Sliding Cycle Time-based MAC Protocol for Service Level Agreeable Ethernet Passive Optical Networks

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***Abstract*-This paper presents a novel dynamic bandwidth allocation (DBA) scheme, called SLICT, for service level agreeable EPON. To guarantee the upper bound of maximum polling interval, we introduce sliding cycle time constraint. A new concept of shared time and remnant time is used to calculate extended bandwidth allocation. For service level agreeable EPON, we propose a design method to support multiple services such as fixed, guaranteed and extended bandwidth service. We show that simple remnant time management based on greedy contention guarantees steady state fairness. Simulation results show that proposed scheme outperforms existing schemes in aspects of throughput, delay, loss, and average queue size under self similar traffic**.

***Keywords*- EPON, DBA, sliding cycle time, remnant time management, multi-service capability**

I. INTRODUCTION

As the Internet gains worldwide popularity and demands for multimedia services grow rapidly, access technologies are evolving from digital subscriber lines (DSL) to passive optical networks (PON) for reliable broadband access. Amongst various PONs, Ethernet PON (EPON) is considered one of the best candidates of fiber to the home (FTTH) solution due to its cost effectiveness and high performance. EPON has a point-to-multi-point topology comprising optical line termination (OLT) in central office and optical line units (ONU) in a home or in a building. Multiple ONUs are connected to one OLT via passive optical splitter. Fig.1 shows a typical EPON topology.

In EPON, a downstream packet is broadcasted by OLT to all ONUs, and each ONU filters the received packet depending on its logical link ID (LLID). For upstream transmission, ONUs share a single fiber, from splitter to OLT, so only one ONU can send packets during permitted timeslots. Multipoint control protocol (MPCP) is responsible for medium access control and defined in IEEE 802.3ah standard [1]. MPCP is mainly based on two messages; REPORT message sent by ONU to OLT contains a *request* indicating how many timeslots ONU needs. GATE message sent by OLT to ONU contains a *grant* indicating the start time of transmission and its duration. MPCP is only a handshaking procedure and does not specify a bandwidth allocation algorithm. In consequence, dynamic bandwidth allocation (DBA) scheme, which affects greatly upstream performance, remains an important topic of EPON.

G. Kramer proposed for DBA the Interleaved Polling with Adaptive Cycle Time (IPACT) with various kinds of implementation such as fixed, limited, constant and linear credit service [2,3,4]. M. Ma proposed bandwidth guaranteed polling scheme for both guaranteed and best-effort bandwidth [5]. C. M. Assi suggested fixed cycle time-based DBA for quality of services [6]. Among various DBA schemes, IPACT is popular due to its simplicity and efficiency. However, its throughput degrades under non-uniform traffic [7]. Especially, if many ONUs are in idle state of transmitting only control message, guard time occupies large position of variable cycle time and it degrades aggregated utilization as well as lowers utilization of each ONU. In this paper, we propose a new scheme to resolve this low utilization and improve performances of delay, loss, and average queue size by remnant time management. Furthermore, in order to support multiple services, we present a design method using proposed scheme for fixed, guaranteed, and extended bandwidth service.

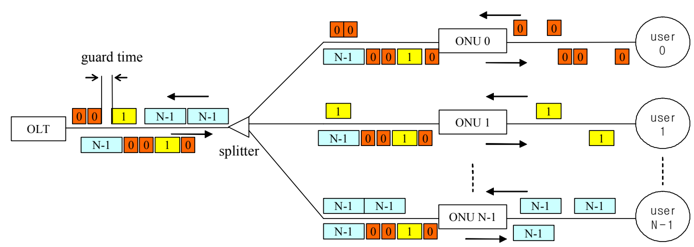


Fig. 1 Point-to-multi-point topology of EPON

In section 2, we propose a sliding cycle time-based DBA scheme. In section 3, SLA design using the proposed DBA is presented. Analysis of steady state fairness is given in section 4, and simulation results are provided in section 5 followed by conclusion.

II. PROPOSED BANDWIDTH ALLOCATION SCHEME

A. Proposed Sliding Cycle Time Constraint

For leased line or interactive services, delay is one of fundamental factors determining a quality of service.

Conventional DBA algorithms usually specify the upper bound of cycle time to limit maximum polling interval. However, maximum polling interval of ONU_i can be almost as much as two times of maximum cycle time as follows; at present cycle, timeslot for ONU_i is placed almost in the beginning of cycle because precedent *i*-1 ONUs does not consume timeslots so much. Then, at the next cycle, on the contrary, precedent *i*-1 ONUs consume many timeslots, and timeslot for ONU_i is placed almost at the end of cycle. To guarantee the maximum polling interval be bounded by maximum cycle time, we propose the *sliding cycle time constraint* as follows.

$$S_i^{k+1} - S_i^{k} \leq T_{MAX} \quad for \ \forall i, k \qquad (1)$$

where S_i^k is the start time of upstream transmission of ONU_i at *k* th cycle and T_{MAX} is the maximum cycle time. The term *sliding* means that cycle time is measured like sliding window for any instance of *i* and *k* as illustrated in Fig. 2.

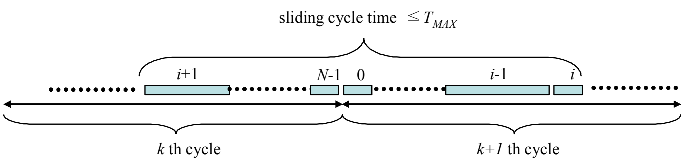


Fig. 2 Sliding cycle time constraint

B. GATE scheduling

When OLT receives a REPORT R_i from ONU_i, OLT sends out a GATE immediately after determining start time S_i and grant size G_i. OLT simply schedules S_i as follows. OLT knows the time t1 when the last bit of ONU_{i-1} arrives at OLT and can determine the time t2 when the first bit of ONU_i should arrive at OLT after minimum time gap T_g, called guard time, elapes. T_g is a kind of optical overhead. From t2 and round trip time (RTT) of ONU_i, S_i is calculated as t2 – RTT_i, and GATE = {S_i, G_i} is sent out before t3 = t2 – RTT_i – processing time at ONU_i. However, in case OLT does not receive R_i before t3, OLT should wait until it receives R_i, and S_i as well as t3 must be delayed by the amount of waiting time.

C. SLICT: Sliding Cycle Time-based DBA

First, we divide cycle time into two group: a guaranteed time and a shared time. The guaranteed time is defined as $T_G = \sum_{i=0}^{N-1} C_i$ where credit C_i is a reserved timeslot for guaranteed service of ONU_i and *N* is the number of ONUs. Then, a shared time is defined as

$$T_S = T_{MAX} - T_G - NT_g \qquad (2).$$

If $R_i \leq C_i$, bandwidth request of ONU_i complies with pre-determined service level agreement (SLA), and OLT sets grant size G_i as R_i. If $R_i > C_i$, the bandwidth request exceeds the guaranteed bandwidth by SLA. Then, OLT is not obliged to allocate timeslots exceeding C_i. However, if there are timeslots left unused by precedent *N-1* ONUs, OLT can allocate remnant time to ONU_i. To decide grant size G_i, OLT first calculates remnant time $T_{R,i}$ using the precedent *N*-1 grants $\{G_{i-1}, G_{i-2}, \ldots, G_{(i-N+1)mod\ N}\}$. According to (1), $T_{R,i}$ should be less than min ($T_{MAX} - \sum_{j=(i-N+1) \bmod N}^{i-1} G_j - C_i - NT_g$, T_S). In addition, C_i must be always available without violating (1). If we define over-grant O_i = max ($G_i - C_i$, 0) and under-grant U_i = min (G_i, C_i), then $G_i = U_i + O_i$ and $T_{R,i}$ is determined as

$$T_{R,i} = T_S - \sum_{j=(i-N+1) \bmod N}^{i-1} O_j \qquad (3).$$

Fig. 3 shows the calculation of remnant time. For reduction of arithmetic operation, (3) can be updated by

$$T_{R,i+1} = T_{R,i} - O_i + O_{(i-N+1) \bmod N} \qquad (4).$$

In sum, the grant size is determined as follows.

$$G_i = \begin{cases} R_i & if \quad R_i \leq C_i \\ \min(C_i + \alpha_i T_{R,i}, R_i) & otherwise \end{cases} \qquad (5)$$

where $0 < \alpha_i < 1$ is the degree of greediness of ONU_i. Equation (2) and (5) states that IPACT is a subset of SLICT: the limited service [2] is when $T_S = 0$, and the elastic service [2] is when $C_i = 0$ and $\alpha_i = 1$.

The compliance of sliding cycle time constraint (1) is proven as follows. $\sum_{j=(i-N+1) \bmod N}^{i} U_j$ is bounded by T_G and $\sum_{j=(i-N+1) \bmod N}^{i} O_j$ is bounded by T_S. Because $G_j = U_j + O_j$, $\sum_{j=(i-N+1) \bmod N}^{i} (G_j + T_g) \leq T_G + T_S + NT_g = T_{MAX}$. The name of this algorithm, *SLICT*, stands for Sliding Cycle Time.

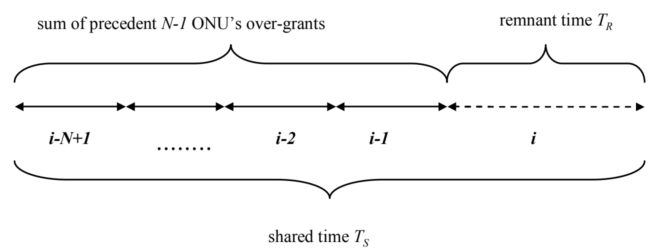


Fig. 3. Calculation of the remnant time $T_{R,i}$ from the shared time T_S and over-grants O_j {j = i-N+1, …, i – 1}

The core of SLICT lies in the management of remnant time $T_{R,i}$, which varies dynamically in accordance with traffic condition; if aggregated traffic is light-loaded such that $R_i < C_i$, $T_{R,i}$ becomes large. If over-loaded such that $R_i > C_i + T_{R,i}$, $T_{R,i}$ becomes small. Large $T_{R,i}$ induced from precedent light-loaded ONUs can be used to process busy ONU_i. In IPACT, non-uniform traffic shortens cycle time and increases optical overhead ratio NT_g/cycle time, which is the main reason of low utilization. In a corner case, if 16 ONUs are connected to OLT, and just a single ONU is in active state, the utilization of IPACT deteriorates below 0.6 in case of 5 usec guard time and 2 msec maximum cycle time [2]. In SLICT, $T_{R,i}$ can prevent cycle time shrinkage because busy ONU can use remnant time left by precedent light-loaded ONUs. Thus, it contributes to improve utilization and also reduce delay time, packet loss, and queue size.

III. SERVICE LEVEL AGREEMENT DESIGN

For multiple services, we assume that intra ONU queue scheduling is enabled as in [8].

A. Fixed bandwidth service

SLICT can support a fixed bandwidth service such as leased line or plain old telephone service (POTS) using minimum credit $C_{i,MIN}$. This service mandates constant bitrate such as 1.544/2.048 Mbps for T1/E1, or $N\times 64$ kbps. For this, $C_{i,MIN}$, should be exclusively dedicated for ONU$_i$. G_i, in (5) is modified as $G_i = \max(C_{i,MIN}, R_i)$ if $R_i < C_i$. Fixed bitrate $B_{F,i}$ is determined as $(C_{i,MIN}/T_{MAX})L_P$ where L_P is an optical link rate in PON.

B. Guaranteed bandwidth service

The minimum bitrate of a guaranteed bandwidth $B_{G,i}$ is $(C_i - C_{i,MIN})/T_{MAX}\times L_P$. Light-loaded condition may make $B_{G,i}$ larger because unused timeslots reduces cycle time.

C. Extended bandwidth service

The virtue of SLICT is an extended bandwidth service. Sharing T_S can give busy ONU$_i$ an extended bandwidth. The amount of extended bandwidth depends on traffic condition. If many ONUs are light-loaded, $T_{R,i}$ becomes large and ONU$_i$ can get much bandwidth as a bonus. The maximum of an extended bandwidth $B_{E,i}$ is

$$B_{E,i} = \alpha_i T_S / (C_i + \alpha_i T_S + (N-1)C_{i,MIN} + N T_g)\times L_P \quad (6).$$

NT_g is one of main reasons to degrade upstream throughput, especially when cycle time shrinks. SLICT prevents cycle shrinkage by introducing the shared time T_S.

D. Example of SLA design

Table I summarizes design parameters for multiple services. Fixed bandwidth service: $C_{i,MIN} = T_{MAX} \times B_F / L_P = 8$ usec is exclusively dedicated. Guaranteed bandwidth: $C_i - C_{i,MIN} = T_{MAX} \times B_G / L_P = 24$ usec is reserved. Extended bandwidth: $T_G = 512$ usec, and $T_S = 1408$ usec. Extended bandwidth is calculated from (6) as $B_{E,i} = 850$ Mbps at $\alpha_i = 0.9337$. Note that greediness α_i is also used to determine the maximum of extended bandwidth.

IV. ANALYSIS OF FAIRNESS

A. Steady state fairness under greedy contention

If M out of N ONUs are over-loaded, M ONUs try to get the remnant time by greedy contention with α_i. If $\alpha_i=1$, ONU$_i$ greedily consumes whole $T_{R,i}$, and yet, this will deprive subsequent ONUs of potential remnant time. If $\alpha_i=0$, ONU$_i$ has no right to consume remnant time. α_i is determined by SLA. Under over-loaded condition, it is important to guarantee that the shared time is fairly distributed. In order to analyze steady state fairness, recursive formula of $T_{R,i}$ at k th cycle is obtained as

$$\begin{aligned} T_{R,i}(k) &= \alpha_i T_{R,i}(k-1) + (1-\alpha_{i-1})T_{R,i-1}(k) \quad && \text{if } i \neq 0 \\ T_{R,0}(k) &= \alpha_0 T_{R,0}(k-1) + (1-\alpha_{N-1})T_{R,N-1}(k-1) \quad && \text{if } i = 0 \end{aligned} \quad (7).$$

To analyze the steady state fairness under over-loaded condition, we assume $\alpha_i = \alpha, \forall i$. Then, the steady state value of O_i $(=\alpha_i T_{R,i})$ converges to

$$O_i = \frac{T_S}{(M-1)+1/\alpha} \quad (8).$$

The derivation of convergence is omitted in this paper due to page limitation. Then, the utilization of shared time is calculated as

$$U_s = \frac{M}{(M-1)+1/\alpha} \quad (9).$$

Fig. 4 shows the steady state utilization of the shared time when M ONUs are over-loaded. U_s monotonically increases as M or α grows. Note that if $M \geq 16$ and $\alpha \geq 0.9$, $U_S \geq 0.993$. Fig. 5 shows the convergence of O_i under over-loaded condition. The convergence speed depends on α. Large α yields high utilization but lowers convergence speed. During transient time, (7) implies large α_i and $T_{R,i}(k-1)$ makes $T_{R,i}(k)$ large in the next cycle. Thus, over-loaded ONUs at *k-1* th cycle can have large $T_{R,i}$ at the k th cycle again, and it contributes to process traffic burstiness: it is called memory effect.

TABLE I
SLA DESIGN PARAMETERS

Multiple Services under SLA	
Fixed bandwidth (B_F) for voice and visual phone	4 Mbps
Guaranteed bandwidth (B_G) for interactive TV and high speed Internet	12 Mbps
Extended bandwidth (B_E) for personal web server, P2P, FTP or other highly burst application	850 Mbps
Environment	
Number of ONUs (N)	16
Link rate of EPON (L_P)	1 Gbps
Maximum cycle time (T_{MAX})	2 msec
Guard time (T_g)	5 usec
Design Parameters	
Minimum credit ($C_{i,MIN}$)	8 usec
Credit (C_i)	32 usec
Guaranteed time (T_G)	512 usec
Shared time (T_S)	1408 usec
Weighted fairness (α_i)	0.9337

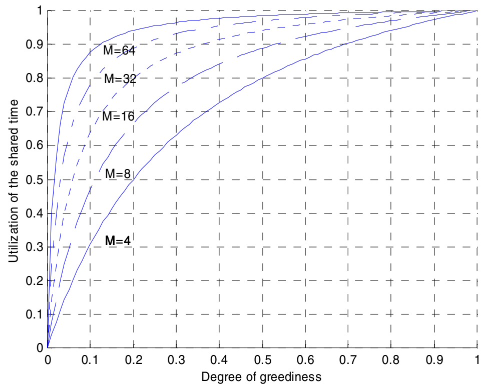
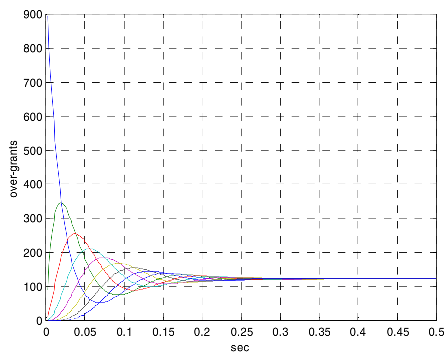
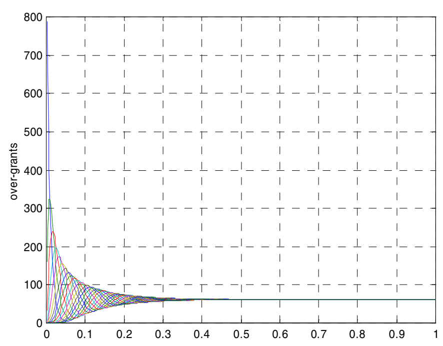


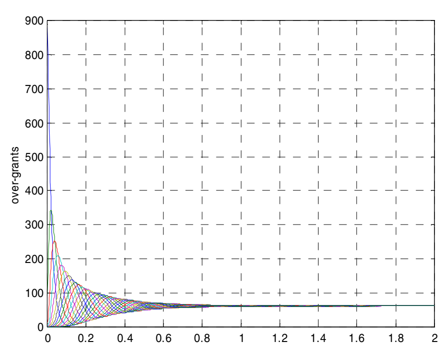
Fig. 4. Utilization of the shared time in steady state when M ONUs are over-loaded



(a)



(b)



(c)

Fig. 5. Convergence of O_i under greedy contention for T_s = 1000 usec (a) α = 0.9, M=8, (b) α = 0.8, M =16 (c) α = 0.9, M =16

V. SIMULATION RESULTS

We generate the self-similar traffic by aggregating 32 Pareto-distributed on-off sources and shaping parameter is 1.4 [9]. Ethernet frames are equally distributed from 64 byte to 1518 byte. Table II summarizes parameters in the simulation. We set T_g=5 usec to demonstrate the degradation due to guard time effect and its overcome. Fig. 6 shows throughput under extremely non-uniform traffic; one ONU sends 950 Mbps and 15 ONU are idle. Under the test condition of table II, theoretical maximum throughput of SLICT is calculated as $T_S/(T_S + N\ T_g)\times L_P$ = 960 Mbps while limited service of IPACT is 600 Mbps [2]. Fig. 6 shows that SLICT achieves 877 Mbps but limited service of IPACT reaches only 437 Mbps. Note that IPACT is the specific embodiment of SLICT at $\gamma = T_S/T_{MAX}$ =0. As γ grows, throughput increases, and especially, the slope of improvement is noticeable around γ = 0, which means just small portion of T_S greatly improves throughput. Greediness α_i also affects the throughput; as α_i grows, throughput increases.

TABLE II
SIMULATION PARAMETERS

Parameter	Value
Number of ONUs (N)	16
Link rate of EPON (L_P)	1 Gbps
Maximum cycle time (T_{MAX})	2 msec
Guard time (T_g)	5 usec
Credit (C_i)	0 ~ 120 usec
$\gamma = T_S/T_{MAX}$	0 ~ 0.96
Distance from OLT to ONUs	10 km
Queue size	10 Mbyte
ONU input	Self similar traffic

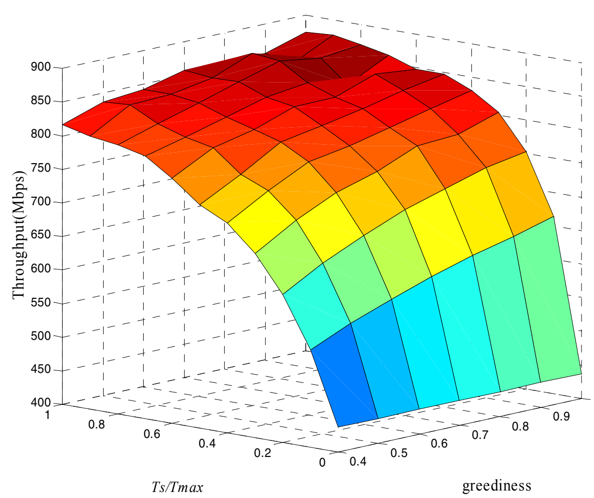


Fig. 6. Throughput for various $\gamma = T_S/T_{MAX}$ and greediness α_i. Test ONU transmits 950 Mbps while 15 ONUs are idle. Note that $\gamma = 0$ stands for IPACT.

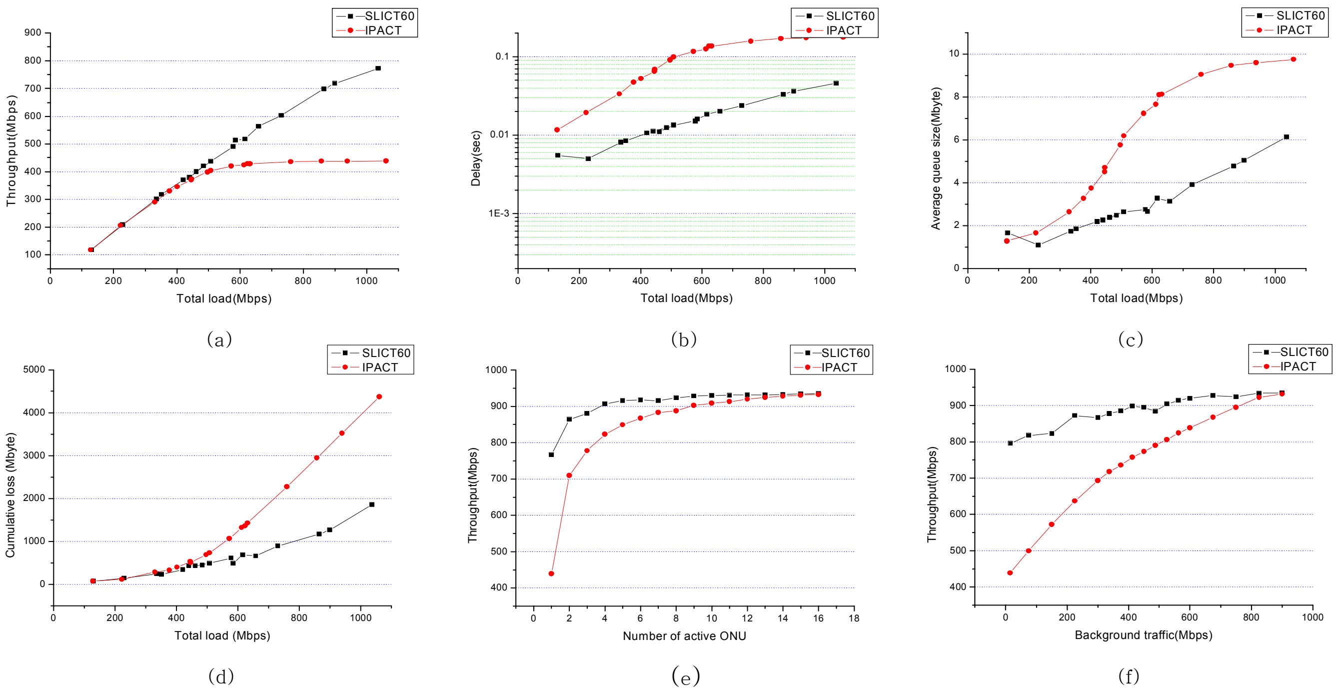


Fig. 7. Test under Ci is 60 usec and α_i=0.9. (a)-(d) Performance of SLICT and IPACT when one ONU sends from 50 to 950 Mbps while 15 ONUs are idle: (a) Throughput (b) Delay (c) Average queue size (d) Loss (e) Aggregated throughput of M ONUs equally sharing the uplink (f) Aggregated throughput when 15 ONUS send background traffic from 0 to 950 Mbps while one ONU sends 1G – background traffic, so the aggregated load is 1 Gbps.

Fig. 7 (a)-(d) shows throughput, delay, average queue size, and loss when one ONU sends from 50 to 950 Mbps and 15 ONU are idle. It is the corner case of non-uniform traffic. It shows a significant improvement in throughput, delay, loss and queue size. Fig. 7 (e) shows throughput when 1 Gbps is equally shared by M ONUs while $16 - M$ ONUs are idle. As non-uniformity is high, i.e., M is low, throughput improvement is significant. At M = 16, proposed scheme and the conventional one shows same performance. Fig. 7 (f) shows upstream capacity of test ONU with various background traffics. Upstream capacity reflects how much bandwidth the test ONU can use when background traffic exists. It should be 1 Gbps – background load in ideal condition, but degraded by overheads such as guard time, round trip time, processing delay, etc. SLICT shows a significant improvement in upstream capacity as well.

VI. Conclusion

In this paper, we proposed a novel dynamic bandwidth allocation scheme, called SLICT, which provides multiple services such as fixed, guaranteed or extended bandwidth services in accordance with service level agreement. New concept of sliding cycle time and remnant time was introduced under sliding cycle time constraint. We presented a design method to provide multiple services. The management of remnant time is the core of proposed scheme, and we analyzed the steady state fairness under simple greedy contention. Simulation results show that SLICT achieves a significant improvement in utilization, delay, loss and queue size under various traffic conditions, especially non-uniform traffic.

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