

**Field Measurement and Analysis of
Next-Generation Optical Access Network with
Optical Amplifiers**

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Preface

Telecommunication carriers must respond to recent increasing traffic demands through research and development for optical access networks, which require vast economical investments. This thesis discusses high-splitting-ratio (HSR) and long-reach (LR) 10 Gb/s Ethernet passive optical network (10G-EPON) systems with optical amplifiers (OAs) for reducing operational expense (OPEX) and capital expenditure (CAPEX). The feasibility of the system is demonstrated through field measurements on a commercial infrastructure. The automatic configurable OA (AC-OA) is also proposed to solve the optical overloading problem. An optical amplifier layout problem (OALP) is formulated for optimizing the layout of LR-PONs in order to design cost-effective optical access networks.

First, the thesis reviews the history of communication technology and explains how communication technology has evolved. Then, the important issue for the access network is described to reduce the costs in terms of the vast size of the access network infrastructure. 10G-EPON can be a candidate for the next-generation optical access network that meets wide-communication-bandwidth demands.

Next, the thesis describes the scheme in which 10G-EPON with OAs satisfies requirements for a next-generation optical access network based on a survey of previous research studies. It is also essential to reduce the CAPEX and OPEX of PON so that telecommunication carriers can enhance their profitability by investing in the next-generation PON. In order to offer 10G-EPON services to more customers efficiently, it is useful to improve the acceptable link budget of access systems by using burst-mode OAs. Increasing the splitting ratio reduces both CAPEX and OPEX by improving the number of subscribers that one optical line termination (OLT) can accommodate. Extending the transmission distance reduces OPEX by eliminating intermediate offices. The thesis also describes the basic structure of HSR- and LR-PON with OAs for amplifying a degraded optical signal. The discussion concludes that semiconductor optical amplifier (SOA) is the most promising of the OAs for next-generation

access networks.

The theory and mechanism of the 10G-EPON using optical amplifiers are explained, so it is necessary to analyze and discuss the result of the field measurement. Then, the concept of optical budget, the structure of the optical transceiver and the optical overloading problem of the optical devices are introduced. Also, the mechanism of the N:1 redundant protection system is explained. The N:1 redundant protection enhances the reliability of the 10G-EPON. DBA technology is explained for the frame transmission so as to share the fair bandwidth and priority control among optical network units (ONUs). These technologies control the quality of service (QoS) of the system required for providing multi-service accommodation with the PON system.

As an experiment, the thesis demonstrates a HSR- and LR-10G-EPON system with N:1 OSU protection in order to confirm high system reliability. The effectiveness of dual-rate automatic level control (ALC) SOA is introduced for extending the optical loss budget with N:1 redundant topologies. The system can switch from active to redundant channels without any frame loss. The quality of bidirectional frame transmission is not degraded after switching to the redundant channels. The 10G-EPON described in this study combines the OLT and OA with dual-rate functionality and the N:1 protection system.

Based on the experimental results, the thesis presents an analysis method for optimally designing the 10G-EPON system with the splitting ratio and the transmission distance needed to suit the subscriber distribution. As the relationship between input power to SOAs and output power from SOAs is non-linear, a special analysis model is required for the HSR- and LR-10G-EPON system to calculate the total transmission distance. Our solution is to map the total transmission distance based on the parameter of the splitting ratio. Based on this analysis, telecommunication carriers can flexibly design the network architecture and realize OPEX savings.

To avoid optical overloading, the thesis proposes an auto-configurable OA (AC-OA). AC-OA can flexibly and automatically support various PON architectures. AC-OA simplifies and automates network operation by handling various types of OA applications in a unified manner. AC-OA has variable optical attenuators (VOAs) at the input and a controller synchronized with a centralized calculator (CC) and external facility database (FDB). The VOA value is determined by the CC and FDB, and is used to adaptively control the input power of

the OA. AC-OA suits various PON architectures because the mechanism of AC-OA provides simple plug and play OA operation and also suits various HSR- and/or LR-PON architectures. The results of a simulation that clarify the feasibility and the installation expenditure reduction effect are described. The thesis confirms AC-OA operation by using the field measurement results gathered from a commercial access network.

The effect of the office reduction ratio (ORR) is also discussed of LR-PON in order to quantify its profitability. This thesis also formulates an optical amplifier layout problem (OALP) dedicated to planning the optimum facility layout of the LR-PON using OAs to extend the transmission distance. The objective of OALP is to minimize the number of central offices (COs) on LR-PON, and to clarify an ORR with various specifications of OAs. OALP is applicable regardless of the types and specifications of OAs.

Finally, the 10G-EPON for the next-generation network is summarized. In addition, future studies are also indicated for successive improvements of the next-generation optical access network.

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Abbreviations

ADSL	Asymmetric digital subscriber line
AES	Advanced Encryption Standard
AGC	Automatic gain control
ALC	Automatic level control
AO	Aggregated office
APD	Avalanche photo diode
AR	Anti-reflection
ARPANET	Advanced Research Projects Agency Network
ASE	Asynchronous spontaneous emission
ATT	Optical attenuator
BER	Bit error rate
BPF	Band pass filter
BSD	Berkeley Software Distribution
CAGR	Compound annual growth rate
CAPEX	Capital expenditure
CC	Centralized computer
CDR	Clock data recovery
CO	Central office
CW	Continuous wave
CWDM	Coarse wavelength division multiplexing
DARPA	Defense Advanced Research Projects Agency
DBA	Dynamic bandwidth allocation
DCN	Data communication network
DFB	Distributed feedback
EDFA	Erbium-doped fiber amplifier

EFM	Ethernet in the first mile
EPON	Ethernet passive optical network
ER	Extinction ratio
FB	Feedback
FP	Fabry-perot
FDB	Facility database
FEC	Forward error correction
FF	Feed-forward
FLP	Facility layout problem
FTM	Fiber termination module
FTTH	Fiber to the home
GHz	Gigahertz
HSR	High-splitting-ratio
IDM	Integrated distribution module
IETF	Internet Engineering Task Force
IEEE	Institute of Electrical and Electronics Engineers
IP	Internet Protocol
ISDN	Integrated services digital network
ITU	International Telecommunication Union
LAN	Local area network
LD	Laser diode
LLC	Logical link control
LR	Long-reach
MAC	Medium access control
MHz	Megahertz
MO	Migrated office
ms	Miliseconds
MPCP	Multi-point control protocol
NG-PON2	Next-generation passive optical network 2
OA	Optical amplifier

OEO	Optical-electronic-optical
OFA	Optical fiber amplifier
OFDM	Orthogonal frequency division multiplexing
OTDR	Optical time domain reflectometer
OLT	Optical line terminal
ONU	Optical network unit
OPEX	Operating expense
ORR	Office reduction rate
OSI	Open systems interconnection
OSU	Optical subscriber unit
P2MP	Point to multipoint
PBX	Private board exchange
PC	Personal computer
PCS	Physical coding sublayer
PD	Photo diode
PDFA	Praseodymium-doped fiber amplifier
PDS	Passive double star
PER	Packet error rate
PHY	Physical layer
PLL	Phase-locked loop
PMA	Physical medium attachment
PMD	Physical media dependent
PON	Passive optical network
QAM	Quadrature amplitude modulation
QoS	Quality of service
QPSK	Quadrature phase shift keying
RF	Radio frequency
RO	Relay office
Rx	Receiver
Sec.	Section

SNR	Signal to noise power ratio
SLA	Service level agreement
SNR	Single mode fiber
SRS	Stimulated Raman scattering
SS	Single star
SW	Switch
TCP	Transmission control protocol
TDFA	Thulium-doped fiber amplifier
TDM	Time division multiplexing
TDMA	Time division multiple access
Tx	Transmitter
UDP	User Datagram Protocol
UTP	Unshielded twisted pair
VOA	Variable optical attenuator
VNI	Visual Networking Index
w/	With
w/o	Without
WAN	Wide area network
WDM	Wavelength division multiplexing

Chapter 1

Introduction

1.1 Overview

First, the history of communication technologies is reviewed. The thesis historically explains how communication technology has evolved to the contemporary optical communication network. Next, the cost reduction of the access network is argued as most important issue because the size of the access network infrastructure represents the highest proportion of an entire network infrastructure. Requirements for the next-generation optical access network are also clarified. Finally, this thesis introduces the 10G-EPON system which is the most applicable system to next-generation optical access networks owing to its wide communication bandwidth and its feasibility.

1.2 History of communication technology

“Communication” is one of the oldest human concepts, as humans have to share essential information over a life-span. Humankind has also improved how to communicate by “Conversation,” which can express information between humans through vocal organs by transmitter devices (Tx) and eardrums as receiver devices (Rx). In the next development of communication, humankind invented “Documents” to conserve historical and cultural phenomena with highly systematized pragmatic contexts. The transport system for exchanging “Documents” was then improved using a “Postal system.” The postal system represents the original concept of the packet exchange protocol used in contemporary network systems, such as the destination and sender address, the delay, and the reliability of the data transmission.

In the 19th century, humankind tried to establish telecommunication technologies with

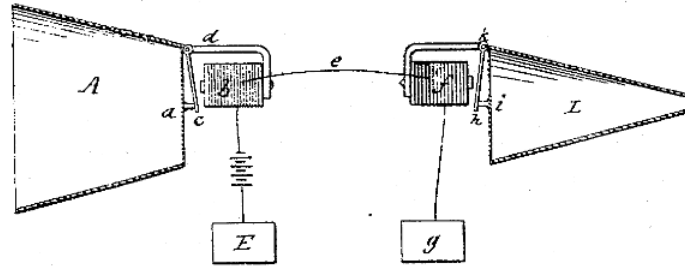


Fig. 1.1 The first telephone system was invented by Graham Bell in 1876 [1].

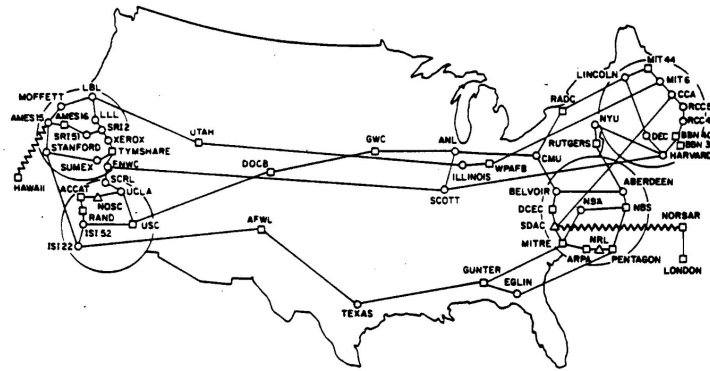


Fig. 1.2 ARPANET was developed to interconnect client nodes in the US Defense Department in 1969. ARPANET employs a packet exchange method, which is the fundamental protocol for current communication systems. Although ARPANET was demonstrated as a small network connecting 4 nodes, it was developed as a larger network with 34 nodes in only 3 years. In 1975, TCP/IP was standardized by the Internet engineering task force (IETF) of the ARPANET project [2].

electronic signals over metal cables installed between subscribers. In 1837, the telecommunication service was commercialized. A telecommunication service for voice exchange became known as the "Telephone." The first telephone system was invented by Graham Bell in 1876 [1] as shown in Fig. 1.1. It employs a relay station which has a private branch exchange (PBX) to establish communication links.

This circuit exchange system with PBX was evolved as a packet exchange system by ARPANET. As shown in Fig. 1.2, ARPANET was developed to interconnect client nodes in the US Defense Department in 1969. ARPANET employs a packet exchange method, which

is the fundamental protocol for current communication systems. Communication packets employ a set of data consisting of overhead data such as a source/destination address and a datagram type/length/value. Although ARPANET was demonstrated as a small network connecting 4 nodes, it was developed as a larger network with 34 nodes in only 3 years. In 1975, Transmission control protocol/Internet protocol (TCP/IP) was standardized by the Internet engineering task force (IETF) of the ARPANET project [2].

In 1983, TCP/IP was applied as a standard connection protocol for ARPANET and implemented in Berkley-software-distribution (BSD) UNIX. In 1988, the first Internet service was commercialized based on the TCP/IP technology. In 1995, the Internet has explosively spread because of Windows 95. Windows 95 employed TCP/IP as the standard for fundamental functions involving Internet connection.

While developing TCP/IP, the fundamental principle of the Ethernet was invented by Xerox Corporation's Palo Alto Research Center in 1972. In 1980, IEEE established the 803 Committee to establish 10BASE5 as the first Ethernet standard. As shown in Fig. 1.3, Ethernet covers the functions of physical media dependent (PMD) and medium access control (MAC) in the OSI reference model. TCP/IP includes packet exchange functions on the Network and Transport layers.

Although the 10BASE series originally applied coaxial cables or unshielded twisted pair (UTP) cables as the transmission medium, the 10BASE-F series first adopted multi-mode optical fibers (MMFs) in 1995. The 1000BASE and 10GBASE series were also standardized for the transmission medium of single-mode optical fibers (SMFs) after 2002 [3]. Thus, the Ethernet has become the current standard for local area networks (LANs). With these technologies, many subscribers can access information through optical fibers from any servers or clients distributed areas across the globe.

1.3 Network architectures

This section introduces overviews of contemporary network system architectures. Network systems are essentially classified into core networks, metro networks, and access networks, as shown in Fig. 1.4.

Core networks are located at the top of the network architecture, and transport large

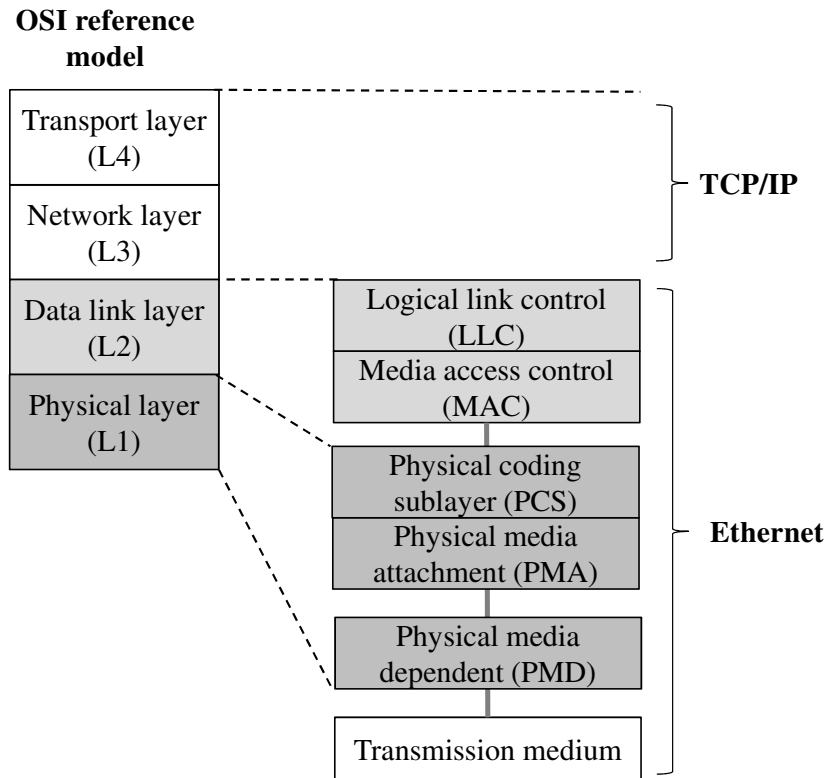


Fig. 1.3 Ethernet handles the physical media dependent (PMD) and medium access control (MAC) functions in the OSI reference model. TCP/IP handles packet exchange functions over network and transport layers.

amounts of data traffic among the large area units through large-capacity optical fibers. Metro networks are located in the next-lower layer of the core network, and interconnect the local area units using a ring architecture. Access networks are located in the lowest layer of the network, and distribute data traffic to subscribers using a star topology.

It should be noted that access networks represent the majority of costs in the network because they have to connect central offices (COs) with a large number of subscribers by optical fibers, known as "Ethernet in the first mile (EFM)." In addition, the access network requires a large amount of infrastructure, including cable poles, optical splitters, and fiber termination modules (FTMs) [4, 5]. In the literature [6], the total cost of access networks represents 80% of the cost of a network infrastructure. Therefore, it is especially important to develop cost-effective access networks to improve the profitability of a telecommunications carrier and decrease environmental loads.

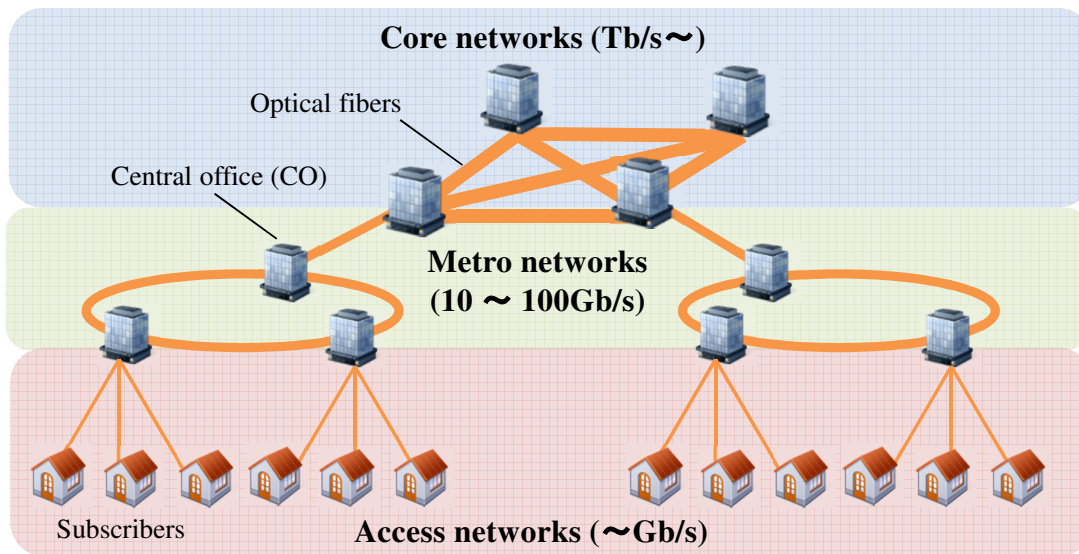
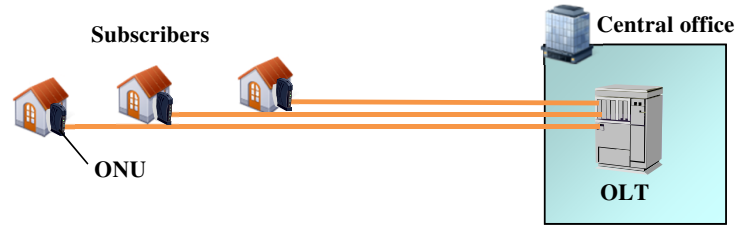


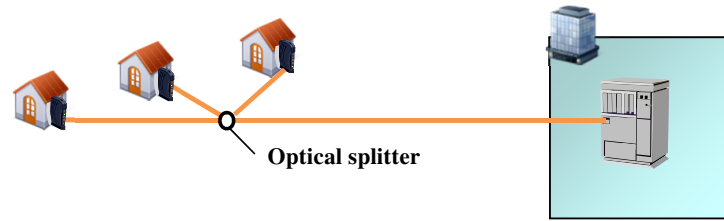
Fig. 1.4 Core networks are located at the top of the network architecture, and transport large amounts of data traffic among large area units through large-capacity optical cables. Metro networks are located in the next-lower layer of the core network, and interconnect the local area units using a ring architecture. Access networks are located in the lowest layer of the network, and distribute data traffic to subscribers using a star topology.

Originally, copper cables, which are already deployed for the legacy telephone system [7], were reused as a transmission medium to access network services. Reusing copper cables was more cost-effective than newly-installed transmission mediums. In the 2000s, Integrated Services Digital Network (ISDN) [8–10] and Asymmetric Digital Subscriber Line (ADSL) [11, 12] spread rapidly as the major access network services in Japan. However, they caused traffic congestion, which degraded the quality of services (QoS).

In the middle of the 2000s, fiber-to-the-home (FTTH) service were deployed as an alternative to ISDN and ADSL. In FTTH, an optical line terminal (OLT) installed in a CO is connected to optical network units (ONUs) through optical fibers. Due to the wide communication bandwidth specification of an optical signal, FTTH can offer an access network service of over 1 Gb/s. As a result, Internet services continued to be developed and diversified into areas such as on-line shopping, video distribution services [13–15], e-book services, social network services (SNS), cloud storage service, and so on. These services facilitate transactions without requiring physical stores. The development of business services including



(a) Single star topology.



(b) PDS topology.

Fig. 1.5 The difference in topologies between a single star (SS) and a passive double star (PDS). SS topology connects an OLT with ONU on the subscriber side. PDS topology is more advantageous than SS topology in terms of a cost-effective access network system, because it can share a single OLT among many ONUs.

financial transactions also provides various economic activities regardless of the environment (e.g., urban or rural areas). Along these lines, increasing the number of mobile terminals requires high quality of service through optical access networks performing as mobile backhaul networks [16, 17].

1.4 Passive optical network for FTTH services

The optical access network systems for FTTH services can be classified into a single star (SS) topology and passive double star (PDS) topology as shown in Fig. 1.5. The SS topology depicted in Fig. 1.5a simply connects an OLT in a CO with an ONU on the subscriber side. On the other hand, the PDS topology is more advantageous in terms of cost-effective access network systems, because the PDS topology allows sharing of a single OLT among many ONUs as shown in Fig. 1.5b.

Fig. 1.6 depicts the transition of the number of FTTH subscribers. The number of subscribers reached 29.00 million in 2016 [18]. As a result, total download and upload traffic

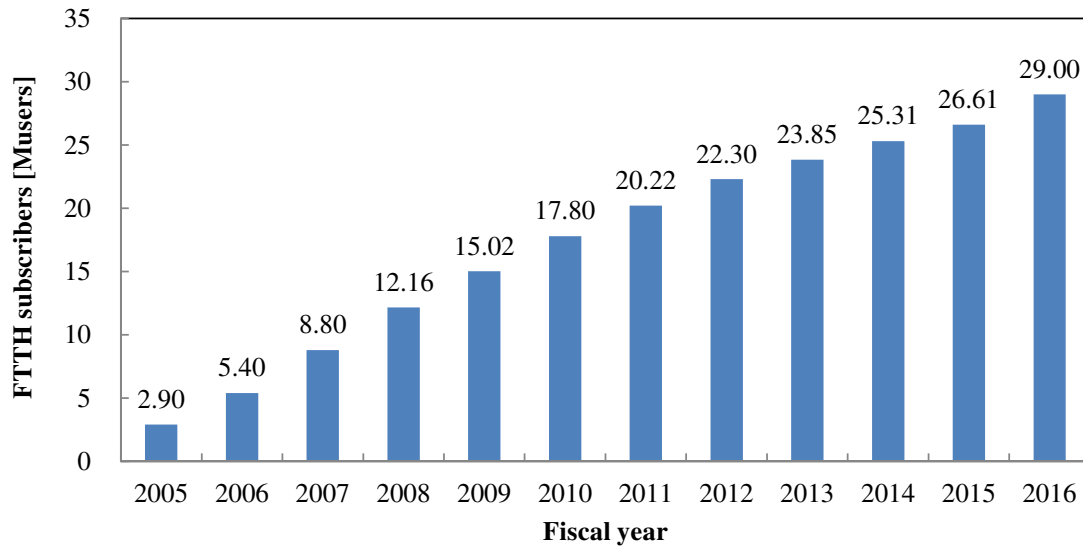


Fig. 1.6 The transition of the number of FTTH subscribers. The number of subscribers reached 29.00 million in 2016 [18].

of FTTH subscribers in Japan grew at rates of 53.5% and 35.5%, respectively, for the same month one year apart, as shown in Fig. 1.7. To meet the increasing demands of Internet traffic, telecommunication carriers must develop the next-generation access network with wider communication bandwidth.

Cisco's Visual Networking Index (VNI) estimates that mobile traffic will increase explosively by 11 times over the next five years [19]. More importantly, modern society will never willingly go back to previous low-speed networks because current technology completely forms and controls our social activities in daily life, business, research, and other areas such as national security. Therefore, telecommunication carriers must respond to future traffic demands by researching and developing optical access networks, although these require vast economical investments.

The above-mentioned survey clearly indicates that the required bandwidth of optical access networks has increased year over year. Transmission bit rates have also evolved in response to the rapid growth of the communication bandwidth. Fig. 1.8 shows the relationship between the maximum bandwidth and the standardization year of the optical access network. The maximum bandwidth approximately increases at a rate of 10 times every 10 years [20].

The representative system for FTTH is passive optical network (PON) with PDS topology.

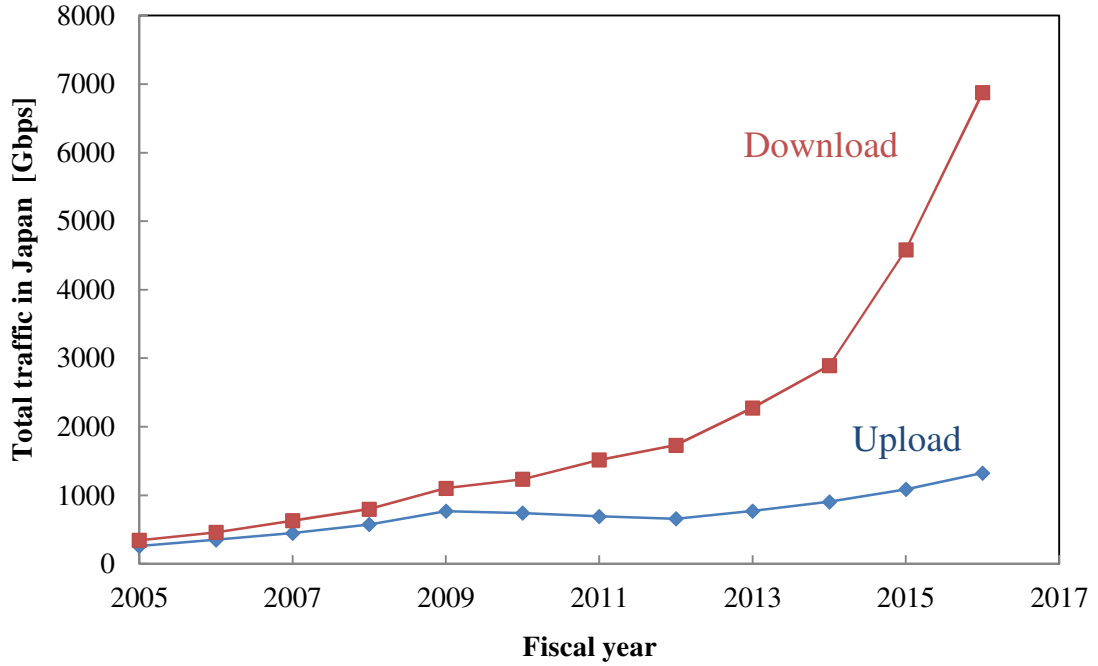


Fig. 1.7 The transition of uploaded and downloaded Internet traffic [18].

The standard of PON is mainly classified into Institute of Electrical and Electronics Engineers (IEEE) system [3,21] and International Telecommunication Union Telecommunication Standardization Sector (ITU-T) system [22–24].

Currently, 1-Gb/s-class PON systems, i.e. Ethernet PON (EPON) or Gigabit-capable PON (GPON), are offering FTTH services to the public [25]. As the next-generation optical access network, 10-Gb/s Ethernet PON [3] (10G-EPON) and Next-generation PON stage-2 [23] (NG-PON2) were standardized in 2009 and 2015, respectively. 10G-EPON is expected to be one of the the upcoming next-generation access network due to its wide communication bandwidth and the positive results of many feasibility studies.

1.5 Requirements for the next-generation access network

This section discusses requirements of the next-generation access network that can meet the exponential increase in Internet traffic demands with a low investment cost. When telecommunication carriers deploy the next-generation access network as the alternative of the legacy FTTH network, they will select one or a combination of the following two strategies;

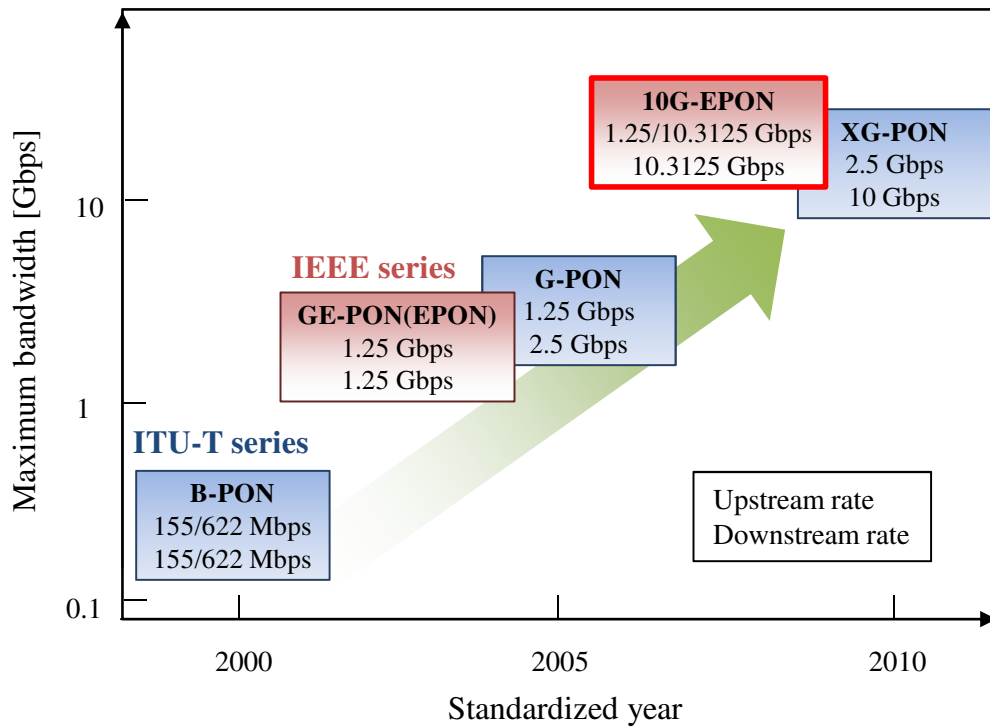


Fig. 1.8 The standards of PON type (ITU-T and IEEE) related to maximum bandwidth. The maximum bandwidth tends to increase at the rate of 10 times every 10 years [20]. ©2016, IEICE

- Introduction of new infrastructures,
- Coexistence with legacy infrastructures.

With the strategy to introduce 10G-EPON as new infrastructure, telecommunication carriers can independently develop and install optical access networks. In this case, they can design new systems without considering interoperability with the legacy infrastructure. The strategy simplifies the system architecture and decreases development costs for the system design; however, the installation costs will be very high because infrastructures must be newly installed on top of legacy infrastructures.

On the other hand, the strategy to maintain interoperability with legacy infrastructures means that telecommunication carriers can reuse and utilize legacy optical access infrastructures such as optical fibers, optical splitters, and FTMs. The strategy is desirable for telecommunication carriers because they can rapidly deploy new services utilizing legacy access infrastructures. However, requirements for the new system to maintain interoperability

and compatibility with legacy systems will be complicated.

In order to discuss the strategy mentioned above, this thesis considers the following economic conditions;

$$Revenue > OPEX + CAPEX, \quad (1.1)$$

Above, *Revenue*, *OPEX* and *CAPEX* are the revenue collected by offering new access network services, the operational expenditure (OPEX) necessary for maintaining the access network infrastructure, and the capital expenditure (CAPEX) required to replace infrastructures, respectively.

Revenue indicates the gross profit gained by providing access network services using FTTH. In order to increase *Revenue*, it is important not only to expand the bandwidth but also provide new access services which increase profits by offering applications tailored to the improved broadband specifications.

OPEX consists of the running costs and the maintenance costs. The running costs are for example manpower costs, air conditioning fees, lighting fees, office maintenance fees, taxes, and so on. The maintenance costs consist of periodic maintenance costs, equipment repair costs, emergency operation costs for sudden failures, and so on. To decrease OPEX, communication carriers must decrease the infrastructure and enhance system reliability.

CAPEX includes not only the infrastructure and installation costs, but also the replacement cost of the operating system. Therefore, telecommunication carriers have to consider the system interoperability between next-generation and legacy optical access network systems to decrease the CAPEX.

To summarize the above discussion, the next-generation optical access network requires the following two specifications;

- Advanced functions for offering new services to increase *Revenue*,
- Interoperability and compatibility with legacy optical access networks to reduce *CAPEX* and *OPEX*.

1.6 Target specification of 10G-EPON

For telecommunication carriers that already provide FTTH services with legacy EPON systems, the 10G-EPON system is a strong candidate for next-generation access network systems. Requirements of next-generation optical access network are summarized by the following five items.

Revenue increase

1. New services development

CAPEX reduction

2. Interoperability with legacy services
3. Equipment cost reduction

OPEX reduction

4. Running cost reduction
5. Maintenance cost reduction

Fig. 1.9 shows the conditions required for the 10G-EPON device and corresponding technologies. Next, the thesis classifies the functions of 10G-EPON for each requirement.

1. New service development

In order to expand the revenue of next-generation access network systems, it is important to develop new services that were difficult to provide with legacy systems. The wide communication bandwidth of 10G-EPON allows the development of multi-services accommodation such as high-resolution video distribution [14] and a mobile backhaul service [17]. The strength lies in improving profits by providing enhanced access services. The overview of the 10G-EPON is addressed in Chapter 2.

Also, the system reliability must be improved to accommodate various high-reliability services such as business and mobile applications. A redundant OLT architecture is effective for improving system reliability with minimum investment. The thesis applies an N:1 protection

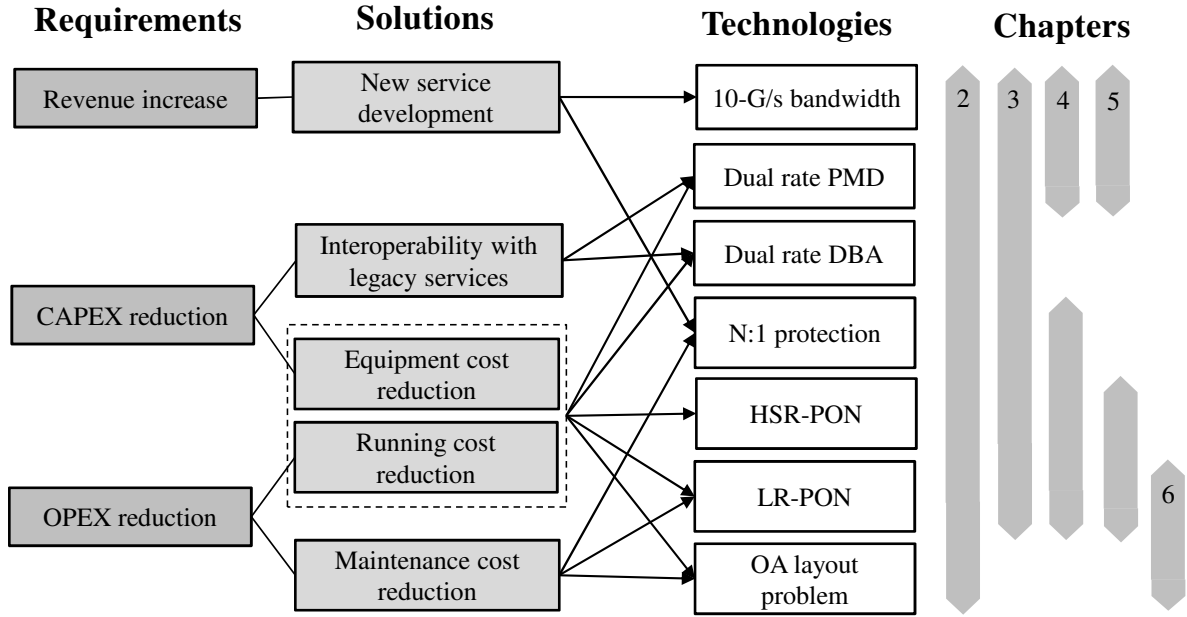


Fig. 1.9 This classifies requirements, solutions and technologies for the 10G-EPON system as a next-generation access network.

system in order to enhance system reliability. N:1 protection is explained and demonstrated in Chapter 2.

2. Interoperability with legacy systems

Interoperability with legacy systems is required for smooth system integration while minimizing the CAPEX for the initial investment of the next-generation access system. In order to ensure interoperability with legacy optical access networks, the following two functions are required for 10G-EPON systems.

- Dual-rate PMD function
- Dual-rate dynamic bandwidth allocation (DBA) function

The first function means that optical transceivers on OLT can transmit and receive optical signals with dual-rates of 1-Gb/s and 10-Gb/s so that the 10G-OLT can accommodate both legacy 1G-ONUs and next-generation 10G-ONUs as shown in Fig. 1.10. Systems using dual-rate operational modules with data rates of 1-Gb/s and 10-Gb/s have been developed in the literature [26, 27]. This multi-service accommodation efficiently decreases CAPEX

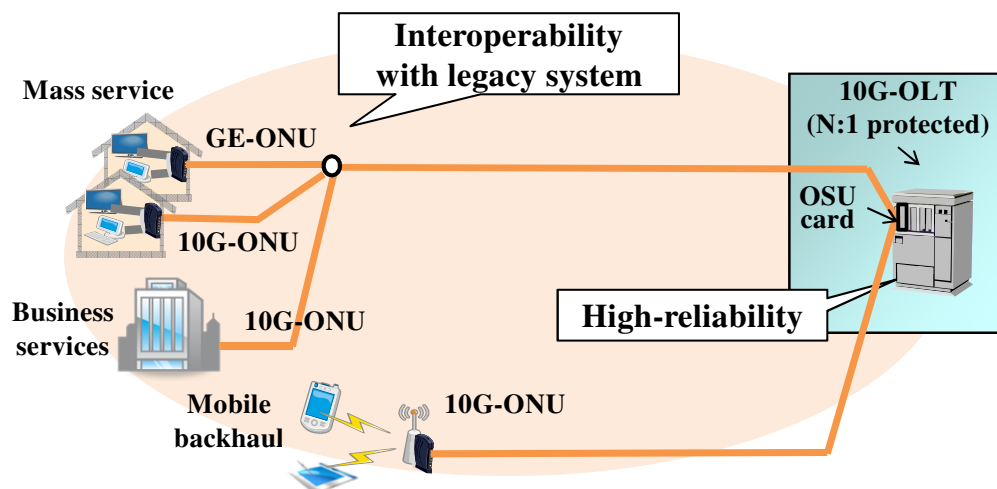


Fig. 1.10 Interoperability between EPON and 10G-EPON systems is realized by dual-rate optical transceivers on the OLT and ONU side, which can transmit and receive an optical signal with dual-rates of 1-Gb/s and 10-Gb/s so that the 10G-OLT can accommodate both legacy 1G-ONUs and next-generation 10G-ONUs. ©2017, OSA, IEEE

and OPEX by sharing the infrastructure among multi-services including legacy 1-Gb/s-class PONs. The developed module can accommodate both legacy and next-generation services without any physical interference. Similarly, 10G-EPON systems must not interfere with other co-existing services using the same legacy facilities and optical fibers. The signals of the legacy and new system must be separated. These PMD functions appear in Chapter 2 in the thesis.

The second function, dynamic bandwidth allocation (DBA), fairly allocates the upstream bandwidth to each ONU based on time division multiple access (TDMA) so as to satisfy service level agreements (SLAs) even if 1G- and 10G-ONUs are connected to a 10G-OLT. DBA functions are discussed in Chapter 2 and Chapter 3 in detail.

3. Equipment cost reduction

Dual rate PMD and DBA functions are effective for reducing equipment costs by integrating 1G and 10G functions on an OLT.

To further reduce equipment costs, a 10G-EPON system with high-splitting-ratio topology over the standardized 32 splits is a strong solution. In the high-splitting-ratio topology, it is

possible to reduce CAPEX by reducing the number of OLTs if the system can accommodate more subscribers. The thesis discusses accomplishing this action using a high-splitting-ratio (HSR) PON, which has an increased splitting-ratio compared to the standard PON.

Additionally, a simple means to decrease equipment costs is to extend the reachable distance and integrate COs by effectively accommodating distributed ONUs to OLTs in the same COs. This thesis defines the long-reach (LR) PON with an extended transmission distance compared to the standard PON.

In order to realize HSR- and LR-PON, there are three solutions;

- (a) high-powered and high-sensitivity OLT/ONU,
- (b) low-loss optical fiber,
- (c) optical amplifiers (OAs).

The first and second solutions are not reasonable because these solutions require replacing large numbers of OLTs, ONUs and optical fibers. These additional operations imply replacing infrastructure, which increases OPEX.

The third solution is the most feasible; installing additional OAs. HSR- and LR-PON with OAs are effective to decrease equipment costs. HSR- and LR-PON have been widely studied by various research institutes. This thesis mainly discusses issues from the viewpoint of practical application. Designability that optimally accommodates subscribers is also an important issue to effectively reduce equipment costs. An analysis method to map D_{Total} using the splitting ratio of HSR- and LR-PON is also offered. With the analysis proposed, telecommunication carriers can optimize the splitting-ratio and reachable distance according to the subscriber distribution. HSR- and LR-PON are introduced and discussed in Chapter 2.

An optical amplifier layout problem (OALP) is also introduced for LR-PON to minimize the number of COs and to clarify the office reduction ratio. OALP makes it possible to optimally design according to the distribution of COs so that it becomes possible to efficiently accommodate more subscribers with a smaller number of OLTs. OALP for LR-PON is explained and formulated in Chapter 2 and Chapter 6.

4. Running cost reduction

Fundamentally, the running cost reduction can be achieved for the same reasons as equipment cost reduction. Dual-rate PMD and DBA functions are obviously effective for reducing the running costs due to the reduction of infrastructure required for EPON and 10G-EPON. HSR- and LR-PON contribute to cut the running costs by effectively reducing the quantity of equipment and COs. Additionally, a simple way to decrease the running cost is to reduce the number of COs by extending the transmission distance between an OLT and connected ONUs. Then, the OALP is critical in effectively minimizing the number of COs, namely, by decreasing total OPEX.

5. Maintenance cost reduction

For reducing OPEX, it is also necessary to minimize the maintenance costs of infrastructures. Maintenance costs include repair costs and emergency operation costs for a sudden failure. If 10G-OLT can switch to a redundant system and continue access services without any interruption even if the system failure or error occurs in a normal system, the system reduces OPEX because it reduces night-time operations to accomplish an exchange.

LR-PON is also the more effective way of reducing maintenance costs. Because the LR-PON can reduce the number of COs as mentioned above, operations for office maintenance can be drastically reduced. Then, an OALP is also important in terms of maintenance cost reduction as well as equipment and running cost reductions.

Summarizing above, 10G-EPON realizes a plug-and-play function to establish communication links by standardized physical and media access control specifications. Also, HSR- and LR-10G-EPON with OAs can reduce various costs including OPEX and CAPEX.

However, there is no systematic research from the viewpoint of items described below.

- The commercial feasibility of dual-rate HSR- and LR-10G-EPON with burst-signal OAs.
- The determination and standardization method for the transmission distance of HSR- and LR-10G-EPON with the various splitting ratio.
- The optical overload which is a specific issue for HSR- and LR-10G-EPON with OAs.
- The layout design of central offices after applying OAs to 10G-EPON.

The thesis discusses the feasibility of HSR- and LR-10G-EPON while clarifying these items with measurement and simulation results.

1.7 Summary

This chapter reviewed the history of communication technologies and explained how communication technology has evolved into contemporary communication systems. The chapter also argued that the cost reduction of the access network is an important issue in terms of the vast size of the access infrastructure. 10G-EPON is the leading candidate to allow the next-generation optical access networks to meet wide communication bandwidth requirements while satisfying increasing traffic demands.

The remainder of this thesis is organized as follows. Chapter 2 examines system requirements for the next generation access network mentioned in Chapter 1. Also, Chapter 2 explains the physical requirements and system theory in order to accurately understand the transmission capabilities of HSR- and LR-PON. In Chapter 3, the results of an actual field measurement of HSR- and LR-PON are presented. Chapter 4 analyzes the transmission distance of HSR- and LR-PON based on the experimental results described in Chapter 3. In Chapter 5, the optical overloading issue that occurs in the case of applying optical amplifiers to PON is discussed. The chapter proposes auto-configurable OAs (AC-OAs) to avoid optical overloading, and discusses the effect of the AC-OA using a simulation-based analysis. In Chapter 6, the thesis describes the layout of optical amplifiers to optimally deploy PON from the viewpoint of the facility placement problem (FLP). In Chapter 7, the 10G-EPON system as the next-generation network is summarized. In addition, future research is also discussed involving successive improvements for future optical access networks.

Chapter 2

Transmission principles of 10G-EPON

2.1 Overview

In this chapter, the principles and concepts behind the 10G-EPON using an optical amplifier (OA) are explained, since this is required to analyze and discuss the results of the field measurement described in the next chapter.

First, this chapter introduces the concept of an optical budget, which determines the transmission distance. The structure of the optical transceiver and the optical overloading problem of the optical devices, including OAs, are also described.

Next, the basic structures of HSR- and LR-PONs with OAs for amplifying an attenuated optical signal are explained. In order to enhance system reliability, the usefulness of the N:1 protection system, which enhances the reliability of the 10G-EPON, is discussed. Furthermore, this chapter explains the importance of flexible design of the transmission distance of the HSR- and LR-PON in order to optimally reduce CAPEX and OPEX.

Finally, the fundamental principle required for understanding the frame transmission control function is introduced. DBA technology is also explained for the frame transmission so as to share the fair bandwidth and priority control among ONUs.

The descriptions in Section 2.1, 2.2 and 2.3 have been already standardized contents by IEEE standard. The descriptions in Section 2.4, 2.5, 2.6, 2.7 and 2.8 are main issues studied in the thesis.

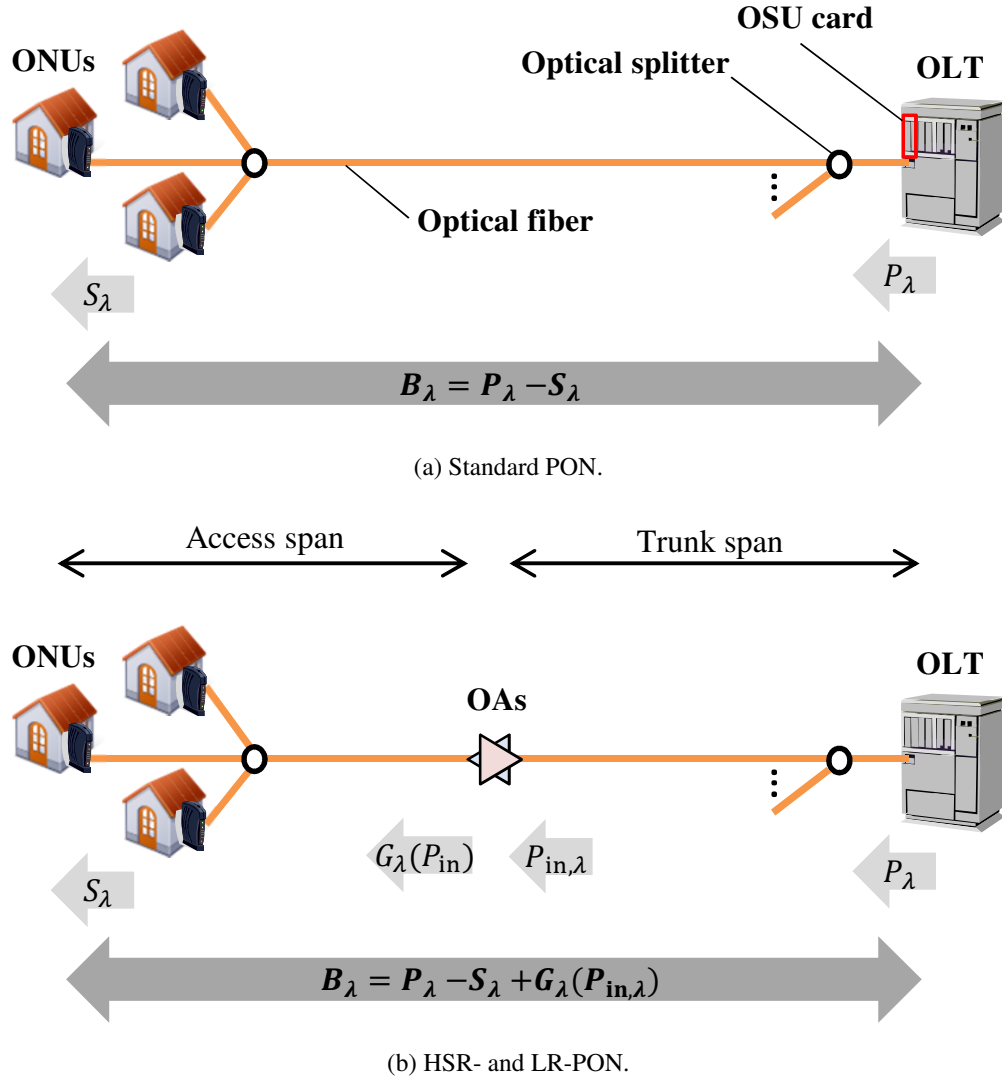


Fig. 2.1 The fundamental concept of an optical budget in the case of the standard PON, HSR-PON, and LR-PON. HSR- and LR-PONs consist of OLTs, OAs, ONUs, optical fibers, and optical splitters. In order to communicate between the Tx and Rx transceivers, the optical budget with the wavelength λ (B_λ) has to exceed the total optical loss of the optical path.

2.2 Transmission condition

2.2.1 Optical budget

Fig. 2.1 shows the fundamental concept of an optical budget in the cases of the standard PON, HSR-PON, and LR-PON. A PON consists of an OLT, ONUs, optical fibers, and optical

splitters. The OLT has multiple optical subscriber unit (OSU) cards so as to communicate with the ONUs through the employed optical transceivers. HSR- and LR-PONs additionally employ OAs on the route of the optical fibers. The span between the OLT and the OAs is defined as the trunk span, and the span between the OAs and ONUs is defined as the access span. Upstream and downstream signals are defined as the signals traveling from the OLT to the ONUs and from the ONUs to the OLT, respectively. The optical signals are multiplexed with a different wavelength.

In order to communicate between the Tx and Rx transceivers, the optical budget with the wavelength λ (B_λ) has to exceed the total optical loss of the optical path. In the 10G-EPON system, the bit-error-rate (BER) has to be equal to or less than 10^{-12} with forward-error-correction (FEC). B_λ is expressed as the following equation:

$$B_\lambda = P_\lambda - S_\lambda, \quad (2.1)$$

where P_λ and S_λ indicate the optical output power and the maximum sensitivity of Rx with the wavelength λ , respectively. P_λ and S_λ have units of decibel milliwatts (dBm), which is the base ten logarithmic ratio to 1 milliwatt. Furthermore, B_λ is in decibels (dB), which means the base ten logarithmic ratio such as the optical loss and the optical gain. In the following description, dBm and dB are used as the units for expressing the optical quantities.

When optical signals are amplified in the intermediate route of the optical path, B_λ is expressed as the following equation:

$$B_\lambda = P_\lambda - S_\lambda + G_\lambda(P_{\text{in},\lambda}), \quad (2.2)$$

where $G_\lambda(P_{\text{in},\lambda})$ is the optical gain function of the OAs.

2.2.2 Optical loss

The total optical loss of the optical path ($L_{\text{Total},\lambda}$) is expressed as the following equation:

$$L_{\text{Total},\lambda} = L_{\text{tr},\lambda} + L_{\text{sp}} + \delta_\lambda + \epsilon_\lambda, \quad (2.3)$$

where $L_{\text{tr},\lambda}$, L_{sp} , δ_λ and ϵ_λ express the optical transmission loss, splitting loss, sensitivity penalty due to the optical dispersion, and sensitivity penalty caused by the degradation of

the extinction ratio (ER), respectively. Using these parameters, the transmission condition is expressed as the following:

$$B_\lambda \geq L_{\text{Total},\lambda}. \quad (2.4)$$

Therefore, the optical budget has to exceed the total optical loss based on Constraint (2.4). It is clear that the effective ways to satisfy Constraint (2.4) are to improve B_λ and/or decrease $L_{\text{Total},\lambda}$.

Transmission loss

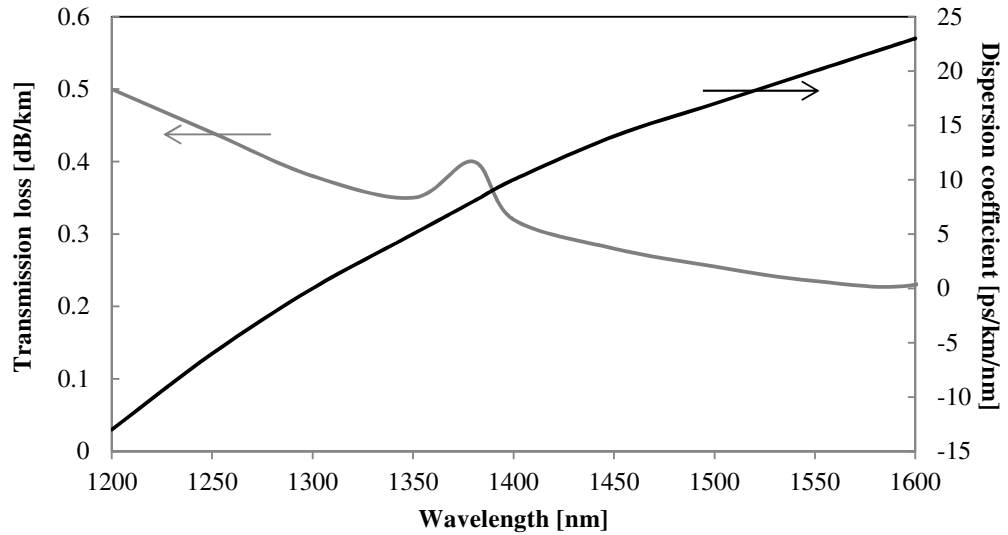


Fig. 2.2 The typical optical transmission loss and the chromatic dispersion dependency of an SMF.

Transmission loss originates from the absorption and reflection of an optical signal traveling in the core glass of the SMF. The transmission loss, $L_{\text{tr},\lambda}$, is a linear factor to the transmission distance D , expressed by the following equation:

$$L_{\text{tr},\lambda} = \alpha_\lambda D, \quad (2.5)$$

where α_λ indicates the optical attenuation rate per distance [dB/km] of the SMF. Typically, α_λ has a dependence on the wavelength λ , as shown in Fig. 2.2. In the thesis, the experimental value of α_λ is measured with the commercial infrastructure for field measurements.

Splitting loss

Optical signals are split by optical splitters in order to share optical fibers and infrastructure among the many ONUs. Then, the splitting loss, L_{sp} , is logarithmically degraded by the splitting of the optical signal power. L_{sp} is expressed as the following formula:

$$L_{sp} = 10 \log_{10} N, \quad (2.6)$$

where N is defined as the splitting ratio. Then, L_{sp} has no dependency to the wavelength λ . For example, when the optical signal is divided into two splits, the optical power of the signal is attenuated by about 3 dB.

Chromatic dispersion

When optical signals travel in the optical fiber, the quality of the optical signal is degraded by the chromatic dispersion. A typical chromatic dispersion dependency of the SMF is depicted in Fig. 2.2. The chromatic dispersion degrades the optical receiver sensitivity. The degradation of the sensitivity, δ_λ , is expressed as

$$\delta_\lambda = -5 \log_{10} [1 - (4B_\lambda D_\lambda d_\lambda \sigma_\lambda)^2]. \quad (2.7)$$

B_λ , d_λ , and γ_λ are the bit rate, dispersion coefficient and root mean square (RMS) width of the optical signal, respectively [28].

Extinction ratio degradation

The OAs generate asymmetric spontaneous emission (ASE) noise, which degrades the extinction ratio of the output optical power [28]. The concept of the extinction ratio (ER) is shown in Fig. 2.3. The ER ($r_{ex,\lambda}$) is defined as the power ratio of the off-state signal ($E_{0,\lambda}$) to the on-state signal ($E_{1,\lambda}$). With $r_{ex,\lambda}$, the quantities of the sensitivity degradation (ϵ_λ) are formulated with the following equation;

$$r_{ex,\lambda} = \frac{E_{1,\lambda}}{E_{0,\lambda}} \quad (2.8)$$

$$\epsilon_\lambda = 10 \log_{10} \left(\frac{1 + r_{ex,\lambda}}{1 - r_{ex,\lambda}} \right). \quad (2.9)$$

Therefore, the low ER degrades transceiver sensitivity.

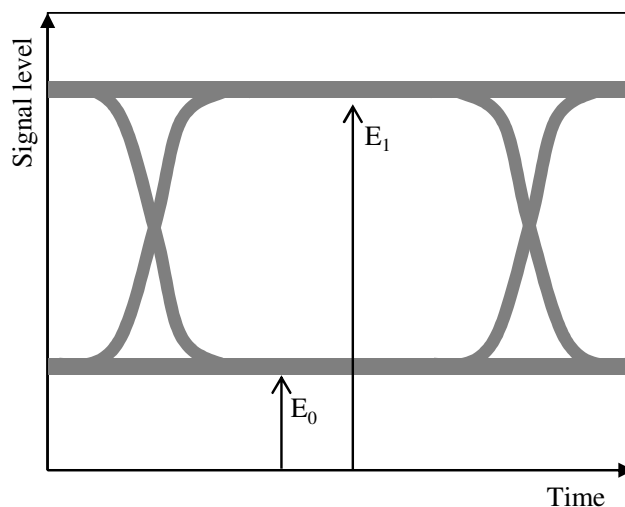


Fig. 2.3 The eye diagram for explaining the concept of the extinction ratio (ER), which is the power ratio of the off-state signal (E_0) to the on-state signal (E_1). Low ER causes the sensitivity degradation of the optical receiver.

2.3 Optical transceiver

The previous section explained that the optical budget determines the transmission distance and the splitting ratio of the optical communications system. This section introduces the structure of the optical transceivers that perform the functions of optical transmission and reception. Table 2.1 shows the standardized parameters of the Tx and Rx of the EPON and 10G-EPON systems. Fig. 2.4 also depicts the wavelength allocation of the EPON and 10G-EPON systems. Optical transceivers consist of laser diodes (LD) for the Tx function, photo diodes (PD) for the Rx function, wavelength division multiplexing (WDM) filters, optical isolators, and so on.

Fig. 2.5 illustrates the block diagram of a 10G-OLT transceiver. The OLT transceiver employs two LDs for sending 10G ($\lambda = 1575$ nm) and 1G ($\lambda = 1490$ nm) signals in order for the 10G- and 1G-ONUs to coexist. Downstream 10G and 1G optical signals are mixed with the WDM coupler and transmitted from the output port of the optical transceiver.

The OLT transceiver has to also receive optical signals from the 10G- and 1G-ONUs through a PD with a wide sensitivity bandwidth. The avalanche PD (APD) is mainly used

Table. 2.1 Standard optical characteristics of EPON and 10G-EPON transceivers.

Item	Upstream	Upstream	Downstream	Downstream
Type	PR30 (10G)	PX20 (1G)	PR30 (10G)	PX20 (1G)
Central wavelength [nm]	1260 to 1280	1260 to 1360	1575 to 1580	1480 to 1500
Average output power [dBm]	+4 to +9	-1 to +4	+2 to +5	+2 to +7
Minimum receive sensitivity [dBm]	-28.5	-24	-28	-27
Damage threshold [dBm]	-9	+7	-5	+4
Transmitter and dispersion penalty [dB]	3	2.3	1.5	1.8

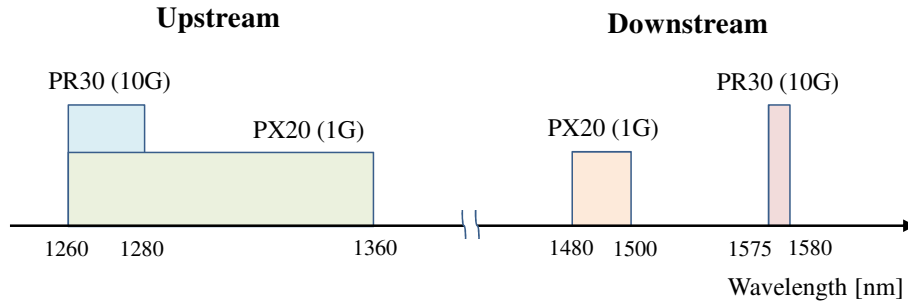


Fig. 2.4 Wavelength allocation for EPON and 10G-EPON.

for 10G-OLT transceiver because it features the high sensitivity due to the electron avalanche phenomenon. Upstream signals are separated from downstream signals by the WDM filter. While downstream signals features continuous wave, upstream signals features bursty behavior because ONUs are connected different distance and send signals with TDMA. The upstream signals are received and converted to electronic signals by APD. The electronic signals are amplified by the electrical pre- and post-amplifier, which generally employ the rate-selection function for receiving dual-rate signals. Finally, the bursty upstream signals are processed through clock data recovery (CDR) for signal reshaping, re-timing and regeneration.

Fig. 2.6 shows the block diagram of the 10G-ONU transceiver. The ONU transceiver employs an FP-LD ($\lambda = 1310$ nm) for the 1G-ONU and a DFB-LD ($\lambda = 1280$ nm) for the 10G-ONU. For 10G-ONUs, the DFB-LD is mainly used due to the low sensitivity penalty for the optical dispersion. The upstream signal is dynamically modulated by an LD driver with a burst controller, which controls the timing of multiple upstream signals sent from each

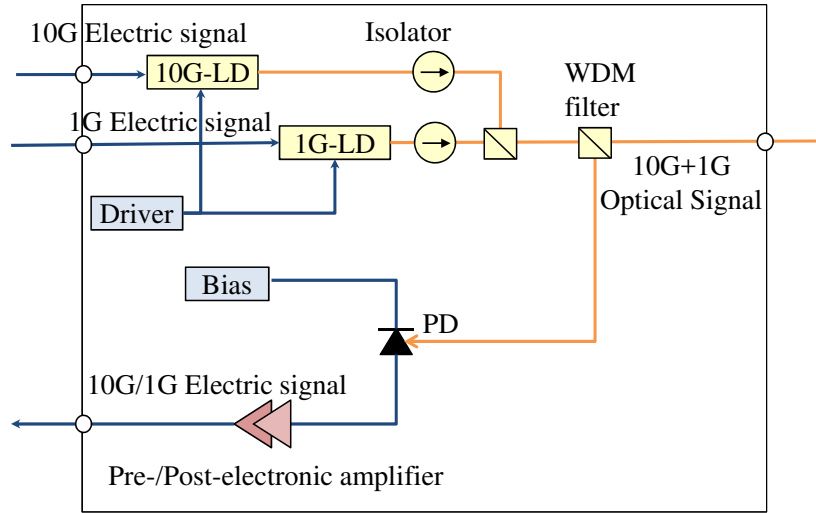


Fig. 2.5 The block diagram of a 10G-OLT transceiver. The OLT transceiver employs two LDs for sending the downstream 10G and 1G signals in order to coexist with the 10G- and 1G-ONUs. The downstream 10G and 1G optical signals are multiplexed with a WDM coupler and transmitted from the output port of the optical transceiver. An APD is applied for Rx since the OLT transceiver has to receive burst signals from the 10G- and 1G-ONUs with a PD by the wide sensitivity bandwidth.

ONU so as to avoid data collision among the signals. The upstream signal and the optical signals from the 1G- and 10G-ONUs are transmitted by time division multiplexing (TDM). The downstream signal is filtered for isolation from other signals such as video distribution service and/or upstream signals. Finally, they are amplified with the pre- and post-amplifiers after the optical-electrical conversion as well as the OLT transceiver.

2.4 Classification of OAs

As mentioned above, it is useful to improve the acceptable link budget of access systems by using OAs. In order to offer 10G-EPON services to more customers efficiently, the OAs for improving the acceptable link budget of the access systems will contribute towards increasing the splitting ratio and extending the transmission distance. Many researchers have attempted to extend the transmission distances of PONs using OAs. OAs are classified into two groups: 3R-type OA (3R-OA) [29] and 1R-type OA (1R-OA) [30].

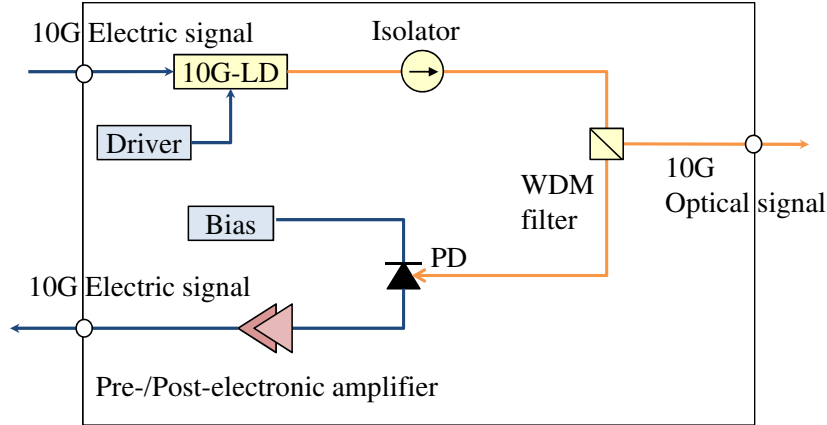


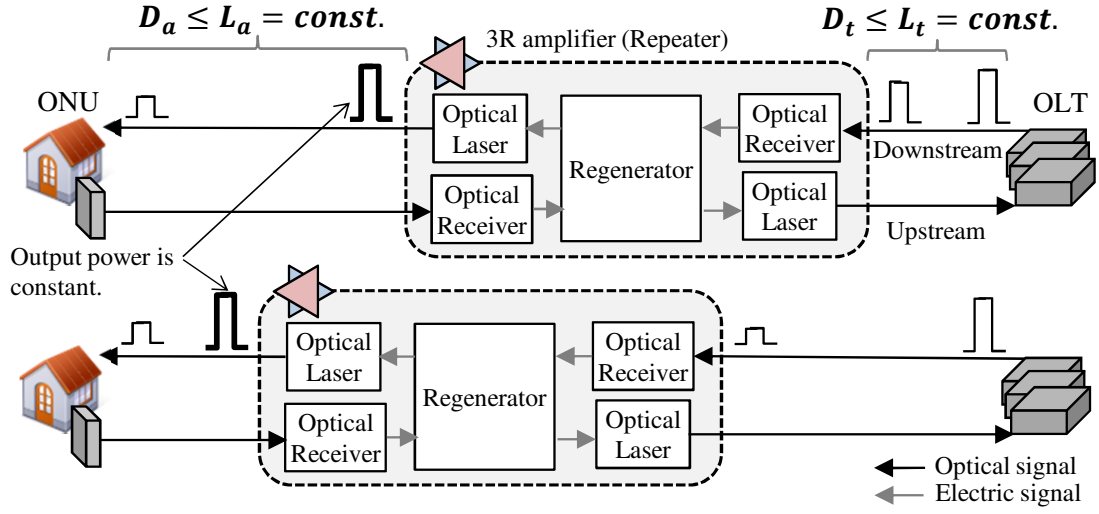
Fig. 2.6 The block diagram of the 10G-ONU transceiver. The ONU transceiver employs Fabry–Perot (FP)-LD for the 1G-ONU and DFB-LD for the 10G-ONU. For 10G-ONUs, DFB-LD is mainly used due to the low sensitivity penalty for the optical dispersion. The upstream signal is dynamically modulated by an LD driver with a burst controller, which controls the timing of multiple upstream signals sent from each ONU so as to avoid the data collision among the signals. The downstream signal to the ONU is filtered to isolate other signals with other wavelengths. Finally, they are amplified with the pre- and post-electrical amplifiers after conversion by the APD as well as the OLT transceiver.

2.4.1 3R-OA

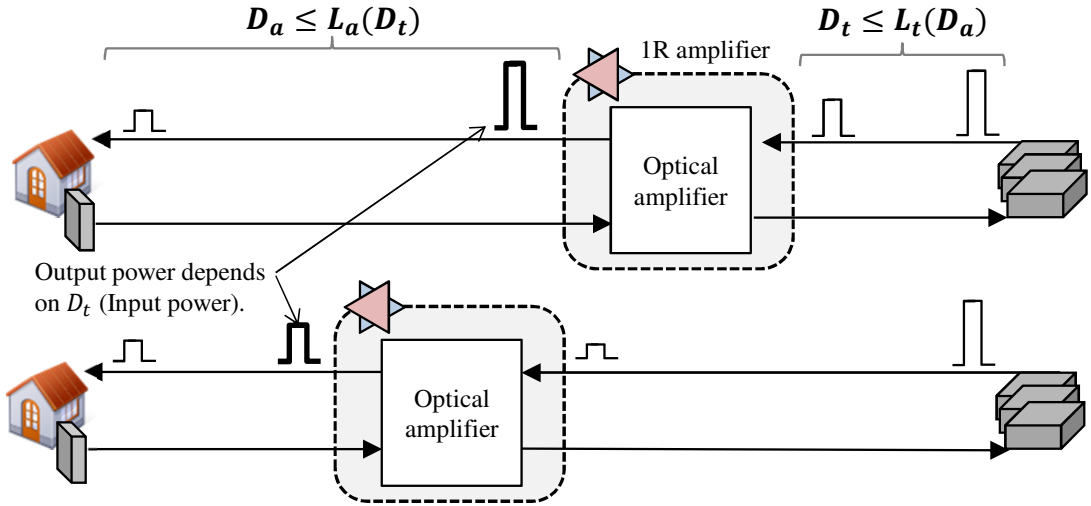
Fig. 2.7 shows the differences between the two groups of OAs. A 3R-OA has an optical-electrical-optical (OEO) structure, where the optical receiver and the transmitter are serially connected as shown in Fig. 2.7a. In the OEO structure, a received optical signal is temporarily converted into an electric signal, and then it is re-converted into the optical signal. When a 3R-OA is employed in a PON, L_t and L_a are uniquely determined by the optical output power and received sensitivity between the OLT and OA, and the OA and ONU, respectively. The trunk distance D_t and access distance D_a cannot exceed the maximum distances L_t and L_a , respectively. The relationships between these parameters are given by:

$$D_t \leq L_t = \text{const.} \quad (2.10)$$

$$D_a \leq L_a = \text{const.} \quad (2.11)$$



(a) The principle of a 3R-OAs. The received optical signal is temporarily converted into an electric signal, and then it is re-converted into the optical signal.



(b) The principle of 1R-OAs. The received optical signal is directly amplified with optical devices.

Fig. 2.7 Comparison between 3R- and 1R-OAs.

For example, in [31], the transmission distance of the ITU-T G.984 Gigabit-capable PON (GPON) was extended to 135 km using 3R-OAs. The authors of [32] stated that the COs can be integrated by using 3R-OAs called Extender Boxes. They also discussed the relationship between the trunk distance D_t and the access distance D_a .

2.4.2 1R-OA

The architecture of a 1R-OA is illustrated in Fig. 2.7b. The received optical signal is directly amplified with optical devices such as semiconductor optical amplifiers (SOAs), optical fiber amplifiers (OFAs), and fiber Raman amplifiers (FRAs). Since the optical signal is not converted into an electric signal, the output optical power from the 1R-OA strongly depends on the input optical power. Considering the downstream signal, when the input optical power to the 1R-OA increases as the trunk distance D_t decreases, the corresponding increase in the output optical power extends the maximum access distance L_a . Conversely, a larger D_t induces a reduction in L_a . Thus, L_a can be formulated as a function of D_t . For the upstream signal, L_t is expressed as a function of D_a in the same way. The constraints for D_t and D_a are described by:

$$D_t \leq L_t(D_a), \quad (2.12)$$

$$D_a \leq L_a(D_t). \quad (2.13)$$

The type and parameters for these functions depend on the specifications of the 1R-OA. Therefore, the types and specifications of OAs need to be considered to optimally locate them and integrate COs. HSR- and LR-PONs with OAs have been studied by many researchers. The OAs contribute to the extension of the transmission distance between the CO and subscribers.

In Eq. (2.2), as described in Section 2.2, $G_\lambda(P_{in,\lambda})$ of the 3R-OA is a constant value. On the other hand, $G_\lambda(P_{in,\lambda})$ of the 1R-OA is a function of the input optical power of the OA. The output power from the OAs depends on the input power according to the 1R-OA's optical nonlinear specifications. The output power is also controlled with an auto level function so that the optical spectrum is not distorted by the gain saturation of OAs. Therefore, B_λ is dynamically changed by the optical gain of the 1R-OAs nonlinearly as the function $G_\lambda(P_{in,\lambda})$.

Optical fiber amplifier (OFA)

The fundamental principle behind OFAs is shown in Fig. 2.8. OFAs amplify the optical signal input through interactions with the excitation beam from pump laser diodes (LDs) and the doped ions of a rare earth element. The interactions occur in the core regions of the

optical fiber. The amplification wavelength can be controlled by the doped ions in OFAs, e.g., erbium-doped fiber amplifiers (EDFAs, $\lambda = 1.5 \mu\text{m}$), praseodymium-doped fiber amplifiers (PDFAs, $\lambda = 1.3 \mu\text{m}$) and thulium-doped fiber amplifiers (TDFAs, $\lambda = 1.4 \mu\text{m}$). In particular, the EDFA, which can amplify a wavelength of $1.55 \mu\text{m}$, is suitable for the downstream optical amplification in the EPON system. OFAs are especially used in core and metro networks due to their features such as high optical gain, broad bandwidth, and polarization independence. The drawbacks are the large equipment size and the high power consumption. Therefore, it is difficult to apply OFAs to the access networks in terms of cost-efficiency.

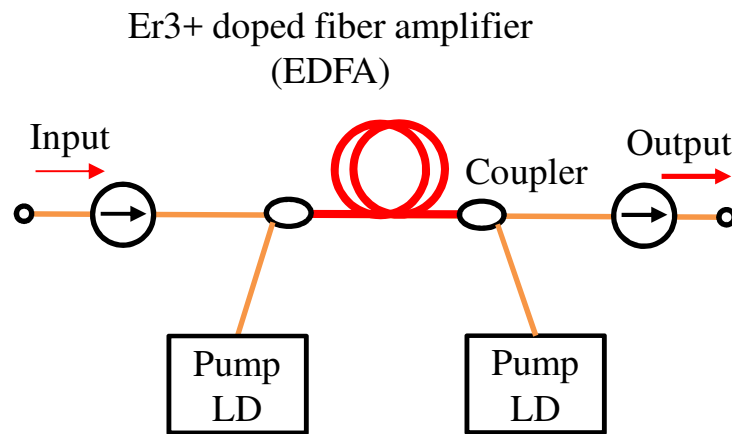


Fig. 2.8 The principle behind OFAs. OFAs amplify the optical signal input through the interactions with the excitation beam from pump LDs and the doped ions of a rare earth element.

Fiber Raman amplifier (FRA)

The fundamental configuration of a Fiber Raman amplifier (FRA) is shown in Fig 2.9. The nonlinear effect called stimulated Raman scattering (SRS) is applied to amplify the optical signal. It can adaptively change the amplification gain depending on the wavelength of the excitation laser with the normal SMF. On the other hand, it is disadvantageous in terms of the high excitation laser power and a long SMF over several kilometers. Since these features limit the scaling of the device, it is not applicable to optical access networks.

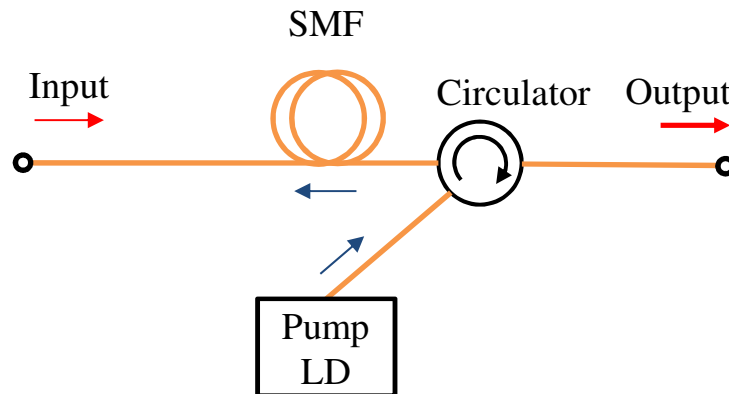


Fig. 2.9 The principle behind a fiber Raman amplifier. The nonlinear effect called stimulated Raman scattering (SRS) is the principle behind the amplification. It can adaptively change the amplification gain depending on the wavelength of the excitation laser with the normal SMF.

Semiconductor optical amplifier (SOA)

The fundamental principle behind SOAs is shown in Fig 2.10. SOA has an equivalent structure to a DFB laser without resonators. SOA employs the anti-reflection (AR) film on both its end edges in order to suppress the laser oscillation. SOA features high optical gain, high response speed, and cost-efficiency. Furthermore, the amplification bandwidth of SOAs can be modified by semiconductor band engineering. Since 10G-EPON and EPON use the L-band and O-band optical wavelengths for the downstream optical signals, respectively, the SOA is suitable for the optical access network.

10G-EPON systems with SOA have been widely studied and their feasibility confirmed. For these reasons mentioned above, SOAs are applied to 10G-EPON for constructing HSR- and LR-PONs.

2.5 HSR- and LR-PONs with OAs

This section clarifies the requirements that the 10G-EPON with OAs must satisfy if it is to realize cost-effective multi-service accommodation. HSR-PONs are defined to have splitting ratios of 64 ONUs or greater, as shown in Fig. 2.11. LR-PONs are defined to have

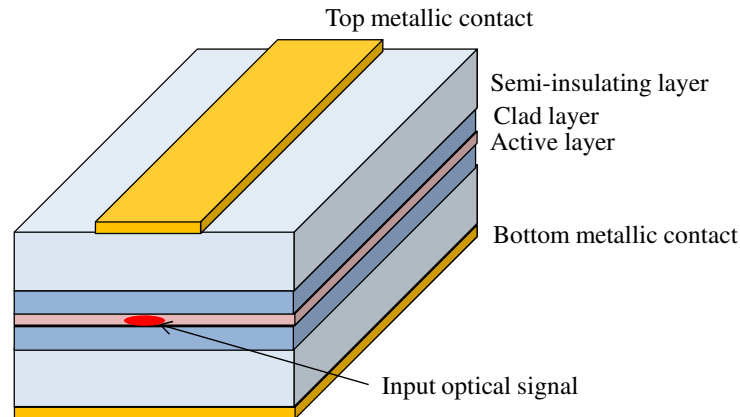


Fig. 2.10 The principle behind SOA. The SOA has an equivalent structure to a DFB laser without resonators. It employs the anti-reflection film on both its end faces in order to suppress laser oscillations.

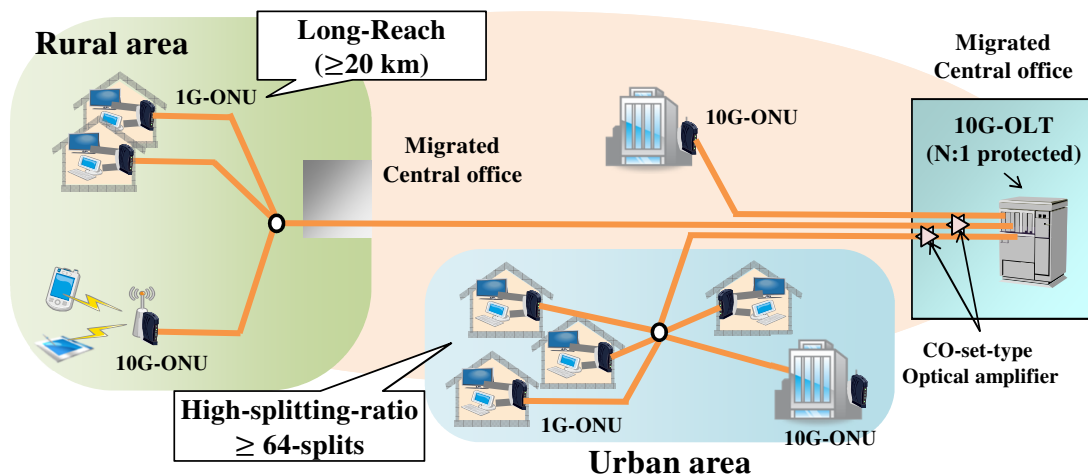


Fig. 2.11 HSR-PONs are defined to have splitting ratios of 64 ONUs or greater. LR-PONs are defined to have transmission distances over 20 km. ©2017, OSA, IEEE

transmission distances over 20 km.

2.5.1 HSR-PON

[33–36] are the key papers on HSR-PON research. Using relay OAs, [33] achieved error-free transmission with a 128x8-split EPON system over a distance of 80 km. [34] proposed a hybrid OA for supporting 1024-split 80-km 10G/1G-EPON mixed bit rate upstream signals.

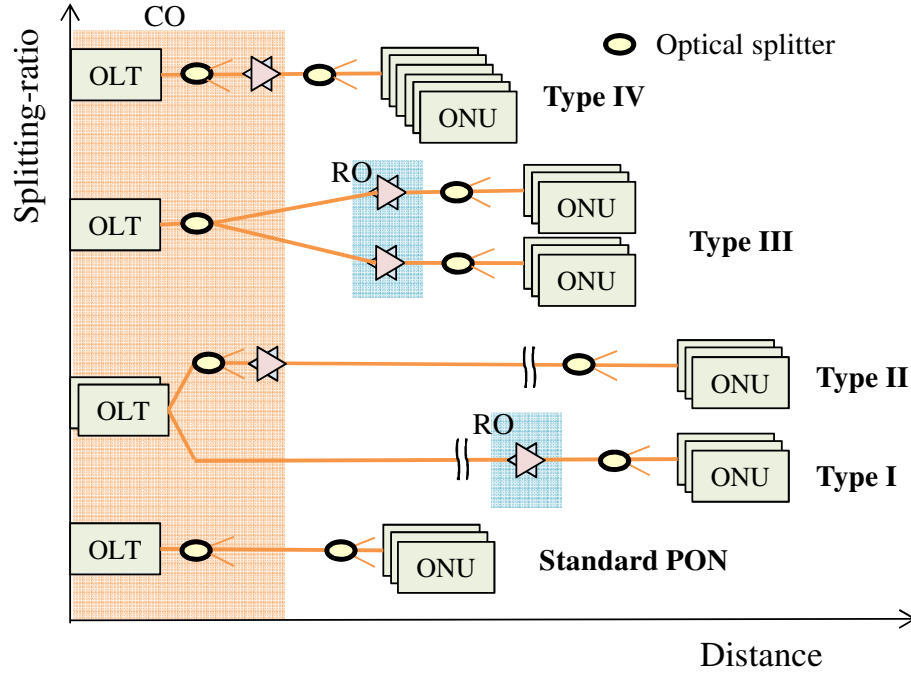


Fig. 2.12 The classification of HSR- and LR-PONs with OAs. Note that the combinations of splitting ratios and transmission distances shown are just examples and vary with the PON architecture parameters adopted. Type I or II for long-reach use is effective at accommodating sparsely-distributed ONUs to the OLT in rural areas. Type III or IV for high-splitting-ratio use are suitable for accommodating closely-aggregated ONUs in urban areas. ©2017, OSA, IEEE

These architectures also achieved reach-extensions of over 20 km.

[35] experimentally analyzed 256- and 512-split next-generation PON 2 (NG-PON2) systems with CO-set OAs. [36] introduced the field trial of a 1024-split 40-Gb/s WDM-PON that uses OAs and a high-speed λ -selective ONU.

2.5.2 LR-PON

Key papers on the LR-PON include [37–39]. Using OAs located at the relay office, [37] realized a 10G-EPON with 100-km transmission even though the infrastructure of an actual access network was used. Furthermore, [38] designed a 120-km WDM-PON by setting the EDFA at the ROs. For an OA located at the central office (CO), [39] successfully transmitted a highly modulated output power signal exceeding +9 dBm over 80 km of optical fiber by

Table. 2.2 Classification examples of HSR- and LR-PONs.

Type	Architecture	OA Location	References
I	Long-reach	RO	[37, 38]
II	Long-reach	CO	[39]
III	High-splitting-ratio / Long-reach	RO	[33, 34]
IV	High-splitting-ratio	CO	[35, 36]

using an L-band extended reach electro-absorption distributed feedback (EA-DFB) laser with SOAs.

The above discussion summarizes that there are four types of PONs with OAs, as shown in Fig. 2.12 and Table 2.2. Note that the combinations of the splitting ratios and the transmission distances shown are just examples and vary with the PON architecture parameters adopted. The OA is applicable to various architectures of PON in order to realize simple network operation.

Then, OAs installed on a CO is defined as CO-set OA as shown in Type II and IV. Also, OAs installed on a RO is defined as relay OA as shown in Type I and III. This topic regarding OAs location are discussed in Section 2.8. For example, Type I or II for long-reach use is effective at accommodating sparsely-distributed ONUs to the OLT in rural areas. Type III or IV for high-splitting-ratio use is suitable for accommodating closely-aggregated ONUs in urban areas. In this case, high- and low-splitting-ratio ONUs are connected together to the same OA. Given the wide variety of systems possible, an auto-configurable OA (AC-OA) is required. The AC-OA is introduced in Chapter 5.

While an optical input power has to exceed the minimum receiver sensitivity for error-free transmission, it must not also exceed the maximum receiver power determined in the standardization. If an optical signal with excess power is inputted to the optical transceivers or OAs, the optical devices are irreversibly damaged by the huge photovoltaic current in the devices [40, 41]. Moreover, the optical signals transmitted from LDs may cause permanent thermal damage to the PD. The maximum receiver powers to the optical transceiver are standardized in Table 2.1.

For HSR- and LR-PONs with OAs, close and distant ONUs from the OLT are connected

together to the same OA. Overloading protection is required so that the OLT can accommodate distant ONUs without excess optical attenuation and protect close ONUs from optical overloading. Overloading protection is also required so that the OLT can accommodate high-splitting-ratio ONUs without excess optical attenuation and protect low-splitting-ratio ONUs from optical overloading. Thus, an operator has to install OAs with a complicated manual sequence. The optical overloading issue has to be resolved to optimally attenuate optical signals in the various architectures.

2.6 N:1 OSU protection system

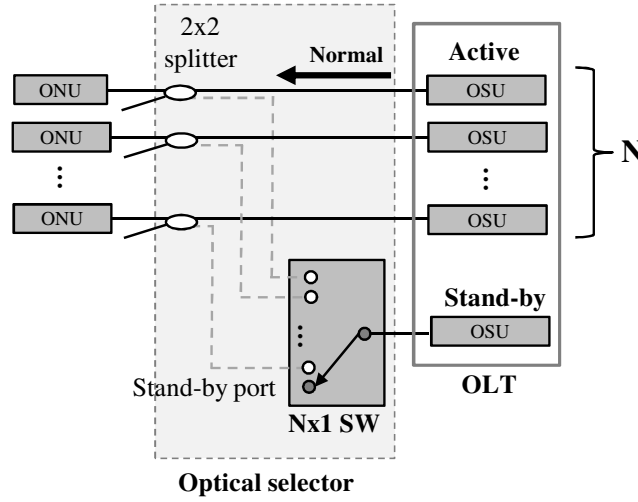
Because business and mobile backhaul applications are demanding even higher system reliability, all 10G-EPON system components should be improved. It is difficult to improve the system reliability by the expensive duplication of OLTs and/or optical fibers, since telecommunications carriers have to economize on the OPEX and CAPEX due to the requirements described in Chapter 1.

The N:1 protection system is effective at enhancing the system reliability at low cost. For improving system reliability, N:1 OSU protection with the Nx1 optical switch (Nx1 SW) is an effective solution. Recently, some network topologies of N:1 protection systems have been defined and standardized by the ITU-T [42].

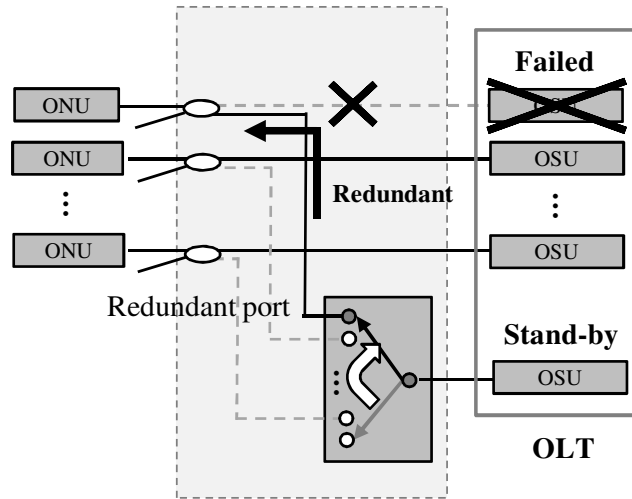
Fig. 2.13 shows the N:1 OSU protection system with Nx1 SW in normal operation with normal path (a) and after failure with redundant path (b). Nx1 SW connects active and standby OSU cards with N:1 redundancy using a duplex system, which offers high reliability and significant cost advantages.

The system forms a redundant architecture with a redundant OSU card so that the OLT can switch to the redundant OSU in case of the failure of an OSU card. In order to construct the N:1 redundant system, an optical switch for connecting each OSU is required to form a redundant path.

However, it is not practical from the viewpoint of availability in a configuration in which all users accommodated in the N OSUs stop communications when a failure and/or change in the optical switch occurs. The configuration of the system is such that the optical signal is optically divided into the normal system and the redundant system by the 2x2 optical



(a) Normal operation with normal path.



(b) Operation after failure with redundant path.

Fig. 2.13 The N:1 OSU protection system with Nx1 SW in normal operation with normal path (a) and after failure with redundant path (b). Nx1 SW connects active and standby OSU cards with N:1 redundancy using a duplex system, which offers high reliability and significant cost advantages. ©2015, OSA, IEEE

splitter in the optical selector. Then, the optical switch is inserted into the optical redundant path. The configuration makes it possible to change the optical switch without affecting the communication continuity of subscribers while enhancing the system reliability at low cost for N:1 protection.

Furthermore, the upstream and downstream signals are buffered to buffer memories during optical switching so that packets are not lost during the switching sequence. Therefore,

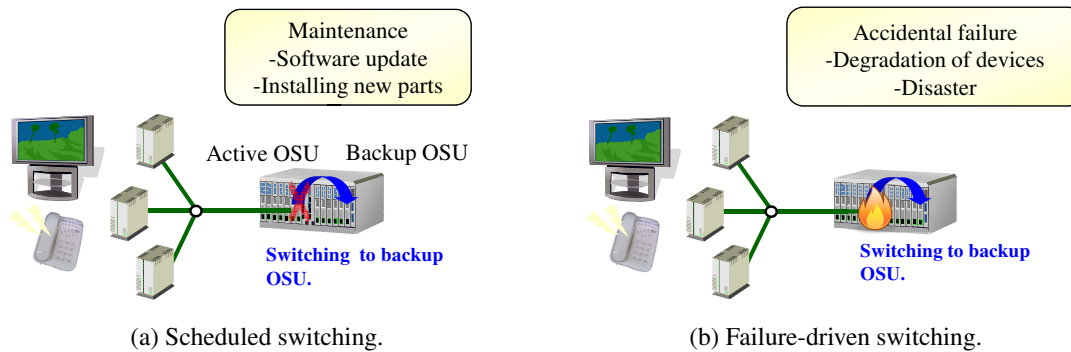


Fig. 2.14 The N:1 OSU protection system has two switching modes: scheduled switching and failure-driven switching. Scheduled switching can switch without any frame loss because the switching time is shorter than the ONU and OLT buffer capacities.

the N:1 OSU protection system can switch to the redundant path without any frame loss. Moreover, the logical link is not affected even if the Nx1 SW fails. Thus, active OLTs can continually provide services even with Nx1 SW failure as the failed Nx1 SW can be repaired or replaced without interrupting services.

This N:1 OSU protection system has two switching modes: scheduled switching and failure-driven switching, as shown in Fig. 2.14. Scheduled switching can switch without any frame loss because the switching time is shorter than the ONU and OLT buffer capacities. This mode is applicable to planned maintenance of the system, such as software/hardware updates or fiber rerouting due to a construction. The mechanism reduces the number of maintenance operators needed for repairing the system equipment and continues the communication link without a service interruption. Furthermore, telecommunications carrier can update the OSU's firmware and/or periodically conduct maintenance without a service interruption by switching the OSU to be maintained in the redundant system. The mechanism eliminates operating costs for late-night maintenance that causes service interruption through late-night work reduction.

Since N:1 OSU protection increases system reliability and shortens system failure time, multi-service migration becomes possible with our N:1 redundant 10G-EPON system. After Chapter 3, the thesis especially focuses on the N:1 OSU protection system for making the reliability of the whole HSR- and LR-PON system equal to or higher than that of the conventional PON system.

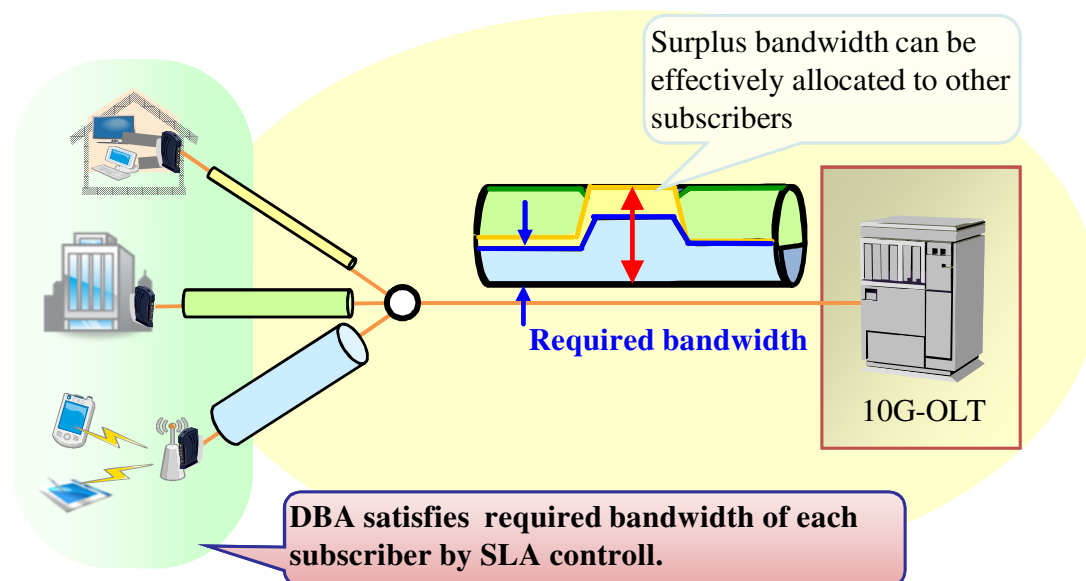


Fig. 2.15 An overview of DBA technology. When ONUs with different bit rates or SLAs are mixed, the transmission timings of the ONUs are controlled so as to satisfy the SLA for each user while efficiently allocating the bandwidth. ©2016, IEICE

2.7 Dynamic bandwidth allocation (DBA)

Fig. 2.15 shows the overview of the DBA. The ONU has queues with the priorities of multiple classes so that it can distinguish between multiple services with different priorities. Fig. 2.16 illustrates the detailed operation diagram of the DBA function that is implemented in the OLT. ONUs have queues with multiple priority classes so that they can accommodate multiple services. The DBA on the OLT receives the REPORTs from ONUs [43]. REPORTs have information about the accumulated queue on the ONU with multiple classes. Based on the REPORTs, the DBA allocates the bandwidth to each ONU with the GATE messages. The frame priority is considered while also satisfying the minimum guaranteed bandwidth and the maximum bandwidth. Then, the DBA calculates and allocates an appropriate frame transmission time for each ONU so as not to generate useless empty bandwidth and cause each upstream frame to collide. The algorithm makes it possible to achieve both high bandwidth efficiency and low latency in any situation.

For 10G-EPON, two kinds of ONUs, namely 1G-ONUs and 10G-ONUs, are dually con-

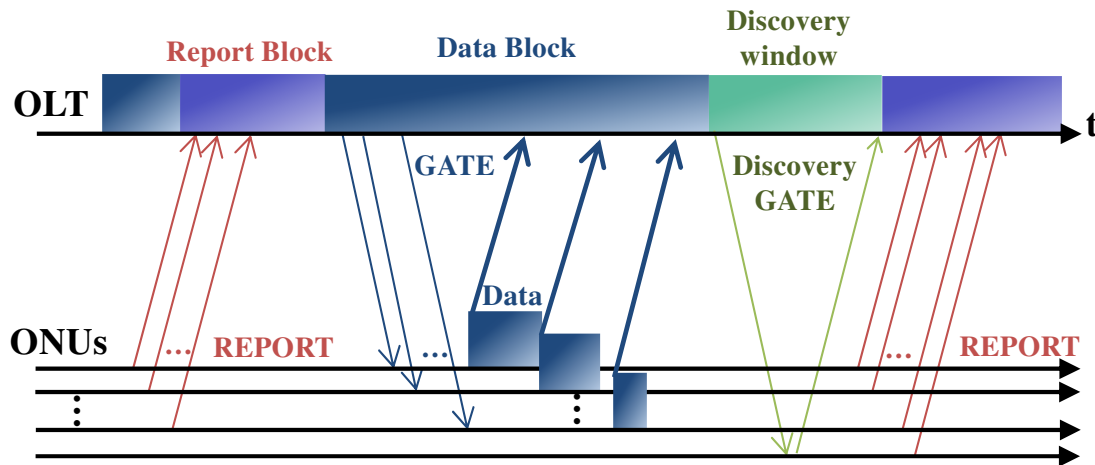


Fig. 2.16 The detailed operation diagram of the DBA function implemented on the OLT. The DBA on the OLT receives REPORTs from ONUs with the message of the GATE. Based on the REPORTs, the DBA allocates the bandwidth to each ONU. Then, the DBA calculates an appropriate frame transmission time for each ONU so as not to generate useless empty bandwidth and cause upstream frames to collide.

nected to the same 10G-OLT. In addition, the SLAs have to be controlled by each of the ONUs, which have different required SLAs. When ONUs with different data-rates and SLAs are mixed, the dual-rate DBA controls the transmission timing of the ONU so as not to cause imbalances among the ONUs.

2.8 Location issue of OAs

Consider the kind of OAs required for amplifying the optical signal to increase the splitting ratio and/or extend the transmission distance of the PON. Telecommunications carriers have to understand the relationship between the transmission distance and the splitting ratio to effectively design the infrastructure for reducing CAPEX and OPEX with OAs. They also have to establish a method for evaluating the transmission distance with the parameter of the splitting ratio because the transmission distance changes non-linearly with the input power to the 1R-OAs. Without an accurate estimation method, telecommunications carriers cannot plan the strategy required for the cost-effective deployment of 10G-EPON systems.

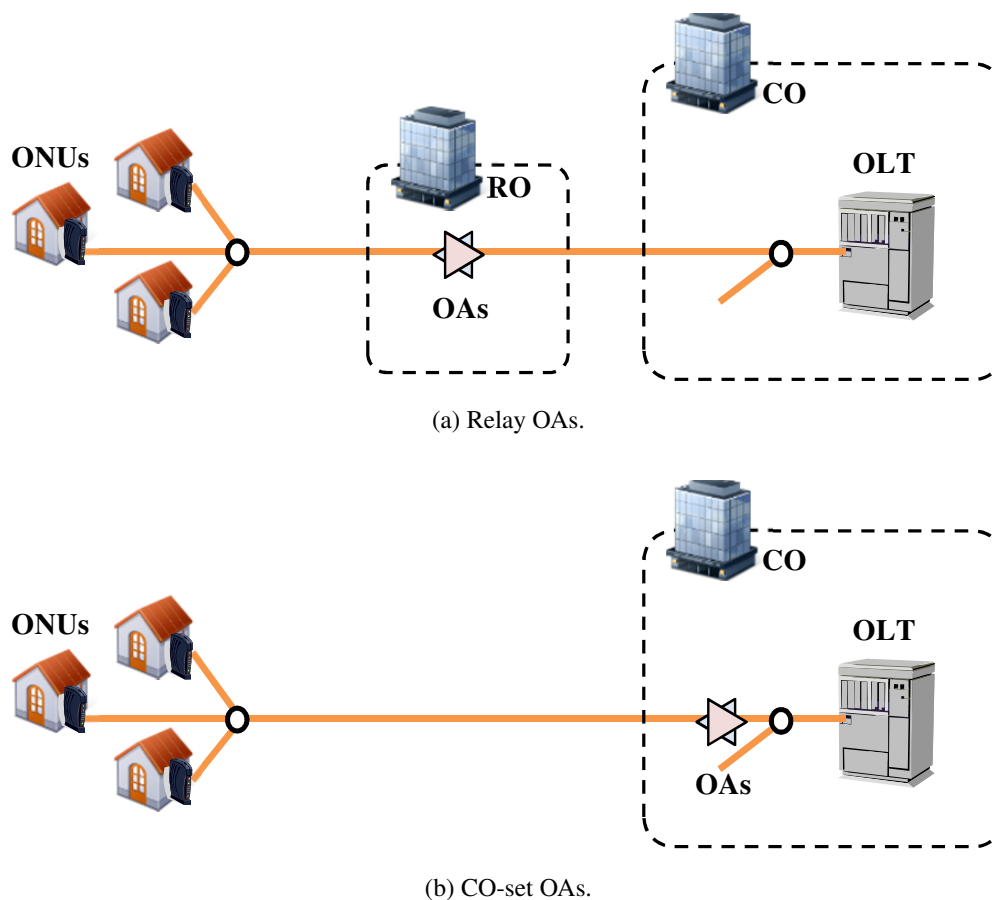


Fig. 2.17 The structures of relay OAs and CO-set OAs. Relay OAs, which are set in a relay office (RO) between the CO and subscribers, are advantageous for extending the transmission distances. CO-set OAs can increase the splitting ratio and reduce the number of COs compared to relay OAs.

2.8.1 Relay and CO-set OAs

OAs fall into two classes according to the installation location, as shown in Fig. 2.17: relay OAs and CO-set OAs. Relay OAs, which are set in an RO between the CO and subscribers, are advantageous for extending the transmission distances, shown in Fig. 2.17a. However, they fail to reduce infrastructure costs since they need ROs. On the other hand, CO-set OAs can increase the splitting ratio and reduce the number of COs compared to relay OAs, as shown in Fig. 2.17b.

To create a truly efficient LR-PON, it is important to plan how to effectively apply OAs to the 10G-EPON while maximizing reductions in CAPEX and OPEX. There are three issues

that must be addressed if telecommunications carriers plan to develop HSR- and LR-10G-EPON systems:

- A) Installation locations of the OAs.
- B) Developing an analysis method for the transmission distance.
- C) Where to locate the OAs.

2.8.2 Facility layout problem (FLP)

The optical budget increase with 1R-OAs is not linear with respect to the optical insertion loss in the trunk and access spans. This is because the output power of an OA is not linear with respect to the input power. The complex relationship of the transmission distance with the optical insertion loss complicates the process of designing a 10G-EPON system to suit actual subscriber distributions. This problem creates the following two difficulties:

- Telecommunications carriers cannot decide which COs should be removed.
- The cost reduction effect cannot be accurately evaluated.

Thus, the accommodation design of a LR-PON has been a difficult problem because the criterion of the transmission distance is not numerically understood.

Past studies have only focused on the architecture of the LR-PON. No work has discussed the optimal deployment of the OAs of LR-PON systems, even though it is an essential issue for the cost reduction of access networks. The problems with optimally locating OAs are discussed as the facility layout problem (FLP).

The history of FLP in operations research dates back to the 1960s [44]. The research purpose is mainly the optimal layout of factories, warehouses, and distribution centers to improve the efficiency of the logistics. Several FLP studies for telecommunications facilities have been reported so far.

For example, in [45–47], the efficient arrangement of optical fibers and optical splitters was discussed. In terms of LR-PONs, [48] investigated the planning of an optical fiber installation to minimize the initial investment in a rural area considering geographical factors. Also, [49] proposed an optimal facility layout method for LR-PONs ensuring system availability. [50]

reported on the dynamic node integration problem considering a declining population over time. This research discussed how to maximize the long-term cost reduction by closing and restructuring COs under the condition of a dynamically declining population in the planning region.

However, these works mainly focused on the optimal deployment of COs and optical fibers. It has not been investigated how to optimally integrate COs using LR-PONs considering the types and specifications of the OAs. The office reduction effect depending on the types and specifications of the OAs has not yet been discussed either. Use of OALP to optimally locate OAs and integrate COs is described in Chapter 6. Then, the relationship between the office reduction effect and the types and specifications of the OAs is evaluated.

2.9 Summary

This chapter described the fundamental principles and theories required to understand and discuss data transmission for the 10G-EPON system. This chapter also explained the principles and concepts of the 10G-EPON using OAs, required to analyze and discuss the results of a field measurement. The chapter introduced the concept of optical budget, the structure of optical transceiver, and the optical overloading problem of optical devices.

The chapter described the mechanism of the N:1 protection system that enhances the reliability of the 10G-EPON. DBA technology for frame transmission, to share the bandwidth and priority control fairly among the ONUs, is also explained. These technologies control the QoS of the system required for providing multi-service accommodation with the PON system.

This chapter also showed that it is important to flexibly design the transmission distance of the HSR- and LR-PONs in order to save resources and attain a high profitability with the system. It is also important to reduce the CAPEX and OPEX of the PON so that telecommunications carriers can enhance their profitability by investing in the HSR- and LR-PONs.

Chapter 3

Field measurement of 10G-EPON

3.1 Overview

This chapter demonstrates a HSR- and LR-10G-EPON system with N:1 OSU protection in order to confirm the high reliability of the system. Conventional HSR- and LR-PON systems with OAs degrade the system reliability because the whole system fails if either the OSU, OA or SOA. The thesis also denotes the effectiveness of the dual-rate automatic level control semiconductor optical amplifiers (ALC-SOA) for extending the optical loss budget with N:1 redundant topologies. The system can switch from active to redundant channels without any frame loss. The quality of bidirectional frame transmission is not degraded after switching to the redundant channels. Finally, the chapter concludes the 10G-EPON system is suitable for next-generation access network system.

3.2 Experimental setup

3.2.1 Architecture for field measurement

Fig. 3.1 explains the experimental N:1 redundant HSR- and LR-10G-EPON system; it is implemented on a commercial access network infrastructure that consists of CO, relay office (RO), subscribers, trunk span connecting CO and RO, and access span connecting RO and subscribers. It is implemented on a commercial access network actually being operated by NTT WEST Corporation to demonstrate the feasibility of the system.

Fig. 3.2 depicts the pictures of the field measurement setup for the N:1 redundant 10G-EPON system with SOA in three locations: CO, RO and simulated subscribers. The distance

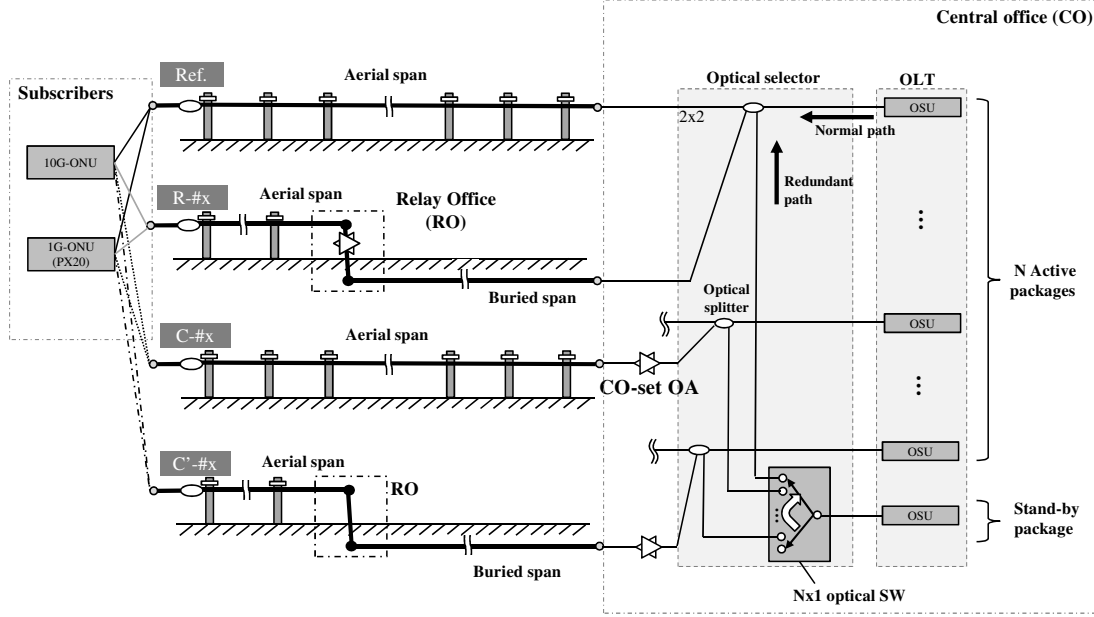
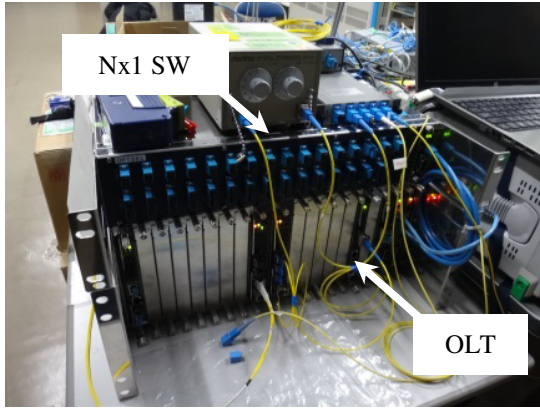


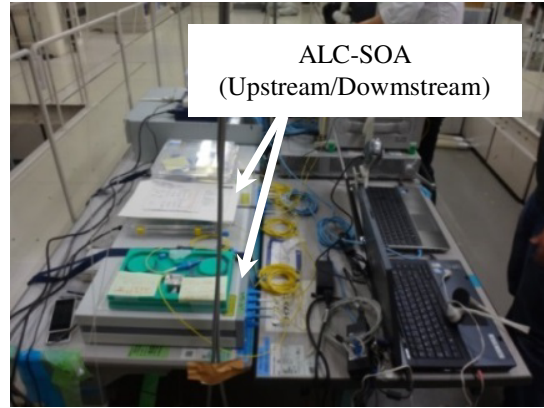
Fig. 3.1 N:1 redundant 10G-EPON system with SOAs on commercial access network infrastructure. It consists of CO, relay office (RO), subscribers, trunk span connecting CO and RO, and access span connecting RO and subscribers. ©2017, OSA, IEEE

of the buried span is 20.0 km, while aerial spans are 0.6, 5.0, 10.0, and 18.5 km. The distance is measured by optical time domain reflectometer (OTDR) in advance. The integrated distribution module (IDM) that is widely applied in NTT infrastructure in RO, is used for splitting the optical signal into four and distributing optical fibers to the subscribers. The optical fibers terminate at OLT or 10G-ONU (PR30) and 1G-ONU (PX20). The N:1 OSU protection system (Type-B architecture [42]) is connected under normal operation with normal path (a) and operation after failure with redundant path (b) as described in Chapter 2. The insertion loss of the Nx1 optical switch (Nx1 SW) is 3.5 dB on normal path and 5.5 dB on the redundant path.

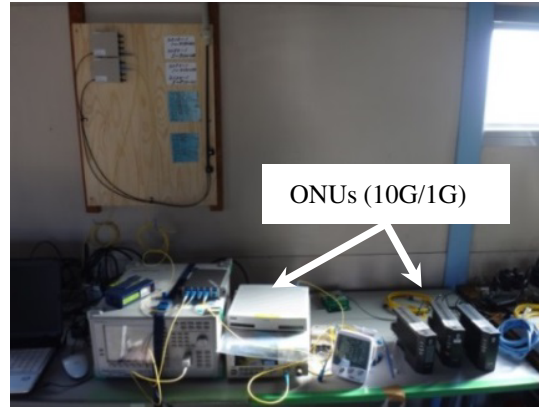
Table 3.1 lists the parameters of the demonstration setup. Three architectures are examined: Reference (Ref.), relay structures (R-#x), and CO-set structures (C-#x, C'-#x). Relay structures (R-#1 and R-#2) and all CO-set structures are connected to the output port of the 2x2 optical splitter after the Nx1 SW in order to extend the link budget of the system. In this N:1 OSU protection architecture, the splitting ratio on the OLT side should be over two since a 2x2 coupler is inserted to form path redundancy. Relay structure aims to especially extend



(a) OLT and N:1 optical switch installed in the central office.



(b) Relay OA installed in the relay office.



(c) ONUs in the subscriber.

Fig. 3.2 The pictures of the field measurement setup of the N:1 redundant 10G-EPON system with SOA. ©2015, OSA, IEEE

the transmission distance by amplifying degraded optical signals with OAs located on RO. CO-set structure aims to increase the splitting ratio of the system. CO'-set structure focuses to increase the splitting ratio while keeping the transmission distance of the system.

The buried and aerial span of the relay structure are defined as the trunk span and the access span, respectively. Also, both of the buried and aerial span of CO- and CO'-set structure are defined as the trunk span. N_t and N_a stand for the total splitting ratio on OLT side and ONU side, respectively.

Table. 3.1 Access infrastructures used in field measurement.

Structure	Splitting ratio			D_t [km]	D_a [km]	RO through	Protection
	N_{Total}	N_t	N_a				
Ref.	128	2	64	0	10	x	x
R-#1	128	2	64	20	0.6, 5, 10, 18.5	x	o
R-#2	32	2	16	20	0.6, 5, 10, 18.5	x	o
R-#3	64	1	64	20	0.6, 5, 10, 18.5	x	x
R-#4	32	1	32	20	0.6, 5, 10, 18.5	x	x
C-#1	64	4	16	0	0.6, 5, 10, 18.5	x	o
C-#2	64	2	32	0	0.6, 5, 10, 18.5	x	o
C-#3	128	8	16	0	0.6, 5, 10, 18.5	x	o
C-#4	128	4	32	0	0.6, 5, 10, 18.5	x	o
C'-#1	32	4	8	0	20.6, 25, 30, 38.5	o	o
C'-#2	32	2	16	0	20.6, 25, 30, 38.5	o	o

3.2.2 Optical characteristics of optical transceivers

The downstream and upstream optical signals of 10G-EPON are multiplexed in a same optical fiber by wavelength division multiplexing (WDM). The optical transceiver characteristics used in the field measurement are shown in Table 3.2. Both upstream and downstream characteristics are superior to the standardized specifications of PR30 (10G) and PX20 (1G). The OLT uses DFB lasers as downstream sources for co-existing 10G-EPON and EPON systems. For 1G-ONU, PX20 is adopted in order to compare the wavelength dependency of the upstream signal against the 10G- and 1G-ONU with DFB laser. Also, the transmission distance is not shortened since the power penalty caused by chromatic dispersion of the upstream and downstream transmission is negative and negligible (not more than 0.12 dB) without OAs.

Table. 3.2 Optical characteristics of transceivers used in the measurement.

Standard	Upstream	Upstream	Downstream	Downstream
Type	PR30 (10G)	PX20 (1G)	PR30 (10G)	PX20 (1G)
Central wavelength [nm]	1270.3	1310.5	1576.7	1489.3
Average output power [dBm]	+6.3	+1.4	+4.5	+4.9
Minimum receive sensitivity [dBm]	-30.2	-35.7	-31.9	-33.0
Dispersion penalty w/o OA @ 40 km [dB]	-0.74	0.11	0.03	0.12

3.2.3 Optical characteristics of optical amplifier

Relay OA

Relay OA is installed in a RO in order to enhance the loss budget and realize long-reach transmission. Fig. 3.3 illustrates the architecture of the dual-rate relay OA used. Burst signals are amplified at wavelengths of 1576.3 nm/1489.0 nm (10G/1G downstream), and 1271.7 nm/1310.1 nm (10G/1G upstream). For downstream amplification, two SOAs are used for controlling by a feed-forward (FF) circuit. Input upstream signals are divided to 10G/1G wavelengths and amplified at each wavelength using the respective SOA. On the other hand, upstream amplification is more complicated since the signals are bursty; signals from near and far ONUs have quite different powers. To overcome this difficulty, SOAs for upstream signal consist of pre- and post-SOA, coarse WDM (CWDM) filter, and a variable optical attenuator (VOA) driven by a feed-forward (FF)/feedback (FB) circuit. The pre-SOA raises the input power to match the input power ranges of the VOA. Next, fast auto-level-control (ALC) with VOA is implemented for quick adjustment of output optical signal power. Finally, post-SOA raises the output signal to the target output power set at the FF/FB circuit to protect the transceiver from excessive optical inputs. Relay OAs are applicable to various access networks regardless of fiber length, splitting ratios, and the number of connection points.

When telecommunication carriers construct an access network, they have to prevent the power input to the OLT and ONU transceiver from exceeding the receiver's acceptable optical power. While optical overloading is not possible given the system described in this thesis, it is possible if some fibers are short or the splitting ratio is small. If SOA does not employ the

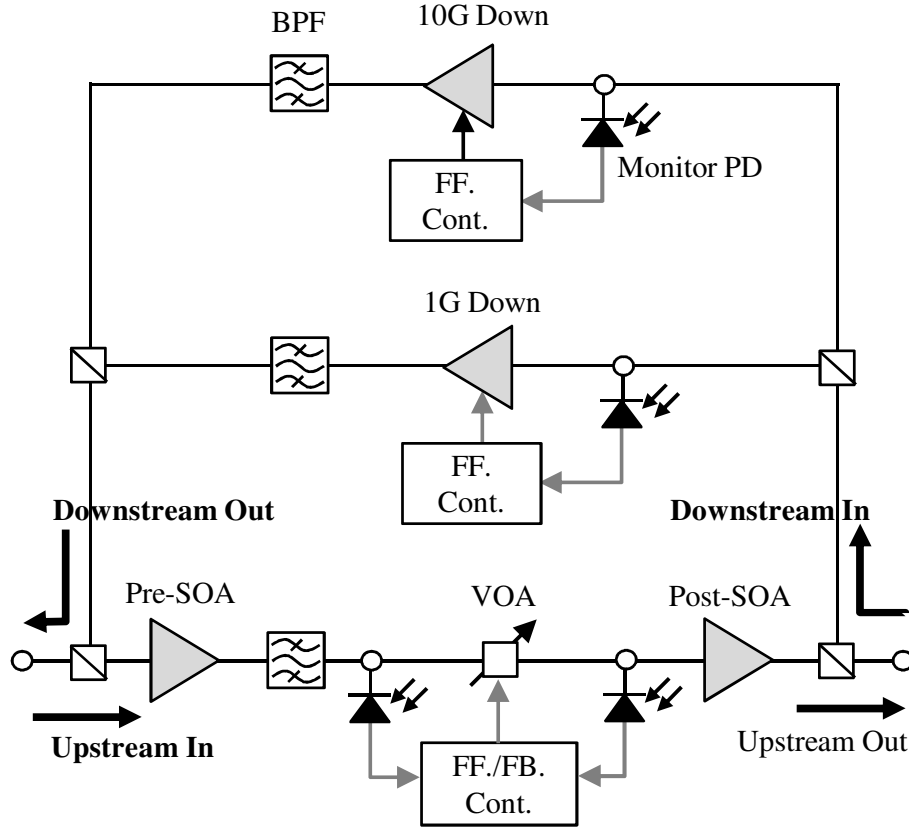
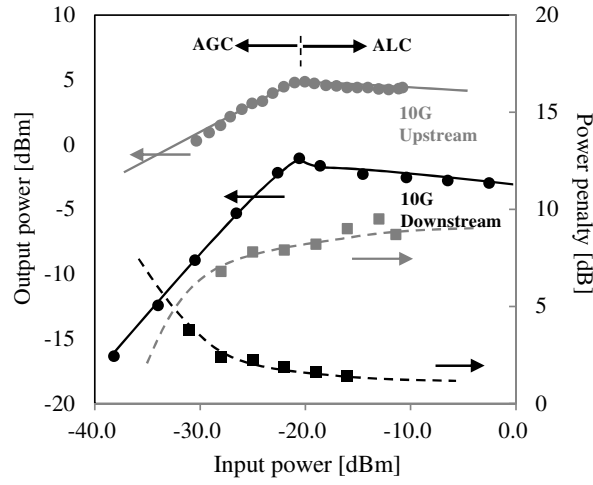


Fig. 3.3 Architecture of dual-rate (10G/1G) relay SOA used. For downstream amplification, two SOAs are used for controlling by a feed-forward (FF) circuit. Input upstream signals are divided to 10G/1G wavelengths and amplified at each wavelength using the respective SOA. Upstream amplification is more complicated since the signals are bursty; signals from near and far ONUs have quite different powers. To overcome this difficulty, SOAs for upstream signal consist of pre- and post-SOA, coarse WDM (CWDM) filter, and a variable optical attenuator (VOA) driven by a feed-forward (FF)/feedback (FB) circuit.

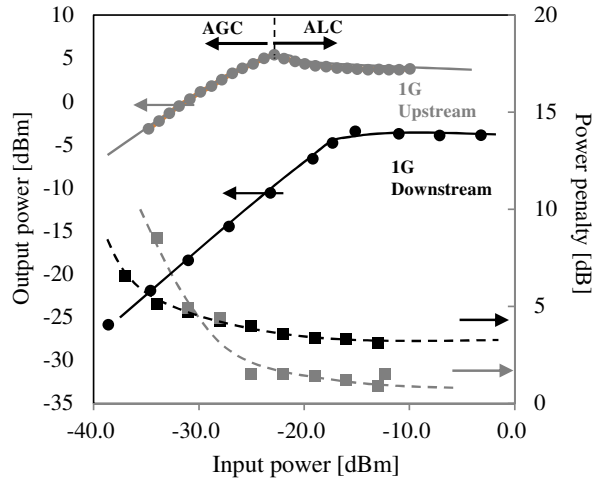
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ALC function, the optical gain of each SOA would have to be manually adjusted. This makes the operation and maintenance of the access network far more complicated. On the other hand, adding the ALC function simplifies system operation by avoiding optical overloads. Therefore, the ALC function is required when the SOA is widely applied to various access networks. While the ALC function cannot prevent overloading of SOA itself, the system to prevent the optical overloading to SOA is proposed in Chapter 5.

Fig. 3.4 shows input/output characteristics of the relay SOAs depicted in Fig. 3.3. 10G-



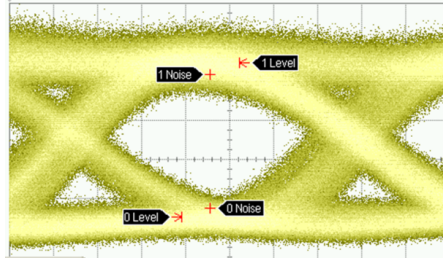
(a) PR30 (10G).



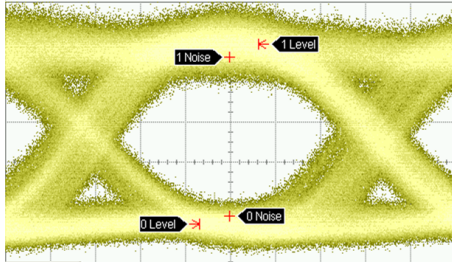
(b) PX20 (1G).

Fig. 3.4 The characteristics of relay SOA for 10G-EPON system. 10G-signal on the downstream/upstream is amplified with the optical gain of 25 dB/15 dB in AGC mode with set saturation power of +0 dBm/+5 dBm in ALC mode. 1G-signal on the downstream/upstream is amplified with the optical gain of 15 dB/30 dB in AGC mode with set saturation power of -5 dBm/+5 dBm in ALC mode. The upstream signal has the higher optical gain than the downstream optical gain in order to offset the higher transmission loss.

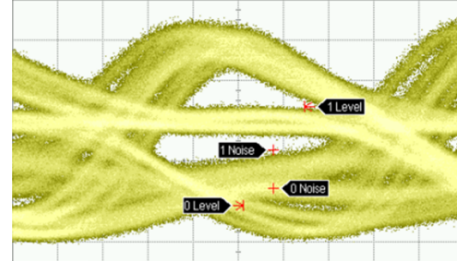
signal on the downstream is amplified with the optical gain of 25 dB in AGC mode with set saturation power of +0 dBm in ALC mode. 10G-signal on the upstream is amplified with the optical gain of 15 dB in AGC mode with set saturation power of +5 dBm in ALC mode. 1G-signal on the downstream is amplified with the optical gain of 15 dB in AGC mode with



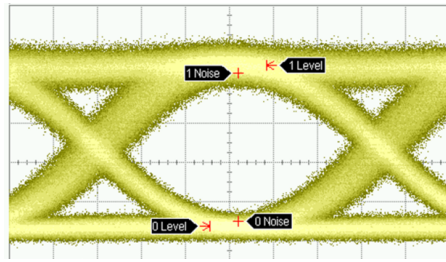
(a) Upstream (Ref.)



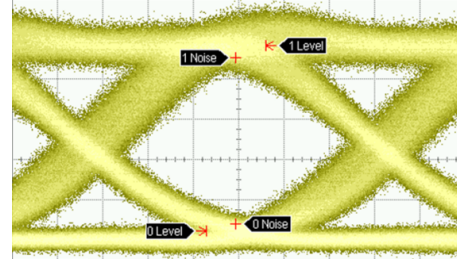
(b) Upstream (CO-set OA + 40-km transmission)



(c) Upstream (Relay OA + 40-km transmission)



(d) Downstream (Ref.)



(e) Downstream (Relay/CO-set OA + 40-km transmission)

Fig. 3.5 Eye pattern of optical output from ALC-SOA ($P_{in} = -20$ dBm).

set saturation power of -5 dBm in ALC mode. 1G-signal on the upstream is amplified with the optical gain of 30 dB in AGC mode with set saturation power of +5 dBm in ALC mode. The upstream signal has the higher optical gain than the downstream optical gain in order to offset the higher transmission loss.

Fig. 3.5 indicates eye diagrams of optical output from OAs. Fig. 3.5 (a) and Fig. 3.5 (d) show eye diagrams of Ref. structure (without OAs) on the upstream and downstream signal, respectively. Fig. 3.5 (b) shows the eye diagram of CO-set structure with the transmission distance of 40 km on the upstream signal. Fig. 3.5 (c) indicates the eye diagram of relay structure with the transmission distance of 40 km on the upstream signal. Fig. 3.5 (e) shows

the eye diagram of CO-set and relay structure with the transmission distance of 40 km on the downstream signal.

Eye diagrams (b) and (e) are not degraded as well as the reference pattern of (a) and (d). However, the eye diagram (c) on the upstream signal is distorted in comparison to the reference pattern of (a). This is the technological problem to be solved for keeping the quality of the amplified optical signals.

CO-set OA

Fig. 3.6 illustrates the architecture of the CO-set SOA. Fundamental architecture of a CO-set OA is equivalent to that of a relay OA. In CO-set structure, single SOA for the upstream signal is applied in order to avoid overloading to OLT installed at the back of OAs. SOA for the downstream signal is set with the same parameter setting of relay structure. Therefore, the optical characteristics of OAs for downstream signal correspond between relay and CO-set structure at following descriptions.

Fig. 3.7 shows CO-set SOA characteristics. 10G-signal on the downstream is amplified with the optical gain of 25 dB in AGC mode with set saturation power of +0 dBm in ALC mode. 10G-signal on the upstream is amplified with the optical gain of 15 dB in AGC mode with set saturation power of -10 dBm in ALC mode. 1G-signal on the downstream is amplified with the optical gain of 15 dB in AGC mode with set saturation power of -5 dBm in ALC mode. 1G-signal on the upstream is amplified with the optical gain of 10 dB in AGC mode with set saturation power of -15 dBm in ALC mode. Power penalty by ASE noise is about 2 dB for both upstream and downstream at optical input powers in excess of -30 dBm.

3.2.4 Frame transmission condition

Forward error correction (FEC), RS (255, 233), is implemented to match the 10G-EPON specifications. With these conditions, optical characteristics and frame transmission characteristics are measured assuming error-free transmission, i.e. bit-error-rate (BER) $\leq 10^{-12}$. transmission distance is defined as the maximum distance at which the BER exceeds 10^{-12} given the specified splitting ratio. Downstream frames are encrypted with advanced encryption standard (AES) encryption method [51], to prevent a wiretapping, falsification and im-

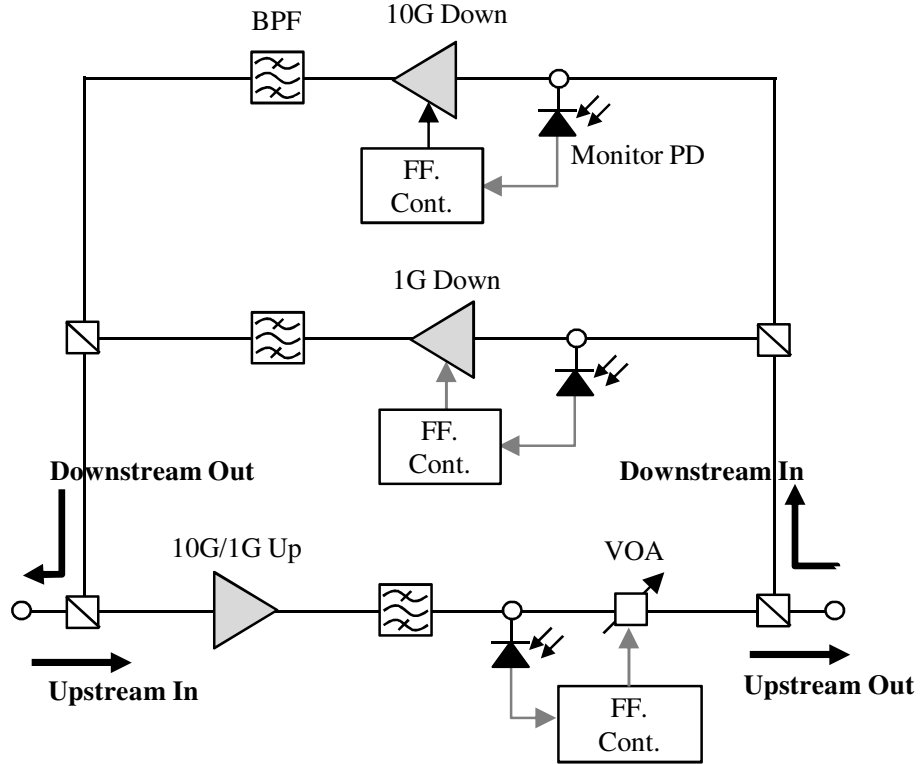


Fig. 3.6 The architecture of dual-rate (10G/1G) CO-set SOA. Single SOA for the upstream signal is applied in order to avoid overloading to OLT installed at the back of OAs. SOA for the downstream signal is set with the same parameter setting of relay structure. ©2017, OSA, IEEE

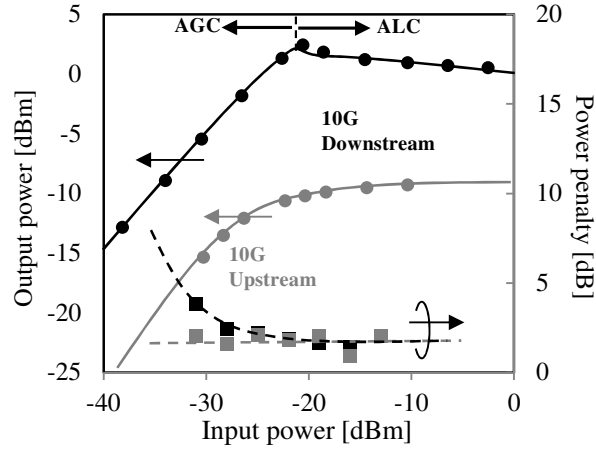
personation.

3.3 Measurement results

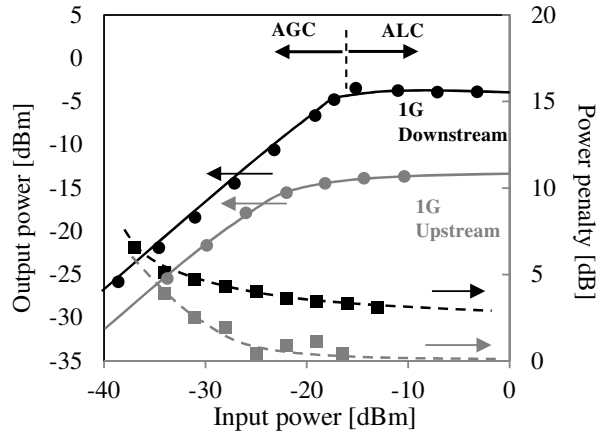
3.3.1 Transmission distances

Table 3.3 summarizes the measurement results of the transmission distance. For Ref. structure, the transmission distances are 10 km before switching and 18.5 km after switching with the splitting ratio of 128.

For relay structure, all transmission distances are the maximum distance, 38.5 km, on both of before and after switching. These results indicate the effect for extending the transmission distance is high on the relay structure. Also, there are the power margins on Rx for the



(a) PR30 (10G).



(b) PX20 (1G).

Fig. 3.7 The characteristics of CO-set SOA for 10G-EPON system. 10G-signal on the downstream/upstream is amplified with the optical gain of 25 dB/15 dB in AGC mode with set saturation power of +0 dBm/-10 dBm in ALC mode. 1G-signal on the downstream/upstream is amplified with the optical gain of 15 dB/10 dB in AGC mode with set saturation power of -5 dBm/-15 dBm in ALC mode. Power penalty by ASE noise is about 2 dB for both upstream and downstream at optical input powers in excess of -30 dBm.

transmission for each structure. The actual transmission distance is expected to be longer than the measured distance. The actual transmission distance is estimated by adding a value dividing the power margin by the transmission loss.

For CO-set structure, the all transmission distances are the same, 18.5 km, regardless of the splitting ratio, on normal or redundant system. This indicates that the OAs allow the splitting ratio to be increased 64 (C-#1 and C-#2) or 128 (C-#3 and C-#4) from 32, as determined by

Table. 3.3 Measurement results of the transmission distances.

Structure	Splitting ratio			Distance of PR30 (10G) [km]		Distance of PX20 (1G) [km]	
	N_{Total}	N_t	N_a	Normal	Redundant	Normal	Redundant
Ref.	128	2	64	10	-	18.5	-
R-#1	128	2	64	20+18.5	20+18.5	20+18.5	20+18.5
R-#2	32	2	16	20+18.5	20+18.5	20+18.5	20+18.5
R-#3	64	1	64	20+18.5	-	20+18.5	-
R-#4	32	1	32	20+18.5	-	20+18.5	-
C-#1	64	4	16	18.5	18.5	18.5	18.5
C-#2	64	2	32	18.5	18.5	18.5	18.5
C-#3	128	8	16	18.5	18.5	18.5	18.5
C-#4	128	4	32	18.5	18.5	18.5	18.5
C'-#1	32	4	8	30	25	30	30
C'-#2	32	2	16	30	25	25	25

the standards of both PR30 and PX20 for the transmission distance around 20 km.

For 10G on C'-#1 and C'-#2, the transmission distance on the normal path is extended to 30 km. On the redundant path, the transmission distance is shortened to 25 km due to the additional insertion loss of the Nx1 SW. On the other hand, the transmission distance of 1G on C'-#2 is 25 km and 30 km on C'-#1 regardless of the switching state. Assuming the additional 4-dB loss after switching (compared to that before switching) due to reflection loss at the Nx1 SW, transmission characteristics were measured for the transmission distance of 25 km. To improve the transmission distance after switching, a lower loss Nx1 SW and/or a higher budget OLT transceiver for a redundant path can be applied.

In theory, the actual transmission distance is longer than the demonstrated transmission distance because there are loss margin in the optical received power compared to the optical sensitivity of OLT and ONU as shown in Table 3.2. Actual transmission distance can be calculated from optical received power and sensitivity of OLT and ONU transceiver. This means it is necessary to handle the complex behavior of the non-linear characteristics and power penalty created by ASE noise from SOA and chromatic dispersion. A formulation and model for estimating transmission distance will be introduced in Chapter 4 with a comparison

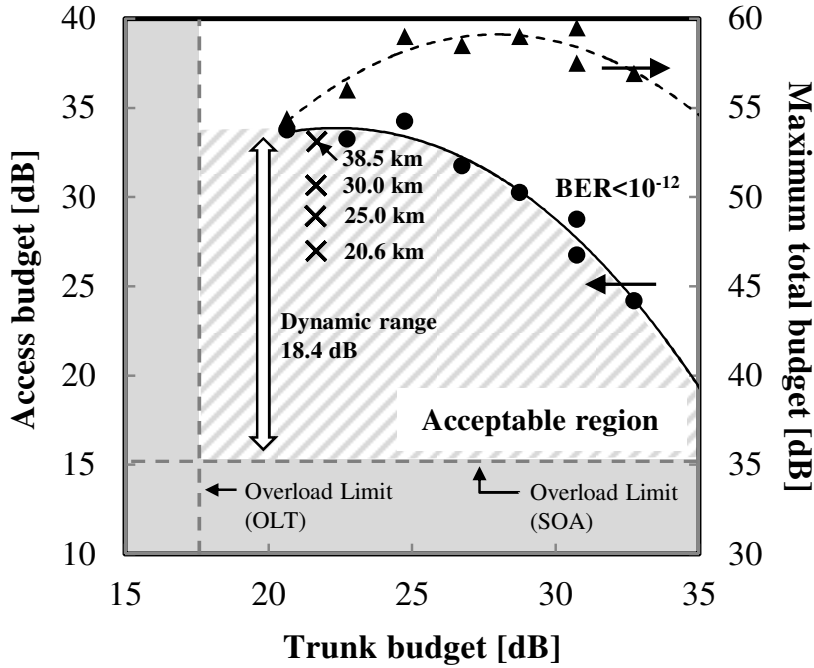


Fig. 3.8 The applicable combinations of trunk and access budget of R-#1 for a 10G-upstream signal. ©2015, OSA, IEEE

to the results of the demonstration.

3.3.2 Optical characteristics

This section describes the optical characteristics of the representative experimental system. The 10G-upstream received optical power on OLT side is also described for estimating the transmission distance. Detailed analysis including the 10G- and 1G-signals on the upstream and the downstream is described in Chapter 4.

Fig. 3.8 shows the applicable combinations of trunk and access budget of R-#1 for a 10G-upstream signal. This figure indicates that the maximum total budget of upstream can exceed 55 dB for the trunk budget range from 21 dB to 35 dB. In order to realize the 40-km and 128-split access network with Nx1 SW, the trunk budget is 21.5 dB and access budget is 34.3 dB if only optical transmission loss and splitting loss are considered. Compared to the requirement, this result indicates that the estimated budget combination is nearly optimum. The upstream signal is focused in terms of optical characteristics since its higher transmission loss limits distance expansion.

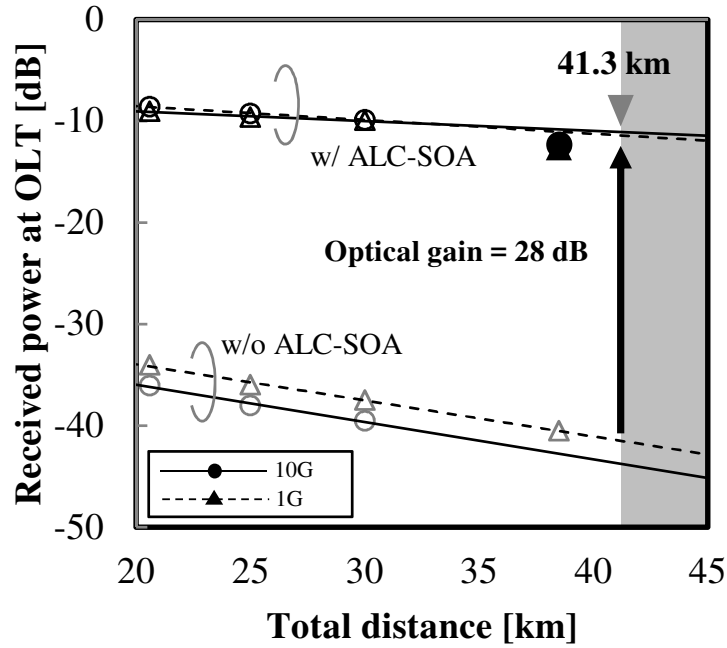


Fig. 3.9 The upstream received power with the parameter of the total transmission distance for R-#1. Open points indicate calculated value based on measured characteristics of optical fiber and ALC-SOA. ©2015, OSA, IEEE

This figure also shows experimental operation points and dynamic range of the 10G-EPON with relay OA as a function of trunk and access budget. The results indicate that relay OAs can operate within the applicable region of the system at all distances examined, 20.6, 25.0, 30.0, 38.5 km. Dynamic range of the system is experimentally estimated to be 18.4 dB at the trunk span distance of 20.0 km.

Fig. 3.9 shows upstream received powers at OLT. Optical gains by relay OA are 28 dB (10G) and 30 dB (1G). The total transmission distance of this system is 38.5 km. If the measured upstream results is subtracted from the insertion loss of passive devices, the transmission distance is estimated to be 41.3 km. The distance is as long as legacy EPON systems with 32 optical splits.

Fig. 3.10 indicates the applicable combinations of trunk and access budget of C-#1 for a 10G-upstream signal. Compared with R-#1, that the maximum total budget of upstream is lower due to the upstream optical gain cannot be increased to prevent overloading to OLT.

This figure also presents experimental operation points and dynamic range of the 10G-

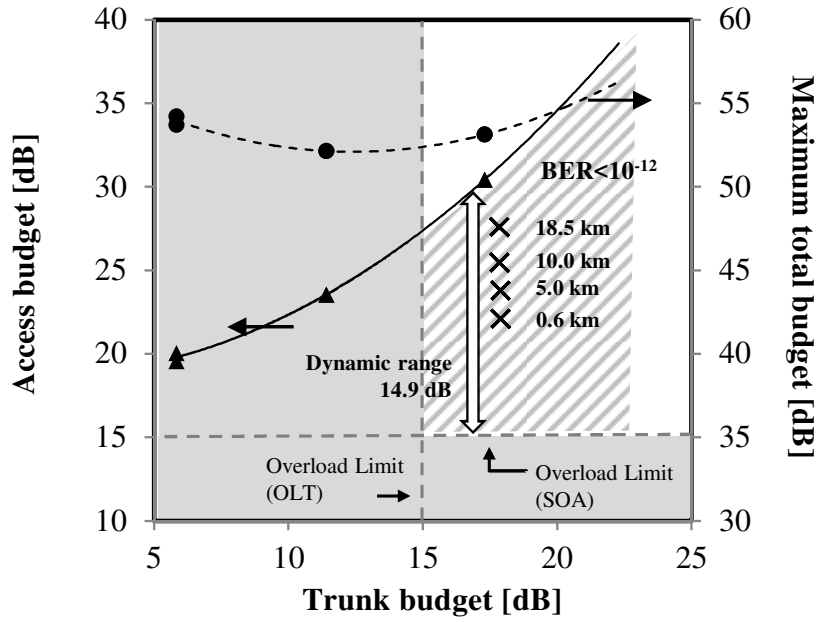


Fig. 3.10 The applicable combinations of trunk and access budget of C-#1 for a 10G-upstream signal.

EPON with CO-set OA as a function of trunk and access budget. The results indicate that relay OAs can operate within the applicable region of the system at all distances examined, 0.6, 5, 10, 18.5 km. Dynamic range of the system is experimentally estimated to be 10 dB at the trunk span distance of 18.5 km. Therefore, this 10G-EPON system offers reasonable optical characteristics for extending the transmission distance to the target fiber length of 40.0 km.

Fig. 3.11 indicates upstream received powers at OLT. Optical gains by CO-set OA are 10 dB (10G and 1G). The total transmission distance of this system is 18.5 km. If the measured upstream results is subtracted from the insertion loss of passive devices, the transmission distance is extrapolated to be around 30 km.

3.3.3 Frame transmission characteristics

Fig. 3.12 shows the measured bit-error-rate (BER) of a bidirectional transmission experiment with a bitrate of 10 Gb/s. $P_{OA,in}$ represents optical input power to OAs. These results correspond to optical characteristics described in Table 3.2. Measured optical sensitivities on

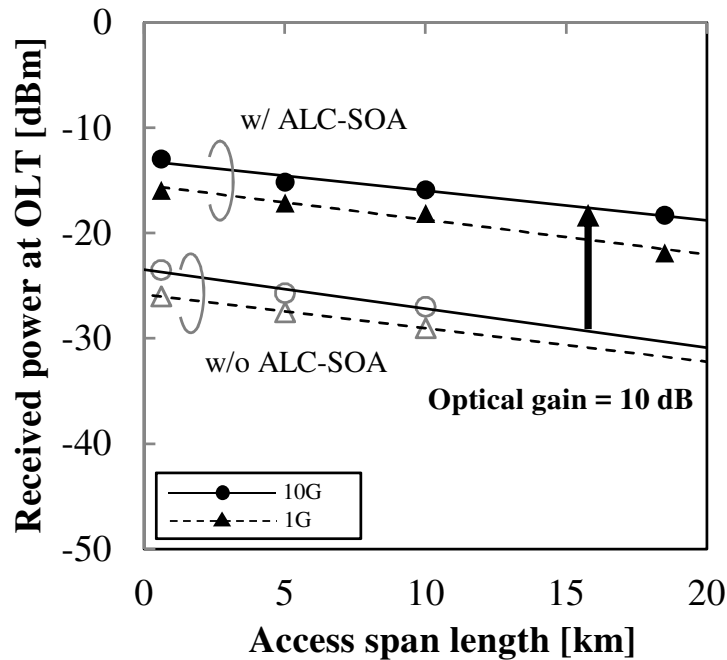


Fig. 3.11 The upstream received power with the parameter of the total transmission distance for C-#1. Open points indicate calculated value based on measured characteristics of optical fiber and ALC-SOA.

Table. 3.4 Switching results on R-#2 structure.

Item	Upstream	Upstream	Downstream	Downstream
Standard type	PR30	PX20	PR30	PX20
Frame loss	0	0	0	0
Switching time [ms]	29.6	30.6	29.6	30.6

the condition of $BER = 10^{-12}$ satisfies receiver sensitivities of IEEE standard.

Table 3.4 is the switching results on R-#2 structure. No frame loss was observed during scheduled switching because the interruption time during switching is very short, around 30 ms. In the case of no traffic congestion, the latency originated from switching time quickly converges to steady-state latency.

Fig. 3.13 indicates measured frame transmission characteristics on a normal path (before switching) and redundant path (after switching) for representative structures of the 10G-EPON system. The length of each frame is randomly set.

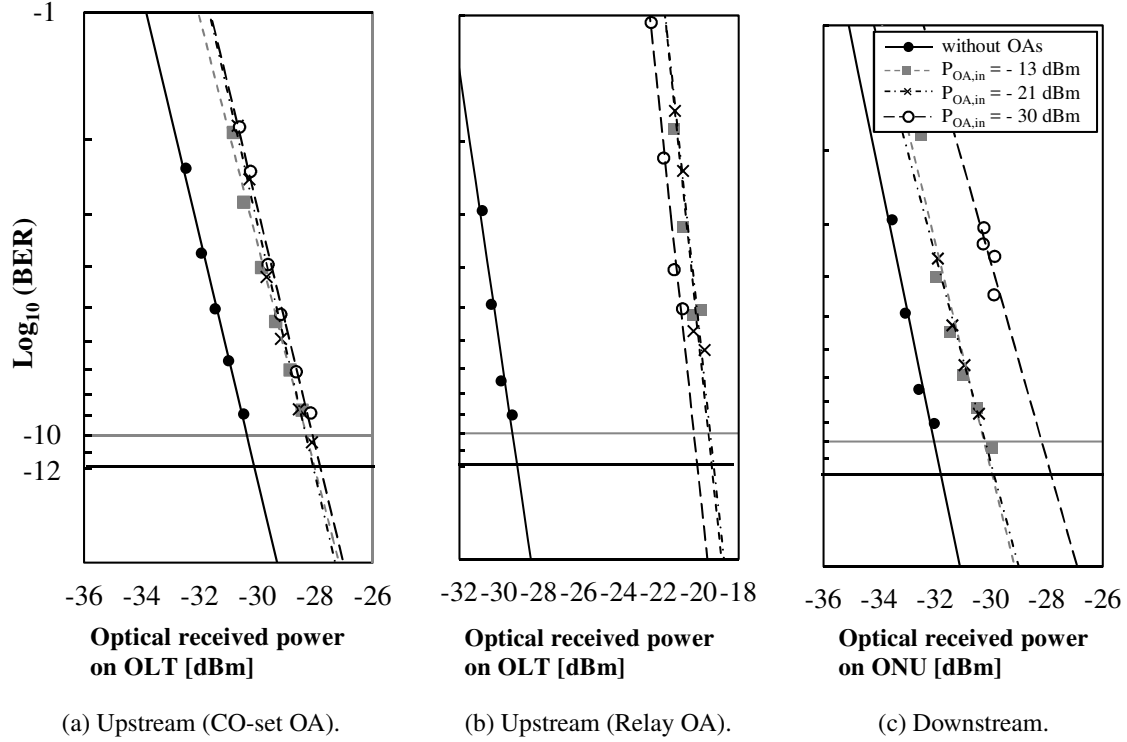
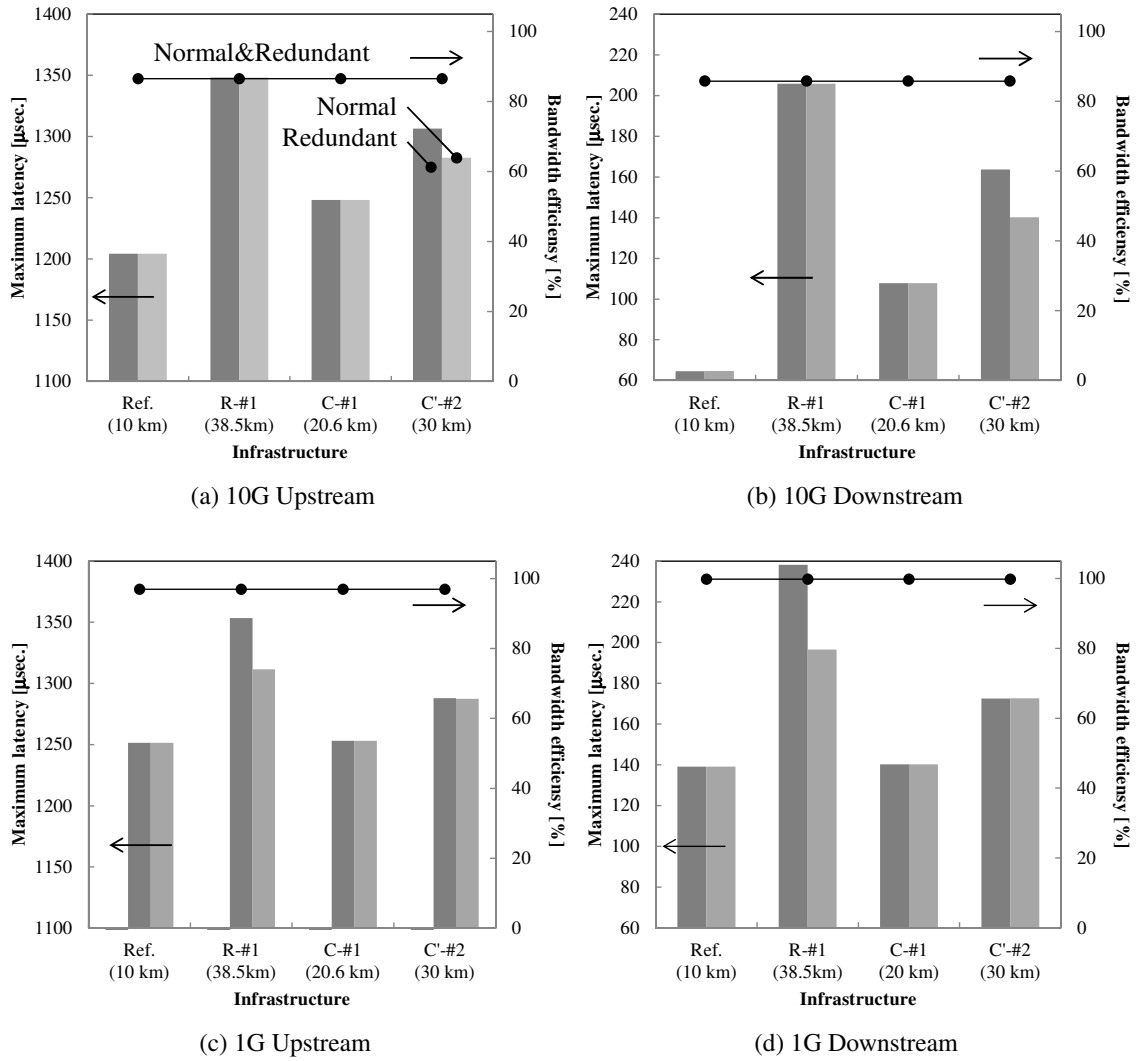


Fig. 3.12 Measured BER versus input power to OAs ($P_{OA,in}$).

The maximum value of latency is about $1350 \mu s$ (upstream) and $200 \mu s$ (downstream) for R-#1. For C-#1, the maximum value of latency is about $1260 \mu s$ (upstream) and $110 \mu s$ (downstream). These differences of latency is derived from transmission latency due to the difference of the transmission distance of R-#1 and C-#1. For C'-#2, the maximum latency is about $1300 \mu s$ (upstream) and $170 \mu s$ (downstream) for C'-#2 on normal path. After redundant path, the latency slightly reduced by about $20 \mu s$ on the redundant path because the distance on redundant path is shorter than that on normal path.

For all structures, no frame loss was observed during scheduled switching because the interruption time during switching is very short, around 30 ms, and transmitted frames do not occur the overflow of OLT or ONU buffer memory. DBA cycles ($560 \mu s$) yield the greater upstream latency, not the insertion of the N:1 protection system. Thus, these results indicate that the transmission characteristics are independent of the physical N:1 redundant topology.

Bandwidth efficiency is also not impacted by switching. The drop in bandwidth efficiency of 10 Gb/s to around 86% from 100% is due to FEC overhead of the frames; it is not caused by SOA or Nx1 SW. The drop in bandwidth efficiency is due to the encryption overhead of

Fig. 3.13 Transmission characteristics for $BER \leq 10^{-12}$.

short frames, it is not caused by the N:1 protection system.

Table 3.5 shows the frame transmission results with 4-class priority control using two 10G-ONUs after switching to the redundant OSU. The frame transmission with 4-class priority control is performed on R-#2 structure. The total downstream and upstream bit-rates were 8.7 Gb/s and 10 Gb/s, respectively. The frame loss observed in only low class traffic is due to the total bandwidth being exceeded; no frame loss occurred in high, medium-high, and medium low class traffic. Therefore, priority control operated correctly in our N:1 redundant 10G-EPON system with SOA.

Table. 3.5 Frame transmission results with 4-class priority control using two 10G-ONUs on redundant path on R-#2 structure.

Priority	Downstream		Upstream	
	Frame loss [%]	Latency [μ s]	Frame loss [%]	Latency [μ s]
High	0	161.86	0	1031.02
Medium-high	0	161.87	0	1035.29
Medium-low	0	161.97	0	1037.06
Low	2	18218.96	15	25508.26

3.3.4 Long-term feasibility

Long-term feasibility of the system using two 10G-ONUs was demonstrated on R-#1 structure. The upstream and downstream bit rates were 2.5 Gb/s. Under this condition, error-free transmission for over 130 hours was successfully achieved. This error-free time corresponds to a BER of better than 10^{-14} , therefore this significant level of feasibility will yield practical applications of the 10G-EPON system.

3.4 Summary

This chapter introduced a experimental HSR- and LR-10G-EPON system with N:1 OSU protection in order to confirm high system feasibility. The explained dual-rate ALC-SOA contributes to extend the optical loss budget with N:1 redundant topologies. The system can switch from active to redundant channels without any frame loss. The chapter also showed that the quality of bidirectional frame transmission was not degraded after switching to the redundant channels. Also, N:1 protection ensured system reliability so that it well supported the high-end services even though SOAs were used to realize a cost-effective 10G-EPON system.

Chapter 4

Analysis method of transmission distance of PONs

4.1 Overview

In this chapter, the thesis proposes an analysis method for optimally designing the 10G-EPON system to maximize an office reduction effect with the parameter of the splitting-ratio and the transmission distance. Since the relationship between input power to SOAs and output power from SOAs is non-linear, an analysis model is required for the 10G-EPON system with OAs in order to calculate the total transmission distance, D_{Total} . Our solution is to map D_{Total} using the parameter of splitting ratio. Based on the concept described in this chapter, telecommunication carriers can flexibly design the network architecture and realize OPEX savings.

4.2 Formulation

This section estimated the intrinsic D_{Total} [km] based on the following five simple formulae and the parameters are shown in Fig. 4.1 and Table 4.1.

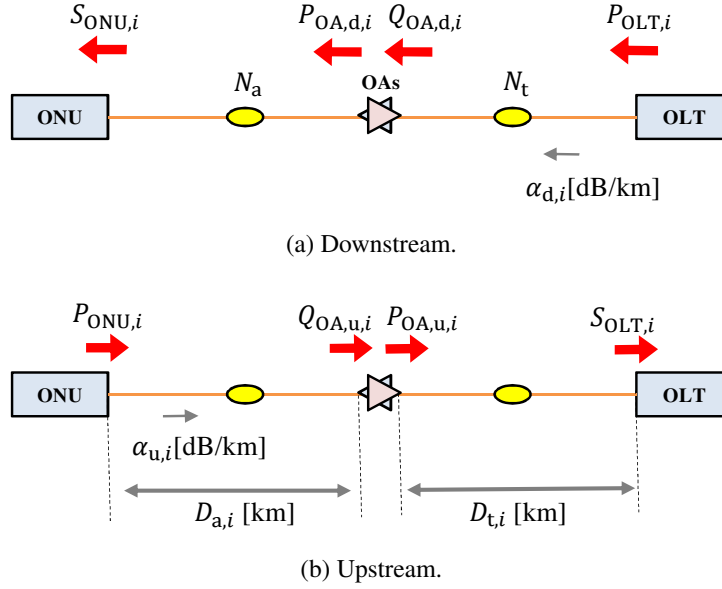


Fig. 4.1 Variables for the calculation of the transmission distance.

$$D_{\text{Total}}(N_b, N_a) = \min_{i=10G, 1G} (D_{a,i} + D_{t,i}) \quad (4.1)$$

$$P_{OA,d,i}(Q_{OA,d,i}) - (S_{ONU} + \delta_{ONU,i} + \epsilon_{ONU,i}) \geq \alpha_d D_{a,i} + 10 \log_{10} N_a \quad (4.2)$$

$$P_{OLT,u,i}(Q_{OA,u,i}) - (S_{OLT,i} + \delta_{OLT,i} + \epsilon_{OLT,i}) \geq \alpha_d D_{t,i} + 10 \log_{10} N_t \quad (4.3)$$

$$Q_{OA,d,i} = P_{OLT,i} - (\alpha_{d,i} D_{t,i} + 10 \log_{10} N_t) \quad (4.4)$$

$$Q_{OA,u,i} = P_{ONU,i} - (\alpha_{u,i} D_{a,i} + 10 \log_{10} N_a) \quad (4.5)$$

Eq. (4.1) determines D_{Total} by selecting the shorter total transmission distance (10G or 1G service), which is indicated by i . This analysis can be extended by simply assigning i values to other co-existing services such as video distribution service and/or future NG-PON2 service, and so on. Formula (4.2) and Formula (4.3) represent the transmission condition, i.e. optical budget exceeds the transmission loss, for the downstream and upstream transmission, respectively. N and β is not identified because these parameters are common for all services due to the wavelength independence of the network. α and β must be clarified

Table. 4.1 Variables for the calculation of the transmission distance.

Variable	Definition
D_{Total} [km]	Available total transmission distance.
$D_{t,i}, D_{a,i}$ [km]	The transmission distance on the trunk and access span, respectively.
N_t, N_a	The splitting ratios on the trunk and access span, respectively.
$\alpha_{d,i}, \alpha_{u,i}$ [dB/km]	Optical transmission loss per kilometer on the downstream and upstream transmission.
$P_{\text{OLT},i}, P_{\text{ONU},i}$ [dBm]	Average output power of OLT and ONU.
$S_{\text{OLT},i}, S_{\text{ONU},i}$ [dBm]	Minimum receive sensitivity of OLT and ONU.
$P_{\text{OA},d,i}, P_{\text{OA},u,i}$ [dBm]	Output power from OAs on the downstream and upstream signal.
$Q_{\text{OA},d,i}, Q_{\text{OA},u,i}$ [dB]	Input power to optical amplifier on the downstream and upstream signal.
$\delta_{\text{OLT},i}, \delta_{\text{ONU},i}$ [dB]	Sensitivity degradation by the chromatic dispersion on OLT and ONU, respectively.
$\epsilon_{\text{OLT},i}, \epsilon_{\text{ONU},i}$ [dB]	Sensitivity degradation by the extinction ratio degradation on OLT and ONU, respectively.

by the measurements on the actual commercial access network service. Characteristics of SOAs can be uniquely determined from the measured curve shown in Fig. 3.4 and Fig. 3.7. δ is derived from the sensitivity degradation by the chromatic dispersion on OLT and ONU, respectively. In this analysis, since the effect of chromatic dispersion is negligible given the distance of around 40 km, δ is simply determined by the ASE noise from the SOAs. Also, ϵ is derived from the sensitivity degradation by the extinction ratio degradation on OLT and ONU due to ASE noise from the SOAs. ϵ can be uniquely determined from the measured curve shown in Fig. 3.4 and Fig. 3.7. Eq. (4.4) and Eq. (4.5) give the input power to SOAs for the downstream and upstream transmission, respectively. These equations and formulae exactly estimate the value of D_{Total} with arbitrary parameters by using actual measured characteristics

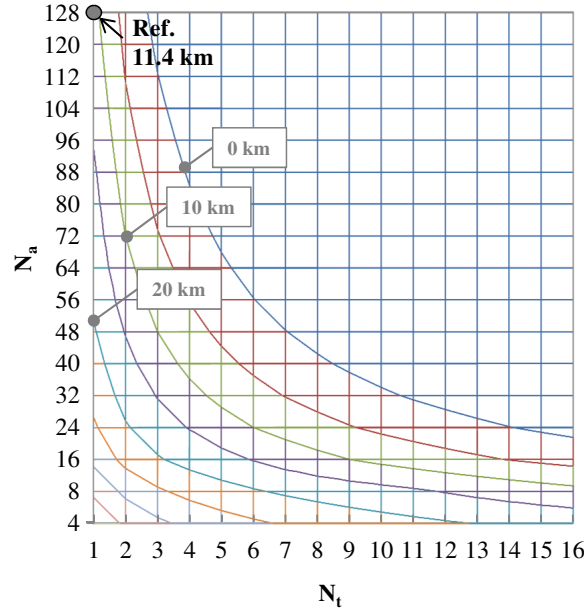


Fig. 4.2 Evaluated reference transmission distance map without OA with splitting ratio as the parameter, OLT side (N_t) and ONU side (N_a). ©OSA, IEEE, 2017

of the transceivers, SOAs, and commercial access network.

Our analysis approach casts D_{Total} as a two dimensional map with the parameter of splitting ratio; the criterion is to satisfy the required condition. Of course, an approximated relation is employed such as $D_{Total} = f(N_t, N_a)$ with the certain function of f instead of the two-dimensional map. Also, more detailed analyses method can be developed for estimating D_{Total} using other parameters such as optical characteristics of each device of OLT, OAs (relay or CO-set), ONU. In CO-set structure, $D_{t,i}$ is assumed to be 0 km.

4.3 Analysis results

Reference

Fig. 4.2 shows the D_{Total} map for Ref. measured in Chapter 3. Estimated D_{Total} is 11.4 km with the splitting ration of 128. This distance is shorter than the original specified distance (20 km with 32 splits) of PR30/PX20 due to the optical splitting loss created by the 128 splits. The map behaves as hyperbolic curve so D_{Total} is constant if the total splitting ratio is the same.

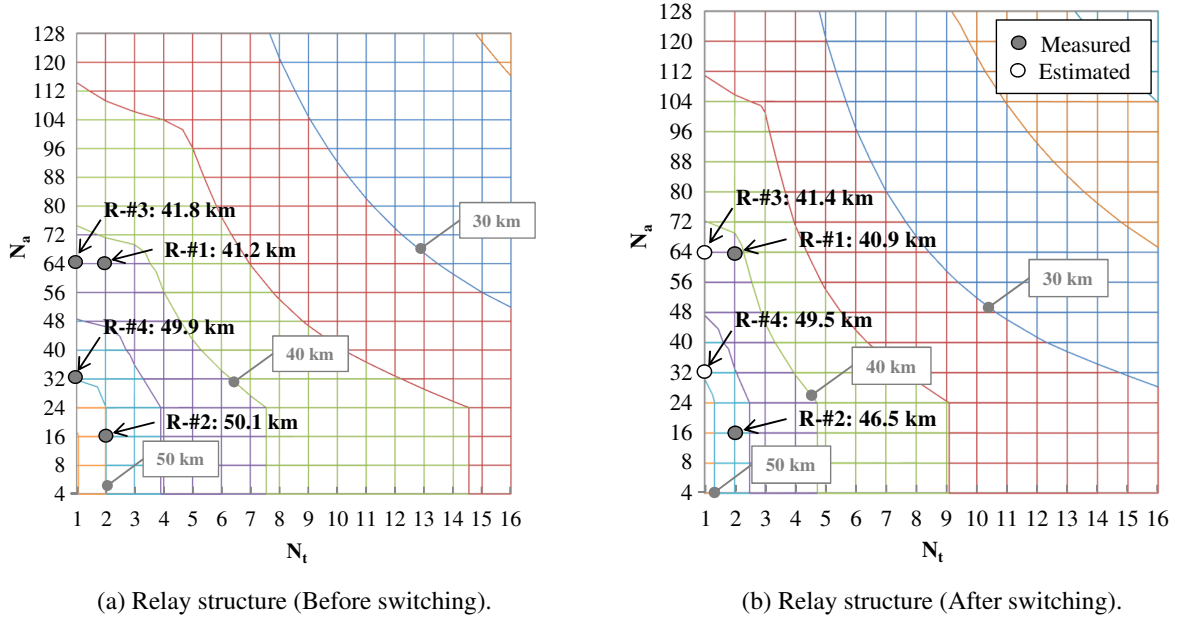


Fig. 4.3 Evaluated extended transmission distance map by relay OA with splitting ratio as the parameter, OLT side (N_t) and ONU side (N_a).

Relay structure

Fig. 4.3 shows the D_{Total} map for relay structure before switching. The contour of Fig. 4.3a consists of a vertical and horizontal lines due to the saturation by upstream and downstream optical power from OAs, respectively.

D_{Total} of R-#1 (41.2 km) and R-#3 (41.8 km) are almost same in spite of the deference of the splitting ratio. In this case, telecommunication carriers can cost-effectively double the number of subscribers accommodated by an OLT without shortening D_{Total} by adopting R-#1 structure.

D_{Total} of R-#2 (50.1 km) and R-#4 (49.9 km) are also almost the same. This reason is explained as follows. First, D_{Total} is limited by the downstream signal received by ONU for both $(N_t, N_a) = (2, 16)$ for R-#2, and $(N_t, N_a) = (1, 32)$ for R-#4. Thus the SOAs operate in AGC mode (not ALC mode) for downstream transmission. Therefore, if the total splitting ratio ($N_t \times N_a$) is constant regardless of the value of N_t or N_a , D_{Total} is not changed because the downstream power received by ONU remains the same.

After switching, as shown in Fig. 4.3b, D_{Total} is shortened due to the additional insertion

loss in the Nx1 optical SW. To improve D_{Total} after switching, telecommunication carriers can use a lower loss Nx1 SW and/or a higher optical budget redundant OSU transceiver.

CO-set structure

Fig. 4.4a shows the D_{Total} map for CO-set structure with normal path. The contour consists of a parabolic curve (right side) and a horizontal line (left side). D_{Total} in the region of the parabolic curve is limited by upstream transmission with SOAs in AGC mode, and in the region of horizontal line, it is limited by downstream transmission with SOAs with ALC mode.

D_{Total} of C-#1 (29.1 km) and C-#2 (27.6 km) are extended from Ref. (18.3 km). For C-#2, the optical loss of 32 splits of N_a between SOAs and ONU weakens the downstream input power to the ONU and reduces the transmission distance compared to C-#1.

D_{Total} is almost the same in C-#3 (23.8 km) and C-#4 (23.5 km). This is explained as follows. First, D_{Total} is limited by the downstream signal received by ONU for both $(N_t, N_a) = (8, 16)$ on C-#3 and $(N_t, N_a) = (4, 32)$ on C-#4. Thus the SOAs operate in AGC mode (not ALC mode) for downstream transmission. Therefore, if the total splitting ratio $(N_t \times N_a)$ is constant regardless of the value of N_t or N_a , D_{Total} is not changed in the same reason as R-#2 and R-#4.

This map can also further estimate that D_{Total} of $(N_t, N_a) = (2, 64)$ and $(4, 64)$ is almost the same, 18.6 km and 17.8 km, respectively, even if D_{Total} are not measured. This means that telecommunication carriers can cost-effectively double the number of subscribers accommodated by an OLT without shortening D_{Total} . Moreover, Fig. 4.4b also clarifies that inserting the 2x2 coupler in N:1 optical SW before the SOAs is advantageous for extending D_{Total} , when D_{Total} at the split ratio of $(N_t, N_a) = (1, 32)$ is 27.8 km. These results clarify that CO-set structure are very advantageous in increasing the splitting ratio of the N:1 redundant 10G-EPON system.

After switching, as shown in Fig. 4.4a, D_{Total} is shortened due to the 2-dB additional insertion loss on the OLT side. Therefore, telecommunication carriers can use a lower loss Nx1 SW and/or a higher optical budget redundant OLT transceiver as well as relay structure.

Fig. 4.4c and 4.4d show the D_{Total} map of CO'-set structure for normal path and redundant

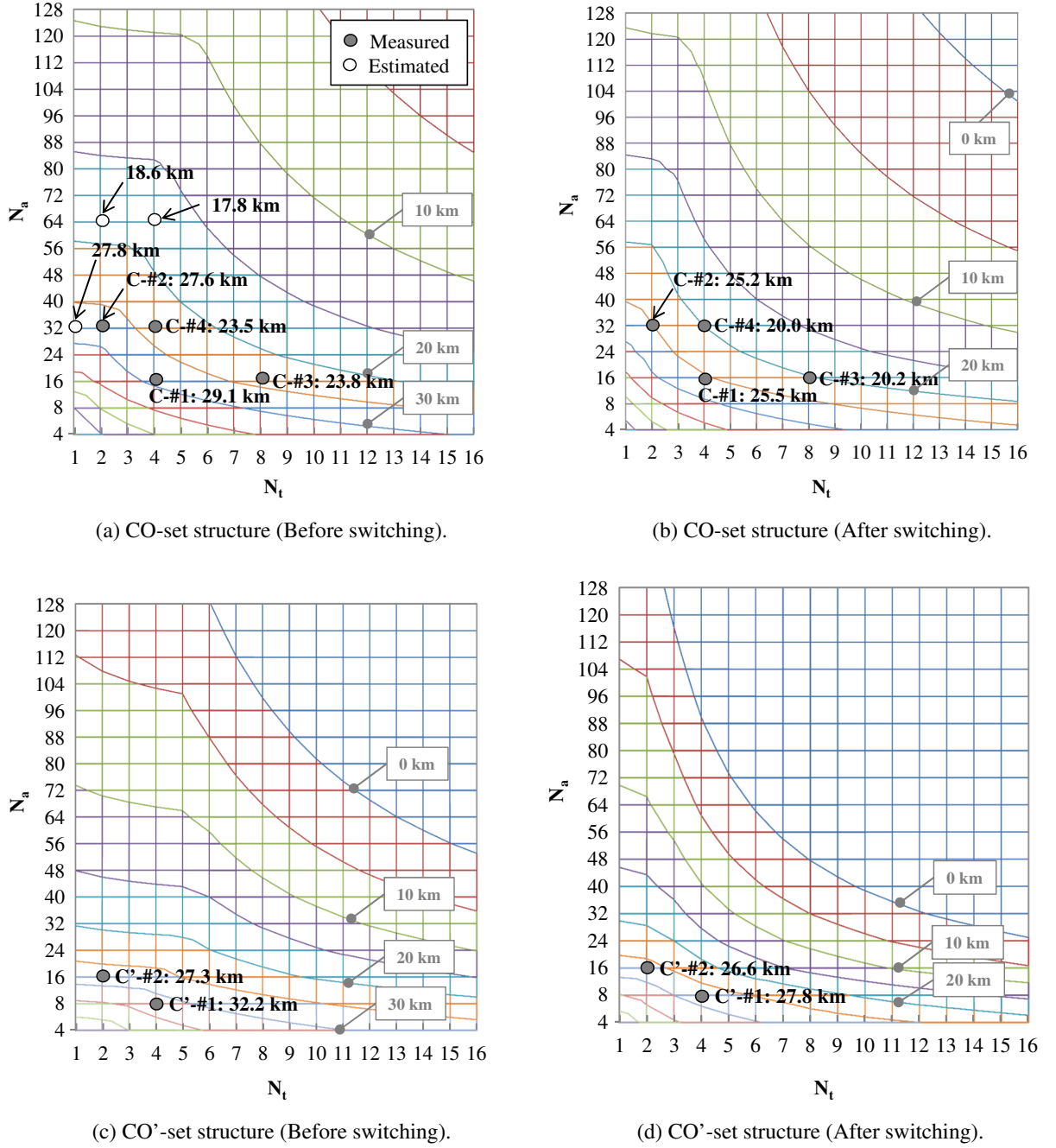


Fig. 4.4 Evaluated extended transmission distance map by CO-set OA with splitting ratio as the parameter, OLT side (N_t) and ONU side (N_a). ©2017, OSA, IEEE

path, respectively. Though the reach-extension effect on CO'-set structure is limited compared with CO-set structure, D_{Total} is extended from 23.5 km to 27.8 km with C'-#1 and to 26.6 km with C'-#2. On the redundant path, D_{Total} is shortened from 32.2 km to 27.8 km with C'-#1 and from 27.3 km to 26.6 km with C'-#2. The reason is that the additional loss on the

redundant path attenuates the downstream input power to AGC-mode SOAs. Thus, the output downstream power from SOA is also decreased, and D_{Total} is shortened by the additional loss at the Nx1 SW.

Telecommunication carriers can also estimate D_{Total} in other conditions simply by altering the optical characteristics of OAs, OLT and ONU and the optical losses. Thus, telecommunication carriers can flexibly design the architecture of a 10G-EPON system to realize the split-ratio and D_{Total} needed to suit the subscriber distribution. This formulation and design method allows us to easily and accurately estimate the D_{Total} based on actual field measurement results.

4.4 Summary

This chapter proposed a analysis method for optimally designing the 10G-EPON system to realize the splitting-ratio and transmission distance needed to suit the subscriber distribution. Since the relationship between input power to SOAs and output power from SOAs is non-linear, an analysis model is required for the 10G-EPON system with OAs in order to easily estimate the total transmission distance. Our solution was to map the transmission distance using the parameter of splitting ratio. Based on the concept described in this chapter, telecommunication carriers can flexibly design the network architecture for OPEX savings.

Chapter 5

Auto-configurable optical amplifier

5.1 Overview

When communication carriers apply OAs to PON, an optical overloading to optical devices has to be considered. In the chapter, the thesis proposes an auto-configurable OA (AC-OA). AC-OA has variable optical attenuators (VOAs) at the input and a controller synchronized with a centralized calculator (CC) and external facility database (FDB). VOA value is determined by CC and FDB, and used to adaptively control the input power of the OA. AC-OA suits various PON architectures because the mechanism of AC-OA provides simple plug and play OA operation and suits various HSR- and LR-PON architectures. The results of a simulation that clarify the feasibility are explained. Finally, the installation expenditure reduction effect is evaluated.

5.2 Conventional auto-level-control optical amplifier

(ALC-OA)

This section explains the conventional ALC-OA before the proposal of AC-OA. Fig. 5.1 illustrates the simplified architecture of ALC-OA. ALC-OAs, which is described and applied in Chapter 3, have generally been applied to HSR- and LR-PON for amplifying the optical power while preventing optical overloading of OLT and ONU transceivers. ALC-OA uses different OA devices to separately amplify the downstream and upstream optical signals at their respective wavelengths. The OA candidates include SOAs, OFAs, FRAs, and even OEO repeater devices.

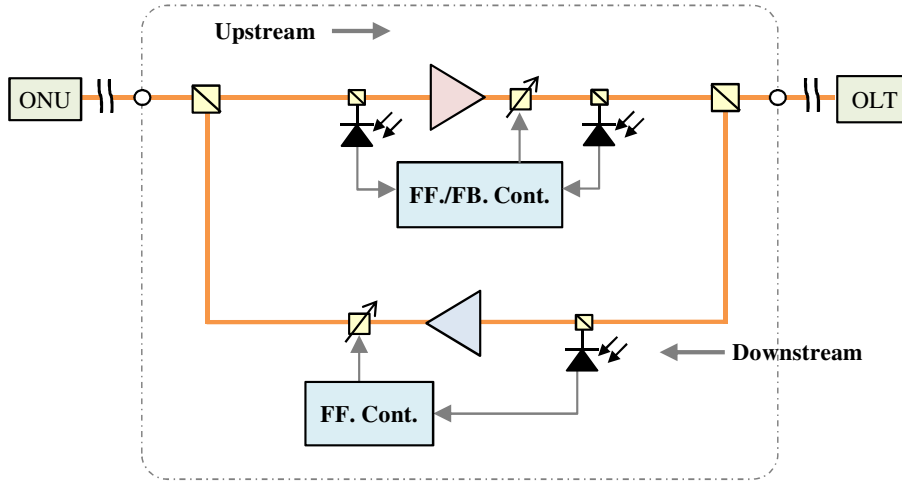


Fig. 5.1 A conventional OA with ALC function. ALC-OA uses different OA devices to separately amplify the downstream and upstream optical signals at their respective wavelengths. ALC-OA also employs VOA-based devices for output signal power control. However, the ALC function cannot prevent optical overloading toward OA on both upstream and downstream due to the technological issues with controlling input power to OA. ©2017, OSA, IEEE

ALC-OA also employs VOA-based devices for output signal power control as described in Chapter 3. The output power of downstream and upstream signal can be controlled by a FF and FB circuit that adjusts output VOA value. The fast ALC function with VOA provides quick adjustment of output upstream optical signal power and prevents optical overloading towards OLT. The ALC function is required if the OA is to be widely applied to various access networks while avoiding optical overload toward ONU and OLT.

However, the ALC function cannot prevent optical overloading toward OA on both upstream and downstream due to the two fundamental issues with controlling input power to OA.

- VOA with FB control cannot stably control the input power to the OA due to the short feedback delay.
- Upstream VOA cannot be measured in advance because upstream optical power cannot be observed after authentication and link-up with OLT through the multi-point control protocol (MPCP).

These ALC-OA issues strongly limit the possible areas of application [32, 52].

To meet the various application areas of FTTx, we must not only maximize the optical link-budget, but also prevent optical overloading to the optical devices on OLT, ONU and OA. Optical overloading will irreversibly break optical transceivers, and the conventional solution is to insert optical attenuators (ATTs) to control the input power of an optical signal to each optical device. However, the use ATTs raises two serious concerns.

- The manual work required to set ATTs of appropriate value is time-consuming and extremely expensive.
- The severity and frequency of human errors are worsened by the manual network operations that must be performed.

Especially, the some automated mechanism for preventing optical overload is required because OAs easily causes the optical overload while the optical amplification. Therefore, it is essential to develop AC-OAs to reduce both operational costs and human errors.

5.3 Auto-configurable optical amplifier (AC-OA)

This section describes AC-OA. It is applicable to various HSR- and LR-PON architectures and can prevent optical overloading of all optical devices while not degrading the optical link budget. AC-OA optimizes the VOA values by referencing an external facility database (FDB); the information retrieved is used in solving the search problem formulated so that all subscribers can be accommodated.

5.3.1 Structure

Fig. 5.2 indicatess the architecture of the proposed AC-OA. The additional external devices are the centralized calculator (CC) and facility database (FDB). Each AC-OA consists of OA devices, monitor PDs, WDM couplers, input/output VOAs and a controller.

Output VOA value is controlled by the ALC function based on FF and FB control as described as Chapter 3. Input VOA value is calculated and set by referencing FDB entries because input power, especially bursty upstream input power, cannot be stably attenuated with

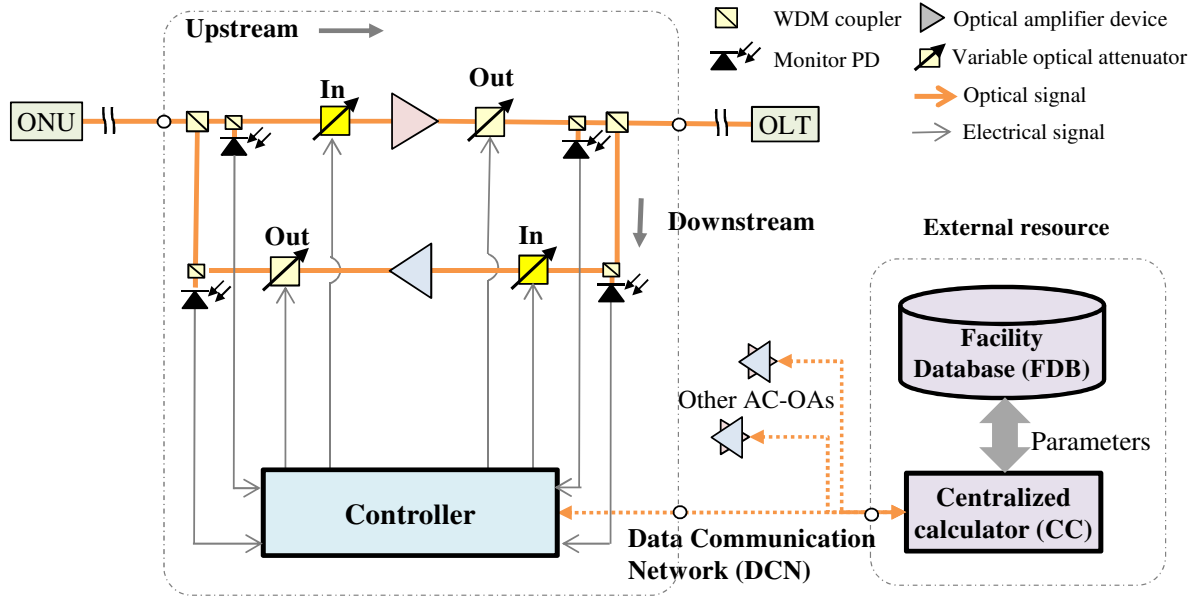


Fig. 5.2 Architecture of proposed Auto-Configurable Optical Amplifier (AC-OA). AC-OA can control the input power toward itself by an VOA autonomously controlled by the centralized calculator and facility database. The automated process simplifies network operation while reducing installation costs and human errors. ©2017, OSA, IEEE

fast enough response speeds. Note that the input VOA value is constant unless the structure of the PON is changed.

The AC-OA controller is connected to the CC by a management network for the use of the telecommunication carrier. The management network already exists as existing OA architectures use to realize remote monitoring and operation. The CC determines the input VOA value based on FDB information and returns the value to the OA controller.

Importantly, VOA value of AC-OA is not changed after connecting AC-OA and firstly setting VOA value while ALC-OA have to be adaptively changed depending on the various powers of each burst signal from ONUs. Therefore, AC-OA is also cost-effective since the reliability of AC-OA is higher than that of ALC-OA.

5.3.2 Installation sequence

Fig. 5.3 compares the operator's installation procedures for conventional OA and AC-OA architectures. It is clear the AC-OA has the much simpler procedure.

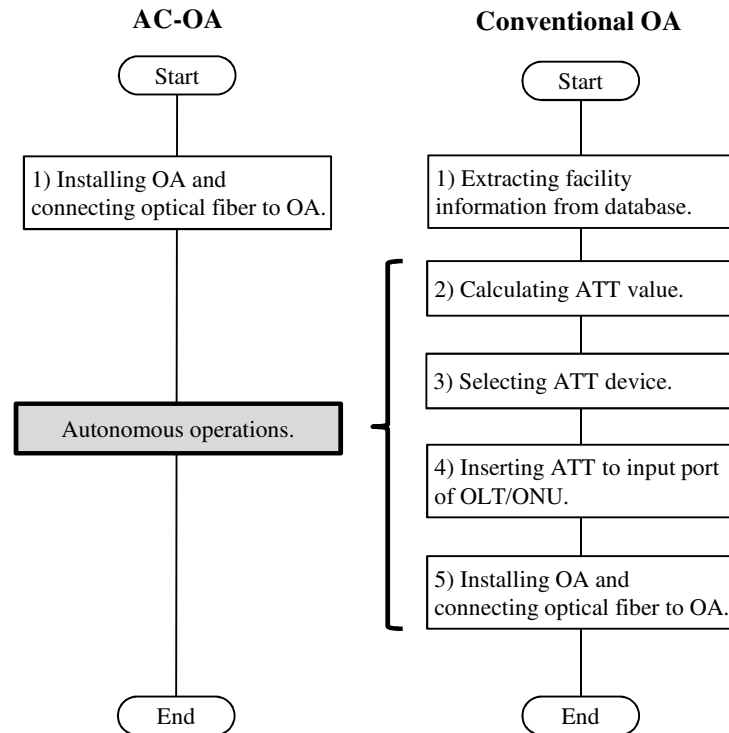
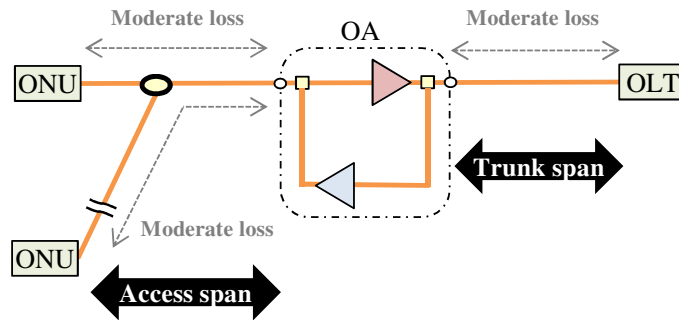


Fig. 5.3 Comparison of operator's installation procedures between conventional OA and AC-OA. Conventional OA complicated manual-based operations incur large additional installation costs and greatly raise the risk of human error. On the other hand, AC-OA's automated process allow us to merge various operations into one while reducing the cost of setting ATT and decreasing or eliminating the risk of human error. ©2017, OSA, IEEE

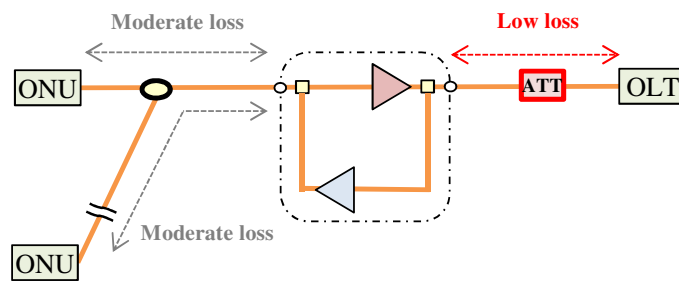
Conventional OA The sequence of conventional OA is described below.

· Operator sequence

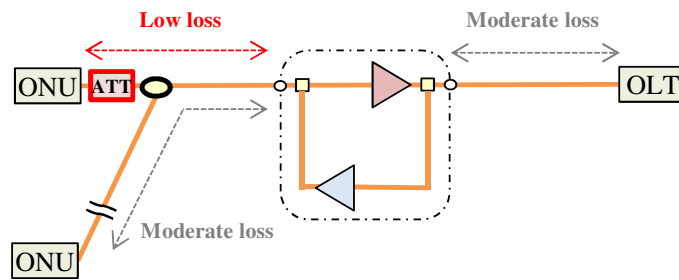
- 1) Operator extracts facility information of OA location from facility database.
- 2) Operator calculates the value of ATTs for both downstream and upstream transmission based on the extracted parameters.
- 3) Operator selects and checks ATT devices in both OLT and ONU as to whether 2) is satisfied or not.
- 4) Operator manually inserts ATTs of the correct values to the input ports of OLT or/and ONU and connects optical fiber to OA as needed.
- 5) Operator installs OA and only then connects optical fiber to OA.



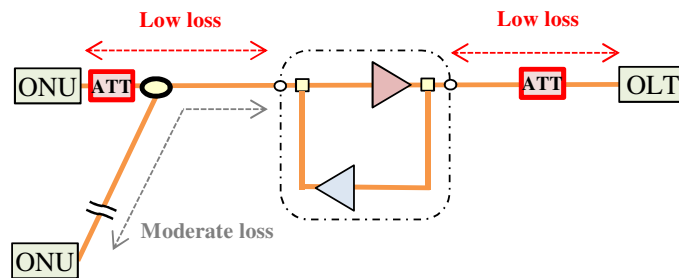
(a) Unnecessary.



(b) Only trunk span.



(c) Only access span.



(d) On both of trunk and access span.

Fig. 5.4 The four cases in which overload is prevented by installing optical attenuators. (a) is the ideal condition since no additional control is required for preventing optical overload. (b) is the case in which the trunk loss is too small. (c) is the case in which the access loss is too small. (d) is the mixture of (b) and (c). ©2017, OSA, IEEE

With conventional OA, operators have to manually insert the optimum ATT to each OA. Fig. 5.4 summarizes the four cases in which overload is prevented by installing optical attenuators. Here, the span between OLT and OA is defined as the trunk span, while the span between OA and ONU span is defined as the access span as described above. Also, the lengths of the trunk span and access span are defined as trunk and access distance, respectively.

- (a) No control is required (Fig. 5.4a).
- (b) Control of trunk span is required (Fig. 5.4b).
- (c) Control of access span is required (Fig. 5.4c).
- (d) Control of trunk and access spans is required (Fig. 5.4d).

(a) is the ideal condition since no additional control is required for preventing optical overload while realizing the desired input power amplification. (b) is the case in which the trunk loss is too small due to low splitting-ratio or short trunk distance, including CO-set OA. (c) is the case in which the access loss is too small due to low splitting-ratio or short access distance. (d) is the mixture of (b) and (c).

Given that access distances will vary significantly, a mixture of ATT-required and non-required ONUs will be needed. The important thing is that if an ATT is connected to an ONU to a high loss span, the ONU may not be able to communicate with its OLT because its received optical power could be lower than its minimum receiver sensitivity. Such complicated manual-based operations incur large additional installation costs and greatly raise the risk of human error.

AC-OA Sequence of adjusting VOA is described below. Autonomous AC-OA sequence is also shown in Fig. 5.5. Since the sequence is simple, implementation is also simple.

- Operator sequence

- 1) Operator inputs the identification data (the installation office and input/output optical fiber) and connects optical fiber to OA (VOA value is initially set at maximum to prevent overload).

- Automatic OA sequence

- 1) OA Controller sends identification data to external CC over DCN.

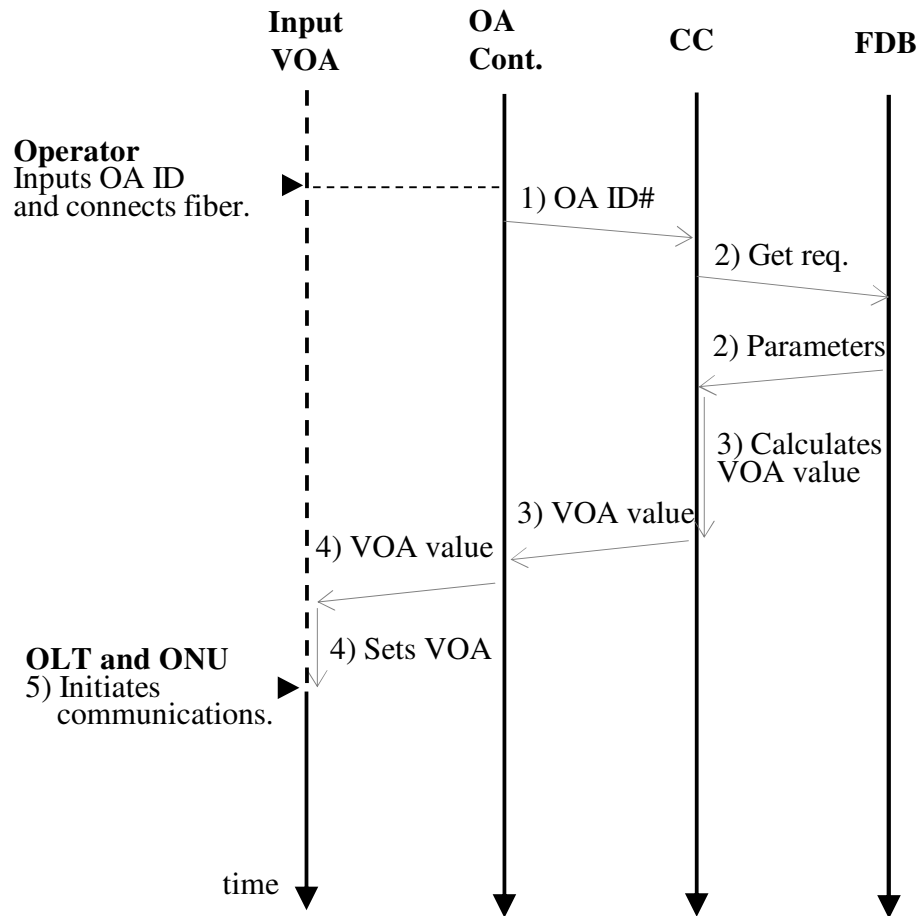


Fig. 5.5 AC-OA sequence for setting VOA value. 1) OA Controller sends identification data to external CC over DCN. 2) The CC extracts the required parameters (fiber lengths, splitting ratios, and so on) from the external FDB. 3) CC calculates VOA value from extracted parameters and sends the determined VOA value to the AC-OA controller. 4) Controller of AC-OA sets VOA value to prevent optical overload while ensuring sufficient gain. 5) After setting VOA, OLT and ONU initiate communication via the Multi-point-control protocol. ©2017, OSA, IEEE

- 2) The CC extracts the required parameters (fiber lengths, splitting ratios, and so on) from the external FDB.
- 3) CC calculates VOA value from extracted parameters and sends the determined VOA value to the AC-OA controller.
- 4) Controller of AC-OA sets VOA value to prevent optical overload while ensuring sufficient gain.

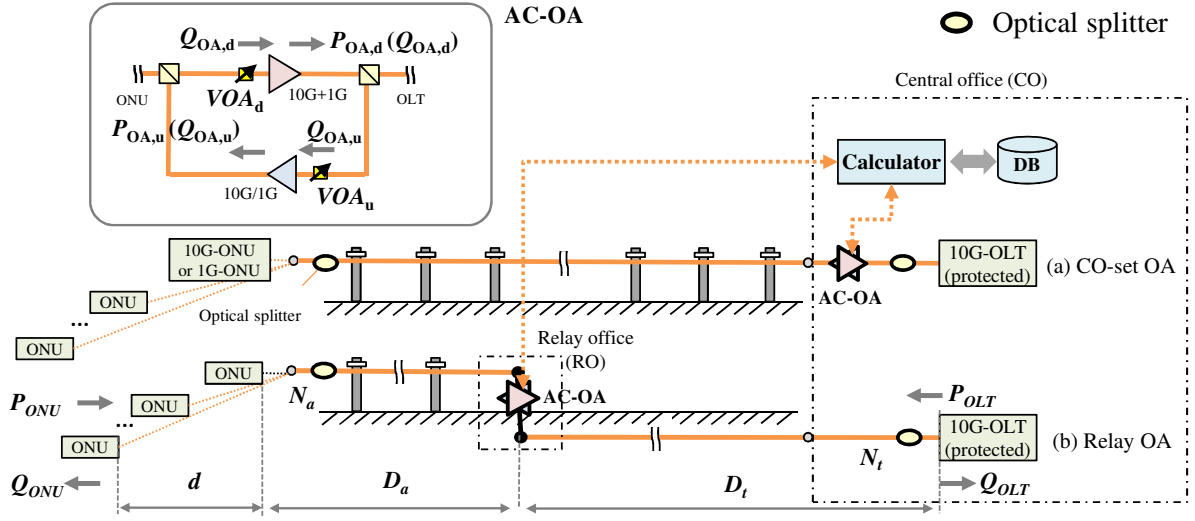


Fig. 5.6 Explanation of infrastructure parameters. ©2017, OSA, IEEE

- 5) After setting VOA, OLT and ONU initiate communication via the Multi-point-control protocol (MPCP).

MPCP is the protocol which operates between an OLT and ONUs connected with a Point-to-Multi-Point (P2MP) topology so as to allow efficient upstream transmission of data. This automated process allow us to merge various operations into one while reducing the cost of setting ATT and decreasing or eliminating the risk of human error.

5.3.3 Algorithm

FDB parameters are shown in Fig. 5.6 and Table 5.1. Actually, the parameters of optical fibers connected to the AC-OA are given by statistical analysis of prior measurement results in advance.

Objective parameters

VOA_j is target value of input VOA realized by solving the search problem. j represents VOA location side, namely, $j = \text{upstream (u) on access span or downstream (d) on trunk span}$.

Structural parameters of PON

D_t and D_a are the trunk and access distances, respectively. d is the accommodation range for nearest and farthest ONU from optical splitter. N_t and N_a represent the optical splitting

Table. 5.1 Database parameters for AC-OA operation.

Parameter	Type	Definition
D_t	Variable	The distance of trunk span between OLT and OA.
D_a	Variable	The distance of access span between OA and nearest ONU from optical splitter.
d	Variable	The distance between nearest and farthest ONU from optical splitter.
N_t, N_a	Variable	The optical splitting ratio of trunk and access span.
$\alpha_{t,ij}, \alpha_{a,ij}$	Given	Optical transmission loss per kilometer.
β_t, β_a	Given	Miscellaneous optical loss by connectors and fusion points and so on.
$P_{OA,ij}(Q)$	Given	Optical output power of OA for input power Q .
$S_{OLT,i}, S_{ONU,i}, S_{OA,ij}$	Given	Required minimum input power to OLT, ONU, OA, respectively.
$T_{OLT,i}, T_{ONU,i}, T_{OA,ij}$	Given	Damage threshold of OLT, ONU, OA, respectively.

ratios of trunk and access span, respectively. These parameters are extracted from the facility database since each optical line has different values.

Optical fiber parameters α_{ij} represents the optical transmission loss per kilometer for all i and j . j represents the kind of access service provided such as GPON [22], EPON, 10G-EPON [3], NG-PON2 [23] and 100G-EPON [53].

β_t and β_a mean miscellaneous optical losses on trunk and access spans, respectively. Miscellaneous loss is the summation of losses due to connectors, fusion points, and so on.

These parameters can be commonly determined based on actual measurements of used optical fiber, modules and construction technology as standardized in [54]. Of course, these parameters can be set to different values for each optical line, if they can be extracted from the facility database correctly.

Optical device parameters The optical specifications or characteristics such as S_x, T_x, P_y ($x=OLT, ONU, OA,u, OA,d, y=OA,u, OA,d$) are given in advance. S_x, T_x indicate minimum sensitivity and average received power as standardized in IEEE or ITU-T. P_y is the response function of output power to input power of the OA including the effect of the ALC function. These parameters are determined in advance based on the actual condition of target area.

Affiliation information The FDB also includes the affiliation information indicating how CO, OLT and ONU are connected to each other. By collating an ID number of OA to con-

nected affiliation information, AC-OA can determine the parameters required for calculating the VOA value.

5.3.4 Formulation

The function for determining VOA values is written in the form of the following search problem Formula (5.1) to Formula (5.9).

Objective:

$$\mathbf{Find} \quad VOA_j \quad (j = t, a) \quad (5.1)$$

Subject to:

$$S_{OLT} < Q_{OLT}(D_t, D_a + d) \leq Q_{OLT}(D_t, D_a) < T_{OLT} \quad (5.2)$$

$$S_{ONU} < Q_{ONU}(D_t, D_a + d) \leq Q_{ONU}(D_t, D_a) < T_{ONU} \quad (5.3)$$

$$S_{OA,d} < Q_{OA,d}(D_t) < T_{OA,d} \quad (5.4)$$

$$S_{OA,u} < Q_{OA,u}(D_a + d) \leq Q_{OA,u}(D_a) < T_{OA,u} \quad (5.5)$$

$$\begin{aligned} Q_{OA,d}(D_t) \\ = P_{OLT} - \{\alpha_d D_t + 10 \log_{10} N_t + \beta_t + VOA_t\} \end{aligned} \quad (5.6)$$

$$\begin{aligned} Q_{ONU}(D_t, D_a) \\ = P_{OA,d}(Q_{OA,d}) - \{\alpha_d D_a + 10 \log_{10} N_a + \beta_a\} \end{aligned} \quad (5.7)$$

$$\begin{aligned} Q_{OA,u}(D_a) \\ = P_{ONU} - \{\alpha_u D_a + 10 \log_{10} N_a + \beta_a + VOA_a\} \end{aligned} \quad (5.8)$$

$$\begin{aligned} Q_{OLT}(D_t, D_a) \\ = P_{OA,u}(Q_{OA,u,i}) - \{\alpha_u D_t + 10 \log_{10} N_t + \beta_t\} \end{aligned} \quad (5.9)$$

Objective (5.1) is the objective of the problem and means identifying the input VOA value for the OA. Formula (5.2) to Formula (5.5) ensures that the input powers of Q_x have to satisfy the following conditions in order to satisfy the minimum sensitivity and avoid overloading

the transceiver or OA. Since ONUs are spatially connected at different distances from the optical splitter, ONUs connected at D_a and $D_a + d$ from OA have to satisfy the constraints described above. Eq. (5.6) to Eq. (5.9) determine the received power to downstream OA, ONU, upstream OA and OLT, respectively. By finding the VOA values that satisfy these constraints, AC-OA can increase the optical budget while preventing overload.

5.4 Simulation of AC-OA operation

The first objective of this section is to confirm that AC-OA can determine and set acceptable VOA values given the structure, sequences, and formulation. The second objective is to validate the feasibility of AC-OA. The section also simulates the operation of AC-OA with realistic parameters on various actual HSR- and LR-PON architectures. Then the calculation time is also evaluated for solving the search problem.

5.4.1 Conditions

The objective of the simulation is to find the VOA values that prevent optical overloading while allow OLT to accommodate all ONUs. Table 5.2 shows the PON structural parameters, which consist of N_t , D_t , N_a , and D_a . R-#0 and C-#0 are assumed structure for intentionally making the overloading condition. In C-#0 to #4 and C'-#1 to #2, D_t is assumed to be zero since OA is installed at CO.

The optical fiber parameter (α_{ij} , β_t and β_a) based on actual field measurement described in Chapter 3 is used for the simulation in order to acquire a realistic value range and thus confirm the feasibility of AC-OA. The distribution range of ONU (d) is set to 1 km in this simulation. The optical device parameters of the dual-rate 10G- and 1G-OLT, which conforms to the specifications of PR30, are assumed for the simulation. In addition, 10G-ONU and 1G-ONU conform to the specifications of PR30 and PX20 applied in Chapter 3, respectively. Thus index i indicates two services, 1G or 10G.

Here, OA is assumed to use a SOA, and that the ALC function is used to control output VOA. SOA characteristics are shown in Chapter 3. The optical gain for the downstream signal is around 15 dB (10G) / 25 dB (1G) while that for the upstream signal exceeds 30 dB

Table. 5.2 Structural parameters of PON.

Structure	N_t	D_t [km]	N_a	D_a [km]
R-#0	2	20	8	0.6, 5, 10, 18.5
R-#1	2	20	64	0.6, 5, 10, 18.5
R-#2	2	20	16	0.6, 5, 10, 18.5
R-#3	1	20	64	0.6, 5, 10, 18.5
R-#4	1	20	32	0.6, 5, 10, 18.5
C-#0	2	0	8	0.6, 5, 10, 18.5
C-#1	4	0	16	0.6, 5, 10, 18.5
C-#2	2	0	32	0.6, 5, 10, 18.5
C-#3	8	0	16	0.6, 5, 10, 18.5
C-#4	4	0	32	0.6, 5, 10, 18.5
C'-#1	4	0	8	20.6, 25, 30
C'-#2	2	0	16	20.6, 25, 30

(10G/1G). Maximum and minimum levels of optical power to AC-OA are -10 and -30 dBm, respectively, so optical signal quality is not degraded by non-linear distortion in the SOA.

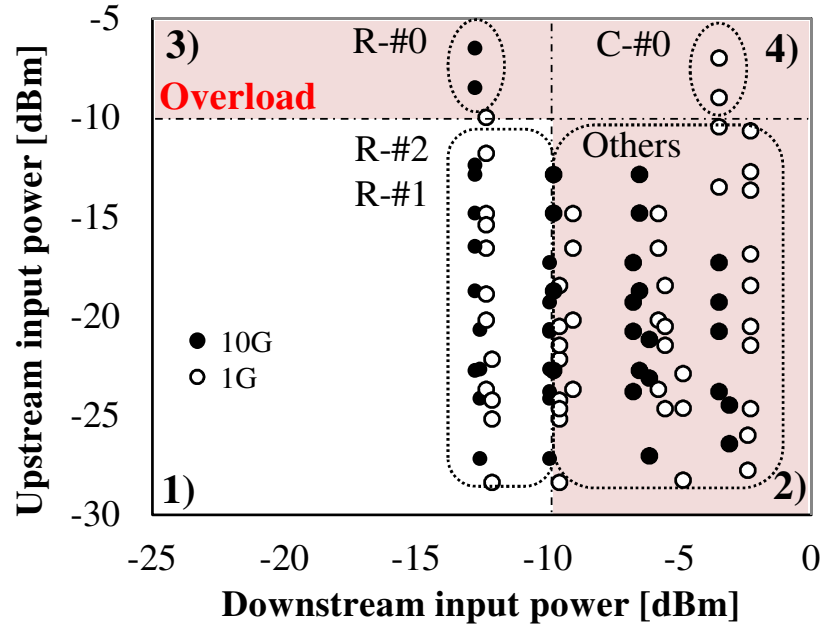
The optimum attenuation value, which satisfies Formula (5.2) to Formula (5.5) and Eq. (5.6) to Eq. (5.9), is calculated by a genetic algorithm with solution size and mutation rate of 100 and 7.5%, respectively.

5.4.2 Results and discussion

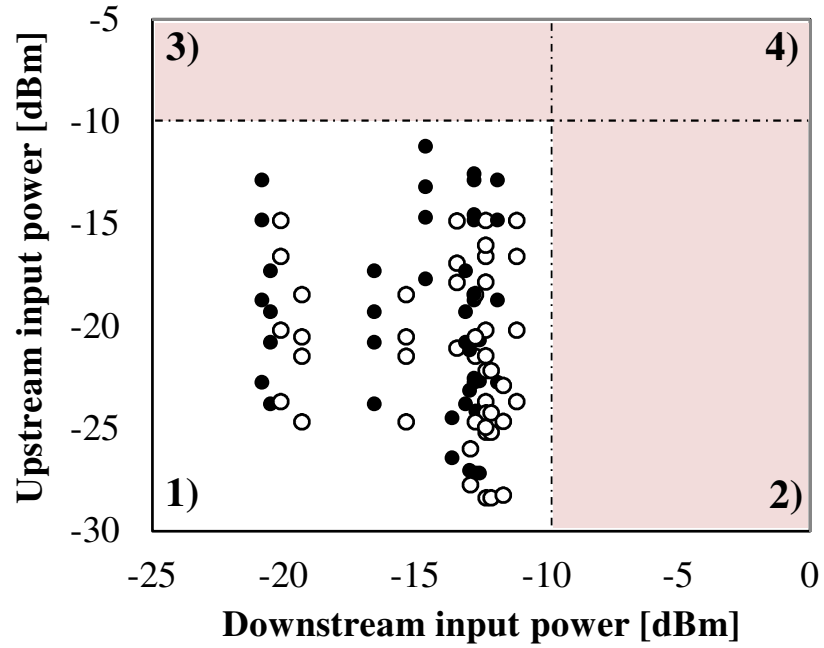
Fig. 5.7 shows the simulation results of upstream and downstream input powers for the various systems. Red region indicates optical overloading. These overload patterns can be classified into 1), 2), 3) and 4). Each pattern has its own ATT-setting pattern following the description.

- 1) ATT is not required.
- 2) ATT on trunk span is required.
- 3) ATT on access span is required.

-
- 4) ATTs on both trunk and access span are required.



(a) Conventional OA.



(b) AC-OA.

Fig. 5.7 These figures shows measured upstream and downstream input powers of commercial infrastructure. Fig. 5.7a shows the input power to conventional OA without any ATT-setting. Since ATTs with appropriate attenuation value for these spectrum patterns must be manually inserted, installation costs and human errors will be excessive. Fig. 5.7b shows the input power for the proposed AC-OA. In all cases, input powers are lower than overload level and exceed the required level. ©2017, OSA, IEEE

Table. 5.3 Calculation results of input VOA value.

Structure	VOA_t [dB]	VOA_a [dB]						
		$D_a = 0.6$ km	5 km	10 km	18.5 km	20.6 km	25 km	30 km
R-#0	0	6.4	6.2	6.3	6.4	-	-	-
R-#1	0	0	0	0	0	-	-	-
R-#2	0	0	0	0	0	-	-	-
R-#3	2.9	0	0	0	0	-	-	-
R-#4	3.2	0.3	1.3	1.7	0.3	-	-	-
C-#0	11.1	4.1	4.1	4.2	4.1	-	-	-
C-#1	16.9	0	0	0	0	-	-	-
C-#2	10.5	0	0	0	0	-	-	-
C-#3	9.8	0	0	0	0	-	-	-
C-#4	4.8	0	0	0	0	-	-	-
C'-#1	0	-	-	-	-	0	0	0
C'-#2	14.2	-	-	-	-	11.4	4.9	0

Fig. 5.7a shows the input power to conventional OA without any ATT-setting. In this figure, both R-#1 and R-#2 belong to region 1). Also, R-#0 and C-#0 are in regions 2) and 4), respectively. All other infrastructures (R-#3, R-#4, C-#1, C-#2, C-#3, C-#4, C'-#1 and C'-#2) belong to region 3). Since ATTs with appropriate attenuation value for these spectrum patterns must be manually inserted, installation costs and human errors will be excessive.

Fig. 5.7b shows the input power for the proposed AC-OA. In all cases, input powers are lower than overload level (-10 dBm) and exceed the required level (-30 dBm). Thus, AC-OA prevents optical overload by setting the input VOA value calculated by the CC.

Table 5.3 lists the calculated input VOA values. R-#0 in region 2) validates the VOA_a value so as to attenuate upstream optical input power to AC-OA. Also, C-#0 in region 4) sets both VOA_t and VOA_a so as to avoid excessive upstream and downstream optical input power, respectively. Other systems in region 3) set the value of VOA_t to control downstream optical input power. Some calculated VOA_a values lie in region 3) due to the use of the generic algorithm in the randomly search procedure. Thus AC-OA can determine and set adequate VOA values for realistic PON architectures.

The optimization time is between 0.1 and 3.0 sec. on a general purpose PC (CPU: Core i5 2 Cores 2.4 GHz, RAM: 2 GB). If the input VOA does not have to be controlled, the calculation is finished virtually instantly. Therefore, the calculation time is acceptable for actual application to a PON. Moreover, fewer CC are required because the calculation is only performed when the operator connects an OA.

The above results confirm that AC-OA can uniformly and automatically handle various HSR- and LR-PON architectures since AC-OA autonomously calculates and adaptively sets VOA value depending on the application case.

5.5 Cost evaluation

Next discussion is the cost impact of the implementation of the AC-OA. Regarding the price of the AC-OA, it is not increased by the additional VOAs since VOAs has a lower cost compared to the whole cost of OA components. Regarding the reliability of the AC-OA, it is at the same level or higher than that of the conventional ALC-OA. The first reason behind that is the human errors that can be negligible thanks to autonomous adjustment of VOA values. The second reason is that the mechanical reliability of the AC-OA is not degraded since input VOA values are adjusted once when the AC-OA is connected to PON, while the ALC-OA has to quickly adjust the VOA value within the burst interval below sub-micro seconds.

This section dedicates to compare installation costs for deploying conventional OA or AC-OA and show the superiority of AC-OA. The section also focuses on the evaluation method of installation costs and do not discuss the validity of parameter values used in the calculation.

5.5.1 Assumptions

Assumptions made for the cost evaluation are as follows.

1. OAs are applied to existing optical access network infrastructure.
2. Running costs of OA are same for conventional OA and AC-OA.
3. Units of price, unit of cost, standard operation time and mean time to failure period are defined using arbitrary units.
4. Conventional OA employs only ALC function on output port.

5. AC-OA employs both auto-configuration and ALC functions.
6. Conventional OA and AC-OA are installed by operations described in Section 5.3.

Then, conventional OA does not incur ATT-installation cost at OLT because operators can simultaneously set ATT when OA is installed. However, conventional OA incurs ATT-installation cost at each ONU. Thus, telecommunication carriers have to check each ONU as to whether ATT is needed or not, and rush to the subscriber's location if the ATT is needed.

5.5.2 Formulation

The subsection formulates installation costs (C_{inst}) for conventional OA and AC-OA system. Parameters for the evaluation are shown in Table 5.4.

Installation costs are estimated by following equations.

$$C_{\text{inst}} = C_{\text{calc}} + N\gamma'w_{\text{chk}}p_{\text{chk}} + \frac{N}{N_a}(C_{\text{oa}} + \gamma_t w_{\text{olt}}p_{\text{olt}} + w_{\text{set}}p_{\text{set}}) + N \times (w_{\text{calc}}p_{\text{calc}} + \gamma_a w_{\text{onu}}p_{\text{onu}}) \quad (5.10)$$

$$\gamma' = 1 - (1 - \gamma_t)(1 - \gamma_a) \quad (5.11)$$

The first term in Eq. (5.10) is CC installation cost. The second term represents the installation and operation costs incurred to avoid optical overloading of OAs. γ' in Eq. (5.11) is the risk of overloading either OLT or ONU. Third term in Eq. (5.10) means OA installation cost, and the operation cost needed to avoid optical overloading of OLT. Fourth term means the operation cost incurred to avoid optical overloading of ONU.

5.5.3 Results and discussion

Fig. 5.8 shows the installation-cost evaluation results based on the parameters mentioned above. With the assumptions made, installation costs can be reduced when N is greater than 1000. When $N \geq 10000$ and the price of AC-OA ≤ 1.25 , the installation-cost reduction can be more than 23%.

The proposed method can quantitatively evaluate the effect of AC-OA usage in reducing installation costs. Thus AC-OA is effective for reducing infrastructure cost while eliminating

Table. 5.4 Parameters used in calculating capital expenditure.

Parameter	Definition	Value	
		Conventional OA	AC-OA
C_{inst}	Total installation costs for introducing OA to PON.	-	
N	Total number of subscribers under OA.	Variable	
C_{calc}	Installation cost of CC including own price.	0	100000
C_{oa}	Price of a OA.	2000	Variable
N_t & N_a	The splitting ratio of trunk and access span, respectively.	4 & 8	
γ_t & γ_a	The overload risk of trunk and access span, respectively.	0.2 & 0.1	
$w_{\text{calc}} \times p_{\text{calc}}$	Standard unit cost $\times$ operation time for calculating ATT value.	100×1	0
$w_{\text{chk}} \times p_{\text{chk}}$	Standard unit cost $\times$ operation time for checking and selecting ATT device.	100×1	0
$w_{\text{olt}} \times p_{\text{olt}}$	Standard unit cost $\times$ operation time for connecting ATT on OLT side.	100×1	0
$w_{\text{onu}} \times p_{\text{onu}}$	Standard unit cost $\times$ operation time for connecting ATT on ONU side.	100×1	0
$w_{\text{set}} \times p_{\text{set}}$	Standard unit cost $\times$ operation time for installing OA.	100×5	
ϕ_{calc}	Failure rate per unit period of CC.	0	0.1
ϕ_{oa}	Failure rate per unit period of OA.	0.2	Variable
$w_{\text{maint,calc}} \times p_{\text{maint,calc}}$	Standard unit cost $\times$ operation time for maintenance of CC.	0	500×2
$w_{\text{maint,oa}} \times p_{\text{maint,oa}}$	Standard unit cost $\times$ operation time for maintenance of OA.	500×2	500×2

human errors.

5.6 Summary

This chapter proposed an auto-configurable OA (AC-OA), which can flexibly and automatically support various PON architectures; it simplifies and automates network operation by handling various kinds of OA applications in a unified manner. AC-OA has VOAs at the

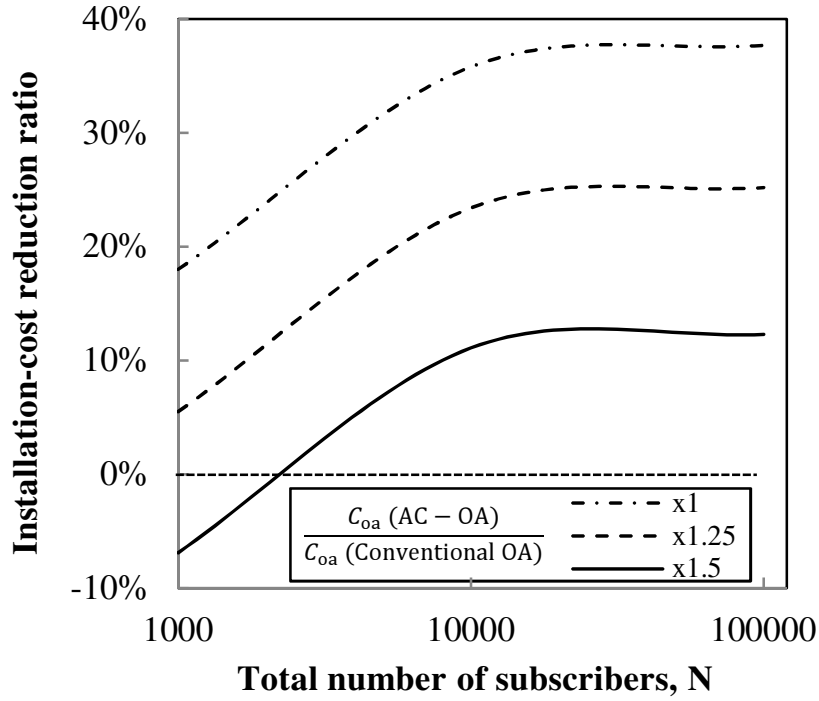


Fig. 5.8 Estimation result of installation-cost reduction ratio. With the assumptions made, installation costs can be reduced when N is greater than 1000. When $N \geq 10000$ and the price of AC-OA ≤ 1.25 , the installation-cost reduction can be more than 23%. ©2017, OSA, IEEE

input and a controller synchronized with a CC and FDB. VOA value is determined by CC and FDB, and used to adaptively control the input power of the OA. AC-OA suits various PON architectures because the mechanism of AC-OA provides simple plug and play OA operation and suits various HSR- and LR-PON architectures. The results of a simulation clarified the feasibility and the installation expenditure reduction effect.

Chapter 6

Optical amplifier layout problem

6.1 Overview

This chapter discusses the office reduction effect (ORR) with LR-PON in order to quantify the profitability. Optical amplifier layout problem (OALP) is formulated to plan the optimum office layout of the LR-PON which employs OA to extending the transmission distance. The two key contributions of OALP are; 1) to formulate OALP, which minimizes the number of COs on LR-PON, 2) to clarify ORR by solving OALP with the various specifications of OAs. The chapter also formulates OALP and solves it with Monte-Carlo-based method as the case study.

6.2 Office integration with HSR- and LR-PONs

To allow telecommunication carriers to further increase the cost-efficiency of FTTx, many institutes and organizations have been enhancing the acceptable PON link budget by applying OAs as described in previous chapters. Infrastructure costs can be reduced by increasing the link budget with the HSR-PON and LR-PON. HSR-PON is suitable for accommodating densely-aggregated subscribers with fewer OLTs as in urban areas. LR-PON is effective for low subscriber densities as it uses the fewest central offices [50].

COs in LR-PON are classified into three kinds of COs, i.e. aggregated office (AO), relay office (RO) and migrated office (MO) as shown in Fig. 6.1. In order to effectively deploy LR-PON, telecommunication carriers have to perform some operations to an original PON. OAs are installed in ROs. Original OLTs on ROs are aggregated to a specified AO. An AO can access to distant ONUs through RO by amplification of optical signals. This office integration

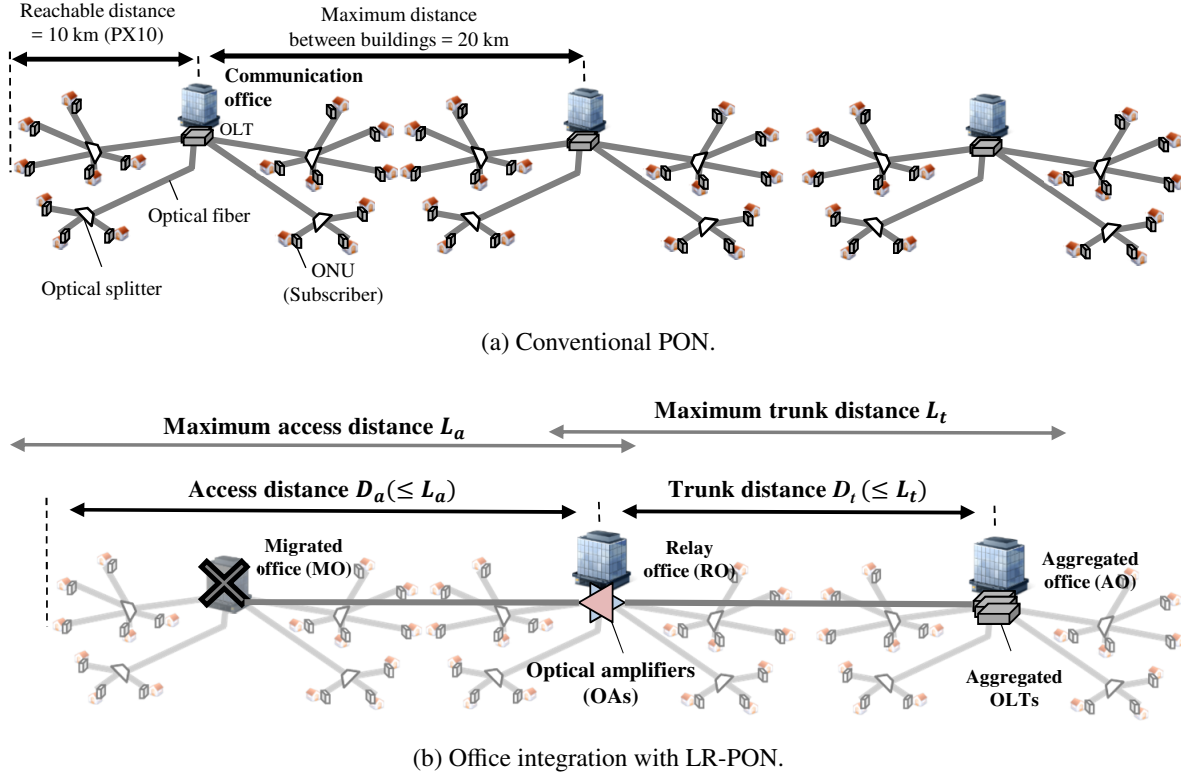


Fig. 6.1 COs in LR-PON are classified into three kinds of COs, i.e. aggregated office (AO), relay office (RO) and migrated office (MO). OAs are installed in ROs. Original OLTs on ROs are aggregated to a specified AO. An AO can access to distant ONUs through RO by amplification of optical signals. This office integration significantly reduces OPEX because unnecessary COs are removed as MOs.

significantly reduces OPEX because unnecessary COs are removed as MOs.

The distance between AO and the RO is defined as the trunk distance (D_t), and the distance between the RO and the ONU are defined as the access distance (D_a) as same as a previous definition. The maximum distance between AO and the RO, which is limited by OA specifications, is defined as the maximum trunk distance (L_t). The maximum distance between the RO and the ONU are defined as the maximum access distance (L_a). L_t and L_a are determined by the specification of optical transceiver of OLTs, ONUs and OAs. D_t and D_a have to be shorter than L_t and L_a , respectively.

6.3 Office reduction rate

Fig. 6.2 shows the office reduction rate (ORR) as achieved by relay and CO-set OAs on the assumption that the optical fiber between OLT and ONU can accept the insertion of an OA, and relay fiber between COs have been already installed in advance. For simplification, the thesis defines the maximum distance of accommodation between CO and subscribers as $d_0 = \text{const}$. Then, the distance between offices is $2d_0$ in order to accommodate all subscribers. OA location fails to reduce infrastructure costs since they need ROs as shown in Fig. 6.2a. On the other hand, CO-set OAs can increase the splitting ratio and reduce the number of COs compared to ROs as shown in Fig. 6.2b.

Table 6.1 lists the ORR of relay and CO-set OAs, based on Fig. 6.2. D_{Total} is the maximum total transmission distance of the PON. ORR represents the percentage of offices that can be eliminated by applying OAs. $\text{ORR} = 0\%$ means that no COs are eliminated by applying OAs while $\text{ORR} = 100\%$ means that all COs are eliminated.

ORR for relay OA and CO-set architectures were calculated by Eq. (6.1) and Eq. (6.2), respectively.

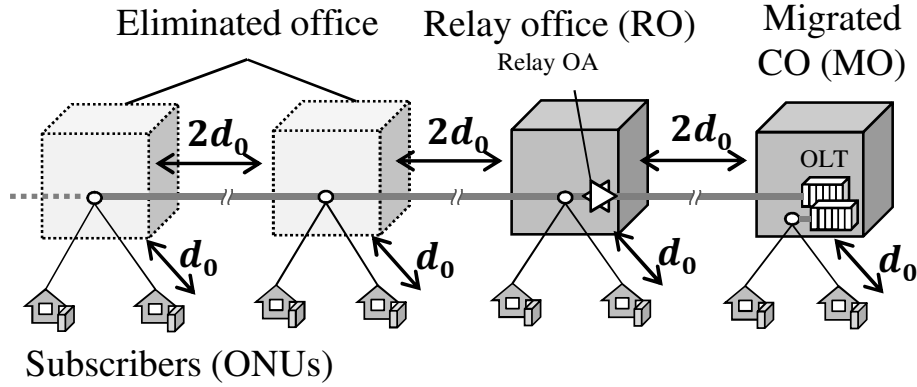
relay OA :

$$\text{ORR} = \begin{cases} 0 & (D_{\text{Total}} < 3d_0) \\ \frac{\lfloor (D_{\text{Total}} - 3d_0)/2d_0 \rfloor}{\lfloor (D_{\text{Total}} - 3d_0)/2d_0 \rfloor + 2} & (D_{\text{Total}} \geq 3d_0) \end{cases} \quad (6.1)$$

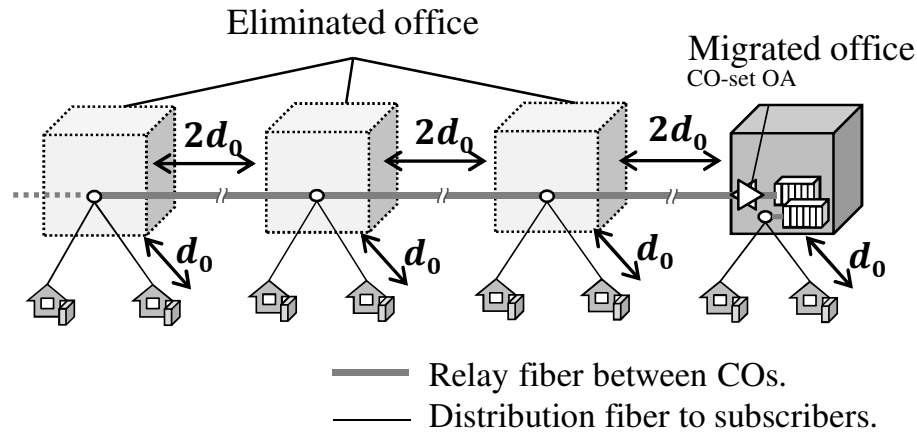
CO-set OA :

$$\text{ORR} = \frac{\lfloor (D_{\text{Total}} - d_0)/2d_0 \rfloor}{\lfloor (D_{\text{Total}} - d_0)/2d_0 \rfloor + 1} \quad (6.2)$$

In these equations, $\lfloor x \rfloor$ indicates the largest integer number less than x . ORR of CO-set OA is higher than that of relay OA because only one CO is required for installing CO-set OA. On the other hand, since relay OA required both CO and RO for installation of OA, ORR of relay OA is relatively lower than that of CO-set OA. The ORR, namely, the cost-reduction effect is sensitively changed by the transmission distance. Therefore, it is important for telecommunication carrier to accurately estimate the ORR in order to plan the cost reduction.



(a) relay OAs.



(b) CO-set OAs.

Fig. 6.2 ORR of CO-set OA is higher than that of relay OA because only one CO is required for installing CO-set OA. On the other hand, since relay OA required both CO and RO for installation of OA, ORR of relay OA is relatively lower than that of CO-set OA. It is important for telecommunication carrier to accurately estimate the ORR in order to apply the cost reduction plan. ©2017, OSA, IEEE

Moreover, most of researches have been focused on the reach-extension effect regarding one-dimensional distance while LR-PON has been widely studied so far. Since COs and ONUs are practically two-dimensionally distributed, the quantitative office reduction effect should be investigated upon the optimized OA layout. The chapter expansively addresses OALP to solve the optimum office layout for two-dimensionally distributed COs.

Table. 6.1 Office reduction rates of relay and CO-set structure.

Transmission distance	relay	CO-set
$D_{\text{Total}} < 3d_0$	0%	0%
$3d_0 \leq D_{\text{Total}} < 5d_0$	0%	50%
$5d_0 \leq D_{\text{Total}} < 7d_0$	33%	67%
$7d_0 \leq D_{\text{Total}} < 9d_0$	50%	75%

6.4 Optical amplifier layout problem (OALP)

This section formulates OALP with assumptions before and after the office integration. The OALP can solve the optimum office layout for two-dimensional distributed COs.

6.4.1 Assumptions

Before the office integration

- A) PON has been already deployed.
- B) Any CO cannot be integrated without OAs.
- C) The optical fibers between each CO have been already installed in order to establish a physical data-link to upper network. Telecommunication carriers reuse these exist optical fibers and does not newly install for the office integration.

The conditions (A) and (B) express that COs have been already efficiently installed within the range of the transmission distance of 1000BASE-PX10 (10 km [3]) without OAs. The condition (C) means that telecommunication carriers have not to install new optical fibers for the office integration.

After the office integration

- D) Each CO is reallocated as either aggregated office (AO), relay office (RO) or migrated office (MO).
- E) ROs are not serially connected each other.
- F) The trunk distance (D_t) have to be shorter than maximum trunk distance (L_t).

- G) The access distance (D_a) have to be shorter than maximum access distance (L_a).
- H) Objective function is to maximize the number of MOs.

Requirement (D) expresses a fundamental concept of OALP as following operations.

- COs which employ OAs are defined as ROs.
- Original OLTs installed in ROs are relocated to another AOs.
- COs, which are not either AO or a RO, are defined as MOs.

Requirement (E) means a cascade connection of ROs does not be permitted so as to simplify the problem in this thesis. Requirements (F) and (G) mean that the distance between COs have to be shorter than the maximum transmission distance as described in Constraints (2.10) to (2.13). Requirement (H) means that telecommunication carriers can reduce OPEX by integrating unnecessary COs as MOs.

6.4.2 Formulation

Table 6.2 is the definition and explanation of variables for OALP. Fig. 6.3 is the optical access network structure with defined variables before and after the office integration. i, j, k indicate identifier for distinguishing COs. In the figure, the network topology after the office integration has a tree structure expressed as AO-root, RO-branch and MO-leaf node. The structure formed with AO-root and RO-branch, or isolated AO are also permitted.

As the given variables, N_0 , D_{ij} , L_t , L_a and e_{ij} represent the total number of COs before the office integration, the distance between CO i and CO j , the maximum trunk distance, the maximum access distance and optical fiber links before the office integration, respectively. If optical fiber links exist between CO i and CO j , e_{ij} is 1, otherwise 0.

Also, the binary variables are x_i , y_{ij} and z_{ij} . If CO i is AO, x_i is 1, otherwise 0. And if CO j is RO connected from CO i , y_{ij} is 1, otherwise 0. Similarly, if CO j is MO connected from CO i , z_{ij} is 1, otherwise 0. Requirement (E) are automatically satisfied by the variable definition.

The total number of COs after the office integration are expressed as N_{Total} , which is the

Table. 6.2 Definition of variables for OALP.

Type	Symbol	Definition
Given	N_0	Total number of COs before the office integration.
Given	D_{ij}	Distance between CO i and CO j .
Given	L_t	Maximum trunk distance between AO and RO.
Given	L_a	Maximum access distance between RO and ONU.
Given	e_{ij}	If CO i connects to CO j with optical fiber before the office integration, $e_{ij} = 1$, otherwise 0.
Given	n_{ij}	Number of optical fiber links between CO i and CO j .
Given	c_{ij}	Maximum capacity of optical fiber links between CO i and CO j .
Binary	x_i	If CO i is AO after the office integration, $x_i = 1$, otherwise 0 ($\sum_i x_i = N_{AO}$).
Binary	y_{ij}	If CO j is RO connected from AO i after the office integration, $y_{ij} = 1$, otherwise 0 ($\sum_i y_i = N_{RO}$).
Binary	z_{ij}	If CO j is MO connected from RO i after the office integration, $z_{ij} = 1$, otherwise 0.

summation of the number of AOs (N_{AO}) and ROs (N_{RO}). The ORR is defined as follows.

$$ORR := 1 - \frac{N_{Total}}{N_0} \quad (6.3)$$

$$N_{Total} = N_{AO} + N_{RO} \quad (6.4)$$

For example, ORR of 87% means that telecommunication carriers can reduce 100 initial COs to 13 integrated COs after the office integration.

With these assumptions and variables, OALP is formulated as follows.

Objective:

$$\text{Maximize } \sum_{i,j} z_{ij} \quad (6.5)$$

Subject to:

$$e_{ij} - y_{ij} \geq 0 \quad (\forall i, \forall j) \quad (6.6)$$

$$e_{ij} - z_{ij} \geq 0 \quad (\forall i, \forall j) \quad (6.7)$$

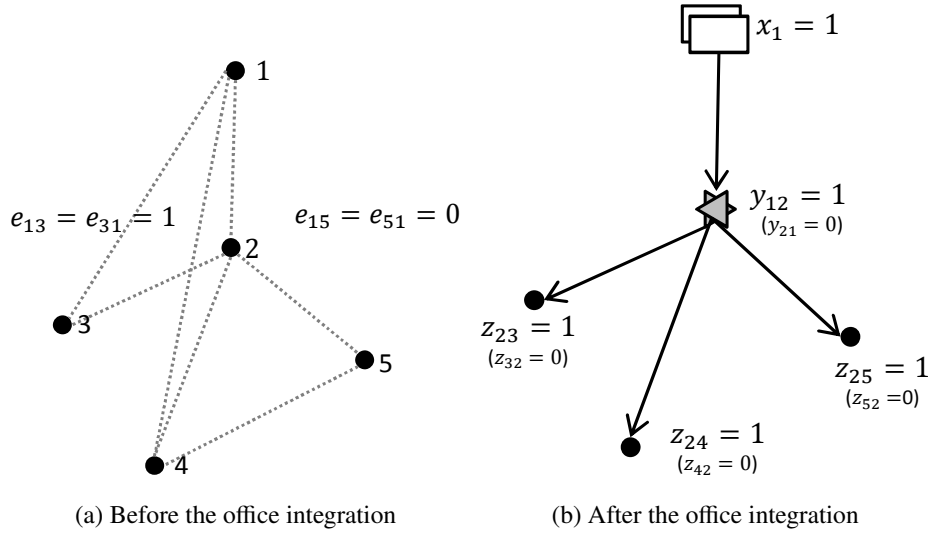


Fig. 6.3 Tree structure of integrated access networks ($N_0=5$). The network topology after the office integration has a tree structure expressed as AO-root, RO-branch and MO-leaf node.

$$e_{ii} = 0 \ (\forall i) \quad (6.8)$$

$$e_{ij}n_{ij} \leq c_{ij}(\forall i, \forall j) \quad (6.9)$$

$$x_i + \sum_j y_{ji} + \sum_j z_{ji} = 1 \ (\forall i) \quad (6.10)$$

$$\sum_k y_{ik} + \sum_k y_{kj} \leq 1 \ (\forall i, \forall j) \quad (6.11)$$

$$\sum_j z_{ji} + \sum_j z_{ij} \leq 1 \ (\forall i) \quad (6.12)$$

$$x_i + \sum_j z_{ij} \leq 1 \ (\forall i) \quad (6.13)$$

$$y_{ij}D_{ij} \leq L_t(z_{jk}D_{jk}) \ (\forall i, \forall j, \forall k) \quad (6.14)$$

$$z_{jk}D_{jk} \leq L_a(y_{ij}D_{ij}) \ (\forall i, \forall j, \forall k) \quad (6.15)$$

The Objective (6.5) is the objective function of OALP based on the requirement (H). It means that an optimal layout of COs which has the minimized total number of COs after the office integration can be found out.

The Constraint (6.6) and (6.7) means that additional infrastructures are not newly installed after the office integration (Requirements (A), (B) and (C)). The Constraint (6.8) means that optical fiber links do not connect from own CO to the CO. Constraint (6.9) means the capacity on optical fiber links between CO i and CO j . If there are enough optical fiber links between each CO, we can assume $c_{ij} \rightarrow \infty$. The Constraint (6.10) indicates that COs after the office integration have to be assigned to either AO, RO or MO (Requirement (D)). The Constraint (6.11) and (6.12) indicate that optical fiber links are not connected from RO to another RO and from MO to another MO, respectively. The Constraint (6.13) indicates that the optical fiber links are not connected from AO to MO.

Constraint (6.14) requires that D_{ij} between AO i and RO j have to be shorter than L_t (Requirement (F)). Similarly, Constraint (6.15) requires that D_{jk} between MO k and RO j have to be shorter than L_a (Requirement (G)).

In 3R-OA, the right side of Constraint (6.14) and (6.15) are constant as mentioned in Chapter 2. However, in 1R-OA, $L_t(z_{jk}D_{jk})$ on the right side of Constraint (6.14) is a function of $z_{jk}D_{jk}$ on Constraint (6.15) as shown in Fig. 6.4a and Fig. 6.4b. Similarly, $L_t(y_{ij}D_{ij})$ on the right side of Constraint (6.15) is determined by $y_{ij}D_{ij}$ on Constraint (6.14) as shown in Fig. 6.4c and Fig. 6.4d. In other words, L_t and L_a cannot be determined until the location of COs are determined in case of 1R-OA.

6.5 Calculation of OALP

6.5.1 Precondition of initial office layout

Fig. 6.5 shows the initial office layout. The number of COs (N_0) in the target area is set to 39. All offices are closely installed with the same distance of 14 km. The transmission distance is assumed as 7 km because the detour distance from standardized distance (10 km) of 1000BASE-PX10 have to be considered in order to avoid obstacles from a redundant route and/or allow a margin due to the sagging of optical fiber. The footprint area is about 7000 km², which approximately correspond to the average area (8042 km²) of a prefecture in Japan.

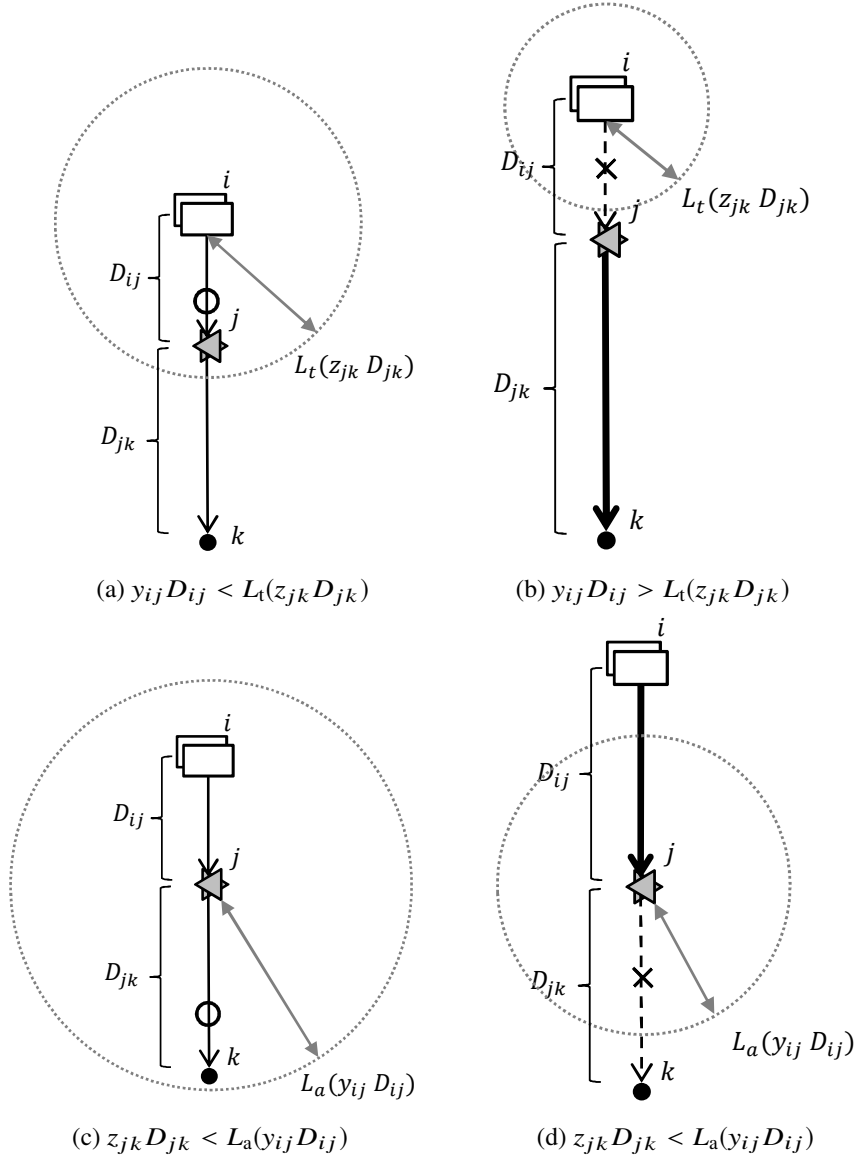


Fig. 6.4 Explanation of constraint condition (6.14), (6.15). In 1R-OA, $L_t(z_{jk} D_{jk})$ on the right side of Constraint (6.14) is a function of $z_{jk} D_{jk}$ on Constraint (6.15) as shown in Fig. 6.4a and Fig. 6.4b. Similarly, $L_t(y_{ij} D_{ij})$ on the right side of Constraint (6.15) is determined by $y_{ij} D_{ij}$ on Constraint (6.14) as shown in Fig. 6.4c and Fig. 6.4d. In other words, L_t and L_a cannot be determined until the location of COs are determined in case of 1R-OA.

6.5.2 Calculation method and conditions

Formulated OALP is solved by Monte-Carlo-based method as shown in Fig. 6.6. The method seeks the optimum layout solution by randomly assigning AO and RO to the initial

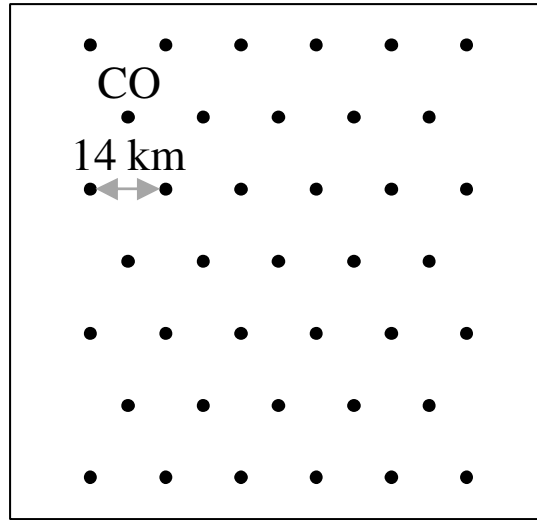
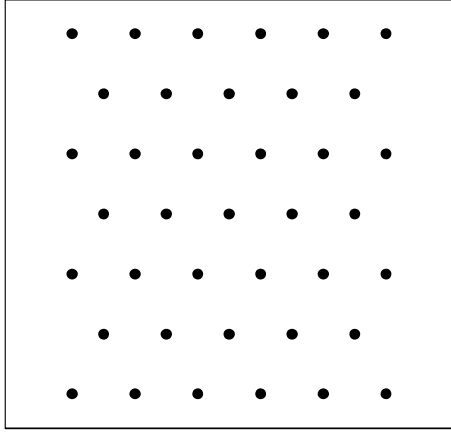


Fig. 6.5 The transmission distance is assumed as 7 km because the detour distance from standardized distance (10 km) of 1000BASE-PX10 have to be considered in order to avoid obstacles from a redundant route and/or allow a margin due to the sagging of optical fiber.

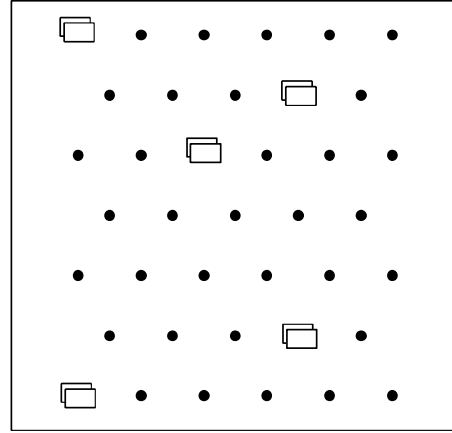
CO layout. The total number of N_{AO} and N_{RO} are given in advance. If the optimum layout solution exists, the solver outputs it as a temporary solution. The algorithm repeatedly tries to update the temporary layout solution with reducing N_{AO} and N_{RO} . When the temporary layout solution cannot be updated with the given number of N_{AO} and N_{RO} , the temporary layout solution is outputted as the optimal layout solution. With the method, the optimum layout solution can be found even if specifications have complicated nonlinear dependency between input and output optical signal in case of 1R-OA.

For the calculation, a general-purpose personal computer with the following specifications was used.

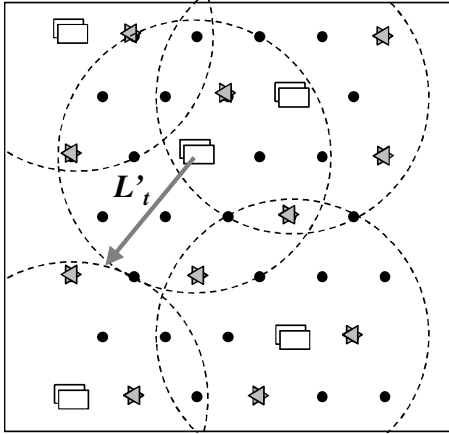
- CPU: Intel Core i7-3770 3.40 GHz
- Memory: 8 GB



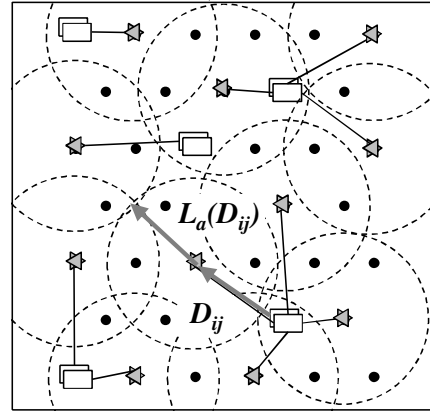
(a) Initial state of central offices before migration ($N_0=39$).



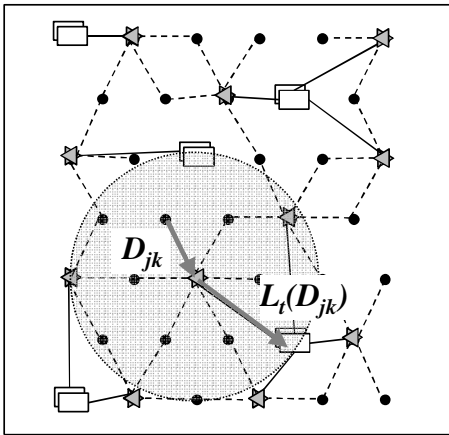
(b) Selecting aggregated offices randomly ($N_{AO}=5$).



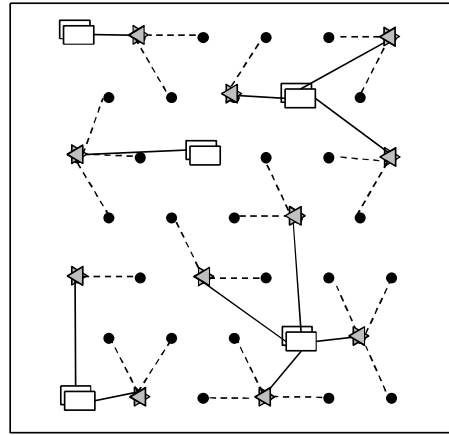
(c) Selecting relay offices randomly ($N_{RO}=11$).



(d) Checking migration possibility on the access span.



(e) Checking migration possibility on the trunk span.



(f) Forming links between each node.

Fig. 6.6 Calculation algorithm for the office integration.

6.6 Simulation results of the OALP

6.6.1 3R optical amplifier

The subsection evaluates the total number of AOs and ROs, and the optimum layout after the office integration. Parameters of the specification of 3R-OA are expressed with L_t and L_a . The values of L_t and L_a are set to the combination of 25 km and 35 km since these values are feasible as described in [55] in terms of the optical loss budget.

Fig. 6.7 shows the optimum layout solution after the office integration. In Fig. 6.7a, L_t and L_a are set to both 35 km (condition (a)). In Fig. 6.7b, L_t and L_a are set to 25 and 35 km, respectively (condition (b)). In Fig. 6.7c, L_t and L_a are set to 35 and 25 km, respectively (condition (c)). In Fig. 6.7d, L_t and L_a are set to both 25 km (condition (d)).

Calculation results on each condition indicate that the total number of offices (N_{Total}) is reduced to condition (a) 5 offices, (b) 7 offices, (c) 11 offices and (d) 13 offices from the initial office number of 39, respectively.

6.6.2 1R optical amplifier

Fig. 6.7 shows the optimum layout solution with 1R-OA described in Fig. 6.8. The transmission distance is determined by upstream signal because O-band upstream optical signals are more lossy than downstream optical signals. This thesis assumes that the specifications of 1R-OA are expressed by the threshold distance on the trunk span ($L_{t,\text{th}}$) and the saturation distance on the access span ($L_{a,\text{sat}}$). When D_{ij} is shorter than $L_{t,\text{th}}$, L_a is constant at $L_{a,\text{sat}}$ due to the saturation of optical output power from 1R-OA. If D_{ij} is longer than $L_{t,\text{th}}$, L_a parabolically shortens in proportion to the attenuation of optical input power to 1R-OA.

Fig. 6.9 shows optimal layout solutions according to the specifications of the 1R-OA. In Fig. 6.9a, $L_{t,\text{th}}$ and $L_{a,\text{sat}}$ described in Fig. 6.8 are set to 25 km and 35 km, respectively (condition (a)). In Fig. 6.9b, $L_{t,\text{th}}$ and $L_{a,\text{sat}}$ are set to 30 km and 25 km, respectively (condition (b)). In Fig. 6.9c, $L_{t,\text{th}}$ and $L_{a,\text{sat}}$ are set to 25 km and 15 km, respectively (condition (c)). In Fig. 6.9d, $L_{t,\text{th}}$ and $L_{a,\text{sat}}$ are set to 20 km and 10 km (condition (d)).

Calculation result on each condition indicates that N_{Total} is reduced to (a) 5 offices, (b)

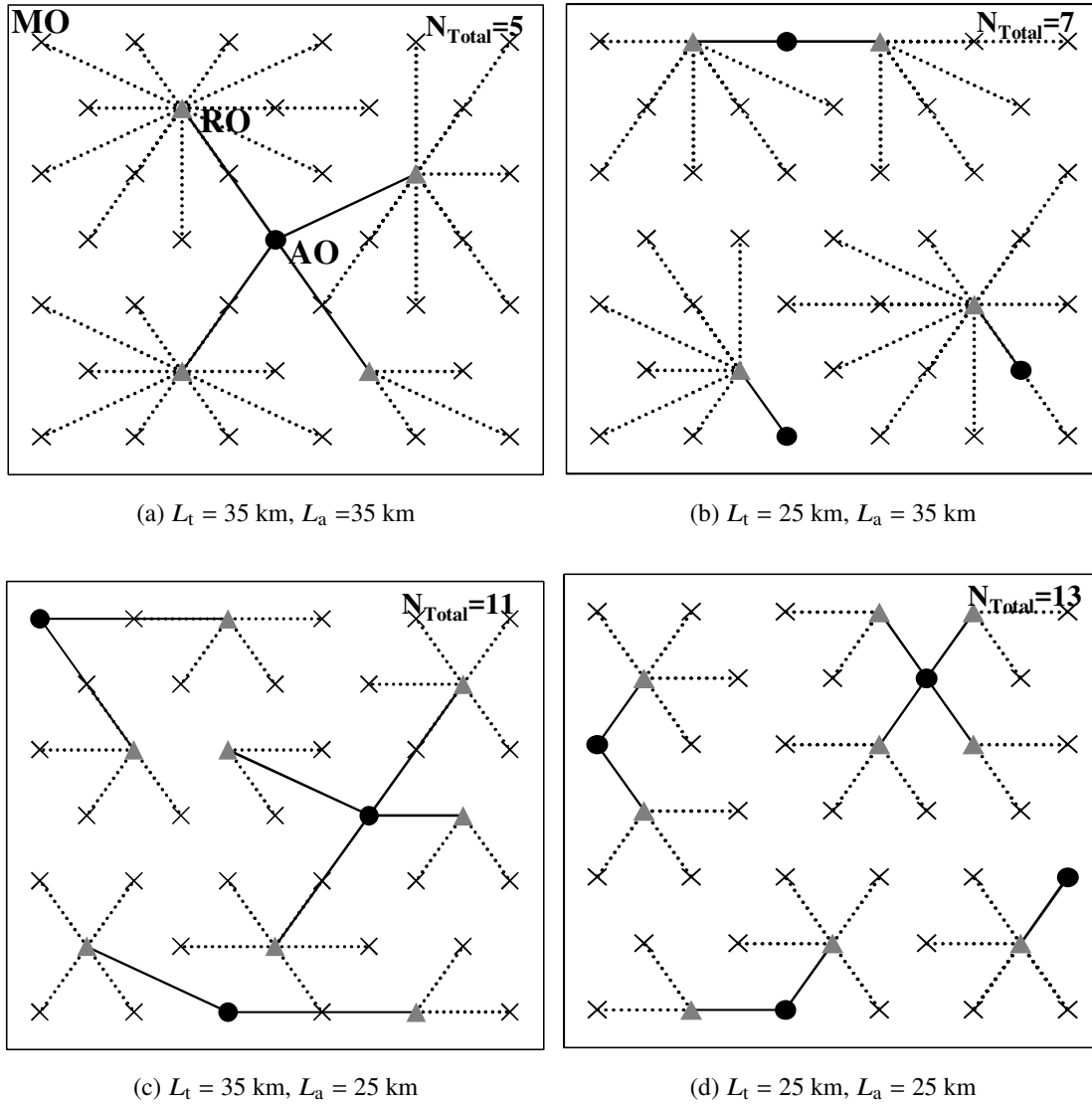
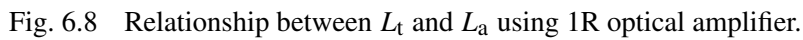


Fig. 6.7 Optimum layout solutions of the integrated optical access network with 3R optical amplifiers.

8 offices, (c) 13 offices and (d) 13 offices from the initial 39 offices, respectively. On the conditions (a) and (b), L_a become longer while L_t is shorter (RO α , RO β) according to specifications of Fig. 6.8. If L_t is becomes short, L_a becomes short (RO γ , RO δ).

6.6.3 Discussion

Table 6.3 is a summary of the calculation results of the ORR of 3R-OA and 1R-OA. Comparing ORR of 3R-OA (a), 3R-OA (b) and 3R-OA (c), ORR can be enhanced by enlarging



The ORR of 3R-OA (a) corresponds to 1R-OA (a). Similarly, the ORR of 3R-OA (d) corresponds to 1R-OA (c) and (d). The result indicates that telecommunication carriers can choose 1R-OA to cost-effectively integrate COs when the manufacture cost of 1R-OA is lower than that of 3R-OA. These knowledges have not been clarified until OALP have been formulated and solved. This chapter formulated OALP and compared the optimal layout solution and ORR with given specifications of OA. As further study, it is required to study realistic formulation considering the cascade connection of OAs, the number of distributed users, the capacity of optical fiber links, or infrastructure/maintenance costs.

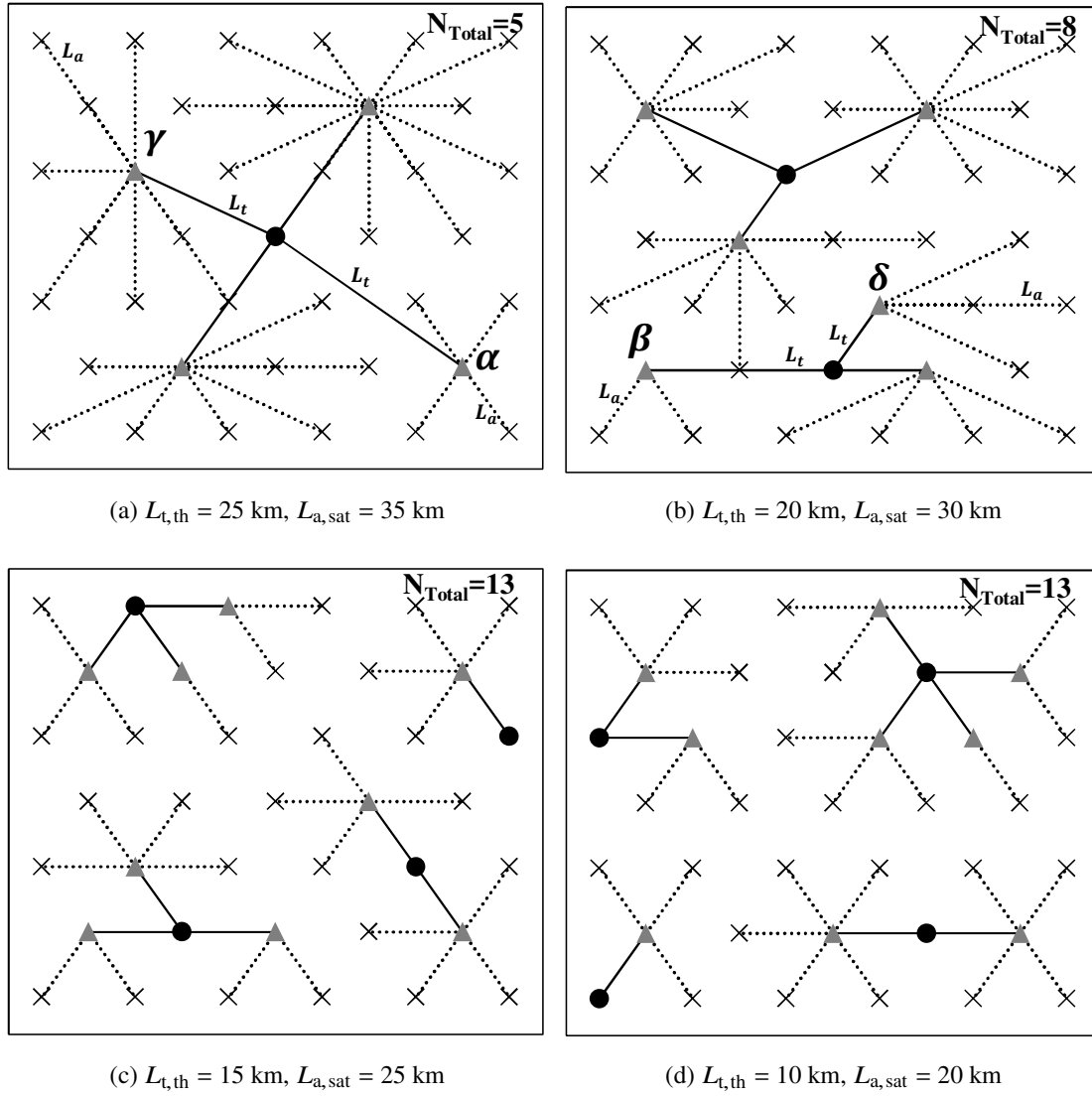


Fig. 6.9 Optimum layout solutions of integrated optical access network with 1R optical amplifiers.

6.7 Summary

This chapter discussed the effect of ORR of LR-PON in order to quantify the profitability. The thesis also proposed OALP dedicated to planning the optimum office layout of the LR-PON which employs OA to extending the transmission distance. The objective of OALP was to minimize the number of COs on LR-PON, and to clarify ORR with the various specifications of OAs. Moreover, formulated OALP was solved by Monte-Carlo-based method as the case study. With the method, the thesis showed that the optimum layout solution can be found

Table. 6.3 Calculated results of office reduction rate (ORR).

OA type	Specification	ORR
3R-OA	(a) $L_t/L_a = 35/35$ km	87.2%
	(b) $L_t/L_a = 25/35$ km	82.1%
	(c) $L_t/L_a = 35/25$ km	71.8%
	(d) $L_t/L_a = 25/25$ km	66.7%
1R-OA	(a) $L_{t,th}/L_{a,sat} = 25/35$ km	87.2%
	(b) $L_{t,th}/L_{a,sat} = 20/30$ km	79.5%
	(c) $L_{t,th}/L_{a,sat} = 15/25$ km	66.7%
	(d) $L_{t,th}/L_{a,sat} = 10/20$ km	66.7%

even if specifications have complicated nonlinear dependency between input and output optical signal in case of 1R-OA. As further study, it is required to study realistic formulation considering the cascade connection of OAs, the number of distributed users, the capacity of optical fiber links, or infrastructure/maintenance costs. Constraint condition (6.14) and (6.15) might be approximately linearized by introducing a distance table. Then, OALP can be handled as a linear problem and solved with a certain solver. Moreover, the analyzed result of the transmission distance map described in Chapter 4 can be applied to the OALP in order to consider the realistic optical and physical parameter of the system.

Chapter 7

Conclusions

This thesis proposed the HSR- and LR-10G-EPON systems with OAs for reducing OPEX and CAPEX, and certified the feasibility of the system through the field measurements using a commercial infrastructure. The thesis also proposed AC-OA for preventing optical overload of the optical devices in PON, and formulates the OALP for optimizing the layout of LR-PONs to achieve a cost-effective optical access network. In the following, conclusions of the study are described along with future research aimed at improving the proposed system.

7.1 Requirements and fundamental principles for next-generation 10G-EPON

Chapter 1 historically reviewed the history of communication technologies and explained how communication technology has evolved into contemporary optical communication systems. The chapter also argued that cost reduction of the access network is most important in terms of the vast cost of the infrastructure in relationship to the cost of an entire network. Finally, 10G-EPON was proposed as a strong candidate for the next-generation optical access network to satisfy the continuously-increasing Internet traffic demands.

Chapter 2 explained the theories and principles of the 10G-EPON using optical amplifiers, which required analysis, and the results of the field measurement were also discussed. The chapter further introduced the concept of the optical budget, the structure of the optical transceiver, and the optical overloading problem of optical devices. The mechanism of the N:1 protection system, which enhances the reliability of the 10G-EPON, was also described. Chapter 2 also mentioned that 10G-EPON with the optical amplifier satisfies the requirements for next-generation optical access networks including a survey of previous research studies.

The chapter described that it is important to flexibly design the transmission distance of the HSR- and LR-PON in order to save resources and achieve high profitability. In order to offer 10G-EPON services to more customers efficiently, it is useful to improve the acceptable link budget of access systems by using burst-mode OAs. Increasing the splitting ratio reduces both CAPEX and OPEX by increasing the number of subscribers that one OLT can accommodate. Extending the transmission distance reduces OPEX by eliminating intermediate offices. The chapter also described the basic structure of HSR- and LR-PON with an optical amplifier to reconstruct and relay an attenuated optical signal.

Moreover, DBA technology was also explained for frame transmission so as to fairly share the bandwidth and priority controls among ONUs. These technologies control the QoS of the system required for providing multi-service accommodation with the PON system.

7.2 Field measurement and analysis of N:1 protection

10G-EPON with optical amplifiers

Chapter 3 demonstrated a HSR- and LR-10G-EPON system with N:1 OSU protection in order to realize high system reliability. The chapter explained the effectiveness of dual-rate ALC-SOA for extending the optical loss budget with N:1 redundant topologies. The system can switch from active to redundant channels without any frame loss, and the quality of the bidirectional frame transmission is not degraded after switching to the redundant channels. The 10G-EPON described in this thesis combines the OLT and OA with dual-rate functionality and the N:1 protection system.

Chapter 4 discussed a method for optimally designing the 10G-EPON system to realize the splitting-ratio and the transmission distance needed to suit the network's subscriber distribution. Because the relationship between input power to SOAs and output power from SOAs is non-linear, an analysis model is required for the 10G-EPON system with OAs in order to calculate the total transmission distance. Our solution was to map the transmission distance using the splitting ratio parameter. Based on the concept proposed in this section, telecommunication carriers can flexibly design their network architecture and realize OPEX savings.

7.3 Auto-configurable optical amplifier

For raising PON efficiency, Chapter 5 proposed an AC-OA, which can flexibly and automatically support various PON architectures; it simplifies and automates network operation by handling various types of OA applications in a unified manner. AC-OA has VOAs at the input and a controller synchronized with a CC and external FDB. The VOA value is determined by the CC and FDB, and is used to adaptively control the input power of the OA. AC-OA suits various PON architectures because the mechanism of AC-OA provides simple plug and play OA operation and suits various HSR- and LR-PON architectures. The results of a simulation that clarify the feasibility and the installation expenditure reduction effect were discussed. The chapter confirmed AC-OA operation by using the field measurement results gathered from a commercial access network described in Chapter 4.

7.4 Optical amplifier layout problem

Chapter 6 discussed the effect of ORR on LR-PON in order to quantify the profitability. The chapter also formulated OALP dedicated to planning the optimum office layout of the LR-PON employing OAs to extend the transmission distance. The objective of OALP is to minimize the number of COs, and to clarify ORR based on the various specifications of OAs. OALP is applicable regardless of the types and specifications of OAs. With the proposed method, it was demonstrated that the optimum layout solution can be found even if specifications have complicated nonlinear dependencies between input and output optical signals in case of 1R-OA.

7.5 Further study

This thesis demonstrated and analyzed HSR- and LR-10G-EPON systems with N:1 OSU protection using a commercial network infrastructure. The AC-OA was also proposed to solve the optical overloading problem. For improving cost efficiency, the thesis formulated OALP and indicated office layout solutions. However, further studies are necessary to further

realize and commercialize the improved future access network system.

In order to develop the 10G-EPON system demonstrated in Chapter 3, an actual trial service with monitor subscribers should be performed in terms of the stability, usability, and long-reliability. Moreover, innovative services have to be developed to maximize the profitability by utilizing the specifications for broad bandwidth and reliability.

In terms of the analysis method described in Chapter 4, an extended cost analysis is recommended, as it is not useful to analyze only the transmission distance with the parameter of the splitting ratio. Perhaps the most important issue is to estimate the cost reduction effect based on the extended transmission distance or increased splitting ratio. Therefore, the analysis should be extended to an evaluation of the all cost reduction effects.

AC-OA proposed in Chapter 5 must be designed and implemented as actual equipment. With the equipment, the operation stability of the optimization of VOA values and the amplification specifications can be tested and verified even if multiple ONUs are connected to an AC-OA. Field measurements should also be performed with the AC-OA equipment so as to certify the feasibility of the physical and logical characteristics under actual service conditions.

OALP formulated in Chapter 6 should be re-formulated to consider the cascade connection of OAs, the number of distributed users, the capacity of optical fiber links, and infrastructure/maintenance costs. Moreover, the analyzed results of the transmission distance map can be organically applied to the OALP to consider the realistic optical and physical parameters of the system. If actual layouts of COs are obtained from telecommunication carriers, the solutions by the OALP will contribute to optimally reducing OPEX and CAPEX of the entire access system.

Finally, the bandwidth of the access network system will become wider (over 100 Gb/s) by applying innovative signal multiplexing technologies such as a quadrature amplitude modulation (QAM) [56, 57] and/or quadrature phase shift keying (QPSK) [58, 59] to core networks. Semiconductor device technology advances may also accelerate the evolution of the optical access network, especially SiGe-based or InP-based devices [60–62] for high frequency operation are under research by various communication carriers, vendors, and some universities. To commercialize these future systems cost-effectively, innovative technologies including the device field should be organically combined with the discussion in this thesis

for continuously-increasing traffic demands and successive improvements of the supporting communication technology.

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Author's Publication List

Journal papers

1. T. Tsutsumi, T. Sakamoto, Y. Sakai, T. Fujiwara, H. Ou, Y. Kimura, and K-I. Suzuki, "Long-reach and high-splitting-ratio 10G-EPON system with semiconductor optical amplifier and N:1 OSU protection," *Journal of Lightwave Technology*, vol. 33, no. 8, pp. 1660-1665, Apr. 2015.
2. T. Tsutsumi, T. Sakamoto, Y. Sakai, T. Fujiwara, H. Ou, Y. Kimura, K-I. Suzuki, M. Kubota, and A. Otaka, "Field demonstration and analysis of N:1 redundant 10G-EPON with optical amplifier in central office," *Journal of Lightwave Technology*, vol. 35, no. 10, pp. 1775-1784, May 2017.
3. T. Tsutsumi, Y. Nakayama, S. Kanai, M. Kubota, and A. Otaka, "Auto-configuration optical amplifier for simplifying network operation and flexible access network design for passive optical network," *Journal of Optical Communications and Networking*, vol. 9, no. 5, pp. 446-455, May 2017.

Invited paper

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International conferences

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1. T. Tsutsumi, H. Sato, Y. Kojima, H. Mori, Y. Sakai, T. Sakamoto, T. Fujiwara, H. Ou, and K-I. Suzuki, “Structural optimization for 10G-EPON system with in-line semiconductor optical amplifier,” in *IEICE Communication Conference '14*, B-8-8, p. 118, Sep. 2014. (in Japanese)
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Award

- IEICE Young Engineer Award, 2014.