MPCP based active optical access network with PLZT high-speed optical switch

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Abstract

An active optical access network architecture with our newly developed PLZT ((Pb, La) (Zr, Ti)O3) high-speed optical switch is introduced, with a view to realizing the next-generation high capacity scalable access network. This system is developed based on the latest IEEE standard of PON (10G-EPON; IEEE802.3av) in consideration of the coordination with future high capacity PON. PLZT high-speed optical switches are able to switch an optical signal at nano-second speed (<5–10 ns). Generally, the merits of using optical switches are increasing the number of subscribers and transmission distance easily, preventing malicious ONUs from interfacing with the communication between OLT and the other ONUs, realizing fast fiber and OLT protection/restoration and providing various services by controlling optical switches dynamically. This paper focuses on two key technologies; a PLZT optical switch and a new discovery process for active optical access network based on MPCP defined at IEEE802.3. A major challenge in designing active optical access network is supporting the discovery process of MPCP because it does not offer broadcast transmission unlike the regular PON. We propose here a new discovery process; it has been tested successfully in an implementation of our proposed system.

1. Introduction

IP network traffic has increased rapidly in recent years with the popularization of optical fiber access networks [1]. Several optical fiber access networks are researched and developed (e.g. passive, active, Wavelength Division Multiplexing (WDM) type and such). The best example of those is Passive Optical Network (PON). PON architecture basically is point-to-multipoint (P2MP) network, and consists of three components, Optical Line Terminal (OLT), Optical Network Unit (ONU), and optical splitters. Currently, Gigabit-PON (G-PON; ITU G.984) [2] and Gigabit-Ethernet PON (1G-EPON; IEEE802.3ah) [3] are very popular. In order to realize 10 Gbps access networks, X Gigabit-PON (XG-PON; ITU-T G.987) [4] and 10 Gigabit-Ethernet PON (10 G-EPON; IEEE802.3av) [5] were standardized. Additionally, Long-Reach Passive Optical Network (LR-PON) is researched recently as a more cost effective solution [6,7]. The advantage of LR-PON is to consolidate the number of central offices holding OLTs. So, LR-PON can simplify the network infrastructure, reduce the number of network components, and merge the metro and access network segments.

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On the other hand, as an approach to a scalable access network, optical fiber access networks with an active device such as an optical switch are researched [8–10]. In Ref. [8], to mainly increase the distance and the number of subscribers, the optical access network architecture using optical waveguide switches was proposed. Refs. [9,10] aim to reduce costs for testing and improve the service quality such as protection by controlling optical switches remotely.

Authors also focus on this active type system and have proposed active optical access network [11–16] using our newly developed PLZT waveguide high-speed optical switch [17–22]. Called Active Optical access Network (ActiON), our proposal is based on the latest IEEE standard of PON (10 G-EPON; IEEE802.3av), in consideration of the coordination with PON.

In ActiON, by switching the PLZT high-speed optical switch, an ONU is allocated the time period, where it transmits and receives data, like time division multiplexing and time division multiple access. The optical switch system has a simple mechanism and provides all-optical and transparent data transmission without analyzing the header of a frame. OLT controls the scheduling of the switching at the optical switch system remotely.

The general merits of using optical switches are as follows. Firstly, the optical switch provides the increase of the number of subscribers and the transmission distance easily due to its low insertion loss, while the optical splitter has large insertion loss because it divides the optical power among its ports.

Secondly, in the active optical access network, malicious ONUs is prevented continuously from transmitting the light signal, while, in PON, malicious ONUs can interface with the communication between OLT and the other ONUs. This advantage of security realizes peer-to-peer secure connection between OLT and each ONU. Therefore, the use of optical switches realizes providing lease-line service as well as the conventional access network service.

Third merit is providing various services by switching OLTs dynamically. Since peer-to-peer secure connection is allocated for each ONU, and the optical switch does not analyze the header of frame electrically, each ONU can transport any data signal formats transparently through the optical switch in our proposal. So, the active optical access network has capability to aggregate various types of networks (e.g., access networks for residential users, the above leased line services for business users, and mobile backhauls).

Fourth, the optical switch is useful for improving service quality such as protection/restoration due to the original characteristic of a switch. Conventionally the protection schemes using optical switches [23,24] have been proposed, which merge several PON trees by using optical switches and enhance the performance of protection. The use of optical switches realizes fast fiber and OLT protection/restoration by controlling optical switches remotely. The approaches of Verizon, Inc. in Refs. [9,10] include achieving this benefit.

Moreover, a power scalable optical access network is realized by applying the mechanism of the above protection. The system changes the number of active OLTs based on the number of active ONUs. For example, two access network trees are consolidated by a high speed optical switch, and two OLTs are connected to the optical switch. When a few ONUs exist, one of two OLTs is set to power-down to suppress the power consumption, and another OLT accommodates ONUs. According to Ref. [25], the access network is overrepresented of the energy consumption of present network, and OLT has the most power consumption among network components constitute PON. Therefore, the power-down of OLT is very effective for energy saving of the optical access network. The use of a large scale optical switch causes a big effect on energy saving because the large scale switch accommodates a lot of access network trees.

Additionally the use of all optical waveguide-based switches for the power scalable system is more effective for energy saving because this type switch generally uses much lesser power than an Ethernet switch with the electrical analysis of a frame. So, the scalability of the optical switch is high for the future because its power consumption is not very dependent of the transmission rate.

With the standardization of next generation high-speed access networks such as XG-PON, 10G-EPON and the development of WDM technology, the research on active access networks that potentially have several merits is expected to be pursued more strongly. Our future goal is to realize the next generation high capacity, scalable, and long-reach optical access system by combining high capacity WDM-PON and a scalable active access system that supports various services.

Currently, Next Generation (NG)-PON2 [26] is planned to be standardized by 2015 at Full Service Access Network (FSAN) community toward realizing a large scale metro and access network using various technologies. The target of NG-PON2 is the same as our goal in terms of consolidating various types of networks and merging the metro and access network segments. Therefore, our proposal is useful for developing the next generation optical access network as NG-PON2.

This paper introduces ActiON and focuses on two key technologies; a PLZT optical switch and a new discovery process for the active optical access network based on Multi Point Control Protocol (MPCP) defined at IEEE802.3 [27]. A major challenge in designing ActiON is supporting the discovery process of MPCP because ActiON does not offer broadcast transmission unlike the regular PON with optical splitters. We propose here a new discovery process; it has been tested in an implementation of ActiON.

The remaining sections of this paper are organized as follows. Section 2 outlines PON system and MPCP. Section 3 introduces our proposal; MPCP based ActiON system. Section 4 shows our new PLZT high-speed optical switch. Section 5 proposes discovery processes for the active optical access network. Section 6 provides a discussion and an evaluation about the discovery process. Section 7 shows our conducted experiments. Section 8 summarizes the current activities.
2. EPON series

2.1. Configuration

Fig. 1 shows the regular E-PON architecture. The device connected at the root of the tree is called an OLT located at a central office and the devices connected as the leaves are referred to as ONUs. Optical splitters are set at between OLT and ONUs. In a PON with the split ratio of at 1:32, 1 × 4 splitter and 1 × 8 splitter are used. It defines up to three optical power budgets that support split ratios of at least 1:16 and at least 1:32, and distances of at least 10 km and at least 20 km. High power budget class supports P2MP media channel insertion loss of 29 dB e.g., a PON with the split ratio of at least 1:32 and the distance of at least 20 km.

2.2. MPCP

To prevent the collision of data at the optical splitter and to control data transmissions in the upstream direction, IEEE802.3av defines MPCP [27]. MPCP specifies a mechanism between an OLT and ONUs to allow an efficient transmission in the upstream direction; (1) "Discovery process" establishing connections between OLT and ONUs, and (2) "Gate and Report process" operating upstream data transmissions from ONUs to OLT. Fig. 2 shows MPCP frame format. MPCP defines five messages. Opcode field identifies each message. Four types of MPCP messages are used in the discovery process: "GATE and DISCOVERY_GATE (GATE with Discovery Flag set)", "REGISTER_REQ", "REGISTER" and "REGISTER_ACK", "GATE" and "REPORT" messages are used in the gate and report process.

ONUs do not transmit data autonomously. OLT instructs ONUs to transmit data, and ONUs transmit data within the time period permitted by OLT. OLT controls the transmission time of each ONU so that the collision of data transmission from ONUs does not occur. OLT has to measure the distance between it and an ONU in order to grasp the timing when a message from the ONU reaches OLT. OLT grasps the timing by a discovery process.

2.3. Discovery process based on MPCP

The discovery process has three functions. One is discovering active ONUs. Second is registering 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 routinely 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.

Fig. 3 shows the typical discovery process. 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 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 \( t_4 \), which is calculated so as to avoid collision among all signals from other ONUs. After receiving GATE, the ONU sends REGISTER_ACK at \( t_5 \). 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.
3. Proposal system: active optical access network (ActiON)

3.1. Configuration

With a view to the high capacity scalable access network, a new optical access network architecture using optical switches named ActiON has been proposed. Fig. 4 shows the basic configuration of ActiON. It consists of OLT, ONU and Optical Switching Unit (OSW) which has PLZT high-speed optical switches. OSW synchronizes OLT and ONUs on the timescale of the switching time (nanoseconds order), and automatically self-switches to each ONU based on the switching schedule determined by OLT. An optical wavelength is divided into variable length time period, and OLT flexibly and dynamically allocates each ONU the time period to transmit and receive data by scheduling the switching of OSW. In Fig. 4, $t$ means a switching start time. Therefore, the period from the switching start time $t_1$ to $t_2$ is the allocated length for ONU#1. The number of subscribers and the transmission distance are increased easily due to the optical switch's low insertion loss. The target of basic ActiON is the access optical network that supports 128 ONUs and the maximum transmission distance of 40 km. Also, by using the optical switch, malicious ONUs is prevented continuously from transmitting the light signal, while, in PON, malicious ONUs can interface with the communication between OLT and the other ONUs.

We consider not only the model to set OSW at telephone poles such as optical splitters in current PON, but also to set in the central office holding OLTS and the subscribers’ buildings.

We also design a hybrid passive/active system by applying the technology of ActiON. To realize a high capacity and scalable access network by combining ActiON with high capacity PON such as WDM-PON in the future, ActiON has been developed based on the latest IEEE standard of PON (10G-EPON; IEEE802.3av) in consideration of the coordination with future high capacity PON.

3.2. Data transmission and switch control

The data transmission of ActiON is executed in basically the same way as that of the regular PON. By using GATE and REPORT as per IEEE802.3, the Dynamic Bandwidth Allocation (DBA) function in OLT flexibly and dynamically allocates to an ONU its transmission time according to the demands from/to ONUs. The main difference from PON is that OLT controls the switching schedule of OSW based on the result of DBA.

OLT informs OSW of the determined switching schedules with a switch control frame preceding of data frame transmission. Then, the switch controller on OSW controls the optical switches based on the switching schedules. The purpose is to simplify the switching mechanism by not equipping the function of frame-by-frame data-analysis for extracting the information on destination. Also, since the optical switch does not analyze the header of frame electrically, each ONU can transport any data signal formats transparently through the optical switch. So, the active optical access network has capability to aggregate various types of networks by switching OLTS dynamically.

We have already developed a prototype of OSW with our developed $1 \times 128$ PLZT optical switch control procedure [15,16]. A format of a switch control frame based on MPP frame is shown in Fig. 5. Fig. 5 shows only the different fields from MPD frame format shown in Fig. 2. The switching schedule is designed for supporting $M \times N$ optical switch. $M$ is the number of ports on the side of OLTS. $N$ is the number of ports on the side of ONUs. This frame format holds the information about switching schedules at a data field. The field includes a direction field to indicate which optical switch (downstream optical switch or upstream optical switch) should be controlled by it, the number of switching schedules set in the frame, and $x$ switching schedules. The switching schedule is composed of switching start time $t_x$ and $M$ switched ports for ports on the side of OLTS. Switching start time $t_x$ shows the start time of allocated period for ONU#x at OSW, as depicted in Fig. 4 (For more detail on data transmission, see the data switching procedure in our previous works [15,16].) The length of switching schedule is determined by the number of ports on the side of OLTS. Currently, it is assumed to use $1 \times N$ optical switch for basic ActiON, or $2 \times N$ optical switch which connects the primary OLT and the backup OLT in terms of protection.

Fig. 6 depicts the configuration example of OSW to operate time schedule allocation transmission. This figure shows the case including the backup OLT by using $2 \times N$ switch. This system mainly consists of PLZT optical
switches, switch drivers and a switch controller. The system also provides the efficient protection of OLTs and each ONU by switching. Switch control frames are sent from OLT on the in-band or out-band another control line.

In the case of an out-band control line (i), another network cable for sending switch control frames is connected to the switch controller directly. In the case of an in-band control line (ii), a new network cable is not required, one output port of the downstream optical switch is connected to O/E converter, and one input port of the upstream optical switch is connected to E/O converter on OSW. When OSW is set away from a central office such as the optical splitter of PON, the in-band control line is useful because the cost of laying a long network cable for the switch control is not required. When OSW is set in the central office, the out-band control line is useful because using output ports for control lines is avoided.

The switch controller extracts the switching schedules from the switch control frame, and controls the downstream optical switch or the upstream optical switch.

To realize the optical access network using this self-switching OSW, ActiON requires a high-speed optical switch for frequent switching and a new discovery process through the optical switch. Details about our proposal are described in the later sections.

4. High-speed PLZT optical switch

4.1. Configuration

This section describes the PLZT high-speed optical switch [17–22] used in ActiON. As a waveguide material, PLZT ((Pb, La)(Zr, Ti)O₃) is very attractive due to its high-speed control, low power dissipation, dense integration, and device miniaturization. A PLZT waveguide was fabricated by the epitaxial growth process and dry etching on a semiconductor substrate. The building block of the PLZT optical switch is a balance bridge type 1 × 2 switch. The balance bridge type switch is composed of a Mach–Zehnder (MZ) modulator with top electrodes and 3 dB input and output couplers. Fig. 7 shows the balance bridge type 1 × 2 switch in cross and bar states. MZ type optical switch is based on Mach–Zehnder interferometer (MZI) theory [28]. Two 3 dB couplers are used for a phase shift. By utilizing the interference effect of a MZI, MZ type switch switches a signal. The injected optical signal is delivered to the cross port under no voltage condition (A and B are off). By applying a voltage to one of the top electrodes (A/On or B/On), the signal is promptly switched to the bar port due to the resulting electro-optic index change. Fig. 8 shows the PLZT optical switch chip. The chip has a length of about 20 mm. Fig. 9 shows the 1 × 8 switch architecture, so the introduced optical signal can be delivered to any one of the 8 output ports. The 1 × 8 switch has a simple tree structure. Fig. 10 shows a switching waveform within the guard time. It shows that the switching time is about 6 ns. A network based on this PLZT high-speed switch can switch frequently to allocate the bandwidth efficiently. On the other hand, a network based on the MEMS switch is not so efficient because its switching overhead is large at around 10 ms.

The PLZT waveguide optical switch achieves low insertion loss; Coupling loss: 0.6 dB/coupling, Waveguide loss: 1 dB/cm, Electrode loss: 1 dB/cm, Radiation loss: 1 dB. Total insertion loss of 1 × 8 PLZT switch is around 5 dB since the waveguide length is 2 cm and the electrode length is 1 cm. Accordingly, the insertion loss of optical switch is low since an insertion loss of 1 × 8 optical coupler is 9 dB in theory (in fact 10–11 dB due to other loss). Additionally, Epiphotonics Corp. currently continues to be improving PLZT switch to minimize the insertion loss, and developing the non-blocking N × N type optical switch [21].
4.2. Effect of PLZT optical switch

The high switching speeds allow slot overhead (guard time) to be minimized. Fig. 11 shows this effect. As shown in Fig. 11(a), the conventional MEMS switch has guard times of the order of ms. The PLZT optical switch, on the other hand, can shorten the guard time down to about 6 ns as shown in Fig. 11(b). Because of this reduction in guard time, data transfer with the time division method is efficient. At 10 Gbps rates, minimum IFG (Inter Frame Gap) is 96 bit times, which is 9.6 ns, so the switching speed is realistic. The equal or close to dynamic bandwidth allocation of PON is achieved by the use of PLZT optical switch.

5. Discovery process for active optical access networks

This section introduces the discovery process for active optical access networks, based on MPCP in consideration of the coordination with future high capacity PON. Since optical switch based access networks have no inherent broadcast function, it must execute the discovery process to each ONU individually. Two discovery processes are introduced for active optical access networks with optical switches. The first is a typical method. The second is our proposal; an efficient and scalable ranging method of the discovery process.

5.1. Typical method

One approach to implementing the discovery process is to open a discovery window for each ONU in rotation, as explained in Section 2.3. Therefore, in the upstream direction, the optical switch system reserves the same direction used to send the DISCOVERY_GATE during the discovery window to pass the REGISTER_REQ. However, it is inadvisable to adopt this ranging method since a vast amount of network resources is consumed by keeping the discovery window open to each ONU in turn. As a result, this method suffers from long discovery completion times and poor bandwidth utilization efficiency. Additionally, it is difficult for the conventional ranging method to precisely synchronize the PLZT self-switched system.

5.2. Proposal method

Our solution is an efficient and scalable discovery process that can be adapted to suit active optical access systems of any high bit rate. The new method is executed through periodically setting Communication Channel (CC); a minimal period for channel control. The feature of this method is that CC position is identified by the sending of consecutive REGISTER_REQs.

5.2.1. Communication channel

Fig. 12 shows the details of CC. CCs periodically are set in rotation to all ONUs. The period between CCs is Data Channel (DC) used for data communication. DC is shared among registered ONUs by the DBA function of OLT. The length of period from CC to CC is defined as CC Cycle. CC Cycle is constant. The feature of our new discovery process is that it uses only CCs. Therefore, the process for channel control such as “Discovery process” is executed independently of data transmission using DC. Each CC is extremely small since it only has to be long enough to allow one REGISTER_REQ to pass through the PLZT self-switch system. Accordingly, this new method offers high bandwidth utilization efficiency. Since it does not know the timing of its own CCs, each ONU sends consecutive REGISTER_REQs to use its own CCs. The new ranging method consists of MPCP-based two phases: Discovery Phase and Precise Ranging Phase.
5.2.2. Discovery Phase

Fig. 13 shows the Discovery Phase. With regard to downstream transmission (from OLT to ONU), ONUs are assured of receiving MPCP frames from OLT through the PLZT self-switch system because the optical switches lie within the carrier’s network. By using CC’s at the downstream switch, OLT repeatedly sends DISCOVERY_GATEs to ONUs which are disconnect and has not been registered yet. When an ONU becomes active and receives DISCOVERY_GATE, the discovery process starts.

First, at $T_0$, OLT sends the DISCOVERY_GATE with Grant Start Time $T_1$ to ONU#X through CC at the downstream switch. After receiving the DISCOVERY_GATE, ONU#X continuously sends REGISTER_REQs to OLT starting from $T_1$. Since OLT instructs ONU#X to send an adequate amount of REGISTER_REQs in consideration of RTT and the time interval between upstream CC and downstream CC, a few REGISTER_REQs can reach OLT through the CC of ONU#X’s period at the upstream PLZT switch. In Fig. 13, OLT firstly receives the REGISTER_REQ#4 with the time stamp $T_4$ at $T_6$, and receives the REGISTER_REQ#5 with the time stamp $T_5$ at $T_7$. After receiving the consecutive REGISTER_REQs, OLT keeps the time stamp $T_4$ of the first received REGISTER_REQ and determines RTT as $T_6 - T_4$. OLT finds the gate timing which enables ONU#X’s message to pass through CC and reach OLT.

Next, OLT assigns an LLID to ONU#X by sending a REGISTER through ONU#X’s next CC at the downstream switch. Next, OLT sends the GATE with ONU#X’s Grant Start Time $T_4$ through ONU#X’s next CC. After receiving the GATE, ONU#X sends the REGISTER_ACK at the specified Grant Start Time $T_4$. On this occasion, ONU#X sends only one message unlike the case of sending the REGISTER_REQs. This is the end of the Discovery Phase.

The Discovery Phase has an error of 1 frame size. The reason is explained based on the timing of switching CC as follows. As shown in Fig. 14(a), in case CC is switched for ONU#X just before REGISTER_REQ from ONU#X reaches the upstream PLZT switch, the time stamp of the REGISTER_REQ indicates the Grant Start Time suited for almost the start time of CC for ONU#X. It is the best case. On the other hand, as shown in Fig. 14(b), in case CC is switched for ONU#X just after REGISTER_REQ from ONU#X reaches the upstream PLZT switch, the time stamp of the REGISTER_REQ indicates the Grant Start Time fitting the timing after 1 frame size’s delay from the switching time of CC. MPCP message size is 64 bytes, so 1 frame size is defined as 84 bytes including the preamble size (8 bytes) and the Inter Frame Gap size (12 bytes). Transfer time of 84 bytes is 672 ns in the 1 G environment and 67.2 ns in the 10 G environment. In principle, the discovery process of PON can measure RTT to an accuracy of 1 Time_Quantum (TQ) (12 TQ in IEEE802.3av).

TQ is the time unit used in IEEE802.3av, and each TQ is set to 16 ns [5]. One way of solving this problem is to reduce the size of REGISTER_REQ. Our alternative, the Precise Ranging Phase, achieves the measurement accuracy of 1 TQ.
5.2.3. Precise Ranging Phase

The Precise Ranging Phase minimizes data loss by minimizing the guard time. An ONU delays the timing of sending REGISTER_REQs by 1 TQ (16 ns); by executing this ranging process many times, it is possible to specify the position of CC very precisely.

To grasp the position of CC accurately, it is important that the REGISTER_REQ passes through the CC at the instant of CC switching. The Precise Ranging Phase is shown in Fig. 15. OLT repeatedly sends a DISCOVERY_GATE with the Grant Start Time when ONU#X starts to send REGISTER_REQ. OLT staggered the Grant Start Time by 1 TQ, and the Grant Start Time changes in the sequence $T_1, T_1 + \Delta 1 (= 1 TQ), T_1 + \Delta 2 (= 2 TQ), T_1 + \Delta 3 (= 3 TQ), \ldots$. This $\Delta$ value is defined as the Precise Ranging value, and this value is the additional delay time for the timing of sending REGISTER_REQs. OLT adjusts the Precise Ranging value and changes the Grant Start Time so that the REGISTER_REQ from an ONU passes through CC at the instant of CC switching.

In an example of Fig. 15, firstly, ONU#X starts to send REGISTER_REQs at $T_1$ designated by the DISCOVERY_GATE from OLT. Then, REGISTER_REQ#4 is received at first by OLT. By delaying the timing of the Grant Start Time repeatedly, the time gap between the instance of CC switching and the transit time of REGISTER_REQ#4 is made bigger and bigger. Finally, at the fourth trial, the number of the first received REGISTER_REQ changes from #4 to #3. At this time, it is judged that REGISTER_REQ#3 passes through the instance of CC switching. OLT uses the time stamp $T_3 + \Delta 3$ of REGISTER_REQ#3 as the gate timing of ONU#X. Therefore, OLT can grasp the position of CC with an accuracy of 1 TQ when the message number of the first received REGISTER_REQ changes (for example, from message number #4 to #3).

When $\Delta$ is 1 TQ, the number of iterations is up to 42 times in the 1 G environment and 4 times in the 10 G environment. CC size is set at the time needed to transfer 168 bytes (2 frame) plus 1 TQ for error. This new method is a highly-scalable discovery-ranging process. It can achieve the same precision in 10 G and above high-speed access networks because the consecutive sending interval is independent of the network’s transmission speed.

6. Performance evaluation and discussion

This section evaluates and discusses discovery process and the supportable number of subscribers. The completion time of three discovery ranging methods are compared: PON method, the typical method of active optical access networks and our proposed precise ranging method. The completion discovery time is defined as the time from when a certain ONU becomes active to when OLT receives REGISTER_ACK from the ONU and the discovery process for the ONU finishes. The nomenclature used in this section is given below.

$O$ Number of undiscovered ONUs
$RTT$ Round Trip Time of the maximum distance
$D$ Maximum random delay $d$ for avoiding frame collision

First, the formula used to determine the PON value is shown below.

$$W = RTT + D \quad (1)$$

$W$ Total size of discovery windows
$CC$ Communication channel size
$\alpha$ The number of ranging of ONUs in precise ranging method

$$E = 1 - \frac{W}{Discovery\_cycle} \quad (2)$$

$E$ Bandwidth efficiency
$T$ Maximum completion discovery time
$CC\_cycle$ Cycle period between CC's.

Discovery window $W$ is defined as the period from sending DISCOVERY_GATE to receiving REGISTER_REQ. The speed of light on an optical fiber is $2.0 \times 10^8$ m/s, so the RTT of 20 km is 200 µs and that of 40 km is 400 µs. The discovery process is routinely needed since ONUs can randomly connect to or disconnect from the access network unless all ONUs are discovered. As a rule, when $D$ is adequately set, the number of repetitions of the discovery process is just one in the 10 Gbps environment because the data transfer time of REGISTER_REQ (84 bytes) is 67.2 ns, so there is virtually no chance that message collisions will occur. In the unlikely event that message collision does occur, another maximum waiting time is added to $T$. Maximum completion discovery time $T$ is calculated according to the following equation.

$$T = Discovery\_cycle + 2RTT + D \quad (3)$$
Fundamentally, a round trip is required twice until the completion of discovery process, as shown in the Eq. (3). Discovery_cycle is defined as the maximum waiting time to receive the DISCOVERY_GATE from when the ONU receives the previous DISCOVERY_GATE. However, Discovery_cycle needs a long period compared with RTT, considering bandwidth efficiency $E$ from the Eq. (2). Therefore, $T$ depends heavily on Discovery_cycle. The relation between $E$ and Discovery_cycle is trade-off.

Second, the formula used to determine the typical method for active optical access networks is shown below.

$$W = RTT \times O.$$  \hspace{1cm} (4)

$E$ and $T$ are also calculated from the Eqs. (2) and (3) ($D = 0$). It is easy to see that the communication bandwidth consumed by this method for the discovery process is drastically higher than that of PON. This method has to open as many the size of discovery window as there are ONUs. Therefore, Discovery_cycle has to be increased to achieve high bandwidth efficiency $E$. This is because the typical method has to lengthen the time interval between when OLT sends DISCOVERY_GATE to ONU#1 and when OLT sends the next DISCOVERY_GATE to ONU#1.

Finally, the case of the proposed precise ranging method is explained. The bandwidth efficiency $E$ is determined by the following equation.

$$E = 1 - \frac{CC}{CC\_cycle}.$$  \hspace{1cm} (5)

This is because CC is periodically allocated to each ONU, and only CC is used for the discovery process. The relationship between Discovery_cycle and CC_cycle is expressed as below.

$$\text{Discovery\_cycle} = CC\_cycle \times O.$$  \hspace{1cm} (6)

This is because CC is allocated to one ONU in one CC_cycle as shown in Fig. 12. In the precise ranging method, the maximum time interval from when an ONU becomes active to when the discovery process for the ONU starts is Discovery_cycle. Also, based on Fig. 15, CC_cycle $\times O \times \alpha$ is required for $\alpha$ trails of consecutive sending because the time interval from allocating CC to a certain ONU to allocating the next CC to the same ONU is CC_cycle $\times O$. In the same manner, CC_cycle $\times O$ is required for OLT's sending REGISTER for the ONU, and RTT is required for exchanging GATE and REGISTER_ACK. As a result, the maximum completion discovery time $T$ is calculated according to the following equation.

$$T = \text{Discovery\_cycle}$$

$$+ CC\_cycle \times O (\alpha + 1) + RTT.$$  \hspace{1cm} (7)

In the precise ranging method, $T$ increases with the number of iterations, $\alpha$. The amount of ranging of ONUs $\alpha$ is 4 in 10 Gbps environment (please see Section 5). By the first consecutive sending, OLT can grasp the position of CC with an accuracy of 1 frame size defined as 84 bytes. This proposed method can minimize CC size. CC size is set at 150.4 ns needed to transfer 2 frame (168 bytes) plus 1 TQ for error, because OLT certainly receives one REGISTER_REQ at the consecutive sendings.

In the proposed method, CC_cycle is calculated by substituting the values of $E$ and CC into the Eq. (5). The decrease of CC leads to the decrease of CC_cycle due to the Eq. (5). Therefore, in 10 G environment where CC size is very small, it is expected that Discovery_cycle of the proposed method is smaller than those of other methods, and, as a result, $T$ of the proposed method becomes very short compared to other methods.

Based on the above discussion, Table 1 shows the maximum completion time of discovery processes. The maximum random delay $D$ is set to 100 $\mu$s, the size of CC is 168 bytes, and $\alpha$ is 42 in 1 Gbps environment and 4 in 10 Gbps environment. To ensure fairness, they are compared under the same condition, i.e. that the ratio of Discovery_window $W$ to the communication bandwidth for data transmission is 0.001 (the bandwidth efficiency $E$ is 0.999 (99.9%)). For E-PON, we assume that it uses optical amplifiers for supporting a lot of ONUs and the discovery process is complete on one's first try without message collisions.

The typical method is not suitable for future optical access networks because of its huge completion time $T$ of 51.2 s. This time would trigger strong user frustration about the delay posed by communication establishment. The proposed precise ranging method is able to shorten the maximum completion time $T$ compared to the typical method. This is because only CC is used for our proposed precise ranging. Therefore, the proposed method reduces the bandwidth required for the discovery process. Additionally, an increase in the transmission speed leads to a decrease in CC, resulting in a decline in the number of iterations $\alpha$. Therefore, the proposed method offers future improvements in bandwidth efficiency and completion time $T$. In 10 Gbps environment, $T$ of the proposed method is 115.9 ms, which is shorter than the 500.9 ms required by E-PON system.

The reason is written as follows. In E-PON system, the maximum completion time of discovery processes is determined based on Discovery_cycle and RTT as indicated by the Eq. (3). Discovery_cycle is dependent on the discovery window $W$ which is determined based on the propagation delay between OLT and ONUs. So, in case of our target, the maximum completion time of discovery processes becomes long due to the increase of Discovery_cycle and RTT with long-distance transmission.

On the other hand, in the proposed method, the maximum completion time is determined based on Discovery_cycle, CC_cycle, the number of ONUs $O$, the number of iterations $\alpha$ and RTT as indicated by the Eq. (7). Discovery_cycle is dependent on not RTT but CC size which is determined by the transmission rate, and $\alpha$ is also dependent on the transmission rate. Since CC size and $\alpha$ in 10 G environment are much smaller than those in 1 G environment, the decrease of CC size and $\alpha$ has an impact on the maximum completion time more than the increase of $O$ and RTT. Therefore, the maximum completion time of the proposed method is very short in case of our target.

In this way, this newly proposed ranging method is highly effective for high capacity optical access networks. Fig. 16 shows the maximum completion time except the typical method in case of 10 Gbps environment with a large a mount of subscribers. As stated in the
Table 1
Maximum completion time of discovery processes.

<table>
<thead>
<tr>
<th>Method</th>
<th>1 G 32 ONUs 20 km (basic 1G-EPON)</th>
<th>10 G 128 ONUs 40 km (our target)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PON</td>
<td>300.5 ms</td>
<td>500.9 ms</td>
</tr>
<tr>
<td>Typical method</td>
<td>6.4 s</td>
<td>51.2 s</td>
</tr>
<tr>
<td>Precise ranging</td>
<td>1915.3 ms</td>
<td>115.9 ms</td>
</tr>
</tbody>
</table>

Fig. 16. Maximum completion time of discovery processes in case of 10 Gbps and 40 km support environment with a large amount of subscribers.

introduction, the active optical access network has an advantage of fast protection/restoration of fiber and OLT. So, in Fig. 16, the maximum completion time of the precise ranging with protection is evaluated to weigh the scalability in considering protection. The precise ranging with protection assumes that the discovery process is also executed for the backup fiber, which protects one primary fiber, in preparation for quick recovery in fiber failure. The use of optical switches realizes fast fiber protection by controlling optical switches remotely. The results show that this extended MPCP allows at least 256 ONUs (with fiber protection) and 512 ONUs (without fiber protection) because the maximum completion time of the precise ranging is shorter than that of E-PON.

Of course, the determining factor in the number of subscribers is not just MPCP. The essential requirement for realizing the many subscriber system is an optical switch with many switch ports. Also, the hybrid passive/active optical access network is considered as a method to realize the many subscriber system without a large-scale optical switch. In the hybrid passive/active system, each feeder fiber from an optical switch in the central office connects to a $1 \times N$ splitter ($N$: 8, 16 or 32) in customer neighborhoods. For example, by using $1 \times 16$ PLZT optical switch commercially produced from Epiphotonics Corporation [22] and $1 \times 32$ optical splitters, the hybrid passive/active system supports up to 256 ONUs (with fiber protection) and 512 ONUs (without fiber protection). Therefore, future works are to develop the PLZT optical switch with many switch ports and the hybrid passive/active optical access network.

7. Experiments

We are using a 1G network environment to conduct demonstration experiments on the feasibility of our discovery-ranging process. Fig. 17 shows the experimental setup. We combined an OLT, three ONUs, a delay simulator, and a PLZT optical switch emulator. We developed prototypes of OLT and ONUs that incorporate the proposed method and the PLZT optical switch emulator. Each ONU is given a different distance by the delay simulator.

Fig. 18 shows the measured performance of the proposed discovery-ranging process. The shown results were captured by using Wireshark [29] between OLT and the optical switch emulator. CC Cycle is 1 ms, CC size is 10 µs, and DC size is 990 µs. Transmission interval of consecutive REGISTER_REQs is 1200 ns. CCs periodically are set in rotation from ONU#1 to ONU#3. The delay simulator set the distance between OLT and ONU#2 (#3) to 20 (40) km. MPCP frames to each ONU can be captured in sequence through each CC. They proved that CC position was identified by consecutive sending of the REGISTER_REQs. In the Precise ranging phase, OLT repeatedly sent the DISCOVERY_GATE and precise
Fig. 18. Successful experimental result of the new discovery process.

synchronization with the upstream switch was achieved. Fig. 18 shows that the better ranging timing, on which REGISTER_REQ passes through CC, is indicated by GATE (for GATE to ONU#1, the second ranging timing at which eight REGISTER_REQs passed through CC is selected.) Our proposed discovery-ranging process functions well regardless of the delay situation. This ranging process can support 10 G and above networks without modification because the transmission interval does not depend on bandwidth. Therefore, the same accuracy can be expected from these prototypes even if they operate in a 10 G network environment.

8. Conclusion

An active optical access network architecture with our newly developed PLZT high-speed optical switch has been introduced. This system is based on the latest IEEE standard of PON (10 G-EPON; IEEE802.3av) in consideration of its use with future high capacity PON. Generally, the merits of using optical switches are increasing the number of subscribers and transmission distance easily, preventing malicious ONUs from interfacing with the communication between OLT and the other ONUs, realizing fast fiber and OLT protection/restoration and providing various services by controlling optical switches dynamically. This paper described the PLZT optical switch and the new efficient and scalable discovery process for the active optical access network; Discovery Phase and Precise Ranging Phase. PLZT high-speed optical switches are able to switch an optical signal at nano-second speed (< 5–10 ns). The new discovery process is based on the CC for channel control. The feature of this method is that CC position can be accurately identified by sending consecutive REGISTER_REQs. We implemented the proposals on prototype devices and evaluated their performance in terms of ranging ability. The results proved the effectiveness of the new discovery process and the feasibility of ActiON. In the future, we will engage in the development of a 10 Gbps system for realizing access networks based on optical switches. Our future goal is to develop a hybrid passive/active/WDM optical access network by taking advantage of active access networks.

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