A Thesis for the Degree of Ph.D. in Engineering

Energy-efficient Reliable Optical Metro/Access Integrated Network Using Virtualization Technology

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Summary

The amount of worldwide network traffic continues to increase due to the growth in wired/wireless broadband subscribers and the popularization of bandwidth-hungry applications such as video streaming. This increase in network traffic is raising the power consumption of network equipment by 12 percent per year [0-1]. Several researches have estimated that about 60–80% of the power consumption is consumed in the access network area [0-2][0-3].

In the present access network, Passive Optical Network (PON) system is widely deployed for residential users. The PON system provides broadband access service at low cost by sharing an Optical Line Terminal (OLT) and a trunk fiber by subscribers. Non-residential services such as virtual private line and mobile fronthaul are also about to be provided over existing optical access network. Therefore, a technique for high reliability with moderate cost is necessary.

From these backgrounds, the next-generation optical access network requires supporting not only capacity enhancement and cost efficiency, but also energy efficiency, high reliability, and multi-service accommodation.

To support aforementioned requirements at the same time, the optical metro/access integrated network has been studied. The optical metro/access integrated network expands the coverage of the present access network to the metropolitan area network. By increasing the number of subscribers per OLT, the optical metro/access integrated network aggregates subscribers' traffic efficiently and achieves low power consumption by reducing

the amount of electrical switches. This network is also expected to improve disaster tolerance at low cost since backup equipment can be shared by a lot of subscribers. We have proposed the Elastic Lambda Aggregation Network (EλAN) that accommodates multiple services by using programmable equipment and reconfigurable Optical Distribution Network (ODN).

This dissertation proposes techniques for high energy efficiency and reliability by exploiting network virtualization technology in EλAN. The power consumption in central offices is decreased by aggregating network functions into a limited number of OLTs and making unused OLTs sleep according to the traffic fluctuation. In case of massive failures, a single OLT keeps connectivity of excessive subscribers by switching connecting subscriber groups by Time Division Multiple Access (TDMA).

This dissertation is organized as follows. Chapter 1 describes the problem in the present optical access networks and clarifies the target of this dissertation. Chapter 2 introduces related optical network technologies and existing techniques for energy saving and high reliability. Chapter 3 focuses on the energy saving. To realize selective OLT sleep in the multi-service environment, the migration of network functions between OLTs is proposed. The optimization problem that obtains the placement of functions that minimizes the number of running OLTs is modeled as an Integer Linear Programming (ILP) problem. Numerical results show that the number of sleeping OLTs increases 16.7% on average and 35.8% at a maximum. Chapter 4 focuses on the high reliability. A network topology based on Mach-Zehnder 2×2 optical waveguide switches is proposed as a part of EλAN ODN. The proposed topology provides protection and TDMA-based subscriber accommodation. After that, a communication method that accommodates excessive subscribers is proposed. To alleviate the effect of large communication intervals of subscribers, a proxy that provides several functions such as traffic shaping is generated. Improvements in UDP packet loss rate and TCP throughput by the proxy are measured by implementation experiments. Chapter 5 concludes this dissertation.

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Chapter 1

Introduction

Chapter 1 describes the background of this dissertation. Requirements for the next-generation optical metro/access integrated network and the target of this dissertation are also clarified.

1.1 Background

The amount of worldwide network traffic continues to increase exponentially. Figure 1.1 and 1.2 show the forecasts of global IP and mobile data traffic carried out by a major network equipment vendor [1-1][1-2]. The global IP traffic is growing 23% per year and is forecasted to reach 168 exabytes per month in 2019. These results of survey also show that mobile data traffic in particular is increasing sharply, as much as 57% per year. This traffic increase is due to the growth in wired/wireless broadband Internet users and the popularization of bandwidth-hungry applications such as video streaming and cloud services. In Japan, the number of Fiber To The Home (FTTH) subscribers has increased 6.3% from 2012 to 2013 and reached 25 million, and that of Long Term Evolution (LTE) users has increased 2.3 times during the same period and reached 46 million [1-3].

The increase in network traffic raises the power consumption of network equipment. Figure 1.3 shows the forecast of worldwide power consumption of Information and Communication Technology (ICT) equipments [1-4]. The power consumption of network equipment grows about 12% per year and is expected to be over 97 gigawatts in 2020.

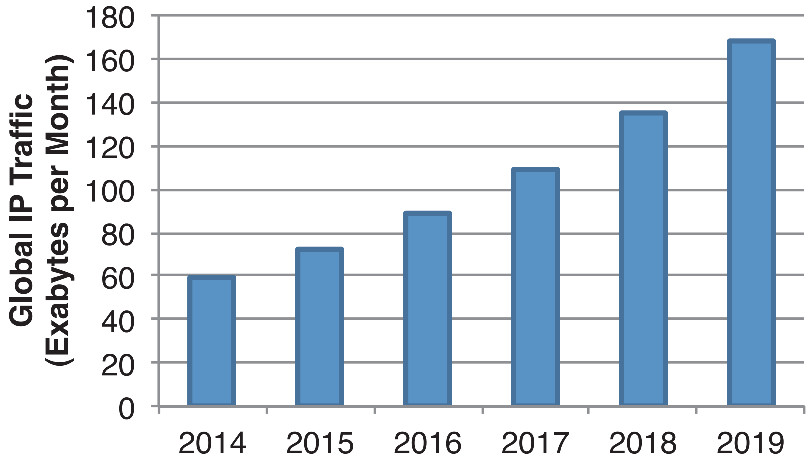

Figure 1.1: Forecast of global IP traffic.

Therefore, network operators have to deal with both network capacity enhancement and power reduction simultaneously.

Some surveys have estimated that about 60–80% of the power consumption of the current IP network comes from the access network area [1-5][1-6]. In today's access networks, Passive Optical Network (PON) systems are widely deployed to provide broadband Internet access to residential users. The PON system is a cost-efficient FTTH solution since a single Optical Line Terminal (OLT) and a feeder fiber are shared by multiple Optical Network Units (ONU) by using passive optical splitters. At the present time of writing, gigabit-class PON systems such as IEEE Gigabit Ethernet-PON (GE-PON) [1-7] and ITU-T Gigabit-PON (GPON) [1-8] have been commercialized. To deal with the increase in network traffic, PON systems that realize 10-Gbps transmission rate have been already standardized in both IEEE and ITU-T [1-9][1-10], and the standardization of Next Generation-PON 2 (NG-PON2) that uses four 10-Gbps channels is under discussion [1-11][1-12]. In addition, PON systems are going to be utilized to provide not only residential Internet access but also other non-residential services such as virtual private line, mobile fronthaul, and datacenter network.

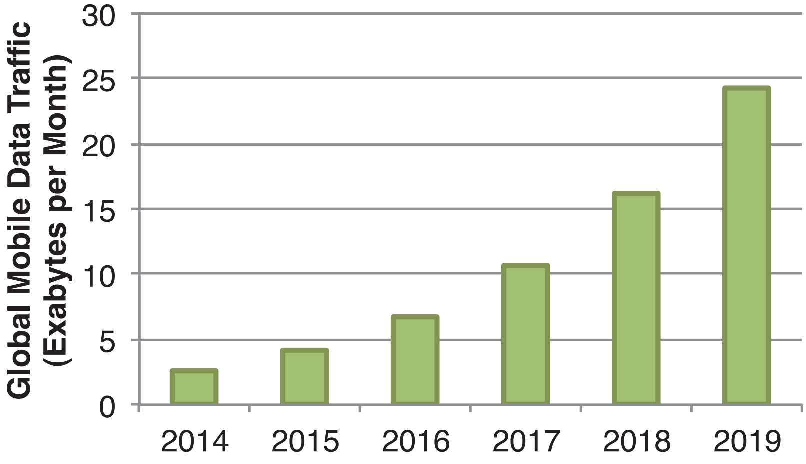

Figure 1.2: Forecast of mobile data traffic.

On the other hand, the communication network has been recognized as a social infrastructure. Especially in Japan, the importance of network reliability has been acknowledged again after Tohoku earthquake and tsunami in 2011. In this tremendous disaster, 385 buildings of NTT East became incapacitated and approximately 1.5 million lines were damaged [1-13]. It took approximately 50 days to restore services in customer residential areas. To improve the reliability of PON, protection schemes have been standardized by ITU-T [1-8][1-14]. In the PON protection schemes, backup equipments such as spare OLTs and feeder fibers are deployed. Connectivity between an OLT and ONUs is recovered by using the backup equipments when a failure occurs. In actual fact, protection schemes are rare to implement in present PON systems since most of subscribers are best-effort Internet users, who require low connection fees. However, high reliability becomes necessary when non-residential services are provided on the optical access network.

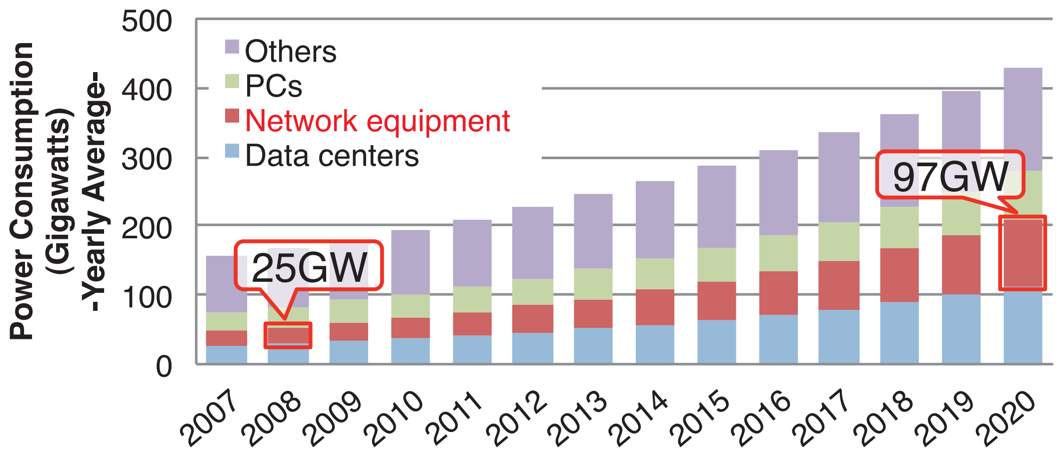

Figure 1.3: Forecast of power consumption of ICT equipments.

1.2 Requirements for optical metro/access integrated network

1.2.1 Required features

Based on the background in Section 1.1, the next-generation access network should satisfy the following features.

- Huge traffic handling
  - To deal with the increase in network traffic, network capacity enhancement and/or improvement of network utilization efficiency is required.
- Energy efficiency
  - The power consumption of network has to be reduced.
- Cost efficiency

  - The network operator has to continue providing network services for subscribers at the almost same cost as today.

- Multi-service accommodation
  - Multiple network services that have different protocols and Quality of Service (QoS) requirements should be supported on a single network.

- Reliability
  - The network has to tolerate failures in order to provide high reliability especially for non-residential services.

Generally, some of these features have trade-off relationships. For example, the increase in transmission capacity causes the raise of cost and power consumption of network equipment.

1.2.2 Possible solutions

Figure 1.4 summarizes possible solutions to satisfy the required features shown in 1.2.1. Among these possible solutions, this dissertation especially focuses on the metro/access integration and the network virtualization since these solutions have a potential to satisfy multiple features at the same time.

Metro/access integration

The long-reach optical access network has been studied actively [1-15][1-16]. In this network, the transmission distance and the number of accommodated ONUs per OLT are increased compared to the conventional access network by introducing optical amplifiers. Since the traffic in the access network is bursty and low in the average, expanding

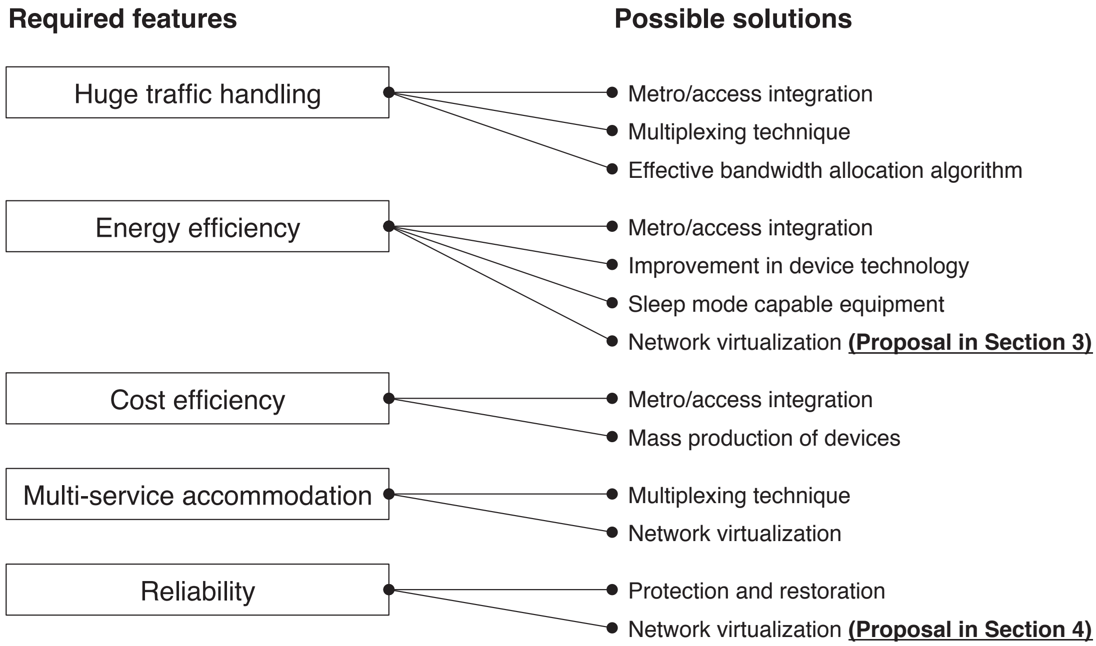

Figure 1.4: Required features and possible solutions for next-generation optical access network.

the coverage of the access network is effective way to aggregate subscribers' traffic efficiently. The network system that covers conventional metropolitan and access networks is especially called the "optical metro/access integrated network" in this dissertation.

By reducing the number of network equipments such as OLTs, electrical switches, and routers, the optical metro/access integrated network reduces Capital Expenditure (CapEx), Operational Expenditure (OpEx), and even power consumption. On the other hand, a technique for high reliability becomes necessary since the failure probability is increased by extending the transmission distance.

Network virtualization

The concept of network virtualization has appeared following the popularization of virtualization in server and client machines. Figure 1.5 shows the concept of network

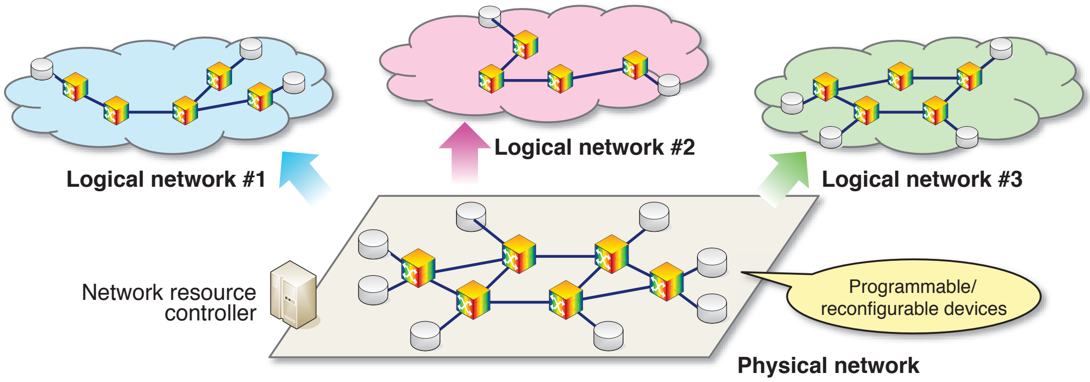

Figure 1.5: Concept of network virtualization.

virtualization. A centralized network resource controller configures physical network resources to provide logical networks for various network services.

Software Defined Networking (SDN) is a technology to realize adaptive configuration of logical networks by software. OpenFlow [1-17] is a representative technology of SDN. Network Functions Virtualization (NFV) [1-18] that realizes network functions such as routers and firewalls on a general-purpose server has also emerged. By collaborating with SDN, NFV realizes flexible utilization of network resources and reduction of CapEx and OpEx.

The network virtualization technique has mainly been applied to the datacenter network and the carrier-class network. Our laboratory has proposed Elastic Lambda Aggregation Network (EλAN) that introduces the idea of virtualization into the optical metro/access integrated network [1-19][1-20][1-21][1-22]. To support multiple services on a single network system, EλAN introduces programmable OLTs/ONUs and reconfigurable Optical Distribution Network (ODN) (see 2.2.4).

Other solutions

- Multiplexing technique

  - A multiplexing technique is used to transfer several different data signals on a shared medium at the same time. In the optical fiber communication system, Wavelength Division Multiplexing (WDM) that allocates different wavelengths to each signal is commonly used. Signals of multiple services are transferred on a single optical fiber since wavelengths do not interfere with each other (except nonlinear effects). WDM can also be used to increase the transmission capacity per fiber. In addition, flexible grid technology that uses optical Orthogonal Frequency Division Multiplexing (OFDM) has been studied [1-23][1-24][1-25]. Instead of a wavelength, multiple low-bandwidth subcarriers that are orthogonally modulated are allocated to each service. By changing the number and modulation format of subcarriers, optical OFDM realizes optical paths that have elastic bandwidth. The flexible grid technology is expected to achieve more efficient utilization of spectrum resource compared to WDM.

- Effective bandwidth allocation algorithm

  - In the commercialized PON system, an OLT allocates upstream bandwidth to ONUs by using Dynamic Bandwidth Allocation (DBA). The amount of bandwidth allocated to each ONU is dynamically changed according to reports of the upstream queue length from all active ONUs. An efficient DBA algorithm that realize higher bandwidth utilization with a short calculation time is required.

- Improvement in device technology

  - Improvement in device technology reduces the power consumption of access network equipment such as an OLT and an ONU. The power saving has been achieved by various technical innovations, such as adoption of Application

Specific Integrated Circuit (ASIC) instead of Field Programmable Gate Arrays (FPGA), miniaturization of the semiconductor process, and so on (see 2.3.1).

- Sleep mode capable equipment
  - The sleep mode of an ONU realizes more reduction of its power consumption. Several function blocks such as a transmitter and a receiver are suspended according to the condition of downstream and upstream traffic (see 2.3.2). The selective sleep of an OLT has also been studied in the long-reach optical access network that equips multiple OLTs (see 2.3.3).
- Mass production of devices
  - The mass production of devices brings the price down of the network equipment. However, before starting the production, the prospect of sufficient penetration of the network system is needed.
- Protection and restoration
  - As mentioned in Section 1.1, protection schemes for PON systems have been standardized by ITU-T to improve the reliability. There have also been many researches on network architectures that provide protection cost-effectively (see Section 2.4). In addition, an restoration scheme is applicable on a network that has adequate redundancy. In the restoration scheme, a new traffic route is computed and configured just after a failure occurs. Several architectures of the optical metro/access integrated network has the potential to apply the restoration scheme.

1.3 Target of this dissertation

Among the five required features shown in Section 1.2, this dissertation focuses on techniques for high energy efficiency and reliability. In the optical metro/access integrated network, the network virtualization is mainly used for multi-service accommodation. This dissertation aims to exploit this virtualization to realize energy saving and disaster recovery.

The research in Chapter 3 targets the energy saving in the optical metro/access integrated network. As shown in Fig. 1.4, there are several approaches to achieve high energy efficiency. Chapter 3 brings the idea of network virtualization to achieve reduction of the power consumption of OLTs. The proposal method aggregates virtualized network functions into minimum OLTs and makes unused OLTs sleep according to traffic fluctuation.

The research in Chapter 4 targets the fault-tolerant design of the optical metro/access integrated network. An optical switch network topology that provides high availability by protection is proposed at first. After that, a communication method in a time of massive failures that a single OLT keeps connectivities of excessive ONUs is proposed.

Through these researches, this dissertation contributes the realization of the energy-efficient and highly-reliable optical metro/access integrated network.

1.4 Outline of this dissertation

The remaining chapters of this dissertation are organized as follows.

Chapter 2 introduces fundamental technologies of the optical access network and existing researches on the optical metro/access integrated network. Since this dissertation especially focuses on energy efficiency and reliability, several energy-saving and protection techniques in the optical access network are also introduced. The position of this dissertation is described at the end of Chapter 2. Chapter 3 and 4 describe main proposals in this dissertation. Table 1.1 shows the outline of the proposals in each chapter. These proposals are assumed be worked on EλAN, which supports multi-service accommodation by using network virtualization. Proposed techniques can be applied to EλAN independently so as to achieve both high energy efficiency and high reliability at the same time. Finally, Chapter 5 concludes this dissertation.

Table 1.1: Outline of proposals in this dissertation.

Chapter 3	Research issue	Energy saving by logical OLT migration and selective OLT sleep
	Purpose	In the Elastic Lambda Aggregation Network (EλAN), multiple Programmable OLTs (P-OLT) are deployed in a single network and various types of services are supported by configuring Logical OLTs (L-OLT). Selective OLT sleep according to the daily traffic fluctuation is attractive for network operators since the power consumption of OLT per unit is much larger than that of ONU. However, different from the conventional optical access network, network traffic of different services cannot be aggregated in a single L-OLT.
	Proposal	(1) L-OLT migration is introduced. (2) L-OLT placement optimization problem is modeled to obtain the placement of L-OLTs that minimizes the number of running P-OLTs.
	Achievement	L-OLTs of each service are aggregated into a few number of P-OLTs and unused P-OLTs are placed into sleep mode. The energy reduction effect of the L-OLT placement optimization is evaluated on the assumption that the arrival rate of connection requests fluctuates sinusoidally on a daily basis. The number of P-OLTs in sleep mode increases 16.7% on average and 35.8% at a maximum, compared to the situation without the optimization. Communication suspension time caused by L-OLT migration is also estimated.
Chapter 4	Research issue	Network topology and communication method for high reliability
	Purpose	High reliability is essential for the optical metro/access integrated network. To deal with sporadic failures that can happen in a normal operation, a network topology that provides protection is necessary for Optical Distribution Network (ODN). It is required to keep the optical loss between an OLT and ONUs low and reduce the number of total optical switches in terms of deployment cost and power consumption. In addition, the optical metro/access integrated network must tolerate massive failures to support non-residential services. In case of an outage of Central Office (CO), there is a chance of recovering connectivity of ONUs from another OLT in a different CO by reconfiguring ODN. However, there is a limit on the number of ONUs that a single OLT can accommodate in a normal time.
	Proposal	(1) An optical network topology that uses Mach-Zehnder 2$\times$2 optical waveguide switches is proposed. (2) A communication method that a single OLT maintains connectivity of excessive ONUs is proposed.
	Achievement	The proposed optical network topology provides high availability by setting two different routes that do not share any optical switches for subscribers. The design example shows that the proposed network satisfies targets of reliability and optical loss by using 28% fewer optical switches compared to a duplex tree topology. The proposed communication method shares a single OLT by multiple ONU groups of different services by Time Division Multiple Access (TDMA). A proxy is inserted to alleviate the effect of large communication intervals between the OLT and each ONU, and realize low-bandwidth but stable communication. Experimental result shows that UDP packet loss at the OLT is prevented and TCP throughput of each ONU improves 4.3 Mbps when the OLT accommodates quadruple number of ONUs as many as normal by inserting the proxy.

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Chapter 2

Technologies for optical metro/access integrated network

Chapter 2 introduces technologies related to researches in this dissertation. First, from a historical standpoint, fundamental technologies of the optical access network are introduced. Second, existing researches on the optical metro/access integrated network are introduced. Techniques to improve energy efficiency and reliability of the optical access network are also described. Finally, the specific position of this dissertation is illustrated.

2.1 Optical access network technologies

In this section, technologies of the optical access network are explained.

Figure 2.1 shows an overview of the present network hierarchy model. The core network (a.k.a. backbone network or long-haul network) is a high-capacity network that connects large cities by a mesh topology. Multiplexing method such as dense WDM is utilized to provide large bandwidth, and Optical Cross Connects (OXC) are deployed to set optical paths. The metropolitan area network (a.k.a. aggregation network) has a ring topology and is connected to the core network via a core router. Specifically, the metropolitan area network can be divided into the metro-core network and the metro-access network. The metro-core network uses a Reconfigurable Optical Add/Drop Multiplexer (ROADM) ring that configures optical paths between nodes. On the other hand, the metro-access network uses a Resilient Packet Ring (RPR) that transfers data in the gran-

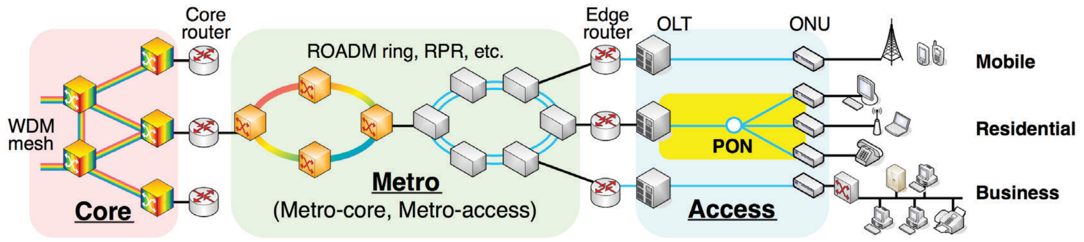


Figure 2.1: Overview of present network hierarchy model.

ularity of packets. The metropolitan area network and the access network are connected via an edge router. In Fig. 2.1, three access networks for different services are described; mobile, residential, and business. As mentioned in Section 1.1, PON systems are widely deployed to provide an FTTH service for residential users. Active optical network systems that use a high-speed optical switch to connect an OLT and ONUs have also been studied. At present, different network services such as residential Internet access, mobile fronthaul, and private line are provided over individual access network systems due to differences in protocols and QoS requirements.

2.1.1 Passive Optical Network (PON)

Fundamental technologies of PON

Figure 2.2 shows the basic architecture of PON. The PON system provides Point-to-Multipoint (P2MP) communication that a single OLT accommodates multiple ONUs. The OLT is deployed in a Central Office (CO) of a telecom carrier. On the other hand, the ONUs are deployed in subscribers' premises. The OLT and the ONUs are connected by ODN that consists of optical fiber cables and an optical splitter. All of ODN components are passive, i.e., these components do not need power supply.

In the commercialized PON systems, WDM is used to transmit downstream and upstream optical signals on a simplex fiber cable. Time Division Multiplexing (TDM) and

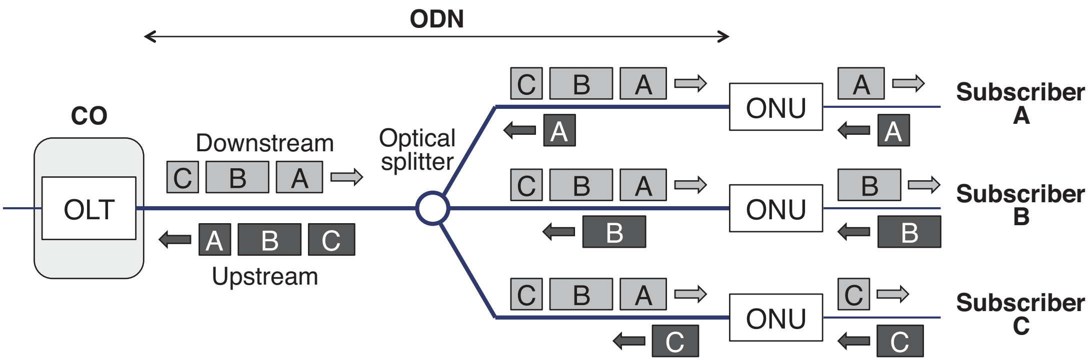


Figure 2.2: PON architecture.

Time Division Multiple Access (TDMA) are used for downstream and upstream communication, respectively. In downstream, continuous optical signal is split at the optical splitter and broadcasted to all ONUs. Each ONU receives downstream data frames selectively by looking PON link identifier in the frame header, such as Logical Link ID (LLID), and transfers received data frames to the subscriber's network. Security of downstream data frames between ONUs is ensured by using encryption. In upstream, bursty optical signal is transmitted from each ONU according to bandwidth allocation from the OLT. To avoid collisions of upstream signal from multiple ONUs at the optical splitter, the OLT measures Round Trip Times (RTT) to each ONU and decides the timing of upstream transmission.

Figure 2.3 shows the development history of PON systems. IEEE and ITU-T take an active role in the PON standardization. IEEE Gigabit Ethernet-PON (GE-PON) [2-1] and ITU-T Gigabit-capable PON (GPON) [2-2] are widely commercialized at the present time of writing. To realize 10-Gbps transmission rate, 10 Gigabit Ethernet-PON (10GE-PON) [2-3] and 10 Gigabit-capable PON (XG-PON) [2-4] have been standardized in 2009 and 2010, respectively. In addition, the deliberation of Next-Generation PON (NG-PON) is in progress.

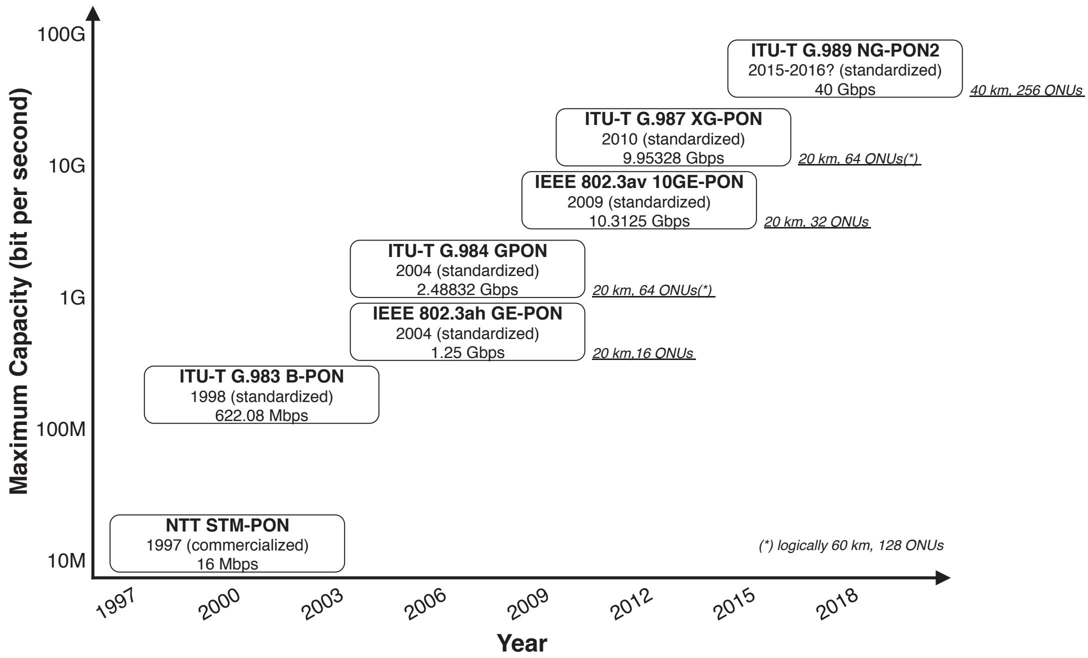


Figure 2.3: Development history of PON systems.

Ethernet PON (E-PON) series

E-PON series standardized by IEEE features a high affinity with the Internet since Ethernet frames are used in the MAC layer. An OLT and an ONU have a simple architecture since data frame conversion is not needed to provide Ethernet-based services.

Multi-Point Control Protocol (MPCP) is used to control multiple ONUs from a single OLT in E-PON series. Figure 2.4 and 2.5 show MPCP-based operation sequences of E-PON.

Discovery process shown in Fig. 2.4 is executed to establish connections between an OLT and ONUs. The OLT broadcasts DISCOVERY_GATE messages to ONUs periodically. An unregistered ONU responds to the OLT by REGISTER_REQ message after a random delay to avoid message collision. After receiving REGISTER_REQ message, the OLT allocates LLID to the ONU by REGISTER message. The OLT also allocates upstream bandwidth to the ONU by GATE message. Finally, the ONU responds to the

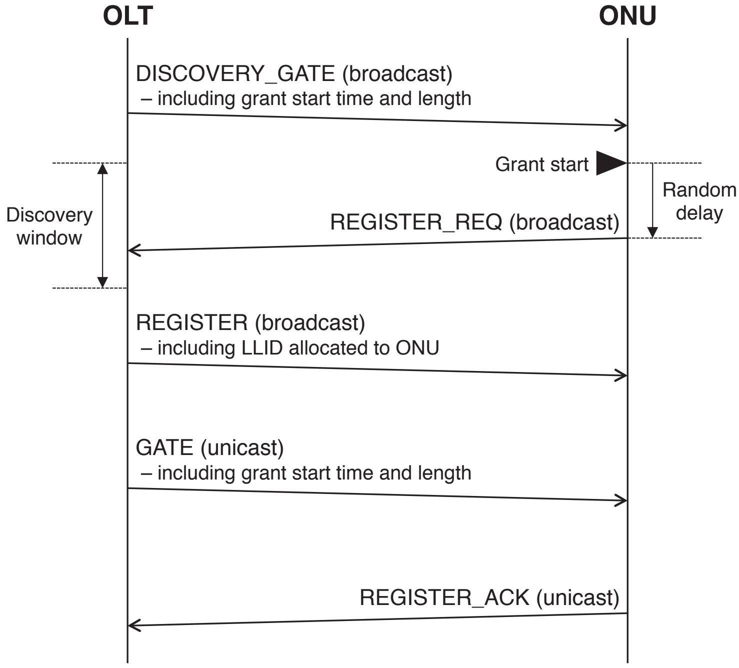


Figure 2.4: Discovery process using MPCP.

OLT by REGISTER_ACK message within the allocated time period. During this process, RTT between the OLT and the newly-registered ONU is measured by using timestamps included in each message.

Figure 2.5 shows the control of upstream transmission after finishing the discovery process. Registered ONUs request upstream bandwidth to the OLT by sending REPORT messages that include upstream queue lengths of each ONU. Based on these REPORT messages and RTT informations, the OLT calculates upstream bandwidth allocation by using a DBA algorithm. After the calculation, the OLT notifies ONUs of upstream transmission timing granted to each ONU by GATE messages.

Transmission distance of GE-PON is 20 km at a maximum, and the number of ONUs is more than 16 (generally 32). GE-PON systems are mainly deployed on East Asia, such as Japan and South Korea. To migrate from GE-PON to 10GE-PON smoothly, the 10GE-PON standard specifies the coexistence of GE-PON ONUs and 10GE-PON ONUs on a

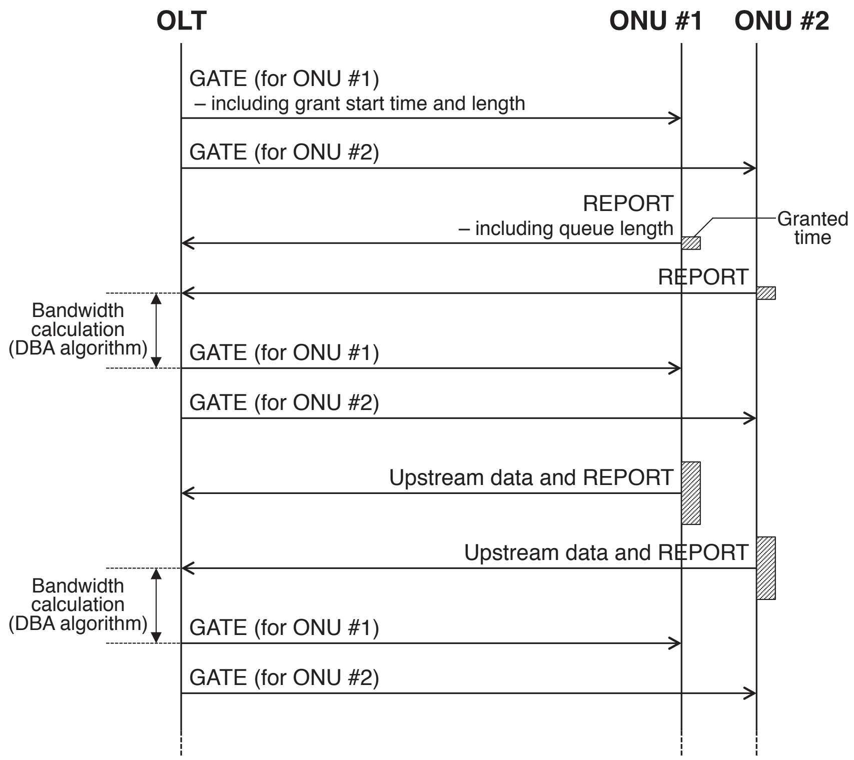


Figure 2.5: Upstream transmission control using MPCP.

single system.

Gigabit-capable PON (GPON) series

GPON series standardized by ITU-T features supporting a variety of services such as Ethernet, Asynchronous Transfer Mode (ATM), and Synchronous Digital Hierarchy (SDH). GPON Transmission Convergence (GTC) frames that have fixed length are used in the MAC layer. Data frames of each service are mapped in GPON Encapsulation Method (GEM) segment in the GTC frame.

Transmission distance is 20 km (logically 60 km), and the number of ONUs is more than 64 (logically 128). GPON has several options for downstream/upstream bit rates and supports 2.48 Gbps at a maximum. GPON systems are mainly deployed on Europe and

North America.

Next-generation PON (NG-PON)

Following the standardization of 10-Gbps PON systems, NG-PON has been discussed at the forum for telecommunications industry named Full Service Access Network (FSAN). NG-PON places importance on the coexistence with legacy PON equipments and supporting multiple services in addition to capacity enhancement and expansion of network coverage. The deliberation of NG-PON has been conducted under two time phases. NG-PON1, including XG-PON technology, is a short-term solution that leverages the current commercialized PON equipment. NG-PON2 has been discussed from a longer-term perspective compared to NG-PON1. The transmission scheme and ODN of NG-PON2 are not limited to conventional TDM and a simple tree topology. As a result, the first recommendation document of NG-PON2 about its general requirement has been published as ITU-T G.989.1 in 2013 [2-5]. The standardization of all of G.989 series is expected to be completed in 2015 or 2016.

Figure 2.6 shows the architecture of NG-PON2. NG-PON2 adopts the hybrid of TDM and WDM. Four wavelengths are used for each direction and each wavelength supports 2.5-Gbps or 10-Gbps TDM transmission. Therefore, the total capacity is 40 Gbps at a maximum for each direction. Colorless ONUs are adopted in NG-PON2 to reduce the cost for stock control and avoid improper connection. The transmission distance between the OLT and ONUs is 40 km, and the number of ONUs is 256. A point-to-point WDM overlay on the same ODN is also defined as a option. This overlay is expected to be utilized for services that require low latency, such as datacenter networks and mobile fronthauls.

Apart from the standard of NG-PON2, various PON systems have been proposed as candidates of the next-generation optical access network system. For example, coher-

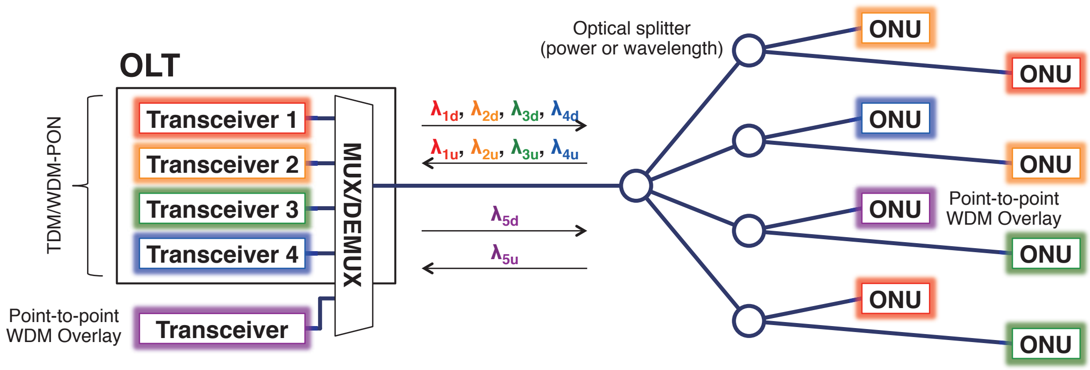


Figure 2.6: NG-PON2 architecture.

ent WDM-PON [2-6][2-7][2-8], OFDM-PON [2-9], Optical Code Division Multiplexing (OCDM)-PON [2-10][2-11], and hybrid systems of these multiplexing methods with TDM have been studied.

2.1.2 Active optical network

Optical access network systems that adopt a high-speed optical switch on ODN instead of an optical splitter has been studied [2-12][2-13][2-14][2-15].

In comparison to commonly-used PON systems, the values of studying active optical network systems are as follows.

First, the number of accommodated ONUs per OLT and the transmission distance are increased by using an optical switch. An optical splitter has large splitting loss since it divides optical signal power to every output port. An optical switch increases the output signal power compared to a splitter since there are no splitting loss. This feature leads to the improvement of bandwidth utilization efficiency of the access network area.

Second, the use of an optical switch prevents a malicious ONU from eavesdropping on downstream data destined for other ONUs. In the PON system, ONUs can receive all of downstream optical signal due to the characteristic of an optical splitter. An optical switch

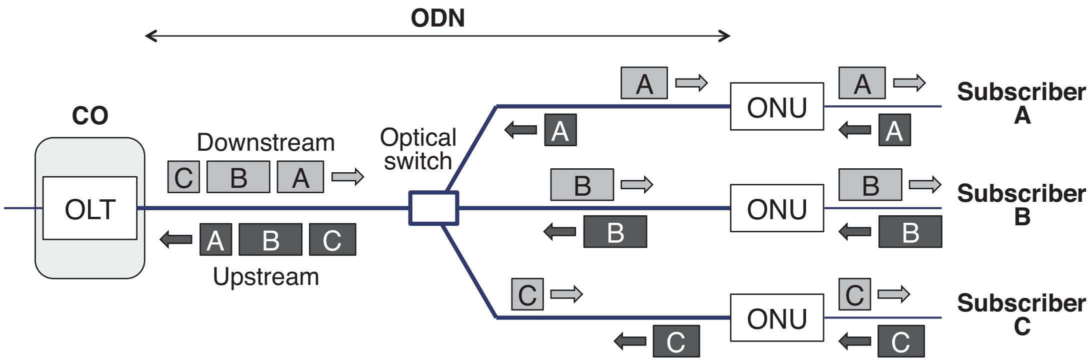


Figure 2.7: Active optical network architecture.

realizes transient point-to-point connections between an OLT and each ONU. In addition, an optical switch facilitates deployment of backup paths for protection. Therefore, the active optical network is suitable to support highly-confidential services such as virtual private line.

On the other hand, there are several challenges to implement the active optical network, such as deployment cost and power feeding for an optical switch. However, additional cost per subscriber can be reduced by increasing the number of accommodated ONUs per OLT.

Figure 2.7 shows the general architecture of the active optical network. In the following, implementation examples of active optical network systems are described.

Gigabit Ethernet-Optical Switched Access Network (GE-OSAN)

Gigabit Ethernet-Optical Switched Access Network (GE-OSAN) [2-12][2-13][2-14] adopts an optical switch module on the branch point of ODN. Figure 2.8 shows the internal structure of the optical switch module of GE-OSAN [2-12]. This module equips two 1×n (Pb,La)(Zr,Ti)O_3 (PLZT) optical switches [2-16][2-17] for downstream and upstream. The PLZT optical switch is a Mach-Zehnder optical waveguide switch that achieves switching speed of less than 10 nanoseconds. The PLZT optical switch also

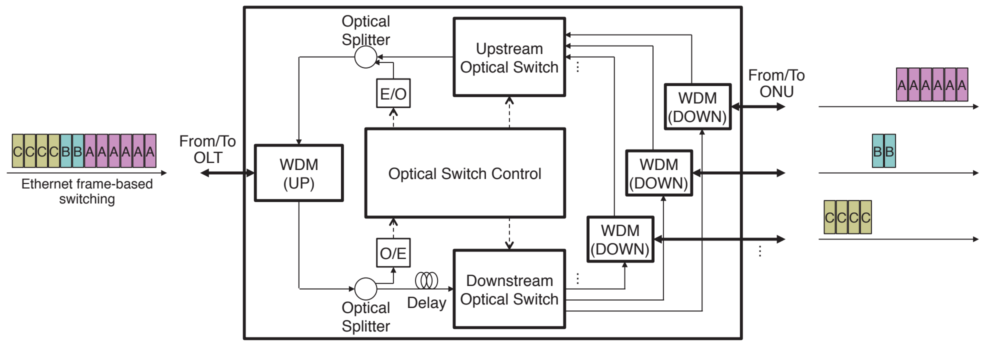


Figure 2.8: Optical switch module of GE-OSAN.

achieves low insertion loss and low polarization dependence [2-17]. In the optical switch module of GE-OSAN, downstream optical signal from the OLT is divided at an 1:2 optical splitter. Split optical signals are input into an Optical/Electrical (O/E) converter and a delay line respectively. The switch controller looks LLID in the header of input Ethernet frame, and controls the downstream optical switch to an adequate output port. The switch controller also detects MPCP GATE messages that are utilized to inform ONUs of the timing of sending upstream optical signal, and controls the upstream optical switch. By supporting MPCP of GE-PON, the optical switch module of GE-OSAN switches Ethernet frames without buffering.

Active Optical access Network (ActiON)

Active Optical access Network (ActiON) [2-15] also adopts the PLZT optical switch on ODN, but the optical switch module is more simplified than that of GE-OSAN. Figure 2.9 shows the internal structure of the optical switch module of ActiON [2-15]. The OLT schedules the switch timing of downstream/upstream optical switches and controls the optical switch module in ActiON, while the switch controller looks Ethernet frame headers and controls optical switches in GE-OSAN. All-optical transparent data transfer between the OLT and each ONU is enabled in ActiON since the optical switch module

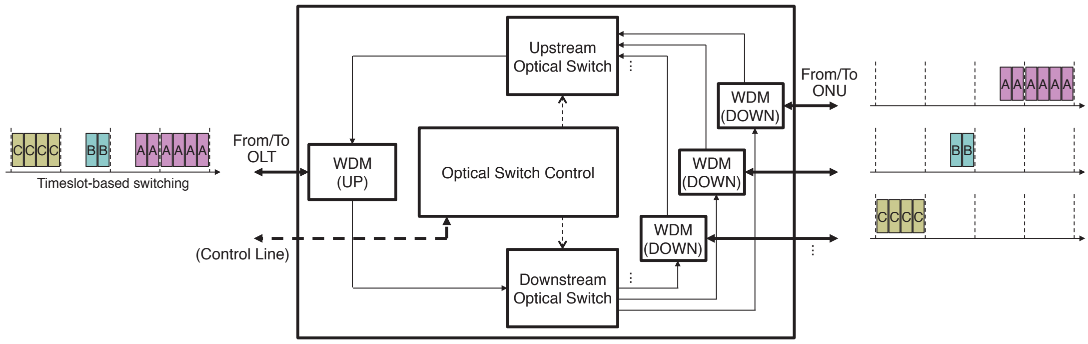


Figure 2.9: Optical switch module of ActiON.

does not care the format of data frames. On the other hand, high-precision synchronization between the OLT and the optical switch module becomes necessary to transfer optical signal to/from correct ONUs. To simplify the control of optical switches, ActiON adopts fixed-length timeslot switching in both downstream and upstream. ActiON has a compatibility with 10GE-PON and supports MPCP. The target of transmission distance is 40 km, and the number of ONUs is 128.

2.1.3 Summary of optical access network technologies

In this section, technologies of the optical access network was introduced. PON systems have been deployed to provide broadband access services to residential subscribers at low cost. To deal with the increase in traffic demand, 10-Gbps PON systems have also been standardized. At present, the standardization activity of NG-PON2 has been conducted. NG-PON2 aims for not only capacity enhancement and network coverage expansion, but also coexistence with legacy PON equipments and supporting multiple services.

In the wake of this trend, researches on the optical metro/access integrated network has been grown. In the next section, existing researches on the optical metro/access integrated network are described.

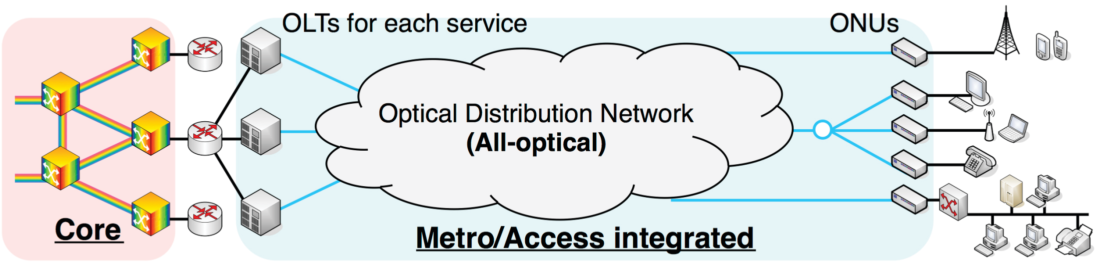


Figure 2.10: Network model including optical metro/access integrated network.

2.2 Optical metro/access integrated network technologies

Figure 2.10 shows the network model of the optical metro/access integrated network. The optical metro/access integrated network covers today's metropolitan and access networks based on the optical access network technology. OLTs are deployed on the boundary of today's core and metropolitan area network. The optical metro/access integrated network accommodates much more ONUs compared to the present PON system, like one thousand or more. In this section, existing researches on the optical metro/access integrated network are described.

2.2.1 Scalable Advanced Ring-based passive Dense Access Network Architecture (SARDANA)

Scalable Advanced Ring-based passive Dense Access Network Architecture (SARDANA) project has aimed to realize a scalable WDM/TDM-PON that provides broadband communication to a large number of subscribers at low CapEx [2-18][2-19].

Architecture

Figure 2.11 shows the architecture of SARDANA [2-18]. SARDANA has a hybrid topology of a WDM metro ring and TDM access trees. Passive Remote Nodes (RN) that

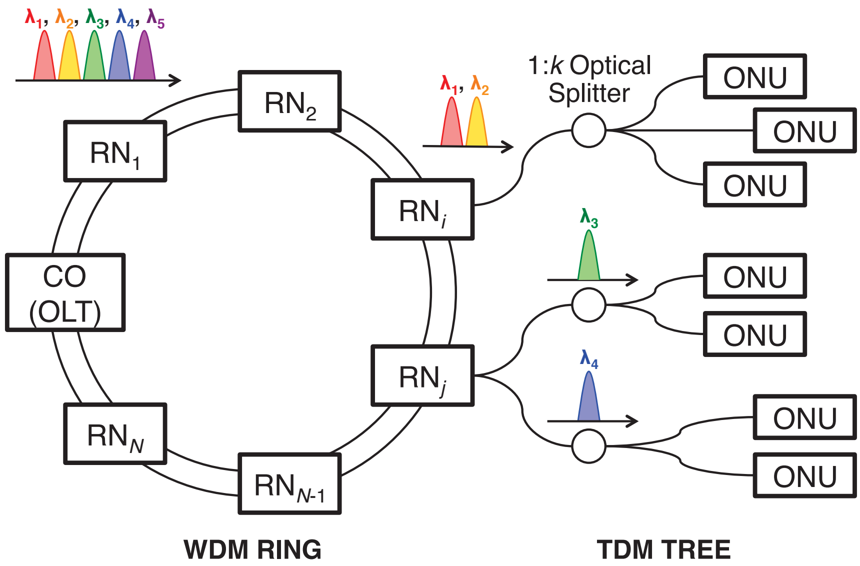


Figure 2.11: SARDANA architecture.

add/drop wavelengths and amplify optical signal are deployed on the metro ring. Each RN connects with two access trees that are compatible with GPON (except wavelengths). Reflective Semiconductor Optical Amplifier (RSOA)-based colorless ONUs are deployed in subscribers' premises. The number of RNs on the ring is 16 at a maximum, and each access tree accommodates up to 32 ONUs. Therefore, total 1024 subscribers (16 RNs $\times$ 2 trees $\times$ 32 ONUs) are accommodated in a single SARDANA system at a maximum. The target of transmission distance is 100 km at a maximum. A field trial was conducted by using facilities of France Télécom (Orange) on October 2010.

Features

SARDANA is a cost-efficient WDM/TDM-PON solution since equipments of the today's access network can be diverted to the TDM tree. The adoption of passive RNs realizes the reduction of OpEx and power consumption. In addition, not only GPON but also other services such as GE-PON can be supported by using WDM overlay due to the transparency of the network. However, SARDANA has a tolerance only for a single failure in the metro ring, and there are no protections in tree sections. That means SARDANA has almost the same reliability as the conventional separated metropolitan and access network systems.

2.2.2 Optical aggregation network

The optical aggregation network has been proposed as a concept of the future Internet that simplifies the present Internet architecture and reduces the power consumption drastically [2-20][2-21].

In the present Internet, the major traffic type has been shifted from peer-to-peer type to client-to-datacenter type. This is because the rise of “Hyper giants” (Google, Yahoo, Akamai, etc.) has changed the Internet from hierarchical model to densely interconnected model [2-22]. With the popularization of cloud services, network traffic is becoming centralized onto the datacenters of the hyper giants. However, as shown in Fig. 2.12, the present physical Internet structure is redundant and has not been changed to suit to the traffic centralization [2-21]. This situation causes not only the waste of electricity, but also the degradation of the QoS due to excessive Round Trip Time (RTT) and delay jitter.

Architecture

Figure 2.13 shows the overview of the optical aggregation network [2-21]. Routers that the present Internet contains are collected up to a solitary power-scalable giant router. The giant router and service servers constitutes the service cloud. The optical aggregation network connects the giant router to users transparently by using all-optical circuit switches, wavelength multiplexers/demultiplexers, and wavelength converters. All IP traffic is aggregated by the optical aggregation network and transferred to the giant router in one hop.

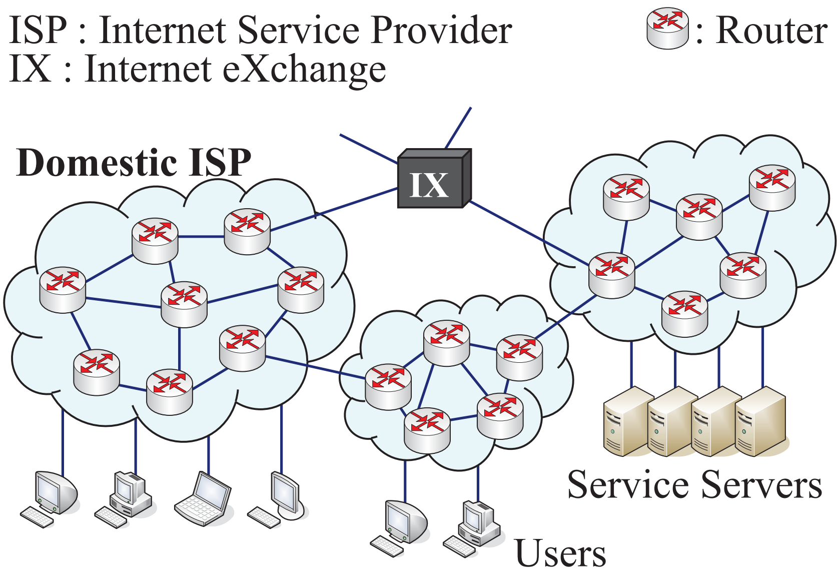


Figure 2.12: Schematic view of present Internet.

According to the estimation [2-20], the ideal model of optical aggregation network reduces the power consumption of the present Internet to 1/1000 ultimately. In the more realistic architecture that considers smooth migration from the present Internet [2-21], the energy-saving effect shrinks to 1/20 – 1/30 of the present Internet, but still having a big impact.

Features

The research of the optical aggregation network has cited an emphasis on the reduction of power consumption. The energy saving is achieved by replacing electrical routers by all-optical devices. The aggregation of network traffic into the giant router brings further energy-saving effect since the power consumption per bit becomes smaller as the capacity of router increases. Multi-service accommodation can be realized by using WDM overlay. On the other hand, a research for improving reliability has not been conducted in spite of its huge tree-based architecture.

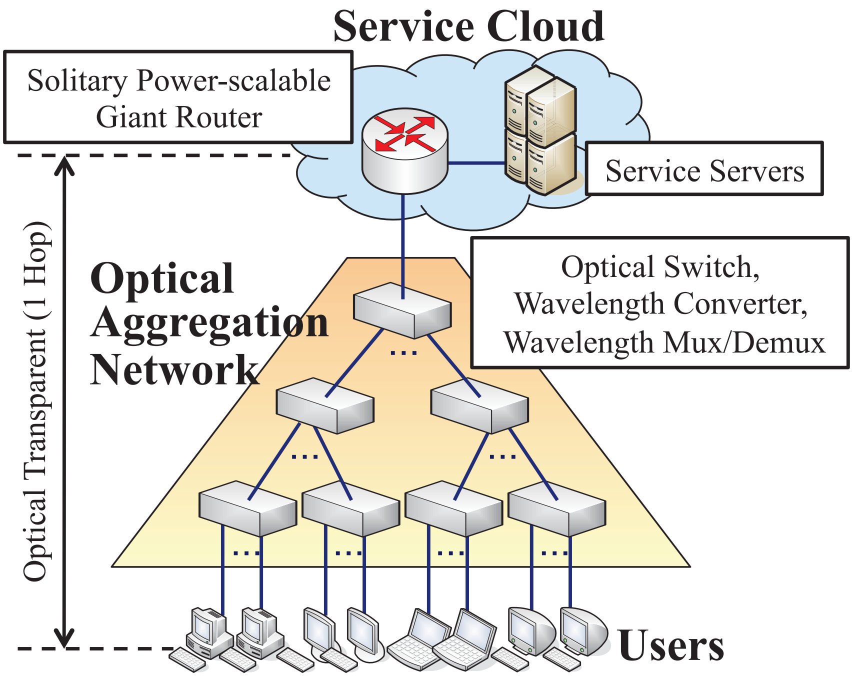


Figure 2.13: Overview of optical aggregation network.

2.2.3 Service Adaptive Access/Aggregation Network (SAAN)

Service Adaptive Access/Aggregation Network (SAAN) has been proposed to support multiple services on a single network platform [2-23][2-24]. As mentioned in the beginning of Section 2.1, different network services are currently provided over different access network systems due to differences in protocols and QoS requirements. For example, a private line service is possibly provided by using legacy ATM or SDH equipment and requires bandwidth guarantee and high reliability. A datacenter network uses Fibre Channel (FC) equipment and requires low packet delay. A mobile fronthaul requires high-precision time synchronization additionally. SAAN aims to aggregate such different services by using virtualization of network resources.

Architecture

Figure 2.14 shows the overview of SAAN [2-24]. SAAN adopts a Programmable OLT (P-OLT) and Programmable ONUs (P-ONU) to support functions required for each network service. Logical OLTs (L-OLT) and Logical ONUs (L-ONU) are configured within the P-OLT and the P-ONU respectively. ODN can be chosen from several types, such as Active Double Star (ADS) like ActiON, Passive Double Star (PDS) like PON, and Single Star (SS) like a conventional private line.

Features

The programmability in a OLT and ONUs brings more flexibility for providing multiple services on a single network. SAAN also increases the network utilization efficiency in the metropolitan and access network area by sharing programmable network resources by multiple services. This feature also leads to the reduction of network cost and power consumption by reducing the number of network equipment. However, there is a concern that the programmability raises the power consumption of a OLT and ONUs compared to single-purpose equipments. In the aspect of reliability, SAAN has only illustrated the duplication of access lines between a P-OLT and a P-ONU as an example.

2.2.4 Elastic Lambda Aggregation Network (EλAN)

By extending the idea of SAAN, Elastic Lambda Aggregation Network (EλAN) has been proposed in our laboratory [2-25][2-26][2-27]. In addition to the programmability of an OLT and an ONU, EλAN adopts reconfigurable ODN and the flexible grid technology. Optical access paths that have flexible bandwidths are set on ODN to provide network services from L-OLTs to L-ONUs with QoS guarantees. In other words, EλAN allocates virtualized network resources including OLT/ONU functions and sufficient bandwidth to

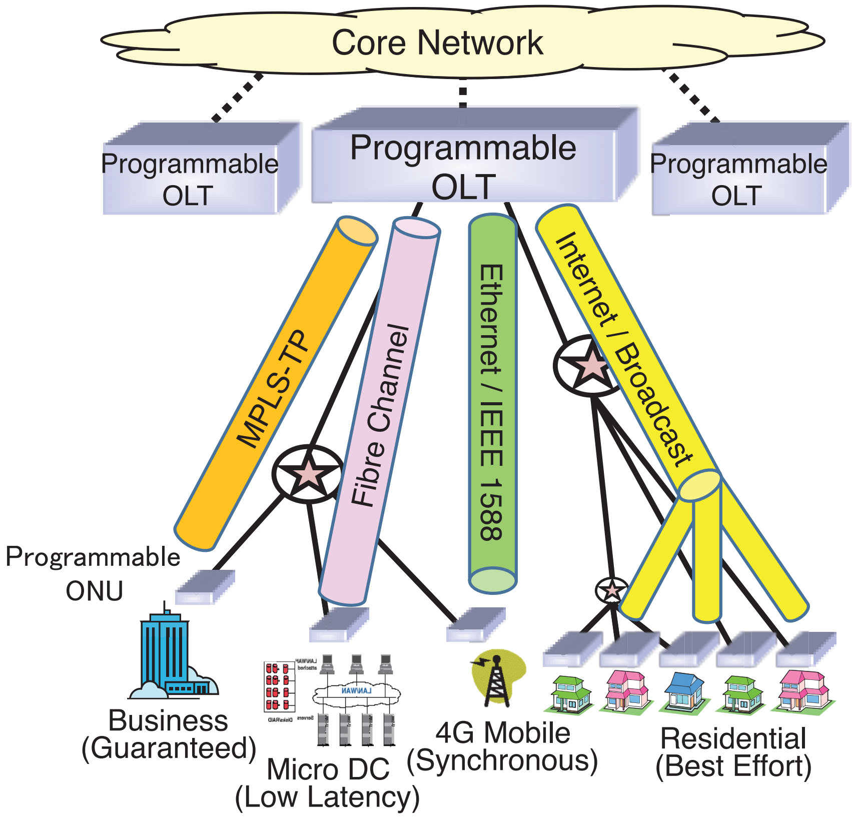


Figure 2.14: Overview of SAAN.

each network service adaptively. Network Management System (NMS) is deployed to manage these network resources.

Architecture

Figure 2.15 shows the architecture of EλAN. As same as SAAN, EλAN integrates access networks of different services by exploiting programmability of OLTs and ONUs. In addition, optical access paths that have suitable bandwidth for each network service are adaptively configured by using the flexible grid technology [2-28]. Considering the smooth transition from the present network system to EλAN, it is reasonable to use WDM/TDM at first and ultimately move to the flexible grid that uses optical OFDM.

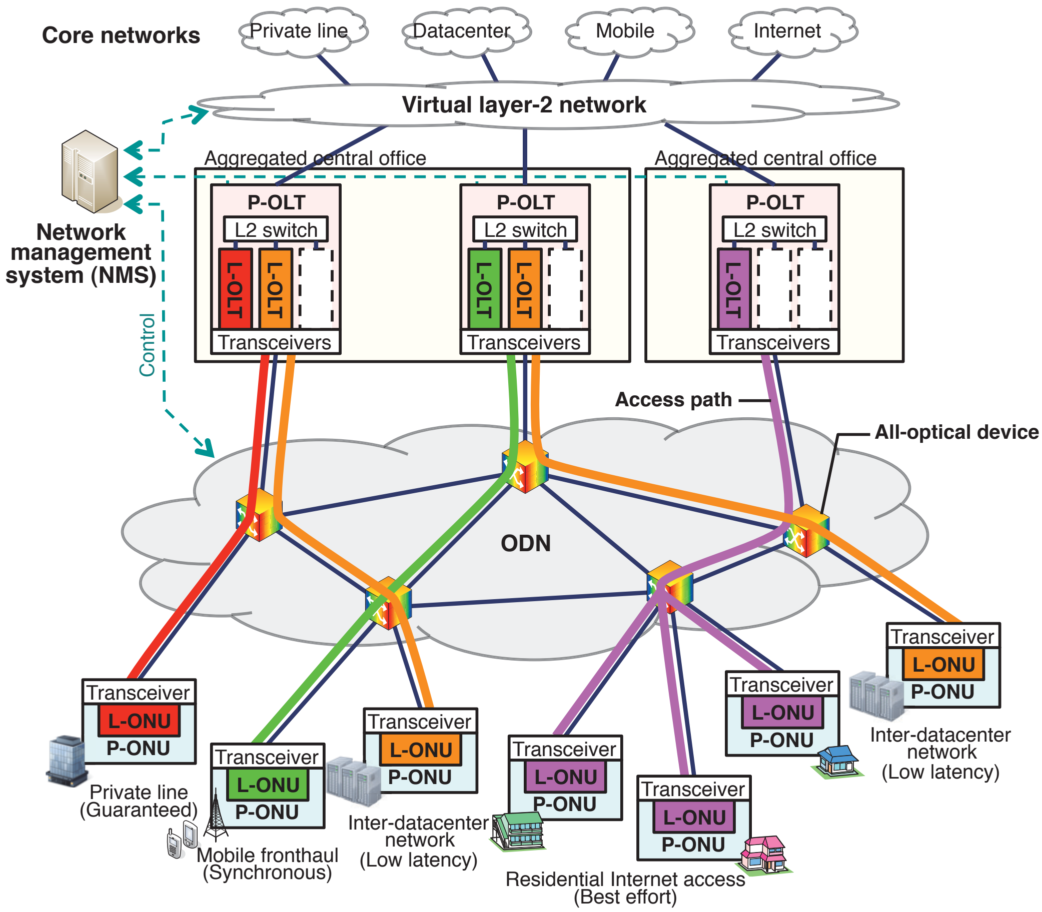


Figure 2.15: EλAN architecture.

Figure 2.16 shows an example of bandwidth allocation in a P-OLT when the flexible grid technology is adopted. A necessary number of contiguous frequency slots are allocated to each access path according to the QoS requirements of each network service. Compared to WDM, the flexible grid technology realizes bandwidth allocation in higher granularity (e.g., 12.5 GHz or 6.25 GHz). TDM is used in combination for a point-to-multipoint network service such as residential Internet access.

Functions of each component is briefly described below.

Virtual layer-2 network consists of distributed real layer-2 switches. This network transfers data frames of each service to/from appropriate P-OLTs.

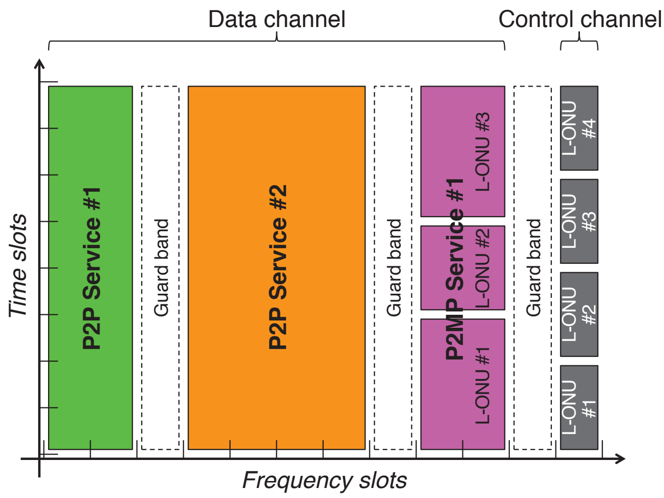


Figure 2.16: Example of bandwidth allocation.

P-OLTs are deployed at a number of aggregated COs. Each P-OLT configures L-OLTs and provides MAC and PHY functions required for each service such as frame processing, time synchronization, MPCP, DBA, rate adaptation, and Forward Error Correction (FEC) coding. The specific implementation method of P-OLTs is still under study, but there is a high possibility that P-OLTs will use programmable logic devices such as FPGA to process data frames at high speed. Figure 2.17 shows one possible implementation architecture of P-OLT. A single P-OLT hosts a number of configuration boards to realize several L-OLTs. Each configuration board has FPGAs for MAC and PHY, and these FPGAs are reconfigured to provide aforementioned functions. Transceivers are capable of flexible grid technology such as optical OFDM.

P-ONUs are deployed at subscribers' premises. As same as an P-OLT, each P-ONU supports MAC and PHY functions by generating L-ONUs.

ODN consists of all-optical devices such as optical switches and splitters. In particular, a Bandwidth Variable Wavelength Cross Connect (BV-WXC) is a key device to realize an elastic access path that can change its bandwidth flexibly. The BV-WXC switches optical signals at the granularity of frequency slots. Figure 2.18 shows the BV-WXC architecture

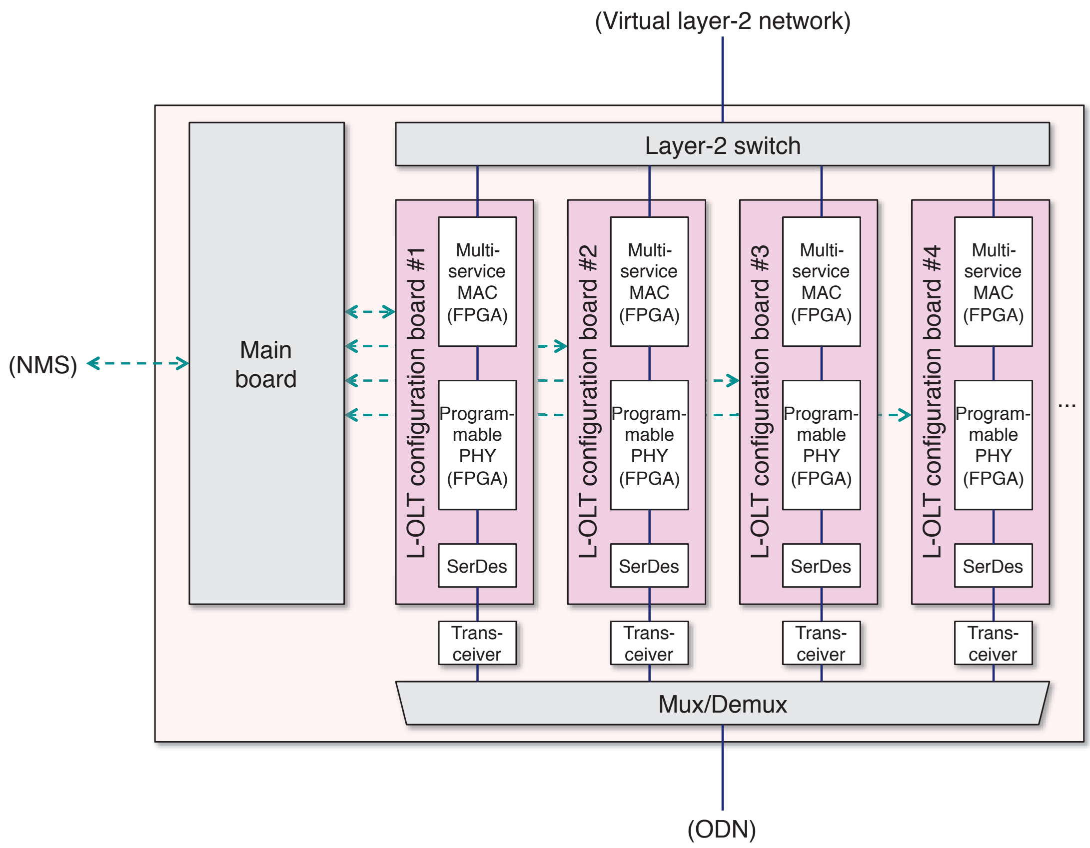


Figure 2.17: Example of P-OLT implementation architecture.

assumed in this thesis. This architecture is designed by reference to the Spectrum-Sliced Elastic Optical Path Network (SLICE) node model [2-28] and consists of optical splitters and Bandwidth Variable Wavelength Selective Switches (BV-WSS). This architecture is multicast-capable and able to set tree-like access paths on ODN. Therefore, point-to-multipoint type services (like PON) can be provided by using this BV-WXC. Optical amplifiers are used on ODN to compensate the optical loss of BV-WXC and increase the transmission distance.

NMS performs coordinated control of the virtual layer-2 network, P-OLTs, and ODN. NMS provisions a L-OLT configured on a P-OLT and an access path for a new connection request from a subscriber.

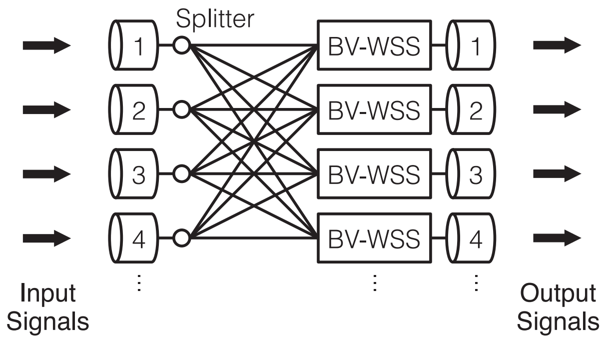


Figure 2.18: Architecture of BV-WXC.

EλAN targets to accommodate more than 256 P-ONUs per P-OLT. The target of transmission distance is more than 40 km.

Features

EλAN supports a variety of network services and topologies by not only programmable OLTs and ONUs, but also reconfigurable ODN based on BV-WXCs. By setting elastic access paths that have sufficient bandwidth for each network services, EλAN achieves further increase of network utilization efficiency. EλAN also enables flexible change of pairs of an OLT and ONU(s) by reconfiguring ODN. Therefore, protection and restoration are applicable without deploying backup resources. On the other hand, the concern about the power consumption of programmable devices still remains.

2.2.5 Summary of optical metro/access integrated network technologies

In this section, existing researches on the optical metro/access integrated network were introduced. The optical metro/access integrated network accommodates thousands of subscribers currently located in several access networks. By aggregating traffic of much

Table 2.1: Comparison among optical metro/access integrated network systems.

	Energy efficiency	Reliability
SARDANA	(Pros) Fully passive ODN	(Cons) Almost same reliability as conventional network
Optical aggregation network	(Pros) Replacing electrical routers by all-optical devices, Power-scalable giant router	(Cons) Huge tree-based architecture
SAAN	(Pros) Sharing network resources by multiple services (Cons) Programmability can raise power consumption	(Pros) Duplication of access lines can be applicable
EλAN	(Pros) Sharing network resources by multiple services (Cons) Programmability can raise power consumption	(Pros) Reconfigurable ODN enables protection and restoration

more subscribers than the conventional PON, this network improves the network utilization efficiency. Reduction of OpEx and power consumption is also expected by replacing equipments that execute electrical signal processing by all-optical devices. In addition, multi-service accommodation is emphasized as same as the next-generation PON systems.

Table 2.1 shows the comparison of energy efficiency and reliability among optical metro/access integrated network systems introduced in this section.

2.3 Energy-saving techniques

In the previous Section 2.1 and 2.2, the transition of research trend in the optical access network architecture was described. The expansion of the network coverage leads to the

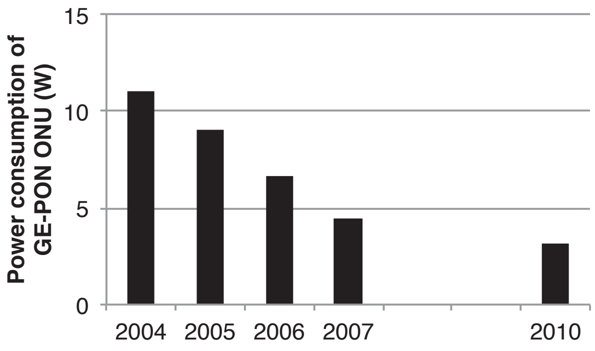


Figure 2.19: Power consumption of GE-PON ONU.

reduction of network equipments and thus energy saving is achieved. In this Section 2.3, other related works on energy saving mentioned in 1.2.2 are detailed.

2.3.1 Improvement in device technology

Improvement in device technology reduces the power consumption of access network equipment itself. Especially it is effective for energy saving to reduce the power consumption of ONUs. This is simply because the number of deployed ONUs is large and they consume a huge amount of power. According to the report in [2-29], the total power consumption of ONUs accounts for 60% of that of the access network area presently.

Figure 2.19 shows the power consumption of a GE-PON ONU [2-30]. The power consumption of a single ONU has fallen below 4 watts in 2010; this is a 67 percent decrease from 2004. This power saving has been achieved by following technical innovations [2-30].

Conversion from FPGA to ASIC

Original GE-PON ONUs introduced in 2004 use FPGAs to implement necessary functions. The use of FPGAs brings several advantages in the development and production in an early stage, such as facile reconfiguration of functions, low initial investment cost, and short development period. However, an FPGA consumes more electricity than an ASIC since an FPGA needs more transistors to implement the same circuit. Therefore, it is conceivable that FPGAs in ONUs have been replaced by ASICs with the popularization of GE-PON systems.

Miniaturization of semiconductor process

The linewidth of semiconductor chip has been reduced continuously for nearly a half-century. The narrower the linewidth becomes, the more transistors can be implemented on the same semiconductor chip. Therefore, the increase in chip performance and the reduction of manufacturing cost can be expected. In addition, the power consumption of the chip is also reduced since transistors operate at a low voltage.

On the other hand, leakage current has emerged as a new challenging issue in the recent semiconductor manufactured with nanoscale process. Leakage current is a phenomenon that electrons pass through a thin insulator. To achieve more energy-saving effect by the miniaturization of process, the waste of electricity caused by this phenomenon must be solved.

Adoption of low-power PHY

In the physical layer, the development of energy-efficient optical components has made progress.

The power consumption of semiconductor laser is decreased according to the threshold current. In addition, a conventional semiconductor laser requires a temperature controller since the output power of the laser degrades at high temperature. An optical transmission module that operates with low power consumption can be realized by removing the temperature controller. Therefore, the semiconductor laser that have low threshold current and good temperature characteristics at high temperature has been researched. For example, a metamorphic laser with high characteristic temperature (220 K) and high operating temperature (200 °C) by inserting an electron stopper layer has been reported in [2-31].

Adaptive Link Rate (ALR) function in an optical transceiver is another solution for achieving low-power PHY. As mentioned in 2.1.1, the dual-rate (coexistence) mode that supports both 10 Gbps and 1 Gbps data rates is supported in the 10GE-PON system to realize a smooth transition from GE-PON. By exploiting this dual-rate mode, ALR in the downstream link of 10GE-PON has been proposed [2-32]. In this proposal, an ONU has two optical receivers corresponding to both rates. When the traffic amount is low, a receiver of 1 Gbps that consumes less electricity than that of 10 Gbps is used. Therefore, efficient power reduction according to the traffic fluctuation is realized.

2.3.2 ONU sleep

An ONU sleep mode has been studied to reduce the power consumption of ONUs further. In the ONU sleep mode, several function blocks of an ONU are suspended according to the condition of network traffic. Since ONUs share a single OLT and transmit upstream traffic only during the time period granted by the OLT, ONUs have much chance to sleep most of the time.

In ITU-T, three categories of ONU power saving techniques are standardized [2-33]. Figure 2.20 shows the taxonomy of the power saving techniques of ONU [2-33].

ONU power shedding

ONU power shedding powers off specific services and functions that are not essential, while the transmitter and the receiver remains power on. A GPON ONU used in North America has several service interfaces such as Gigabit Ethernet, cable television (CATV), Multimedia over Coax Alliance (MoCA) service, and Plain Old Telephone Ser-

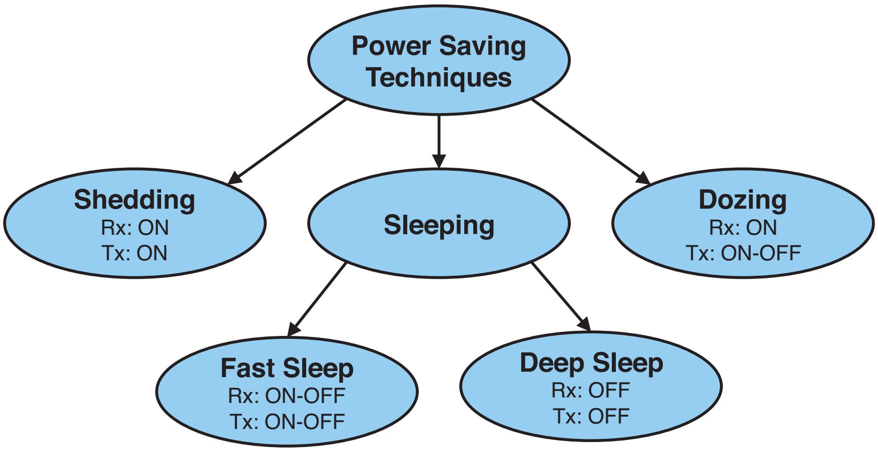


Figure 2.20: Taxonomy of ONU power saving techniques.

vice (POTS). An estimation in [2-33] has shown that the power shedding can save over 70% of active ONU power.

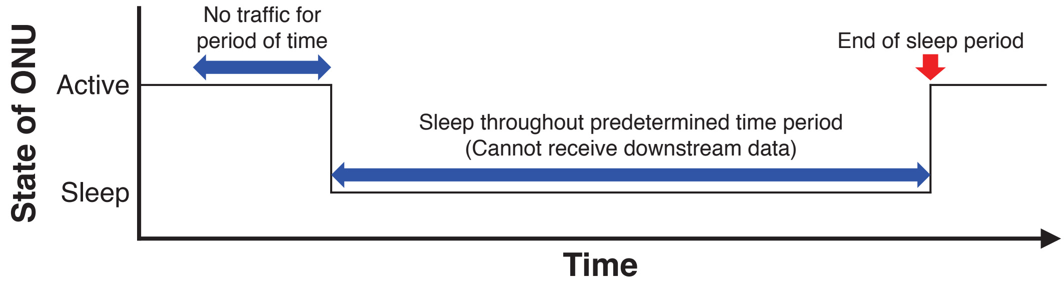
ONU dozing

ONU dozing powers off the transmitter of PON interface when there is no upstream traffic from subscriber's network, while the receiver remains power on. The dozing ONU receives upstream grants from the OLT, but does not respond as long as there is no upstream traffic to send. When the dozing ONU receives upstream traffic from subscriber's network or any message that requires a response from the OLT, the ONU wakes up and requests upstream bandwidth to the OLT.

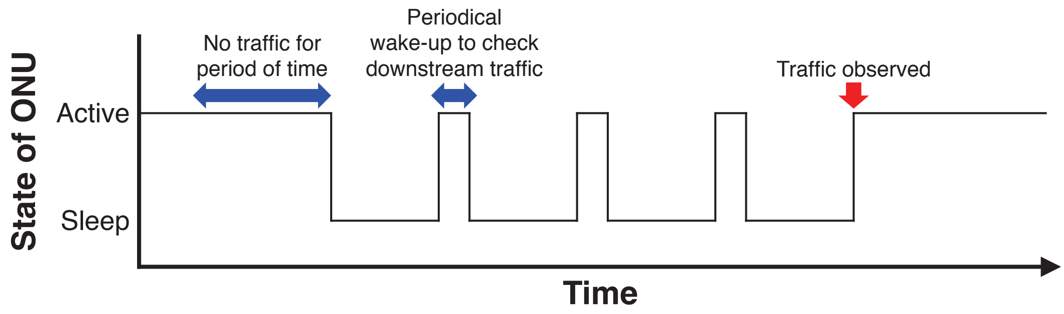
ONU sleeping

ONU sleeping powers off both the transmitter and the receiver of PON interface for a period of time. Figure 2.21 shows two operation modes of ONU sleeping.

In *Deep sleep* mode (Fig. 2.21(a)), the transmitter and the receiver continue to sleep throughout the predetermined time period when there are no downstream and upstream



(a) Deep sleep mode.



(b) Fast sleep mode.

Figure 2.21: Operation of ONU sleeping.

traffic. Deep sleep maximizes the power saving effect of the ONU, but the ONU cannot receive downstream frames until the end of the sleep period so that loss of frames might occurs.

In *Fast sleep* mode (Fig. 2.21(b)), the ONU periodically wakes up for a short time to check whether downstream frames have been arrived to the OLT. When the OLT receives downstream traffic destined to the sleeping ONU, the OLT buffers the traffic and sends it to the ONU after awaking.

2.3.3 Selective OLT sleep

While the sleep mode in ONUs has been researched and standardized, researches on the energy saving technique at the OLT side are less active. This is because the total power

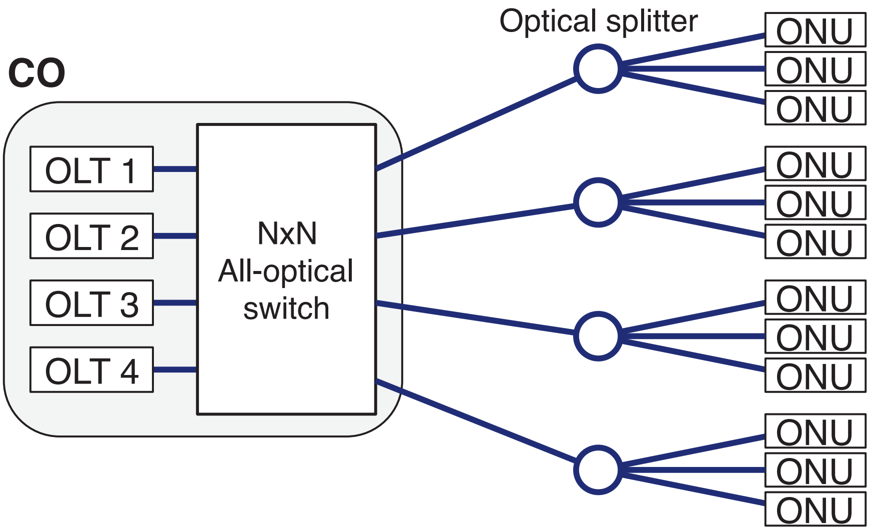


Figure 2.22: Power efficient optical access network capable of selective OLT sleep.

consumption of OLTs accounts for only 7% of that of the access network area [2-29], thus it is not expected to achieve drastic power reduction in the current-generation TDMA-PONs [2-34]. However, on the network where multiple OLTs are deployed, a selective OLT sleep according to traffic fluctuation becomes applicable. The selective OLT sleep is an attractive power-saving technique in COs since the power consumption of OLT is much larger than that of ONU. In addition, the reduction of OpEx by this selective OLT sleep can lead to the reduction of connection fee of subscribers.

For example, a power efficient optical access network architecture that changes the number of active OLTs dynamically has been proposed [2-35]. Figure 2.22 shows the network architecture [2-35]. The proposed architecture is a hybrid of TDMA-PON and ActiON. Several PON trees are connected each other by using a N×N non-blocking PLZT optical switch in a CO. In proportion with the number of active ONUs, a minimal number of OLTs are activated and other OLTs go into sleep mode. As the same analogy, a selective sleep of transceivers in an OLT is available in NG-PON2, which is described in 2.1.1.

2.4 Techniques for high reliability

In this section, related works on improving reliability in the optical access network are described.

Generally, protection and restoration methods are applied to connection recovery from a network failure. The protection method deals with a sporadic failure that occurs in nodes or links. In the protection method, backup equipments are deployed in addition to main equipments in advance. When a failure occurs in the main system, traffic flow is switched to the backup system so that the connection is recovered in a short time.

The restoration method works on a network architecture with adequate redundancy, such as a mesh topology. The in-advance reservation of backup equipments is not needed in the restoration method. When a network failure occurs, a new traffic route that passes over a failure point is computed. Therefore, the restoration method provides a chance of recovery from massive failures. Of course there is a possibility to fail to recover the connection due to a lack of available network resources.

In the commercialized PON systems, protection methods have been studied well since the network topology is very simple. In the following, protection methods for the optical access network are introduced.

2.4.1 Standardized protection methods

Several protection methods for PON systems have been standardized by ITU-T. Figure 2.23 shows four types of protection methods standardized in ITU-T G.983.1 and G.984.1 [2-36][2-2]. Type A protection (Fig. 2.23(a)) deploys a backup feeder fiber so that this method only deals with a cut of the feeder fiber. Type B protection (Fig. 2.23(b)) deploys a backup OLT additionally. Type C protection (Fig. 2.23(c)) defines duplication of the entire network. This method handles a failure on any components in the network and

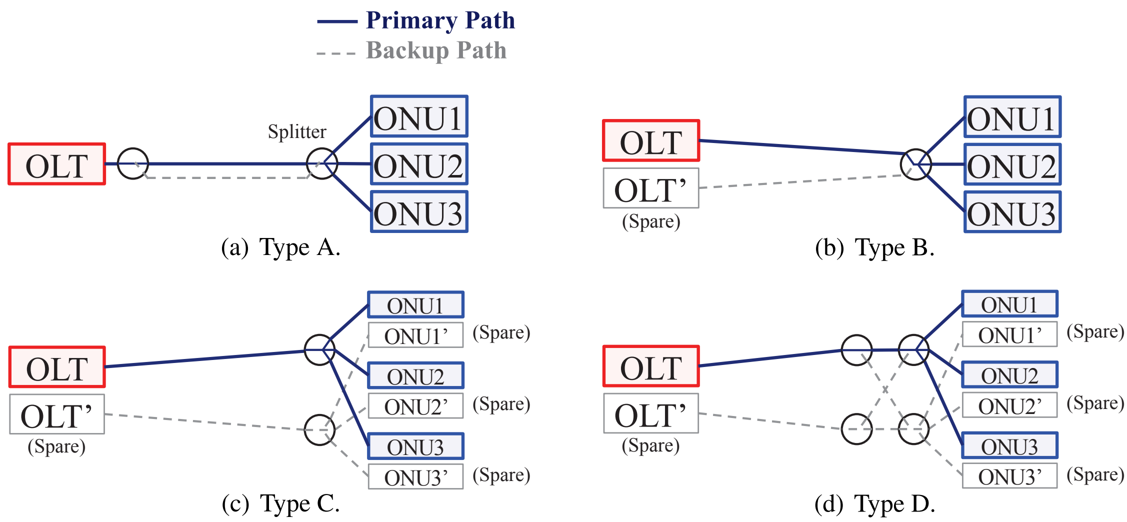


Figure 2.23: Standardized PON protection methods.

guarantees high availability to subscribers, but the deployment cost increases considerably. Type D protection (Fig. 2.23(d)) is similar to type C, but has flexibility for a failure. For example, when the feeder fiber of the primary path is cut, subscribers receive data from the spare OLT without switching ONUs in type D, while subscribers have to switch to spare ONUs in type C. The network operator can choose an appropriate protection method based on subscribers' needs.

In actual fact, types A and D have been almost abandoned by the industry [2-37]. ITU-T G.983.5 [2-38] that defines the enhancement of survivability of PON only states types B and C.

The service halt time of the PON protection is defined as less than 50 ms without extra traffic options.

2.4.2 Cost-effective protection methods

One of the disadvantages of the standardized protection methods is additional deployment cost for backup components. Therefore, the protection methods are rare to imple-

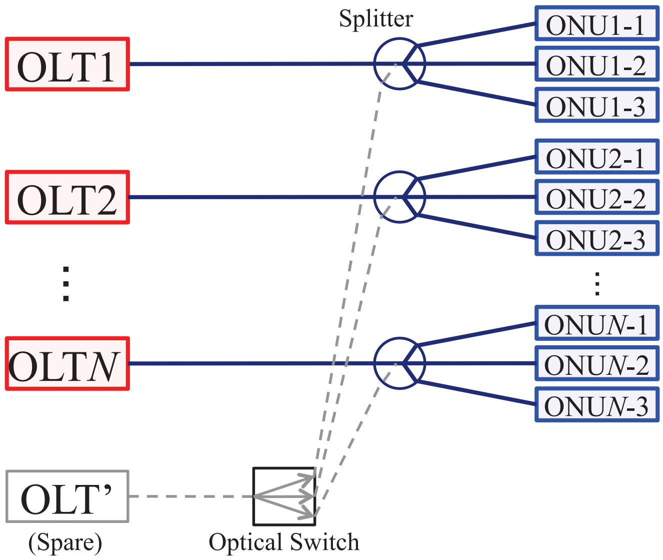


Figure 2.24: PON protection type H.

ment in the commercialized PON systems for residential Internet access. To improve reliability in more cost-effective way, several non-standardized protection methods that share backup equipment by multiple PON trees have been proposed.

Figure 2.24 shows a protection method named type H [2-39]. In type H, several PON trees are protected by 1:N scheme, that means, a spare OLT is shared by N working OLTs. The spare OLT is connected to optical splitters of PON trees by using a 1×N optical switch. Type H deals with a single point failure in OLTs or feeder fibers more economically than type B.

Figure 2.25 shows another protection method that does not have a redundant OLT [2-40]. Four PON trees with backup feeder fibers are connected by using an optical switch, and each OLT accommodates 32 ONUs in a normal time. When an OLT fails, another working OLT recovers connections of ONUs served by the failed OLT. In other words, this protection method keeps connectivity of more ONUs in a case of failure at the expense of bandwidth per subscriber.

There have been many other economical protection methods that share network equip-

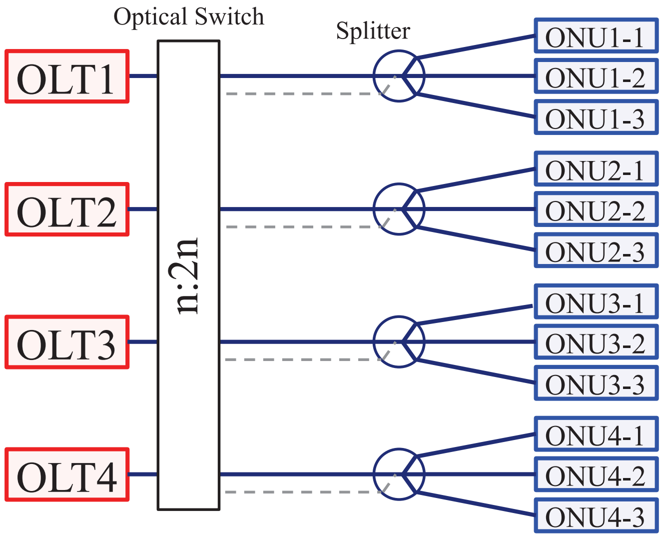


Figure 2.25: PON protection without redundant OLT.

ment [2-41][2-42].

2.4.3 Comparison of protection methods

As can be seen from 2.4.1 and 2.4.2, there is a trade-off between reliability and cost efficiency when applying protection methods. Among the standardized protection methods, type D has the highest reliability and requires the highest deployment cost, and both parameters decrease in the order of type C, B, and A. If it is assumed that the probability of simultaneous occurrence of multiple failures is negligibly small, it can be said that the methods in 2.4.2 provides almost the same reliability as the standardized ones. However, non-residential services such as virtual private line and mobile fronthaul must tolerate to massive failures since these services have a large impact on society.

In the network that supports multi-service accommodation, required reliability varies among services. Therefore, it makes more sense to provide optical paths between an OLT and ONUs flexibly according to service types. In addition, as mentioned before, the restoration method can be applied on a network architecture with redundancy. Although it is difficult to recover from a failure without service outage, the restoration method improves the chance of recovering connectivity.

2.5 Position of this dissertation

Based on the related technologies and researches described in Section 2.1 to 2.4, positions of researches in this dissertation are summarized as shown in Fig. 2.26 (excepting the improvement in device technology). The ultimate goal is to realize an optical metro/access integrated network system that supports high energy efficiency and high reliability, without sacrificing network capacity and cost efficiency. To support multi-service accommodation, researches in this dissertation are based on EλAN. The integration of metro and access networks itself realizes the reduction of network cost and power consumption. In addition, flexible use of network resources brings in more energy saving in COs and high reliability that non-residential services require. Network virtualization plays an important role to introduce this flexibility into the optical metro/access integrated network.

2.5.1 Axis of energy efficiency

Approaches for high energy efficiency in the optical access network system are categorized as follows.

- Improvement in device technology (omitted in Fig. 2.26)
- Expansion of network coverage (i.e., metro/access integration)
- ONU sleep
- Selective OLT sleep

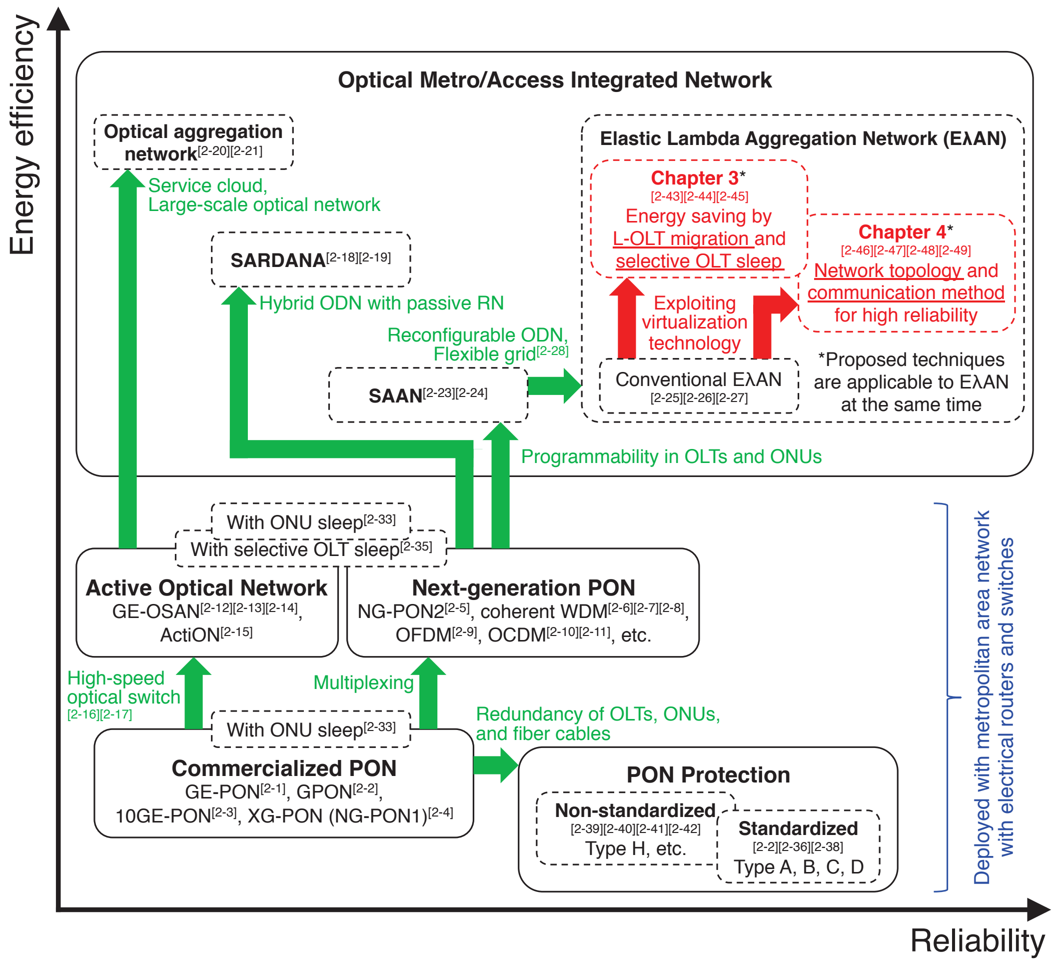


Figure 2.26: Position of this dissertation.

It is preferable to combine these approaches to reduce the power consumption.

The expansion of network coverage leads to the reduction of electrical processing equipments such as OLTs, routers, and layer-2 switches. As seen in Section 2.1 and 2.2, it can be said that this approach is a trend in the research area of optical access network. The integration of access networks of multiple services also promotes the power reduction since subscribers of various services share common network resources.

ONU sleep is one of the effective approaches to reduce the power consumption since the number of deployed ONUs is very large. This approach is generally applicable without depending on network scale, topology, and protocol.

Selective OLT sleep is compatible with the integration of metropolitan and access networks since this approach is only applicable in the network that has multiple OLTs. The related work described in 2.3.3 has taken into account the network that supports a single service. In the network supporting multiple services, the effectiveness of selective OLT sleep becomes worse if the service provided from each OLT is fixed. In addition, as mentioned in 2.2.5, there is a concern that the programmability raises the power consumption of network equipments.

The proposal in Chapter 3 uses the programmability in OLTs to aggregate network traffic of different services and breaks through the aforementioned situation [2-43][2-44][2-45]. L-OLT migration that replicates network functions from one P-OLT to another P-OLT is proposed to realize efficient selective OLT sleep. The L-OLT placement optimization problem that minimizes the number of running P-OLTs is also modeled to maximize the energy saving effect.

2.5.2 Axis of reliability

As mentioned in Section 2.4, there are two types of network failures; a sporadic failure and a massive failure. In the PON system, protection methods for a sporadic failure have been researched mainly since the PON system has a simple tree topology as shown in Fig. 2.2. However, in a time of large-scale disaster, multiple failures might happen simultaneously on OLTs, ODN, and ONUs. If a main system and a backup system fail at the same time, the protection method becomes unable to operate. To support services that require high reliability, it is necessary to deal with both sporadic and massive failures.

SARDANA has a hybrid topology of a metro ring and access trees and tolerates a single failure in a ring. Therefore, SARDANA has almost the same reliability as the conventional separated metropolitan and access network systems since there are no protections in tree sections. The optical aggregation network has a huge tree-based topology, but a research on highly-reliable architecture has not been conducted. SAAN has only illustrated the duplication of access lines as an example of ODN configuration.

In contrast to the above works, EλAN has a potential to provide not only protection but also restoration since ODN is reconfigurable and provides access paths suitable for each service. Therefore, a highly-reliable optical network design based on EλAN is discussed in Chapter 4. The requirements for EλAN ODN are as follows.

- To provide sufficient availability for subscribers by protection in a normal time
- To keep connectivity of subscribers by restoration in case of massive failures

In Chapter 4, a novel optical network topology that provides high availability is proposed as a part of EλAN ODN at first [2-46][2-47]. The proposed topology sets two switch-disjoint routes for protection to subscribers by using 2×2 optical waveguide switches. A novel communication method in a time of massive failures is also proposed in Chapter 4 [2-48][2-49]. Generally, there is a limit on the number of ONUs that a single OLT can accommodate. The proposal communication method keeps connectivity of excessive ONUs from a single OLT by using network virtualization.

Proposals in Chapter 3 and 4 have a trade-off relationship in the strict sense. This is because the proposed techniques in Chapter 4 require additional network components for improving reliability and thus cause the increase in power consumption. However, as mentioned in 1.4, proposals in Chapter 3 and 4 can be applied to EλAN independently. Since the power consumption of a P-OLT is large enough, the energy saving effect achieved by the proposals in Chapter 3 is not so diminished by the proposals in Chapter 4.

2.6 Chapter conclusion

This chapter illustrates fundamental optical access network technologies at first, and then existing researches on the optical metro/access integrated network are introduced. This is because the basic idea of the optical metro/access integrated network is to expand the coverage of the conventional optical access network. By increasing the transmission distance and the number of accommodated ONUs per OLT, the optical metro/access integrated network achieves reduction of network cost and power consumption from the architectural approach. This chapter also describes energy-saving techniques from other approaches and techniques for improving reliability on the optical access network. Finally, positions of researches in this dissertation are clarified.

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Chapter 3

Energy saving by logical OLT migration and selective OLT sleep

Chapter 3 focuses on the energy saving in Central Offices (CO) of EλAN by using network virtualization [3-1] [3-2] [3-3]. L-OLT migration is proposed to realize selective OLT sleep in EλAN, which supports multiple services on a single network system. An Integer Linear Programming (ILP) model for obtaining the optimal placement of L-OLTs is also proposed. Simulation results show that the number of P-OLTs in sleep mode increases 16.7% on average and 35.8% at a maximum by executing the L-OLT placement optimization periodically. In addition, the communication suspension time caused by L-OLT migration is investigated. Simulation results show that the communication suspension time can be reduced to 57 milliseconds without degrading the energy efficiency and reduced to 10 milliseconds at the cost of making two more active P-OLTs.

3.1 Chapter introduction

As mentioned in Chapter 1, the power consumption of network equipment is increasing sharply. About 60–80% of the power consumption of the current IP network comes from the access network area. To tackle this problem, there have been various approaches for realizing high energy efficiency in the optical access network. The expansion of the network coverage, i.e., the metro/access integration, is one of these approaches. By reducing the number of network equipments, not only CapEx and OpEx but also power consumption are reduced. The improvement in device technology reduces the power consumption of network equipments themselves. The sleep mode in ONUs is another effective approach since the number of deployed ONUs is very large.

To reduce the power consumption further, this Chapter 3 proposes the energy saving technique that exploits the network virtualization in the optical metro/access integrated network [3-1] [3-2] [3-3]. The proposed method realizes the selective OLT sleep among coordinated COs in the multi-service network environment, such as EλAN. As mentioned in 2.3.3, the total power consumption of OLTs accounts for a small percentage of that of the access network area at the present time. However, the power consumption of OLTs is considerable for network operators since OLTs are deployed in their COs, while ONUs are deployed in subscribers' premises. In addition, the power consumption of OLT per unit is much larger than that of ONU.

In contrast with the related research in 2.3.3, network traffic of different services cannot be aggregated in a single L-OLT in EλAN. In the proposal, L-OLTs of each service are migrated between P-OLTs like virtual machines in a data center. Energy saving is achieved by aggregating L-OLTs within a limited number of P-OLTs and making unused P-OLTs sleep. Although the possibility of L-OLT migration in EλAN has already been suggested prior to this research [3-4][3-5], there have been no studies about the detail. This research presents the migration procedure including cooperation between P-OLTs for the first time, and proposes a calculation model for obtaining the placement of L-OLTs that minimizes the number of running P-OLTs.

Communication between P-OLT and P-ONU is suspended temporarily when L-OLT migration is performed since the migration procedure includes reconfigurations of an L-OLT and an access path. Therefore, the impact of the communication suspension on provided services has to be clarified. In the latter part of this Chapter, the communication suspension time caused by L-OLT migration is discussed. Several versions of L-OLT migration procedure are presented and the difference in energy saving effect is evaluated.

The rest of this chapter is organized as follows. An overview and a procedure of L-OLT migration are introduced in Section 3.2. After that, L-OLT placement optimization problem is proposed as an ILP model in Section 3.3. Communication suspension time caused by L-OLT migration is discussed in Section 3.4. Energy saving effect of L-OLT placement optimization is evaluated by using the ILP model in Section 3.5. Finally, this chapter is concluded in Section 3.6.

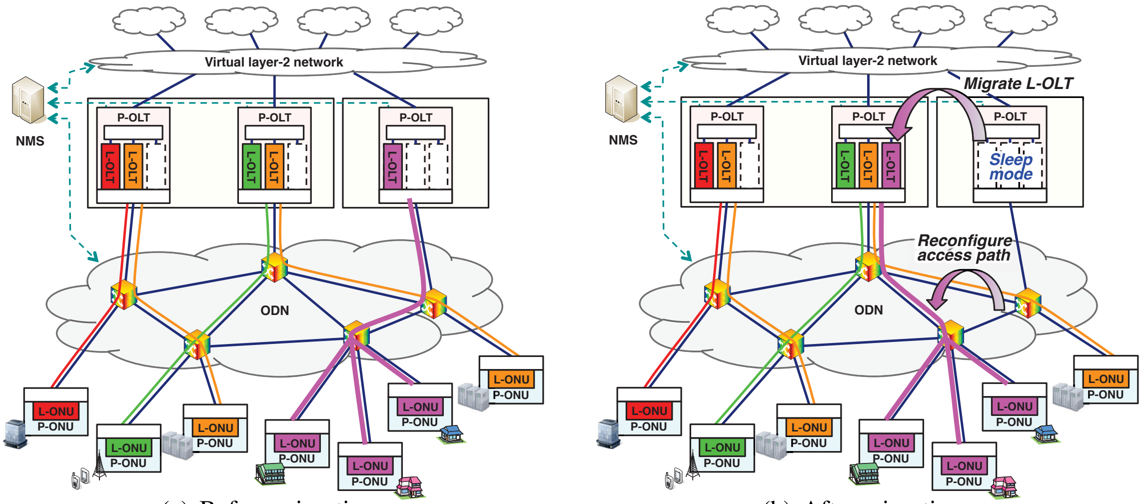
3.2 Logical OLT migration

3.2.1 Overview

L-OLT migration is proposed to achieve more flexible utilization of P-OLTs in EλAN [3-1] [3-2]. Figure 3.1 shows the image of L-OLT migration. In the migration procedure, a L-OLT is replicated from one P-OLT to another P-OLT as directed by NMS. NMS also reconfigures the virtual layer-2 network and ODN at the same time so that data frames are transferred via the newly-replicated L-OLT. An access path on ODN is reconfigured according to the replication of L-OLT. Frequency slots that are allocated to the access path may be changed. As a result, subscribers continue to receive the same network service via the other P-OLT. The unused L-OLT in the original P-OLT is released after finishing L-OLT migration.

3.2.2 Advantages of L-OLT migration

There are some advantages to implementing L-OLT migration in EλAN. The most notable merit is the energy saving effect in COs in proportion as the daily traffic fluctuation. Figure 3.2 shows the concept of L-OLT migration for energy saving. L-OLTs are aggre-



(a) Before migration. (b) After migration.

Figure 3.1: Image of L-OLT migration.

gated into a limited number of P-OLTs when the total traffic amount is low. By making unused P-OLTs sleep, the network operator can reduce total power consumption. The power consumption of an P-OLT decreases when it has no active L-OLTs. This is because not only configuration boards but also common blocks such as a main board and a layer-2 switch can be placed into sleep mode. Note that the actual power consumption of a P-OLT depends on its implementation method.

Another merit is the improvement in fault tolerance. When a failure occurs in a P-OLT or optical devices on an access path, P-ONUs under the P-OLT become unable to receive network services. If the control line between NMS and P-OLTs is still alive, NMS searches for another P-OLT that can support an access path to these P-ONUs. Then NMS switches the L-OLTs from the faulty P-OLT to the other P-OLT which recovers the connections.

In this chapter, L-OLT migration under the energy saving scenario is focused mainly.

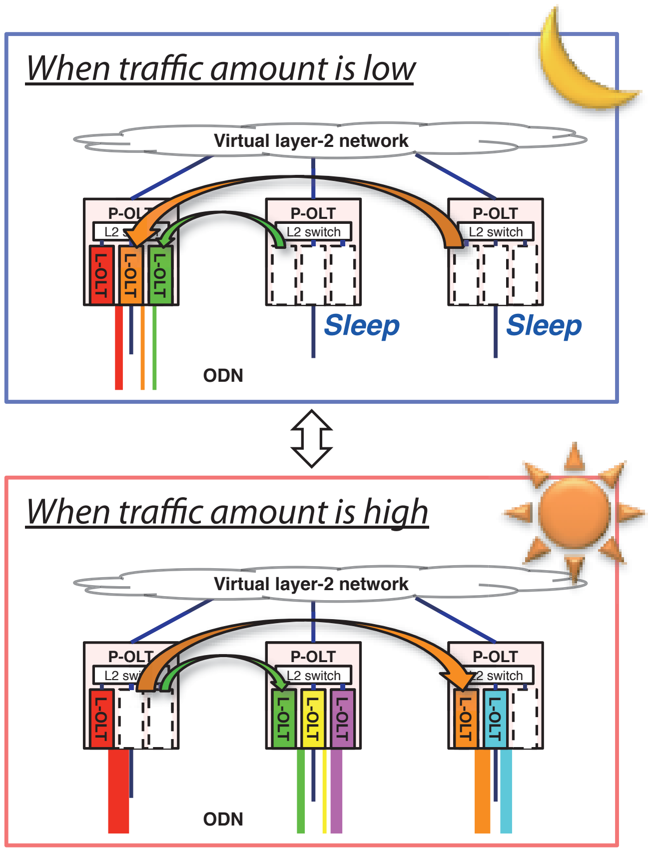


Figure 3.2: Concept of L-OLT migration for energy saving.

3.2.3 L-OLT migration procedure

Figure 3.3 shows the original L-OLT migration procedure proposed in [3-2]. In Fig. 3.3, L-OLT migration between two P-OLTs (from P-OLT(origin) to P-OLT(destination)) is illustrated. Related actions including computation of a new L-OLT placement and sleep of an unused P-OLT are also shown.

(a) Each P-OLT reports the number of active L-OLTs and the number of frequency slots requested from each L-OLT to NMS periodically. Based on these reports, NMS computes a new placement of L-OLTs. If the new placement obtained by the computation is different from the current placement, optimization of the L-OLT placement is triggered.

(b) NMS sends MAC/PHY parameters and slot allocation of the original L-OLT in P-OLT(origin) to P-OLT(destination). P-OLT(destination) starts to configure a replica of the original L-OLT on its configuration board. P-OLT(destination) also tunes its transponders. In addition, NMS directs the original L-OLT and L-ONUs under the L-OLT to stop data sending. The original L-OLT waits to finish sending data frames in its downstream buffer. NMS also sends new MAC/PHY parameters and slot allocation to the L-ONUs. The L-ONUs start to buffer upstream data frames and tune their transponders. P-OLT(destination) inherits the information of the original L-OLT such as MAC addresses of the L-ONUs and bandwidth allocation from P-OLT(origin).

(c) NMS reconfigures the virtual layer-2 network so that downstream data frames are sent to P-OLT(destination). The newly-generated L-OLT in P-OLT(destination) buffers downstream data frames. On the other hand, as soon as the original L-OLT finishes sending data frames in its downstream buffer, the original L-OLT reports it to NMS. Then NMS reconfigures access paths on ODN that connects the newly-generated L-OLT and the L-ONUs. NMS directs the newly-generated L-OLT and the L-ONUs to restart data sending.

(d) (b) and (c) are iterated until the placement of L-OLTs becomes optimized. After that, unused P-OLT(origin) goes into sleep mode.

3.3 L-OLT placement optimization problem

To achieve energy saving by L-OLT migration and selective OLT sleep, the L-OLT placement optimization problem is modeled as an ILP problem [3-2][3-3]. Figure 3.4 shows the image of L-OLT placement optimization problem. In this problem, the optimal state is defined as that the number of running P-OLTs (i.e., P-OLTs that have one or more

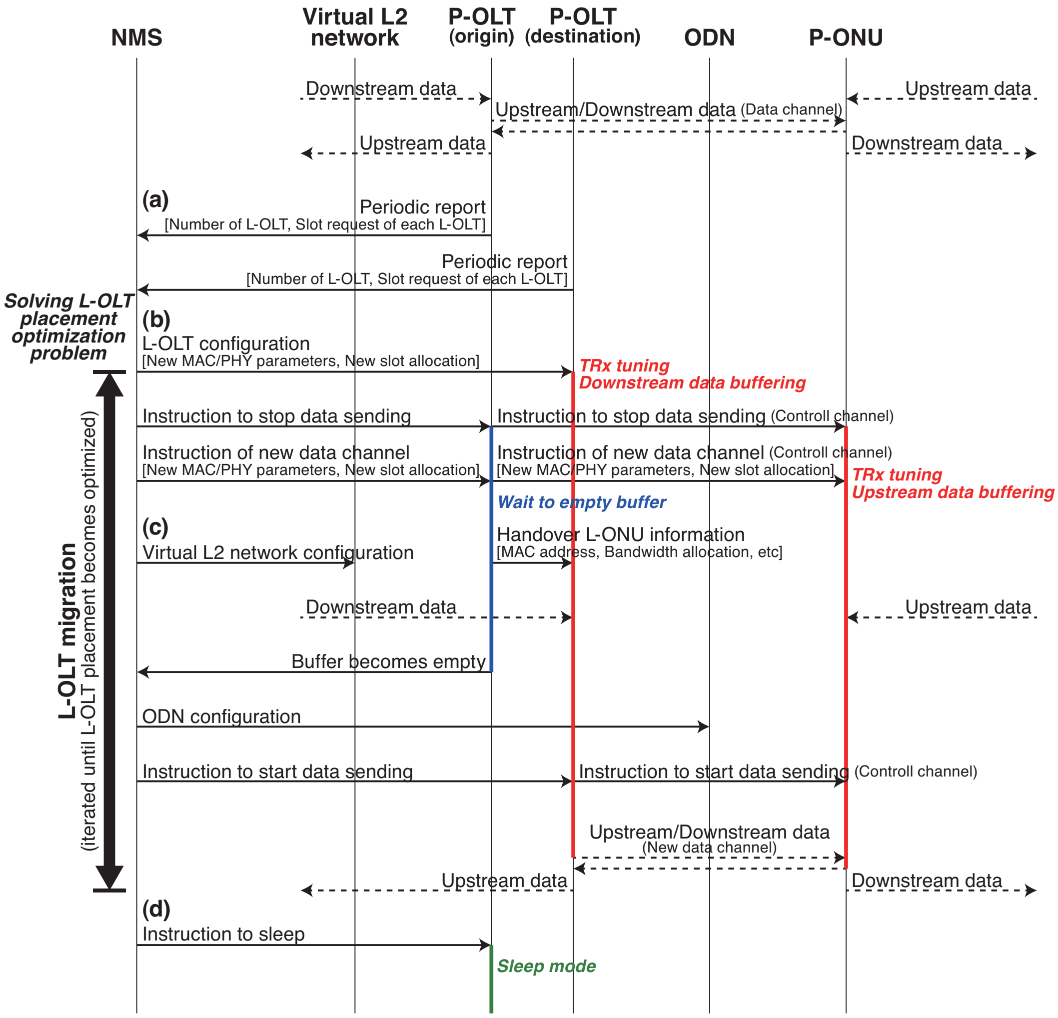


Figure 3.3: Original procedure of L-OLT migration.

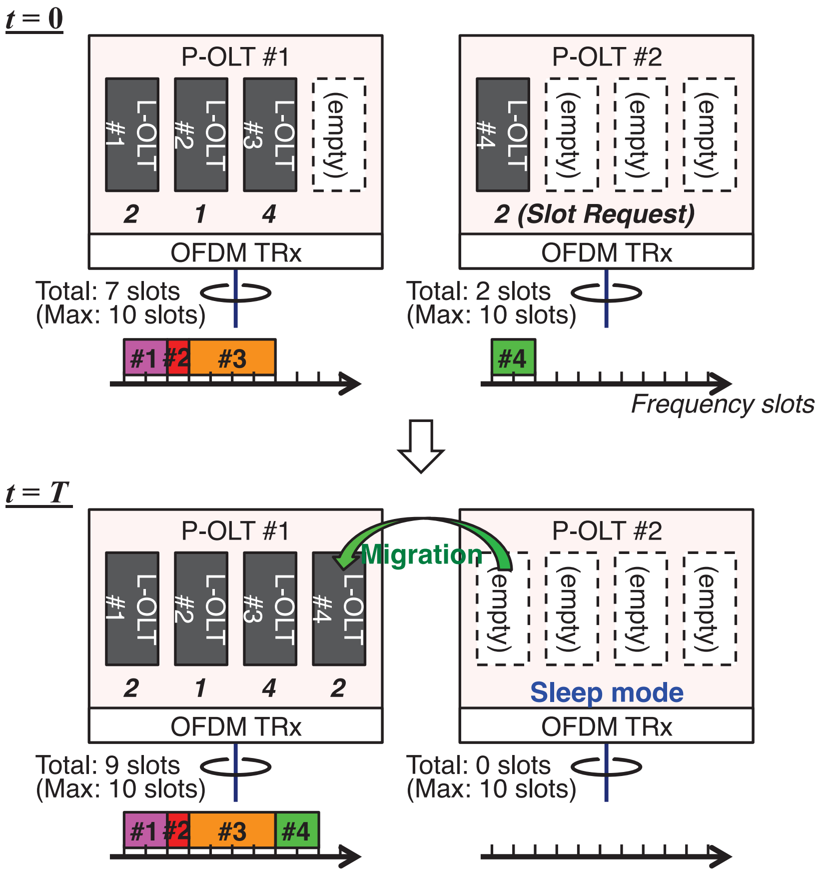


Figure 3.4: Image of L-OLT placement optimization problem.

active L-OLTs) is minimized while providing all services required from subscribers. As mentioned in 3.2.2, the power consumption of a P-OLT surely decreases when it has no active L-OLTs since functional blocks shared by multiple L-OLTs can sleep. The use of flexible grid technology is assumed in this problem. Input parameters are the current placement of L-OLTs and route and frequency slot allocation of access paths for each L-OLT.

Two models of the L-OLT placement optimization problem are used for evaluation in Section 3.5. One model does not include constraints of ODN, and assumes that ODN is non-blocking. Routing and Spectrum Allocation (RSA) for each L-OLT is not considered in this model. Defragmentation of allocated frequency slots is assumed to be finished just before executing L-OLT placement optimization. The other model includes ODN constraints and considers RSA for each L-OLT. This model obtains not only the L-OLT placement, but also routes and frequency slot assignments of access paths from decision variables. The objective function is common between both models.

Note that this L-OLT placement optimization problem only decides bandwidth allocation on the frequency axis, and does not decide that on the time axis shown in Fig. 2.16. Time slot allocation is executed independently between an L-OLT and L-ONUs of a point-to-multipoint service after establishing an access path between them. A DBA algorithm that is used in the conventional PON system is applicable. The modulation format of OFDM subcarriers is assumed to be decided in advance and not taken into account in this problem.

3.3.1 Model description

An ILP model of L-OLT placement optimization problem is presented as below. The detailed mathematical formulation is described in Appendix A.

Definition of symbols

Table 3.1 defines the symbols for L-OLT placement optimization problem. Symbols flagged with an asterisk (*) are used only in the ILP model with ODN constraints.

In this problem, n_{POLT} P-OLTs, n_{PONU} P-ONUs, and ODN consisting of links and n_{WXC} WXCs are taken into account. The term "node" includes P-OLTs, P-ONUs, and WXCs. The existence of a unidirectional link that connects node α to node β is represented by $e_{\alpha\beta}$.

Each P-OLT has b L-OLT configuration boards. n_{LOLT} ($\leq n_{\mathrm{POLT}} \times b$) L-OLTs are configured in several configuration boards at P-OLTs. L-OLT i requests w_i ($1 \leq w_i \leq c$) frequency slots to provide a network service. In this model, it is assumed that the value

Table 3.1: Definition of symbols for L-OLT placement optimization problem.

Given parameters

n_{POLT}	Number of P-OLTs
n_{LOLT}	Number of L-OLTs
b	Number of L-OLT configuration boards per P-OLT
c	Number of total frequency slots
w_i	Number of frequency slots that L-OLT i requires
T	Maximum number of steps of L-OLT migration
r	Maximum rate of allocated frequency slots at each P-OLT ($0 < r \leq 1$)
(*) n_{PONU}	Number of P-ONUs
(*) n_{WXC}	Number of WXCs
(*) d	Maximum distance (links) of access path
(*) G	Number of guardband slots
(*) M	A large positive constant
(*) x_{ij}^{LONU}	1 if L-ONU that receives a network service from L-OLT i is configured in P-ONU j; 0 otherwise
(*) $e_{\alpha\beta}$	1 if link that connects node α to node β exists; 0 otherwise

Decision variables (Values at $t = 0$ are given)

$x_{ijk}^{\text{LOLT}}(t)$	1 if configuration board k of P-OLT j is allocated to L-OLT i after tth step; 0 otherwise
$y_j(t)$	1 if P-OLT j is running after the tth step; 0 otherwise
$Z_{ijk}^{\text{IN}}(t)$	1 if L-OLT i is migrated to configuration board k of P-OLT j at the tth step; 0 otherwise
$Z_{ijk}^{\text{OUT}}(t)$	1 if L-OLT i is migrated from configuration board k of P-OLT j at the tth step; 0 otherwise
(*) $p_{\alpha\beta ih}(t)$	1 if link (α, β) is selected as the hth hop of access path that starts from L-OLT i after the tth step; 0 otherwise
(*) $q_{\alpha\beta im}(t)$	1 if frequency slot m is allocated to access path that starts from L-OLT i on link (α, β) after the tth step; 0 otherwise

of w_i does not change before and after optimization.

Each P-ONU has a single configuration board in this model. If there are P-ONUs under one optical splitter, these P-ONUs are regarded as a single P-ONU that has multiple L-ONUs. The configuration of a L-ONU in each P-ONU is represented by x_{ij}^{LONU}.

WXCs are assumed to be bandwidth-variable (i.e., BV-WXC) and multicast-capable in this model. Tree-like access paths can be set on ODN for point-to-multipoint services.

An access path is set between corresponding P-OLT and P-ONU(s). Only unidirectional (downstream) access paths are considered in this model.

Maximum number of steps of L-OLT migration, T, is usually set to $T = 1$. In this case, $t = 0$ represents the state before optimization, and $t = 1$ represents the state after optimization. Multiple L-OLTs can be migrated at one step as long as their destinations are not overlapped each other.

Maximum rate of allocated frequency slots at each P-OLT, r, can be set to less than 1 when the network operator limits the number of allocatable frequency slots to $r \times c$. By having vacant frequency slots at a time of L-OLT placement optimization, the network operator can be deal with increase of required frequency slots from L-OLTs between executions of the optimization.

Maximum distance (links) of access path, d, is introduced to avoid setting unnecessary long access paths on the ODN. Guardband slots, G, are inserted between adjacent sets of frequency slots that are allocated to different access paths to separate them reliably at each WXC and receiver.

Six binary decision variables are defined in this ILP model. $x_{ijk}^{\mathrm{LOLT}}(t)$ represents the placement of each L-OLT in configuration boards. $y_j(t)$ represents the operational status (active or sleeping) of each P-OLT. $Z_{ijk}^{\mathrm{IN}}(t)$ and $Z_{ijk}^{\mathrm{OUT}}(t)$ represent the migration movement of L-OLTs among configuration boards. $p_{\alpha\beta ih}(t)$ represents the allocation of links to each access path. $q_{\alpha\beta im}(t)$ represents the allocation of frequency slots in each link to each access path. Note that values of each decision variable at $t = 0$ are given as input parameters.

This ILP model also can be applied to a WDM-based system in addition to an optical OFDM-based system. In this case, c means the number of total wavelengths and w_i is set as $w_i = 1$ for all L-OLTs. The number of guardband slots is set to $G = 0$ since wavelengths are allocated to each L-OLT according to a fixed frequency grid.

Objective function

The objective of this ILP model is to obtain the placement of L-OLTs that minimizes the number of running P-OLTs. If multiple solutions that minimize the number of running P-OLTs are found, the solution that minimizes the number of L-OLTs that have to be migrated is chosen. This is to reduce network resources that are needed to execute the optimization. In the equation of objective function presented in Section A.1, the number of migrated L-OLTs is placed in the second term. This term does not affect the main objective (i.e., minimization of the number of running P-OLTs) since a small number ϵ is multiplied.

Constraints

The constraints of this ILP model are as follows. In this problem, at most one L-OLT occupies a single configuration board in a running P-OLT. In a single step of L-OLT migration, at most one L-OLT is migrated to/from a configuration board. The total number of allocated frequency slots on each running P-OLT is less than or equal to $r \times c$ at the final state of the L-OLT placement optimization.

In the model with ODN constraints, constraints related to the route and frequency slot allocation to access paths are added. A P-OLT that has one or more active L-OLTs becomes the starting point of an access path. An egress link of this P-OLT is selected as the first hop of the access path. In contrast, a P-ONU that has an active L-ONU becomes the end point of an access path. The route of the access path is decided to reach the P-ONU within d hops. WXCs switch or split optical signals at the granularity of frequency slots. Routes and frequency slot allocations of each access path are decided so as to guarantee the spectrum continuity and the spectrum contiguity [3-6]. The spectrum continuity means that same frequency slots are allocated to all links on an access path. The spectrum contiguity means that a series of contiguous frequency slots is allocated to an access path. Access paths do not make a loop on ODN. In addition, guardband slots are set in all links on ODN.

3.4 Communication suspension time by L-OLT migration

In this section, the communication suspension time caused by L-OLT migration is discussed. In this discussion, the ILP model with ODN constraints is used.

To control the total power consumption of P-OLTs according to traffic fluctuation, the L-OLT placement should be reoptimized periodically (e.g., once every hour). However, communication between P-OLT and P-ONU is suspended temporarily in the migration procedure to allow L-OLT configuration, access path setting, and the tuning of P-OLT and P-ONU transponders. If the communication suspension time exceeds the timeout value of an upper-layer protocol, subscribers experience an interruption of network service.

One of the general methods to avoid service interruption is to set two independent access paths between P-OLT and P-ONU and implement hitless switching. In the conventional PON system, this type of redundancy is available on type C protection configuration in the ITU-T Recommendation [3-7] (See also 2.4.1). Two independent access paths can be configured more easily in EλAN than in the PON system since ODN connects multiple P-OLTs and P-ONUs. However, P-ONU cost becomes high since each P-ONU must have at least two transponders to configure this redundancy. This is a disadvantage for accommodating residential Internet subscribers since they are very cost-conscious but are expected to be a major service in EλAN.

On the basis that EλAN accommodates P-ONUs with single transponders, an L-OLT migration procedure that reduces communication suspension time is discussed instead of hitless switching in this section. When the sequence of L-OLT migration is modified, additional constraints should be taken into account in the process of deciding the L-OLT placement and access paths. The degradation in energy efficiency caused by these additional constraints is also explained.

3.4.1 Analysis of communication suspension time

The time required for finishing individual processes executed during L-OLT migration procedure is estimated to clarify the bottleneck. The L-OLT migration procedure includes following processes;

- Setting access path on ODN
- Configuring L-OLT in the destination P-OLT
- Tuning transponder of the destination P-OLT
- Tuning transponders of P-ONUs
- Re-ranging between the destination P-OLT and each P-ONU

Setting access path

In this process, an access path that has been set between the original P-OLT (P-OLT that the L-OLT is migrated from) and P-ONUs is reconfigured so as to connect the destination P-OLT (P-OLT that the L-OLT is migrated to) and P-ONUs. Setting time of the access path depends on that of the ODN optical devices, especially BV-WXCs. Liquid Crystal on Silicon (LCOS) technology is widely utilized to realize high-granularity wavelength selective switching in a BV-WSS [3-8]. To the best of the author's knowledge, current commercialized LCOS-based BV-WSS products take hundreds of milliseconds for configuration. For example, the response time of 103 milliseconds has been reported in [3-9], and setting time of 500 milliseconds has been specified in a product brief [3-10]. However, it has been mentioned that the response time of LCOS can be reduced to 50 milliseconds if the condition of the liquid crystal is optimally controlled [3-9]. Considering the development of LCOS technology in the near future, the access path setting time is assumed to be 50 milliseconds in this discussion.

Configuration of L-OLT

In this process, an L-OLT is replicated from the original P-OLT to the destination P-OLT under the direction of NMS. Configuration time of FPGAs on a L-OLT configuration board varies according to product specifications and circuit design. One of the candidate FPGAs that is planned to utilize for implementation in EλAN project takes at least 857 or 107 milliseconds (depending on configuration scheme) to configuration [3-11]. Considering the worst-case scenario that full reconfiguration of FPGA is required, the L-OLT configuration time is assumed to be one second in this discussion. There is a possibility that the required time becomes shorter by using partial reconfiguration of FPGA or configuring functions of multiple services in advance.

Tuning transponders of P-OLT and P-ONUs

Transponders of a P-OLT and P-ONUs have to change transmitting and receiving frequency slots if different frequency slots are allocated to a new access path. In the latest research, a λ-tunable transponder for WDM/TDM-PON that tunes within 3 milliseconds has been reported [3-12]. In the case of using optical OFDM, modulation format and the number of subcarriers may also need to be changed. However, it is estimated that changing these parameters takes less than a microsecond. In this discussion, the tuning time of transponders is assumed to be 3 milliseconds.

Re-ranging

In the commercialized PON systems such as E-PON series [3-13][3-14] and GPON series [3-15][3-16], RTTs between an OLT and each ONU are measured to avoid collisions of upstream data frames. This is called ranging procedure. An OLT executes ranging when the OLT discovers and registers a newly-connected ONU. After ONU registration, the OLT updates RTT information continuously by exchanging control messages (GATE and REPORT in E-PON series, Ranging request and Ranging transmission in GPON series).

In the case of EλAN, ranging is executed when a point-to-multipoint type service is provided from a L-OLT. Re-ranging between a P-OLT and P-ONUs becomes necessary when L-OLT migration is executed since the distance and frequency slots of the access path change. To the best of author's knowledge, ranging takes less than 10 milliseconds even on the long-reach optical access network system that accommodate more ONUs than today's commercialized PON systems. For example, paper [3-17] has reported an OLT that measures RTTs to 1024 ONUs in approximately 7 milliseconds from cold start in a long-reached XG-PON system. In this discussion, the time required for re-ranging is assumed to be 7 milliseconds.

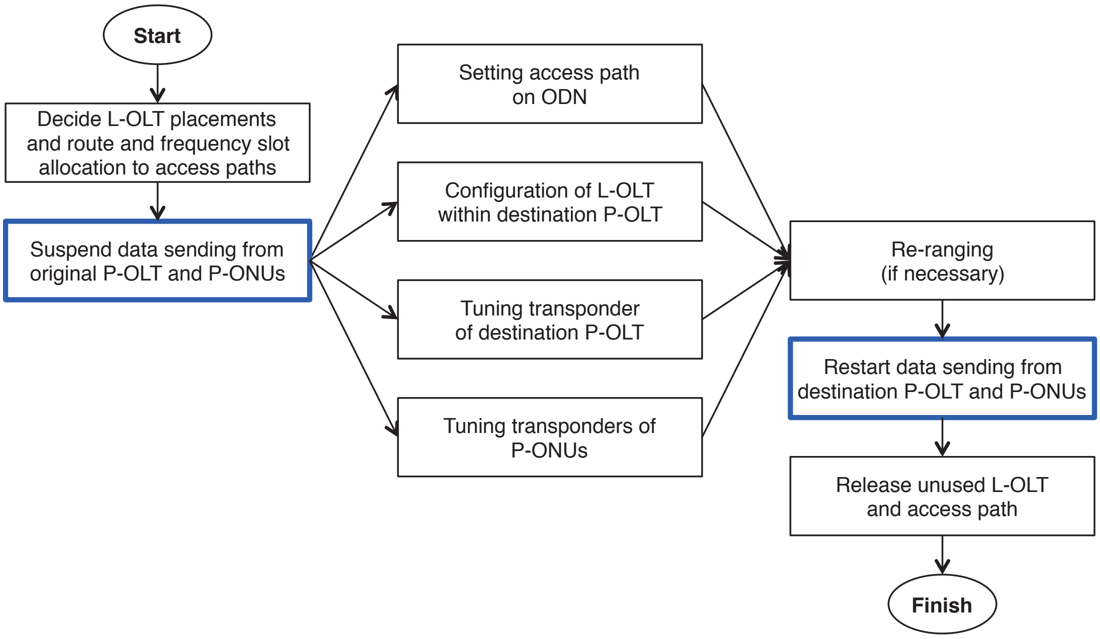


Figure 3.5: L-OLT migration procedure without additional constraints.

3.4.2 Logical OLT migration procedure to reduce communication suspension time

From the analysis in 3.4.1, it is revealed that L-OLT configuration is the biggest bottleneck (1 s) in L-OLT migration procedure. When the communication suspension time due to L-OLT migration becomes excessive, subscribers may experience an interruption of network service. Therefore, the procedure of L-OLT migration has to be organized so as not to cause service interruptions. The first target is the timeout value of MPCP messages in E-PON series that is defined as one second. Another target is the service halt time of PON protection in the ITU-T Recommendation [3-7] that is defined as 50 milliseconds.

Figure 3.5, 3.6, and 3.7 show several versions of L-OLT migration procedure. The procedure shown in Fig. 3.3 corresponds to Fig. 3.6.

Figure 3.5 shows the basic procedure of L-OLT migration. First, NMS computes the L-OLT placement, routes of access paths, and frequency slots of access paths. Second,

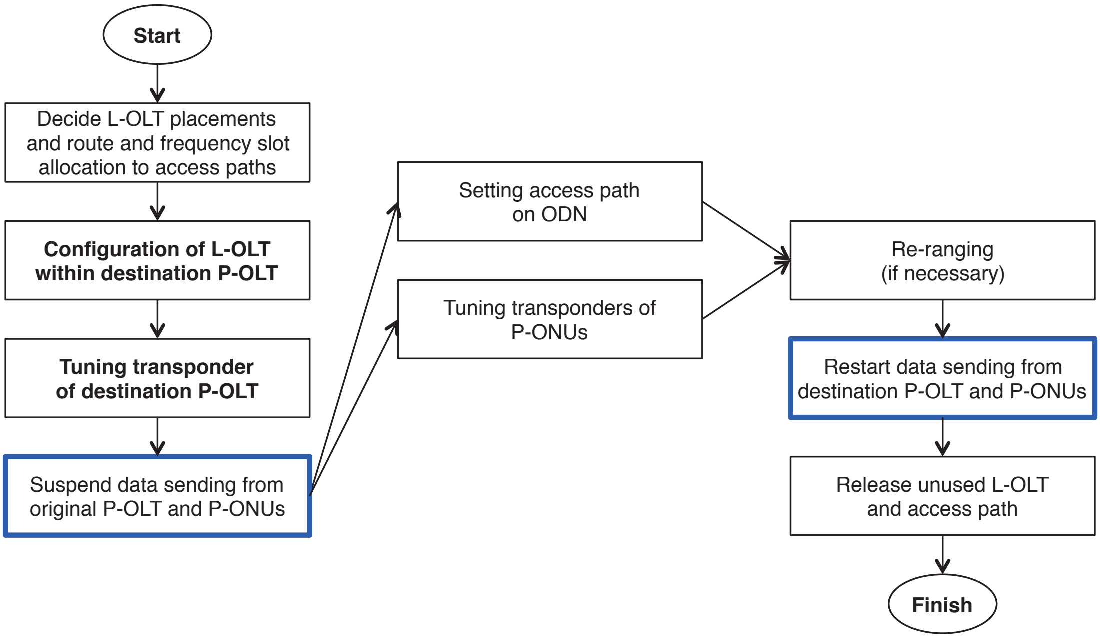


Figure 3.6: L-OLT migration procedure configuring L-OLT in advance of suspension of data sending.

NMS instructs the original P-OLT and P-ONUs to suspend sending data frames/ After that, following processes are executed.

- Setting access path on ODN
- Configuring L-OLT in the destination P-OLT
- Tuning transponder of the destination P-OLT
- Tuning transponders of P-ONUs

After finishing these processes, re-ranging is executed between the destination P-OLT and each P-ONU if a point-to-multipoint type service is provided from the migrated L-OLT. Finally, the destination P-OLT and P-ONUs restart the sending of data frames. The unused L-OLT in the original P-OLT and the unused access path are released.

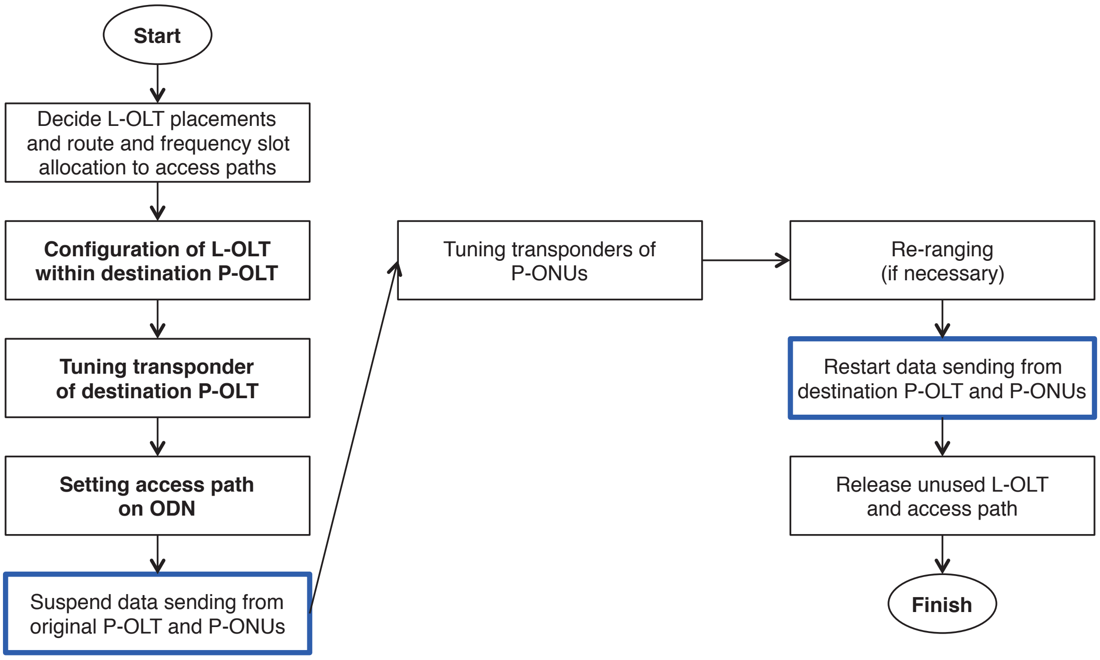


Figure 3.7: L-OLT migration procedure configuring L-OLT and access path in advance of suspension of data sending.

In the procedure of Fig. 3.5, the communication suspension time is the sum of L-OLT configuration time (1 s) and re-ranging time (7 ms). Therefore, the total communication suspension time goes over the timeout value of MPCP messages. That means, L-ONUs are deregistered every time L-OLTs are migrated when an Internet access service based on E-PON is provided on EλAN.

Figure 3.6 shows the procedure that configures L-OLT and tunes transponder of P-OLT in advance of suspension of data sending. In this procedure, the biggest bottleneck during suspension of data sending is moved to access path setting. The communication suspension time of this procedure is the sum of access path setting time (50 ms) and re-ranging time (7 ms). Therefore, the total suspension time is reduced to 57 milliseconds in total. This value satisfies the timeout value of MPCP messages (1 s).

Figure 3.7 shows the procedure that sets the access path in advance of suspension of data sending additionally. The communication suspension time of this procedure is the sum of tuning time of transponders of P-ONUs (3 ms) and re-ranging time (7 ms). Therefore, the total suspension time is reduced further to 10 milliseconds in total. This value satisfies the service halt time of PON protection (50 ms). Tuning the P-ONU transponders and re-ranging have to be executed during the suspension of data sending since P-ONUs with a single transponder are assumed in this discussion.

By applying these modified migration procedures in Fig. 3.6 and 3.7, communication suspension time is reduced drastically. However, when L-OLT configuration and access path setting are executed in advance of suspension of data sending, constraints are added to the ILP model. Therefore, the energy saving effect might degrade due to these additional constraints.

Constraint for in-advance L-OLT configuration If L-OLT configuration is executed in advance of suspension of data sending, the L-OLT must be replicated on an idle configuration board in another P-OLT; configuration boards on which the L-OLT can be replicated are limited. More specifically, it is forbidden to release an existing L-OLT and reconfigure another L-OLT on a single configuration board at the same time (See Eq. (A.37) in Appendix A for detail).

Constraint for in-advance access path setting If access path setting is executed in advance of suspension of data sending, the new access path must be configured so as not to interrupt existing access paths, including the access path belonging to the L-OLT that is going to be migrated. More specifically, it is forbidden to change input port and output port of frequency slots that are already allocated to any access path in each BV-WXC (See Eq. (A.38)–(A.41) in Appendix A for detail). Due to this constraint, different frequency slots are inevitably allocated to the new access path.

3.5 Performance evaluation and discussion

In this section, the energy saving effect of the L-OLT placement optimization is evaluated. The ILP model without ODN constraints is used to evaluate the energy saving effect according to traffic fluctuation in 3.5.1. The ILP model with ODN constraints is used to discuss the trade-off between energy efficiency and communication suspension time triggered by L-OLT migration in 3.5.2.

3.5.1 Energy saving effect of L-OLT placement optimization

First, the energy saving effect according to traffic fluctuation is evaluated by computation simulation. In this simulation, the ILP model without ODN constraints is used to obtain the optimized L-OLT placement. P-OLT sleeping rate is used as an indicator of the energy saving effect since the actual power consumption of a P-OLT depends on its implementation method. Equation (3.1) is the definition of the P-OLT sleeping rate.

$$\text{P-OLT sleeping rate} = \frac{\text{Number of P-OLTs having no active L-OLTs}}{\text{Total number of P-OLTs}} \tag{3.1}$$

Simulation environment

Table 3.2 shows the simulation parameters used in this evaluation.

In this simulation, the optimization of L-OLT placement is executed among 16 P-OLTs. All of c frequency slots can be used efficiently when the number of L-OLT configuration boards per P-OLT b satisfies the following Eq. (3.2).

$$\frac{c}{w_{\max}} \leq b \tag{3.2}$$

Here, $w_{\max}$ is the maximum number of frequency slots that each L-OLT requests. However, the increase in b is expected to raise implementation cost of P-OLTs. In this simula-

Table 3.2: Simulation parameters in evaluation of energy-saving effect of L-OLT placement optimization.

Network architecture

Number of P-OLTs n_{POLT}	16
Number of L-OLT configuration boards per P-OLT b	8
Number of total frequency slots c	192
Maximum number of steps of L-OLT migration T	1
Maximum rate of allocated frequency slots at each P-OLT r	0.8
Maximum number of L-ONUs that a single L-OLT accommodates (P2MP service)	256
Number of L-ONUs that a single P-ONU configures	1

Connection requests from P-ONUs

Fluctuation of connection request rate	
Pattern of fluctuation	Sinusoidal pattern (24-hour cycle)
Fluctuation range	Average connection request rate ± 80% (See Fig. 3.8)
Average connection request arrival rate (Poisson arrival)	
P2P service	7 requests per hour
P2MP service	127 requests per hour
Mean holding time (Exponential distribution)	
P2P service	12 hours
P2MP service	2 hours
Number of required frequency slots (Unidirectional)	
P2P service	1 – 12 (Change randomly every hour)
P2MP service	1 (Shared by 256 L-ONUs at a maximum)

Trial conditionss

Interval of executing optimization	1, 2, 4, 6 hours
Simulation time section	168 hours
Number of trial per condition	40 times

tion, the number of L-OLT configuration boards per P-OLT *b* is set to 8. The number of L-ONUs that a single P-ONU configures is set to 1. That means, a single P-ONU could request only a single service in this simulation.

Two types of network services are assumed; Point-to-Point type (P2P) and Point-to-Multipoint type (P2MP). The P2P service is characterized by long mean holding time and fluctuation of the number of requested frequency slots. The same number of frequency slots is requested in upstream and downstream of a service. When a connection request of P2P service is arrived, a single L-OLT is generated and allocated to the requesting L-ONU. The generated L-OLT is preferentially configured in a running P-OLT. On the other hand, the P2MP service is characterized by short mean holding time and sharing a single frequency slots in each direction by 256 L-ONUs at a maximum. When a connection request of P2MP service is arrived, an existing L-OLT that could accommodate more L-ONUs at that time is allocated to the requesting L-ONU. If there are no such L-OLTs, a single L-OLT is newly generated and preferentially configured in a running P-OLT.

Connection request rate from P-ONUs is assumed to fluctuate sinusoidally on a daily basis as shown in Fig. 3.8. The ratio of the average connection request rate of P2P and P2MP service is set by reference to the ratio of subscribers of private line (including IP-VPN and wide-area Ethernet) and FTTH [3-18].

Interval of executing L-OLT placement optimization is set to one, two, three, and six hours. These results are compared with the situation that the optimization is not executed. Simulation time section of a single trial is set to 168 hours (one week). Number of trial per condition is set to 40, and the average of 40 trials is calculated as a result.

Simulation results

Figure 3.9 shows the result of the average of P-OLT sleeping rate. The reason why sleeping P-OLTs are appeared even when the optimization is not executed is since newly-

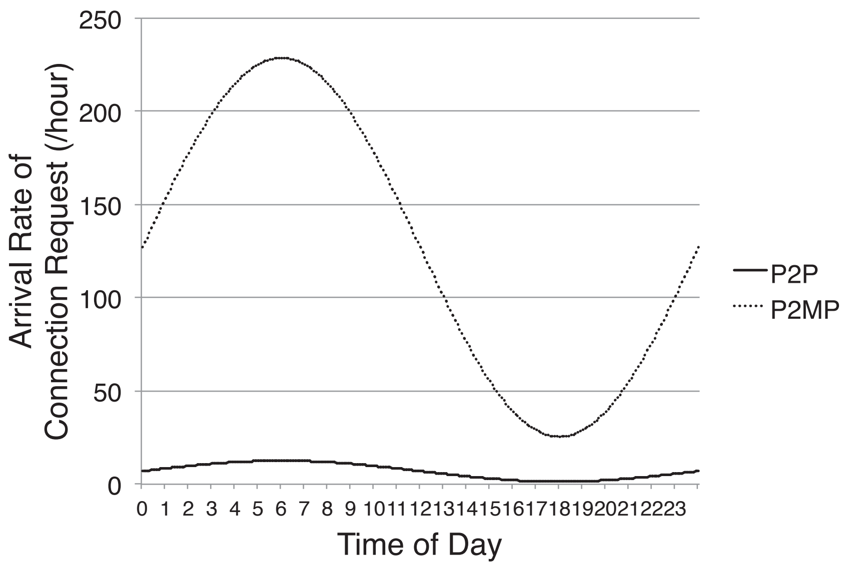


Figure 3.8: Time fluctuation of arrival rate of connection request.

generated L-OLTs are preferentially deployed in a running P-OLT. The P-OLT sleeping rate improves more than 10% by executing the L-OLT placement optimization periodically. When the interval of optimization is set to one hour, the number of P-OLTs in sleep mode increases 16.7% compared to the case without optimization. The difference between 1-hour interval and 6-hour interval is only 3%.

Figure 3.10 shows the hourly fluctuation of P-OLT sleeping rate of a day. The P-OLT sleeping rate increases following the decrease of connection request rate. The difference of P-OLT sleeping rate between optimization intervals is appeared in these hours. When the interval is one hour, P-OLT sleeping rate reaches to 50% at maximum. P-OLT sleeping rate increases by 35.8% compared to the case without optimization.

As mentioned in Section 3.3, the proposed ILP model selects the solution that minimizes the number of migrating L-OLTs when multiple solutions that minimize the number of running P-OLTs are found. The minimization of the number of L-OLT migrations is included in the second term of objective function (See Eq. (A.1a) in Appendix A for

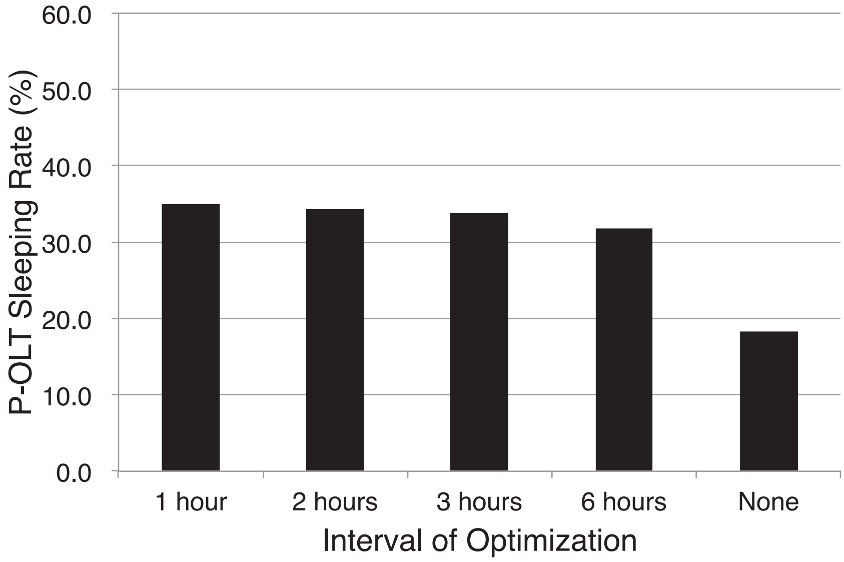


Figure 3.9: Average of P-OLT sleeping rate.

detail). Figure 3.11 shows the total number of L-OLT migrations in 168 hours when the minimization of the number of L-OLT migrations is considered and not considered. The interval of optimization is set to one hour. The total number of L-OLT migrations is reduced by 91% by considering the number of L-OLT migrations in the objective function. Note that the consideration of the number of L-OLT migrations does not affect the minimization of the number of running P-OLTs (the first term of objective function).

Figure 3.12 shows the total number of L-OLT migrations in 168 hours. Figure 3.13 shows the average number of L-OLT migrations per optimization. The total number of migrations decreases when the optimization interval is set longer. However, these parameters are not in inverse relationship. The average number of migrations per optimization increases according to the optimization interval.

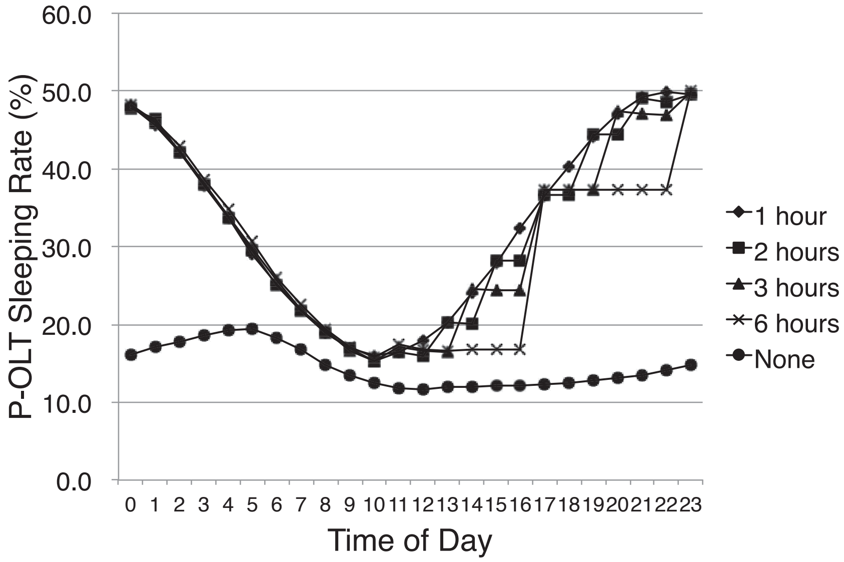


Figure 3.10: Time fluctuation of P-OLT sleeping rate.

3.5.2 Trade-off between energy efficiency and communication suspension time

The impact of the additional constraints introduced in 3.4.2 on the energy saving effect of L-OLT placement optimization is evaluated. The ILP model with ODN constraints is used in this simulation. The number of running P-OLTs is used as the index of energy consumption.

Simulation environment

Figure 3.14 shows the network topology used in this simulation. To simplify the discussion and reduce computation time, WDM-like parameters are used. Table 3.3 summarizes simulation parameters. The simulation network has eight P-OLTs that equip four L-OLT configuration boards each. A single L-OLT occupies a single configuration board in a P-OLT and requires a single wavelength. It is assumed that only point-to-multipoint type

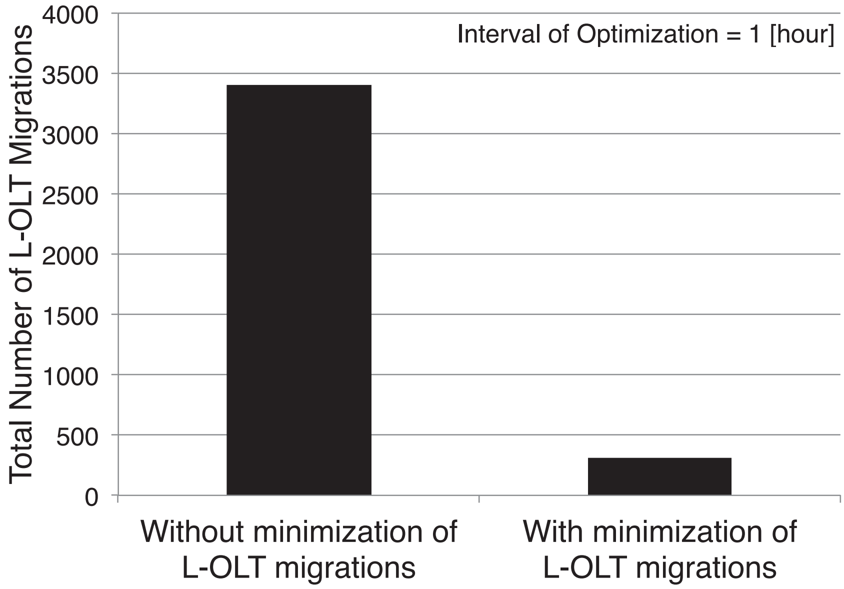


Figure 3.11: Effect of minimization of L-OLT migrations under condition of minimization of running P-OLTs.

services (i.e., residential Internet access) are provided in this simulation. A single L-OLT accommodates up to 64 L-ONUs. ODN consists of four BV-WXCs and bidirectional links. P-ONUs form several ONU groups and connect to the ODN via optical splitters. In this simulation, eight ONU groups are configured and each group includes 256 P-ONUs. Note that P-ONUs under the same optical splitter can be regarded as a single P-ONU having multiple L-ONUs in the ILP model.

The procedure of this simulation is as follows. Constraints described in 3.4.2 are added when in-advance L-OLT configuration and access path setting are applied.

1. P-ONUs that have an active L-ONU are randomly selected
2. Active L-ONUs in ONU group #j belong to L-OLTs configured on P-OLT #j so as to minimize the total number of L-OLTs
3. Initial access paths are set on ODN

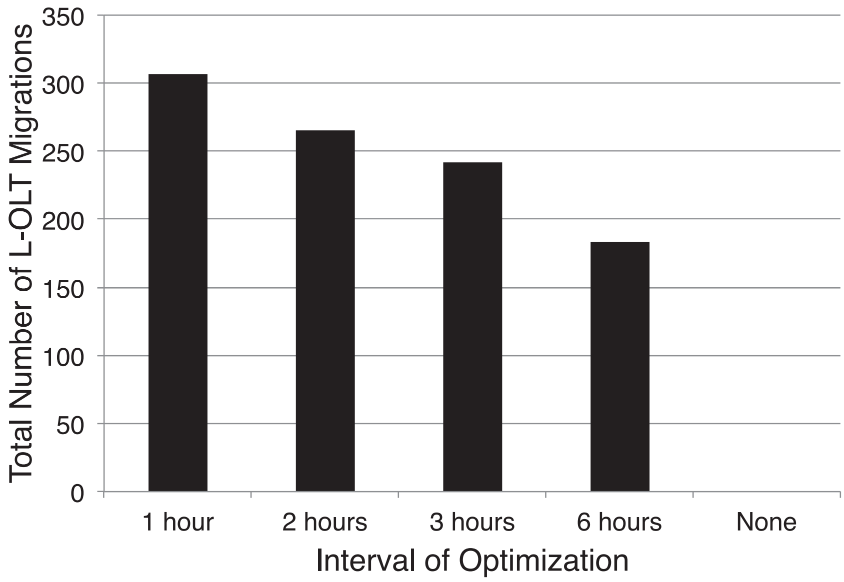


Figure 3.12: Total number of L-OLT migrations.

4. Placement of L-OLTs and the route and wavelength allocation of access paths are optimized by applying three different ILP models
   - With constraints of in-advance L-OLT configuration and access path setting
   - With constraint of in-advance L-OLT configuration
   - No additional constraints
5. The number of running P-OLTs is compared between the results of the three different ILP models

Simulation results

Figure 3.15(a), 3.15(b), 3.15(c) and 3.15(d) are the simulation results when the number of available wavelengths are seven, six, five and four, respectively. Horizontal axis is the ratio of active L-ONUs. Vertical axis is the average number of running P-OLTs obtained from 100 trials.

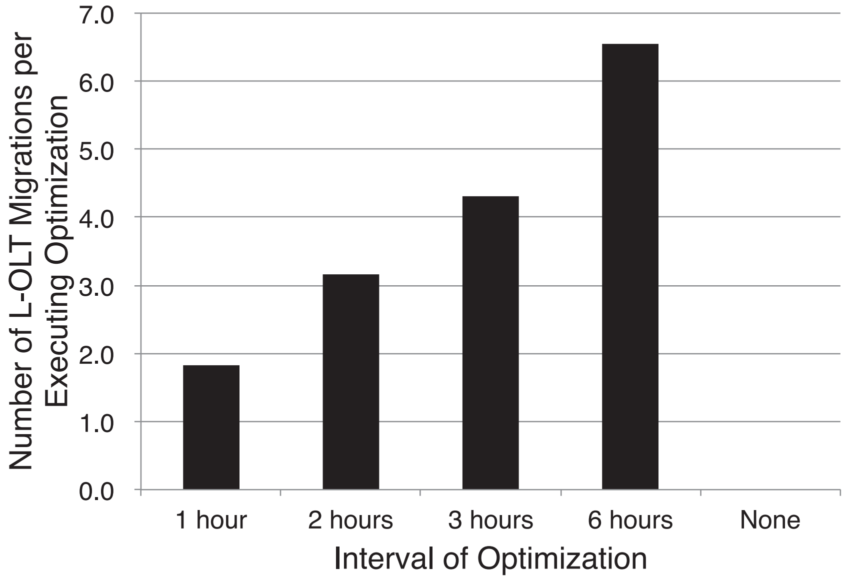


Figure 3.13: Number of L-OLT migrations per executing optimization.

When the number of wavelengths is enough (Fig. 3.15(a)), there is no difference among the three ILP models in the number of running P-OLTs after optimization. However, when the number of wavelengths is limited (Fig. 3.15(b), 3.15(c) and 3.15(d)), the number of running P-OLTs increases when the constraint of in-advance access path setting is added. The impact of the constraint corresponds to just two P-OLTs at a maximum. In other words, communication suspension time is reduced to 10 milliseconds and the switching time of PON protection is satisfied at the cost of making two more active P-OLTs. The impact of the constraint of in-advance L-OLT configuration does not appear in the results. It can be said that the communication suspension time can be reduced to approximately 57 milliseconds without degrading the energy efficiency in this simulation environment.

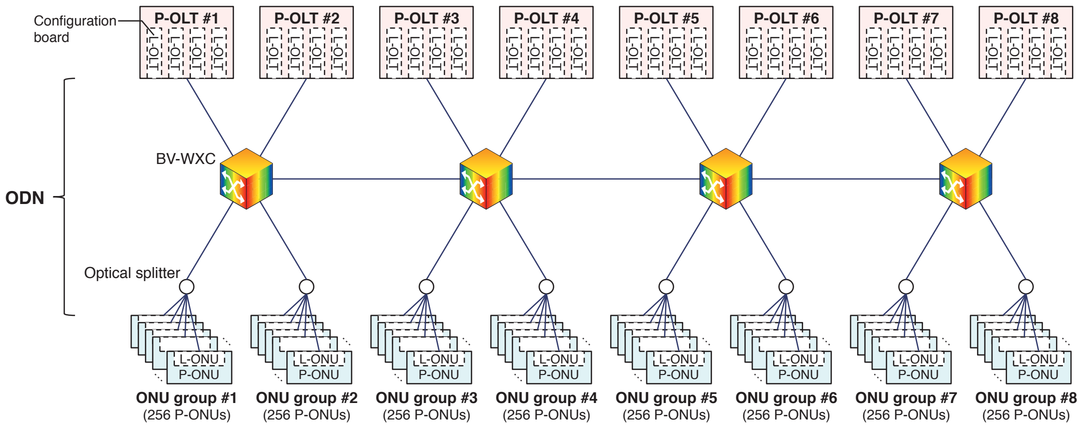
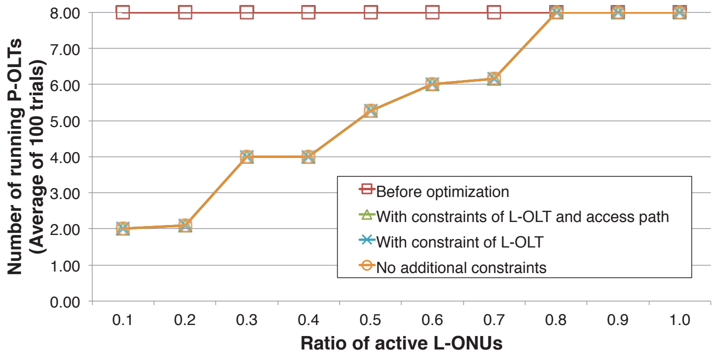


Figure 3.14: Simulation topology for evaluating impact of additional constraints.

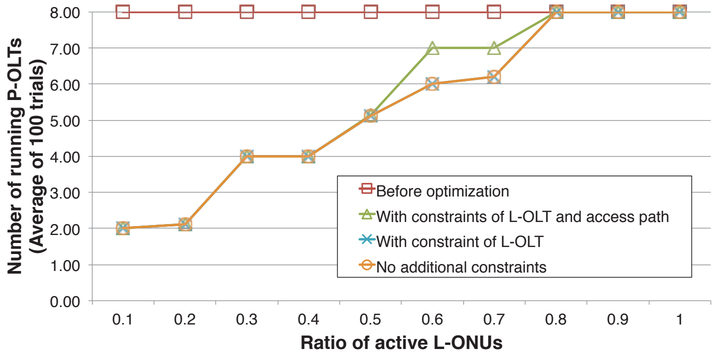
3.6 Chapter conclusion

Chapter 3 focuses on the energy saving technique in the optical metro/access integrated network in order to address the increase in the power consumption of network equipment. There have been several approaches such as the expansion of the network coverage, the improvement in device technology, and the sleep mode in ONUs to reduce the power consumption. However, to the best of author's knowledge, there are no approaches that realize the energy saving among coordinated COs since the idea of the optical metro/access integrated network has been emerged recently.

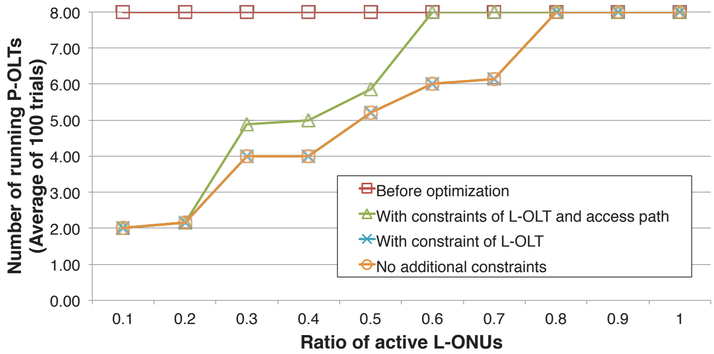
This Chapter proposes the selective OLT sleep by applying the network virtualization technique in EλAN. At first, L-OLT migration is proposed to realize selective OLT sleep in the multi-service environment. The L-OLT placement optimization problem that obtains the placement of L-OLTs that minimizes the number of running P-OLTs is modeled as an ILP problem. By using the ILP model, the energy-saving effect of L-OLT placement optimization is evaluated. Simulation results show that the number of P-OLTs in sleep mode increases 16.7% on average and 35.8% at a maximum, compared to the situation without L-OLT placement optimization.



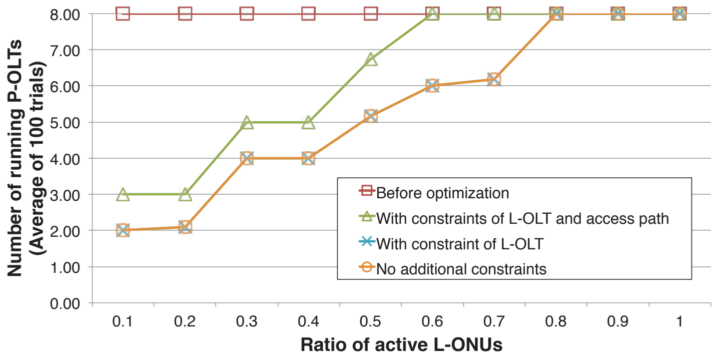
(a) Number of wavelengths = 7.



(b) Number of wavelengths = 6.



(c) Number of wavelengths = 5.



(d) Number of wavelengths = 4.

Figure 3.15: Simulation results of impact of additional constraints.

Table 3.3: Simulation parameters in evaluation of impact of additional constraints.

Number of P-OLTs	8
Number of P-ONUs	2048
Number of WXCs	4
Number of L-OLT configuration boards per P-OLT	4
Total number of wavelengths	≥ 4
Number of requested wavelength from each L-OLT	1
Maximum number of steps of L-OLT migration	1
Maximum rate of allocated frequency slots at each P-OLT	1
Maximum distance (links) of access path	5
Number of guardband slots	0
Number of P-ONUs per ONU group	256
Number of L-ONUs per P-ONU	1
Number of L-ONUs accommodated by a single L-OLT	64 (at a maximum)

In addition, the communication suspension time that occurs with L-OLT migration is discussed. It is revealed that the process of L-OLT configuration and access path setting are the dominant time wasters in the migration sequence. To reduce the communication suspension time, modified versions of L-OLT migration procedure that execute L-OLT configuration and access path setting in advance of suspension of data sending are introduced. Simulation results show that the additional constraint added by in-advance access path setting degrades the energy efficiency by, at most, two active P-OLTs, while the additional constraint added by in-advance L-OLT configuration has no impact on the energy efficiency.

As a future work, a heuristic algorithm of the L-OLT placement optimization problem that has moderate computation time is needed to apply the problem to larger-scale network. It is preferable to apply different migration procedures discussed in 3.4.2 according to allowable communication suspension time of each service to reduce power consumption efficiently without affecting quality of provided services. The simulation using real traffic data of the access network is necessary in order to review the effectiveness of the algorithm precisely.

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Chapter 4

Network topology and communication method for high reliability

Chapter 4 focuses on techniques that realize high reliability in EλAN. First, an optical network topology that supports protection with a small number of optical switches is proposed as a part of ODN [4-1][4-2]. The proposed topology tolerates a sporadic failure at anywhere in ODN and achieves high availability. The design example shows that an optical switch network that accommodates 2^{10} users and provides unavailability of 10^{-6} can be designed at 28% fewer optical switches compared to a duplex tree topology. Second, a communication method that enables an OLT to maintain connectivity of excessive ONUs by using network virtualization is proposed [4-3][4-4]. This communication method increases subscribers' chances of keeping minimum communications when a massive failure such as an outage of a Central Office (CO) happens. The implementation experiment shows that UDP packet loss at the OLT is prevented and TCP throughput of each ONU improves 4.3 Mbps by applying the proposed method when the OLT accommodates quadruple number of ONUs of a normal time.

4.1 Chapter introduction

As discussed in Chapter 1, the reliability of the optical access network has become an important issue. In the conventional access network (i.e., PON), cost-efficiency is given priority over reliability since the main service is residential Internet access. However, high reliability becomes necessary when non-residential services such as virtual private lines and mobile fronthauls are provided. The optical metro/access integrated network especially needs a disaster recovery method since the transmission distance becomes longer than the commercialized PON system.

Protection schemes deal with a sporadic failure and improve the reliability of the conventional access network. As mentioned in Section 2.4, a variety of protection schemes for the PON system including standardized and non-standardized ones have been proposed. In addition, a restoration scheme is applicable on a network system that has adequate redundancy. In the restoration scheme, a new traffic route is computed and configured just after a failure occurs. If a sufficient number of equipment on ODN operates normally after the failure, there is a chance of recovering connectivity of ONUs from a surviving OLT. However, there is a limit on the number of ONUs that a single OLT can accommodate due to limitations of buffer memory, link IDs, and so on. In a case of a massive failure, there is a possibility that several COs become incapacitated. When the number of surviving OLTs is very limited, some ONUs cannot be accommodated even if ONUs are available and have reachability to OLT.

Chapter 4 proposes a highly-reliable network design that deals with both sporadic and massive failures for EλAN. The network virtualization technique is used to increase subscribers' chances of keeping minimum communications in a case of a massive failure.

This Chapter consists of two parts. The first part (Section 4.2 to 4.5) proposes an optical switch network topology [4-1][4-2]. The proposed topology is a TDM network and assumed to be deployed in the downstream edge of ODN, where optical access networks are deployed presently. The proposed topology provides two node-disjoint routes for subscribers who require high availability. Therefore, the proposed topology tolerates a sporadic failure at anywhere in ODN by protection. The number of optical switch is reduced by using Mach-Zehnder 2×2 optical waveguide switches. The second part (Section 4.6 and 4.7) proposes a communication method that keeps minimum connectivity of a large number of subscribers [4-3][4-4]. This communication method can be adopted in the network topology proposed at first. The proposed communication method enables an P-OLT to maintain connectivity of more P-ONUs than the normal restoration method by using the network virtualization. In the proposed communication method, P-ONUs are divided into multiple groups and communicate with the P-OLT in TDMA manner. The effect of large communication intervals between the P-OLT and each P-ONU is alleviated by inserting a proxy between the core network and the P-OLT. Therefore, the proposed communication method realizes low-bandwidth but stable communication for excessive P-ONUs.

The rest of this chapter is organized as follows. The design policy of the optical switch network topology is described in Section 4.2. Features of typical network topologies are analyzed in Section 4.3. The proposed optical switch network topology is introduced in Section 4.4. The design method of the proposed network topology is described by using an example in Section 4.5. Next, the communication method in a time of massive failure that uses the network virtualization is proposed in Section 4.6. The performance of the proposed method is measured by the implementation experiment in Section 4.7. Finally, this chapter is concluded in section 4.8.

4.2 Policy of optical network topology design

The first target of this research is to design a highly-reliable optical network topology suitable for EλAN ODN. To support non-residential services, the provision of high availability is given the first priority in this design. In addition, there are several other parameters that are regarded important in the network design.

- Low optical loss

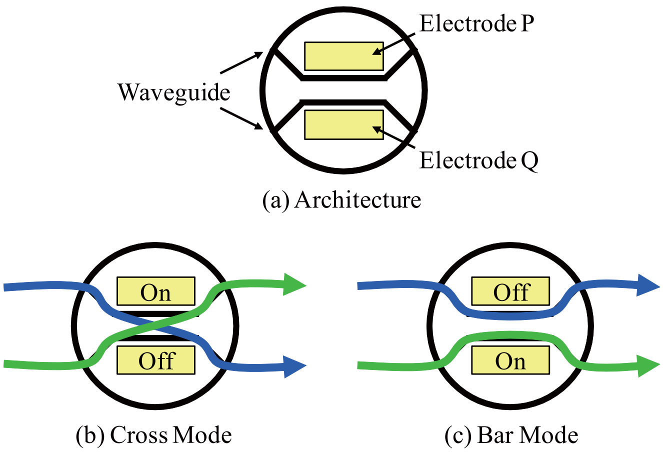


Figure 4.1: Symbol of 2×2 optical switch element.

 - In the optical metro/access integrated network, subscribers are widespread in a large-scale area. It is preferable to reduce the number of optical amplifiers in terms of both deployment cost and energy consumption. Therefore, it is required to reduce total optical loss between an OLT and each ONU.

- Low deployment cost
  - As can be expected from the reason why PON systems have become popular, subscribers are very cost-conscious. The deployment cost of the network directly affects the network connection fee. Therefore, the total number of components such as optical switches should be reduced.

In this research, Mach-Zehnder optical waveguide switches are utilized for the design of the optical switch network. A PLZT optical switch [4-5][4-6] is a typical example of Mach-Zehnder optical switches. Figure 4.1 describes the symbol of a 2×2 optical switch element in this chapter. A 2×2 switch element is the minimum unit of the Mach-Zehnder optical waveguide switch. The switch element changes signal output in two patterns (cross mode and bar mode) in less than 10 nanoseconds when voltage is applied to electrodes.

4.3 Features of typical network topologies

In this section, features of typical network topologies that are constructed by 2×2 optical switches are evaluated. The following parameters are focused in this analysis.

- Unavailability
  - It is the probability that a user cannot communicate with the OLT due to a failure of a 2×2 optical switch. It is equal to 1 minus availability. In the following, the unavailability of user i ($i = 0, 1, 2, \ldots, N-1$) is expressed as U_i.
- Optical loss
  - It is a sum of insertion losses of 2×2 optical switches that are placed between the OLT and each user. In the following, the optical loss between the OLT and user i ($i = 0, 1, 2, \ldots, N-1$) is expressed as L_i.
- Number of optical switches
  - It is the number of 2×2 optical switches that is required to connect N users with the OLT. In the following, it is expressed as S.

The values of U_i and L_i are different among users respectively, so these parameters are evaluated by worst-case conditions, $\max_i U_i$ and $\max_i L_i$. The logical features of topologies are focused on in this analysis, and any effect of other components or devices (e.g. an optical fiber cable that connects two 2×2 optical switches) is ignored.

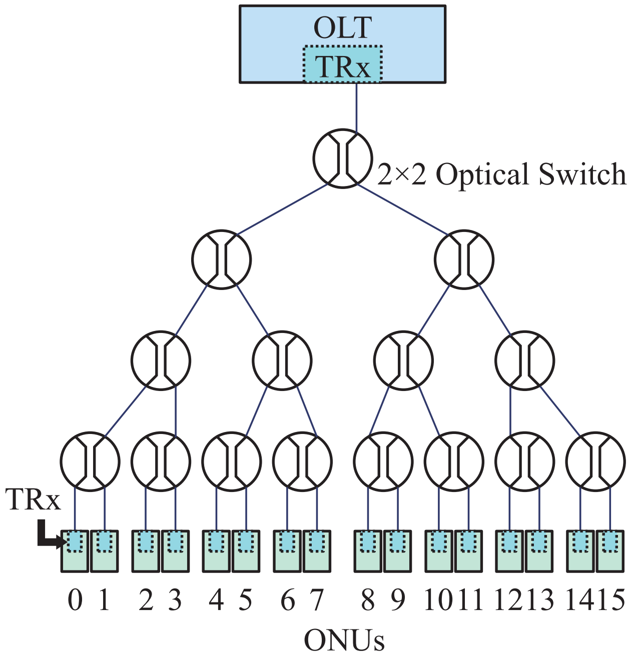


Figure 4.2: Tree topology (N = 16).

4.3.1 Analysis

Tree topology

A tree topology is often used in access networks (e.g. PON). Figure 4.2 shows the tree topology that is constructed by 2×2 optical switches. When it is a complete binary tree, each parameter is expressed as follows.

$$\max_i U_i = 1 - (1 - u)^{\lceil \log_2 N \rceil} \quad (4.1)$$

$$\max_i L_i = \lceil \log_2 N \rceil l \quad (4.2)$$

$$S = N - 1 \quad (4.3)$$

u is the unavailability of a 2×2 optical switch itself, and l is the insertion loss of the optical switch. When N is power of two, U_i and L_i of all users are equal to $\max_i U_i$ and $\max_i L_i$ respectively.

In the simple tree topology, at least one user becomes unable to communicate with the

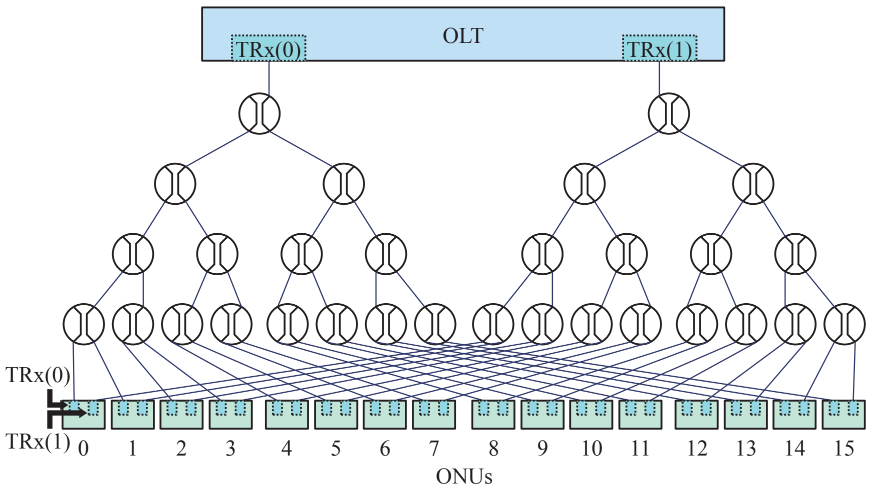


Figure 4.3: Duplex tree topology (N = 16).

OLT inevitably when any one of 2×2 optical switches fails. A duplex configuration is referred as the protection architecture "type C" to enhance the reliability of PON in ITU-T recommendation [4-7]. Figure 4.3 shows the duplex tree topology that is constructed by 2×2 optical switches. When it is a complete binary tree, each parameter is expressed as follows.

$$\max_i U_i = (1 - (1 - u)^{\lceil \log_2 N \rceil})^2 \tag{4.4}$$

$$\max_i L_i = \lceil \log_2 N \rceil l \tag{4.5}$$

$$S = 2(N - 1) \tag{4.6}$$

Ring topology

A ring topology is often used in a metropolitan area network such as ROADM ring and RPR. Figure 4.4 shows the ring topology that is constructed by 2×2 optical switches. Each parameter is expressed as follows.

$$\max_i U_i = u + (1-u)(1-(1-u)^{\lceil \frac{N-1}{2} \rceil})(1-(1-u)^{\lfloor \frac{N-1}{2} \rfloor}) \tag{4.7}$$

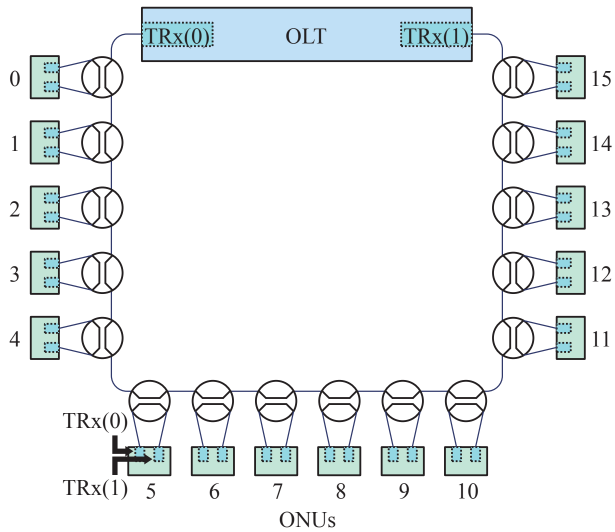


Figure 4.4: Ring topology ($N = 16$).

$$\max_i L_i = Nl \tag{4.8}$$

$$S = N \tag{4.9}$$

The user that meets $U_i = \max_i U_i$ is $i = \frac{N}{2} - 1, \frac{N}{2}$ (when N is even) or $\frac{N-1}{2}$ (when N is odd). Equation (4.7) means that the user cannot communicate with the OLT when the 2×2 optical switch that is connected directly with the user fails, or when both of its routes to the OLT (clockwise or counterclockwise) are unavailable concurrently due to failures of switches on each route. The user that meets $L_i = \max_i L_i$ is $i = 0, N - 1$.

4.3.2 Comparison

Figure 4.5, 4.6 and 4.7 show $\max_i U_i$, $\max_i L_i$ and S of each topology respectively. It is assumed that the unavailability of a 2×2 optical switch u is 10^{-6} and the insertion loss of the optical switch l is 1 dB.

$\max_i U_i$ of the ring topology is lower than that of the tree topology, except when N is extremely large. This is because users can communicate with the OLT by using one of

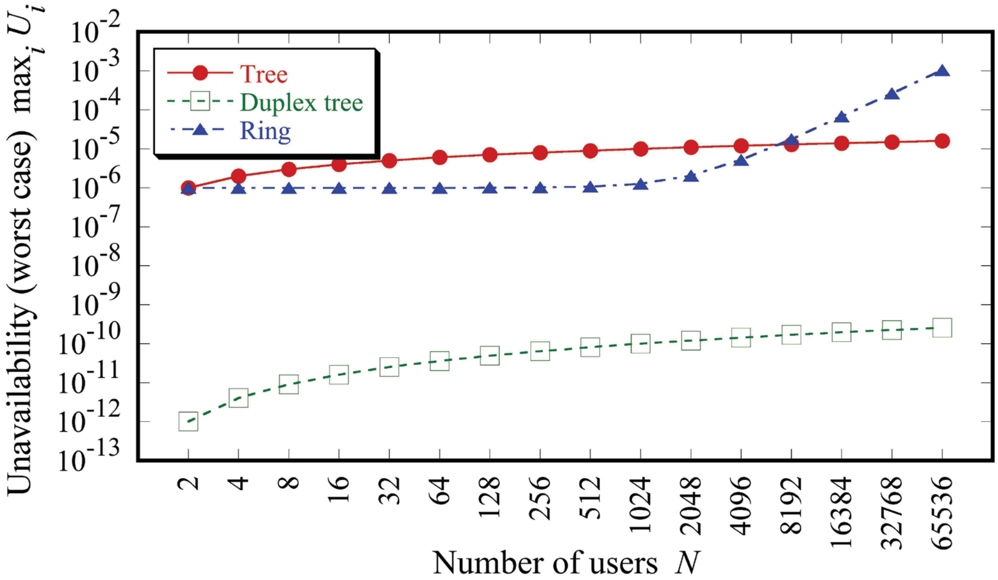


Figure 4.5: Worst case of unavailability $\max_i U_i$ of typical topologies.

the two routes (clockwise or counterclockwise) in the ring topology.

By contrast, $\max_i L_i$ of the tree topology is lower than that of the ring topology. This is because the number of optical switches that are placed between the OLT and the worst-case user is N in the ring topology, and $\lceil \log_2 N \rceil$ in the tree topology.

The duplex tree topology achieves very low $\max_i U_i$ due to setting two different routes for subscribers that do not share any optical switch between the OLT and the user. However, S of this topology is twice as many as that of the tree topology and the ring topology.

Based on above argument, a novel optical switch network topology that achieves high availability and low optical loss together is proposed in the next section.

4.4 Proposed optical switch network topology

Figure 4.8 shows the proposed topology for EλAN ODN. Considering the accommodation of non-residential services, ONUs that equip two transponders are illustrated.

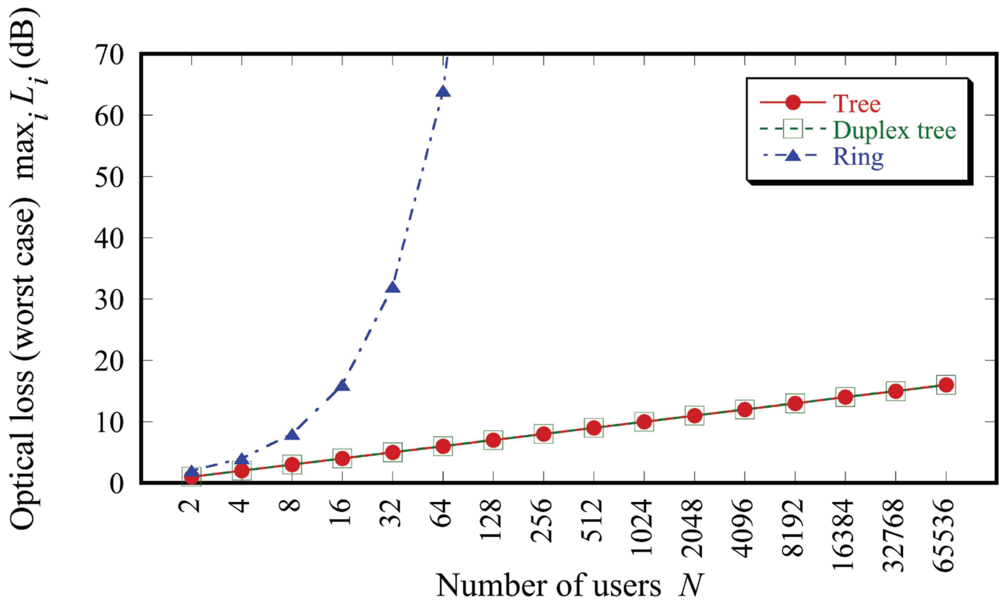


Figure 4.6: Worst case of optical loss $\max_i L_i$ of typical topologies.

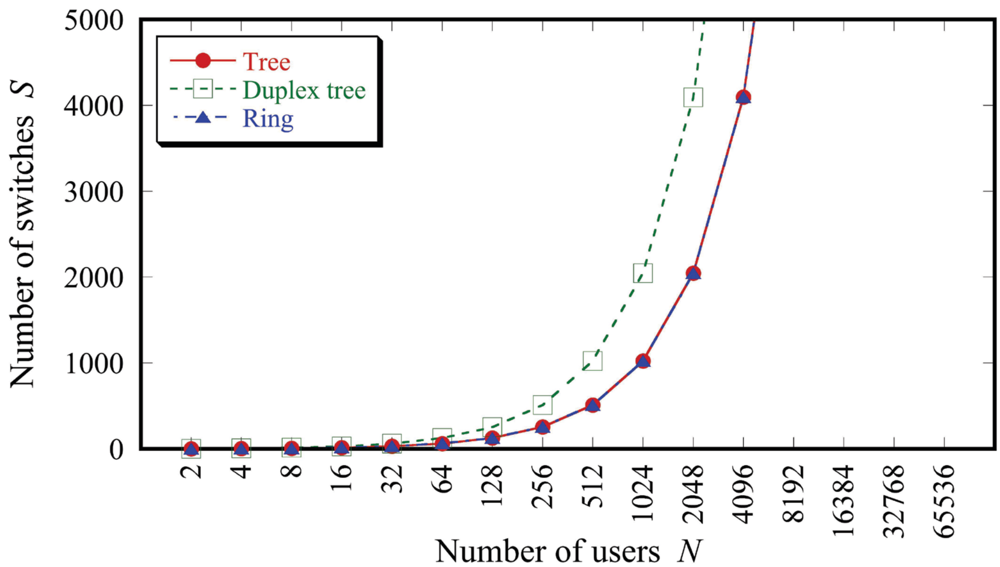


Figure 4.7: Number of switches S of typical topologies.

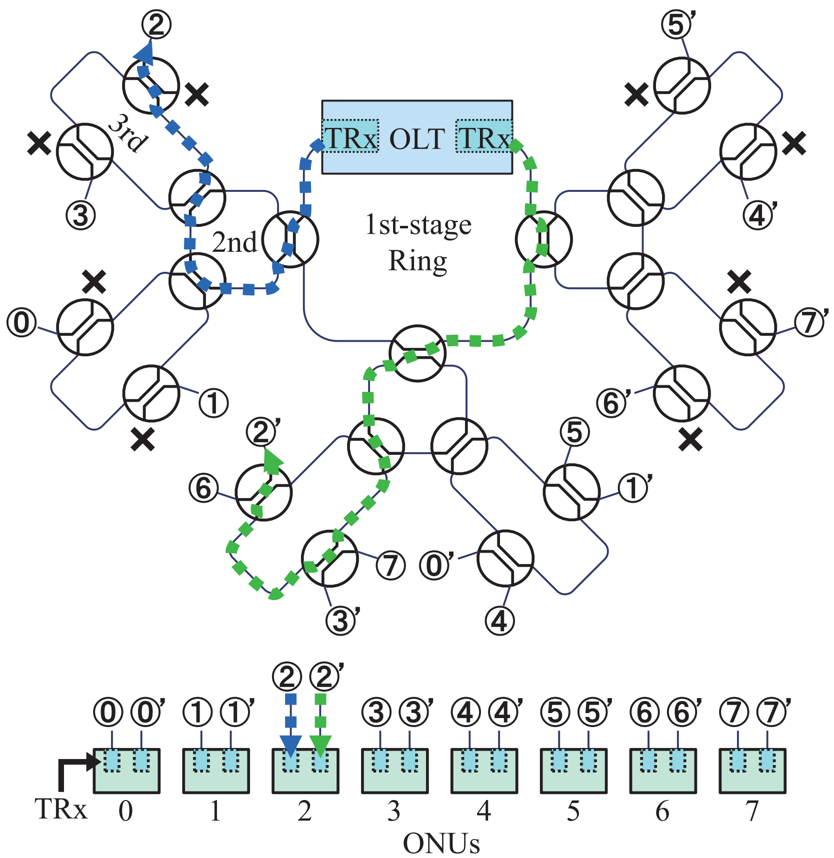


Figure 4.8: Proposed topology (N = 8, M = 3 (S_1 = 3, S_2 = 2, S_3 = 2)).

In this topology, small-sized rings are connected like a tree topology by using 2×2 optical switches. Figure 4.8 is the proposed topology whose number of ring stages M is 3. Optical signal can be switched to upper/lower rings at each optical switch. Due to the operational characteristic of optical waveguide switch, the rotation direction of optical signal in each ring is determined by the incidence direction of optical signal. Therefore, the route from each port to the OLT is determined uniquely. Optical signal entering from one port reaches one of the two transceivers of the OLT.

With the introduction of tree structure, the proposed topology reduces the optical loss between the OLT and users. In addition, two different routes that do not share any optical switch are set to users who require high availability. Therefore, users can continue to communicate with the OLT when any one of 2×2 optical switches fails. In Figure 4.8, two different routes for user 2 are shown as dotted arrows. ×-marked ports are unused since it is unable to provide two node-disjoint routes to users who connect with these ports. Optical signal for a ×-marked port goes through all switches in the 1st-stage ring. Therefore, another node-disjoint route cannot be set since two routes are inevitably overlapped in the 1st-stage ring. ONUs can connect with these ports only if users do not require high availability by protection. Due to using all ports of a 2×2 optical switch (except ×-marked ports), this topology reduces the total number of optical switches S compared to the duplex tree topology.

Following is the rule to choose ports of 2×2 optical switches where ONUs are connected. This rule maximizes the number of ONUs that have two node-disjoint routes by using all ports except ×-marked ones.

1. Choose an arbitrary port (except ×-marked one) as the first port. The route from the chosen port to one transceiver of the OLT is determined uniquely. Let **Z** stand for the optical switch that adds/drops the optical signal on the 1st-stage ring.

2. Choose the port that can be reached from another transceiver of the OLT via the switch that is adjacent to **Z** on the 1st-stage ring and not used by the first route as the second port.

As mentioned in 4.1, the proposed topology is a TDM network. A PLZT optical switch has wavelength insensitivity, but all of input frequency slots (or wavelengths) are switched to the same output port. Therefore, the proposed network topology can provide only several network services that can be multiplexed by TDM. To make the proposed network topology compatible with OFDM (or WDM) completely, bandwidth-variable wavelength selective switches (BV-WSS) and the number of proposed network topologies equivalent to the number of provided services have to be deployed.

4.5 Design method of proposed network topology

In this section, a design method of the proposed topology is shown by using an example. It is assumed that all of ONUs equip two transponders in this example.

4.5.1 Parameters indicative of network shape

The shape of the proposed network topology is characterized by the following parameters.

- Number of ring stages M
- Number of 2×2 optical switches on an mth-stage ring s_m $(m = 1, 2, \ldots, M)$

Here, an optical switch that connects mth and $m+1$th-stage ring is counted as a switch of mth-stage ring.

The number of users that can connect to the proposed network topology increases by setting M and/or s_m large. If M is set large, the total number of optical switches S increases since the number of switches used to connect rings becomes large. On the other hand, if s_m is set large, the worst case of optical loss $\max_i L_i$ becomes high since the number of switches on the route between the OLT and users becomes large. Therefore, M and s_m have to be decided in consideration of the loss budget between the OLT and users.

The general formulation of the design method of the proposed topology can be presented as below.

Subject to :

$$(s_1 - 1) \times s_2 \times s_3 \times \ldots \times s_M \geq N \quad (4.10)$$

$$\max_i U_i \leq \mathcal{U} \; (i = 0, 1, 2, \ldots, N-1) \quad (4.11)$$

$$\max_i L_i \geq \mathcal{L} \; (i = 0, 1, 2, \ldots, N-1) \quad (4.12)$$

Objective :

$$\min S \ (i = 0, 1, 2, \ldots, N-1) \tag{4.13}$$

$$S = s_1 \times (1 + s_2 \times (1 + s_3 \times \ldots \times (1 + s_M) \ldots)) \tag{4.14}$$

Constraint (4.10) means that the number of users that can connect with optical switches of Mth-stage rings is equal to or larger than N. $1 - \mathcal{U}$ is the guaranteed availability that the network provider set based on Service Level Agreement (SLA). $\mathcal{L}$ is the loss budget between the OLT and users.

4.5.2 Design example

Based on constraints and objective function in 4.5.1, a design example is shown below. In the following design example, it is assumed that the number of users N is 2^{10} and the unavailability of a 2×2 optical switch u is 10^{-6}. The insertion loss of the optical switch l is assumed to be 1 dB in expectation of the future development of optical waveguide switch technology. The transmission loss of optical fiber cables (e.g., 0.2 dB/km) is ignored to compare logical features of network topologies. The guaranteed availability $1 - \mathcal{U}$ is set to 99.9999% (six nines). The loss budget $\mathcal{L}$ is set to -29 dB in reference to that of IEEE 10GE-PON [4-8].

Networks whose number of ring stages is M ($M = 1, 2, 3, \ldots, \lceil \log_2 N \rceil$) are created as shown in Fig. 4.9. For simplicity, the number of 2×2 optical switches of an mth-stage ring is set to 2^x (x is a positive integer), with the exception that that of a 1st-stage ring is set to $2^x + 1$. The difference of the number of optical switches between mth-stage rings is minimized. All networks are created to meet constraint (4.10) in this example.

Figure 4.10, 4.11 and 4.12 show $\max_i U_i$, $\max_i L_i$ and S of each created network. Figure 4.10 shows that all created networks meet constraint (4.11). Figure 4.11 shows that networks whose number of ring stages is $4 \leq M \leq 10$ meet constraint (4.12). There-

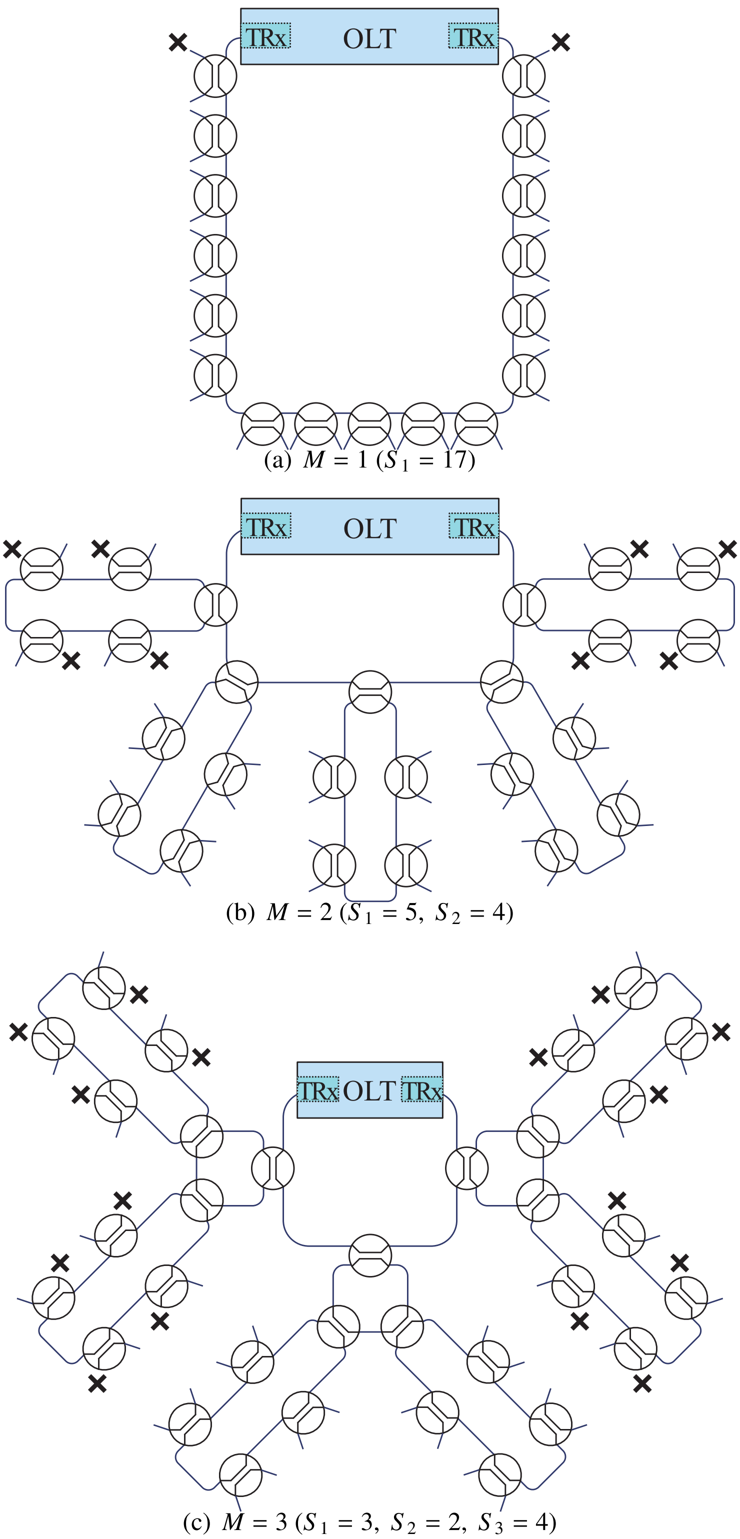


Figure 4.9: Networks having M ring stages ($N = 16$).

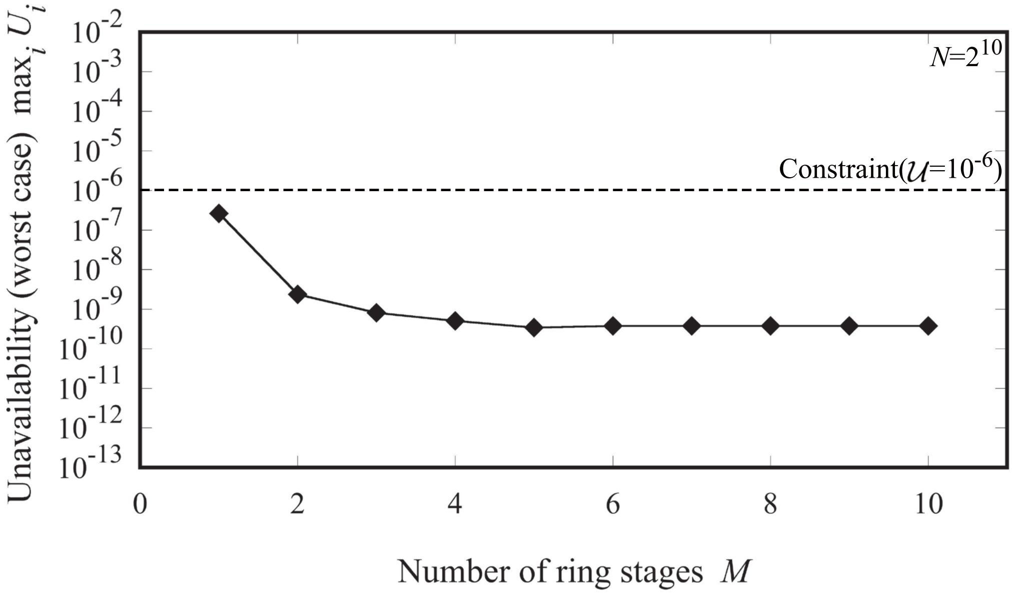


Figure 4.10: Worst case of unavailability $\max_i U_i$ of created networks.

fore, the network of $M = 4$ is selected as the solution since it has the smallest S among $4 \leq M \leq 10$.

Figure 4.13 shows S of the duplex tree topology and that of the network created by using the proposed design method. Assumed conditions except N are same as the above design example. Note that the tree topology and the ring topology reduce S compared to the proposed design method, but they cannot create the network which meets all constraints under these assumed conditions. The proposed design method can create the network which meets all constraints when the number of users is $2 < N < 2^{14}$. The network created by using the proposed method reduces S compared to the duplex tree topology, except when $N = 2$. For example, it reduces S by 28% when $N = 2^{10}$.

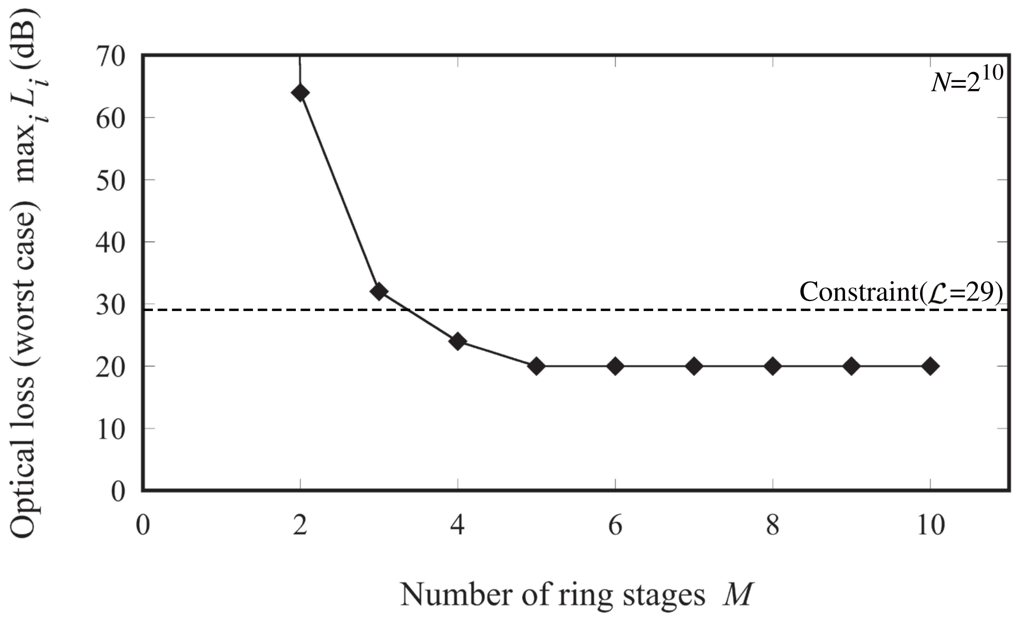


Figure 4.11: Worst case of optical loss $\max_i L_i$ of created networks.

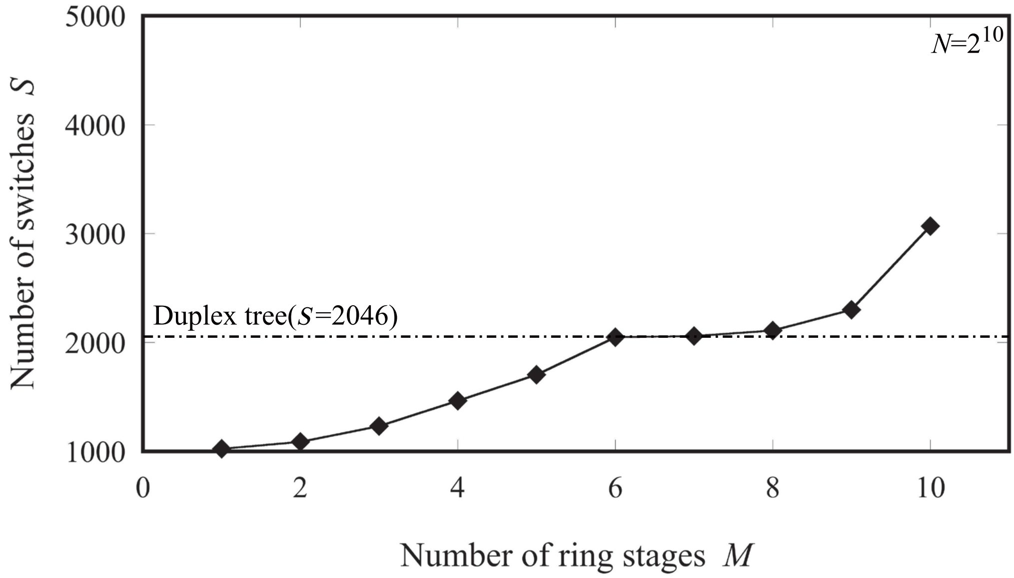


Figure 4.12: Number of switches S of created networks.

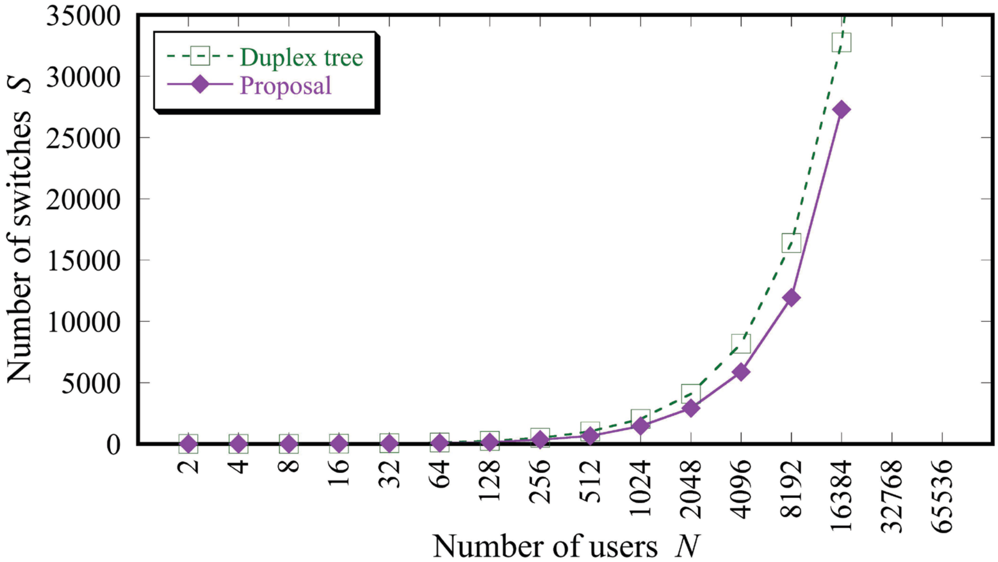


Figure 4.13: Number of switches S of duplex tree topology and created network.

4.6 TDMA-based OLT sharing method

4.6.1 Overview

The second proposal of this chapter is a communication method to maintain connectivity of excessive ONUs from a single OLT in EλAN. Figure 4.14 shows the overview of the proposed TDMA-based OLT sharing method. This Figure illustrates that CO A becomes incapacitated and a P-OLT in CO B recovers P-ONUs that is originally accommodated by a P-OLT in CO A. In this proposal, P-ONUs are divided into multiple groups and communicate with the P-OLT in TDMA manner. In Fig. 4.14, only the ONU group #1 and #2 are described due to limitations of space. Each ONU group consists of equal or smaller number of P-ONUs than the maximum number of P-ONUs that a single P-OLT can accommodate in a normal time. In the case of EλAN, each ONU group includes equal or less than 256 P-ONUs [4-9]. How to configure ONU groups efficiently is beyond the scope of this chapter, but the simplest way is to gather P-ONUs that locate geographically

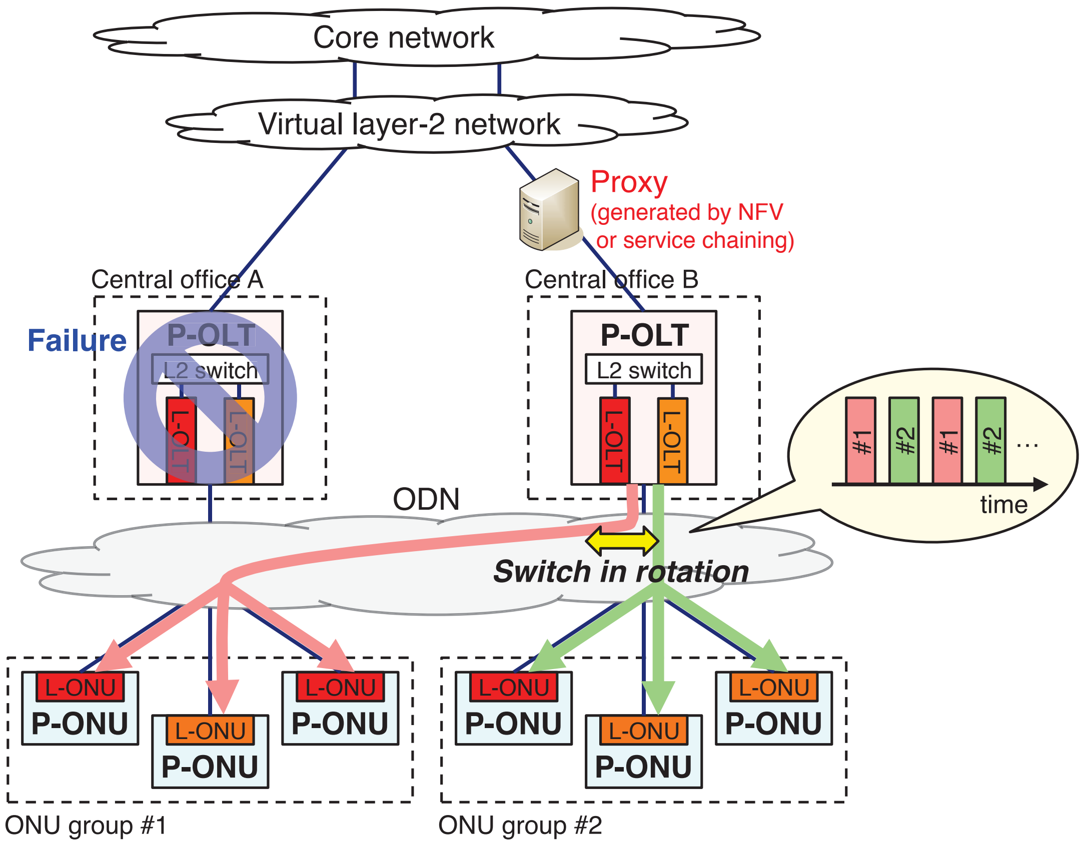


Figure 4.14: Overview of TDMA-based OLT sharing method

close and originally received a service from the same P-OLT.

The operation sequence of the TDMA-based OLT sharing method is as follows. For simplicity, the number of ONU groups is assumed to be two. Frequency slots used in this communication method are needed to be determined in advance of a failure.

1. A L-OLT configured in a P-OLT operates as virtual L-OLT #1 for ONU group #1. An access path is configured on ODN to connect the L-OLT and ONU group #1. Registration and ranging procedure are executed between the L-OLT and each L-ONUs in ONU group #1. Setting parameters for ONU group #1 are stored in the L-OLT.

2. The L-OLT operates as virtual L-OLT #2 for ONU group #2. The access path is

reconfigured to connect the L-OLT and ONU group #2. Registration and ranging procedure are executed between the L-OLT and each L-ONUs in ONU group #2. Setting parameters for ONU group #2 are stored in the L-OLT.

3. The L-OLT exchanges virtual L-OLT #1 and virtual L-OLT #2 periodically, and communicate with each ONU group by using MPCP [4-10] in rotation.

HOLDOVER messages [4-11] are utilized to maintain a logical link between the virtual L-OLT and each L-ONU even if a L-ONU detects optical signal loss by reconfiguring an access path. Right before the L-OLT switches virtual L-OLTs, the L-OLT sends a HOLDOVER(start) message to accommodating L-ONUs. A L-ONU stops communication when it receives a HOLDOVER(start) message. A L-ONU resumes communication when they receives a HOLDOVER(end) message from the L-OLT.

The switching time of virtual L-OLTs is assumed to take less than 50 ms. This is to allow this proposal to be used in both cases that ONU groups are divided at optical waveguide switches (discussed in 4.2) and BV-WXCs (discussed in 3.4.1). To reduce the overhead such as the switching time of L-OLTs, few seconds of communication time is allocated to each ONU group per cycle. During the communication time allocated to one ONU group, downstream data frames to other ONU groups are discarded in the L-OLT due to its buffer capacity. To resolve the problem of a limit of buffer memory and stabilize throughput, a proxy is inserted.

4.6.2 Proxy for alleviating effect of large communication interval

In the proposed communication method, the communication interval between the L-OLT and each L-ONU becomes large. Therefore, subscribers might suffer frame losses and unstable throughput. To alleviate the effect of large communication interval, a proxy is inserted into the upstream of P-OLT by exploiting NFV [4-12] and service function chaining [4-13][4-14] on the virtual layer-2 network.

The proxy provides three functions mainly; buffering data, shaping traffic, and steadying TCP throughput.

- Buffering data from core network
  - The proxy buffers downstream data to each ONU group and transfers them to the P-OLT in synchronization with switching of ONU groups. Therefore, frame loss in the L-OLT is avoided.
- Traffic shaping of bursty traffic from L-OLT
  - In the proposed communication method, upstream traffic becomes bursty since the communication interval is large. The proxy control upstream packet-sending intervals to eliminate the interruption of service.
- Steadying TCP throughput
  - The proxy terminates a TCP session between a client in the subscriber's network and a server, and creates a new session. This is effective in preventing retransmission and throughput degradation caused by large-time buffering.

By providing these functions by the proxy, the proposed TDMA-based OLT sharing method realizes low-bandwidth but stable communication for excessive ONUs.

4.7 Implementation experiment

In this section, the implementation experiment of the proposed communication method using an EλAN prototype system is reported. UDP packet loss rate and TCP throughput are measured to evaluate the effect of proxy by using Iperf [4-15].

Figure 4.15 and 4.16 show the EλAN prototype system in this experiment. Table 4.1 shows the parameters used in this experiment. Instead of deploying a commercialized OLT and ONUs, software that provides several functions of an L-OLT and L-ONUs, such as insertion of a logical link identifier into the Ethernet frame header, is implemented on Linux servers. The proxy is mounted fixedly on the upstream of P-OLT. EλAN targets 10-Gbps transmission rate and accommodating 256 P-ONUs per P-OLT. However, due to the limitation of laboratory instrument, this experiment uses 1-Gbps links in all connections, and assumes to accommodate 32 P-ONUs per P-OLT like GE-PON. The number of L-ONUs that a single P-ONU configures is set to 1.

Figure 4.17 shows the upstream communication in the experimental network. One second of communication time is allocated to each ONU group every cycle. DBA like the PON system is not implemented, and the bandwidth is assumed to be allocated to accommodated ONUs equally. To emulate the accommodation of 32 L-ONUs per group, 1/32 of communication time for an ONU group is allocated to an implemented L-ONU. Data transmission is suspended in actuality during the time period when bandwidth is allocated to other 31 unimplemented L-ONUs. The number of ONU group is set to 2, 3, and 4. Switching time of ONU groups is set to 50 ms. Therefore, in every cycle, the virtual L-OLT #x (x = 1, 2, 3 and 4) sends data for one second and waits for $0.05 + 1.05 \times$ (number of ONU groups $-$ 1) seconds.

Delay in the core network is also emulated by a software. Inserting transmission delay between the L-OLT and the L-ONU is skipped since it is relatively small (approximately 200 μs at 40 km, one way).

Figure 4.18 shows the effect of traffic shaping by the proxy when the number of ONU groups is four. The vertical axis is the number of upstream packets received at the server host. Figure 4.18(a) shows the result without proxy, and Fig. 4.18(b) shows the result with proxy. Bursty traffic at intervals of approximately 4 seconds is observed in the result

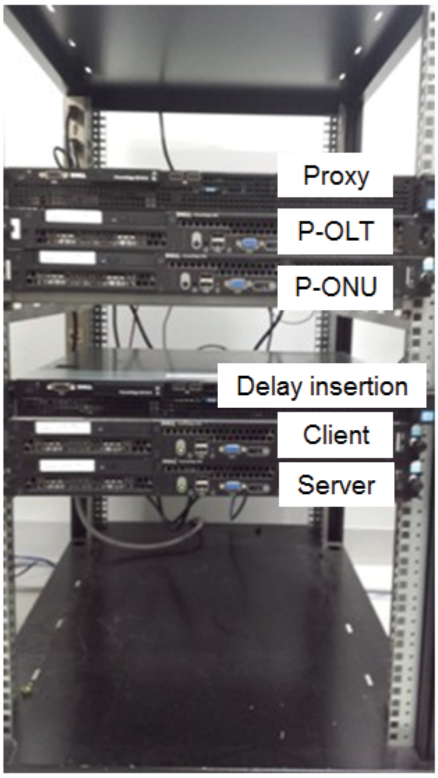


Figure 4.15: Photograph of experimental network.

without proxy. On the other hand, almost no bursty traffic is observed in the result with proxy. Of course the transmission rate per L-ONU in this system is smaller than in normal time since a single L-OLT is shared by a lot of L-ONUs. However, it is expected to reduce the influence for QoS of services by smoothing traffic and reducing jitter.

Figure 4.19 shows the result of packet loss rate when making a UDP packet flow between the server host and the client host. In the case of without proxy, the packet loss rate is 52% when accommodating 2 ONU groups, and 77% when accommodating 4 ONU groups. This means that downstream data frames to disconnected ONU groups at that moment are discarded in the L-OLT, as mentioned in Section 4.6. On the other hand, no packet loss is observed in the case of with proxy. This is realized by transferring data frames destined for each ONU group from the proxy in synchronization with the switch-

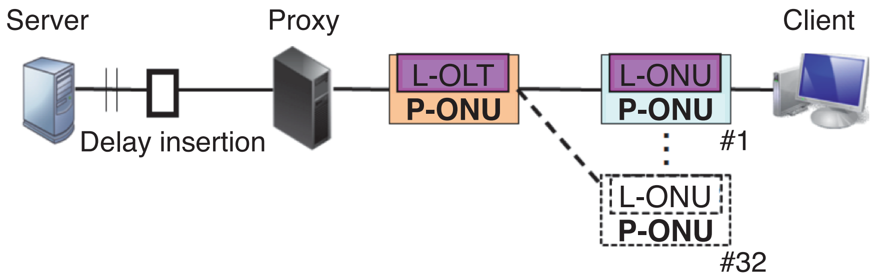


Figure 4.16: Architecture of experimental network.

Table 4.1: Parameters used in implementation experiment of TDMA-based OLT sharing method.

Number of P-ONUs per group	32
Number of ONU groups	2, 3, 4
Allocated communication time for a single ONU group	1 sec/cycle
Switching time of ONU groups	50 ms
Link speed	1 Gbps
Delay insertion	Server – P-OLT: 10 ms
	P-OLT – P-ONU: none

ing of ONU groups.

Figure 4.20 and 4.21 show the result of TCP throughput. Figure 4.20 is the TCP throughput when the number of ONU groups is changed. Delay insertion in the core network is fixed to 10 milliseconds. TCP throughput improves 9.8 Mbps when accommodating 2 ONU groups, and 4.3 Mbps when accommodating 4 ONU groups by inserting the proxy. Figure 4.21 is the TCP throughput when insertion delay is changed. The number of ONU groups is fixed to four. In the case of without proxy, TCP throughput decreases sharply following the increase of insertion delay. This is thought to be due to the increase of retransmissions by discarding frames at the L-OLT. After inserting the proxy, TCP throughput improves and keeps 2 Mbps even when the inserted delay is 50 milliseconds.

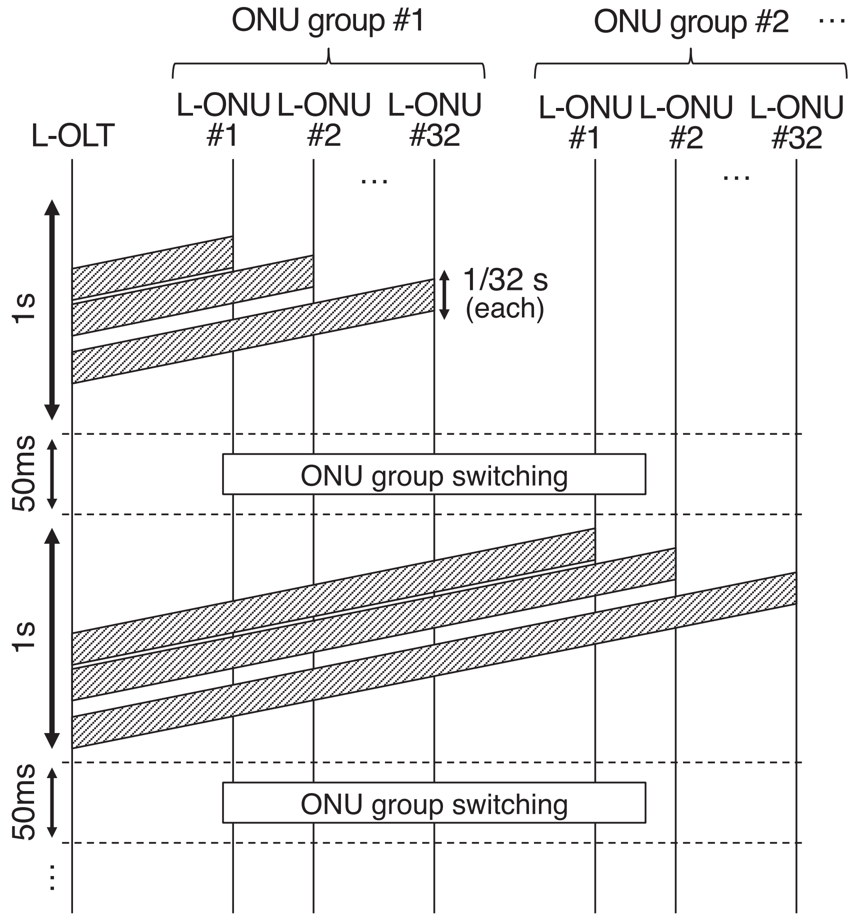
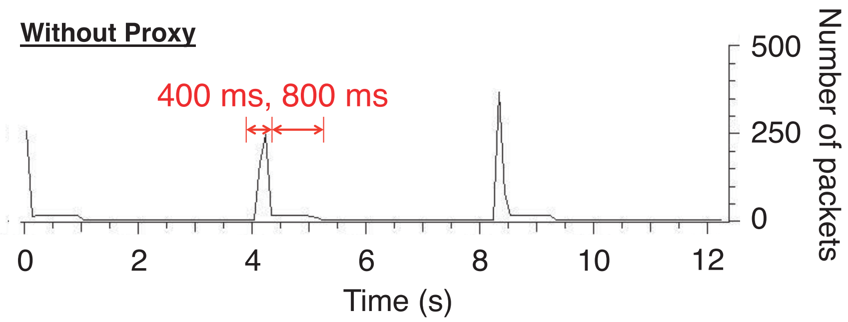


Figure 4.17: Upstream communication in experimental network.

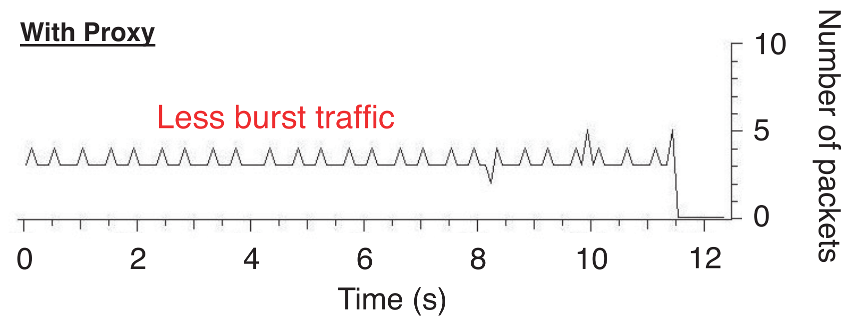
4.8 Chapter conclusion

Chapter 4 focuses on the highly-reliable optical network design for the optical metro/access integrated network in order to support non-residential services. In the conventional PON system, protection schemes have been proposed to tolerate a sporadic failure. The optical metro/access integrated network with adequate redundancy has the potential to provide not only protection but also restoration. However, there is a limit on the number of ONUs that a single OLT can accommodate even in a time of massive failure.

This Chapter proposes a network topology and a communication method for the highly-



(a) Upstream traffic without proxy.



(b) Upstream traffic with proxy.

Figure 4.18: Effect of traffic shaping by proxy.

reliable optical metro/access aggregation network. In the first part, the optical switch network topology using Mach-Zehnder 2×2 optical waveguide switches is proposed as a part of EλAN ODN. The proposed topology consists of small-sized rings that are connected like a tree topology and achieves high availability and low optical loss at the same time by using a small number of optical switches. The design example shows that an optical switch network that accommodates 2^{10} users and provides unavailability of 10^{-6} can be designed at 28% fewer optical switches compared to a duplex tree topology when the loss budget is set to 29 dB.

In the second part, the communication method in a time of massive failure that exploits the network virtualization is proposed. The proposed TDMA-based OLT sharing method enables a P-OLT to keep connectivity of excessive P-ONUs in EλAN. In the

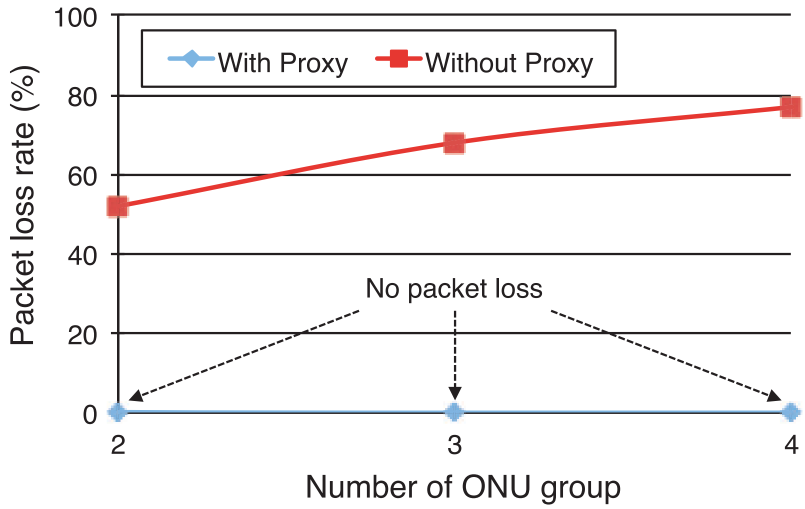


Figure 4.19: UDP packet loss rate.

proposed method, P-ONUs are divided into multiple groups and communicate with the P-OLT in TDMA manner. To alleviate the effect of large communication interval, the proxy that provides buffering data, shaping traffic, and steadying TCP throughput is inserted by exploiting NFV and service function chaining. The feasibility of the proposed communication method is examined by the implementation experiment. By inserting the proxy, UDP packet loss at the L-OLT is prevented and TCP throughput of each L-ONU improves 4.3 Mbps when the P-OLT accommodates quadruple number of P-ONUs of a normal time. Although the transmission rate per L-ONU becomes smaller than in normal time, the proposed communication method achieves steady communication for a lot of L-ONUs.

To achieve the practical use of the proposed communication method, more detailed procedure has to be established. For example, the discovery of surviving network equipment and the configuration of ONU groups are included in future works.

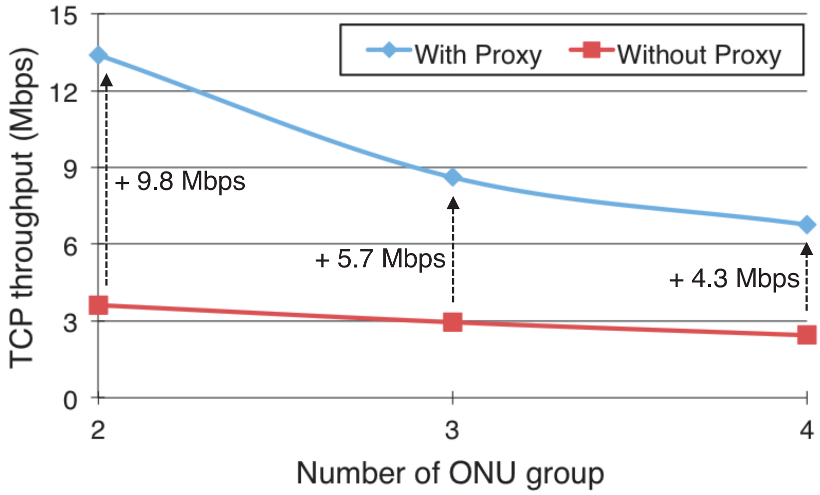


Figure 4.20: TCP throughput when the number of ONU groups changes.

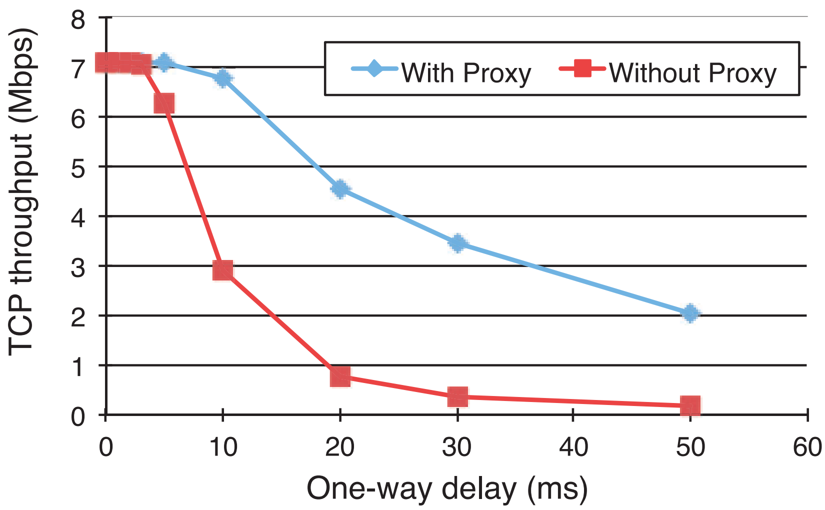


Figure 4.21: TCP throughput when the inserted delay changes.

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Chapter 5

Overall conclusion

This dissertation has focused on the optical metro/access integrated network as a strong candidate of the next-generation optical access, and discussed techniques to achieve high energy efficiency and reliability by using the network virtualization.

The power consumption of network equipment is growing rapidly, as much as 12% per year, according to the increase in the network traffic. Especially, the power consumption of the access network area accounts for 60–80% of that of the current IP network. On the other hand, the demand for network reliability is rising since the communication network has already become a social infrastructure. The momentum of service integration on the access network accelerates this demand.

There are various approaches to resolve the problem of the network power consumption. The optical metro/access integration achieves the power saving in ODN since the number of network equipments is decreased. The improvement in device technology and the sleep mode capable equipment reduce the power consumption of an OLT and an ONU. On the other hand, protection schemes that deal with a sporadic failure are proposed in the conventional access network to improve the reliability. The restoration scheme is applicable on a network system that has adequate redundancy.

In this dissertation, the network virtualization technology has been used to achieve further energy efficiency and reliability on the optical metro/access integrated network. The concept of network virtualization that abstracts physical network resources and configures logical networks to provide various network services has appeared recently. Our laboratory has proposed EλAN that introduces the idea of virtualization into the optical metro/access integrated network to support multiple services that have different protocols and QoS requirements.

Two research topics have been described in this dissertation to achieve energy-efficient and highly-reliable optical metro/access integrated network based on EλAN.

Chapter 3 has proposed adaptive energy saving in COs according to a daily traffic fluctuation. To introduce selective OLT sleep in a multi-service environment, L-OLT migration that replicates network functions between P-OLTs is proposed. The L-OLT placement optimization problem is modeled as an ILP problem to obtain the placement of L-OLTs that minimizes the number of running P-OLTs. Simulation results show that the number of P-OLTs in sleep mode increases 16.7% on average and 35.8% at a maximum, compared to the situation without L-OLT placement optimization. In addition, communication suspension time that occurs with L-OLT migration is also discussed. By modifying the L-OLT migration procedure, the communication suspension time is reduced in exchange for several additional constraints in the ILP problem. Simulation results show that the communication suspension time is reduced to 57 milliseconds without degrading the energy efficiency, and 10 milliseconds at the cost of making two more active P-OLTs.

Chapter 4 has proposed the design of optical switch network that tolerates a sporadic failure as a part of EλAN ODN. In the optical metro/access integrated network, high availability should be provided for non-residential subscribers. In addition, it is required to keep the optical loss between an OLT and ONUs low and reduce the number of total optical switches in terms of deployment cost and power consumption. To achieve these requirements at the same time, a novel optical switch network topology that uses Mach-Zehnder type 2$\times$2 optical switches is proposed. The proposed topology consists of small-sized rings that are connected like a tree topology to achieve both high availability and low optical loss at the same time. The proposed topology provides two different routes that do not share any optical switches to every ONUs for protection. The design example shows that a large-scale optical switch network that satisfies targets of availability and optical loss is designed by using 28% fewer optical switches compared to a duplex tree topology. Chapter 4 has also proposed a novel communication method in a time of massive failure such as a disaster. In the network system that accommodates multiple OLTs, pairs of OLTs and ONUs can be changed flexibly by reconfiguring ODN. To keep connectivity of a lot of ONUs from few survived OLTs, TDMA-based OLT sharing method is proposed. The proposed communication method accommodates several ONU groups in rotation. The proxy that provides buffering data, shaping traffic, and steadying TCP throughput is inserted by exploiting NFV and service function chaining to alleviate the effect of large communication interval. Therefore, low-bandwidth but steady communication are provided for a lot of subscribers. In the implementation experiment, UDP packet loss at the L-OLT is prevented and TCP throughput of each L-ONU improves 4.3 Mbps when the P-OLT accommodates quadruple number of P-ONUs of a normal time by inserting the proxy.

The overall conclusion is that this dissertation has contributed the realization of the energy-efficient and highly-reliable optical metro/access integrated network.

Appendix A

ILP formulation of L-OLT placement optimization problem

This appendix details the ILP formulation of L-OLT placement optimization problem in Chapter 3. In Chapter 3, two models of the problem are used for evaluation; without and with ODN constraints. The objective function A.1a is common between both models. Constraints related to ODN are valid only in the latter model.

A.1 Objective function

Objective:

$$\min \sum_{j=1}^{n_{\mathrm{POLT}}} y_j(T) + \epsilon \sum_{t=1}^{T} \sum_{i=1}^{n_{\mathrm{LOLT}}} \sum_{j=1}^{n_{\mathrm{POLT}}} \sum_{k=1}^{b} Z_{ijk}^{\mathrm{IN}}(t) \tag{A.1a}$$

$$\epsilon = \frac{1}{n_{\mathrm{LOLT}} T + 1} \tag{A.1b}$$

Equation (A.1a) is the objective function of this problem. The objective is to minimize the number of running P-OLTs at the final state of optimization ($\sum_{j=1}^{n_{\mathrm{POLT}}} y_j(T)$) and the number of migrated L-OLTs in the optimization process ($\sum_{t=1}^{T} \sum_{i=1}^{n_{\mathrm{LOLT}}} \sum_{j=1}^{n_{\mathrm{POLT}}} \sum_{k=1}^{b} Z_{ijk}^{\mathrm{IN}}(t)$). In this problem, the solution that minimizes the number of migrated L-OLTs is chosen when there are multiple solutions that minimize the number of running P-OLTs. Therefore, the small number, ϵ, is multiplied to the second term to prioritize the first term over the second term. ϵ is given by Eq. (A.1b).

A.2 Constraints

In the model without ODN constraints, constraints of Eq. (A.2)–(A.9) and decision variables of (A.31)–(A.34) are used. A constraint for the case of in-advance L-OLT configuration, Eq. (A.37), is also valid in the evaluation in 3.5.1.

On the other hand, in the model with ODN constraints, constraints of Eq. (A.2)–(A.30) and decision variables of (A.31)–(A.36) are used. A constraint for the case of in-advance L-OLT configuration, Eq. (A.37), and constraints for the case of in-advance access path setting, Eq. (A.38)–(A.41), are added depending on the situation (see 3.5.2).

Subject to:

$$x_{ijk}^{\mathrm{LOLT}}(t+1) - Z_{ijk}^{\mathrm{IN}}(t+1) + Z_{ijk}^{\mathrm{OUT}}(t+1) = x_{ijk}^{\mathrm{LOLT}}(t)$$

$$(\forall i, j \text{ in P-OLT}, \forall k, 0 \le t \le T-1) \tag{A.2}$$

$$\sum_{i=1}^{n_{\mathrm{LOLT}}} Z_{ijk}^{\mathrm{IN}}(t) \le 1 \; (j \text{ in P-OLT}, \forall k, 1 \le t \le T) \tag{A.3}$$

$$\sum_{i=1}^{n_{\mathrm{LOLT}}} Z_{ijk}^{\mathrm{OUT}}(t) \le 1 \; (j \text{ in P-OLT}, \forall k, 1 \le t \le T) \tag{A.4}$$

$$\sum_{i=1}^{n_{\mathrm{LOLT}}} \sum_{k=1}^{b} w_i x_{ijk}^{\mathrm{LOLT}}(t) \le c y_j(t) \; (j \text{ in P-OLT}, 0 \le t \le T-1) \tag{A.5}$$

$$\sum_{i=1}^{n_{\mathrm{LOLT}}} \sum_{k=1}^{b} w_i x_{ijk}^{\mathrm{LOLT}}(T) \le r c y_j(T) \; (j \text{ in P-OLT}) \tag{A.6}$$

$$\sum_{j=1}^{n_{\mathrm{POLT}}} \sum_{k=1}^{b} x_{ijk}^{\mathrm{LOLT}}(t) = 1 \; (\forall i, 0 \le t \le T) \tag{A.7}$$

$$\sum_{i=1}^{n_{\mathrm{LOLT}}} x_{ijk}^{\mathrm{LOLT}}(t) \le 1 \; (j \text{ in P-OLT}, \forall k, 0 \le t \le T) \tag{A.8}$$

$$\sum_{i=1}^{n_{\mathrm{LOLT}}} \sum_{k=1}^{b} x_{ijk}^{\mathrm{LOLT}}(t) \le b y_j(t) \; (j \text{ in P-OLT}, 0 \le t \le T) \tag{A.9}$$

$$\sum_{k=1}^{b} x_{ijk}^{\mathrm{LOLT}}(t) \le \sum_{\beta=0:(j,\beta) \text{ in Link}}^{n_{\mathrm{POLT}}+n_{\mathrm{PONU}}+n_{\mathrm{WXC}}-1} p_{j\beta ih}(t)$$

$$(\forall i, j \text{ in P-OLT}, h = 1, 0 \le t \le T) \tag{A.10}$$

$$\sum_{\beta=0:(j,\beta) \text{ in Link}}^{n_{\mathrm{POLT}}+n_{\mathrm{PONU}}+n_{\mathrm{WXC}}-1} p_{j\beta ih}(t) \le n_{\mathrm{PONU}} \sum_{k=1}^{b} x_{ijk}^{\mathrm{LOLT}}(t)$$

$$(\forall i, j \text{ in P-OLT}, h = 1, 0 \le t \le T) \tag{A.11}$$

$$\sum_{\beta=0:(j,\beta)\text{ in Link}}^{n_{\mathrm{POLT}}+n_{\mathrm{PONU}}+n_{\mathrm{WXC}}-1} p_{j\beta ih}(t) = 0$$

$$(\forall i, j \text{ in P-OLT}, h \ne 1, 0 \le t \le T) \tag{A.12}$$

$$\sum_{\alpha=0:(\alpha,j)\text{ in Link}}^{n_{\mathrm{POLT}}+n_{\mathrm{PONU}}+n_{\mathrm{WXC}}-1} p_{\alpha jih}(t) = 0$$

$$(\forall i, j \text{ in P-OLT}, \forall h, 0 \le t \le T) \tag{A.13}$$

$$x_{ij}^{\mathrm{LONU}} = \sum_{\alpha=0:(\alpha,j)\text{ in Link}}^{n_{\mathrm{POLT}}+n_{\mathrm{PONU}}+n_{\mathrm{WXC}}-1} \sum_{h=1}^{d} p_{\alpha jih}(t)$$

$$(\forall i, j \text{ in P-ONU}, 0 \le t \le T) \tag{A.14}$$

$$\sum_{\beta=0:(j,\beta)\text{ in Link}}^{n_{\mathrm{POLT}}+n_{\mathrm{PONU}}+n_{\mathrm{WXC}}-1} p_{j\beta ih}(t) = 0$$

$$(\forall i, j \text{ in P-ONU}, \forall h, 0 \le t \le T) \tag{A.15}$$

$$\sum_{\alpha=0:(\alpha,j)\text{ in Link}}^{n_{\mathrm{POLT}}+n_{\mathrm{PONU}}+n_{\mathrm{WXC}}-1} p_{\alpha jih}(t)$$

$$\le \sum_{\beta=0:(j,\beta)\text{ in Link}}^{n_{\mathrm{POLT}}+n_{\mathrm{PONU}}+n_{\mathrm{WXC}}-1} p_{j\beta i(h+1)}(t)$$

$$(\forall i, j \text{ in WXC}, h \ne d, 0 \le t \le T) \tag{A.16}$$

$$\sum_{\beta=0:(j,\beta)\text{ in Link}}^{n_{\mathrm{POLT}}+n_{\mathrm{PONU}}+n_{\mathrm{WXC}}-1} p_{j\beta i(h+1)}(t)$$

$$\le n_{\mathrm{PONU}} \sum_{\alpha=0:(\alpha,j)\text{ in Link}}^{n_{\mathrm{POLT}}+n_{\mathrm{PONU}}+n_{\mathrm{WXC}}-1} p_{\alpha jih}(t)$$

$$(\forall i, j \text{ in WXC}, h \ne d, 0 \le t \le T) \tag{A.17}$$

$$\sum_{\alpha=0:(\alpha,j)\text{ in Link}}^{n_{\mathrm{POLT}}+n_{\mathrm{PONU}}+n_{\mathrm{WXC}}-1} \sum_{h=1}^{d} p_{\alpha jih}(t) \le 1$$

$$(\forall i, j \text{ in WXC}, 0 \le t \le T) \tag{A.18}$$

$$\sum_{\beta=0:(j,\beta)\text{ in Link}}^{n_{\mathrm{POLT}}+n_{\mathrm{PONU}}+n_{\mathrm{WXC}}-1} p_{j\beta ih}(t) = 0$$

$$(\forall i, j \text{ in WXC}, h = 1, 0 \le t \le T) \tag{A.19}$$

$$\sum_{\alpha=0:(\alpha,j)\text{ in Link}}^{n_{\mathrm{POLT}}+n_{\mathrm{PONU}}+n_{\mathrm{WXC}}-1} p_{\alpha jih}(t) = 0$$

$$(\forall i, j \text{ in WXC}, h = d, 0 \le t \le T) \tag{A.20}$$

$$\sum_{h=1}^{d} p_{\alpha\beta ih}(t) \le e_{\alpha\beta} \; (\forall \alpha, \forall \beta, \forall i, 0 \le t \le T) \tag{A.21}$$

$$\sum_{h=1}^{d} p_{\alpha\beta ih}(t) + \sum_{h=1}^{d} p_{\beta\alpha ih}(t) \le 1 \ (\forall\alpha, \forall\beta, \forall i, 0 \le t \le T) \tag{A.22}$$

$$w_i \times \sum_{h=1}^{d} p_{\alpha\beta ih}(t) = \sum_{m=1}^{c} q_{\alpha\beta im}(t) \ (\forall\alpha, \forall\beta, \forall i, 0 \le t \le T) \tag{A.23}$$

$$\sum_{i=1}^{n_{\mathrm{LOLT}}} q_{\alpha\beta im}(t) \le 1 \ (\forall\alpha, \forall\beta, \forall m, 0 \le t \le T) \tag{A.24}$$

$$\sum_{m_2:\max(0,m_1-G)\le m_2\le\min(c,m_1+G)} \ \sum_{i_2:i_1\ne i_2} q_{\alpha\beta i_2 m_2}(t) \le \left\{1 - q_{\alpha\beta i_1 m_1}(t)\right\} \times M \quad (\forall\alpha, \forall\beta, \forall i_1, \forall m_1, 0 \le t \le T) \tag{A.25}$$

$$\sum_{m_2:\max(0,m_1-G)\le m_2\le\min(c,m_1+G)} \ \sum_{i_2:i_1\ne i_2} q_{\beta\alpha i_2 m_2}(t) \le \left\{1 - q_{\alpha\beta i_1 m_1}(t)\right\} \times M \quad (\forall\alpha, \forall\beta, \forall i_1, \forall m_1, 0 \le t \le T) \tag{A.26}$$

$$\sum_{m_2:m_1+2\le m_2\le c} q_{\alpha\beta im_2}(t) \le -c \times \left\{q_{\alpha\beta im_1}(t) - q_{\alpha\beta i(m_1+1)}(t) - 1\right\} \quad (\forall\alpha, \forall\beta, \forall i, \forall m_1 (1 \le m_1 \le c-1), 0 \le t \le T) \tag{A.27}$$

$$\sum_{\alpha=0:(\alpha,j)\text{ in Link}}^{n_{\mathrm{POLT}}+n_{\mathrm{PONU}}+n_{\mathrm{WXC}}-1} q_{\alpha jim}(t) \le \sum_{\beta=0:(j,\beta)\text{ in Link}}^{n_{\mathrm{POLT}}+n_{\mathrm{PONU}}+n_{\mathrm{WXC}}-1} q_{j\beta im}(t) \quad (\forall i, j \text{ in WXC}, \forall m, 0 \le t \le T) \tag{A.28}$$

$$\sum_{\beta=0:(j,\beta)\text{ in Link}}^{n_{\mathrm{POLT}}+n_{\mathrm{PONU}}+n_{\mathrm{WXC}}-1} q_{j\beta im}(t) \le n_{\mathrm{PONU}} \sum_{\alpha=0:(\alpha,j)\text{ in Link}}^{n_{\mathrm{POLT}}+n_{\mathrm{PONU}}+n_{\mathrm{WXC}}-1} q_{\alpha jim}(t) \quad (\forall i, j \text{ in WXC}, \forall m, 0 \le t \le T) \tag{A.29}$$

$$\sum_{i=1}^{n_{\mathrm{LOLT}}} q_{\alpha\beta im}(t) + \sum_{i=1}^{n_{\mathrm{LOLT}}} q_{\beta\alpha im}(t) \le 1 \quad (\forall\alpha, \forall\beta, \forall m, 0 \le t \le T) \tag{A.30}$$

$$x_{ijk}^{\mathrm{LOLT}}(t) \in \{0, 1\} \ (\forall i, j \text{ in P-OLT}, \forall k, 0 \le t \le T) \tag{A.31}$$

$$y_j(t) \in \{0, 1\} \; (j \text{ in P-OLT}, 0 \le t \le T) \tag{A.32}$$

$$Z^{\mathrm{IN}}_{ijk}(t) \in \{0, 1\} \; (\forall i, j \text{ in P-OLT}, \forall k, 0 \le t \le T) \tag{A.33}$$

$$Z^{\mathrm{OUT}}_{ijk}(t) \in \{0, 1\} \; (\forall i, j \text{ in P-OLT}, \forall k, 0 \le t \le T) \tag{A.34}$$

$$p_{\alpha\beta ih}(t) \in \{0, 1\} \; (\forall(\alpha,\beta), \forall i, \forall h, 0 \le t \le T) \tag{A.35}$$

$$q_{\alpha\beta im}(t) \in \{0, 1\} \; (\forall(\alpha,\beta), \forall i, \forall m, 0 \le t \le T) \tag{A.36}$$

Constraint for the Case of In-advance L-OLT Configuration:

$$\sum_{i=1}^{n_{\mathrm{LOLT}}} \left\{ Z^{\mathrm{IN}}_{ijk}(t) + Z^{\mathrm{OUT}}_{ijk}(t) \right\} \le 1$$
$$(j \text{ in P-OLT}, \forall k, 1 \le t \le T) \tag{A.37}$$

Constraint for the Case of In-advance Access Path Setting:

$$\sum_{i=1}^{n_{\mathrm{LOLT}}} q_{j\beta im}(t) - \sum_{i=1}^{n_{\mathrm{LOLT}}} q_{j\beta im}(t+1)$$
$$\le 2 - \left\{ \sum_{i=1}^{n_{\mathrm{LOLT}}} q_{\alpha jim}(t) + \sum_{i=1}^{n_{\mathrm{LOLT}}} q_{\alpha jim}(t+1) \right\}$$
$$(\forall \alpha, \forall \beta, j \text{ in WXC}, \forall m, 0 \le t \le T-1) \tag{A.38}$$

$$\left\{ \sum_{i=1}^{n_{\mathrm{LOLT}}} q_{\alpha jim}(t) + \sum_{i=1}^{n_{\mathrm{LOLT}}} q_{\alpha jim}(t+1) \right\} - 2$$
$$\le \sum_{i=1}^{n_{\mathrm{LOLT}}} q_{j\beta im}(t) - \sum_{i=1}^{n_{\mathrm{LOLT}}} q_{j\beta im}(t+1)$$
$$(\forall \alpha, \forall \beta, j \text{ in WXC}, \forall m, 0 \le t \le T-1) \tag{A.39}$$

$$\sum_{i=1}^{n_{\mathrm{LOLT}}} q_{\alpha jim}(t) - \sum_{i=1}^{n_{\mathrm{LOLT}}} q_{\alpha jim}(t+1)$$
$$\le 2 - \left\{ \sum_{i=1}^{n_{\mathrm{LOLT}}} q_{j\beta im}(t) + \sum_{i=1}^{n_{\mathrm{LOLT}}} q_{j\beta im}(t+1) \right\}$$
$$(\forall \alpha, \forall \beta, j \text{ in WXC}, \forall m, 0 \le t \le T-1) \tag{A.40}$$

$$\left\{ \sum_{i=1}^{n_{\mathrm{LOLT}}} q_{j\beta im}(t) + \sum_{i=1}^{n_{\mathrm{LOLT}}} q_{j\beta im}(t+1) \right\} - 2$$
$$\le \sum_{i=1}^{n_{\mathrm{LOLT}}} q_{\alpha jim}(t) - \sum_{i=1}^{n_{\mathrm{LOLT}}} q_{\alpha jim}(t+1)$$
$$(\forall \alpha, \forall \beta, j \text{ in WXC}, \forall m, 0 \le t \le T-1) \tag{A.41}$$

Equations (A.2)–(A.9) are constraints related to the migration movement of L-OLTs. Equation (A.2) defines the transition of placement of L-OLT i from tth step to $t+1$th step. Equation (A.3) means that at most one L-OLT is migrated to configuration board k of P-OLT j. Equation (A.4) means that at most one L-OLT is migrated from configuration board k of P-OLT j. Equation (A.5) means that the total number of allocated frequency slots on running P-OLT j is less than or equal to c at tth ($t < T$) step of the L-OLT migration. Equation (A.6) means that the total number of allocated frequency slots on running P-OLT j is less than or equal to $r \times c$ at Tth step (the final state) of the L-OLT migration. Equation (A.7) means that a single L-OLT i occupies a single configuration board in a P-OLT. Equation (A.8) means that a single configuration board k of P-OLT j is occupied by at most one L-OLT. Equation (A.9) means that L-OLTs can be configured on configuration boards of P-OLT j only when P-OLT j is running.

Equations (A.10)–(A.13) are constraints related to the behavior of P-OLTs. Equation (A.10) means that at least one egress link of P-OLT j is selected as a first hop of an access path belonging to L-OLT i if L-OLT i is configured in P-OLT j. Equation (A.11) means that at most n_{PONU} egress links of P-OLT j are selected as a first hop of an access path belonging to L-OLT i if L-OLT i is configured in P-OLT j. Equation (A.12) means that egress links of P-OLT j can be selected only as a first hop of access paths. Equation (A.13) means that no ingress links of P-OLT j are allocated to access paths. This is because only downstream access paths are considered in this problem.

Equations (A.14) and (A.15) are constraints related to the behavior of P-ONUs. Equation (A.14) means that an ingress link of P-ONU j is allocated to an access path belonging to L-OLT i if a L-ONU that receives network service from L-OLT i is configured on P-ONU j. Equation (A.15) means that no egress links of P-ONU j are allocated to access paths. This is because only downstream access paths are considered in this problem.

Equations (A.16)–(A.20) are constraints related to the behavior of WXCs. Equation

(A.16) means that at least one egress link of WXC j is selected as the $h + 1$th hop of an access path belonging to L-OLT i if one ingress link of WXC j is selected as the hth hop of this access path. Equation (A.17) means that at most n_{PONU} egress links of WXC j are selected as the $h + 1$th hop of an access path belonging to L-OLT i if one ingress link of WXC j is selected as the hth hop of this access path. Equation (A.18) means that at most one ingress link of WXC j is selected as the *something*th hop of an access path belonging to L-OLT i. Equation (A.19) means that no egress links of WXC j are selected as the first hops of access paths. Equation (A.20) means that no ingress links of WXC j are selected as the dth hops of access paths.

Equations (A.21) and (A.22) are constraints related to the behavior of links that connects between P-OLTs, P-ONUs and WXCs. Equation (A.21) means that access paths can be set on link (α, β) only if link (α, β) exists. Equation (A.22) means that an access path belonging to L-OLT i can be set unidirectionally on link (α, β).

Equations (A.23)–(A.30) are constraints related to frequency slot allocation. Some equations are defined by reference to [A-1]. Equation (A.23) means that w_i frequency slots are allocated to an access path belonging to L-OLT i on link (α, β) if link (α, β) is selected as the *something*th hop of this access path. Equation (A.24) means that frequency slot m can be allocated to at most one access path on link (α, β). Equations (A.25) and (A.26) mean that if frequency slot m_1 is allocated to an access path belonging to L-OLT i_1 on link (α, β), frequency slots around m_1 including guardband slots cannot be allocated to other access paths on link (α, β), regardless of its direction (α to β, or β to α). Equation (A.27) means that if frequency slot m_1 is allocated to an access path belonging to L-OLT i and frequency slot $m_1 + 1$ is not allocated on link (α, β), all frequency slots further than $m_1 + 2$ are also not allocated to this access path on link (α, β). This equation ensures the contiguity of allocated frequency slots. Equation (A.28) means that frequency slot m is allocated to an access path belonging to L-OLT i on at least one egress link of WXC j

if frequency slot m is allocated to this access path on one ingress link of WXC j. This equation ensures the continuity of allocated frequency slots. Equation (A.29) means that frequency slot m is allocated to an access path belonging to L-OLT i on at most n_{PONU} egress links of WXC j if frequency slot m is allocated to this access path on one ingress link of WXC j. Equation (A.30) means that frequency slot m can be allocated unidirectionally on link (α, β).

Equations (A.31)–(A.36) are definitions of decision variables (see Table 3.1 in Chapter 3 for details).

Equation (A.37) is the constraint when configuration of L-OLT is executed in advance of suspension of data sending. It forbids the simultaneous occurrence of L-OLT release ($\sum_{i=1}^{n_{\text{LOLT}}} Z_{ijk}^{\text{OUT}}(t) = 1$) and L-OLT configuration ($\sum_{i=1}^{n_{\text{LOLT}}} Z_{ijk}^{\text{IN}}(t) = 1$) on configuration board k in P-OLT j at tth step. This additional constraint ensures that an L-OLT is migrated to a vacant configuration board.

Equations (A.38)–(A.41) are the constraint when setting an access path is executed in advance of suspension of data sending. It means that if an access path that uses frequency slot m is routed through WXC j at both tth and $t+1$th steps, an ingress link and an egress link of this access path do not change between tth and $t+1$th steps. This additional constraint ensures that a new access path is configured so as not to interrupt any existing access path.

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List of the related papers

Journal papers

Papers related to this dissertation

(1) **Takehiro SATO**, Kunitaka ASHIZAWA, Kazumasa TOKUHASHI, Daisuke ISHII, Satoru OKAMOTO, Eiji OKI, and Naoaki YAMANAKA, "A Design Method of High-Reliability and Low-Optical-Loss Optical Aggregation Network Using 2×2 Optical Switch," IEICE Transactions on Communications (Japanese Edition), Vol. J94-B, No. 8, pp. 1508-1512, November 2011. (in Japanese)

(2) **Takehiro SATO**, Yuki HIGUCHI, Hidetoshi TAKESHITA, Satoru OKAMOTO, Naoaki YAMANAKA, and Eiji OKI, "Logical OLT Migration in Elastic Lambda Aggregation Network," IEICE Transactions on Communications (Japanese Edition), Vol. J97-B, No. 7, pp. 474-485, July 2014. (in Japanese)

(3) **Takehiro SATO**, Kunitaka ASHIZAWA, Hidetoshi TAKESHITA, Satoru OKAMOTO, Naoaki YAMANAKA, and Eiji OKI, "Logical Optical Line Terminal Placement Optimization in the Elastic Lambda Aggregation Network With Optical Distribution Network Constraints," IEEE/OSA Journal of Optical Communications and Networking, Vol. 7, Issue 9, pp. 928-941, September 2015.

(4) **Takehiro SATO**, Asato KOTSUGAI, Hidetoshi TAKESHITA, Satoru OKAMOTO, Naoaki YAMANAKA, and Eiji OKI, "TDMA-based OLT Virtualization for ONU

Connection Retention in Elastic Lambda Aggregation Network," IEICE Transactions on Communications (Japanese Edition), Vol. J99-B, No. 3, March 2016 (to be published). (in Japanese)

Other papers

(1) Kunitaka ASHIZAWA, **Takehiro SATO**, Kazumasa TOKUHASHI, Daisuke ISHII, Satoru OKAMOTO, Naoaki YAMANAKA, and Eiji OKI, "On-Demand Multicast Slot Allocation Scheme For Active Optical Access Network Using PLZT High-Speed Optical Switches," Cyber Journals: Journal of Selected Areas in Telecommunications (JSAT), Vol. 2, No. 5, pp. 19-27, May 2011.

(2) Kunitaka ASHIZAWA, **Takehiro SATO**, Kazumasa TOKUHASHI, Daisuke ISHII, Satoru OKAMOTO, Naoaki YAMANAKA, and Eiji OKI, "Scalable Active Optical Access Network Using Variable High-Speed PLZT Optical Switch/Splitter," IEICE Transactions on Communications, Vol. E95-B, No. 3, pp. 730-739, March 2012.

(3) Naoaki YAMANAKA, Hidetoshi TAKESHITA, Kazumasa TOKUHASHI, and **Takehiro SATO**, "Next Generation Green Metro/Access Network Architecture using Time-slot-based Optical Aggregation Network for Multi-service Access," Cyber Journals: Journal of Selected Areas in Telecommunications (JSAT), Vol. 3, No. 2, pp. 7-12, February 2013.

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Patents

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