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

Multi-Service Adaptable and Low-Power Consumption Active Optical Access Network Using High-Speed PLZT Optical Switches

September 2015

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Summary

This dissertation focuses on a next-generation active optical access network by using the Plumbum Lanthanum Zirconate Titanate (PLZT) optical switches. In Japan, the number of the whole broadband service users reached 95 million, and the number of Fiber To The Home (FTTH) access service users reached 25 million in 2013. Also, demands are increasing to support multi services in access networks, including Internet protocol television (IPTV) , Video on Demand (VoD) , and Voice over Internet Protocol (VoIP). Unfortunately, expanding transmission capacity will increase the power consumption of network equipment. The access networks already constitute about 70 percent of overall Internet power consumption due to the presence of a huge number of active elements.

There are three requirements for next-generation optical access networks to handle rapidly increasing traffic volume, support multi-services and reduce power consumption of network equipments: 1) scalability, 2) flexibility (multi-service adaptability), and 3) low-power consumption.

The Passive Optical Network (PON) is widely used as an access network. The PON provides a low-cost and low-power network due to its use of an optical splitter. It also supports multicast services thanks to the broadcast nature. However, already deployed Ethernet Passive Optical Network (EPON), Gigabit-Ethernet Passive Optical Network (G-EPON) and 10 Gigabit-Ethernet Passive Optical Network (10G-EPON) are limited in terms of the maximum number of Optical Network Units (ONUs) (32) and the maximum transmission distance (20 km). This is because the optical power is divided at the splitter

and decreases as the number of ONUs increases.

To provide scalable access services, the active optical access network using Mach-Zehnder (MZ) type PLZT optical switches was proposed, called Active Optical Access Network (ActiON) . It quadruples the number of ONUs (128) per Optical Line Terminal (OLT) and doubles the maximum transmission distance (40 km) between OLT and ONUs under 10 Gbps, compared to the 10G-EPON. However, as the ActiON uses slot-based switching, the transmission waiting time exceeds user's allowable delay in the slot allocation, and it needs a large number of slots to deliver contents to the requesting users in multicast. Moreover, the ActiON consumes the power higher than the 10G-EPON because it needs additional optical switches when supporting multi-services.

To satisfy above three requirements, this dissertation proposes a multi-service adaptable and low-power consumption active optical access network, while keeping the advantages of ActiON, which realize the scalable access network. This dissertation is organized as follows. Chapter 1 describes the background of the dissertation and clarifies the requirements for next-generation optical access network. Chapter 2 illustrates next-generation optical access network technologies, the target of the dissertation, and the position of the dissertation. Chapter 3 proposes a delay-sensitive slot allocation method, which designs the ActiON parameters that are the transmission cycle for controlling the PLZT optical switch and the number of slots per a cycle, and minimizes the switching idle time, considering the user's allowable delay. Numerical results show that the proposed method reduces the number of switching times by up to 88 percent, compared to the conventional method. Chapter 4 proposes a multi-service adaptable Active Optical Access Network (multi-service adaptable ActiON) by using the PLZT optical switch as the variable splitter mode in order to support the multicast function in addition to the delay-sensitive slot allocation method. Numerical results show that the proposed network dramatically reduces the required number of slots by up to 81 percent, compared to the conventional ActiON. Chapter 5 proposes a low-power consumption slot allocation method that reduces the number of mode changes in each switch element, while keeping the required number of slots in the multi-service adaptable ActiON. Numerical results show that the proposed network with the low-power consumption slot allocation method reduces the power consumption by up to 75 percent compared to the 10G-EPON, by up to 41 percent compared to the conventional ActiON, and by up to 21 percent compared to the multi-service adaptable ActiON, according to the reduction of the number of mode changes. Also tests on the experiment system by using the PLZT optical switch as the variable splitter mode confirm the capability of the proposed network. Chapter 6 draws this dissertation to its conclusion with a useful summary of the advances raised herein.

Chapter 1

Introduction

Chapter 1 describes the background of the dissertation and clarifies the requirements for next-generation optical access network.

1.1 Background

1.1.1 Growth in broadband service

Figure 1.1 shows the number of the broadband service users from 2009 to 2014 in the world [1-1]. The number of overall broadband service users has been increasing 11 percent every year, and reached 3035 million in 2014. Figure 1.2 shows the number of the broadband service users from 2009 to 2014 in Japan [1-2]. The number of overall broadband service users has been increasing 24 percent every year, and reached 95 million in 2014. Additionally, the number of the Fiber To The Home (FTTH) access service users has been increasing 11 percent every year, and reached 25 million in 2013. Fig. 1.3 shows the upload and download traffic volume of the broadband service from 2008 to 2013 in Japan [1-3]. The upload traffic volume has been increasing 5 percent every year, and reached 742 Gbps in 2013. Also, the download traffic volume has been increasing 22 percent every year, and reached 2191 Gbps in 2013.

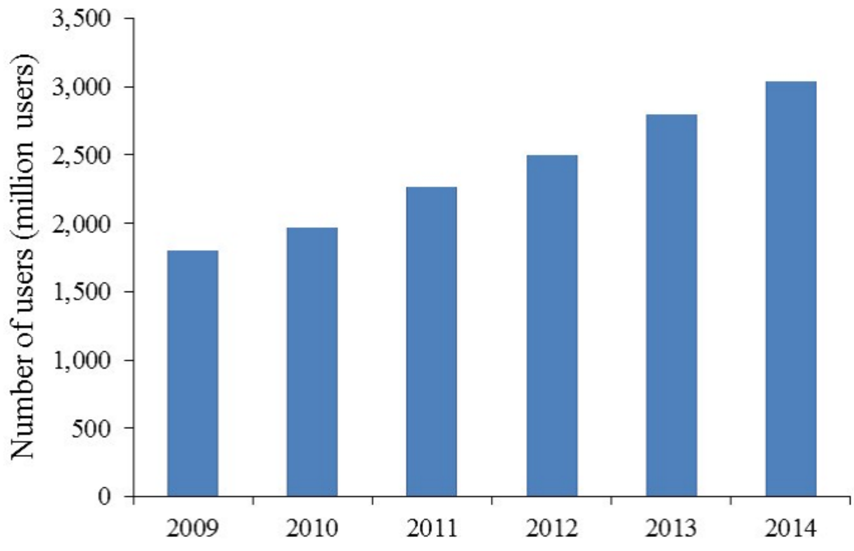

Figure 1.1: Number of broadband service users from 2009 to 2014 in the world. [1-1]

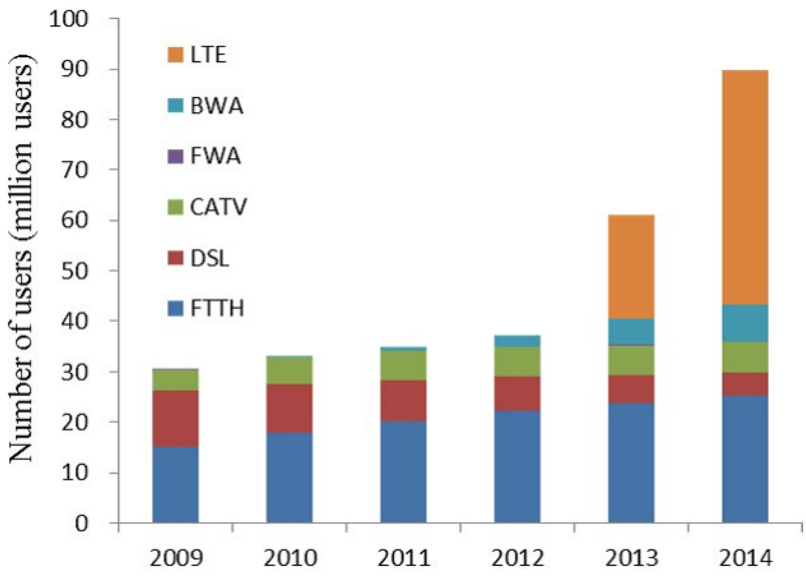

Figure 1.2: Number of broadband service users from 2009 to 2014 in Japan. [1-2]

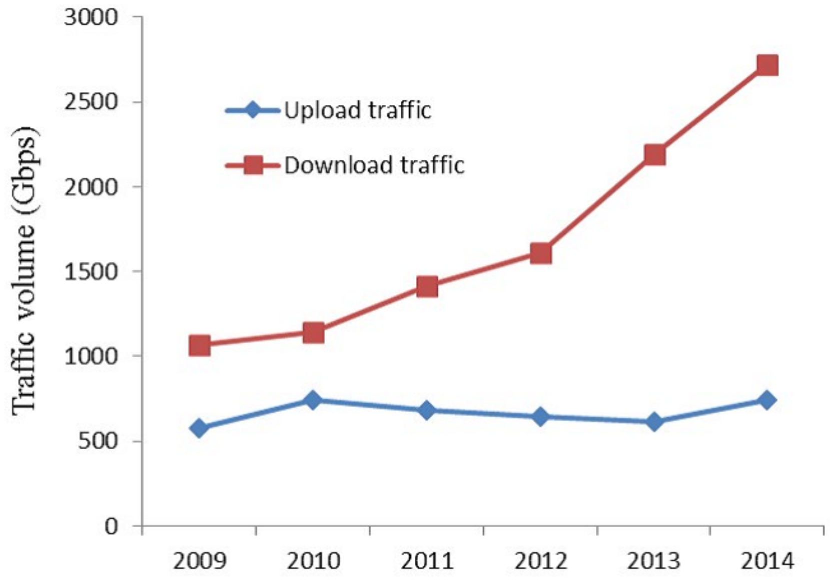

Figure 1.3: Traffic volume of broadband service from 2009 to 2012 in Japan. [1-3]

1.1.2 Diversification of services

The demand that access networks support multi-services, including Internet Protocol TeleVision (IPTV) , Video on Demand (VoD) , broadband Internet services, and Voice over Internet Protocol(VoIP) , has been increasing. In Japan, main IPTV services include ”Hikari TV” provided by NTT Plala, ”Hikari one TV service” provided by KDDI, ”BBTV” provided by BB cable. In Fig. 1.4, the number of IPTV service users in Japan has been increasing 57 percent every year from 2009 and reached 3 million in 2012 [1-4].

1.1.3 Increase in power consumption

The total power consumption of Information and Communication Technology (ICT) systems and network equipment has been increasing rapidly. Fig. 1.5 shows the ICT power consumption from 2007 to 2020 in the world [1-5]. The overall ICT power consumption grew to 168 Gigawatt in 2008, and will reach 430 Gigawatt in 2020. Additionally, the power consumption of network equipment grew to 25 Gigawatt in 2008, and will

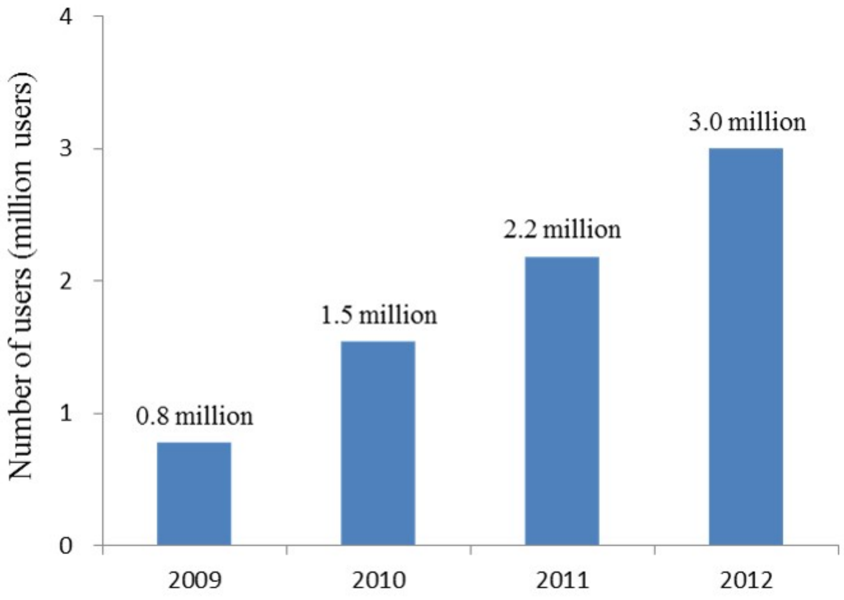

Figure 1.4: Number of IPTV service users from 2009 to 2012 in Japan.[1-4]

reach 97 Gigawatt in 2020. The power consumption of the access network is around 81 percent and the power consumption of Optical Network Units (ONUs) is around 60 percent in Passive Optical Network (PON), as shown in Fig. 1.6 [1-6]. In Japan, the power consumption of network equipment reached 25,700 Gigawatt Hour in 2012 [1-7]. The power consumption of the access networks is around 70 percent of overall power consumption of network equipment due to the presence of a huge number of active elements, as shown in Fig. 1.7.

1.2 Requirements for next-generation optical access network

In order to handle rapidly increasing traffic volume, support multi-services, and reduce power consumption of network equipments, there are three requirements for the next-generation optical access network in Fig. 1.8.

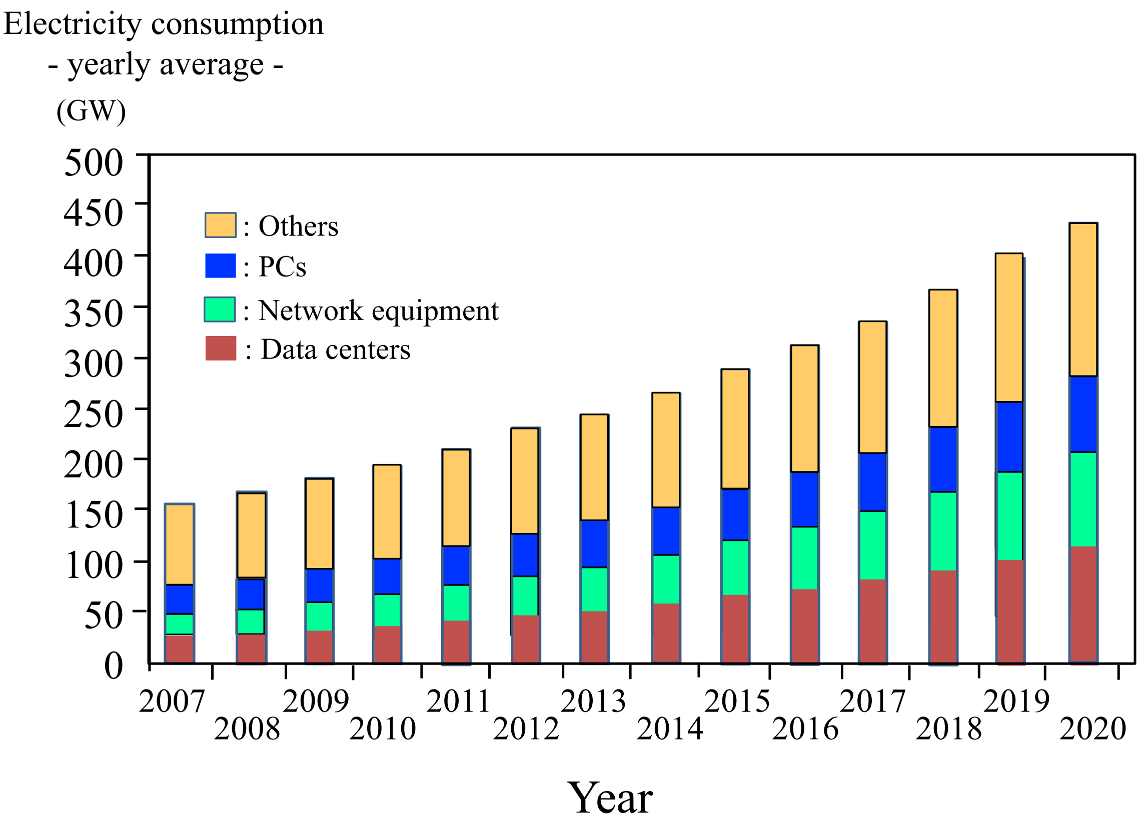

Figure 1.5: ICT power consumption.[1-5]

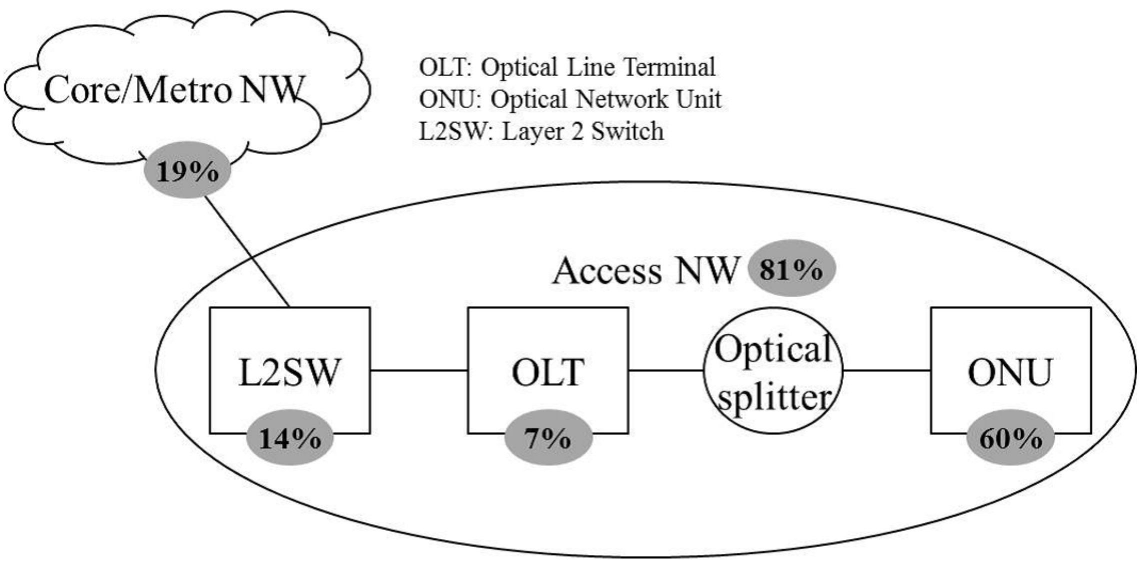

Figure 1.6: Power consumption of network equipment in world.[1-6]

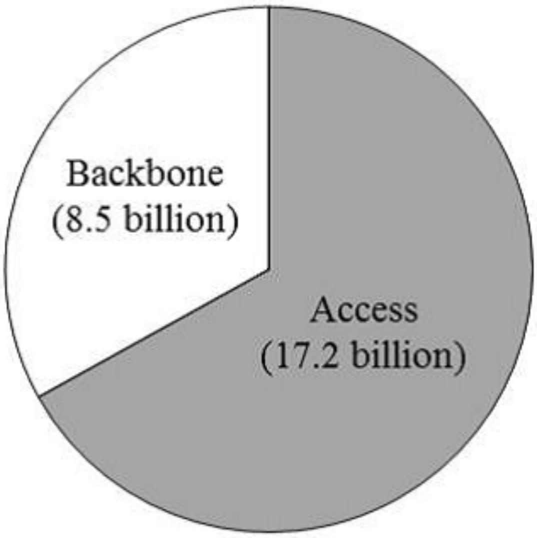

Figure 1.7: Power consumption of network equipment in Japan.[1-7]

#	Requirements for next-generation optical access networks	Concrete explanation
1	Scalability	• To satisfy the requirements of NG-PON2 – Bandwidth: 10 Gbps per one wavelength – Maximum transmission distance from OLT to ONUs: 40 km – Maximum number of users (ONUs): 256
2	Flexibility	• To support multi-services, including IPTV, VoIP, and VoD – Delay-sensitive communication, which well suits multi-services, of which delay constraints are 150ms – Multicast function
3	Low-Power Consumption	• To consume the power as low as the 10G-EPON when extending the network

Figure 1.8: Requirements for next-generation optical access network.

1.2.1 Scalability

In Japan, the number of the FTTH access service users has been increasing 11 percent every year and reached 25 million in 2013 [1-2]. To realize 10 Gbps access networks, 10 Gigabit-Ethernet Passive Optical Network (10G-EPON; IEEE802.3av) [1-8] and Next Generation-Passive Optical Network1 (NG-PON1) [1-9] have already been standardized. The 10G-EPON is specified that the bandwidth is 10 Gbps and the maximum transmission distance is 20 km and the maximum number of users is 32 users in Institute of Electrical and Electric Engineers (IEEE). The NG-PON1 is specified that the bandwidth is 10 Gbps and the maximum transmission distance is 60 km and the maximum number of users is 64 users in International Telecommunication Union Telecommunication Standardization Sector (ITU-T). For the future, in order to realize more scalable access networks, Next Generation-Passive Optical Network2 (NG-PON2) [1-10] is discussed by Full Service Access Network (FSAN) community [1-11] and ITU-T. The NG-PONs sets the requirements that the bandwidth is 10 Gbps per one wavelength and the maximum transmission distance is 40 km and the maximum number of users is 256 users in order to support a 40-Gbit/s capable aggregate downstream capacity for residential, business, mobile backhaul, and other applications, such as IPTV. In terms of ”Scalability”, to satisfy the above requirements of NG-PON2 is needed in order to provide scalable access services, which is adopted for compatibility the state-of-the-art standardization trend of PON.

1.2.2 Flexibility

The demand that access networks support multi-services, including IPTV, VoD, and VoIP, has been increasing. In Japan, the number of IPTV service users in Japan has been increasing 49 percent every year and reached 3 million in 2012 [1-2]. In terms of ”Flexibility”, in order to support multi-services, the delay-sensitive communication which well suits multi-services and the multicast function are required. Also, the delay constraint for supporting multi-services is 150 ms [1-15].

1.2.3 Low-Power Consumption

In Japan, the electricity consumption of network equipment reached 25,700 Gigawatt hour in 2012 and the access networks consumes around 70 percent of overall that of network equipment due to the presence of a huge number of active elements [1-7]. The conventional optical access networks consume the power higher by exploiting additional equipments, including optical amplifiers and optical switches, than the 10G-EPON when extending the network. In terms of ”Low-Power Consumption”, it is required to consume the power as low as the 10G-EPON when extending the network.

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Chapter 2

Optical access network technologies

Chapter 2 illustrates optical access network technologies which are Passive Optical Network (PON) and Active Optical Network, the target of the dissertation, and the position of the dissertation.

2.1 Passive Optical Network (PON)

2.1.1 Standardization trend of Passive Optical Network

The PON [2-1] is widely used as an access network. The standardizations of PON have been carried out by the IEEE and ITU-T. Figure 2.1 shows a historical shift of PONs which are representative architectures of FTTH [2-2]. Currently, Gigabit-Ethernet Passive Optical Network (G-EPON) of IEEE 802.3ah [2-3] and Gigabit-class PONs such as Gigabit-Passive Optical Network (G-PON) of ITU-T G.984 series [2-4] service have been standardized and are popularly being employed. In order to realize 10 Gbps access network, 10G-EPON of IEEE 802.3av [2-5] and NG-PON1 of ITU-T G.987 series [2-6] were standardized. The bandwidth of the PON has been increasing; Broadband Passive Optical Network (BPON) [2-7] supports 600 Mbps, G-EPON supports 1 Gbps, G-PON supports 2.5 Gbps, and 10G-EPON and NG-PON1 support 10 Gbps. For the future, in order to realize more scalable optical access networks, NG-PON2 is discussed by ITU-T / FSAN [2-8]. The requirements to realize NG-PON2 define that the bandwidth is 10 Gbps per one wavelength and the maximum transmission distance is 40 km and the maximum

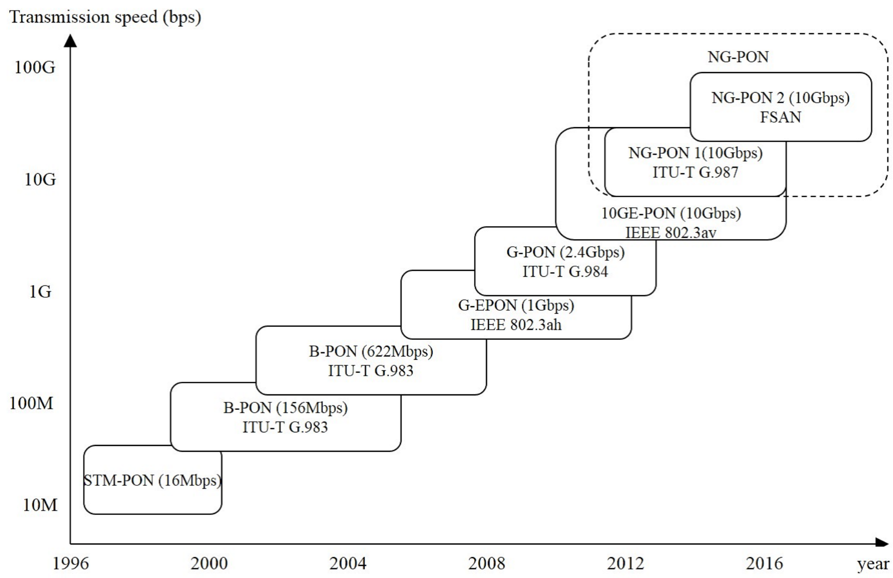

Figure 2.1: History of PON systems.[2-2]

number of users is 256 users. The introductions of Wavelength Division Multiplexing (WDM), Orthogonal Frequency Division Multiplexing (OFDM) and Optical Code Division Multiplexing (OCDM) in addition to conventional Time Division Multiplexing (TDM) technologies in the PONs are considered in NG-PON2.

2.1.2 Standard Time Division Multiplexing-Passive Optical Network (TDM-PON)

Architecture

Fig. 2.2 shows that the TDM-PON architecture, which is comprised of Optical Line Terminal (OLT) which connects to backbone network, ONUs which communicate with the user terminal, and an optical splitter [2-1]. The TDM-PON architecture is the basic architecture of the PON systems including the 10G-EPON [2-5] and the NG-PON1 [2-6] which were standardized. For the upstream data transmission, the ONUs transmit the data to the OLT by sharing the upstream capacity by using Time Division Multiplexing Access (TDMA), where the OLT receives the burst data, which varies optical intensity and timing. For the downstream data transmission, the OLT broadcasts the same multiplexed data to all ONUs, and each ONU selects the data destined to itself. The different wavelengths are used for the upstream and downstream data transmission. In the 10G-EPON (Upstream: 1 Gbps / Downstream: 10 Gbps), the wavelength from 1260 to 1360 nm (O-band) is allocated in the upstream and that from 1575 to 1580 nm (L-band) is allocated in the downstream. In the 10G-EPON (Upstream: 10 Gbps / Downstream: 10 Gbps) and NG-PON1, the wavelength from 1260 to 1280 nm (O-band) is allocated in the upstream and that from 1575 to 1580 nm (L-band) is allocated in the downstream. In the optical loss budget [2-9], the 10GE-PON maximally supports 29 dB, including 15 dB in the splitting loss of 32 users, 10 dB in the fiber loss of 20 km (0.5 dB / km), 1 - 3 dB in the connection loss and the insertion loss of the splitter. The NG-PON1 maximally supports 31 dB, including 18 dB in the splitting loss of 64 users, 10 dB in the fiber loss of 20 km (0.5 dB / km), 1 - 3 dB in the connection loss of the splitter. The range of output power in OLT is from 2 to 5 dBm [2-10]. Fig. 2.3 shows the internal structures of OLT and ONU under 10 Gbps [2-11]. The OLT transmits the 10 Gbps continuous data by using Electro-absorption Modulator-integrated Laser (EML). The OLT receives the 10 Gbps burst data by using Avalanche Photo Diode (APD), Burst-Transimpedance Amplifier (Burst-TIA), Burst-Limiting Amplifier (Burst-LA), and Burst-Clock and Data Recovery (Burst-CDR). The APD changes the optical signal into the current signal. The Burst-TIA changes the current signal into the voltage signal while amplifying a current signal. In order to set a most suitable amplification rate instantly, the Burst-TIA uses two value of feedback resister. When an input signal is feeble, it works at a high amplification rate by high feedback resistance. When an input signal exceeds the level that was set, it works at a low amplification rate by low feedback resistance. The Burst-LA changes a feeble or a

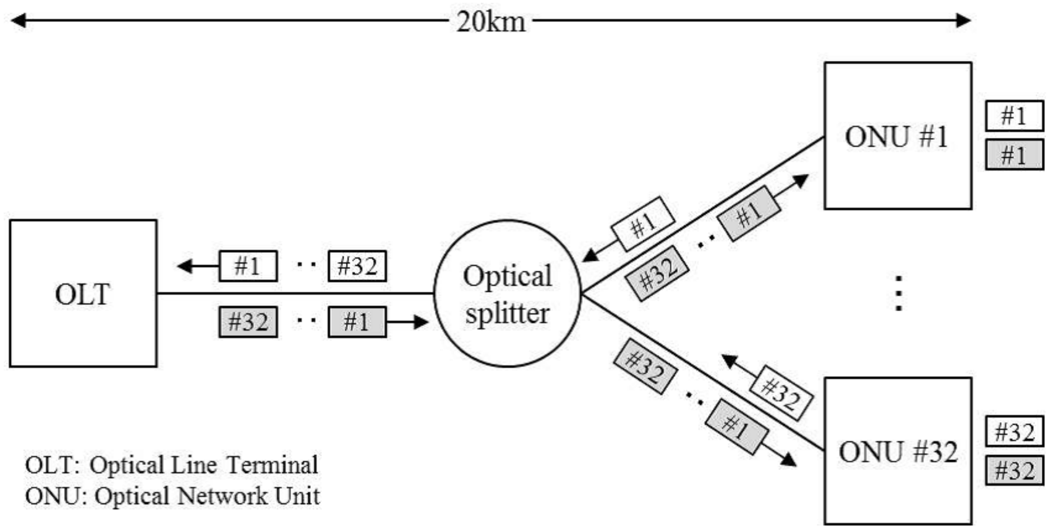

Figure 2.2: TDM-PON architecture.[2-5]

relatively big voltage signal into a voltage signal of the constant amplitude. In order to support a burst signal, the Burst-LA needs to make the voltage signal levels of positive phase and opposite phase even very fast. The total response time of the Burst-TIA and the Burst-LA is within 800 ns. The Burst-CDR extracts the timing of the voltage signal of the constant amplitude very fast by using Voltage Controlled Oscillator (VCO), and gets a wave pattern fixed with a clock with a few noises. The response time of the Burst-CDR is within 400 ns. On the other hand, the ONU transmits the 10 Gbps burst data by using Distributed Feedback-Laser Diode (DFB-LD) with burst control. The ONU receives the 10 Gbps continuous data by using APD, TIA, LA, and CDR which do not support a burst signal.

Multi Point Control Protocol (MPCP)

In the Ethernet-based PON including G-EPON and 10G-EPON, MPCP [2-12] defined in IEEE 802.3av is used to prevent the collision of upstream data transmission at the optical splitter. The MPCP specifies a control mechanism between an OLT and ONUs to

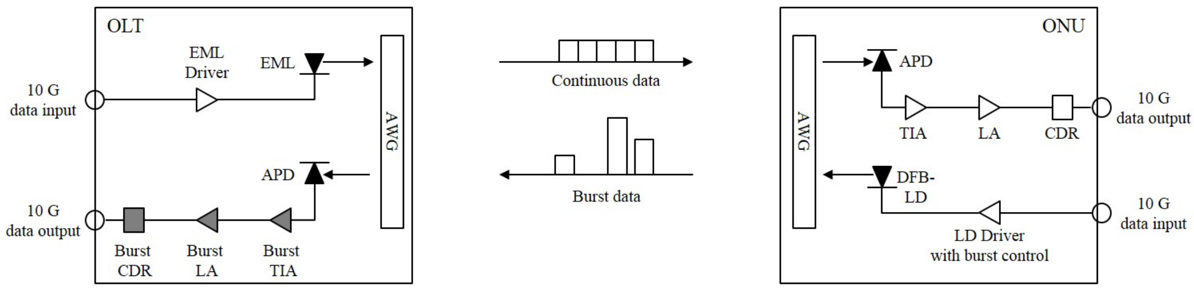

Figure 2.3: Internal structures of OLT and ONU of 10G-EPON. [2-11]

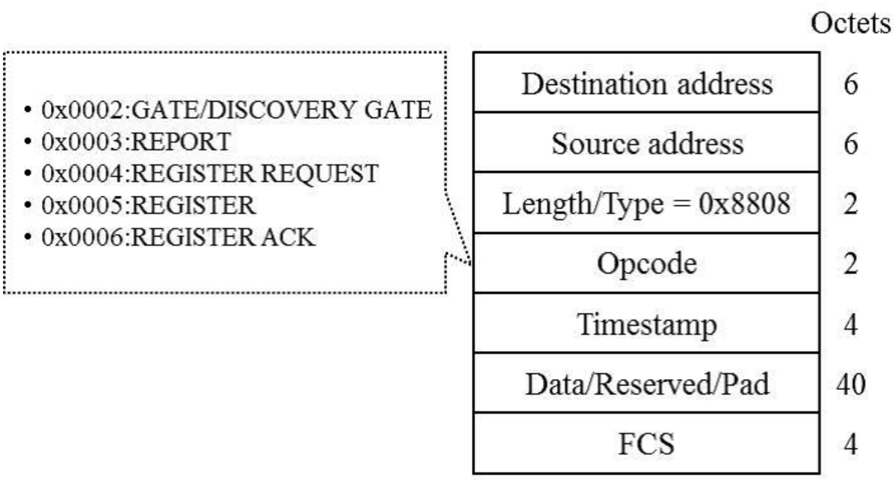

Figure 2.4: MPCP Frame Format. [2-12]

realize an efficient upstream data transmission; 1) discovery process establishing connections between OLT and ONUs, and 2) gate and report process operating the upstream data transmissions from ONUs to OLT. Fig. 2.4 shows the MPCP frame format based on the Ethernet frame. The MPCP defines five messages. The opcode field identifies each message.

Discovery process

Fig. 2.5 shows the protocol sequence of the discovery process of the PON. The discovery process has three functions. One is discovering active ONUs. Second is register-

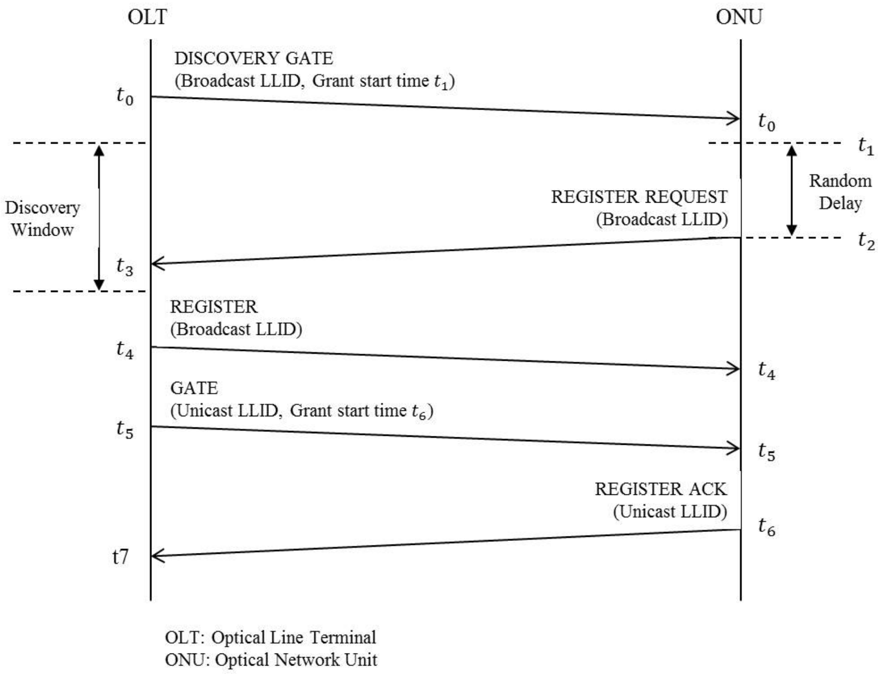

Figure 2.5: Protocol sequence of discovery process of PON.

ing discovered ONUs to the access network system by assigning Logical Link Identifier (LLID) to them. Each ONU receives all signals from OLT but accepts only the Ethernet frames that carry its assigned the LLID. Third is ranging the distance between OLT and registered ONUs in order to measure the timing when a message from the discovered ONU reaches OLT. The discovery process is periodically needed since ONUs can randomly connect to or disconnect from the access network. In most implementations, this process is executed as long as some ONUs have not been discovered and are not active. The discovery window represents the time-to-live period used to receive REGISTER_REQs. First, at t_0, OLT broadcasts DISCOVERY_GATE with Grant Start Time t_1 to ONUs. Grant Start Time denotes the time at which an ONU can start sending a message. After receiving the DISCOVERY_GATE, unregistered ONUs set their clock time at t_0, and send REGISTER_REQs to OLT at t_2. Random delay d is used to reduce the probability of collision at the optical splitter. After receiving this REGISTER_REQ at t_3, which

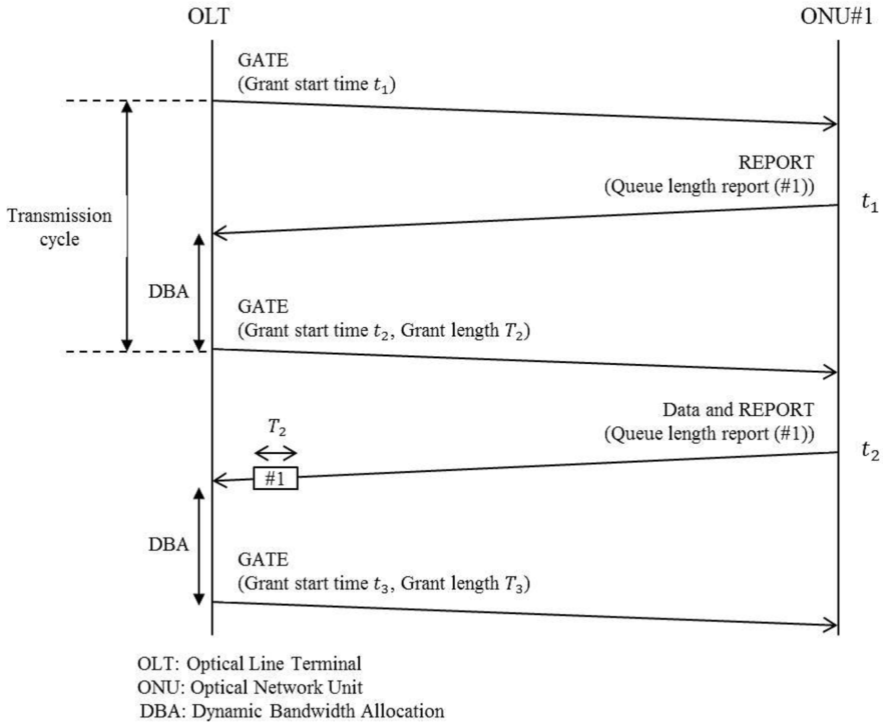

Figure 2.6: Protocol sequence of Gate and Report process of PON.

lies within the discovery window, OLT determines the round trip time $t_3 - t_2$. If REGISTER_REQ is accepted, OLT assigns an LLID to this ONU via REGISTER. The ONU accepts only the REGISTER that holds its MAC address, and extracts its LLID. Next, OLT sends GATE with Grant Start Time t_6, which is calculated so as to avoid collision among all signals from other ONUs. After receiving GATE, the ONU sends REGISTER_ACK at t_6. Finally, OLT receives REGISTER_ACK. In the event of collision among REGISTER_REQs at the splitter, OLT tries to send DISCOVERY_GATE again in the next discovery process.

Gate and Data process

Fig. 2.6 shows the protocol sequence of the gate and report process of the PON. For easy understanding, the transmission cycle shows only GATE and REPORT without the expression of data. The OLT instructs cyclically ONUs by using GATE in order to realize upstream transmission without the data collision, and the ONUs transmit data within the time period permitted by OLT. REPORT stores a queue length of the buffer of the ONU. GATE stores Grant Start Time (t_x) and Grant length (T_X) which is duration time. After receiving queue status reports from ONUs, each bandwidth is calculated by Dynamic Bandwidth Allocation (DBA) function for ONUs. In IEEE802.3av, the gate and report process is defined, but the DBA algorithm is not defined.

Co-existence technology

The 10G-EPON and NG-PON1 are expected to respectively support coexistence with the G-EPON and the G-PON in the same optical access network. The coexistence feature enables the seamless upgrade of individual customers without disrupting services of other customers. It is required to support a common Transmission Convergence (TC) layer for NG-PON based on G-PON's TC layer with necessary enhancements: TC layer is above the physical media layer of PON necessary to accommodate various types of client signals as well as to control the TDMA in the PON [2-13]. It is possible to overlay multiple XG-PONs on the same ODN to create even higher capacity. The Spectrum allocation is critical for this overlay approach to work. It should be noted that some approaches may require different flavors (or colors) of ONUs depending on the specific wavelength that each individual ONU must be working on.

Fig. 2.7 shows a migration scenario from existing G-PON to NG-PON1 as an example of NG-PON1 migration in a service oriented introduction scenario [2-6].

At first, the OLT and ONUs of G-PON are deployed, and OLT and ONUs of NG-PON1 are placed for the migration later. The fiber and the power splitter of G-PON are not replaced or changed during the migration to NG-PON1 in order to avoid service outage for the customers who are not being migrated. The WDM filter is installed to combine

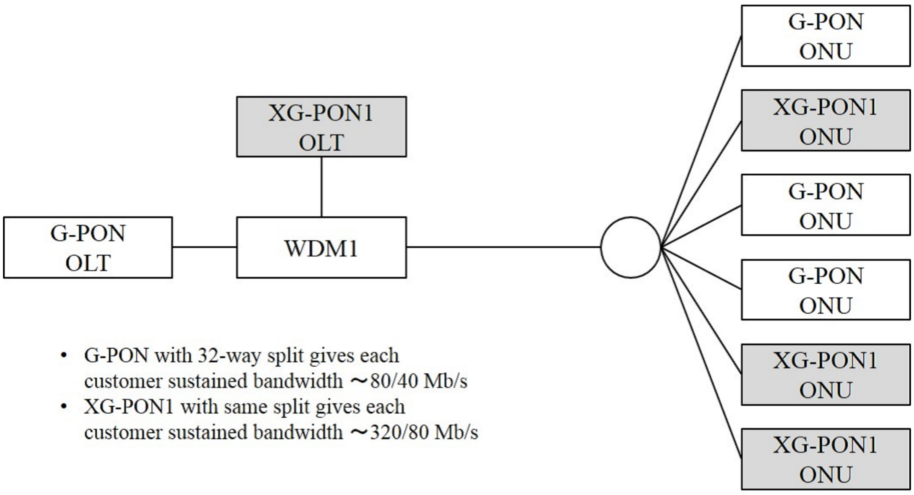

Figure 2.7: Migration from G-PON to NG-PON1.[2-6]

and separate signals of G-PON and NG-PON1 into and out of the common optical access network. In addition, the coexistence of G-EPON and 10G-EPON is basically realized in the same way as a coexistence of G-PON and NG-PON. However, there is a difference between two coexistence architectures due to the wavelength allocation of upstream and downstream. Fig. 2.8 shows the wavelength allocation of IEEE EPON series and ITU-T G-PON series [2-14]. In the coexistence of G-PON and NG-PON1, four wavelength simply used for two pair of up and downstream. On the other hand, in the coexistence of G-EPON and 10G-EPON, three wavelength only used for two downstream and one upstream because the upstream is a same wavelength range in G-EPON and 10G-EPON. Therefore, the OLT mounts a dual-rate burst signal receiver since the OLT receives both 10 Gbps and 1 Gbps upstream signals in a TDMA manner.

Power saving technique for PON

In the PON system, there are mainly two types of power saving techniques, ”ONU power saving” and ”Adaptive Link Rate (ALR)”.

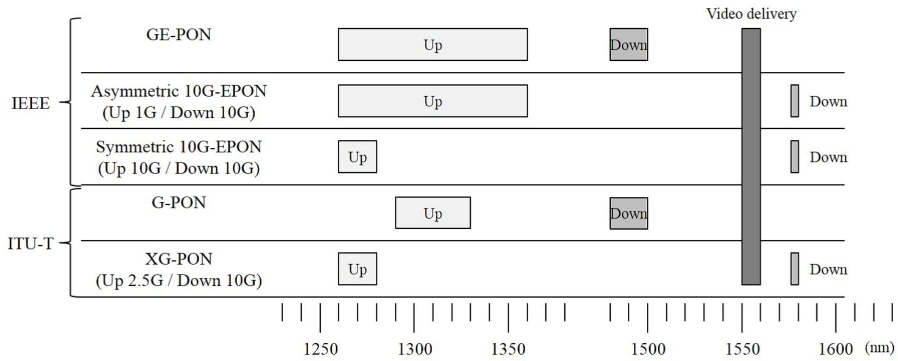

Figure 2.8: Wavelength allocation of IEEE EPON series and ITU-T G-PON series. [2-14]

ONU power saving

At first, the ONU power saving has four types in ITU-T Series G Supplement 45 G-PON power conservation, ”Shedding”, ”Fast sleep”, ”Deep sleep”, and ”Dozing” [2-15]. Fig. 2.9 and Figure 2.10 show the taxonomy of ONU power saving and the structure of ONU. The shedding is a power-saving technique for User Network Interfaces (UNIs), and the fast sleep, deep sleep, and dozing are power-saving techniques for the PON interface. The shedding makes the unused UNIs sleep constantly. The deep sleep makes the ONU transmitter and receiver sleep when no traffic is observed. The deep sleep reduces the most power of ONUs by making the most functions sleep. However it cannot detect the arrival of downstream data during the sleep period. The dozing makes the ONU transmitter sleep when no upstream traffic is observed. The dozing can always detect the downstream data by keeping the ONU receiver active even during the sleep period. However, it reduces the power less than the deep sleep. In addition to the above four types, the cyclic sleep makes the ONU transmitter and receiver sleep and wake up periodically when no traffic is observed. The cyclic sleep reduce the number of data which cannot be detected during sleep and low-power consumption services stably by making the ONU transmitter and receiver sleep in the assigned sleep period calculated by DBA in OLT. However, it is required the advance control for calculating the assigned sleep quickly in the short active

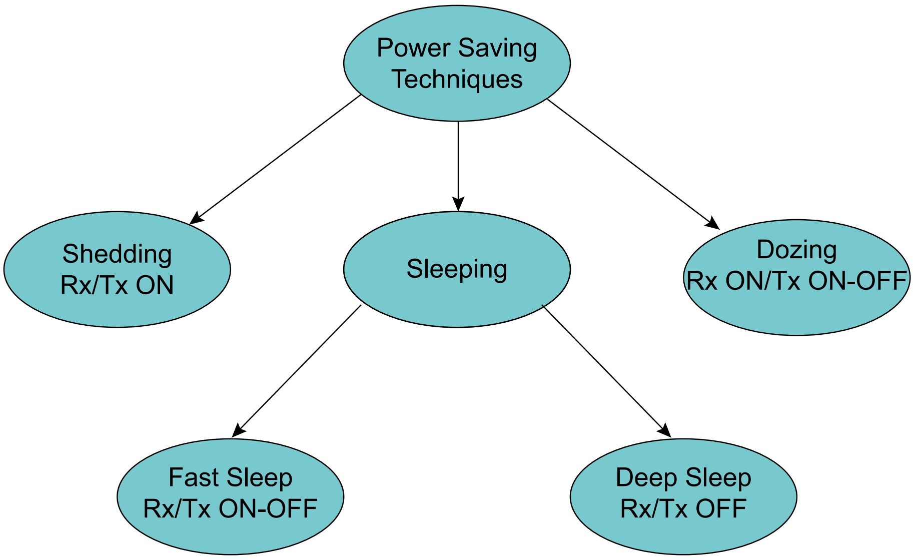

Figure 2.9: Taxonomy of ONU power saving.[2-15]

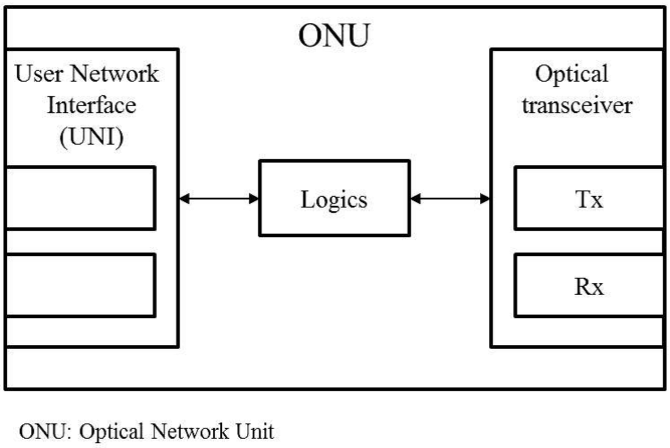

Figure 2.10: Structure of ONU.[2-15]

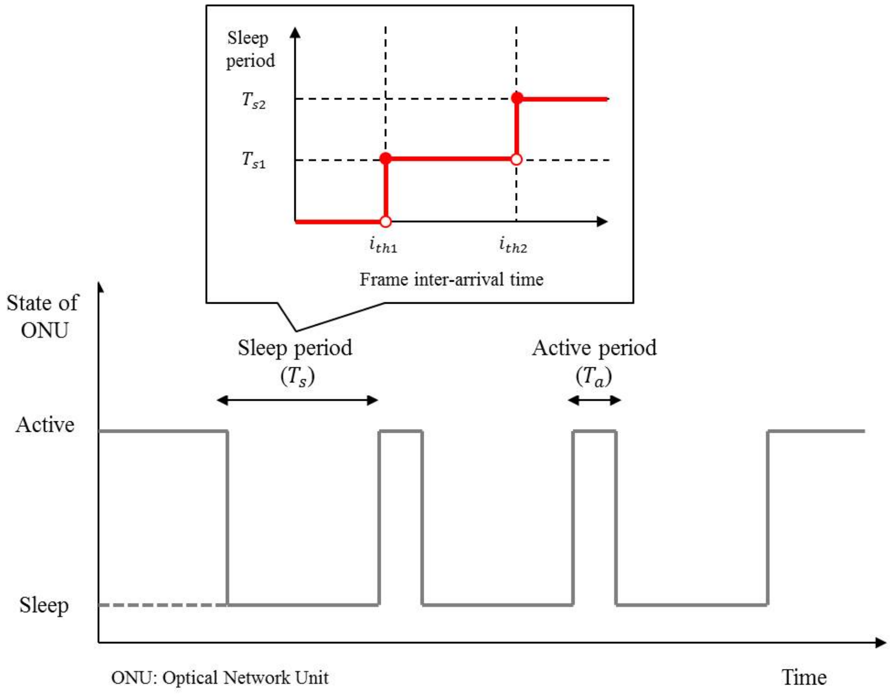

Figure 2.11: State of ONU versus time of cyclic sleep mode.[2-15]

period of ONU. Fig. 2.11 shows the relation between the state of ONU and time of the cyclic sleep mode. The active and the sleep period appear periodically and the sleep period changes according to the frame inter-arrival time. When the frame inter-arrival time is longer than the threshold 1 of inter-arrival time (i_{th1}), the sleep period is T_{s1} and When the frame inter-arrival time is longer than the threshold 2 of inter-arrival time (i_{th2}), the sleep period is T_{s2}.

Adaptive Link Rate (ALR)

Next, the ALR realizes the low-power consumption 10G-EPON by changing both 1 Gbps and 10 Gbps wavelengths according to the traffic load [2-16]. The downstream data transmission of 10G-EPON uses the several wavelengths for 1 Gbps and 10 Gbps by using the WDM technologies. The ALR of 10G-EPON uses the dual threshold policy for switching between the 1 Gbps and the 10 Gbps down link depending on the quantity of

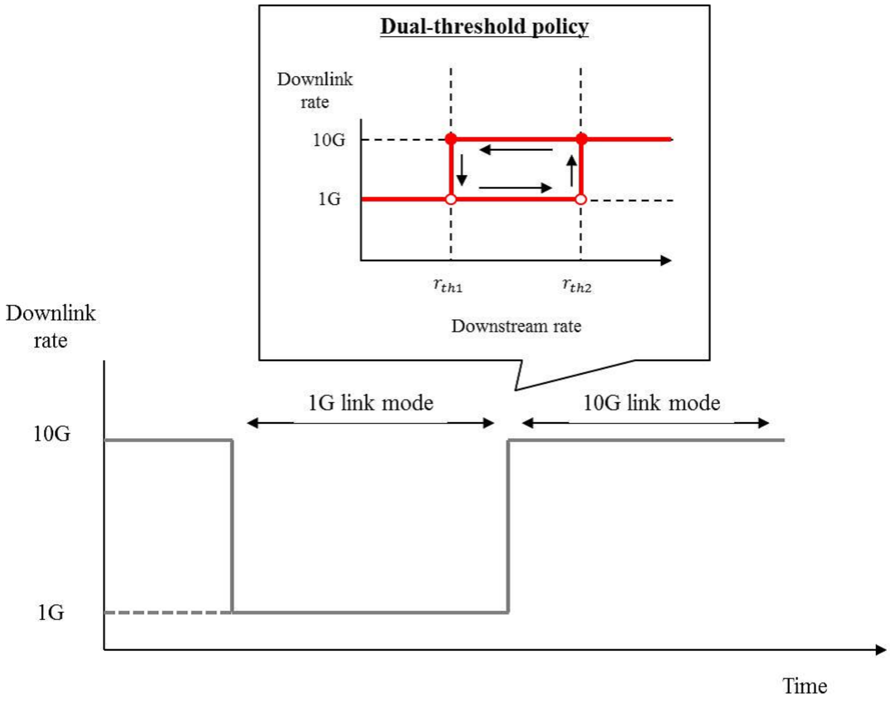

Figure 2.12: Downlink rate versus time of ALR.[2-16]

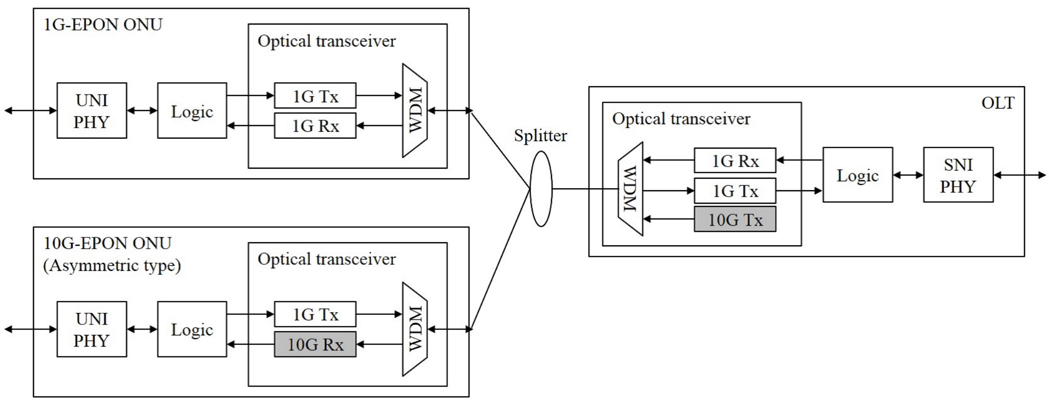

Figure 2.13: Architecture using hybrid power saving technique.[2-16]

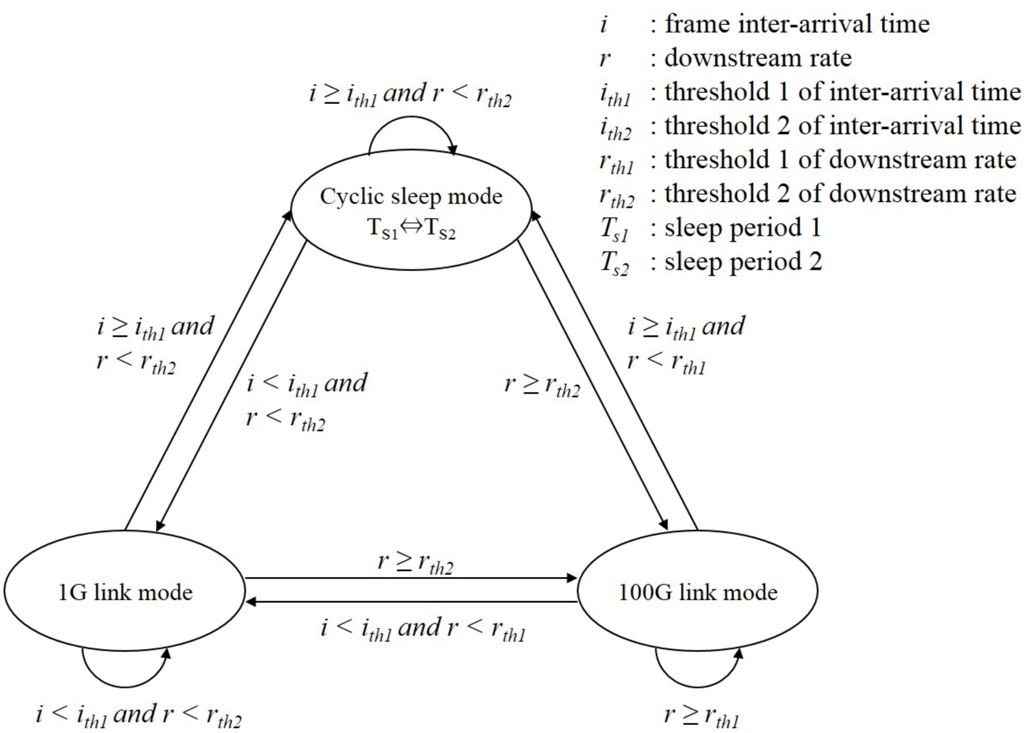

Figure 2.14: Control of the hybrid power saving.[2-16]

downstream traffic. Fig. 2.12 shows the relation between the down link rate and time of the ALR. When the downstream rate is higher than the threshold 2 of downstream rate (r_{th2}), the transmission speed of 10 Gbps is used and when the downstream rate is lower than the threshold 1 of downstream rate (r_{th1}), the transmission speed of 1 Gbps is used. However, the switching time between 1 Gbps and 10 Gbps is longer than the acceptable time of application and the link rates of 1 Gbps and 10 Gbps are only used statically in 10G-EPON by using the ALR.

In order to provide more energy efficient in 10G-EPON, the hybrid power saving technique between the ONU power saving and ALR has already been proposed in [2-16]. Fig. 2.13 and Fig. 2.14 show the architecture using hybrid power saving technique and the control of the hybrid power saving. There are three modes, ”Cyclic sleep mode”, ”1 Gbps link mode”, and ”10 Gbps link mode”. The cyclic sleep function for the cyclic sleep mode introduces the variable sleep period to enable the appropriate adjustment of the sleep period according to traffic conditions. The ALR function for the 1 Gbps and 10 Gbps link modes introduces dual-threshold policy to prevent the frequent switching of link rates.

Evaluations of requirements for realizing the next generation optical access network (TDM-PON)

The TDM-PON architecture [2-5][2-6] realizes the bandwidth of 10 Gbps, the transmission distance of 20 km (10G-EPON) and 60 km (NG-PON1), and the number of users of 32 users (10G-EPON) and 64 users (NG-PON1). In terms of the scalability, it does not meet the requirements of NG-PON2 which are the bandwidth of 10 Gbps, the transmission distance of 40 km, and the number of users of 256 users theoretically. In terms of the flexibility, it supports both delay-sensitive communication and multicast function thanks to the broadcast nature. In terms of the low-power consumption, it provides a low-power consumption network because it uses a passive optical splitter which does not

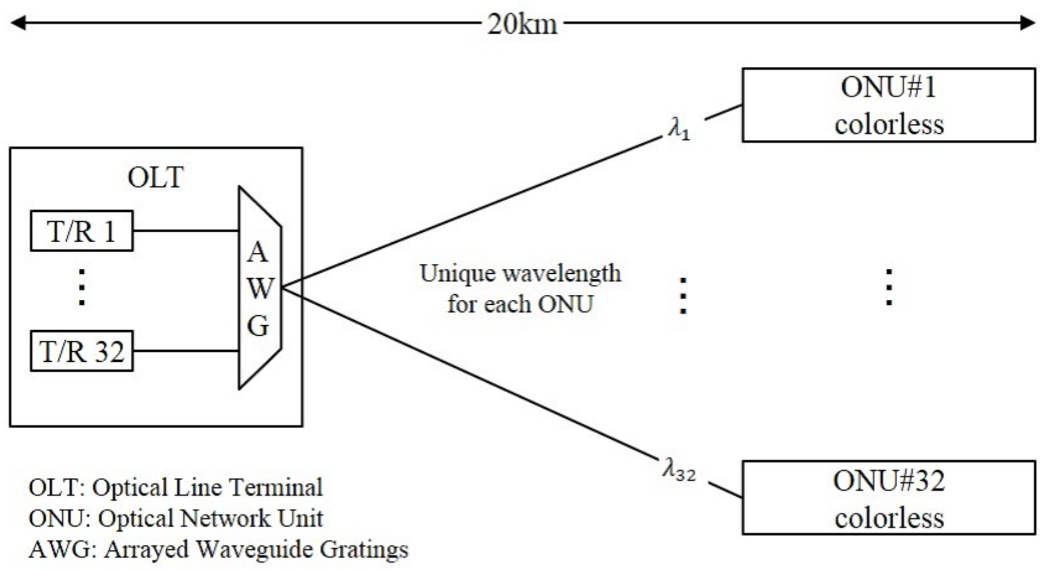

Figure 2.15: Basic WDM-PON architecture.[2-17]

consume electric power and introduces the power-saving techniques which are the ONU power saving defined by ITU-T Series G Supplement 45 G-PON power conservation and the ALR.

2.1.3 Wavelength Division Multiplexing-Passive Optical Network (WDM-PON)

Fig. 2.15 shows the basic WDM-PON architecture, which is comprised of OLT, Arrayed Waveguide Gratings (AWG) wavelength multiplexer/demultiplexer which combines and splits optical signals of different wavelengths, and the colorless ONUs whose characteristics do not depend on the wavelength [2-17]. In the WDM-PON, the data transmission between OLT and ONUs is that the sender transmits the data to the receiver by assigning the unique wavelength to each receiver. The WDM-PON [2-17] realizes the bandwidth of 40 Gbps (1.25 Gbps per a wavelength) for upstream and downstream, the transmission distance of 20 km, and the number of users of 32 users. The wavelength from 1530 to 1565 nm (C-band) or 1565 to 1625 nm (L-band) is allocated in the upstream and that from 1575 to 1580 nm (L-band) is allocated in the downstream.

Evaluations of requirements for realizing the next generation optical access network (WDM-PON)

In terms of the scalability, it realizes the scalable network by using the unique wavelength, compared to the 10G-EPON, but it does not meet the requirements of NG-PON2 which are the bandwidth of 10 Gbps, the transmission distance of 40 km, and the number of users of 256 users in publications to date. In terms of the flexibility, it supports the delay-sensitive communication and does not supports the multicast function due to a use of separate wavelength for each ONU. In terms of the low-power consumption, it consumes the power higher than the 10G-EPON by introducing the WDM technologies into the OLT and ONUs used in the 10G-EPON.

2.1.4 Time and Wavelength Division Multiplexing-Passive Optical Network (TWDM-PON)

In order to realize the scalable and multi-service adaptable network, the TWDM-PON is recently discussed and becoming popular [2-18]. This network is a hybrid network of TDM-PON and WDM-PON. Fig. 2.16 shows the TWDM-PON architecture which uses the optical splitter and the optical amplifiers (SOA: Semiconductor Optical Amplifier) in addition to the components of the basic WDM-PON which has OLT, the AWG wavelength multiplexer/demultiplexer, and the colorless ONUs. The TWDM-PON [2-18] realizes the bandwidth of 40 Gbps (10 Gbps per a wavelength) for upstream and downstream, the transmission distance of 40 km, and the number of users of 1024 users. The wavelength from 1524 to 1544 nm (C-band) is allocated in the upstream and that from 1596 to 1603

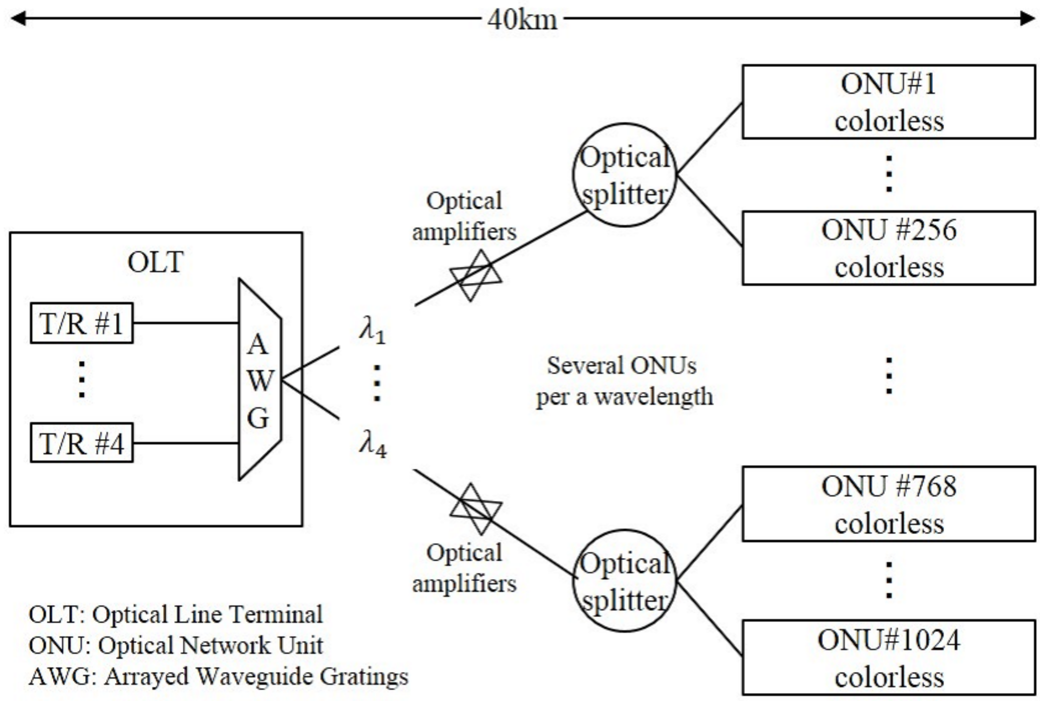

Figure 2.16: Hybrid TWDM-PON architecture.[2-18]

nm (L-band) is allocated in the downstream.

Evaluations of requirements for realizing the next generation optical access network (TWDM-PON)

In terms of the scalability, it meets the requirements of NG-PON2 which are the bandwidth of 10 Gbps, the transmission distance of 40 km, and the number of users of 256 users by using the hybrid TDM and WDM technologies. In terms of the flexibility, it supports both delay-sensitive communication and multicast function by using the optical splitter. In terms of the low-power consumption, it consumes the power higher than the 10G-EPON by introducing the WDM technologies into the OLT and ONUs used in the 10G-EPON.

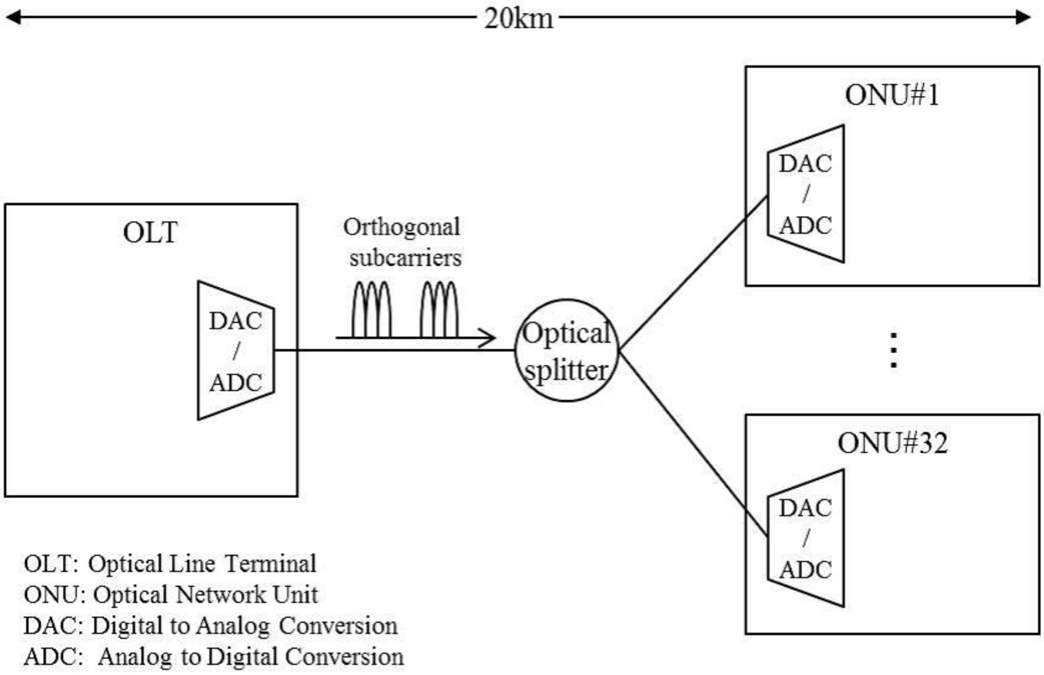

Figure 2.17: OFDM-PON architecture.[2-19–22]

2.1.5 Orthogonal Frequency Division Multiplexing-Passive Optical Network (OFDM-PON)

Fig. 2.17 shows the OFDM-PON architecture, which is comprised of OLT which includes the high-speed Digital Signal Processor (DSP) to realize the OFDM technology, ONUs which include the high-speed DSP to realize the OFDM technology, and an optical splitter [2-19–22]. Fig. 2.18 shows the OFDM spectrum and the frequency and time domain partitioning of an OFDM frame for downstream broadcast [2-20]. The OFDM signal contains N sub-carriers, which are overlapped in the frequency domain and orthogonal to each other. The frequency and time two-dimensional bandwidth allocation is adopted. The data transmission between OLT and ONUs shows that the sender converts the digital symbols into the narrow-band orthogonal sub-carriers by using Digital to Analog Conversion (DAC) and transmits the analog symbols which contain several subcarries and the

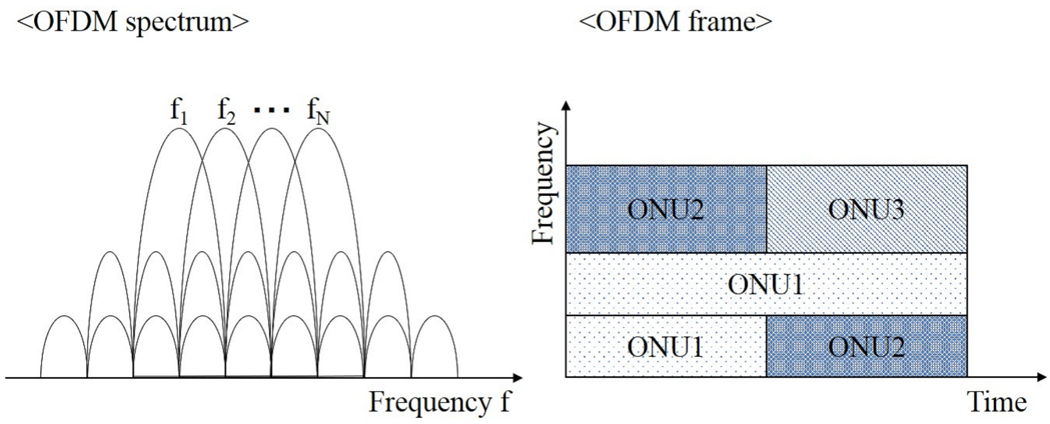

Figure 2.18: OFDM spectrum for N orthogonal frequency domain sub-carriers and frequency and time domain partitioning of an OFDM frame for downstream broadcast [2-20].

receiver receives the analog symbols and converts them into the digital symbols by using Analog to Digital Conversion (ADC). The OFDM-PON [2-19–22] realizes the bandwidth of 40 Gbps (16QAM) for upstream and downstream, the transmission distance of 20 km, and the number of users of 32 users. The wavelength from 1260 to 1280 nm (O-band) is allocated in the upstream and that from 1575 to 1580 nm (L-band) is allocated in the downstream. For supporting future large amounts of data traffic, hybrid solutions of the OFDM-PON with the TDMA and Wavelength Division Multiplexing Access (WDMA) technologies are discussed [2-22], as shown in Fig. 2.19. The OFDMA-PON is basic OFDM-PON architecture that different users are assigned different OFDM sub-carriers within one OFDM band of total N sub-carriers. The OFDMA+TDMA-PON is that different users are assigned different OFDM sub-carriers and TDM slots within one OFDM band; 2-dimensional dynamic bandwidth allocation. The OFDMA+TDMA+WDMA-PON is that different users are assigned different OFDM sub-carriers, TDM slots, and WDM wavelengths.

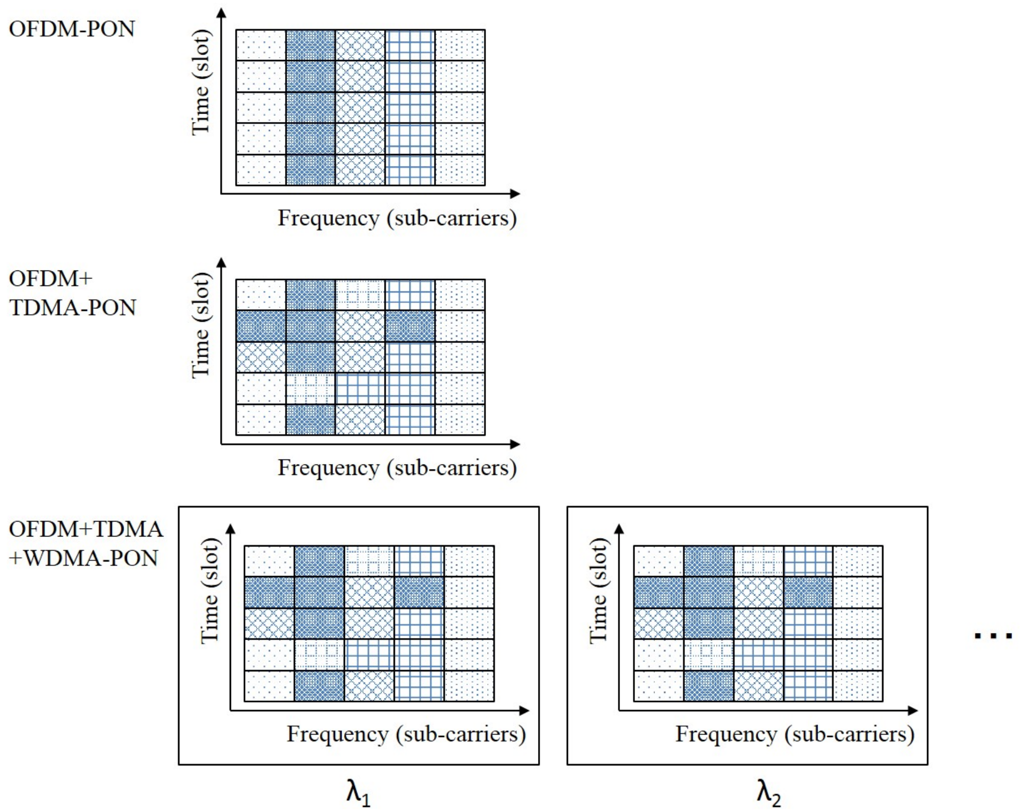

Figure 2.19: Hybrid sollutions of OFDM-PON with TDMA and WDMA technologies. [2-22].

Evaluations of requirements for realizing the next generation optical access network (OFDM-PON)

In terms of the scalability, it realizes the scalable network by using several subchannels, compared to the 10G-EPON, but it does not meet the requirements of NG-PON2 which are the bandwidth of 10 Gbps, the transmission distance of 40 km, and the number of users of 256 users in publications to date. In terms of the flexibility, it supports both delay-sensitive communication and multicast function by using the optical splitter. In terms of the low-power consumption, it consumes the power higher than the 10G-EPON by introducing the OFDM technologies into the OLT and ONUs used in the 10G-EPON.

2.1.6 Optical Code Division Multiplexing-Passive Optical Network (OCDM-PON)

Fig. 2.20 shows the OCDM-PON architecture, which is comprised of OLT which includes the encoder and the decoder by using the Single phase-shifted Super Structure Fiber Bragg Grating (SSFBG), ONUs which include the encoder and the decoder by using the SSFBG, and an optical splitter [2-23–25]. In the OCDM-PON, the data transmission between OLT and ONUs is that the sender encodes the data by using a unique optical code word and transmits the data in the optical code word and the receiver receives the data and decodes it by using the same key which is used for encoding own data. The optical code words are generated by dividing the original optical signal pulse into finer pulses called chip and encoding them with the phase difference between 0 and π. For the coherent Time Spreading (TS) OCDMA, the multi-port OCDMA Encoder/Decoder (E/D) has the unique capability of simultaneously processing multiple time-spread optical code words with single device, which makes it a potential cost-effective device to be used in the OLT to reduce the number of encoder/decoders. On the other hand, the SSFBG E/D is another attractive TS-OCDMA E/D, which has the ability to process ultra-long TS-OC with polarization independent performance, low and code-length independent insertion loss, compactness as well as low cost for mass production. The OCDM-PON system using hybrid multi-port E/D and SSFBG E/Ds [2-25] has been presented to significantly improve the system flexibility and performance, as shown in Fig. 2.21. The multi-port encoder with periodic frequency response can be used in the OLT to process multiple OCs in multiple wavelength bands with a single device. In the ONU, the OCDMA decoding could be simultaneously carried out by employing a low cost multi-level phase-shifted SSFBG decoder. The OCDM-PON [2-23–25] realizes the bandwidth of 40 Gbps (10 Gbps per an optical cord word) for upstream and downstream, the transmission distance of 20 km, and the number of users of 128 users. The wavelength from 1260 to 1280 nm (O-band) is allocated in the upstream and that from 1575 to 1580 nm (L-band) is allocated in the downstream. Additionally, by combining OCDM-PON with WDM technologies, high-capacity transmission in access networks can be achieved, which in prospective can enable a 10 Gbps-class. The hybrid system also adopts eight 16-chip, 16-level phase-shifted SSFBG E/Ds and a 16×16 port E/D in the hybrid encoder and decoder.

Evaluations of requirements for realizing the next generation optical access network (OCDM-PON)

In terms of the scalability, it realizes the scalable network by using several subchannels, compared to the 10G-EPON, but it does not meet the requirements of NG-PON2 which are the bandwidth of 10 Gbps, the transmission distance of 40 km, and the number of users of 256 users in publications to date. In terms of the flexibility, it supports both delay-sensitive communication and multicast function by using the optical splitter. In terms of the low-power consumption, it consumes the power higher than the 10G-EPON by introducing the OCDM technologies into the OLT and ONUs used in the 10G-EPON.

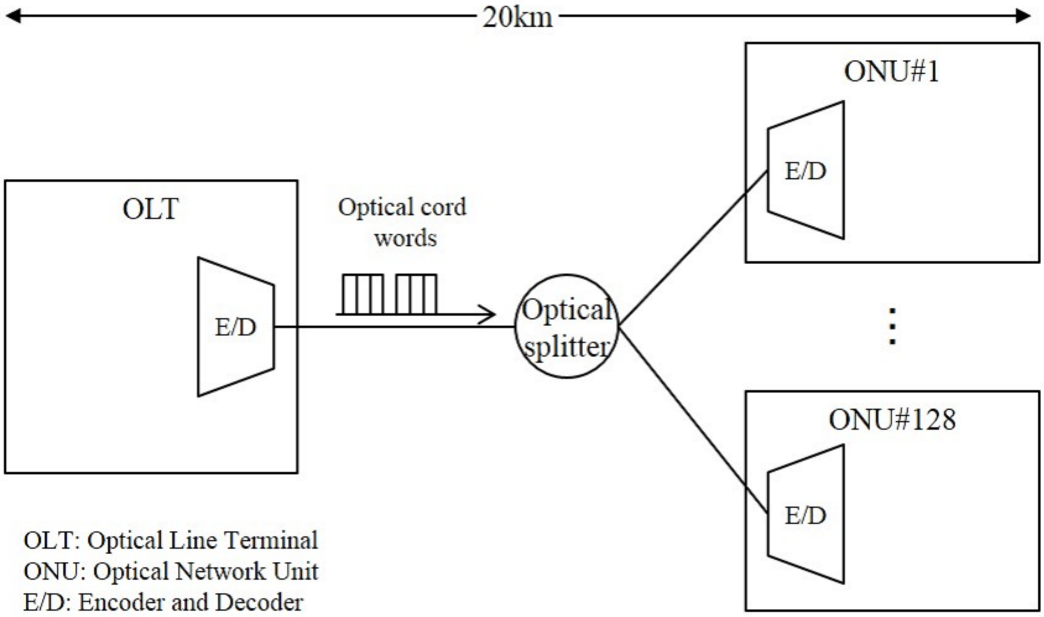

Figure 2.20: OCDM-PON architecture.[2-23–25]

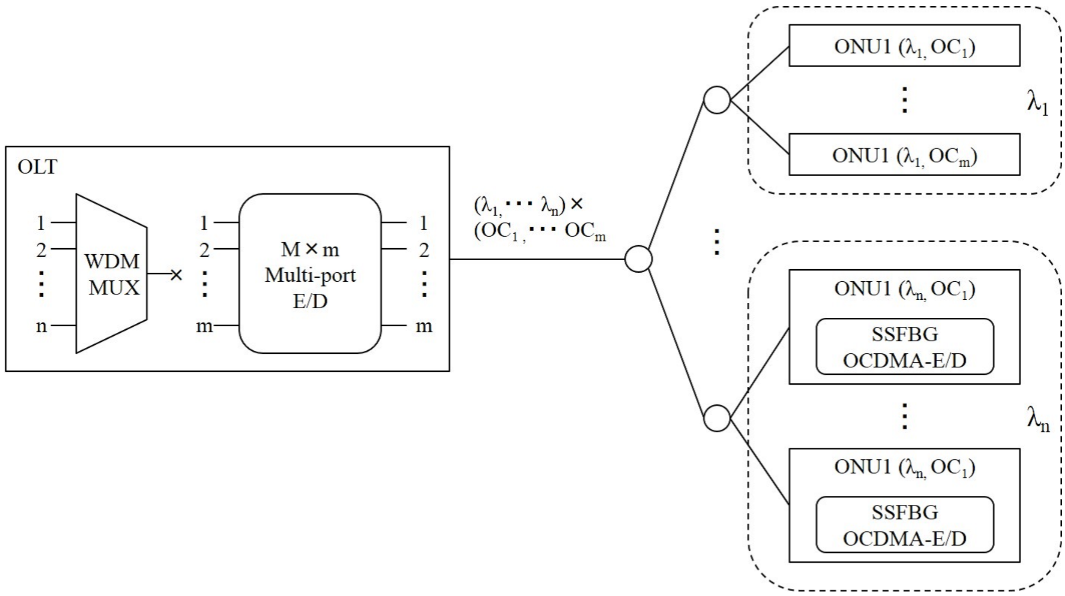

Figure 2.21: OCDM-PON using hybrid multi-port E/D and SSFBG E/Ds.[2-25]

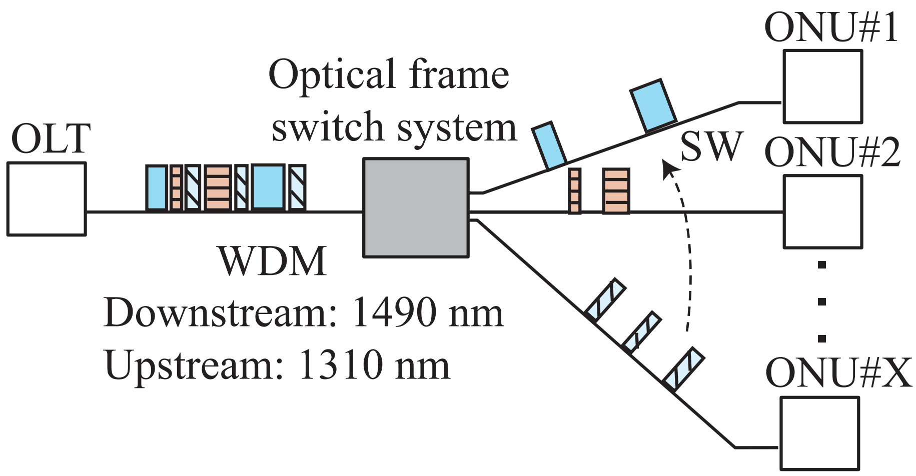

Figure 2.22: GE-OSAN architecture.[2-26–28]

2.2 Active Optical Network

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

To provide a scalable access services, the active access network using packet-based optical switching was presented. The GE-OSAN is one interesting example of access networks using packet-based optical switching [2-26–28]. Fig. 2.22 shows the GE-OSAN architecture, which is comprised of OLT, ONUs, and an optical frame switch system that has one port to OLT and *x* ports to the ONUs. In the GE-OSAN, the data transmission between OLT and ONUs is that the sender transmits the data to the receiver by using a packet-based switching with the Optical Switching Module (OSM). Fig. 2.23 shows the basic functional block of OSM. The downstream optical signals from OLT are extracted at the WDM (UP) block. The downstream optical signal is divided into two; one is sent to the downstream optical switch via the Delay block. The other is sent to an Optical/Electrical (O/E) converter to electrically control downstream optical packet switching.

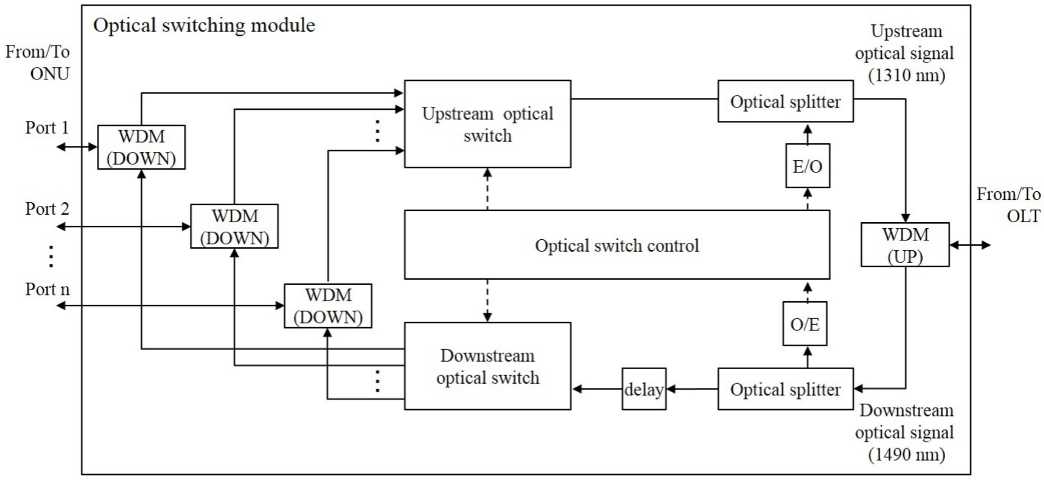

Figure 2.23: Basic functional block of OSM. [2-28]

Evaluations of requirements for realizing the next generation optical access network (GE-OSAN)

The GE-OSAN [2-26–28] realizes the bandwidth of 1 Gbps, the transmission distance of 40 km, and the number of users of 128 users (theoretically over 256 users). In terms of the scalability, it provides longer transmission distance than the 10G-EPON, it dose not meet the requirements of NG-PON2 which are the bandwidth of 10 Gbps, the transmission distance of 40 km, and the number of users of 256 users theoretically because analyzing each packet's header for packet-by-packet switching with O/E conversions is required and it becomes a bottleneck and is not cost-effective for the 10 or more Gbps high bandwidth environments. In terms of the flexibility, it dose not support neither delay-sensitive communication nor multicast function because it uses the packet-based switching and needs a large amount of bandwidth in multicast. In terms of the low-power consumption, it consumes the higher power consumption than the 10G-EPON because it needs additional packet-based optical switches.

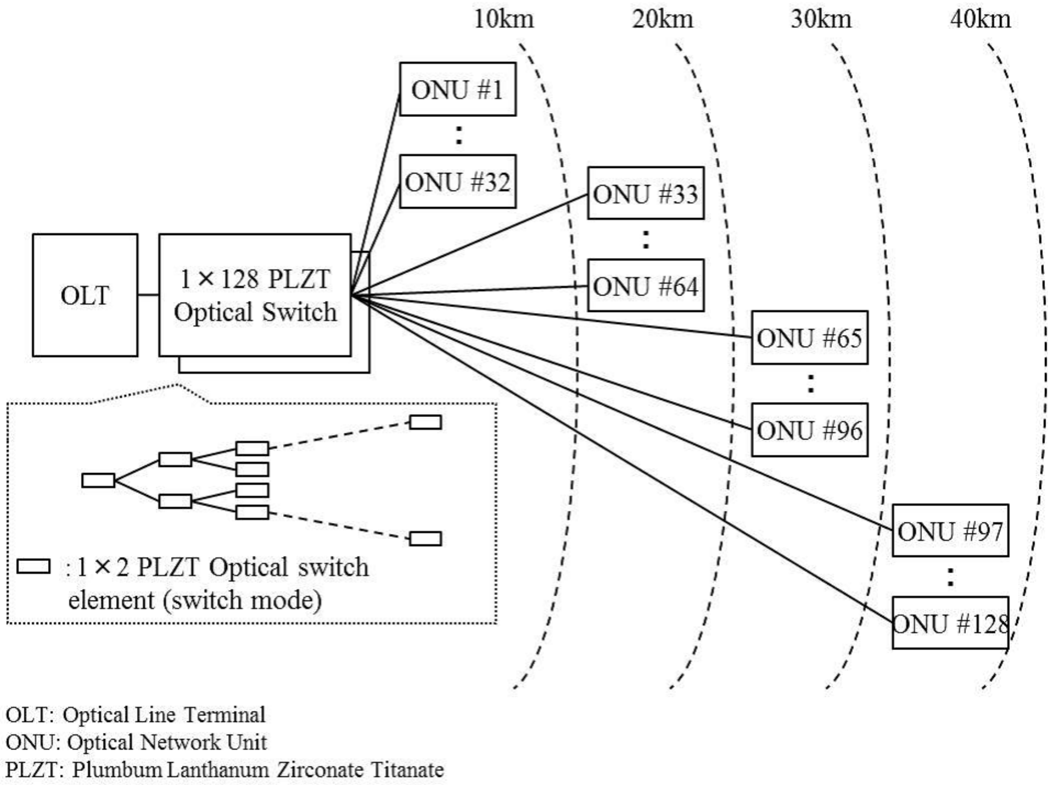

Figure 2.24: ActiON architecture.[2-29–34]

2.2.2 Active Optical Access Network (ActiON)

To realize a scalable network and achieve transparent transmission without O/E conversions, ActiON has been proposed by using a slot-based optical switching [2-29–34].

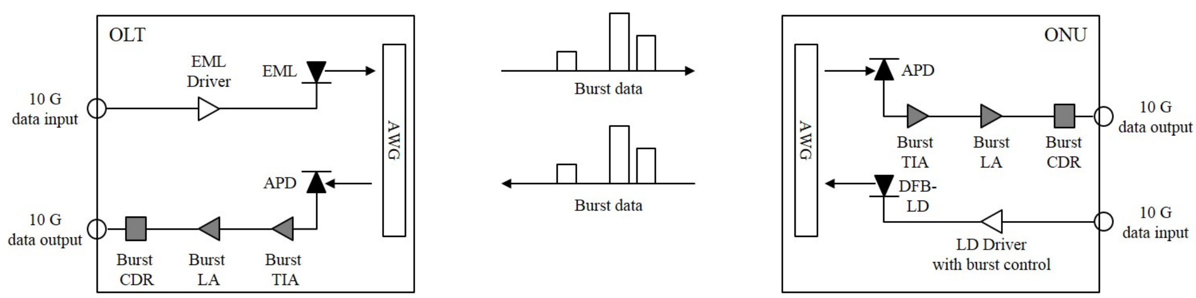

Figure 2.25: Internal structures of OLT and ONU of ActiON.

Architecture

Fig. 2.24 shows the ActiON architecture, which is comprised of OLT, ONUs, and two Plumbum Lanthanum Zirconate Titanate (PLZT) optical switches for upstream and downstream data transmissions. The ActiON architecture quadruples the number of ONUs (128) per OLT and doubles the maximum transmission distance (40 km) between OLT and ONUs under 10 Gbps due to a low optical loss of Mach-Zehnder (MZ) type PLZT optical switches, compared to the 10G-EPON. The 1×128 PLZT optical switch sets the 1×2 PLZT optical switch elements in a multistage (7 stages) configuration [2-30]. In the ActiON, the data transmission between OLT and ONUs is that the sender transmits the burst data to the receiver by using a slot-based switching. Both OLT and ONU support the burst data by introducing the Burst-TIA, Burst-LA, and Burst-CDR, which are used in OLT of the 10G-EPON, as shown in Fig. 2.25. The wavelength allocation of ActiON in the upstream and downstream data transmission is the same as those of 10G-EPON (Upstream: 10 Gbps / Downstream: 10 Gbps), where the wavelength from 1260 to 1280 nm (O-band) is allocated in the upstream and the wavelength from 1575 to 1580 nm (L-band) is allocated in the downstream. The maximum optical loss budget of the ActiON is set to 29 dB, which is the same as that of the 10G-EPON. This optical loss budget includes 20 dB in the fiber loss of 40 km (0.5 dB / km) and 1 - 3 dB in the connection loss and the insertion loss of the PLZT optical switch, which is the same as that of the optical splitter. It dose not include the splitting loss. Thus, the ActiON can extend the transmission distance and the number of users, compared to 10G-EPON.

Structure of the 1×2 PLZT optical switch

Fig. 2.26 and Table 2.1 show the structure of a 1×2 PLZT optical switch and the relationship between mode, splitting ratio, splitting loss, and voltage. The 1×2 PLZT optical switch element is a MZ type wave guide structure [2-40–47], so the optical signal

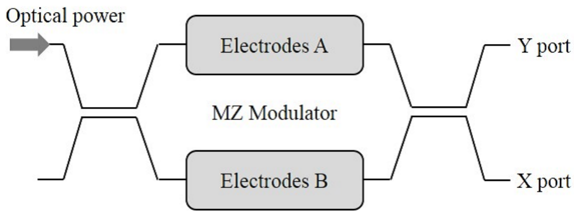

Figure 2.26: Structure of 1×2 PLZT optical switch.

Table 2.1: Measured relationship between mode, splitting ratio, splitting loss, and voltage.

	Mode of PLZT optical switch	Splitting ratio (X to Y)	Splitting loss (X, Y (dB))	Voltage (A, B (V))
(a)	Switch mode (Bar)	0.0 to 1.0	10.9, 0.0	0.0, 8.0
(b)	Switch mode (Cross)	1.0 to 0.0	0.0, 23.0	10.5, 0.0

is switched by changing the voltage applied to the electrodes A or B. The voltage is applied to the electrodes only when changing modes in each switch element.

The optical signal is output in X port by applying the voltage (8.0V) only to the electrodes B, called the bar state (a) and the optical signal is output in Y port by applying the voltage (10.5V) only to the electrodes A, called the cross state (b). Also, the switching time between the bar and cross states of the switch mode is within 10 ns.

In the power consumption of 1×2 PLZT optical switch [2-46, 47], the switch element consumes 0.02 W and the switch driver board consumes 2.5 W, which consists of the main board (2.4 W) and the sub board (0.1 W), at 10 MHz, which means a change between switch modes at 100 ns. Both switch element and sub board consume the power during only switching from the current mode to other modes. The main board always consumes the power regardless any mode changes. The power consumption of $1 \times N$ PLZT optical switch is computed by main board (2.4 W) + (switch element + sub board) (0.12 W) $\times$ (N - 1).

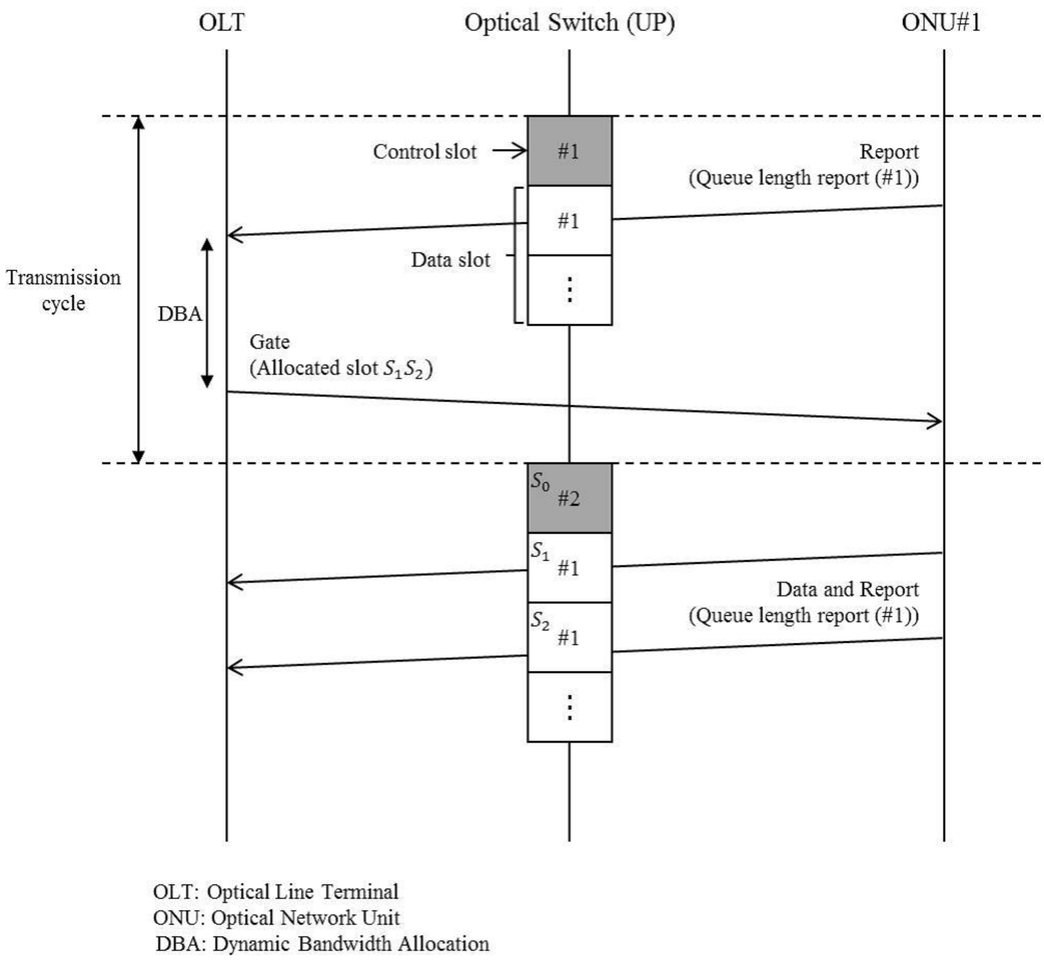

Figure 2.27: ActiON data transmission.

On the other hand, in the comparison with other optical switches having the latching mode capability, in which the power is only needed during switching, the Micro Electro Mechanical Systems (MEMS) switch consumes the power efficiently, where the required voltage is 3 - 190 V and the power consumption is 4 - 250 mW for a switching element [2-48, 49]. However, the MEMS switch is not applicable in the ActiON, which requires the switching at nano-second speed, since its switching speed is large at around 10 ms [2-34].

Data transmission

In ActiON, the MPCP [2-12] is adopted for compatibility with 10G-EPON (IEEE802.3av) [2-5]. The OLT first discovers ONU with the power supply, called Discovery process, and the data is transmitted to the registered ONU. Fig. 2.27 shows the ActiON data transmission. The bandwidth is allocated to each user by assigning fixed-length time periods, called ”Slot”. The optical switch is controlled by using ”Transmission cycle”, which is composed of multiple slots. In the transmission cycle, the first slot, called ”Control slot” is used for Discovery process. This slot appears periodically, so the automatic ranging that measure the distance from OLT to ONU can be achieved by using the slot. Other slots are used for the data transmission. In the data transmission of ActiON, the ONU transmits the REPORT message which stores a queue length of the buffer of the ONU to the OLT. Next, the OLT calculates the allocated slots for each ONU by using the DBA function based on the received queue status reports from ONUs, and transmits the GATE message which stores allocated slots for each ONU. According to GATE message, each ONU transmits the data by using the allocated slots.

Evaluations of requirements for realizing the next generation optical access network (ActiON)

The ActiON [2-29–34] realizes the bandwidth of 10 Gbps, the transmission distance of 40 km, and the number of users of 128 users (theoretically over 256 users). In terms of the scalability, it meets requirements of NG-PON2 which are the bandwidth of 10 Gbps, the transmission distance of 40 km, and the number of users of 256 users. In terms of the flexibility, the transmission waiting time exceeds the user’s allowable delay in the slot allocation, and it needs a large number of slots in multicast. In terms of the low-power consumption, it consumes the higher power consumption than the 10G-EPON system because it needs additional PLZT optical switches.

This dissertation focuses on the problems and the proposed method in the ActiON, so the detailed problems is described as follows.

1. Problem in the flexibility when supporting the slot allocation The conventional slot allocation method shortens the switching idle time, which is a product of the switching guard time and the number of switching times, to increase the bandwidth utilization efficiency. The bandwidth utilization efficiency is assumed to be ”(total slot allocation time - switching idle time) / total slot allocation time”. However, the transmission waiting time, which is incurred by because a user cannot transmit in slot allocated to other users, could exceed the user’s allowable delay. There is a trade-off between the switching idle time and the transmission waiting time of each user. Examples 1 and 2 in Fig. 2.28 show the conventional slot allocation methods. The number of slots allocated to users #1 and #2 are four slots per transmission cycle. Each user’s allowable delay is two slots. This parameter is decided according to the user’s application type and buffer size. In example 1, the user is changed every slot. The transmission waiting time, during which a user has to wait for transmission while the slots have been used by other users, is one slot, which is within the allowable delay. On the other hand, the switching idle time is eight$\times$guard time within a transmission cycle. In example 2, whole consecutive slots are allocated to a user before switching to the next user. The transmission waiting time is four slots, which exceeds the allowable delay. On the other hand, the switching idle time is two $\times$ guard time within a transmission cycle.

In this way, the conventional method requires the trade-off between the switching idle time and the transmission waiting time. Therefore, in order to provide high bandwidth utilization efficiency in the slot allocation, compared to the conventional slot allocation method in the ActiON, the delay-sensitive slot allocation method is proposed, where the ActiON parameters that are the transmission cycle and the number of slots per a cycle are designed, and the proposed method minimizes the switching idle time in the PLZT optical

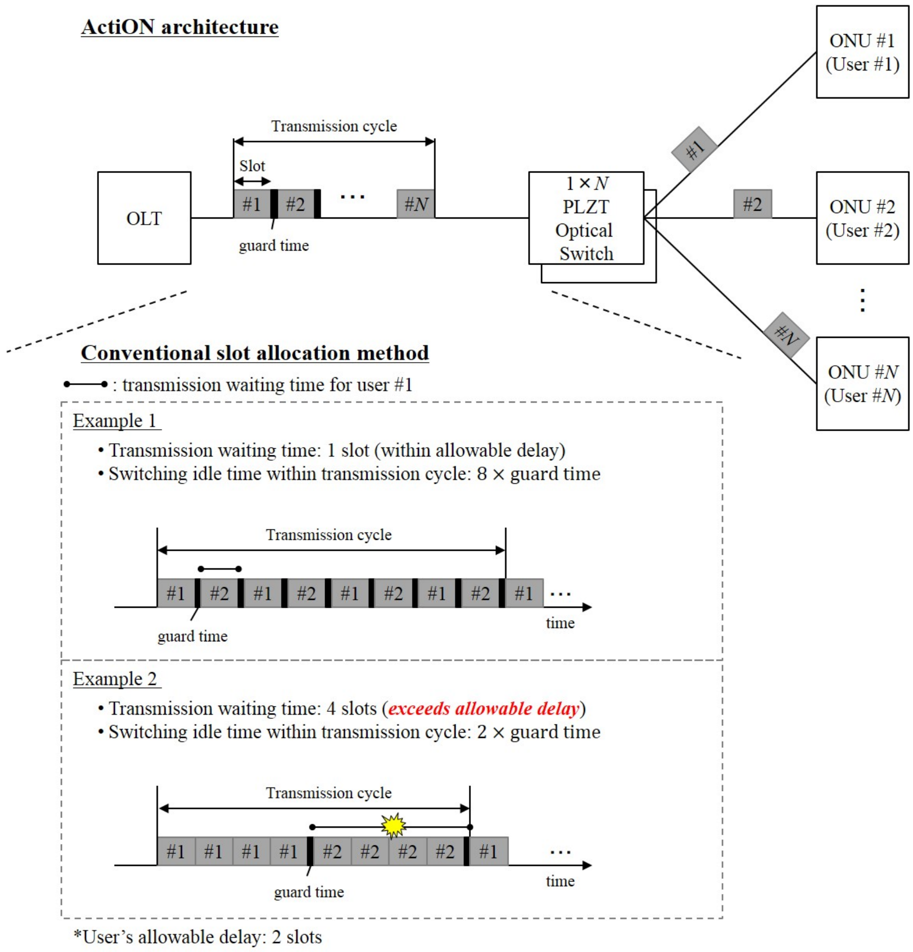

Figure 2.28: ActiON architecture and conventional slot allocation method

switch based on the ActiON parameters in Chapter 3.

2. Problem in the flexibility when supporting multicast In multicast, the ActiON needs a large number of slots to deliver contents to the requesting users using multicast. Fig. 2.29 shows the multicast slot allocation method in the ActiON. To simplify the discussion on the slot switching, the downstream data transmission on multicast is only considered. The 1×4 PLZT optical switch, which sets 1×2 optical switch elements in three-stages configuration, are used. The users (ONUs) #1, #2, #3, and #4 are multicast users. The ActiON does not directly support multicast, so OLT copies the data for each

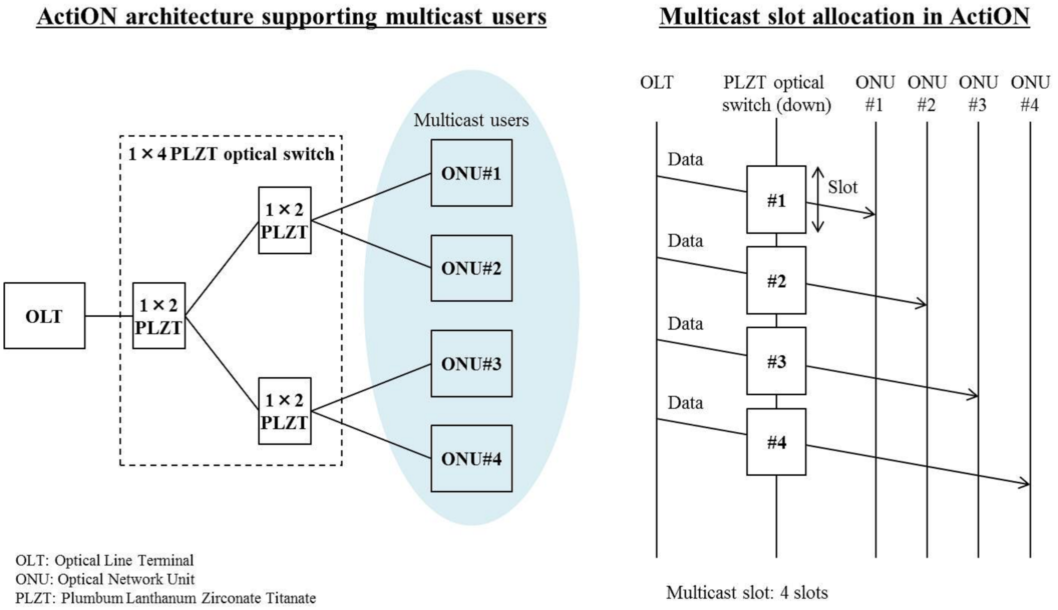

Figure 2.29: Multicast slot allocation of ActiON.

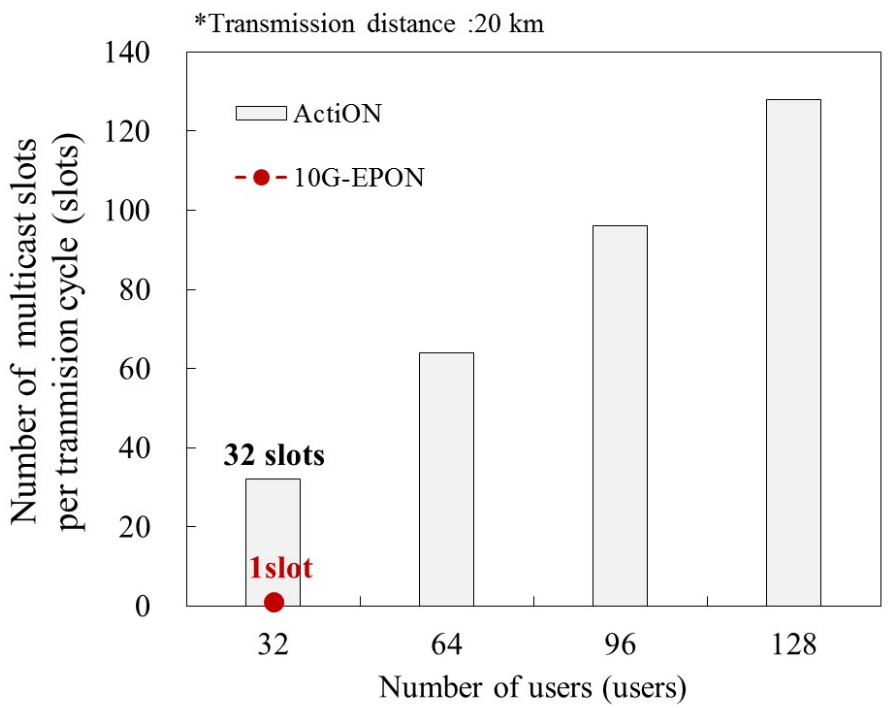

Figure 2.30: Number of multicast slots per a transmission cycle versus number of users.

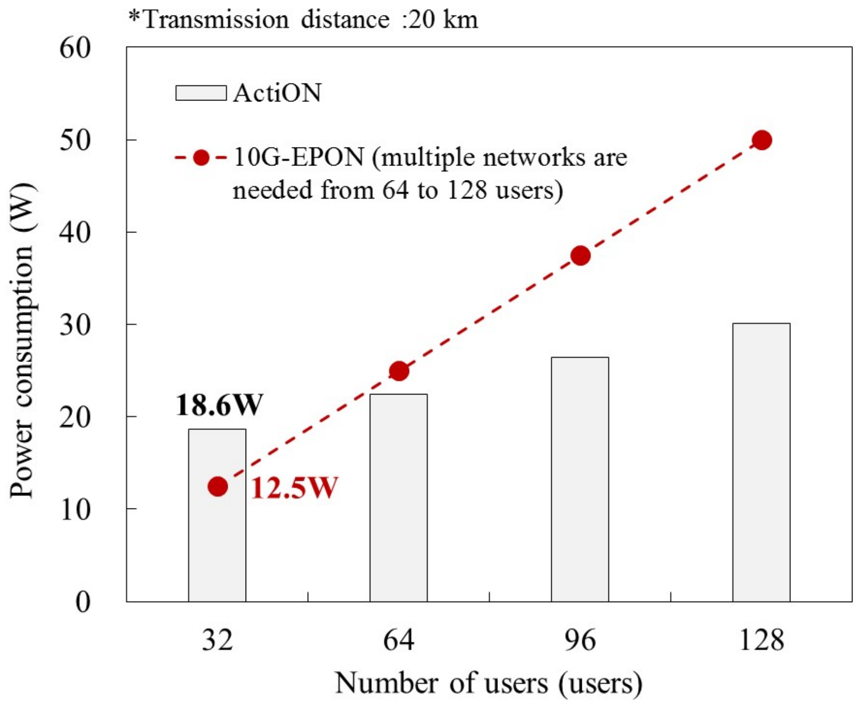

Figure 2.31: Power consumption versus number of users.

user and transmits the data to each user by slot switching. The number of multicast slots needed is four.

Fig. 2.30 shows the relationship between the number of multicast slots per transmission cycle and tne number of users in the 10G-EPON and the ActiON. The transmission distance is set to 20 km. The 10G-EPON needs only one slot due to the broadcast nature in the number of users of 32. However, the ActiON needs 32 times as many slots as the 10G-EPON due to the slot switching needs in the number of users of 32, and the required number of slots increases with the number of multicast users when extending the network.

Therefore, in order to reduce the required number of slots in multicast compared to the conventional ActiON, the multi-service adaptable Active Optical Access Network (multi-service adaptable ActiON) by using the PLZT optical switch at the variable splitter mode is proposed in Chapter 4.

3. Problem in the low-power consumption The ActiON consumes the power higher than the 10G-EPON because it needs additional PLZT optical switches in addition to the components of the PON which are OLT and ONUs (The optical splitter does not consume power.). Fig. 2.31 show the relationship between the power consumption and the number of users. The simulation parameters are shown below. The power consumption of OLT is 12.5 W [2-50]. The power consumption of $1 \times N$ PLZT optical switch is calculated based on the Eq. (2.1a).(N is the number of users.) The power consumption of each ONU is not included because it is a common element in each network. The transmission distance is set to 20 km.

$$\begin{aligned}&\text{Power of } 1 \times N \text{ PLZT optical switch} = \\ &\text{Power of } 1 \times 2 \text{ PLZT optical switch chip (with sub board) (0.12 W) [2-46, 47]} \\ &\times(N-1) + \text{Standby Power of PLZT optical switch driver (main board)} \\ &\text{(2.4 W) [2-46, 47]}\end{aligned} \tag{2.1a}$$

In the existing network range of the 10G-EPON, where the number of users is 32, the ActiON consumes the power higher approximately 1.5 times than the 10G-EPON. When extending the existing network, the power consumption of the ActiON is less than the 10G-EPON. Because 10G-EPON needs multiple networks when the number of users is from 64 to 128 users. For example, two 10G-EPONs are needed when the number of users is 64 because the maximum number of users is 32 users per one 10G-EPON. On the other hand, the ActiON can cover 128 users in one network due to a low insertion loss of PLZT optical switch when extending the network. Additionally, the TWDM-PON and the OCDM-PON can cover 128 users in one network. However, their power consumption is more than the 10G-EPON because of the increase in electricity power of OLT and ONU by introducing multiplexing technologies. Therefore, in order to consume the power as low as the 10G-EPON regardless of a network range, the low-power consumption slot allocation method in the ActiON is proposed in Chapter 5.

2.3 Target of the dissertation

Table 2.2: Network scale in each optical access network.

Type		(optical amplifier)	Network scale		
			Bandwidth	Distance	Users
Passive optical network	10G-EPON		40 G (up/down)	20 km	32
	WDM-PON		40 G (up/down) /32 wavelengths	20 km	32
	TWDM-PON	√	40 G (up/down) /4 wavelengths	40 km	1024
	OFDM-PON		40 G (up/down) /16 QAM	20 km	32
	OCDM-PON		40 G (up/down) /4 optical codes	20 km	128
Active optical network	GE-OSAN		1 G (up/down) /1 wavelength	40 km	128 (theoretically 256)
	ActiON		10 G (up/down) /1 wavelength	40 km	128 (theoretically 256)

Tabs 2.2 and 2.3 show the network scale in each optical access network and the target of this dissertation by comparing with described above conventional optical access networks. In terms of scalability, it is evaluated whether each network model satisfies the

Table 2.3: Target of the dissertation.

Network type	1. Scalability	2. Flexibility		3. Low-power consumption	Reference
		Delay sensitivity	Multicast function		
10G-EPON		√	√	√	[2-5]
WDM-PON		√			[2-17]
TWDM-PON	√	√	√		[2-18]
OFDM-PON		√	√		[2-19–22]
OCDM-PON		√	√		[2-23–25]
GE-OSAN					[2-26–28]
ActiON	√			√ (over 64 users)	[2-29–34]
Target	√	√	√	√	[2-35–39]

requirements of NG-PON2 that the bandwidth is 10 Gbps and the maximum transmission distance is 40 km and the maximum number of users is 256 users or not. In terms of flexibility, it is evaluated whether each network model can provide both delay-sensitive communication which well suits multi-services and multicast function or not. In terms of low-power consumption, it is evaluated whether each network model consume power consumption as low as the 10G-EPON system when extending the network or not.

At first, the evaluations of requirements for passive optical networks are explained as follows. The 10G-EPON [2-5] realizes the bandwidth of 10 Gbps, the transmission distance of 20 km, and the number of users of 32 users. In terms of the scalability, it does not meet the requirements of NG-PON2 which are the bandwidth of 10 Gbps, the transmission distance of 40 km, and the number of users of 256 users theoretically. In terms of the flexibility, it supports both delay-sensitive communication and multicast function thanks to the broadcast nature. In terms of the low-power consumption, it provides a low-power consumption network because it uses a passive optical splitter which does not consume electric power and introduces the power-saving techniques which are the ONU power saving defined by ITU-T Series G Supplement 45 G-PON power conservation and the ALR.

The WDM-PON [2-17] realizes the bandwidth of 40 Gbps (1.25 Gbps per a wavelength), the transmission distance of 20 km, and the number of users of 32 users. In terms of the scalability, it provides the high bandwidth by using the unique wavelength, compared to the 10G-EPON, but it does not meet the requirements of NG-PON2 in publications to date. In terms of the flexibility, it supports the delay-sensitive communication and does not supports the multicast function due to a use of separate wavelength for each ONU. In terms of the low-power consumption, it consumes the power higher than the 10G-EPON by introducing the WDM technologies into the OLT and ONUs used in the 10G-EPON.

The TWDM-PON [2-18] realizes the bandwidth of 40 Gbps (10 Gbps per a wavelength), the transmission distance of 40 km, and the number of users of 1024 users. In terms of the scalability, it meets the requirements of NG-PON2. In terms of the flexibility, it supports both delay-sensitive communication and multicast function by using the optical splitter. In terms of the low-power consumption, it consumes the power higher than the 10G-EPON by introducing the WDM technologies into the OLT and ONUs used in the 10G-EPON.

The OFDM-PON [2-19–22] realizes the bandwidth of 40 Gbps (16 QAM), the transmission distance of 20 km, and the number of users of 32 users. In terms of the scalability, it realizes the scalable network by using several subchannels, compared to the 10G-EPON, but it does not meet the requirements of NG-PON2 in publications to date. In terms of the flexibility, it supports both delay-sensitive communication and multicast function by using the optical splitter. In terms of the low-power consumption, it consumes the power higher than the 10G-EPON by introducing the OFDM technologies into the OLT and ONUs used in the 10G-EPON.

The OCDM-PON [2-23–25] realizes the bandwidth of 40 Gbps (10 Gbps per a optical cord word), the transmission distance of 20 km, the number of users of 128 users. In terms of the scalability, it realizes the scalable network by using several optical code words, compared to the 10G-EPON, but it does not meet the requirements of NG-PON2 in publications to date. In terms of the flexibility, it supports both delay-sensitive communication and multicast function by using the optical splitter. In terms of the low-power consumption, it consumes the power higher than the 10G-EPON by introducing the OCDM technologies into the OLT and ONUs used in the 10G-EPON.

In this way, the PON-based networks using multiplexing technologies can realize more scalable and flexible network, compared to the 10G-EPON. However, their power consumption is more than the 10G-EPON because of the increase of electricity power in OLT and ONU by introducing multiplexing technologies. The power consumption of OLTs and ONUs in the PON-based networks is approximately twice as high as that of the current PON network [2-52]. Additionally, to introduce multiplexing technologies into OLT and ONU used in the 10G-EPON leads to heavy cost of the whole access network, compared to the 10G-EPON.

Next, the evaluations of requirements for the active optical networks are explained as follows. The active optical networks can realize more scalable network, compared to the 10G-EPON, like the above PON-based networks. Moreover, compared to the PON-based networks using various multiplexing technologies, the active optical networks suppress power and cost because they only change an optical splitter of the 10G-EPON into an optical switch and can use existing OLT and ONU used in the 10G-EPON.

The GE-OSAN [2-26–28] realizes the bandwidth of 1 Gbps, the transmission distance of 40 km, and the number of users of 128 users (theoretically pver 256 users). In terms of the scalability, it provides longer transmission distance than the 10G-EPON. However, it does not meet the requirements of NG-PON2 theoretically because analyzing each packet header for packet-by-packet switching with O/E conversions is required and it becomes a bottleneck and is not cost-effective for the 10 or more Gbps high-bandwidth environments. In terms of the flexibility, it dose not support neither delay-sensitive communication nor multicast function because it uses the packet-based switching and needs a large amount of bandwidth in multicast. In terms of the low-power consumption, it consumes the power higher than the 10G-EPON because it needs additional packet-based optical switches.

In order to achieve transparent transmission without O/E conversions, while keeping the advantage of the GE-OSAN, the ActiON [2-29–34] realizes the bandwidth of 10 Gbps, the transmission distance of 40 km, and the number of users of 128 users (theoretically over 256 users) by using high-speed PLZT optical switches. In terms of the scalability, it meets the requirements of NG-PON2. In terms of the flexibility, the transmission waiting time exceeds the user's allowable delay in the slot allocation, and it needs a large number of slots to deliver contents to the requesting users in multicast. In terms of the low-power consumption, it consumes the power higher than the 10G-EPON in the network range of the 10G-EPON because it needs additional PLZT optical switches. When extending the network of the 10G-EPON, it can reduce the power due to an expansion of the cover range in one network, compared to the 10G-EPON.

Therefore, in order to satisfy three requirements, this dissertation focuses on the ActiON-based network. The proposed network in this dissertation realizes a multi-service adaptable and low-power consumption network, while keeping the advantage of ActiON, which is to support the scalable network.

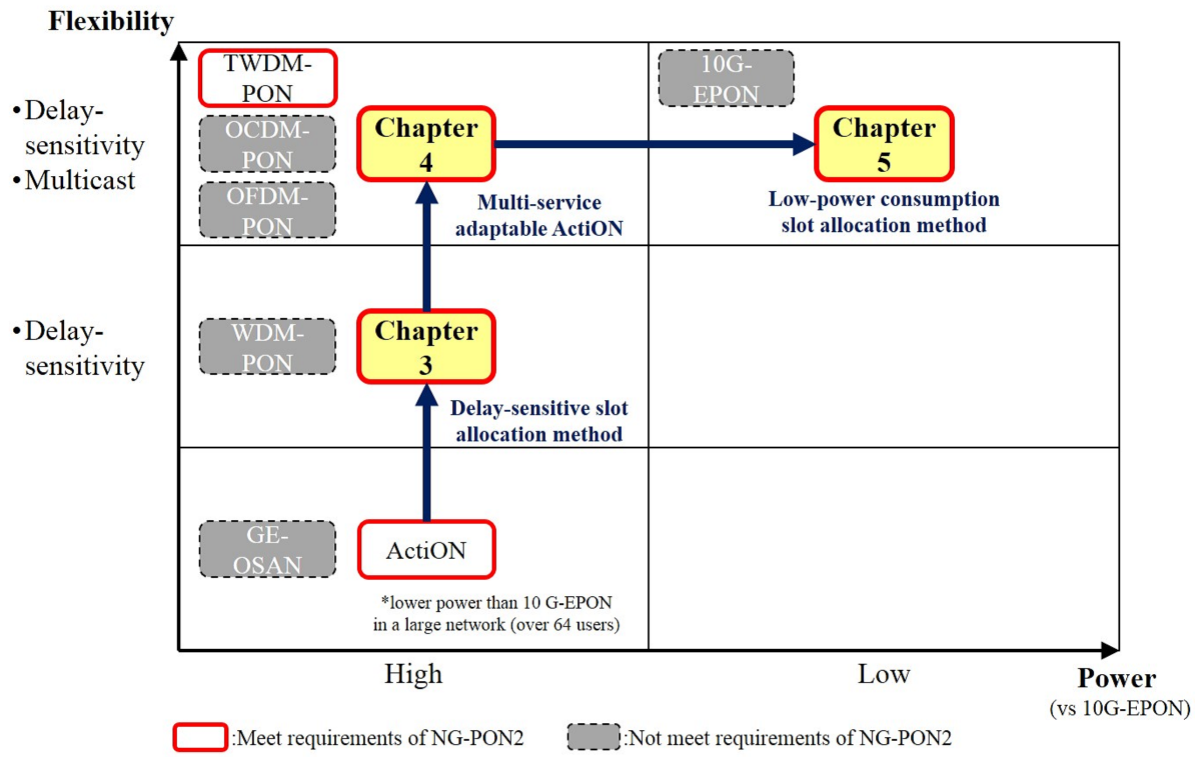

Figure 2.32: Position of the dissertation for next generation optical access network.

2.4 Position of the dissertation

Fig. 2.32 shows the position of the dissertation, compared to the conventional optical access networks. The target of this dissertation is to satisfy three requirements which are scalability, flexibility (multi-service adaptability), and low-power consumption. The vertical line shows the flexibility which has the delay-sensitive communication which well suits multi-services and the multicast function. The horizontal one shows the power which means a comparison of the power consumption with 10G-EPON. In order to provide the delay-sensitive communication, Chapter 3 proposes a delay-sensitive slot allocation method that designs the ActiON parameters which are the transmission cycle and the slot size, and minimizes the switching idle time in the PLZT optical switch considering the user's allowable delay [2-35, 36]. In order to provide the multicast function in addition to the delay-sensitive communication, Chapter 4 proposes multi-service adaptable ActiON using PLZT optical switches with variable splitter mode in order to reduce the required number of slots in multicast [2-37, 38]. In order to realize a low-power consumption network, while keeping the advantage of the multi-service adaptable ActiON, Chapter 5 proposes a low-power consumption slot allocation method that reduces the number of mode changes in the PLZT optical switch in order to reduce the power consumption higher than the conventional optical access networks [2-39]. In this way, this dissertation satisfy three requirements which are scalability, flexibility (multi-service adaptability), and low-power consumption.

Table 2.4: Problems with existing research and advances of this research.

Chapter 3	Purpose	Flexibility (Supporting the delay-sensitive communication)
	Problem	In ActiON, the transmission waiting time exceeds the user's allowable delay in the slot allocation.
	Proposal	Delay-sensitive slot allocation method is proposed, which designs the ActiON parameters which are the transmission cycle and the slot size, and minimizes the switching idle time in the PLZT optical switch considering the user's allowable delay.
	Achievement	The experiment system using the designed parameters (transmission cycle: 0.14 s / slot size: 4 μs or more) confirmed the capability of the proposed network to maintain the TCP throughput. Numerical results show that the proposed method reduces the number of switching times by up to 88 percent compared to the conventional method in the ActiON.
Chapter 4	Purpose	Flexibility (Supporting the multicast function)
	Problem	The ActiON needs a large number of slots to deliver multicast contents to the requesting users due to the slot-based switching.
	Proposal	Multi-service adaptable ActiON is proposed by using the PLZT optical switches as the variable splitter mode in order to support the multicast function in addition to the delay-sensitive slot allocation method in Chapter 3.
	Achievement	Numerical results show that the proposed network dramatically reduces the required number of slots by up to 81 percent, compared to the conventional ActiON.
Chapter 5	Purpose	Low-Power Consumption
	Problem	The ActiON consumes the power higher than the 10G-EPON because it needs additional slot-based optical switches.
	Proposal	Low-power consumption slot allocation method is proposed, which reduces the number of mode changes in each switch element, while keeping the required number of slots given by the multi-service adaptable ActiON in Chapter 4.
	Achievement	Numerical results show that the proposed network with the low-power consumption slot allocation method reduces the power consumption by up to 75 percent compared to the 10G-EPON, by up to 41 percent compared to the conventional ActiON, and by up to 21 percent compared to the multi-service adaptable ActiON, according to the reduction of the number of mode changes.

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Chapter 3

Delay-sensitive slot allocation method for Active Optical Access Network

3.1 Abstract

Chapter 3 proposes a delay-sensitive slot allocation method that designs the ActiON parameters which are the transmission cycle (7.8 ms) and the slot size (4 μs), and minimizes the switching idle time in the PLZT optical switch while considering the user's allowable delay in order to provide the high bandwidth utilization efficiency in the slot allocation. The bandwidth utilization efficiency is assumed to be (total slot allocation time - switching idle time) / total slot allocation time. The experiment system using the designed parameters confirms the capability of the proposed network to maintain the TCP throughput in the slot allocation. Numerical results show that the proposed method reduces the number of switching times by up to 88 percent according to the users' allowable delay, compared to the conventional method in the ActiON.

3.2 Introduction

The conventional slot allocation method [3-1,2] shortens the switching idle time, which is a product of the switching guard time and the number of switching times, to provide high bandwidth utilization efficiency. However, the transmission waiting time, which is incurred by because a user cannot transmit in slot allocated to other users, could exceed the user's allowable delay. There is a trade-off between the switching idle time and the transmission waiting time of each user. This problem is described in the problem in the flexibility when supporting the slot allocation of Chapter 2. Therefore, in order to provide high bandwidth utilization efficiency while considering the user's allowable delay in the slot allocation, Chapter 3 proposes the delay-sensitive slot allocation method for the ActiON. The ActiON parameters are designed, which are the transmission cycle for controlling the PLZT optical switch [3-3–10] periodically and the slot size [3-11]. The proposed slot allocation method minimizes the switching idle time in the PLZT optical switch considering the user's allowable delay, based on the designed ActiON parameters [3-12]. The experiment system using the designed parameters confirms the capability of the proposed network to maintain the TCP throughput the slot allocation. Numerical results show that the proposed method reduces the number of switching times in the PLZT optical switch by up to 88 percent, compared to the conventional slot allocation method in the ActiON.

3.3 Design of parameters of Active Optical Access Network

When supporting the TCP, the ActiON possibly decreases TCP throughput according to the transmission cycle in which the PLZT optical switch is periodically controlled due to the slot-based switching. The TCP throughput decreases drastically when the transmission cycle exceeds the retransmission timeout. To maintain the TCP throughput and provide high bandwidth utilization efficiency, the transmission cycle and the slot size are designed in ActiON [3-11]. The transmission cycle and the slot size are important parameters. The transmission cycle is a parameter that indicates the transmission interval of ONU because ONU transmits once per the transmission cycle in ActiON. The slot size is a parameter that indicates the granularity of the bandwidth allocation because it is possible to allocate flexibly by detailing the slot size (the number of slots per transmission cycle is increased).

3.3.1 Transmission cycle

At first, in order to design the transmission cycle, it is required to consider two constraint values as follows.

- Minimum retransmission timeout of TCP: 200 ms (Defined by Network Simulation2 (NS2)) [3-13]
- MPCP timeout: 1000 ms [3-14]

The retransmission timeout of TCP means the time to do the TCP window size small when the acknowledgment message doesn't come from receiving side. Figure 3.1 shows the relationship between the bandwidth utilization efficiency and the transmission cycle. The relationship is computed based on the simulation using NS2 [3-13]. The simulation parameters are as follows:

- Number of ONUs: 128
- Bandwidth between OLT-ONU: 10 Gbps
- Distance between OLT-ONU: 40 km
- Slot switch: One slot is allocated to each ONU (128 slots per a transmission cycle).
- Packet size of TCP: 1500 bytes
- Type of TCP: Reno
- Minimum retransmission time-out of TCP: 200 ms (Defined by NS2)

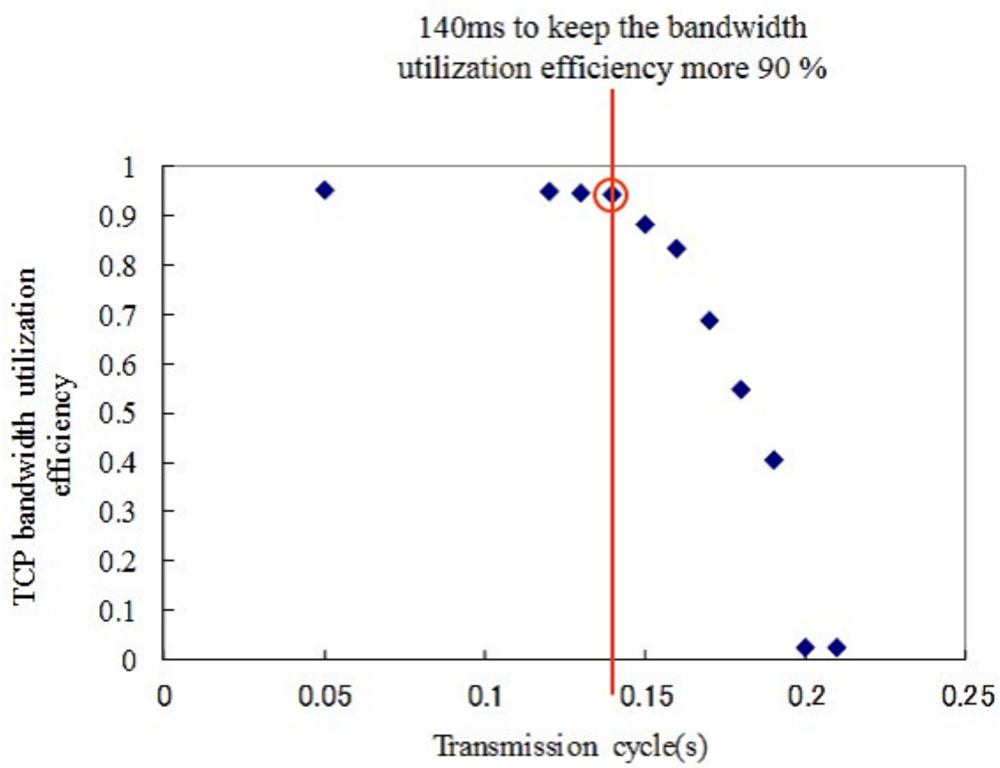

Figure 3.1: Bandwidth utilization efficiency versus transmission cycle.

As the transmission cycle is closer to the retransmission timeout (200 ms), TCP throughput decreases greatly. Therefore, the upper bound value of the transmission cycle for maintaining the TCP throughput is decided at 140 ms to keep the bandwidth utilization efficiency more 90 percent.

The MPCP timeout [3-14] is the maximum transmission interval of the control message from OLT in order to discover ONUs with the power supply. Fig. 3.2 shows how to use the MPCP control message in the ActiON discovery process. In the ActiON, the control message is transmitted periodically once per 128 transmission cycles by using the control slot, so the upper bound value of the transmission cycle is to decide at 7.8 ms (1000 ms / 128) not to exceed the MPCP timeout (1000 ms). By considering the above two constraint

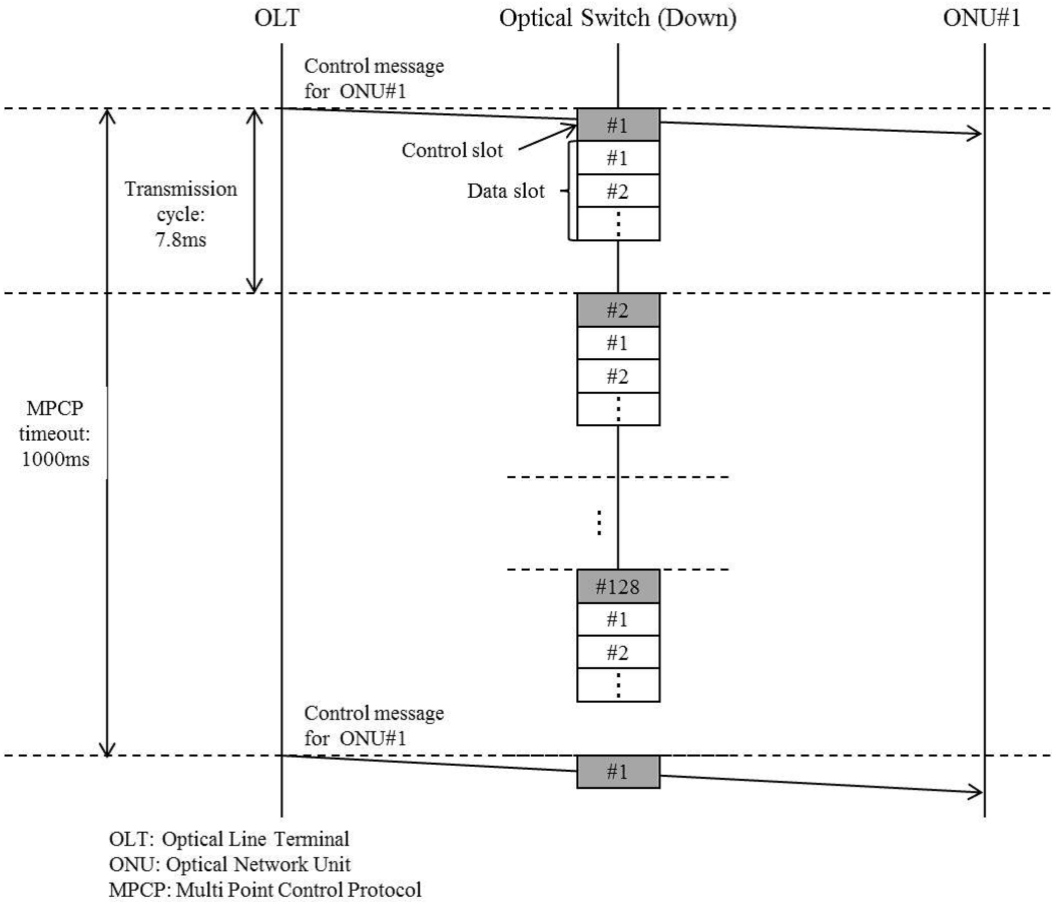

Figure 3.2: How to use MPCP control message in ActiON discovery process.

values, the maximum of transmission cycle is set to 7.8 ms in order to maintain the TCP throughput and move the MPCP efficiently.

3.3.2 Slot size

Next, in order to design the slot size, it is required to consider the switching guard time of PLZT optical switch. Fig. 3.3 shows the switching time of PLZT optical switch. It is necessary to make the slot size small to achieve a flexible bandwidth allocation because the more detailed the slot granularity is, the easier the reflection of the demand traffic is. However, in ActiON, there is a problem that the overhead at the switching guard time increases when the slot granularity is detailed. The switch speed of the PLZT optical switch so far is 10 ns, so the guard time is decided at 20 ns (10 ns $\times$ 2). Then, it is necessary to adjust the slot size to about 4 μs or more to suppress the influence by the guard time to less than 0.5 percent. The influence of guard time is assumed to be ”guard time / (slot size + guard time)”.

Fig. 3.4 shows the relationship between the slot size and the number of slots per the transmission cycle. To maintain the TCP throughput and provide high bandwidth utilization efficiency, the ActiON parameters, which are the slot size and the number of slots per the transmission cycle, need to be decided within the gray range.

3.3.3 Experiment system of ActiON using the designed parameters

Fig. 3.5 shows the experiment system of ActiON using the designed parameters. There are one OLT, three ONUs, a delay insertion machine and one PLZT optical switch emulator. It is confirmed that the proposed network system is possible to provide the TCP between OLT ans each ONU to maintain the TCP throughput by using the designed parameters that the transmission cycle (7.8 ms) and the slot size (4 μs).

3.4 Proposed delay-sensitive slot allocation method

3.4.1 Overview

The proposed slot allocation method minimizes the switching idle time while considering the allowable delay [3-12]. The network conditions when using the proposed method, including the maximum number of users (128), the maximum transmission distance (40 km), the wavelength allocation (upstream: 1260-1280 nm / downstream: 1575-1580 nm), the maximum optical loss budget (29 dB), and the breakdown of optical loss are the same

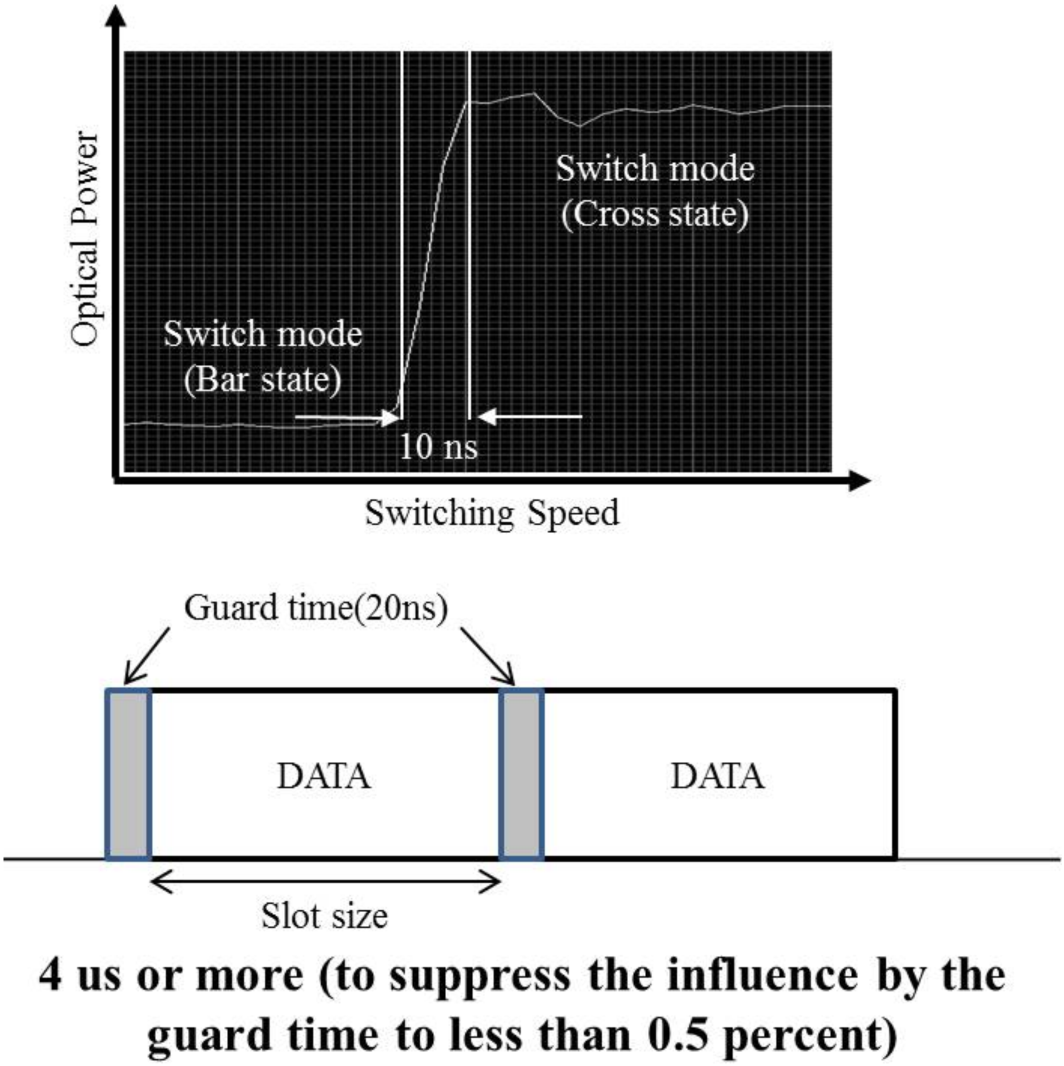

Figure 3.3: Switching time of PLZT optical switch.

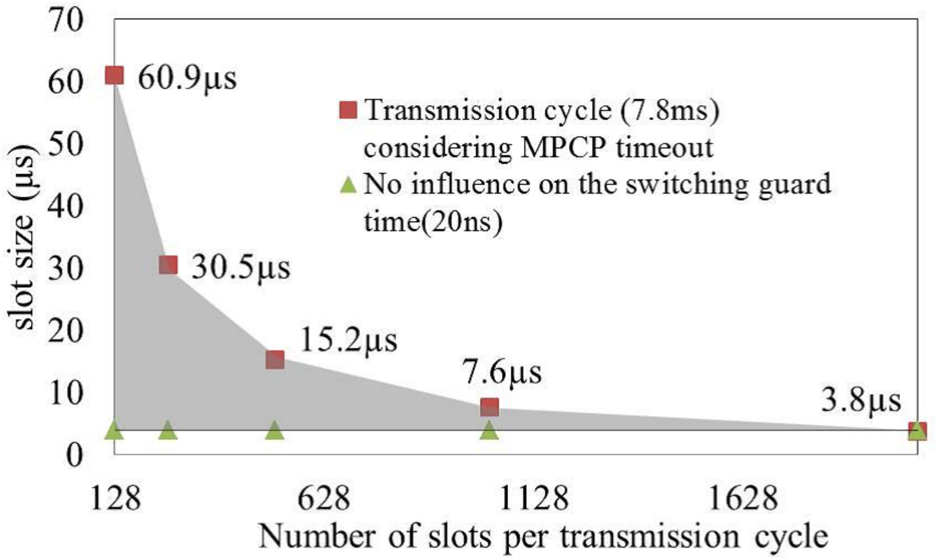

Figure 3.4: Slot size versus number of slots per transmission cycle.

as those of the conventional ActiON. Fig. 3.6 shows the corresponding example of proposed method. The proposed method reduces the switching idle time to four guard times within a transmission cycle, while keeping the transmission waiting time to two slots, which is within the allowable delay. In order to minimize the switching idle time, calculated by multiplying the number of switching times and the guard time, the proposed method formulates the optimization problem that minimizes the number of switching times as an ILP problem in Section 3.4.2.

3.4.2 Integer Linear Programming (ILP) Formulation of proposed method

We introduce the following ILP formulation of the optimization problem to minimize the number of switching times.

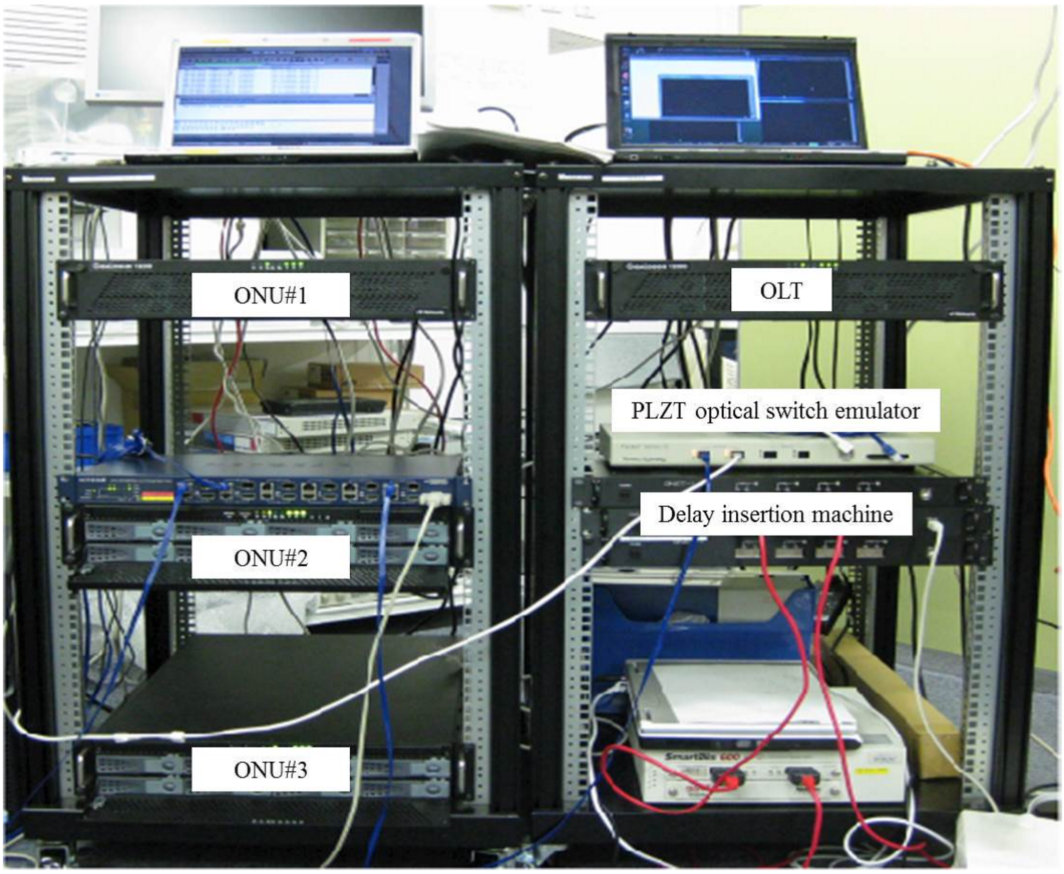

Figure 3.5: Experiment system of ActiON using parameters.

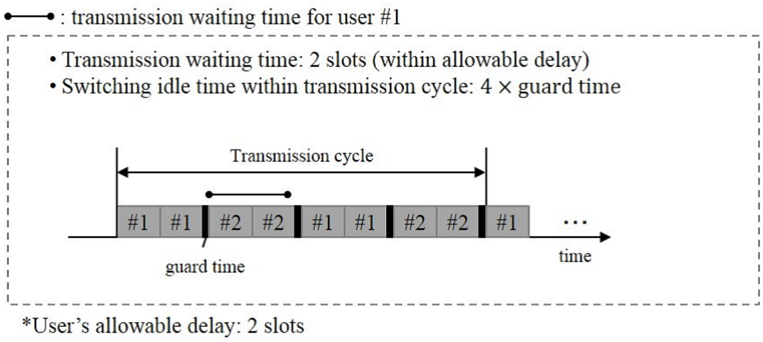

Figure 3.6: Proposed delay-sensitive slot allocation method minimizing the switching idle time

Definitions

The nomenclature used in this ILP formulation is given below.

N	Number of users (given parameter).
u	Index of user, $1 \leq u \leq N$.
U	Set of users, $\lvert U \rvert = N$.
D_u	Number of slots needed for allowable delay of uth user, during which uth user can wait for transmission in other user's slots (given parameter).
S_{total}	Total number of slots within a transmission cycle (given parameter).
S_u	Number of allocated slots of uth user within a transmission cycle. $\sum_{u \in U} S_u = S_{total}$. $S_u \geq \frac{S_{total}}{D_u+1}$ must be satisfied to get a feasible solution.
t	Index of slot number.
T	Set of time slots within a transmission cycle, $1 \leq t \leq S_{total}$.
T^-	Set T without the last slot within a transmission cycle, $1 \leq t \leq S_{total} - 1$.
k	Index of first slot number of the period to be comprised of D_u, which is slided by 1 slot within a transmission cycle.
K	Set of k, $1 \leq k \leq S_{total} - D_u$.
$P_u(t)$	Binary variable. If the uth user is allocated tth time slot, $P_u(t) = 1$. Otherwise, $P_u(t) = 0$.
$Z_u(t)$	Binary variable. If $P_u(t)$ is equal to $P_u(t+1)$, $Z_u(t) = 0$. Otherwise $Z_u(t) = 1$.

Objective function and constraints

The ILP problem used to minimize the number of switching times is described below.

$$\min \sum_{u \in U} \sum_{t \in T^-} \frac{Z_u(t)}{2} \tag{3.1a}$$

$$s.t \quad P_u(t+1) - P_u(t) \leq Z_u(t), \forall u \in U, \forall t \in T^- \tag{3.1b}$$

$$P_u(t+1) - P_u(t) \geq -Z_u(t), \forall u \in U, \forall t \in T^- \tag{3.1c}$$

$$\sum_{u \in U} P_u(t) = 1, \forall t \in T \tag{3.1d}$$

$$\sum_{t \in T} P_u(t) = S_u, \forall u \in U \tag{3.1e}$$

$$\sum_{t=k}^{k+D_u} P_u(t) \geq 1, \forall u \in U, \forall k \in K \tag{3.1f}$$

The objective function in Eq. (3.1a) minimizes the number of switching times within a transmission cycle. Eqs. (3.1b) and (3.1c) indicate a change of assigned users between the tth and $t+1$th time slots. Eq. (3.1d) indicates that one slot is allocated to only one user. Eq. (3.1e) indicates that the uth user is allocated all of its required slots within a transmission cycle. Eq. (3.1f) indicates that the number of slots allocated to uth user during $D_u + 1$ must be more than or equal to 1 slot in order to satisfy the allowable delay. If the boundaries of neighbor cycles need to be considered, an constraint of $\sum_{t=k}^{k+\frac{D_u}{2}} P_u(t) \geq 1, u \in U$, where $k = \{1, S_{total} - \frac{D_u}{2}\}$, is added in the ILP formulaion.

3.4.3 Performance evaluation

We evaluate the performance of our proposed method. The simulation conditions are shown below. The number of users (N) is 128. The minimum number of slots allocated of the uth user in transmission cycle (S_u) is one slot for all users. The total number of slots in a transmission cycle (S_{total}) is 1024 slots, calculated by the maximum transmission cycle (7.8 ms) and the slot size (4 μs or more) described in Section 3.3. The allowable delay

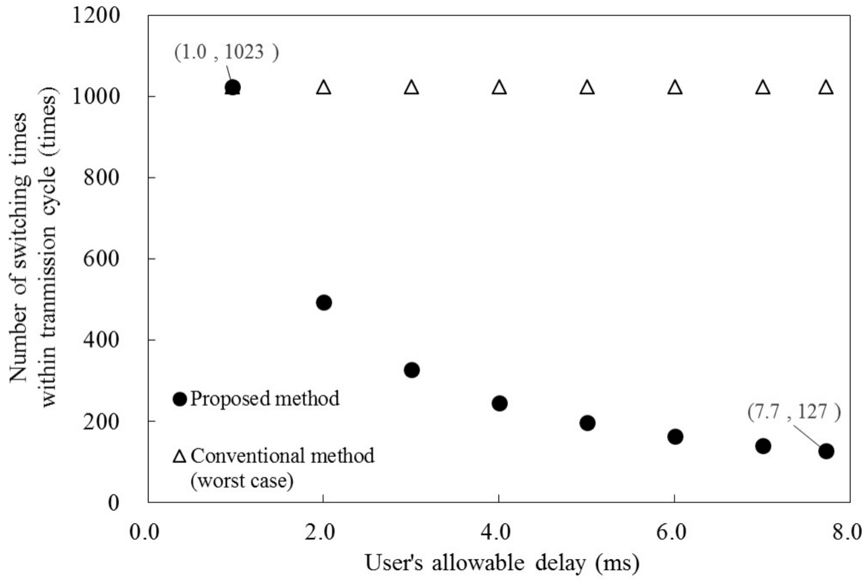

Figure 3.7: Number of switching times within transmission cycle versus user's allowable delay for conventional and proposed methods

is expressed by multiplying the number of slots needed for the user's allowable delay, D_u and the slot size. The slot size is set to 7.6 μs (7.8 ms /1024 slots). CPLEX Interactive Optimizer 12.5.0.0 is used to solve the ILP optimization problem in this evaluation [3-15].

Fig. 3.7 shows the relationship between the number of switching times within a transmission cycle and the user's allowable delay for the conventional and proposed methods. In this evaluation, the number of slots allocated of the uth user in transmission cycle (S_u) is eight slots for all users and all users' allowable delay is set to be the same. The proposed method reduces the number of switching times by up to 88 percent, compared to the conventional method that realizes the worst number of switching times. In the proposed method, the user's allowable delay should be set to between 1.0 ms and 7.7 ms, where the lower and upper bounds of allowable delay are obtained by slot size $\times$ $(N-1)$ and slot size $\times$ $(S_{total} - S_u)$, respectively. Also, the number of switching times changes from 1023 times to 127 times as the user's allowable delay increases, where the maximum and

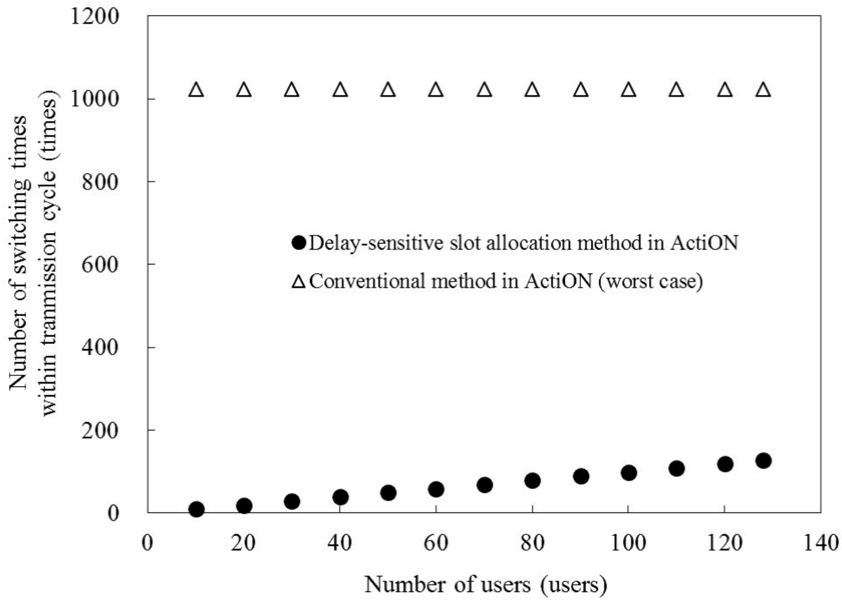

Figure 3.8: Number of switching times within transmission cycle versus number of users for conventional and proposed methods

minimum number of switching times are obtained by $S_{total} - 1$ and $N - 1$, respectively. Thus, the proposed method needs fewer switching times than the conventional method while considering the allowable delay. The maximum computation time for selecting how to switch in the proposed method is less than 5.0 ms, which can be calculated within a maximum transmission cycle (7.8 ms). Therefore, the OLT decide to select how to switch in each switch element within the computation time after reciving the request from each user.

Fig. 3.8 shows the relationship between the number of switching times within a transmission cycle and the number of users for the conventional and proposed methods. In this evaluation, the users' allowable delay is calculated by slot size $\times$ $(S_{total} - S_u)$. The proposed method reduces the number of switching times by average of 93 percent, compared to the conventional method that realizes the worst number of switching times.

3.5 Conclusion

Chapter 3 proposed the delay-sensitive slot allocation method for the ActiON. The ActiON parameters are designed to maintain the TCP throughput and provide the high bandwidth utilization efficiency, where the transmission cycle is 7.8 ms and the slot size is 4 μs. The experiment system using the designed parameters confirmed the capability of the proposed network to maintain the TCP throughput in the slot allocation. Using the designed ActiON parameters, the proposed method minimizes the switching idle time in the PLZT optical switches, while considering the user's allowable delay. To achieve our objective, we formulated the problem to minimize the number of switching times as an ILP problem. Numerical results show that the proposed method reduces the number of switching times by up to 88 percent according to the users' allowable delay, compared to the conventional method in the ActiON. Minimizing the switching idle time leads to increased bandwidth utilization efficiency.

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Chapter 4

Multi-service adaptable Active Optical Access Network

4.1 Abstract

Chapter 4 realizes a multi-service adaptable ActiON using the PLZT optical switches as the variable splitter mode in order to support the multicast function in addition to the delay-sensitive slot allocation method in Chapter 3. The proposed network dramatically reduces the required number of slots by up to about 81 percent, compared to the conventional ActiON, and the required computation time for selecting users is less than 30 ms, which is acceptable for on-demand according to users' various requirement.

4.2 Introduction

When supporting multicast, the conventional ActiON [4-1, 2] needs a large number of slots to deliver contents to the requesting users using multicast. As described in the problem in flexibility (multi-service adaptability) of Chapter 2, the ActiON does not directly support multicast, so the OLT copies the data for each user and transmits the data to each user by slot switching. The number of slots required increases with the number of multicast users, so the slot allocation efficiency is poor. The slot allocation efficiency is assumed to be the number of slots per a slot. In order to provide high slot allocation efficiency in multicast compared to the conventional ActiON, Chapter 4 proposes the multi-service adaptable ActiON by using the PLZT optical switch as the variable splitter mode, which controls the split ratio of the optical power according to users' requirement. The proposed network realizes the multicast function in addition to the delay-sensitive slot allocation method in Chapter 3.

4.3 Proposed multi-service adaptable Active Optical Access Network

4.3.1 Creating the PLZT optical switch with the variable splitter mode

The MZ-type PLZT optical switch element [4-3–10] is possible to yield the variable multicast state, where the optical power is output in the different split ratio (e.g. 0.5 to 0.5, 0.6 to 0.4, 0.7 to 0.3, 0.8 to 0.2, 0.9 to 0.1, and so on) by applying the variable voltage to each electrode [4-11, 12]. We call this the variable splitter mode. The conventional ActiON yields only the switch mode (the bar and cross states) by applying the voltage to either electrode A or B. Figure 4.1 and Table. 4.1 show the structure of 1×2 PLZT optical switch and the relationship between mode, splitting ratio, splitting loss, and voltage. The split ratio of the switch mode is (a) and (k), and the split ratio of the variable splitter mode is from (b) to (j). In the optical insertion gain, it is set to 0 dB in the switch mode ((a) and (k)) and the optical insertion gain of each other mode (from (b) to (j)) is the difference between the switch mode and the other mode. The optical insertion loss is a negative value in the optical insertion gain. The optical insertion loss of the splitter mode is 3 dB. The voltage is applied to the electrodes only when changing modes in each switch element. The exception is changing mode to the 0.5 - 0.5 splitting ratio mode (f) as no voltage is needed; this is because this mode does not need any voltage to be applied to the electrodes.

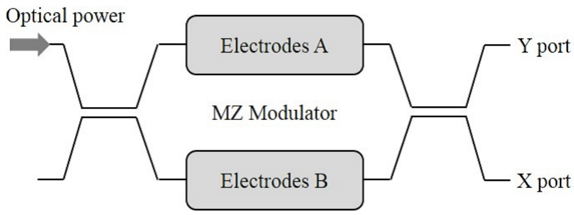

Figure 4.1: Structure of 1×2 PLZT optical switch.

Table 4.1: Measured relationship between mode, splitting ratio, splitting loss, and voltage.

	Mode of PLZT optical switch	Splitting ratio (X to Y)	Splitting loss (X, Y (dB))	Voltage (A, B (V))
(a)	Switch mode (Bar)	0.0 to 1.0	10.9, 0.0	0.0, 8.0
(b)	Variable splitter mode	0.1 to 0.9	9.5, 0.1	0.0, 7.0
(c)		0.2-0.8	6.7, 0.7	5.0, 0.0
(d)		0.3-0.7	4.8, 1.3	3.5, 0.0
(e)		0.4-0.6	3.9, 2.1	2.0, 0.0
(f)		0.5-0.5	3.0, 3.0	0.0, 0.0
(g)		0.6-0.4	2.2, 3.6	0.0, 1.0
(h)		0.7-0.3	1.9, 5.3	0.0, 4.0
(i)		0.8-0.2	0.9, 6.6	0.0, 5.5
(j)		0.9-0.1	0.5, 10.1	0.0, 7.5
(k)	Switch mode (Cross)	1.0 to 0.0	0.0, 23.0	10.5, 0.0

4.3.2 Proposed network

Fig. 4.2 shows the multi-service adaptable ActiON using the PLZT optical switch with the variable splitter mode [4-11, 12]. The proposed network adopts PLZT optical switch elements in two modes, which are the switch mode and the variable splitter mode. It creatively uses the two modes according to the variable users' requirements. The users' requirements include the transmission distance, the number of required multicast users, and the transmission method using unicast or multicast.

The network conditions of the proposed network is different from those of the conventional ActiON partially. The maximum number of users (128), the wavelength allocation (upstream: 1260-1280 nm / downstream: 1575-1580 nm), the maximum optical loss bud-

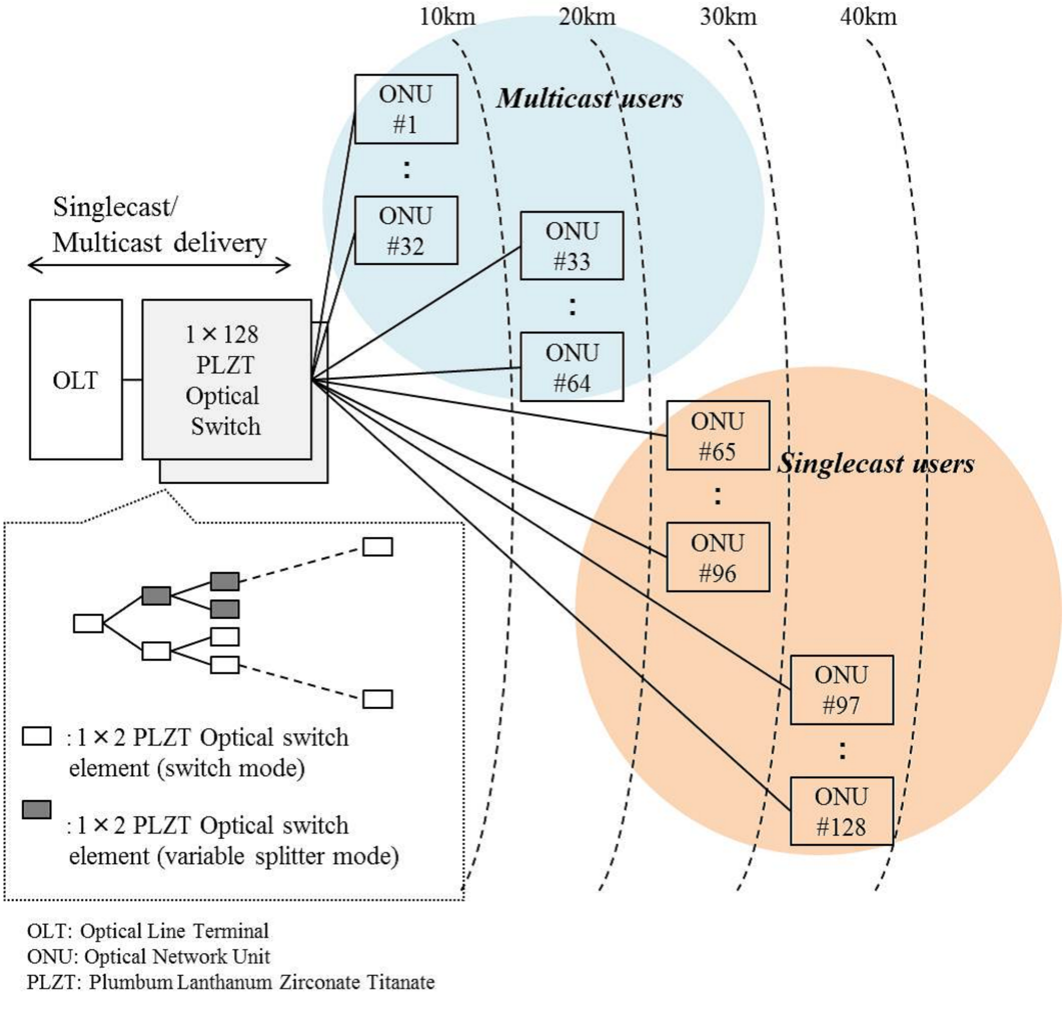

Figure 4.2: multi-service adaptable ActiON.

Table 4.2: Relationship between transmission distance, limit on number of stages of variable splitter mode, fiber loss, and splitting loss.

Maximum transmission distance	Limit on number of stages of variable splitter mode	Fiber loss	Splitting loss
8 km	7 stages	4 dB	21 dB
14 km	6 stages	7 dB	18 dB
20 km	5 stages	10 dB	15 dB
26 km	4 stages	13 dB	12 dB
32 km	3 stages	16 dB	9 dB
38 km	2 stages	19 dB	6 dB
44 km	1 stages	22 dB	3 dB
50 km	0 stages	25 dB	0 dB

get (29dB), and the connection loss and the insertion loss of the PLZT optical switch (1-3 dB) are the same as those of the conventional ActiON. On the other hand, the maximum transmission distance, the fiber loss, and the splitting loss are different from those of the conventional ActiON because they varies based on Table 4.2. The fiber loss and the splitting loss are decided based on the transmission distance in each user and the number of stages of variable splitter mode in the network. The fiber loss is calculated based on 0.5 dB / km.

4.3.3 Multicast slot allocation with the variable splitter mode

The proposed network provides the flexible multicast tunable users' requirement using the variable splitter mode and supports the high slot allocation efficiency in a scalable network.

Figures 4.3 shows multicast slot allocation of the conventional ActiON and the proposed network. Users #1, #3, and #4 are multicast users. The distance between OLT to user #1 is 12 km and the required maximum optical power loss is 19 dB. The distance between OLT to user #3 is 36 km and the required maximum optical power loss is 7 dB. The distance between OLT to user #4 is 40 km and the required maximum optical power loss is 5 dB.

In the conventional ActiON, the number of multicast slots needed is three because the ActiON uses the PLZT optical switch elements as only the switch mode, so the OLT copies the data for each user and transmits the data to each user by slot switching. The number of slots required increases with the number of multicast users, so the utilization efficiency of the slot allocation scheme is poor.

On the other hand, in the proposed network using the variable splitter mode, the number of multicast slots needed is just one because the proposed network creatively uses the PLZT optical switch elements as the switching mode and the variable splitter mode that the PLZT optical switch element a is used as the 0.5 to 0.5 variable splitter mode and the PLZT optical switch element c is used as the 0.2 to 0.8 variable splitter mode. In Table. 4.1, when the split ratio is 0.8 to 0.2, the optical power loss of X port and Y port is 0.9 dB and 6.6 dB. The proposed network is able to control the split ratio of the optical power according to the transmission distance between OLT and ONUs when using the variable splitter mode.

To increase the slot allocation efficiency in the multicast slot allocation, it is necessary to reduce the required number of slots by selecting which optical switch elements are placed into which mode, the switch mode and the variable splitter mode. Additionally, based on the required number of slots, the proposed network introduces the delay-sensitive slot allocation method in Chapter 3.

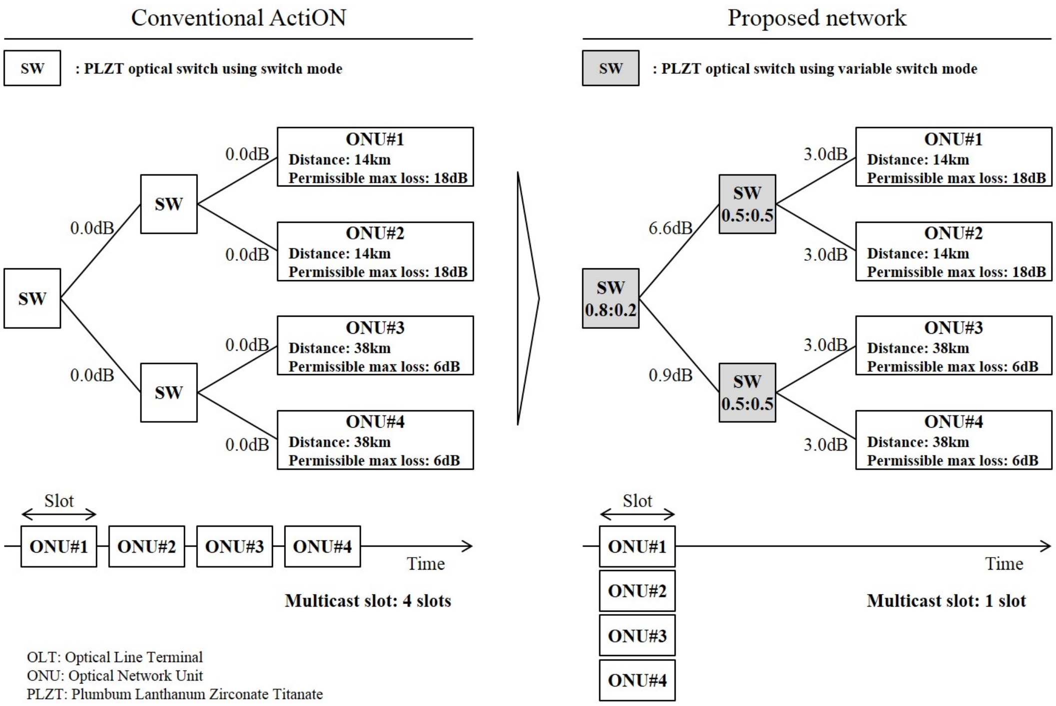

Figure 4.3: Multicast slot allocation of conventional ActiON and proposed network.

4.3.4 Heuristic approach for multicast slot allocation

Overview

The proposed network introduces the flexible multicast slot allocation by using two modes, the switch mode and the variable splitter mode. To maximize the slot allocation efficiency, it is necessary to minimize the required number of slots used to realize multicast service. The naive approach is to consider all possible combinations for multicast slot allocation. Let x be the number of all possible combinations for N multicast users. x lies in the range of $\prod_{k=1}^{N\times 2^{-H}} 2^{(N-(k-1))\times 2^{H}} \leq x \leq \prod_{k=1}^{N} 2^{N-(k-1)}$, where H is the limit on the number of stages. In this approach, with $N = 128$, it is not feasible to obtain the *optimal* solution within practical time. Therefore, the proposed network takes a heuristic approach. It tries to find the maximum number of multicast users every multicast slot in a sequential manner, without considering all possible combinations. However, it does

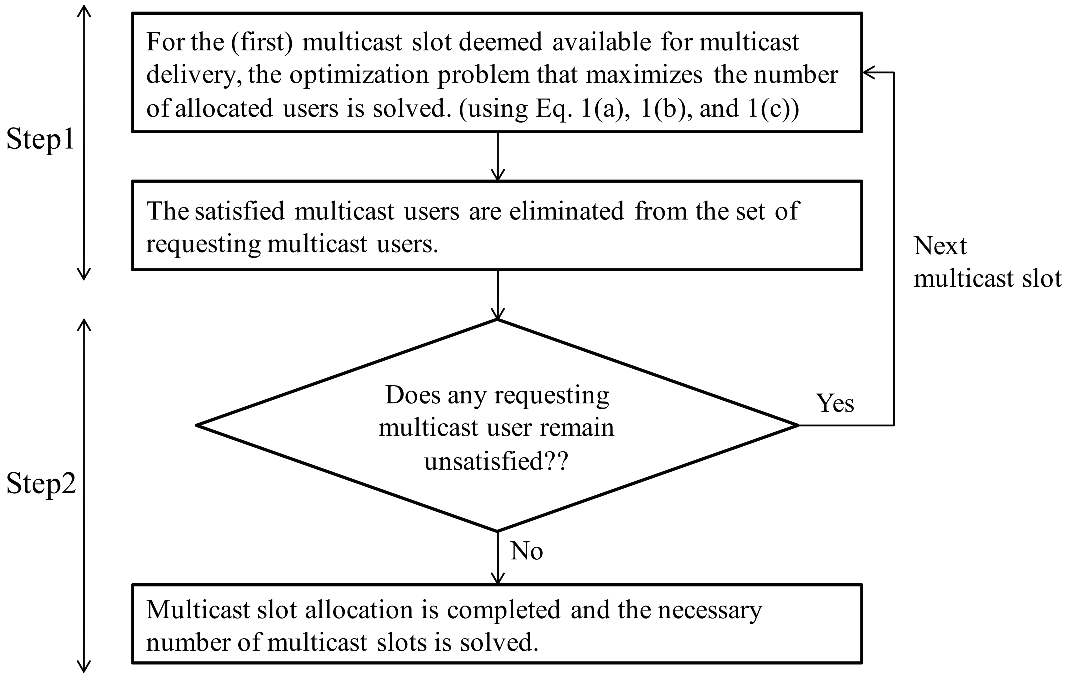

Figure 4.4: Flow chart of the heuristic approach of proposed network.

not always obtain the *optimal* solution in terms of minimizing the required number of multicast slots. The heuristic approach proceeds shown in Fig. 4.4.

- Step 1: For the first multicast slot deemed available for multicast, the optimization problem that maximizes the number of allocated users is solved using Eq.(1a), Eq.(1b), and Eq.(1c). The satisfied multicast users are eliminated from the set of requesting multicast users.

- Step 2: If any requesting multicast user remains unsatisfied, the next multicast slot is allocated following Step 1. Otherwise, the multicast slot allocation is completed and the necessary number of multicast slots is solved.

Maximizing the number of allocated users

The necessary number of multicast slots is solved by using two steps for required multicast users.

This subsection shows how to solve the optimization problem that maximizes the number of allocated users in Step 1 above. The multicast slot allocation for the proposed network is possible to formulate the optimization problem as a Non Linear Programming (NLP) for details to Section 4.2.2. In multicast slot allocation for the proposed network, the power loss of each optical switch element is calculated according to the following formula. Power loss (dB) $= 10 \times \log_{10}(\mathrm{P}_1/\mathrm{P}_2), \mathrm{P}_1 = \mathrm{P}_2 \times \mathrm{S}$, where P_1 is the output of optical power, P_2 is the input of optical power, and S is the split ratio. The optical power when receiving the data is solved by multiplying the input of optical power by the split ratio in the number of steps, thus solving the optical power loss of each optical switch element uses non linear equation.

Definitions The nomenclature used in this paper is given below.

N	Number of users. N is set to 2^x, where x is a natural number.
i	Switch index, where $1 \leq i \leq N-1$.
j	Link index, where $1 \leq j \leq 2N-1$.
u	User index, where $1 \leq u \leq N$.
I	Set of i.
J	Set of j.
U	Set of u.
S_i	Split ratio of ith switch, where $0 \leq S_i \leq 1$.
L_j	Optical power of jth link, where $L_1 = 1.0$.
R_u	Required minimum optical power of uth user.
P_u	If uth user receives the optical power, $P_u = 1$. Otherwise, $P_u = 0$.

Formulation The NLP problem used to maximize the number of multicast user per multicast slot is described below.

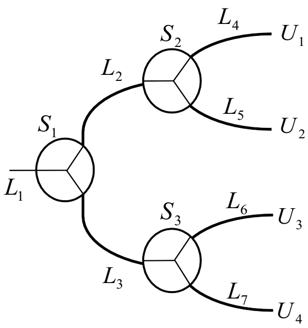

Figure 4.5: Example of network configuration.

$$\max \sum_{u \in U} P_u \tag{4.1a}$$

$$s.t \quad L_i \times S_i = L_{2i}, \quad \forall i \in I,$$

$$L_i \times (1 - S_i) = L_{2i+1}, \quad \forall i \in I \tag{4.1b}$$

$$R_u \times P_u \leq L_{u+N-1}, \quad \forall u \in U \tag{4.1c}$$

The objective function in Eq. (4.1a) indicates the selection of the maximum number of multicast users. The constrained condition in Eq. (4.1b) indicates the relationship between the use of each optical switch element and the optical power. The constrained condition in Eq. (4.1c) indicates the relationship between required minimum optical power of each user and the actual optical power of each bottom link. As L_i and S_i are decision variables, $L_i \times (1 - S_i)$, the left side of Eq. (4.1b), is a non-linear term. Therefore, the optimization problem expressed in Eq. (4.1a), Eq. (4.1b), and Eq. (4.1c) is an NLP problem. Figures 4.5 shows an example of an network configuration of the optimization problem for four users and the following formulas from Eq. (4.2a) to Eq. (4.2j) show the constraints of the example.

$$L_1 \times S_1 = L_2 \quad (4.2a)$$

$$L_1 \times (1 - S_1) = L_3 \quad (4.2b)$$

$$L_2 \times S_2 = L_4 \quad (4.2c)$$

$$L_2 \times (1 - S_2) = L_5 \quad (4.2d)$$

$$L_3 \times S_3 = L_6 \quad (4.2e)$$

$$L_3 \times (1 - S_3) = L_7 \quad (4.2f)$$

$$U_1 \times P_1 \leq L_4 \quad (4.2g)$$

$$U_2 \times P_2 \leq L_5 \quad (4.2h)$$

$$U_3 \times P_3 \leq L_6 \quad (4.2i)$$

$$U_4 \times P_4 \leq L_7 \quad (4.2j)$$

4.4 Performance evaluation

This simulation evaluated the required number of multicast slots for the proposed network using the PLZT optical switch with the variable splitter mode, whose flow chart is shown in Fig. 4.4 and the average computation time for selecting multicast users in the proposed network. The simulator was coded by using the C language combined with NUOPT Programming Kit [4-13], which is an NLP solver. Parameters used in our simulation are shown below. The maximum number of ONUs is 128. Each user (randomly selected) is taken as demanding the same multicast content. The maximum transmission distance between the OLT and ONUs (users) is 40 km. The number of the trials was set to 10^6 for each proportion of multicast users. The 1×128 PLZT optical switch has a 7 stage cascade of 1×2 optical switch elements. The proposed network is run on the PC whose processor is an Intel Pentium 4 2.80 GHz, and which has 256 MB RAM.

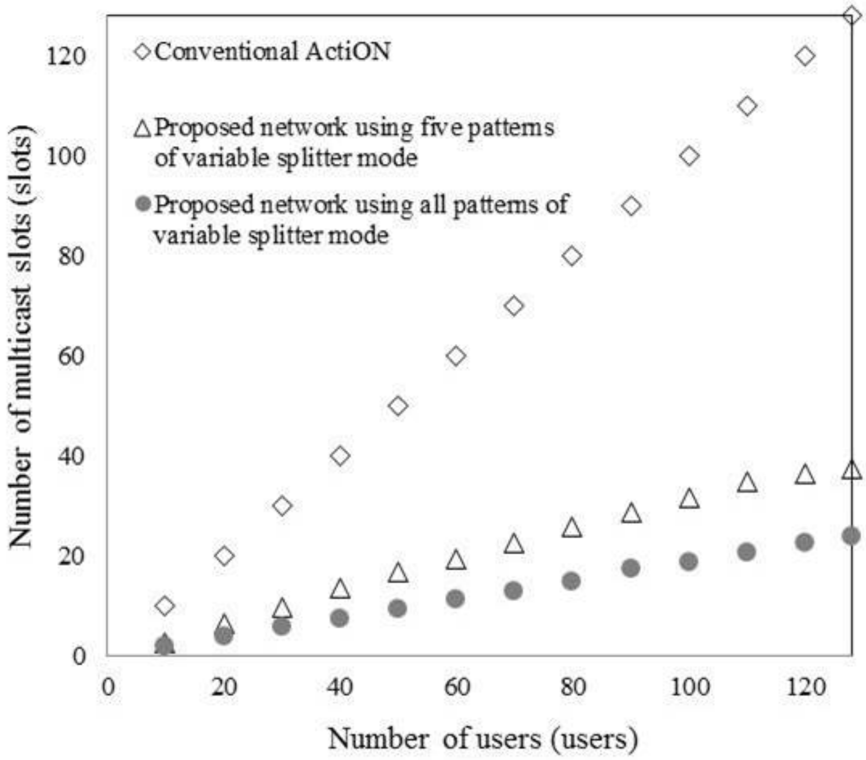

Figure 4.6: Number of multicast slots versus number of users of conventional ActiON and proposed network

Fig. 4.6 shows that the more the proposed network employs patterns of the variable splitter mode, the more the number of multicast slots is possible to be reduced, by using comparison of the number of multicast slots required between the proposed network and the conventional ActiON. To maximize the slot allocation efficiency, it is necessary to minimize the required number of slots used to realize multicast service. The transmission distance between the OLT and ONUs is 10, 20, 30, and 40 km, which is randomly selected. According to the transmission distance, the required minimum optical power of each user is designated. The proposed network has two types, the first type using five patterns of the variable splitter mode, whose split ratio is 0.5 to 0.5, 0.6 to 0.4 (0.4 to 0.6), 0.7 to 0.3 (0.3 to 0.7), 0.8 to 0.2 (0.2 to 0.8) and 0.9 to 0.1 (0.1 to 0.9) and the second

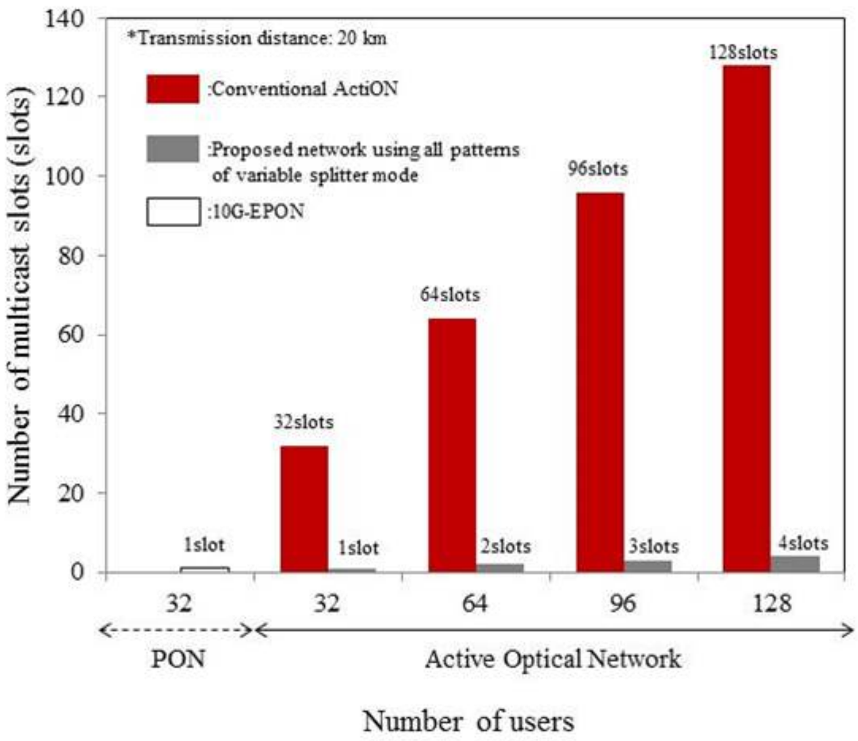

Figure 4.7: Number of multicast slots versus number of users of 10G-EPON, conventional ActiON, and proposed network in 20 km of transmission distance.

type using all patterns of the variable splitter mode, whose split ratio is variable form 0 to 1. The conventional ActiON uses only the switch mode. At all loads examined, the proposed networks dramatically reduced the number of multicast slots, compared to the conventional ActiON. The proposed network using all patterns of variable splitter mode reduces the required number of slots by up to 81 percent, compared to the conventional ActiON. Table. 4.3 shows the comparison of the number of multicast slots between the proposed network using all patterns and the optimal solution in a small network from 10 to 30 users, where the optimal solution can be solved in practical time. The difference between the solution of the proposed network and the optimal solution is within 0.1 percent.

Fig. 4.7 shows the relationship between the number of multicast slots and number of

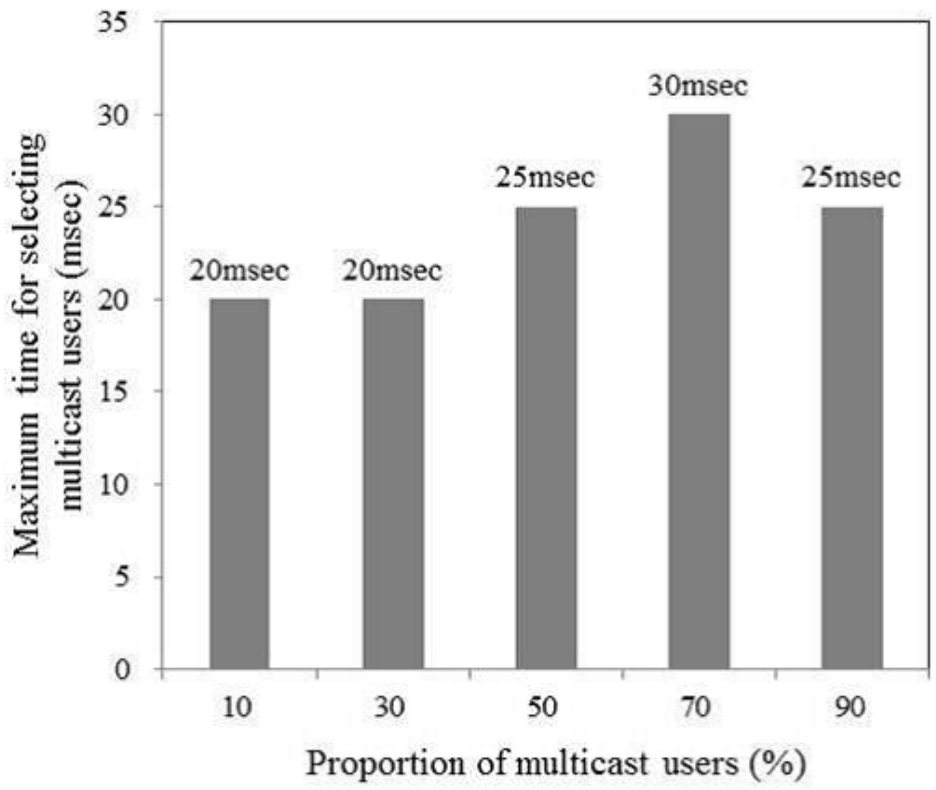

Figure 4.8: Maximum time for selecting multicast users (ms) versus proportion of multicast users.

users when the transmission distance is constant at 20 km. The proposed network uses the PLZT optical switch using all patterns of the variable splitter mode. Compared to the conventional ActiON, the proposed network reduced the number of multicast slots by up to 97 percent by using the five stages of the variable splitter mode which is possible to transmit multicast data to 32 users by using one slot. Compared to the 10G-EPON, the proposed uses the number of multicast slots as many as the 10G-EPON in 32 of the number of multicast users, and is able to provide scalable access services because the 10G-EPON is limited in terms of the maximum number of users (32) and the maximum transmission distance (20 km).

Table 4.3: Comparison of the number of multicast slots between the proposed network using all patterns and the optimal solution in a small network.

Number of users	Solution of the proposed	Optimal solution	Difference
10 users	2.7 slots	2.5 slots	0.08 %
20 users	6.4 slots	6.3 slots	0.02 %
30 users	9.8 slots	9.7 slots	0.01 %

Fig. 4.8 shows the relationship between the maximum time for selecting multicast users and the proportion of multicast users. The maximum number of multicast users is 128. In the proposed network using all patterns of the variable splitter mode, the maximum computation time for selecting multicast users is less than 30 ms. This computation time is supposed to be used when multicast applications are connected, thus approximately 30 connections per 1 sec (= 1000 ms / 30 ms) is the well suits on-demand broadcast services. Also, the OLT decide to select modes in each switch element within the computation time after receiving the request from each user.

4.5 Conclusion

Chapter 4 realized the multi-service adaptable ActiON using PLZT optical switches with the variable splitter mode, which controls the split ratio of the optical power according to users' requirement. Numerical results show that the proposed network dramatically reduces the required number of slots by up to about 81 percent, compared to the conventional ActiON. Moreover, the required computation time for selecting users is less than 30 ms, which is acceptable for on-demand according to users' various requirement.

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Chapter 5

Low-power consumption slot allocation method for Active Optical Access Network

5.1 Abstract

Chapter 5 proposes a low-power consumption slot allocation method that reduces the number of mode changes in each switch element, while keeping the required number of slots in the multi-service adaptable ActiON in Chapter 4. To meet our objective, we formulate the problem (minimizing the number of mode changes) as an ILP problem. We adopt a heuristic approach that breaks the ILP problem into several smaller problems that can be solved in practical time. Numerical results show that the proposed network with the low-power consumption slot allocation method reduces the power consumption by up to 75 percent compared to the 10G-EPON, by up to 41 percent compared to the conventional ActiON, and by up to 21 percent compared to the multi-service adaptable ActiON, according to the reduction of the number of mode changes. Also tests on the experiment system by using the PLZT optical switch as the variable splitter mode confirms the capability of the proposed network.

5.2 Introduction

The conventional ActiON [5-1, 2] consumes the power higher than the 10G-EPON because it needs additional PLZT optical switches in addition to the components of the PON which are OLT and ONUs (the optical splitter does not consume power.). As described in the problem in low-power consumption of Chapter 2, the conventional ActiON consumes the power higher approximately 1.5 times than the 10G-EPON when the number of users is 32, the power consumption of the 1×2 PLZT optical switch in the ActiON increases linearly when extending the number of users further. On the other hand, in Chapter 4, the multi-service adaptable ActiON adopts a slot allocation method [5-3] by using the PLZT optical switch [5-4–11] as a variable splitter that can control the splitting ratio of the optical power, in addition to the normal switch modes. The slot allocation method uses a heuristic approach to maximizing the number of allocated users in each slot to reduce the required number of slots. However, it does not consider how often the switch must change modes; electric power consumption increases with the number of mode changes in each switch element. Chapter 5 proposes a low-power consumption slot allocation method that reduces the frequency with which the PLZT optical switch changes modes, while keeping the required number of slots in the multi-service adaptable ActiON [5-12]. To meet our objective, we formulate the problem (minimizing the number of mode changes) as an ILP problem. We adopt a heuristic approach that breaks the ILP problem into several smaller problems that can be solved in practical time. Numerical results show that the proposed method reduces the number of mode changes by up to 63 percent, compared to the slot allocation method in the multi-service adaptable ActiON, and by up to 81 percent compared to the conventional slot allocation method in the ActiON, when supporting multicast. Moreover, the proposed network with the low-power consumption slot allocation method reduces the power consumption by up to 75 percent compared to the 10G-EPON, by up to 41 percent compared to the conventional ActiON, and by up to 21 percent compared to the multi-service adaptable ActiON, according to the reduction of the number of mode changes. Also tests on the experiment system by using the PLZT optical switch as the variable splitter mode confirms the capability of the proposed network.

5.3 Low-power consumption slot allocation method reducing mode change in PLZT optical switch

5.3.1 Slot allocation method in the multi-service adaptable ActiON.

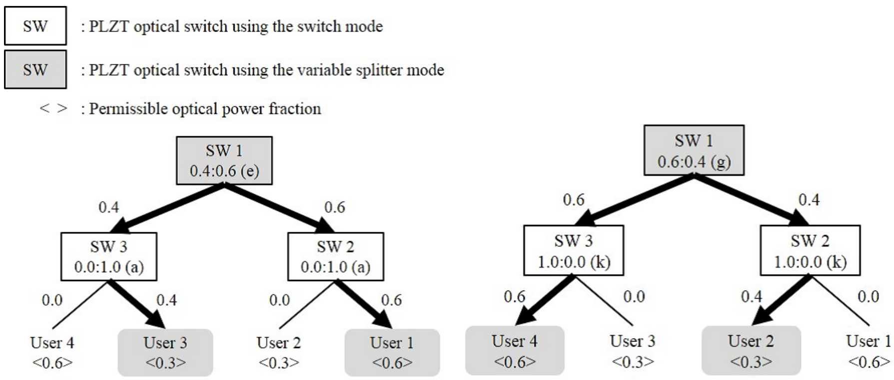
In Chapter 4, the multi-service adaptable ActiON uses a slot allocation method, which creatively applies two modes (normal switch mode and variable splitter mode), to meet various user requirements including the minimum permissible optical power calculated by network scale and optical loss.

The network conditions when using the proposed method, including the maximum number of users (128), the maximum transmission distance which varies according to the splitting loss, the wavelength allocation (upstream: 1260-1280 nm / downstream: 1575-1580 nm), the maximum optical loss budget (29 dB), and the breakdown of optical loss are the same as those of the multi-service adaptable ActiON. Table 5.1 shows the relationship between network, optical loss, maximum optical loss budget, and users' permissible power fraction. The users' minimum permissible optical power fraction is calculated from the optical splitting loss.

Fig. 5.1 shows an example of the slot allocation method in the multi-service adaptable ActiON. There are four users (ONUs). The minimum permissible optical power for user 1, 2, 3, and 4 is 0.6, 0.3, 0.3, and 0.6, respectively, where optical power input to SW 1 (PLZT optical switch 1) is 1.0. The slot allocation method needs two slots, where users 1 and 3 are transmitted in the first slot and users 2 and 4 are transmitted in the second slot, and changes modes according to users' permissible optical power fraction. The slot allocation method uses a heuristic approach to maximize the number of allocated users in each slot; it considers the number of users and the transmission distance from OLT to each user, as shown in Fig. 5.2. As a result, it reduces the required number of slots, and provides highly bandwidth-efficient service when supporting unicast or multicast.

Table 5.1: Relationship between network, optical loss, maximum optical loss budget, and users' permissible power fraction.

Network			Optical loss			Maximum optical loss budget	Permissible power fraction
Type	Distance (km)	Users (users)	Fiber (dB)	Splitting (dB)	Connection /Insertion (dB)		
PON	20	32	10	15	1-3	29	0.03
ActiON	20	128	10	15	1-3	29	0.03
	30	128	15	10	1-3	29	0.10
	40	128	20	5	1-3	29	0.32
	50	128	25	0	1-3	29	1.00



(a) First slot (b) Second slot

Figure 5.1: Example of conventional multicast slot allocation method.

Problem in the multi-service adaptable ActiON

The slot allocation method of ActiON does not consider the number of mode changes needed in each switch element, even though these changes directly impact the electric power consumption of the PLZT optical switch.

Table 5.2 shows the number of mode changes in Fig. 5.1. There are three mode changes

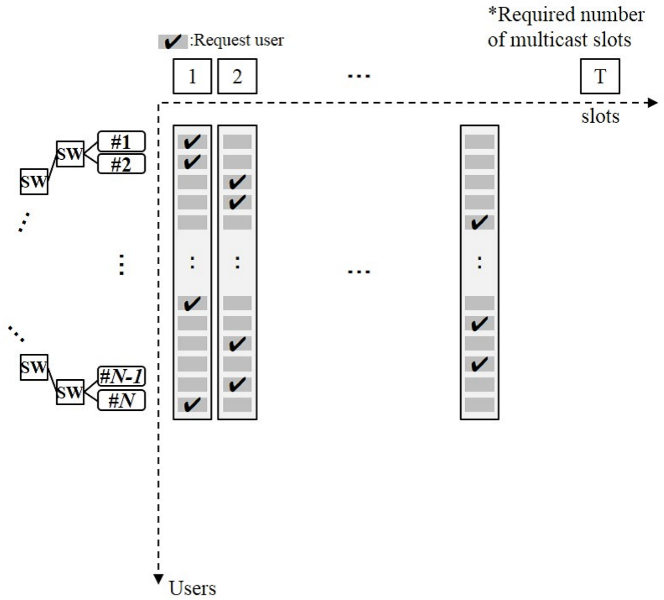


Figure 5.2: Heuristic approach of slot allocation method to maximize the number of allocated users in each slot in order to reduce the required number of slots.

between the first and second slots; the splitting ratio of SW 1 is changed from 0.4-0.6 (e) to 0.6-0.4 (g), the splitting ratio of SW 2 is changed from 0.0-1.0 (a) to 1.0-0.0 (k), and the splitting ratio of SW 3 is changed from 0.0-1.0 (a) to 1.0-0.0 (k). This example represents the worst case mode change for all switch elements in each slot. In this way, the conventional method may increase the number of mode changes and the electric power consumption of the switch.

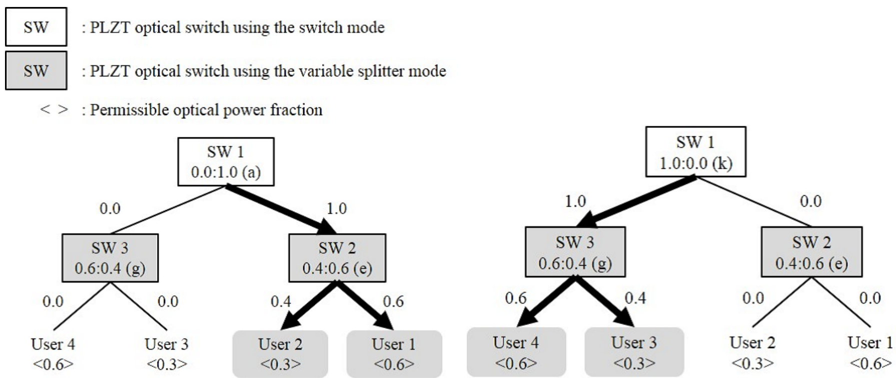
Table 5.2: Number of mode changes in conventional method.

SW	Change of mode in switch		Number of mode changes
	1st slot	2nd slot	
1	0.4-0.6 (e)	0.6-0.4 (g)	1 time
2	0.0-1.0 (a)	1.0-0.0 (k)	1 time
3	0.0-1.0 (a)	1.0-0.0 (k)	1 time
Total			3 times

5.3.2 Overview of low-power consumption slot allocation method

The low-power consumption slot allocation method reduces the number of mode changes in each switch element [5-12]. The proposed method uses the required number of multicast slots, T, that is given by the in the multi-service adaptable ActiON.

Fig. 5.3 and Table 5.3 show the corresponding example of the proposed multicast slot allocation method and the number of mode changes. The network conditions are those of Fig. 5.1. The proposed method needs two multicast slots, where users 1 and 2 are transmitted in the first slot of Fig. 5.3(a) and users 3 and 4 are transmitted in the second slot of Fig. 5.3(b). The number of mode changes in the proposed method is only one between the first and second slots, where the splitting ratio of SW 1 is changed from 0.0-1.0 (a) to 1.0-0.0 (k), the splitting ratios of SW 2 and 3 are kept at 0.4-0.6 (e) and 0.6-0.4 (g) modes, respectively. In order to minimize the number of mode changes, the proposed slot allocation method formulates the optimization problem as an ILP problem as detailed in Section 5.3.3.



(a) First slot (b) Second slot

Figure 5.3: Example of proposed multicast slot allocation method.

Table 5.3: Number of mode changes in proposed method.

SW	Change of mode in switch		Number of mode changes
	1st slot	2nd slot	
1	0.0-1.0 (a)	1.0-0.0 (k)	1 time
2	0.4-0.6 (e)	0.4-0.6 (e)	0 time
3	0.6-0.4 (g)	0.6-0.4 (g)	0 time
Total			1 time

5.3.3 Integer Linear Programming (ILP) Formulation of proposed method

We introduce the following ILP formulation of the optimization problem to minimize the number of mode changes. The definitions are given in Section 5.3.3 and the objective function and the constrained condition are described in Section 5.3.3.

Definitions

The nomenclature used in this ILP formulation is given below.

N	Number of users. N is set to 2^a, where a is a natural number. (given parameter.)
T	Required number of multicast slots given by the conventional method. (given parameter.)
i	Switch index, where $1 \leq i \leq N-1$.
u	User index, where $N \leq u \leq 2N-1$.
t	Index of required slot number, where $1 \leq t \leq T$.
k	Pattern index of optical power ratio, where $\forall k \in K = \{0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10\}$.
I	Set of i.
U	Set of u.
K	Set of k.
$S^R_{i,k}(t)$	Binary variable, where if the lower right-side link in the ith switch in the tth time slot uses the kth pattern of optical power ratio, $S^R_{i,k}(t) = 1$. Otherwise, $S^R_{ik}(t) = 0$.
$S^L_{i,k}(t)$	Binary variable, where if the lower left-side link in the ith switch in the tth time slot uses the kth pattern of optical power ratio, $S^L_{i,k}(t) = 1$. Otherwise, $S^L_{ik}(t) = 0$.
R_k	kth pattern of optical power ratio, where $R_k = 0.1k$ is set as a given parameter.
x	Pattern index of optical splitting ratio, where $\forall x \in X = \{1, 2, 3, \cdots, 33\}$.
X	Set of x.
q_x	xth pattern of optical splitting ratio, where $\forall q_x \in Q =$ $\{0, \frac{1}{10}, \frac{1}{9}, \frac{1}{8}, \frac{1}{7}, \frac{1}{6}, \frac{1}{5}, \frac{2}{9}, \frac{1}{4}, \frac{2}{7}, \frac{3}{10}, \frac{1}{3}, \frac{3}{8}, \frac{2}{5}, \frac{3}{7}, \frac{4}{9}, \frac{1}{2}, \frac{5}{9}, \frac{4}{7}, \frac{3}{5}, \frac{5}{8}, \frac{2}{3}, \frac{7}{10}, \frac{5}{7}, \frac{3}{4}, \frac{7}{9}, \frac{4}{5}, \frac{5}{6}, \frac{6}{7}, \frac{7}{8}, \frac{8}{9}, \frac{9}{10}, 1\}$
Q	Set of q_x. The number of elements in Q is $\lvert Q \rvert = 33$.
M_u	Minimum permissible optical power fraction of uth user, which is set as a given parameter.
$P_u(t)$	Binary variable, where if the uth user in the tth time slot receives optical power, $P_u(t) = 1$. Otherwise, $P_u(t) = 0$.
$Z_{i,x}(t)$	Binary variable.
$D_{i,x}(t)$	Binary variable.

Objective function and constraints

The ILP problem used to minimize the number of mode changes is described below.

$$\min \sum_{i\in I, x\in X, t\in T-1} D_{i,x}(t) \tag{5.1a}$$

$$s.t \quad \sum_{k\in K} S^{R}_{(\frac{i}{2}),k}(t)R_k = \sum_{k\in K} S^{R}_{i,k}(t)R_k + \sum_{k\in K} S^{L}_{i,k}(t)R_k, \tag{5.1b}$$

$$\forall i \in I(i : \text{even}, i \geq 2), \forall t \in T$$

$$\sum_{k\in K} S^{L}_{(\frac{i-1}{2}),k}(t)R_k = \sum_{k\in K} S^{R}_{i,k}(t)R_k + \sum_{k\in K} S^{L}_{i,k}(t)R_k, \tag{5.1c}$$

$$\forall i \in I(i : \text{odd}, i \geq 1), \forall t \in T$$

$$\sum_{k\in K} S^{L}_{0,k}(t)R_k = 1, \forall t \in T \tag{5.1d}$$

$$\sum_{k\in K} S^{R}_{i,k}(t) = 1, \forall i \in I, \forall t \in T \tag{5.1e}$$

$$\sum_{k\in K} S^{L}_{i,k}(t) = 1, \forall i \in I, \forall t \in T \tag{5.1f}$$

$$Z_{i,x}(t) \geq S^{R}_{(\frac{i}{2}),k_1}(t) + S^{L}_{i,k_2}(t) - 1, \forall i \in I(i : \text{even}, i \geq 2), \forall x \in X, \tag{5.1g}$$

$$\forall k_1, k_2(k_1 \geq k_2, k_1 \neq 0) \in K, \forall t \in T$$

$$Z_{i,x}(t) \geq S^{L}_{(\frac{i-1}{2}),k_1}(t) + S^{L}_{i,k_2}(t) - 1, \forall i \in I(i : \text{odd}, i \geq 1), \forall x \in X, \tag{5.1h}$$

$$\forall k_1, k_2(k_1 \geq k_2, k_1 \neq 0) \in K, \forall t \in T$$

$$\sum_{x\in X} Z_{i,x}(t) = 1, \forall i \in I, \forall t \in T \tag{5.1i}$$

$$Z_{i,x}(t+1) - Z_{i,x}(t) \leq D_{i,x}(t), \forall i \in I, \forall x \in X(\neq 17), \forall t \in T \tag{5.1j}$$

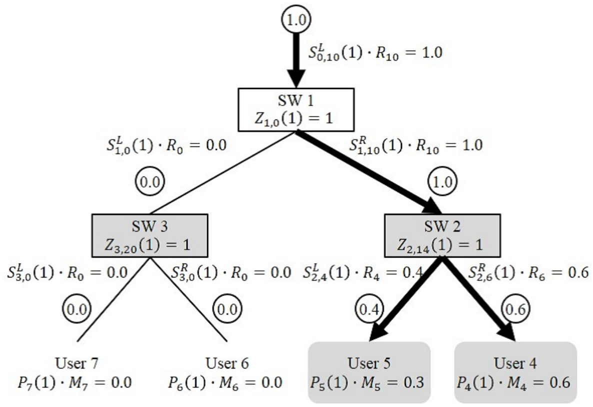
$$\sum_{k\in K} S^{R}_{\frac{u}{2},k}(t)R_k \geq M_u \times P_u(t), \forall u \in U(u : \text{even}), \forall t \in T \tag{5.1k}$$

$$\sum_{k\in K} S^{L}_{\frac{u-1}{2},k}(t)R_k \geq M_u \times P_u(t), \forall u \in U(u : \text{odd}), \forall t \in T \tag{5.1l}$$

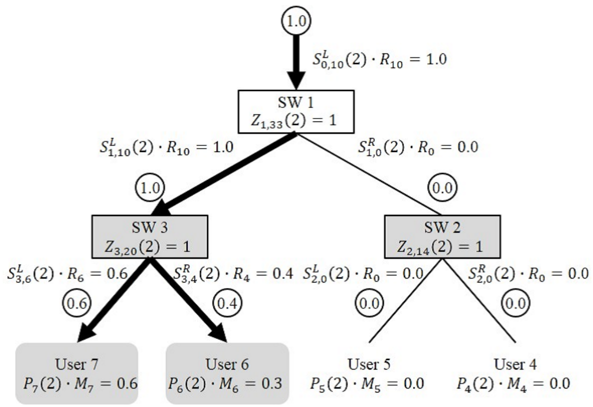
$$\sum_{t\in T} P_u(t) = 1, \forall u \in U \tag{5.1m}$$

The objective function in Eq. (5.1a) minimizes the number of mode changes in each switch element. Fig. 5.4 shows an example of switch configuration using the ILP formulation based on the condition of Fig. 5.3.

The constraints defined by Eqs. (5.1b) and (5.1c) indicate the relationship of the optical power ratios between the upper link and the lower left-side and right-side links, as shown



(a) First slot



(b) Second slot

Figure 5.4: Example of switch configuration using the ILP formulation based on the condition of Fig. 5.3.

in Fig. 5.5. At SW 2 in Fig. 5.4(a), the optical power ratio in the upper link (1.0) is computed by adding that in the lower left-side link (0.4) and that in the lower right-side link (0.6).

The constraint posed by Eq. (5.1d) indicates that the input optical power ratios in the upper link at SW 1 in Fig. 5.4 is set to 1.0.

The constraints of Eqs. (5.1e) and (5.1f) indicate that each link must select just one

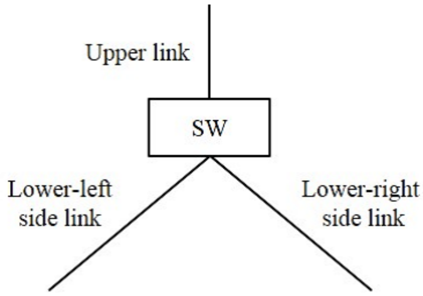


Figure 5.5: Example of 1×2 switch configuration.

optical power ratio pattern.

The constraints of Eqs. (5.1g) and (5.1h) indicate the optical splitting ratio of the ith switch, which is defined as the optical power ratio in the lower left-side link divided by that in the upper link. The constraint of Eq. (5.1i) indicates that each switch must select just one optical splitting ratio pattern. Table 5.4 indicates the values of optical splitting ratios, q_x, and Table 5.5 indicates the pattern indexes, x, each of which corresponds to q_x. Table 5.5 is generated by using Table 5.4 and Q. For example, in Table 5.4, if $R_6 = 0.6$ ($k_1 = 6$) and $R_2 = 0.2$ ($k_2 = 2$), then the optical splitting ratio is $\frac{1}{3}$, which is the 12th pattern (element) in Q. We get $\frac{1}{3} = q_{12}$ ($x = 12$). We impose the following constraints.

$$Z_{i,x}(t) = S^R_{(\frac{i}{2}),k_1}(t) \times S^L_{i,k_2}(t), \forall i \in I(i : \text{even}, i \geq 2), \forall x \in X, \tag{5.2a}$$
$$\forall k_1, k_2(k_1 \geq k_2, k_1 \neq 0) \in K, \forall t \in T$$
$$Z_{i,x}(t) = S^L_{(\frac{i-1}{2}),k_1}(t) \times S^L_{i,k_2}(t), \forall i \in I(i : \text{odd}, i \geq 1), \forall x \in X, \tag{5.2b}$$
$$\forall k_1, k_2(k_1 \geq k_2, k_1 \neq 0) \in K, \forall t \in T$$

Eqs. (5.2a) and (5.2b) indicate that $Z_{i,x}(t) = 1$ if the optical splitting ratio at the ith switch is equal to q_x in the tth time slot, and $Z_{i,x}(t) = 0$ otherwise. Eqs. (5.2a) and (5.2b) are transformed into linear forms of Eqs. (5.1g), (5.1h), and (5.1i). At SW 2 in Fig. 5.4(a), the optical power ratio in the upper link is R_{10}=1.0 ($k_1 = 10$) and that in the lower left-side link is $R_4 = 0.4$ ($k_2 = 4$), then the optical splitting ratio is $q_{14} = \frac{2}{5}$ ($x = 14$) and $Z_{2,14}(1) = 1$. The exception is that when the optical power ratios in both upper and lower left-side links are set to 0.0 (i.e., $k_1 = k_2 = 0$), any optical splitting ratio is available. At SW 2 in Fig. 5.4(b), the optical power ratios in both upper and lower left-side links are 0.0. Thus, the optical splitting ratio (q_{14}), which is the same as that at SW 2 in Fig. 5.4(a), can be used not to change the mode change at the switch.

The constraint of Eq. (5.1j) indicates a change in the optical splitting ratio pattern of the switch between the tth and $t + 1$th time slots, where if $Z_{i,x}(t + 1) = 1$ and $Z_{i,x}(t) = 0$, $D_{i,x}(t) = 1$, otherwise $D_{i,x}(t) = 0$. At SW 1, $Z_{1,0}(1) = 1$ ($Z_{1,33}(1) = 0$, on the other hand.) in Fig. 5.4(a) and $Z_{1,33}(2) = 1$ in Fig. 5.4(b), then, the number of changes in the optical splitting ratio patterns of the SW 1 between first and second time slots is $D_{1,33}(1) = 1$. This constraint is not applicable when setting x in the $t + 1$th time slot to 17 if q_{17} and the 0.5-0.5 variable splitter mode is used, because this mode does not need voltage applied to the electrodes.

The constraints of Eqs. (5.1k) and (5.1l) indicate the relationship between minimum permissible optical power fraction for each user and the actual optical power of each lowest link. At SW 2 in Fig. 5.4(a), the lower right-side link is 0.6 within the minimum permissible optical power fraction in User 4, which is 0.6.

The constraint of Eq. (5.1m) indicates that every user needs to receive optical power once within the required number of slots. At User 4 in Fig. 5.4, $P_4(1) + P_4(2) = 1$.

We note that the naive approach of considering all combinations of users and slots in the above ILP formulation is not feasible as the optimum solution cannot be found in practical time. Therefore, the proposed method introduces a heuristic approach that find the minimum number of mode changes by breaking the ILP problem into smaller tractable problems, and not all users and all slots are considered. It is not assured of finding the optimum solution.

Table 5.4: Optical splitting ratio of optical switch (q_x), which is defined as the optical power ratio in the lower left-side link (R_{k_2}) divided by that in the upper link (R_{k_1}).

Optical power ratio in upper link (R_{k_1})	Optical power ratio in low left-side link (R_{k_2}): 0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
0.0	0	-	-	-	-	-	-	-	-	-	-
0.1	0	1	-	-	-	-	-	-	-	-	-
0.2	0	$\frac{1}{2}$	1	-	-	-	-	-	-	-	-
0.3	0	$\frac{1}{3}$	$\frac{2}{3}$	1	-	-	-	-	-	-	-
0.4	0	$\frac{1}{4}$	$\frac{1}{2}$	$\frac{3}{4}$	1	-	-	-	-	-	-
0.5	0	$\frac{1}{5}$	$\frac{2}{5}$	$\frac{3}{5}$	$\frac{4}{5}$	1	-	-	-	-	-
0.6	0	$\frac{1}{6}$	$\frac{1}{3}$	$\frac{1}{2}$	$\frac{2}{3}$	$\frac{5}{6}$	1	-	-	-	-
0.7	0	$\frac{1}{7}$	$\frac{2}{7}$	$\frac{3}{7}$	$\frac{4}{7}$	$\frac{5}{7}$	$\frac{6}{7}$	1	-	-	-
0.8	0	$\frac{1}{8}$	$\frac{1}{4}$	$\frac{3}{8}$	$\frac{1}{2}$	$\frac{5}{8}$	$\frac{3}{4}$	$\frac{7}{8}$	1	-	-
0.9	0	$\frac{1}{9}$	$\frac{2}{9}$	$\frac{1}{3}$	$\frac{4}{9}$	$\frac{5}{9}$	$\frac{2}{3}$	$\frac{7}{9}$	$\frac{8}{9}$	1	-
1.0	0	$\frac{1}{10}$	$\frac{1}{5}$	$\frac{3}{10}$	$\frac{2}{5}$	$\frac{1}{2}$	$\frac{3}{5}$	$\frac{7}{10}$	$\frac{4}{5}$	$\frac{9}{10}$	1

5.3.4 Heuristic approach for reducing the number of mode changes in each switch element

We adopt the heuristic approach that breaks the ILP problem into several smaller problems that can be solved in practical time.

Fig. 5.6 shows the overall proposed heuristic approach. The nomenclature used in the heuristic approach is given below.

- G Small tree group index.
- S Maximum number of slots in each small tree group that can be solved in practical time. (This is set as a given parameter.)
- N_G Maximum number of users selected in small tree group #G according to the users' minimum permissible optical power.

This heuristic approach divides the required number of slots (T), which is given by the solution of slot allocation method in the multi-service adaptable ActiON, of the original tree among small tree groups. Each small tree group is selected in order from the edge of the original tree. There is one overlap slot between adjacent small tree groups in order to reduce mode change in each switch element in this slot. The heuristic approach

Table 5.5: Pattern index for optical splitting ratio (x), which is computed by using the pattern index of optical power ratio in the upper link (k_1) and that in the lower left-side link (k_2) ($k_1 \geq k_2$), where the number of pattern indexes is $|Q| = 33$

Pattern index of optical power ratio in upper link (k_1)	Pattern index of optical power ratio in low left-side link (k_2)										
	0	1	2	3	4	5	6	7	8	9	10
0	1	-	-	-	-	-	-	-	-	-	-
1	1	33	-	-	-	-	-	-	-	-	-
2	1	17	33	-	-	-	-	-	-	-	-
3	1	12	22	33	-	-	-	-	-	-	-
4	1	9	17	25	33	-	-	-	-	-	-
5	1	7	14	20	27	33	-	-	-	-	-
6	1	6	12	17	22	28	33	-	-	-	-
7	1	5	10	15	19	24	29	33	-	-	-
8	1	4	9	13	17	21	25	30	33	-	-
9	1	3	8	12	16	18	22	26	31	33	-
10	1	2	7	11	14	17	20	23	27	32	33

continues to solve the optimization problem to minimize the number of mode changes in each small tree group from #1 to $\#T/S$, which is the total number of small tree groups. When using small tree groups to solve the ILP optimization problem described in Section 5.3.3, N (Required number of users) is changed into N_G and T (Required number of slots) is changed into S.

We show that the heuristic approach can reduce the number of mode changes by solving the optimization problem within practical time, while offering the required number of slots.

5.4 Performance evaluation

This section describes the simulation parameters of the proposed method and the results of simulations conducted to evaluate the number of mode changes in each switch element and the power consumption of the network.

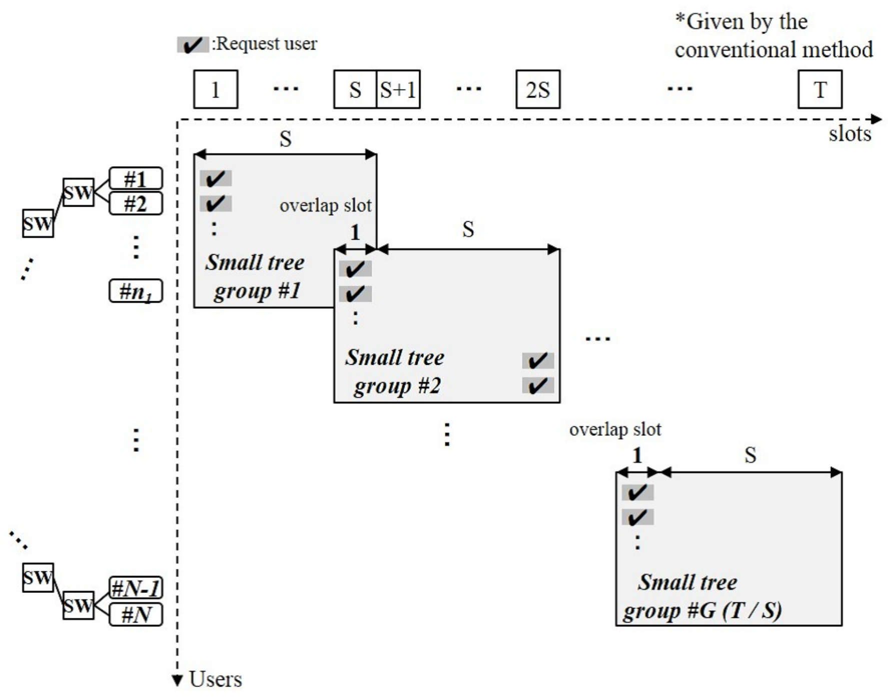


Figure 5.6: Heuristic approach to minimize the number of mode changes in each small tree group, while keeping the required number of slots(T)

5.4.1 Evaluation overview

The simulation parameters are shown below. The maximum number of users (ONUs) is 128 for requesting unicast or multicast. The maximum transmission distance between OLT and each ONU is 50 km. The 1×128 PLZT optical switch consists of a seven-stage cascade of 1×2 PLZT optical switch elements using two modes, normal switch mode and variable splitter mode. The power consumption data of each component used in the simulation is shown below. One OLT consumes 12.5 W [5-14]. The power consumption of $1 \times N$ PLZT optical switch is calculated based on the Eq. (5.1a).(N is the number of users.) The power consumption of each ONU is not included because it is a common element in each network.

Power of $1 \times N$ PLZT optical switch =

Power of 1×2 PLZT optical switch chip (with sub board) (0.12 W) [5-10, 11]

$\times(N-1)$ + Standby Power of PLZT optical switch driver (main board)

(2.4 W) [5-10, 11]

(5.3a)

There are three systems for comparison. The first system is the 10G-EPON [5-16] that the maximum number of ONUs per OLT is 32 ONUs and the maximum transmission distance is 20 km and the optical amplifiers (EDFA: Erbium-Doped Fiber Amplifier) are needed when extending the network. The maximum number of the optical amplifiers using the 17dB EDFA is supposed to be four because the 10G-EPON sets up one 1×4 optical splitter in the OLT and sets up four 1×8 optical splitters. The second one is the ActiON that the maximum number of ONUs per OLT is 128 ONUs and the maximum transmission distance is 40 km and the PLZT optical switch acts as only a switch mode. The third one is the multi-service adaptable ActiON that the maximum number of ONUs per OLT is 128 ONUs and the maximum transmission distance is 40 km and the PLZT optical switch acts as a switch mode and a variable splitter mode in Chapter 4. The CPLEX Interactive Optimizer 12.5.0.0 is used to solve the ILP optimization problem in this evaluation [5-13].

5.4.2 Evaluation results and discussions

Fig. 5.7 shows the relationship between the number of mode changes and the number of users in the conventional slot allocation method in the ActiON, the slot allocation method in the multi-service adaptable ActiON, and the proposed method. The proposed method reduces the number of mode changes by up to 63 percent, compared to the slot

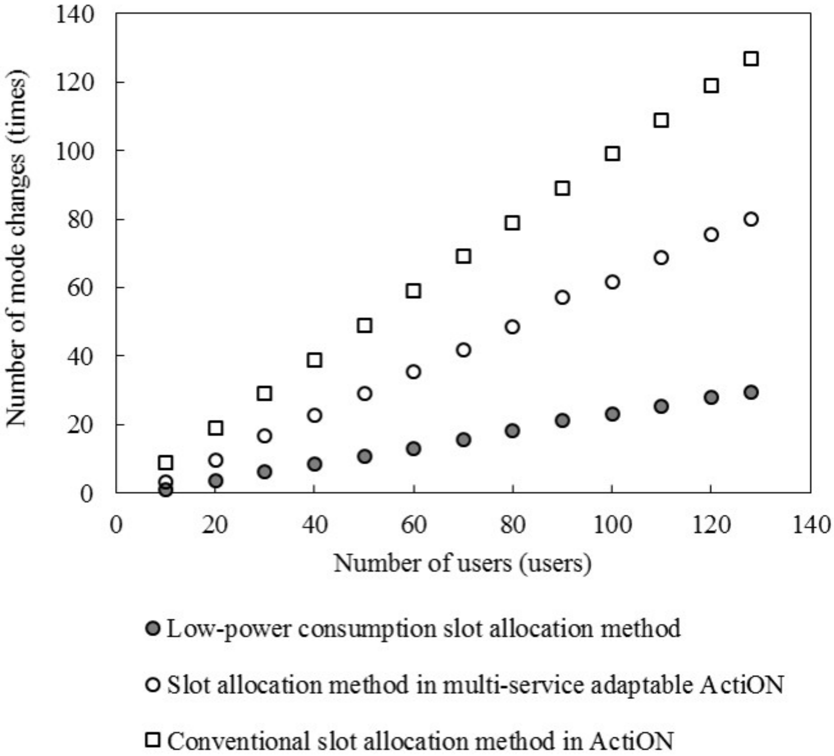


Figure 5.7: Number of mode changes versus number of users for the conventional slot allocation method in the ActiON, the slot allocation method in the multi-service adaptable ActiON, and the low-power consumption slot allocation method.

allocation method in the multi-service adaptable ActiON, and up to 81 percent, compared to the conventional slot allocation method in the ActiON. In this evaluation, the proposed method adopts the heuristic approach setting S to three slots, and users are distributed over the distance ranges given by 20, 30, 40, and 50 km, based on the relationship between population density and distance from the center of Tokyo, Japan [5-15]. users' permissible optical power fraction is calculated for the above distances, referring to the relationship given in Table 5.1.

Fig. 5.8 shows the average number of mode changes in each users' allocation pattern for the proposed method. There are three allocation patterns; pattern A allocates users in

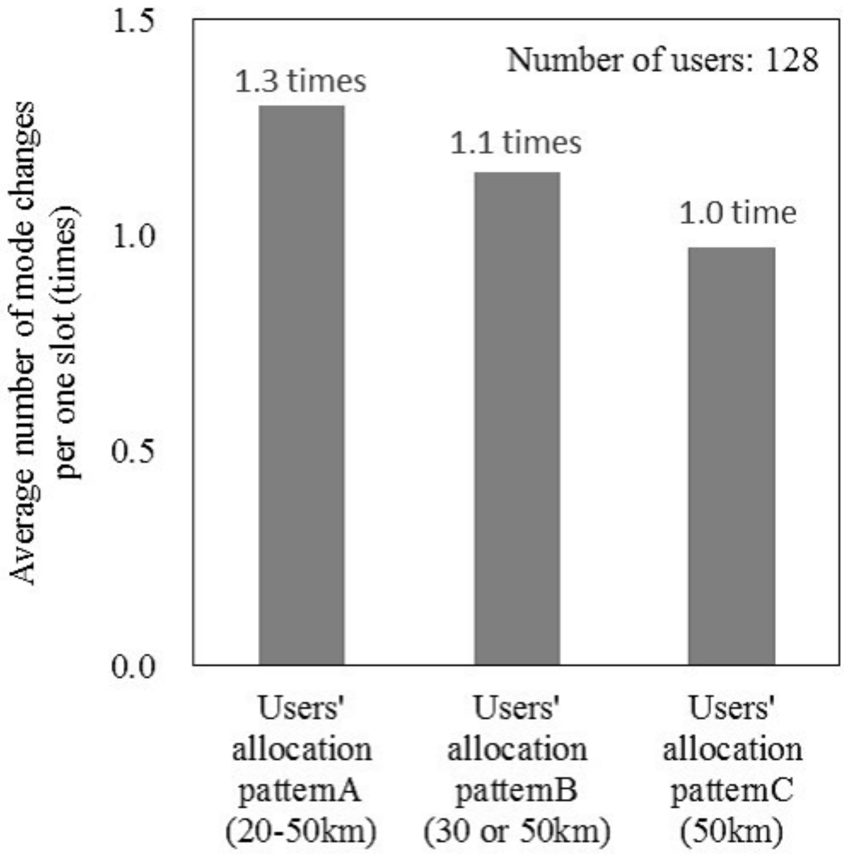


Figure 5.8: Average number of mode changes in each users' allocation pattern for proposed method.

increments of 10 km from 20 to 50 km range, pattern B allocates each user to either 30 or 50 km range, and pattern C allocates each user to the 50 km range. When changing from pattern A to pattern C, the difference in range and permissible optical power of each user is reduced. The average number of mode changes per slot reduces in accordance with the change from pattern A to pattern C. The proposed method is more effective as the distance distribution becomes smaller. In this evaluation, the proposed method sets S to three slots and the number of users to 128.

Fig. 5.9 shows the number of mode changes demanded by the proposed method for each small tree group size. Setting S to three slots reduces the number of mode changes

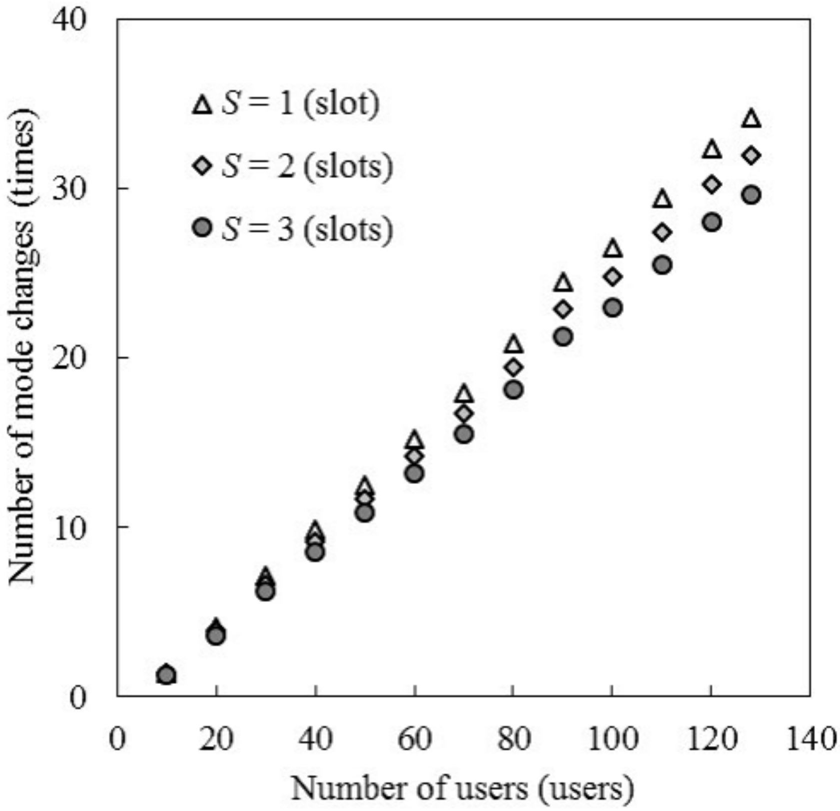


Figure 5.9: Number of mode changes versus small tree group size for proposed method.

by up to 7 percent, compared to setting S to two slots, and by up to 13 percent, compared to setting S to one slot. The proposed method needs fewer mode changes as the maximum number of slots in each small tree group increases. In this evaluation, each user is distributed over distance ranges of 20, 30, 40, and 50 km, following the condition shown in Fig. 5.7.

Fig. 5.10 shows the relationship between the power consumption and number of users in the ActiON, the multi-service adaptable ActiON, and the proposed network (multi-service adaptable ActiON with the low-power consumption slot allocation method). The proposed network reduced the power consumption by up to 75 percent compared to the 10G-EPON, by up to 41 percent compared to the conventional ActiON, and by up to 21

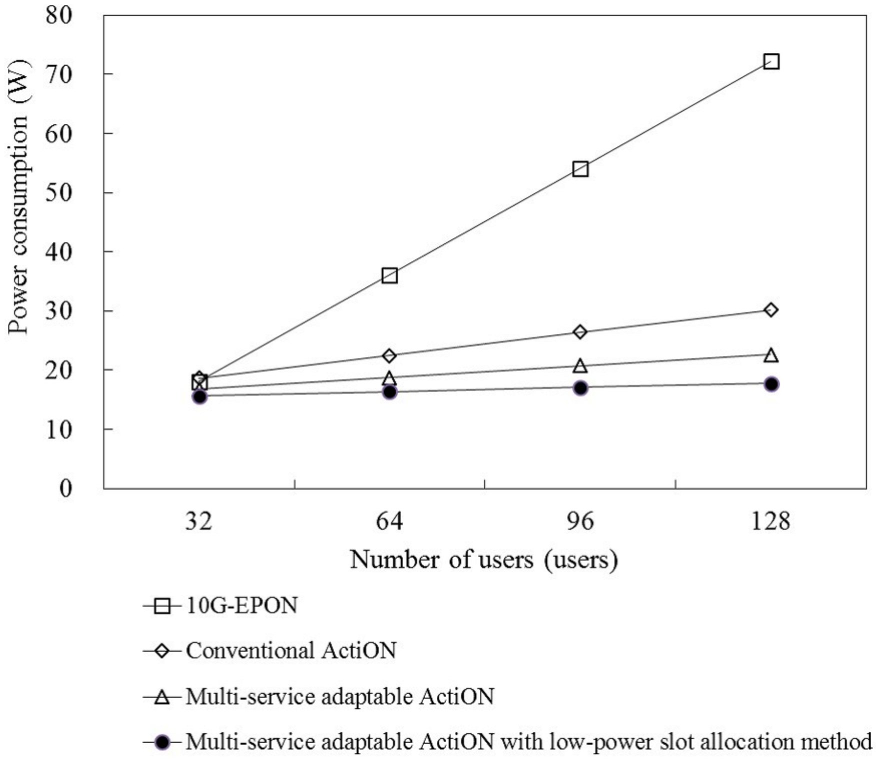


Figure 5.10: Power consumption versus number of users for the 10G-EPON, the conventional ActiON, and the multi-service adaptable ActiON.

percent compared to the multi-service adaptable ActiON, according to the reduction of the number of mode changes in Fig. 5.7. In this evaluation, the low-power consumption slot allocation method in the proposed network adopts the heuristic approach setting S to three slots, and users are distributed over the distance ranges given by 20, 30, 40, and 50 km, based on the relationship between population density and distance from the center of Tokyo, Japan [5-15].

Fig. 5.11 shows the maximum computation time required to select modes in each small tree group size, S, for the proposed method. The proposed method needs more computation time as the maximum number of slots in each small tree group, S, increases. The maximum computation time is 91 ms. This value is less than 150 ms, which is the de-

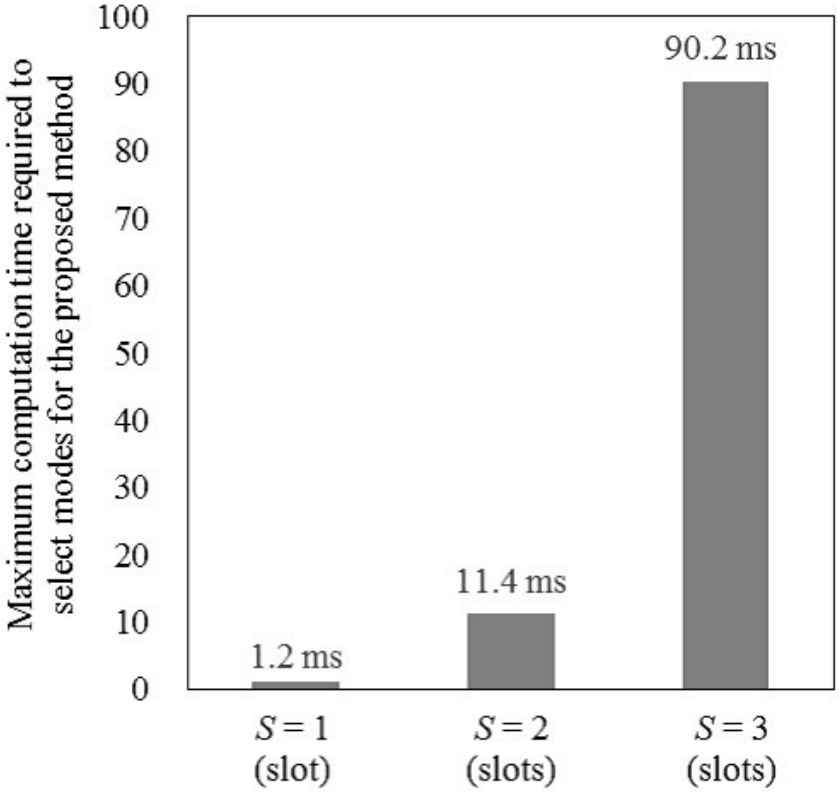


Figure 5.11: Maximum computation time required to select modes in each small tree group size for proposed method.

lay constraints [5-17] in order to well suit multi-services, including IPTV, VoIP, and VoD. Therefore, the OLT decide to select modes in each switch element within the computation time after receiving the request from each user. In this evaluation, the distance ranges in each user are the same as those of Fig. 5.7 and the number of users is 128.

Based on the above evaluation results, the low-power consumption slot allocation method needs fewer mode changes in each switch element than the conventional method. Additionally, the proposed network with the low-power consumption slot allocation method reduces the power consumption of the network, compared to the 10G-EPON, the conventional ActiON, and the multi-service adaptable ActiON. Moreover, the computation time for the proposed method is within the delay constraints [5-17] for supporting multi-services.

5.5 Experiment system of prototype of proposed network

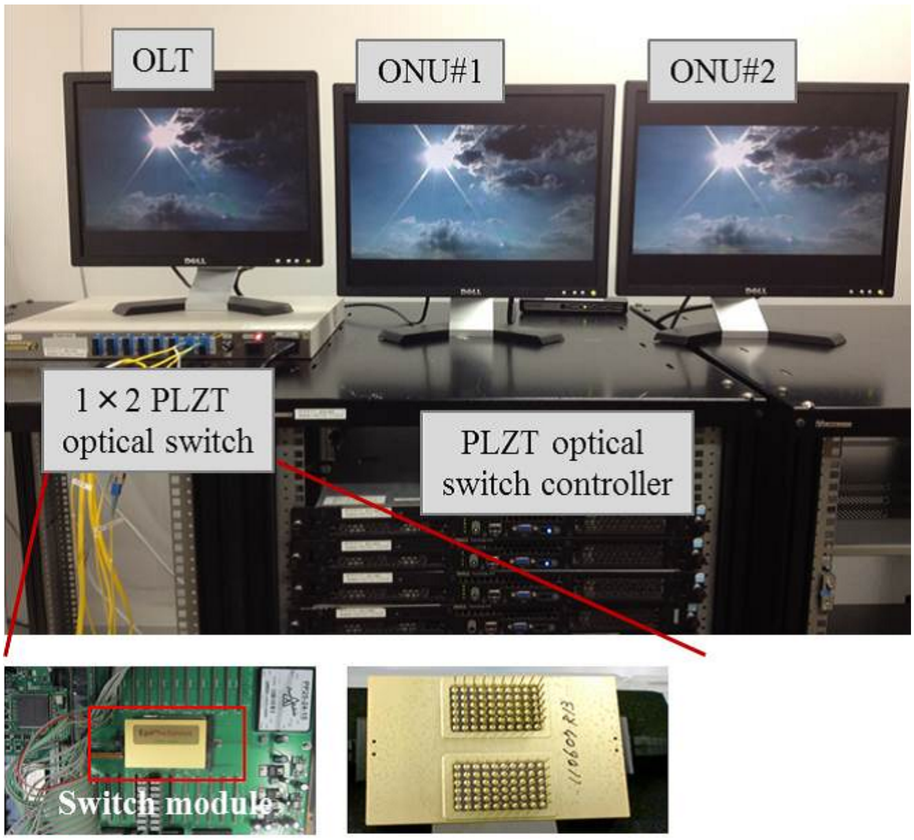


Figure 5.12: Prototype system of proposed system.

Fig. 5.12 shows the prototype system of proposed system. In the prototype system, there are one PC for the OLT (sender), two PCs for the ONUs (receiver), one 1×2 PLZT optical switch, one PLZT optical switch emulator. In the experiment system of the prototype of proposed network, we show two capabilities of the proposed network, 1) supporting unicast and multicast for providing multi services, and 2) reducing power consumption of the access network compared to conventional access networks. To con-

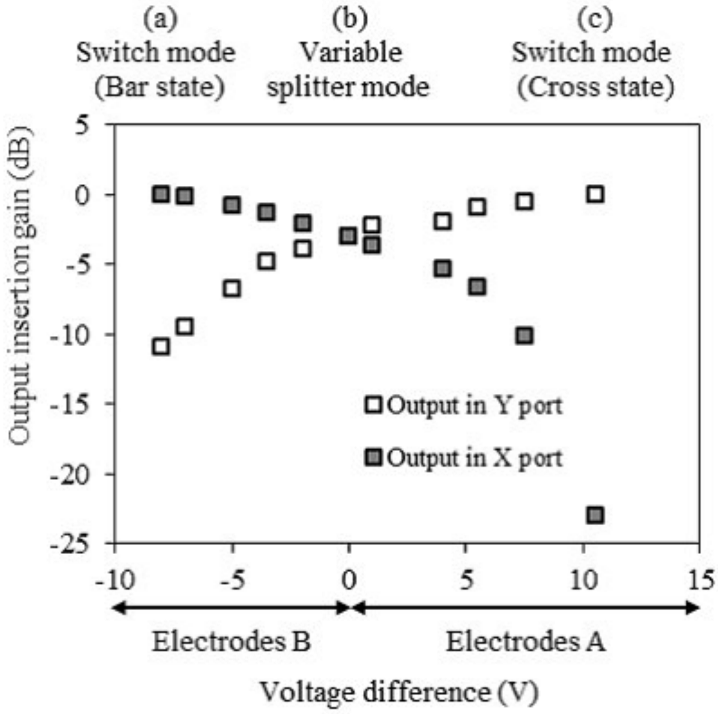


Figure 5.13: Optical insertion gain versus voltage difference in switch mode and power-saving splitter mode of 1×2 PLZT optical switch.

firm the two capabilities of the proposed network, we demonstrated that the PC for OLT is possible to transmit unicast and multicast data to two PCs for ONUs by switching the switch mode and the variable splitter mode. Also, we demonstrated the operation of the 1×2 PLZT optical switch that when using the switch mode, the optical signal is output in X port by applying the voltage (8.0V) only to the electrodes B (bar state (a)) and in Y port by applying the voltage (10.5V) only to the electrodes A (cross state (c)) in the switch mode and when using the variable splitter mode, the optical signal is output in both X and Y ports without applying any voltage (0.0V) neither to electrode A nor B (b). The switching time between (a), (b), and (c) is 10 ns as shown in Fig. 5.13 and Fig. 5.14 The tests on the experiment system using the PLZT optical switch using the power-saving splitter mode confirmed the capability of the proposed network.

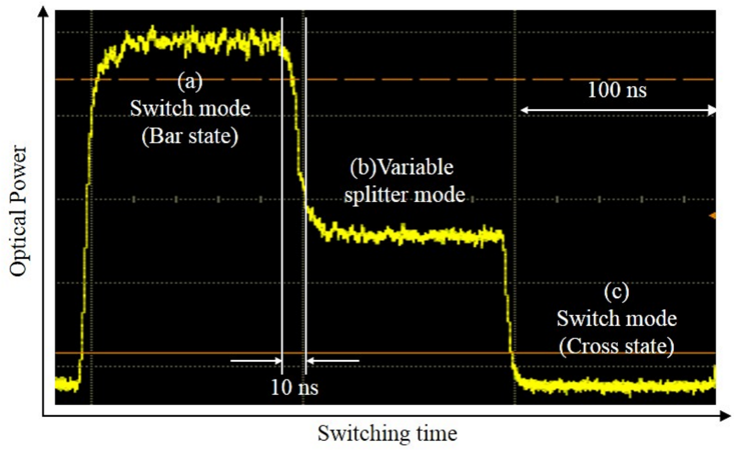


Figure 5.14: Optical power versus switching time in switch mode and variable splitter mode of 1×2 PLZT optical switch.

5.6 Conclusion

Chapter 5 proposed a low-power consumption slot allocation method that reduces the mode changes made to the PLZT optical switch, while keeping the required number of slots in the multi-service adaptable ActiON. To achieve our objective, we formulated the problem of minimizing the number of mode changes in each switch element as an ILP problem. We introduced a heuristic approach that reduces mode changes in each switch element by solving a series of smaller subproblems. Numerical results show that the proposed method reduces the number of mode changes by up to 63 percent, compared to the slot allocation method in the multi-service adaptable ActiON, and by up to 81 percent, compared to the conventional slot allocation method in the ActiON. Moreover, the proposed network reduces the power by up to 75 percent, compared to the 10G-EPON, by up to 41 percent, compared to the conventional ActiON, and by up to 21 percent compared to the multi-service adaptable ActiON, according to the reduction of the number of mode changes. Also tests on the experiment system by using the PLZT optical switch as the variable splitter mode confirmed the capability of the proposed network.

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Chapter 6

Overall conclusion

This dissertation has discussed a next-generation active optical access network by using active optical switches.

In Japan, the number of the whole broadband service users reached 95 million, and the number of Fiber To The Home (FTTH) access service users reached 25 million in 2013. Also, demands are increasing to support multi services in access networks, including Internet protocol television (IPTV) , Video on Demand (VoD) , and Voice over Internet Protocol (VoIP). Unfortunately, expanding transmission capacity will increase the power consumption of network equipment. The access networks already constitute about 70 percent of overall Internet power consumption due to the presence of a huge number of active elements.

There are three requirements for next-generation optical access networks to handle rapidly increasing traffic volume, support multi-services and reduce power consumption of network equipments: 1) scalability, 2) flexibility (multi-service adaptability), and 3) low-power consumption.

The Passive Optical Network (PON) is widely used as an access network. The PON provides a low-cost and low-power network due to its use of an optical splitter. It also supports multicast delivery thanks to the broadcast nature. However, already deployed Ethernet Passive Optical Network (EPON) and Gigabit-Ethernet Passive Optical Network (G-EPON), and 10 Gigabit-Ethernet Passive Optical Network (10G-EPON) are limited in terms of the maximum number of Optical Network Units (ONUs) (32) and the maximum transmission distance (20 km). This is because the optical power is divided at the splitter and decreases as the number of ONUs increases.

To provide scalable access services, Active Optical Access Network (ActiON) using Mach-Zehnder (MZ) type Plumbum Lanthanum Zirconate Titanate (PLZT) optical switches was proposed.

The ActiON realizes the bandwidth of 10 Gbps, the transmission distance of 40 km, and the number of users of 128 users (theoretically over 256 users). In terms of the scalability, it satisfies the requirements of NG-PON2 which are the bandwidth of 10 Gbps, the transmission distance of 40 km, and the number of users of 256 users. In terms of the flexibility, the transmission waiting time exceeds the user's allowable delay in the slot allocation, and it needs a large number of slots in multicast. In terms of the low-power consumption, it consumes the higher power than the 10G-EPON system because it needs additional PLZT optical switches.

This dissertation realized a multi-service adaptable and low-power consumption active optical access network, while keeping the advantages of the ActiON, which are to support scalable access services. In order to realize the delay-sensitive communication in the multi-service adaptable network, the delay-sensitive slot allocation method for the ActiON is proposed in Chapter 3. At first, the ActiON parameters, which are the transmission cycle (7.8 ms) and the slot size (4 μs), are designed in order to maintain the TCP throughput and provide the high bandwidth utilization efficiency. The experiment system using the designed parameters confirmed the capability of the proposed network to maintain the TCP throughput in the slot allocation. Next, a delay-sensitive slot allocation method is proposed, which minimizes the switching idle time in the PLZT optical switches, while considering the user's allowable delay. To achieve our objective, we formulated the problem to minimize the number of switching times as an Integer Linear Programming (ILP) problem. Numerical results show that the proposed method reduces the number of switching times by up to 88 percent, compared to the conventional method. Minimizing the switching idle time leads to increased bandwidth utilization efficiency.

In order to provide the multicast function in addition to the delay sensitive communication in the multi-service adaptable network, the multi-service adaptable Active Optical Access Network (multi-service adaptable ActiON) is proposed in Chapter 4. The proposed network uses the PLZT optical switch as the variable splitter mode, which controls the split ratio of the optical power according to users' requirement. Numerical results show that the multi-service adaptable ActiON dramatically reduces the required number of slots by up to 81 percent and supports high slot allocation efficiency, compared to the conventional ActiON.

In order to realize the low-power consumption network, while keeping the advantage of the multi-service adaptable ActiON, the low-power consumption slot allocation method is proposed in Chapter 5. The proposed method reduces the frequency with which the PLZT optical switch changes modes, while keeping the required number of slots in the multi-service adaptable ActiON. To achieve our objective, we formulated the problem of minimizing the number of mode changes in each switch element as an ILP problem. We introduced a heuristic approach that reduces mode changes in each switch element by solving a series of smaller subproblems. Numerical results show that the low-power consumption slot allocation method reduces the number of mode changes by up to 63 percent, compared to the slot allocation method in the multi-service adaptable ActiON, and by up to 81 percent compared to the conventional slot allocation method in the ActiON, when supporting multicast. Moreover, the proposed network with the low-power consumption slot allocation method reduces the power consumption by up to 75 percent compared to the 10G-EPON, by up to 41 percent compared to the conventional ActiON, and by up to 21 percent compared to the multi-service adaptable ActiON, according to the reduction of the number of mode changes. Also tests on the experiment system by using the PLZT optical switch as the variable splitter mode confirmed the capability of the proposed network.

In this way, this dissertation can satisfy three requirements, which are 1) scalability, 2) flexibility (multi-service adaptability), and 3) low-power consumption.

As an overall conclusion of this dissertation, this dissertation contributes to realize the next-generation optical access network by taking advantage of active access networks. On the other hand, it is necessary that a core network also supports multi service. For example, the virtual optical slice core network by using elastic optical technologies has been proposed in order to provide multi Quality of Service (QoS). Thus, the access network needs to guarantee the various Quality of Experience (QoE) requirements of each user, based on QoS levels in the core network. The future goal is to develop a new application-centric and energy-efficient network by combining the proposed access network in this dissertation and the core network.

Appendix A

Control method of PLZT optical switches in Active Optical Access Network

In order to control the PLZT optical switches, the ActiON introduces the Optical Switching Unit (OSU).

Fig. A.1 shows the configuration of the OSU, which is comprised of the downstream and upstream PLZT optical switches, the switch drivers, and the switch controller. The OLT informs the OSU of the determined switching schedule patterns by using switch control frames in an out-band control line (i) or an in-band control line (ii). The switch controller on the OSU controls the downstream and upstream PLZT optical switches based on the switching schedule patterns. When using an out-band control line (i), the another cable for controlling the switches from the OLT is connected to the switch controller directly. This case is effective when the OSU is set in the OLT because installing new cable between the OLT and the OSU dose not need huge cost due to a short network cable. When using an in-band control line (ii), out output port of the downstream PLZT optical switch on the OSU is connected to O/E converter and one input port of the upstream PLZT optical switch on the OSU is connected to E/O converter. This case is effective when the OSU is set away from the OLT as the optical splitter of the 10G-EPON because installing new cable between the OLT and the OSU needs huge cost due to a long network cable.

Fig. A.2 shows a format of a switch control frame based on MPCP frame. This frame format holds the information about switching schedule patterns at a data field. The switch-

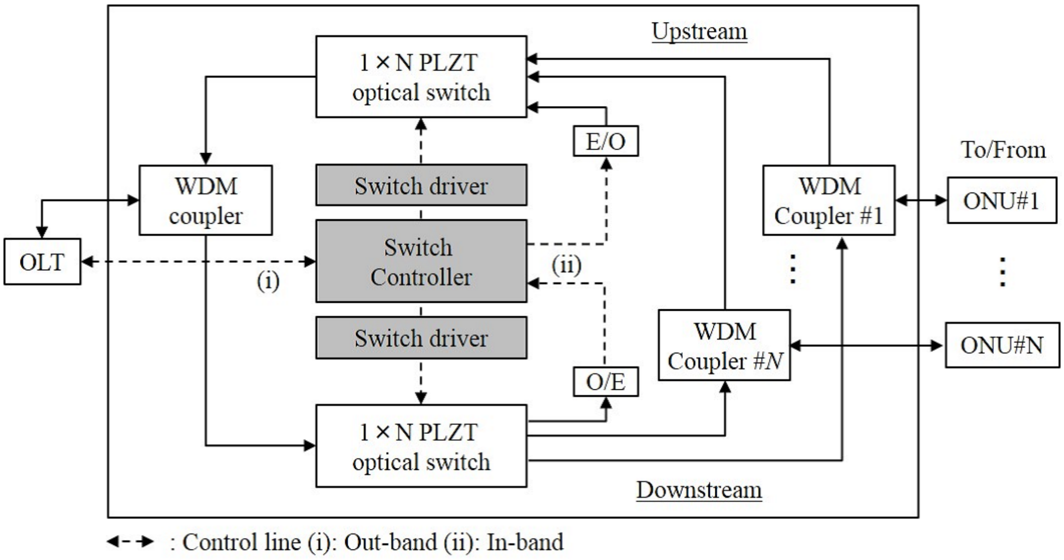

Figure A.1: Configuration of Optical Switching Unit.

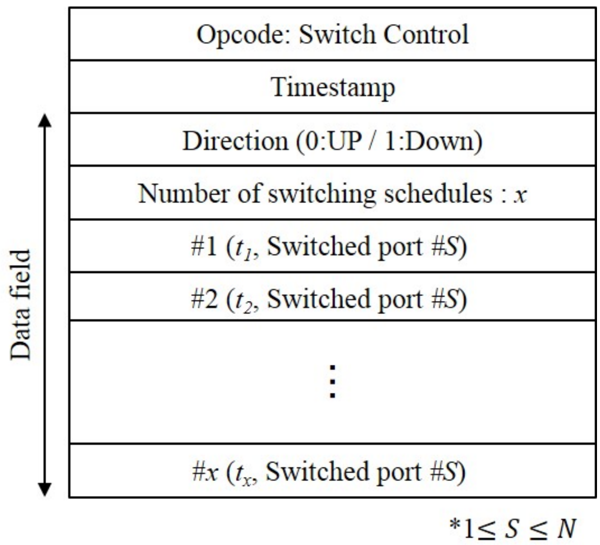

Figure A.2: Format of MPCP frame based switch control frame.

ing schedule patterns are comprised of switching start time t_x and the switched port #S ($1 \leq S \leq N$, N is the number of ports on the side of ONUs). The switching start time t_x shows the start time of allocated period for ONU#x at the OSU. The length of switching schedule is determined by the number of ports on the side of OLTs.

Appendix B

Cost evaluation of optical access networks

In order to introduce ActiON with PLZT optical switches, Capital Expenditure (CAPEX) for replacing regular PON with ActiON and Operating Expenditure (OPEX) for maintaining the ActiON are important factors. In this evaluation, as a first step, we make a CAPEX comparison between ActiON and PON in terms of costs of required components. The relative costs of key components in optical access networks are as shown in Table B.1 [B-1]. The trasmission distance is set to 20 km, which is the maximum transmission distance of the PON. Also, the transmission distances of the base line and the branch line are set to 18 km and 2 km, respectively.

Table B.1: Relative costs of key components in optical access networks.

OLT	150
ONU	5
Optical splitter	1
Optical fiber (per one kilometer)	0.5
PLZT optical switch	150

Figure B.1 shows the relationship between the normalized total cost of components (CAPEX) and the number of users. The normalized total cost of ActiON is cheaper than that of the PON when the number of users exceeds 64. Because the ActiON can reduce the number of total network components, including the OLT and the optical fiber, by aggregating the network components due to a low insertion loss of PLZT optical switch. In this way, the ActiON realizes a cost-effective network compared to the PON in the

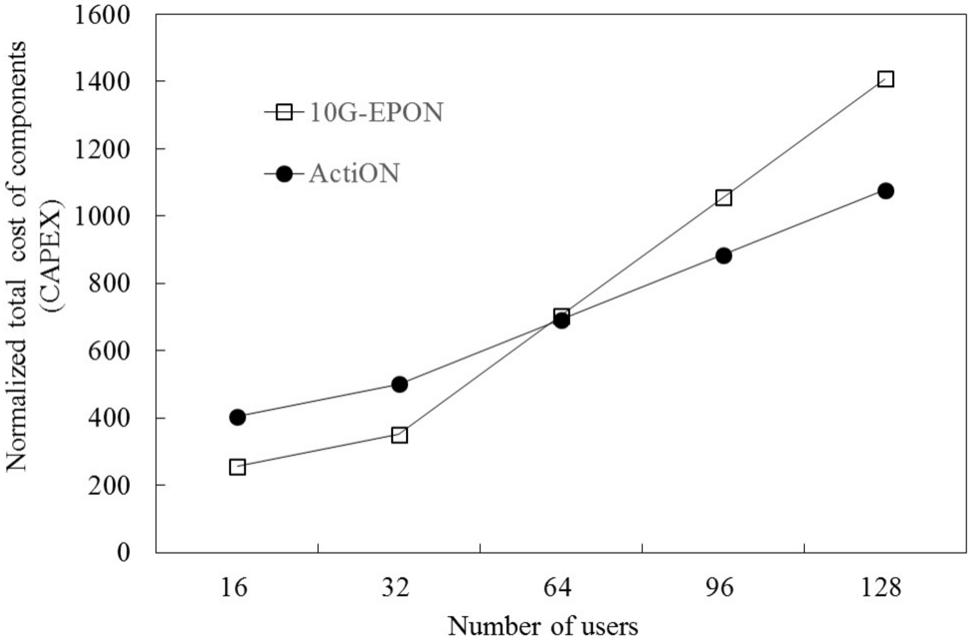

Figure B.1: Normalized cost of components (CAPEX) versus number of users.

scalable optical access network.

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Appendix C

Acronym

Chapter 1	10G-EPON	10 Gigabit-Ethernet Passive Optical Network
	FSAN	Full Service Access Network
	FTTH	Fiber To The Home
	ICT	Information and Communication Technology
	IEEE	Institute of Electrical and Electric Engineers
	IPTV	Internet protocol television
	ITU-T	International Telecommunication Union Telecommunication Standardization Sector
	NG-PON1	Next Generation-Passive Optical Network1
	NG-PON2	Next Generation-Passive Optical Network2
	ONU	Optical Network Unit
	PON	Passive Optical Network
	VoD	Video on Demand
	VoIP	Voice over Internet Protocol
Chapter 2	ActiON	Active Optical Access Network
	ADC	Analog to Digital Conversion
	ALR	Adaptive Link Rate
	APD	Avalanche Photo Diode
	AWG	Arrayed Waveguide Gratings
	BPON	Broadband Passive Optical Network

Chapter 2	CDR	Clock and Data Recovery
	DAC	Digital to Analog Conversion
	DBA	Dynamic Bandwidth Allocation
	DSP	Digital Signal Processor
	DFB-LD	Distributed Feedback-Laser Diode
	E/D	Encoder/Decoder
	EML	Electro-absorption Modulator-integrated Laser
	GE-OSAN	Gigabit Ethernet Optical Switched Access Network
	G-EPON	Gigabit-Ethernet Passive Optical Network
	G-PON	Gigabit-Passive Optical Network
	LA	Limiting Amplifier
	LLID	Logical Link Identifier
	MEMS	Micro Electro Mechanical Systems
	MPCP	Multi-Point Control Protocol
	multi-service adaptable ActiON	multi-service adaptable Active Optical Access Network
	MZ	Mach-Zehnder
	O/E	Optical/Electrical
	OCDM	Optical Code Division Multiplexing
	OCDM-PON	Optical Code Division Multiplexing-Passive Optical Network
	OFDM	Orthogonal Frequency Division Multiplexing
	OFDM-PON	Orthogonal Frequency Division Multiplexing-Passive Optical Network
	OLT	Optical Line Terminal
	OSM	Optical Switching Module
	PLZT	Plumbum Lanthanum Zirconate Titanate
	SOA	Semiconductor Optical Amplifier
	SSFBG	Single phase-shifted Super Structure Fiber Bragg Grating
	TC	Transmission Convergence
	TDM	Time Division Multiplexing
	TDMA	Time Division Multiplexing Access
	TDM-PON	Time Division Multiplexing-Passive Optical Network
	TIA	Transimpedance Amplifier
	VCO	Voltage Controlled Oscillator

Chapter 2	TS	Time Spreading
	TWDM-PON	Time and Wavelength Division Multiplexing-Passive Optical Network
	UNIs	User Network Interfaces
	WDM	Wavelength Division Multiplexing
	WDMA	Wavelength Division Multiplexing Access
	WDM-PON	Wavelength Division Multiplexing-Passive Optical Network
Chapter 3	ILP	Integer Linear Programming
	NS2	Network Simulation2
Chapter 4	NLP	Non Linear Programming
Chapter 5	EDFA	Erbium-Doped Fiber Amplifier
Chapter 6	QoS	Quality of Service
	QoE	Quality of Experience
Appendix B	CAPEX	Capital Expenditure
	OPEX	Operating Expenditure

List of the Related Papers

Journal papers

Papers Related to this Ph.D. Dissertation

(1) **Kunitaka Ashizawa**, Takehiro Sato, Kazumasa Tokuhashi, Daisuke Ishii, Satoru Okamoto, Naoaki Yamanaka, and Eiji Oki, "On-Demand Multicast Slot Allocation Scheme For Active Optical Access Network Using PLZT High-Speed Optical Switches," *Cyber Journals: Multidisciplinary Journals in Science and Technology, Journal of Selected Areas in Telecommunications (JSAT)*, Vol. 2, No. 5, pp. 19-27, May Edition, 2011.

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Acknowledgments

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

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

I owe a great deal of thanks to the members of dissertation committee, Prof. Iwao Sasase in Department of Information and Computer Science, Keio University, Japan, Prof. Hideharu Amano in Department of Information and Computer Science, Keio University, Japan, Prof. Hiroyuki Tsuda in Department of Electronics and Electrical Engineering, Keio University, Japan, Prof. Andrea Fumagalli in the University of Texas at Dallas, USA, Prof. Malathi Veeraraghavan in University of Virginia, USA for their comments, suggestions, and careful and critical reading of this dissertation.

I am deeply grateful to Prof. Satoru Okamoto of Yamanaka Lab., Department of Information Technology, Keio University, Japan. He gave insightful comments and suggestions, especially about future network.

I am very grateful to thank to Prof. Eiji Oki in Faculty of Informatics and Engineering, The University of Electro-Communications, for his valuable supports and comments about my studies and dissertation.

I would like to thank to Dr. Hidetoshi Takeshita, Assistant of Yamanaka Lab. in Department of Information and Computer Science, Keio University, Japan. He gave me constructive comments and warm encouragements.

I thank to other current and old members of Yamanaka Lab., Mr. Takehiro Sato, Mr. Soushi Yamamoto, Mr. Shanming Zhang, Mr. Akiyuki Imamura, Mr. Asato Kotsugai, Mr. Takuro Okano, Mr. Tetsuhiro Uchida, Mr. Teppei Yamaguchi, Mr. Naoki Maruichi, Mr. Julien Thieffry, Mr. Kousuke Asami, Mr. Mitsuyasu Endo, Mr. Shoichi Nagata, Mr. Takahiro Miyazaki, Mr. Guillaume Ludinard, Ms. Kei Nakamura, Ms. Mayu Ota, Mr. Mirai Chino, Mr. Ryo Kutsuzawa, Mr. Yoshihiro Isaji, Mr. Yusuke Nakajima, Mr. Akira Yamashita, Ms. Mai Arase, Mr. Masayuki Hirono, Ms. Misato Kamio, Mr. Naoya Takemura, Mr. Yukihiro Imakiire, Dr. Yutaka Arakawa, Dr. Daisuke Ishii, Dr. Sho Shimizu, Mr. Masahiro Hayashitani, Mr. Hiroyuki Ishikawa, Mr. Hiroyuki Miyagi, Mr. Teruo Kasahara, Mr. Tomohiro Tsuji, Mr. Kazuki Irie, Dr. Kou Kikuta, Mr. Masahiro Nishida, Mr. Mikio Kaneko, Mr. Ryota Usui, Mr. Taku Kihara, Mr. Hirofumi Yamashita, Dr. Kazumasa Tokuhashi, Ms. Midori Terasawa, Ms. Motomi Akagi, Mr. Syan Gao, Mr. Yusuke Okazaki, Ms. Aya Turusaki, Mr. Junpei Marukawa, Ms. Kazuko Yonezawa, Mr. Shota Yamada, Mr. Yuki Susa, Ms. Haruka Yonezu, Mr. Haruki Takahashi, Mr. Jun Matsumoto, Mr. Kenta Nakahara, Mr. Sunbuer Alateng, Mr. Yutaro Hara, Mr. Naohiko Shibuta, Mr. Takashi Tazoe, Ms. Rumi Akimunem, Mr. Yuji Shimada, Mr. Yuki Nomura, Ms. Akiko Hirao, Mr. Harunaga Onda, Mr. Yuki Higuchi. All members inspired me in my research life.

I appreciate the works of secretaries of Yamanaka Lab., Ms. Ayumi Sato, Ms. Kaori Kozakai, Ms. Yasuyo Komai, and Ms. Atsuko Morimoto.

I wish to express my sincere gratitude to Dr. Keiichi Nashimoto who is founder, president and CEO of EpiPhotonics Corp. A high speed optical switch such as PLZT optical switch developed by EpiPhotonics Corp. is essential for an active optical access network.

Finally, I would like to express my deepest gratitude to Maki Ashizawa of my wife, Yutaka Ashizawa of my son, and Kodai Ashizawa of my father, Tomoko Ashizawa of my mother, and Mina Ashizawa of my sister for moral support and warm encouragements. This dissertation could not be completed without their supports and encouragements.

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September, 2015