Efficient Singlecast / Multicast Method For Active Optical Access Network Using PLZT High-speed Optical Switches

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Abstract—We propose a new efficient singlecast / multicast method for active optical access network using PLZT 10 nsec high-speed optical switches. The Active Optical Network, called ActiON, has been proposed using slot type switched optical network. Compared with Passive Optical Network (PON), ActiON can quadruplicate the number of subscribers (128 users) per OLT and double the maximum transmission distance (40 km) between OLT and ONUs. However, ActiON uses slot based switching method, so it is difficult to realize the multicast delivery. In this paper, we propose the efficient singlecast / multicast method for ActiON by using PLZT optical switch elements which are controlled as “distribution mode” like an optical splitter by applying mid-control voltage. In addition, a new efficient multicast slot allocation method is proposed and formulated as a linear programming problem. This formula develops the maximum number of users which is able to be connected by multicast and the minimum number of slots is used for multicast users.

I. INTRODUCTION

Today, Passive Optical Network (PON) system is widely prevalent for access network. Gigabit Ethernet Passive Optical Network (GE-PON) [1] is the representative example of the access network. Figure 1 shows PON architecture. PON consists of three contents, Optical Line Terminal (OLT) which connects to backbone network, Optical Network Unit (ONU) which communicates with a user terminal and an optical splitter. Currently, to realize 10 Gbps access network, 10 Gigabit Ethernet Passive Optical Network (10 GE-PON) [2] is becoming the standard now. The advantages of PON are low-cost and low-power due to a passive optical splitter. However, PON system has limitations of the maximum number of ONU (32 ONUs) and the maximum transmission distance (20 km) between OLT and ONUs. This is because the optical power is divided at a splitter and decreases as the number of ONUs increases. Moreover, PON system is a low-security architecture in principle because all ONUs receive all signals from OLT. A malicious user can intercept all data.

To resolve these problems, we propose an active optical access network architecture using PLZT 10 nsec high-speed optical switches [3] without optoelectrical conversion. We call this proposed network Active Optical Network (ActiON) [4]. ActiON can quadruplicate the number of subscribers (128 users) per OLT and double the maximum transmission distance (40 km) between OLT and ONUs. Moreover, a user can establish secure communication in ActiON.

However, in ActiON, it is difficult to realize the multicast delivery by broadcast system like the PON system because ActiON uses not broadcast system but slot based switching system. Recently, the demand for the multicast delivery in the access network has increased as the broadcast service spreads.

In this paper, we propose the efficient singlecast / multicast method for ActiON by using PLZT optical switch elements which are controlled as the distribution mode like an optical splitter by applying mid-control voltage. In addition, a new efficient multicast slot allocation method is proposed and formulated as a linear...
programming problem. The remaining sections of this paper are organized as follows. Section II describes the ActiON system, Section III describes the proposed singlecast / multicast method for ActiON, Section IV describes the formulation of the efficient multicast slot allocation as a linear programming problem, Section V shows the simulation results for the efficient multicast slot allocation by using ILP solver and Section VI describes the conclusion.

II. ACTIVE OPTICAL NETWORK (ACTION)

A. Architecture

Figure 2 shows an ActiON architecture. Two optical switches (Upstream switch and Downstream switch) are used between OLT and ONUs. ActiON employs a switch to achieve much less optical power loss than an optical splitter for the conventional PON system. Therefore, ActiON can contain more ONUs than PON. Compared with PON, ActiON can quadruplicate the number of subscribers (128 users) per OLT and double the maximum transmission distance (40 km) between OLT and ONUs.

B. Data transmission

In ActiON, Multi Point Control Protocol (MPCP) is adopted for compatibility with 10 GE-PON (IEEE802.3av). The bandwidth is allocated to each user by fixed-length time for easy control [5]. This fixed-length time is called "slot". An optical switch is controlled by the unit of periodic "cycle" composed of many slots. Figure 3 shows the cycle which is composed of many slots. OLT allocates the slot to each user and transmits to each user by using the slot, so OLT cannot transmit many users at once by using the slot. In ActiON, it is necessary to realize the multicast delivery like broadcast services. When the same data is transmitted to some users, the data is copied for users and transmitted to each user by switching. The number of the multicast users increases according to the number of the multicast users, so the utilization efficiency of slot allocation decreases. Therefore, we propose the efficient singlecast / multicast method for ActiON.

III. THE PROPOSED EFFICIENT SINGLECAST / MULTICAST METHOD FOR ACTION

A. Singlecast / Multicast method by using $1 \times 2$ PLZT optical switch elements

1) Structure of the $1 \times 128$ PLZT optical switch: PLZT 10 nsec high-speed optical switches are used in ActiON. Figure 4 shows the structure of the $1 \times 128$ PLZT optical switch [6]. The $1 \times 128$ PLZT optical switch has the multistage (7 stages) configuration of $1 \times 2$ optical switch elements.

2) The switching of the Mach-Zehnder type optical switch: The $1 \times 2$ optical switch element is the guided-wave structure of Mach-Zehnder type, so the optical signal is output in each direction by changing the voltage low and high. Figure 5(a) shows the switching operation of the $1 \times 2$ optical switch element. The optical signal from Port A is output to Port X or Port Y by giving the low voltage or the high voltage.

3) The use method of controlling the optical switch elements as the distribution mode: As shown in Figure 5(b), the optical signal can be output in both output ports by applying mid-control voltage in this
Mach-Zehnder type structure. By using this feature, we propose the use method of controlling the optical switch elements as the distribution mode like an optical splitter. By controlling optical switch elements as the distribution mode, several multicast users can be connected at the same time.

4) The singlecast / multicast method by using optical switch elements as the distribution mode: Figure 6 shows the singlecast / multicast method for ActiON by controlling optical switch elements as the distribution mode. User #1, #2, #5 and #7 are supposed to be multicast users. When the optical switch element are used as the normal mode, OLT copies the data for each user and transmits the data to each user by slot switching. The number of the multicast slots is 4 slots by using switching. On the other hand, when the optical switch elements are used as the distribution mode, the user #1, #2, #5 and #7 can be connected by multicast by using the optical switch elements (a, c and d) as the distribution mode. The number of the multicast slots is only 1 slot. The singlecast users can be also connected by switching according to the demand delivery method of the users. By using the optical switch elements as the distribution mode, the singlecast / multicast method can be realized.

5) The power loss of the optical signal per each user: In the normal mode, there is no fundamental loss. To simplify the discussion about the constrained condition of each optical switch, the power loss of the optical signal when using the optical switch as the normal mode is decided at 0 dB and the connection loss and so on 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. When the optical switch elements are used as the normal mode, the power loss of the optical signal per each user (#1, #2, #5 and #7) is 0dB (= 0dB + 0dB + 0dB). However, when the optical switch elements are used as the distribution mode, the power loss of the optical signal per each user (#1, #2, #5 and #7) is 7dB (= 3dB + 3dB + 0dB), so the power loss of the optical signal increases.

When the optical switch elements are used as the distribution mode, the multicast slots decreases and the utilization efficiency of slot allocation increases. However, the power loss of the optical signal per each user increases. Therefore, it is necessary to limit the number of stages for the optical switch elements using the distribution mode and decide the limit on the power loss of the optical signal.

B. Limit on the number of stages for the optical switch elements using the distribution mode

In the PON system, the power loss of the optical signal per each user is decided at 15dB. The 1 x 32 optical splitter of the PON system has the multistage (5 stages) configuration of 1 x 2 optical splitter, so the power loss of the optical signal is 15dB (= 3dB x 5). In the singlecast / multicast method for ActiON, in order to realize the scalable access system of transmission distance 20 km (the maximum transmission in the PON system) or more, the limit on the power loss of the optical signal is decided at the 12dB, and the limit on the number of stages of the optical switch elements using the distribution mode is 4 stages of 7 stages. It is necessary to select which optical switch elements can be controlled as the distribution mode within 4 stages. Figure 7 shows the singlecast / multicast method for ActiON by using the optical switch elements as the distribution mode in 4 stages. By using the optical switch elements as the distribution mode in 4 stages,
IV. FORMULATION OF THE EFFICIENT MULTICAST SLOT ALLOCATION AS A LINEAR PROGRAMMING PROBLEM

In order to realize the efficient multicast slot allocation, it is necessary to decrease the number of the multicast slots. The method of selecting the maximum number of users which can be connected by multicast every one slot is proposed. In case the number of the multicast user increases, it takes a great amount of time to search the multicast users which can be connected. When the number of the multicast users is 128, the number of times for searching becomes \(2^{128}\). Therefore, we formulate the efficient multicast slot allocation method as a linear programming problem. Three variables are used in the formulation of the singlecast / multicast method for ActiON.

- \(U_j\) (1 or 0) : Multicast user \(j\) demands \((U_j = 1)\) or not \((U_j = 0)\).
- \(S_i\) (1 or 0) : The optical switch element \(i\) is used as the distribution mode \((S_i = 1)\) or not \((S_i = 0)\).
- \(P_{u\rightarrow d}\) (1 or 0) : The link between the optical switch element \(u\) and the optical switch element \(d\) has the optical power \((P_{u\rightarrow d} = 1)\) or not \((P_{u\rightarrow d} = 0)\).
- \(U_j\) (1 or 0) : Multicast user \(j\) demands \((U_j = 1)\) or not \((U_j = 0)\).

The objective function and the constrained condition are defined as follows.

A. Objective function

Selection of the maximum number of the multicast users which can be connected is defined as the objective function. A linear expression is shown as follows.

\[
Max \sum (P_{LB\rightarrow user})
\]

\(LB\) is the optical switch element’s identifier of the lower stages and \(user\) is the demand multicast user’s identifier. This formula means maximizing the total of the optical power of the links between the demand multicast user and the adjacent optical switch element.

B. Constrained condition

The constrained condition is defined for each optical switch element and each multicast user.

1) Constrained condition of each optical switch element: Two linear expressions are shown as the constrained conditions in each optical switch element.

First linear expression indicates the relation between the use of optical switch element and the optical power.

\[
P_{u\rightarrow i} + S_i = P_{i\rightarrow leftlower} + P_{i\rightarrow rightlower}
\]

\(P_{u\rightarrow i}\) is the optical power in the upper stage of the optical switch element \(i\). \(P_{i\rightarrow leftlower}\) is the optical power in the lower stage and the left side of the optical switch element \(i\). \(P_{i\rightarrow rightlower}\) is the optical power in the lower stage and the right side of the optical switch element \(i\).

Figure 8 shows three patterns in the relation between the use of an optical switch element and the optical power.
Second linear expression indicates the limit on the number of stages for the optical switch elements using the distribution mode.

\[ \sum_{n=0}^{Max-1} (S_{LB/2^n}) \leq H \quad (4) \]

\( Max \) is the number of stages of the optical switch element in the optical switch and \( H \) is the limit on the number of stages for the optical switch elements using the distribution mode.

2) Constrained condition of each multicast user:
The relation between the demand of the multicast users and the optical power is defined as a linear expression.

\[ U_j \geq P_{LB-user} \quad (5) \]

Figure 9 shows the example of the formulation of the efficient multicast slot allocation as a linear programming problem. User #9, #10, #11 and #12 are supposed to be multicast users. At first, \( U_j \) is allocated 0 or 1 according to the demand multicast users as follows. \( U_9, U_{10}, U_{11}, U_{12} = 1 \), \( U_4, U_{13}, U_{14}, U_{15} = 0 \)

Next, by selecting all patterns allocating \( S_i \) and \( P_{u→d} \) 0 or 1 in the constrained condition (formula (2), (3), (4), and (5)), the objective function is solved. According to the solution of the objective function (1), the maximum number of the multicast users which can be connected is solved. In Figure 9, User #9, #10, #11 and #12 are able to be connected at the same time. The objective function and each variable are defined as follows.

The objective function: \( Max(P_{4,9} + P_{5,10} + P_{5,11} + P_{6,12}) = 4 \)

The variables:
\( S_1, S_2, S_5 = 1, S_3, S_4, S_6, S_7 = 0 \),
\( P_{1→2}, P_{1→3}, P_{2→4}, P_{2→5}, P_{3→6}, P_{4→9}, P_{5→10}, P_{5→11}, P_{6→12} = 1 \),
\( P_{3→7}, P_{4→8}, P_{6→13}, P_{7→14}, P_{7→15} = 0 \)

\[ \begin{align*}
S_1 &
\end{align*} \]

\[ \begin{align*}
S_2 &
\end{align*} \]

\[ \begin{align*}
S_3 &
\end{align*} \]

\[ \begin{align*}
S_4 &
\end{align*} \]

\[ \begin{align*}
S_5 &
\end{align*} \]

\[ \begin{align*}
S_6 &
\end{align*} \]

\[ \begin{align*}
S_7 &
\end{align*} \]

\[ \begin{align*}
P_{1→2} &
\end{align*} \]

\[ \begin{align*}
P_{1→3} &
\end{align*} \]

\[ \begin{align*}
P_{2→4} &
\end{align*} \]

\[ \begin{align*}
P_{2→5} &
\end{align*} \]

\[ \begin{align*}
P_{3→6} &
\end{align*} \]

\[ \begin{align*}
P_{4→9} &
\end{align*} \]

\[ \begin{align*}
P_{5→10} &
\end{align*} \]

\[ \begin{align*}
P_{5→11} &
\end{align*} \]

\[ \begin{align*}
P_{6→12} &
\end{align*} \]

\[ \begin{align*}
P_{3→7} &
\end{align*} \]

\[ \begin{align*}
P_{4→8} &
\end{align*} \]

\[ \begin{align*}
P_{6→13} &
\end{align*} \]

\[ \begin{align*}
P_{7→14} &
\end{align*} \]

\[ \begin{align*}
P_{7→15} &
\end{align*} \]

By allocating to the maximum number of the multicast users which can be connected according to the dynamic demand of the multicast users per one slot, the proposed efficient multicast slot allocation can decrease the number of the multicast slots and increase the utilization efficiency of the slot allocation.

V. THE SIMULATION RESULTS FOR THE EFFICIENT MULTICAST SLOT ALLOCATION BY USING ILP SOLVER

We evaluate the capability of the proposed efficient multicast slot allocation by solving the formulation of the proposed efficient multicast slot allocation with ILP solver. Simulation parameters are shown below.

- Number of ONUs: 128
- The proportion of the multicast users: 10%, 30%, 50%, 70%, 90%
- Max: 7 stages
- H: 2 stages
- Number of the trials: 1000000
- Lower bound of the multicast slots: Allocation to 5 multicast users (the minimum number of the multicast users which can be connected within 4 stages) per one slot
- Upper bound of the multicast slots: Allocation to 5 multicast users (the maximum number of the multicast users which can be connected within 4 stages) per one slot

![Fig. 10. The number of the multicast slots of according to the demand of the multicast users.](image_url)

Figure 10 shows the number of the multicast slots for the demand of the multicast users. The number of the multicast slots of the proposed efficient multicast slot allocation is close to Lower bound. Figure 11 shows the frequency distribution of the number of the multicast slots according to the demand of the multicast users. The number of the multicast slots can be used within (Lower bound + 1) in every proportion of the multicast users. Figure 12 shows the maximum time for selecting the maximum number of the multicast users which can
be connected. The maximum number of the multicast users can be derived within 300 ms according to the demand of 128 multicast users. Therefore, the proposed efficient multicast slot allocation can connect the multicast users in a little number of slots, so increase the utilization efficiency of the slot allocation. Moreover, the proposed method can allocate the slot to each multicast user dynamically within 300ms, and is effective in the broadcast delivery.

VI. CONCLUSION

We proposed the efficient singlecast / multicast method for ActiON by using PLZT optical switch elements which are controlled as mode like an optical splitter by applying mid-control voltage. In addition, a new efficient slot allocation method is proposed and formulated as a linear programming problem. This formula develops the maximum number of users which is able to be connected by multicast and the minimum number of slots is used for multicast users, so the utilization efficiency of the slot allocation increases. For the future, we would like to implement the proposed efficient singlecast / multicast method for ActiON.

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