Hybrid Passive/Active Optical Access Network Architecture that Reduces OLT Power Consumption

Kazumasa Tokuhashi, Daisuke Ishii, Satoru Okamoto, and Naoaki Yamanaka

***Abstract*—This paper proposes a power efficient optical access network architecture that reduces OLT power consumption. Several PON trees are aggregated thanks to waveguide optical switches with nano second-order switching speed. The proposed network dynamically activates/deactivates OLT according to ONU traffic load, and reduces OLT power use while maintaining transmission fairness.**

***Index Terms*—Optical access network, Optical switch, Power consumption, Passive optical network, 10G-EPON (IEEE802.3av)**

I. Introduction

IP network traffic has increased rapidly in recent years with the popularization of optical fiber access networks [1]. Currently, Passive Optical Network (PON) is used around the world as a Fiber-To-The-Home (FTTH) broadband access network. Fig. 1 depicts the PON architecture based on Time Division Multiplexing (TDM) transmission. The device connected at the root of the tree is called an Optical Line Terminal (OLT) located at a Central Office (CO) and the devices connected as the leaves are referred to as an Optical Network Unit (ONU). Optical coupler is set between OLT and ONUs. PON is a cost effective since ONUs share optical fiber by broadcast-and-select network. In the near future X Gigabit-PON (XG-PON: ITU-T G.987) [2] and 10 Gigabit-Ethernet PON (10GEPON: IEEE802.3av) [3] will become mainstream. Also, various types of next-generation optical access networks are currently researched, taking into account long-reach, large capacity of user, high reliability and such [4]–[6].

As approach to a large-scale access network, authors have proposed an active optical access network [7]–[11] using (Pb,La)(Zr,Ti)O_3 (PLZT) waveguide all-optical switch [12], [13] which is jointly-developed with EpiPhotonics Corp. [14]. PLZT switch offers nano second order high-speed switching, low insertion loss and low power consumption. Fig. 2 depicts the basic active optical access network architecture, which consists of an OLT, ONUs and an Optical Switching Unit (OSW) including two waveguide optical switches. This is a point-to-point network by switching. The OSW, which is in a Remote Node (RN), generates the increase in the number of users and the transmission distance due to its low insertion loss of switching, while the optical coupler divides the optical power intensity among its ports. The OSW has a simple mechanism and provides all-optical and transparent data transmission without buffering and analyzing the header of a frame. Therefore, the active optical access network has least impact in the change of protocol due to waveguide all-optical switch, and is developed based on the latest IEEE standard of PON (10G-EPON; IEEE802.3av) [3].

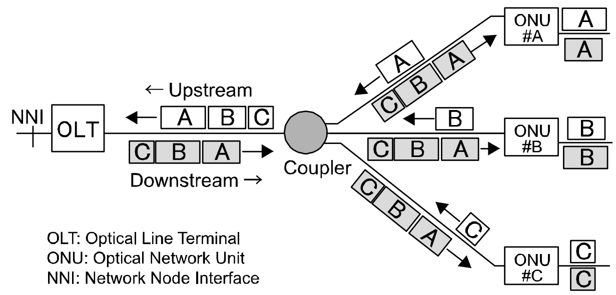

Fig. 1. Basic PON architecture.

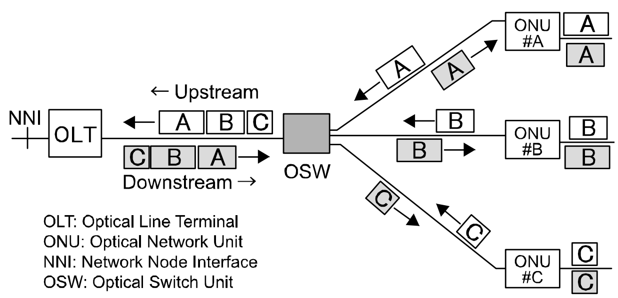

Fig. 2. Basic active optical access network architecture.

On the other hand, power consumption of network equipments reached 25 Giga Watt in 2008, and is expected to exceed 97 Giga Watt in 2020 due to the increase in transmission speed [15]. In reference [16], access networks consume around 70 percent of overall Internet power consumption due to the presence of a huge number of active elements. Hence, resolving a problem of the power consumption of access network is

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necessary. Long-Reach (LR)-PON is considered to be one of the effective ways of reducing the power consumption of access network [17], [18]. One tactic of LR-PON is to consolidate and reduce the number of CO holding OLTs. LR-PON technology, which supports the migration of metro networks and access networks into a next-generation large-scale access network, simplifies the network and will lead to cost savings [19]. Also, the power consumption of different next-generation optical access networks has been compared in reference [20]. As in other schemes reducing power consumption, it can utilize ONU sleep mode or doze mode methods [21]-[24]. Also for 10G-EPON systems, ONU sleep and adaptive link rate (ALR) control functions, which is based on energy efficient Ethernet (IEEE 802.3az [25], [26]), have been proposed in reference [27]. Accordingly, power consumption can be best reduced by implementing large-scale optical access networks with sleep mode enabled devices.

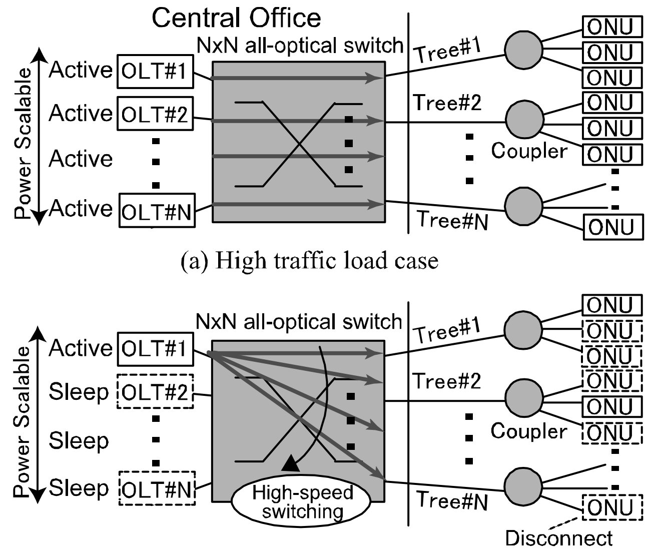
This paper proposes a power saving method for the optical access network. Our key advanced is a scheme for reducing OLT power consumption. Current COs host many OLTs, each with several PON cards. Each OLT is always powered on to avoid service disruption regardless of whether it contains the full user set (32 users in EPON series) or not. Therefore, OLT power consumption is excessive if the OLT supports just a few users. To solve this problem, our proposed network is based on hybrid passive/active architecture. For greater efficiency, OLTs are dynamically activated/deactivated according to the ONU's traffic load such as the number of active ONUs. In addition, this paper describes a power saving and fairness algorithm that determines the number of active OLTs and the average number of ONUs controlled by one OLT. Evaluation results confirmed that the proposed network reduces OLT power consumption while maintaining transmission speed fairness among the ONUs. This system is constructed by applying our previously researched active optical access network.

The remaining sections of this paper are organized as follows. Section II proposes the new access network that reduces OLT power consumption. Section III provides an evaluation and a discussion about power consumption and transmission fairness. Section IV summarizes the current activities.

II. Power Saving Hybrid Passive/Active Optical Access Network

A. Concept of Power Saving Optical Access Network

In the proposed network, several PON trees are aggregated by using $N \times N$ waveguide all-optical switches [28] in the CO, as depicted in Fig. 3. The architecture can be dynamically reconfigured to effectively reduce OLT power use while maintaining transmission fairness. One OLT is assigned to one tree when the network load is high, as depicted in Fig. 3 (a). Only a few OLTs control all trees when the network load is low, as depicted in Fig. 3 (b). This power scaling leads to power saving. Additionally, the number of users per PON port is currently less than the maximum capacity of PON port (32, 64



(a) High traffic load case

(b) Low traffic load case

Fig. 3. Power Saving Optical Access Network based on Hybrid Passive/Active Architecture.

users). According to reference [17], a filling ratio, which is the number of user connected over the maximum capacity of one GPON port (64 users), is currently about 25 percent. It shows that one PON tree containing 32 (in EPON series) or 64 (in GPON series) users is actually rare. Therefore, our proposed technique that aggregates PON trees is expected to fundamentally reduce OLT power consumption regardless of each ONU' traffic condition. Additionally, the use of optical switch realizes fast fiber and OLT protection/restoration by controlling optical switches remotely [29], [30]. This is the original characteristic of a switch. Protection methods are essential for next-generation large-scale access networks like LR-PON.

Incidentally, the proposed hybrid passive/active network is more suitable for urban areas with high population density. This is because basic PON, which is currently very popular, is also basically suitable for urban areas. Accordingly, many feeder fibers and optical couplers have been already connected to residents or offices. And these PON architectures consume vast amounts of power in overall Internet, as already described. In consideration of this current situation, the proposed network, which is a network solution with existing equipments, is better for densely-populated area. In contrast, our previously proposed active optical access network in Fig. 2 is more suitable for low population areas, such as a rural area and an area where FTTH has not been developed yet. This is because a long-distance transmission is required due to its low population density. Of course in the hybrid passive/active proposed network, it is reasonable way to place a $1 \times N$ type of OSW in a RN instead of a coupler for developing more large-scale architecture. However, in order to simply evaluate the power-saving effect of proposed technique compared to power consumption of basic PON, this paper introduces the hybrid passive/active architecture with optical couplers and the $N \times N$ type of OSW which is placed in a CO to reduce OLT power consumption.

B. Power Scalable OLT

While there are many kinds of OLT chassis, the most common type accommodates several PON cards, each of which provides 2, 4, or as many as 8 PON ports. So the power scalable OLT system works in units of OLT chassis or PON card. One of the OLTs, the master OLT, controls the slave OLTs in the proposed network. The new functions, an optical switch control (with switching scheduler) and a judgment of OLT activation/deactivation as described later in section II-E, are added to the master OLT. Slave OLTs need to notify master OLT of the state of ONUs within their own chassis. Therefore, the master OLT activates/deactivates slave OLTs by processing information about ONU traffic from the slave OLTs. However, because a slave OLT is basically no different from the usual OLT, it communicates with the ONUs via Multi-Point Control Protocol (MPCP) [31] defined in IEEE802.3av (10G-EPON).

C. Optical Switching Unit (OSW)

Fig. 4 depicts the configuration example of the OSW in the proposed access network. The OSW with $N \times N$ waveguide all-optical switches adopts the technology of an active optical access network [9], [10], [32]. For details on the structure of $N \times N$ waveguide all-optical switch, refer to reference [28] (which is about non-blocking PLZT 4 × 4 optical switch). The OSW is driven by the switching schedule decided by Dynamic Bandwidth Allocation (DBA) function of master OLT. DBA is used in PON to manage the upstream data transmission schedules. The OSW is controlled by the master OLT which informs it of the switching schedule via switch control frames on the inband or outband control line. The switch controller then activates the appropriate waveguide optical switches via switch drivers, based on the switching schedule. This simplifies the switching mechanism since it does not need the function of buffering and frame-by-frame data-analysis for extracting information on the destination.

D. Switching Cycle and Data Transmission

Fig. 5 shows an example of switching schedule for data transmission in hybrid passive/active optical access network. The OSW repeats the received switching schedule until it receives the next switch control frame. This cycle is called "switching cycle". The size of one switching cycle is from 200 μsec to 1000 μsec, which is based on DBA cycle. DBA cycle is mainly determined by considering TCP throughput and round trip time (RTT) [8], [33], [34]. T_c is processing delay of switch control frame by the switch controller in OSW. T_c is 3.2 μsec according to the related reference [32]. T_{sw} is switching delay of waveguide optical switch. T_{sw} is under 10 $n$sec which is the switching speed of 4 × 4 non-blocking PLZT waveguide optical switches [14], [28], so the speed is enough fast for the switching control procedure. The OSW can also compensate for T_c, as depicted in Fig. 5. This is because the process of switch control frame runs in the background, and a switching schedule is updated from the time of the next switching cycle. At the time, it takes only 1 clock to change a switching cycle by the previously developed prototype optical switch system [35].

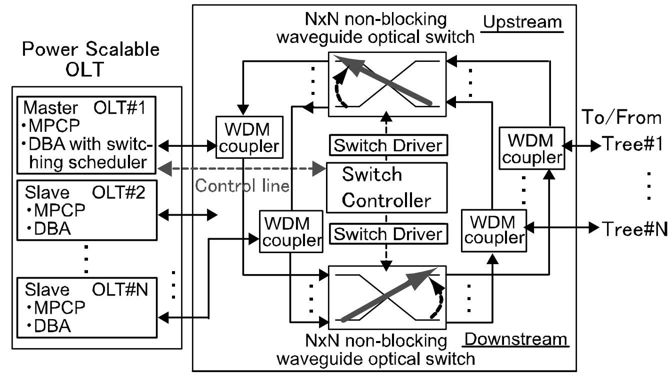


Fig. 4. Configuration of NxN optical switching unit (OSW)

Our proposed network utilizes MPCP [31] defined in IEEE802.3 (EPON) to prevent the collision of data at the optical coupler and to control data transmissions in the upstream direction. Firstly, OLT is synchronized with ONUs by a discovery process specified in MPCP. Authors already discussed the discovery process for an active optical access network with OSW in the reference [9] (Please see the reference if you want to know the details.). After synchronization, OLT transmits GATE message specified in MPCP. GATE message informs ONU of "transmission time and length" to avoid collisions of data. These time and length are called grant start time t_x and grant length T_x, written in GATE message. OLT instructs ONUs, and ONUs transmit data within the time period (from t_x to t_x+T_x) permitted by OLT since ONUs do not transmit data autonomously. In Fig. 5, OLT#X controls ONU#1 and ONU#2 in tree#1, and ONU#3 and ONU#4 in tree#2 in the same time line. So, a switching duration assigned to each tree is flexibly shared among ONUs in each tree. As in Fig. 5, OLT flexibly assigns bandwidth to each ONU on a tree-by-tree basis although there is no difference between *nth* and *(n + 1)th* switching cycle. Therefore, $T_1 + T_2$ equals $T'_1 + T'_2$, and $T_3 + T_4$ equals $T'_3 + T'_4$.

E. Power Saving and Fairness Algorithm

The nomenclature used is given below.

N_{ONU_max}	Max supportable number of ONU per OLT e.g.) 32, 64
S	Switch size, e.g.) $S = 4$, 4 × 4 switch
i	Index of tree, where $1 \le i \le S$
$N_{ONU\ i}$	Number of active ONUs on tree #i
N_{ONU_total}	Total number of active ONUs on the system
N_{OLT}	Number of active OLTs
$\overline{N_{ONU}}$	Calculated average number of ONUs per OLT
$\lceil x \rceil$	Smallest integer greater than or equal to x
Flag [i]	Flag of tree #i (1 origin array); The value is set to 0 or 1.
CHECK	Determining the algorithm converged; The value is set to 0 or 1.

This section describes a power saving and fairness algorithm

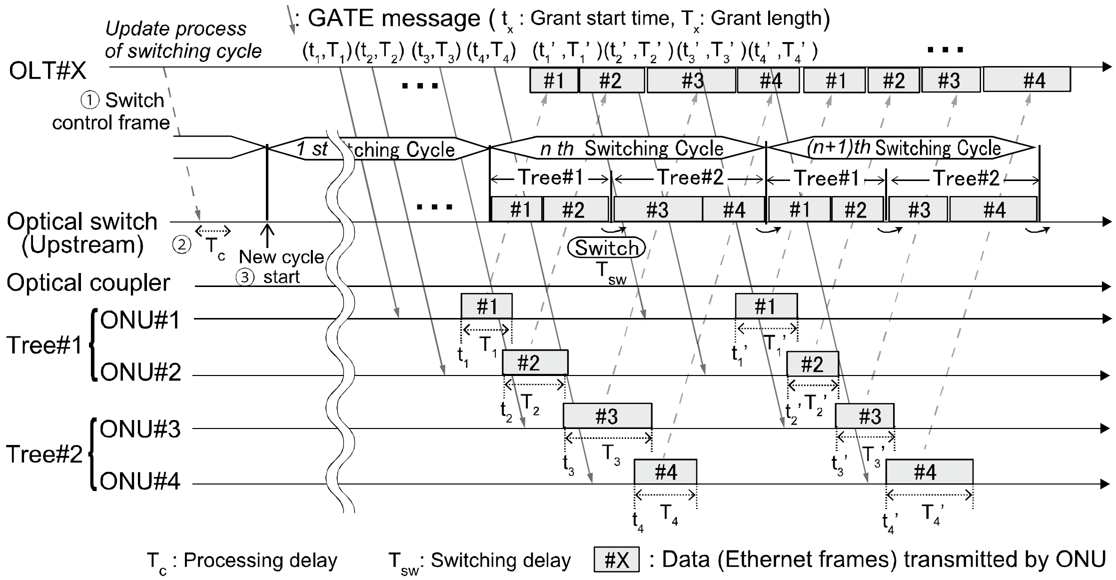


Fig. 5. Example of switching schedule at low traffic load (Upstream).

based on the number of active ONUs (N_{ONU_i} , N_{ONU_total}). An active ONU is defined as a registered ONU not in the deep sleep [24] or disconnected state. OLT discovers active ONUs by the use of MPCP. This algorithm determines the number of active OLTs (N_{OLT}) and the average number of ONUs controlled by one OLT ($\overline{N}_{ONU}$). Master OLT periodically executes this algorithm and controls the OSW as shown in section II-C. The policy of the algorithm is to ensure appropriate fairness in terms of the transmission speed of each ONU even though some OLTs are deactivated, and to eliminate "dead time" explained later in this section.

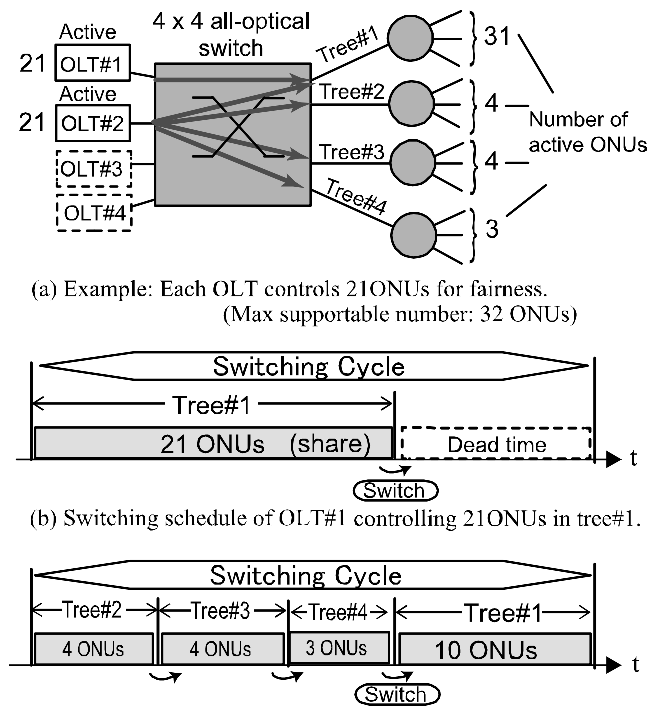
To begin with, a bad example generating dead time is introduced. First, for a given N_{ONU_total}, N_{OLT} is calculated from eq. (1).

$$N_{OLT} = \left\lceil \frac{N_{ONU\_total}}{N_{ONU\_\max}} \right\rceil \tag{1}$$

Secondly, $\overline{N}_{ONU}$ is calculated from eq. (2).

$$\overline{N}_{ONU} = \frac{N_{ONU\_total}}{N_{OLT}} \tag{2}$$

Eq.(2) yields the ideal ONU number per OLT to evenly disperse the OLT load for fairness. However, if this $\overline{N}_{ONU}$ is used, dead time often occurs because there is high imbalance among trees, as depicted in the example in Fig. 6. In Fig. 6(a), N_{OLT} is 2 OLTs, and $\overline{N}_{ONU}$ is 21 ONUs since N_{ONU_total}, is 42 in the case that N_{ONU_max} is 32. As depicted in Fig. 6(b)(c), OLT#1 cannot transfer/receive data to/from anywhere since ONUs in tree#2, #3 and #4 are managed by OLT#2 and tree#1 switches to OLT#2 during this dead time. It is impossible to disperse the load of the tree #*i* more highly loaded than $\overline{N}_{ONU}$. This is a bad example.



(a) Example: Each OLT controls 21ONUs for fairness. (Max supportable number: 32 ONUs)

(b) Switching schedule of OLT#1 controlling 21ONUs in tree#1.

(c) Switching schedule of OLT#2 controlling 4 ONUs in tree#2, 4 ONUs in tree#3, 3 ONUs in tree#4, and 10 ONUs in tree#1

Fig. 6. Bad example: dead time at the architecture using 4x4 optical switch.

So, the algorithm which aims to ensure appropriate fairness while eliminating dead time is proposed, as shown in Fig. 7. First and second equations are same as equations of the bad example. Next, the trees #*i* more highly loaded than $\overline{N}_{ONU}$ are searched for their elimination, and *Flag* [*i*] is on. Each tree #*i* with "*Flag* [*i*] equals 1" is simply allocated to one OLT since the high loaded tree cannot be balanced. Next, subtract 1 OLT from N_{OLT}, and N_{ONU_i} from N_{ONU_total}, respectively. After subtracting

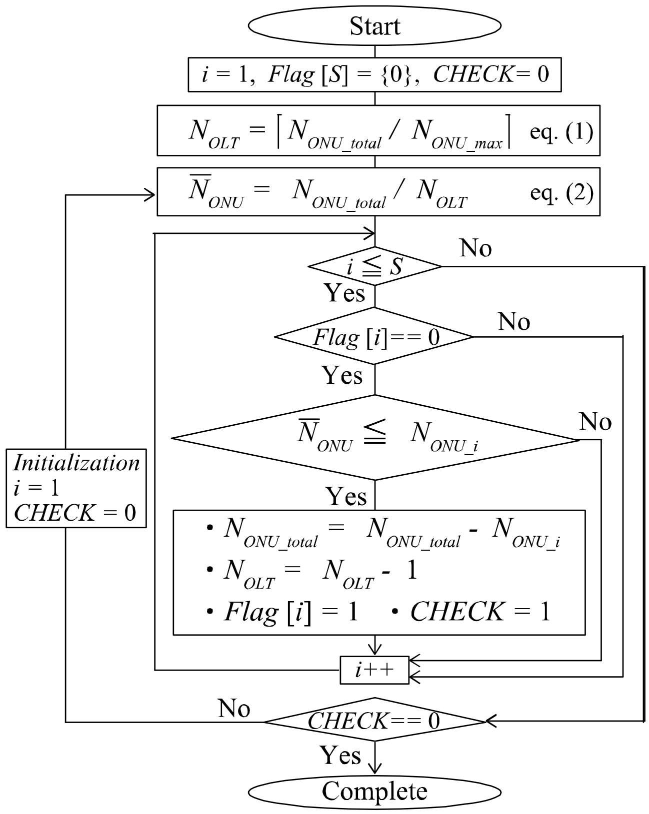


Fig. 7. Power saving and fairness algorithm based on the number of active ONUs.

all high loaded trees, this process returns to the top of loop while initializing *i* and *CHECK*. Then, $\overline{N}_{ONU}$ is recalculated based on the changed N_{OLT} and N_{ONU_total} for the remaining trees. Next, the high loaded trees than recalculated $\overline{N}_{ONU}$ are searched and subtracted again. Finally, $\overline{N}_{ONU}$ converges when *CHECK* is 0 at the final conditional expression. The proposed network is reconfigured with reference to N_{OLT} calculated from eq. (1), converged $\overline{N}_{ONU}$ and *Flag* [*i*]. As a calculated result, in Fig.6, N_{OLT} is 2, $\overline{N}_{ONU}$ is 11, *Flag* [1] is 1 and *Flag* [2] is 0.

Here, a transmission speed (allocated bandwidth) of tree#*i* at each OLT are described. The nomenclature used is given below.

j	Index of OLT, where $1 \leq j \leq S$
B_{max}	Maximum transmission speed (bandwidth) e.g.) 1Gbps (1G-EPON), 10Gbps (10G-EPON)
N^j_{ONU}	Number of active ONUs controlled by OLT#*j*
$N^j_{ONU\_i}$	Number of active ONUs controlled by OLT#*j* in tree#*i*
B^j_i	Transmission speed (bandwidth) of tree#*i* allocated by OLT#*j*
$\overline{B}^j$	Average ONU transmission speed (bandwidth) allocated by OLT#*j*

B^j_i is determined according to the number of active ONUs controlled by OLT#*j* (N^j_{ONU} and $N^j_{ONU\_i}$). N^j_{ONU} and $N^j_{ONU\_i}$ are determined by the result of the algorithm in Fig. 7. B^j_i is calculated as follow.

$$B^j_i = B_{\max} \times \frac{N^j_{ONU\_i}}{N^j_{ONU}} \quad (3)$$

As depicted in Fig. 8, when a OLT#X with 1Gbps transmission speed ($B_{\max}$ = 1Gbps) manages 2 ONUs in tree#1 ($N^X_{ONU\_1} = 2$), 2 ONUs in tree#2 ($N^X_{ONU\_2} = 2$), 4 ONUs in tree#3 ($N^X_{ONU\_3} = 4$) and 8 ONUs in tree#4 ($N^X_{ONU\_4} = 8$), each transmission speed of tree#1 (B^X_1), #2 (B^X_2), #3 (B^X_3) and #4 (B^X_4) is 125 Mbps, 125 Mbps, 250 Mbps, and 500 Mbps. The average ONU transmission speed $\overline{B}^j$ is 62.5 Mbps (=$B_{\max}$ / N^j_{ONU} = 1Gbps/16).

III. Evaluation And Discussion

A. Simulation Model

We evaluate and discuss the power consumption and fairness of transmission speed (bandwidth) allocated to ONU. In this simulation, the proposed power saving architectures with 2 × 2, 4 × 4 or 8 × 8 optical switch are compared with PON architectures. Each tree has a maximum of 32 ONUs (N_{ONU_max} equals 32). The 2 × 2, 4 × 4 and 8 × 8 non-blocking optical switches consume 2.3, 4.9 and 16.4 Watt, respectively. Values of 2 × 2 and 4 × 4 optical switches are extracted from the data sheet of non-blocking PLZT optical switch subsystem which is jointly-developed with EpiPhotonics Corp. [14]. In regard to the 8 × 8 optical switch, which has not been developed yet, we calculated the power consumption based on values of non-blocking PLZT 2 × 2 and 4 × 4 optical switch subsystems. The power consumption depends on switch size. However because these switch systems mount only one PLZT waveguide optical switch unlike Fig. 4, so simulation parameters of OSWs are double that of PLZT optical switch subsystems for upstream and downstream. The power consumption of one OLT with 1Gbps transmission speed is 12.5 Watt. This value is determined by reference to a vender's OLT with eight OLT ports [16] whose power consumption is 100 Watt. ONU power consumption is not included because it is a common element in both architectures.

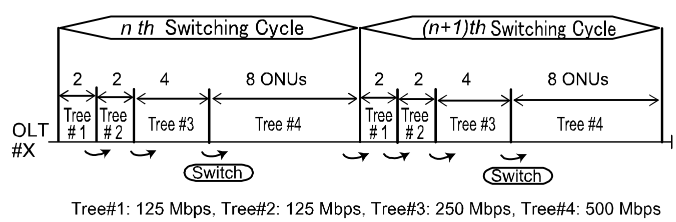


Fig. 8. Example of switching schedule allocation.

B. Power Consumption

Total power consumption P is calculated as follow.

$$P = N_{OLT} \times P_{OLT} + P_{SW} \tag{4}$$

N_{OLT} is calculated from eq. (1). P_{OLT} and P_{SW} stand for power consumption of OLT and OSW. Fig. 9 shows the total power consumption P versus the active ratio. The active ratio means the ratio of active ONUs in each tree (For example: active ratio 0.5 equals 16 active ONUs, active ratio 1 equals 32 active ONUs). In Fig. 9, one proposed architecture with 2 × 2 (, 4 × 4 or 8 × 8) optical switch is compared with two (, four and eight) PON architectures. At high active ratio, almost all ONUs are active, and the proposed architecture is not effective in consequence of P_{SW}. The proposed power saving architectures reduce P at low-middle active ratio because each tree has a small number of active ONUs. Actually, P of the proposed architectures with 2 × 2, 4 × 4 and 8 × 8 optical switch get above that of PONs at approximately 0.5, 0.7 and 0.6 of active ratio, respectively. Therefore, among the three proposed architectures, 4 × 4 architecture that has the widest range in active ratio is the most efficient. Additionally, a filling ratio is currently about 25 percent as mentioned in section II-A. Active ratio should not be more than the filling ratio since the filling ratio means the ratio of users per one PON. So, when calculated in active ratio 0.25 (25 percent), the proposed architectures with 2 × 2, 4 × 4 and 8 × 8 optical switch fundamentally reduce the power consumption by at least approximately 32, 44 and 36 percent, respectively.

Generally, the power consumption of network equipments increase with increasing in transmission speed [36], [37]. So, P increases further in future high speed environments such as 10G-EPON. However, the power consumption of the waveguide optical switch is basically independent of the transmission speed in the proposed architecture. This is because it provides all-optical and transparent data transmission without buffering and analyzing the header of a frame (packet) electrically. Therefore, the proposed architecture can be expected to yield the power-saving effect more clearly in future high speed environments. Additionally, P_{SW} is expected to be reduced in future since this OSW is still a prototype.

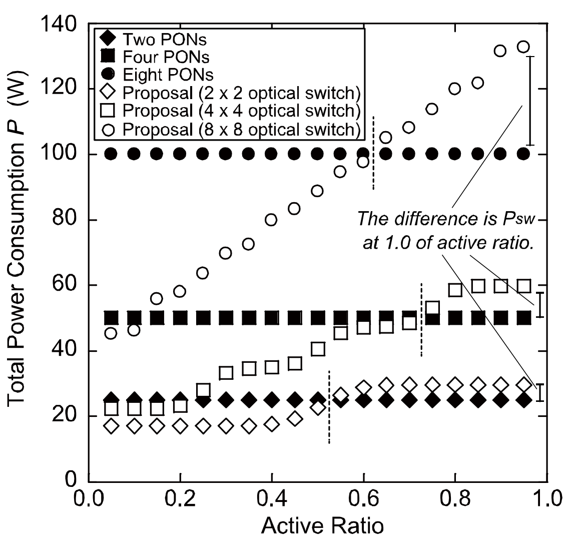


Fig. 9. The total power consumption versus the active ratio.

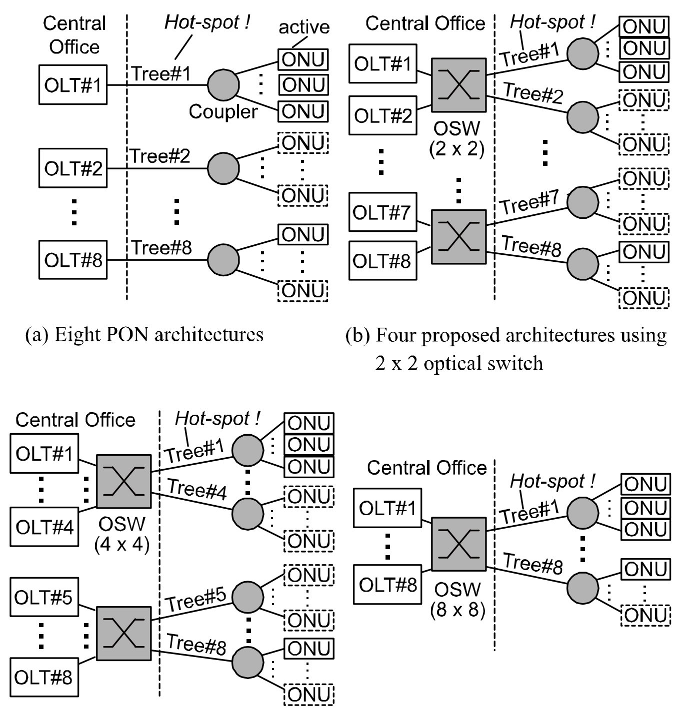
C. Fairness: average ONU transmission speed

Here, the fairness in terms of an average ONU transmission speed is evaluated among each architecture. Fairness is evaluated by the fairness index F [38] which is defined as

$$F = \frac{\left(\sum_{j=1}^{N_{OLT}} \overline{B}^{j}\right)^2}{N_{OLT} \times \sum_{j=1}^{N_{OLT}} \left(\overline{B}^{j}\right)^2} \tag{5}$$

$\overline{B}^{j}$ is the average ONU transmission speed allocated by OLT #j, as shown in section II-E. When the fairness index F is near to 1, the difference in average ONU transmission speed is small.

Fig. 10 shows simulation models for the evaluation of fairness. In this section, the performance under the hot-spot environment is evaluated. This environment is created when a lot of active ONUs are concentrated on a certain PON or tree. Specifically, the number of active ONUs is widely different among each tree as depicted in Fig. 10 (Tree#1 is the hot-spot in this example). As the current architecture, the model of the eight PON architectures shown in Fig. 10 (a) is used. For the proposed architecture, the model using four 2 × 2 optical switches, the model using two 4 × 4 optical switches, and the



(a) Eight PON architectures
(b) Four proposed architectures using 2 x 2 optical switch
(c) Two proposed architectures using 4 x 4 optical switch
(d) One proposed architectures using 8 x 8 optical switch

Fig. 10. Simulation models for the hot-spot environment evaluation.

model using one 8 × 8 optical switch, as depicted in Fig. 10 (b)(c)(d), are evaluated. Several of eight trees are set to hot-spot trees. The active ratio of each hot-spot tree is higher than other trees whose active ratio is fixed at 0.1.

Fig. 11, 12 and 13 show the fairness index *F* versus the active ratio of each hot-spot tree, based on Fig. 10. Fig. 11 shows the case that one hot-spot tree (tree #1) exists, Fig. 12 shows the case that two hot-spot trees (tree #1, #5) exist and Fig. 13 shows the case that four hot-spot trees (tree #1, #3, #5, and #7) exist. The fairness value of PON is used only as a guide since OLT is always activated and allocates excessive bandwidth to ONUs (its tree) in PON. *F* declines overall at high active ratio since the difference between the active ratio of hot-spot trees and other trees is very big. In all evaluations, the proposed architecture using 8 × 8 optical switch achieves the most fair. This is because

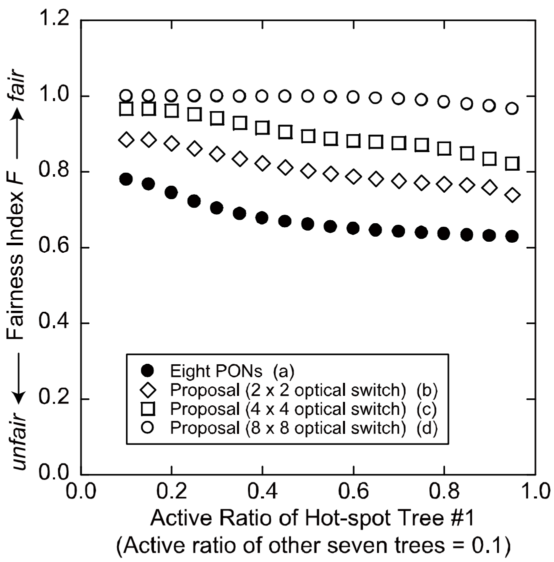


Fig. 11. Fairness index *F* versus the active ratio of hot-spot tree #1.

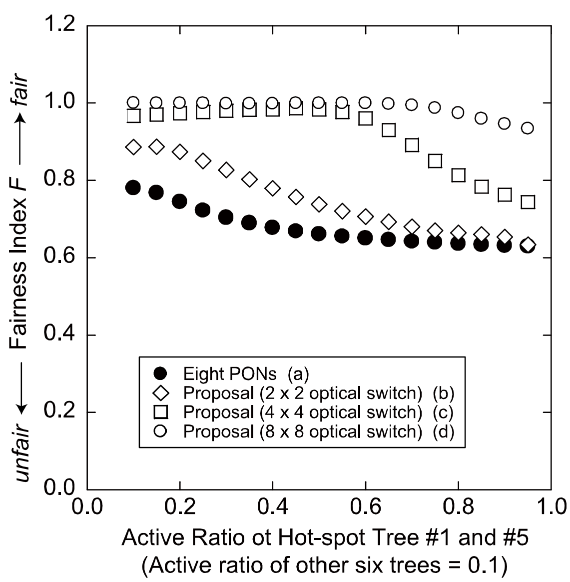


Fig. 12. Fairness index *F* versus the active ratio of hot-spot tree #1 and #5.

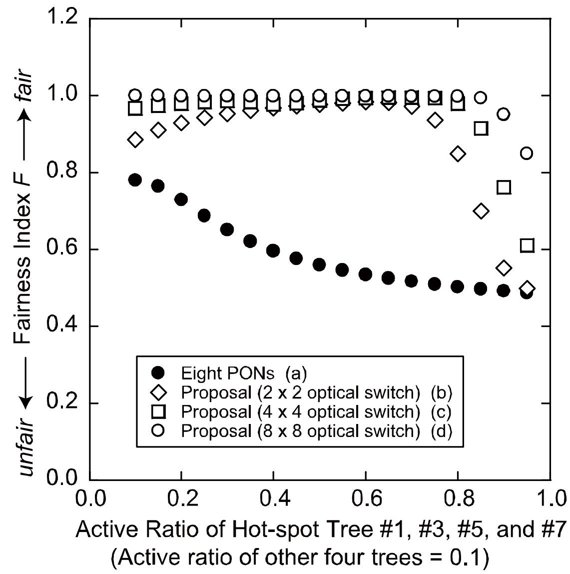


Fig. 13. Fairness index *F* versus the active ratio of hot-spot trees #1, #3, #5, and #7.

the use of the 8 × 8 optical switch enables more flexible assignment of ONUs for each OLT compared to the other architectures. Given active ratio 0.25 in the same way as section III-B, *F* of the proposed architectures with 2 × 2, 4 × 4 and 8 × 8 optical switch are approximately 0.861, 0.952 and 0.999 in Fig. 11, 0.851, 0.977 and 0.999 in Fig. 12, and 0.942, 0.983 and 0.999 in Fig. 13, respectively. The performance of architecture using the 4 × 4 optical switches approaches that of architecture using the 8 × 8 optical switch. Considering from Fig. 9, 11, 12 and 13, the proposed 4 × 4 architecture is most useful since fairness value is high as well as most reducing power consumption. These results show that the proposed network reduces power consumption while maintaining high transmission fairness.

IV. Conclusion

This paper has proposed a power saving optical access network based on a hybrid passive/active architecture. The proposed network can dynamically reconfigure access trees according to the number of ONUs to effectively cut down on OLT power use. Only a few OLTs control all ONUs under low network load. Evaluation results confirmed that the proposed network reduces OLT power consumption while maintaining transmission speed fairness among the ONUs. Future work is to implement and demonstrate the power saving optical access network on the basis of this research result.

Acknowledgment

This work was a part of Global COE Program "High-Level Global Cooperation for Leading-Edge Platform on Access Spaces (C12)."

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