A study on the bulk transfer protocol in the next generation optical network

November 2008

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Overall Abstract

The explosive growth of Internet Protocol (IP) traffic on the Internet is driving the demands for new high-speed transmission and switching technologies. In this dissertation, the high-performance bulk transfer protocols using optical technologies are studied. Its goal is to propose efficient optical data transfer schemes for realizing the stable transmission of increasing bulk data such as large contents or streaming data.

In this dissertation, three proposed schemes are introduced. The first one is a fair burst dropping scheme to improve the unfairness about the packet loss probability by the number of hops in Optical Burst Switching (OBS) network. The proposed fair burst dropping scheme configures the threshold for determining whether the head-dropping (HD) technique is applied or not. The HD technique is the burst dropping technique which reduces packet loss due to burst contention in Optical Composite Burst Switching (OCBS) network. By computer simulation, it is shown that the proposed fair burst dropping scheme can achieve the fair packet loss probability regardless of the number of hops to the destination edge node compared with the conventional one.

Secondly, a self-learning route selection scheme in OBS network is proposed. The proposed route selection scheme reduces the probability of burst contention by controlling the route at an edge node without resolving burst contention at a core node. Each edge node learns a suitable route to the destination edge node autonomously by

using newly employed feedback packets and search packets. Due to the self-learning at each edge node, the traffic load is distributed in an OBS network. Therefore, the proposed self-learning route selection scheme can reduce the probability of burst contention. According to computer simulations, under non-uniform traffic, o the proposed self-learning route selection scheme can reduce approximately one decade smaller burst loss probability compared with the conventional shortest path routing method.

The third one is a novel lightpath route selection scheme in an optical GRID network where Generalized Multi Protocol Label Switching (GMPLS) is used to manage communication resources. The self-learning mechanism, which is introduced in the above-mentioned self-learning route selection scheme in OBS network, is used for the lightpath route selection. Each source node updates the priority of each route (the route priority) according to the results of the lightpath setup, and uses the route with a high route priority. Also, in setting the lightpath, each source node sends PATH messages for the lightpath setup on several routes. And, each PATH message collects the link usage information of the route. The destination node selects the route to reserve the wavelength based on the information of PATH messages. The proposed lightpath route selection scheme can distribute the traffic by considering the route priority and current link usage information. Using simulation for non-uniform traffic, our proposed scheme can reduce nearly 20-50 percent lower blocking probability as compared with the conventional shortest path routing scheme.

These proposed schemes are expected to contribute to realize an efficient optical network for bulk data transfer.

Chapter 1

Introduction

The explosive growth of Internet Protocol (IP) traffic on the Internet is driving the demands for new high-speed transmission and switching technologies. In this thesis, the high-performance bulk transfer protocol using optical technologies are studied. Its goal is to propose effective optical data transfer schemes for realizing the stable transmission of increasing bulk data such as large contents or streaming data.

An optical network consists of transport layer and control layer. Transport layer transmits data in optical domain. And, control layer controls nodes in transport layer. In transport layer, three types of optical switching techniques are used: Optical Circuit Switching (OCS), Optical Burst Switching (OBS), and Optical Packet Switching (OPS). As main problems of an optical network, there are contention resolution, route assignment, wavelength assignment, protection/restoration, and control technique in control layer. In this thesis, contention resolution in OBS network and route assignment in OBS network and OCS network are focused on.

The composition of this thesis is explained blow. In Chapter 2, the background, the architecture and problems of an optical network are explained. Also, it is clarified the position of the thesis.

From Chapter 3 to Chapter 5, three proposed schemes are introduced. Table 1.1 shows the outline of the proposed schemes. In Chapter 3, contention resolution in OBS network is focused on. As a contention resolution scheme for OBS, Optical Composite Burst Switching (OCBS) that can improve the performance of the packet loss probability without wavelength conversion and optical buffering is proposed. However, OCBS has the problem that it is unfair about the number of hops to the destination edge node. So, a fair burst dropping proposed scheme is proposed to improve the unfairness about the packet loss due to burst contention in OCBS. By computer simulation, it is shown that the proposed fair burst dropping scheme can achieve the fair packet loss probability regardless of the number of hops to the destination edge node compared with a conventional one.

In Chapter 4, route assignment in OBS network is focused on in order to reduce generates of contention. To avoid contention, it is desirable to distribute traffic in the network. Conventionally, a load-sensitive routing approach is studied. This approach assigns the route with low traffic by monitoring the traffic condition in the network. The real time management of traffic information and the scalability for a large scale network are its challenges. In Chapter 4, a distributed control approach is studied. A self-learning route selection scheme in OBS network is proposed. The proposed route selection scheme reduces the probability of burst contention by controlling the route at an edge node without resolving burst contention at a core node. Each edge node learns a suitable route to the destination edge node autonomously by using newly employed feedback packets and search packets. Due to the self-learning at each edge node, the traffic load is distributed in an OBS network. Therefore, the proposed self-learning route selection scheme can reduce the probability of burst contention. According to computer simulations, under non-uniform traffic, o the proposed self-learning route selection scheme can reduce approximately one decade smaller burst loss probability compared with the conventional shortest path routing method.

In Chapter 5, route assignment in OCS network is focused on. An optical GRID network is considered as the application of OCS network. Generalized Multi Protocol Label Switching (GMPLS) is used to manage communication resources. A novel lightpath route selection scheme is proposed by extending Chapter 4 's proposed scheme for OCS. Each source node updates the priority of each route (the route priority) according to the results of the lightpath setup, and uses the route with a high route priority. Also, in setting the lightpath, each source node sends PATH messages for the lightpath setup on several routes. And, each PATH message collects the link usage information of the route. The destination node selects the route to reserve the wavelength based on the information of PATH messages. The proposed lightpath route selection scheme can distribute the traffic by considering the route priority and current link usage information. Using simulation for non-uniform traffic, our proposed scheme can reduce nearly 20-50 percent lower blocking probability as compared with the conventional shortest path routing scheme.

Finally, Chapter 6 includes conclusions and future work of the thesis.

Table 1.1: Outline of the proposed approaches.

Chapter 3	Purpose	Improve the fairness of packet loss about the number of hops in Optical Composite Burst Switching (OCBS) which can reduce packet loss by the Head-Dropping (HD) technique
	Research Issue	By repeatedly applying the HD technique in intermediate core nodes, the burst with many hops is more likely to be discarded.
	Proposed Scheme	Apply the HD technique in consideration of the number of hops by configuring the threshold for determining whether the HD technique is applied or not
	Achievement	Reduce the difference of packet loss probability per hop compared with the conventional one
Chapter 4	Purpose	Reduce the probability of burst contention in OBS network
	Research Issue	A burst is forwarded on the shortest path route. However, the traffic load is concentrated on a certain link, and it causes burst contention.
	Proposed Scheme	Each edge node learns a suitable route autonomously by using newly employed feedback packets and search packets.
	Achievement	The traffic load is distributed, and the probability of burst contention is reduced.
Chapter 5	Purpose	Reduce the block of the lightpath setup in Generalized Multi Protocol Label Switching (GMPLS)-based optical GRID network
	Research Issue	Since the shortest path route is used, the access to computing resources is restricted because of the bias of traffic.
	Proposed Scheme	Select a suitable lightpath route by considering the past empirical information and the current wavelength usage information
	Achievement	Distribute traffic and suppress the occurrence of bottlenecks

Chapter 2

Background

2.1 Development of Internet and Change of Internet Traffic

Due to the dissemination and development of the Internet, our lifestyle has been changed dramatically. "Internet" is the network connecting networks as its name indicates. In the 1990s, the commercial use of the Internet was developed rapidly. Internet Service Provider (ISP) appeared, and the service of connecting to Internet started for home users and business users. In 1989, World Wide Web (WWW) was invented by Tim Berners Lee. Through WWW, users can not only get information but also transmit information easily. WWW realized a new business providing services and contents on the Internet.

In Japan, ISP appeared in 1993, and commercial services on the Internet started. While the penetration rate of the cell-phone was up over 10% in fifteen years, the penetration rate of the Internet was up over 10% in only five years. This fact shows how fast the spread of the Internet was. The Internet continued to grow, and it is currently essential in our life. Also, due to the growth of the Internet, broadband service is developed. Figure 2.1 shows the number of broadband subscribers in Japan [1]. The total number of broadband subscribers is increasing. Digital Subscriber Line (DSL) occupies the majority of the number of broadband subscribers. However, the number of DSL declines since December 2005. Meanwhile, the number of Fiber To

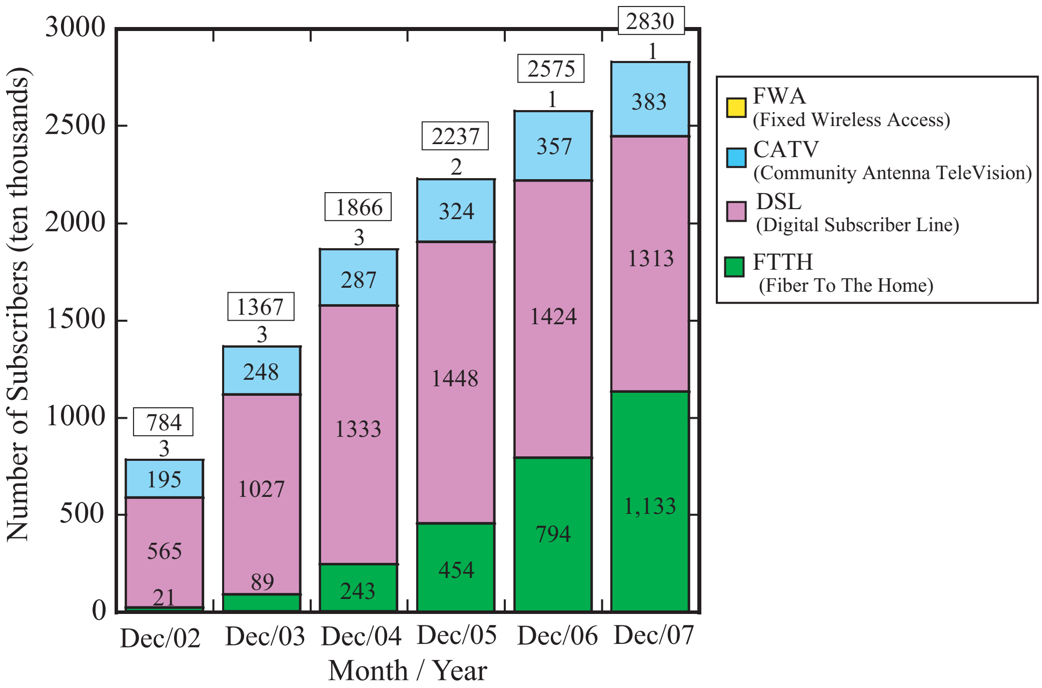

Figure 2.1: The number of broadband subscribers in Japan.

The Home (FTTH), which provides faster data transmission than DSL, is increasing drastically. From Fig. 2.1, it is shown that an increase of broadband subscribers and a shift from DSL to FTTH promote the development of broadband in an access network.

Figure 2.2 shows the backbone traffic volume at Internet eXcange (IX) of JaPan Internet eXchange (JPIX) [2]. JPIX is one of major companies managing IXs in Japan. Backbone internet traffic in Japan has been increasing due to the increase of the number of broadband subscribers and the development of broadband technologies. Currently, the minimum traffic volume is over 40Gbps, and the maximum traffic volume is over 100Gbps. In a backbone optical network, it is a big problem how to manage the increasing traffic.

Due to the development of broadband technologies, the usage of the Internet has been changed. At first, the main purpose of use was an exchange of an e-mail, the browsing of a Web page, the transfer of files, and so on. The use for transmitting

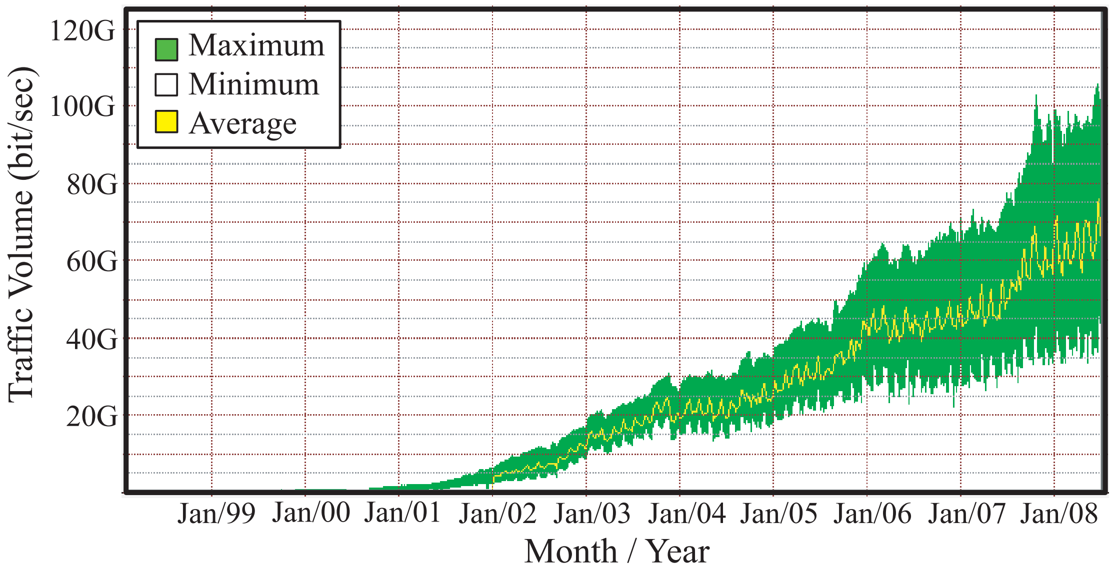

Figure 2.2: The backbone traffic volume of JaPan Internet eXchange (JPIX).

large volumes of data, such as the download of music and movie contents and the delivery of streaming data, is increasing. And, recently, the volume of the Internet traffic is increasing due to the file transfer by the Peer-to-Peer (P2P) applications, such as Winny and WinMX. Figure 2.3 shows the traffic change of "FLET'S" connection service [3], which is Japanese broadband service provided by Nippon Telegraph and Telephone (NTT) East Corp. and NTT West Corp., users for a whole day. The traffic considered as P2P traffic from the port number occupies about seventy-percent of the downstream traffic. It also occupies more than eighty-percent of the upstream traffic. P2P applications enabled us to exchange large capacity files easily. Therefore, the total volume of traffic increases due to the appearance of P2P applications.

Currently, the emergence of a video-sharing site, such as YouTube, increases Hypertext Transfer Protocol (HTTP) traffic again. Figure 2.4 shows the usage of broadband users in North America surveyed by Ellacoya Networks [4], which is a networking equipment vendor in North America. From Fig. 2.4, it is shown

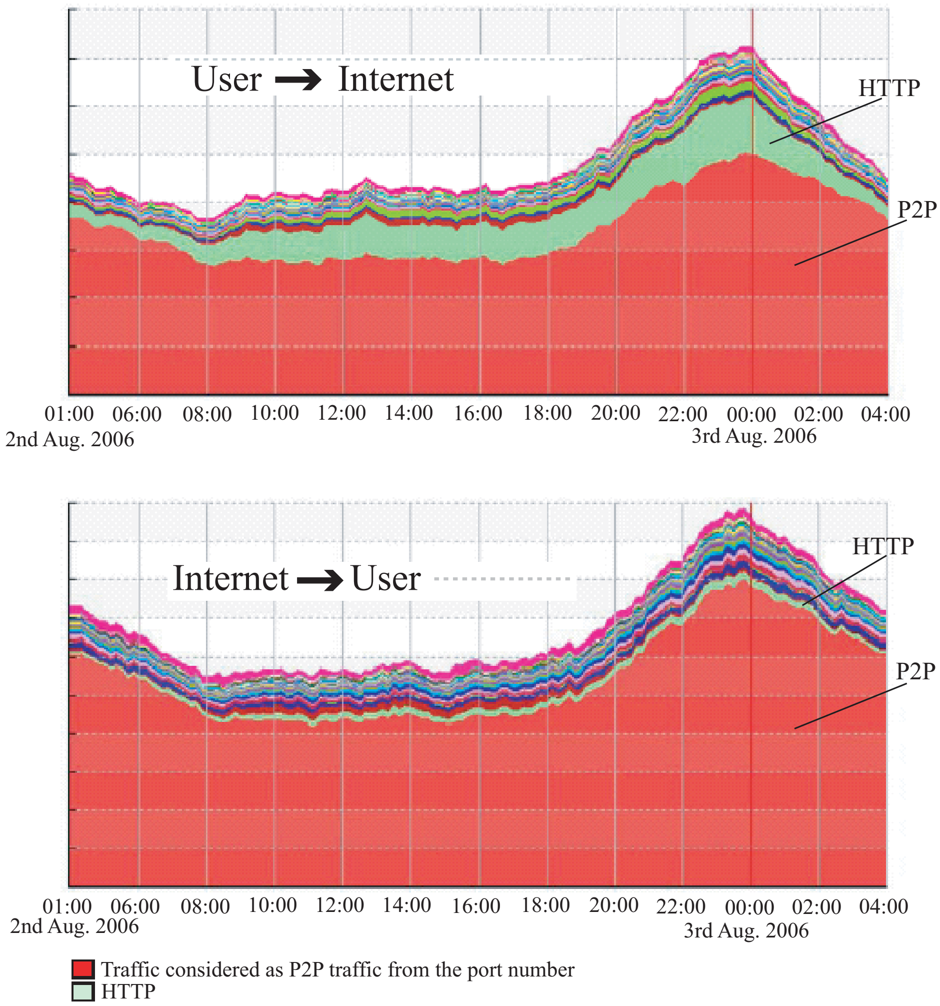

Figure 2.3: The traffic change of "FLET'S" connection service users for a whole day (searched by Internet Iniiative Japan Inc.).

that HTTP traffic is more than P2P traffic. According to the survey of Ellacoya Networks, P2P traffic is more than HTTP traffic in the past four years. The video-sharing site enabled users to upload and download video files easily. So, the traffic of the video streaming is increasing. In Japan, a similar change is supposed to be happening.

In this way, due to the development and dissemination of the Internet, various services have been created, for example, Social Networking Site, Second Life, Triple

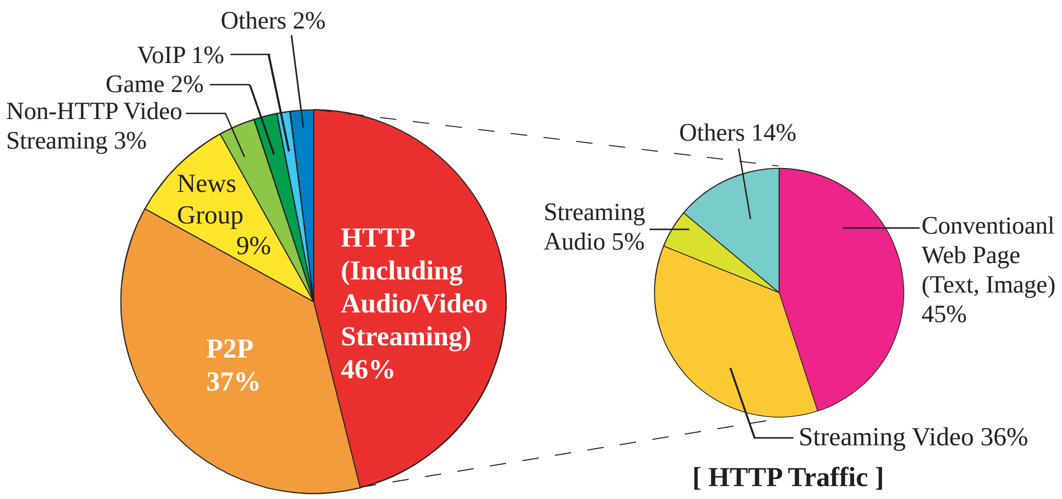

Figure 2.4: The usage of broadband users in North America.

/ Quadro Play Service, GRID Network [5], and so on. And, the Internet traffic continues to increase quickly and steadily. By the transition of popular services, the type of main traffic changes, and several types of traffic appear. Therefore, a backbone optical network is required to realize the large capacity network and to handle a wide variety of traffic and support the communication quality.

2.2 Architecture of Optical Network

Figure 2.5 shows architecture of the optical network focused on this thesis. The optical network consists of transport layer and control layer.

Transport layer has the function to transmit data in optical domain. In transport layer, an edge node and a core node exist. Nodes in transport layer are connected by Wavelength division multiplexing (WDM) link. An edge node sends data to the destination edge node. The edge node has the legacy interface (e.g.,Gigabit Ethernet, IP over Asynchronous Transfer Multiplexing (ATM) etc). A core node switches data in optical domain. So, data is cut through in optical domain. The core node is mainly composed of an optical switching matrix and a switch control

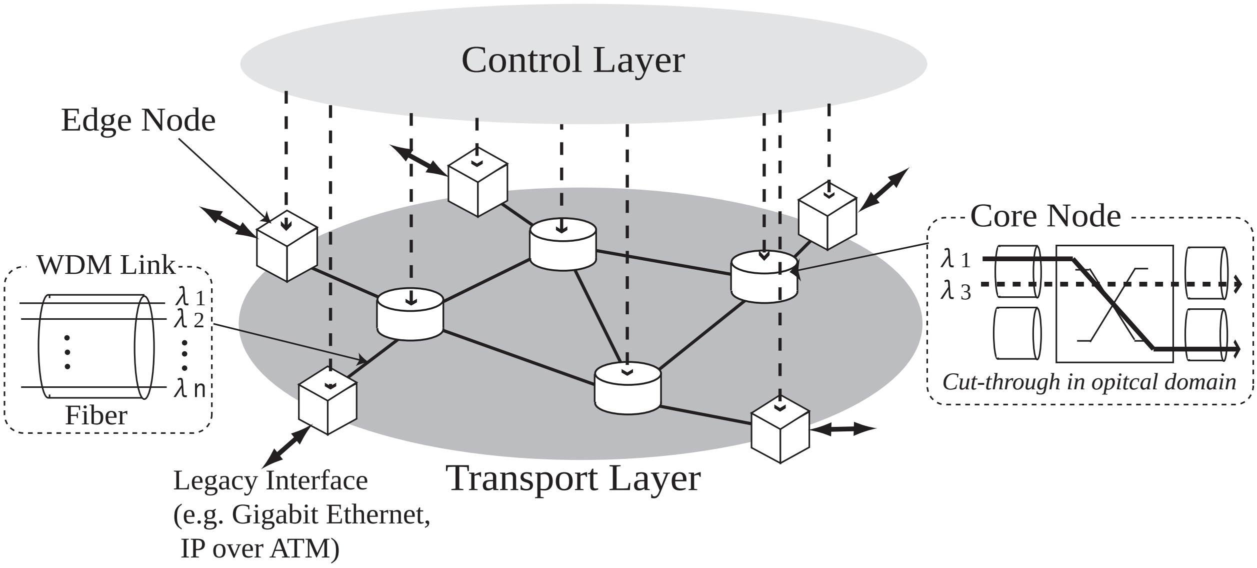

Figure 2.5: Architecture of the optical network.

unit.

Control layer controls the nodes in transport layer. Control layer configures the switching function of each node so as to establish a data communication path and provide the required transmission quality.

In this section, WDM technology and optical switching technique are introduced. These are key technologies in transport layer. Also, the control technique in control layer is introduced.

2.2.1 Wavelength Division Multiplexing (WDM)

WDM technology enables concurrent transmissions by multiple users into the optical communication network, and has a large increase in transmission capacity in a single fiber.

WDM is a solution to exploit huge bandwidth of the optical fiber. In WDM, the bandwidth of the fiber is divided into a set of parallel channels, each operating with a different wavelength. WDM introduces concurrent transmissions by multiple users into the optical communication network, while end stations access the network by electronic speed. An emergence of WDM technology made carriers easy to have a large increase in speed of the backbone network, applying an existing infrastructure of optical fibers.

In addition to the number of wavelengths multiplexed into one fiber having increased, long-distance transmission has been attained by improvement in a performance of an optical amplifier. It leads to using WDM technology for the backbone network. It is expected for the future that 1000 wavelengths are multiplexed into one fiber. In order to transmit the increasing traffic efficiently, in the future high speed backbone network, the simplification of the protocol between IP layer and a WDM layer is required.

Dense Wavelength Division Multiplexing (DWDM), in which hundreds of channels are squeezed into a single fiber strand, is a promising method for the backbone network. DWDM uses close spectral spacing of individual optical wavelengths to take advantage of desirable transmission characteristics (e.g., minimum dispersion or attenuation) within a given fiber.

Figure 2.6 shows relationship between channel capacity and the number of channels. You can see that under the condition that the total capacity is constant, channel capacity is inversely proportional to the number of channels multiplexed in a single fiber. In DWDM systems, since the spectral spacing of individual optical wavelengths is very close, a high-precision WDM laser and a high-precision WDM filter are needed. They have to be able to tune a wavelength of a laser or a filter to the desired one quickly. In general, it costs so much to achieve the high accuracy of tuning. This is the factor of increasing the cost to construct DWDM systems.

Meanwhile, the standard for Coarse Wavelength Division Multiplexing (CWDM)

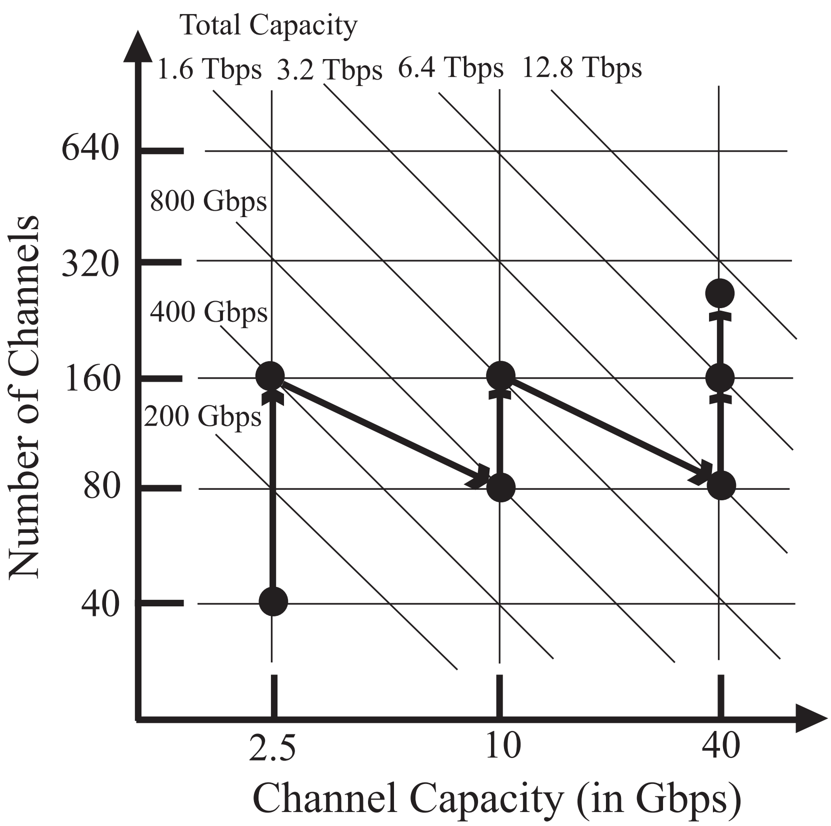

Figure 2.6: Channel capacity and the number of channels.

is approved by International Telecommunication Union Telecommunication Standardization Sector (ITU-T). The coarse kind of system provides far fewer channels: the CWDM grid explicitly defines only 18 wavelengths, 20-nm spacing. Since keeping the wavelengths so far apart means lasers and filters can be easier and cheaper to be made, CWDM is a candidate for metropolitan area network (MAN) [6].

Thus, the breathtaking success of the WDM technology in backbone networks also pushes the development and implementation of WDM local and metropolitan area networks. Local and metropolitan area optical WDM networks are emerging as viable and cost-effective solutions for many telecommunication operators and service providers that have to face an extremely growing bandwidth demand and expensive additional fiber installation costs. Table 2.1 shows comparison of DWDM and CWDM.

Table 2.1: Comparison of DWDM and CWDM.

	DWDM	CWDM
Number of wavelengths	more than a few dozens	about dozens
Wavelength spacing	about 0.4 to 0.8 nm	about 20 nm
WDM filter and laser	accuracy is needed	accuracy is alleviated

Due to the development of WDM technique, the technique to realize 1 Tbit/s per one fiber has been in practical use, and about 20 Tbit/s was attained in the trials [7], [8].

2.2.2 Optical Switching Technique

A core node switches data transmitted on WDM link. In this section, optical switching techniques in a core node are explained. Optical switching techniques are classified into the following three types according to the criterion for switching.

(A) Optical Circuit Switching (OCS)

(B) Optical Burst Switching (OBS)

(C) Optical Packet Switching (OPS)

(A) Optical Circuit Switching (OCS)

Optical Circuit Switching (OCS) is a technique to switch physical communication channels, which are independent specially. In OCS, the circuit for an optical signal is set up according to the physical property of each optical signal, such as a wavelength, a time-slot, and a waveform. The line set up for each optical signal is called "path". An OCS node switches data according to an established path.

OCS node systems are classified into several types according to a type of a path, for example, Spatial Path Switching to switch data according to a spatially independent path, Time Slot Path Switching used in Time Division Multiplexing, and Virtual Path Switching used in Code Division Multiplexing.

As an OCS using WDM technique, Lightpath Switching has been studied and developed. In Lightpath Switching, a path called "lightpath" is established between sending and receiving nodes by reserving a wavelength on the path. And, data is switched and forwarded according to a wavelength without O/E/O conversion.

Figure 2.7 shows an example of data transmission in Lightpath Switching. A source node sends the request packet demanding a connection toward its destination node. Into the received request packet, each intermediate node stores the wavelength usage information about the link between itself and its next node. And, the intermediate node transmits the request packet to its next node. When the destination node receives the request packet, the destination node decides the wavelength to reserve based on the wavelength usage information included in the received request packet. And, the destination node sends back a reserve packet including the wavelength to reserve toward the source node. Each intermediate node receives the request packet, and reserves the wavelength designated by the received reserve packet. After the reservation of the wavelength is finished, the lightpath is established, and the source node starts to send data packets. The source node sends a release packet after finishing sending all data packets. By sending the release packet, the reserved wavelength is released.

Figure 2.8 shows the concept of a Lightpath Switching node system. A Lightpath Switching node system is mainly composed of an optical cross connect and an electronic controller. High-performance optical devices, such as an optical buffer, are not required. An optical cross connect executes to switch lightpathes according to

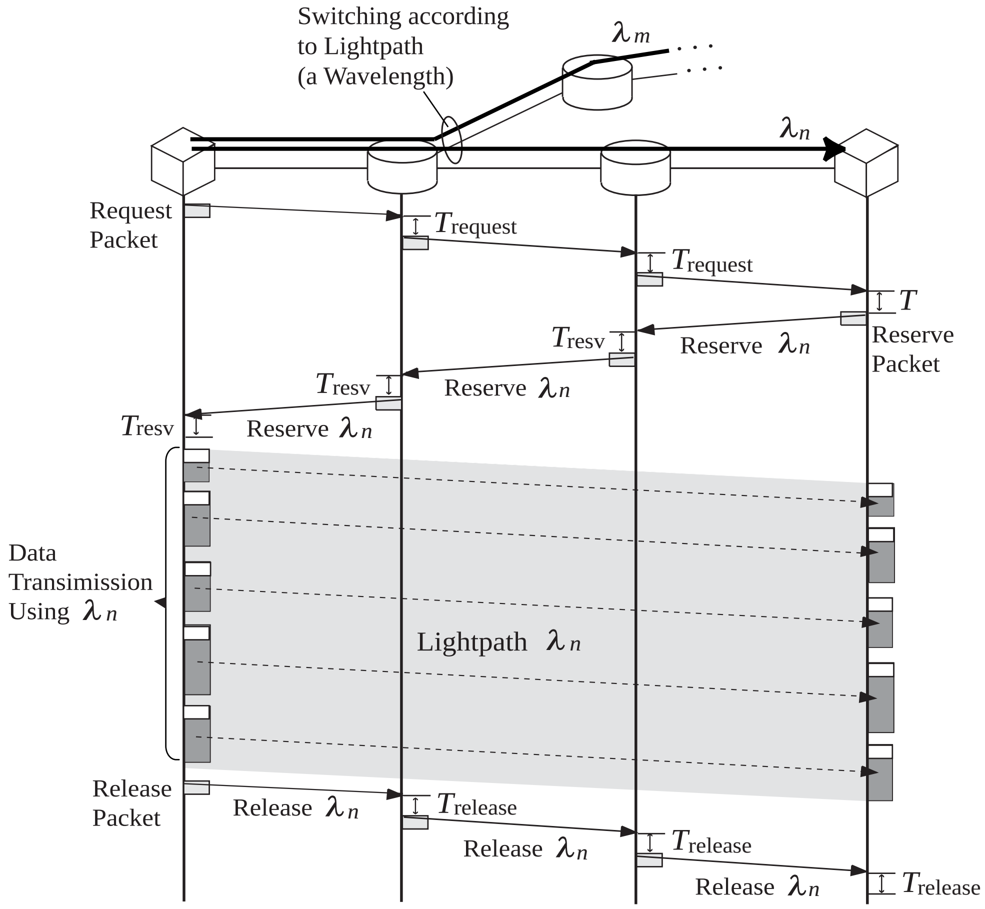

Figure 2.7: An example of data transmission in Lightpath Switching.

an order from an electronic controller. The electronic controller sends orders based on the information of established lightpath. Figure 2.9 shows examples of an optical cross connect architecture [9]. As shown in Fig. 2.9(a), in a rigid type, one wavelength maps to one port. A type shown in Fig. 2.9(b) can rearrange a combination of one wavelength and one port by using a space switch. A type shown in Fig. 2.9(c) realizes non-blocking switching by using a wavelength converter. In this thesis, this Lightpath Switching is called OCS.

The merit of Lightpath Switching is that WDM networks can be realized without a high-performance switching node system. However, in order to establish a lightpath, the usage information of wavelength resources must be managed in all links. When

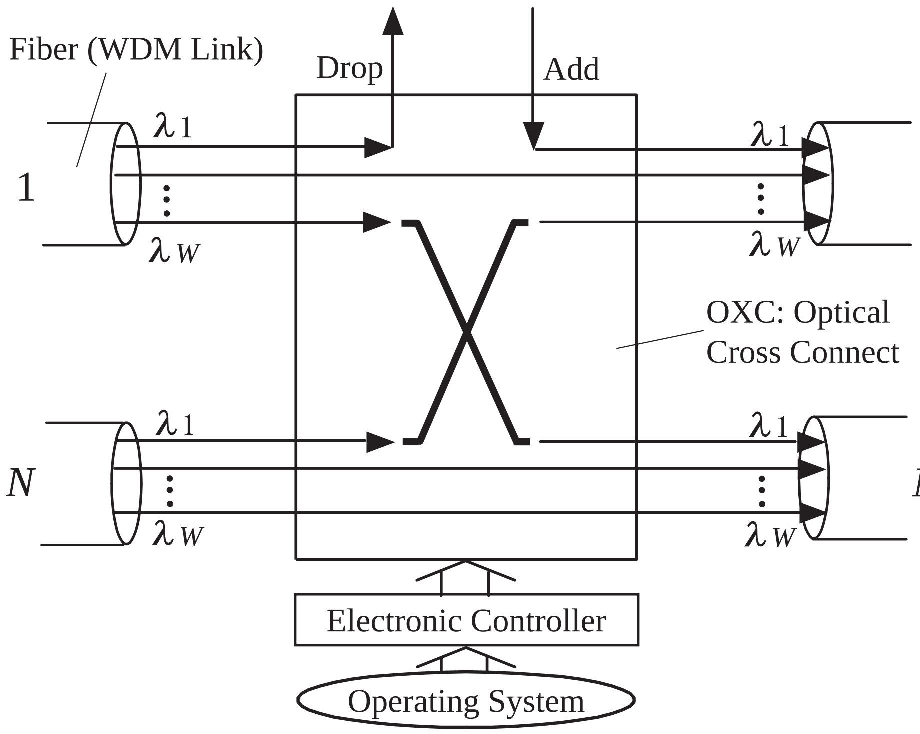

Figure 2.8: A structure of Lightpath Switching node system.

the traffic is low, the effective of the wavelength usage is not good.

(B) Optical Burst Switching (OBS)

In order to solve the waste of wavelength resources in Lightpath Switching, Optical Burst Switching [10]-[12] was proposed. In OBS, several IP packets with the same destinations are assembled into a burst, and forwarded through the network. By switching by bursts, the circuit is established only while sending live data. So, after sending data, the circuit can be released quickly for other sessions.

Figure 2.10 shows an example of data transfer in OBS. At first, a source node sends a control packet, which is the header packet of a burst. Each intermediate node reserves a wavelength for the burst based on the received control packet.

Several wavelength reservation schemes have been proposed. The wavelength reservation schemes are classified into two types: one-way reservation and two-way

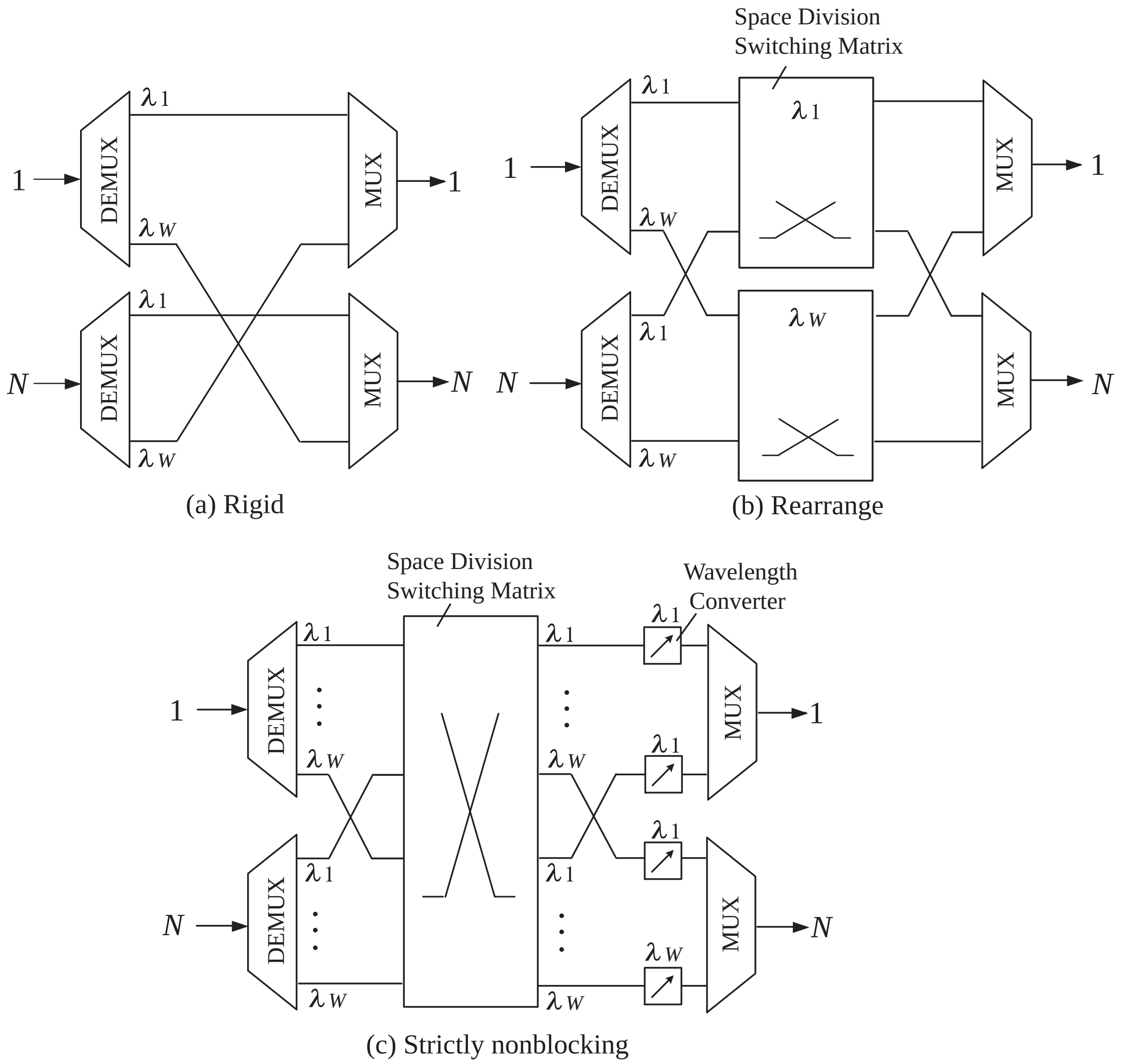

Figure 2.9: Examples of an optical cross connect architecture.

reservation. In one-way reservation, a burst follows a control packet without waiting for acknowledgement of a wavelength reservation. Therefore, a burst can be sent as soon as the burst arrives at an edge router. However, one-way reservation has the problem that burst is discarded when the reservation is failed. On the other hand, in two-way reservation, a burst is sent after acknowledgement of a wavelength reservation. Therefore, the success of transmission of a burst is guaranteed. However, the delay is longer than one-way reservation since a burst must wait at an edge router until the acknowledgement of a wavelength reservation arrives.

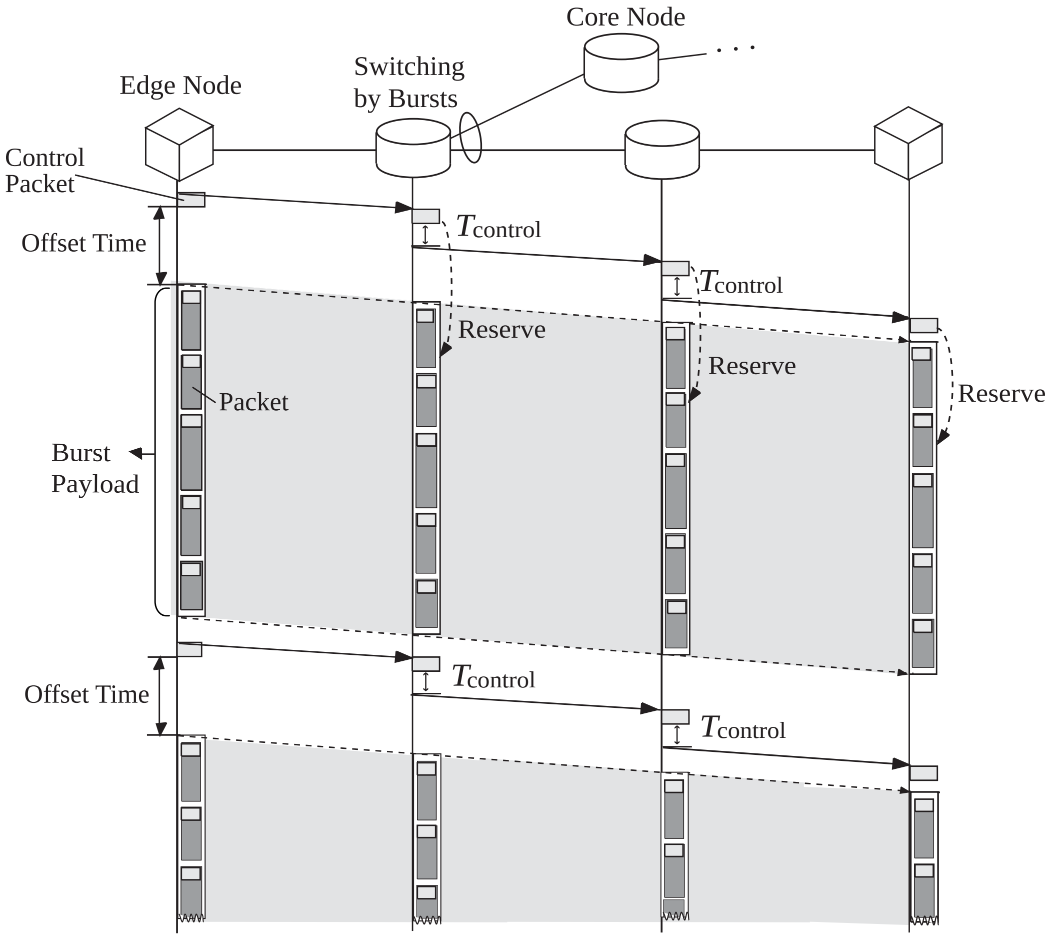

Figure 2.10: An example of a data transmission in OBS.

Figure 2.11 shows wavelength reservation schemes in OBS. Figure 2.11 (a) shows Tell-And-Wait (TAW) [17]. TAW is two-way reservation scheme. An edge node sends a burst after confirming whether the reservation of a wavelength is succeeded or not. A control packet is sent from the source edge node to the destination edge node. A control packet reserves a wavelength at a core node. The destination edge node sends an acknowledgement packet which indicates the completion of reservation. The transmission of a burst is guaranteed, and no buffer is needed in the network. They are merits of TAW. Due to the setup time, the transmission time from the beginning of setup to the end of burst transmission is long. It's the demerit.

Tell-And-Go (TAG) [14], [15] shown in Fig. 2.11 (b) a very simple one-way reservation scheme. A control packet and a burst payload are sent together. At each core node, a wavelength is reserved. When a wavelength can be not reserved, the burst is discarded. TAG is based on the assumption that the process time of a control packet is small enough to be neglected. Actually, the process time is needed to be considered. As one-way reservation considering the process time, Just In Time (JIT) [10] and Just Enough Time (JET) [16] have been proposed.

In JIT, as shown in Fig. 2.11 (c), a burst is sent after the offset time which is the cumulative sum of the process time of a control packet on a path. A control packet reserves a wavelength at each core node. The source node sends a release packet and releases the reserved wavelength. In JIT, at the beginning of the setup, a burst length is not determined. So, the source node can send packets which arrive by the end of the offset time. Therefore, the queuing delay of packets at an edge node is short. However, the wavelength utilization is low since a wavelength is reserved from the arrival time of a control packet to the arrival time of a release packet. It is the demerit of JIT.

JET shown in Fig. 2.11 (d) is most used. Unlike JIT, after generating a burst, the source edge node sends a control packet. The information of a burst length and an offset time are included in the control packet. Based on these two values, each core node reserves a wavelength just from the arrival time of the burst to the end time of the burst. So, the wavelength utilization is high. However, packets arriving during the offset time are not included into the burst. So, the queuing delay of packets at an edge node is longer than JIT. Each core node is required to estimate the arrival time precisely. Therefore, JET is sensitive to fluctuation such as a jitter.

In Fig. 2.10, Just-Enough-Time (JET) scheme adopted most in the study of OBS is shown. In JET scheme, a control packet includes the information of an offset time and a burst length from the control packet. And, based on the offset time and the

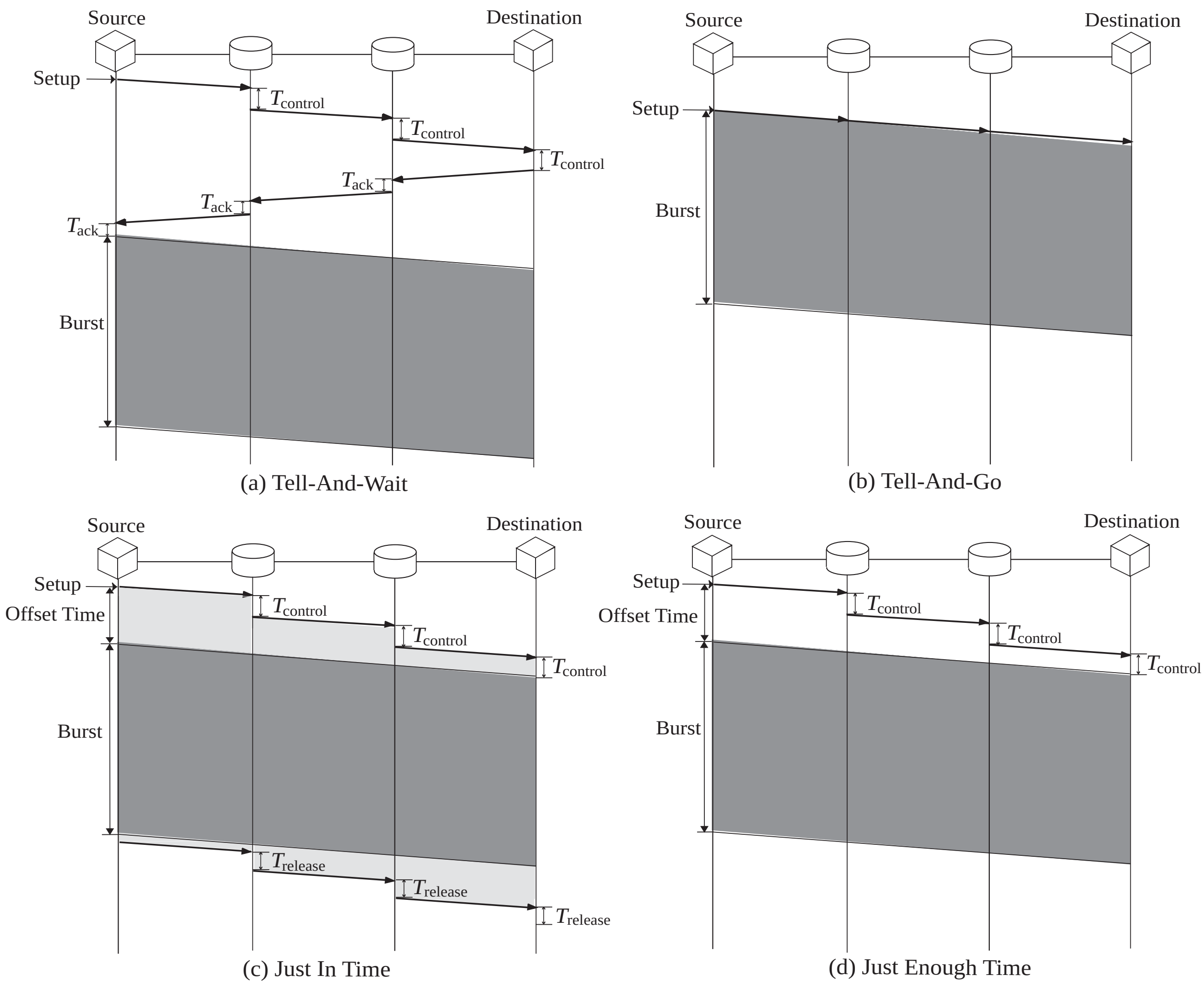

Figure 2.11: Wavelength reservation schemes in OBS.

burst length, the transit time of the arriving burst is calculated. The intermediate node can reserve a wavelength for the transit time. Therefore, unlike OCS, the switch of a burst can be realized as a packet transmission.

Figure 2.12 shows OBS node system. In OBS network, a burst payload follows a control packet on a separate channel. Channels carrying data bursts are called data channels, and channels carrying control packets are called control channels. In a core router, only a control packet is processed electrically, and a burst payload is forwarded through the network in optical domain.

Figure 2.13 shows an example of the optical switch in a core router [13]. A struc-

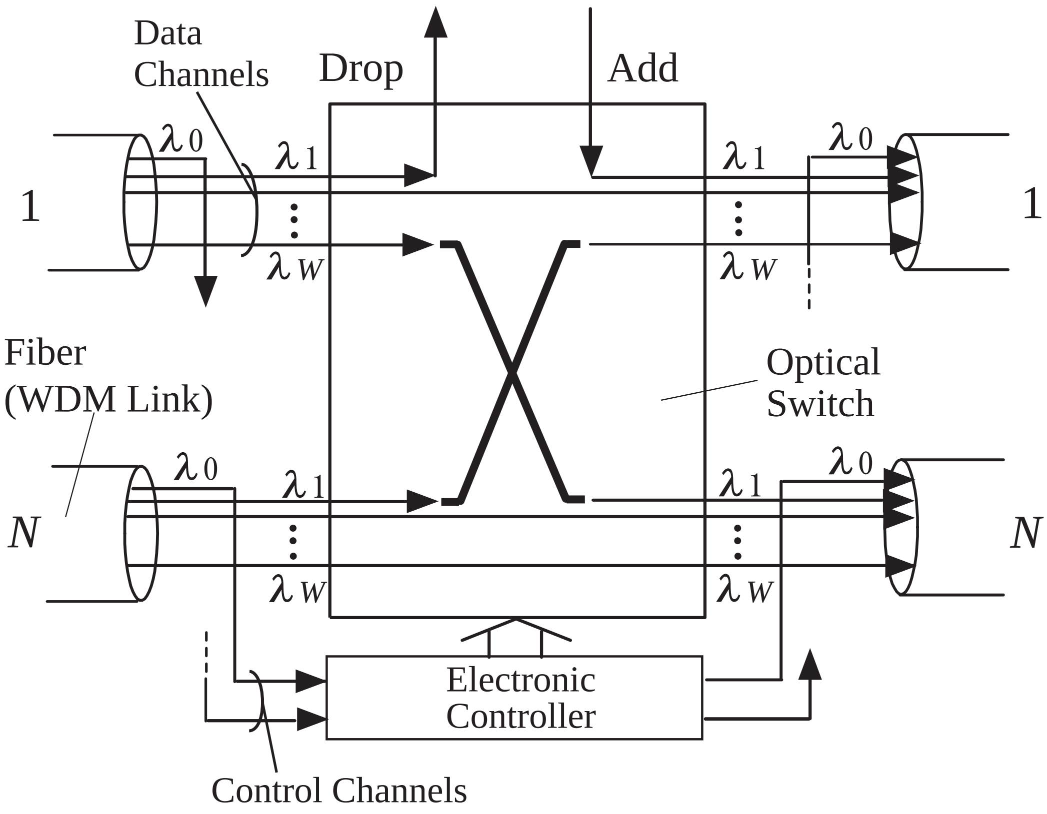

Figure 2.12: Optical Burst Switching node system.

ture of the optical switch is more complex than optical cross connects of Lightpath Switching node system shown in Fig. 2.9. It is because, in OBS, the switching not by wavelengths but by bursts is required. The optical switch is composed of tunable wavelength converters, gate optical switches, and passive couplers. The optical switch switches a burst to an output data channel.

In OBS, transmitting several IP packets as a burst and processing only a control packet electrically can reduce bottlenecks caused by the electrical processing in intermediate routers. In this way, OBS has advantages of OCS and the packet switching, and is suitable for the optical network with the burst traffic.

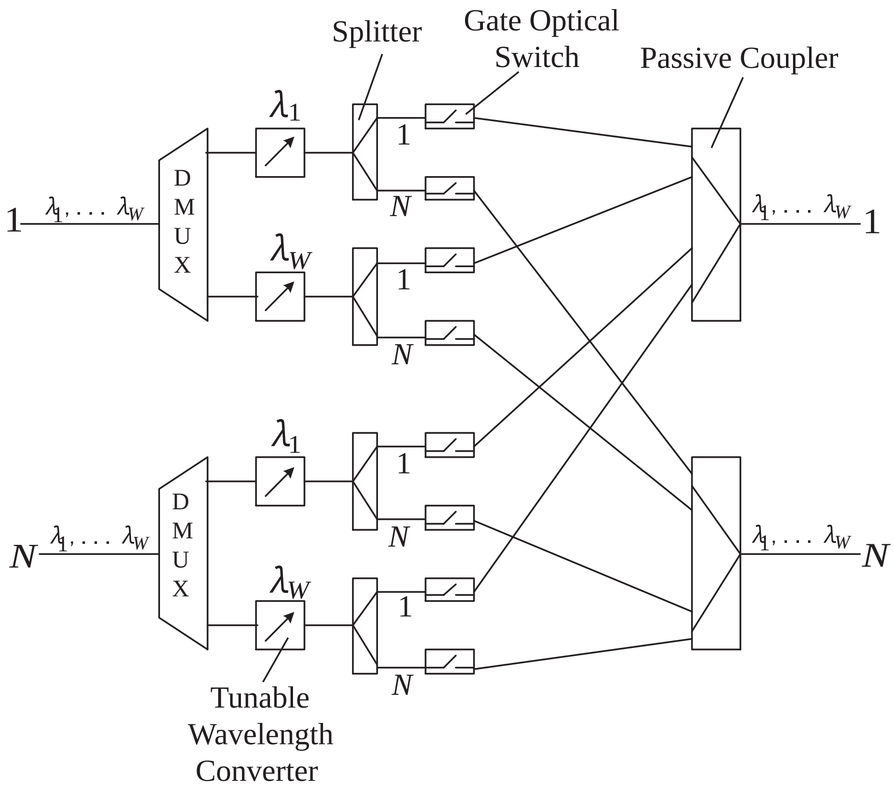

Figure 2.13: An example of the optical switch in a core router.

(C) Optical Packet Switching (OPS)

In Optical Packet Switching (OPS) [18]-[20], IP packets are processed optically packet-by-packet. Figure 2.14 shows an example of the data transmission in OPS. Each packet is stored and forwarded packet-by-packet without the procedure of reserving a wavelength. The granularity of data transmission is the minimum among these three switching techniques. Therefore, the network resource (wavelengths) can be used very effectively.

Figure 2.15 shows OPS node system.. In OPS node, a high speed optical switch is necessary since packets which are very short data are switched. Also, the buffering is imperative in order to avoid the contention of packets. An optical random access memory (RAM) doesn't exist currently. As a substitute for the optical RAM, an optical buffer using fiber delay lines is considered. Also, "slow-light" technique is

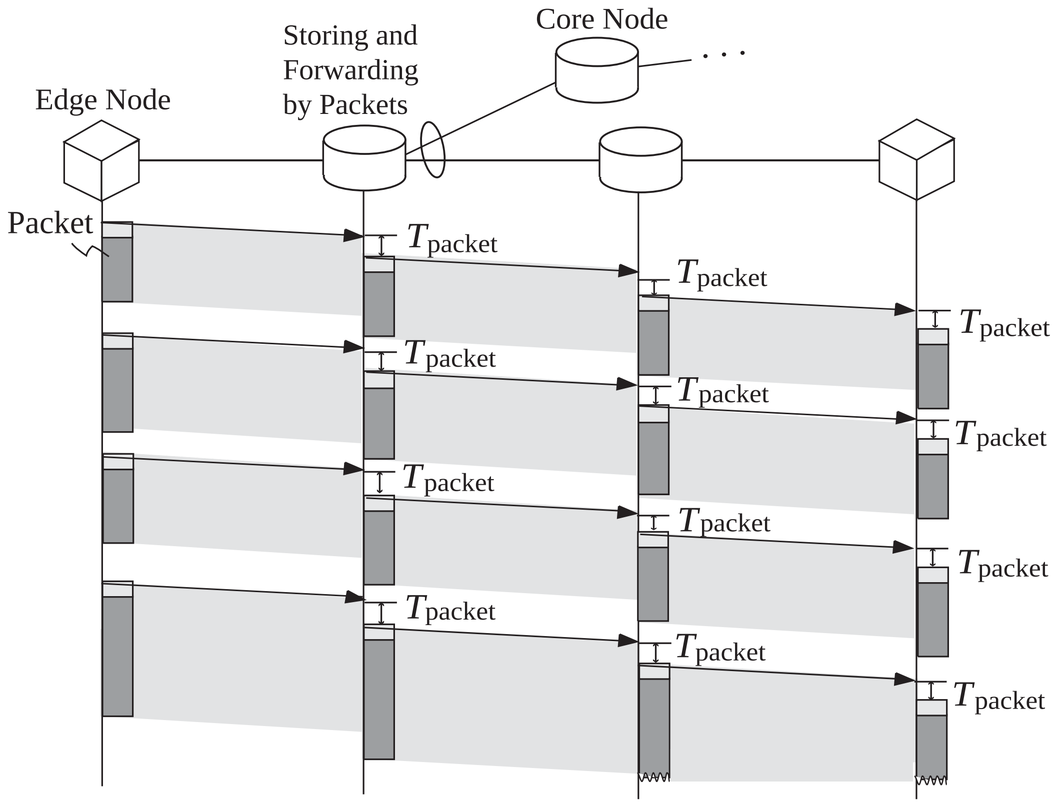

Figure 2.14: An example of the data transmission in OPS.

studied as an elemental technology [21], [22]. A processor of a header is one of important functions in OPS node system. The header processor using O/E conversion and the all-optical header processor have been researched.

Currently, prototypes of a ultra high speed optical packet switch have been developed, such as 160 Gbit/s/port interface optical packet switch [23]. However, an OPS node system is not in use since the above mentioned device techniques are immature. OPS is expected to realize economical, high-speed, and large-volume optical network since OPS system node doesn't need O/E and E/O conversions and the electrical process of packets.

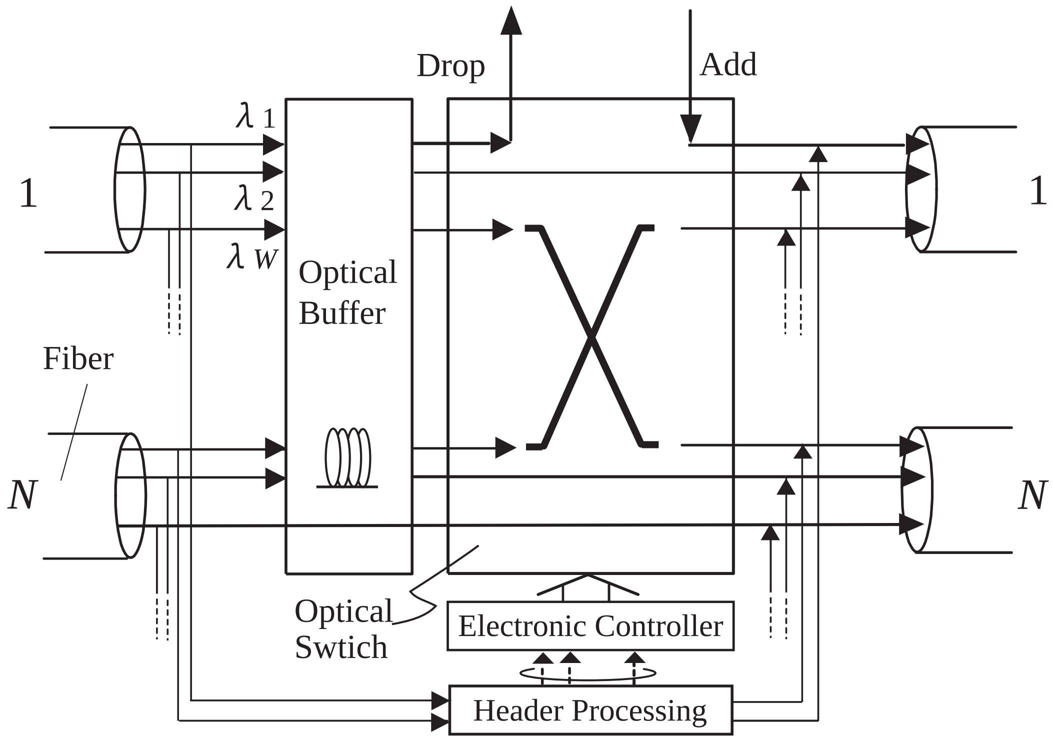

Figure 2.15: OPS node system.

Summary of Optical Switching Techniques

Figure 2.16 shows the summary of three optical switching techniques. OCS has low dependency on optical devices but low utilization efficiency of wavelengths. The required switching speed is slow. OPS has high efficiency of wavelengths but high dependency on optical devices. The required switching speed is fast. OBS has the performance between OCS and OPS. By considering utilization efficiency of wavelengths, the required switching speed, and the dependency of optical devices, three switching techniques are used. In this thesis, OCS and OBS are the targets of the research.

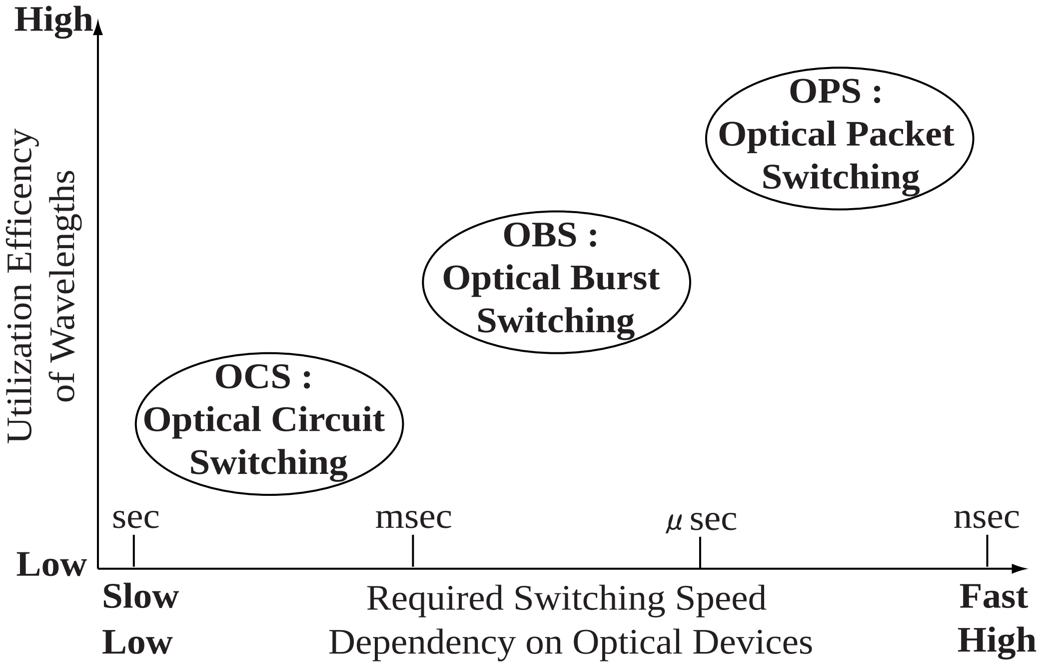

Figure 2.16: The summary of three optical switching techniques.

2.2.3 Control Technique in Control Layer

The technique of configuring nodes efficiently is an important challenge. As the control technique in control layer, Generalized Multi-Protocol Label Switching (GMPLS) [24] has been developed and standardized in the world.

GMPLS is a set of network control protocols for configuring links and nodes in transport layer according to the demand of data communication. Figure 2.17 shows network control protocols of GMPLS. Control nodes in control layer control nodes in transport layer. GMPLS consists of three kinds of protocols. The first one is Link Management Protocol (LMP). LMP is the protocol to discover the adjacency relationship between nodes in transport layer and manage the adjacent link. Second protocol is routing protocol. Routing protocol is used to discover the route for a connection path. In routing protocol, control nodes exchange the link state information. And, each control node calculates the route based on the collected link

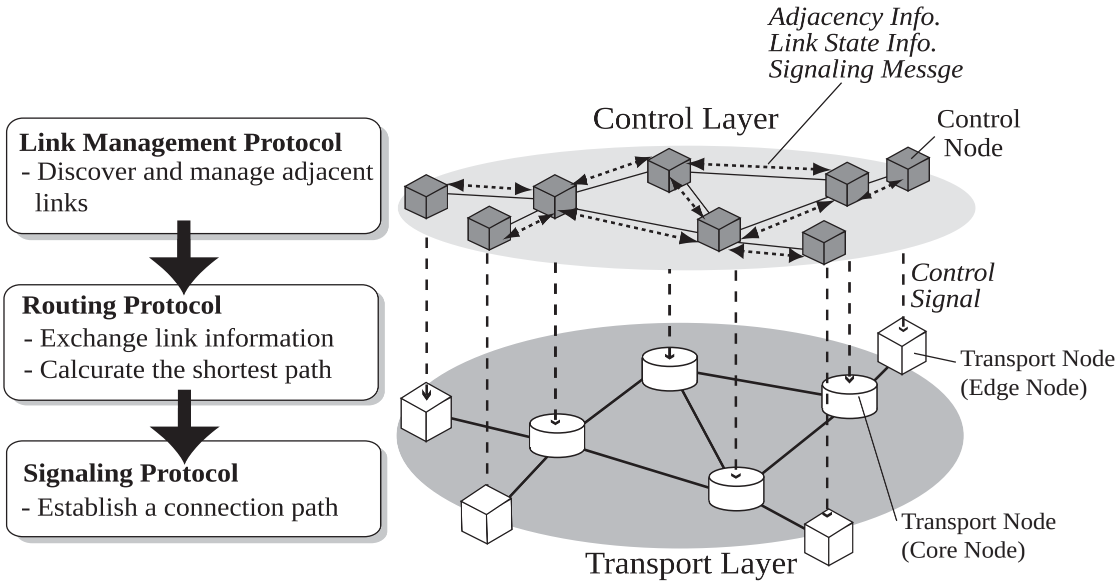

Figure 2.17: Network control protocols of GMPLS.

state information. The third one is signaling protocol. Signaling protocol is used for establishing a connection path. Due to these three protocols, GMPLS can automate the provisioning of a connection path in transport layer.

In GMPLS, control node manages labels. The label indicates the network resource of a node in transport layer. To secure a label in control layer means to reserve the network resource in transport layer. The label is presented MPLS [25], [26]. MPLS is used for packet transmission layer. GMPLS expands the concept of the label for various transport layers including optical network. Figure 2.18 shows examples of labels in GMPLS. Figure 2.18(a) shows a label switching of packet transmission layer in MPLS. In GMPLS, 2.18(a) is applied to other layers. For example, a time slot is a label in Time Division Multiplexing (TDM) layer as shown in Fig. 2.18(b), a wavelength is a label in lambda (wavelength) switching capability layer as shown in Fig. 2.18(c), and a fiber in a link is a label in fiber switching capability layer as shown in Fig. 2.18(d).

The main purpose of GMPLS is not an introduction of a new transmission function

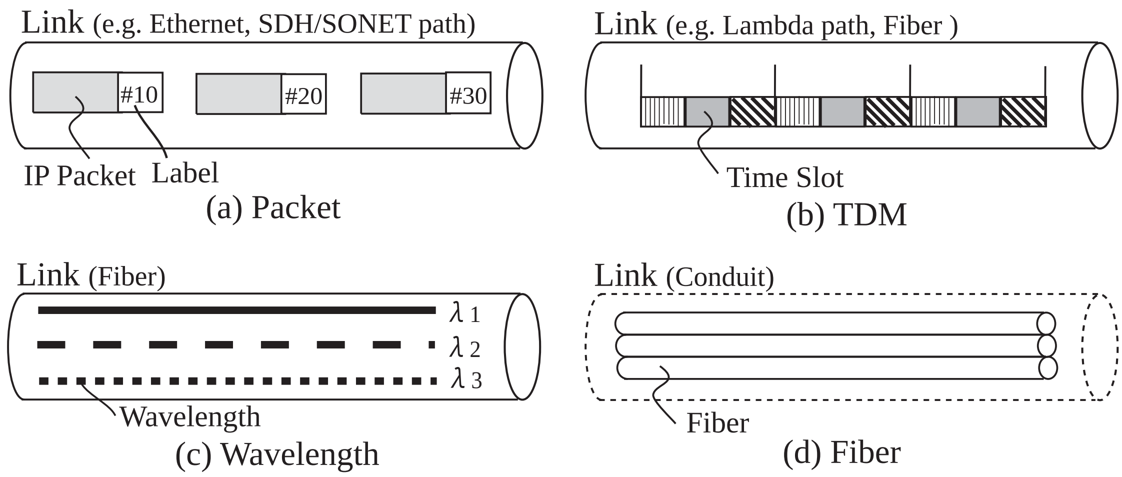

Figure 2.18: Examples of labels in GMPLS.

but a joint operation of multi layers. Figure 2.19 shows a joint operation of multi layers in GMPLS. In the conventional network, the operation, management, and control for each layer network are executed separately as shown in Fig. 2.19(a). So, an administrator is needed for each layer. Therefore, the cooperation among layers is weak, and it is difficult to use network resources effectively. By introducing GMPLS, one administrator can manage and control several layers together. Also, GMPLS enables the automated control which means the remote operation and the auto-recovery during failures.

Automatically Switched Optical Network (ASON) Architecture

Automatically-Switched Optical Network (ASON) has been standardized in ITU-T G.8080 [27]. Figure 2.20 shows ASON architecture. ASON architecture consists of optical networks and user networks. Each optical transport network is composed of several domains. Internal Network-to-Network Interface (I-NNI) is used in each domain. I-NNI needn't be standardized. So, I-NNI needn't be GMPLS. Between domains, External Network-to-Network Interface (E-NNI) is used. E-NNI is standardized. User Network Interface (UNI) is used between an optical network and a

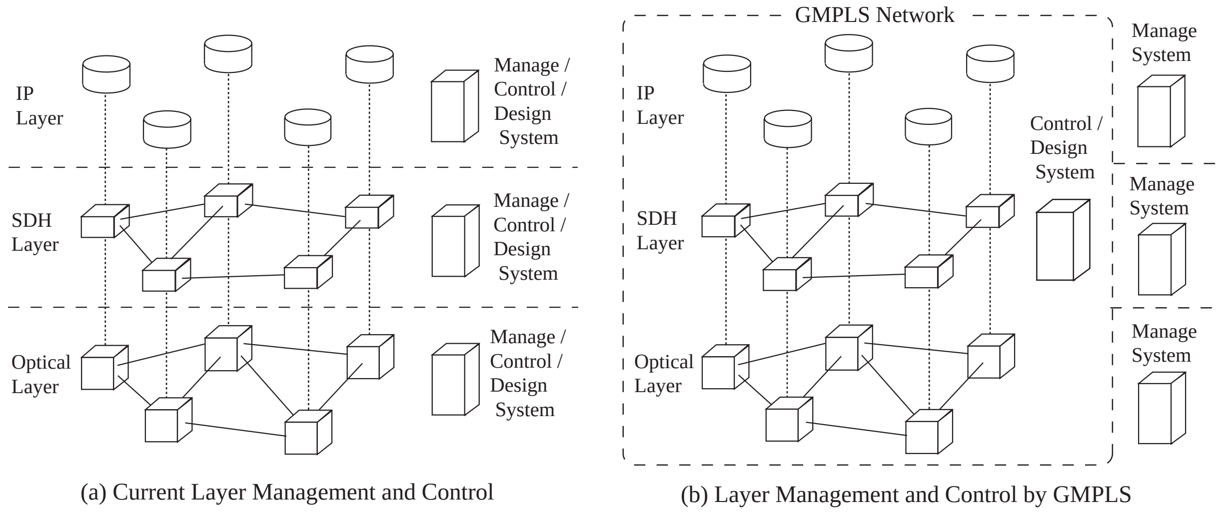

Figure 2.19: An operation of multi-layers by GMPLS.

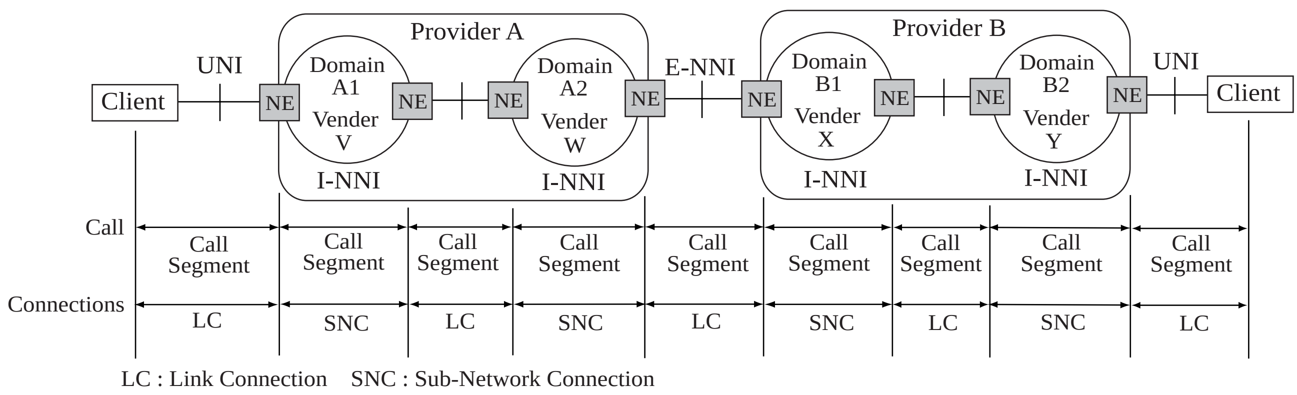

Figure 2.20: ASON architecture.

user network. UNI is also standardized. In ASON architecture, between end-to-end nodes, 'call' is configured. Call consists of several connections (call segments). In order to specify the end point of the call, a certain address is attached independently of the user. The address is called Transport Network Assigned address (TNA).

GMPLS Architecture

Figure 2.21 shows GMPLS architecture [24]. GMPLS architecture consists of IP networks and optical networks. One single connection, called Traffic Engineering

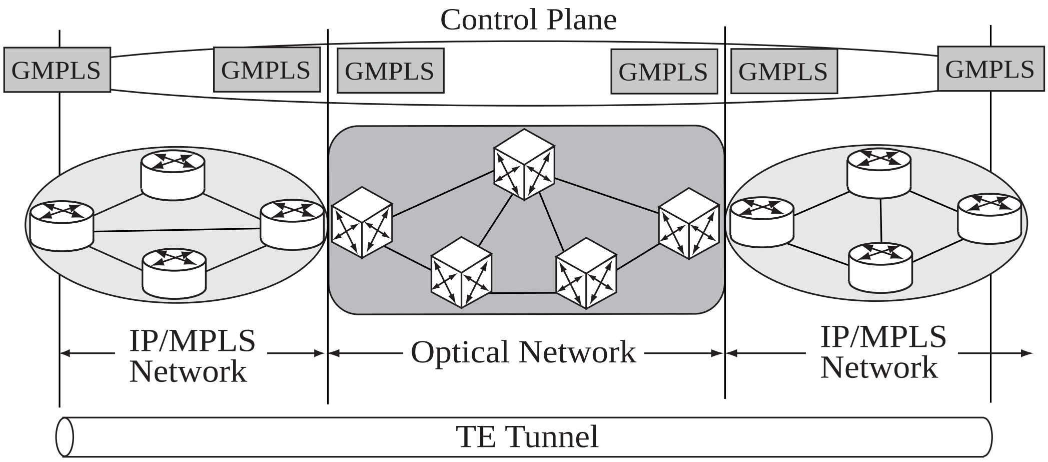

Figure 2.21: GMPLS architecture.

(TE) tunnel, is established between end-to-end nodes. This point is a major difference from ASON architecture. To establish the end-to-end connection path, each edge node needs the link information (TE link information) in the network which is a segment. Therefore, the routing protocol is required to distribute TE link information. In GMPLS architecture, E-NNI, I-NNI, and UNI are not defined apparently. GMPLS protocols standardized by Internet Engineering Task Force (IETF) are used in control nodes.

2.3 Main problems in Optical Network

2.3.1 Contention Resolution

Contention means that two or more data, which are transmitted on the same wavelength, are directed to the same output simultaneously. When contention occurs, only one data is sent to the next node and other data are discarded. In OBS network and OPS network, one of important problems because the connection path is not established in advance.

Figure 2.22 shows approaches to resolve the contention problem. First approach

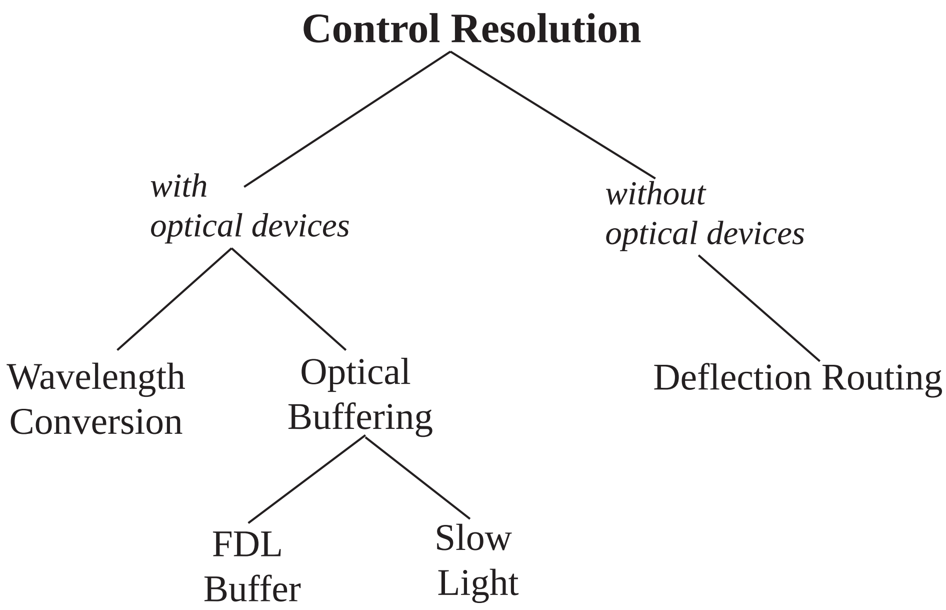

Figure 2.22: Approaches to resolve the contention problem.

is to use optical devices. Two devices can be used in a core node to suppress contention. One is a wavelength converter, and another is an optical buffer.

A wavelength converter converts the wavelength of one data to another wavelength. The performance improvement possible with a wavelength converter has been extensively studied with analytical and simulation-based methods [28], [29]. However, the problem with wavelength conversion is the immaturity of the technology [30], [31]. All-optical conversion technologies without optical-to-electrical and electrical-to-optical conversions are desirable and have been developed over a number of years. However, all-optical conversion technologies are no longer practical because of issues with performance and cost. Eliminating wavelength conversion can greatly simplify the switching fabric and reduce the cost.

An optical buffer delays one data. As an optical buffer, FDL (Fiber Delay Line) buffer is proposed. FDL buffer realizes the function of buffering by using fibers in a variety of lengths. FDL can be used for temporary storage of the data until the resources become available. The scheduling algorithms using FDL buffer have been researched and proposed [32], [33]. Recently, slow light technique has been developed [34], [35]. The slow light technique gives data variable delays without FDLs. Optical buffers using slow light have been proposed [36], [37]. As current optical buffers are typically limited to delay values of a few tens of ms [38], [39] in FDL buffer, a few tens of ns in slow light, it is not easy to store long optical data. Moreover, implementing optical buffers involves a great amount of hardware and complex electronic controls.

An approach not to use optical devices is to change the output link of one data. It is called deflection routing [40]-[42]. Deflection routing is easy to implement for not requiring special optical devices and can be rather effective under light or medium traffic load. However, the deflection routing gets poor performance under high traffic load.

2.3.2 Route Assignment

There are several routes for the connection path between a source node and a destination node. So, it is an important problem which route to use. In an optical network, the objective of route assignment is to minimize data transmission time, to reduce the amount of used links and wavelengths, and to avoid contention.

To minimize the data transmission time, the route calculation gives priority to bandwidth, or distance. To reduce the amount of used links and wavelengths, a route using little network resources, such as the shortest hop route, is calculated. To avoid contention, a suitable route for distributing traffic is calculated. In this way, route assignment approaches vary by policies.

Figure 2.23 shows approaches in route assignment problem. Cost-based routing is to determine the route by using costs assigned to links. The value of cost is configured by considering distance, bandwidth, and so on. The information about

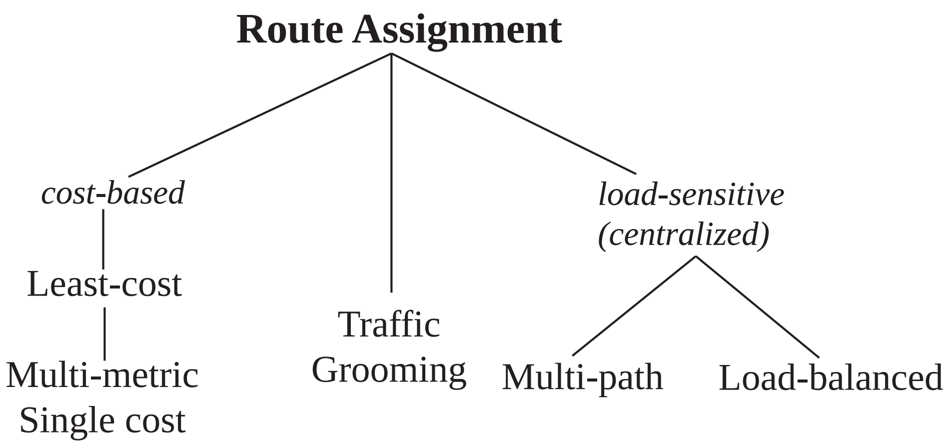

Figure 2.23: Approaches for route assignment problem.

cost is exchanged by using the link-state routing protocol such as the open shortest path first (OSPF) protocol. The least-cost routing [43] is popular as the cost-based routing. It determines only one route based on cost. In the least-cost routing, it is important how to configure cost.

Traffic grooming [44], [45] has other approach. In traffic grooming, several traffic flows are transmitted into one wavelength or one link. Therefore, the least-cost route is not always selected. But, grooming can suppress the consumption of wavelengths, links, and network interface devices.

Load-sensitive approach considers traffic load in the network. The object of this approach is distributing traffic and avoiding contention. Its goal is an optimal route assignment for the traffic in the network. It means the maximization of the number of established connections. It is an optimization problem, and it is so complicated. Multi-path routing [46] uses several routes for the destination node. Load balanced routing [47], [49] distributes traffic for considering the network load. This approach needs global information.

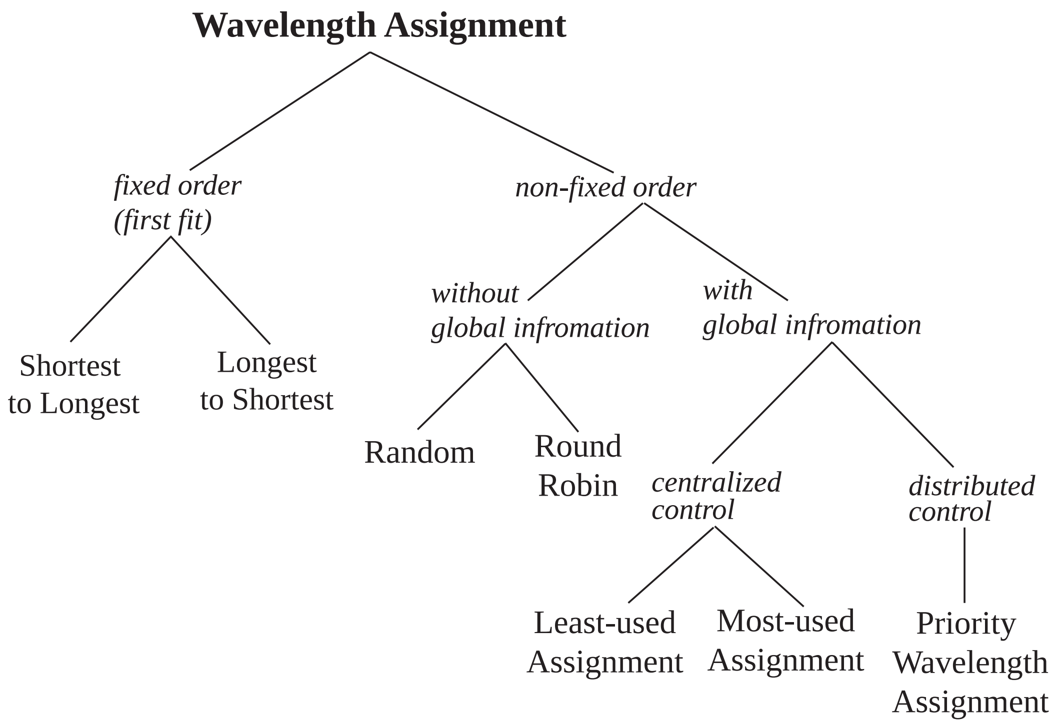

Figure 2.24: Approaches for wavelength assignment problem.

2.3.3 Wavelength Assignment

Wavelength assignment is as important as route assignment. If all edge nodes transmit data on the same wavelength, contention frequently occurs. How to select a use wavelength is an important problem.

Figure 2.24 shows approaches for wavelength assignment problem. Simple approach is fix-order (or first-fit) assignment [50]. In the predetermined order, for example, from shortest to longest or from longest to shortest, a use wavelength is selected. All nodes select a wavelength in the same order. So, the synchronous of selecting a wavelength often occurs, and the probability of contention is high.

Non-fixed order approach has been researched in order to avoid the synchronous of selection. Non-fixed order approach has two main types: without global information and with global information. Global information means the information about the wavelength usage in all links. As the approach without global information, the approaches using random policy [50] or round-robin policy [51] have been proposed. In these wavelength selection schemes, each node doesn 't know which wavelength other nodes select.

As the approach using global information, the least-used assignment [50] and the most-used assignment [52]. In the least-used assignment, each node selects the least used wavelength in the network, from the set of wavelengths on the path. The idea of the least-used assignment is that is more likely that a shorter route is found on the least-used wavelength than a most-used wavelength. The most-used assignment uses just opposite logic from the least-used assignment. In the most-used assignment, each node selects the most used wavelength in the network. It was shown [53] that the most-used assignment has better performance than the least-used assignment. Both assignment methods require centralized control.

In distributed control, Priority-based Wavelength Assignment (PWA) [54] has been proposed. In PWA, each node learns a suitable wavelength by receiving feedback packets. Each node cannot know an optimal wavelength, but can know the wavelength with high success probability in the network.

Route assignment and wavelength assignment are often discussed together as Routing and Wavelength Assignment (RWA).

2.3.4 Protection/Restoration

Nodes, links, and network interfaces may be at fault. Protection and restoration are the techniques for fault recovery. Figure 2.25 shows approaches for protection/restoration. Protection [55] is the technique that a backup path for a main path is established in advance. The merit of protection is fast recovery because of the pre-establishment of the backup path. The demerit is low link utilization because network resources are reserved for the backup path.

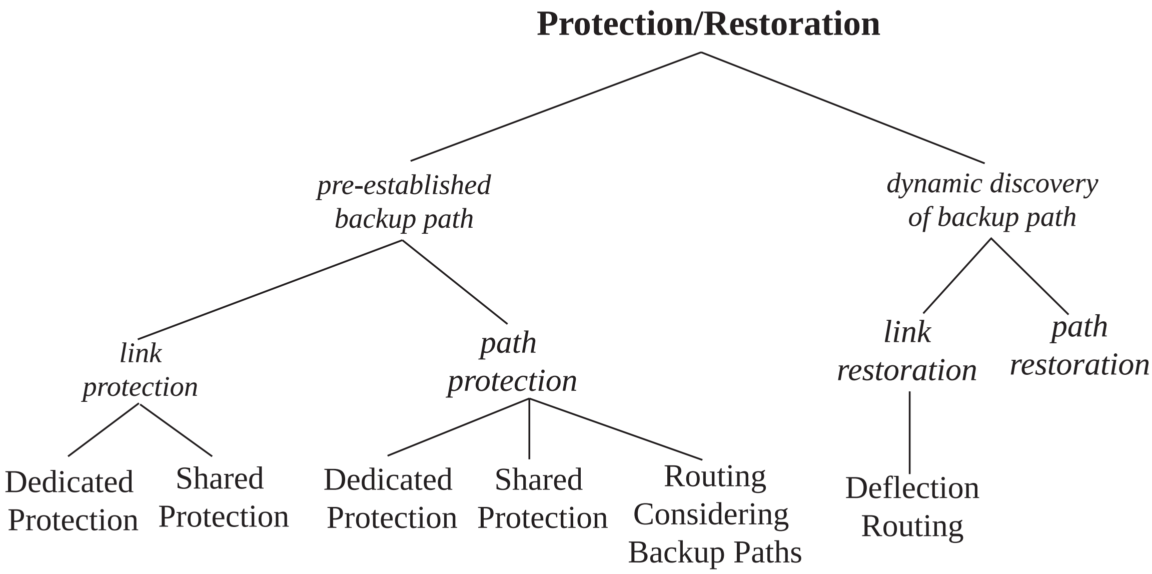

Figure 2.25: Approaches for protection/restoration.

There are two types of protection; link protection and path protection. In link protection, the node which has a fault link executes recovery. The route is switched at the node with the fault link. In path protection, end-to-end nodes switch the main path to the backup path. Link protection realizes faster recovery than path protection. However, path protection uses less links than link protection because, in link protection, the intermediate node executed the reroute and, in path protection, the reroute is executed between end nodes.

In order to improve the utilization of links for establishing a backup path, shared protection [56], [57] has been researched. Several main paths share one backup path or link. So, shared protection can reduce the number of links used for backup paths. Shared protection cannot deal with several faults simultaneously.

The routing for protection has been studied. The routing considering not only the cost of a main path but also the cost of a backup path has been proposed. The policy of this routing is to minimize the sum of the cost of a main path and the cost of a backup path. In this routing, total costs can be minimized. However, the least-cost route is not always selected for a main path.

Restoration [58] is the technique that an alternative path is established in failure occurrence. So, the link utilization is high compared with protection. However, the recovery time in restoration is longer than that in protection. In restoration, like protection, there are path restoration and link restoration. In path restoration, end-to-end nodes established the alternative path for the fault main path. It is important to minimize the time from the generation of fault to the acknowledgement of each node. In link restoration, the node which has a fault link executes the establishment of the alternative path. Deflection routing has been proposed as the link restoration scheme.

2.3.5 Control Technique in Control Layer

Control layer must control optical switching techniques, routing assignment, wavelength assignment, protection/restoration and so on. Also, control layer is required the control technique to provide the transmission quality for applications/services. To realize to the control technique, the method of configuring node devices in transport layer is an important problem. It is also important to what message should be exchanged in control layer.

Experiments about GMPLS controlled optical network have been done. In [59], for various multiple-failure scenarios, GMPLS based pre-planned restoration scheme has been proposed, implemented, and experimented. Also, the interworking trials [60], [61] have been taken in the world.

As the application using an optical network, GRID network is studied. GRID computing is the technique that makes a high performance virtual machine by combining geographically dispersed computing resources over a network. GRID computing requires a large capacity network because large volumes of data are exchanged amongst computing resources. As the network model to realize GRID computing, λ GRID employing WDM and lightpaths has been studied [62], [63]. Also, several experimental GMPLS-based optical GRID networks are implemented, for example, Dynamic Resource Allocation via GMPLS Optical Network (DRAGON) [64], Circuit-switched High-speed End-to-End Transport Architecture (CHEETAH) [65], and the GMPLS network service for GRID computing using the network resource management system [66]. In [67], dynamic path provisioning of 10 Gigabit-Ethernet using GMPLS was successfully achieved between Japan and the USA for the first time. And, the quality of GMPLS connection path is verified to be sufficient to support high-end data and GRID networking services.

2.4 Position of this Ph.D. Dissertation

The position of this thesis is explained based on the architecture of an optical network and main problems. Figure 2.26 is a view showing the position of this thesis. This study covers contention resolution in OBS, route assignment in OBS, and route assignment in OCS. The target of Chapter 3 is contention resolution in OBS network. As a contention resolution scheme for OBS, Optical Composite Burst Switching (OCBS) [13] that can improve the performance of the packet loss probability without wavelength conversion and optical buffering is proposed. However, OCBS has the problem that it is unfair about the number of hops to the destination edge node. So, a new burst dropping technique is proposed in order to improve the unfairness about the packet loss probability by the number of hops. The target of Chapter 4 and 5 is route assignment. In order to distribute traffic, load-sensitive route assignment schemes with global information are proposed. However, the centralized control is required to get global information, and the scalability and the management of global information are problems. Conventionally, a load-sensitive routing approach

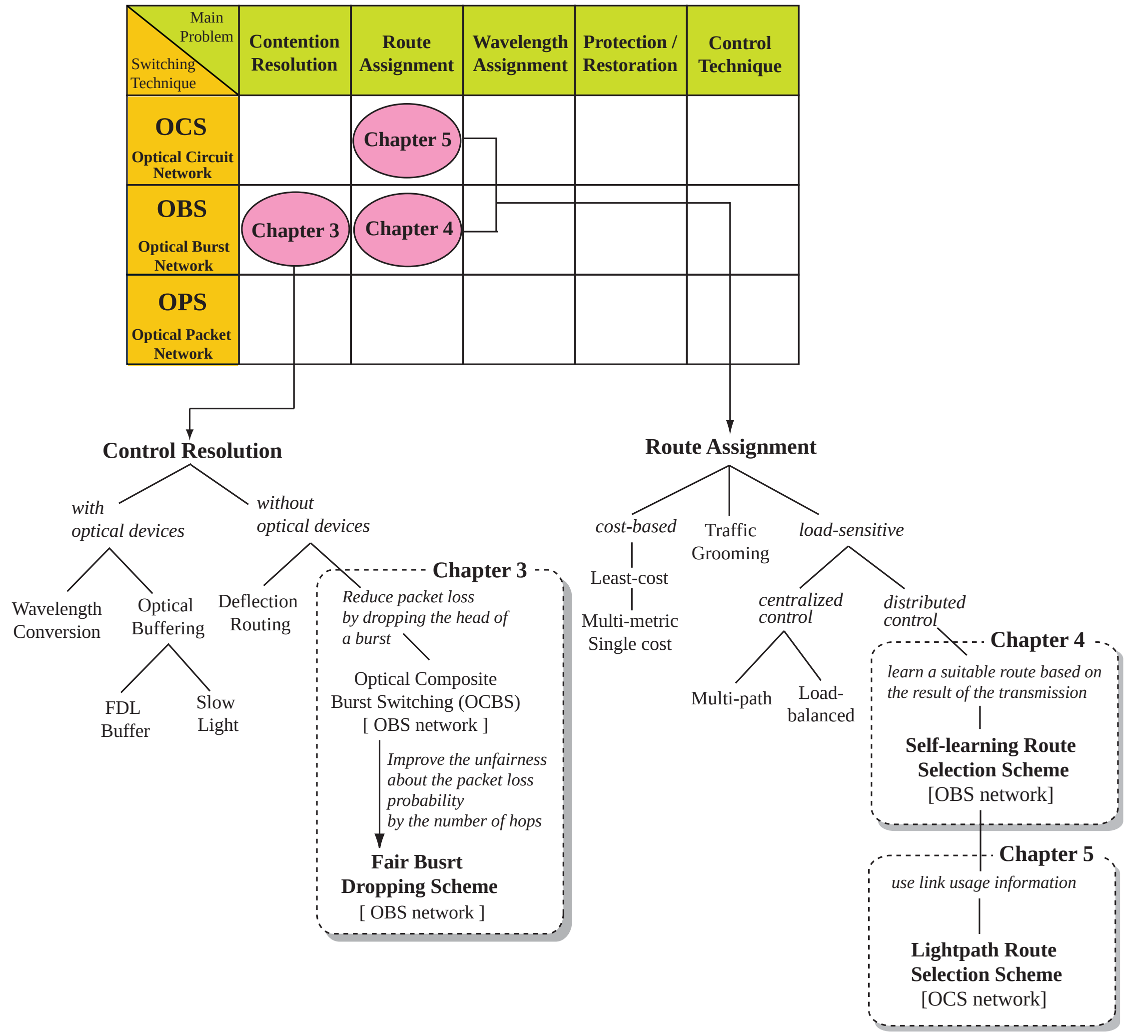

Figure 2.26: Position of this Ph.D. Dissertation.

is studied to distribute traffic. This approach assigns the route with low traffic by monitoring the traffic condition in the network. The real time management of traffic information and the scalability for a large scale network are its challenges. So, a new route selection scheme by distributed control is proposed. At first, in Chapter 4, the self-learning route selection scheme for OBS is proposed. Next, in Chapter 5, the lightpath route selection scheme for OCS is proposed by extending the self-learning route selection scheme in Chapter 4.

Figure 2.27 shows the relationship among works in Chapter 3-5. In Chapter

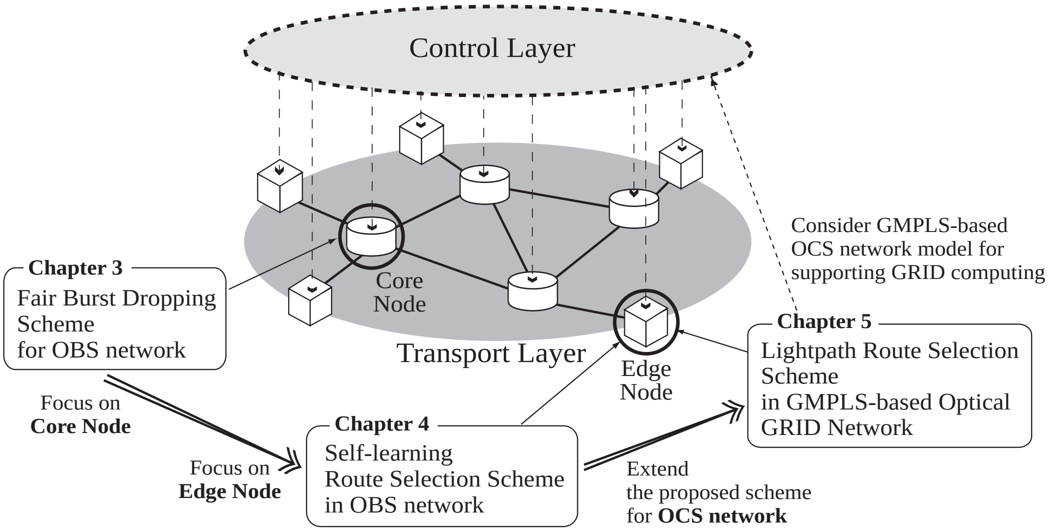

Figure 2.27: Relationship among works in Chapter 3-5.

3, the function of a core node in OBS network is focused on, and the fair burst dropping scheme is proposed. The purpose of Chapter 4 is to reduce the probability of burst contention by controlling the transmission of bursts at an edge node without resolving burst contention at a core node. So, route assignment in an edge node is focused on, and the self-learning route selection scheme is proposed. In Chapter 5, I intend to apply the self-learning route selection scheme in Chapter 4 for OCS network. Also, control technique in control layer stated in Section 2.4.5 is considered, and I proposed the lightpath route selection scheme in GMPLS-based GRID network by extending the proposed scheme in Chapter 4.

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Chapter 3

A Fair Burst Dropping Scheme for Optical Composite Burst Switched Multi-Hop Network

3.1 Introduction

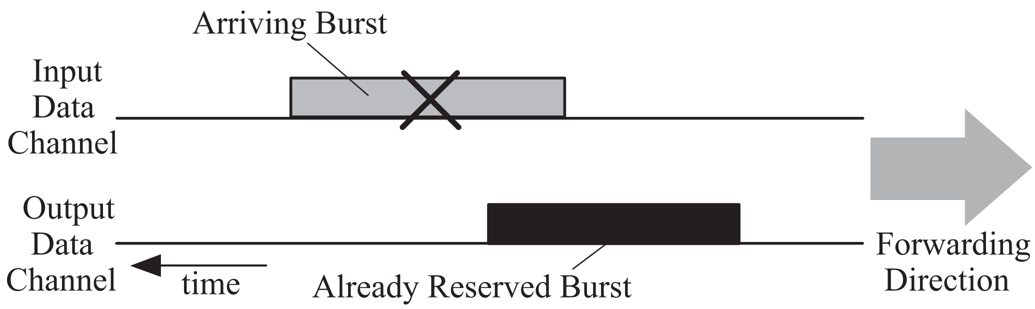
In this chapter, contention resolution (see section 2.4.1) in OBS network is focused on. Optical Composite Burst Switching (OCBS) [1], which reduces packet loss due to burst contention without using optical buffering and wavelength conversion, has been proposed. In OCBS, when burst contention occurs, a head-dropping (HD) technique is applied. The HD technique is a burst dropping technique which discards only the initial part of the burst that arrives later. In OCBS, the number of discarded packets can be reduced compared with OBS since only the initial part of the burst is discarded, and all the packets within the burst are not discarded when burst contention occurs. In OCBS, however, since a burst becomes short by repeatedly applying the HD technique in intermediate core routers, the burst with many hops to the destination edge router are more likely to be discarded before arriving at the destination edge router. Therefore, in OCBS, there is the problem that the HD technique causes the unfairness about the packet loss probability by the number of hops. For example, when Quality of Service (QoS) is applied in OCBS, the unfairness causes the problem that the packet loss probability of the high priority burst with many hops exceeds that of the low priority burst with small hops.

In this chapter, a new fair burst dropping scheme technique is proposed. In order to achieve the fair packet loss probability regardless of the number of hops, the proposed scheme configures the threshold for determining whether the HD technique is applied or not. the proposed scheme can reduce the difference of packet loss due to the number of hops by applying the HD technique in consideration of the number of hops, and can achieve the fair packet loss probability regardless of the number of hops. By computer simulation, it is shown that the proposed scheme can achieve the fair packet loss probability regardless of the number of hops to the destination edge node compared with a conventional one.

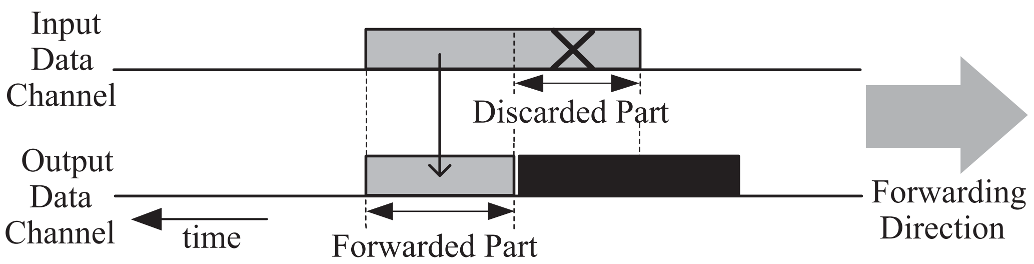
3.2 OCBS

In OCBS, when burst contention occurs, only the initial part of the burst that arrives later is discarded by the HD technique as long as there is a channel able to be allocated for a part of the burst. And the remaining part of an arriving burst is forwarded to the next node along with OBS. Figure 3.1 shows the burst dropping technique when burst contention occurs. In OBS, an entire burst is discarded as shown in Fig. 3.1(a), whereas in OCBS, only the initial part of an arriving burst is discarded by the HD technique as shown in Fig. 3.1(b). And the final part of an arriving burst is forwarded to the next node along with OBS. In OCBS, the number of discarded packets can be reduced compared with those in OBS, since only the initial part of the burst is discarded and all the packets within the burst are not discarded when burst contention occurs.

The process of HD technique in a core node is explained blow. Firstly, a core node receives a control packet. Based on an offset time and a burst length included in the control packet, the core node calculates the arrival time of the burst. From



(a) OBS



(b) OCBS

Figure 3.1: The burst dropping technique when burst contention occurs.

the calculated arrival time, the core node confirms whether burst contention occurs or not. When burst contention occurs, the core node determines a dropped length considering the part of overlap with other bursts. Then, the core node calculates the burst length after applying the HD technique. The information of the burst length in the control packet is replaced by the calculated value. The burst payload is just cut in optical domain. No data is added to the burst payload newly.

In order to disassemble the burst to packets, Simple Data Link (SDL) [2], [3] protocol is used. Figure 3.2 shows an example of the burst payload structure using SDL [1]. The burst payload consists of several SDL frames. SDL frame is composed of Length Indicator (LI) field, Header Cyclic Redundancy Check (CRC) field, Information field, and Frame Check Sequence (FCS) field. LI field contains the length of the information field (IP packet) in bytes. This length allows the receiver node

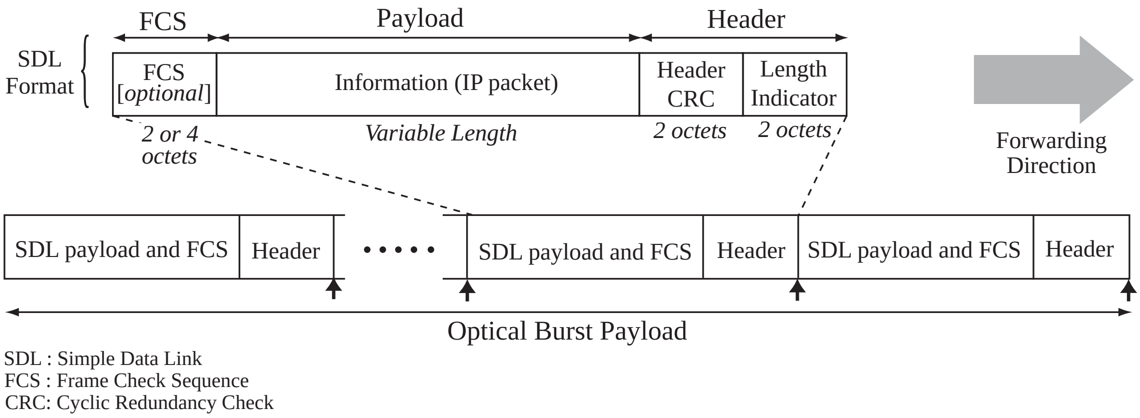


Figure 3.2: An example of the burst payload structure using SDL.

to identify the end of the current SDL data unit and the beginning of the next one. Header CRC contains the value calculated over all bits in LI field. CRC operation is designed to allow correction of all single-bit error and detection of most multiple bit error in the SDL header. Information field within the SDL payload field carries the IP packet. FCS field is an optional field. The polynomials used are the same as those used in IP-point-to-point protocol (PPP) - high-level data link control (HDLC) frames, as described in [4]. The field is calculated over all bits in the SDL payload field.

The main function of SDL is to allow high-speed delineation of asynchronous variable-length datagram contained in the burst payload. To achieve this, the SDL receiver analyzes the LI field at the beginning of each SDL data unit to extract the framed datagram in the SDL payload and to determine the standard point the next SDL data unit. Under normal operation, the SDL receiver can extract the IP packets without processing every single byte on the data link. This is one of the aspects that make SDL particularly suitable for very high transmission speeds with respect to HDLC. Another important function of SDL is to allow resynchronization of the receiver after the delineation is lost; this is realized by finding the match of the LI and header CRC fields. In OCBS, the frame check and the error correction for each packet are executed. However, they for each burst are executed since burst payload is cut by the HD technique in the optical domain.

In OCBS, the entire burst with many hops are more likely to be discarded in the intermediate core node before the burst arrives at the destination edge node, since the burst becomes short by repeatedly applying the HD technique as shown in Fig. 3.3. Therefore, in OCBS, there is the problem that the HD technique causes the unfairness about the packet loss probability by the number of hops.

This unfairness about the number of hops has a negative impact on providing the transmission quality. For example, when a certain service A is provided, the difference about the transmission quality occurs between the service A for a burst with 1 hop and the service A with a burst 3 hops. So, the unfairness about the number of hops is one of problems to be solved. This problem is how much traffic each edge node sends for achieving the fairness about the packet loss probability by the number of hops. The goal of the problem is an optimal assignment of the traffic in the network. It is an optimization problem, and it is so complicated. In this chapter, a simple distributed controlled scheme is proposed in the next section.

3.3 Proposed Burst Dropping Scheme

In order to achieve the fair packet loss probability regardless of the number of hops, the proposed scheme which configures the threshold $Th_i (0 \leq Th_i \leq 1)$ at i hops for determining whether the HD technique is applied or not. The difference of packet loss due to the number of hops can be reduced by applying the HD technique in consideration of the number of hops.

J is defined to indicate the ratio of the forwarded part length to the initial burst

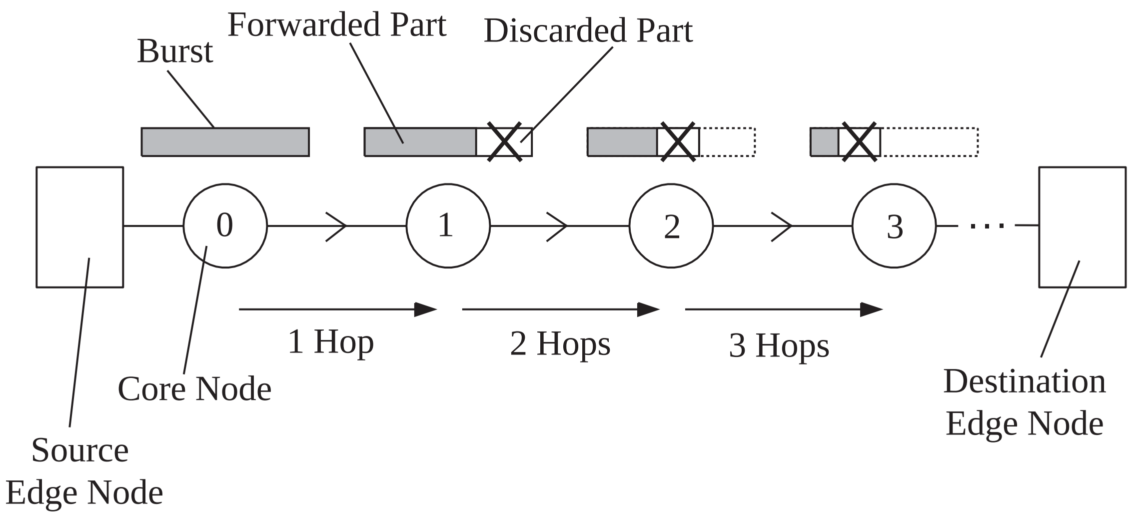


Figure 3.3: The effect of the number of hops in the OCBS network.

length. This parameter J is used for judging whether the HD technique is applied or not. When $J > Th_i$, the HD technique is applied. When $J \leq Th_i$, the HD technique is not applied, and the entire burst which arrives later is discarded. Therefore, setting the value of Th_i high increases the probability that an entire burst is discarded without applying the HD technique in the intermediate core node. Setting the value of Th_i low increases the probability that a part of a burst arrives at the destination edge node by applying the HD technique in the intermediate core node. To increase the probability that the HD technique is applied to the burst with more hops, the proposed scheme configures Th_i of the burst with many hops as a smaller value.

Figure 3.4 shows the proposed burst dropping scheme. Fig. 3.4(a) shows the case of the burst with 1 hop, and Fig. 3.4(b) shows the case of the burst with 7 hops. In Fig. 3.4, the threshold Th_1 of the burst with 1 hop is 1.0, and the threshold Th_7 of the burst with 7 hops is 0.40. Also, in both Fig. 3.4(a) and Fig. 3.4(b), $J = 0.50$. The entire burst with 1 hop is discarded since $J < Th_1$ as shown in Fig. 3.4(a). In Fig. 3.4(b), since $J > Th_7$, the HD technique is applied to the burst with 7 hops.

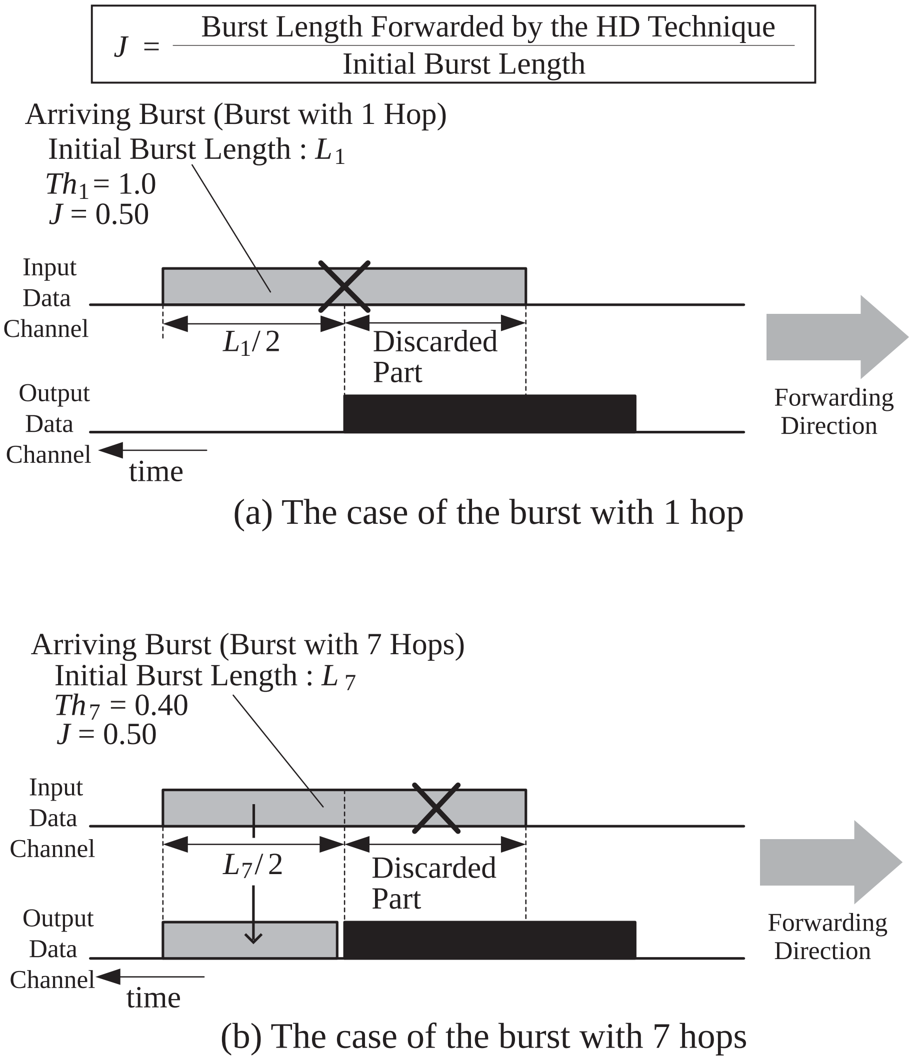


Figure 3.4: The proposed burst dropping scheme.

Therefore, the initial part of the burst with 7 hops is discarded, and the remaining part of the burst with 7 hops is forwarded to the next node along with OBS. the proposed scheme can reduce the difference of packet loss due to the number of hops by applying the HD technique in consideration of the number of hops. And, the proposed scheme can achieve the fair packet loss probability regardless of the number of hops by reducing the difference of packet loss probability.

The judgment for applying the HD technique is executed when a core node processes a control packet. A control packet includes the number of hops to a destination node and an initial burst length newly. Like OCBS, the core node confirms the existence or nonexistence of burst contention based on a burst length and an offset time. When burst contention occurs, the core node judges the application of the HD technique by using the number of hops and the initial burst length included in a control packet.

In the proposed scheme, it is important how to decide the threshold Th_i. It is desirable that the threshold decision method is independent of the number of hops, and the calculation is not complex. Here, as the threshold decision method, Exponential Threshold (ET) method and Linear Threshold (LT) method are proposed.

3.3.1 Exponential Threshold (ET) Method

Exponential Threshold (ET) method decides the threshold by using an exponent function. By the following formula, the threshold is decided according to the number of hops.

$$Th_i = a^i \tag{3.1}$$

In this formula, a is the base of the exponent function. By configuring only $a(0 \leq a \leq 1)$, the threshold can be calculated. Therefore, ET method is comparatively easy.

3.3.2 Linear Threshold (LT) Method

Linear Threshold (LT) method decides the threshold by using a linear function. By the following formula, the threshold is decided according to the number of hops.

$$Th_i = \frac{H_{\max} - Th_{\min} - (1 - Th_{\min})i}{H_{\max} - 1} \tag{3.2}$$

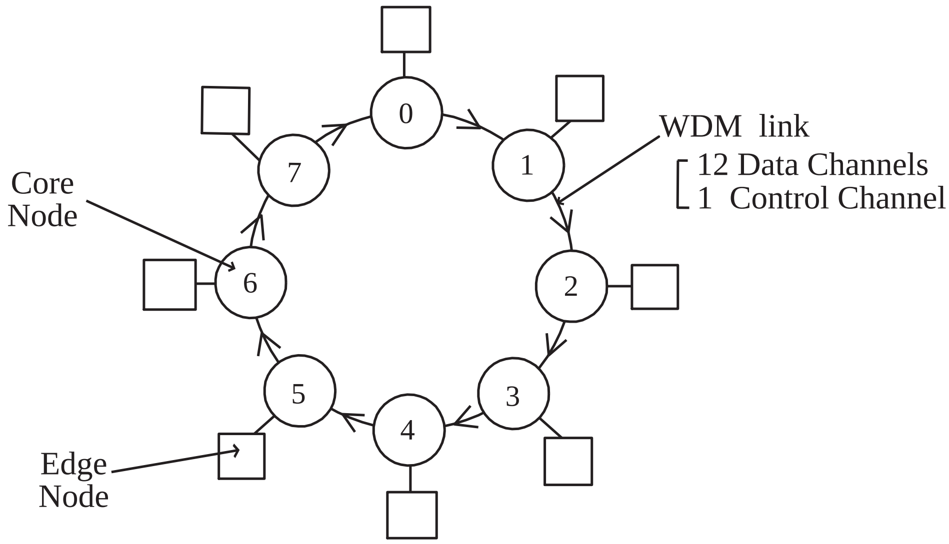


Figure 3.5: The simulation model.

In this formula, $Th_{\min}$ is the minimum value of the threshold. Since the proposed scheme configures the threshold of the burst with many hops as a smaller value, $Th_{\min}$ is equal to $Th_{H_{\max}}$. By configuring only $Th_{\min}$, the threshold can be calculated linearly. Therefore, LT method is comparatively easy like ET method.

3.4 Simulation Results

Computer simulations are carried out to evaluate the performance of the proposed scheme. Figure 3.5 shows the simulation model. To investigate the effect of the number of hops, a multiple hop network model with an 8-node ring topology [5] is considered. The number of core nodes is 8, and each core node connects one edge node. Each link is assumed to have 12 data channels and one control channel. Also, a burst is transmitted in one direction, and the maximal value of hops $H_{\max}$ is 7. The data channel rate is 10 Gbps. It is assumed that the contention of control packets doesn't occur. An offset time is set to 0 sec.

Each edge router generates the bursts according to an on/off model. And, the

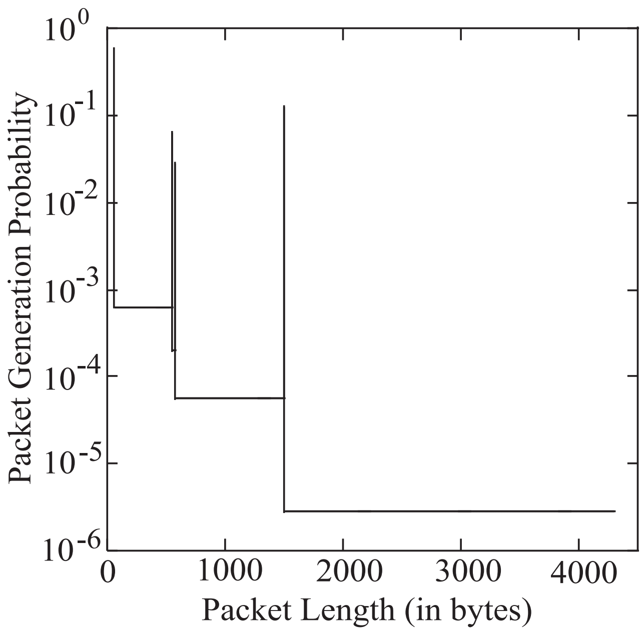


Figure 3.6: The probability distribution of packet length.

burst length L_{ave} is assumed to be exponentially distributed with the average of 12500 bytes [5]. By applying the HD technique, a part of a burst is discarded. Therefore, it is necessary to consider the composition of packets in a burst. In this simulation, the composition of packets is determined based on the packet distribution assuming the Internet. Figure 3.6 shows the probability distribution of packet length [6]. 44 Byte packet is corresponding to Internet Control Message Protocol (ICMP) Message. 552 Byte packet and 576 Byte packet are Maximum Segment Size (MSS). 1500 Byte packet is corresponding to Maximum Transfer Unit (MTU). When l_{p} is the packet length, $\Pr[l_{\mathrm{p}} = 44]$=0.5, $\Pr[l_{\mathrm{p}} = 552]$=0.05, $\Pr[l_{\mathrm{p}} = 576]$=0.03, $\Pr[l_{\mathrm{p}} = 1500]$=0.12, $\Pr[45 \leq l_{\mathrm{p}} \leq 551]$=0.25, $\Pr[553 \leq l_{\mathrm{p}} \leq 575]$=0.005, $\Pr[577 \leq l_{\mathrm{p}} \leq 1499]$=0.035, and $\Pr[1501 \leq l_{\mathrm{p}} \leq 4300]$=0.01.

In the simulation, the packet loss probability and throughput performance of the proposed scheme are compared with those of OCBS. It is important how to decide the threshold of the proposed scheme. So, to investigate the effect of the threshold,

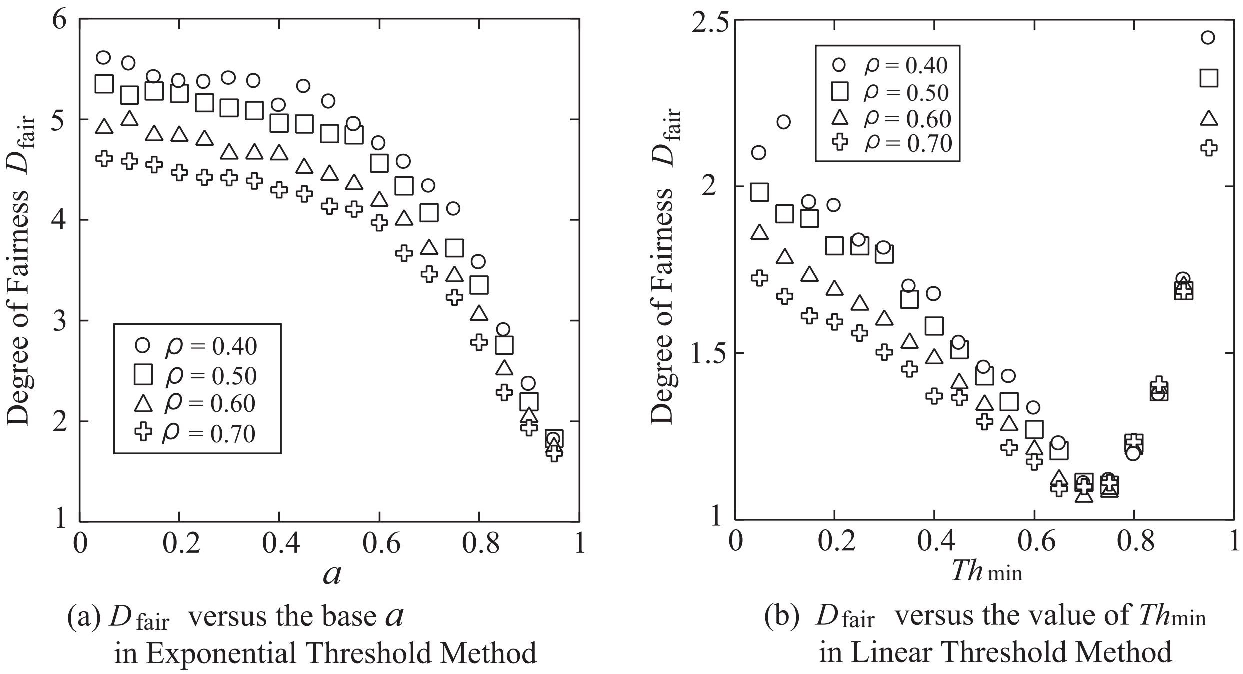


Figure 3.7: The degree of fairness about the number of hops for the packet loss probability D_{fair} versus the parameter in ET method and LT method.

this simulation evaluates the performance for the number of hops, the performance under non-uniform traffic, the performance for the distribution of burst traffic, and the performance for a deformational ring topology.

3.4.1 Fairness about Number of Hops for Packet Loss Probability

Figure 3.7 shows the degree of fairness about the number of hops for the packet loss probability D_{fair} versus the parameter in ET method and LT method. Figure 3.7(a) shows the degree of fairness D_{fair} versus the base a in the formula (3.1), and Figure 3.7(b) shows the degree of fairness D_{fair} versus the value of $Th_{\min}$ in the formula (3.2).

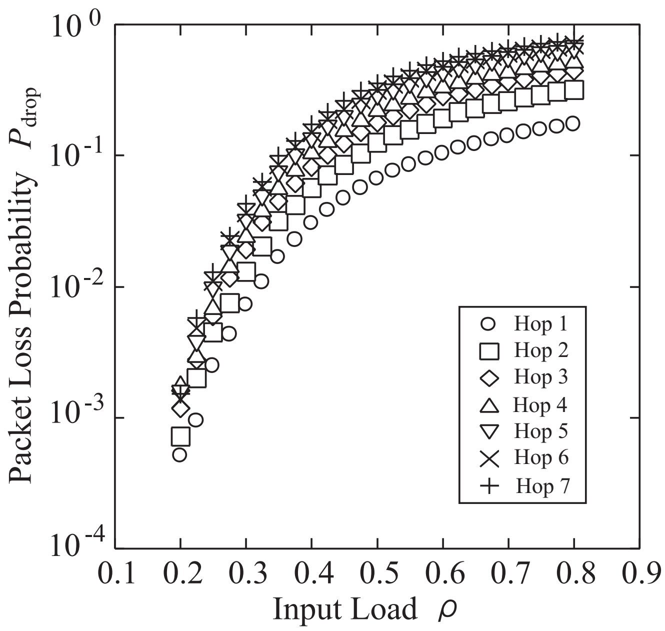


Figure 3.8: The packet loss probability P_{drop} versus input load ρ by the number of hops in OCBS.

This degree of fairness D_{fair} is calculated by the following formula,

$$D_{\mathrm{fair}} = \frac{P_{\max}}{P_{\min}} \tag{3.3}$$

In this formula, P indicates the packet loss probability. And, P_i indicates the packet loss probability of bursts with i hops. $P_{\max}$ is the max value from P_1 to $P_{H_{\max}}$. $P_{\min}$ is the minimum value from P_1 to $P_{H_{\max}}$.

From Fig. 3.7(a), it is shown that D_{fair} is near to 1 when the value of a is large. This is because, when the value of a is small, the difference for the number of hops is also small. From Fig. 3.7(b), it is found that, when the value of $Th_{\min}$ is about 0.7, D_{fair} is high. It is because, when the value of $Th_{\min}$ is small, the difference of the thresholds is large, and the packet loss of the burst with small hops increases. On the other hand, when the value of $Th_{\min}$ is large, the difference for the number of hops is also small. From Fig. 3.7, $a = 0.95$ in ET method and $Th_{\min} = 0.70$ are

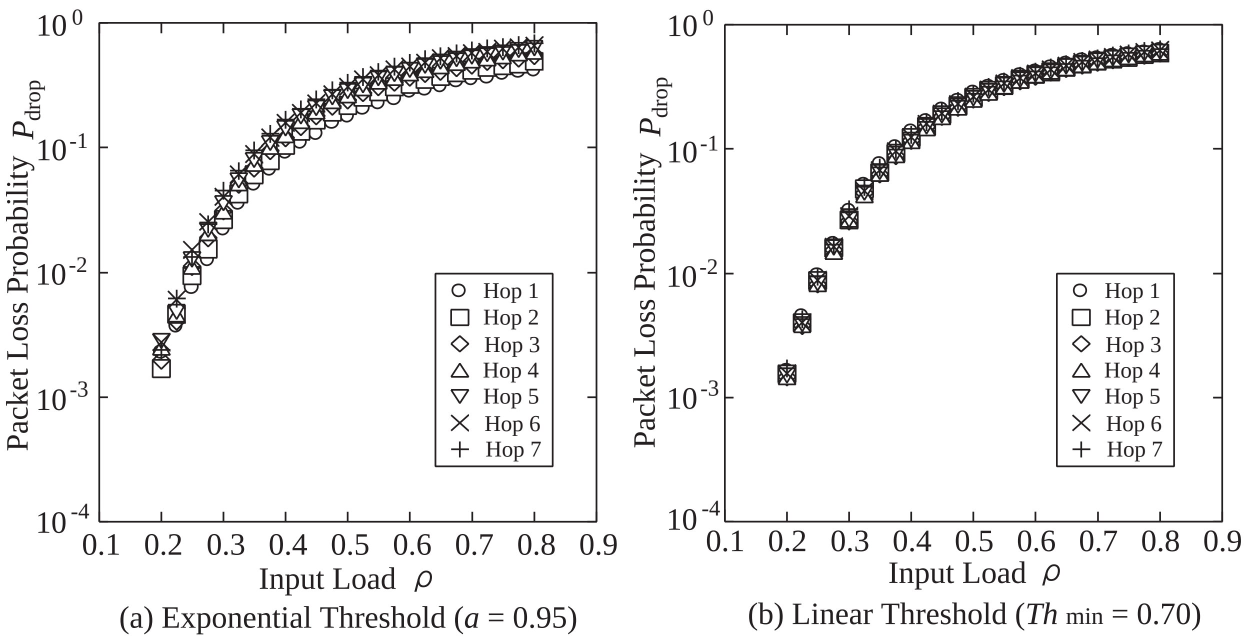


Figure 3.9: The packet loss probability P_{drop} versus input load ρ by the number of hops in the proposed scheme.

used from the next evaluation.

Figure 3.8 and Figure 3.9 shows the packet loss probability of OCBS and the proposed scheme by the number of hops versus input load, respectively. From Fig. 3.8 and Fig. 3.9, it is shown that the proposed scheme reduces the difference of the packet loss probability by the number of hops compared with OCBS. This is because the proposed scheme increases the probability that the burst with many hops is reserved at the output channel by configuring the threshold for determining whether the HD technique is applied or not. Thus, the proposed scheme achieves the fair packet loss probability regardless of the number of hops compared with OCBS.

Figure 3.10 shows the degree of fairness about the number of hops for the packet loss probability D_{fair} versus input load ρ. D_{fair} of The proposed scheme is nearer to 1 than OCBS, and it indicates that the proposed scheme achieves the fair packet loss probability regardless of the number of hops compared with OCBS. Also, it is

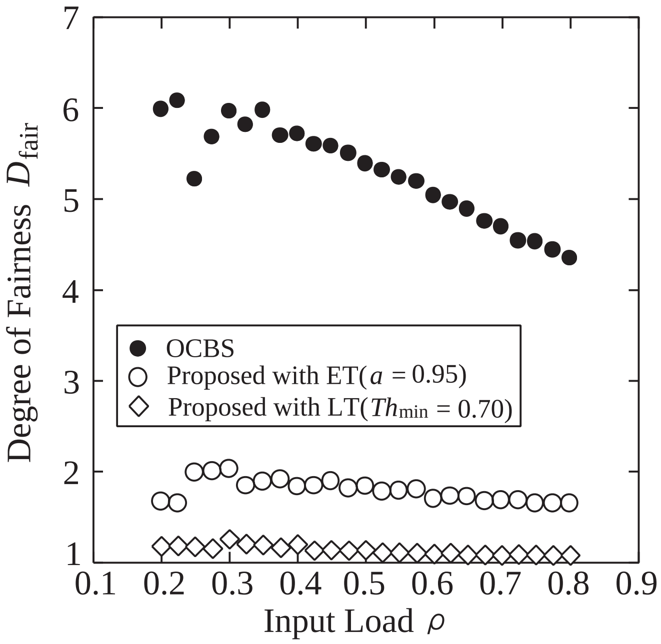


Figure 3.10: The degree of fairness about the number of hops for the packet loss probability D_{fair} versus input load ρ.

found that LT method has better performance than ET method.

3.4.2 Throughput Performance

Figure 3.11 shows the throughput performance versus input load ρ. The throughput is defined as an effective data rate normalized by the transmission rate. In Fig. 3.11, throughput performance of the proposed scheme is compared with those of OCBS and OBS. Based on the result of Fig. 3.10, LT method is evaluated as the proposed scheme. From Fig. 3.11, it is shown that the proposed scheme improves the throughput performance compared with OBS, and the proposed scheme does not degrade the performance compared with OCBS. This is because in the proposed scheme, with hardly the increase of the total number of discarded packets, the number of allocating the burst with many hops increases instead of decreasing

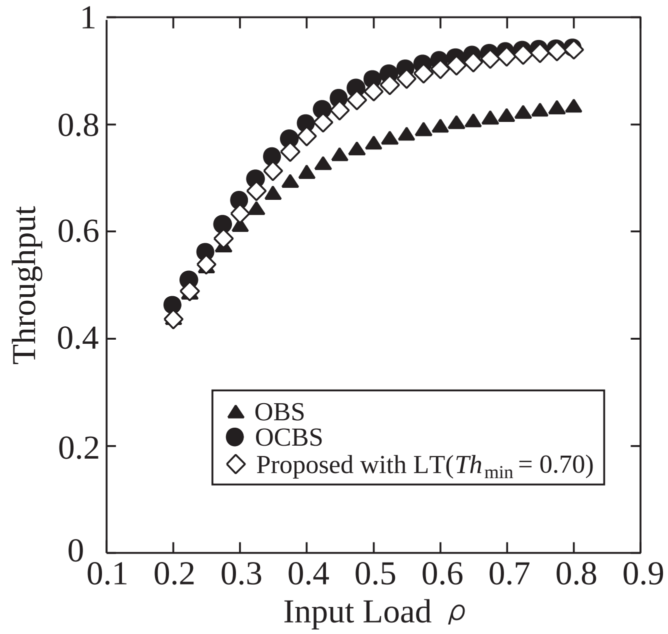


Figure 3.11: The throughput performance versus input load ρ.

the number of allocating the burst with small hops by configuring the threshold for determining whether the HD technique is applied or not. From Fig. 3.11, it is found that the proposed scheme can achieve the fair packet loss probability regardless of the number of hops compared with OCBS, and the proposed scheme hardly degrades the throughput performance compared with OCBS.

3.4.3 Performance for Number of Core Nodes

Figure 3.12 shows the degree of fairness about the number of hops for the packet loss probability D_{fair} versus the number of core nodes. From Fig. 3.12, it is found that, in OCBS, the value of D_{fair} gets small as the number of core nodes increases. This reason is explained blow. When the number of core nodes increases, the traffic flow increases in the network. The overall packet loss probability becomes high since the number of data channels is steady regardless of the number of core nodes in this

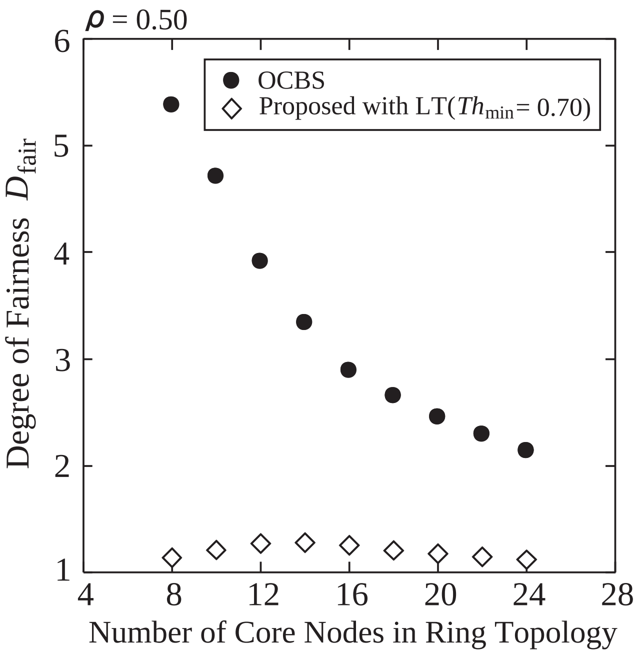


Figure 3.12: The degree of fairness about the number of hops for the packet loss probability D_{fair} versus the number of core nodes.

evaluation. So, the packet loss probability of a burst with small hops is high, and the difference between a burst with small hops and a burst with large hops. On the other hand, the value of D_{fair} in the proposed scheme is near to 1 regardless of the number of core nodes. This result shows that the proposed scheme can achieve the fairness about the number of hops for the packet loss probability in case of about 30 nodes ring topology.

3.4.4 Performance under Non-uniform Traffic

Figure 3.13 shows the packet loss probability versus the number of hops in case the values of input load are different according to the number of hops. ρ_n indicates the input load of a burst with n hops. Figure 3.13 shows two cases. One case is that more bursts with small hops exist than bursts with large ($\rho_1 = 0.80, \rho_2 = \rho_3 = \rho_4 =$

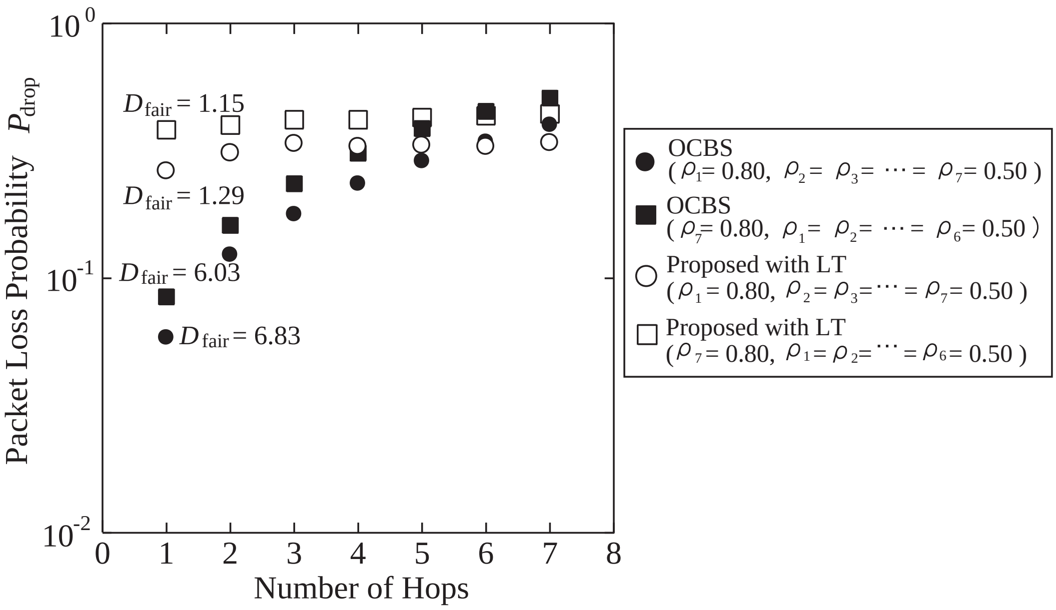


Figure 3.13: The packet loss probability P_{drop} versus the number of hops in case the values of input load are different according to the number of hops.

$\rho_5 = \rho_6 = \rho_7 = 0.50$). Another case is, conversely, that more bursts with large hops exist than those with small hops ($\rho_7 = 0.80, \rho_1 = \rho_2 = \rho_3 = \rho_4 = \rho_5 = \rho_6 = 0.50$). From Fig. 3.13, it founds that, in both cases, the proposed scheme can reduce the difference for the number of hops. Therefore, regardless of the bias of traffic, the proposed scheme is effective.

3.4.5 Performance for Distribution of Burst Length

The proposed scheme is effective in case that the HD technique can be used; two more bursts overlap in time domain. The length of this overlap depends on the length of each burst. Therefore, the effectiveness of the proposed scheme varies with the burst length distribution. Here, for the packet loss probability, the geometrical distribution is compared with the normal distribution. Figure 3.14 shows the packet loss probability versus the number of hops according to the distribution of

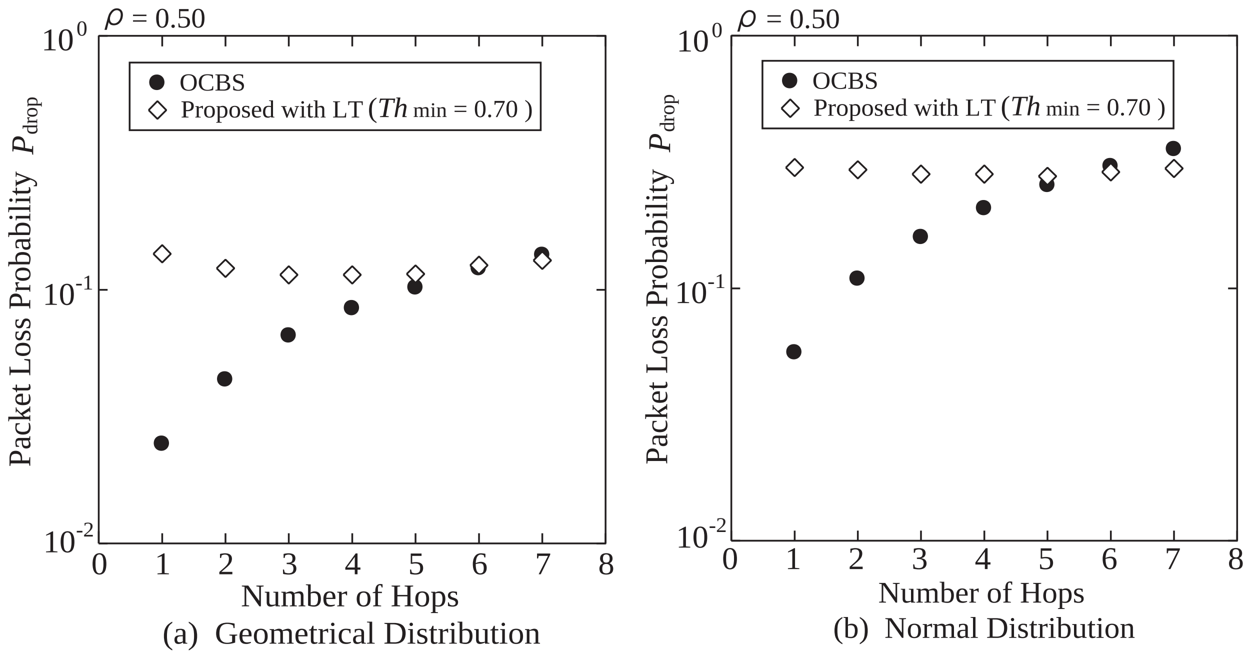


Figure 3.14: The packet loss probability P_{drop} versus the number of hops according to the distribution of the burst length.

the burst length. The deviation of the normal distribution is 1. From Fig. 3.14(a), it is shown that the proposed scheme increase the packet loss probability of bursts with small hops and achieve the fairness for the number of hops. In the geometrical distribution, short bursts are generated. The probability of applying the HD technique to bursts with large hops is low. On the other hand, from Fig. 3.14 (b), it is shown that the proposed scheme achieve the fairness not only by increasing the packet loss probability of bursts with large hops. In the normal distribution, many short bursts and many long bursts are not generated. The probability of applying the HD technique is high compared with the probability in the geometrical distribution. From Fig. 3.14, the effectiveness of the proposed scheme varies with the distribution of the burst length. And, in the distribution of the burst length like the normal distribution, the proposed scheme is effective.

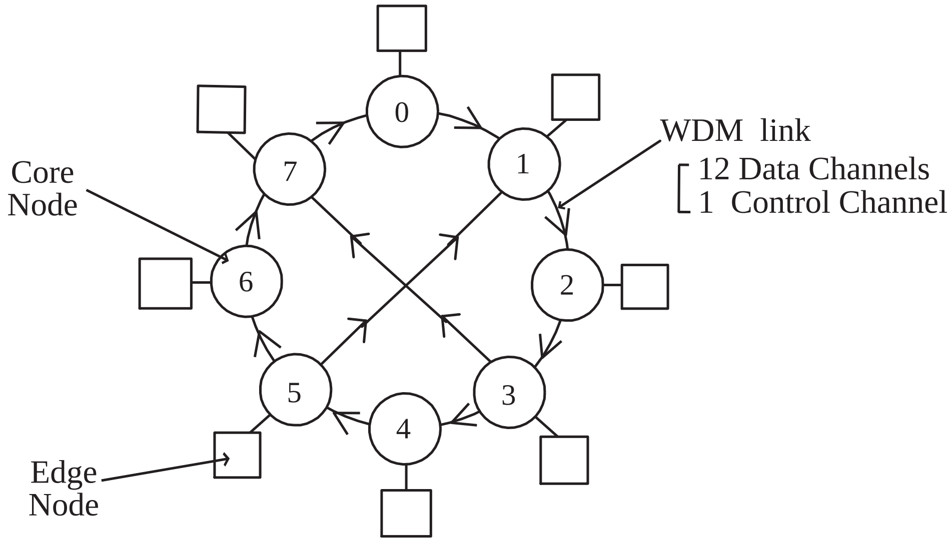


Figure 3.15: 8-node deformational ring topology.

3.4.6 Performance for Deformational Ring Topology

The performance of the proposed scheme is evaluated in the 8-node deformational ring topology shown in Fig. 3.15. The link from node 3 to node 7 and the link from node 5 to node 1 are added in the 8-node ring topology shown in Fig. 3.5. Figure 3.16 shows the degree of fairness about the number of hops for the packet loss probability versus the value of $Th_{\min}$ in the proposed scheme with LT. In a deformational ring topology, when $Th_{\min}$ is near to 1, the value of D_{fair} is large. When $Th_{\min}$ is near to 0, D_{fair} is near to 1. The performance shown in Fig. 3.16 is different from that of Fig. 3.7. This is because the balance of traffic changes and, in this topology, the difference of the packet loss probability for the number of hops.

Figure 3.17 shows the packet loss probability versus the number of hops. ρ is set to 0.50. $Th_{\min}$ is set to 0.20 based on the result shown in Fig. 3.16. It is shown that the proposed scheme reduces the difference of the packet loss probability by the number of hops compared with OCBS. This is because the proposed scheme increases the probability that the burst with many hops is reserved at the output

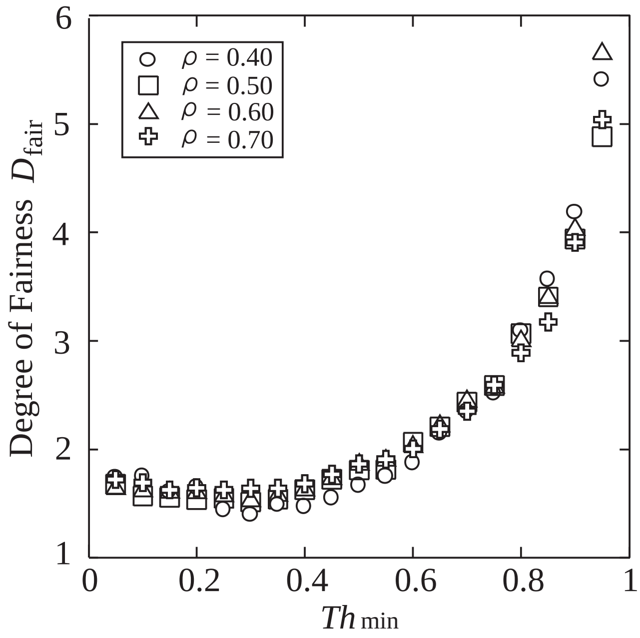


Figure 3.16: The degree of fairness about the number of hops for the packet loss probability D_{fair} versus the value of Th_{min} in the proposed scheme with LT.

channel by configuring the threshold for determining whether the HD technique is applied or not. Thus, the proposed scheme achieves the fair packet loss probability regardless of the number of hops compared with OCBS.

From Fig. 3.16 and Fig. 3.17, the proposed scheme can improve the packet loss probability in a deformational ring topology as well as a ring topology. Also, it found that the effective value of the threshold varies with network configuration. Therefore, not only the number of hops but also network topology is important in configuring the threshold in the proposed scheme.

3.5 Conclusion

The fair burst dropping scheme technique has been proposed in order to achieve the fair packet loss probability regardless of the number of hops in OCBS. The pro-

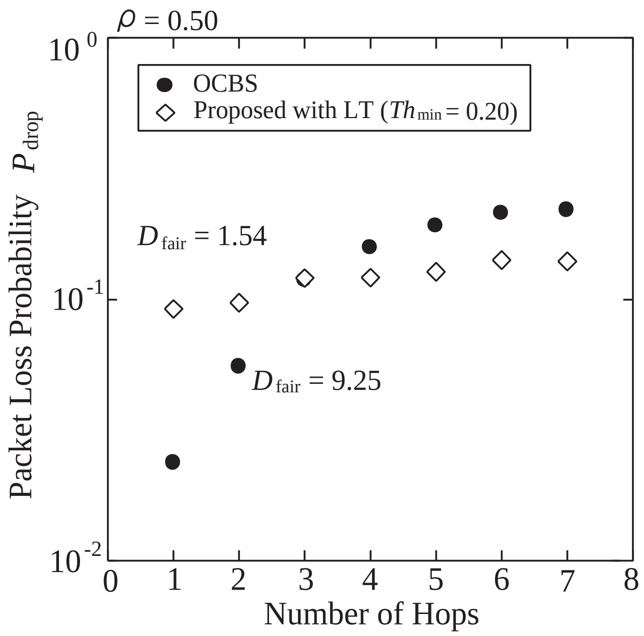


Figure 3.17: The packet loss probability P_{drop} versus the number of hops.

posed scheme adjusts the threshold for determining whether the HD technique is applied or not. The proposed scheme can reduce the difference of packet loss due to the number of hops by applying the HD technique in consideration of the number of hops. By computer simulation, it was shown that the proposed scheme can achieve the fair packet loss probability regardless of the number of hops to the destination edge node compared with a conventional one.

From simulation results, it is said that the proposed scheme is effective in a ring topology under uniform traffic. Under non-uniform traffic and a deformational ring topology, the proposed scheme is effective. However, this simulation evaluates performances in only limited conditions. So, more evaluations are needed to study the effectiveness for non-uniform traffic and a general topology.

The proposed scheme achieves the fairness by heightening the packet loss probability of a burst with small hops and lowering the packet loss probability of a burst with large hops. In the results of computer simulations, it is found that the proposed scheme cannot lower the packet loss probability of a burst with large hops very much. It is a future issue of the proposed scheme.

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Chapter 4

A Self-learning Route Selection Scheme Using Multi-Path Searching Packets in OBS Network

4.1 Introduction

In this chapter, we propose the scheme that reduces the probability of burst contention by controlling the transmission of bursts at an edge node without resolving burst contention at a core node. An edge node can control a burst length, an offset time, a route, the wavelength used in the transmission, and the transmission rate. In the proposed scheme, each edge node controls the route to the destination edge node. In a conventional OBS network, a burst is forwarded on the shortest path route. A deterministic routing using a shortest path route is easy to apply in term of costs. In particular, considering the operation costs at the link failure, a deterministic routing is useful. However, in a deterministic routing, the traffic load is concentrated on a certain link, and it causes burst contention. In the proposed scheme, each edge node learns a suitable route to the destination edge node autonomously by using newly employed feedback packets and search packets. Due to the self-learning at each edge node, the traffic load is distributed in an OBS network. Therefore, the proposed scheme can reduce the probability of burst contention. According to computer simulations, under nonuniform traffic, the proposed scheme can reduce approximately one decade smaller burst loss probability compared with the conventional shortest path routing method.

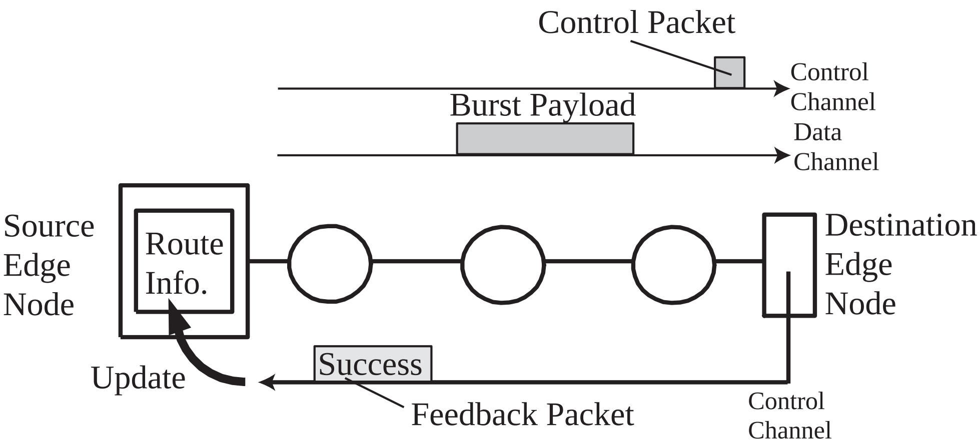
4.2 Proposed Self-learning Route Selection Scheme

The proposed scheme introduces the transmission of feedback packets and some search packets. By using feedback packets and search packets, each edge node learns a suitable route to the destination edge node autonomously.

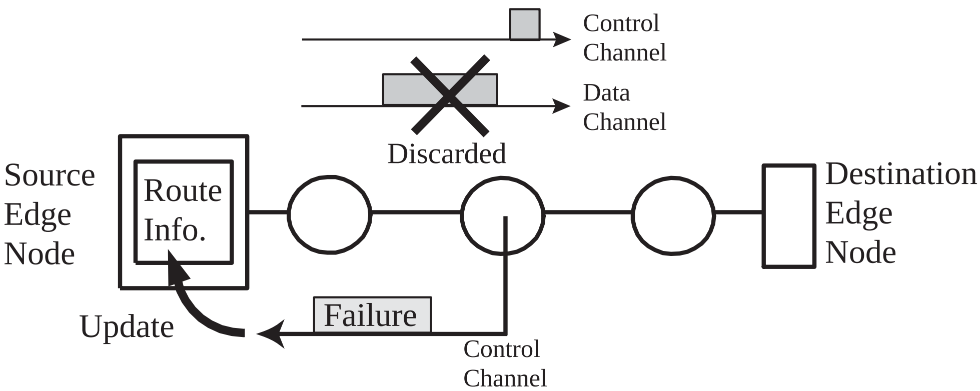
4.2.1 Self-learning method

Each edge node keeps the information of all routes to each destination edge node by using the link-state routing protocol such as the open shortest path first (OSPF) protocol. The priority is set for each route. The source edge node receives a feedback packet after sending a burst. Figure 4.1 shows the reception of a feedback packet. When a burst was forwarded successfully, the destination edge node sends back the feedback packet that indicates the success of the transmission as shown in Fig. 4.1(a). When a burst was discarded at an immediate core node, the core node sends back the feedback packet that indicates the failure of the transmission as shown in Fig. 4.1(b). Note that, core nodes can detect burst contention with control packets. In other words, an optical domain transfers optical burst signals without any sophisticated function. Details are describes here after. Feedback packets are forwarded on the control channel as well as control packets.

Each ingress edge node receives feedback packets and updates the priority of the route based with the information of feedback packets. And, next time, an edge node sends a burst on the route that has the highest priority of all the routes. The update of the priority is as follows. Each route has two values P, and N_{f}. P is the priority



(a) The success of the transmission



(b) The failure of the transmission

Figure 4.1: The reception of a feedback packet.

($0 \leq P \leq 1$), and N_{f} is the number of received feedback packets. The default value of P is 1, the default value of N_{f} is also 1. On receiving feedback packets, edge nodes update P and N_{f} by using calculating formula [1] written below,

- When the feedback packet indicates the success of the transmission,

$$P = \frac{P \times N_{\mathrm{f}} + 1}{N_{\mathrm{f}} + 1}, \quad N_{\mathrm{f}} = N_{\mathrm{f}} + 1 \tag{4.1}$$

- When the feedback packet indicates the failure of the transmission,

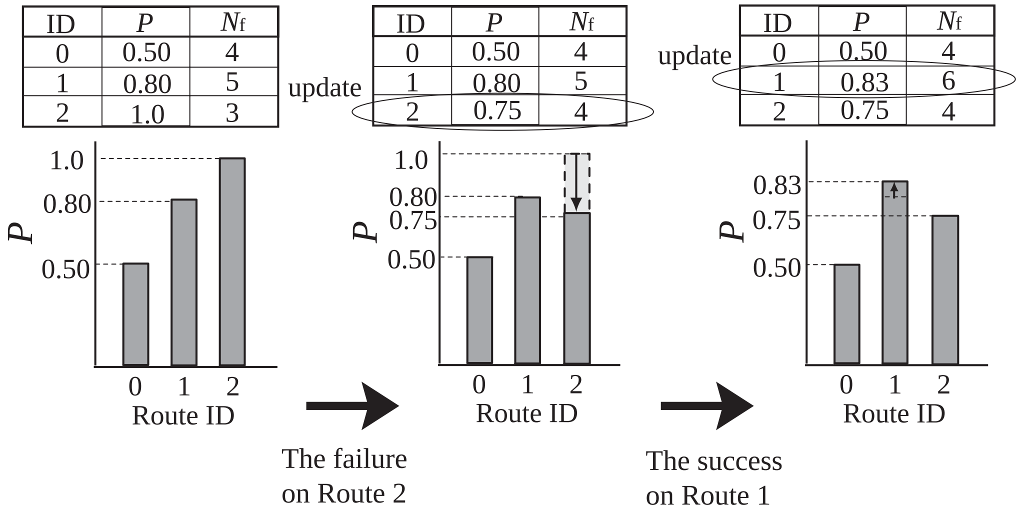


Figure 4.2: An example of updating the priority.

$$P = \frac{P \times N_{\mathrm{f}}}{N_{\mathrm{f}} + 1}, \quad N_{\mathrm{f}} = N_{\mathrm{f}} + 1 \tag{4.2}$$

Figure 4.2 shows an example of updating the priority. In Fig. 4.2, at first, the source edge node receives the feedback packet that indicates the failure of the transmission on the route 2. P and N_{f} on the route 2 are updated as below,

$$P = \frac{1.0 \times 3}{3 + 1} = 0.75, \quad N_{\mathrm{f}} = 3 + 1 = 4 \tag{4.3}$$

In Fig. 4.2, second, the source edge node receives the feedback packet that indicates the success of the transmission on the route 1. P and N_{f} on the route 1 are updated as below,

$$P = \frac{0.80 \times 5}{5 + 1} \doteqdot 0.83, \quad N_{\mathrm{f}} = 5 + 1 = 6 \tag{4.4}$$

When the priority P is close to 1, the route has a high probability of the success. When the priority P is close to 0, the route has a high probability of the failure.

4.2.2 Transmission of a search packet

In the proposed scheme, in order to improve the performance of the self-learning, the source edge node sends not only a burst but also some search packets on the control channel. Search packets are forwarded on several routes except the route used for the transmission of a burst. In the proposed scheme, the number of search packets N_s is set. An edge node selects $N_s + 1$ routes in descending order of the priority, transmits a burst on the route that has the highest priority, and transmits search packets on the remaining N_s routes. When N_s is larger than the total number of the routes, an edge node transmits a burst on the route that has the high priority, and transmits search packets on all the other routes. Figure 4.3 shows an example of transmitting search packets.

Figure 4.3 shows the case that the source edge node E0 sends a burst to the destination edge node E1. In Fig. 4.3, the number of search packets N_s is set to 2. In the case of $N_s = 2$, the source edge node sends search packets on the route that has the second highest priority and on the route that has the third highest priority. A search packet includes the burst length, offset time, and data channel of the burst forwarded. A search packet is forwarded on a control channel, and is processed electrically at core nodes as well as a control packet. Also, the burst is not forwarded on the route where a search packet is forwarded. On receiving a search packet, a core node judges whether, when the burst arrives at the core node, burst contention occurs, or not. When burst contention doesn't occur, the core node forwards the search packet to the next node. When burst contention occurs, the core node sends back the feedback packet that indicates the failure of the transmission. On receiving a search packet, the destination edge node sends back the feedback packet that indicates the success of the transmission.

By sending search packets, an edge node searches whether the transmission of a

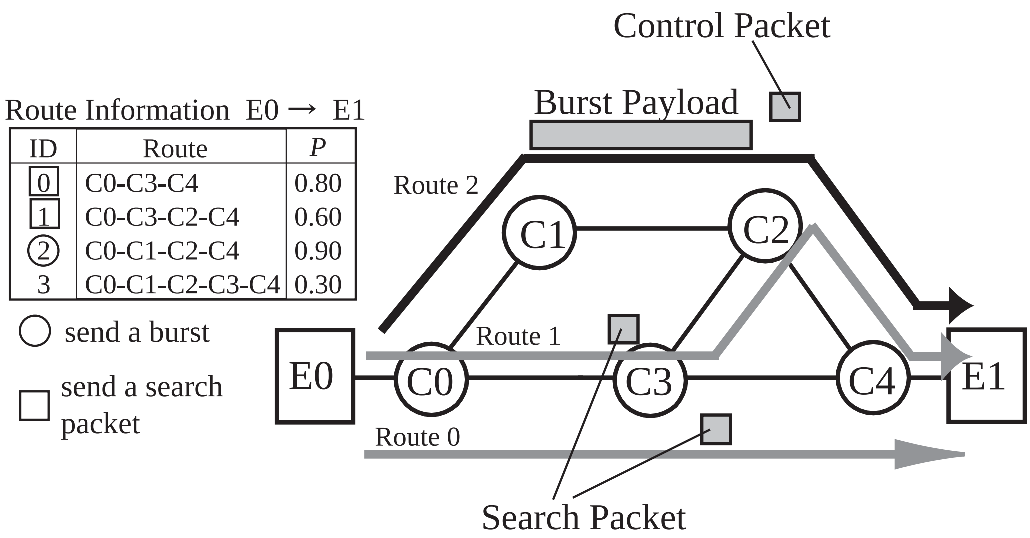


Figure 4.3: An example of transmitting search packets (N_s=2).

burst is succeeded or failed on the route except the route used for the transmission of the burst. The transmission of search packets enable an edge node to learn a suitable route without sending a burst payload, and discarded burst number can be reduced in the process of the self-learning. Also, the transmission of search packets enables an edge node to receive feedback packets for several routes at the transmission of one burst. Therefore, an edge node can respond to the change of the traffic immediately. The transmission of search packets improves the performance of the self-learning. In the proposed scheme, each edge node learns a suitable route by using feedback packets and search packets. The traffic load is distributed due to the self-learning at each edge node. Therefore, the proposed scheme reduces the probability of burst contention.

4.3 Simulation Results

4.3.1 Simulation Model

Computer simulations are carried out to evaluate the performance of the proposed scheme. We compare the proposed scheme with the conventional scheme where a burst is forwarded on the shortest path route. We consider a mesh network as shown in Fig. 4.4. The number of core nodes is 6, and each core node connects one edge node. There is no wavelength converter and optical buffer in all core nodes. In Fig. 4.4, there is 30 combinations of source edge node and destination edge node, 20 combinations have 4 routes, 8 combinations have 5 routes, and 2 combinations have 8 routes. The distance between two successive nodes is taken to be 10 km. Each link is assumed to have W-wavelengths data channel and one-wavelength control channel. We assume that each wavelength runs at 10 Gbps. Each edge node generates the bursts according to an on/off model. The burst length is assumed to be exponentially distributed with the average of 12500 bytes [2]. We assume the nonuniform traffic where the traffic load is different in each combination of source edge node and destination edge node.

In our simulation, we set the offered load for each combination of source edge node and destination edge node. ρ is defined as the offered load of the traffic from edge node E0 to edge node E3, and the traffic from edge node E1 to edge node E4. And, ρ/α is defined as the offered load of the other traffic($\alpha \geq 1.0$), which emulates traffic unbalance or hot-spot in the network. Therefore, when a burst is forwarded on the shortest path route, the traffic load is concentrated on link C1$\rightarrow$C2. With increasing the value of α, the load of link C1$\rightarrow$C2 is larger than that of the other links. In this paper, α is called the traffic bias.

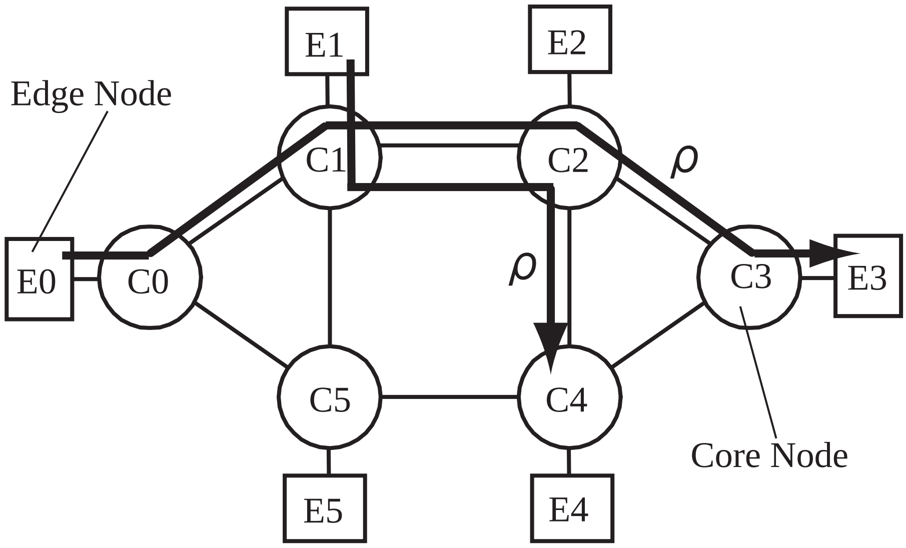


Figure 4.4: The simulation network model.

4.3.2 Simulation Results

Figure 4.5 shows the burst loss probability versus the number of search packets N_s in the proposed scheme. This was done at the number of wavelength $W = 32$, the offered load of $\rho = 0.50$, and the traffic bias of $\alpha = 20, 40$. It shows that the proposed scheme with search packets offers lower burst loss probability than that without search packets. This is because the transmission of search packets enables edge nodes to get more information and to reduce the number of discarded bursts in the process of the self-learning. However, it also shows that increasing search packets doesn't improve the burst loss probability. This reason is as follows. When the route with many hops is used, a burst is more likely to be discarded at an intermediate core node. Therefore, each edge node doesn't need the routes with many hops, and have only to search the routes with a few hops. From Fig. 4.5, it is clear that, in the network shown in Fig. 4.4, it is enough by $N_s = 2$.

Figure 4.6 shows the burst loss probability versus the offered load ρ. This is done at the number of wavelength $W = 32$, and the traffic bias α of 20. N_s is denoted as

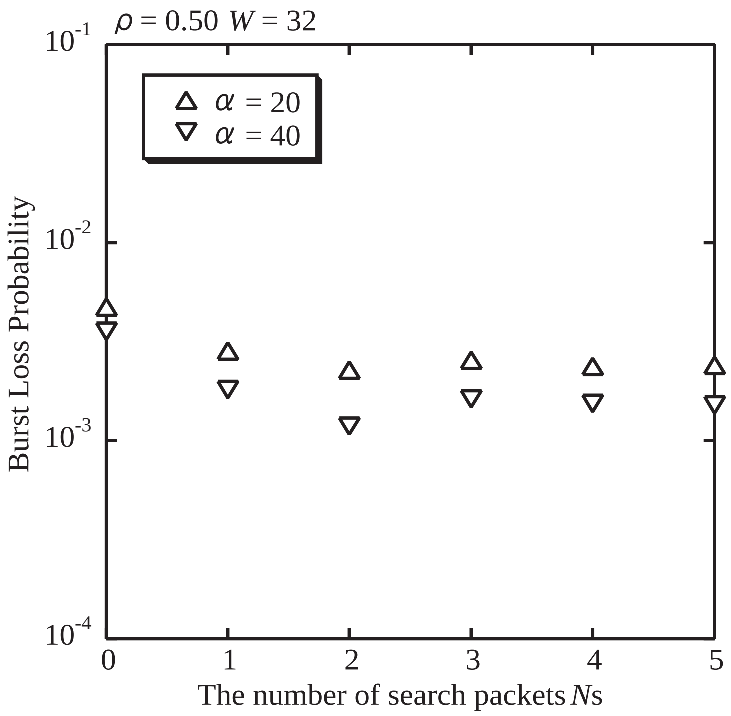


Figure 4.5: The burst loss probability versus the number of search packets N_s.

the number of search packets in the proposed scheme. It shows that the proposed scheme offers lower burst loss probability than the conventional scheme. This is because in the proposed scheme, due to the self-learning at each edge node, the traffic is not concentrated on link C1→C2. Also, the proposed scheme with $N_s = 2$ offers lower burst loss probability than that with $N_s = 0$, where N_s is the number of search packets. This is because the transmission of search packets enables edge nodes to get more information and to reduce the number of discarded bursts in the process of the self-learning. From Fig. 4.6, it is clear that the proposed scheme improves that burst loss probability due to the self-learning at each edge node, the transmission of search packets improves the performance of the learning.

Figure 4.7 shows the improvement rate I of the burst loss probability versus the traffic bias α. The improvement rate I is defined as,

$$I = \frac{B_{\text{conventional}}}{B_{\text{proposed}}}, \tag{4.5}$$

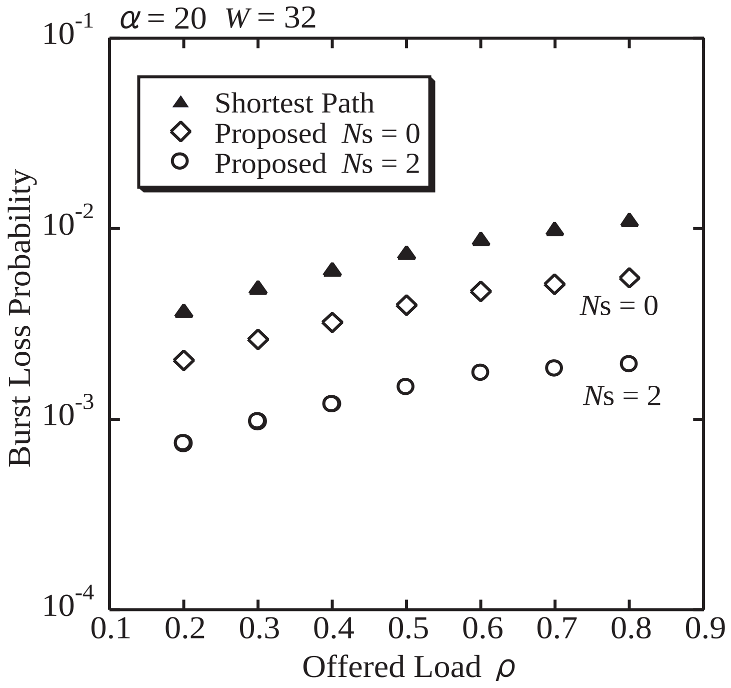


Figure 4.6: The burst loss probability versus the offered load ρ.

where $B_{\text{conventional}}$ is the burst loss probability of the conventional scheme, and B_{proposed} is the burst loss probability of the proposed scheme. This was done at the number of wavelength $W = 32$, and the offered load $\rho = 0.40$. In the proposed scheme, the number of search packets N_{s} is set to 2. When the value of α is large, the improvement rate I is high. This reason is as follows. In the conventional scheme, the load of link C1→C2 is larger with α increasing, and the number of bursts discarded on link C1→C2 is increased. On the other hand, in the proposed scheme, the traffic load is distributed, and the loss of many bursts on link C1→C2 can be avoided. From Fig. 4.6, it is clear that the proposed scheme improves the burst loss probability under the nonuniform traffic where the traffic load is different in each combination of source edge node and destination edge node.

Figure 4.8 shows the hop distribution. This was done at the number of wavelength $W = 32$, the offered load of $\rho = 0.40$, the traffic bias of $\alpha = 20$, and the number of search packets N_{s} of 2. We see that, in the proposed scheme, the probability of the

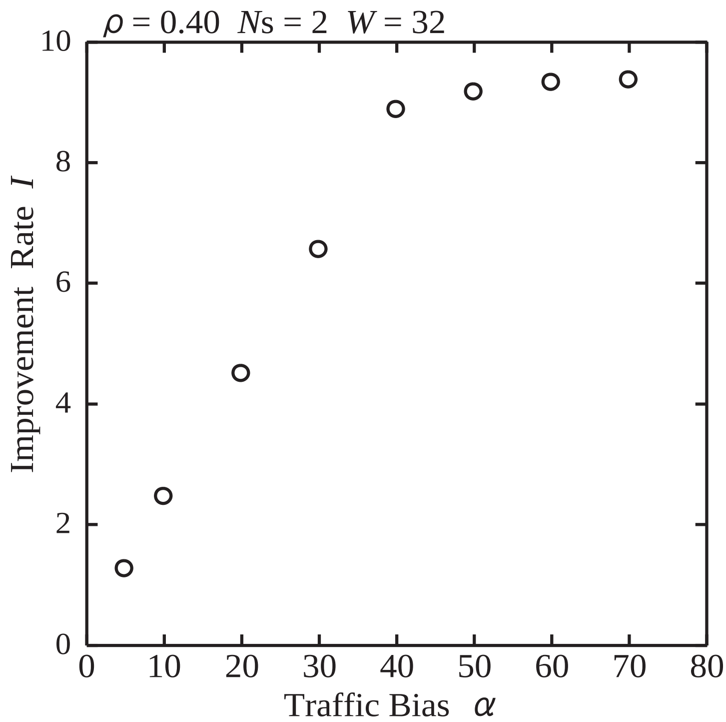


Figure 4.7: The improvement rate I versus the traffic bias α.

lower number of hops is reduced and that of the higher number of hops is increased. This reason is that, in the proposed scheme, each edge node learns a suitable route, and selects the route except the shortest path route for the transmission of a burst. From Fig. 4.8, we see, in the proposed scheme, each edge node changes the route based with the result of learning, and the probability of burst contention is reduced. However, increasing of the number of hops need more network resource. So it causes negative impact on the network load. Both route selection and the number of hops determine the burst loss probability.

Figure 4.9 shows the number of changing a route at intervals of 0.01 μ seconds. From Fig. 4.9, it is shown that the number of changing a route is large at the start of the learning, the number of changing a route is few after about 1.0 μ sec. Therefore, each edge node can determine only one suitable route by the proposed scheme. However, after time passed, the number of changing a route doesn't become zero

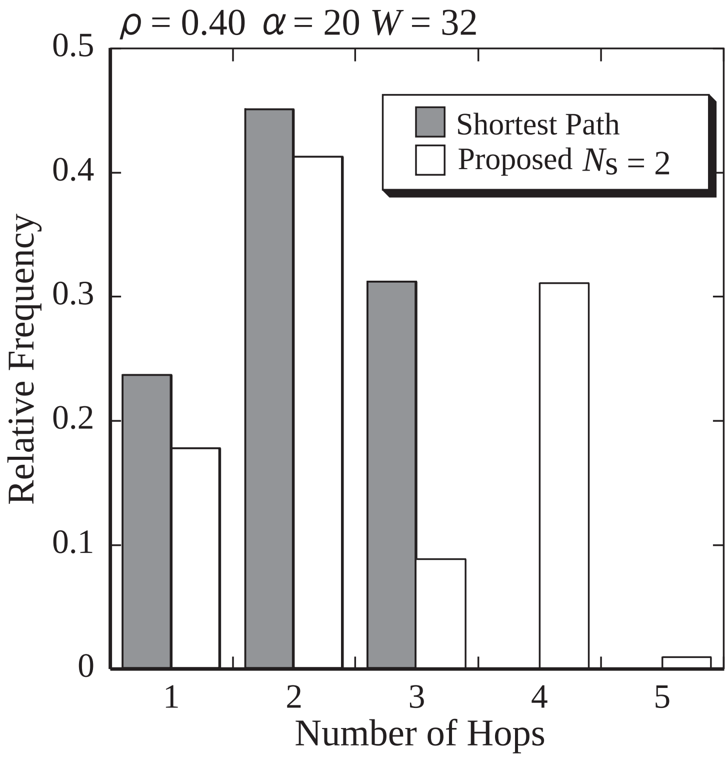


Figure 4.8: The hop distribution.

perfectly. This result shows that some combinations of source edge node and destination edge node can't determine only one route and uses a few routes. Therefore, for a perfect stability, some damping mechanism is needed.

Figure 4.10 shows the burst loss probability versus the number fo wavelengths W. This was done at the offered load of $\rho = 0.40$, and the traffic bias of $\alpha = 20$. In the proposed scheme, the number of search packets N_s is set to 2. It shows that, regardless of the value of W, the proposed scheme offers lower burst loss probability than the conventional one. This reason is as follows. As the value of W increases, the number of bursts transmitted in one link increases. So, as the value of W increases, the probability of burst contention decreases. However, in the conventional scheme, regardless of the value of W, the traffic load is concentrated on link C1→C2, and a lot of bursts are discarded on link C1→C2. On the other hand, in the proposed scheme, the traffic load is distributed, the traffic load is not concentrated on link C1→C2.

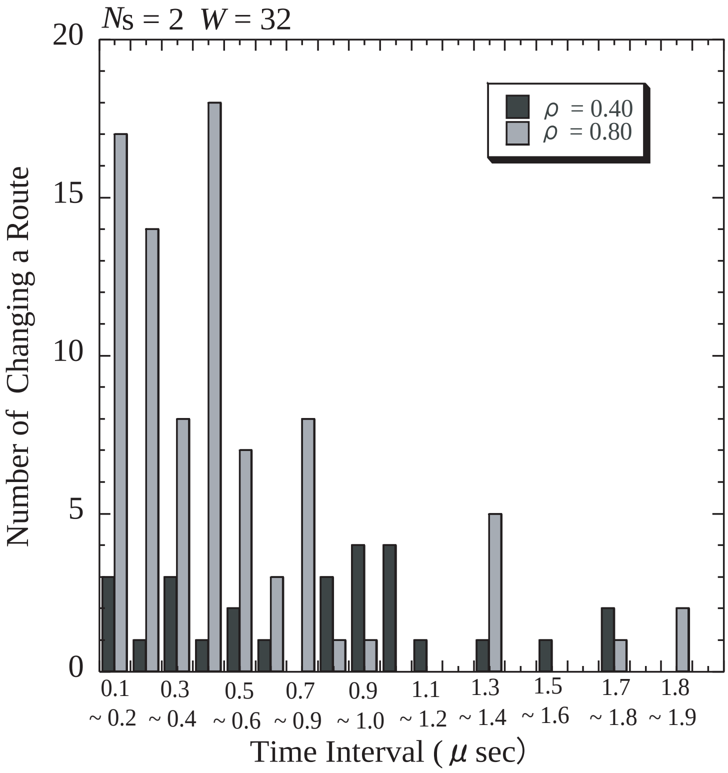


Figure 4.9: The number of changing a route.

From Fig. 4.10, it is clear that the proposed scheme is effective regardless of the number of wavelengths, and the proposed scheme can achieve a desired performance about the burst loss probability with the smaller number of wavelengths than the conventional scheme.

4.3.3 Study on Network Topologies

In this section, we evaluate the performance of the proposed scheme on the 8-node dual-ring network and on the 16-node NSFNET network shown in Fig. 4.11. In both topologies, there is no wavelength converter and optical buffer in all core nodes. Also, each core node connects one edge node shown as Fig. 4.4. The numbers on the links represent link distances in units of 1 km.

In Fig. 4.11(a), ρ is defined as the offered load of the traffic from edge node E0

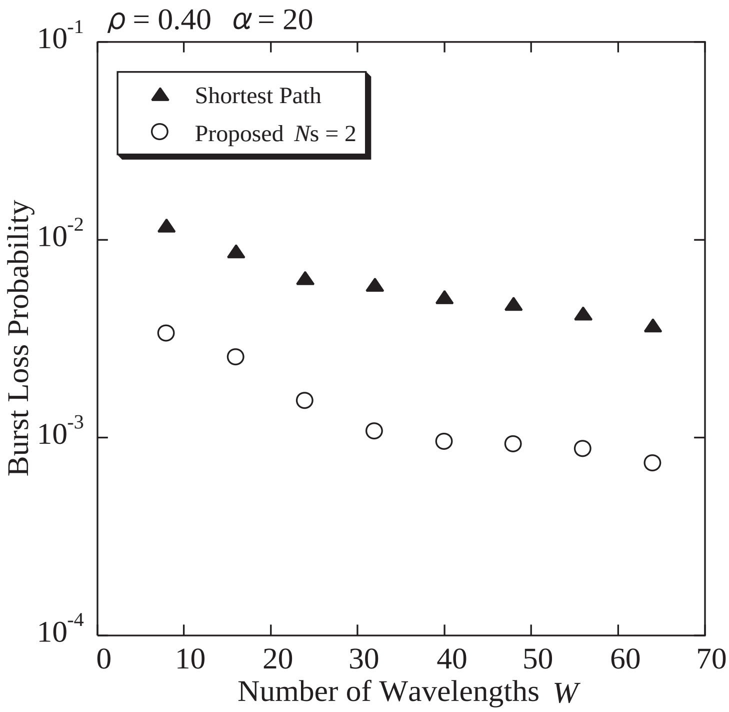
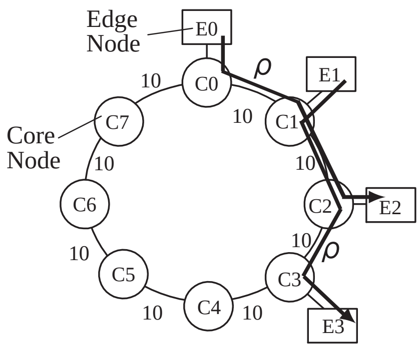


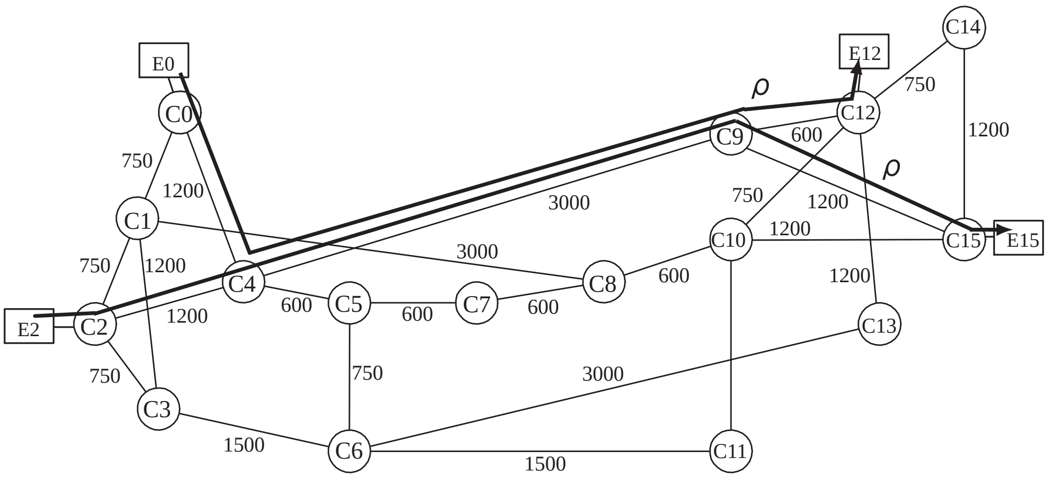
Figure 4.10: The burst loss probability versus the number of wavelengths W.

to edge node E2, and the traffic from edge node E1 to edge node E3. And, ρ/α is defined as the offered load of the other traffic($\alpha \geq 1.0$). Therefore, when a burst is forwarded on the shortest path route, the traffic load is concentrated on link C1→C2. Also, in Fig. 4.11(b), ρ is defined as the offered load of the traffic from edge node E2 to edge node E15, and the traffic from edge node E0 to edge node E12. And, ρ/α is defined as the offered load of the other traffic($\alpha \geq 1.0$). Therefore, when a burst is forwarded on the shortest path route, the traffic load is concentrated on link C4→C9.

Figure 4.12 shows the burst loss probability versus the offered load ρ in the 8-node dual-ring network (Fig. 4.11(a)). This is done at the number of wavelength W = 32, and the traffic bias α = 20, 100. In the proposed scheme, the number of search packets N_s is set to 2. On a simple mesh network like Fig. 4.4, at the traffic bias α = 20, the proposed scheme can improve the burst loss probability. However, on the



(a) 8-node ring network



(b) 16-node NSFNET network

Figure 4.11: The 8-node dual-ring network and the 16-node NSFNET network.

ring topology, the proposed scheme cannot improve the burst loss probability at the traffic bias $\alpha = 20$, and the proposed scheme can improve the burst loss probability at the traffic bias $\alpha = 100$. This reason is as follows. On the dual-ring network, only two routes can be used. The route that is not the shortest path route has many hops. So, when this route is used, a burst is more likely to be discarded due to burst contention. Therefore, except when the very large traffic load is concentrated on a certain link, the use of the route that is not the shortest path route is not effective. From Fig. 4.12, the proposed scheme is effective on the network where several routes which have small hops can be used except the shortest path route.

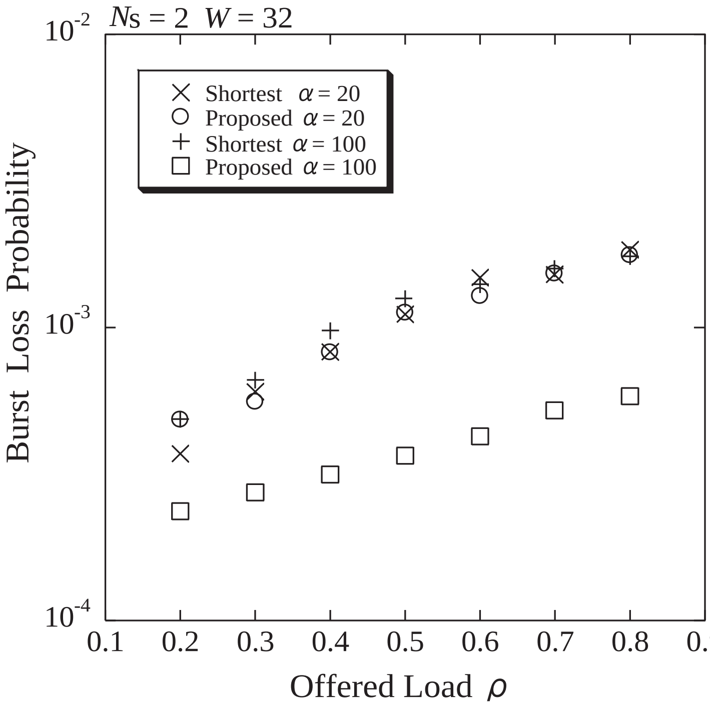


Figure 4.12: The burst loss probability versus the offered load ρ in the 8-node dual-ring network.

Figure 4.13 shows the burst loss probability versus the offered load ρ on the 16-node NFSNET network (Fig. 4.11(b)). This is done at the number of wavelength $W = 32$, and the traffic bias $\alpha = 20$, 100. In the proposed scheme, the number of search packets N_s is set to 2. It shows that, like a dual-ring network, the proposed scheme cannot improve the burst loss probability at the traffic bias $\alpha = 20$, and the proposed scheme can improve the burst loss probability at the traffic bias $\alpha =$ 100. This reason is as follows. When the shortest path routes are used on a simple mesh network like Fig. 4.4, many combinations of source edge node and destination edge node use the same link. However, when the shortest path routes are used on the NFSNET network, many combinations don't use the same link. So, when the traffic load is concentrated on a certain link, few combinations are affected, the total performance is not very improved. Therefore, when the very large traffic load

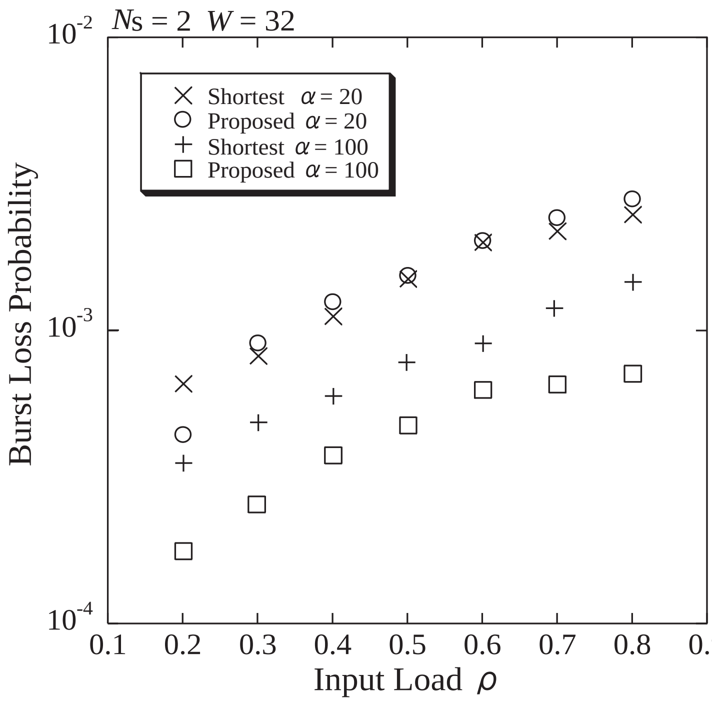


Figure 4.13: The burst loss probability versus the offered load ρ on the 16-node NFSNET network.

is concentrated on a certain link, the proposed scheme is effective. From Fig. 4.13, the proposed scheme is effective on the network where many combinations of source edge node and destination edge node use the same link.

From Fig. 4.12 and Fig. 4.13, the proposed scheme is effective on the network topology where several routes which have small hops can be used except the shortest path route, and many combinations of source edge node and destination edge node use the same link.

4.4 Conclusion

In this chapter, the self-learning route selection scheme in OBS network has been proposed. In the proposed scheme, each edge node learns a suitable route to the destination edge node autonomously by using feedback packets and search packets newly. Due to the self-learning at each edge node, the traffic load is distributed in an OBS network. Therefore, the proposed scheme can reduce the probability of burst contention.

The performance of the proposed scheme is evaluated by computer simulation. As a result, it is shown that, under nonuniform traffic, the proposed scheme can reduce approximately one decade smaller burst loss probability compared with the conventional shortest path routing method. When the bias of traffic becomes larger, the proposed scheme has better performance. Also, it is shown that the proposed scheme is effective on the network topology where several routes which have small hops can be used except the shortest path route, and many combinations of source edge node and destination edge node use the same link.

In this chapter, a simple learning scheme is adopted in order to investigate the effect of the route selection by the self-learning. It is shown that the route selection by the simple learning scheme is effective. However, on a large topology, a complex topology, or a ring topology, the simple learning is not very effective. Therefore, in order to improve the performance of the proposed scheme in these topologies, we need examine the learning scheme in consideration for the intelligent schemes [3]-[5]. Also, other future works are to add some damping mechanism for the perfect stability, and to study combination the proposed scheme and contention resolutions using optical buffering and wavelength conversion at a core node.

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Chapter 5

A Lightpath Route Selection Scheme Considering Route Priority and Wavelength Usage in GMPLS-Based Optical GRID Network

5.1 Introduction

In the GMPLS-based optical GRID network, a lightpath is established among computer resources by reserving communication resources such as an interface, a node, a link, a wavelength and so on. The route of the lightpath is decided by the routing protocol in GMPLS. Conventionally, the shortest path route is calculated based on a link metric which is exchanged by the routing protocol. The route decision calculating the shortest path route is simple, and able to reduce the propagation delay. However, in setup a lightpath, the existence of other lightpaths is not considered. Therefore, in this routing, the traffic load is concentrated on a certain link which may cause bottlenecks. When bottleneck occurs, the blocking of lightpath setup is increased. It means that, while a computing resource is available, the computing resource cannot be connected due to the bottleneck. Therefore, it is necessary to distribute the traffic and prevent occurrence of bottlenecks.

Several methods of distributing traffic are studied [1], [2]. These methods are based on the assumption that each node knows all lightpaths in the network. The methods can provide a near optimal solution by computation based on the information on all lightpaths. However, in a large-scale GRID network, it is unrealistic to manage the information on all lightpaths. So, each node needs to consider the condition of the network autonomously.

In this chapter, the lightpath route selection scheme is proposed in order to improve the blocking probability of the lightpath setup. In our proposed scheme, the route priority is introduced as the new parameter for the lightpath route selection. Each source node updates the route priority according to the results of the lightpath setup. Also, in setting up the lightpath, each source node sends lightpath setup request message on several paths. And, each request message collects the wavelength usage information in the route. The destination node selects the route to reserve the bandwidth based on the information from the request message. Each pair of nodes selects a suitable route by considering the past empirical information and the current wavelength usage information. Thus, the proposed scheme can distribute traffic and suppress the occurrence of bottlenecks.

Based on computer simulation model, under nonuniform traffic, the proposed scheme can reduce nearly 20 to 50 percent smaller blocking probability as compared to the conventional GMPLS-based optical GRID network using shortest path route.

5.2 GMPLS-based Optical GRID Network

Figure 5.1 shows a GMPLS-based optical GRID network architecture. This network consists of a GRID site and a GMPLS optical network. Computing resources exist in each site, and a master node controls the local computing resources of the site. The GMPLS optical network connects master nodes. In the GRID network, computing resources and communication resources are needed to be managed. The

GRID resource manager manages computing resources by connecting master nodes in each site. Communication resources are managed by using GMPLS.

When a GRID user executes a job, the GRID user inquires for the GRID resource manager about the available computing resources. Based on the information from the GRID resource manager, the GRID user reserves the computing resources. In the GMPLS optical network, a lightpath is set up between the computing resources distributed geographically. According to the conditions which the GRID user specifies, the lightpath route from the source node to the destination node is calculated by the routing protocol of GMPLS such as OSPF-TE. And, by the reservation protocol of GMPLS such as RSVP-TE, the communication resources, which are wavelengths, on the lightpath route are reserved.

Figure 5.2 shows an example of the lightpath setup. Firstly, a source node sends a PATH message to a destination node along the calculated route. The PATH message collects the wavelength usage information on its way to the destination node. When the destination node receives the PATH message, the destination node can determine on which wavelength to reserve based on the information provided by the PATH message. In this example, the destination node selects λ_3 of two idle wavelengths on the route λ_1, λ_3. Then, a RESV message is sent back to the source node to configure the appropriate wavelength on each link along the route. The data transmission can begin after the source node receives the RESV message.

The route from a source node to a destination node is calculated by using the link cost which is exchanged at the routing protocol of GMPLS. And, the request of the lightpath is forwarded on the route with lowest costs. Also, the interval of exchanging the costs of the link is much longer than the holding time of the lightpath. So, dynamic network traffic change cannot be considered for the routing protocol of GMPLS. Therefore, the traffic load is concentrated on a certain link, and it causes

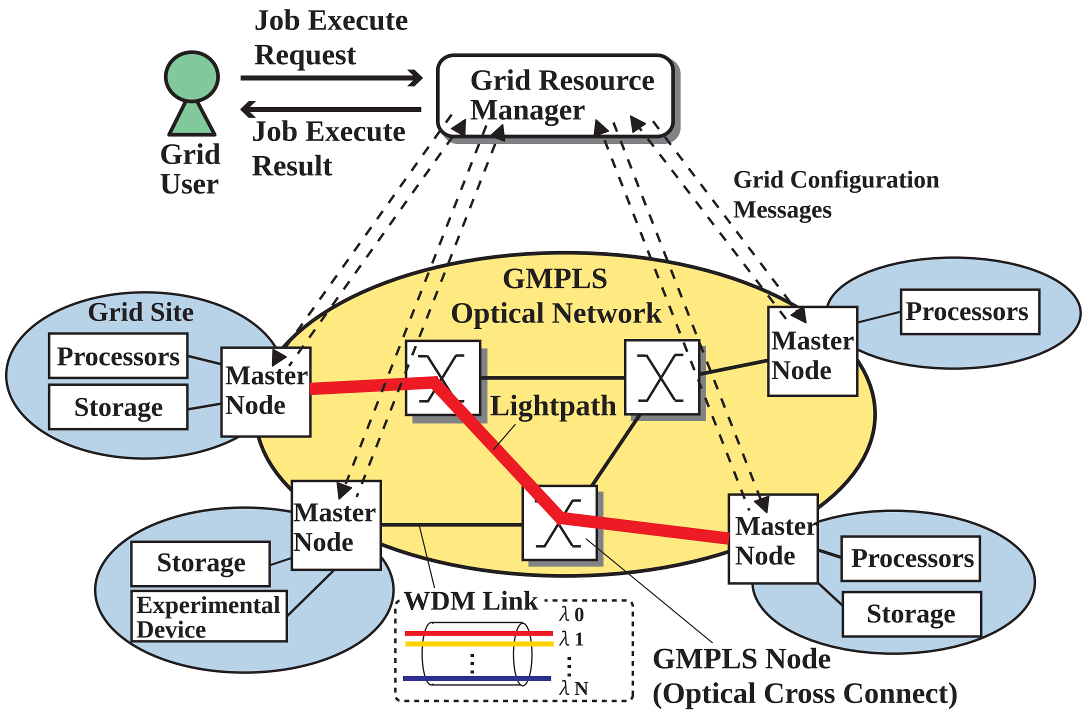

Figure 5.1: A GMPLS-based optical GRID network.

some bottlenecks. And, it causes the degrade of success rate of the lightpath setup.

5.3 Proposed lightpath route selection scheme

The lightpath route selection scheme is proposed in order to improve the blocking probability of the lightpath setup. The proposed scheme introduces the route priority as the parameter for determining the lightpath route. A lightpath route is decided by considering the route priority based on the past empirical information and the link usage information which indicates the current network condition.

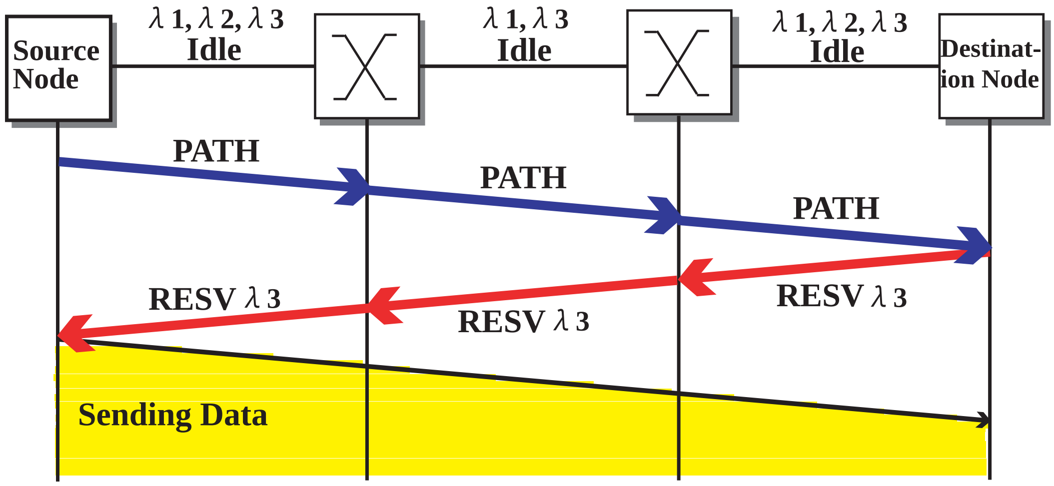

Figure 5.2: An example of the lightpath setup.

5.3.1 Use of the route priority based on the past empirical information

Each node keeps the information of all routes to each destination node by using the routing protocol of GMPLS. The route priority is set for each route. The route priority is calculated as the probability to succeed in the lightpath setup. So, the range of the route priority R is $0 \leq R \leq 1$. The source node receives RESV message in the success of the lightpath setup. And, the source node receives NACK message in the failure. The source node updates the route priority R by using calculating formulas [3] written blow,

- When recieving RESV message (Success):

$$R = (R \times N_t + 1)/(N_t + 1), N_t = N_t + 1 \tag{5.1}$$

- When recieving NACK message (Failure):

$$R = R \times N_t/(N_t + 1), N_t = N_t + 1 \tag{5.2}$$

N_t is the number of the lightpath setup trial. When the route priority R is close to 1, the route has a high priority of success. Also, when the route priority R is close to 0, the route has a high priority of failure. When a source node sends a PATH message, the source node sends a PATH message on a route with a high route priority.

Figure 5.3 shows an example of updating the route priority. As shown in Fig. 5.3 (i), when a source node receives RESV message from its destination node, the source node calculates the route priority and sets the route priority to a higher value. In this example, the route priority of Route ID 1 turns from 0.70 to 0.76 ($= (1 + 0.70 \times 4) / (1 + 4)$). As shown in Fig.5.3 (b), when a source node receives NACK message from an intermediate node, the source node sets the route priority to a lower value. The route priority of Route ID 2 turns from 0.80 to 0.76 ($= 0.80 \times 3 / (1 + 3)$). In this way, the route priority is updated at every lightpath setup.

By using the route priority, each node can survey a suitable route to destination nodes autonomously. So, each node can respond to the change of network traffic, and the traffic load is distributed.

5.3.2 Determination of the route based on the current link usage

When a source node sends PATH message, the source node selects k candidate routes for the lightpath. k routes with higher route priority are selected candidate routes. And, the source node sends PATH messages on candidate routes. Each PATH message collects the information of the link usage of each link on the route. The link usage means the number of idle wavelengths W_{idle}. Each PATH message keeps the value of the minimum number of idle wavelengths among the links on the route. After receiving all PATH messages, the destination node decides one route to send a RESV message on. The route with the largest minimum number is selected.

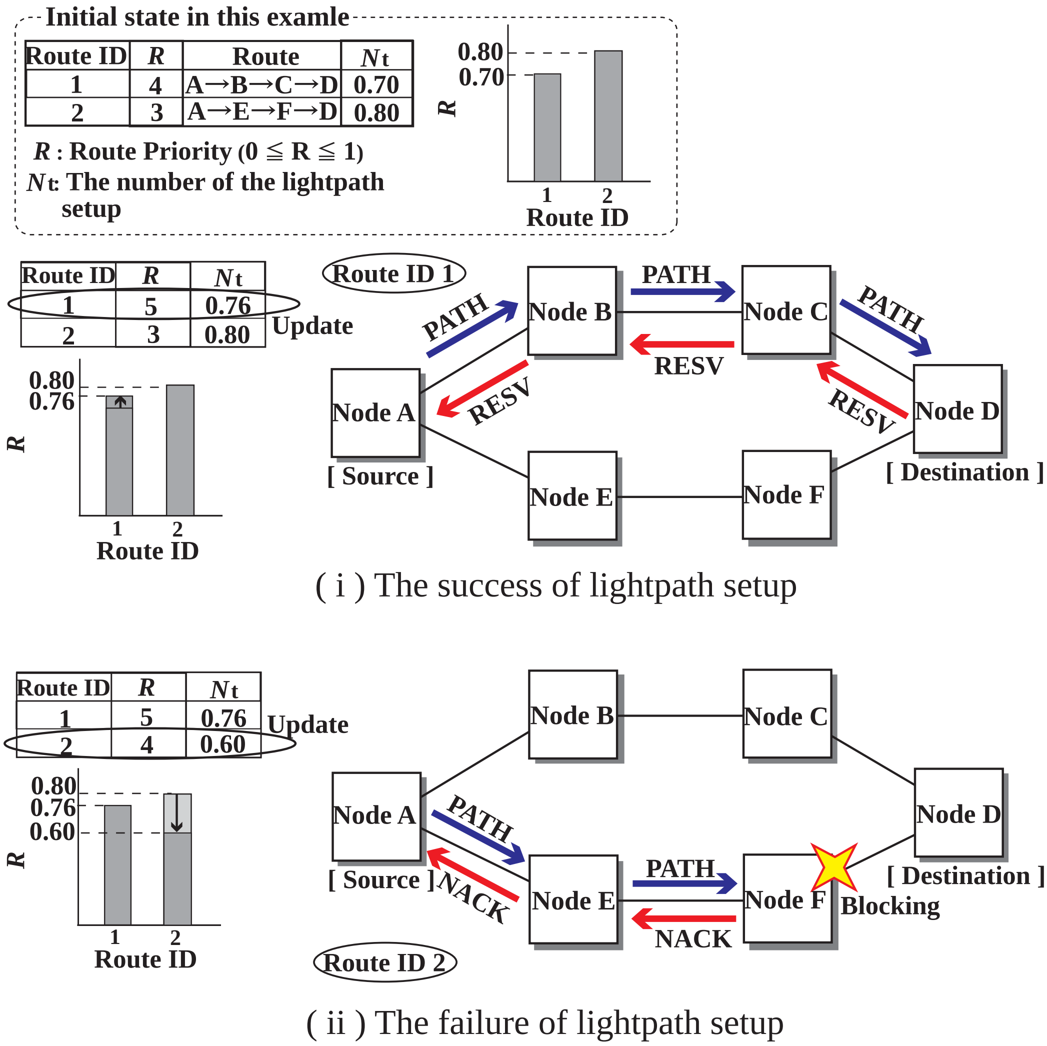

Figure 5.3: An update of the route priority.

Figure 5.4 shows an example for a determination of the lightpath route by using multi-PATH messages. In the example of Fig. 5.4, the source node A selects k = 2 candidate routes of the three routes. By considering the route priority, the source node sends PATH messages on Route 1 (A $\rightarrow$ B $\rightarrow$ D) and on Route 3 (A $\rightarrow$ C $\rightarrow$ E $\rightarrow$ D). By considering the minimum number of idle wavelengths on each route, the destination node selects Route 3 as the route to send a RESV message on. By sending PATH messages on several routes, the determination in consideration of the current network condition can be done. Also, at one lightpath setup, the

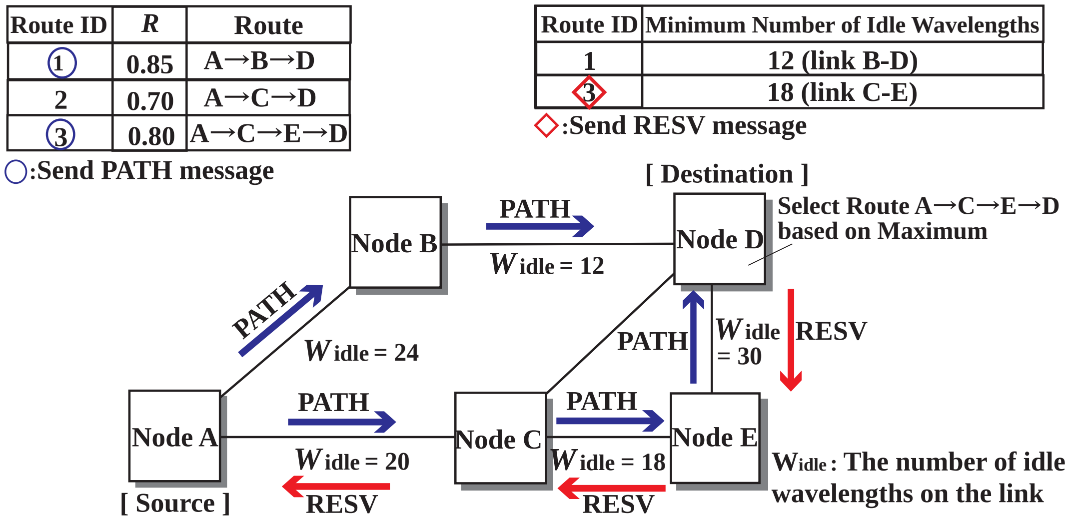

Figure 5.4: A determination of the lightpath route by using multi-PATH messages ($k = 2$).

source node can receive the feedback information about several routes and update the route priorities. Therefore, the source node can respond to the change of the traffic immediately.

By considering both the route priority as the past empirical information and the link utilization as the current network information, the proposed scheme reduces the blocking probability.

5.4 Simulation Results

Computer simulations models were developed to evaluate the performance of the proposed scheme. This simulation compare the proposed scheme with the conventional scheme where a source node sends a PATH message on the shortest path route. A mesh network as shown in Fig. 5.5 is considered. HOPI (Hybrid Optical and Packet Infrastructure Project) testbed topology is used in USA [4] as reference. The number of GMPLS nodes in the network is 11. There is no wavelength converter

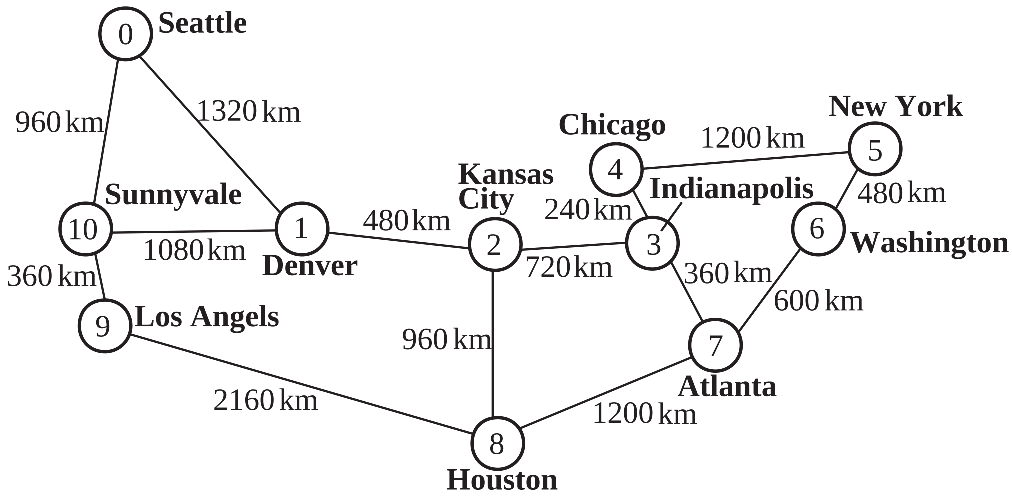

Figure 5.5: Simulation network model.

and optical buffer in all nodes. Every link has 32 wavelengths.

The nonuniform traffic is assumed in this simulation. Here, the nonuniform traffic means that the traffic load is different in each combination of source edge node and destination edge node. Compared to other combinations, 20 times heavy connection requests from node 1 to node 5 and from node 7 to node 0 arrives. Also, the holding time of the established lightpath is 1 sec.

Figure 5.6 shows the blocking probability versus the offered load. In the proposed scheme, the number of candidate routes k in sending multi-PATH messages is set to 3. This figure shows that the proposed scheme offers about 20-50 percent smaller blocking proposed probability compared with the conventional scheme. This is because, in the conventional scheme, the traffic loads are concentrated on certain links, especially on the links along the shortest path route from node 1 to node 5 and from node 7 to node 0. So, bottlenecks occur on these links, and it causes high blocking probability. On the other hand, in the proposed scheme, by considering the route priority and the current link usage, the traffic is distributed and the traffic is not concentrated on a certain link. So, the proposed scheme reduces the generation of

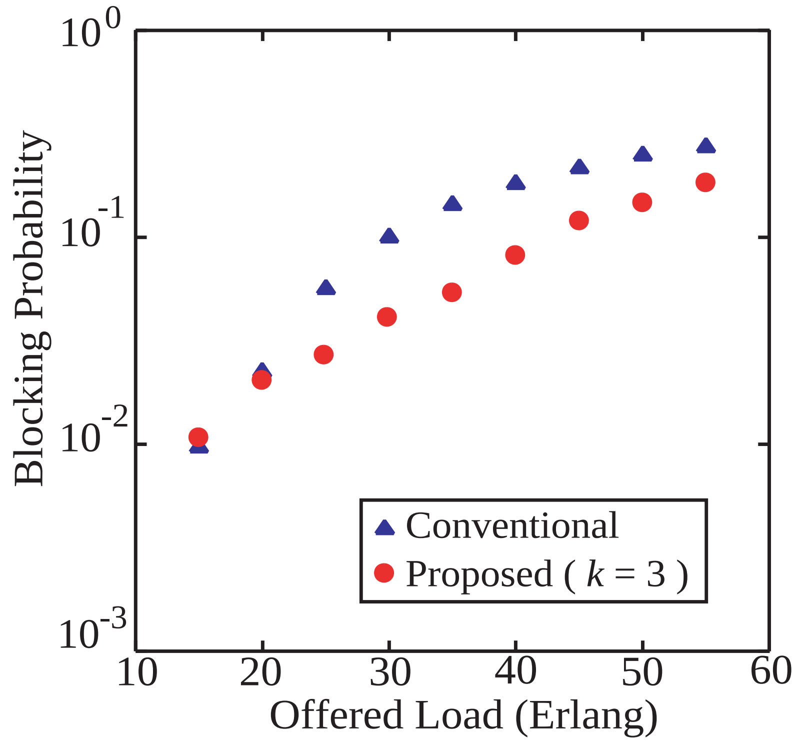

Figure 5.6: The blocking probability versus the offered load ($k = 3$).

blocking.

Next, the link utilization performance is evaluated. Figure 5.7 shows the average link utilization of all links versus the offered load. Figure 5.8 also shows the maximum link utilization and the minimum link utilization versus the offered load. From Fig. 5.7, it is shown that the proposed scheme has higher average link utilization than the conventional scheme. And, from Fig. 5.8, it is shown that the difference between the maximum link utilization and the minimum link utilization in the proposed scheme is smaller than that in the conventional scheme. This is because, in the conventional scheme, the traffic is concentrated on a few links and other links have a low traffic load. So, the difference is large and blockings of lightpath setup is generated on the links with high link utilization. On the other hand, in the proposed scheme, the traffic is distributed by selecting the route based on the route priority

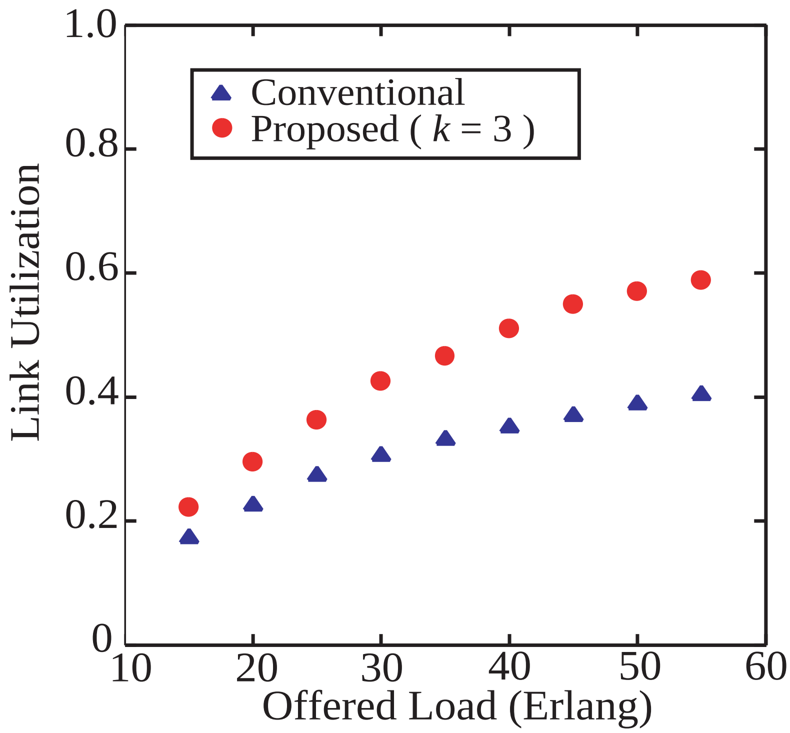

Figure 5.7: The average of link utilization versus the offered load ($k = 3$).

and the current link usage. Therefore, the proposed scheme uses all links effectively, and reduces the number of blockings. From Fig. 5.6, 5.7 and 5.8, it is clear that the proposed scheme improves the blocking probability by distributing traffic and using links of the network effectively.

Next, the connectivity between nodes is evaluated. In the GRID network, it is important to connect every node all the same. Figure 5.9 shows an example of unfairness about the connectivity. In Fig. 5.9, the blocking probability of the lightpath setup from Node A to Node D is lower than that from Node E to Node D. In this case, Node A is easier to be connected to Node D than Node E. It means the unfairness about the connectivity to Node D. Also, the blocking probability of the lightpath setup from Node A to Node D is lower than that from Node F to Node G. So, the success probability of establishing a connection is unfair by pairs of a source

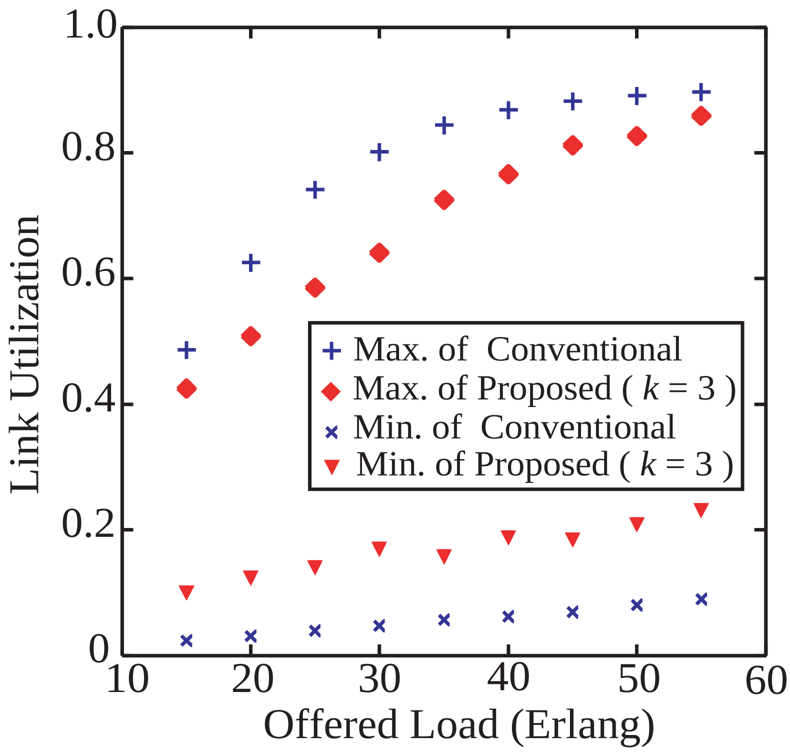

Figure 5.8: The maximum and minimum of link utilization versus the offered load ($k = 3$).

node and a destination node.

The fairness index [5] is used for the evaluation about the connectivity. The fairness index F is defined as

$$F = \frac{(\sum_{i=0}^{M-1} \sum_{j=0}^{M-1} B_{ij})^2}{N_{\rm p} \times \sum_{i=0}^{M-1} \sum_{j=0}^{M-1} B_{ij}^2} \tag{5.3}$$

M is the number of nodes in the network, and $N_{\rm p}$ is the number of pairs of the source node and the destination node. Also, B_{ij} indicates the blocking probability for the request of the lightpath from the source node i to the destination node j. When the fairness index F is near to 1, the difference of the blocking probability by pairs is small. In other words, the connectivity between nodes in the network is almost equal regardless of the combination of the source node and the destination

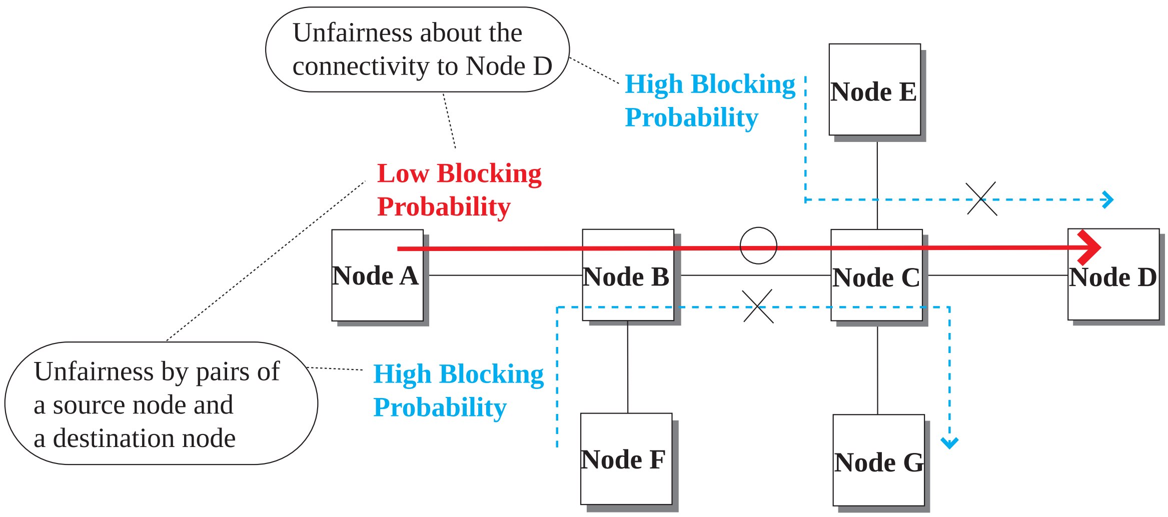

Figure 5.9: An example of unfairness about the connectivity.

node. In the simulation network model shown in Fig. 5.5, $M = 11$ and $N_p = 110$.

Figure 5.10 shows the fairness index versus the offered load. From Fig. 5.10, it is shown that the fairness index of the proposed scheme is higher than that of the conventional scheme. In the conventional scheme, since the traffic concentrates on a certain link, the blocking probability for the lightpath of a particular source-destination pair is high. The proposed scheme distributes the traffic, and reduces the occurrence of bottlenecks. However, the difference of the fairness index gets smaller and smaller as the offered load becomes large. Therefore, the effect of the proposed scheme is small in the high offered load.

Figure 5.11 shows the setup time of lightpath versus the offered load. Here, the setup time means the time from the start of sending PATH message to the end of receiving RESV message at a source node. From Fig. 5.11, the setup time of the proposed scheme is about as long as that of the conventional scheme. In the proposed scheme, the shortest path is not always used. So, the propagation delay time between a source node and a destination node is long. Also, multi PATH messages reach the destination node at different times because the route of each PATH mes-

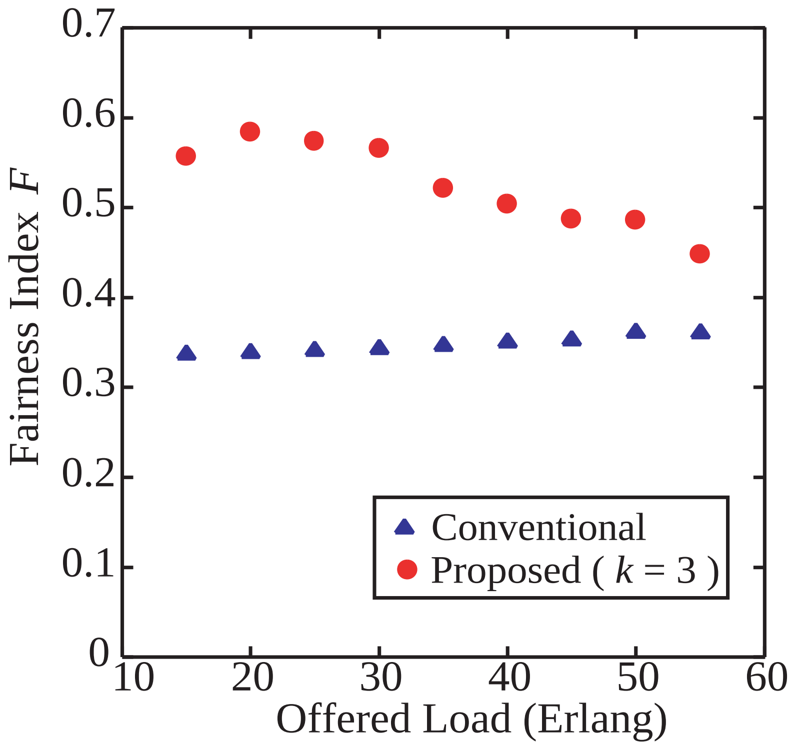

Figure 5.10: Fairness index F versus the offered load ($k = 3$).

sage is different. The destination node cannot send RESV message until receiving all PATH messages. Due to these factors, the setup time of the proposed scheme is long. Therefore, the proposed scheme has bad performance in the wavelength utilization. For example, when the holding time of the lightpath is 1 sec, the setup time in the proposed scheme is about 4 percents of the holding time. So, the degree of a negative impact depends on the holding time.

From Fig. 5.6 to Fig. 5.11, the proposed scheme improves the blocking probability and the fairness about the connectivity by distributing traffic. However, the proposed scheme makes the setup time of lightpath long, and gives a negative impact to the performance for the setup time. Therefore, in using the proposed scheme, this trade-off must be considered.

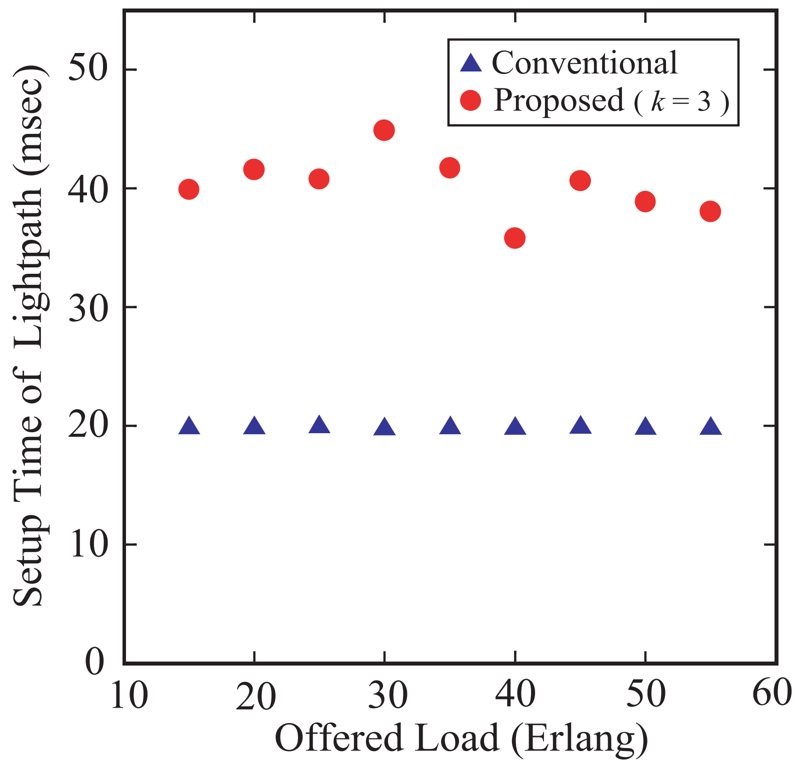

Figure 5.11: The setup time of the lightpath versus the offered load ($k = 3$).

5.5 Conclusion

The lightpath route selection scheme has been proposed in order to improve the blocking probability of a GMPLS-based optical GRID network. In the proposed scheme, the route priority is introduced as the new parameter for the lightpath route selection. Each source node updates the route priority according to the results of the lightpath setup, and learns the suitable route autonomously. Also, in setting the lightpath, each source node sends PATH messages on several routes. And, each PATH message collects the link usage information of the route. The destination node selects the route to reserve the bandwidth based on the information from the PATH messages. The proposed scheme can distribute the traffic by considering the past information and the present information. According to computer simulations, under nonuniform traffic, the proposed scheme can reduce nearly 20-50 percent smaller blocking probability as compared to the conventional optical GRID network using shortest path route.

Future research directions include the performance evaluation considering the dynamic change of traffic. Under the dynamic traffic, the holding time, and the frequency of lightpath setup requests are variable. The function considering time interval may be important, such as the initialize mechanism. Also, the study of the resource reservation scheme considering not only communication resources but also computing resources is also an area of research interest.

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Chapter 6

Conclusions and Future Works

In this thesis, three efficient optical data transfer schemes are proposed for the next generation optical network. By computer simulation, it is clarified that performances and effectiveness of the proposed schemes. Works in Chapter 3-5 are summarized blow.

In Chapter 3, the fair burst dropping scheme technique was proposed in order to achieve the fair packet loss probability regardless of the number of hops in OCBS. The proposed scheme configures the threshold for determining whether the HD technique is applied or not. The proposed scheme can reduce the difference of packet loss due to the number of hops by applying the HD technique in consideration of the number of hops. By computer simulation, it was shown that the proposed scheme can achieve the fair packet loss probability regardless of the number of hops to the destination edge node compared with a conventional one.

In Chapter 4, the self-learning route selection scheme in OBS network was proposed. In the proposed scheme, each edge node learns a suitable route to the destination edge node autonomously by using feedback packets and search packets newly. Due to the self-learning at each edge node, the traffic load is distributed in an OBS network. The performance of the proposed scheme is evaluated by computer simulation. As a result, it is shown that, under nonuniform traffic, the proposed scheme can reduce approximately one decade smaller burst loss probability compared with the conventional shortest path routing method. When the bias of traffic becomes larger, the proposed scheme has better performance. Also, it is shown that the proposed scheme is effective on the network topology where several routes which have small hops can be used except the shortest path route, and many combinations of source edge node and destination edge node use the same link.

In Chapter 5, the lightpath route selection scheme was proposed in order to improve the blocking probability of a GMPLS-based optical GRID network. In the proposed scheme, the route priority is introduced as the new parameter for the lightpath route selection. Each source node updates the route priority according to the results of the lightpath setup, and learns the suitable route autonomously. Also, in setting the lightpath, each source node sends PATH messages on several routes. And, each PATH message collects the link usage information of the route. The destination node selects the route to reserve the bandwidth based on the information from the PATH messages. The proposed scheme can distribute the traffic by considering the past information and the present information. According to computer simulations, under nonuniform traffic, the proposed scheme can reduce nearly 20-50 percent smaller blocking probability as compared to the conventional optical GRID network using shortest path route. The proposed scheme has the trade-off between the setup time and the blocking probability.

I summarize challenges of the proposed schemes remained as future works. The performance evaluation is needed for the dynamic change of traffic and the variety of topologies. In Chapter 3, more evaluations are needed to study the effectiveness for non-uniform traffic and a general topology. In Chapter 4 and 5, it is an important issue to study mechanisms for the temporal change of traffic, for example, an initialize mechanism and a damping mechanism. The implementation and experiment of the proposed schemes are also big challenges. By implementing prototypes, practicalities of the proposed schemes should be evaluated (about the implementation and experiment, some works have been tried. These works are explained in Appendix.).

These proposed schemes are expected to contribute to realize an efficient optical network for bulk data transfer. The fair burst dropping technique in Chapter 3 is applied to the mechanism for achieving the fairness about the location of each node. By the route selection schemes in Chapter 4 and 5, bottlenecks in the network are reduced. In my researches, all-optical network, where not only data payload but also a header are processed in an optical domain, is not focused as the next generation optical network. In the future, all-optical network is expected to be developed. A core node is required to process optical signals quickly. So, it may be difficult for the core node to execute complicated process. Therefore, it is important to control the transmission before sending data by the cooperation with the edge nodes and control plane. I believe that, in future optical network, the edge node is required more intelligent functions, and the core node is required high-speed optical switching. For future optical network, approach in Chapter 3 may be difficult to be realized. It is because this approach needs complicated optical header processing. The optical header processing method and the cooperation with control plane should be considered. Fairness problem itself will become more important due to the development network services. Approaches in Chapter 4 and 5 seem useful for future optical network in terms of proposing the autonomous distributed transmission control scheme. These approaches are expected to be developed by considering more sophisticated algorithms and cooperation schemes with control plane. In this way, my researches are expected to contribute for future optical network.

Acknowledgments

This dissertation has been written under the direction and guidance of Professor Naoaki Yamanaka in Department of Information and Computer Science, Keio University.

My sincere gratitude and deepest appreciation should be first given to my supervisor Professor Naoaki Yamanaka for their valuable suggestions, guidance and continuous encouragements throughout my works. With the guidance of Prof. Yamanaka, I did good studies and got splendid experiences in the doctoral cource.

I wish to express my sincere gratitude to Professor Iwao Sasase in Department of Information and Computer Science, Keio University. Prof. Sasase was my supervisor for my graduation thesis and master thesis. So, this dissertation includes studies carried out under the guidance of Prof. Sasase during 2002-2004, and studies carried out under the guidance of Prof. Yamanaka during 2005-2008.

I also wish to express my sincere gratitude to Professor Bijan Jabbari in Department of Electrical Engineering, George Mason University, Fairfax, VA, USA. Prof. Jabbari taught me for about 3 months on an overseas study program. I could do the work in Chapter 5 with the direction and guidance of Prof. Jabbari.

I owe a great deal of thanks to the member of dissertation committee, Professor Masao Nakagawa in Department of Information and Computer Science, Keio University, and Professor Hideharu Amano in Department of Information and Computer Science, Keio University, for their comments, suggestions, and careful and critical reading of this dissertation. Prof. Sasase and Prof. Jabbari attended the dissertation committee. I thank Prof. Sasase and Prof. Jabbari again.

I'm very grateful to thank to Dr. Yutaka Arakawa, Assistant of Yamanaka Lab. in Department of Information and Computer Science, Keio University, for his valuable discussions and comments throughout my studies. Dr. Arakawa has taught and supported me for about 7 years since I was a senior student.

I'm grateful to thank to Dr. Satoru Okamoto, Associate Professor of Yamanaka Lab. in Department of Information and Computer Science, Keio University. Dr. Okamoto gave me opportunities of attending the interoperability experiments and implementing protocol software. With them, I got good experiences for researchers.

I'm also grateful to thank to old and active members in Yamanaka Laboratory, Dr. Kohei Okazaki, Mr. Takanori Ito, Mr. Sho Shimizu, Mr. Masahiro Hayashitani, Mr. Junichiro Honma, Mr. Teruo Kasahara, Mr. Hiroyuki Miyagi, Mr. Tomohiro Tuji, Mr. Hiroyuki Ishikawa, Mr. Masahiro Tateno, Mr. Ryota Usui, Mr. Masahiro Nishida, Mr. Mikio Kaneko, Mr. Taku Kihara, Mr. Shinpei Koda, Ms. Fumiko Uehara, Mr. Kazuki Irie, Mr. Kou Kikuta, Mr. Kazumasa Tokuhashi, Mr. Yusuke Okazaki, Mr. Syan Gao, Mr. Hirofumi Yamashita, Ms. Midori Terasawa, Ms. Motomi Akagi, Ms. Jia Zhou, Mr. Kunitaka Ashizawa, Mr. Junpei Marukawa, Ms. Aya Turusaki, Mr. Shota Yamada, Mr. Yuki Susa, Ms. Kazuko Yonezawa, Mr. Takashi Kurimoto, Ms. Mika Ishiduka, Ms. Yuki Uchiyama, Ms. Kaori Kozakai, Ms. Haruko Iwama, Ms. Tomoko Kawasaki, and Ms. Ayumi Sato. All members inspired me in my research life. For the writing of this dissertation, especially I'm grateful to members in 2007 and 2008.

My friends and colleagues supported and encouraged me very kindly. I am especially thankful for colleagues in Sasase Laboratory, colleagues in Archery Club of Keio University and colleagues in Archery Club of Asano High School.

I am thankful for Dr. Makoto Sakuta, Medinet Global, Inc., and Dr. Yoshiyuki

Nishino of CEO, Medinet Global, Inc., who take care of me at part-time job and so on.

I am also thankful for Mr. Manabu Hirano, Student Counselor in Keio University. Mr. Hirano supported and encouraged me in what has been a very difficult time.

At last, I would like to express my gratitude to my father and mother. I really worried my parents and caused them trouble. But, my parents nourished me, and gave their utmost support to fulfill my educational aims. That resulted in this dissertation.

For making this dissertation, I caused many people trouble. However, everyone supported me very kindly. I really think that I'm blessed with professors, friends, colleagues, and families. I am really grateful to everyone around me for supporting and encouraging.

I'll make good use of this experience about this dissertation. I wish to express my sincere gratitude again.

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October 20, 2008

Appendix A

Implementation and Experiment for the Next Generation Optical Network Control Technique

A.1 An experiment of Optical Slot Switching

In Yamanaka Laboratory which I belong to, Optical Slot Switching (OSS) is designed and implemented for bulk contents data transfer. Figure A.1 shows OSS network. All OSS nodes are synchronized and share the fixed-length time-period named slot. Each slot carries multiple packets. One user is allocated all bandwidth in a slot.

However, it is very difficult to realize the slot switching network with conventional optical switches such as Micro Electro Mechanical System (MEMS) switch. Since the switching time of the MEMS switch is several hundred msec and the overhead between slots in large, a network based on the MEMS switch cannot transfer contents efficiently. In OSS, the guard time is reduced by using the PLZT (Lead-Lanthanum Zirconate-Titanate) optical switch [1]-[2]. The switching time of the PLZT optical switch is very high speed with less than 10 nsec. This ultra-high speed PLZT switch can improve the bandwidth utilization unlike the MEMS switch. Generalized Multi-Protocol Label Switching (GMPLS) [4] extension protocol is employed as the slot reservation scheme. PLZT optical switch is configured by GMPLS control plane.

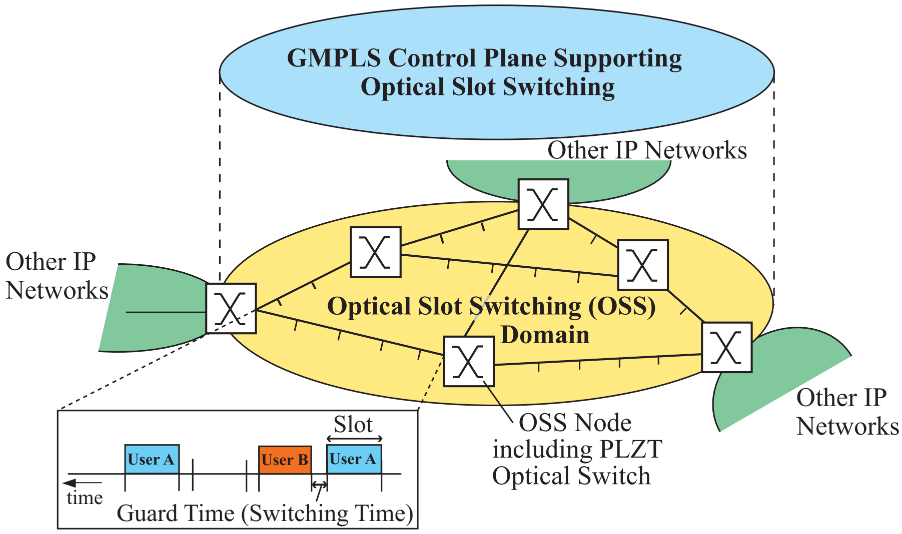

Figure A.1: OSS network.

Resource reSerVation Protocol-Traffic Engineering (RSVP-TE) [5] is extended and optical slot reservation is realized. RSVP-TE is standarized as the GMPLS signaling protocol. Figure A.2 shows an example of slot reservation in OSS. Each vertical line is a time line, and each time line is divided into frames consisting of several slots. In Fig. A.2, the number of slots in a frame is 3. OSS node 1 sends a PATH message to OSS node 4 as a request message of connection between OSS node 1 and OSS node 4. OSS node 2 and OSS node 3, which are intermediate nodes, receive the PATH message and confirm whether there are vacant slots. If there are vacant slots, these intermediate nodes store the information about vacant slots and send the PATH message to the next node. Upon receiving the PATH message, OSS Node 1 selects Slot 2, the earliest slot the PATH message to the next node. Upon receiving the PATH message, OSS node 1 selects Slot 2, the earliest slot among all available slots on all available slots on all the links of the route, and sends a RESV message for OSS node 1. Two intermediate nodes receiving the RESV message reserve Slot 2 and send the RESV message to the next node. Each intermediate node maintains information about the reserved slots and the corresponding output

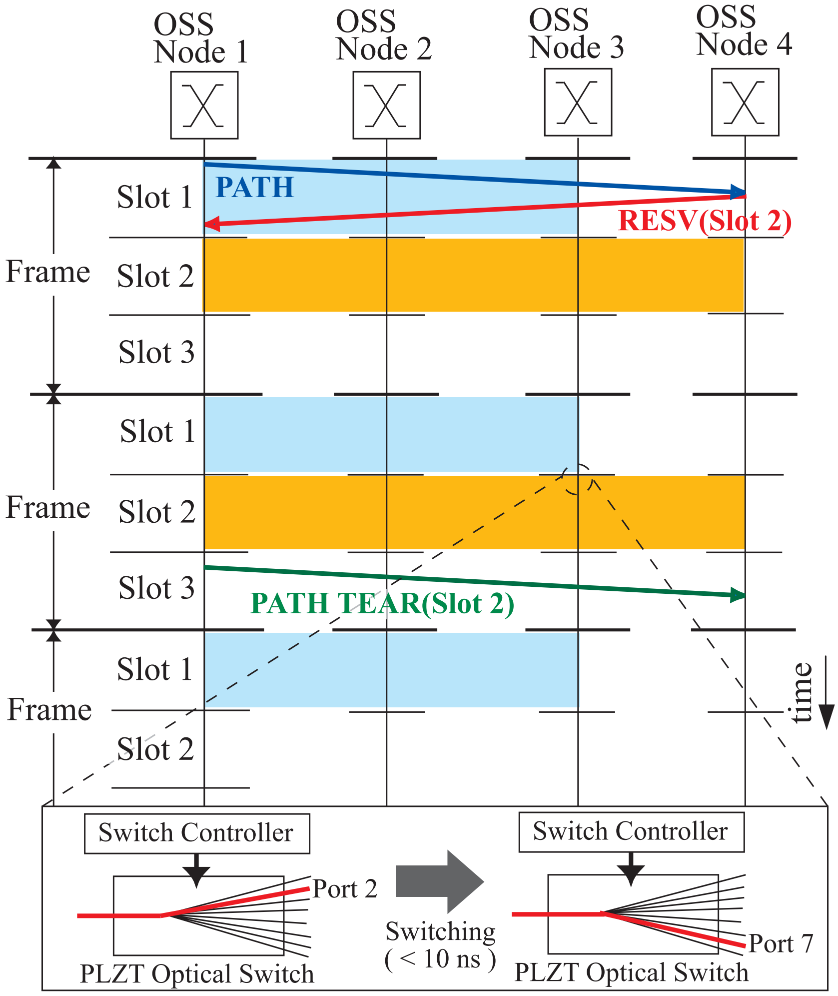

Figure A.2: An example of slot reservation in OSS.

port in the PLZT switch. Upon receiving the RESV message, OSS node 1 transfers the content by using the reserved slots in each frame. OSS node 1 sends a Path Tear Down message for OSS node 4 and releases the slots after finishing content transfer. Each intermediate node sends a switch control signal to the PLZT switch based on the information about the reserved slots and the corresponding output port. Each PLZT switch selects an output port based on the switch control signal. In Fig. A.2, the switch in OSS node 3 switches from Port 2 to Port 7. Therefore, OSS node 4 can receive the content in Slot 2.

Next, the experiment about OSS network and my work about implementing OSS node system are explained. Figure A.3 shows an OSS node system. This OSS node system consists of a Linux-based PC with GMPLS software and a PLZT optical switch unit. The Linux-based PC is connected to the PLZT optical switch unit via a serial cable. Figure A.4 shows a diagram of the OSS node system. In this experiment, I mainly worked about extending GMPLS signaling protocol (RSVP-TE) for OSS. I implemented two functions. One function is to calculate the scheduling of optical slots according to received signaling messages. Another function is to call a PLZT Optical Switch Controll Program based on the results of scheduling. By implementing these two functions, the Linux PC can control the PLZT switch in conjunction with RSVP-TE. Figure A.5 shows an experimental OSS network structure. In the network, the number of slots in a frame 2, and slot size can be changed as needed. It was confirmed that the streaming contents data is transmitted to Receivers by reserving optical slots. About this experiment, the demonstration was held in 2nd International Conference on IP+Optical Network (iPOP2006) shown in Fig. A.6.

In Yamanaka Lab., A study about OSS continues. In MPLS 2006 International Conference, Yamanaka Lab. took part in a national inter-operability trail of GMPLS, and tested the performance about the inter-connectivity of the OSS node system. A new access-distribution network architecture using OSS was designed and implemented [6]. Also, a new high-speed HDTV contents delivery network with OSS was designed and implemented by using Ethernet/Optical Slot protocol converter as an edge node in OSS network [7].

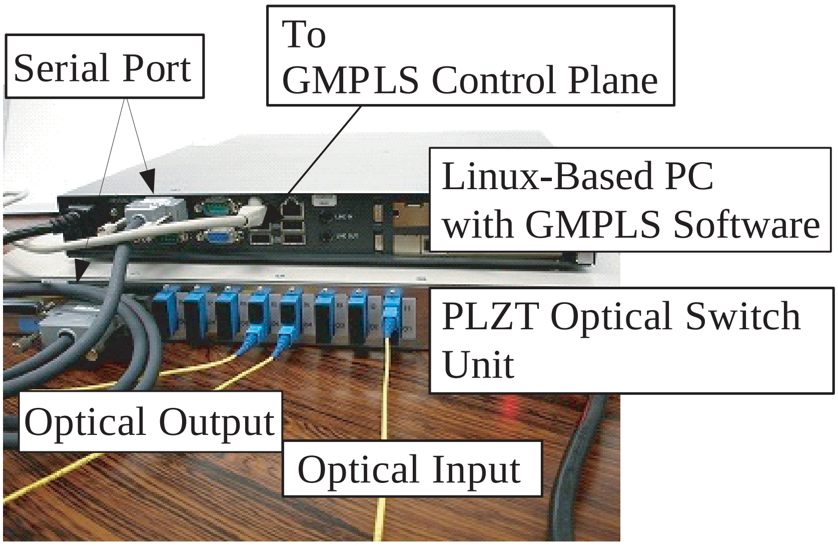

Figure A.3: An OSS node system.

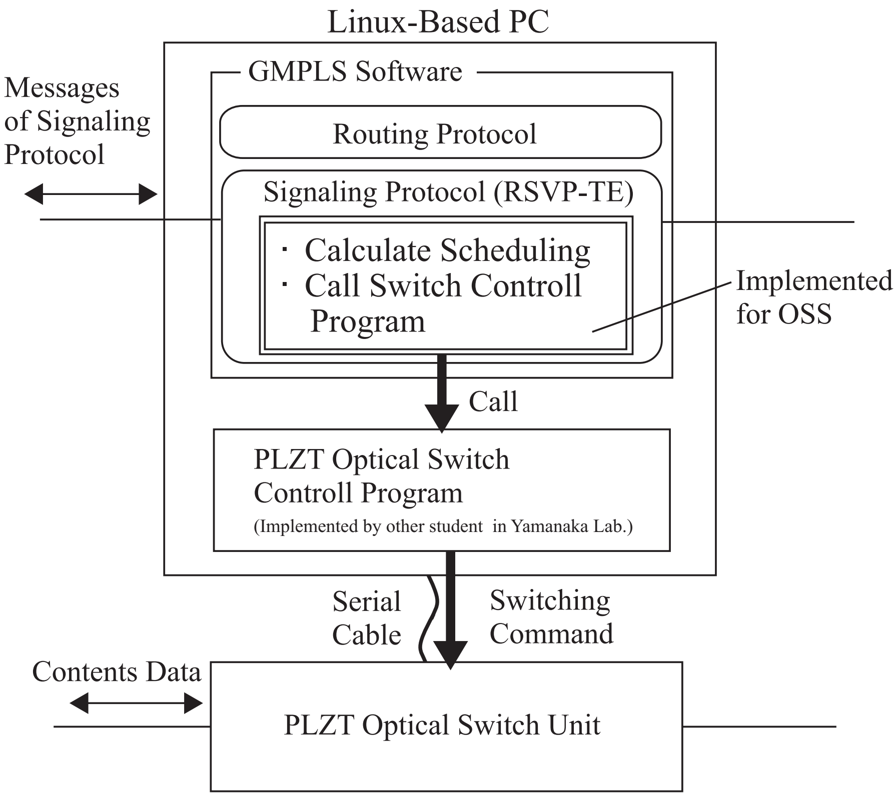

Figure A.4: A diagram of the OSS node system.

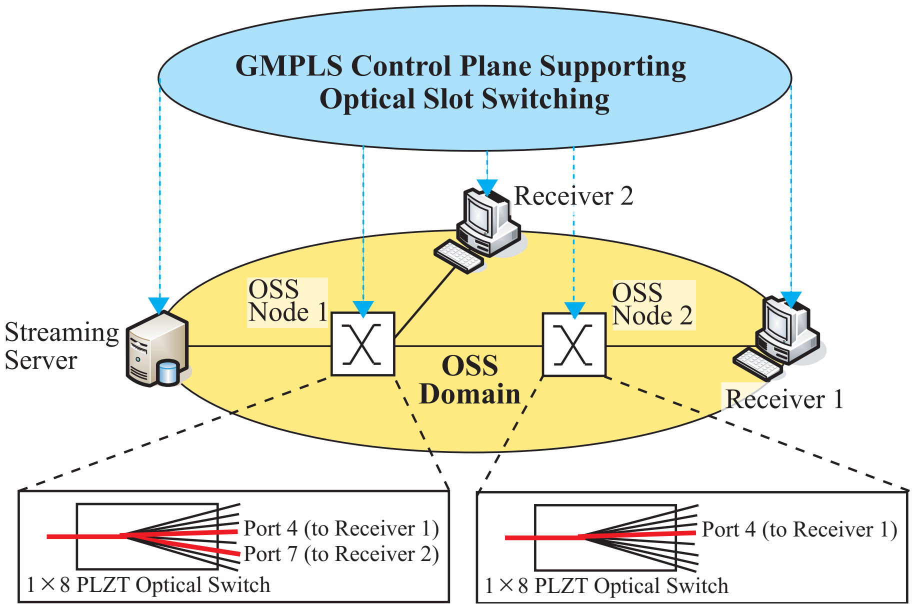

Figure A.5: An experimental OSS network structure.

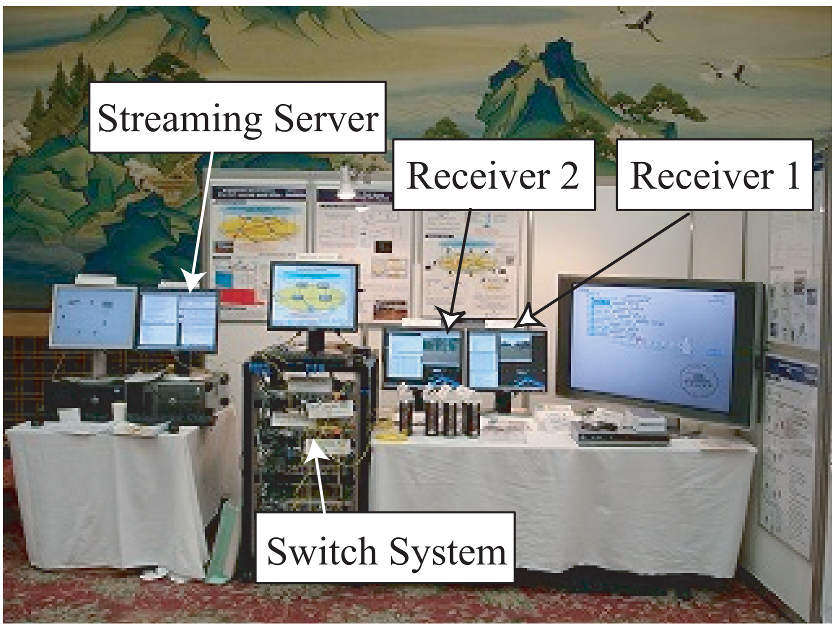

Figure A.6: A picture of the experimental network.

A.2 Interoperability Trial about the Next Generation Optical Network Control Technique

Interoperability trials about the next generation optical network control technique have been held. I have tested the interoperability of GMPLS software used in Yamanaka Lab. which I belongs to. In this section, the interoperability trials which I took part in are introduced.

A.2.1 Interoperability Trial about Signaling Interworking of Multi-carrier ASON/GMPLS Network Domains

GMPLS is a set of network control protocols to envision a next generation high performance transport networks. GMPLS based transport networks are divided into two categories. One is ITU-T's Automatically Switched Optical Networks (ASON) overlay network [8], and the other is IETF's GMPLS overlay and peer networks [4], [9]. Although both networks can use almost the same GMPLS protocols as an internal network to network interface (I-NNI) protocol [10], [11], their user network interface (UNI) protocols, so-called ASON UNI and GMPLS UNI, are slightly different from each other. Since the architectural choice of GMPLS networks differs among carriers, the consideration to introduce a GMPLS based external network to network interface (E-NNI) protocol is indispensable in order for carriers/service providers to provide a seamless end-to-end call set up service to all users without being restricted by the adopted network architecture.

In this trial, the interoperability was tested among four operators' total of seven ASON and GMPLS network domains. Figure A.7 shows the network domain overview. Seven network domains were interconnected by ASON E-NNI. Ten Gigabit Ethernet (GbE) E-NNI links and one Synchronous Transport Module-16 (STM-16) E-NNI

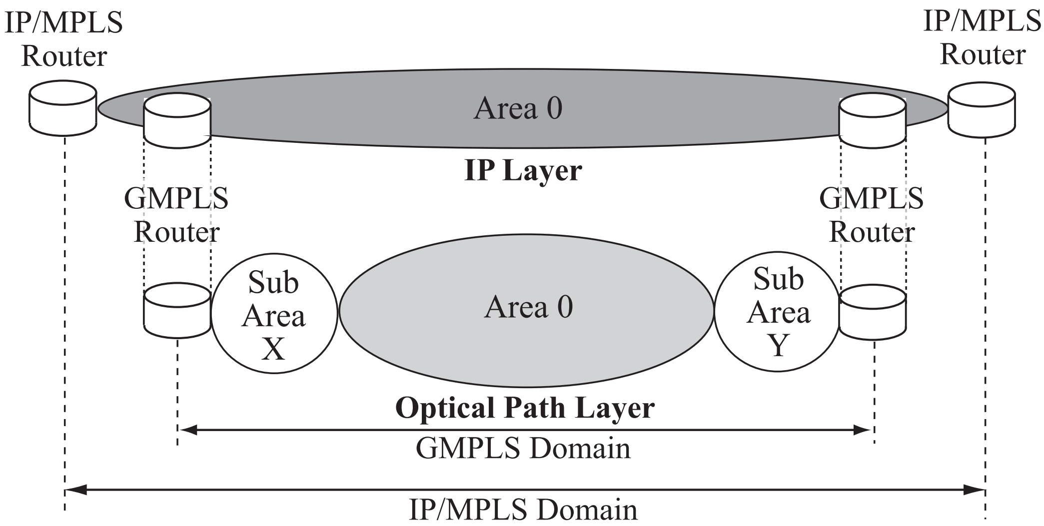

Figure A.7: The network domain overview.

link were created among domains. The evaluated overall network consisted of ASON and GMPLS trial networks by NTT Laboratories, a GMPLS trial network by KDDI Laboratories, ASON and GMPLS trial networks by NICT, and the NICT JGN II GMPLS network. This field trial of ASON and GMPLS interworking was conducted on a nationwide scale, and seamless call set up over multi-carrier domains over the distance of 1000 km or more was successfully achieved for the first time.

Next, the test about Keio node is explained. Figure A.8 shows the connection established via Keio node. Keio node locates in NICT GMPLS Domain. It is assumed that Keio node is a cross connect (XC). In this trial, Keio XC has only a control plane function, and doesn't have a device for data plane. TDM Label Switched Path (LSP) is established via Keio XC between NEC XC and Fujitsu XC by using Open Shortest Path First-Traffic Engineering (OSPF-TE) and RSVP-TE. Figure A.9 shows the results of OSPF-TE. It was confirmed that the process was executed correctly for connecting next nodes (NEC XC and Fujitsu XC). Figure A.10 shows an advertize of TE link information. From this figure, it is confirmed that the link information such as available bandwidth was transmitted. Figure A.11 shows

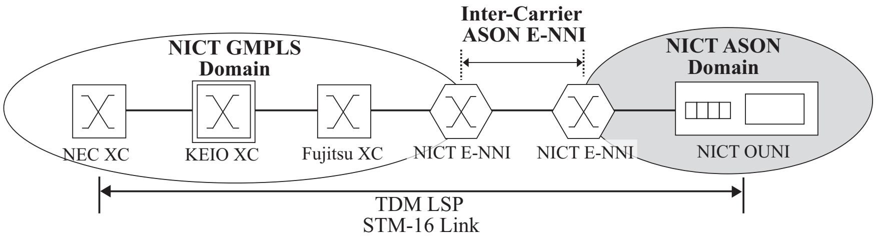

Figure A.8: The connection established via Keio node.

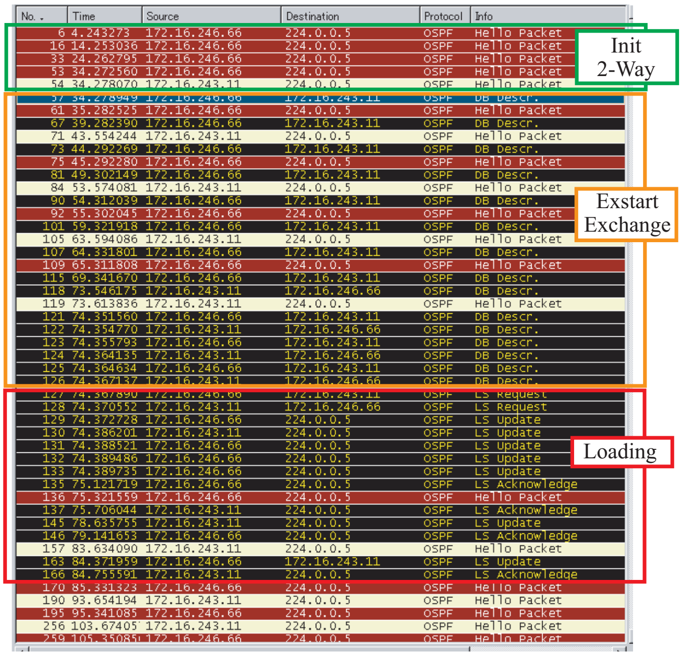

Figure A.9: The results of OSPF-TE.

the results of RESV-TE. Keio XC processed each signaling message as a transit node, and TDM LSP was established.

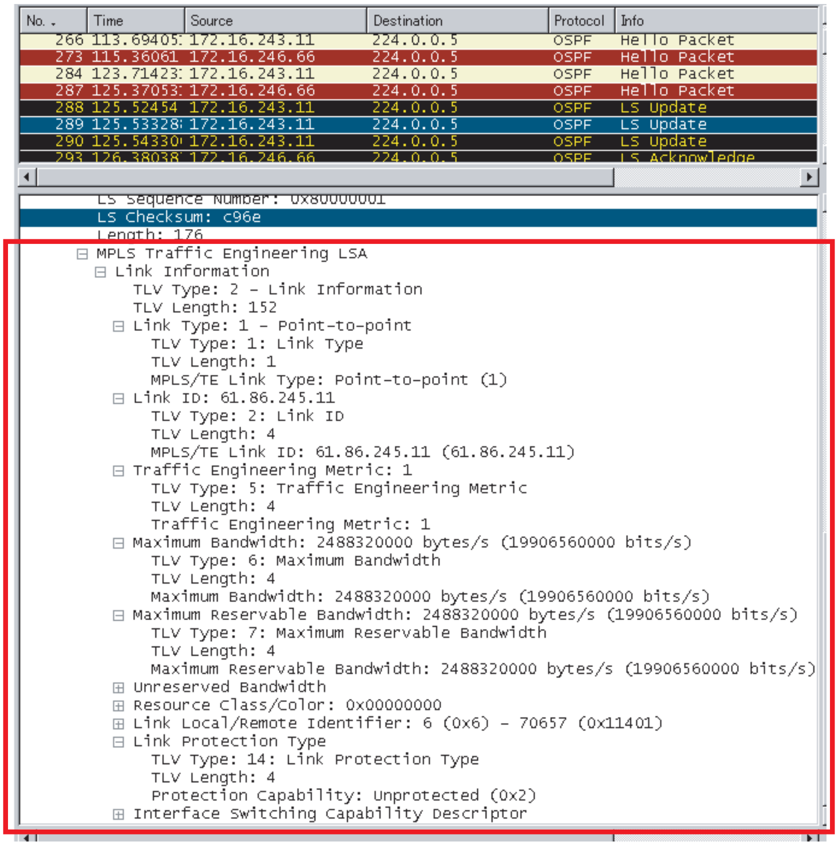

Figure A.10: An advertize of TE link information.

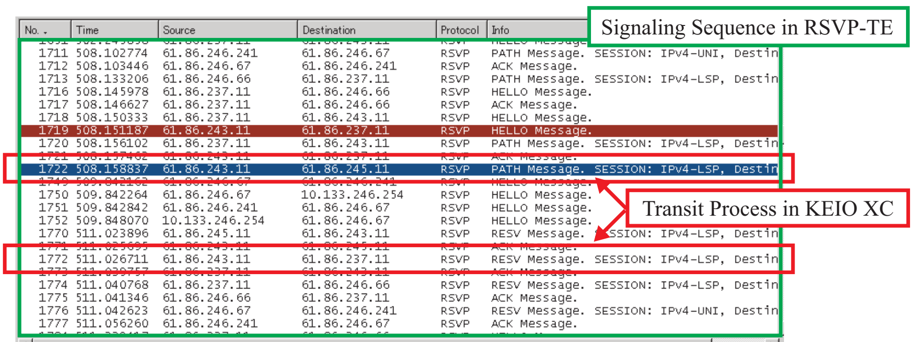

Figure A.11: The results of RESV-TE.

A.2.2 Multi-area MPLS/GMPLS Interoperability Trial in Packet / TDM / ROADM/ OXC Network

In this trial, multi-area MPLS/GMPLS interoperability was tested. The interoperability trial employs the interior gateway routing protocol (IGP) based multi-area routing architecture, which is unlike any previous trial employing single-area [12], [13], hierarchical [14], and inter-AS routing architecture [15]. This functional evaluation is quite important in overcoming the scalability limit of the single-area routing architecture and to the operation of hundreds of NEs within a nationwide carrier domain.

Figure A.12 shows an overview of the IGP routing architecture in the MPLS/GMPLS test-bed. The test-bed network, which comprises IP/MPLS routers, TDM-XCs, reconfigurable OADMs (ROADMs), OXCs, and (G)MPLS test equipment from 14 vendors, was constructed over a transpacific control network between the Toyo Corporation in Japan and the Isocore in the United States. The GMPLS layer comprises the backbone area and three sub-areas in the overall test-bed network. Figure A.13 shows a detailed configuration of the test-bed network. The network comprises STM-16, optical GbE, and STM-16/GbE multi-rate optical links. Keio node, which is an optical cross connect, locates in Area 3. This KEIO OXC works as a transit node in GMPLS network. A multi-area MPLS/GMPLS interoperability trial was successfully conducted using various types of network elements from 14 vendors for the first time.

In Yamanaka Lab., the interoperability test was tried between this multi-area MPLS/GMPLS network and Yamanaka Lab.'s Optical Slot Switching (OSS) network. Figure A.14 shows the network configuration. Keio OXC in Area 3 is connected to OSS node 1 and Receiver 2. To establish OSS path between Streaming Server and Receiver 2 is tested. As a result, it was that the connection was estab-

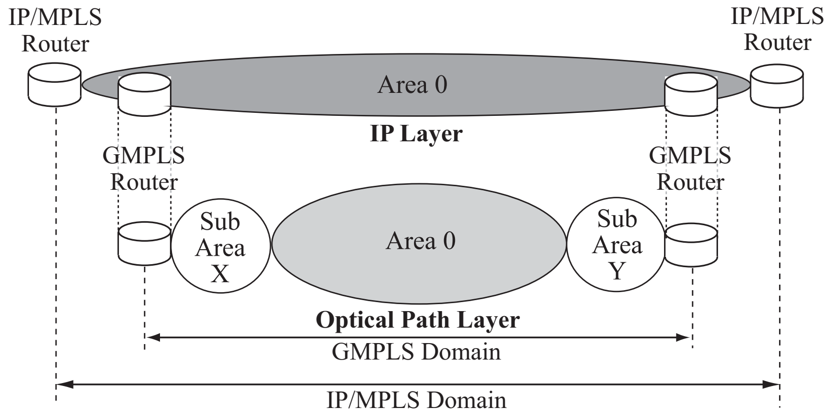

Figure A.12: An overview of the IGP routing architecture.

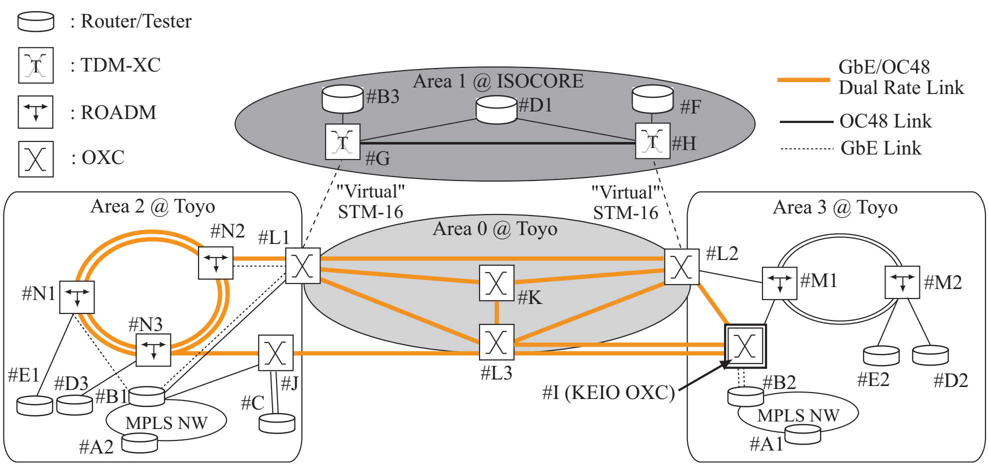

Figure A.13: A detailed configuration of the test-bed network.

lished by RSVP-TE in a control plane. However, in a data plane, the connection couldn't be established. It is thought that the connection between OXC device in Keio OXC and PLZT optical switch unit had some problems. This is a next challenge.

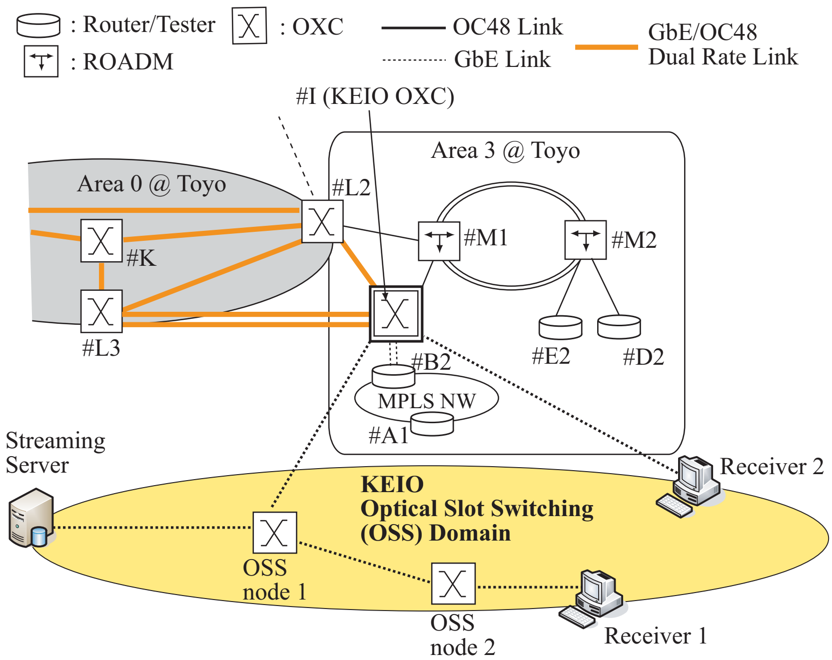

Figure A.14: A detailed configuration around Keio OSS domain.

A.3 An Experiment for Controlling Wide Area Ethernet by GMPLS supporting Layer-2 Switching Capability

High speed and large capacity Ethernet technologies have been developed as represented by GbE and 10 Gigabit Ethernet (10GbE). Currently, due to the growth of Ethernet technologies, Ethernet has been deployed in Wide Area Network (WAN) as well as Local Area Network (LAN). Therefore Wide Area Ethernet is focused on as a high performance transport network.

In Wide Area Ethernet network, an Ethernet private line (EPL) and an Ethernet virtual private line (EVPL) are major basic services. To realize EPL and EVPL, a connection is established by setting up Virtual LAN (VLAN). Therefore, the technique of setting up VLAN efficiently in a wide area is an important challenge.

In order to accomplish the challenge, an experiment of virtual private line setup over GMPLS controlled gigabit Wide Area Ethernet was held. Figure A.15 shows network architecture of gigabit Wide Area Ethernet. This network consists of a backbone domain and a provider domain. Provider edge/switching nodes are connected with GbE link. Backbone nodes are connected with 10GbE link. This 10GbE link accommodates several L2 LSPs from the provider domain.

A resource manager collects the resource information, such as available VLAN tags and bandwidth, of each node periodically. When a provider edge node receives an L2 LSP setup request, the node asks the resource manager to obtain the route information to the destination node. The resource manager calculates a suitable route and informs the route information such as node ID, port No., and VLAN Tag ID to the source node. Path Computation Element (PCE) [19] can be used as the resource manager.

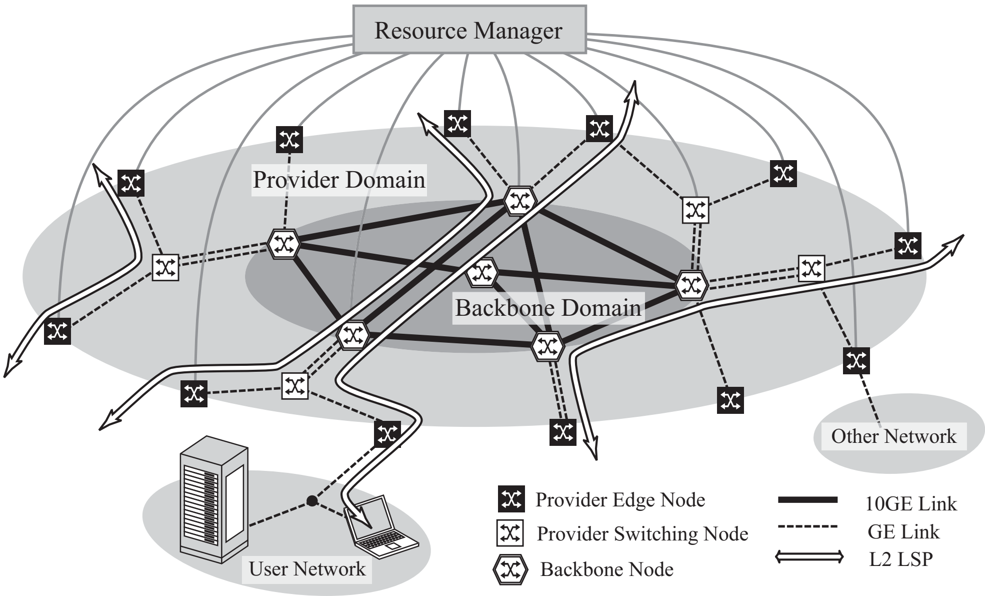

Figure A.15: Network architectrue of gigabit Wide Area Ethernet.

Figure A.16 shows the usage type of L2 LSP supposed in Wide Area Ethernet. Two VLAN types are used. One is tagged-VLAN, and another is untagged(port based)-VLAN [20]. In the backbone domain, several L2 LSPs are accommodated into one link. So, tagged-VLAN is used. In the provider domain, tagged-VLAN or untagged-VLAN is used based on the request of a user and the resource usage of each L2 switch. When a user requests to communicate with multiple destination nodes using one Ethernet interface, an L2 LSP consists of only tagged-VLAN, as shown in Fig. A.16(a), is applicable to establish an EVPL. When a user requests EPL i.e. untagged-VLAN, an L2 LSP shown in Fig. A.16(b) or an L2 LSP shown in Fig. A.16(c) is used based on the resource availability in the provider domain. When an L2 LSP can be established without the backbone domain, an L2 LSP consists of only untagged-VLAN shown in Fig. A.16(d) can be also applicable.

Figure A.17 shows an experimental network structure used in this trial. This network emulates a part of the Wide Area Ethernet network shown in Fig. A.15. Figure A.18 shows a picture of the setup experimental network. Four commercially

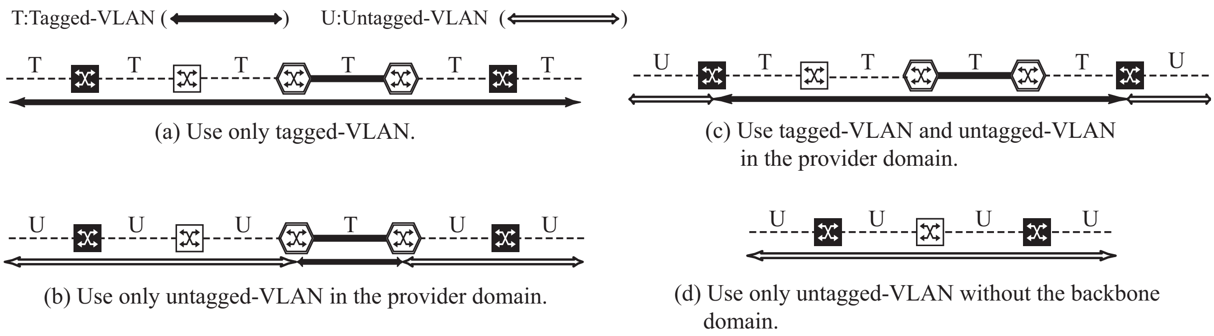

Figure A.16: The usage type of L2 LSP supposed in Wide Area Ethernet.

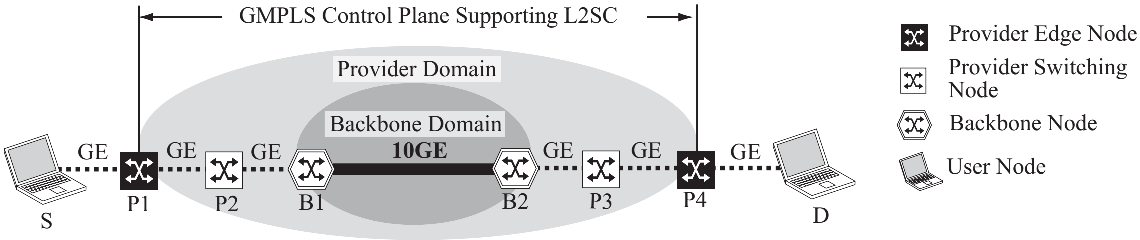

Figure A.17: An experimental network structure.

produced GbE L2 switches are used for a provider edge/switching node. Two commercially produced 10GbE/GbE L2 switches are used for a backbone node. Six L2 switches are controlled by six Linux-based PCs with GMPLS software via a serial cable.

In this experiment, four types of L2 LSPs between the provider edge node P1 and the provider edge node P4 are set up by using GMPLS, and the connection between the user node S and the user node D is established. RSVP-TE protocol is used as a signaling protocol. Figure A.19 shows a generalized label object format extended for supporting EPL and EVPL. In order to store VLAN configuration information in the label, 32-bits label information is divided into three fields. A label value is represented by decimal format and assigned to one digit for indicating a type of the Ethernet link (tagged=1 or untagged=0), three digits for representing a port

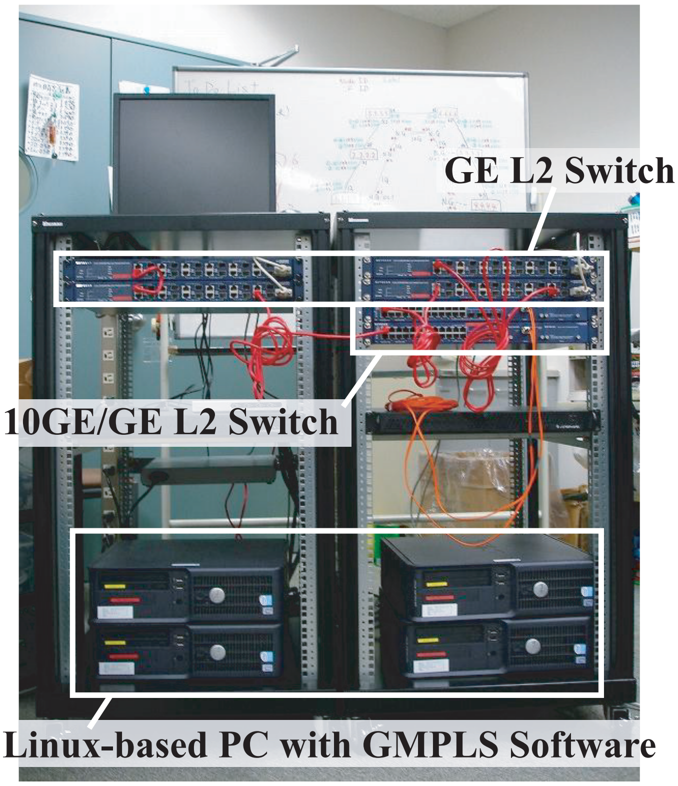

Figure A.18: A picture of the setup experimental network.

number of the L2 switch (0-999), and last four digits for representing VLAN ID (1-4094).

It is assumed that the route of the L2 LSP has been calculated by the resource manager, and each node can get the information about resources and labels. Under this assumption, the provider edge node P1 creates a PATH message with full strict explicit route object (ERO)s, and sends the PATH message to the provider edge node P4.

Table A.1 shows the list of successful L2 LSPs in this experiment. Four types of L2 LSPs shown in Fig. A.16 were successfully established. Also, it was confirmed that L2 switch was configured in conjunction with RSVP-TE protocol, and the requested VLAN was correctly set up. This results show that L2 LSPs supposed in Wide Area Ethernet can be established by using the label format shown in Fig.

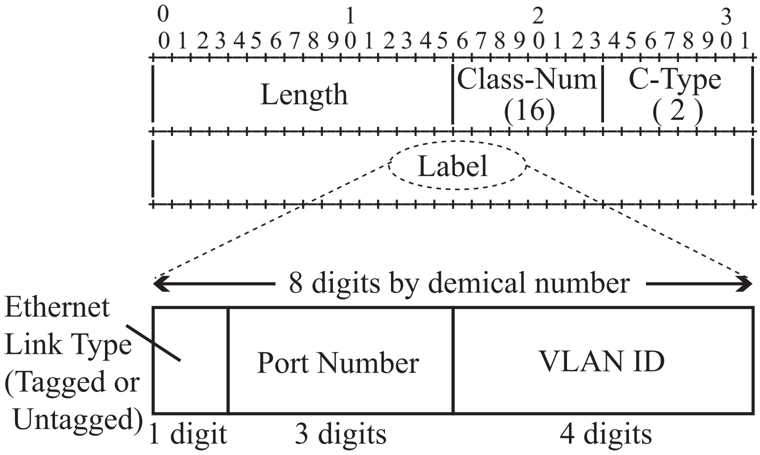

Figure A.19: A generalized label object format extended for supporting EPL and EVPL.

Table A.1: The list of successful L2 LSPs.

LSP \ Link	S-P1	P1-P2	P2-B1	B1-B2	B2-P3	P3-P4	P4-D
LSP1 (Fig.2(a))	T	T	T	T	T	T	T
LSP2 (Fig.2(b))	U	U	U	T	U	U	U
LSP3 (Fig.2(c))	U	T	T	T	T	T	U
LSP4 (Fig.2(d))	U	U	U	U	U	U	U

|←—— L2 LSP set up by GMPLS ——-→|

A.19. The experimental network was constructed with GbE links and 10 GbE links. Therefore, mixed processing of tagged-VLAN and untagged-VLAN for setting up the L2 LSP should be required not only on the provider edge switch but also on the backbone switch.

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List of the Related Papers

(As of October 20, 2008)

Journal Papers

Papers Related to this Ph. D. Dissertation

(1) **Daisuke Ishii**, Takahito Fujii, Yutaka Arakawa, and Iwao Sasase, "Fair Burst Drooping Technique for Optical Composite Burst Switched Multi-Hop Network," *IEICE Trans. Commun.*, vol.J87-B, no.6, pp.812-828, June 2004 (in Japanese).

(2) **Daisuke Ishii**, Naoaki Yamanaka, and Iwao Sasase, "Self-learning route selection scheme using multipath searching packets in an OBS Network," *Journal of Optical Networking*, vol.4, no.7, pp.432-445, July 2005.

Other Papers

(1) Takanori Ito, **Daisuke Ishii**, Kohei Okazaki, and Iwao Sasase, "A Scheduling Algorithm for Reducing Unused Timeslots by Considering Head Gap and Tail Gap in Time Sliced Optical Burst Switched Networks," *IEICE Trans. Commun.*, vol.J88-B, no.8, pp.1422-1433, Aug. 2005 (in Japanese).

(2) Hiroyuki Miyagi, Masahiro Hayashitani, **Daisuke Ishii**, Yutaka Arakawa, and Naoaki Yamanaka, "Advanced Wavelength Reservation Method based on

Deadline-Aware Scheduling for Lambda Grid Networks," *Journal of Lightwave Technology*, vol.25, no.10, pp.2904-2910, Oct. 2007.

(3) Masahiro Hayashitani, Teruo Kasahara, **Daisuke Ishii**, Yutaka Arakawa, Satoru Okamoto, Naoaki Yamanaka, Naganori Takezawa, and Keiichi Nashimoto, "10ns High-speed PLZT optical content distribution system having slot-switch and GMPLS controller," *IEICE Electronics Express*, vol. 5, no. 6, pp. 181-186, March 2008.

(4) Masahiro Hayashitani, Teruo Kasahara, **Daisuke Ishii**, Yutaka Arakawa, Satoru Okamoto, Naoaki Yamanaka, Naganori Takezawa, Keiichi Nashimoto, "GMPLS-based optical slot switching access-distribution network with a 10 ns high-speed PLZT optical switch,' ' *Journal of Optical Networking*, vol.7, no.8, pp.744-758, Aug. 2008.

International Conference Papers

(1) **Daisuke Ishii**, Takahito Fujii, Yutaka Arakawa, and Iwao Sasase, "Fair Burst Dropping Technique for Optical Composite Burst Switched Multi-Hop Network," *2003 IEEE Pacific Rim Conference on Communications, Computers and Signal Processing (PACRIM '03)*, pp.405-408, Victoria, Canada, August 2003. (Presented by **Daisuke Ishii**)

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