On-Demand Multicast Slot Allocation Scheme For Active Optical Access Network Using PLZT High-Speed Optical Switches

Kunitaka Ashizawa, Takehiro Sato, Kazumasa Tokuhashi, Daisuke Ishii, Satoru Okamoto,
Naoaki Yamanaka, and Eiji Oki

***Abstract*—This paper proposes an on-demand multicast slot allocation scheme for an active optical access network that uses Mach-Zehnder-type high-speed optical switches, which are achieved by the Plumbum Lanthanum Zirconate Titanate (PLZT) switching technology. The Active Optical Network, called ActiON, is based on slot-based switching. Compared to the Passive Optical Network (PON), ActiON quadruples the number of subscribers (128 users) per optical line terminal (OLT) and doubles the maximum transmission distance (40 km) between OLT and optical network units (ONUs). However, as ActiON uses slot-based switching, it needs a large number of slots to deliver multicast contents to the requesting users. This greatly lowers network utilization rates. The proposed multicast slot allocation scheme overcomes this problem to provide on-demand multicast services, while keeping the advantages of ActiON. Multicast delivery is realized by running the Mach-Zehnder-type high-speed optical switch elements in distribution mode, which forces the switch to behave as an optical splitter. The proposed scheme iteratively solves the integer linear programming (ILP) problem to associate multicast users with slots. Numerical results show that the proposed scheme dramatically reduces the required number of slots, compared to non-multicast ActiON and provides comparable the performance of bandwidth efficiency to 10 G-EPON, and the required computation time of the proposed scheme is less than 0.3 sec, which is feasible for on-demand services.**

***Index Terms*—Access protocol, Optical fiber networks, Optical switches, and Time division multiple access.**

I. INTRODUCTION

The Passive Optical Network (PON) [1] system is widely used as an access network. Gigabit Ethernet Passive Optical Network (GE-PON) [2] is the representative example of the access network.

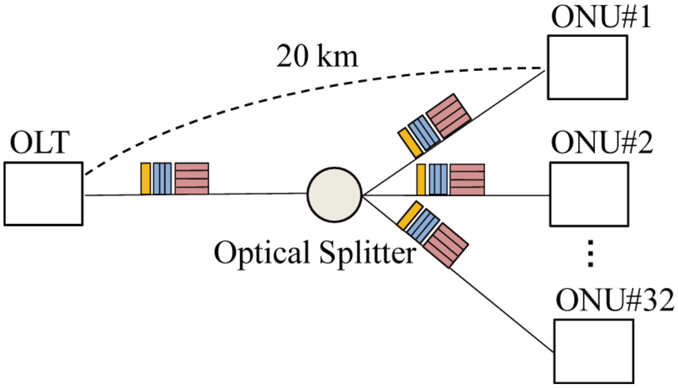


Fig. 1. PON architecture.

Figure 1 shows that the PON architecture consists of three components: Optical Line Terminal (OLT), which connects to backbone network; Optical Network Unit (ONU), which communicates with the user terminal; and an optical splitter. The data transmission of PON is that all data is broadcasted by the optical splitter to all ONUs, and each ONU selects its own data from all data. The current target in access networks is the 10 Gigabit Ethernet Passive Optical Network (10 G-EPON) [3]. The advantages of PON include low-cost and low-power consumption due to its use of a passive optical splitter.

However, PON systems are limited in terms of the maximum number of ONUs (32) and the maximum transmission distance (20 km) between OLT and ONUs. This is because the optical power is divided at the splitter and decreases as the number of ONUs increases. Moreover, PON system is a low-security architecture in principle because each ONU receives all signals from OLT. A malicious user can intercept all data.

PON systems have been extensively studied for next generation optical broadband access networks. Wavelength Division Multiplexing (WDM)-PON [4] [5] provides high-bandwidth and high-security by using a unique wavelength to each ONU. However, WDM-PON does not achieve the high bandwidth efficiency because the number of available wavelengths is limited to each ONU. Long-Reach (LR)-PON [6] [7] extends the transmission distance of PON systems by exploiting optical amplifiers and WDM technologies. However, LR-PON consumes highly the power consumption by using optical amplifiers and its security is low.

To increase the bandwidth efficiency and provides highly secure services with longer distances than conventional PON systems [3], active access networks using packet-based optical

---

A part of this paper was presented at 11th International Conference on High Performance Switching and Routing (HPSR 2010), Richardson, TX, Jun. 2010.

Kunitaka Ashizawa, Takehiro Sato, Kazumasa Tokuhashi, Daisuke Ishii, Satoru Okamoto, and Naoaki Yamanaka are with the Yamanaka Laboratory, Department of Information and Computer Science, Keio University, 3-14-1 Hiyoshi, Kohoku, Yokohama, Kanagawa, JAPAN 223-8522 (e-mail:ashizawa@yamanaka.ics.keio.ac.jp)

Eiji Oki is a Visiting Associate Professor, Graduate school, Faculty of Science and Technology, Keio University, Kanagawa, 223-8522 Japan, and is an Associate Professor, Department of Communication Engineering and Informatics, Graduate School of Informatics and Engineering, The University of Electro-Communications, Tokyo, 182-8585 Japan.

switches were presented [8]–[10]. The literatures provide longer transmission distance than conventional PON systems and high-security by using optical packet switches without optical buffers. However, analyzing each packet's header for packet-by-packet switching with Optical/Electrical (O/E) conversions is required. It becomes a bottleneck and is not cost-effective for the 10 or more Gbps high-bandwidth environments. Moreover, the access network architectures with packet-based switching do not provide transparent transmission without O/E/O conversions.

To achieve transparent transmission without O/E conversion, while keeping the advantages of active access networks [8]–[10], the active optical access network using slot-based optical switches has been presented. It is called Active Optical Network (ActiON) [11]. ActiON employs Mach-Zehnder-type Plumbum Lanthanum Zirconate Titanate (PLZT) high-speed optical switches [12]–[14]. It replaces an optical splitter, which is used in PON systems, with a slot-based switch to make the optical power loss independent of the splitter number. It quadruples the number of subscribers (128 users) per OLT and doubles the maximum transmission distance (40 km) between OLT and ONUs, compared to 10G-EPON. Moreover, ActiON provides a high-security architecture and transparent transmission without O/E conversion because each ONU receives only own data by PLZT switching technology.

The demands that the access network support multicast delivery are increasing with the spread of broadcast service. The broadcast services in an access network should be provided in a scalable and secure manner according to users' requirements. In PON systems for multicast delivery, the multicast data is broadcasted to all ONUs using a optical splitter. The PON systems may increase the bandwidth efficiency for multicast delivery thanks to the broadcast nature.

However, the PON systems do not provide a scalable and high security architecture. Some ONUs which do not belong to the same multicast group receives non-related multicast data from OLT.

On the other hand, ActiON provides a scalable and secure access network by high-speed slot-based optical switches. However, as ActiON uses slot-based switching, it needs a large number of slots to deliver multicast contents to the requesting users. This greatly lowers the utilization rate of the network.

This paper proposes a multicast slot allocation scheme for on-demand multicast services that overcomes this problem, while keeping the advantages of ActiON. This paper is an extended version of [15], where the extensive literature surveys are described, discussions on the structure of the PLZT optical switch by using the experimental results and the control of switches for multicast delivery are extensively added and the proposed scheme are described in a mathematical, and the comparison between existing approaches and out approach is described in the related work. Numerical results show that the proposed scheme dramatically reduces the required number of slots, compared to non-multicast ActiON and provides comparable the performance of bandwidth efficiency to 10 G-EPON, and the required computation time of the proposed scheme is less than 0.3 sec, which is applicable to on-demand services.

The remaining sections of this paper are organized as follows. Section II describes the ActiON system, Section III describes the proposed multicast slot allocation scheme. Section IV describes the heuristic approach for the multicast slot allocation scheme. Section V shows the results of slot allocation via the ILP solver [16]. Section VI shows the related works. Finally, Section VII describes our conclusions.

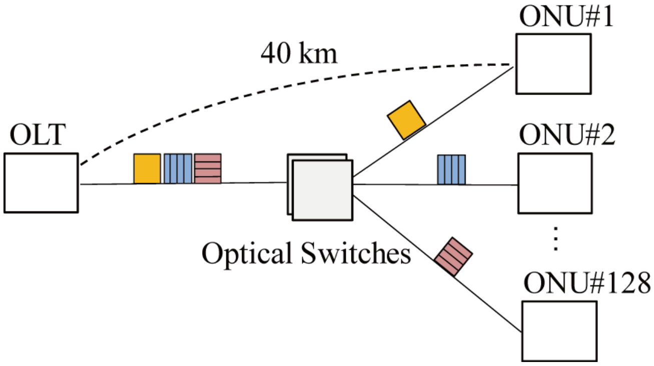


Fig. 2. ActiON architecture.

II. ACTIVE OPTICAL NETWORK

A. Architecture

Figure 2 shows the basic ActiON architecture [11]. Two optical switches (Upstream switch and Downstream switch) are set between the OLT and ONUs.

B. Structure of the 1 ×128 PLZT optical switch

PLZT 10 nsec high-speed optical switches are used in ActiON. Figure 3 shows the structure of a 1×128 PLZT optical switch [17]. The 1×128 PLZT optical switch sets 1×2 optical switch elements in a multistage (7 stages) configuration. The 1×2 optical switch element is a Mach-Zehnder-type wave-guide structure [12]–[14], so the optical signal is switched by changing the voltage applied to the electrodes A or B. Figure 4 shows the driving the Mach-Zehnder-type optical switch. The voltage (9.5V) applied to the only electrodes A sets the cross state in Figure 5 and the voltage (9.0V) applied to the only electrodes B yields the bar state in Figure 6. We refer to these states as the switching mode.

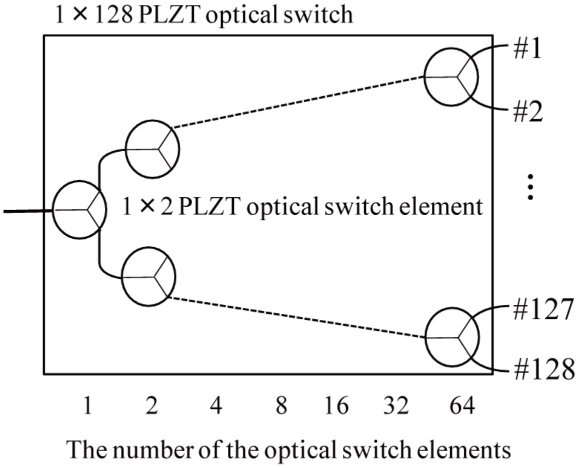


Fig. 3. Structure of the PLZT optical switch.

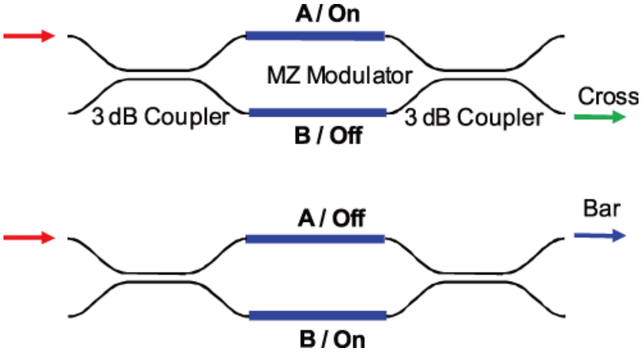


Fig. 4. Driving the Mach-Zehnder-type optical switch as switching mode.

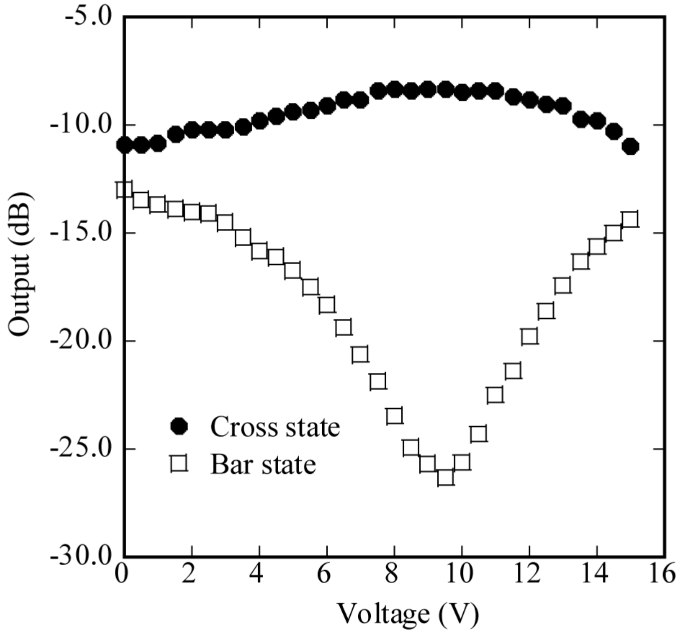


Fig. 5. Changing optical signal by the voltage applied to only electrodes A.

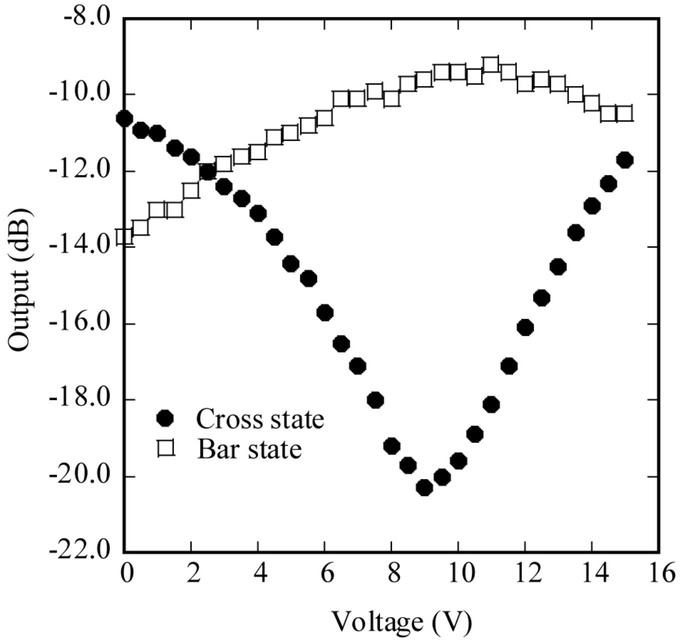


Fig. 6. Changing optical signal by the voltage applied to only electrodes B.

C. *Control of switches*

In ActiON, the Multi-Point Control Protocol (MPCP) [3] is adopted for compatibility with 10 G-EPON (IEEE802.3av) [3]. The bandwidth is allocated to each user by assigning fixed-length time periods for easy control [18]. This period is called a ”slot”. The optical switch is controlled by the unit of ”cycle”, which is composed of multiple slots, see Figure 7.

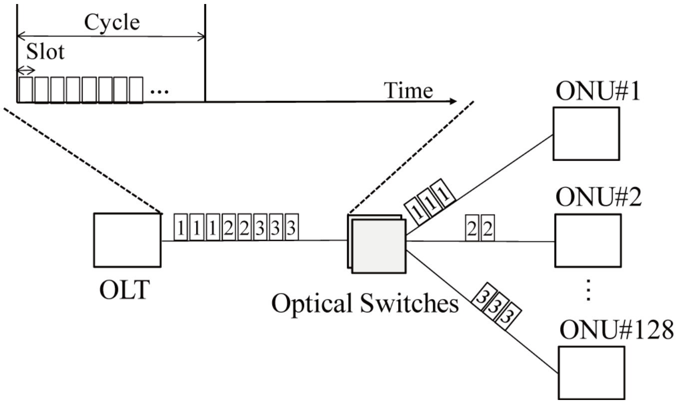
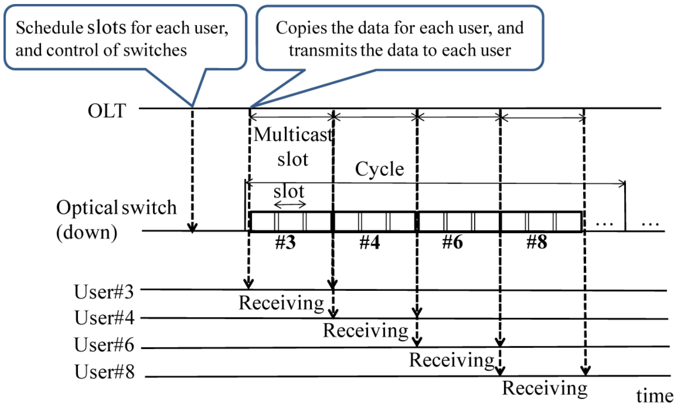


Fig. 7. Slot switching.



✓Number of the multicast slot: **4slot**

Fig. 8. Example of multicast slot allocation with the slot switching.

This control of the switches is called ”slot switching”. Figures 8 and 9 show an example of multicast slot allocation and the control of switches with slot switching. A multicast slot is a set of several slots that are used to deliver multicast contents. To simplify the discussion on the slot switching, we focus on the downstream on the multicast delivery. The 1×8 PLZT optical switch, which sets 1×2 optical switch elements in three-stage configuration, are used. Users (ONUs) #3, #4, #6, and #8 are multicast users. First of all, each user transmits the demand traffic to OLT. Next, OLT schedules several slots (in this example, three slots per multicast slot) for each user by calculating the demand traffic of each user, transmits the switching control message to the optical switches, and transmits multicast data to that user in the assigned slot. ActiON does not directly support multicast delivery, so OLT copies the data for each user and transmits the data to each user by slot switching. The number of multicast slots needed is four, in other words, the number of slots is 12 (= 3×4). The number of slots required increases with the number of the multicast users, so the utilization efficiency of the slot allocation scheme is poor. Our proposed extension of ActiON is introduced below.

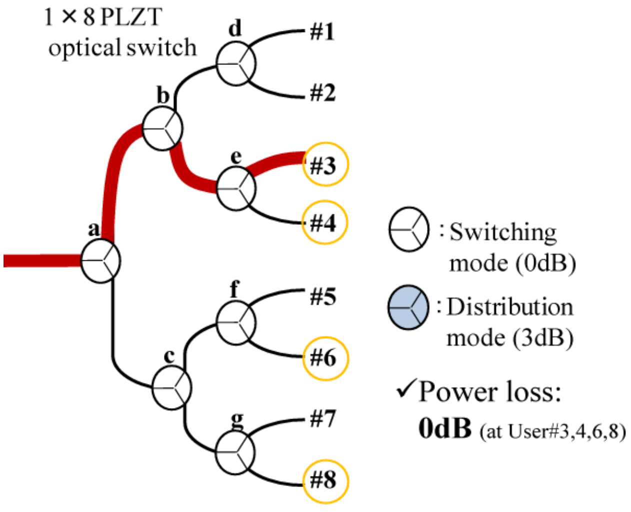


Fig. 9. Control of switches with slot switching.

III. PROPOSED MULTICAST SLOT ALLOCATION SCHEME FOR ACTION

A. *Creating the distribution mode*

The Mach-Zehnder-type optical switch is possible to yield the multicast state in which the switch acts as a splitter without applying any voltage to both electrodes A and B, see Figure 10, while it was originally intended for only switching mode operation. We call this the distribution mode.

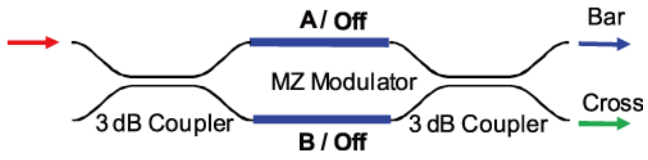


Fig. 10. Driving the Mach-Zehnder type optical switch as distribution mode.

B. *Multicast slot allocation scheme for distribution mode operation*

Figures 11 and 12 show the examples of multicast slot allocation and the control of switches with the distribution mode. The 1 × 8 PLZT optical switches which sets 1×2 optical switch elements in three-stage configuration are used. Users #3, #4, #6, and #8 are multicast users. With the distribution mode, the OLT multicasts the data to users #3, #4, #6, and #8 by setting the optical switch elements (a , c, and e) to the distribution mode. Just one multicast slot (three slots) is needed to perform the multicast. Singlecast users are served in the switching mode.

C. *Power loss of the optical signal to each user*

In the switching mode, the switch suffers no additional intrinsic loss. To simplify the discussion about the constrained condition of each optical switch, we focus on the difference in power loss between the switching and distribution modes. Figures 9 and 12 show the difference in power loss between the switching and distribution modes. The power loss of the optical signal when using the optical switch in the switching mode is taken to be 0 dB; connection losses are not considered. On the other hand, the power loss of the optical signal when using the optical switch element as the distribution mode is 3dB per switch. In the switching mode, the power loss of the optical signal to each user (#3, #4, #6, and #8) is 0dB (= 0dB + 0dB + 0dB). However, in the distribution mode, the power loss of the optical signal to each user (#3, #4, #6, and #8) is 6dB (= 3dB + 3dB + 0dB), so the optical signal experiences a significant power loss. It is clear that the distribution mode creates a tradeoff between utilization efficiency and the power loss experienced by the optical signal to each multicast user.

D. *Limit on the number of optical switch stages in distribution mode*

In the PON system, the power loss of the optical signal per user is required to be at most 15dB. The 1×32 optical splitter of the PON system has a multistage (5 stages) arrangement of 1×2 optical splitters, so the power loss of the optical signal is 15dB (= 3dB×5). In the multicast slot allocation scheme for ActiON, in order to realize a practical access system with transmission distance 20 km (the maximum transmission in the PON system) or more, the limit on the power loss of the optical signal is 12dB, and the maximum number of optical switch stages using the distribution mode is 4 of 7 stages. This makes it necessary to carefully select which optical switch elements are placed into distribution mode.

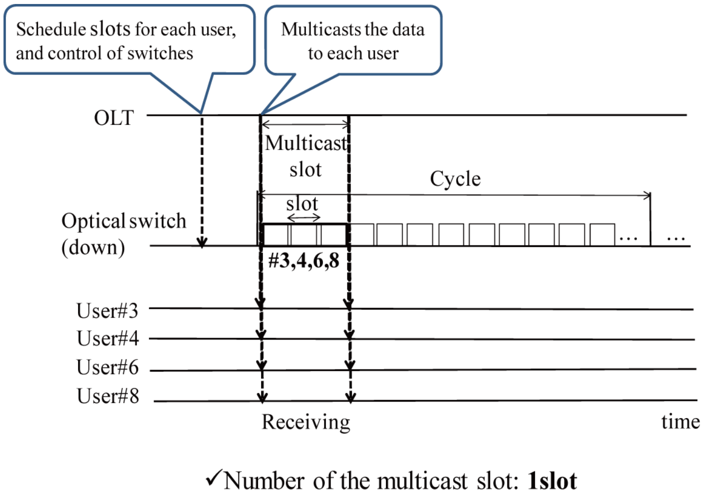


Fig. 11. Example of multicast slot allocation with distribution mode.

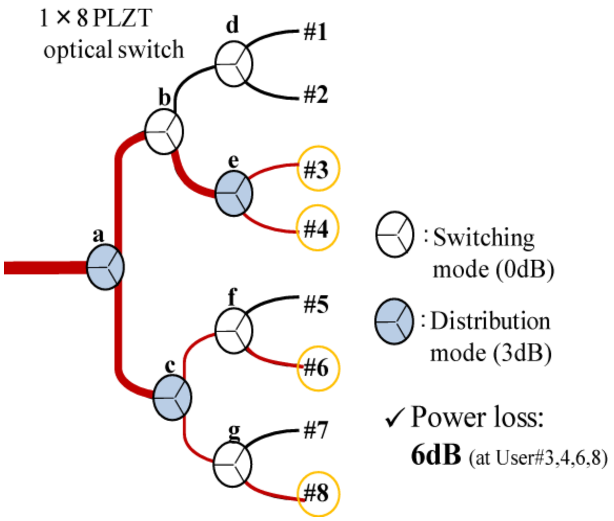


Fig. 12. Control of switches with distribution mode.

IV. HEURISTIC APPROACH FOR THE MULTICAST SLOT ALLOCATION SCHEME

A. *Overview*

To maximize the bandwidth efficiency, it is necessary to minimize the required number of slots used to realize the multicast service. The naive approach is to consider all possible combinations for the multicast slot allocation. Let *x* be the number of all possible combinations for *N* multicast users. *x* lies in the range of $\prod_{k=1}^{N2^{-H}} 2^{N-(k-1)2^H} \le x \le \prod_{k=1}^{N} 2^{N-(k-1)}$, 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 scheme 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 not always obtain the *optimal* solution in terms of minimizing the required number of multicast slots. The proposed scheme proceeds as follows.

1) *Step1:* For the first multicast slot deemed available for multicast delivery, the ILP problem described below is solved so as to maximize the number of multicast users that can be assigned to the multicast slot. The satisfied multicast users are eliminated from the set of requesting multicast users.

2) *Step2:* If any requesting multicast user remains unsatisfied, the next multicast slot is allocated following Step 1. Otherwise, multicast slot allocation is completed.

C. *Maximizing the number of allocated users*

This subsection formulates the optimization problem that maximizes the number of allocated users in Step 1 above.

1) *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.
$\lceil x \rceil$	Smallest integer greater than or equal to *x*.
i	Index of switch stage, where $0 \le i \le \log_2 N$.
j	Index of switch at *i*th stage, where $1 \le j \le \frac{N}{2^i}$
u	User index, where $1 \le u \le N$.
I	Set of i.
J	Set of j.
J_{odd}	Set of j, where j is an odd number.
s_{ij}	*i*th-stage *j*th switch.
l_{ij}	Link between $s_{i+1\lceil \frac{j}{2} \rceil}$ and s_{ij}.
S_{ou}	If user *u* has a request, $S_{ou} = 1$. Otherwise, $S_{ou} = 0$.
S_{ij}	If s_{ij} is set to distribution mode, $S_{ij} = 1$. If s_{ij} is set to non-distribution mode, $S_{ij} = 0$. $(i \ne 0)$
L_{ij}	If l_{ij} has optical signal, $L_{ij} = 1$. Otherwise, $L_{ij} = 0$.
H	Limit on the number of stages for the optical switch elements using distribution mode.

2) *Formulation:* The ILP problem used to maximize the number of multicast user per multicast slot is described below.

$$\max \sum_{u, where S_{ou=1}} L_{ou} \tag{1a}$$

$$\text{s.t} \quad L_{i+1\lceil \frac{j}{2} \rceil} + S_{i\lceil \frac{j}{2} \rceil} = L_{ij} + L_{ij+1}, \quad i \in I, j \in J \tag{1b}$$

$$L_{i+1\lceil \frac{j}{2} \rceil} \ge S_{i\lceil \frac{j}{2} \rceil}, \quad j \in J_{odd} \tag{1c}$$

$$\sum_{i \in I} S_{i\lceil \frac{2p-1}{2^i} \rceil} \le H, \quad 1 \le p \le \frac{N}{2} \quad \text{(p:integer)} \tag{1d}$$

The objective function in Eq. (1a) indicates the selection of the maximum number of multicast users. The constrained conditions in Eqs. (1b) and (1c) indicate the relationships between the use of each optical switch element and the optical power. Figures 13, 14, and 15 show three relationships between the use of each optical switch element and the optical power. The constrained condition in Eq. (1d) indicates the limit on the number of stages in which the optical switch elements are set in distribution mode.

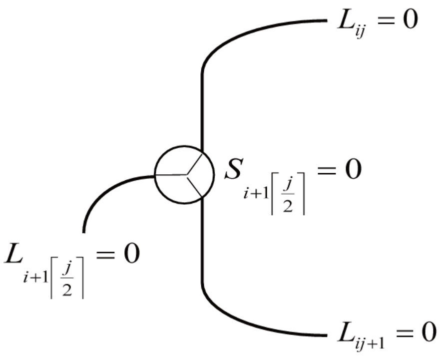


Fig. 13. Constrained conditions of each optical switch element (Upper link of the optical switch has no optical power and distribution mode is not used).

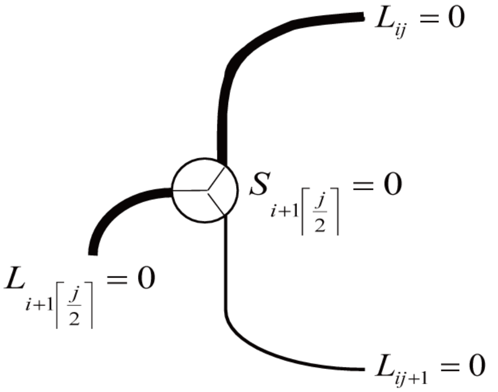


Fig. 14. Constrained condition of each optical switch element (Upper link of the optical switch has an optical power and distribution mode is not used).

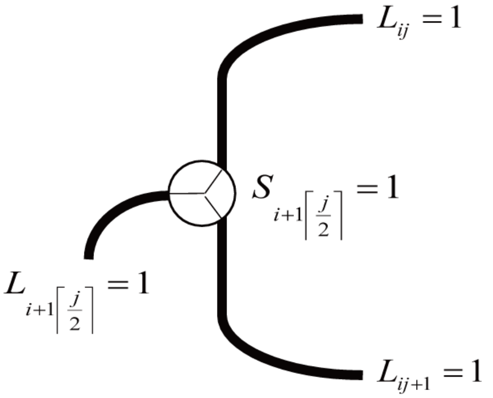


Fig. 15. Constrained condition of each optical switch element (Upper link of the optical switch has an optical power and distribution mode is used).

V. SIMULATION OF THE MULTICAST SLOT ALLOCATION SCHEME

This simulation evaluated the required number of multicast slots for the multicast in each slot allocation and the maximum computation time for selecting multicast users in the proposed allocation. The simulator was coded by using the C language combined with GNU Liner Programming Kit (GLPK) [16], which is an ILP solver. Parameters used in our simulation are shown below. The number of ONUs is 128. 10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 110, 120, and 128 of all users (randomly selected) are taken as demanding the same multicast content. The number of the trials was set at 10^6 for each proportion of the multicast users. The 1×128 PLZT optical switch has a 7 stage cascade of 1×2 optical switch elements and the maximum number of optical switch stages is four. The multicast slot allocation scheme is run on the PC whose processor is an Intel Pentium 4 2.80GHz, and which has 256MB RAM.

Figure 16 shows the number of multicast slots required to satisfy the multicast user demands. To maximize the bandwidth efficiency, it is necessary to minimize the required number of slots used to realize the multicast service. At all loads examined, the proposed slot allocation scheme closely approached the theoretical lower bound, which is the minimum number of multicast slots for any request pattern. The proposed scheme dramatically reduced the number of multicast slots and increased the bandwidth efficiency, compared to the conventional ActiON. The theoretical lower bound is the number of multicast slots obtained by statically allocating to 2^H users for each slot. It is solved by using $\left\lceil \frac{R}{2^H} \right\rceil$. R is the number of multicast users. H is the limit on the number of stages for the optical switch elements using distribution mode. In this simulation, H is set at 4. For example, when the number of users is 30, the theoretical lower bound becomes 2 ($= \left\lceil \frac{30}{2^4} \right\rceil$).

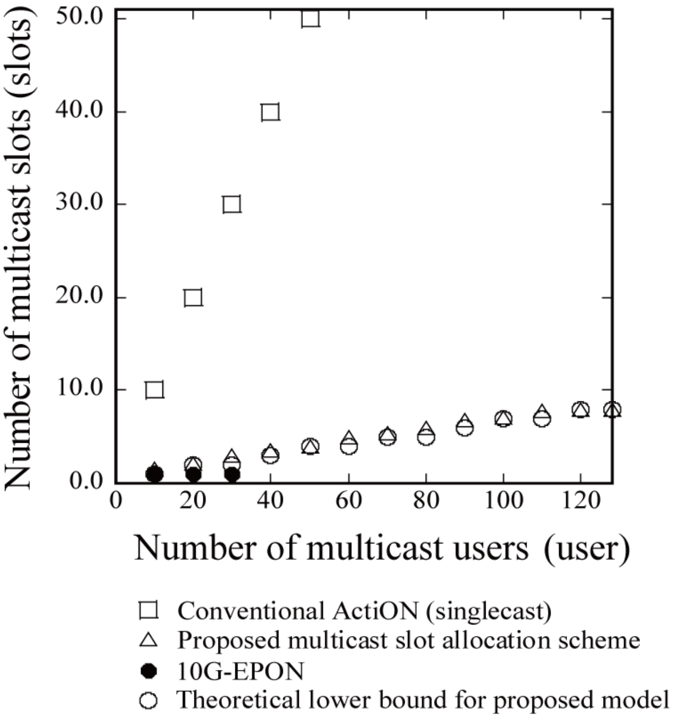


Fig. 16. Number of multicast slots versus multicast user demand.

Figure 16 also compares the required number of multicast slots between 10 GE-PON and the proposed scheme. In 10 G-EPON, the maximum number of ONUs is 32 and the maximum transmission distance is 20 km. In conventional ActiON, the maximum number of ONUs is extended to 128 and the maximum transmission distance is extended to 40 km. In the proposed slot allocation scheme for ActiON, the required number of multicast slots is only a few slots larger than that of 10 GE-PON within 30 users. This means that the proposed scheme provides comparable the performance of bandwidth efficiency to 10 GE-PON when the number of users is small, while the proposed scheme extends the limitation of the number of users for 10 GE-PON to 128.

Figures 17, 18, 19, 20, and 21 show the frequency distributions of the number of the multicast slots for the multicast user demands considered. For all demands, the distributions are very tight. The average differences between the number of multicast slots obtained by the proposed scheme and the theoretical lower bounds are shown in Table I. The difference between the maximum number of slots and the theoretical lower bound is at most 1 regardless of the level of demand.

Figure 22 shows that the maximum computation time of the proposed scheme is less than 0.3 sec, which well suits on-demand services.

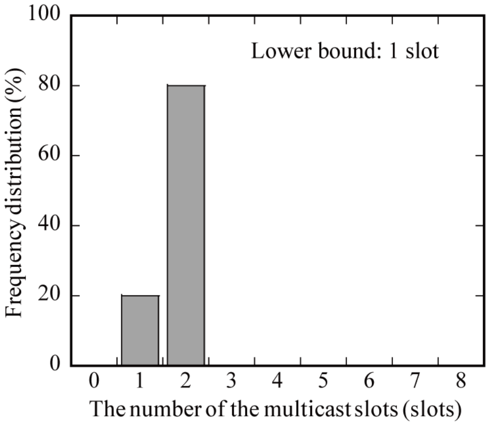


Fig. 17. Frequency distribution of the number of multicast slots versus multicast user demand (Proportion of the multicast users: 10 percent).

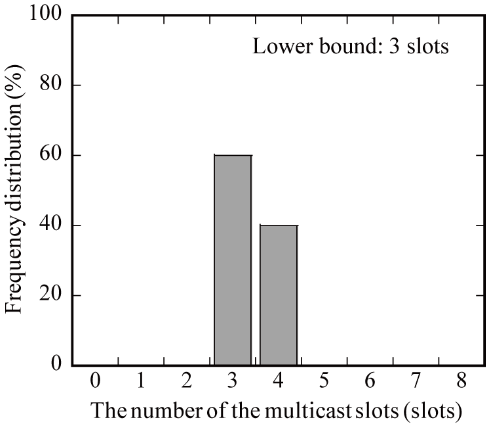


Fig. 18. Frequency distribution of the number of multicast slots versus multicast user demand (Proportion of the multicast users: 30 percent).

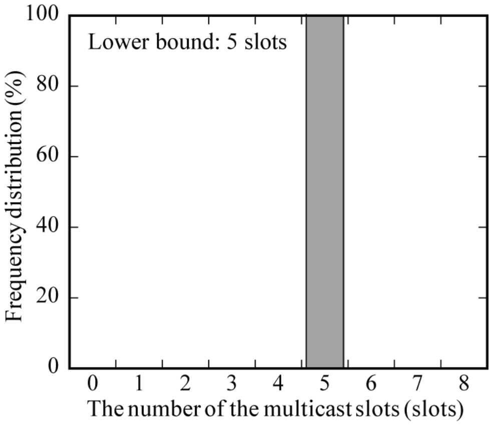


Fig. 19. Frequency distribution of the number of multicast slots versus multicast user demand (Proportion of the multicast users: 50 percent).

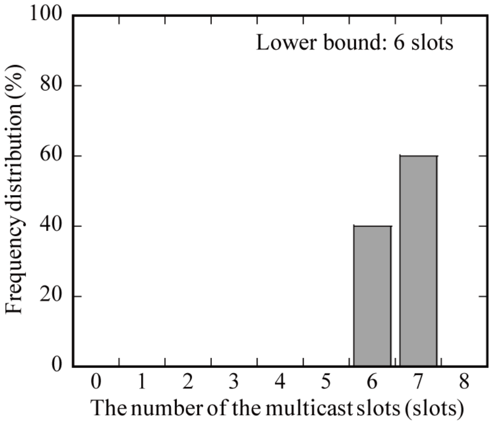


Fig. 20. Frequency distribution of the number of multicast slots versus multicast user demand (Proportion of the multicast users: 70 percent).

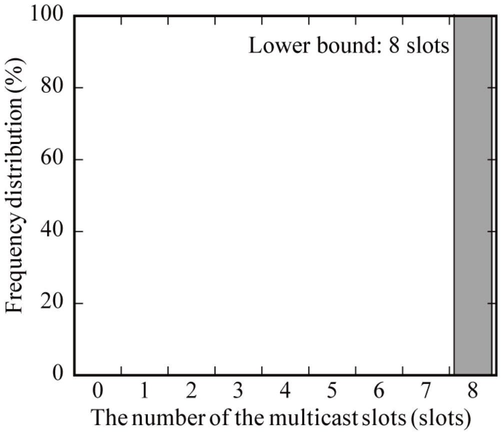


Fig. 21. Frequency distribution of the number of multicast slots versus multicast user demand (Proportion of the multicast users: 90 percent).

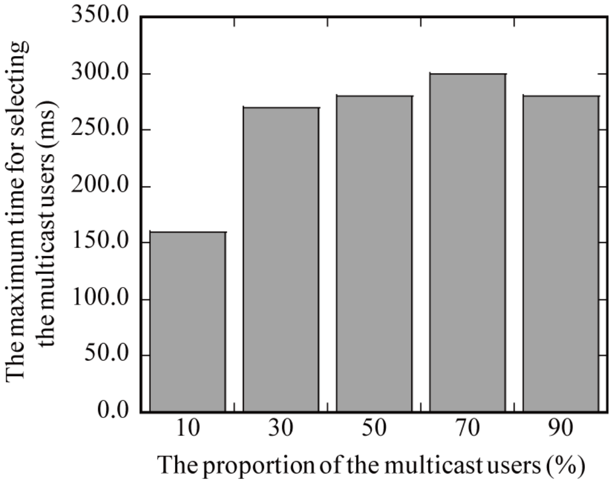


Fig. 22. Time to find the maximum number of multicast users per multicast slot.

TABLE I
Comparison of the number of multicast slots between the proposed and theoretical lower bounds

Proportion of the multicast users (%)	10	30	50	70	90
Average differences between the number of multicast slots obtained by the proposed scheme and the theoretical lower bounds	0.8	0.4	0	0.6	0

TABLE II
Comparison between existing approaches and our approach

		Applicability	Target distance	Maximum number of users	Bandwidth	Security	Utilization efficiency of Multicast	Switching control	References
Passive Optical Network	10G-EPON	Access	20 km	32 users	10 Gbps	Low	High	N.A	[3]
	WDM-PON	Access & Metro	60 km	192 users	1Gbps per user	High	Low	N.A	[4] [5]
	LR-PON	Access & Metro	100 km	1024 users	10 Gbps	Low	High	N.A	[6] [7]
Active Optical Network	Packet-based switching	Access	40 km	128 users	1 Gbps	High	Low	Required	[8]–[10]
	Slot-based switching (ActiON)	Access	40 km	128 users	10 Gbps	High	Low	Required	[11]
	Slot-based switching with multicast functions	Access	40 km	128 users	10 Gbps	High	High	Required	Our approach

VI. RELATED WORK

Table II compares existing approaches to our approach, which summarizes Sections I, II, and V. The categories are applicability, target distance, maximum number of users, bandwidth, security, utilization efficiency of Multicast delivery, and switching control. Our approach provides a scalable and secure access network, while supporting multicast delivery in an efficient manner. It requires a mechanism to control optical switches as presented in Section II. This is an additional function compared to the conventional PON approaches.

VII. CONCLUSION

This paper proposed an on-demand multicast slot allocation scheme for ActiON. The proposed scheme assumes the use of cascaded PLZT optical switch elements that are run in the newly described distribution mode, which forces the element to behave as an optical splitter. The proposed scheme solves an ILP problem to maximize the number of multicast users that can receive service in each slot. Numerical results show that the proposed scheme dramatically reduces the required number of slots compared to the original ActiON and that the required computation time of the proposed scheme is less than 0.3 sec, which is acceptable for on-demand services.

ACKNOWLEDGMENT

This work was a part of the R & D on photonic network promoted by Ministry of Internal Affairs and Communications, and supported by National Institute of Information and Communications Technology. This work was also supported by the Japan Society for the Promotion of Science's (JSPS) Grant-in-Aid for Scientific Research(C)(22500068).

REFERENCES

[1] Paul W. Shumate, "Fiber-to-the-Home: 1977-2007," *JOURNAL OF LIGHTWAVE TECHNOLOGY.*, pp.1093-1103, Vol. 26, No.9, May 1. 2008.

[2] "IEEE802.3ah, Ethernet in the First Mile Task Force," http://grouper.ieee.org/groups/802/3/ah/indev.html.

[3] "IEEE802.3av, 10GE-PON Task Force," http://www.ieee802.org/3/av/indev.html.

[4] J. Klaus Grobe, Markus Roppelt, Achim Autenrieth, Jorg-Peter Elbers, and Michael Eiselt, "Cost and energy consumption analysis of advanced WDM-PONs ," *Communications Magazine, IEEE, pp. s25-s32, Vol.49, 2011*

[5] C. C. Bouchat, C. Dessauvages, F. Fredricx, C. Hardalov, R. Schoop, and P. Vetter, "WDM-upgrade PONs for FTTH and FTTBusiness," in *Proc. Int Workshop Opt. Hybrid Access Netw.*, Florence, Italy, pp. 231-238, Jun. 2002.

[6] Fabienne Saliou, Philippe Chanclou, Fabien Laurent, Naveena Genay, Jose A. Lazaro, Francesc Bonada, and Josep Prat, "Reach Extension Strategies for Passive Optical Networks [Invited]," *OPT. COMMUN. NETW.*, pp. C51-C60, Vol. 1, No.4, Sep. 2009.

[7] Darren P. Shea and John E. Mitchell, "Long-Reach Optical Access Technologies," *Network, IEEE.*, pp. 5-11, Vol. 21, 2007.

[8] Takumi NOMURA, Hiromi UEDA, Chikashi ITOH, Hiroaki KUROKAWA, Toshinori TSUBOI, and Hiroyuki KASAI, "Design of Optical Switching Module for Gigabit Ethernet Optical of Optical Switching Module for Gigabit Ethernet Optical 3031, Vol. E89-B, No.11, Nov. 2006.

[9] H.Ueda, T.Nomura, K.Makino, T.Tsuboi, H.Kurosawa, and H.Kasai, "New optical access network architecture using optical packet switches," *IEICE Trans. on comm.*, pp.724-730, Vol. E89-B, No.3, Mar. 2006.

[10] T.Nomura, H.Ueda, T.Tsuboi, and H.Kasai, "Novel Optical Packet Switched Access Network Architecture," in *Optical Fiber Communication Conference and Exposition and the National Fiber Optic Engineers Conference,* Technical Digest (CD) (Optical Society of America, 2006), paper OTuJ6.

[11] Kazumasa Tokuhashi, Kunitaka Ashizawa, Daisuke Ishii, Yutaka Arakawa, Naoaki Yamanaka and Koji Wakayama., "Secure and Scalable Optical Access Network using PLZT High-speed Optical Switches,' 'HPSR(High Performance Switching and Routing)2009, No. 6-2, June 2009.

[12] Keiichi Nashimoto, "Epitaxial PLZT Waveguide Technologies for Integrated Photonics," Integrated Optics Devices: Devices, Materials, and Technologies IX (Proceedings of SPIE), Bellingham, WA, 2005 Vol. 5728, p. 34.

[13] Keiichi Nashimoto, Nobuyuki Tanaka, Mitchell LaBuda, Dwight Ritums, Jeffrey Dawley, Madhan Raj, David Kudzuma, Tuan Vo, "High-Speed PLZT Optical Switches for Burst and Packet Switching," BroadNets 2005, The Fifth International Workshop on Optical Burst/Packet Switching (2005) 195.

[14] Keiichi Nashimoto, “PLZT Waveguide Devices for High Speed Switching and Filtering,” OFC2008, OThE4.

[15] Kunitaka Ashizawa, Kazumasa Tokuhashi, Daisuke Ishii, Satoru Okamoto, Naoaki Yamanaka, Eiji Oki., “Efficient Singlecast / Multicast Method For Active Optical Access Network Using PLZT High-speed Optical Switches,” HPSR(High Performance Switching and Routing)2010, pp. 14-19, June 2010

[16] “GLPK (GNU Linear Programming Kit),” http://www.gnu.org/software/glpk/glpk.html.

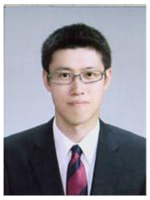
[17] Masahiro Hayashitani, Teruo Kasahara, Daisuke Ishii, Yutaka Arakawa, Satoru Okamoto, Naoaki Yamanaka, Naganori Takezawa, and Keiichi Nashimoto., “10ns High-speed PLZT Optical Content Distribution architecture having Slot-switch and GMPLS controller,” IEICE Electron. Express, Vol. 5 No. 6, pp.181-186, Mar. 2008.

[18] Teruo Kasahara, Masahiro Hayashitani, Yutaka Arakawa, Satoru Okamoto and Naoaki Yamanaka., “Design and Implementation of GMPLS-based Optical Slot Switching Network with PLZT High-speed Optical Switch,” 2007 IEEE Workshop on High Performance Switching and Routing, May. 30. 2007.

Kunitaka Ashizawa received the B.E. and M.E. degrees from Keio University, Japan, in 2009 and 2011, respectively. He is currently working toward the Ph.D. degree in Graduate School of Science and Technology, Keio University, Japan. Since 2009, he has researched about network architecture and traffic engineering on the next generation optical network.

Takehiro Sato received B.E. from Keio University, Japan, in 2010. Currently, he is 1st year master’s degree student at Keio University. Since 2009, he has researched about network survivability and protection and traffic engineering on the next generation optical network. He is a student member of the IEICE.

Kazumasa Tokuhashi received the B.E. and M.E. degrees from Keio University, Japan, in 2008 and 2010, respectively. He is currently working toward the Ph.D. degree in Graduate School of Science and Technology, Keio University, Japan. His research interests include communication protocol and network architecture on the next generation optical network. In 2010, he became a research assistant of Keio University Global COE Program, ”High-level Global Cooperation for Leadingedge Platform on Access Spaces” by Ministry of Education, Culture, Sports, Science and Technology, Japan. He is a student member of the IEEE, and the IEICE.



Daisuke Ishii graduated from Keio University, Japan where he received B.E., M.E., and Ph. D. degrees in electronics engineering in 2003, 2005 and 2009, respectively. Since 2003, he has been researching the traffic engineering of an opitcal network, especially optical burst switched network, and optical circuit switched network. He is currently researching a next generation photonic network architecture and an optical network control technique such as GMPLS. He is currently an Assistant with Yamanaka Laboratory, Department of Information and Computer Science, Keio University. From 2005 to 2007 and from 2007 to 2008, he was the Research Assistant with the Keio University COE (Center of Excellence) program ”Optical and Electronic Device on Access Network” and Global COE Program ”High-Level global cooperation for leading-edge platform on access spaces” of the Ministry of Educatuion, Culture, Sports, Science, and Technology, Japan, respectively. From 2007 to 2008, he was a research fellow of Japan Society for the Promotion of Science. Daisuke Ishii is a member of IEEE Comsoc., OSA and IEICE.

Satoru Okamoto received the B.S.,M.S, and Ph.D. degrees in electronics engineering from Hokkaido University, Hokkaido, Japan in 1986, 1988 and 1994 respectively. In 1998, he joined nippon Telegraph and telephone Corporation (NTT), Japan. Here, he engaged in research on ATM cross-connect system architectures, photonic switching system, optical path network architectures, and developed GMPLS controlled HIKARI router (Photonic MPLS router) systems. He lead several GMPLS related interoperability trials in Japan, such as the Photonic Internet Lab (PIL), OIF world wide interoperability demo, and Keihanna Interoperability Working Group. From 2006, he has been an Associate Professor of Keio University. He is a vice co-chair of Interoperability Working Group of Kei-han-na Info-communication Open Laboratory. He is now promoting several research projects in the photonic network area. He received the young Researchers’Award and the Achievement Award in 1995 and 2000, respectively. He has also received the IEICE/IEEE HPSR2002 outstanding paper award. He is associate editor of the IEICE transactions and the OSA Optics Express. He is an IEEE Senior Member and an IEICE Fellow.

Naoaki Yamanaka graduated from Keio University, Japan where he received B.E., M.E., and Ph. D. degrees in engineering in 1981, 1983 and 1991, respectively. In 1983 he joined Nippon Telegraph and Telephone Corporation’s (NTT’s) Communication Switching Laboratories, Tokyo, Japan, where he was engaged in research and development of a high-speed switching system and high-speed switching technologies for Broadband ISDN services. Since 1994, he has been active in the development of ATM base backbone network and system including Tb/s electrical/Optical backbone switching as NTT’s Distinguished Technical Member. He is now researching future optical IP network, and optical MPLS router system. He is currently a professor of Keio Univ. and representative of Photonic Internet Lab. (PIL). He has published over 126 peer-reviewed journal and transaction articles, written 107 international conference papers, and been awarded 182 patents including 21 international patents. Dr. Yamanaka received Best of Conference Awards from the 40th, 44th, and 48th IEEE Electronic Components and Technology Conference in 1990, 1994 and 1998, TELECOM System Technology Prize from the Telecommunications Advancement Foundation in 1994, IEEE CPMT Transactions Part B: Best Transactions Paper Award in 1996 and IEICE Transaction Paper Award in 1999. Dr. Yamanaka is Technical Editor of IEEE Communication Magazine, Broadband Network Area Editor of IEEE Communication Surveys, and was Editor of IEICE Transaction as well as vice director of Asia Pacific Board at IEEE Communications Society. He is an IEEE Fellow and an IEICE Fellow.

Eiji Oki Eiji Oki is an Associate Professor of The University of Electro- Communications,Tokyo Japan. He received B.E. and M.E. degrees in Instrumentation Engineering and a Ph.D. degree in Electrical Engineering from Keio University, Yokohama, Japan, in 1991, 1993, and 1999, respectively. In 1993, he joined Nippon Telegraph and Telephone Corporation’s (NTT’s)Communication Switching Laboratories, Tokyo Japan. He has been researching IP and optical network architectures, traffic control methods, high-speed switching systems, and communications protocols. From 2000 to 2001, he was a Visiting Scholar at Polytechnic University, Brooklyn, New York, where he was involved in designing tera-bitswitch/router systems. He joined The University of Electro-Communications, Tokyo Japan, in July 2008. He is active in organizing international conferences. He served as a Co-Chair of Technical Program Committee for 2006 and 2010 Workshops on High-Performance Switching and Routing (HPSR), a Co-Chair of Technical Program Committee for International Conferenceon IP+Optical Network (iPOP 2010), and Track Co-Chair on Optical Networking, ICCCN 2009. Dr. Oki was the recipient of the 1998 Switching System Research Award and the 1999 Excellent Paper Award presented by IEICE, and the 2001 Asia-Pacific Outstanding Young Researcher Award presented by IEEE Communications Society for his contribution to broadband network, ATM, and optical IP technologies. He co-authored two books, “Broadband Packet Switching Technologies,” published by John Wiley, New York, in 2001 and “GMPLS Technologies,” published by RCPress, Boca Raton, in 2005. He is an IEEE Senior Member and an IEICE Senior Member.