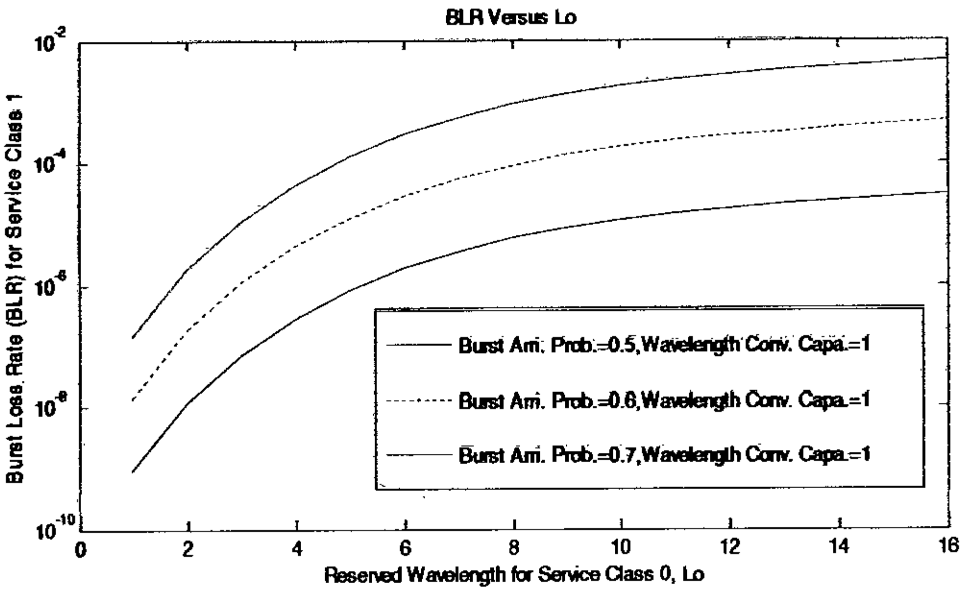


Fig. 4.36: Burst loss rate of service class 1 versus reserved wavelengths of service class 0 with different burst arrival probabilities and full wavelength conversion capability. Here N =16, S_0 =0.4, S_1= 0.6, $L_1 = N - L_0$ and ℓ =100.

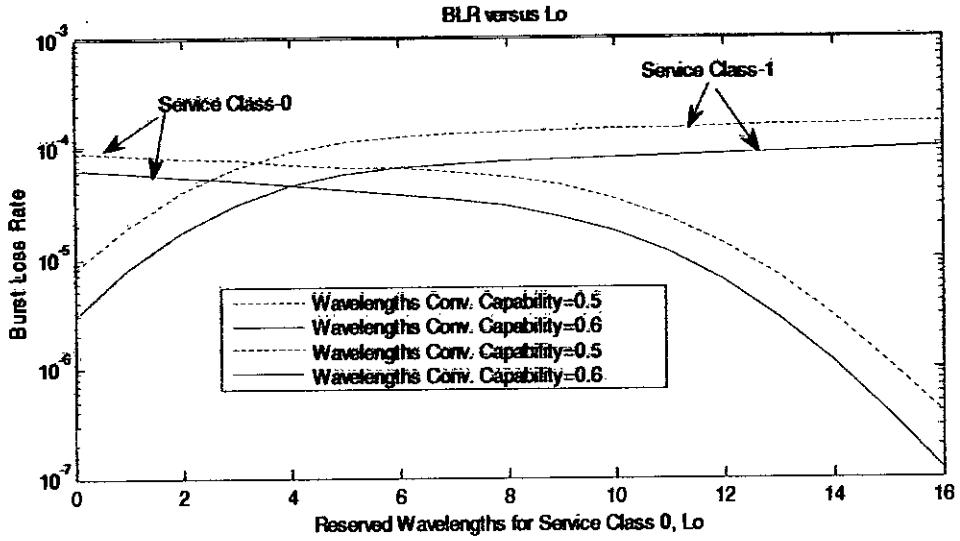


Fig. 4.37: Burst loss rate versus reserved wavelengths of service class 0 with different wavelength conversion capabilities. Here N =16, A=0.5, S_0 =0.4, S_1 = 0.6, $L_1 = N - L_0$ and ℓ =100.

The burst loss rate (BLR) versus the number of reserved wavelengths (L_0) of service class 0 has been plotted in the above Figs. (4.31 - 4.37). First we see that the burst loss rate of service class 0 decreases as L_0 increases, while the burst loss rate of service class 1 increases as L_0 increases. This is expected since an increase in L_0 means that more wavelengths are reserved for service class 0 and less wavelengths are reserved for service class 1. Simulation results also show the effect of wavelength conversion capability and burst arrival probability. The BLR of any service classes decreases with the increasing of the wavelength conversion capability but BLR increases with increasing of network traffic or burst arrival probability.

Chapter 5

CONCLUSIONS AND FUTURE WORKS

5.1 Conclusions

A detailed analytical approach is presented to evaluate the burst loss rate (BLR) of an optical burst switching network with wavelength conversion capability. The analytical result of burst loss rate is also extended for two service classes where each service class has a fixed number of reserved wavelengths. The analytical results exhibit promising features that will be useful for future high speed WDM optical networks.

Burst loss rate is an important performance measure to evaluate the system performance. It is observed that when two or more bursts are destined for the same output port at the same time, contention occurs, as a result of burst dropping. We can reduce the burst dropping by using wavelength converter. Burst loss rate decreases with the increasing of the wavelength conversion capability.

For constant number of slots per burst, network traffic increases with the increasing of the burst arrival probability. On the other hand network traffic is also increasing with the increasing number of slots per burst while the burst arrival probability is constant. Burst loss rate increases with the increasing of the network traffics.

System performance improves as the number of wavelength increases i.e. burst loss rate is inversely related with the number of wavelengths.

For two service classes with constant number of wavelengths, if we increase the reserved wavelengths of one service class burst loss rate decreases of that service class but burst loss rate of other service class increases.

5.2 Future Works

Further research can be carried out to calculate the burst loss rate of an optical burst switching network with fiber delay lines (FDL) or deflection routing or FDL with wavelength converter.

Research can also be initiated for service classes greater than two of an optical burst switching networks with wavelength conversion capability or fiber delay lines (FDL) or deflection routing or FDL with wavelength converter.

Other wavelength reservation protocol can be used to reserve wavelength for the data burst except Just-in-Time (JIT), such as Just-Enough-Time (JET).

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Appendix - A

Probability of 1-λ(r_1, r_2, r_3), 2-λ(r_{21}, r_{32}, r_{31}) and 3-λ(r_{321}) state without wavelength conversion capability when $\ell = 3$ and $w \geq \ell$:

We get the following relations from equations (3.1) in chapter 3

$$r_1 = A(m + r_3) \tag{A.1}$$

$$r_2 = (1 - A + \frac{A}{w})(r_1 + r_{31}) \tag{A.2}$$

$$r_3 = (1 - A + \frac{A}{w})(r_2 + r_{32}) \tag{A.3}$$

$$r_{21} = (A - \frac{A}{w})(r_1 + r_{31}) \tag{A.4}$$

$$r_{31} = (A - \frac{A}{w})(r_2 + r_{32}) \tag{A.5}$$

$$r_{32} = (1 - A + \frac{2A}{w})(r_{21} + r_{321}) \tag{A.6}$$

$$r_{321} = (A - \frac{2A}{w})(r_{321} + r_{21}) \tag{A.7}$$

From equation (A.7), we get

$$r_{321} = \frac{A - \frac{2A}{w}}{1 - A + \frac{2A}{w}} . r_{21} \tag{A.8}$$

Equation (A.6) can be written as

$$r_{32} = (1 - A + \frac{2A}{w})(r_{21} + \frac{A - \frac{2A}{w}}{1 - A + \frac{2A}{w}} . r_{21})$$

$$\Rightarrow r_{32} = (1 - A + \frac{2A}{w}).r_{21}.(\frac{1 - A + \frac{2A}{w} + A - \frac{2A}{w}}{1 - A + \frac{2A}{w}})$$

$$\Rightarrow r_{32} = r_{21} \qquad \text{(A.9)}$$

From equation (A.4), we get

$$r_{21} = (A - \frac{A}{w})(r_1 + r_{31})$$

$$\Rightarrow r_{21} = (A - \frac{A}{w})[r_1 + (A - \frac{A}{w})(r_2 + r_{32})]$$

$$\Rightarrow r_{21} = (A - \frac{A}{w})[r_1 + (A - \frac{A}{w})(r_2 + r_{21})]$$

$$\Rightarrow r_{21} = \frac{(A - \frac{A}{w})[r_1 + (A - \frac{A}{w})r_2]}{1 - (A - \frac{A}{w})^2} = r_{32} \qquad \text{(A.10)}$$

Equation (A.5) can be expressed as

$$r_{31} = (A - \frac{A}{w})[r_2 + \frac{(A - \frac{A}{w})\{r_1 + (A - \frac{A}{w})r_2\}}{1 - (A - \frac{A}{w})^2}]$$

$$\Rightarrow r_{31} = (A - \frac{A}{w})[\frac{(A - \frac{A}{w})r_1 + r_2}{1 - (A - \frac{A}{w})^2}] \qquad \text{(A.11)}$$

From equation (A.3), we get

$$r_3 = (1 - A + \frac{A}{w})[r_2 + \frac{(A - \frac{A}{w})\{r_1 + (A - \frac{A}{w})r_2\}}{1 - (A - \frac{A}{w})^2}]$$

$$\Rightarrow r_3 = \frac{(A - \frac{A}{w})r_1 + r_2}{1 + A - \frac{A}{w}} \tag{A.12}$$

From equation (A.2), we get

$$r_2 = (1 - A + \frac{A}{w})(r_1 + r_{31})$$

$$\Rightarrow r_2 = (1 - A + \frac{A}{w})[r_1 + (A - \frac{A}{w})\{\frac{(A - \frac{A}{w})r_1 + r_2}{1 - (A - \frac{A}{w})^2}\}]$$

$$\Rightarrow r_2 = (1 - A + \frac{A}{w})[r_1 + (A - \frac{A}{w})\{\frac{(A - \frac{A}{w})r_1 + r_2}{1 - (A - \frac{A}{w})^2}\}]$$

$$\Rightarrow r_2 = \frac{(A - \frac{A}{w})r_2 + r_1}{1 + A - \frac{A}{w}}$$

$$\Rightarrow r_2 = r_1 \tag{A.13}$$

We get from equation (A.12)

$$r_3 = \frac{(A - \frac{A}{w})r_1 + r_1}{1 + A - \frac{A}{w}}$$

$$\Rightarrow r_3 = r_1 = r_2 \tag{A.14}$$

We can write from equation (A.1)

$$r_1 = A(m + r_3)$$

$$\Rightarrow r_1 = A(m + r_1)$$

$$\Rightarrow r_1 = \frac{A}{1 - A}.m$$

$$\Rightarrow \quad r_1 = \frac{A}{1 - A}.m$$

$$\Rightarrow \quad r_1 = r_2 = r_3 = \frac{w}{w.\dfrac{1 - A}{A}}.m \tag{A.15}$$

From equation (A.10), we get

$$r_{21} = \frac{(A - \dfrac{A}{w})[r_1 + (A - \dfrac{A}{w})r_1]}{1 - (A - \dfrac{A}{w})^2}$$

$$\Rightarrow r_{21} = \frac{(A - \dfrac{A}{w})}{1 - A + \dfrac{A}{w}}.r_1$$

$$\Rightarrow r_{21} = \frac{(A - \dfrac{A}{w})}{1 - A + \dfrac{A}{w}}.\frac{A}{1 - A}.m$$

$$\Rightarrow r_{21} = r_{31} = r_{32} = \frac{w}{w.\dfrac{1 - A}{A}}.\frac{w - 1}{w.\dfrac{1 - A}{A} + 1}.m \tag{A.16}$$

From equation (A.8), we get

$$r_{321} = \frac{A - \dfrac{2A}{w}}{1 - A + \dfrac{2A}{w}}.r_{21}$$

$$r_{321} = \frac{A - \dfrac{2A}{w}}{1 - A + \dfrac{2A}{w}}.\frac{w}{w.\dfrac{1 - A}{A}}.\frac{w - 1}{w.\dfrac{1 - A}{A} + 1}.m$$

$$r_{321} = \frac{w}{w.\dfrac{1 - A}{A}}.\frac{w - 1}{w.\dfrac{1 - A}{A} + 1}.\frac{w - 2}{w.\dfrac{1 - A}{A} + 2}.m \tag{A.17}$$

Appendix – B

Probability of n-λ state e_n with wavelength conversion capability:

Let the n-λ state

$$r_{i_n, i_{n-1}, i_{n-2}, \ldots, i_2, i_1} = e_n$$

So we get the following relations from equation (3.8) and (3.9) in chapter 3

$$r_{i_n, i_{n-1}, i_{n-2}, \ldots, i_2, i_1} = [A - (1-\rho)\frac{(n-1)A}{w}] \mathrm{x} (r_{i_n - 1, i_{n-1}-1, \ldots, i_2 - 1} + r_{\ell, i_n - 1, i_{n-1}-1, \ldots, i_2 - 1}) \quad \text{(B.1)}$$

And

$$r_{i_n, i_{n-1}, i_{n-2}, \ldots, i_2, i_1} = [1 - A + (1-\rho)\frac{nA}{w}] \mathrm{x} (r_{i_n - 1, i_{n-1}-1, \ldots, i_1 - 1} + r_{\ell, i_n - 1, i_{n-1}-1, \ldots, i_1 - 1}) \quad \text{(B.2)}$$

So from equation (B.1)

$$e_n = [A - (1-\rho)\frac{(n-1)A}{w}]\left(e_{n-1} + e_n\right)$$

$$\Rightarrow e_n = \frac{A - \frac{A}{w}.(n-1)(1-\rho)}{1 - A + \frac{A}{w}.(n-1)(1-\rho)} e_{n-1}$$

And from equation (B.2)

$$e_n = [1 - A + (1-\rho)\frac{nA}{w}]\left(e_n + e_{n+1}\right)$$

$$\Rightarrow e_{n+1} = \frac{A - \frac{A}{w}.n(1-\rho)}{1 - A + \frac{A}{w}.n(1-\rho)} e_n$$

$$\Rightarrow e_{n+1} = \prod_{i=0}^{n} \frac{A - \frac{A}{w}.i.(1-\rho)}{1 - A + \frac{A}{w}.i.(1-\rho)} e_0$$

$$\Rightarrow e_{n+1} = \prod_{i=0}^{n} \frac{w - .i.(1-\rho)}{w.\frac{1-A}{A} + i.(1-\rho)} m$$

$$\Rightarrow e_k = \prod_{i=0}^{k-1} \frac{w - .i.(1-\rho)}{w.\frac{1-A}{A} + i.(1-\rho)} m \qquad \text{(B.3)}$$

The value of the initial probability m can be determined by imposing the condition that the sum of all probabilities equals to 1:

$$m + \sum_{n=1}^{\ell \wedge w} \binom{l}{n} e_n = 1$$

$$m = \left[1 + \sum_{n=1}^{\ell \wedge w} \binom{\ell}{n} \prod_{i=0}^{n-1} \frac{w - i(1-\rho)}{w.\frac{1-A}{A} + i(1-\rho)} \right]^{-1}$$

So we can write from equation (B.3)

$$e_k = \frac{\prod_{i=0}^{k-1} \frac{w - i(1-\rho)}{w.\frac{1-A}{A} + i(1-\rho)}}{1 + \sum_{n=1}^{\ell \wedge w} \binom{\ell}{n} \prod_{i=0}^{n-1} \frac{w - i(1-\rho)}{w.\frac{1-A}{A} + i(1-\rho)}} \qquad \text{(B.4)}$$