Traffic Load Distribution-Based Excess Bandwidth Allocation in Time-Division-Multiplexed PONs

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Abstract—**Time-division-multiplexed passive optical networks (TDM–PONs) have been successful solutions for providing the huge bandwidth needed for quadruple-play services in last-mile networks. In this paper, the effects of excess bandwidth provisioning applied to a reservation-based TDM are analyzed in detail, and noble adaptive excess timeslot provisioning (ETP) mechanisms are proposed in the interoptical network unit (ONU) and intra-ONU domain in the TDM–PONs. Using traffic load distribution information observed in an optical line termination (OLT), a proposed deficit reservation-based dynamic bandwidth allocation, called dr-DBA, controls the amounts of excess timeslot bandwidths in order to efficiently serve the burst traffic of heavy-loaded ONUs while guaranteeing strict fair link-sharing. The authors also introduce a service work-based ETP bandwidth reservation as well as an optimal reservation class selection mechanism to support prioritized service in an intra-ONU so that serious node light-load penalty and bandwidth overbooking can be minimized. The performance results achieved by numerical analysis and simulations prove that proposed ETP mechanisms provide fair and optimal excess bandwidths to the ONUs according to the changes in traffic load distribution, while compensating the systematic weakness of each mechanism in both ONU domains.**

Index Terms—**Excess timeslot provisioning, fair link sharing, full access service, traffic load distribution.**

I. INTRODUCTION

Time-division-multiplexed passive optical networks (TDM–PONs) have been successful solutions in broadband access networks for providing end users with quadruple-play services due to their economical advantages achieved by deployment of passive optical devices and simplicity in operation and management [1]–[3]. The optical line termination (OLT) in a TDM–PON controls packet transmission, using reservation-based TDM to prevent traffic collision in a shared uplink and to provide the interoptical network units (ONUs) with fair amounts of bandwidths [4], [5]. In the case of Ethernet PON (EPON), the ONU reports the amount of buffered data bits to the OLT and then transmits packets during a transmission window allocated by the OLT, which is called a timeslot [6], [7]. Thus, it is a critical issue how to efficiently allocate timeslots to competing ONUs, which is defined as inter-ONU scheduling. The authors of [7] proved that pipelined dynamic bandwidth allocation (DBA), called interleaved polling with adaptive cycle time (IPACT), provides a high link utilization, seamless packet transmission, and fairness in an evenly distributed traffic load. However, because control messages used for bandwidth reservation and allocation are delivered by a single data link along with normal data packets, the frequency in control message transmission has an impact on the downstream throughput. If control messages are transmitted very frequently in the downstream because of a low upstream load, the amount of bandwidth that can be allocated for data transmission decreases. In this paper, this control overhead is defined as a network light-load penalty. It differs from a normal definition of light-load penalty, which represents starvation of low-priority traffic in strict priority queuing (SP) in the intra-ONU. To clarify the differences, the former is defined as a network light-load penalty, while the latter is defined as a node light-load penalty in this paper.

Choi and Huh [8] proposed cyclic polling to prevent a network light-load penalty by restricting the GATE message issuing interval, but interleaved polling without a cease of the DBA is no longer achieved. Shami *et al.* [9] proposed a similar approach, using packet scheduling in both inter-ONU and intra-ONU. The proposed hybrid granting protocol (HGP) supports QoS requirement-based transmission control. Explicit forwarding (EF) traffic are served in the designated EF subcycle that starts first in every cycle in a deterministic manner, while assured forwarding and best-effort traffic are served dynamically according to traffic loads. Meanwhile, in order to achieve bandwidth-guaranteed service, Ma *et al.* [10] have proposed a parameter-based call admission control using controlled polling method. It categorizes ONUs into a bandwidth guaranteed (BG) group and non-BG group and serves the ONUs differently using an even distribution algorithm and dynamic contention algorithm. Using a similar approach in timeslot bandwidth arbitration, Banerjee *et al.* [11] proposed a service level agreement-based link-sharing by which timeslot bandwidths are determined by the fairness indexes observed in both the inter-ONU and intra-ONU.

To minimize the drawbacks resulting from a long-service waiting time in a reservation-based TDM, the authors of [12]

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proposed a prediction-based timeslot allocation that allocates an unused cycle bandwidth to the ONUs in advance based on the prediction of traffic arrival. The traffic prediction has also been dealt with in detail in a least mean square (LMS) error-based excess timeslot reservation [13], sliding cycle time-based bandwidth allocation [14], and load-based reservation [15]–[17]. More generalized excess bandwidth allocation mechanisms aim to provide optimal excess bandwidth to the ONU according to the changes in estimated traffic rate; IPACT with grant estimation (IPACT–GE) [18], estimation-based DBA (EB–DBA) [19], and limited sharing with traffic prediction (LSTP) [20] reserve excess bandwidth, using weighted traffic prediction with GATE message interval estimation or packet arrival history and queue state in previous cycles. Because more bandwidth except for backlog queue is reserved for new packet arrivals, performance in terms of delay and the node light-load penalty, i.e., service starvation of low priority traffic due to the consistent bandwidth preemption of high priority traffic in the SP, can be improved.

The excess bandwidth allocation mechanisms have to minimize bandwidth overbooking, resulting from the error in traffic prediction to guarantee high throughput and utilization. In the inter-ONU, a queue-based dynamic bandwidth allocation that distributes remaining bandwidths of light-loaded queues to heavy-loaded queues is also proposed to meet the bandwidth demands of heavy-loaded queues based on the priority queue status information [21]. To achieve optimal performance in prediction-based bandwidth reservation and provisioning, Yin *et al.* [22] have also proposed a prediction-based dynamic bandwidth allocation, using a non-linear predictor and controlled QoS provisioning. Analysis in terms of controllability and eligibility in traffic prediction has also been dealt with in detail. To mitigate a node light-load penalty, the authors of [23] proposed a two-stage priority queuing architecture. It resolves bandwidth monopolization of high priority traffic, but a multiple stage buffer has to be deployed in every ONU. Although a class-based multiple timeslot reservation improves the accuracy in polling [24], it only moves the intra-ONU scheduling from the ONU to the OLT. Because DBA mechanisms of TDM–PONs guarantees high service granularity in bandwidth allocation and high link utilization, those have also been employed in wavelength-division multiplexing (WDM)-based TDM–PONs [25]–[27]. In the WDM–TDM hybrid architecture, wavelength provisioning and bandwidth allocation have to be coordinated simultaneously to guarantee service continuity in both wavelength level and timeslot level. Overall comparison of the properties of bandwidth allocation in the TDM–PONs and related technical issues are dealt with in detail in [28] and [29].

In this paper, adaptive excess timeslot provisioning (ETP) mechanisms are proposed in order to achieve fair and efficient bandwidth allocation in both scheduling domains by optimal distribution of the remaining cycle bandwidth to competing ONUs and traffic classes. First, the proposed ETP efficiently achieves full access service and fair link sharing in the inter-ONU by coordinating the amounts of excess bandwidths according to the changes in the traffic loads of ONUs. At the same time, the ETP applied in the intra-ONU scheduling adjusts the amount of ETP reservation bandwidth according to the changes in the traffic load distribution over traffic classes in order to improves the performance of differentiated service. Both ETP mechanisms compensate the systematic weakness of each one while minimizing the overbooking problem of prediction-based reservation mechanism. The structure of this paper is as follows: In Section II, the authors deal with the unique properties of the DBA and introduce the concept of the ETP. The adaptive ETP mechanism in both the inter-ONU and intra-ONU domain are proposed, respectively, in Sections III and IV, and the performance is discussed in Sections V and VI. Section VII concludes this work with some remarks.

II. EXCESS TIMESLOT PROVISIONING MECHANISM

A. Properties of DBA and Scheduling Issues

The DBA controls the amounts of timeslot bandwidths of competing ONUs and the GATE message transmission in order to achieve seamless and fair upstream transmission [7], [15], [24]. Due to the applied reservation-based TDM, the DBA has the following properties:

- *Property 1*: The DBA is a backward recurrence reservation (BRR) since a timeslot is reserved based on the past information, i.e., the amount of buffered data bits [31]. The BRR property guarantees seamless packet transmission and high link utilization, but packet service lags at least one cycle from the packet arrival time.
- *Property 2*: A service vacation exists between timeslots provided to the same ONU, and it varies by a network load (ρ^m). If propagation delay t_p is assumed to be the same in every connection between the OLT and the ONU, and guard time t_{guard} includes the minimal bandwidth needed to transmit control messages, the service vacation of ONU_j in the pipelined polling [7] is the same as $V_j^m = \sum_{i=j+1}^{N} A_i^{m-1}/R + \sum_{i=1}^{j-1} A_i^m/R + (N-1)t_{\text{guard}}$, where $R =$ a link speed and $A_i^m =$ timeslot bandwidth of the ONU_i in the mth cycle. Therefore, if only ONU_j has data packets to transmit, its vacation time is larger than the minimal delay of $(N-1)t_{\text{guard}} + 2t_p$ [24].
- *Property 3*: A service reservation gap that represents the difference between allocated timeslot bandwidth and buffered data bits observed at the gate time can easily occur by new packet arrivals during a service vacation.
- *Property 4*: The frequent GATE message transmissions in a light upstream traffic load affects the downstream throughput due to in-band signaling via a single channel.

The performance of the DBA is directly affected by the above properties. First, a periodic service reservation gap resulting from the BRR property easily brings about the node light-load penalty by which low priority traffic can not be served although a traffic load is low. The node light-load penalty reduces the efficiency of differentiated service and is the reason for incorrect transmission control protocol (TCP) congestion control [23]. In the inter-ONU domain, the network light-load penalty also occurs by Property 4. If an upstream traffic load is low, REPORT and GATE messages are frequently transmitted because of small timeslots. This control overhead ultimately reduces the amount

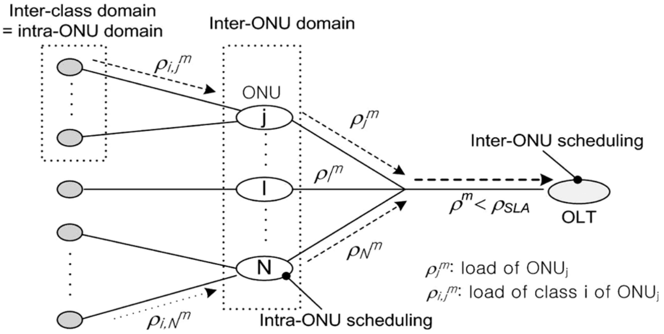

Fig. 1. Traffic load distribution model in the inter- and intra-ONU.

of effective bandwidth that can be allocated for data transmission in the downstream transmission [30].

Scheduling requirements needed to mitigate the above problems can be summarized as follows; the inter-ONU scheduling has to guarantee strict fair link sharing if bandwidth reservation contention occurs. Oppositely, if some ONUs are heavy loaded and others are not, while a network load is low, large bandwidths have to be allocated to the heavy-loaded ONUs, so that those can efficiently be served without a severe network light-load penalty. Meanwhile, the intra-ONU scheduling has to mitigate persistent bandwidth preemption of high priority traffic to prevent the node light-load penalty.

B. Basic Principles of Excess Timeslot Provisioning

The logical load distribution model in the inter-ONU and intra-ONU is shown in Fig. 1, where $\rho =$ network load, $N =$ the number of ONUs, $K =$ the number of traffic classes, $\rho_j^m =$ the load of ONU_j, and $\rho_{i,j}^m =$ the load of class i in the mth cycle. To provide delay bounded service, ρ is restricted to be smaller than the maximum cycle load, called a service level agreement (SLA) load of ρ^{SLA}, as

$$\rho = \sum_{j=1}^{N} \rho_j^m = \sum_{j=1}^{N} \sum_{i=0}^{K-1} \rho_{i,j}^m \leq \rho^{\mathrm{SLA}}. \tag{1}$$

Most scheduling issues have been discussed assuming an evenly distributed load case, but a load metric $[\rho_{i,j}^m, \rho_j^m, \rho^m]$ varies dynamically, and the divergence in load distribution affects the efficiency of the bandwidth allocation mechanism.

Excess timeslot provisioning provides the ONUs with excess bandwidths to mitigate the light-load penalties and improve the performance of the DBA. In the ETP, the amount of excess timeslot bandwidth $(A_{\mathrm{ETP},j}^m)$ that is normally determined by the prediction of traffic arrival and service pattern is provided to the ONU_j in addition to the timeslot bandwidth allocated by the DBA based on buffered data bits $A_{\mathrm{queue},j}^m$. Allocation of excess bandwidths reduces the service reservation gap and the node light-load penalty in the intra-ONU. The ETP also provides full access service for handling burst traffic and reduces unnecessary GATE transmissions, which eventually reduces the network light-load penalty, since more bandwidths are allocated to heavy-loaded ONUs.

We note that the ETP is a forward recurrence reservation (FRR) in contrast to the DBA, since it reserves a timeslot bandwidth based on expectation of future events. Thus, the following problems that easily occur in normal prediction-based traffic engineering have to be resolved [31]:

- *Timeslot overbooking*—If A_{ETP} is much larger than the need of the ONU, a large amount of timeslot bandwidth is wasted, and the channel utilization decreases.
- *Timeslot underbooking*—If A_{ETP} is much smaller than the need of the ONU, a large service reservation gap continues recursively without performance improvement.

A static bandwidth allocation (SBA) that provides a constant timeslot bandwidth is a type of the ETP. Although the SBA prevents the network light-load penalty, it easily results in a low link utilization and cannot handle burst traffic. Thus, to achieve optimal performance, the ETP bandwidth has to be determined adaptively according to the change in the traffic load metric.

C. Feasible Load Range of the ETP

The feasible load range in which the ETP can be applied is determined by the type of bandwidth allocation mechanism. In limited service [23], a maximum timeslot bandwidth of a single ONU is equal to $A^{\mathrm{MIN}} = A^{\mathrm{MAX}}/N = (V^{\mathrm{SLA}} - Nt_{\mathrm{guard}})/R$, where A^{MAX} is the maximum cycle bandwidth that is limited in order to guarantee the SLA cycle time V^{SLA}. The guard time t_{guard} includes a laser turn-on, turn-off, automatic gain control, and clock and data recovery time. Because A_j^{m+1} is equal to $\min(A^{\mathrm{MIN}}, Q_j^m)$ in limited service, the ETP feasible load is derived as [32]

$$\begin{aligned} \rho_j^m + \rho_{j,\mathrm{ETP}}^m = \left(1 + \xi\left(\rho_j^m\right)\right)\rho_j^m \leq \rho^{\mathrm{SLA,ONU}} \\ \rho_j^m \leq \frac{\rho^{\mathrm{SLA,ONU}}}{1 + \xi\left(\rho_j^m\right)} \end{aligned} \tag{2}$$

where $\rho^{\mathrm{SLA,ONU}}$ is the maximum ONU load permitted to a single ONU, and $\xi(\rho_j^m)$ is a function that returns the normalized ratio of the ONU load applicable in the ETP $(\rho_{j,\mathrm{ETP}}^m = \xi(\rho_j^m)\rho_j^m)$. Conversely, the feasible load range of the load-based adaptive bandwidth allocation that limits not a timeslot bandwidth, but a cycle bandwidth is derived as [31] and [33]

$$\begin{aligned} \rho_j^m + \rho_{j,\mathrm{ETP}}^m + \rho^m = \left(1 + \xi\left(\rho_j^m\right)\right) \\ \rho_j^m + \rho^m \leq \rho^{\mathrm{SLA}} \\ \rho_j^m \leq \frac{\rho^{\mathrm{SLA}} - \rho^m}{1 + \xi\left(\rho_j^m\right)}. \end{aligned} \tag{3}$$

It is observed that the ETP in the load-based adaptive bandwidth allocation can provide a heavy-loaded ONU with several times of $\rho^{\mathrm{SLA,ONU}}$, if the network load is unevenly distributed and low $(\rho = 0.52)$, as shown in Fig. 2. Conversely, if the network load is high $(\rho = 0.64)$, a fair amount of bandwidth for $\rho^{\mathrm{SLA,ONU}}$ is not guaranteed, while the feasible load range is small as well. Another important property that has to be considered in the ETP design is a relationship with an overbooking problem. We can observe that the service reservation gap decreases as $\xi(\rho_j^m)$ increases, but the feasible range decreases reversely, and the timeslot overbooking increases. Thus, a supplementary mechanism to guarantee fair link sharing and to achieve optimal performance tradeoff in terms of service reservation gap, fairness, and overbooking is required as well.

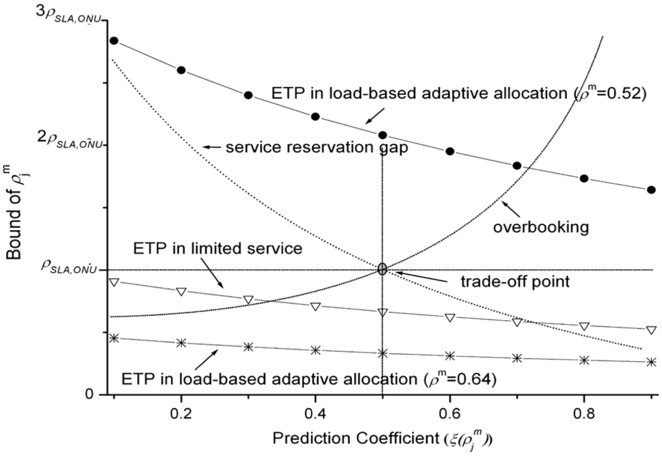

Fig. 2. Performance tradeoff (load unit).

III. INTER-ONU SCHEDULING: DEFICIT RESERVATION-BASED DBA

A. *ETP in the Inter-ONU Domain*

The objective of the ETP in inter-ONU scheduling is to support full access service for burst traffic and fair link sharing simultaneously according to the changes in traffic load distribution. In a full-cycle bandwidth allocation (FCBA), a remaining cycle bandwidth is entirely allocated to the ONU in proportion to the ONU service weight. The FCBA is a kind of normal prediction-based excess bandwidth allocations, such as the DBA 1 and DBA 2 [12] and cyclic DBA [8], [34]. A network light-load penalty is reduced by the FCBA, but timeslot overbooking easily occurs because $A_{\rm ETP}$ is determined by the expectation of the ONU load status in the OLT, and a cycle bandwidth is entirely distributed to the ONUs. Thus, to prevent an overbooking, the ETP has to be initiated by the ONU, i.e., excess bandwidth is reserved by the ONU based on its own load status. Correspondingly, the OLT has to try to satisfy the ETP requests of heavy-loaded ONUs based on the monitored load metric.

B. *GATE Message Transmission for the ETP*

The method used in the ETP bandwidth reservation and allocation may affect the performance of the DBA. If $A_{\rm ETP}$ and $A_{\rm queue}$ are allocated to every ONU at the end of a cycle, it is always possible for the OLT to provide optimal ETP bandwidths to the ONUs, since entire information about the ONU queue states and ETP requests can be utilized in the ETP. However, online granting of the DBA is no longer achieved. Oppositely, in a case $A_{\rm ETP}$ is allocated by an independent ETP process, which uses another ETP GATE message, the network light-load penalty increases and transmission control becomes more difficult. In this paper, it is assumed that $A_{\rm ETP}$ is added to $A_{\rm queue}$ and allocated by the normal DBA process to prevent these problems.

C. *Deficit Reservation-Based DBA*

A proposed deficit reservation-based DBA (dr-DBA) controls the amounts of ETP bandwidths according to the changes in load distribution, so that full access service and fair link sharing are achieved in the inter-ONU. The dr-DBA agent of the OLT calculates the ETP deficit of the ONU that is utilized as a token of the ETP bandwidth allocation. The following pseudocodes show the details of operations of the dr-DBA, where ω_j = the service weight of the ONU$_j$, Δd_j^m = the remaining cycle bandwidth, A_k^m = the timeslot bandwidth allocated to the ONU$_{\rm k}$, $A_j^{\rm MAX}$ = the maximum timeslot bandwidth proportional to ω_j, and $A_j^{\max}$ = the controlled maximum ETP timeslot

Deficit-Reservation DBA

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Begin {
Step 1: Set $\Delta d_j^m = A^{\rm MAX} - \sum_{k=1,k\neq j}^{N} A_k^m$;
Set $A_j^{\rm MAX} = A^{\rm MAX} \cdot (\omega_j)/(\sum_{k=1}^{N} \omega_k)$;
if ($\Delta d_j^m$ is larger than $A_j^{\rm MAX}$)
{ set $A_j^{\max} = \Delta d_j^m$;}
else{ set $A_j^{\max} = A_j^{\rm MAX}$;} go to Step 2;
/* maximum allocable timeslot bandwidth*/
Step 2: if ($D_j^m < A_j^{\max}$): { set $A_j^{m+1} = D_j^m$;}
else { set $A_j^{m+1} = A_j^{\max}$; }
return $A_j^{m+1}$; update $A_j^{m+1}$; go to End; }
End
```

In Step 1, the ETP agent calculates Δd_j^m and compares it with $A_j^{\rm MAX}$. The larger one is chosen as $A_j^{\max}$ in the new ETP cycle that simply starts from the current timeslot of ONU$_j$ and covers the next $N-1$ timeslots. The changes in load distribution are efficiently reflected by the comparison using Δd_j^m, which changes by network load and the ETP result in the previous cycle. In Step 2, $A_j^{\max}$ is compared with the reported bandwidth of D_j^m, and the smaller one is allocated to the ONU$_j$ in order to guarantee pipelined polling of the DBA. This shows that the ETP mechanism is implicitly employed in the timeslot determination process.

In the dr-DBA, a new ETP cycle begins whenever a large ETP bandwidth that is larger than $A_j^{\rm MAX}$ is provided to the heavy-loaded ONU. The resultant large deficit prevents the start of another ETP until the current ETP cycle ends. Thus, the cumulative bandwidth provided to N ONUs in a single cycle is limited not to exceed $A^{\rm MAX}$. The detailed operations of the DBA are as follows: In case ρ^m is much smaller than $\rho^{\rm SLA}$, i.e., a large cycle bandwidth remains, enough bandwidth is provided to a greedy ONU, and Δd_j^m becomes an ETP deficit that restricts bandwidth monopolization in the following cycle. This means that if a large excess bandwidth is provided to an ONU, the lowest priority is given to it in the ETP competition with other greedy ONUs during the following cycle. Meanwhile, if bandwidth reservation contention occurs among ONUs, the ETP is automatically banned, since Δd_j^m decreases to zero. In this case, fair amounts of bandwidths determined by service weights are allocated to the ONUs by Step 1. By this adaptive coordination, cycle bandwidth can efficiently be allocated to nongreedy ONUs and greedy ONUs as wanted, while guaranteeing fair link sharing in any case. The dr-DBA has a similar property of the longest queue first (LQF) scheme in the inter-ONU [34], but it restricts service monopolization automatically while keeping fair link sharing.

The ultimate timeslot bandwidth provided to the ONU_j is yielded as

$$A_j^{m+1} = \min\left(D_j^m, \max\left(A^{\mathrm{MAX}}\frac{\omega_j}{\sum_{k=1}^{N}\omega_k}, \Delta d_j^m\right)\right) \tag{4}$$

Thus, the ETP feasible load range in the load-based adaptive allocation is yielded as

$$\rho_j^m \le \frac{1}{1+\xi\left(\rho_j^m\right)} \max\left(\frac{\omega_j}{\sum_{k=1}^{N}\omega_k}\rho^{\mathrm{SLA}}, \left(\rho^{\mathrm{SLA}} - \rho^m\right)\right) \tag{5}$$

The optimal ETP of the dr-DBA is summarized as follows:

- *Unevenly load* ($\rho_j^m \gg \rho^{\mathrm{SLA,ONU}}, \rho_k^m < \rho^{\mathrm{SLA,ONU}}$ $(j \neq k)$, and $\rho^m \ll \rho^{\mathrm{SLA}}$): The dr-DBA provides a heavy-loaded ONU_j with a large ETP bandwidth to efficiently serve short-term burst traffic. The network light-load penalty fundamentally decreases in every excess bandwidth distribution mechanism, as discussed in [18]–[20]. The proposed dr-DBA also reduces the network light-load penalty by allocating large excess bandwidths to heavy-loaded ONUs in the low network load, which eventually avoids frequent allocation of small size timeslots. At the same time, bandwidth waste is also minimized in any case, since the ETP bandwidth is determined by traffic load distribution over the ONUs and the ETP states.
- *Evenly load* ($\rho_j^m > \rho^{\mathrm{SLA,ONU}}, j \in \forall$, and $\rho^m \simeq \rho^{\mathrm{SLA}}$): Excess bandwidth allocation of the ETP is stopped, and timeslot bandwidth is determined only by ω in order to guarantee the ONUs fair link sharing.

IV. INTRA-ONU SCHEDULING: SERVICE QUALITY PREENGAGEMENT

A. Service Work-Based ETP Reservation

The objective of the ETP in intra-ONU scheduling is to improve the performance of differentiated service and to mitigate the node light-load penalty. A proposed service quality preengagement (SQP) reserves ETP bandwidth using the transmitted class traffic in a single cycle, called the service work of class. In the SQP, a REPORT bandwidth of D_j^m consists of two types of reservation bandwidths, $D_{\mathrm{ETP},j}^m$ determined by the ETP bandwidth reservation, and $D_{\mathrm{queue},j}^m$ determined by a normal queue size-based DBA. To minimize the overbooking and underbooking, the SQP applies ETP bandwidth reservation only to the selected classes, called forward reservation classes (FRCs). By the definition, $D_{\mathrm{ETP},j}^m$ is yielded as

$$D_{\mathrm{ETP},j}^m = \begin{cases} \sum_{d=1}^{N_i(t)} L(P_{i,d}), & i \in \mathrm{FRC} \\ 0, & \mathrm{else} \end{cases} \tag{6}$$

where $L(P_{i,d})$ = the length of the dth service packet $P_{i,d}$ in class buffer i, and $N_i(t) =$ the number of transmitted packets from the timeslot start time to the arbitrary time t. Thus,

$$D_j^m = \sum_{i=0}^{K-1} Q_{i,j}^m + \sum_{d=1, i\in \mathrm{FRC}}^{N_i(t)} L(P_{i,d}) \tag{7}$$

where $Q_{i,j}^m$ is the backlog queue size of class i. Because a service work varies by the change in traffic arrival rate, the SQP applied to selected FRCs, which are normally high priority classes, forces themselves to reserve their own bandwidths in compensation for consistent preemption of the bandwidths reserved by low priority classes. Even though the selection of FRCs is based on an analytic approach, such as the nonlinear prediction proposed by Luo and Ansari [20] and Yin*et al.*[22], which utilizes an estimation credit and LMS to derive stationary expectation, traffic prediction in the SQP is basically achieved by service works that are determined by the ONU load, ONU load distribution over classes, and relative service priority in a current cycle. Although the SQP can be employed in the OLT, the operational complexity is extremely high, since service works of all classes in every ONU and their FRC information have to be managed.

The SQP provides optimal performance for deterministic traffic such as periodic or constant-bit-rate (CBR) traffic because the amount of service work is constant. It also minimizes the problems resulting from a wrong prediction in different traffic types as follows: First, if traffic greater than expected arrives during a service vacation, FRCs preempt the bandwidth reserved by non-FRCs. However, because $D_{\mathrm{ETP},j}$ increases in proportion to the increasing traffic rate of FRCs in that cycle ($\lambda_{\mathrm{FRC},j}^m$), underbooking does not continue. In the opposite case, more non-FRC traffic is transmitted in that cycle, but $D_{\mathrm{ETP},j}$ decreases, and the overbooking is prevented. By this adaptive ETP reservation using service work information, the SQP efficiently handles short-term traffic fluctuation.

Because the feasible range of the SQP is fundamentally limited by the dr-DBA, $\xi(\rho_j^m)$ is yielded as

$$\xi\left(\rho_j^m\right) = \frac{\sum_{i=0}^{P}\rho_{i,j}^m}{\rho_j^m} = \frac{\rho_{\mathrm{ETP},j}^m}{\rho_j^m} \tag{8}$$

where P is the lowest priority class in the FRCs. Thus, the feasible range of the ETP in the SQP is derived as

$$\rho_j^m \le \max\left(\frac{\omega_j}{\sum_{k=1}^{N}\omega_k}\rho^{\mathrm{SLA}}, \left(\rho^{\mathrm{SLA}} - \rho^m\right)\right) - \rho_{\mathrm{ETP},j}^m. \tag{9}$$

B. Selection of Forward Reservation Classes

Accuracy in FRC selection determines the efficiency of the SQP. The overbooking and service reservation gap observed in selection of different numbers of FRCs from eight traffic classes are shown in Fig. 3. The results are the average values observed every 0.05 s when the input traffic load ρ_j is 0.5, and it is evenly distributed over the classes. The transient behavior is almost the same in every run, since the major assumption regarding timeslot allocation is the same. We can observe that the service reservation gap decreases as more classes are selected as the

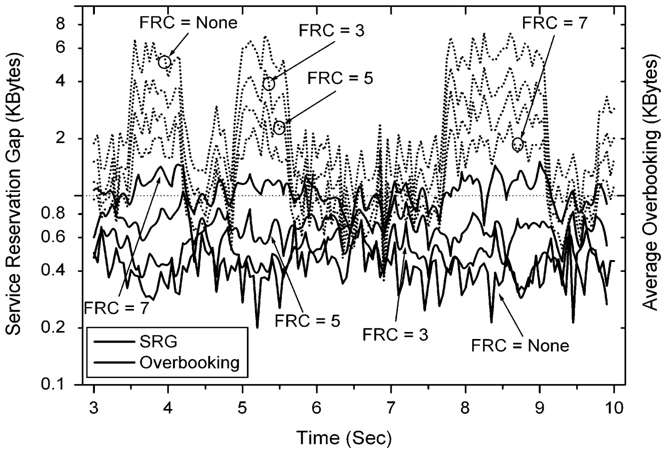


Fig. 3. Average service reservation gap and overbooking.

FRCs, since more ETP bandwidth is provided. However, if most classes are selected as the FRCs, the overbooking is nearly the same as the service reservation gap in the worst-case, which results in a large bandwidth waste. Because the traffic load and its distribution changes dynamically, an adaptive FRC selection is needed to prevent the above problems.

In the ONU, traffic classes are classified into two aggregated classes, $C+1$ preemptive classes from the highest priority class 0 to class C, and $K-C-1$ nonpreemptive classes. By definition, the packets of preemptive classes are serviced to exhaustion every cycle. For analytic simplicity, a single ONU is assumed hereafter. Accordingly, ONU index j is omitted in every case, and the network load index is changed from ρ to ρ_n to prevent confusion (ONU load is ρ). The mean queuing delay of a reservation-based TDM, $E(W)$ is derived as [32]

$$E(W) = E(R_{\mathrm{rd}}) + \frac{E_S(N)}{\mu} + E_r(V) \qquad (10)$$

where $E(R_{\mathrm{rd}}), E_S(N), \mu, E_r(V)$ are the mean residual service time, average number of backlog packets, mean service rate, and mean timeslot reservation delay, respectively. The service of preemptive classes follows an exhaustive service model wherein $E_r(V)$ is zero. Thus, the residual service time of an incoming packet $r(\tau)$ decays linearly, and the mean residual service time is derived as [33]

$$\begin{aligned} E(R_{rd}) &= \lim_{t\longrightarrow\infty} \frac{1}{t}\int_0^t r(\tau)d\tau \\ &= \lim_{t\longrightarrow\infty}\left(\frac{M(t)}{t}\frac{\sum_{i=1}^{M(t)}\frac{1}{2}X_i^2}{M(t)}\right. \\ &\qquad \left.+\frac{J(t)}{t}\frac{\sum_{i=1}^{J(t)}\frac{1}{2}V_i^2}{J(t)}\right) \\ &= \frac{\lambda_{0,C}\overline{X^2}}{2} + \frac{(1-\rho)\overline{V_{\rho_n}^2}}{2\overline{V_{\rho_n}}} \end{aligned} \qquad (11)$$

where $X =$ the packet service time, $M(t) =$ the number of packet service completions, $J(t) =$ the number of service vacations in $[0,t], \lambda_{0,C} =$ the packet arrival rate of preemptive classes $(\lambda_{0,C} = \lambda_0 + \lambda_1 + \ldots + \lambda_C), \rho_{0,C} =$ the traffic load of preemptive classes $(\rho_{0,C} = \rho_0 + \rho_1 + \ldots + \rho_C)$, and $V_{\rho_n} =$ the mean service vacation for ρ_n. Because $E_S(N)/\mu$ is equal to $\rho_{0,C}W_{0,C}$, the average waiting time is yielded as

$$W_{O,C} = E(R_{\mathrm{rd}}) + \frac{\lambda_{0,C}}{\mu}W_{0,C} = E(R_{\mathrm{rd}}) + \rho_{0,C}W_{0,C}. \qquad (12)$$

The service of nonpreemptive classes follows a gated service model in which a reservation delay has to be considered in calculation of the residual service time. Using the same approach, $E(R_{\mathrm{rd}})$ is derived as

$$E(R_{rd}) = \frac{\lambda_{C+1,K-1}\overline{X^2}}{2} + \frac{(1-\rho)\overline{V_{\rho_n}^2}}{2\overline{V_{\rho_n}}} + \overline{V_{\rho_n}}. \qquad (13)$$

Correspondingly, the average waiting time is achieved as

$$W_{C+1,K-1} = R_{\mathrm{rd}} + \rho_{0,C}W_{0,C} + \rho_{C+1,K-1}W_{C+1,K-1}. \qquad (14)$$

The analytic results show that the SQP changes the effective load of preemptive classes as $\rho_{P+1,C}$. To minimize the overbooking, the ETP bandwidth has to be smaller than the mean cumulative backlog queue size of nonpreemptive classes. Therefore, the bound condition (BC) in FRC selection in terms of total traffic of FRCs $(\rho_{0,P})$ is derived as

$$\begin{aligned} \rho_{0,P} =& \frac{\overline{X}}{\overline{V_{\rho_n}}}\frac{\lambda_{C+1,K-1}}{2(1-\rho_{C+1,K-1})}\Big\{\rho_{C+1,K-1} \\ &+ \frac{1}{(1-\rho_{0,C})}\left[\rho_{0,C}^2 + 2C_R(\rho)(3-\rho-\rho_{0,C})\right]\Big\} \end{aligned} \qquad (15)$$

where $C_R(\rho) = \overline{V_{\rho_n}}/2\overline{X}$ and $0 \le P \le C < K-1$. Because $\rho_{0,C}$ varies by the changes in the load metric, the FRCs have to be adjusted adaptively so that the cumulative load of FRCs always satisfies the BC in order to achieve optical performance. A more detailed derivation of (15) has been given in [15].

C. Dynamic FRC Selection With BC-Test

A proposed dynamic FRC selection (DFS) controls the number of FRCs and changes the internal class mapping so that the optimal ETP bandwidth reservation is always achieved in the intra-ONU. The DFS agent observes $(\rho_{0,P}, \rho, \rho_n)$ (recall that an ONU index has been removed) using the service works of classes and the GATE interval. When new flow S arrives, its temporary class j and supportable load ρ_S are determined by a service profile, while the load metric is changed to $(\rho_{0,P}, \rho+\rho_S, \rho_n+\rho_S)$. Then, the feasibility of the current FRC selection is tested by using the BC in order to select the optimal number of FRCs in the changed load metric. First of all, if j is currently not the FRC, j is set to its ultimate class. Otherwise, FRC optimization 1 using the following pseudocodes is activated. Conversely, if flow S ends, the load metric is changed to $(\rho_{0,P}, \rho-\rho_S, \rho_n-\rho_S)$ and FRC optimization 2 is activated. The detailed procedures of the DFS can be clarified by the following pseudocodes:

FRC Optimization 1

```
Begin{
  set $\rho_{\mathrm{test}} = \rho_{0,P} + \rho_S$; set $i = 0$;
  if (BC-test $(\rho_{\mathrm{test}}, \rho, \rho_n)$ is true)
```

```
{ set class of S $= j$; set $\rho_{0,P} = \rho_{0,P} + \rho_S$; }
else {
if ($j$ is P) { set class of S $= P + 1$;}
else {set class of S $= j$; set $\rho_{0,P} = \rho_{0,P} + \rho_S$;
while (BC-test $(\rho_{\text{test}}, \rho, \rho_n)$ is false) do
{$i + +$; set $\rho_{\text{test}} = \rho_{0,P} - \rho_{P-i}$;
do BC-test $(\rho_{\text{test}}, \rho, \rho_n)$); }
set $P = P - i$; }/*FRCs from 0 to $P - i$ */
return $P$ and load metric;}}
End
```

FRC Optimization 2

```
Begin{
set $\rho_{\text{test}} = \rho_{0,P} - \rho_S$; set $i = 0$;
while (BC-test $(\rho_{\text{test}}, \rho, \rho_n)$ is true) do
{$i + +$; set $\rho_{\text{test}} = \rho_{0,P} + \rho_{P+i}$;
do BC-test $(\rho_{\text{test}}, \rho, \rho_n)$; }
set $P = P + i$; }/*FRCs from 0 to $P + i$ */
return $P$ and load metric;}}
End
```

Optimization in long-term ETP reservation using the DFS and in short-term service work-based ETP reservation compensates for the weakness resulting from the FRR property of the ETP and provides the ONU with the optimal ETP performance according to the dynamic changes of traffic load.

V. FAIRNESS AND EFFICIENCY ISSUES

In the proposed ETP mechanism, excess bandwidths are provided to greedy ONUs after serving every ONU by their service weights. The fair amount of bandwidth $(A_i^{\min})$ determined by a service weight, and the ONU queue state is derived as $\min(Q_i, A_i^{\min})$, as previously discussed. The DBA using the above comparison minimizes channel voids, while preventing bandwidth monopolization of a greedy ONU. After providing a minimal fair bandwidth to every ONU, the remaining cycle bandwidth (A^{ex}) has to be distributed only to backlog queues denoted by Ω in order to achieve a high efficiency of the ETP while maintaining fairness. Based on the definition of fairness, the fair ETP bandwidth for a greedy ONU_i is derived as [24]

$$A_i^{ex} = \begin{cases} Q_i - A_i^{\min}, & i \notin \Omega \\ \left(A^{\text{MAX}} - \sum_{j\in\Omega} A_j^{\min} - \sum_{j\notin\Omega} Q_j\right) \dfrac{\omega_i}{\sum\limits_{j\in\Omega} \omega_j}, & i \in \Omega \end{cases} \tag{16}$$

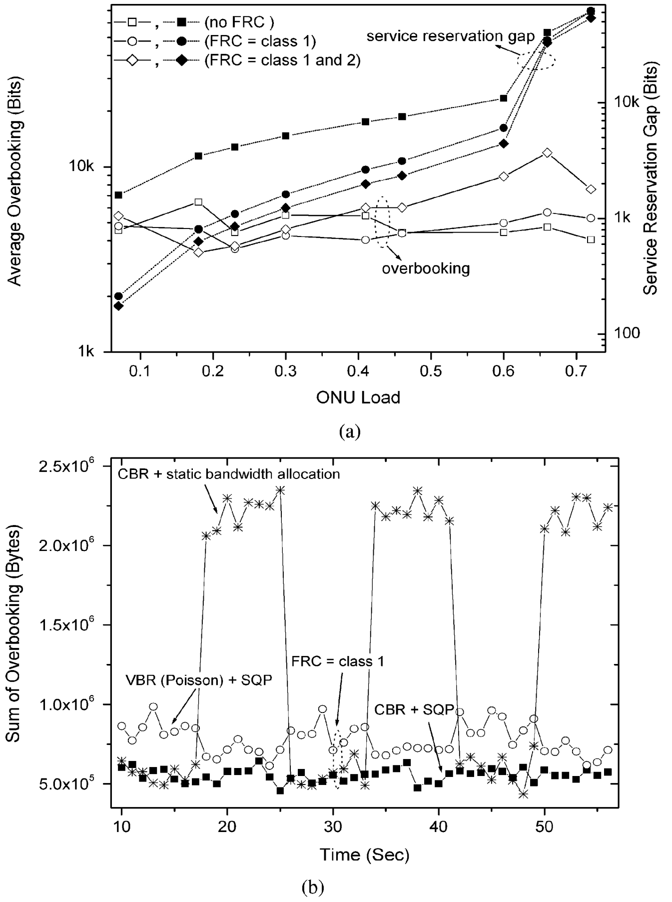
Provisioning of A_i^{ex} does not violate the fairness rule, because all nonbacklogged ONUs have already been entirely served in proportion to their service weights. The DBA using limited service guarantees perfect fairness since r_j is always zero, but a serious network light-load penalty has to be resolved.

The proposed dr-DBA guarantees greedy ONUs long-term fairness in reservation contentions using the reservation deficit. If a network load is low and unevenly distributed, fairness in a single cycle may decrease due to the full access service concentrated to a particular greedy ONU. However, the recursive determination of a reservation deficit prevents bandwidth monopolization, as previously proved, and excess bandwidth is ultimately allocated to greedy ONUs proportionally to their service weights during several cycles. At the same time, the high ETP efficiency in full access service is achieved without the network light-load penalty. Although fairness in the intra-ONU is not an issue in strict priority queuing, fairness in terms of allocation bandwidth versus reservation bandwidth remarkably increases by the SQP.

Efficiency in the ETP is an another important issue. First, efficiency in the intra-ONU is related with reduction of bandwidth preemption of the FRCs. The efficiency is more meaningful to nonpreemptive classes, since preemptive classes are not affected by an ETP bandwidth reservation. We can expect that the efficiency of the ETP increases as more classes are selected as the FRCs, but it is still feasible only within the feasible load range of the ETP. The efficiency in the inter-ONU is a critical performance issue. The efficiency of the dr-DBA in consecutive cycles is much higher than that of a normal DBA using limited service, since the dr-DBA can efficiently provide full access service to greedy ONUs. A cyclic excess bandwidth provisioning can increase efficiency and fairness in a heavy-loaded short epoch, but it cannot handle the changes in load distribution. Because the fairness and efficiency are related with short-term performance and depend not on the average load but on the specific load distribution, the real-time simulation results will be discussed in detail.

VI. SIMULATION RESULTS

A time-varying load distribution model in which load distribution over both ONUs and classes changes dynamically has been introduced in simulations to effectively validate the performance of proposed adaptive ETP mechanism. The numbers of ONUs, traffic classes, and homes attached to a single ONU are assumed to be 16, 8, and 24, respectively. Pareto distributed burst traffic source model $(\text{Hurst parameter} = 0.8)$ is introduced to testify the performance in terms of fair link sharing and full access service. The link speed is assumed to be 1.25 Gbps. Accordingly, the maximum ONU bandwidth, which is provided to a single ONU by limited service scheme $\rho^{\text{ONU,SLA}}$, is about 62.5 Mbps. The efficiency of the SQP in the intra-ONU scheduling and the effectiveness of the dr-DBA in terms of fair link sharing and full access service are basically verified by the performance comparison with the SP and normal bandwidth allocation mechanism, such as SBA, FCBA, and DBA of IPACT. To verify the performance focused on the effectiveness of excess bandwidth provisioning, overall performance is also compared with that of representative excess bandwidth allocation mechanism, such as DBA2 [12], IPACT–GE (the estimation factor in expectation of new packet arrivals, $\alpha = 1$) [18], and EB–DBA



(a)

(b)

Fig. 4. Performance of the SQP with DFS. (a) Average overbooking and (b) sum of overbooking during every second for an ONU $\mathrm{load} = 0.6$, class $1 = \mathrm{CBR}$ traffic (interarrival time $= 0.8$ ms and frame size $= 645$ byte) or VBR traffic, and $\mathrm{FRC} = \mathrm{class}\ 1$.

(the control gain in expectation, $\beta = 0.9$) [19] in both scheduling issues.

We can observe that the DFS guarantees optimal performance in FRC selection in Fig. 4(a). In this test, the optimal number of FRCs derived by the numerical analysis is 1. It is observed that the service reservation gap decreases remarkably by the excess bandwidth reservation if class 1 is selected as the FRC. Meanwhile, if class 2 is also selected as the FRC, which violates the analytic selection of the BC-test, the service reservation gap is almost the same and the overbooking increases. As a result, a channel utilization decreases due to bandwidth leaks and end-to-end delay increases due to increase in bandwidth reservation contentions at the OLT. The SQP guarantees a high efficiency in various traffic types, as shown in Fig. 4(b). In a case, class 1 is CBR traffic, and it is selected as the FRC, the overbooking in the SQP is always smaller than that of variable-bit-rate (VBR) traffic case. Although constant timeslot allocation sometimes guarantees the smallest overbooking for CBR traffic, GATE transmission has to be synchronized with the CBR traffic interval, and a large overbooking is easy to occur, as shown from 17 to 26.

The performance degradation resulting from the node light-load penalty is mitigated by the adaptive excess bandwidth reservation of the SQP using the DFS, as shown in Fig. 5.

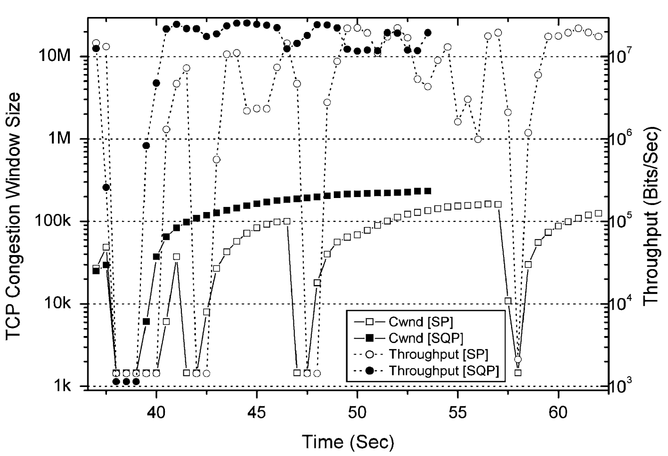
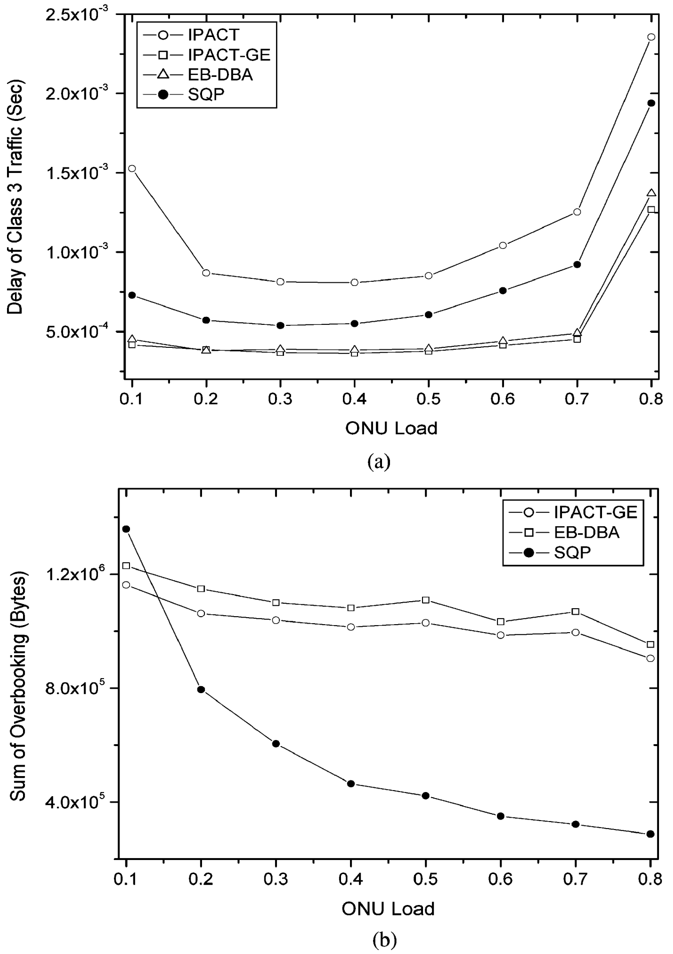


Fig. 5. Effect of the node light-load penalty on TCP traffic control.

In this test, file transfer using TCP is assumed to be the lowest priority class 3 traffic. It is observed that the congestion window size in the SP frequently increases due to a large round-trip time, resulting from the node light-load penalty, and entire file transmission takes a longtime, even though the network load is low ($\rho = 0.1$). Oppositely, file transmission is completed in a short time by the SQP, because the node light-load penalty is always minimized by providing excess bandwidths to preemptive classes.

The overall performance comparison in terms of mitigation of node light-load penalty is shown in Fig. 6(a). We note that the node light-load penalty rarely occurs in the SBA and the DBA2 because a remaining bandwidth is always distributed to the ONUs in proportion to service weight. It is observed that the severe node light-load penalty of the IPACT is efficiently mitigated in every excess bandwidth provisioning mechanism. The transmission delay of the SQP is larger than that of IPACT–GE or EB–DBA, because less bandwidth is provided to the ONU in general. However, it is not large and is still acceptable. The SQP using the DFS also resolves bandwidth overbooking problem, which is the major problem of the ETP mechanism, as shown in Fig. 6(b). Because the SQP applies excess bandwidth reservation to selected FRCs and adjusts the number of FRCs according to the change in class load distribution, continuous bandwidth overbooking is prevented. The overbooking decreases as the ONU load increases, since the amount of backlog data that can be transmitted by using an unused excess bandwidth increases. Meanwhile, IPACT–GE and EB–DBA reserve an excess bandwidth based on the proportional amount of traffic, which has arrived during a previous polling time and the history of queue size, respectively. Thus, overbooking easily occurs by the changes of traffic arrival rate and its distribution over traffic classes in every load range.

The performance of the dr-DBA in terms of full access service and fair link sharing is shown in Fig. 7. When the ONU loads of $\mathrm{ONU}_1, \mathrm{ONU}_3$, and ONU_5 are high, and the network load is low from 10 to 11, i.e., some ONUs are heavy loaded and an overall network load is low, large ETP bandwidths are provided to those up to $2\rho^{\mathrm{ONU,SLA}}$. This full access service improves the efficiency of dynamic bandwidth allocation for burst



(a)

(b)

Fig. 6. Performance comparison. (a) Delay of lowest priority class 3 traffic and (b) sum of overbooking bandwidths observed during 1 s.

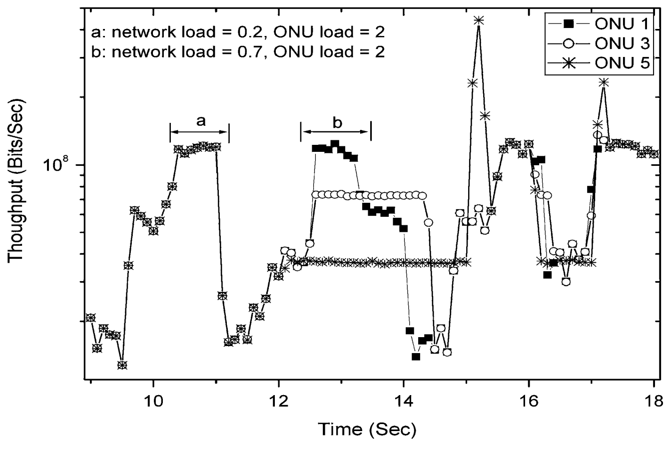


Fig. 7. ONU throughput in the dr-DBA ($\omega_1 : \omega_3 : \omega_5 = 3 : 2 : 1$).

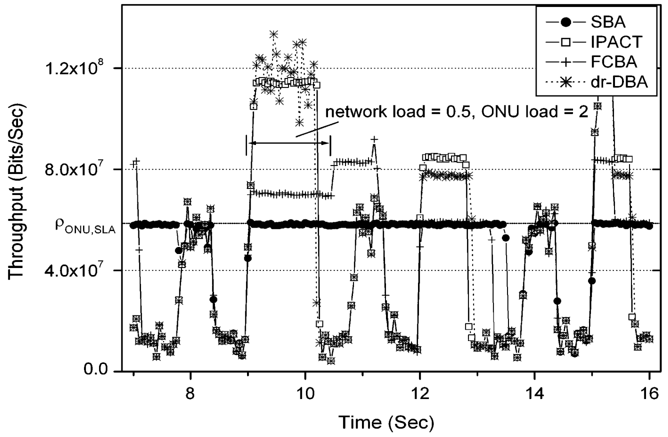
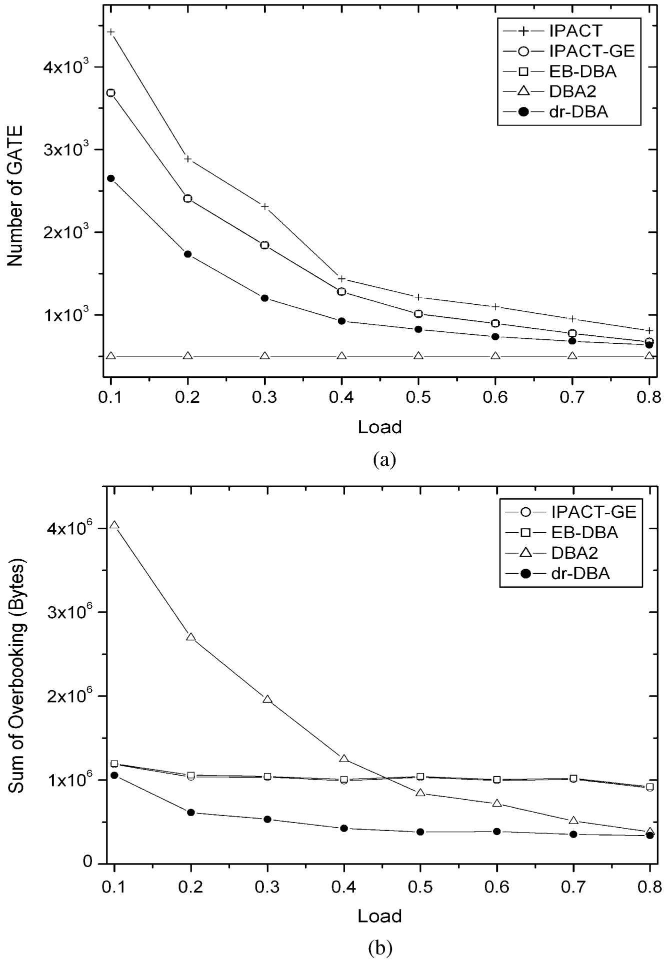


Fig. 8. Comparison of ONU throughput (same-weighted ONUs).



(a)

(b)

Fig. 9. Performance comparison. (a) Number of GATE message transmissions and (b) sum of overbooking bandwidths observed during 1 s.

traffic while minimizing the network light-load penalty. Conversely, when both an ONU load and a network load are high and bandwidth reservation contentions occur from 12.5 to 13.5, the ETP is deactivated and fair link sharing is strictly guaranteed in proportion to relative service weights of the ONUs.

The performance of the dr-DBA is compared with that of fundamental inter-ONU scheduling mechanism in Fig. 8. If the ONU load is $2\rho^{\mathrm{ONU,SLA}}$ and the network load is 0.5 from 9 to 10.5, the SBA limits the ONU throughput by $\rho^{\mathrm{ONU,SLA}}$. Although the FCBA provides more bandwidths to the ONUs, high throughput is not achieved, since a remaining bandwidth is distributed to the ONUs independent of load states. It is observed that both IPACT and dr-DBA provide full access service to greedy ONUs, but the dr-DBA minimizes the network light-load penalty as well.

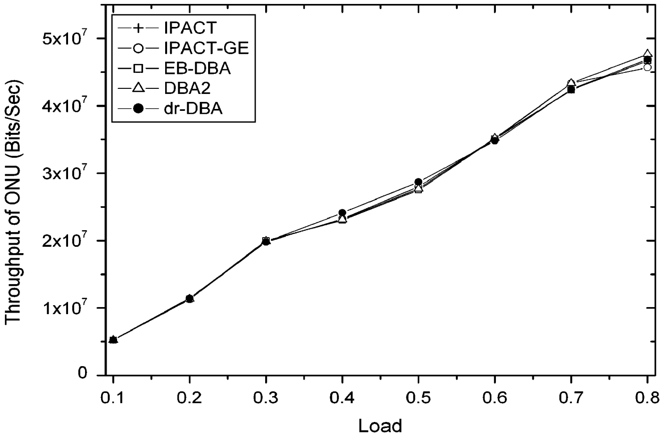


Fig. 10. Average ONU throughput.

The performance of dr-DBA using the SQP is compared with other excess bandwidth reservation mechanisms in Fig. 9(a). It is observed that the number of GATE transmission, which directly affects the network light-load penalty efficiently decreases in the dr-DBA. This is achieved by the full access service provided to the heavy-loaded ONUs and adaptive excess bandwidth reservation of the SQP. Because the IPACT–GE and EB–DBA limits the amount of excess bandwidths so that an entire timeslot bandwidth does not exceed the maximum ONU timeslot, capability of prevention of network light-load penalty is rather weak. The number of GATE transmission of the DBA2 is constant like the SBA, since an entire cycle bandwidth is distributed to the ONUs.

The dr-DBA using the SQP also decreases overbooking bandwidth in the inter-ONU scheduling, as shown in Fig. 9(b). Because the SQP reserves excess bandwidth based on the class load distribution, and the dr-DBA provides excess bandwidths to heavy-loaded ONUs considering the network load, overbooking is always minimized. In the cases of IPACT–GE and EB-DBA, overbooking occurs easily due to the high dependency on the entire backlog queue history or observed traffic rate, which changes dynamically in heavy-loaded ONUs and intra-ONU traffic classes. The overbooking bandwidth observed in the DBA2 decreases as the load increases because increased backlog traffic can be transmitted by an unused bandwidth, as previously discussed. Because timeslot bandwidth is mainly determined by the network load although its distribution over the ONUs changes, an average throughput is the same in every excess bandwidth allocation mechanism, as shown in Fig. 10.

VII. CONCLUSION

We have dealt with the effectiveness of the ETP in inter-ONU scheduling and intra-ONU scheduling in order to improve the performance of a reservation-based TDM in TDM–PONs. First, the feasible load range of the ETP has been analyzed, and noble ETP mechanisms have been proposed. The proposed dr-DBA controls the maximum excess timeslot bandwidth adaptively based on the static service weights and time-varying load distribution over the ONUs. By adaptive ETP bandwidth allocation using a deficit reservation, an entire cycle bandwidth is efficiently distributed to the ONUs according to ONU traffic load status so that large excess bandwidths are provided to heavy-loaded ONUs, while guaranteeing strict fair link sharing if bandwidth reservation contention occurs. In accordance with the adaptive ETP bandwidth allocation of the dr-DBA, the proposed SQP mechanism reserves optimal excess bandwidth based on the service works of selected classes in given traffic loads of classes and improves the performance of differentiated service in the intra-ONU. To minimize the timeslot overbooking and service reservation gap in the SQP, a logical cumulative load of bounded FRCs is derived, and the detailed operations of the DFS mechanism are dealt with as well. The efficiency of the proposed mechanisms has been validated using a variety of simulation results.

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