

Mini-Slot-Based Transmission Scheme for Local Customer Internetworking in PONs

Jae Gwan Kim, Chang-Joon Chae, and Min-Ho Kang

We propose a new mini-slot transmission scheme for a passive optical network (PON) in which each customer can be switched either to access mode or to internetworking mode dynamically. In this paper, we present the system implementation (called LAN-PON) as well as the performance of the proposed transmission scheme to illustrate its feasibility and benefits. A mini-slot scheme can rapidly reduce the queuing delay, which increases due to the flooding of the deflected packets in a deflection scheme. We evaluate the impact of mode switching time on the bandwidth gain (throughput) and delay of local area network (LAN) traffic in the LAN-PON with a mini-slot scheme. We also analyze a theoretical delay model of the proposed scheme. The simulation results demonstrate that switching time has an impact on LAN performance, and the average packet delay of the proposed scheme is significantly improved compared to that of the deflection scheme.

Keywords: Optical access network, passive optical network, customer internetworking.

I. Introduction

Passive optical network (PON) technology is emerging as a viable choice for deploying an access network because it can offer scalability, high-bandwidth capacity, and cost-effective services. A PON has extended the speed from 10 Mbps to 1 Gbps, and more recently, to 10 Gbps. Generally, PONs are attractive due to the reduced number of fibers connecting the central office (CO) and the end-users, and the economical number of optical components, which brings direct and indirect savings [1]-[3]. Moreover, PONs have been seen as an important part of many fiber-to-the-x (FTTx) strategies. A PON could be used to implement fiber-to-the-home (FTTH), fiber-to-the-building (FTTB), or fiber-to-the-curb (FTTC) access networks for residential and business customers. All communications in a PON are performed between an optical line terminal (OLT) on the service provider side and optical network units (ONUs) on the user side. The OLT resides in the CO (or local exchange), connecting an access network to backbone networks. The ONUs can serve single residential or

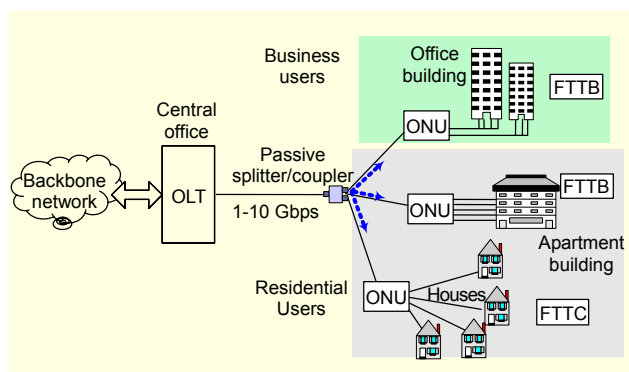


Fig. 1. Network architecture of a PON with LAN internetworking.

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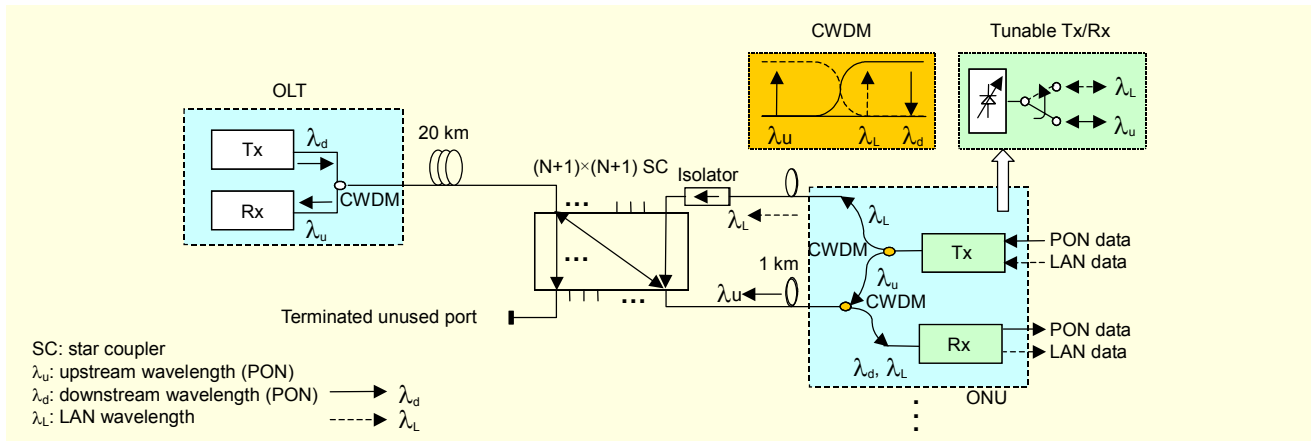


Fig. 2. LAN-PON system architecture.

business subscribers referred to as FTTH/B subscribers, or multiple subscribers referred to as FTTC. In particular, local area network (LAN) traffic, defined in this paper as customer traffic originating from one subscriber to be delivered to all or some subscribers within the same PON, is often generated from ONUs with many subscribers as shown in Fig. 1. Therefore, customers of the PON require inter-communication capability among themselves for various computer applications and telecommunication services, such as file processing, teleconferencing, and information broadcasting.

Communication among ONUs served by an OLT has been the subject of growing attention as a new network service in existing PON systems. Current PON systems can provide this customer internetworking service by using a router attached to an OLT in conjunction with a scheme called shared LAN emulation [2]. However, such a technique sacrifices the available bandwidth for conventional access services because a portion of downstream and upstream channels is used for LAN emulation, resulting in lesser bandwidth for conventional services. Moreover, these routers that provide the emulation protocol are necessarily expensive and complicated. This is neither a cost-effective nor practical solution. Therefore, a few methods have been proposed to provide this functionality in different ways [4]-[7].

A physical-layer solution, proposed in [7], is attractive because the method is bandwidth-efficient and potentially cost-effective. A PON is virtually divided into two independent sub-networks by the use of two low-cost optical switches (OSWs) in each ONU: one for broadband access and the other for local customers. The ONUs can exchange information in LAN mode while they are waiting for access to their OLT in PON mode. It is expected to work fairly well in situations in which mode switching is rarely required. Unfortunately, most real world applications need frequent switching; thus, its performance is degraded in a dynamic environment because

thermo-optic or mechanical OSWs operate in millisecond order.

In this paper, we investigate the performance of a LAN-PON in a dynamic environment with a mini-slot transmission scheme proposed here for local internetworking. This LAN-PON is useful for office buildings or apartment complexes with many users in each ONU as shown in Fig. 1. We focus on the impact of mode switching time on the throughput (or bandwidth gain) and delay of LAN traffic with the proposed scheme. The remainder of this paper is organized as follows. In section II, we describe the architectural details of our proposed LAN-PON system. Section III discusses the operation of a mini-slot transmission scheme and the analytical delay model for LAN. We present performance results obtained through computer simulations in section IV. Finally, section V concludes the discussion.

II. LAN-PON System Architecture

1. System Implementation

Figure 2 illustrates the proposed PON system architecture (LAN-PON) using wavelength-switchable transceivers [8]. An OLT is connected to N ONUs via an $(N+1) \times (N+1)$ optical star coupler (SC) with isolators to block the upstream data from coming back to the ONUs, and one of the ports facing towards the ONUs is terminated in the SC. Each ONU consists of two coarse wavelength division multiplexers (CWDMs), which separate or combine a waveband (PON upstream wavelength, λ_u , and LAN wavelength, λ_L) and another waveband (PON downstream wavelength, λ_d), a high-speed tunable transmitter (Tx) whose wavelength is switched to either λ_u or λ_L , and a high-speed tunable receiver (Rx). Each ONU is interconnected to the SC via two distribution fibers.

In PON mode (transmitting/receiving access traffic toward/from OLT), upstream PON traffic on λ_u is sent out from

an ONU transmitter and goes through CWDMs to the SC. It is finally received by an OLT receiver. Downstream PON traffic on λ_d travels in the reverse direction. In LAN mode (ONUs communicating with each other), LAN traffic on λ_L from a tunable transmitter passes through a CWDM and an optical isolator before entering the SC, where broadcasting to all ONUs takes place through a distribution fiber. This leads to a virtual optical star network, representing a LAN for ONUs to exchange their data. The ONUs are required to switch to one of the two modes by switching Tx and Rx wavelengths to λ_u or λ_L depending on the traffic type. If an ONU finishes its transmission to the OLT in PON mode, then it immediately switches to LAN mode. Downstream transmission from an OLT to the ONUs is synchronized with each ONU's PON mode. This architecture enables separate private customer networking and upstream transmission at each ONU. Consequently, the LAN-PON enhances customer security and improves user flexibility.

2. System Characteristics

The LAN-PON requires ONUs to stay in one of the two modes at a given time. The ONUs that are communicating with their common OLT are in the access (PON) mode while others are in the LAN mode to exchange data with each other. Each ONU could be controlled to switch from one mode to the other. Therefore, the switching time is an important factor in determining performance of the LAN-PON under the dynamic environment. Of course, the slower the switching is, the cheaper the implementation will be.

The PON downstream packets are broadcast from the OLT to all ONUs, and each ONU extracts the packets that are destined to it by using the medium access control (MAC) address on the packet header. Likewise, PON upstream transmission is based on the time division multiple access (TDMA) protocol to guarantee collision-free transport. TDMA is also used as a LAN transmission protocol for communication among ONUs, as described in section III. In addition, as we mentioned in section I,

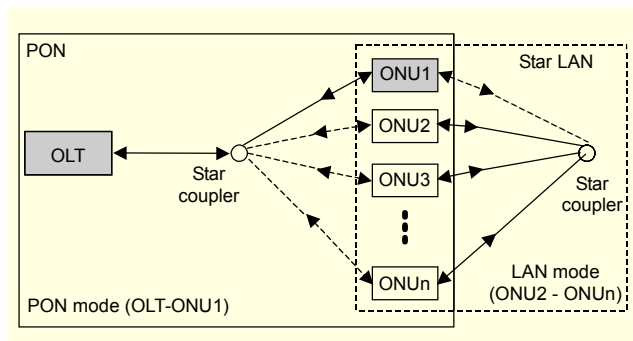


Fig. 3. Two independent virtual networks in LAN-PON.

the LAN-PON is used for the access network based on FTTB or FTTC in which each ONU has multiple subscribers. Therefore, most ONUs request constant bandwidth to the OLT on the average if each ONU aggregates subscribers' traffic statistically. This means that fixed TDMA can be used in the LAN-PON based on FTTB or FTTC.

The LAN-PON consists of two independent sub-networks, switching between PON and LAN modes at each ONU as shown in Fig. 3. This means that each sub-network can use the independent protocol, and the performance of upstream and downstream in a star LAN is not influenced by the PON at all.

III. Transmission Scheme for LAN-PON

1. Mini-slot Transmission Scheme Description

The LAN-PON system operates on TDMA, a MAC protocol used in the upstream direction of a gigabit PON (GPON) [9]. The ONUs are synchronized to a common clock so that each ONU knows exactly when and for how long it can transmit. The time is divided into slots of equal length as shown in Fig. 4. Each ONU is given one time slot to communicate with the OLT in PON mode. Denote the number of ONUs in a network by N , then the duration of one complete transmission cycle is given by $T_c = N t_s$, where t_s is the length of one time slot. The time interval between two consecutive transmission opportunities given to each ONU is wasted in the conventional PON, but is utilized as the time for communication among ONUs in the LAN-PON, resulting in a bandwidth gain. The number of transmission slots is limited by the speed of mode switching (SW). Here, we assume that the switching time is a multiple of t_s because this fits well with the TDMA protocol.

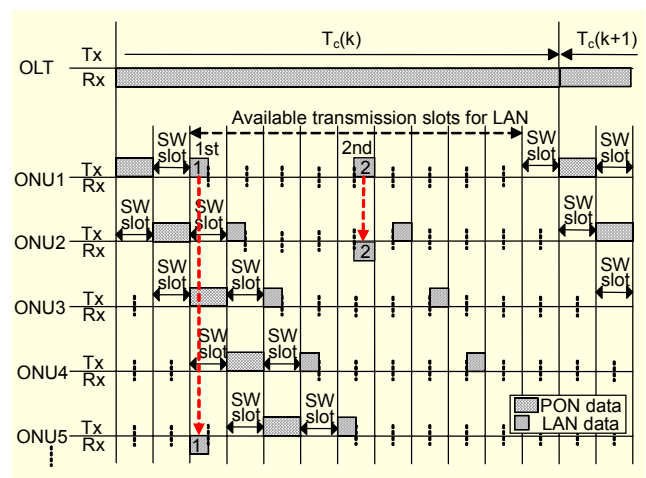


Fig. 4. Mini-slot transmission for switching time equal to one slot.

We already proposed a deflection transmission scheme based on TDMA in a LAN-PON system which can work in the dynamic environment. There is a transmission problem in a LAN-PON if LAN packets are transmitted by a general TDMA protocol. When an ONU sends a packet in LAN mode, some ONUs cannot receive it directly because they are either in PON mode or in the middle of switching time. In order to allow all ONUs to receive data in LAN mode, packets that are destined for those ONUs that cannot receive in that time slot will be deflected to other ONUs sometime later. Then, packets will be received by their intended ONU. However, packet delay increases rapidly after 125 μ s due to flooding of deflected packets in the deflection scheme [8].

The queuing delay due to the deflection transmission scheme can be cut drastically by introducing a mini-slot scheme. Figure 4 illustrates the mini-slot transmission scheme in which switching time is equal to one slot. As previously mentioned, some ONUs cannot receive packets directly because of the switching slots.

For example, ONU2 and ONU4 cannot receive packets from ONU1 because these ONUs are in the middle of mode switching. ONU3 cannot receive packets either because it is communicating with the OLT. In order to make all ONUs receive the data, each LAN transmission slot in LAN mode is divided into two mini-slots. Since each ONU now has two transmission opportunities, although the size is halved, LAN transmission is more flexible. First, all incoming LAN packets are sorted into two transmission buffers, buffer 1 and buffer 2, by a scheduler. Packets in buffer 1 are transmitted first to group 1 ONUs in the first mini-slot, followed by packets from buffer 2 being sent out to group 2 ONUs in the second mini-slot. Each ONU has different group members because those ONUs that cannot receive packets directly are different depending on which ONU is sending packets. For example, group 2 for a sending ONU1 includes ONU2, ONU3, and ONU4. Other ONUs belong to group 1. When two packets, packets 1 and 2, arrive at ONU1 to be transmitted to ONU5 and ONU2, respectively, the scheduler puts packet 1 into buffer 1 and puts packets 2 in buffer 2. Of course, packet 2 experiences a longer delay of roughly half the cycle time. This is true for all packets in buffer 2. In the mini-slot scheme, deflected packets are not accumulated or kept for a long time in the buffer under a moderate offered load or at a moderate switching time. Therefore, it is expected to reduce overall packet delay, and we can expect a slight increase in the throughput. In addition, the guard time overhead adds less than 500 bits (500 ns) in the mini-slot scheme. This guard time is 0.4% of the total slot time. Consequently, this overhead does not greatly affect the overall efficiency.

2. Delay Model of Mini-slot Scheme Based on TDMA

In this section, we analyze the average packet delay performance of LAN mode in LAN-PON networks. We consider LAN packets in this analysis because a PON is separated into two independent logical sub-networks, a PON and a star LAN. Therefore, the performance of LAN traffic is not affected by that of PON traffic in LAN-PON networks.

First, let us consider a network in LAN mode based on TDMA in which T_c [sec] is set to the length of one complete transmission cycle. We have $T_c = N \cdot t_s$, where N is the number of ONUs, and t_s [sec] is the length of one slot.

In this LAN network, packets arrive at the ONU according to the Poisson process with rate λ [pkt/sec]. We model the ONU as an M/G/1 queue, where the service time is the time period between the time epoch when the packet reaches the head of the queue and the time epoch when its transmission is completed [10], [11]. In a mini-slot scheme, although an ONU transmits LAN packets two times in a cycle, the total service time in one cycle is equal to t_s . Therefore, we analyze the packet delay with one slot service time. Clearly, for those packets arriving to find a non-empty queue, their service time is a full transmission cycle, and their first and second moments of service time are T_c and T_c^2 , respectively. If a packet arrives into an empty queue, the service time is a random variable (RV) X and is defined as $X = Y + t_s$, where Y is an RV that represents the time when the packet arrives at the empty queue of the ONU until the end of that transmission cycle. Without loss of generality, we define the transmission cycle as inter-transmission times of the ONU being in LAN mode.

The first and second moments of X can be computed as

$$\begin{aligned} \bar{X} &= \bar{Y} + t_s, \\ \overline{X^2} &= \overline{Y^2} + 2\bar{Y}t_s + t_s^2. \end{aligned} \quad (1)$$

This is an M/G/1 queue in which the first packet of each busy period receives different service treatment from the rest. The packet delay in such a system as a function of an arrival rate λ is given in [11] as

$$D(\lambda) = \frac{\lambda T_c^2}{2(1 - \lambda T_c)} + \frac{\bar{X}}{1 - \lambda(T_c - \bar{X})} + \frac{\lambda(\overline{X^2} - T_c^2)}{2[1 - \lambda(T_c - \bar{X})]}. \quad (2)$$

It remains to determine the first and second moments of Y . Let Z be an RV that represents the length of the idle period which ends upon the arrival of a packet into the empty queue. Since packets arrive according to a Poisson process, Z is an exponential RV with parameter λ . The relationship between Y and Z is shown in Fig. 5, and its cumulative distribution function (cdf) is given by [11] as

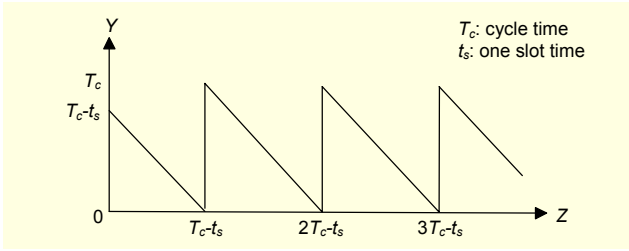


Fig. 5. Relationship between random variable Y and idle period Z .

$$F_Y(y) = \Pr[Y \leq y]$$

$$= \begin{cases} 0 & \text{if } y < 0, \\ \frac{e^{-\lambda(T_c - t_s)}(e^{\lambda y} - 1)}{1 - e^{-\lambda T_c}} + U(y - T_c + t_s) \cdot [1 - e^{-\lambda(T_c - t_s - y)}] & \text{if } 0 \leq y \leq T_c, \\ 1 & \text{if } y > T_c, \end{cases} \quad (3)$$

where

$$U(x) = \begin{cases} 1 & \text{if } x \geq 0, \\ 0 & \text{if } x < 0. \end{cases}$$

The value of \bar{Y} and \bar{Y}^2 can be then computed from (3) as

$$\begin{aligned} \bar{Y} &= (T_c - t_s - \frac{1}{\lambda}) + \frac{T_c e^{-\lambda(T_c - t_s)}}{1 - e^{-\lambda T_c}}, \\ \bar{Y}^2 &= (T_c - t_s - \frac{1}{\lambda})^2 + (\frac{1}{\lambda})^2 + (T_c^2 - \frac{2T_c}{\lambda}) \frac{e^{-\lambda(T_c - t_s)}}{1 - e^{-\lambda T_c}}. \end{aligned} \quad (4)$$

Next, we consider the probabilities P_1 and P_2 to calculate the total packet delay. P_1 is the probability for packets to come into buffer 1 (normal) and P_2 is the probability for packets to come into buffer 2 in LAN mode. Let T_s be the switching time between LAN and PON modes. It is equal to $M \cdot t_s$ where M is fixed.

Assume that each ONU is assigned one slot in each mode for data transmission. Furthermore, assume that t_s is the transmission time for one data burst (packet) in LAN mode. We are interested in the total delay of a packet in LAN mode. Note that in every transmission cycle, there is a period of $N - (2M + 2)$ slots in which the $N - 1$ ONUs, which are in LAN mode, can receive. Thus, the probability is

$$\begin{aligned} P_1 &= \frac{N - (2M + 2)}{N - 1}, \\ P_2 &= 1 - P_1 = \frac{2M + 1}{N - 1}. \end{aligned} \quad (5)$$

With probability P_1 , packets will be received by an ONU after the delay of $D(\lambda)$, and with probability P_2 , packets will be scheduled in buffer 2. After $D(\lambda)$ and $(N/2 - M - 1)$ slots, those

packets will be forwarded to their intended ONU. The total packet delay in this LAN-PON can then be calculated as

$$D_{LAN} = P_1 D(\lambda) + P_2 \{D(\lambda) + (\frac{N}{2} - M - 1)t_s\}. \quad (6)$$

IV. Simulation and Results

To evaluate the performance of the proposed transmission scheme and the effect of switching time on the performance, we undertook a simulation study using an OPNET Modeler with reference to the typical PON architecture and system parameters [12]. The number of ONUs, N , was set to 16 and the line rate for the two modes was 1 Gbps. Thus, each ONU had 62.5 Mbps of average upstream bandwidth. The distance between the OLT and ONUs was 20 km while the ONUs were within 1 km from the star coupler. The PON and LAN traffic was sequentially transmitted at ONUs as described in Fig. 4 based on fixed TDMA with time slots (t_s) of 125 μ s. The PON downstream was not included in this simulation. The traffic was modeled as a single processor of Poisson arrivals with exponential inter-arrival times, and all ONUs were assumed to be uniformly loaded. Every ONU had two separate finite queues for PON and LAN traffic, which were 10 MB or 6,667 packets. The cycle time (T_c) was set to 2 ms while the guard time between adjacent transmission was fixed to 1 μ s. Switching time was allowed to increase by a multiple of t_s .

Figure 6(a) shows PON and LAN traffic throughputs as a function of switching time. Both PON and LAN offered loads were set to 0.8. The PON traffic throughput did not change even though switching time increased, because a PON upstream channel is secured regardless of the switching time. This means that the PON and LAN networks are virtually isolated from each other. On the other hand, LAN traffic throughput is sensitive to the switching time, as the time for a LAN is reduced with increasing switching time in both transmission schemes. The sensitivity or dependency is more pronounced in the deflection scheme than in the mini-slot scheme. The total throughput of the LAN-PON is higher than that of the conventional PON (indicated as PON traffic) for the switching time of up to 6 slots. Thus the hatched area represents the bandwidth gain that the LAN-PON offers.

As shown in Fig. 6(b), the average packet delay of LAN traffic increases as switching time increases in the deflection scheme, while that of PON traffic remains unchanged due to the complete isolation between PON and LAN networks. Deflection transmission requires switching time to be reduced to less than a single time slot of 125 μ s to keep the delay below that of PON traffic. The delay increases sharply as switching time exceeds one slot time due to flooding of deflected packets.

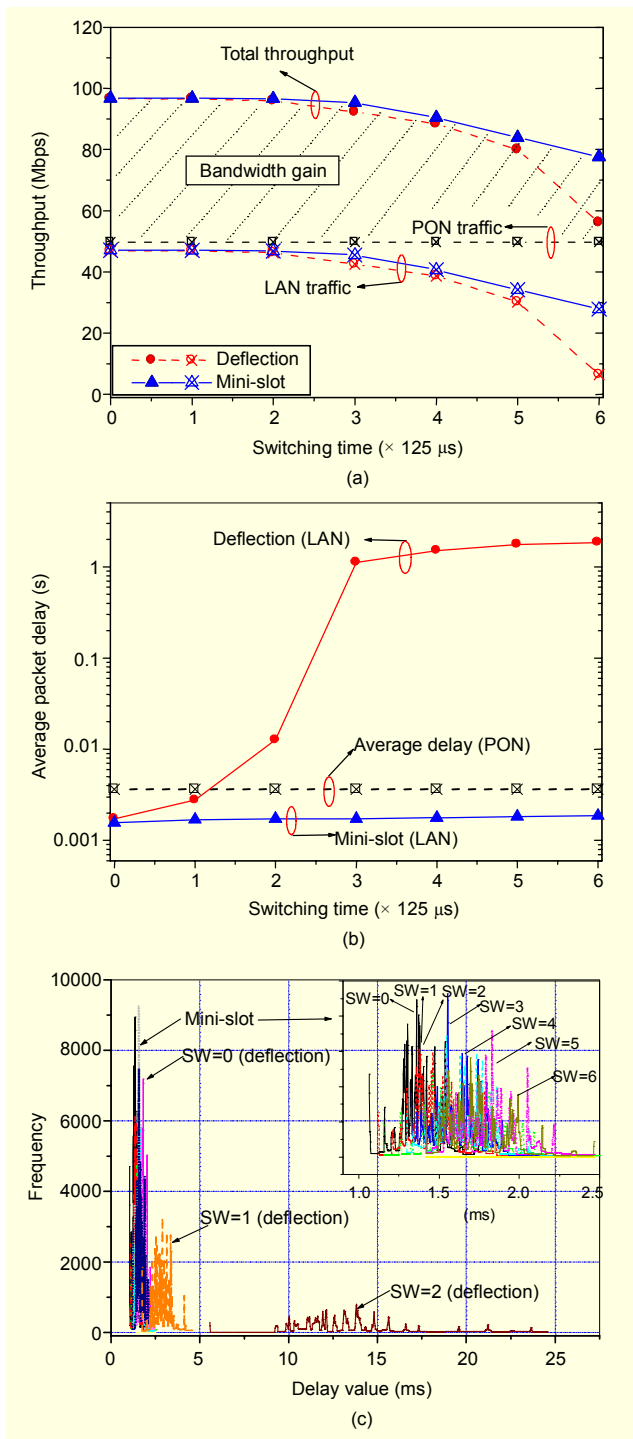


Fig. 6. (a) Throughputs, (b) average packet delays, and (c) delay distributions of LAN traffic as a function of switching time. Offered loads for PON and LAN were set to 0.8. SW = n corresponds to $n \times 125 \mu s$.

However, the delay is capped at around 1 s because of the finite buffer size of 10 MB. The delay is hardly affected by the switching time in a mini-slot transmission scheme. This is because flooding is avoided under a moderate load of 0.8. In

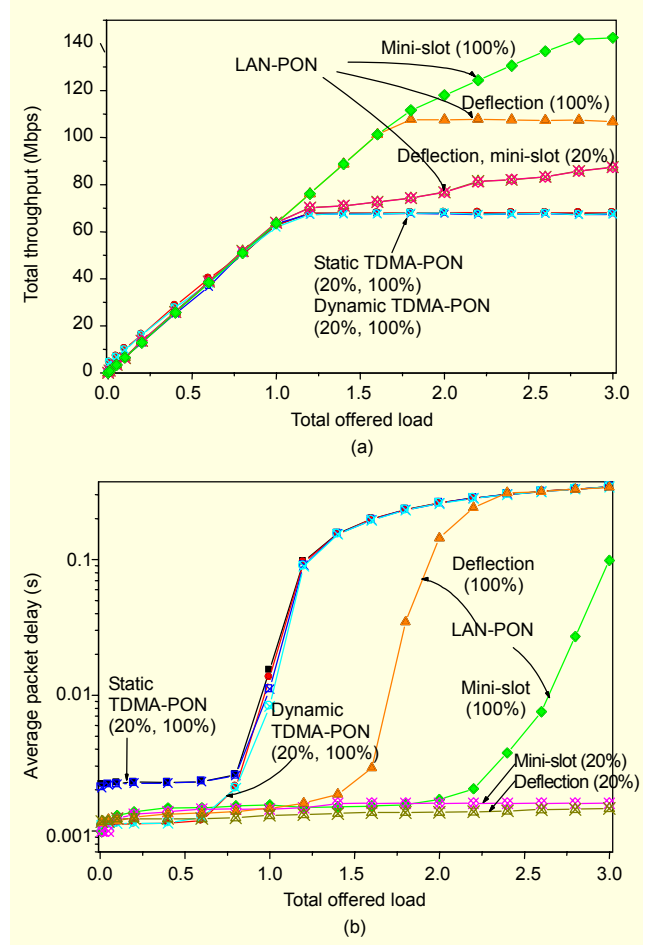


Fig. 7. Performance comparison of LAN-PON (SW time = $125 \mu s$) with static and dynamic TDMA-PONs: (a) total throughput and (b) average packet delay of LAN traffic.

fact, the probability that a given packet will be delivered to group 2 is small, because the ONUs in group 2 are fewer than in group 1 in case of a large N . So, the packets are not likely to be trapped in buffer 2 in the deflection transmission.

Figure 6(c) shows the delay distributions for some switching times. The width of distribution (related to jitter performance) becomes broadened (worsened) in case of the deflection transmission with its average value changing from 1.2 ms to 25 ms for switching time increasing from 0 to 2 slots. This means that packets undergo an increasing number of deflections until they reach final destination ONUs. However, in a mini-slot transmission scheme, the delay distribution is much narrower, and the average is spread from 1.2 ms to 2.0 ms as switching time varies from 0 to 6 slots.

When the offered load was allowed to increase above 1.0, the throughput, packet delay, and jitter LAN traffic were more strongly affected by the switching time than when it was 0.8. This is because the maximum bandwidth capacity was already exceeded.

Figure 7 compares total throughput and average packet delay performance in a LAN-PON employing two transmission schemes with that of a static TDMA PON and a dynamic TDMA PON for two different percentages of LAN traffic content: 20% and 100%. Total offered load is calculated with the following equation: $\rho_T = \alpha + \alpha\beta$, where ρ_T = total offered load, α = PON traffic, and β = LAN traffic ratio relative to PON traffic. To evaluate the performance according to low and high LAN traffic content, we set β to 20% and 100%, respectively. The total offered load was allowed to be greater than 1, because each ONU can generate both PON and LAN traffic beyond its maximum average capacity. Figure 7(a) shows the LAN-PON yields better total throughput than the static TDMA PON or the dynamic TDMA PON when the total offered load is greater than 1. In particular, the LAN-PON employing a mini-slot scheme achieves the best performance under a high LAN traffic environment. The reason is that the static TDMA and dynamic TDMA PON already are using all bandwidth when the offered load is equal to or greater than 1. Figure 7(b) demonstrates that the LAN-PON with a mini-slot scheme outperforms static or dynamic TDMA PON and LAN-PON with a deflection scheme in the broad loading range. One reason is that the LAN-PON has more effective bandwidth than the conventional PON has under a heavy traffic load. The other reason is that the flooding due to deflection is avoided in mini-slot transmission.

V. Conclusion

We investigated the performance of a LAN-PON employing a novel mini-slot transmission scheme in the dynamic service environment. Our simulation results demonstrate that the switching time has a significant impact on the throughput and average packet delay. To achieve more than 90% bandwidth gain, switching time must be less than 375 μ s under our simulation environment. Moreover, a LAN-PON with a mini-slot transmission scheme outperforms conventional PONs and a LAN-PON with a deflection scheme especially under a heavy offered load. We conclude that mini-slot transmission is a better option for the LAN-PON system. The major contribution of this paper is that we have proposed a novel transmission scheme in a LAN-PON and demonstrated its efficiency by mathematical analysis and computer simulations. The study indicates that delivery of internetworking traffic among ONUs can be achieved with our solution, which is an economic method.

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