Dynamic Bandwidth Allocation Schemes to Improve Utilization under Non-Uniform Traffic in Ethernet Passive Optical Networks

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***Abstract*— In this paper, conventional bandwidth allocation schemes in Ethernet Passive Optical Network (EPON) are shown to suffer from poor utilization under the non-uniform traffic, particularly as the number of ONUs, guard time and round-trip time increase. To resolve this problem, we propose a new scheme which intelligently allocates a timeslot in consideration of other ONUs' queue occupancy, instead of strictly enforcing maximum timeslot size. The analysis and simulation results show that the proposed scheme can provide significantly higher utilization than the conventional schemes and support max-min fairness under the non-uniform traffic.**

I. Introduction

Recently the capacity of backbone networks has been increased drastically, but there has been only a little change in access networks. With the rapid growth of the number of users and multimedia services, access networks become bottlenecked. A passive optical network (PON), a point-to-multipoint optical network composed of passive elements without any active elements, is regarded as the most likely technology to solve this problem [1], [2] and considered to be an easy way to implement a fiber-to-the-home (FTTH). Especially Ethernet PON (EPON) is the best candidate for next generation access network because ethernet is cheap, simple and popular [3]. Fig. 1 shows a typical topology of EPON. An optical line terminal (OLT), located at local exchange, is connected with multiple optical network units (ONUs). In downlink transmission from OLT to ONUs, a frame is automatically broadcasted to all ONUs through an optical splitter and each ONU filters the received frame depending on its destination address. In uplink transmission from ONUs to OLT, ONUs must share a single optical fiber trunk. Therefore Multi-Point Control Protocol (MPCP) is developed by IEEE 802.3ah task force to support a bandwidth allocation without collision among ONUs [4]. The MPCP is mainly operated by two control messages, GATE and REPORT. Each ONU informs OLT of the queue occupancy by REPORT to help the OLT make an efficient bandwidth allocation decision. The OLT assigns the transmission timeslot by GATE.

Several dynamic bandwidth allocation schemes such as gated, fixed, limited, constant/linear credit service schemes are suggested in Interleaved Polling with Adaptive Cycle Time (IPACT) [5]. They conclude that neither of the suggested service schemes is better than the limited service scheme. In this paper, we show that not only does limited service scheme suffer from utilization degradation under the non-uniform traffic, but also the degradation can be so severe when the number of ONUs, guard time and round-trip time increase. To resolve this problem, we propose a new scheme which relaxes maximum timeslot restriction and makes a bandwidth allocation decision considering other ONUs' queue occupancy. The proposed scheme can provide higher utilization than the conventional schemes and support max-min fairness under the non-uniform traffic.

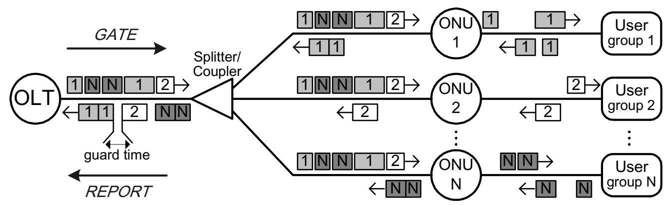

Fig. 1. Typical topology of EPON

The remainder of this paper is organized as follows. In section 2, the mechanism of GATE scheduling is given. In section 3, we present conventional and proposed bandwidth allocation schemes. In section 4 and 5, the utilization analysis and simulation results are provided to verify that our schemes perform well. Finally in section 6, we conclude the paper.

II. GATE Scheduling

Assume that EPON has BW link capacity and consists of a OLT and ONU$_i$, $1 \leq i \leq N$, where N is the total number of ONUs in the EPON. Every time the OLT receives REPORT containing a request (i.e., queue length) from ONU$_i$, it sends GATE containing the transmission $start\ time$ and $duration$ to ONU$_i$ as follows.

1) Update $SEI \leftarrow \max(SEI,\ now + RTT_i)$.
   $start\ time$ = SEI.

2) Decide the timeslot size G_i by the specific bandwidth allocation scheme.
   $duration = G_i$.
3) Update $SEI \leftarrow SEI + G_i + r + g$.
4) Send GATE to ONU$_i$.

where now is the current time, RTT_i is the round-trip time for ONU$_i$ and SEI (Scheduling End-point Indicator) is the last point that has been allocated, that is, the earliest point that new allocation can be started. And r is the time required to send REPORT[1], g is the guard time[2]. When ONU$_i$ receives GATE from the OLT, it sends data during the granted time G_i from $start\ time$, and then sends a new REPORT containing current queue length information R_i at the end of data transmission. If the OLT receives a new REPORT, it repeatedly does the GATE scheduling. In the ordinary case of $SEI \geq now + RTT_i$, the OLT allocates all the timeslots without omission. But in the case of $SEI < now + RTT_i$, the OLT cannot receive data from ONU$_i$ directly after current SEI even if the OLT sends GATE right now since the OLT must wait a previous REPORT to send a new GATE. Thus the SEI value is changed into $now + RTT_i$ in step 1. Utilization degradation may happen because this operation makes an unallocated timeslot. We refer to this phenomenon as *RTT effect*.

III. Bandwidth Allocation Schemes

In this section, we describe conventional and proposed bandwidth allocation schemes. Fixed service scheme always grants the maximum timeslot size G_{max}. It is simple, but it does not consider the amount of traffic from each ONU. Limited service scheme grants as much as timeslot requested but it cannot exceed G_{max}, $G_i^{k+1} = \min(R_i^k,\ G_{max})$ where G_i^k and R_i^k denote the kth timeslot size for ONU$_i$ and the kth request from ONU$_i$ respectively. This scheme can achieve higher utilization, however, it may fail to fully utilize the bandwidth under the non-uniform traffic. Suppose that only one ONU wants to send data. The ONU can use G_{max} per every one cycle consisted of G_{max} and N number of guard time and report time. Therefore the utilization is limited to $\frac{G_{max}}{G_{max}+N(r+g)}$. This is because OLT cannot grant more than G_{max} even if other ONUs do not use any resources. We can expect utilization improvements if bandwidth allocation scheme can grant a timeslot more than G_{max} considering other ONUs' traffic.

A. Proposed Scheme 1 (P1)

We newly define a variable F_i^k, which indirectly indicates how much OLT can grant to ONU$_i$. In the case of $R_i^k > G_{max}$, P1 guarantees at least G_{max} and efforts to grant R_i as much as possible but no more than F_i^k.

$$G_i^{k+1} = \begin{cases} R_i^k & if\ R_i^k \leq G_{max} \\ \max(G_{max},\ \min(R_i^k,\ F_i^k)) & otherwise \end{cases} \tag{1}$$
$$where\ \ F_i^k = NG_{max} - \sum_{j=(i-N+1)\ mod\ N}^{(i-1)\ mod\ N} G_j\ .$$

[1]Fixed service scheme do not need REPORT message, $r = 0$.

[2]The guard time includes ONU's laser turn on/off time, OLT's receiver auto gain control settling time, and clock recovery time.

where G_i is the recently granted timeslot size to ONU$_i$. The utilization will be improved by relaxing maximum timeslot G_{max} constraint. But P1 may cause fairness problem since it is possible to happen that an ONU, which originally has been using up NG_{max} timeslot, yields not $\frac{NG_{max}}{2}$ but only G_{max} timeslot to a new coming ONU.

B. Proposed Scheme 2 (P2)

Now we propose a dynamic bandwidth allocation scheme to maximize utilization and also achieve max-min fairness. P1 uses the recently granted timeslot of other ONUs but P2 uses the recently requested queue length of other ONUs. To calculate fair distribution, if OLT sends GATEs to all ONUs after the requests come from all ONUs, then the polling time will cause bandwidth waste. Therefore a scheme in which the OLT does not wait until all the requests are collected is preferable. The time before GATE is sent to ONU$_i$, M information (reported queue length from ONUs) in request table are not used, and the other $(N - M)$ are already used, that is, new information has not arrived yet. OLT distributes NG_{max} max-min fairly among ONUs based on the N requests and sends GATE to ONU$_i$ with the amount of fair share of ONU$_i$ on the assumption that there is little difference between the already used $(N - M)$ information and the new $(N - M)$ information. P2 allocates a timeslot as follows.

$$G_i^{k+1} = \begin{cases} R_i & if\ s_i = 1 \\ \frac{NG_{max} - \sum_{j=1}^{N} s_j R_j}{N - \sum_{j=1}^{N} s_j} & otherwise \end{cases} \tag{2}$$

$$where\ \ s_j = \begin{cases} 1 & if\ \sum_{k=1}^{N} \min(R_j, R_k) \leq NG_{max} \\ 0 & otherwise \end{cases}$$

where R_i is the recently request from ONU$_i$ and s_i indicates whether or not OLT grants a timeslot as much as ONU$_i$ requests.

IV. Performance Analysis

In this section, we analyze the utilization performance of the fixed, limited and proposed schemes.

A. Utilization without considering RTT effect

Let I_i and O_i respectively denote the rate of input and output at ONU$_i$ normalized to EPON link rate. We will derive output rates $\{O_i\}_{i=1,2,\ldots,N}$ in terms of arbitrary input rates $\{I_i\}_{i=1,2,\ldots,N}$ without considering RTT effect. And then total link utilization will be $U = \sum_{k=1}^{N} O_i$.

1) Fixed service scheme: OLT always grants G_{max}, thus cycle time is equal to constant $c = NG_{max} + Ng$. The output rate can be calculated as

$$O_i = \min\left(I_i,\ \frac{G_{max}}{NG_{max} + Ng}\right) \tag{3}$$

and stable condition (i.e., the output rate is the same as the input rate for all ONU$_i$) is

$$I_i \leq \frac{G_{max}}{NG_{max} + Ng}, \quad for\ all\ \ i. \tag{4}$$

2) Limited service scheme: To determine whether $s_i = 1$ or not, let us assume that $s_i = 1$. If we replace input rate I_k which is larger than I_i by I_i, or $I'_k = min(I_i, I_k)$, then all ONUs will satisfy $s_k = 1$, $O'_k = I'_k$ for all k. Under changed input rates, the cycle time will be $c' = \frac{N(r+g)}{1-\sum_{k=1}^{N} I'_k}$ because the total input rate is equal to $1 - \frac{N(r+g)}{c'}$. In the limited service scheme, granted timeslot G_i must be smaller than G_{max}, $G_i = c'O_i = c'I_i \leq G_{max}$. Therefore we can determine s_i as follows.

$$s_i = \begin{cases} 1 & if \ \frac{N(r+g)}{1-\sum_{k=1}^{N} I'_k} I_i \leq G_{max} \\ 0 & otherwise \end{cases} \quad (5)$$

The cycle time is $c = \frac{G_{max}\sum_{k=1}^{N}(1-s_i)+N(r+g)}{1-\sum_{k=1}^{N} s_i I_i}$ because $c = \sum_{k=1}^{N} G_k + N(r+g) = c\sum_{k=1}^{N} s_i I_i + G_{max}\sum_{k=1}^{N}(1-s_i) + N(r+g)$. The output rate can be calculated as

$$O_i = \min\left(I_i, \ \frac{G_{max}(1-\sum_{k=1}^{N} s_i I_i)}{G_{max}\sum_{k=1}^{N}(1-s_i)+N(r+g)}\right). \quad (6)$$

By using the cycle time and output rate, we can obtain mean granted timeslot size for ONU_i, $G_i = cO_i$ and stable condition is given by

$$\frac{N(r+g)}{1-\sum_{k=1}^{N} I_k} I_i \leq G_{max} \ \ for \ all \ \ i. \quad (7)$$

3) Proposed scheme 1 & 2: The total utilizations of P1 and P2 are equal at the steady state even though O_i may be different from each other. Therefore we will consider only P2 in the following analysis. For every i, we set $s_i = 1$ if $\sum_{k=1}^{N} min(I_i, I_k) \leq \frac{NG_{max}}{NG_{max}+N(r+g)}$, otherwise $s_i = 0$. If there exists i such that $s_i \neq 0$, at least one ONU_i is not satisfied even though OLT grants total NG_{max} per cycle. In this case, the cycle time will be $c = NG_{max} + N(r+g)$. Otherwise, $c = \frac{N(r+g)}{1-\sum_{k=1}^{N} I_k}$ because the total input rate is equal to $1 - \frac{N(r+g)}{c}$. The output rate can be calculated as

$$O_i = \min\left(I_i, \ \frac{\frac{G_{max}}{G_{max}+r+g} - \sum_{k=1}^{N} s_k I_k}{N - \sum_{k=1}^{N} s_k}\right). \quad (8)$$

By using the cycle time and output rate, we can obtain mean granted timeslot size for ONU_i, $G_i = cO_i$ and stable condition is given by

$$\sum_{k=1}^{N} I_k \leq \frac{NG_{max}}{NG_{max}+N(r+g)}. \quad (9)$$

4) Utilization comparison under the uniform and non-uniform traffic: To compare utilization of the fixed, limited and proposed schemes under the uniform and non-uniform traffic, we choose traffic rates of ONUs as $ONU_{1\sim30}$: $ONU_{31\sim32}$ = 1 : k where k is the non-uniformness parameter. Fig. 2 shows utilization of four schemes with k =1, 10, 100. Under the uniform traffic, that is k=1, four schemes have equal utilization. Actually the proposed schemes run almost the same

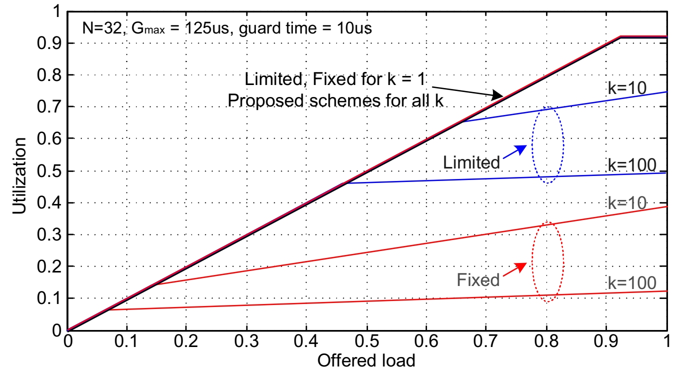

Fig. 2. Utilization comparison under the uniform and non-uniform traffic

as limited service scheme in this case. Note that utilization of conventional schemes decreases as non-uniformness k increases, however, the proposed schemes make it possible to get the same utilization as uniform traffic.

B. Maximum Utilization without considering RTT effect

Now, let us find the maximum utilization when the offered load by ONUs except ONU_1 is $0 \leq \rho \leq \frac{(N-1)G_{max}}{NG_{max}+N(r+g)}$. This can be done by putting (10) into results of previous subsection.

$$I_1 = 1-\rho \ \ and \ \ \sum_{i=2}^{N} I_i = \rho, \ I_i = O_i \ \ for \ i \neq 1 \quad (10)$$

Maximum utilization of fixed, limited and proposed schemes can be obtained as follows.

$$U_{Fixed} = \frac{G_{max}}{NG_{max}+Ng} + \rho \quad (11)$$

$$U_{Limited} = \frac{G_{max}+\rho N(r+g)}{G_{max}+N(r+g)} \quad (12)$$

$$U_{Proposed} = \frac{NG_{max}}{NG_{max}+N(r+g)} \quad (13)$$

C. Maximum Utilization with considering RTT effect

In EPON, geographical distance from an OLT to ONUs can be from several kilometers to $20km$ [4] and round-trip time is not negligible. As seen in Fig. 3, RTT may cause waste of timeslot if condition (14) is satisfied. This is because OLT must wait a previous REPORT to send a new GATE.

$$\sum_{k\neq i} G_k + (N-1)r + Ng < RTT_i \quad (14)$$

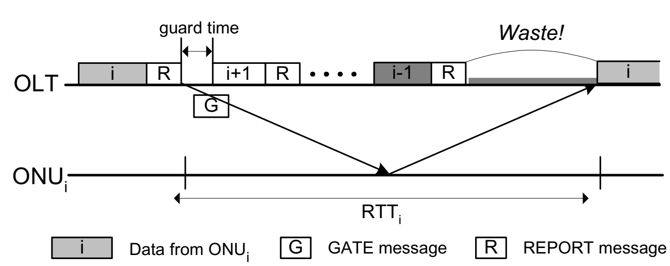

Fig. 3. *RTT effect*: timeslot waste due to round-trip time

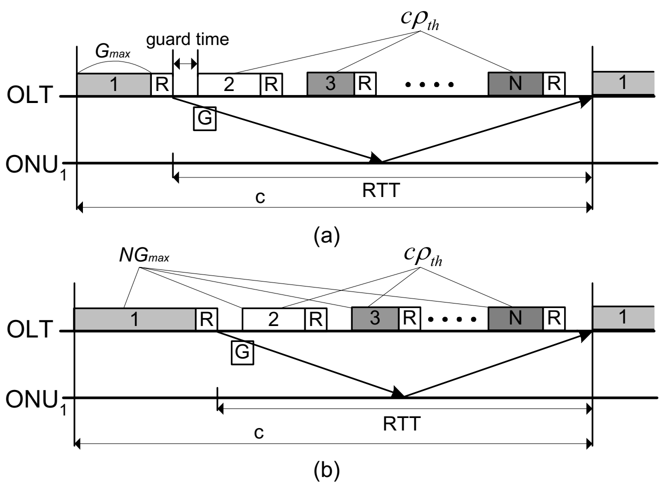

Fig. 4. ρ_{th} calculation (a) Limited service scheme, (b) Proposed schemes

In this case, maximum utilization is smaller than derivations (11)~(13), thus we need a modification. In this subsection, we will take RTT into consideration and derive maximum the utilization as offered load ρ by ONUs except ONU$_1$.

1) Fixed service scheme: Fixed service scheme is not effected by RTT because it does not use REPORT. Therefore maximum utilization is same as previous derivation (11).

$$U_{Fixed} = \frac{G_{max}}{NG_{max} + Ng} + \rho \qquad (15)$$

2) Limited service scheme: Maximum utilization will be achieved when ONU$_1$ uses up G_{max} per one cycle. To find a minimum offered load ρ_{th} to avoid RTT effect, we formulate following equations from Fig. 4(a).

$$RTT = c\rho_{th} + (N-1)r + Ng \qquad (16)$$

$$c = G_{max} + r + RTT \qquad (17)$$

By using (16), (17), we can obtain ρ_{th} as follows.

$$\rho_{th} = \max\left(\frac{RTT - (N-1)r - Ng}{G_{max} + r + RTT}\ ,\ 0\right) \qquad (18)$$

The maximum utilization is modified in the region of $\rho \leq \rho_{th}$.

$$U_{Limited} = \begin{cases} \frac{G_{max}}{G_{max}+r+RTT} + \rho & if\ \rho \leq \rho_{th} \\ \frac{G_{max}+\rho N(r+g)}{G_{max}+N(r+g)} & if\ \rho > \rho_{th} \end{cases} \qquad (19)$$

3) Proposed scheme 1 & 2: Maximum utilization will be achieved when ONUs use up NG_{max} per one cycle. To find a minimum offered load ρ_{th} to avoid RTT effect, we formulate following equations from Fig. 4(b).

$$RTT = c\rho_{th} + (N-1)r + Ng \qquad (20)$$

$$c = NG_{max} + N(g + r) \qquad (21)$$

By using (20), (21), we can obtain ρ_{th} as follows.

$$\rho_{th} = \max\left(\frac{RTT - (N-1)r - Ng}{NG_{max} + N(r+g)}\ ,\ 0\right) \qquad (22)$$

The maximum utilization is modified in the region of $\rho \leq \rho_{th}$.

$$U_{Proposed} = \begin{cases} \frac{NG_{max}(1+\rho)}{NG_{max}+r+RTT} & if\ \rho \leq \rho_{th} \\ \frac{NG_{max}}{NG_{max}+N(r+g)} & if\ \rho > \rho_{th} \end{cases} \qquad (23)$$

V. Simulation Results

In this section, we present simulation results using OPNET simulator [6] to verify the analysis and demonstrate the performance of proposed schemes. Fig. 5 shows simulation model. We generate the self-similar traffic by aggregating 32 pareto-distributed ON-OFF sources [7], [8]. And we generate Ethernet frames exponentially distributed with mean 500bytes from 64bytes to 1518bytes. Table I shows parameters used in this simulation.

TABLE I
Simulation Parameters

EPON Link rate (BW)	1Gbps
Number of ONUs (N)	8, 16, 32
Maximum timeslot (G_{max})	125 μs
Control message length (r)	0.512μs (=64bytes)
Guard time (g)	1, 5, 10μs
OLT/ONU queue size	300kbytes
Distance from OLT to ONUs	10km (RTT=100μs)

Fig. 6 depicts the maximum utilization versus network load (i.e., offered load by ONUs except ONU$_1$). Fixed service scheme still grants the fixed timeslot G_{max} to every ONU even if network load is low. As a result, the maximum utilization is very low. Limited service scheme can achieve higher maximum utilization because ONU$_1$ gets chance to send data earlier as much as other ONUs do not use. However, the maximum utilization of the limited service scheme decreases as the non-uniformness increases (i.e. network load decreases), and moreover RTT effect prevents achieving high maximum utilization in the low offered load region ($\rho < \rho_{th}$). For example, maximum utilization is very low in $\rho < 0.34$ when N=16, g=1μs. The proposed schemes can grant longer timeslot to ONU$_1$ by relaxing maximum timeslot restriction and making bandwidth allocation decision considering other ONUs' information, therefore we can always get full utilization regardless of the network load. In addition, the maximum utilization of conventional schemes decrease as the number of ONUs and guard time increases, but proposed schemes are almost independent of two variables.

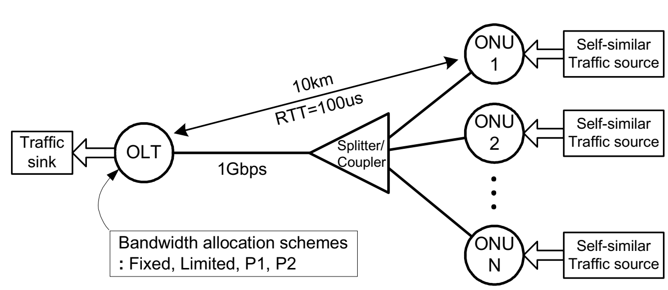

Fig. 5. Simulation model

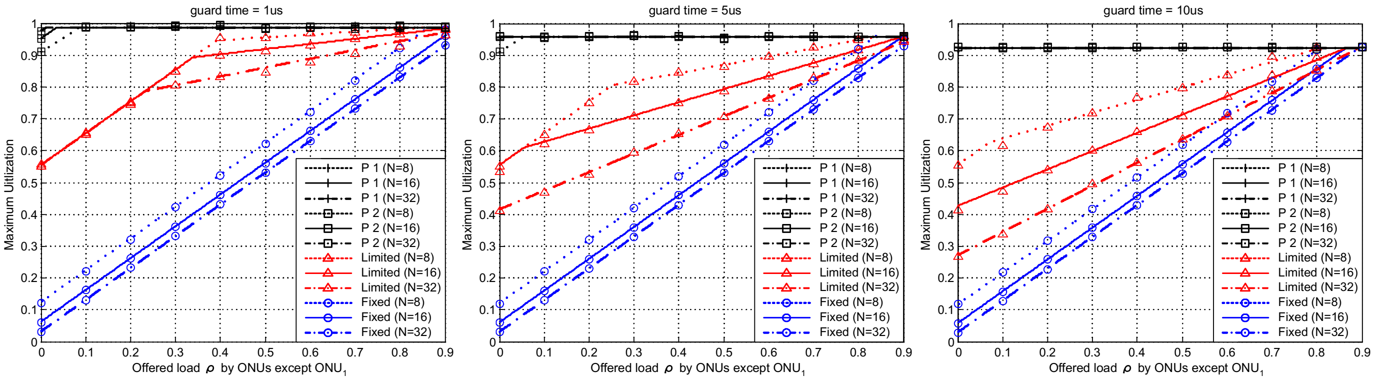

Fig. 6. Maximum utilization of different bandwidth allocation schemes versus offered load by ONUs except ONU_1 with the number of ONUs (N): (a) guard time = 1us, (b) guard time = 5us, (c) guard time = 9us (Line: Analysis, Symbol: Simulation)

TABLE II
FAIRNESS SIMULATION SCENARIO AND RESULTS

	Arr. (sec)	Dept. (sec)	Input Rate (Mbps)	Output Rate (Mbps)			
				Fixed	Limited	P1	P2
ONU_1	0	∞	300	60	180	195	225
ONU_2	10	∞	300	60	180	255	225

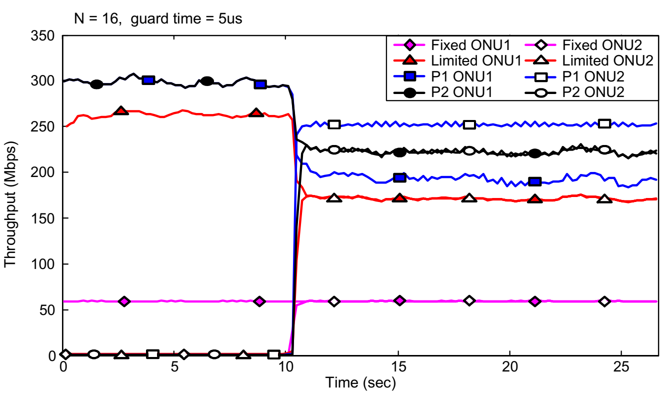

Fig. 7. Comparison of throughput of ONU_1 and ONU_2

To observe the fairness performance of four schemes, we make simulation scenario as follows. ONU_1 sends traffic with 300Mbps from 0sec and ONU_2 starts to send 300Mbps at 10sec under 500Mbps background traffic by ONU_3~ONU_{16}. Fig. 7 compares throughput of ONU_1 and ONU_2. Until 10sec, ONU_1 sends only 60Mbps and 260Mbps in the fixed and limited service scheme. But both P1 and P2 allow to send 300Mbps. After 10sec, throughput of ONU_1 and ONU_2 are 60Mbps in the fixed service scheme. In the limited service scheme, ONU_1 and ONU_2 get 180Mbps equally. ONU_1 and ONU_2 use 195+255=450Mbps in P1 which is 90Mbps higher than 180+180=360Mbps in the limited service scheme, however it is unfair. Unlike P1, ONU_1 and ONU_2 fairly use 225+255=450Mbps in P2.

VI. Conclusion

In this paper, we point out the low utilization problem of the conventional bandwidth allocation schemes under the non-uniform traffic. To resolve this problem, we propose new schemes which relax maximum timeslot restriction and make intelligent bandwidth allocation decision using other ONUs' information. Our proposed schemes always utilize bandwidth more than 90% under any circumstances. Between two proposed schemes, P1 using previous GATE information may fail to guarantee fairness, however, P2 using previous REPORT information guarantees max-min fairness as well. Based on our analysis and simulation, we conclude that our proposed scheme (P2) always fully utilizes the bandwidth under the non-uniform traffic and guarantees max-min fairness.

Acknowledgment

This work was supported in part by University IT Research Center Project and Electronics and Telecommunications Research Institute, Korea.

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