Delay-sensitive slot allocation method minimizing switching idle time in PLZT optical switch for active optical access network

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Abstract: Active Optical Network (ActiON) using a conventional slot allocation method in Plumbum Lanthanum Zirconate Titanate (PLZT) optical switches was proposed. The conventional slot allocation method shortens the switching idle time, which is a product of the switching guard time and the number of switching times. However, the transmission waiting time could exceed a user’s allowable delay. This paper proposes a delay-sensitive slot allocation method, which minimizes the switching idle time while considering the user’s allowable delay. Numerical results show that the proposed method reduces the number of switching times by up to 88 percent when compared to the conventional method.

Keywords: optical access network, PLZT optical switch, slot allocation method

Classification: Fiber-Optic Transmission for Communications

References

1 Introduction

The Passive Optical Network (PON) is widely used as an access network. However, already deployed Gigabit EPON (GE-PON) and 10 Gigabit EPON (10G-EPON) [1] are limited in terms of the maximum allowable number of Optical Network Units (ONUs) (32) and the maximum allowable transmission distance (20 km).

To provide scalable access services, the Active Optical Network (ActiON) [2, 3, 4] using Plumbum Lanthanum Zirconate Titanate (PLZT) optical switches [5, 6] was proposed to increase the number of ONUs per OLT to 128, and the maximum transmission distance to 40 km between the OLT and ONUs. The ActiON adopts a conventional slot allocation method, which switches the output port in each user.

The conventional slot allocation method [2, 3] shortens the switching idle time, which is a product of the switching guard time and the number of switching times, to provide high-bandwidth efficiency. However, the transmission waiting time, which is incurred by because a user cannot transmit in slot allocated to other users, could exceed the user’s allowable delay. There is a trade-off between the switching idle time and the transmission waiting time of each user. This issue is addressed in this paper.

This paper proposes a delay-sensitive slot allocation method that minimizes the switching idle time while considering the user’s allowable delay. To meet our objective, we formulate the problem that minimizes the number of switching times as an Integer Linear Programming (ILP) problem. Numerical results show that the proposed method reduces the number of switching times by up to 88 percent when compared to the conventional method.

2 Active Optical Network (ActiON)

Fig. 1(a) shows that the basic ActiON architecture [2, 3, 4] consists of an OLT, ONUs, and two $1 \times N$ PLZT optical switches [5, 6] for upstream and downstream data transmission. The ActiON adopts the $1 \times 128$ PLZT optical switch, which uses $1 \times 2$ PLZT optical switch elements in a multistage configuration.

In the ActiON data transmission, the Multi-Point Control Protocol (MPCP) [1] is adopted for compatibility with 10G-EPON (IEEE802.3av). The ActiON uses a conventional slot allocation method [2, 3], where the OLT allocates the bandwidth to each user by time slots, and each user transmits data to the OLT in its allocated...
slots. The conventional slot allocation method also supports multicast [3]. To simplify the discussion on slot switching, this paper focuses on unicast. The PLZT optical switch is periodically controlled by the transmission cycle composed of multiple slots. The maximum transmission cycle is set to 7.8 ms not to exceed the timeout (1000 ms) of control messages in MPCP [1], which are transmitted once every 128 transmission cycles. Also, the switching speed is within 10 ns, and therefore the guard time is set to 20 ns. The slot size is set to 4 µs or more to reduce the impact of the guard time to be less than 0.5 percent, based on the calculation (guard time/(slot size + guard time)) [2]. The switching idle time, during which data are not transmitted, is calculated by multiplying the number of switching times and the above guard time. The number of switching times indicates the number of times at slot allocation is changed from one user to another user in a $1 \times N$ PLZT optical switch.

Examples 1 and 2 in Fig. 1(b) show the conventional slot allocation methods. The number of slots allocated to users #1 and #2 are four slots per transmission cycle. Each user’s allowable delay is two slots. This parameter is decided according to the user’s application type and buffer size. In example 1, the user is changed every slot. The transmission waiting time, during which a user has to wait for transmission while the slots have been used by other users, is one slot, which is

![Fig. 1. Overview of ActiON ((a) ActiON architecture and (b) Conventional slot allocation method)](image-url)
within the allowable delay. On the other hand, the switching idle time is seven × guard time within a transmission cycle. In example 2, whole consecutive slots are allocated to a user before switching to the next user. The transmission waiting time is four slots, which exceeds the allowable delay. On the other hand, the switching idle time is one × guard time within a transmission cycle.

In this way, the conventional method requires the trade-off between the switching idle time and the transmission waiting time.

3 Proposed delay-sensitive slot allocation method

3.1 Overview

The proposed slot allocation method minimizes the switching idle time while considering the allowable delay. Fig. 2 shows the corresponding example of proposed method. The network conditions are the same as those of Fig. 1(b). The proposed method reduces the switching idle time to three × guard time within a transmission cycle, while keeping the transmission waiting time to two slots, which is within the allowable delay. In order to minimize the switching idle time, calculated by multiplying the number of switching times and the guard time, the proposed method formulates the optimization problem that minimizes the number of switching times as an ILP problem in Section 3.2.

3.2 Integer Linear Program (ILP) formulation of proposed method

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

3.2.1 Definitions

The nomenclature used in this ILP formulation is given below.

- \( N \) : Number of users (given parameter).
- \( u \) : Index of user, \( 1 \leq u \leq N \).
- \( U \) : Set of users, \( |U| = N \).
- \( D_u \) : Number of slots needed for allowable delay of \( u \)th user, during which \( u \)th user can wait for transmission in other user’s slots (given parameter).
- \( S_{total} \) : Total number of slots within a transmission cycle (given parameter).
- \( S_u \) : Number of allocated slots of \( u \)th user within a transmission cycle. \( \sum_{u \in U} S_u = S_{total} \cdot S_u \geq \frac{S_{total}}{D_u+1} \) must be satisfied to get a feasible solution.
Index of slot number.  

$T$  
Set of time slots within a transmission cycle, $1 \leq t \leq S_{\text{total}}$.  

$T^-$  
Set $T$ without the last slot within a transmission cycle, $1 \leq t \leq S_{\text{total}} - 1$.  

$k$  
Index of first slot number of the period to be comprised of $D_u$, which is slid by 1 slot within a transmission cycle.  

$K$  
Set of $k$, $1 \leq k \leq S_{\text{total}} - D_u$.  

$P_u(t)$  
Binary variable. If the $u$th user is allocated $t$th time slot, $P_u(t) = 1$. Otherwise, $P_u(t) = 0$.  

$Z_u(t)$  
Binary variable. If $P_u(t)$ is equal to $P_u(t + 1)$, $Z_u(t) = 0$. Otherwise $Z_u(t) = 1$.  

3.2.2 Objective function and constraints  

The objective function and constraints in the ILP problem are given below.

\[
\begin{align*}
\min & \sum_{u \in U} \sum_{t \in T^-} \frac{Z_u(t)}{2} \\
\text{s.t. } & P_u(t + 1) - P_u(t) \leq Z_u(t), \forall u \in U, \forall t \in T^- \quad (1a) \\
\ & P_u(t + 1) - P_u(t) \geq -Z_u(t), \forall u \in U, \forall t \in T^- \quad (1b) \\
\ & \sum_{u \in U} P_u(t) = 1, \forall t \in T \quad (1c) \\
\ & \sum_{t \in T^+} P_u(t) = S_u, \forall u \in U \quad (1d) \\
\ & \sum_{t = k + D_u}^{k + D_u + D_u} P_u(t) \geq 1, \forall u \in U, \forall k \in K \quad (1e)
\end{align*}
\]

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

4 Performance evaluation  

We evaluate the performance of our proposed method. The simulation conditions are shown below. The number of users ($N$) is 128. The number of slots allocated of the $u$th user in transmission cycle ($S_u$) is eight slots for all users. The total number of slots in a transmission cycle ($S_{\text{total}}$) is 1024 slots, calculated by the maximum transmission cycle (7.8 ms) and the slot size (4 $\mu$s or more) described in Section 2. All users’ allowable delay is set to be the same. The allowable delay is expressed by multiplying the number of slots needed for the user’s allowable delay, $D_u$ and the slot size. The slot size is set to 7.6 $\mu$s (7.8 ms/1024 slots). CPLEX Interactive Optimizer 12.5.0.0 is used to solve the ILP optimization problem in this evaluation [7].

Fig. 3 shows the relationship between the number of switching times within a transmission cycle and the user’s allowable delay for the conventional and
Proposed methods. The proposed method reduces the number of switching times by up to 88 percent, compared to the conventional method that realizes the worst number of switching times. In the proposed method, the user’s allowable delay should be set to between 1.0 ms and 7.7 ms, where the lower and upper bounds of allowable delay are obtained by \( \frac{\text{slot size}}{C_2(N-1)} \) and \( \frac{\text{slot size}}{C_2(S_{\text{total}}-S_u)} \), respectively. Also, the number of switching times changes from 1023 times to 127 times as the user’s allowable delay increases, where the maximum and minimum number of switching times are obtained by \( S_{\text{total}} - 1 \) and \( N - 1 \), respectively. Thus, the proposed method needs fewer switching times than the conventional method while considering the allowable delay.

5 Conclusion

This paper proposed a delay-sensitive slot allocation method that minimizes the switching idle time in the Plumbum Lanthanum Zirconate Titanate (PLZT) optical switches, while considering the user’s allowable delay. To achieve our objective, we formulated the problem to minimize the number of switching times as an Integer Linear Programming (ILP) problem. Numerical results show that the proposed method reduces the number of switching times by up to 88 percent, compared to the conventional method. Minimizing the switching idle time leads to increased bandwidth efficiency.