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A Study on Distributed Control Method for All-optical Networks

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Tatsuya Fukuda

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2. Tatsuya Fukuda and Ken-ichi Baba, “Network designs for cycle-attack-free logical-tree topologies in optical CDM networks,” *IEICE Transactions on Communications*, vol.E96-B, no.12, pp.3070-3079, Dec. 2013.

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4. Tatsuya Fukuda, Ken-ichi Baba and Shinji Shimojo, “A study on hybrid optical network architecture with OCDM technology,” in *IEEE International Conference on Communications (ICC2012)*, Jun. 2012, pp.3144–3148.
5. Tatsuya Fukuda and Ken-ichi Baba, “Establishing paths on hierarchical logical topologies in OCDM networks,” in *Proceedings of IEEE/IFIP 8th International Conference on Wireless and Optical Communications Networks (WOCN2011)*, May 2011, pp. 1–5.
6. Tatsuya Fukuda and Ken-ichi Baba, “A path establishment method using autonomous logicaltree topology in OCDM networks,” in *Proceedings of 36th European Confer-*

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1. Tatsuya Fukuda, Ken-ichi Baba and Shinji Shimojo, “Restoration method for hierarchical logical topology in distributed controlled OCDM networks,” in *IEICE Technical Report (PN2013-9)*, vol. 113, Aug. 2013, pp. 7-12.
2. Tatsuya Fukuda, Ken-ichi Baba and Shinji Shimojo, “A construction and transmission method of optical broadcast network with OCDM technology,” in *IEICE Technical Report (PN2012-84)*, vol. 112, Mar. 2013, pp. 37-42 (Encouraged Talk).
3. Tatsuya Fukuda, Ken-ichi Baba and Shinji Shimojo, “A construction method of optical broadcast network with OCDM technology,” in *IEICE Technical Report (PN2012-18)*, vol. 112, Aug. 2012, pp. 23-28 (Best Paper Award under 30 age).
4. Tatsuya Fukuda, Ken-ichi Baba and Shinji Shimojo, “Performance evaluation of OCDM based hybrid network,” in *IEICE Technical Report (PN2011-82)*, vol. 111, Mar. 2012, pp. 1-6.
5. Tatsuya Fukuda and Ken-ichi Baba, “A study on hybrid network architecture with OCDM technology,” in *IEICE Technical Report (PN2011-13)*, vol. 111, Aug. 2011, pp. 7-12.
6. Tatsuya Fukuda and Ken-ichi Baba, “A path establishment method with hierarchical logical topology in OCDM networks,” in *IEICE Technical Report (NS2011-39)*, vol. 111, May 2011, pp. 127-132.
7. Tatsuya Fukuda and Ken-ichi Baba, “A path establishment method using autonomous logical tree topology in OCDM networks,” in *IEICE Technical Report (PN2009-87)*, vol. 109, Mar. 2010, pp. 7-12.

Summary

Increasing demands from broadband services requiring high data rates, high degrees of reliability, and shorter delays. Current IP-based electrical switching network faces the difficulty to satisfy these user demands. Therefore, all-optical network is now considered as future backbone network since it can support wide bandwidth, lower propagation delay time and transparent data transmission compared to the current IP-based electrical switching network.

Conventional all-optical network bases fixed-grid wavelength division multiplexing (WDM) technology standardized by International Telecommunication Union Telecommunication Standardization Sector (ITU-T). However, conventional WDM networks have three large issues to use network efficiently and satisfy variety of user requests when user requests arrives at the network dynamically. First, since WDM networks tend to assign too large bandwidth for each connection request, it is difficult for one end-to-end connection to use the entire bandwidth of a wavelength. Therefore, much research attention has been paid to multiplexing technologies that can provide finer granularity bandwidth allocation. Second, since conventional all-optical network architecture assumes to use optical circuit switching (OCS) technology for data transmission, the lightpath setup time becomes large overhead unless the established lightpath holds long enough time. It is also important to consider an architecture that can transmit data traffic without setting up lightpaths for short holding time request. Third, when the requested bandwidth is huge, conventional OCS networks require to establish two or more lightpaths for one request. This leads to waste the network resource such as spectrum for guard band between assigned frequency and computational resource to process more control messages. Therefore, the network architecture that can assign bandwidth flexibly according to the requested bandwidth is required.

In this thesis, control methods for finer granularity all-optical OCS networks are considered. The goal of this thesis is to achieve distributed controlled all-optical network and to improve the network efficiency to assign bandwidth and transmission technology according

to the characteristics of user requests. Distributed control is well suited for dynamic traffic all-optical network which need to setup and release lightpaths in real time. First, each network controller handles only the information concerning associated optical switch and its neighboring nodes. In other words, the number of network nodes and links do not affect to the controller complexity. Second, distributed controllers are durable about network component failures. These characteristics are very suited for dynamic traffic all-optical network which need to setup and release lightpaths in real time.

To address three issues of conventional WDM networks with distributed control, we discuss three network designs. First, we discuss distributedly controlled OCDM network to assign bandwidth with finer granularity. Second, we discuss hybrid optical network which has additional network plane to transmit data without establishing lightpaths to avoid lightpath setup time overhead for short holding time requests. Third, we discuss flexible bandwidth optical network which can assign just enough bandwidth for each connection request.

We first discuss the distributed control architecture for finer granularity OCS network with OCDM technology. OCDM network has multi-access noise loop back problem called “cycle attack.” If a cycle attack occurs, all network traffic are disrupted due to the accumulated noise. We propose methods that prevent cycle attack by constructing cycle-free logical topology. We also propose lightpath establishment methods for each constructed logical topology with distributed controllers. The results of quantitative evaluation of the proposed methods shows better performance than the conventional centralized controlled approach in terms of call loss probability and mean hop count.

Second, a hybrid optical network architecture that combines optical broadcast networks with conventional OCS networks is proposed. The idea of hybrid optical network, which use two or more communication technology for transmission to achieve better performance, requires to use additional specific devices for each communication technology. We logically construct an optical broadcast network that starts data transmission without lightpath establishment on the same physical device of the OCS network. In the simulation, we demonstrate our proposed hybrid optical network which uses optical broadcast network for short holding time connections and OCS network for long holding time connections. Simulation results reveal that our proposed hybrid optical network is very effective in reducing the call loss probability. Also, in conventional cycle-free logical topology, optical broadcast traffic makes collision at the junction. To avoid collision among broadcast traffic, contention-less logical topology which has no junction for each channel for optical broadcast network is proposed. The results show that the proposed contention-less topology dramatically reduces the call loss probability when the network offered load is low.

Finally, we propose a fully distributed control architecture for flexible bandwidth optical network called elastic optical networks (EONs). Different from OCDM network, EON can assign bandwidth flexibly for each connection request. Our proposed architecture extends conventional GMPLS signaling for WDM network in terms of both of signaling and routing, modulation format and spectrum assignment for flexible bandwidth network. Our proposed algorithm can establish lightpath with fully-distributed manner while conventional approaches require sharing information about available frequency range and topology shape during all network nodes. Simulation results reveal that our proposed algorithm achieves lower blocking probability and shorter lightpath establishment time compared with the conventional solutions for EONs.

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1

Introduction

1.1 Background and Motivation

The exponential growth on the Internet traffic and the diversifying service demands from network users are driving the need for scalable and resource-efficient networking technologies. For instance, emerging applications such as ultra-high-definition video multicast or mirroring and backing up data between data centers will require high-bandwidth Tb/s applications on demand across long transmission distances. However, current IP-based networks are limited as far as meeting these requirements go. If we control routing in the electrical domain, we experience large delays due to optical-to-electrical (OE) and electrical-to-optical (EO) conversion. Electrical switching also needs more electrical energy than optical switching does. Therefore, satisfying the above requirements would entail constructing all-optical networks [1, 2].

Since an all-optical networks differ in many aspects from the current optical-electrical-optical (OEO) switching networks, there are many issues that should be addressed [3]. If we use optical packet switching (OPS) for all-optical networks [4, 5], we need optical buffers to store and forward optical packets; however, there is no optical memory for buffering optical packets in the optical domain [6]. Many researchers are studying the possibility of using fiber delay lines (FDLs) [7] and wavelength converters [1] in OPS networks, however, there are many technological problems that must be overcome before they can be implemented in an actual network. For the above reasons, applying OPS directly to the future optical network will be difficult. Therefore, optical circuit switching (OCS) technology, which connects end nodes to each other using optical multiplexing technologies and pre-configures the transfer route, is now attracting attention as a near-term solution for all-optical networks. In this thesis, we refer to a pre-configured propagation route as a “lightpath,” which connects a

source node to a destination node, and we call the propagation route divided by the optical multiplexing technology, e.g. a wavelength on a WDM network or a time slot on a TDM network, as a “channel.”

Current all-optical networks assigns fixed-grid wavelength channel divided by wavelength division multiplexing (WDM) for each connection request in OCS network [1, 2]. These fixed-grid are already standardized by International Telecommunication Union (ITU) and provide large bandwidth for each connection setup request. All-optical WDM networks are constructed with reconfigurable optical add drop multiplexers (ROADMs) [8], optical cross connects (OXC) , and optical fibers. ROADMs are used for edge network nodes to insert or output an optical signal to the network. OXCs are used for the core network nodes to switch optical signals without optical-electrical-optical (OEO) conversion. These components are pre-configured before the actual data transmission. All-optical WDM network can support not only broadband data rate bandwidth but also support format and protocol transparency.

There are two approaches to controlling OCS networks: centralized control and distributed control. In centralized control networks, a centralized controller collects information from all of the network nodes [9]. However, because all transmission requests must be managed by a centralized controller, the controller demands considerable computational resources and faces difficulty scaling the network size. In distributed control networks, each network controller handles only the information concerning itself and its neighboring nodes [10, 11]. Unlike centralized control networks, distributed controllers are durable about network component failures, and it is easy to scale the network size. Therefore, distributed-control networks are considered more suitable for future all-optical networks. From the above perspectives, we assume that distributed control can be used for dynamic traffic networks.

However, conventional fixed-grid WDM OCS network has three serious issues. First, although the conventional fixed-grid WDM technology can support beyond Tb/s data rates, it faces difficulties in accommodating dynamic bandwidth demands from many emerging applications across the network [12–16]. In particular, if the lightpath does not use the bandwidth fully, the data transmission requirements from users cannot be accepted until the channel is released. In the current WDM network, each lightpath is assigned a wavelength grid which is set has equal intervals a fixed bandwidth. This architecture may reduce network efficiency because the assigned bandwidth could be too large for users. Therefore, it is difficult that a connection request uses entire bandwidth of the channel. Furthermore, even if the request does not fully use the bandwidth, other requirements do not use the remaining bandwidth. Consequently, the network efficiency decrease.

Second issue for the all-optical network is the time overhead for establishing a lightpath. In distributed controlled OCS network, the source node tries to establish a lightpath to transmit data traffic [10, 11, 17]. In this lightpath establishment phase, since a reserve message checks the unused channel and reserves a channel hop by hop, the time it takes to establish a lightpath exceeds the round-trip time for reserving channels and returning the acknowledgment to the source node. Therefore, when the bandwidth per channel is large and the transmission data size is small (i.e. the data transmission delay is much smaller than the data propagation delay), this overhead will become too large to ignore. Since the data stream does not start to transmit until the acknowledgment arrives at the source node, the time overhead on each link is larger than the round trip time. One of the solutions for this issue is to start transmitting data traffic without establishing a lightpath.

Third issue for the all-optical network is that it requires to establish two or more lightpaths for one request if the requested bandwidth is larger than the wavelength channel. As a result, the network requires more resources such as guard band between assigned bandwidth or computational resource to process control messages. Therefore, it is important to implement network technology which can assign bandwidth flexibly.

To assign bandwidth in finer granularity, optical code division multiplexing (OCDM) networks [13, 18–24] has attracted much attention. OCDM technology uses optical correlation to discriminate source-destination pairs (SD-pairs). OCDM networks use specific code sets that have a high auto-correlation peak pulse and a low cross-correlation peak; the maximum value of this cross-correlation peak is lower than the specific threshold [25, 26]. Therefore, if the destination node uses the same code as the received signal, it can decode the signal. We assume OCDM-path [13], which encodes each bit in the payload using an optical code (OC), is considered to be a lightpath for OCDM networks. OCDM optical cross connects (OCDM OXCs) can work asynchronously and do not need a buffer since the entire payload is encoded. OCDM OXCs [13] also can swap their OC in the optical domain by setting up each switching node during the signaling phase. Therefore, the flexibility of channel assignment for each connection request improves dramatically, and we can expect to achieve low call loss probability. This also means that intermediate nodes can decide which OC to assign for a request. This characteristic is well suited to the distributed controlled network, where each controller implemented with a switching node has only its local information. In addition, OCDM technology can enhance network security [27, 28]. Architectures of OCDM network are described in references [12, 29, 30]. Data transmitted through the network are multiplexed by distinct codes and multiplexed again by wavelength. We call such lightpaths established in OCDM networks “label switching paths (LSPs)” in this thesis.

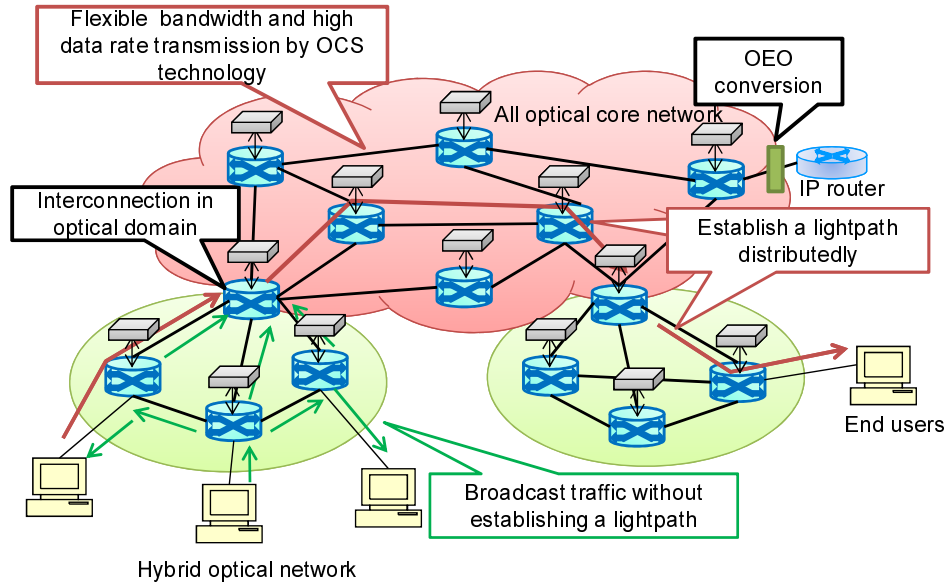


Figure1.1 Image of future all-optical networks

To start transmitting data traffic without establishing a lightpath, hybrid optical network architecture is considered as a good solution. “Hybrid optical network” is defined as a network constructed of two or more communication technologies utilizing their respective advantages. In our proposed hybrid optical network, we propose optical broadcast transmission that can be implemented by extending OCS control plane architecture. After that, we select the OCS network for long holding time data traffic to provide highly reliable and contention-less data transmission, and we select the newly proposed optical broadcast network for small-sized data traffic to provide a shorter time overhead before transmitting the data stream.

To assign flexible bandwidth for data transmission request, elastic optical networks (EONs) [14, 15] has attracted much attention. Instead of using DWDM wavelength channels on fixed-grid WDM, EONs can assign flexible and elastic waveband for a spectrum assignment process. EONs has two different characteristics from conventional WDM networks. First, the optical spectrum can be divided up flexibly. Second, the transceivers can generate variable bit rate paths. The research for EONs has been dramatically progressed in these years, the ITU-T has already started to extend WDM normative documents to flexible frequency grids.

In this thesis, we propose new network architectures for all-optical networks with distributed control (see Fig. 1.1). The goal of this is to achieve distributed controlled all-optical network and to improve the network efficiency to assign bandwidth and transmission technol-

ogy according to the characteristics of user requests. In Chapter 2, we propose a fine grained OCDM network with avoiding multi-access noise loop back problem called “cycle attack.” In Chapter 3, we address the lightpath establishment overhead problem by constructing hybrid optical network which has optical broadcast transmission in addition to conventional OCS transmission. In Chapter 4, we propose a fully distributed control architecture for EONs. Finally in Chapter 5, we conclude this thesis and discuss future direction.

1.2 Related Work and Technologies

1.2.1 All-Optical Transmission Technologies

In this section, we explain the transmission technologies which are needed to design all-optical network. All-optical transmission technologies are classified to OCS technology, optical burst switching (OBS) technology and OPS technology by its data transmission unit.

Optical Circuit Switching (OCS) technology

The OCS network is the easiest technology to implement all-optical network among three transmission technologies. The data are transmitted cut-through in the optical domain after all switches are set up for lightpaths. Therefore, the OCS network needs small implementation cost and easy control. In addition, since the lightpath occupies the whole bandwidth of the channel, there is no contention between any lightpaths. Thus, the OCS network can transmit data with low data propagation delay and high reliability. Generally, OCS network is divided two plane; a control plane and af data plane. The control plane checks unused channels and channel assignments for lightpaths with the electrical control such as generalized multi-protocol label switching (GMPLS) protocol.

The data plane transfers data in the optical domain along the established lightpath. When data connection setup request occurs at a source node, the source node transmit a lightpath establishment requirement to the destination node on the control plane. The algorithm to assign channels and a route to a lightpath is discussed in the specific research area like routing and wavelength assignment (RWA) [31].

Channel reservation method is divided forward type reservation and backward type reservation [32] (see Fig. 1.2). At the forward type reservation method, the source node transmits a *reserve message* and the intermediate nodes which are received the *reserve message* assign a channel and an output port to the lightpath. If the output port has no unused channel, the intermediate node transmits a *NACK message* and a *release message* toward the

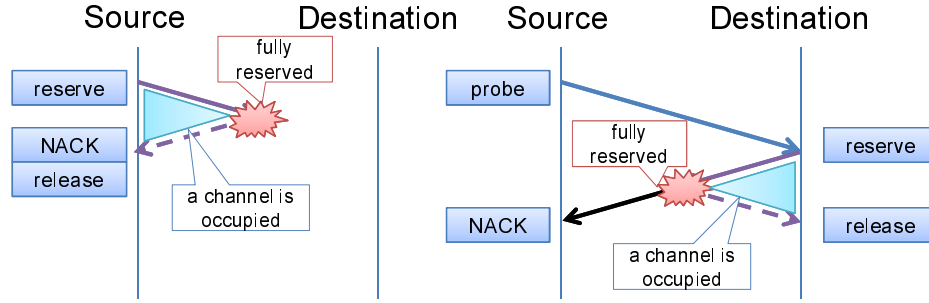


Figure1.2 Channels reservation method; (a) Forward reservation; (b) backward reservation

source node. The *NACK message* tells that the lightpath establishment is failed to the source node and the *release message* releases channels which are assigned for the lightpath. The *reserve message* arrives at the destination node, and the destination node checks all channels of the route are reserved, the destination node returns an *ACK message* toward the source node. The source node starts to transmit data traffic after the node is received the *ACK message*. In contrast, at the backward type channel reservation method, a source node transmit a *probe message* to a destination node. The *probe message* checks the unused channels and is transferred along the establishing lightpath. After the *probe message* arrives at the destination node, the destination node transmits a *reservation message* to the source node along to the route that the *probe message* was transferred. After this *reservation message* arrives at the source node, and the source node check all channels on the lightpath are reserved, the source node starts to transmit data traffic.

In OCS transmission, there is no contention between any lightpaths. On the other hand, since each lightpath occupies all bandwidth of the channel, if data traffic does not fully use the bandwidth, other data traffics do not use the remaining bandwidth. Furthermore, establishing a lightpath in OCS network takes exceeds the round-trip time. Therefore, the overhead time to establish lightpath is large relatively when the data transfer duration time is small.

Optical Burst Switching technology

OBS transmission [33, 34] is the compromise transmission technology between OCS transmission and OPS transmission. In OBS transmission, each data traffic is switched not by a unit of lightpath but a unit of optical burst. Different from the OCS transmission, OBS transmission achieves the multiplexing gain because it reserves channels by the unit of data burst. On the other hand, OBS transmission switches the unit of a certain amount of data, it has lower control overhead than OPS transmission. Figure 1.3 shows the distributed signaling

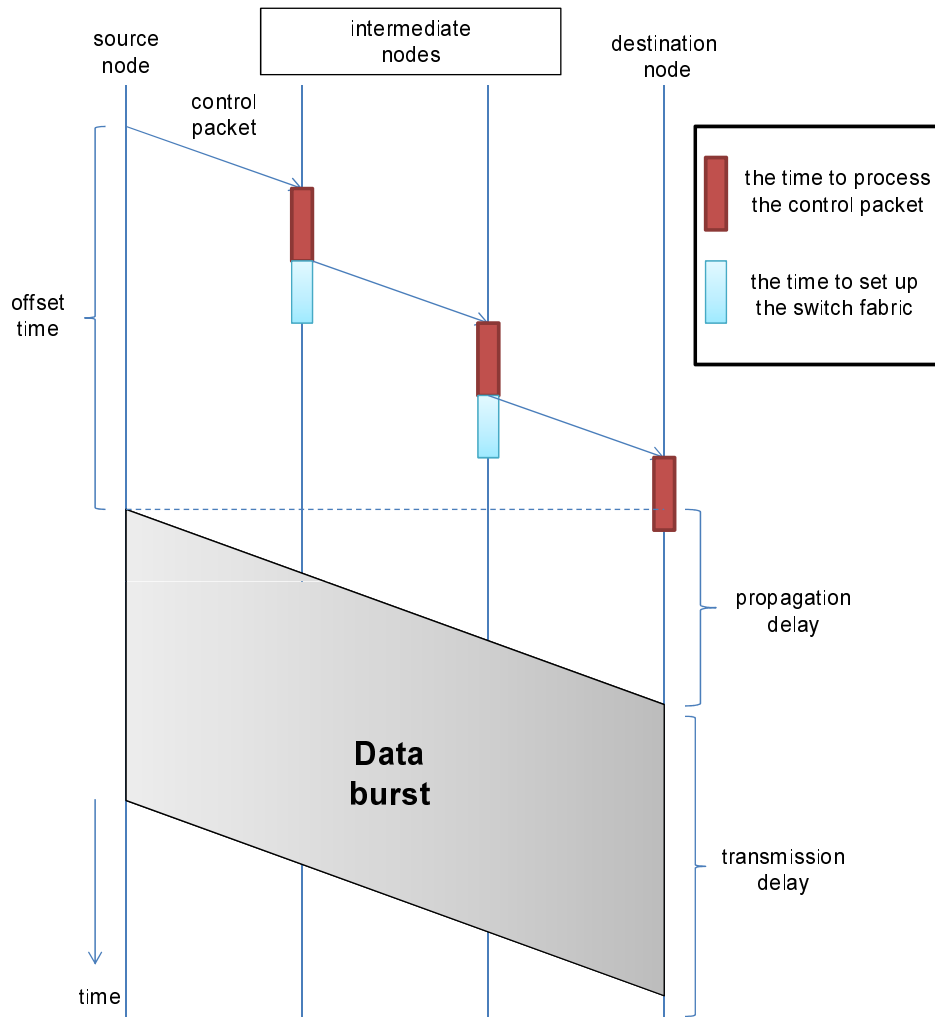


Figure1.3 Distributed signaling in OBS network

in OBS network.

The OBS transmission assigns and releases channels by signaling and “estimating offset.” Offset means the waiting time to transmit data traffic after control messages are transmitted. Therefore, the OBS transmission has the advantage that the time overhead to setup switches to transmit data compared to the OCS transmission. In addition, the OBS transmission is easy to use a channel fully because it assemble the data traffic which have the same destination node. On the other hand, since the OBS transmission start to transmit data traffic without checking that all links on the route is assigned their own channel or not, it does not guarantee that the data burst has arrived at the destination node. Therefore, if the network offered load is very high and the total number of channels are not enough, the network performance may be reduced critically. In addition, since the OBS network assemble data traffic at the edge node of the network, a data traffic is forced to wait to transmit itself at the edge

node.

Optical Packet Switching technology

The OPS transmission [5] is the likeliest transmission to the current IP based electrical packet switching networks. The OPS transmission has similar to the OBS transmission at the point which supports the burst type data traffic efficiently by not multiplexing its gain. The main difference from the OBS transmission is that the OPS transmission does not need to assemble and dismantle a data burst at the edge node of the network. Therefore, compared to the OBS network, the OPS transmission can save the number of channels, transmitters, receivers and it does not need to estimate the appropriate offset. If the network is not controlled by the network manager, this characteristic becomes a very important advantage. On the other hand, OPS transmission does not route intelligently like a current electrical router. This is because there is no optical random access memory for buffering optical packets, and current optical technology cannot do the complicated logical operation in the optical domain. In addition, since OPS switches need to read a header and setup the switch fabric before data payload arrives; it needs the advanced optical devices which can change the switch fabric in very short term.

Figure 1.4 shows the image of three optical networks; OCS network, OBS network, and OPS network. The OPS network is difficult to apply to all-optical network because it has many technological issues for contention avoidance. The OBS network is also not suited for the LAN network. The advantage to assembling data burst is small because most end nodes are the end user. In addition, the time overhead to assemble a data burst cannot ignore. Therefore, OCS transmission is suitable for our assumed network.

1.2.2 Multiplexing Technologies

In OCS transmission, multiplexing technologies like WDM, optical time division multiplexing (OTDM), optical code division multiplexing (OCDM) and optical orthogonal frequency division multiplexing (OOFDM) are used for a fiber with many lightpaths simultaneously. The switching granularity and control complexity of OCS network changes depending on the applying multiplexing technology.

In general, all-optical network is implemented with one or more of these multiplexing technologies. WDM technology is mostly used and researched currently [35, 36]. In the current WDM network, each lightpath is assigned on a frequency grid which is set at even intervals and assigned a fixed bandwidth [2]. WDM network can implement easily because

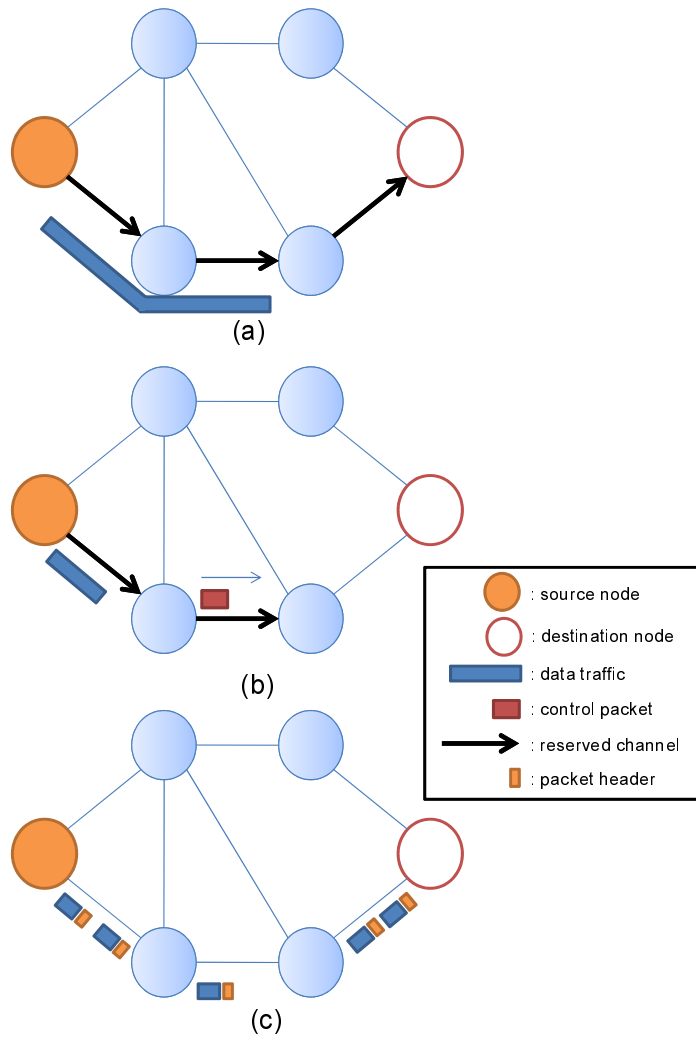


Figure1.4 All optical network ; (a) OCS network, (b)OBS network, (c)OPS network

the network can implement with variable bandwidth laser and optical filter. However, this architecture may reduce network efficiency because the assigned bandwidth could be too large, and it is difficult to use the entire bandwidth.

OTDM technology detects channels and switches by the unit of even interval time. This unit of time is called “time slot.” In general, OTDM technology is used for dividing a Wavelength channel of WDM technology to more fine grained channels. Since all network node need to be strictly synchronized to detect the time slot, the implementation becomes difficult as the network becomes high speed. This is because the time scale to control becomes short.

OCDM technology detects channels and switches by the unit of specific code word [22–24]. Network traffics in the OCDM network are encoded on the transmitter and decoded on the receiver by using optical correlation. OCDM code words have the characteristics that

which have high auto-correlation peak and low cross-correlation sidelobes [25–27, 37–41]. Since this encoding and decoding are worked by passive devices, the OCDM network can work asynchronously and can be implemented easily. Therefore, to multiplex wavelength channels by OCDM technology, we can use more fine granularity lightpath establishment without losing the advantages of WDM technology like asynchronous, fast switching and easily implementation. On the other hand, if we assign a large bandwidth request, OCDM network need to setup multiple lightpaths for one request.

Optical OFDM technology is another solution for very large bandwidth assignment problem by providing subwavelength granularity. In optical OFDM networks, variable bit-rate multi-carrier modulation technology [9, 42, 43] is used to assign a flexible bandwidth lightpath for each connection request. Optical OFDM technology also can combines variety of modulation format to assign more bandwidth with lower frequency range. Different from the OCDM network, optical OFDM network can assign just enough bandwidth for any requested bandwidth. Networks that can assign flexible bandwidth are called elastic optical networks (EONs). However, EONs suffer from the constraint of spectrum continuity, which means all lightpaths need to use the same frequency slots along the route from a source node to a destination node [10, 11].

From above reasons, OCDM over WDM network [13, 18–21] and EONs [9, 42, 43] are suitable for the distributed controlled all-optical network.

1.3 Research Overview

This research aims to investigate three steps of network architecture with finer granularity multiplexing technology to achieve distributed controlled all-optical network and to improve the network efficiency to assign bandwidth and transmission technology according to the characteristics of user requests. Figure 1.5 depicts the overview of this thesis. In Chapter 2, we discuss about fine Granularity OCDM network with avoiding cycle attack. The results of this chapter contribute to achieve finer granularity all-optical network. In Chapter 3, we discuss about distributed hybrid optical network to address the lightpath establishment overhead problem. The results of this chapter contribute to achieve application oriented transmission, that is, the network provide different types of transmission technology according to the characteristics of user request. And finally, in Chapter 4, we discuss distributed elastic optical network which can assign bandwidth flexibly. The results of this chapter contribute to achieve flexible bandwidth assignment for each request.

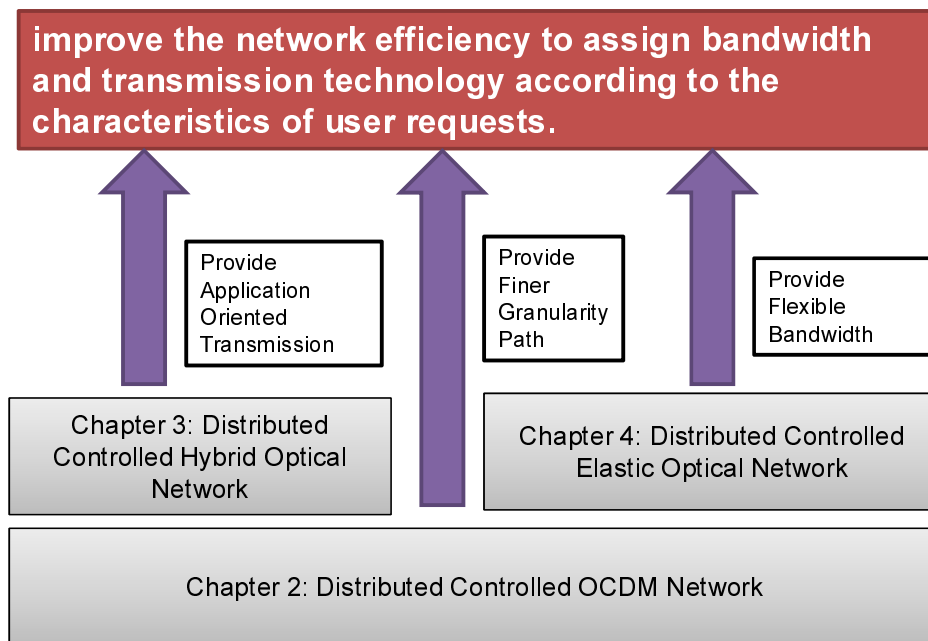


Figure1.5 Research overview

1.3.1 Finer Granularity Optical Network

OCDM circuit switching networks are now considered one of the fine grained network architectures for all-optical networks. Since OCDM networks can be easily controlled and establish lightpaths with smaller granularity, they are well suited for distributed controlled networks. However, previous research has reported that OCDM networks suffer from a cycle attack problem [29]. A cycle attack is a crosstalk noise loop-back problem that can propagate (see Fig. 2.3). Multi-access interference (MAI) is the dominant noise source in OCDM networks. Current all-optical techniques of regeneration cannot remove this MAI from intermediate nodes if no optical-electrical and electrical-optical conversion is allowed in the network [44, 45]. Therefore, MAI will propagate from one lightpath to other lightpaths. Furthermore, if MAI propagates through other lightpaths and loops back to the lightpath causing it, a MAI propagation cycle is formed. Moreover, if a MAI propagation cycle is formed, MAI accumulates endlessly, and no encoded signals can be decoded, which renders the network useless.

In Chapter 2, we introduces the finer granularity optical network using OCDM technology for multiplexing technology. Although, OCDM networks can setup finer granularity lightpath than conventional WDM networks, these network suffer from the cycle attack. We

propose two designs to avoid cycle attack completely and achieve higher performance than conventional approaches with distributed control.

1.3.2 Hybrid Transmission for All-Optical Network

As the variety of the user applications become more diversified, even if the small network like LAN or MAN will be required the large bandwidth and low delay connection. The research to implement the all-optical network is progressed rapidly to fulfill these requirements. However, when we apply OCS technology to small networks such as metropolitan-area networks (MANs), the time overhead for establishing a lightpath can pose a significant problem. The time needed to establish a lightpath exceeds the round-trip time (RTT) for reserving channels and then returning an acknowledgment to the source node. It also requires time to setup all optical cross connects (OXCs) along the lightpaths. Therefore, unless the data-transmission time is much longer than the lightpath-establishment time, this overhead cannot be ignored. One of the solutions to this issue is to begin transmitting a data stream without establishing a lightpath. Even though hybrid optical network approach can be considered as a good solution to solve this lightpath-establishment time overhead problem, it requires additional devices for each communication technology.

In Chapter 3, we proposed hybrid optical network that combines OCS transmission technology and optical broadcast transmission technology to acquire advantages from both technology; The OCS transmission can high reliability transmission and the optical broadcast transmission can start transmission without establishing lightpaths. Our proposed optical broadcast network is constructed logically in the control plane of the OCS network. We also propose a new network architecture for optical broadcast network to avoid collision among broadcast traffic streams. Our simulation results reveals that our propose a hybrid optical network architecture can use network efficiently when both of small and long holding time requests arrives at the network.

1.3.3 Flexible Bandwidth Optical Network

Spectrum allocation in EON has two large different points from the channel allocation in OCDM network. First, each lightpath requires two or more consecutive spectrum slots for transmission. Second, since EON do not change a frequency range and modulation format, all allocated basic slots of a frequency slot must be continuous end-to-end with identical modulation format (unless wavelength/spectral converters and/or format converters are used).

These two constraint are called spectrum-continuity constraint. Therefore, the routing, modulation and spectrum assignment (RMSA) with the spectrum-continuity constraint is one of the most important issue in EON [46].

RMSA algorithms can exploit centralized or distributed control planes. For distributed control planes, generalized multi-protocol label switching (GMPLS) is a practical vehicle to address RMSA. For the GMPLS-based architecture, GMPLS with path computation element (GMPLS/PCE) [47, 48] recently emerged with better resource allocation capabilities compared to the standard GMPLS method designed for EON. In the standard GMPLS, each GMPLS node maintains the network state information of the network from the dynamically disseminated opaque link state advertisements (LSA) from other nodes and performs RMSA based on its own information. On the other hand, the GMPLS/PCE method introduces a centralized PCE (can be stateless or stateful) which maintains the network information for RMSA computation.

However, both GMPLS and GMPLS/PCE methods designed for EONs may suffer from the following two potential problems. First, routing protocol requires large control plane overhead due to the dynamic dissemination of the open shortest path first-traffic engineering (OSPF-TE) messages. Second, GMPLS distributed signaling cannot avoid resource collision among requests due to the signaling-latency [49–51].

In Chapter 4, we design a simplified GMPLS method, we call this “multi-path GMPLS,” for EONs by using extended resource reservation protocol-traffic engineering (RSVP-TE) to perform both signaling and RMSA. The simulation results reveals that our proposed multi-path GMPLS design achieves better performance than conventional GMPLS and GMPLS/PCE in terms of blocking probability and signaling time.

2

Distributed Controlled OCDM Network

2.1 Introduction

OCDM networks suffer from cycle attack problem [29]. Current all-optical techniques of regeneration cannot remove multi-access interference (MAI) from intermediate nodes if no optical-electrical and electrical-optical conversion is allowed in the network, so MAI will propagate from one lightpath to other lightpaths. Furthermore, if MAI propagates through other lightpaths and loop back to the lightpath causing it, an MAI propagation cycle forms. As a result, MAI accumulates endlessly and no encoded signals can be decoded, which renders the network useless.

The “CFLDA” method [30, 52] has been proposed to avoid this problem; it constructs logical tree topologies on each wavelength. However, it needs information about logical topologies shape and all established lightpaths in the network. That is, it requires a centralized control, and the controller has to handle enormous amounts of information, such as routing and resource reservation, in a short period of time. Therefore, one can foresee that very high costs would be involved in implementing this method on an OCDM/WDM network.

In this chapter, we propose a new network architecture with OCDM technology and new path establishment methods. Our key ideas are to construct cycle-free logical topology using spanning tree protocol (STP) [53] and establish lightpaths without calculating a route.

The main contribution of this chapter is to propose a lightpath establishment method combined with cycle-free logical topology construction avoiding cycle attacks through distributed control and to achieve the same or better performance compared with the previous CFLDA method with less implementation cost. First we propose to construct logical tree

topologies using the STP on each wavelength and setting up routing table on each node to establish lightpaths. We call this method the “Optical Spanning Tree Protocol (OSTP) [54].” Second, we propose another logical topology construction method with hierarchical constructing spanning trees to use network resource more efficiently. We also propose lightpath establishment method without routing table by broadcasting probe message to find a route. We call this method the “Broadcasting Optical Spanning Tree Protocol (BOSTP) [54].”

The rest of this chapter is organized as follows. We explain the MAI propagation mechanism, cycle-attack problem, and a conventional method of avoiding cycle attacks in Section 2.2. Cycle-free Logical topology designs and methods of establishing paths are described in Section 2.3. We describe another architecture for constructing hierarchical logical trees and searching for the shortest route using broadcast messages to improve network performance in Section 2.4. Section 2.5 explains the simulation parameters and presents the results of the simulations. Section 2.6 summarizes this chapter.

2.2 MAI Propagation Cycle on OCDM Networks

2.2.1 OCDM Node Architecture

Each node has a control and a data plane. The control plane determines which channel to assign to each lightpath and which port to transfer the signal of each lightpath, whereas the data plane only transfers the signal to the specific port. In all-optical OCDM network, in general, electronic devices are used in the control plane and OCDM OXCs are used in the data plane. The OCDM OXC architecture is shown in Fig. 2.1 [55]. The OCDM OXC is constructed with an N OCDM switching plane, where N is the number of wavelengths. Each switching plane has M decoders (where M means the number of codes of this OXC and also means the number of channels on each wavelength), a switching process, M converters, and an OC multiplexer. These decoders and converters are implemented on each of the L ports. First, the optical signal is demultiplexed into individual wavelengths by the wavelength demultiplexer and transferred to the decoders. Each signal is split into M duplications and enters the decoders. Optical correlation is performed in each decoder, and the target signal is detected. Encoding and decoding in an OCDM network is implemented by a passive device, such as a super structured fiber Bragg grating (SSFBG) encoder/decoder [56]. We assume that the Gold code [57] is used for encoding/decoding. However, it should be noted that, cycle attacks do not depend on a specific OCDM code, and therefore, OCDM network cannot avoid cycle attack no matter what code we select for the network. We obtain M demulti-

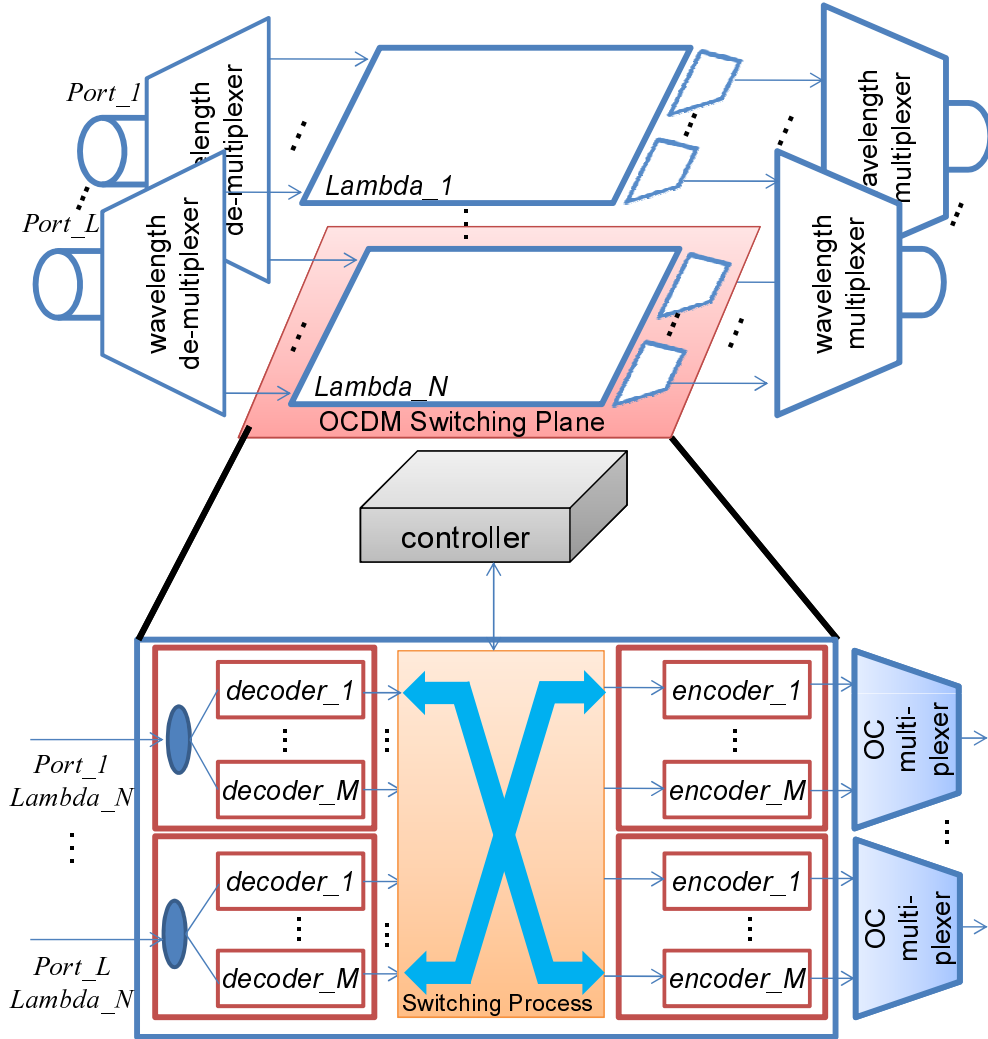


Figure2.1 Architecture of OCDM OXC [55]

plexed LSPs at the output of the decoders. Next, each decoded signal is switched through the pre-configured optical switching process. Each optical signal is then encoded by a specific converter and all the encoded signals are multiplexed through the OC multiplexer. Last, all output signals of the OC multiplexer are multiplexed through the wavelength multiplexer. Our novel OCDM OXC can swap the OCDM code; however, it cannot convert the WDM wavelength.

We can use an electrical network (IP network) or optical-electrical-optical switch in the control plane to read the control message. We call this component the controller. When a control message enters the controller, the switch configures the switching process of its OCDM OXC. The controller in this network has information about the connected link, including its propagation delay, capacity, and remaining channels to neighbor nodes.

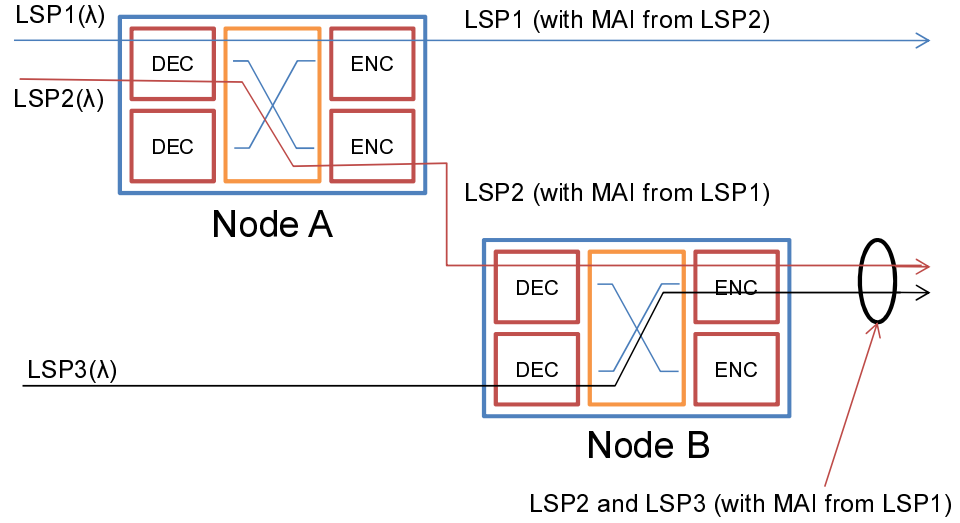


Figure 2.2 Mechanism of MAI propagation

2.2.2 Mechanism of MAI Propagation

The mechanism responsible for MAI propagation on each intermediate node is outlined in Fig. 2.2. Each node is an OCDM OXC. None of the OCDM OXCs allows wavelength conversion. Although we assume the use of Gold Code [22,23], cycle attack occurs regardless of which code we select. LSP1 and LSP2 multiplexed on wavelength λ , are separated by the de-multiplexer and then decoded by the decoder (DEC) on node A. As MAI cannot be removed using the current all-optical regeneration techniques, the encoded signal on LSP2 is affected by MAI from LSP1. In addition, LSP2 (which passes through node A) and LSP3 are multiplexed on node B on the same wavelength at the same output port. Consequently, the output signal from node B is the sum of LSP2, LSP3, and the MAI from LSP1. Thus, the MAI propagates from nodes A to B through LSP2. How MAI propagates can thus be summarized as follows:

1. MAI propagates from one link to other links through an LSP.
2. MAI propagates from an LSP to other LSPs on the shared link on the same wavelength.

An MAI causing flow like LSP1 is called an original attack flow (OAF), and MAI propagation flows like LSP2 and LSP3 are called secondary attack flows (SAFs) in [29]. Note that this MAI propagation mechanism only occurs among LSPs carried by the same wavelength. Therefore, the number of MAI propagation layers equals the number of wavelengths in the

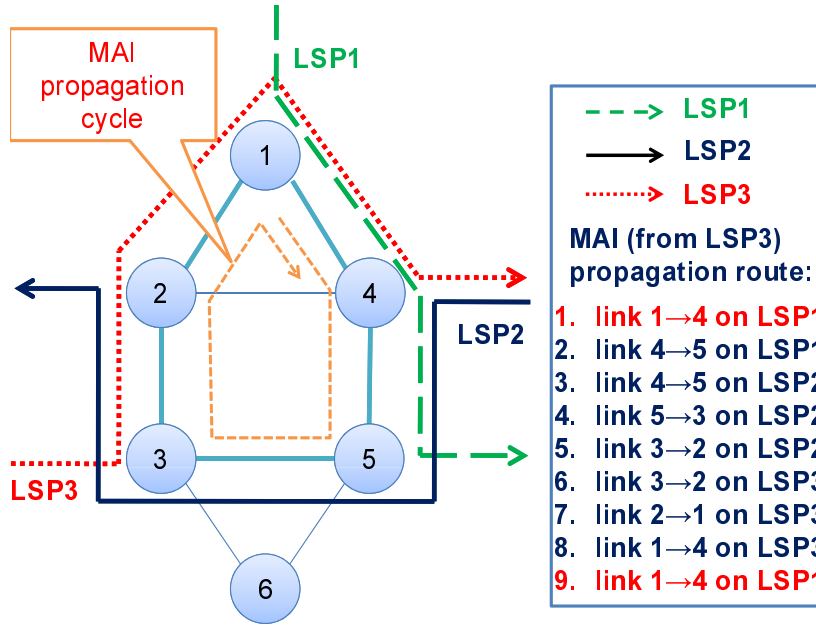


Figure 2.3 Cycle attack caused by MAI propagation

network.

2.2.3 Cycle Attacks Caused by MAI propagation

Cycle attacks are an inherent problem in OCDM networks. When lightpaths are multiplexed onto a wavelength on the same link, each lightpath is attacked by other lightpaths because of cross-correlation. Since the MAI cannot be completely removed before the encoding and switching, both the signals and the MAI are encoded in the downstream node. In this chapter, “upstream” refers to the link or node nearer to the source node, while “downstream” refers to the one nearer to the destination node than the current link or node. In addition, when the MAI on this signal is multiplexed on the downstream node, the MAI from the upstream link affects other lightpaths. In other words, the MAI is propagated to all lightpaths multiplexed at the same node. If the MAI forms a propagation cycle using these two propagation mechanisms, it can accumulate endlessly, resulting in all the signals becoming undecodable.

The example of cycle attacks is shown in Fig. 2.3. The figure assumes that all LSPs share the same wavelength. First, the MAI from LSP3 on link 1→4 propagates to link 4→5 through LSP1. Second, MAI propagates from LSP1 to LSP2 on link 4→5 then from link 4→5 to link 3→2 through LSP2. Third, MAI propagates from LSP2 to LSP3 on link 3→2 then from link 3→2 to link 1→4 through LSP1. Last, MAI propagates from LSP3 to LSP1. In

this case, the MAI originating from link 1→4 propagates and loops back to the same link; in other words, LSP3 interferes with itself. Thus, it is imperative to avoid the cycle-attack problem in this sort of network.

In summary, a cycle attack has three steps:

1. OAF causes MAI.
2. MAI propagates from one LSP to and through other LSPs.
3. MAI loops back to the link that caused it.

It should be noted that a cycle attack is caused by the cross-correlation of OCDM codes. Therefore, the MAI is not propagated from one wavelength to another wavelength. In other words, we can assume that the cycle attack is an independent problem on each wavelength.

Reference [58] describes the crosstalk attack problem that can occur in a conventional WDM network. The crosstalk attack is similar to the cycle attack in that a newly established lightpath affects already established lightpaths sharing the same network switch and degrades their light quality. When an attacker adds a malicious connection which has much higher power than a normal connection has, the leakage energy (crosstalk) affects the normal connections passing through the same switch as the malicious connection. However, as pointed out in [59], since the signal power of the affected normal connection is unlikely to be increased by more than half the normal channel power, we can avoid situations in which the affected lightpath affects other normal lightpaths. That is, in a conventional WDM network, the attack capability does not propagate from a new lightpath to other lightpaths. On the other hand, in an OCDM network, a new lightpath affects the other lightpaths that share the same port on the same wavelength as the MAI and degrades their signal quality. Since current all-optical regeneration technology cannot remove MAI completely, a lightpath affected by the new lightpath affects other lightpaths on downstream nodes. That is, in an OCDM network, the attack capability propagates from one lightpath to another. Due to this propagation, MAI propagates and loops back to the original lightpath and a MAI propagation cycle forms. As a result, MAI accumulates unlimitedly and degrades all lightpaths through this propagation cycle. For the above reasons, the cycle attack problem is inherent to OCDM networks and we cannot neglect its effect.

2.2.4 Conventional Solution

A cycle attack occurs when a new lightpath is established in the network and it forms MAI loop-back cycle. Current all-optical regeneration technology cannot remove MAI com-

pletely, and that means we cannot stop it from propagating. Therefore, we need to find a way to prevent a MAI loop back cycle from forming. The advanced first fit (AFF) method [29] and the cycle-free logical tree assignment (CFLDA) method [30, 52] are the methods used to establish lightpath for OCDM networks. In the AFF method, when a new connection request arrives at the source node, the source node first calculates the shortest path to the destination node. It then diagnoses whether the new lightpath will cause a cycle attack. The CFLDA method constructs the shortest spanning tree using the physical network topology information and the arrival rates of all connection requests. It is used to construct logical topologies by using a traffic matrix for each wavelength. When a request arrives to establish an LSP, a controller in the network selects the tree that has the minimum hop count from the source node to the destination node from trees that can establish an LSP. If an LSP cannot be established in any of the trees, the request results in “call loss.” After the route is decided, the source node transfers a reservation message to the destination node through the pre-configured route. Through these processes, the network avoids the formation of an MAI propagation cycle. All of these spanning tree construction, routing, and available resource confirmation require global and updated information. Therefore, CFLDA method requires a centralized controller.

These two methods require a centralized controller to control network information, because information about the network topology and overall network channel utilization is needed when a lightpath is established. Therefore, they incur overhead caused by the communication with the controller. Although a centralized controller can process all this information, centralized control has its own problems; it has an overhead to communicate with all intermediate nodes, it must keep consistency among all intermediate nodes about channel reservations, and it must process this information in real time. Therefore, it is important to design distributed controlled optical network architecture to scale out to future large area network.

2.3 Cycle-Free Network Design

In this section, we propose network designs to avoid cycle attacks. First, we propose the optical spanning tree protocol (OSTP) method to construct logical trees by using a spanning tree protocol on each wavelength. In this chapter, we assume that “logical trees” means a virtually constructed trees on control plane and traffic are transferred through logical trees. It uses only local information at each intermediate node. Different from the CFLDA method, it can establish lightpath in a distributed manner. Logical trees of our method have different

root nodes to stop traffic from concentrating on a specific node (see Section 2.3.1). It tries to establish a path to fulfill its requirements. Channels are reserved by using reservation messages sent from the source node to the destination node along the logical tree topology. Followings, “channel” means a specific code on a specific wavelength and “link” means a fiber between two nodes. Furthermore, it leverages unused links to improve performance. We call these links “single-hop links.” We explain what a single-hop link is and why we can use it in Section 2.3.2.

2.3.1 Basic Method Using Logical Tree Construction

OSTP constructs logical trees by using a spanning tree protocol on each wavelength [53]. The IDs and costs are set by the network administrator, and here, we use the link capacity as the link cost. The logical tree construction algorithm involves two steps.

1. Select the node that has the lowest node ID as the root node.
2. Select the shortest path from each node to the root node as the logical tree link.

This logical topology is saved as port statistics on all nodes. We assume that a protocol similar to STP is used. Nodes have three port statuses: root port, designated port, and blocked port. The root port has the smallest cost to go to the root node, and all nodes except the root node have a root port. The designated port has the smallest cost on each link. Other ports are called blocked ports.

After constructing the logical tree, all nodes exchange information to create their routing table. First, leaf nodes which have no child nodes transmit their information to the root port. After receiving the information, each node creates a routing table to connect descendant nodes and transfers its routing table information to the root port. Accordingly, all nodes know which ports connect to their descendant nodes. When a destination node is not in the routing table, the node asks it for its parent node. Here, a node connected by the root port is called a “parent node,” and nodes connected to designated ports are called “child nodes.” Nodes that can be reached only through designated ports are called “descendant nodes.”

In addition, we can construct a differential logical tree for each wavelength in the OCDM network by using different node ID sets. Figure 2.4 outlines two types of logical trees and some of routing tables in which all links in the network (see Fig. 2.4(a)) have the same capacity. Figure 2.4(b) shows when the root node is Node 1 and Fig. 2.4(c) shows when the root node is Node 2.

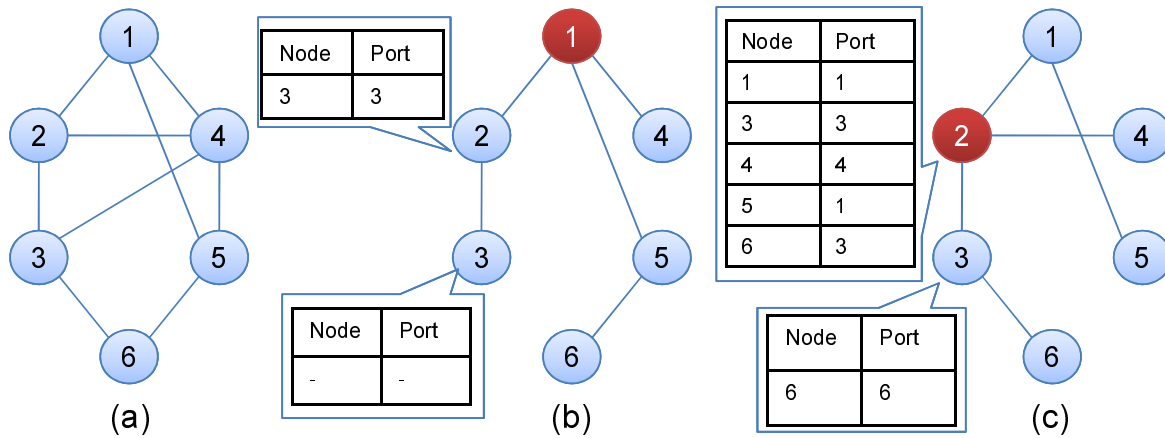


Figure 2.4 An example of differential logical tree construction; (a) Physical topology, (b) the root node is 1 and (c) the root node is 2

2.3.2 Method to Establish LSP on Logical Tree

A new LSP is established in the OCDM networks when a new data-transfer request arrives at a node. The OSTP method establishes a new LSP when a request arrives at the source node:

1. Randomly select a tree.
2. Transmit a reservation message according to its routing table.
3. If the reservation message is on the destination node, go to step 6; if not, go to step 4.
4. If the next link has an unused channel, reserve the channel, then transmit the message to the next node, and go to step 3. If not, the node returns a NACK message to the source node, and the reserved channel is released in reverse order according to the data in the NACK message.
5. Randomly select a tree that has not been selected yet, and follow steps 2–5. If no tree can be selected, the reservation request become call loss and the path-establishment algorithm ends.
6. The destination node transmits an ACK message to the source node and the path-establishment algorithm ends.

We called this path-establishment method the “original OSTP.” However, if we only use logical tree links, we face two problems. The first is load concentration in a specific node and link, and the second is the availability of unused links which are not included in logical trees. To resolve these problems, we leverage unused links. Here, we focus on a destination node

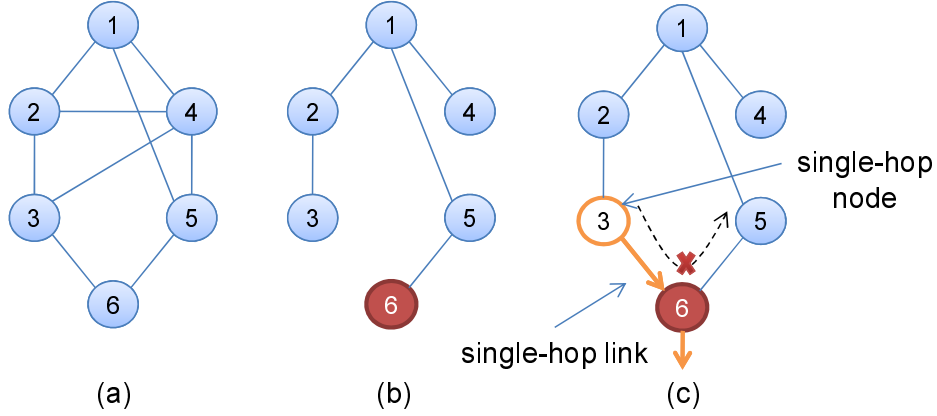


Figure 2.5 An example of single-hop links; (a) Physical topology, (b) logical tree topology, and (c) using the single-hop link method

of each data-transfer request. We can use links to connect the destination node regardless of whether the link is included in the logical tree or not because MAI is terminated at the last hop and does not propagate to other links. Thus, we can also transfer data to a blocked port if the port is connected to the destination node of a data-transfer request. We call the last hop links which are not included in logical tree “single-hop links” and a node connected to a single-hop link a “single-hop node.” Figure 2.5 is an example where a single-hop link is used. Figure 2.5(b) is the logical tree topology, and node 6 is the destination node of the data-transfer request. In this situation, the single-hop link is Link 3→6 (see Fig. 2.5(c)). MAI cannot propagate from Link 3→6 to Link 6→5 because only data-transfer requests whose destination node is node 6 can use Link 3→6. Therefore, there is no LSP to bring a signal from a single-hop link to other links. In other words, MAI is terminated on the single-hop link and no cycle attacks can occur in this network.

We can reduce the call loss probability with our OSTP by using this single-hop link. Figure 2.6 shows how a single-hop link is used. In Fig. 2.6(a), all lines are a physical network and bold lines are links of logical topology. Now, let us assume that a data transfer request arrives at Node 3 and it wants data to be transferred to Node 5. Node 3 is treated as the source node and Node 5 is treated as the destination node for the request. Links 1→5 and 6→5 are single-hop links for this request. Figure 2.6(b) shows the path for the original OSTP, in which a reservation message is transmitted from the source node to the destination node through the logical topology. Consequently, the original OSTP establishes a path, 3→2→1→4→5. However, Link 1→5 can be used on Node 1 because it is a single-hop link. Therefore, in step 4, if Link 1→5 has an unused channel when a reservation message arrives at Node 1, the node establishes an LSP through the single-hop link. If the channels of the single-hop link

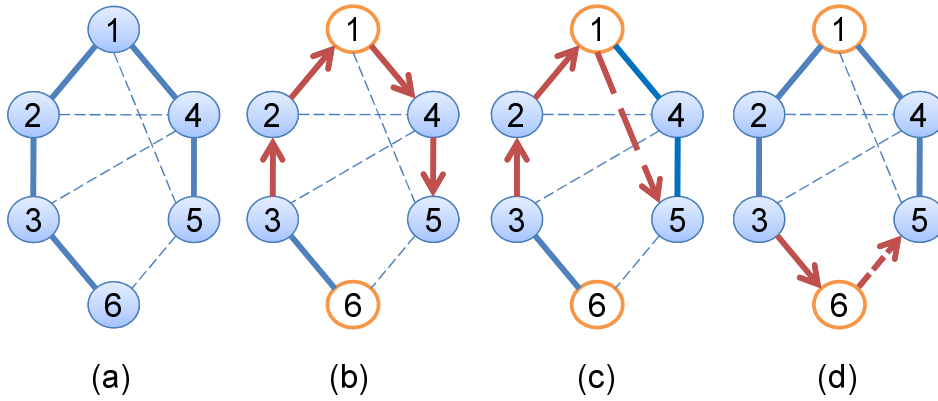


Figure 2.6 Single-hop link using (a) logical tree, (b) OSTP, (c) OSTP with additional hop, and (d) OSTP with minimum hop

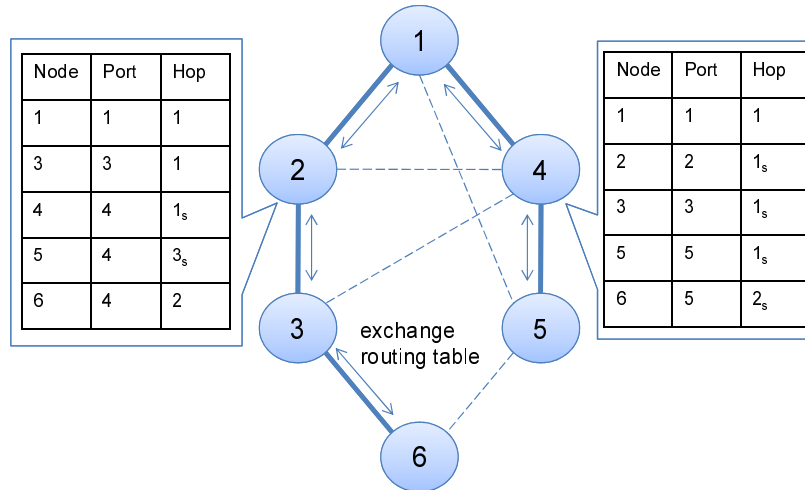


Figure 2.7 Routing tables of OSTP with minimum hops

are full, the controller tries to reserve a channel of the logical tree. This method can establish LSPs with shorter hop counts and distribute the load. We call this method “OSTP with an additional hop.” To make method possible, each node needs to add information about single-hop nodes to its routing table in the logical tree construction phase. Figure 2.6(c) shows an LSP $3 \rightarrow 6 \rightarrow 5$ with the minimum number of hops in this topology. We call this method “OSTP with minimum hops.”

In OSTP with minimum hops, all nodes need to know the minimum number of hops to all other nodes. In what follows, we show how to create the routing tables for this method. After constructing the logical trees, all nodes get their neighbor node IDs. When the neighbor nodes are single-hop nodes, the node turns on the “using single-hop link” flag. After that, the nodes exchange their routing tables with their neighbor nodes in the logical tree. In so doing,

Table 2.1 Output port and minimum hop count of each source-destination pair

source/destination	1	2	3	4	5	6
1	-	2/1	4/2 _s	4/1	5/1 _s	4/3 _s
2	1/1	-	3/1	4/1 _s	1/2 _s	3/2
3	2/2	2/1	-	4/1 _s	6/2 _s	6/1
4	1/1	2/1 _s	3/1 _s	-	5/1	5/2 _s
5	1/1 _s	4/2 _s	4/2 _s	4/1	-	6/1 _s
6	3/3	3/2	3/1	3/2 _s	5/1 _s	-

all nodes come to know which ports connect to which nodes and how many hops it takes to connect to any other node (see Fig. 2.7). When two or more ports have the same hop count to a destination node, any port which has a “using single-hop link” flag takes precedence over the other ports to prevent lightpaths concentrating at the root node. Table 2.1 shows an example of a routing table. Columns show source nodes, and rows show destination nodes. Each cell shows as form of “output port / hop count.” The output port shows the next node to transfer to the destination node. The hop counts labeled with the index “_s” means that the route uses a single-hop link (e.g. 2_s means two hops with using a single-hop link).

2.4 Hierarchical Logical Topology Design

2.4.1 Hierarchical Logical Topology Construction

In this section, we propose a novel logical topology design in which hierarchical construction is implemented. We propose a new network design following three principals:

1. We divide the physical topology into various logical topologies that have no cycles. If we are able to determine the direction of data transfer between every two logical topologies and construct a combined hierarchical logical topology, the constructed logical topology has no cycles. Followings, we call the each logical topology comprised in the constructed hierarchical logical topology “layer.”
2. If two logical topologies do not have a node in common, we do not need to determine a direction between these two topologies.
3. If we construct a logical spanning tree from a physical network, we can transfer data from any source node to a destination node.

The first assumption underlying our logical topology design is that no cycle attacks are caused because no topology has any cycles. MAI does not propagate from a lower to a higher layer. Therefore, no cycle attacks are caused when paths are established. The second assumption reduces the number of logical topologies. If two topologies do not have a node in common, then MAI cannot propagate between these two topologies. The third assumption guarantees that a path can be established around any source-destination pair.

On the basis of these three assumptions, we construct a hierarchical logical topology comprising logical topology “layers.” We assign to the highest layer a layer value of “0” and to lower layers larger layer values. The layer value is saved as the port status on all nodes. The procedure used to construct the hierarchical logical tree topology is as follows.

1. Initialize layer value null on all ports.
2. Initialize maximum layer value $K = 0$.
3. If all ports have already been assigned a layer value, go to step 8.
4. If K is equal to or larger than the predetermined maximum value, go to step 8.
5. Construct a spanning tree.
6. Set K to the topology layer value of all ports included in the spanning trees.
7. Increment K ; then go to step 3.
8. End algorithm.

The first spanning tree is constructed in the same way as in the OSTP method proposed in Section 2.3.

Figure 2.8 is an example illustrating the construction of a hierarchical logical topology and port status at Node 2. In the following, “Port 2→3” signifies that a port on Node 2 connects to Node 3. First, a spanning tree is constructed from the physical network topology using OSTP. This information is set as a port status on each node. For example, at Node 2, the Port 2→0 and Port 2→5 are set as layer 0 (see Fig. 2.8(a)). Different spanning trees are then constructed, using links that are not included in layer 0, and layer value 1 is set for all ports of the newly constructed spanning trees (see Fig. 2.8(b)). This spanning tree construction process is repeated, each time setting a new layer value, until all nodes have set layer values for all ports (see Fig. 2.8(c)). The result at the end of this procedure is a hierarchical logical topology comprising a set of spanning trees (see Fig. 2.8(d)). All messages in this network are transferred from a higher layer to a lower layer. If we determine a maximum value of 2, Link 2→3 and Link 3→2 are not used (see Fig. 2.8(e)).

We construct this hierarchical logical tree on all wavelengths, because we can consider cycle attacks to be an independent problem on each wavelength. It should be noted that we

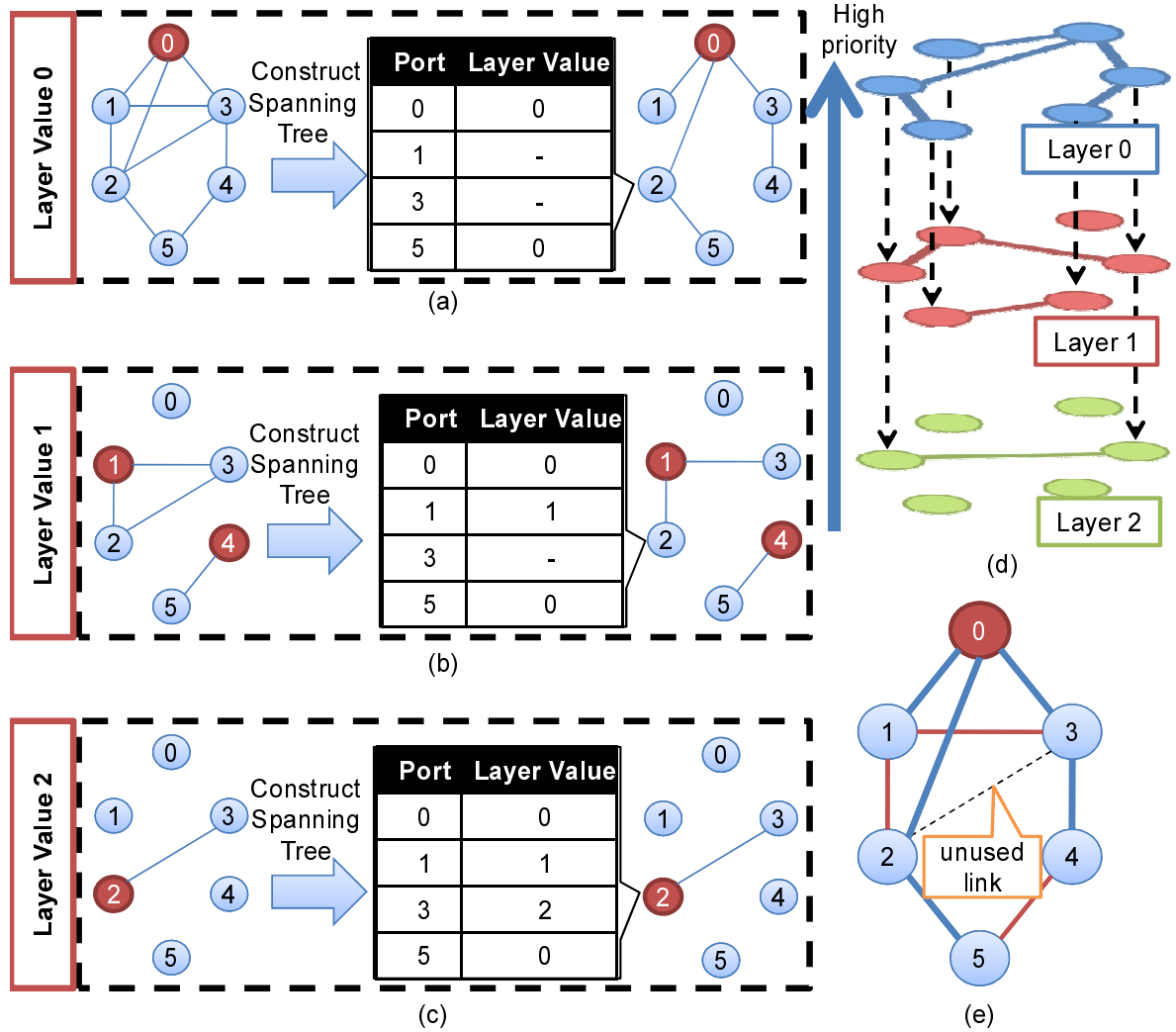


Figure 2.8 Example of hierarchical logical topology on wavelength

change the route node ID on all wavelengths to balance the load on the specific node.

2.4.2 Method of Establishing Lightpath with Broadcasting Search

OCS networks require a route from a source node to a destination node be determined in order to establish a lightpath. However, in a distributed controlled network, the source nodes do not have the logical topology information. Therefore, to determine the route, we equip all nodes with routing tables or make them search for a route from a source node to a destination node when a connection request arrives.

In this section, we propose an approach to finding the shortest path without the network topology information using probe message broadcasting. We define four types of message to establish a lightpath. “Probe messages” are sent from a source node to a destination node to

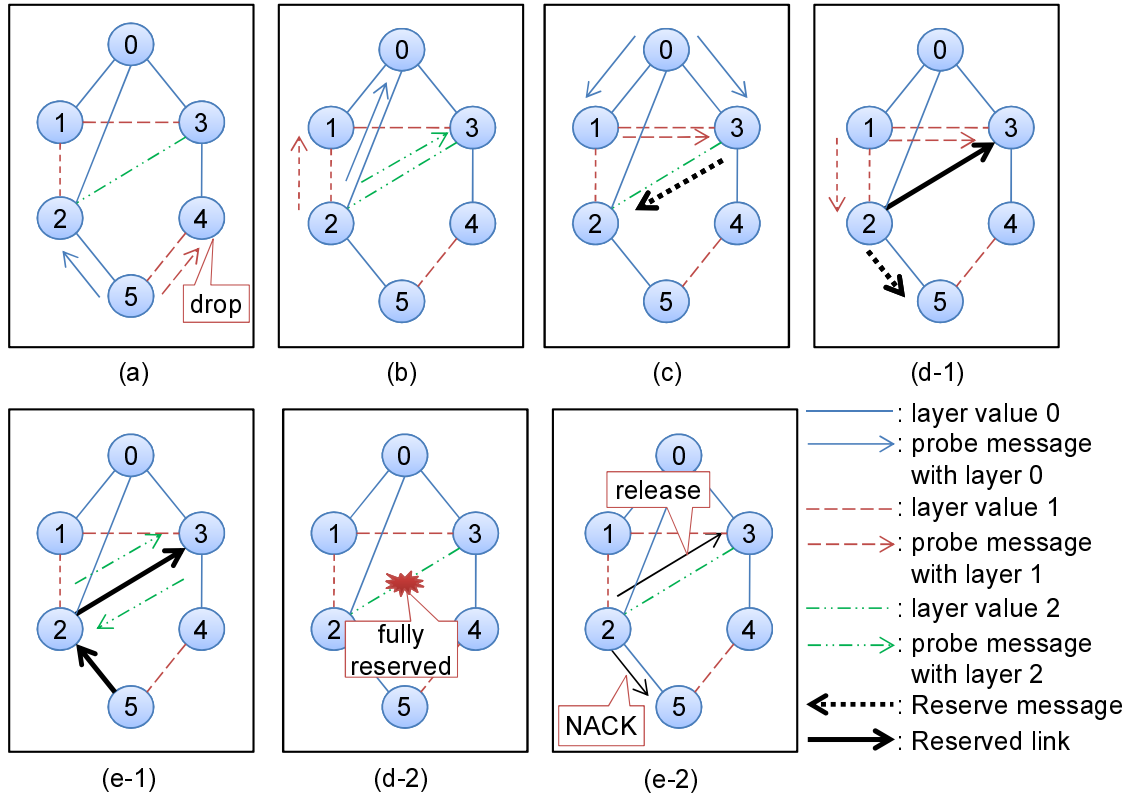


Figure 2.9 Example of lightpath reservation process with broadcasting search

find the shortest path. A “*reserve message*” is sent from the destination node to the source node to reserve a channel on each intermediate node. A “*NACK message*” is sent from an intermediate node or the destination node to the source node to notify that the reservation process failed. A “*release message*” is sent from an intermediate node or the source node to release the reserved channel.

The following process is used to establish a lightpath.

1. The source node selects a wavelength randomly.
2. The source node transmits *probe messages* to all ports.
3. On receiving a *probe message*, an intermediate node copies it and then transfers it to other ports that have an equal or higher topology layer value. If there is no port to transfer the *probe message*, the node drops it. All *probe messages* record the which nodes transferred them.
4. On the arrival of the first *probe message* at the destination node, the destination node returns a *reserve message* to the source node according to the route recorded by the received *probe message*. If the *probe message* is not the first one, the destination node ignores it.

5. On receiving a *reserve message*, the node checks that there are unused channels to the downstream node. If there are channels that can be reserved, the node selects and reserves a channel randomly, and then, transfers the message to the upstream node. If there is no channel that can be reserved, the node transfers a *NACK message* to the source node and returns a *release message* to the destination node requesting it to release the reserved channels.
6. After the *NACK message* arrives at the source node, it selects another wavelength to establish a lightpath. If there is no other wavelength, the connection request becomes a call loss.

Figure 2.9 illustrates an example of the lightpath establishment process. The source, Node 5, transmits probe messages to Port 5→2 and port 5→4 (see Fig. 2.9(a)). Since Port 5→2 has layer value 0, Node 2 copies and transfers the *probe message* to Port 2→0 with layer value 0, Port 2→1 with layer value 1, and port 2→3 with layer value 2 (see Fig. 2.9(b)). At the same time, on Node 4 in Fig. 2.9(a), a *probe message* is dropped because Port 5→4 has layer value 1 and port 4→3 has layer value 0 (see Node 4 in Fig. 2.9(a)). After the destination node receives its first *probe message*, it returns a *reserve message* to the source node with route 3→2→5 (see Fig. 2.9(c)). As can be seen in Fig. 2.9(c), the destination node does not transfer *probe messages*. It should be noted that other *probe messages* are still transferred when the lightpath is established, because intermediate nodes do not know whether the lightpath has been established in distributed control. *probe messages* that reach the destination node after the first *probe message* are not accepted (see Fig. 2.9(d-1)). After it receives a *reserve message*, Node 2 tries to reserve a channel on Port 2→3. If the port has unused channels, Node 2 reserves a channel randomly, and then, transmits a *reserve message* to Node 5 (see Fig. 2.9(d-1)). If Port 2→3 is fully reserved (see Fig. 2.9(d-2)), Node 2 transmits a *NACK message* to Node 5 and a *release message* to Node 3 (see Fig. 2.9(e-2)). The lightpath is established when source Node 5 receives the *reserve message* and reserves a channel on Port 5→2 (see Fig. 2.9(e-1)). We call this lightpath establishment method using broadcasting with the hierarchical logical topology construction the “Broadcasting OSTP (BOSTP)” method.

The BOSTP method has two advantages over the previous OSTP with minimum hops method [60]. First, in the BOSTP method, all links can be used for every source and destination pair. In contrast, in the OSTP with minimum hops method, a source-destination pair can use links only on spanning trees or single-hop links. Second, since the BOSTP method does not need to construct routing tables in the topology construction phase, it can start establish-

ing lightpaths sooner after the network has been implemented or has recovered from network failures. This also means the BOSTP method does not need information about nodes that are not connected to distributed controllers. However, the destination node of BOSTP method requires sufficient memory to confirm whether the received probe message is the first one or not.

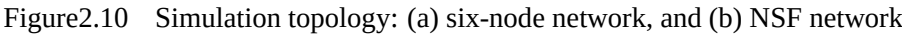
Nevertheless, since our BOSTP method constructs a different hierarchical logical topology on each wavelength, the possibility that there is a less efficient wavelength that does not establish a shortest route lightpath exists. Therefore, to improve performance, we also propose a method that broadcasts probe messages on all wavelengths simultaneously. We call this method the “Multi-wavelength BOSTP (MBOSTP)” method. Like the BOSTP method, the MBOSTP method accepts only the first probe message to establish a lightpath. When the channel reservation fails and a NACK message is returned to the source node, the source node re-transmits probe messages on wavelengths that have not yet attempted to establish a lightpath. Therefore, the MBOSTP method needs to distinguish the new probe messages from previous probe messages that have already failed to establish a lightpath on the same wavelength on the same connection request. MBOSTP is more efficient than BOSTP in terms of hop count paths because it selects fewer of them; however, it requires more control messages to establish a lightpath.

2.5 Evaluation

In this section, we evaluate our proposed distributed methods for OCDM network. The purpose of this section is to confirm following two results. First, our proposed distributed methods can establish lightpaths with less amount of information and less computational complexity compared to conventional centralized control method. Second, we show our proposed method achieve the same or better performance compared with the conventional centralized control method.

2.5.1 Description of Simulations

We conduct simulations to validate our methods with a six-node network and a fourteen-node National Science Foundation (NSF) network, as shown in Fig. 2.10. Each link has bi-directional fibers that have eight wavelengths and five OCDM channels per wavelength. We assume no wavelength conversion on intermediate nodes. The OCDM allows code conversion on all intermediate nodes. The requests for the lightpath connection reach the network with a



We assume the following for each lightpath establishment method. We assume that the original OSTP, OSTP with an additional hop, and OSTP with minimum hops have constructed logical trees and created their routing tables before the simulation starts. In the BOSTP and MBOSTP methods, an intermediate node knows only the topology layer value of its physical ports and which node is connected to its port. In the CFLDA method, the centralized channel manager knows the logical topology information, the connection establishment requirement arrival rate of each node, and the channel reservation information about all links. When a connection establishment request arrives at a source node, the source node tells the centralized channel reserved manager what the destination node is. The manager searches for a route from the minimum mean hop count tree and determines a route where it can reserve channel on all links. After that, the manager logically reserves the channels and tells the source node the determined route. Actual channels on each link are reserved by the

reservation message from the source node. We assume that the control message propagation between the source node and the manager and the route calculation overhead on the manager incur no delay.

2.5.2 Implementing Cost Discussion

We evaluated the costs of the CFLDA method and our methods qualitatively. In the CFLDA method, a centralized controller constructs logical trees using topology and traffic matrix information. The CFLDA method thus assumes that the controller is given the network topology and traffic matrix. In the lightpath establishment phase, a centralized controller selects a logical tree from the logical tree pool and calculates a shortest route in the tree when a new data transfer request arrives at the network. After that, if all ports on the route have unused channels, the controller starts to establish the lightpath; if not, the controller selects another logical tree. Therefore, the CFLDA method requires to manage all reserved channel information on all ports of all nodes in the centralized controller to select an available logical tree. In addition, since the channel reservation is in the form of a distributed resource reservation, each switch needs to register the reserved channel information at the controller.

On the other hand, in our methods, distributed controllers assemble information from all other nodes autonomously; then they construct logical topology to set up their ports and make the routing table (only for OSTP methods). A distributed controller implemented in each node only needs local information around itself, including the number of channels of each port, the bandwidth of each channel, and the nodes connecting to each port. In the lightpath establishment phase, our methods reserve channels in a distributed and autonomous way. Since each controller only uses local information including the routing table and channel information needed to reserve a channel, it does not need to communicate with other controllers. Note that all three of our methods use the same process to establish lightpaths and have the same complexity.

Below, we consider the implementation costs of the CFLDA method and our method by using three indicators.

1. amount of handling information

In the CFLDA method, a centralized controller manages wavelength network topologies and reserved channel information of all nodes. In our OSTP methods, distributed controllers manage the routing table and reserved channel information. In our BOSTP and MBOSTP methods, distributed controllers manage reserved channel information.

Therefore, our BOSTP and MBOSTP methods can manage network resource with fewer information.

2. complexity of processing

In the CFLDA method, a centralized controller selects a logical tree, calculates the shortest route, checks for empty channels and reserves/releases channels on the route. In addition, the controller updates the reserved channel information when a reservation message arrives at a intermediate node. In our OSTP methods, distributed controllers look up information on their routing table, check for empty channels, and reserve a channel. In our BOSTP and MBOSTP methods, distributed controllers check empty channels, and reserve a channel. Therefore, our BOSTP and MBOSTP methods can manage lightpaths in the network with fewer computational resources.

3. communication delay

In the CFLDA method, intermediate nodes need to tell a centralized controller when they reserve or release a channel. That is, many communications, at least twice as many hops, are needed to establish one lightpath. In our methods, since distributed controllers reserve and release channels by referring to the information they hold themselves, they do not need to communicate with other controllers.

The above considerations show that controllers of our methods handle less information and have simpler processes even if the network needs the same number of controllers as network nodes. In addition, distributed controllers can scale out because they only use local information. Therefore, we expect that our methods can manage network with less performance controllers in comparison with the CFLDA method.

2.5.3 Performance Evaluation of Proposed Network Design

Next, we evaluate the basic performance of our proposed network design. Each parameter of the numerical evaluation is defined in Table 2.2. We set three indexes for evaluation as follows;

- Call loss probability L^{cl}

$$L^{cl} = \frac{R - R^e}{R} \quad (2.1)$$

- Mean lightpath establishment time T^m

$$T^m = \frac{\sum_{r=1}^R t_r^s - t_r^a}{R} \quad (2.2)$$

Table 2.2 Evaluation parameters

R	Number of requests
R^e	Number of established requests
t_r^a	Time for r_{th} request to be reached
t_r^s	Time for r_{th} request to be established or lost
h_r	Hop count of r_{th} lightpath. If r_{th} lightpath is lost, $h_r=0$

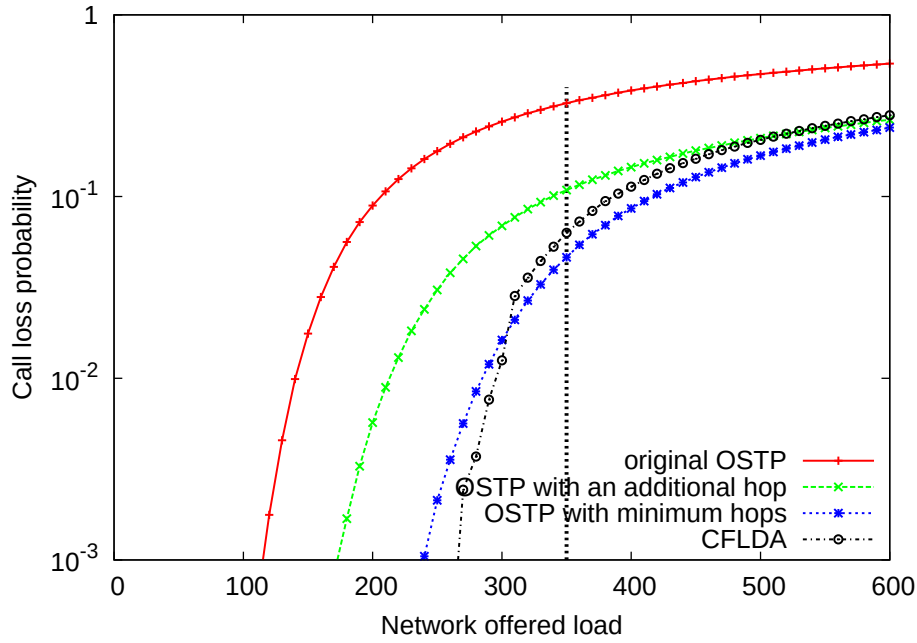


Figure 2.11 Simulated call loss probability on six-node topology

- Mean hop count H^m

$$H^m = \frac{\sum_{r=1}^{R^e} h_r}{R^e} \quad (2.3)$$

Figure 2.11 plots the call loss probabilities for the four methods in the six-node as the network offered load changes. OSTP with an additional hop and OSTP with minimum hops outperform the original OSTP method because they use single-hop links and the original OSTP does not. OSTP with minimum hops has a smaller call loss probability than that of OSTP with an additional hop at all network offered loads in both network topologies. This result means that OSTP with an additional hop cannot establish the shortest lightpath between some source-destination pairs. Although the CFLDA method is the smallest call loss probability when the network offered load is low, OSTP with minimum hops has the smallest call loss probability when the network has larger network offered load than 300. CFLDA does

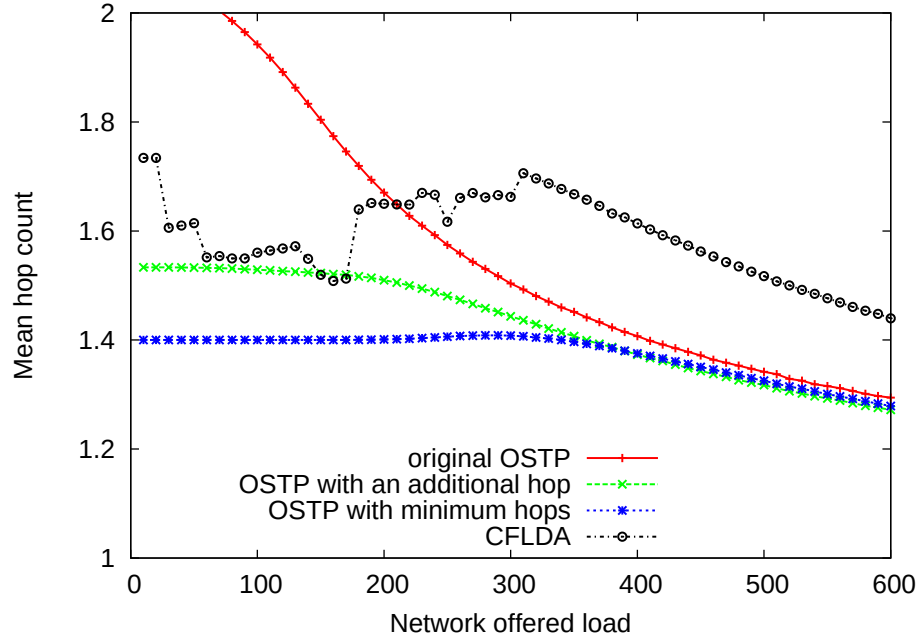


Figure 2.12 Simulated mean hop count on a six-node topology

not smoothly increase the call loss probability as the network offered load increase. This is because CFLDA changes its logical topology according to the network offered load.

Figure 2.12 plots the mean hop count for the four methods on the six-node topology as the network offered load changes. OSTP with minimum hops has the shortest mean hop count among the four methods. In many cases, the single-hop link makes the hop count of the established LSP shorter. Regarding the CFLDA method, the manager calculates the mean hop count for all logical trees and when a LSP is established, the manager searches for routes on the tree with the smallest mean hop count. When the network offered load is low, the CFLDA method assigns precedence to sub-trees if shorter paths can be established on the main trees. The mean hop counts with CFLDA and OSTP with minimum hops become larger in low network-offered-load areas (in the six-node topology, under 310 in both methods) as the network offered load gets higher. This is because call loss rarely occurs in low offered load areas, and LSPs try to get established on a number of wavelengths. As these methods try to establish LSPs on short-route wavelengths first, their routes become longer on longer route wavelengths.

Figure 2.13 plots the mean time to establish a connection for the four methods in the six-node topology as the network offered load changes. All four methods take longer to establish the path as the network offered load increases at first; in contrast, they take less time to establish a path in places where the network offered load is high. The reason for this is

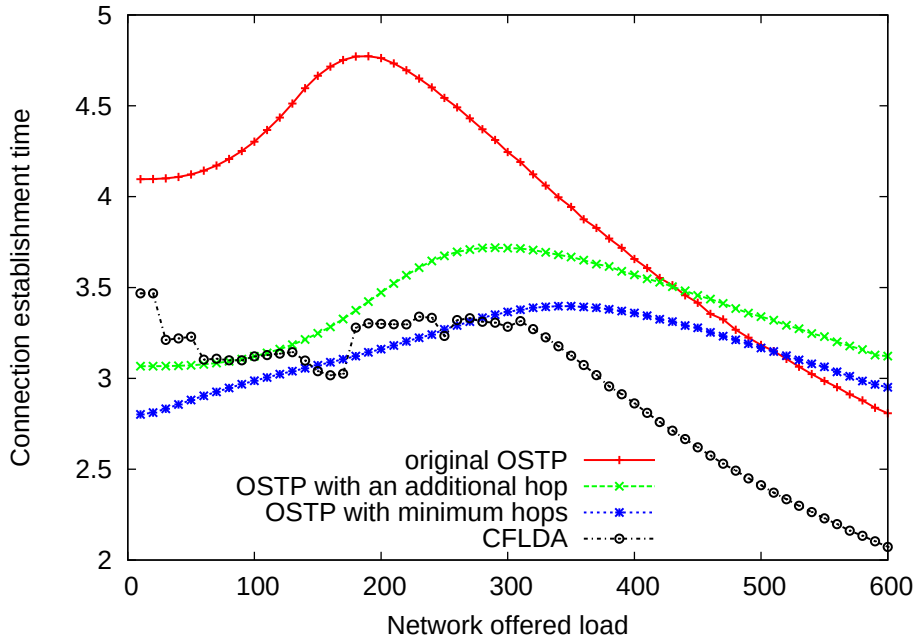


Figure 2.13 Simulated time to establish LSP on six-node topology

that the three OSTP methods try more wavelengths and the time it takes to establish a connection increases with the network offered load because many channels are already reserved. On the other hand, when the network offered load becomes huge, most links can use all their channels, and NACK messages can be transmitted on shorter hops. In particular, the CFLDA method does not try two or more wavelengths to establish LSPs because the centralized controller manages the information on all reserved channels on all nodes. Therefore, the mean connection establishment time depends on the mean hop count (see Fig. 2.12).

Figure 2.14 plots the call loss probabilities for the four methods in the six-node topology as the holding time changes. We assume that the network offered load is 300 in Fig. 2.14. The holding time is normalized by the link propagation delay. None of the methods is affected much when the holding time is larger than 10^2 . Moreover, their call-loss probability increases as the holding time decreases. This is because, the ratio of time overhead to establish lightpath becomes larger if the holding time becomes smaller. For example, if the mean holding time is 10^0 , the time overhead to establish a lightpaths is $2 \times \text{hopcount} \times \text{holdingtime}$. In other words, unless the holding time is long enough, network performance will be degraded by the time overhead needed to establish LSPs.

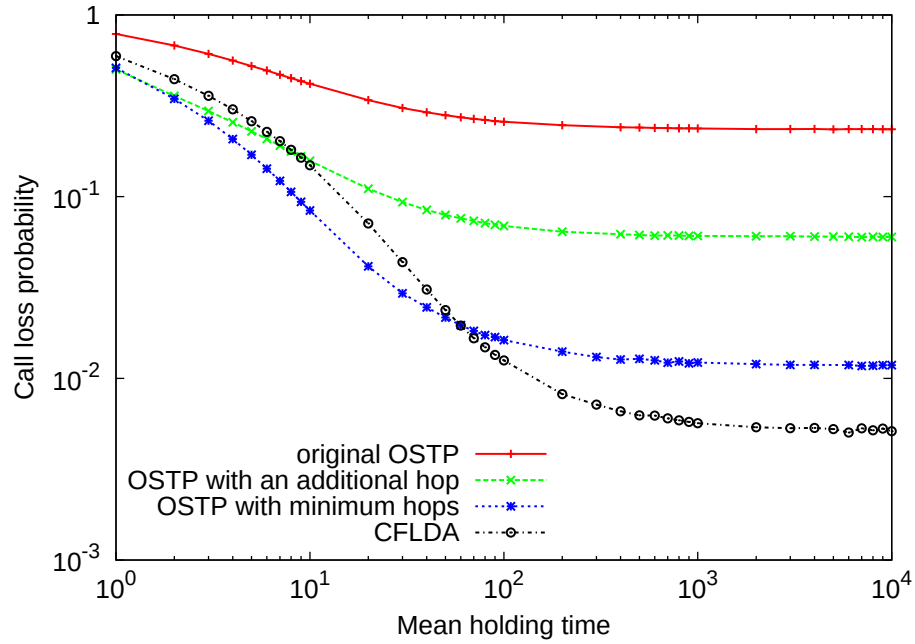


Figure 2.14 Call-loss probability on six-node topology versus holding time

2.5.4 Efficiency Evaluation for Hierarchical Logical Topology

In this section, we report the calculations and simulations conducted using a NSF network (Fig. 2.10(b)) to validate the efficiency of hierarchical logical topology. We compared four logical topology construction and lightpath establishment methods: CFLDA, OSTP with minimum hop, BOSTP, and MBOSTP.

Figure 2.15 shows the plots of the call loss probabilities for the four methods in the NSF topology when the network offered load changes. The CFLDA method has the highest call loss probability. This is because the BOSTP and MBOSTP methods can use any link for all SD-pairs while the CFLDA method can use links only when the SD-pair are included in the same sub-tree. These results also mean that the single-hop links approach in the OSTP with minimum-hops method is more effective than the sub-trees approach in the CFLDA method in the NSF network topology. The CFLDA method does not smoothly increase the call loss probability as the network offered load increases. This is because CFLDA changes its logical topology according to the network offered load. The BOSTP and MBOSTP methods have very low call loss probability as compared to the other two methods. In particular, when ρ is 400, the BOSTP method has a 70% smaller call loss probability than the OSTP with minimum hops method has. This is because the BOSTP and MBOSTP methods can use all links when establishing lightpaths. That is, since the BOSTP and MBOSTP methods can assign more

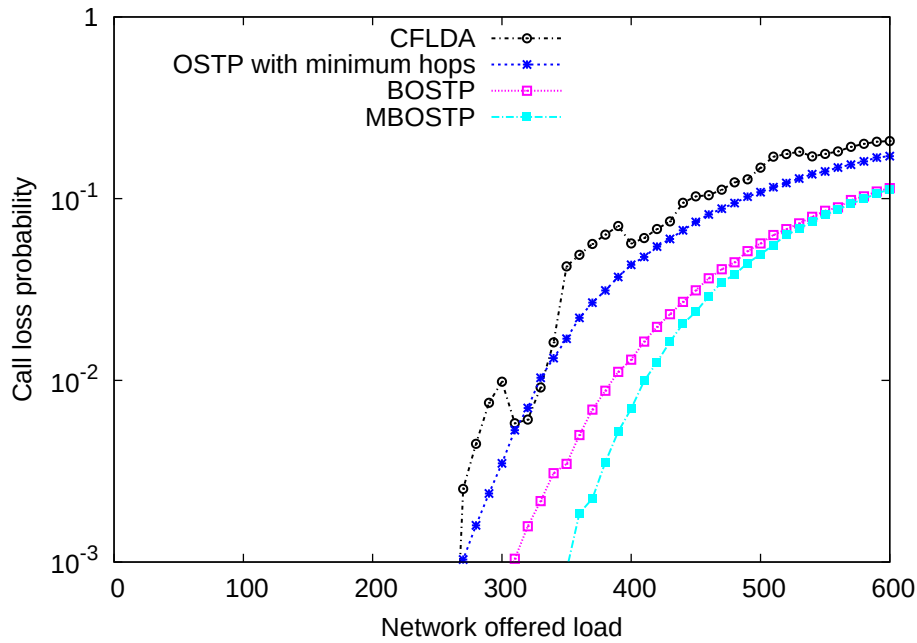


Figure 2.15 Simulated call loss probability on NSF topology

links for each request, they utilize the network more effectively than the other methods. The MBOSTP method has a lower call loss probability than the BOSTP method. MBOSTP selects the shortest path from all wavelengths, unlike BOSTP, which selects the shortest path from one wavelength. Therefore, the MBOSTP method tends to establish shorter lightpaths than the BOSTP method and occupy smaller channels in each lightpath.

Figure 2.16 shows the plot of the mean hop count for the four methods on the NSF topology when the load offered to the network changes. As compared to the OSTP with minimum hops method, the BOSTP method has a larger mean hop count. The OSTP and BOSTP methods construct different logical topologies in each wavelength. Therefore, the shortest hop count to each lightpath establishment request also depends on the selected wavelength. The OSTP with minimum hops method searches for the wavelength that has the shortest hop count when it establishes a lightpath, while the BOSTP method selects a wavelength randomly. The OSTP with minimum hops method increases its mean hop count as the network offered load becomes large in a low network offered load area. This is because there is the possibility of failure to reserve channels on the route to the destination node as the network offered load becomes large, and therefore, the method needs to try another wavelength to establish a lightpath. Since the OSTP with minimum hops method searches for a wavelength that has the shortest hop count, the hop count of the established lightpath becomes large as the number of already searched wavelengths increases. The MBOSTP method has the short-

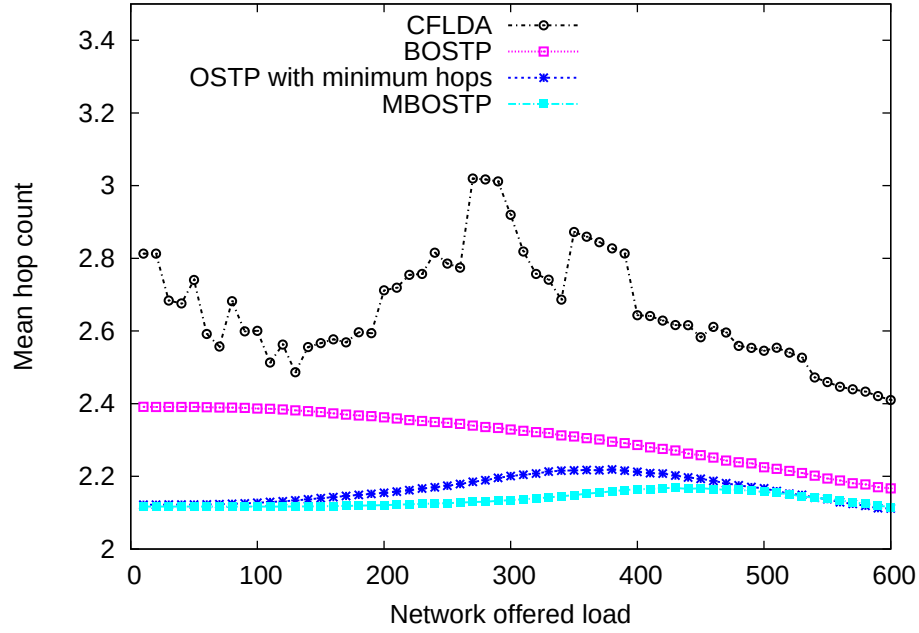


Figure2.16 Simulated mean hop count on NSF topology

est mean hop count because it searches for the shortest route among all wavelengths. All four methods tend to have smaller mean hop counts as the network offered load increases. This is because, as the network offered load becomes large, it becomes possible to occupy all channels on a link to establish a lightpath. Therefore, it becomes difficult to establish a lightpath with a large hop count.

Figure 2.17 shows the plot of the mean time to establish a connection for the four methods in the NSF topology when the network offered load changes. The CFLDA and OSTP with minimum hops methods take a longer time in low network offered load areas; however, as the network offered load becomes high, they take less time in high network offered load areas. In the case of the CFLDA method, since the controller notifies the source node whether the request can establish a lightpath or a call loss is incurred, the connection establishment time is dependent on the hop count of the lightpath. The OSTP with minimum hops method is also dependent on the hop count of the lightpath. In addition, since these methods use many requests in their attempts to try some wavelengths as the network offered load becomes high, the time it takes to establish a connection increases. On the other hand, when the network offered load becomes very high, many more filled links appear, and NACK messages are transmitted on shorter hops. BOSTP and MBOSTP take much longer than the other methods. This is because they use backward channel reservation, which reserves channels from the destination node. When a reserve message cannot reserve a channel on a node, the node pro-

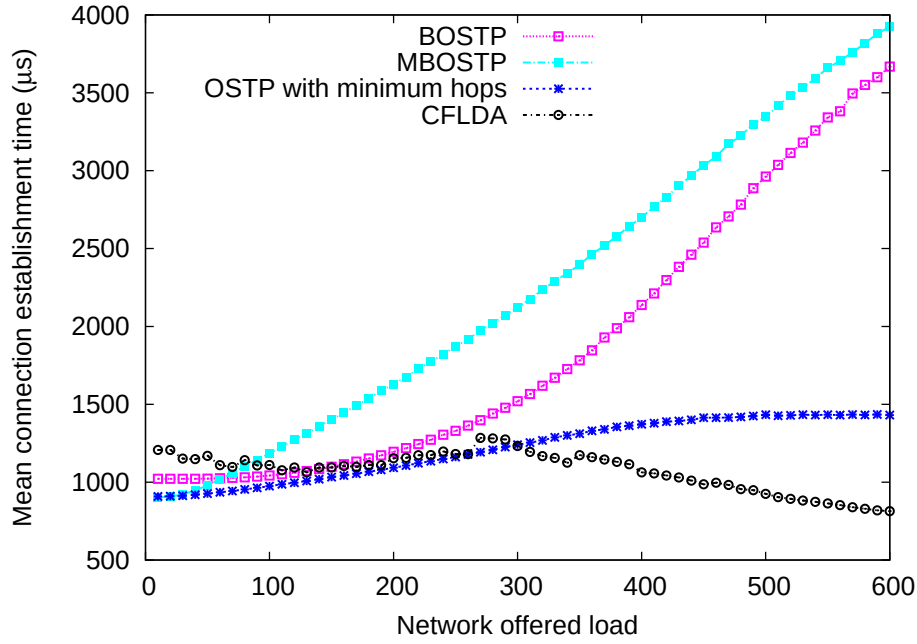


Figure 2.17 Simulated time to establish lightpath on NSF topology

duces and transmits a NACK message to the source node. Therefore, BOSTP and MBOSTP need the round trip time (RTT) to attempt to reserve the next wavelength, even if a link on the route is full. The differences in the reservation methods used are now discussed. The CFLDA and OSTP with minimum hops methods use forward reservation while the BOSTP and MBOSTP methods use backward reservation. BOSTP takes longer than MBOSTP because MBOSTP attempts to establish a lightpath from a wavelength that has the shortest path among the remaining wavelengths.

We also evaluated the number of control messages transferring per arrived connection request during simulation in the NSF topology. The BOSTP method transmits more control messages than the OSTP with minimum hops method because of probe message broadcasting. In particular, when ρ is 200, the BOSTP method executed about seven times more operations than does the OSTP with minimum hops method. However, since most messages in the BOSTP method are probe messages and a very simple operation (copy and transfer the message to lower layer links) is used, we do not think this is a very significant problem. It should be noted that, since controllers in OCDM networks are distributed, the number of control messages does not affect the control plane complexity. The MBOSTP method transmits more control messages than the BOSTP method because probe message are broadcast to all wavelength channels. In particular, when ρ is 200, the MBOSTP method executed about 64.7 times more operations than does the OSTP with minimum hops method. This increase

is strongly dependent on the number of wavelengths in the network.

2.6 Conclusion

In this chapter, we introduced OCDM network which can assign bandwidth with fine grained channels and proposed distributed path establishment method to avoid cycle attack problem which disrupt network. It is important to establish a way for LSPs to avoid cycle attacks, which would otherwise disrupt OCDM networks. Although conventional CFLDA avoids cycle attacks by using logical spanning trees, it needs centralized control to establish LSPs. We proposed the OSTP method that uses less information and reduces the cost of establishing these LSPs. OSTP method constructs a logical spanning tree using STP and leverages unused links by using a single-hop link. We also proposed the BOSTP and MBOSTP methods to establish lightpaths in distributed controlled networks in order to improve network efficiency. The BOSTP method was used to autonomously design hierarchical logical topologies and establish lightpaths by utilizing control-message broadcasting. By virtue of this control message broadcasting, the BOSTP method can establish lightpaths using only local information in distributed controllers. The MBOSTP method extends the signaling of BOSTP to all wavelength simultaneously. Although it can improve the performance of BOSTP in terms of call loss probability, mean hop count, and lightpath establishment time, it requires more control messages for routing. The discussion about implementation cost showed that our proposed methods can manage network with less performance controllers in comparison with the CFLDA method. The results of simulations revealed the OSTP method implemented with a distributed control was superior to the conventional method from the viewpoints of call-loss probability and mean hop count. They also revealed that both the BOSTP and MBOSTP methods were superior to conventional methods in terms of call loss probability, and mean hop count.

3

Distributed Controlled Hybrid Optical Networks

3.1 Introduction

In the previous chapter, we introduce OCDM network which can assign bandwidth with fine grained channels and discuss how we can avoid cycle attack problem which disrupt network. However, when we consider all-optical distributed-control networks in local- and metropolitan-area networks, the time overhead to establish lightpaths can be a serious problem. OCS network needs to establish a lightpath before the data transmission, then it takes at least round trip time to setup a lightpath. Therefore, unless the data-transmission time is much longer than the lightpath-establishment time, this overhead cannot be ignored.

To solve this issue, we propose a hybrid optical-network architecture which have another network plane to transmit a data stream without establishing a lightpath. Here, we define a “hybrid optical network” as a network constructed of two or more communication technologies, such as OCS, optical burst switching (OBS) [33, 34], and OPS [4], utilizing their respective advantages. The idea of conventional hybrid optical network requires to use additional specific devices for each communication technology. Our key idea is to extend the control plane of the OCS network and construct another network plane logically which can transmit data without establishing lightpaths. Therefore it does not require additional devices. We propose optical broadcast transmission which can transmit data without lightpath establishment in OCS network. In our proposed hybrid optical network, we select the OCS network for large-sized data traffic to provide highly reliable and contention-less data transmission, and we select the optical broadcast network for small-sized data traffic to provide a shorter time overhead before transmitting the data stream.

However, in the logical broadcast network, there is a possibility of a contention for simultaneous transmission. Therefore, we also propose contention-less logical topology design to avoid collisions among broadcast streams. We propose two types of logical topology and data transmission design for optical broadcast network. First, we propose a hierarchical logical topology design with carrier sense and an algorithm to broadcast data traffic in the network. Second, we propose contention-less logical topology design by combining star and bus type topologies to avoid contention among data streams.

The remainder of this chapter is organized as follows. In Section 3.2, we discuss related studies and reveal their contributions. In Section 3.3, we describe our hybrid optical-network architecture in detail. In Section 3.4, we propose a contention-less logical topology for optical broadcast network. In Section 3.5, we evaluate our proposed hybrid optical network using computational simulations. In Section 3.6, we summarize and conclude the chapter.

3.2 Categorize of Hybrid Optical Networks

Hybrid optical networks are divided into three major categories from its implementation architecture [61]; client-server, parallel and integrated hybrid optical network [62, 63]. Figure 3.1 shows these three kind of networks. The client-server class is constructed using a lower server layer and a higher client layer. In most cases, an OCS network is used for the lower layer and provides a virtual topology for the intelligent client layer, such as OBS or OPS. The client layer determines the routing and network-resource assignment for each data-transfer request [64].

The parallel class uses two or more optical networks with different communication technologies in tandem. The data stream is transferred to one of these parallel optical networks. The edge node of the network determines the network to use for the transmission. Network resources are occupied by each network or shared by all networks. We can consider both static and dynamic methods of assigning network resources for each request.

In the integrated hybrid optical class, all network nodes use two or more communication technologies. Each network node determines the network to use for transferring the data stream. In the integrated hybrid optical class, each node is set by marker traffic that is pre-transmitted as a data stream. Therefore, the network requires an appropriate offset time to set up a network node before transmitting the data stream [65].

Table 3.1 shows the characteristics of each hybrid optical network. Hybrid optical networks can leverage the merits of each integrated network technology. As the degree of interaction and integration increases for the network technology, the network resources necessary

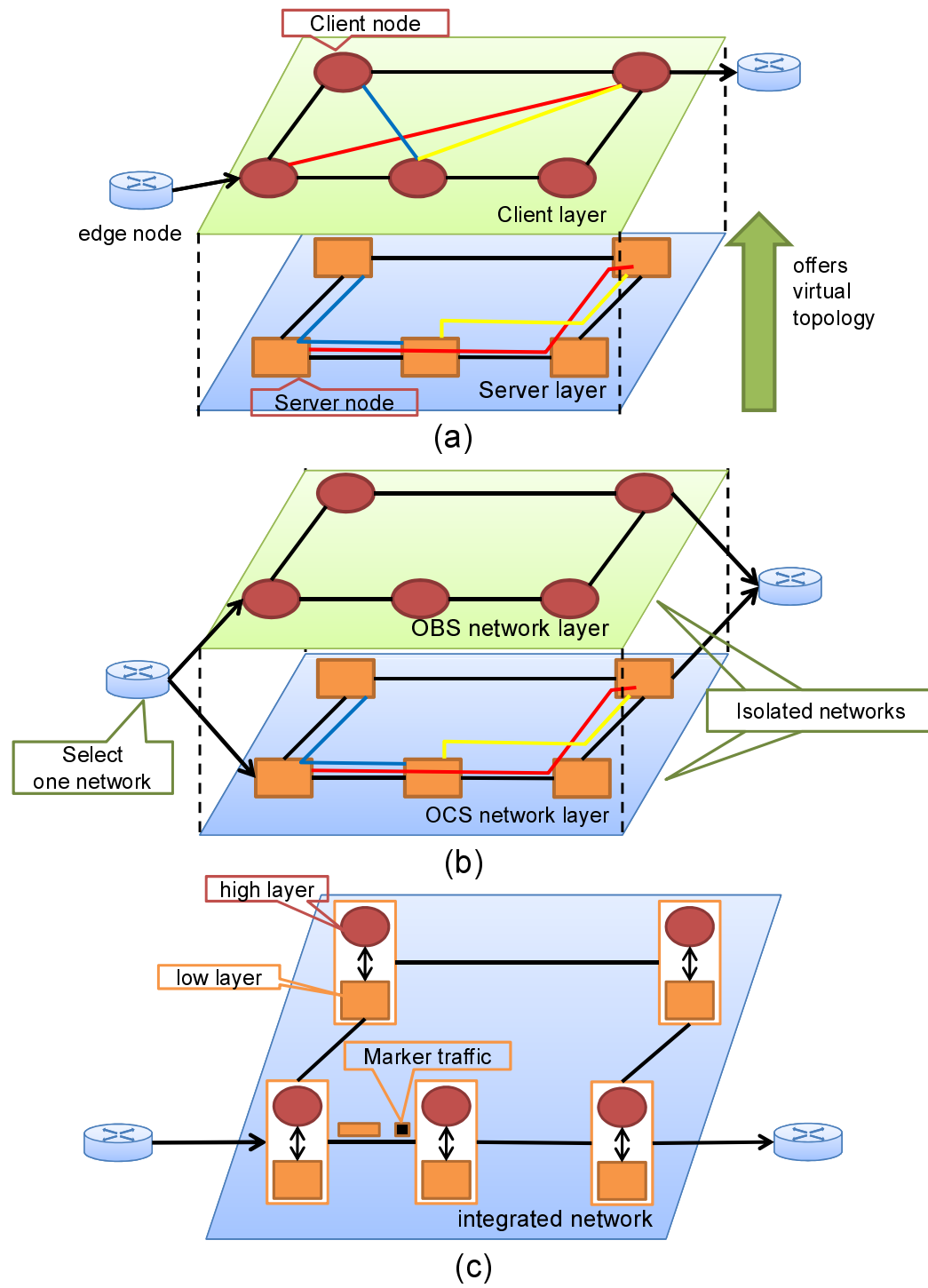


Figure 3.1 Hybrid optical network; (a) client-server, (b) parallel, (c) integrated

Table 3.1 Definition and characteristics of hybrid optical networks.

	Definition	Resource requirement	Technical difficulty	Control difficulty
Client-server	Server layer offers logical topology to client layer	Large	Low	Low
Parallel	Edge nodes offer different network technologies (channels are in use by one technology at once).	Middle	Middle	Middle
Integrated	Edge nodes offer different network technologies (channels are in use by all technologies at once).	Middle	High	High

to control the connections are reduced. On the other hand, highly integrated hybrid optical networks require a higher level of technology and control. Therefore, an appropriate architecture should be designed according to the requirements of the network.

3.3 Architecture for the Proposed Hybrid Optical Network

In this section, we describe the architecture for a hybrid optical network consisting of an OCS network and an optical-broadcast network operating in tandem. In Section 3.3.1, we describe the outline for our proposed hybrid optical network. In Sections 3.3.2 and 3.3.3, we describe a method for transmitting data in an OCS network and an optical broadcast network, respectively.

3.3.1 Outline of the Hybrid Optical Network

In this section, we propose a parallel-class hybrid optical network that uses OCS and optical broadcast transmissions with distributed controllers. That is, the network is constructed by combining an independent OCS network and an optical broadcast network, and a source node selects the network to use for transmitting the data stream. Figure 3.2 illustrates the proposed hybrid optical network. We assume that the network has a LAN- or MAN-scale mesh-type topology, and distributed controllers manage the network. Data-transfer requests arrive dynamically at an arbitrary node with an arbitrary destination node. The time intervals between any two sequential requests are different. Each request has a different data-transmission time. Each network node is constructed by using an OXC to switch the optical signal and a controller to set up the OXC. These devices are shared by both the OCS network

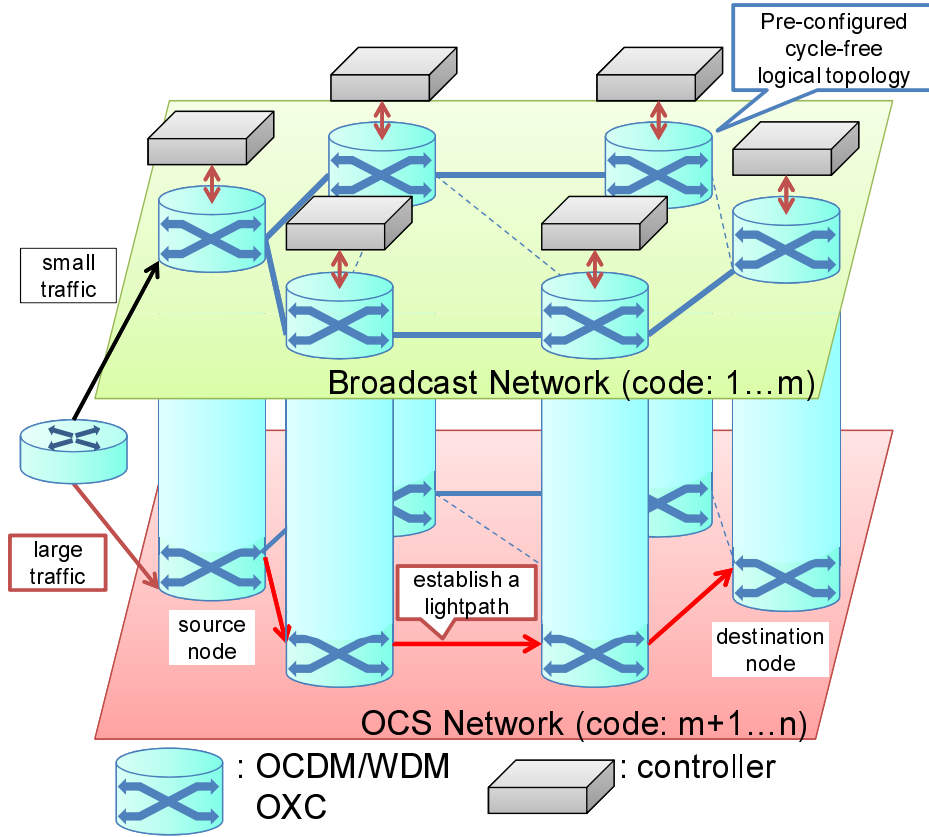


Figure 3.2 Proposed hybrid optical network architecture

and the optical broadcast network. The OCS network and the optical broadcast network are logically divided only by the channel assignments on the controllers. That is, some of the channels are assigned to the optical broadcast network, and the other channels are assigned to the OCS network. All of the network nodes have the same information about the channels assigned to each network.

In the OCS network, a lightpath is established before beginning the transmission of a data stream. Because the lightpaths never contend with one another, the OCS network has the advantage of a lower data-propagation delay, and guarantees that no traffic is lost during each data-transfer request. On the other hand, the time overhead for the OCS network to establish a large lightpath is an issue with small-sized data traffic. An optical broadcast network has the advantage of a smaller time overhead to begin data transmission because establishing a lightpath is unnecessary. On the other hand, when the data-traffic size is large, the possibility of crashes between data streams increases, and the call-loss performance of the network decreases. In order to fully utilize the performance of each network, the source node for our proposed hybrid optical network selects a transmission network for each data-transfer

request by appealing to a threshold for the data size. When the traffic size is larger than the threshold, the node selects an OCS network; otherwise, the node selects an optical broadcast network. Either all network nodes have the same threshold, or each network node determines a threshold according to the unused channel information concerning itself.

The optical broadcast network is configured with a cycle-free logical topology and a transferring policy for all network nodes. In this section, we use the hierarchical logical topology proposed in Chapter 2 for both of OCS and optical broadcast network. Each distributed controller implemented with an OXC manages this information. Therefore, unlike OCS and OBS networks, an optical broadcast network does not need to setup an OXC for each transmission request [66,67], and source nodes can transmit a data stream earlier. In our proposed hybrid optical network, the OCS-network layer and the optical broadcast-network layer are logically divided by OCDM channels. Therefore, by contrast with other hybrid optical-networking technologies, our proposed hybrid optical network can implement the OCS network with a modified control plane.

3.3.2 Connection Setup in OCS Network

When a data-transfer request has a data size that is larger than the network threshold, the source node initiates the establishment of a lightpath in the OCS network. In a distributed-control network, each network node only receives information from itself and its neighboring nodes. Therefore, all nodes must search for a route to establish a lightpath. In this section, we use a BOSTP method proposed in Chapter 2 for OCS network.

Figure 3.3 shows an example of the lightpath-establishment process. When a data-transfer request arrives at a source node, the source node selects a wavelength channel and broadcasts probe messages to the hierarchical logical topology on the wavelength channel (see Fig. 3.3(a)). An intermediate node that receives a probe message copies it and transfers it to the other ports at a layer that is the same or lower than the receiving port. The probe messages contain information about all passed node IDs, wavelength channels, and connection IDs. A destination node returns a reserve message for the arrival of the first probe message (see Fig. 3.3(b)). The destination node records the wavelength channel and connection ID for all the received probe messages. If a newly received probe message has the same wavelength channel and connection ID recorded in the destination node, the node rejects the probe message. A reserve message contains information about the assigned OCDM channel for each hop, in addition to information stored in the probe message. An “upstream port” refers to a port to proceed to the source node, and a “downstream port” refers to a port to proceed

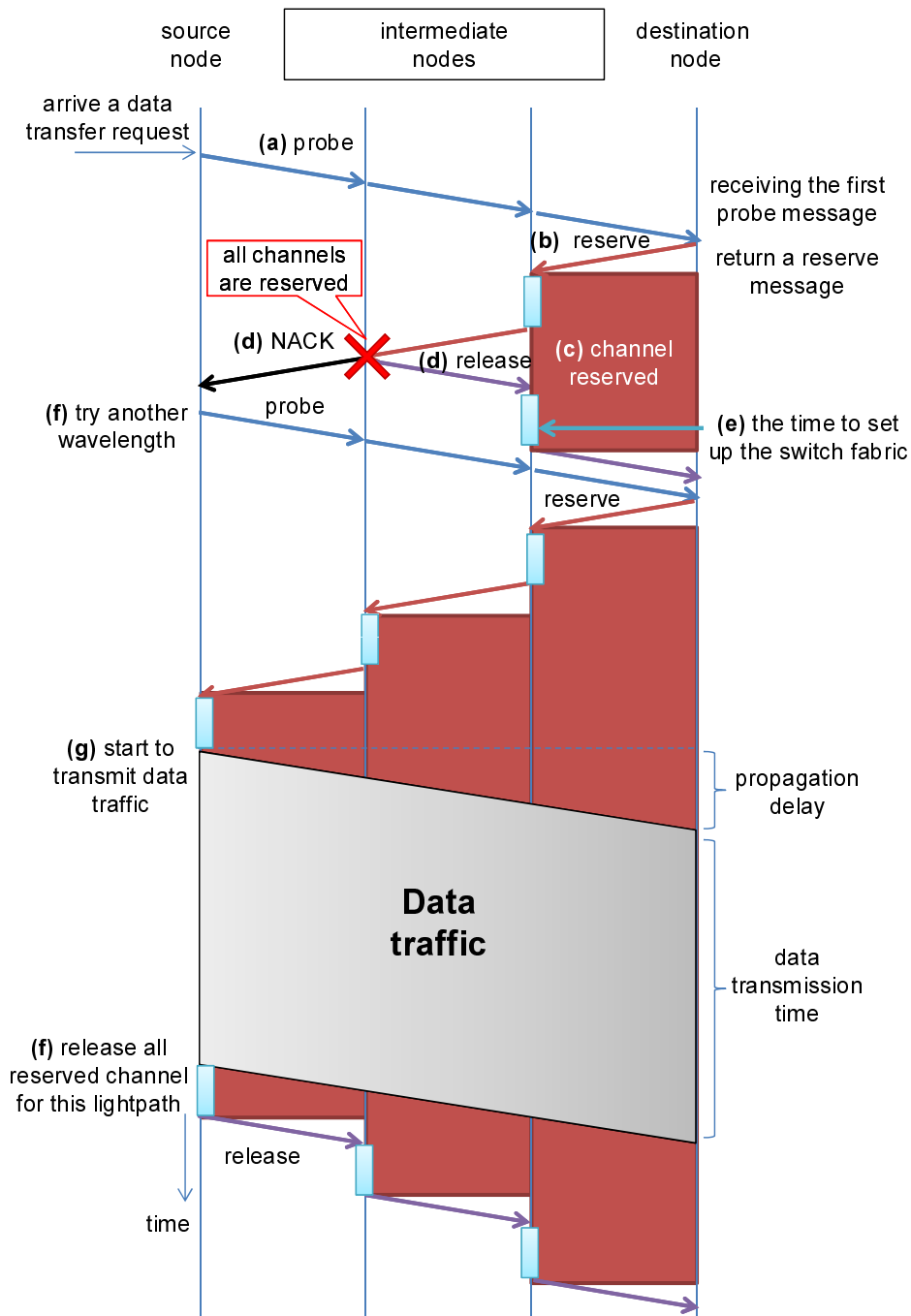


Figure 3.3 Signaling to establish lightpath

to the destination node on a lightpath. An intermediate node receiving a reserve message searches for unused OCDM channels in the downstream ports for each hop. If there are unused OCDM channels, the node assigns one channel for the connection and transfers the reserve message to the upstream port (see Fig. 3.3(c)). If all of the channels are in use, the node transmits a NACK message to the source node and a release message to the destination

node (see Fig. 3.3(d)). Because setting up the OXC requires time, intermediate nodes transfer a reserve message or a release message after changing the OXC setting (see Fig. 3.3(e)). If the source node receives a NACK message, the node selects another wavelength to establish a lightpath and repeats the above process (see Fig. 3.3(f)). If there is no other wavelength, the data-transfer request becomes a call loss. After the source node receives a reserve message and reserves its downstream port, the process for establishing a lightpath is complete. The source node subsequently transmits the data stream and a release message after transmitting the entire data stream (see Fig. 3.3(g)). After the source node transmits the data stream, the node transmits a release message that releases all of the reserved channels (see Fig. 3.3(h)). These control messages are transferred in the optical layer and converted to an electrical layer for each network node. Note that, because the BOSTP method only accepts the probe messages that arrive first, the method always selects the shortest route for each source-destination pair.

3.3.3 Data Transmission for the Optical Broadcast Network in Hierarchical Logical Topology

When a data-transfer request has a smaller data size than the network threshold, the source node begins a broadcast transmission along the hierarchical logical topology. Because the hierarchical logical topology does not have a cycle, we can transmit the data stream without a broadcast storm. All the received traffic is transferred to ports that have an equal or lower layer than the receiving port. The transferring port is set up during the construction of the logical topology, as described in Chapter 2.

The optical broadcast network transmits the data stream using the following process in the optical broadcast network. First, using carrier sensing, a source node selects the wavelength channel from which to transmit. The source node checks the smallest number of available OCDM channels among all Layer-0 links on each wavelength. If any Layer-0 links do not have any available OCDM channels, the source node counts the rate of Layer-0 links that do have available OCDM channels. Then, the source node selects the wavelength with the largest number of available OCDM channels. If any wavelengths have an equal number of OCDM channels, the source node selects one randomly. After the source node selects a wavelength, the node begins to transmit a data stream with a random unused OCDM channel for each output port. The used channels are detected when the source node decodes the received optical signal using optical correlation. If a link has no available OCDM channels, the node waits until a data stream finishes transferring and then selects the OCDM channel

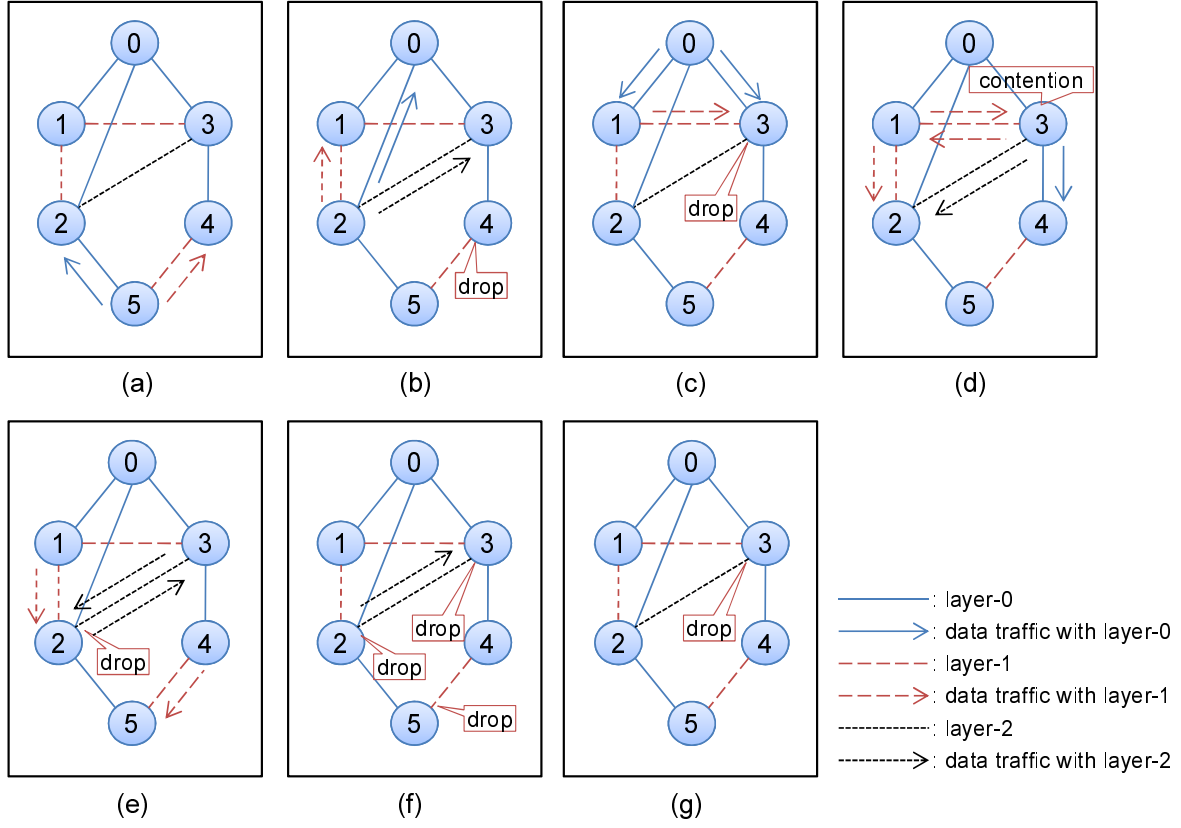


Figure 3.4 Optical broadcast data-transmission process

used by the stream. We assume that channel conversion is not occurring in the OCDM/WDM optical broadcast network.

No data-transfer requests reserve channels in the optical broadcast network before the data is transmitted. Therefore, two data streams will crash when they arrive at a node at shorter intervals of data-transmission time with the same channel and the same output ports. To prevent such a crash, our proposed network blocks the output port from the data stream arriving at the node until the traffic finishes transferring to the node. Other traffic streams arriving at the node do not transfer to the blocked port.

Figure 3.4 provides an example of an optical broadcast transmission in a six-node topology when Node 5 transmits a data stream to Node 3.

All of the links have the same data-propagation delay, and there is no delay in the transfer of a data stream on each node. In the following, “Port 2→3” signifies that a port on Node 2 connects to Node 3, and “Port 3←2” signifies that a port on Node 3 is connected from Node 2.

1. Node 5 transmits the data stream to Port 5→2 (Layer-0) and Port 5→4 (Layer-1) (see Fig. 3.4(a)).

2. Node 4 drops the data stream because there is no port it can transfer to, because Port $4 \rightarrow 3$ (Layer-0) is a higher layer than the receiving Port $4 \leftarrow 5$ (Layer-1). Node 2 transfers the data stream received from Port $2 \leftarrow 5$ (Layer-0) to Port $2 \rightarrow 0$ (Layer-0), Port $2 \rightarrow 1$ (Layer-1), and Port $2 \rightarrow 3$ (Layer-2). At the moment, the destination Node 3 receives the data stream (see Fig. 3.4(b)). Moreover, the destination node transfers the data stream because the optical broadcast network does not assume that the traffic ends at the destination node.
3. Node 0 transfers the data stream received from Port $2 \leftarrow 0$ (Layer-0) to Port $0 \rightarrow 1$ (Layer-0) and Port $0 \rightarrow 3$ (Layer-0). Node 1 transfers the data stream received from Port $1 \leftarrow 2$ (Layer-1) to Port $1 \rightarrow 3$ (Layer-1). Node 3 drops the data stream received from Port $3 \rightarrow 2$ (Layer-2) (see Fig. 3.4(c)).
4. Node 1 transfers the data stream received from Port $1 \leftarrow 0$ (Layer-0) to Port $1 \rightarrow 2$ (Layer-1) and Port $1 \rightarrow 3$ (Layer-1). Node 3 transfers the data stream received from Port $3 \leftarrow 0$ (Layer-0) to Port $3 \rightarrow 1$ (Layer-1), $3 \rightarrow 2$ (Layer-2), and $3 \rightarrow 4$ (Layer-0). In addition, Node 3 transfers the data stream received from Port $3 \leftarrow 1$ (Layer-1) to Port $3 \rightarrow 2$ (Layer-2). In this case, because there are two data streams transferring to Port $3 \rightarrow 2$, the data stream that is received later is blocked on Node 3 (see Fig. 3.4(d)).
5. Node 1 transfers the data stream received from Port $1 \leftarrow 3$ (Layer-1) to Port $1 \rightarrow 2$ (Layer-1). Node 2 transfers the data stream received from Port $2 \leftarrow 1$ (Layer-1) to Port $2 \rightarrow 3$ (Layer-2) and drops a data stream received from Port $2 \leftarrow 3$ (Layer-2) (see Fig. 3.4(e)). Node 3 transfers the data stream received from Port $3 \leftarrow 1$ (Layer-1) to Port $3 \rightarrow 2$ (Layer-2). Node 4 transfers the data stream received from Port $4 \leftarrow 3$ (Layer-0) to Port $4 \rightarrow 5$ (Layer-1).
6. Node 2 transfers the data stream received from Port $2 \leftarrow 1$ (Layer-1) to Port $2 \rightarrow 3$ (Layer-2) and drops the data stream received from Port $2 \leftarrow 3$ (Layer-2). Node 3 drops the received data stream from Port $3 \leftarrow 2$ (Layer-2). Node 5 drops the received data stream from Port $5 \leftarrow 4$ (Layer-1) (see Fig. 3.4(f)).
7. Finally, Node 3 drops the data stream received from Port $3 \leftarrow 2$ (Layer-2) (see Fig. 3.4(g)).

3.4 Contention-less Optical Broadcast Topology

In previous section, we introduce our proposed hybrid optical network architecture and propose optical broadcast network with hierarchical logical topology. However, if we use tree-based logical topology, data traffic streams in the network crash each other at the junction

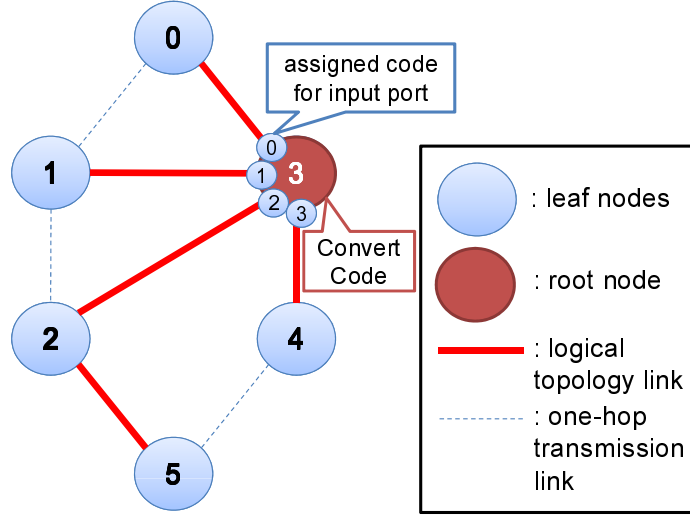


Figure 3.5 Contention-less logical topology for optical broadcast network

node and increase the call loss probability even when the network offered load is low. In this section, we propose a contention-less optical broadcast network to improve the performance when the network offered load is low.

3.4.1 Contention-less Optical Broadcast Topology

The network has a root node which is the center of the star topology, as well as other nodes. In this section, we define the “leaf nodes” as those nodes that are not the root node. Only the root node can have junctions, whereas the other nodes are connected by straight roads from the root node. When the root node receives data from the other nodes, the root node converts its code to the code assigned to each port and transfers it to all the other ports. When data transmission starts from the root node, the node sets the code assigned to each port and transmits it to all the ports. Figure 3.5 shows an example of our proposed network topology and data transmission. In the following, we describe how to construct this bus and star type topology.

3.4.2 New OCDM/WDM OXC Design for Optical Broadcast Topology

Figure 3.6 shows the architecture of our hybrid optical network node. Each node has a control plane and a data plane. Electronic devices are used in the controller and OCDM/WDM optical cross connects (OXCs) are used to transmit data traffic. The OCDM/WDM OXC is constructed with an N OCDM switching plane, where N is the num-

ber of wavelengths. Each switching plane has M decoders (where M is the number of codes of this OXC and is also the number of channels on each wavelength), a switching process, M converters, and an OC multiplexer. These decoders and converters are implemented on each of the L ports. First, the optical signal is demultiplexed into individual wavelengths by the wavelength de-multiplexer. Then the signal is transferred to the fiber delay lines (FDLs) and informs the controller about data traffic arrival to prevent new data traffic from transferring to this node during buffering. Each signal is duplicated to form M signals and these enter the decoders. The decoded signals are transferred to specific encoders through the switching process. This switching process is set up by the controller. Then, these signals are encoded again and multiplexed through an OC multiplexer and wavelength multiplexer.

3.4.3 Contention-less Logical Topology Design

In this subsection, we describe how to construct the star and bus type logical topology. Our proposed logical topology is constructed in three phases. First, the network determines the root node. All the nodes transmit a control signal that includes the number of connected nodes and its node ID. This node ID is assigned by the manager of the network. Then, the node that has the highest number of nodes is the root node. If two or more nodes have the same number of neighbor nodes, the node that has the lower node ID becomes the root node. In our topology, only the root node has three or more neighbor nodes.

Second, the network constructs a bus and star topology. The root node transmits port-cost-calculation messages to all the ports. After a node receives this message, the node transfers the message from all the other ports after adding the cost of the port. In this section, we consider “cost” as the propagation delay of each link, and a smaller cost is better. From this process, all of the nodes know the cost to reach the root node from of the ports. Then, the root node transmits topology-construction messages to all the ports. After receiving this message from the root node, the node selects another port, which is the one with the smallest cost, for the lower node. In this chapter, “upper” implies the direction to the root node and “lower” implies the direction from the root node. When a node receives a message from a non-root node, the node does one of the following three actions. If the node has not set up an upper port yet, the node returns an ACK message and the link is included in the logical topology. If the node has already set up an upper port and the port cost is equal to or less than the port that receives the topology construction message, the node returns a NACK message. If the node has already set up an upper port and the port cost is higher than the new one, the node changes the parent node to the message receiving port. That is, the node returns an ACK

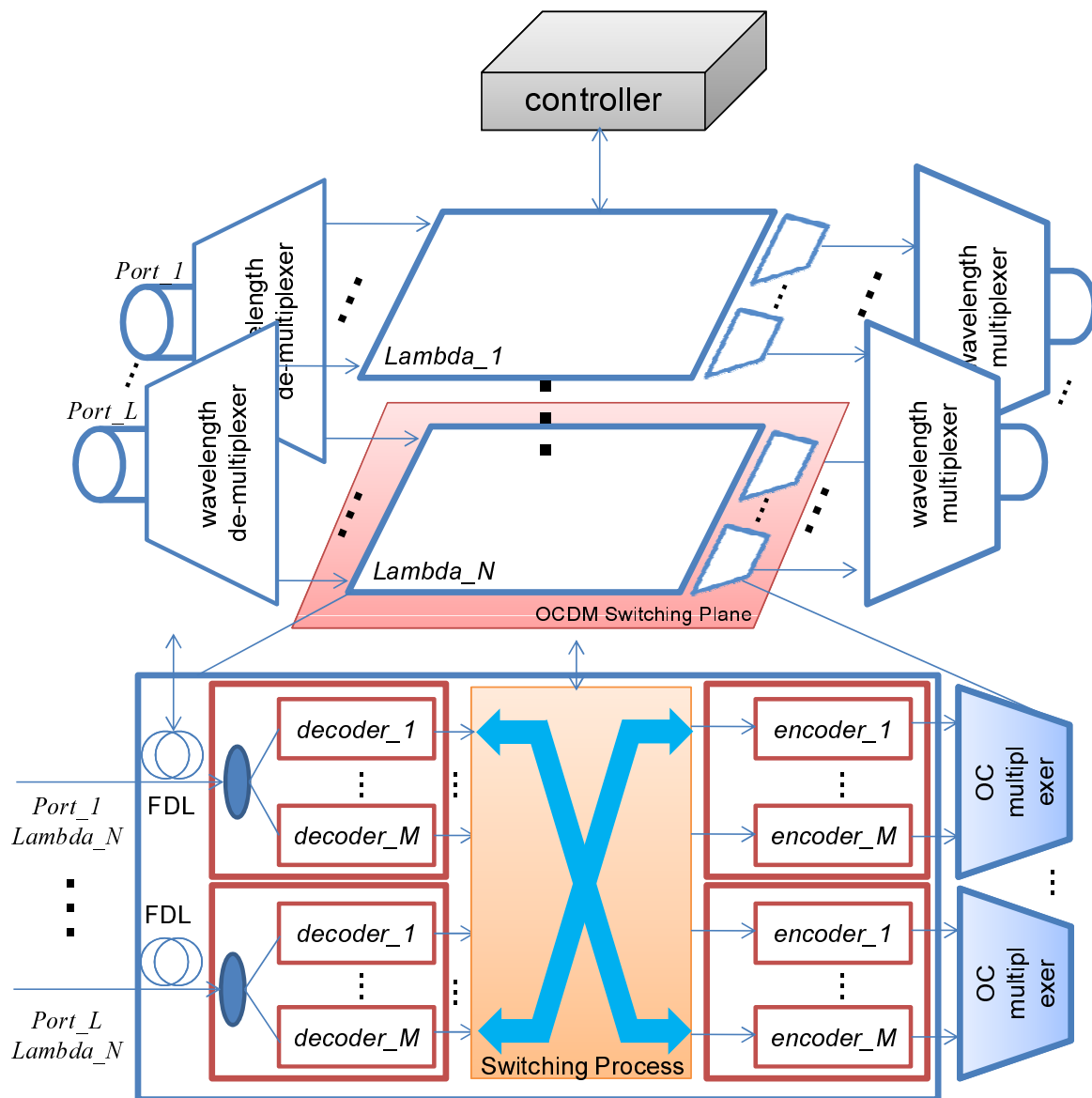


Figure 3.6 OCDM/WDM OXC for Optical Broadcast Network

message and transmits a NACK message to the old upper port. After constructing the bus and star topology, the root node assigns a code to each input port. When data traffic is received from a port, the root node swaps its code with the assigned code. Therefore, the number of OCDM codes in the optical broadcast network needs to be an integral multiple of the degree of the root node.

Last, all the leaf nodes treat the other ports as one-hop transmission ports. In the logical topology construction phase, all the nodes on the control plane recognize the neighbor node ID. Therefore, when data to be transmitted to a neighbor node arrives at a node, the node

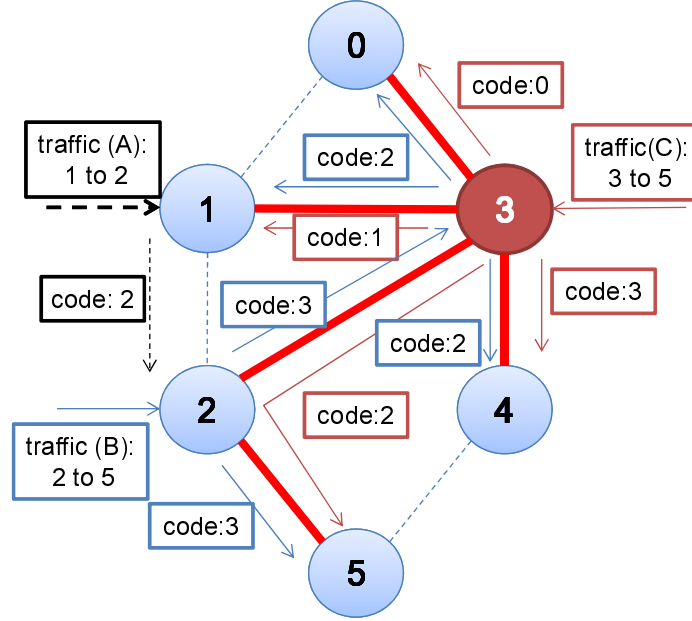


Figure 3.7 Optical broadcast transmission

can transmit data without establishing a lightpath if the receiver permits the distinction between a one-hop transmission and optical broadcasting. In our proposed network, these are distinguished based on the receiving port.

Note that our proposed network design may create isolated nodes. In addition, some types of networks cannot construct a bus and star type topology. Therefore, if some nodes are isolated in our proposed network, we should use the hierarchical logical topology and be careful to avoid data traffic collisions.

3.4.4 Optical Broadcast in Contention-less Logical Topology

In contention-less optical broadcast network, the data transmission process has three phases. First, when a data transmission requirement arrives at a node, the node checks whether it can use a one-hop transmission. Whether the channel can be used or not is decided by the controller. If two or more channels are not in use, the source node selects a channel randomly. Traffic (A) shown in Fig. 3.7 is an example of a one-hop transmission.

Second, if the source node cannot use a one-hop transmission and there is no data traffic in the FDLs, the node checks for unused wavelengths in an upper link. If only parts of codes are in use in the upper link on a wavelength, the node cannot use the unused codes. This is because if two or more data traffic are transmitted to the root node from the same port simultaneously, these data traffic crash at the encoder of the root node. When the source node

is the root node, this process is not used.

Last, if one or more wavelengths are not in use, the source node searches for unused channels at a lower link. If two or more channels are not in use, the source node selects a channel on a wavelength randomly. Traffic (B) shown in Fig. 3.7 is an example of data traffic from leaf nodes. When the source node is the root node, the source node determines for itself whether other data traffic are being transmitted. If not, the source node transmits data traffic to all the ports encoded by the specific code assigned to the node. Traffic (C) shown in Fig. 3.7 is an example of data traffic from the root node.

When data traffic is received at an intermediate node, the traffic is inserted to the FDLs. If data traffic is transferring through the FDLs or output ports when a data transmission requirement arrives at the source node, the source node waits for a random amount of time using a binary back-off algorithm based on the link propagation delay and then senses the transferred carrier again. We assume that our proposed optical broadcast network is used for one layer of a hybrid optical network. In a hybrid optical network, all the traffic is transferred through the OCS network or optical broadcast network according to its data transmission time, using a network threshold. Therefore, if the delay from an FDL is longer than the maximum data transmission time, i.e. longer than the threshold, the source nodes can transmit data without collisions.

3.5 Numerical Results

In this section, we evaluate our proposed hybrid optical network. The purpose of this section is to confirm following three results. First, we show the optical broadcast transmission can improve the performance in terms of call loss probability and call waiting time compared with OCS transmission in case where the requests have small data-transmission time. Second, we confirm our proposed hybrid optical network can receive advantage from both the OCS and the optical broadcast network. To confirm this, we show the hybrid optical network improve call loss probability compared with the pure OCS network and the pure optical optical broadcast network. Third, we show the contention-less logical topology for optical broadcast network can improve call loss probability in case where the collision is the dominant factor.

In Section 3.5.1, we explain our simulation setup. In Section 3.5.2, we describe the simulation performed on a pure OCS network and a pure optical broadcast network and analyze their basic performance. In Section 3.5.3, we evaluate our hybrid optical network and explain its validation. In Section 3.5.4, we compare the hierarchical logical topology and contention-less logical topology for optical broadcast network.

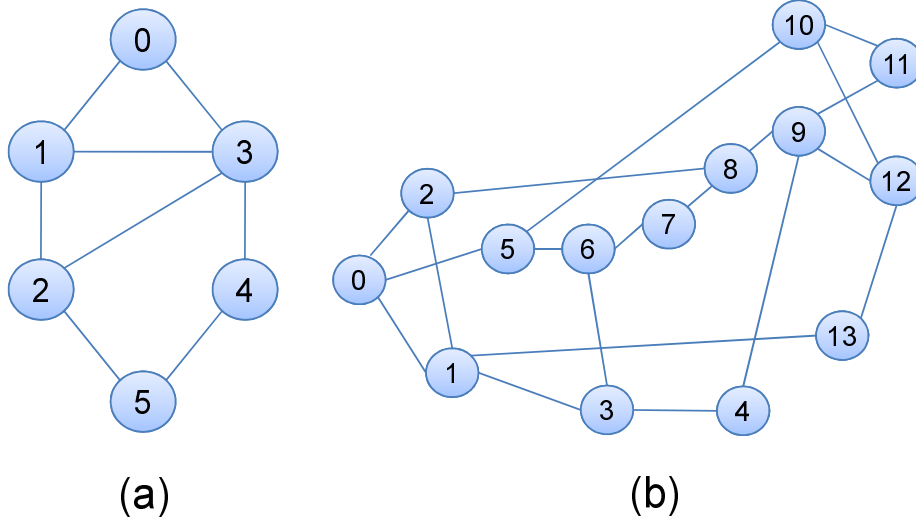


Figure 3.8 Simulation topology: (a) six-node network, and (b) NSF network

3.5.1 Simulation Setup

We used the six-node topology and NSF topology shown in Fig. 3.8 as a network model. Each link has bi-directional fibers that have six wavelengths and six OCDM channels per wavelength. We assumed that there is no wavelength conversion at the intermediate nodes. We further assumed that all intermediate nodes are able to swap OCDM channel on the same wavelength channel in the OCS network. The delay time required for data- and control-message transmission was accounted for as the sum of the link-propagation delay and the OXC-setup time. Data-transfer requests arrive at the network at a rate of λ , according to a Poisson distribution, and they arrive with the same probability among source-destination pairs. Data-transfer requests have a service time at a rate of $1/\mu$, according to an exponential distribution. The network-offered load ρ is defined as λ/μ in our simulations.

All links have the same link propagation delay and link capacity. The data-transmission time T represents the proportion of the data-transmission time to a fixed-link propagation delay (D). We assumed that the OXC setup time is equivalent to the link-propagation delay D . Because control messages are transferred on a dedicated channel in the OCS networks, we further assumed that there would be no collisions in the control channel. Because the cycle-free logical topologies were constructed prior to the simulation, there was no overhead in the construction of the topology. We assumed that there is no time overhead in broadcast networks for locking or releasing the channels of the output ports. We defined the network threshold T_h , which is used to determine the network used by the data stream on the source

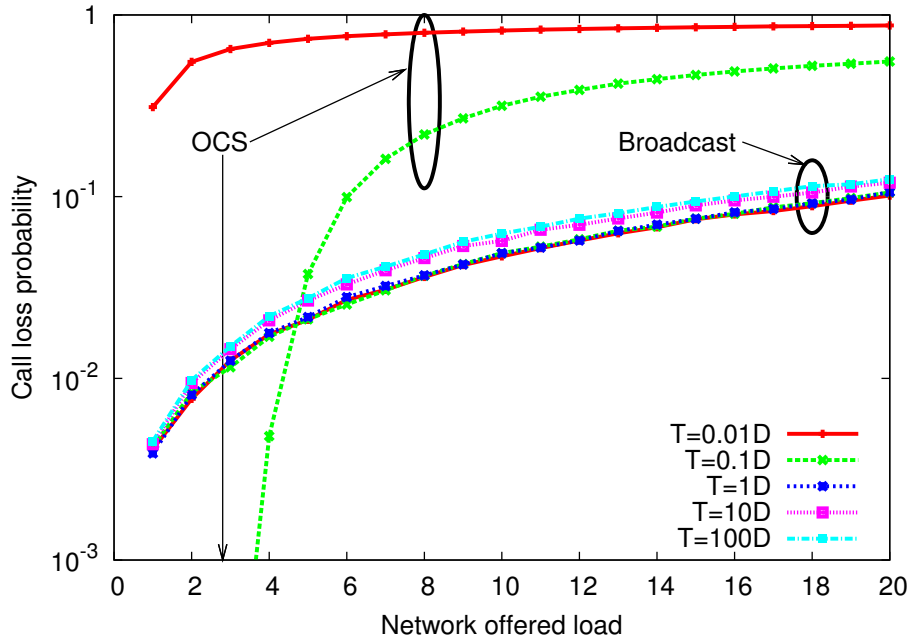


Figure 3.9 Call-loss probability of the independent network

node. If the data transmission time T is larger than T_h , the data is transferred on the OCS network. If it is smaller than T_h , however, the data is transferred on the optical broadcast network. We assumed that all network nodes have the same network threshold T_h . Each broadcast transmission becomes a call loss if it waits ten times longer than its transmission time in the source node.

We used the call-loss probability, call-delay time, and throughput as performance measures. The call-loss probability represents the ratio of unestablished connections in the OCS network and the ratio of unreachable data in the optical broadcast network. The call-delay time represents the time between when the data-transfer request arrives at the network and when the data stream begins to transmit per link-propagation time. In other words, the call-delay time is the time required to establish the lightpaths in the OCS network. In the optical broadcast network, it means the waiting time at the source node. Throughput represents the total traffic-transferring time per simulation time. In other words, the throughput tracks the number of data streams in the network per time unit.

3.5.2 Basic Performance Evaluation

We evaluated the call-loss probability, the call-delay time, and the throughput for both the OCS network and the broadcast network. Figure 3.9 depicts the call-loss probability for

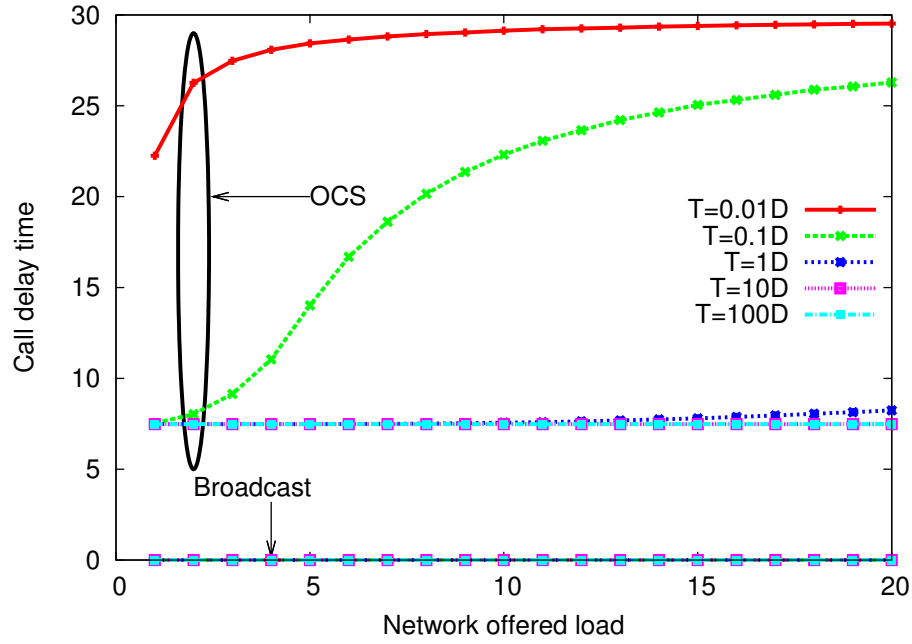


Figure 3.10 Call-delay time for the independent network

the OCS and broadcast networks when the network-offered load and the data-transmission time (T) changes. We can see that the OCS network has a low call-loss probability as T increases. This is because the influence of the time overhead for establishing a path is stronger as T decreases. As a reserve message propagates and the OXCs are setting up, the other reserve messages cannot use the reserved channel despite the fact that the data stream has not yet been transferred. Therefore, when T is small, even given the same network-offered load, the network becomes increasingly crowded. On the other hand, an optical broadcast network has a higher call-loss probability as the data-stream size become large. Because the optical broadcast network has the advantage of multiplexing gain, the network is influenced less by the data stream size than the OCS network. This is different from the case of the OCS network, owing to the stream contention on intermediate nodes. The optical broadcast network loses calls even when the network-offered load is low. When $T = 0.01D$, the optical broadcast network always performs better than the OCS network. When $T = 0.1D$, the OCS network has a lower call-loss probability when the network-offered load is smaller than 5, and the optical broadcast network has a lower call-loss probability when the network-offered load is high. In particular, when the network-offered load is 10, the optical broadcast network has approximately an 85% lower call-loss probability than the OCS network.

Figure 3.10 shows the call-delay time when the network-offered load and data-transmission time changes. The OCS network has a higher call-delay time as T decreases.

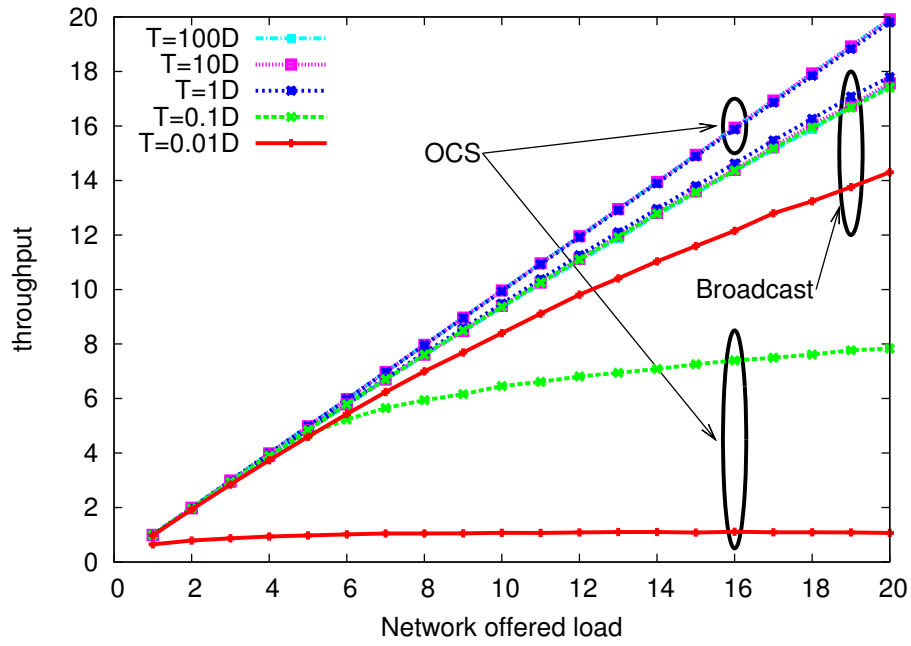


Figure 3.11 Throughput of the independent network

This is because the network with a smaller T is more crowded than the network with larger T . In the OCS network, when the signaling process fails to assign an OCDM channel for an intermediate node, the source node attempts to establish a lightpath on another wavelength channel. Therefore, the more crowded the network, the longer time required to establish a lightpath in the OCS network. When T is larger than D , the OCS network achieves the same call-delay time regardless of the network-offered load. This means that all requests have found the OCDM channel on the first wavelength channel. On the other hand, for the optical broadcast, the call-delay time is almost zero. This means that the network is not as crowded and that many requests can begin transmitting without waiting on the source node. These results show that the optical broadcast network can begin transmissions much faster than the OCS network.

Figure 3.11 shows the throughput when the network-offered load and data-transmission time changes. When T is equal or smaller than $0.01D$, the optical broadcast network has a better throughput than the OCS network. Because the time overhead to establish a lightpath increases, the throughput for the OCS network decreases as the data size becomes smaller. The OCS network has the same throughput value as the network-offered load when T is equal or larger than D . This is because when there is no call loss in the network, the number of lightpaths in the network is the same as the network-offered load. On the other hand, the optical broadcast network—by dint of its merits from multiplexing gain—achieves a high

throughput even if many small data streams arrive at the network. An optical broadcast network with $T = 0.01D$ has a smaller throughput than other optical broadcast networks. This is because when the data stream size is too small, there is an interval of time during which data is not transmitted between two data streams. Because of the call loss, the throughput in optical broadcast networks when T is equal or larger than $0.1D$ is less than the network-offered load. From these basic performance evaluations, we can conclude that when the size of the data stream is small, the optical-broadcast transmission outperforms the OCS transmission.

3.5.3 Hybrid Network Performance Evaluation

In this section, we evaluate the performance of the proposed hybrid optical network. Two types of data-transfer requests arrive at the network with the same network-offered load. One request arrives at the network with $T = 10D$, and the other arrives with $T = 0.1D$. We assume that both types of requests arrive with the same network-offered load. For example, $\rho = 5$ means that both $T = 0.1D$ and $T = 10D$ requests arrive at the network with $\rho = 5$. We used the network threshold $T_h = 1D$ for the simulation. The arriving requests numbered approximately 100,000 for $T = 0.1D$ and 1,000 for $T = 10D$. Two numbers indicate the respective OCDM channels assigned to each network. The first number indicates then number of OCDM channels assigned to the OCS network, and the number following the hyphen indicates the number of OCDM channels assigned to the optical broadcast network. Thus, “6-0” indicates a pure OCS network and “0-6” indicates pure optical broadcast network.

Figure 3.12 plots the call-loss probability when the network-offered load changes. When the network-offered load is especially small ($\rho < 7$), a pure OCS network offers the best performance. This means that the network has sufficient resources to assign channels for each request. The hybrid optical network and the pure optical broadcast network lose part of requests owing to a collision between the broadcast streams. The hybrid optical network performs better than the OCS network when the network-offered load is equal to or more than eight. In particular, when the network offered load is ten, a hybrid optical network with a “1-5” channel has 80% less call-loss probability than the pure OCS network. Among hybrid optical networks, the network with more optical broadcast OCDM channels has a lower call-loss probability. This means that because the OCS network layer has sufficient channels to assign the lightpaths, the number of channels for the optical broadcast network has more influence on the performance. A hybrid optical-broadcast network with three or more OCDM channels for the optical-broadcast network layer achieves a lower call-loss probability than

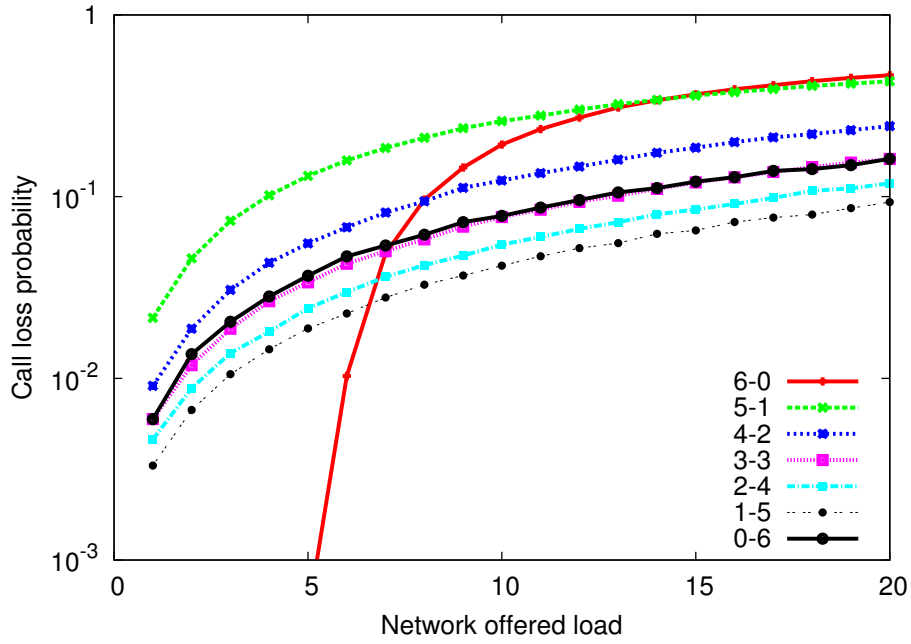


Figure 3.12 Call-loss probability for the hybrid optical network

the pure optical broadcast network. Unlike the pure optical broadcast network, which necessarily transmits a large data stream with $T = 10D$, hybrid optical networks can offload this large data stream to the OCS network layer. Given the above results, we can conclude that when the network has both large and small data streams, the hybrid optical network outperforms both the pure OCS network and the pure optical broadcast network.

Figure 3.13 plots the mean call-delay time for the OCS network layer when the network-offered load changes. We did not provide the delay time for the optical broadcast network layer because most requests begin to transmit without any delay. The pure OCS network has the highest call-delay time. This is because the network becomes especially crowded by several small data streams with $T = 0.1D$, and the network must attempt several wavelengths to establish a lightpath. On the other hand, the OCS network layers for the hybrid optical network achieve a much lower call-delay time than the pure OCS network. In particular, when the network-offered load is ten, the hybrid optical network with a “2-4” channel has a 70% lower call-delay time than the pure OCS network. Hybrid optical networks with a “5-1,” “4-2,” and “3-3” channel have the same call-delay time among all network-offered loads. This means that the network is not crowded and all requests can establish a lightpath on the first wavelength. In the case of hybrid optical networks with a “2-4” and “1-5” channel, the call-delay time increases alongside increases to the network-offered load. From the above results, we can conclude that by using the hybrid optical-network architecture, the load for

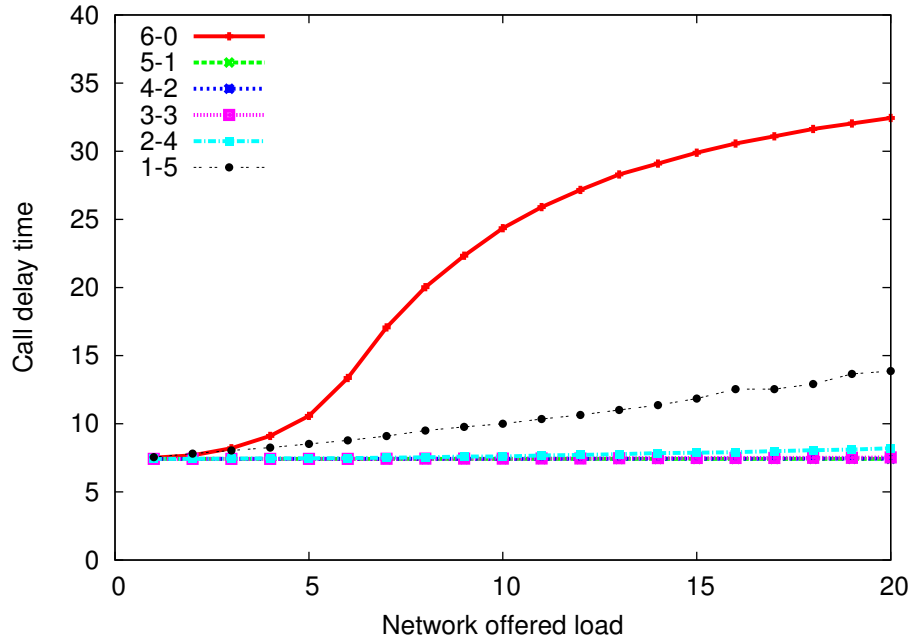


Figure3.13 Call-delay time for the hybrid optical network

the OCS network and the lightpath-establishment time can be reduced.

3.5.4 Optical Broadcast Network Comparison

We use the six-node network shown in Fig. 3.5 and National Science Foundation (NSF) network as a network models. Each link has bi-directional fibers that have eight wavelengths and four OCDM codes per wavelength. In this simulation, we assume that the OCS network has a certain number of OCDM codes and no call loss occurs in the OCS network. We assume that the maximum back-off count on the source node is two. If data traffic is backed off two times, the data traffic is transferred through the OCS network.

Figures 3.14 and 3.15 show the call loss probability in the six-node and NSF network as the network offered load changes respectively. When the network offered load is low, the proposed topology achieves a very low call loss probability. In particular, when the network offered load is five in the NSF network, our proposed topology achieves a call loss probability of less than one tenth. This is because, in our new proposed topology, no collisions occur on any node. On the other hand, when the network offered load is high, our proposed topology has a higher call loss probability than the conventional topology. When the network offered load is high and the network experiences heavy contention, many source node wait to transmit data traffic by back-off. Although a conventional hierarchical logical topology starts

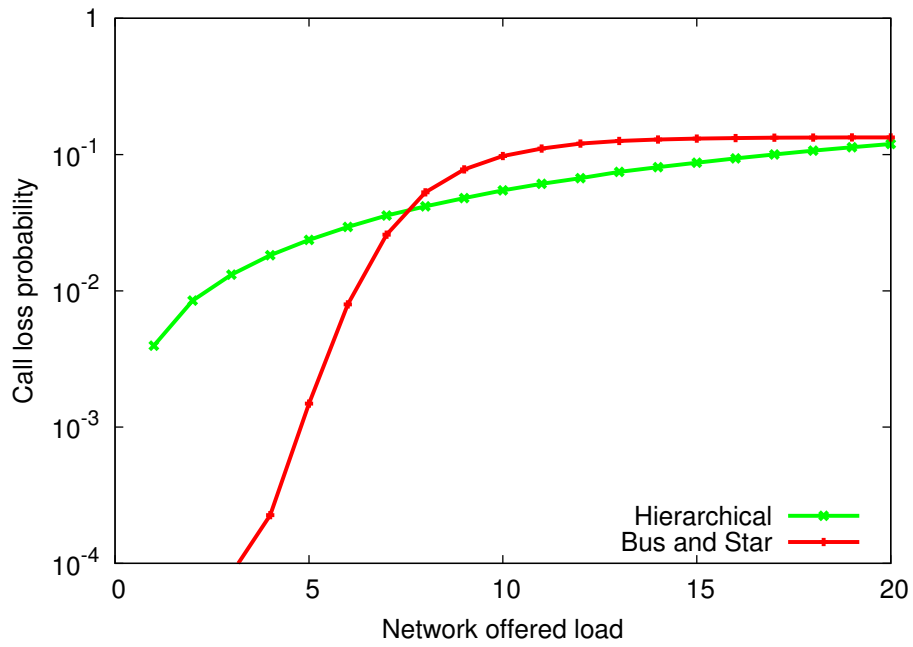


Figure3.14 Call loss probability for the optical broadcast network on a six-node topology

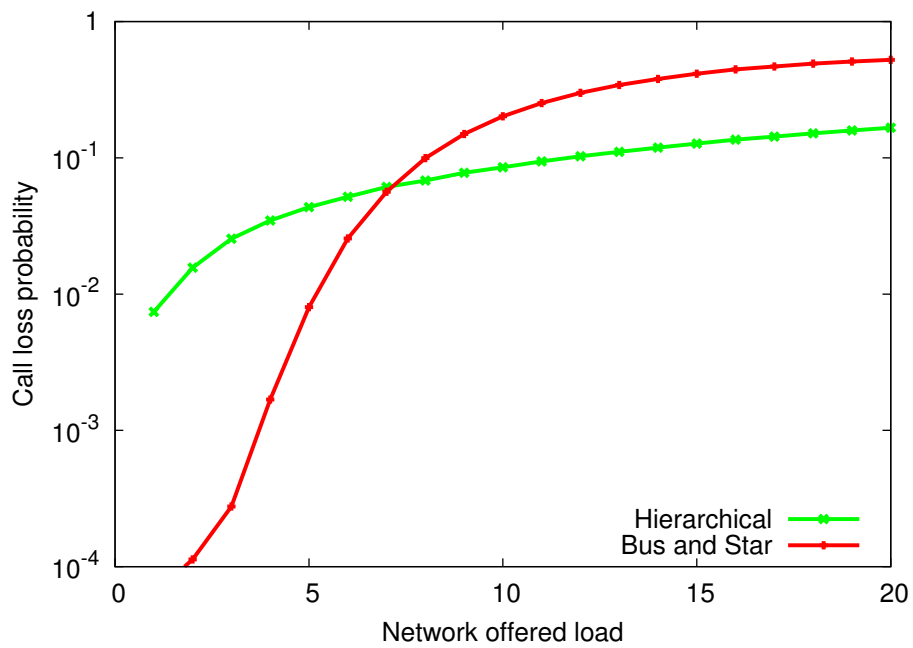


Figure3.15 Call loss probability for the optical broadcast network on a NSF topology

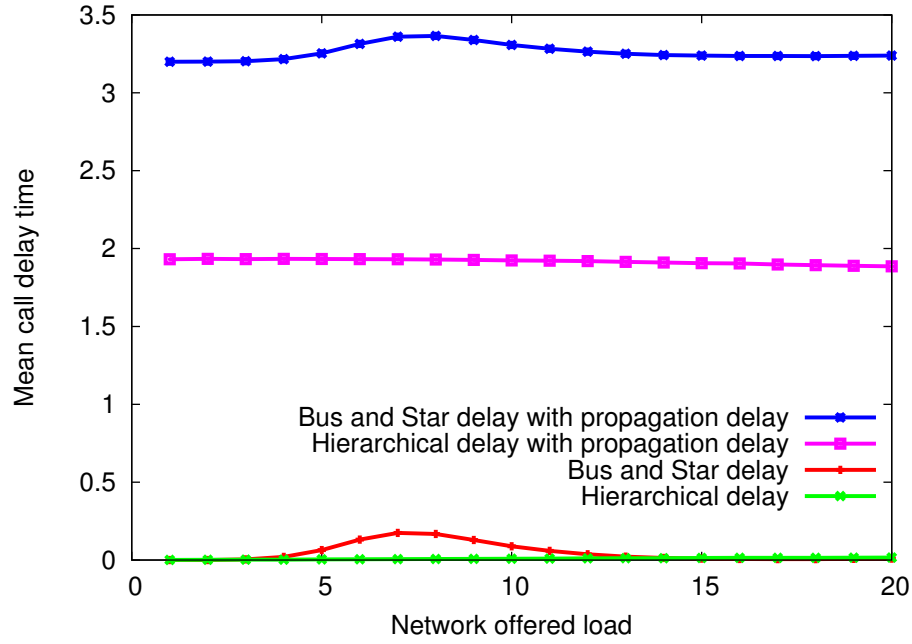


Figure3.16 Call delay time for the optical broadcast network on a six-node topology

to transmit data traffic when one channel can be used, our proposed topology needs to wait until none of the channels are in use to avoid data collisions at the root node. Note that data transmission requirement experiences call loss when the data traffic backs-off many times, then the data have not transmitted yet or the data are transmitted by the OCS network.

Figure 3.16 shows the call delay time in the six-node network. The “with propagation delay” includes the delay time by the link propagation and FDL. Our proposed topology increases the call delay time according to the increase in the network offered load. This is because the probability that the source node transfers other data traffic as the network offered load becomes high. When we consider the total delay, our proposed topology has a higher delay time than the hierarchical logical topology. This is because the topology needs extra time to transfer the FDL. From the above results, we can conclude that contention-less optical broadcast network outperform the broadcast network with hierarchical logical topology when the network offered load is low in terms of call loss probability.

3.6 Conclusion

In this chapter, we introduced hybrid optical network which can select either of OCS network or optical broadcast network according to the characteristics of user requests to improve network efficiency when the variety of bandwidth requests arrive at the network. The time

required for a metropolitan-scale network to establish lightpaths for an OCS transmission can exceed the actual data-transmission time, and network performance suffers as a result. Even though the idea of hybrid optical network can apply to address this issue, it requires additional devices to support another communication technologies. With our proposed architecture, the network can transmit traffic in the optical broadcast network that is logically extended in the control plane in the OCS network. We found that the optical broadcast network performed better than the OCS network when the data size is small in terms of the call-loss probability, call-delay time, and throughput. Furthermore, we explained how our proposed hybrid network architecture reduced the call-loss probability and the call-delay time from pure OCS networks when small and large data streams arrived at the network simultaneously. We also proposed contention-less logical topology for optical broadcast transmissions to reduce the call loss probability in low network offered load area. Simulation results revealed that contention-less logical topology dramatically reduced the call loss probability when the network offered load is low.

4

Distributed Controlled Dynamic Elastic Optical Network

4.1 Introduction

Elastic optical network (EON) is a new networking technology emerged to meet the increasingly diversified traffic demands and the ever changing traffic patterns in the network [14, 15]. Since EON can assign arbitrary number of fine grained spectrum slots for each request, it can assign flexible bandwidth for user requests even if the request is larger than the conventional WDM wavelength channel. On the other hand, EON has the constraint that all flows must have contiguous allocated frequency slots across all fiber links end-to-end. Therefore, the routing, modulation and spectrum assignment (RMSA) is one of the most important considerations in EON. We show an example of RMSA in Fig. 4.1. To address this RMSA with distributed controllers, generalized multi-protocol label switching (GMPLS) is

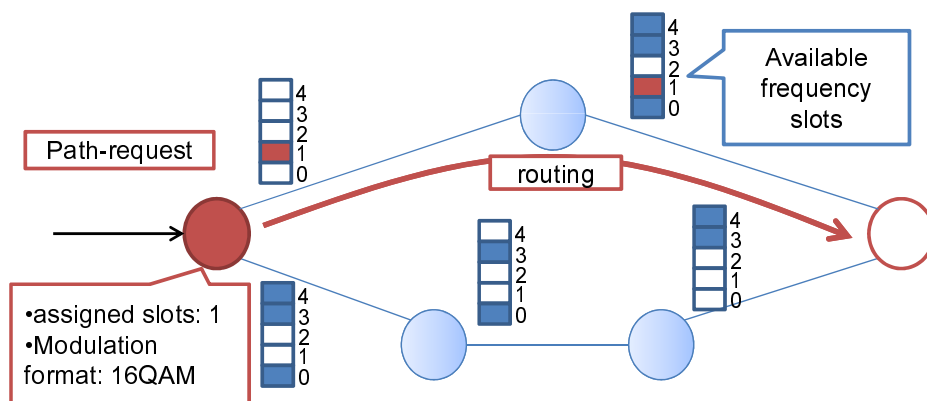


Figure4.1 An example of routing, modulation format, and spectrum assignment

considered as a promising technology. However, conventional GMPLS based approaches have two potential issues. First, routing protocol (OSPF-TE) requires to disseminate network state to synchronize updated information. Second, GMPLS distributed signaling cannot avoid reserve collision among requests due to the signaling-latency [49–51].

In this chapter, we design a simplified GMPLS method, we call this “multi-path GMPLS,” for EONs by using extended resource reservation protocol-traffic engineering (RSVP-TE) to perform both signaling and RMSA. We extend signaling protocol (RSVP-TE) for RMSA to remove OSPF-TE and avoid the large control plane overhead. We also attempt to establish multiple paths to reduce the performance degradation due to the collision in terms of blocking probability.

Our detailed approach to achieve these ideas are shown in the followings. We broadcast PATH messages with recording transferred route to find multi-path from a source node to a destination node. PATH messages also record available frequency slots to determine frequency slots to allocate, and distance information to determine a modulation format. The destination node is responsible for deciding and assigning the modulation format and frequency slots accordingly, and signaling with the possibility for reduced collision as an extension to GMPLS [49–51, 68]. We also propose tentative reservation signaling for arriving PATH messages which arrives lately to avoid “over-reservation.” We define over-reservation in case that a connection request establishes two or more lightpath to transmit traffic at the same time when the request only needs one lightpath. Our proposed multi-path GMPLS performs both signaling and RMSA with fully-distributed GMPLS controllers.

The rest of this chapter is organized as follows: Section 4.2 discusses the RMSA problem and previously studied RMSA approaches. Section 4.3 explains the newly proposed fully-distributed multi-path GMPLS control plane design for establishing lightpaths for EON. Section 4.4 compares the performance of the conventional GMPLS methods and the proposed multi-path GMPLS approach using computational simulations and validate our proposed approach. Finally, Section 4.5 summarizes the findings of this chapter.

4.2 Routing, Modulation and Spectrum Assignment for Dynamic Requests

Both centralized and distributed control plane approaches have been investigated to address the RMSA problem. Refs. [43, 69–71] are the solutions for R(M)SA with centralized control, where a centralized controller (e.g. a stateful PCE or an SDN controller) maintains

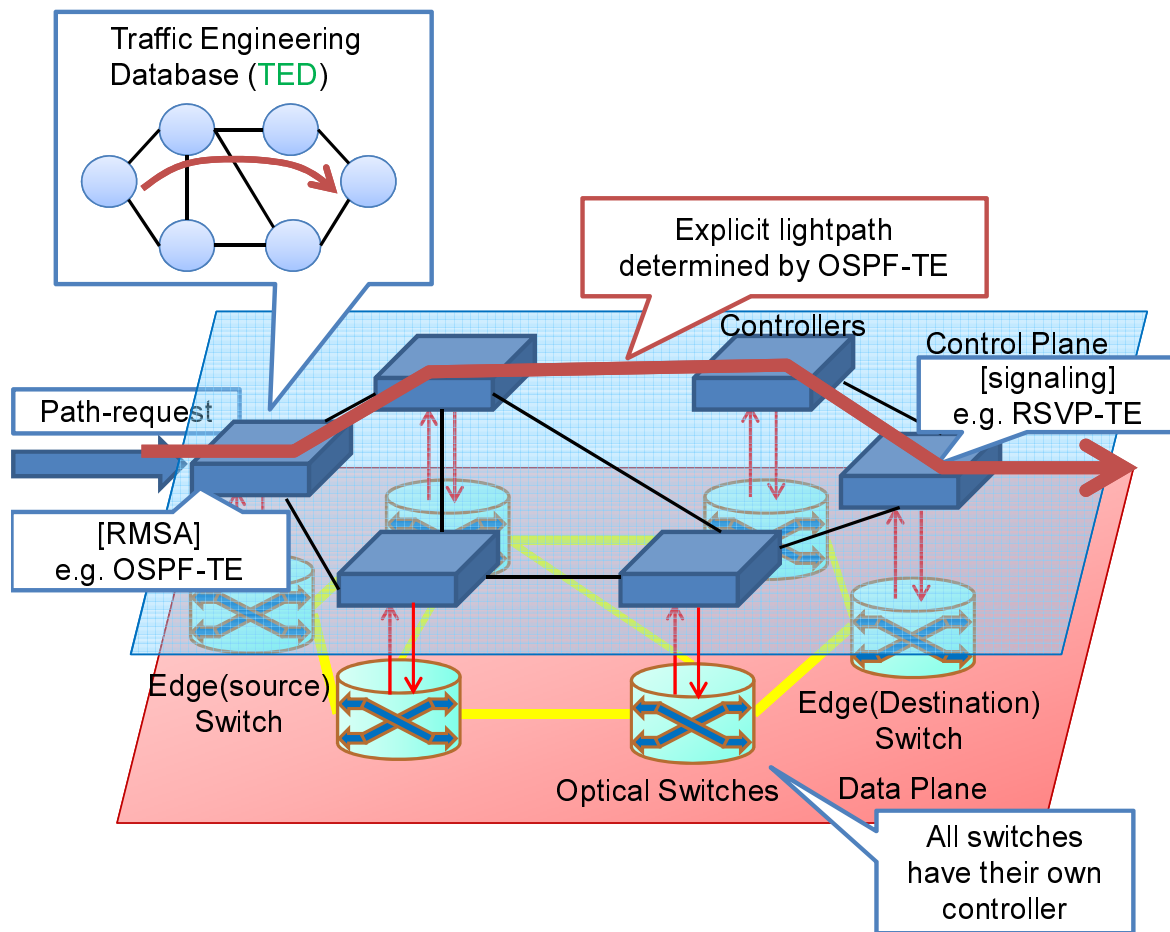


Figure 4.2 Distributed control EON

global and updated information for all established lightpaths [9]. When a lightpath setup request arrives at the network, the controller calculates the path to assign the request. After that, frequency slots of fiber links along the path are allocated by either in a centralized control plane or distributed signaling (e.g. GMPLS RSVP-TE). Figure 4.2 shows an image of distributed control EON using GMPLS.

For the distributed control approach, GMPLS is a promising candidate to address RMSA. So far, GMPLS and GMPLS/PCE approaches are proposed for distributed control dynamic RMSA. In the GMPLS method [10, 11], each GMPLS controller maintains the network information. In contrast, the GMPLS/PCE method [47, 48] uses a centralized PCE to maintain local network information in the local traffic engineering database (TED). Different from centralized control with stateful PCE or an SDN controller, stateless PCEs do not need to remember any computed path and each set of request. Signaling to assign frequency slots on each link is done in a distributed way using GMPLS RSVP-TE.

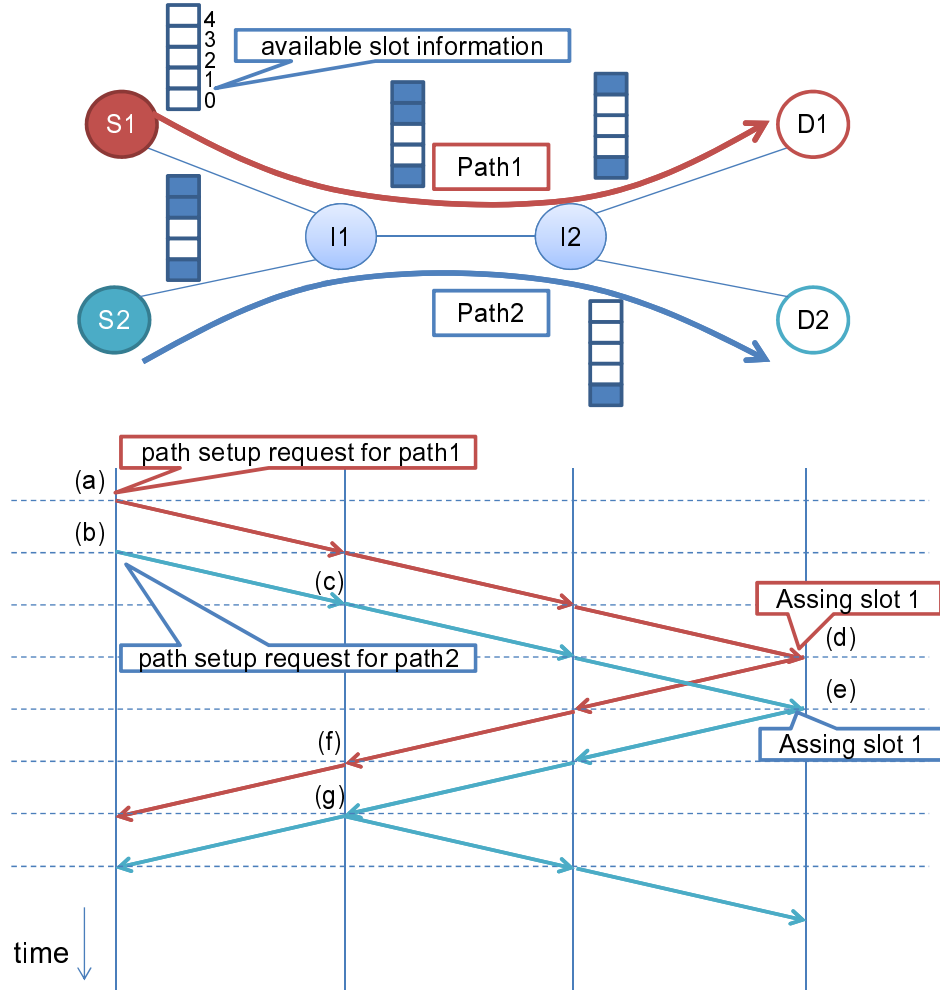


Figure 4.3 Reservation collision due to signaling latency

However, conventional GMPLS based distributed routing solutions have two potential issues. First, they have large control plane overhead to disseminate topology information across the entire network. In conventional GMPLS designs, each GMPLS controller or a stateless PCE calculate path using their TEDs. To keep up to date information in TEDs, link state advertisements (LSAs) are disseminated through OSPF-TE when any change occurs in the network. That is, when a request is established or released, LSAs are dynamically advertised over the network. Compared with the conventional WDM networks which have wavelength channels, EONs need to disseminate fine grained available frequency slots information. Therefore, EONs have potentially higher control plane overhead than conventional WDM networks.

Second, distributed signaling cannot avoid collisions because of the signaling latency [49–51, 68]. Figure 4.3 shows an example of such a collision. One path request (Path1)

has the route of ($S1 \rightarrow I1 \rightarrow I2 \rightarrow D1$) and the other request (Path2) has the route of ($S2 \rightarrow I1 \rightarrow I2 \rightarrow D2$). We assume that the destination nodes use first-fit for spectrum assignment, and both requests require one spectrum slot for their services. Firstly, the path request for Path1 arrives at the network, and Node S1 transmit path message with available slots information (see Fig. 4.3(a)). This path message propagates along the explicit route and updates the available slots information hop-by-hop. When the path message of Path1 arrives at the Node I1, the path request for Path2 arrives at the Node S2 (see Fig. 4.3(b)). The path message for Path2 also propagates along the explicit route for the Path2. After the path message for Path1 arrives at the destination Node D1, the destination node assign slot 1 for the Path1 (see Fig. 4.3(c)). Since slot 1 and 2 are available at all output ports on Path2, the destination node for Path2 also assigns slot 1 for the request (see Fig. 4.3(d)). When a RESV message for Path1 arrives at the intermediate Node I1, the message reserve slot 1 for Path1 (see Fig. 4.3(e)). Although the RESV message for Path2 arrives at the intermediate Node I1 and tries to reserve slot 1 for Path2 at the next step, the slot has already been reserved by Path1 and the reservation process fails (see Fig. 4.3(f)). This collision is caused by the signaling latency between Fig. 4.3(c) and Fig. 4.3(f). We cannot avoid this collision when we use the distributed signaling as mentioned above. In this chapter, we propose fully-distributed RMSA and signaling with the possibility for reduced blocking by collision as an extension to GMPLS RSVP-TE.

4.3 GMPLS control plane extension

In this section, we explain our proposed fully-distributed control plane design to establish lightpaths for EON with GMPLS called “multi-path GMPLS.” In contrast to conventional GMPLS based solution, our proposed design uses an extended RSVP-TE signaling to find a route without a TED. Our proposed design has three key ideas. (1) It looks for multiple routes from the source node to the destination node using PATH message broadcasting; (2) it attempts to establish multiple paths, and (3) it tentatively reserve slots for later arriving PATH messages to avoid over-reservation.

In the Section 4.3.1, we show the extensions to the RSVP-TE protocol. In the Section 4.3.2, we explain our proposed routing using PATH message broadcasting. Finally, in the Section 4.3.3, we discuss the distributed signaling with tentative reservation.

4.3.1 Extension to traditional GMPLS RSVP-TE

To avoid over-reservation of multi-path requests, we introduce a tentative reservation mechanism for the later attempted routes. We use the conventional PATH-RESV protocol only for the first path. In addition to "free" and "reserved," we define a new status for the spectrum slot, called "requested" for this tentative reservation. We define three new types of control messages for this "requested" status in addition to four extended traditional RSVP-TE messages. We show how these messages work in the followings. The examples of each message are shown in Figs. 4.5 and 4.6.

- **PATH message:** The PATH messages are transmitted from a source node to a destination node to find a route and available frequency slots. Each PATH message includes a set of the source node addresses, and the label switched path (LSP)-ID (we call "connection ID") to distinguish each request. PATH message also records the list of transferred node IDs for the routing, transmission distance for modulation assignment, and unused slot numbers for spectrum assignment on the destination node. Such information is updated hop by hop by each node. Available slot information on the PATH message has three types of status same as the status on each port. If a slot of a transferring port is "reserved," the available slot information of the slot changed to the "reserved." If a slot of a transferring port is "requested" and the available slot information of the slot is "available," the available slot information of the slot changed to the "requested."
- **Reservation message (RESV):** The RESV message is transmitted from a destination node to a source node along the route informed by the PATH message to reserve frequency slots assigned to the request. If an intermediate node receives a RESV message, it changes the slots status from "available" or "requested" to "reserved." If some or all of the assigned frequency slots are in "reserved" status, the RESV message fails to reserve the resources for the request. RESV messages are extended to include the degree of the destination node to give the information of the number of candidate paths in the case of collision (we will discuss in Sec. 4.3.2 and 4.3.3).
- **PATHTear message:** The PATHTear message is transmitted from a source node to a destination node to release all reserved frequency slots. Hereafter, "release" means to change the port status from "reserved" or "requested" to "available." The PATHTear messages are also transmitted from an intermediate node to a destination node or a

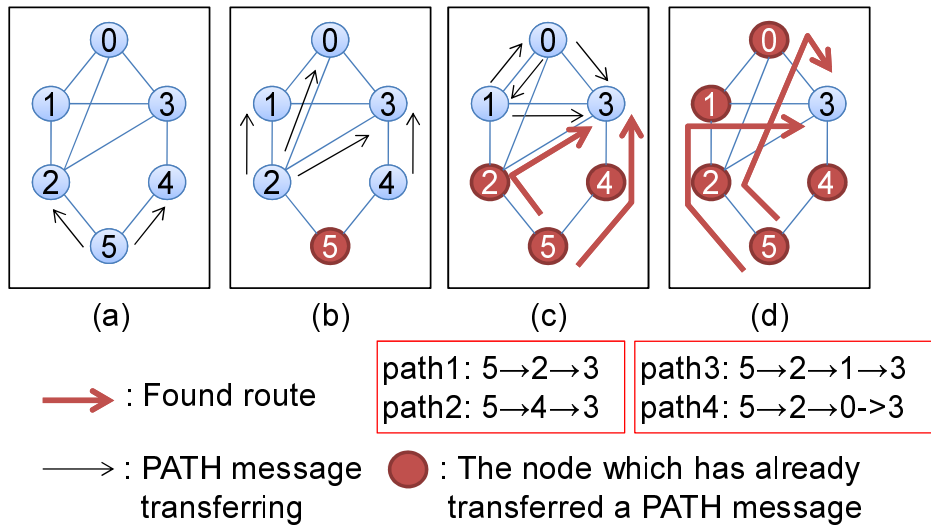


Figure 4.4 An example of routing by PATH message broadcasting

source node to release all reserved and tentative reserved frequency slots during the reservation process.

- **PATHErr message:** The PATHErr message is transmitted from an intermediate node or a destination node to a source node to inform the failure of the reservation. The PATHErr message includes the degree of the destination node.
- **(new) Request message (REQ):** The REQ message is generated by the destination node to make a tentative reservation. The REQ message changes the status of frequency slots from “available” to “requested.” If some or all of the slots are in “requested” or “reserved” status, the REQ message fails the reservation.
- **(new) Activate message (ACT):** The ACT message is generated by the source node to change the status of slots from “requested” to “reserved.” In other words, the ACT message is used to activate the tentative reservation to actual reservation.
- **(new) Acknowledgement message (ACK):** The ACK message is generated by the destination node to inform the source node about the success of the activation.

4.3.2 Distributed Routing, modulation and spectrum assignment

Figure 4.4 shows an example of multi-path searches using the PATH message broadcast in a six-node topology. We assume Node 5 is the source node, and Node 3 is the destination node in Fig. 4.4. When a lightpath setup request arrives at the source node, firstly, the source node transmits PATH messages for all ports including its connection ID and available slots

information of the outgoing port (see Fig. 4.4(a)). When an intermediate node receives a PATH message, the node checks whether it is the first PATH message of the connection ID. If yes, the node transfers the PATH message to all other ports (Fig. 4.4(b)). If not, the node terminates the received PATH message (see Nodes 0 and 1 on Fig. 4.4(d)). This is because the earlier PATH message can find a shorter route through the node if there is no processing or buffer delay on each GMPLS controller. For example, Node 0 transfers PATH messages to Node 1 and Node 3 in Fig. 4.4(c), and then the node receives another PATH message from Node 1 in Fig. 4.4(d). Apparently, the earlier PATH message can find a shorter path to go Node 3. Therefore, the destination node does not transfer the received PATH message to the other ports (see Node 3 in Fig. 4.4(c)). As a result, all nodes in the network, except the destination node, transfer PATH message once for each connection request. That is, the number of PATH messages processed by each GMPLS controller is not affected by the network scale such as the number of nodes or links in the network. In Fig. 4.4, the destination node found four routes ($5 \rightarrow 2 \rightarrow 3$, $5 \rightarrow 4 \rightarrow 3$, $5 \rightarrow 2 \rightarrow 0 \rightarrow 3$, $5 \rightarrow 2 \rightarrow 1 \rightarrow 3$) for the given source and destination pair. Three important observations are: (1) when there are not enough spectrum slots to assign, the destination node may find another path with available spectrum slots, (2) this also works when a collision happens during the signaling process, (3) the destination node finds the same number of path of the degree of the destination node.

When a PATH message arrives at the destination node, the node assigns modulation format and frequency slots according to the information about the distance and available frequency slots given by the received PATH message. We use first-fit for spectrum assignment. Our proposed routing and signaling works independently to assign modulation format and frequency slots. Therefore, we can replace it to advanced RMSA method such as fragmentation-aware RMSA [11, 72–74].

4.3.3 Proposed Distributed Signaling

Multi-path reservation gives higher successful possibility for a path request. However, if one lightpath setup request establish multi-path, it wastes the network resource unnecessarily, and then it prevent for another path request to setup a lightpath. We refer this as an over-reservation. To avoid this over-reservation, we use the conventional PATH-RESV protocol for the first path which has enough frequency slots to be assigned, and then use tentative reservation for later paths. Figure 4.5 shows the signaling process for the PATH-RESV reservation. When the first PATH message arrives at the destination node, the destination node decides the frequency slots to assign and then replies a RESV message to the source node

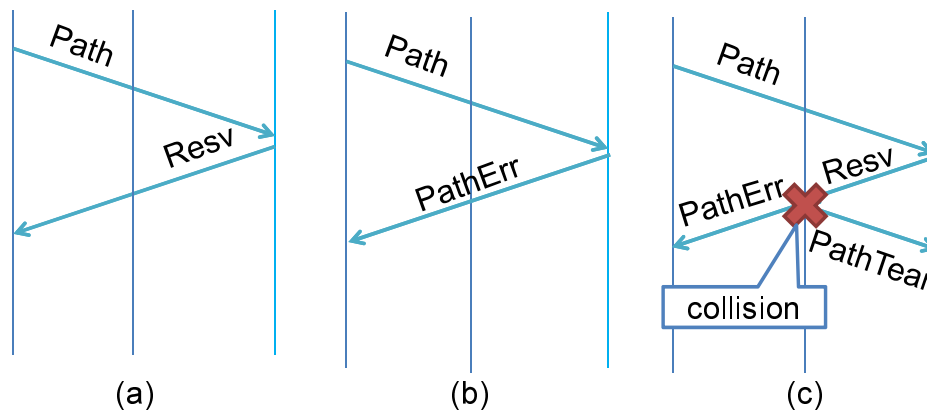


Figure 4.5 Reservation process (a) success, (b) unavailable, (c) collision

according to the route information carried in the received PATH message (see Fig. 4.5(a)). This reservation process can assign slots with “available” and “requested” status. If there are no continuously available slots with the requested bandwidth, the destination node returns a PATHErr message to the source node (see Fig. 4.5(b)). We refer this failure as “resource unavailability” to distinguish the failures from collision. The node that receives the RESV message reserves the assigned spectrum slots (changes the status of slots to “reserved”). If some slots cannot be reserved due to collision, the intermediate node transmits the PATHErr message to the source node and PATHTear message to the destination node (Fig. 4.5 (c)).

If another PATH message arrives at the destination node after the node transmitted a RESV message, the node starts the tentative reservation procedure shown in Fig. 4.6. Note that, if the first path fails reservation due to resource unavailability, the reservation process attempts the path of the second PATH message. The destination node decides the frequency slots to assign tentatively and then returns a REQ message to the source node according to the route information stored in the received PATH message. This tentative reservation process can only assign slots in “available” status. If there are no continuously available slots for the tentative reservation, the destination node returns a PATHErr message to the source node (see Fig. 4.5(b)). When a REQ message arrives at the source node, the source node checks whether the reservation process is successful or not. If yes, the source node transmits a PATHTear message to release all tentatively reserved slots (see Fig. 4.6(a)). If not, the source node transmits an ACT message to activate the tentatively reserved slots (see Fig. 4.6(b)). Both of tentative reservation and activation procedure have a possibility of collision. If tentative reservation fails at an intermediate node, the node transmits a PATHTear message to the destination node to release all tentatively reserved slots for the path and transmits a PATHErr message to the source node. If activation fails at an intermediate node, the node transmits

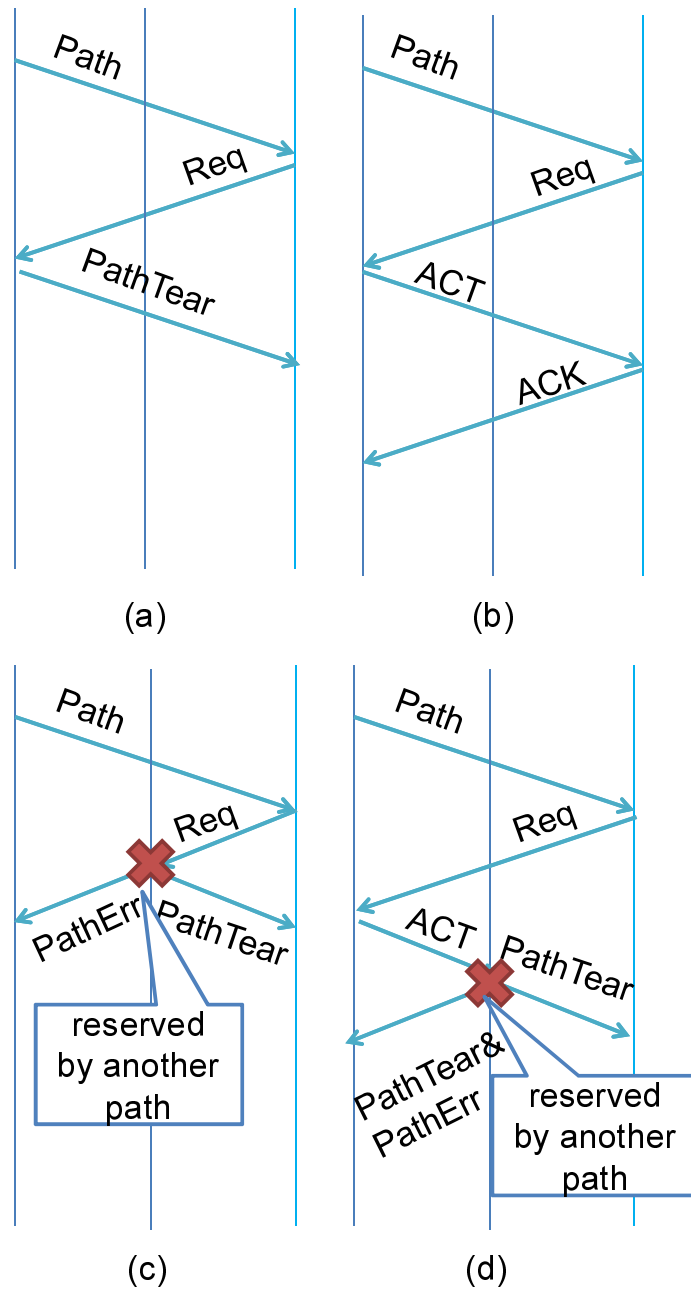


Figure 4.6 Tentative reservation process (a) reserved by RESV message, (b) success of tentative reservation, (c) collision on REQ message, (d) collision on ACT message

PATHTear messages to the source node to release all reserved slots and to the destination node to release all tentatively reserved slots. The node also transmits a PATHErr message to the source node. If the source node receives the same number of PATHErr messages as the degree of the destination node, the node knows that the request is blocked.

We show a summary of our distributed routing, reservation, and tentative reservation

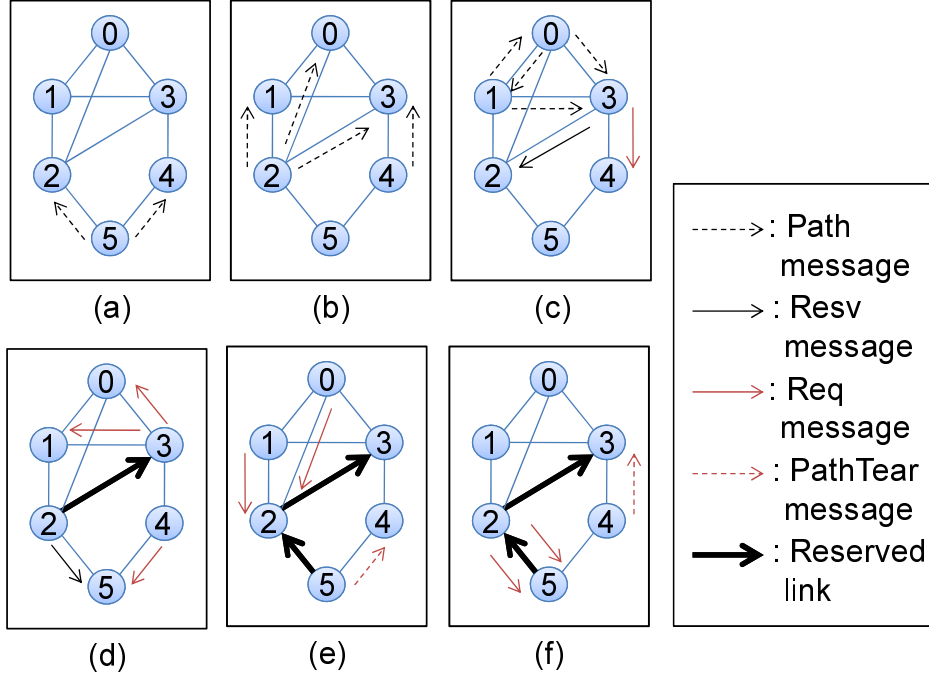


Figure 4.7 An example of routing by PATH message broadcasting

process in Fig. 4.7. When a lighthousepath setup request arrives at the source node, the source node transmits PATH messages to all ports (see Fig. 4.7(a)). The first PATH message arrives at the destination node 3 with the route of $5 \rightarrow 2 \rightarrow 3$, same as the second Path with the route of $5 \rightarrow 4 \rightarrow 3$ (see Fig. 4.7(b)). The destination node returns a RESV message for the first Path and returns a REQ message for the second Path. PATH messages are still transferred at Links $0 \rightarrow 1$, $0 \rightarrow 3$, $1 \rightarrow 0$, $1 \rightarrow 3$, and $1 \rightarrow 2$ (see Fig. 4.7(c)). The destination node also transmits REQ messages for the third and fourth paths (see Fig. 4.7(d)). If the source node receives a RESV message and succeeds to assign frequency slots allocated to the Path, the source node can know that the lighthousepath is established for the request. Since one lighthousepath has been established, the source node sends PATHTear messages for tentatively reserved paths to release all tentatively reserved frequency slots (see Fig. 4.7(e)).

4.4 Numerical Results and Discussion

4.4.1 Simulation Setup

We use the Japan and NSF topologies shown in Fig. 4.8 as the network model [48] to evaluate blocking probability and signaling time. Since the NSF topology has longer distance than the Japan topology, it has higher probability of collision among requests. Each link has

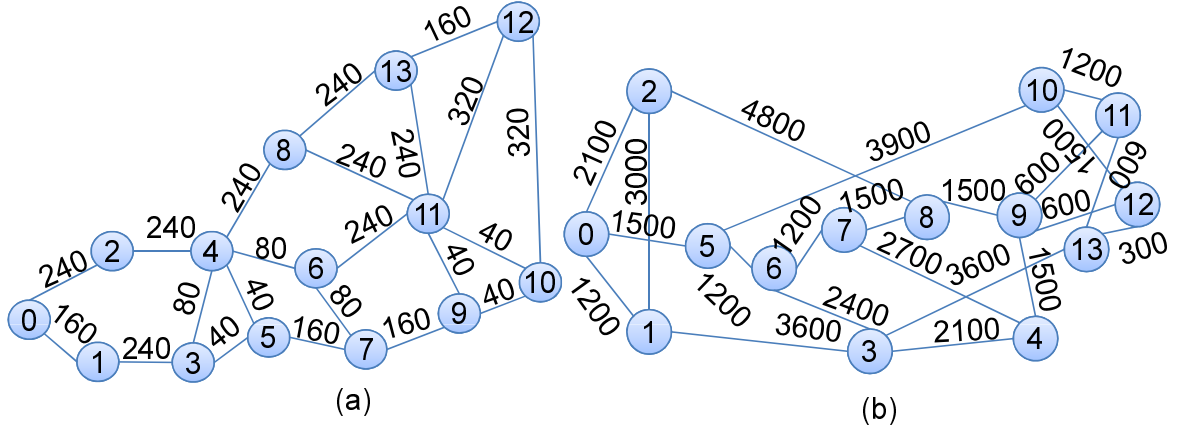


Figure 4.8 Simulation topology

Table 4.1 The number of slots to assign [48]

	4QAM	16QAM
10Gbps	2	1
40Gbps	6	3
100Gbps	14	7

bi-directional fibers that have 128 individual spectrum slots. Lightpath setup requests arrive at the network at a rate of λ , according to a Poisson distribution, and they arrive with the same probability among all source-destination pairs. Lightpath setup requests have a service time at a rate of $1/\mu$, according to an exponential distribution. The network-offered load ρ is defined as λ/μ in our simulations. The requested signal data rate follows an integer random variable, uniformly distributed in the range [1,100] Gb/s. Table 4.1 shows the number of slots assigned to each request mapped to 10, 40 or 100Gb/s. We use 16 QAM for paths shorter than 600km and 4QAM for paths longer than 600km [48]. We assume that there are about 100,000 requests arriving at the network. Since we discuss the blocking performance over 10^{-3} , we have more than 100 blocking for each plotted data. Figure. 4.8 shows the distances in km and each fiber delays the signal by $5.5\mu\text{s/km}$ as general speed of optical fiber. We used the fixed mean holding time ($= 1/\mu = 100\text{s}$) for the requests. We assume there is no delay to process control messages and set up switches.

We assume the following setup for conventional GMPLS design. All nodes have the topology information and calculated the shortest path in advance. When a lightpath setup request arrives at the source node, the node transmits a PATH message along the shortest path and updates information about available slots. Frequency slots are assigned by the destination

node with first-fit. We also assume following configurations for the GMPLS/PCE simulation. The PCE module is located at Node 11 for Japan topology and node 9 for NSF topology respectively. When a request arrives at the network, the source node requests for the PCE to calculate the shortest path which have enough frequency slots to assign at all links. The PCE calculates and replies the shortest path to the source node. These request/reply messages are transmitted along the shortest path with no additional processing delay. After the source node receives this reply message, the source node starts the signaling procedure to set up a lightpath. When a lightpath is established, the source node transmits a message to update the TED information for the PCE.

4.4.2 Performance Evaluation and Discussion

In this section, we evaluate blocking probability and signaling time to validate that our proposed multi-path GMPLS can reduce the effect of collision. We also discuss about control plane overhead from the viewpoint of the number of control messages. Figures 4.9 and 4.10 show the plots of the blocking probabilities for the GMPLS/PCE, conventional GMPLS, and the proposed multi-path GMPLS solution in the Japan and the NSF topology, respectively when the network offered load changes. GMPLS/PCE achieves a better performance than the conventional GMPLS design. This is because, in the GMPLS/PCE network, PCE discards the link that has fewer available frequency slots than the requested slots. Our proposed GMPLS solution has much lower blocking probability than the other two designs for both network topology. In particular, when the network offered load ρ is 60 in the NSF topology, our proposed GMPLS design reduces the blocking probability by factors of 4.56 and 4.86 when compared with conventional GMPLS and GMPLS/PCE architectures. Also, when the network offered load is 10 in the Japan topology, our multi-path GMPLS solution achieves blocking probability lower than 0.1% while conventional GMPLS and GMPLS/PCE approaches exhibit 0.5% blocking probability. These are important improvements in blocking probabilities. If the network requires lower than 1% blocking probability, the multi-path GMPLS approach in the NSF network topology can support more than 70 lightpaths while as conventional GMPLS and GMPLS/PCE approach can support up to 30 lightpaths. This result comes from the following two reasons. First, since our proposed solution attempts to set up a path among multiple paths, it still has a possibility to succeed to set up a path when the first path setup request is failed due to the collision. Our proposed solution also achieves lower blocking in cases where there are no available continuous frequency slots for a path thanks to the multi-path search for each request. This improvement is significant when the network

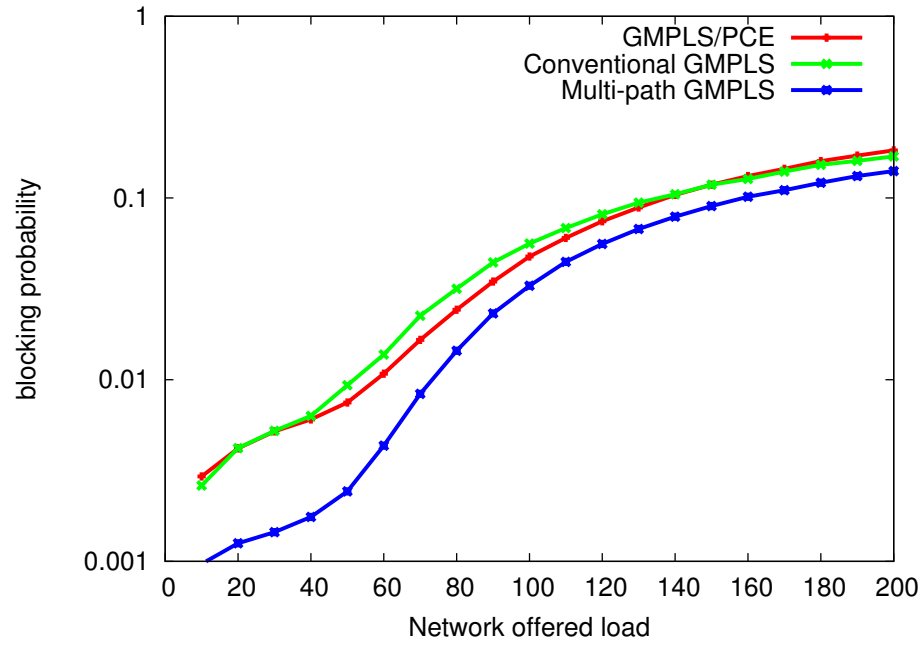


Figure4.9 Blocking probability in the Japan network

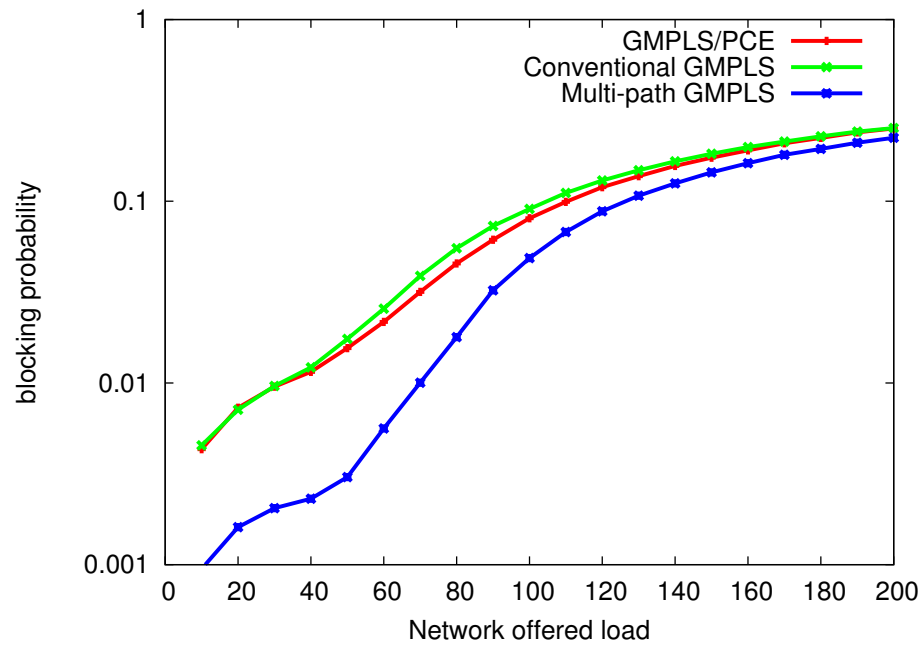


Figure4.10 Blocking probability in the NSF network

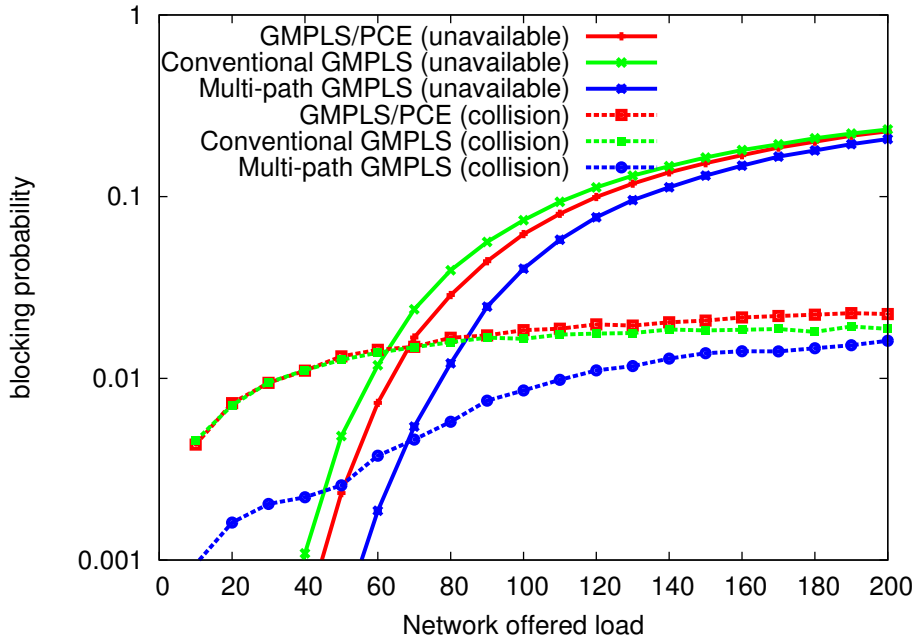


Figure 4.11 Two patterns of blocking in the NSF network

has enough bandwidth to assign but has collisions during the signaling process. Multi-path GMPLS networks can improve the network blocking performance more significantly in the NSF topology than in the Japan topology. This difference comes from the probability of collision events. Since the simulation in the NSF topology involves longer distances and longer signaling time durations for the same inter-arrival time, it accompanies the higher collision probability. Due to the multi-path setup process, our proposed method provides the possibility to establish a lightpath even if the first actual reservation fails due to collisions.

Figure 4.11 shows the plots of the two patterns of blocking probabilities for the GMPLS/PCE, conventional GMPLS, and proposed multi-path GMPLS solution in the NSF topology when the network offered load changes. “Unavailable” shows the case that the request is blocked due to the resource unavailability. “Collision” shows the case that all the reservation processes are failed due to the collision. As we can see from Fig. 4.11, collision is the dominant factor when the network offered load is low, while when the network offered load is high, the blocking probability caused by resource unavailability is dominated. Our proposed solution reduces both collision and resource unavailability problems compared with the other two designs. In particular, when the network offered load is 20 Erlang, the multi-path GMPLS approach reduces the blocking probability by a factor of 4.55 compared to the conventional GMPLS and GMPLS/PCE approaches. This is because the multi-path GMPLS method attempts to activate the tentatively reserved path in case where the actual reservation

fails due to the collision. From this perspective, our proposed multi-path GMPLS method sufficiently solves the performance degradation issue caused by reserve collision. Note that, the time to calculate paths at PCE in the GMPLS/PCE design does not affect the performance of blocking probability. This is because the collision has happened during the transmission latency between a PATH message and a RESV message, and the path calculation has finished before a PATH message is transmitted.

Figures 4.12 and 4.13 show the plots of the blocking probabilities for the conventional GMPLS, GMPLS/PCE and our proposed GMPLS designs in the Japan and NSF topologies, respectively when the network offered load changes. The GMPLS/PCE network requires longer processing time than other two designs. In the GMPLS/PCE network, the source node needs to ask an available path and spectrum slots to the PCE before it transmits a PATH message. On the other hand, conventional GMPLS and our proposed GMPLS designs have similar connection setup time. Since the conventional GMPLS design uses the shortest path and with the local topology information (which is dynamically obtained via OSPF-TE before path computation) at the source node, no time is needed to calculate path in the case where the shortest path is pre-calculated. Our proposed solution broadcasts PATH messages right after the source node receive a Path setup request. Therefore, both of conventional GMPLS design and our proposed GMPLS design only need the propagation time to setup a lightpath.

In the following, we discuss the control plane overhead for three solutions. First of all, as discussed in Ref. [48], control plane overhead depends on several factors such as control plane processing time, control plane link propagation time, topology shape and different options selected for the control plane software (for example, the interval between “HELLO” messages and the condition to disseminate OSPF-TE LSA). Therefore, we briefly discuss about the number of messages transferring in the network. First, the multi-path GMPLS method transmits more PATH messages for reservation. For example, if the source node is Node 5 and the destination node is Node 9 in the NSF topology, the multi-path GMPLS will transmit eleven 25 more PATH messages, eleven more REQ messages, and eleven more PATHTear messages. On the other hand, our proposed multi-path GMPLS removes OSPF-TE from the RMSA process. OSPF-TE disseminates their TE LSA as soon as possible after one of TE attributes changes (i.e. all nodes along the path disseminates TE LSA when the path is established or released). Therefore, if the source node is Node 5 and the destination node is Node 9 in the NSF topology, conventional GMPLS and GMPLS/PCE solutions transmit 84 OSPF-TE LSA messages after the lightpath is established. As a result, the overhead of the proposed multi-path GMPLS approach is typically lower than those of the conventional GMPLS and the GMPLS/PCE approaches.

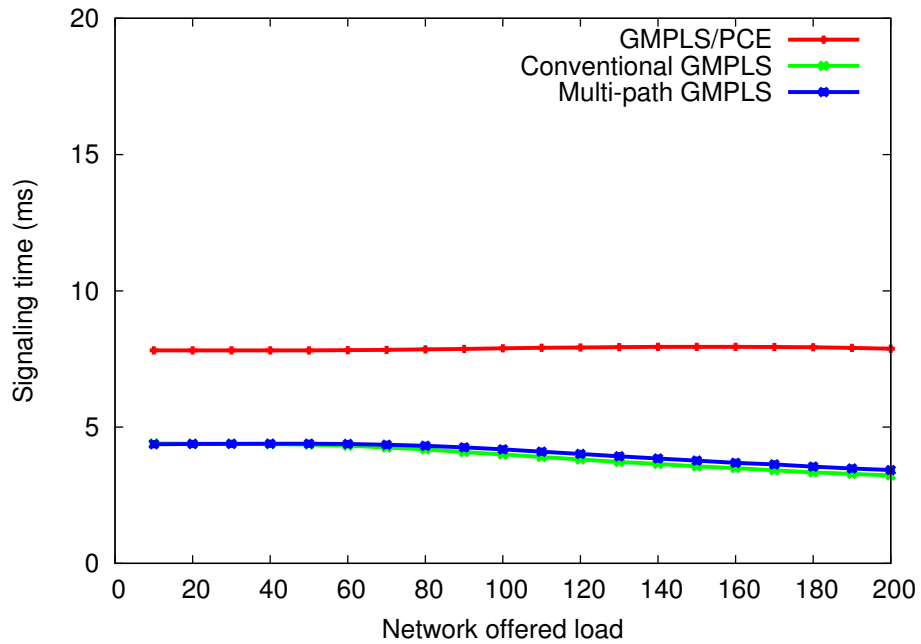


Figure4.12 Lightpath setup time in the Japan network

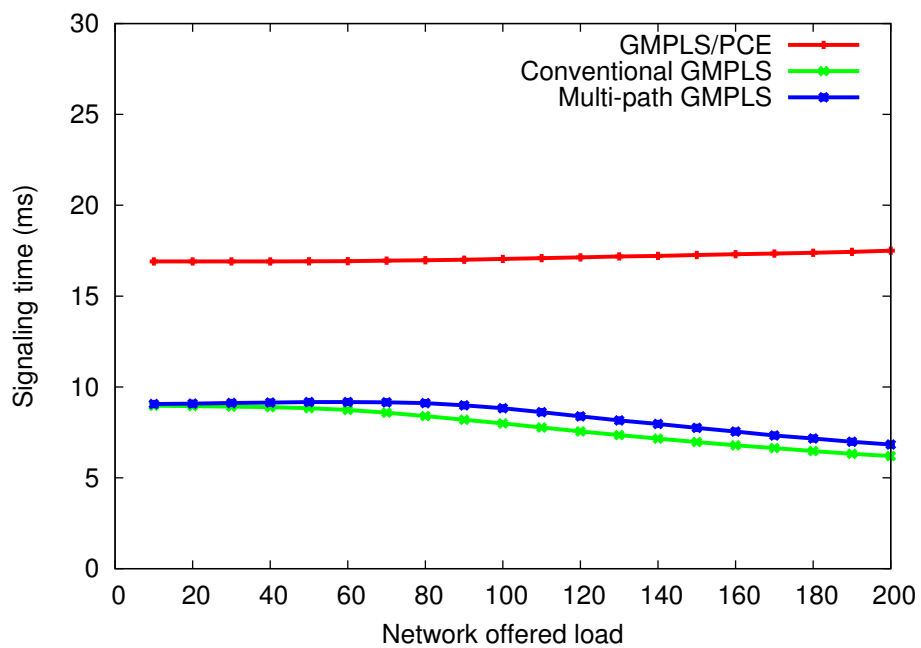


Figure4.13 Lightpath setup time in the NSF network

4.5 Conclusion

In this chapter, we introduced EON which can assign bandwidth flexibly and propose RMSA solution to establish lightpaths with fully-distributed control. Conventional GMPLS based solution for RMSA problems with distributed control suffer large control plane overhead rising from OSPF-TE dissemination and the collision among requests caused by signaling latency. Our proposed solution has three key points. 1) PATH messages are broadcasting to find multiple paths from a source node to a destination node without any topology information dissemination. 2) The proposed solution attempts to establish multi-path to reduce the performance degradation by collision. 3) Tentative reservation to avoid over-reservation. Simulation results showed that our proposed solution achieved lower blocking probability compared with the conventional fully distributed GMPLS and GMPLS/PCE based RMSA solutions. We also evaluated that our proposed method transmit much fewer control messages than conventional GMPLS and GMPLS/PCE architectures by removing the OSPF-TE.

5

Conclusion and Future Directions

5.1 Concluding Remarks

All-optical Networks has attracted much attention for future backbone network since it has large bandwidth, high degrees of reliability, and low latency. However, since conventional all-optical network architecture assumed to use fixed-grid WDM technology in OCS network, there are three large issues. First, although WDM network can assign large bandwidth for each user request, since the wavelength channel is too large for one user's request, it is difficult to support variety of requested bandwidths. Second, conventional OCS based transmission faces the lightpath setup overhead when the user request has short holding time. Therefore, to satisfy variety of user demands, the architecture which can assign just enough frequency range for each request and can support data transmission without lightpath setup is required. Third, when the requested bandwidth is huge, the network need to establish two or more lightpaths for one request. As a result, it lead to waste spectrum resources and requires more computational resource to process additional control messages.

In Chapter 2, we discuss about finer granularity all-optical networks using OCDM technology. All traffic in the OCDM network are multiplexed by OCDM codes after multiplexed by WDM wavelength. The OCDM network can assign bandwidth for each request finer than the conventional WDM network. The OCDM network also has advantage that the network can swap OCDM channel at intermediate nodes. On the other hand, the OCDM network suffer from multi-access noise loop back problem called cycle attack. We proposed two design to avoid this cycle attack completely with distributed controllers. Simulation results reveals our proposed architecture achieves smaller call loss probability than conventional approaches for OCDM network.

In Chapter 3, we discuss about the hybrid optical network architecture. The OCS tech-

nology is the important technology for the future all-optical network. However, the OCS network needs to establish a lightpath before starting the data transmission, and the lightpath establishment need the time overhead at least the round-trip time from the source node to the destination node. Therefore, when the bandwidth per channel is larger and the transmission data size is smaller, this overhead becomes too large to ignore. We proposed hybrid optical network architecture to achieve better performance when the network has variety types of traffic demands. Our proposed hybrid optical network combines conventional OCS network with optical broadcast network which transmit data traffic all over the network without lightpath setup. To achieve broadcast transmission without broadcast storm, we introduce two types of cycle-free logical topology. Simulation results reveal that our proposed hybrid optical network achieves lower call loss probability when the network has both of short and long holding time connection.

In Chapter 4, we introduce EON with fully-distributed controlled GMPLS framework. EON uses flexible bandwidth assignment for each connection request. Since EON has constraint called spectrum-continuity constraint which dictates that the allocated frequency slots must be consecutive and that all allocated basic slots of a frequency slot must be continuous end-to-end with identical modulation format. Therefore, RMSA is one of the most important issue for the EON. We propose algorithm to achieve both of RMSA and signaling with distributed controllers. Simulation results reveal that our proposed solution achieve lower blocking probability and shorter lightpath establishment time compared with the conventional fully distributed GMPLS and GMPLS/PCE based RMSA solutions.

The results given in this thesis achieve more efficient all-optical network control with distributed control manner in terms of network resource management. That is, the network can assign fine granularity and flexible size bandwidth for each user request. It also determine the transmission technology according to the characteristics of the user request. As a result, the network can use network resources more efficiently.

5.2 Future Directions

The overall goal of this thesis is to propose a distributed controlled all-optical network. The development of distributed controlled all-optical network will be one of the most important future subject of studies in the networking field. For future direction, research on centralized/distributed control hybrid optical network architecture for long distance multi-domain network become important. In the real network situation, world wide communication requires to across several service providers which have their own network domain and differ-

ent service policy. Therefore, common architecture to connect different service provider with saving their privacy or setup lightpath without giving private information is required. To overcome this issue, research on distributed control architecture for inter-domain management and signaling while each service provider maintain their network with centralized controller should be performed. Ideas of this thesis can extend to the communication among centralized controllers in all over the network and establish inter-domain lightpaths while each centralized controller protects its private information of intra-domain. For example, the centralized controller of the domain of the source node transmits probe or PATH request messages such as BOSTP method or multi-path GMPLS method to all neighbor domain controllers with just enough information to establish inter-domain lightpath. Each domain controller setup their intra-domain path to connect neighbor nodes while they hide this intra-domain path information. We also can use broadcast transmission for small inter-domain traffic such as control plane messages.

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