Limited sharing with traffic prediction for dynamic bandwidth allocation and QoS provisioning over Ethernet passive optical networks

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As an inexpensive, simple, and scalable solution for broadband access, Ethernet passive optical networks (EPONs) have the capability of delivering integrated broadband services to the end users. A critical issue of EPONs is the utility of a shared upstream channel among the local users, and thus an efficient bandwidth allocation mechanism is required to facilitate statistical multiplexing among the local network traffic. In this paper we propose a dynamic bandwidth allocation scheme, i.e., limited sharing with traffic prediction (LSTP), for upstream channel sharing over EPONs. LSTP enables dynamic bandwidth negotiation between the optical line terminal (OLT) and its associated optical network units (ONUs), alleviates data delay by predicting the traffic arrived during the waiting time and prereserving a portion of bandwidth for delivery, and avoids the aggressive bandwidth competition by upper bounding the allocated bandwidth to each ONU. Theoretical analysis and simulation results verify the feasibility of LSTP by showing that LSTP outperforms other existing schemes with respect to QoS metrics of data delay and data loss. © 2005 Optical Society of America

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1. Introduction

With the expansion of services offered over the Internet, a dramatic increase of bandwidth has been fueled in the backbone network through the use of wavelength division multiplexing, providing tens of gigabits per second per wavelength. At the same time, the local area networks (LANs) have been scaled up from 10 to 100 Mbits/s and are being upgraded to gigabits per second. Such a growing gap between the capacity of the backbone network and the end users' needs results in a serious bottleneck of the access network in between [1], the so-called first mile or last mile problem. As an inexpensive, simple, and scalable solution for broadband access, EPONs have the capability of delivering integrated broadband services. With the recent approval of the IEEE standard 802.3ah [2], EPONs are an attractive and promising solution to the high-speed broadband subscriber access network.

Compared with the current access network technologies, such as the digital subscriber line (DSL) and a hybrid fiber coaxial (HFC), EPONs lower the cost of network deployment and maintenance by eliminating the necessity to install multiplexers and demultiplexers, replacing the active electronic components with the less expensive passive optical splitters. In addition, EPONs cover longer distances from the service provider central offices to the customer sites and provide up to1.25 Gbits/s symmetric bandwidth. With data encapsulated in IEEE 802.3 Ethernet frames, EPONs rely on the ubiquitous Ethernet technology, which is inexpensive and interoperable with legacy equipment. As illustrated in Fig. 1, a typical EPON consists of one optical line terminal (OLT), which is located at the provider's central office, and 16 associated optical network units (ONUs), which deliver data to the end users. A single fiber extends from the OLT to a 1:16 passive optical splitter, fanning out 16 single fiber drops to connect to different ONUs.

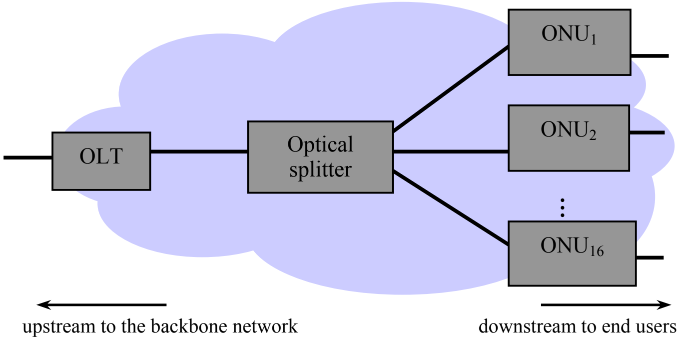

Fig. 1. Ethernet passive optical network.

The broadcasting nature of Ethernet perfectly matches the EPON downstream transmission. Ethernet frames are broadcast from the OLT downstream to the multiple associated ONUs by use of the entire bandwidth of the downstream channel. ONUs filter the frames destined to themselves by matching the destination addresses encapsulated in the Ethernet frames. The process of transporting data upstream to the OLT over EPONs is different from that of transporting data downstream to the end users. In the upstream direction, another wavelength is employed for the upstream traffic, and multiple ONUs share this common upstream channel. Therefore, only a single ONU may transmit during a time slot to avoid data collisions. Ethernet frames from local users would be first buffered at an ONU until the exclusively assigned time slot arrives. The buffered frames would burst out to the OLT in the time slot at the full channel speed. To improve the access network efficiency, the bandwidth management of the upstream channel is a critical issue for the successful implementation of EPONs.

Intensive research endeavors have been devoted to dynamic bandwidth allocation (DBA) over EPONs, and typical schemes are fixed bandwidth allocation (FBA) [3], limited bandwidth allocation (LBA) [3], and excessive bandwidth reallocation (EBR) [4]. FBA works exactly like time division multiple access (TDMA) by granting each ONU a fixed time slot length in each service cycle. The time slot of each ONU is predecided and fixed without considering the on-line traffic dynamics. Even though it is easy to implement, the major disadvantages of FBA include low bandwidth utilization, long data delay, and heavy data loss. An ONU will occupy the upstream channel for its assigned time slot even if it has no data to transmit, thus resulting in an increased delay for all the data buffered in other ONUs, and underutilization of the upstream channel is inevitable. LBA tracks the traffic load by adopting the control messages defined in Multipoint Control Protocol (MPCP) [2] to facilitate bandwidth negotiation. The granted time slot length varies according to the dynamic traffic, and the time slot length is upper bounded by the parameter in service level agreements (SLAs). Its major disadvantages include deferred service for the Ethernet frames that arrive during the waiting time (as will be investigated in Section 2). Extended from LBA, EBR exploits the leftover bandwidth from the lightly loaded ONUs by redistributing it among the heavily loaded ONUs. Therefore, each heavily loaded ONU could obtain an additional bandwidth to facilitate its upward data delivery. To redistribute the excessive bandwidth, the OLT grants the lightly loaded ONUs instantaneously while deferring the grants for heavily loaded ONUs until all the bandwidth reports have been collected, and therefore the Ethernet frames at the heavily loaded ONUs suffer longer delays and heavier losses. Other proposals, such as the bandwidth guaranteed polling (BGP) approach [5], the deterministic effective bandwidth (DEB) approach [6], and the decentralized architecture [7], are either incompatible with the IEEE standard 802.3ah or impractical because of the high complexity and significant overhead.

Most importantly, however, QoS metrics, such as data delay and data loss, have only been addressed in the above studies from an experimental aspect, and no theoretical analysis has been conducted to justify their performance. Here we propose a bandwidth management scheme, called limited sharing with traffic prediction (LSTP), to tackle the DBA issue over EPONs. Our proposal has the following characteristics: First, we enable dynamic bandwidth negotiation by employing the control messages in MPCP, implying that the LSTP scheme is seamlessly compatible with the IEEE standard 802.3ah. Second, online traffic prediction is facilitated based on network traffic self-similarity, and data delay is thus reduced by allocating flexible time slots dynamically. Third, the aggressive bandwidth competition among multiple ONUs is restricted by upper bounding the allocated bandwidth to each ONU. Fourth, improved QoS provisioning is achieved by reducing the data loss in the upstream transmission. Preliminary results were first presented at two conferences [8] and [9], with that in Ref. [8] focused on data delay control and that in Ref. [9] targeted on service differentiation. We have obtained further results; in particular, we conducted an in-depth theoretical analysis of QoS provisioning.

The rest of the paper is organized as follows. The effect of the deferred Ethernet frames is investigated in Section 2, followed by an investigation of the proposed LSTP scheme in Section 3. In Section 4 we evaluate the system performance by theoretical analysis and simulation comparisons. Conclusions are drawn in Section 5.

2. Deferred Data

Figure 2 illustrates the bandwidth negotiation in LBA. The exemplified EPON consists of one OLT and two ONUs. The upstream transmission from ONUs to the OLT is facilitated by the assignment of dedicated time slots to different ONUs. Each ONU transmits buffered data to the OLT in its exclusively assigned time slot. A REPORT [2] message is sent by an ONU to the OLT, indicating the number of data enqueued at the ONU buffer. After processing the report, a GATE [2] message is replied by the OLT to the ONU, informing the ONU when to transmit and for how long it will transmit. When the assigned time slot arrives, the buffered data would burst out from the ONU to the OLT at the full upstream channel speed.

The service interval of an ONU is the time between its data transmission. For example, as shown in Fig. 2, a service interval, say n, with respect to ONU$_1$, ranges from time t_1 to time t_6. Service interval $(n+1)$ of ONU$_1$ begins at time t_6, and the granted time slot from time t_6 to time t_8 is decided on the REPORT message sent at time t_2. With respect to ONU$_2$, service interval n begins at time t_3 and ends at time t_9. Time t_3 to time t_5 is the exclusive time slot assigned to ONU$_2$. Time t_5 to time t_9 is the waiting time of ONU$_2$ in service interval n, during which more data arrive at ONU$_2$. The two consecutive service cycles are from time t_1 to time t_5 and from time t_6 to time t_{11}.

During the time of bandwidth negotiation, each ONU experiences a waiting time, which ranges from sending the bandwidth requirement to sending the buffered data. More data will be enqueued at the buffer during the waiting time. As exemplified in Fig. 2, time t_2 to time t_6 is the waiting time of ONU$_1$ in service interval n, and time t_5 to time t_9 is the waiting time of ONU$_2$ in service interval n. If the reported bandwidth requirement does not include the incoming data, they cannot be transmitted in the next time slot even if the upstream channel is lightly loaded and have to be deferred by at least one more service interval. The deferred data will eventually result in data loss when the buffer overflows.

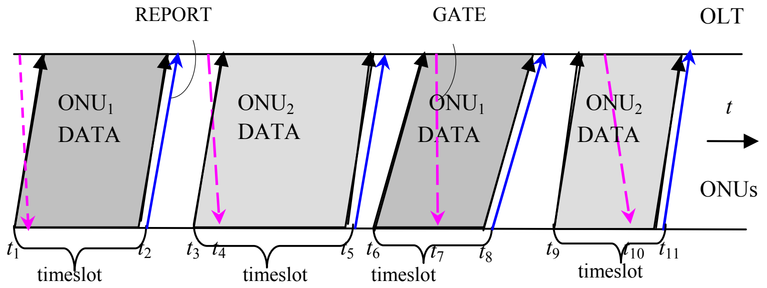

Fig. 2. Bandwidth negotiation and waiting time.

Simulations are conducted to investigate the effect of the deferred data that arrived during the waiting time. B^w denotes the traffic in bytes arrived during the waiting time. B^q represents the enqueued traffic in bytes when sending a REPORT message. Two ONUs and one OLT, as shown in Fig. 2, are deployed in the experiment, and the input trace is self-similar with the Hurst parameter $H = 0.8$. Figure 3 shows the deferral index, which is defined as the ratio of B^w/B^q at ONU_1 in different service intervals. It is observed that in each service interval, data do arrive during the waiting time, and the deferral index mostly falls in the range of 0.4–0.8. Without reporting these data, around 29–44% traffic in bytes arrived during a service interval that must be deferred for at least one more service interval, thus suffering extra delay. Under the constraint of limited buffer size, data must be dropped once the buffer overflows. For example, two bursts arrived at ONU_1 during the waiting time of service interval 28 and 66 result in the soaring of the deferral index. It is almost impossible to hold the huge number of bytes of the bursts at a limited buffer while more data continue to arrive, and thereby data loss due to inevitable dropping.

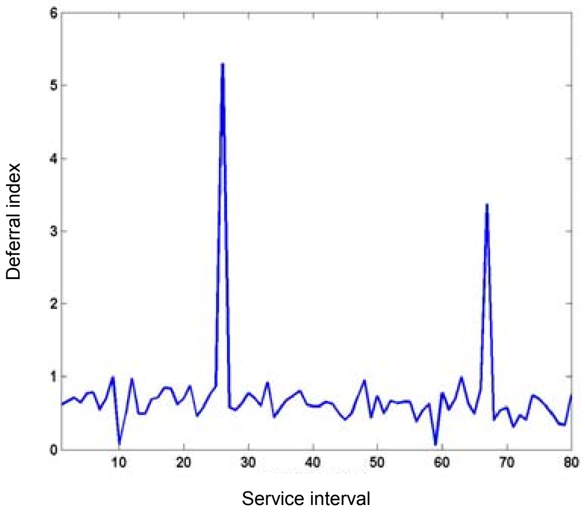

Fig. 3. Deferred data arrived during the waiting time.

3. Limited Sharing with Traffic Prediction Scheme

To alleviate the extra delay experienced by the deferred data, our intuitive idea based on the observation described in Section 2 is that, rather than indicating only the already enqueued data, the bandwidth requirement should consider the incoming data arrived during the waiting time and thereby minimize the effect on the data delay and data loss. Motivated by this, the LSTP scheme embeds the bandwidth requirement of an ONU for the next time slot in a REPORT message, which is piggybacked at the end of the current time slot. Instead of reporting the current queue length, LSTP adds a prediction in the requirement, by considering the incoming data that arrived during the waiting time. The LSTP scheme involves the following.

3.A. Bandwidth Negotiation

Bandwidth negotiation between the OLT and the ONUs is facilitated by employing the control message-aided process as illustrated in Fig. 2. Each ONU requests its next transmission by piggybacking a REPORT message at the end of its current time slot. Instead of reporting the actually buffered data as in LBA and EBR, the REPORT message in LSTP includes a prediction of the data that arrived during the waiting time, with the purpose of enabling delay reduction over the upstream data transmission.

Different from LBA and EBR, the OLT makes the bandwidth allocation decision without collecting the queue status information from all its associated ONUs. A GATE message is then replied downstream to the ONU, containing the information of time slot start time and time slot length. The destined ONU updates its local registers accordingly, and transmits data from the time slot start time in the time slot length. No data fragmentation is allowed within a time slot, and the unfit Ethernet frame will be deferred to the next time slot.

3.B. Bandwidth Prediction at an ONU

When reporting the bandwidth request, an ONU predicts the incoming traffic in bytes arrived during the waiting time based on the actually arrived traffic in previous service intervals. The intuition behind this prediction is the network traffic self-similarity [10], which implies that the actual network traffic exhibits long-range dependence (LRD), and the burstiness of the traffic does not decrease with the time scale from which the traffic is observed or with the amount of multiplexing that occurs at a node. Owing to the self-similarity, the correlation in network traffic does not decay rapidly, and traffic is correlated among time slots. An efficient way to alleviate the delay and loss caused by traffic burstiness is to predict the incoming traffic and prereserve the network resource [11]. With the advantages of low computational complexity, fast convergence, and no prior knowledge of the traffic statistics, the linear predictor (LP) is deemed a practical tool to conduct the on-line traffic prediction [11–13].

In the LSTP scheme, an ONU predicts the data arrived during the waiting time in terms of bandwidth as

$$\hat{B}_i^w(n+1) = \sum_{k=0}^{L-1} \alpha_{i,k}(n)\, B_i^w(n-k)\,. \tag{1}$$

In Eq. (1), the output predicted quantity $\hat{B}_i^w(n+1)$ is a linear function of the observations $B_i^w(n)$ in previous service intervals. L is the order of the traffic predictor. $\alpha_{i,k}(n)$ is the weight factor of the predictor, indicating the effect of the observations on the output predicted result. The weight factor is determined by the traffic pattern, and is adjusted by the least-mean square (LMS) algorithm [14] as

$$\alpha_{i,k}(n+1) = \alpha_{i,k}(n) + \mu(n)\frac{e_i(n)}{B_i^w(n)}, \tag{2}$$

where $\mu(n)$ is the step size, $e_i(n)$ is the prediction error, and

$$e_i(n) = B_i^w(n) - \hat{B}_i^w(n). \tag{3}$$

The update of the weight factor in LSTP is an adaptive process that enhances the bandwidth prediction in Eq. (1) especially in the environment where complete knowledge of the incoming traffic statistics is not available [14]. The predicted incoming traffic in bytes, $\hat{B}_i^w(n)$, if optimal, should be equal to the actually arrived traffic in bytes during the waiting time, $B_i^w(n)$. Owing to the imperfection of the predictor, the predicted results could turn out to be smaller or larger than the actual results. The prediction error in Eq. (3) is thus employed to adjust the weight factor $\alpha_{i,k}(n)$ adaptively, with the intention to improve the prediction accuracy.

In service interval n, ONU$_i$ requests its bandwidth for service interval $(n+1)$ by sending a REPORT message to the OLT. The reported bandwidth request is the sum of the enqueued data $B_i^q(n)$ and the prediction $\hat{B}_i^w(n+1)$, i.e.,

$$B_i^r(n+1) = B_i^q(n) + \hat{B}_i^w(n+1). \tag{4}$$

3.C. Bandwidth Arbitration at the Optical Line Terminal

The OLT instantaneously makes the bandwidth allocation decision after having received a report. The granted bandwidth to ONU$_i$ for service interval $(n+1)$ is

$$B_i^g(n+1) = \min\{B_i^r(n+1), B_i^{\max}\}, \tag{5}$$

where $B_i^{\max}$ is the maximum time slot length in bytes of ONU$_i$, a parameter specified in the SLA. The bandwidth allocated to ONU$_i$ is upper bounded by the smaller value of the bandwidth request $B_i^r(n+1)$, which is included in the REPORT message sent by ONU$_i$, and the maximum time slot length $B_i^{\max}$, which is specified in the contract between the service provider and the customer. When the bandwidth request is no more than the maximum time slot length, an ONU is called underloaded. The assigned bandwidth to an underloaded ONU dynamically changes depending on the on-line traffic. A portion of the upstream bandwidth is prereserved to transmit the traffic arrived during the waiting time, thus dramatically alleviating the traffic deferral phenomenon. When the bandwidth request is more than the maximum time slot length, an ONU is called overloaded. In this case, the ONU violates the agreed SLA. Therefore, $B_i^{\max}$ is employed as an upper bound, limiting the aggressive competition for the upstream bandwidth and ensuring data transmission of the underloaded ONUs. After receiving the GATE message from the OLT, the ONU updates its local clock and programs the local registers with the grant start time and the grant length values. When its dedicated time slot comes, the ONU bursts out its data to the OLT without contention from other ONUs.

4. Performance Analysis and Simulation Results

The LSTP scheme performance is evaluated by theoretical analysis and simulation results. Performance metrics include delay reduction and data loss. The contributions of traffic prediction are the focus of our performance analysis. For notational simplicity, we omit referencing the service interval in the following analysis.

4.A. Success Probability of Prediction

The traffic prediction at an ONU fails if the actually arrived traffic during the waiting time is larger than the predicted one, i.e., $e_i = B_i^w - \hat{B}_i^w > 0$. Otherwise, the traffic prediction at the ONU is said to succeed. There are two subcases of the successful prediction: (1) the actual arrived traffic is equal to the predicted one, and (2) the actual arrived traffic is less than the prediction. The incoming traffic during the waiting time could be delivered in the next time slot in both subcases, given that the request is less than or equal to the SLA parameter. Traffic prediction is said to be successful if $e_i = B_i^w - \hat{B}_i^w \leq 0$. Therefore, the success probability of traffic prediction is $P_i^s = P\{e_i \leq 0\}$.

The LMS algorithm in LSTP has employed the traffic correlation information, and thus the prediction error is approximately uncorrelated. It was also found by numerous simulations that the autocorrelation of the LMS algorithm prediction error for self-similar network traffic is close to that of the Gaussian, a rather uncorrelated process [15, 16]. Hence, the error of the LMS-based adaptive predictor can be assumed to be Gaussian [17] with mean m_i and variance σ_i^2; the success probability of bandwidth prediction is thus

$$P_i^s = P\{e_i \leq 0\} = \frac{1}{\sqrt{2\pi}\sigma_i}\int_{-\infty}^{0} e^{-(x-m_i)^2/2\sigma_i^2}\,dx = Q\left(\frac{m_i}{\sigma_i}\right). \tag{6}$$

The probability that the prediction fails is $P_i^f = 1 - P_i^s$. The inherent property of the Q function [17] implies that the success probability of prediction relies on the prediction error. When m_i decreases, the ONU requests a more upstream bandwidth to transmit the data arrived during the waiting time, and it is more likely that the data arrived during the waiting time can be delivered in the following time slot.

4.B. Data Delay Reduction

Data delay is defined as the average time from enqueuing an Ethernet frame at an ONU buffer to completely transmitting the last bit of the Ethernet frame to the OLT. In the following we focus on the delay of the Ethernet frames arrived during the waiting time. In LSTP, such delay differs according to the prediction result and the OLT bandwidth arbitration. When the prediction succeeds, i.e., $e_i = B_i^w - \hat{B}_i^w \leq 0$, and the assigned bandwidth is the requested value, i.e., $B_i^g = B_i^r$, the allocated time slot is enough to transfer the incoming data, and thus the delay is determined by the service interval length. Assume t_{int} is the average service interval length, and γ is the holding index $(0 < \gamma < 1)$, which is the ratio of the waiting time to the service interval; the delay in the above case is γt_{int}. On the other hand, when the traffic prediction fails, i.e., $e_i = B_i^w - \hat{B}_i^w > 0$, or when the assigned bandwidth is less than the request, i.e., $B_i^g < B_i^r$, the data arrived during the waiting time have to wait for one more service interval to be delivered. The corresponding delay is $(1+\gamma)\,t_{\text{int}}$.

Combining both of the above cases, the average delay of the data arrived during the waiting time becomes

$$D_i = P_i^s P\left\{B_i^g = B_i^r\right\}\gamma t_{\text{int}} + \left(1 - P_i^s P\left\{B_i^g = B_i^r\right\}\right)(1+\gamma)\,t_{\text{int}}. \tag{7}$$

$B_i^g = B_i^r$ occurs when the maximum time slot length is no less than the bandwidth request, i.e., when $B_i^{\max} \geq B_i^r$. Therefore, $P\left\{B_i^g = B_i^r\right\}$ can be further deduced to

$$\begin{aligned} P\left\{B_i^g = B_i^r\right\} &= P\left\{B_i^{\max} \geq B_i^r\right\} = P\left\{B_i^{\max} \geq B_i^q + \hat{B}_i^w\right\} \\ &= P\left\{e_i \geq B_i^q + B_i^w - B_i^{\max}\right\} = Q\left(\frac{B_i^q + B_i^w - B_i^{\max} - m_i}{\sigma_i}\right), \end{aligned} \tag{8}$$

where B_i^q is the enqueued traffic in bytes when ONU$_i$ sends the REPORT message to the OLT. Let $A = Q(m_i/\sigma_i)\,Q\left(B_i^q + B_i^w - B_i^{\max} - m_i/\sigma_i\right)$, and combining Eqs. (6), (7), (8), the average delay becomes

$$D_i = A\gamma t_{\mathrm{int}} + (1-A)\,(1+\gamma)\,t_{\mathrm{int}} = (1+\gamma)\,t_{\mathrm{int}} - At_{\mathrm{int}}. \tag{9}$$

Figure 4 illustrates the numerical results of the average delay when $\gamma = 0.5$. D_i increases as t_{int} increases. Increasing P_i^s leads to a larger value of A, and thus a decreased D_i implies that increasing the success probability of prediction decreases the average delay. As compared to a system without traffic prediction, LSTP improves the frame delay of the frames arrived in the waiting time by

$$\beta = \frac{D_{\text{no prediction}} - D_i}{D_{\text{no prediction}}} = \frac{(1+\gamma)\,t_{\mathrm{int}} - [(1+\gamma)\,t_{\mathrm{int}} - At_{\mathrm{int}}]}{(1+\gamma)\,t_{\mathrm{int}}} = \frac{A}{1+\gamma}. \tag{10}$$

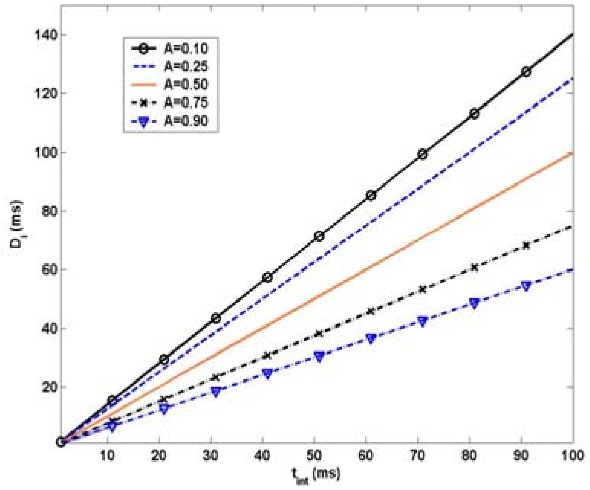

Fig. 4. Average data delay versus t_{int}, $\gamma = 0.5$.

The delay reduction relies on A [8]. In an optimum case, when the prediction succeeds and the assigned bandwidth equals the requested value, $A = 1$, and the maximum delay reduction of $1/1+\gamma$ is thus achieved. In the case of no traffic prediction, $A = 0$; the data arrived during the waiting time are held at the buffer for one more service interval, and thus $\beta = 0$. Increasing the success probability of prediction results in a larger value of A, and therefore a higher delay reduction is achieved.

4.C. Data Loss Control

As mentioned before, an Ethernet frame experiences loss if the ONU buffer is full. Assume that the fixed buffer size at ONU$_i$ is C$_i$ and the data loss probability is $P_i^{\text{loss}} = P\left\{B_i^w + B_i^q > C_i\right\}$. The data loss probability is then

$$\begin{aligned} P_i^{\text{loss}} &= P\left\{B_i^w - \hat{B}_i^w + B_i^q > C_i - \hat{B}_i^w\right\} \\ &= P\left\{e_i > C_i - \hat{B}_i^w - B_i^q\right\} = Q\left(\frac{C_i - \hat{B}_i^w - B_i^q - m_i}{\sigma_i}\right), \end{aligned} \tag{11}$$

where m_i, σ_i, and $\hat{B}_i^w$ are determined by the traffic predictor, and B_i^q is determined by the traffic load. Since the Q function decreases monotonically, two properties can be deduced from Eq. (11): First, decreasing m_i reduces the data loss probability; second, decreasing σ_i also decreases the data loss.

Numerical results of the two properties are illustrated in Figs. 5, 6. The effect of m_i and σ_i on the data loss indicates the contribution of traffic prediction to the data loss control in the LSTP scheme. When m_i decreases, the ONU requests a more upstream bandwidth to transmit the data arrived during the waiting time, and thus data loss that is due to buffer overflow is reduced. When σ_i decreases, the prediction error varies over a relatively smaller range, and the predictor unlikely underestimates the data arrived during the waiting time, thereby resulting in less data loss. In an extreme case, when no traffic prediction is employed, $\hat{B}_i^w = 0$ and $e_i = B_i^w$, then m_i and σ_i essentially are the mean and the standard deviation of B_i^w, which are much larger than the ones with traffic prediction in LSTP. Therefore, an EPON without traffic prediction suffers much heavier data loss in comparison with an EPON with LSTP.

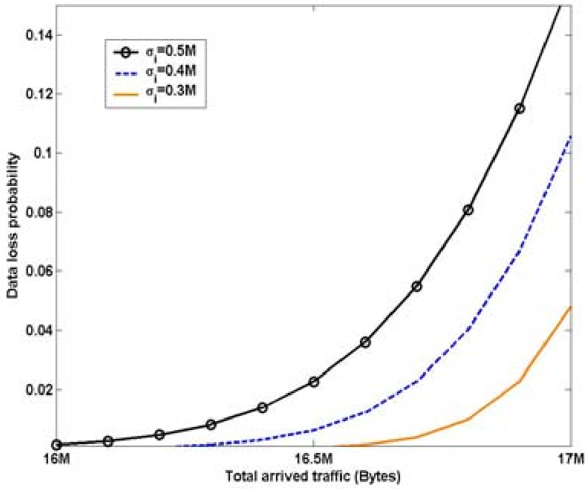

Fig. 5. Data loss versus traffic load $C_i = 20\,\text{M}$ and $\sigma_i = 1\,\text{M}$.

The data loss is also determined by the traffic load. Given a fixed buffer size and a known traffic predictor, the data loss increases as the traffic load, i.e., B_i^q, increases. This implies that, when the traffic load is heavy, more data are enqueued when sending the REPORT message, and more likely the buffer is fully occupied before the assigned time slot arrives, thus resulting in heavier data loss. As the mean and variance of the prediction error decrease, more data could be accommodated by a given fixed buffer and the data loss is thus reduced.

4.D. Simulations

Besides the above theoretical analysis, the LSTP scheme performance is evaluated by use of experimental results. A system model shown in Fig. 1 is set up in the OPNET simulator with one OLT and 16 ONUs. The distance from an ONU to the OLT is assumed to be from 10 to 20 km. Each ONU has a finite buffer of 20 Mbytes, and the downstream and upstream channels are both 1.25 Gbits/s. The length of Ethernet frames randomly varies from 64 to 1518 bytes [9]. The incoming traffic is self-similar with the Hurst parameter of 0.8. The total traffic load of the network, defined as the ratio of the average arrival to the service rate, changes from 0.1 to 0.8. For comparison purposes, we applied FBA, LBA, EBR, and our proposed LSTP scheme on this system model. Östring and Sirisena [11] considered the prediction of self-similar traffic and demonstrated that the long-range dependence has only marginal value in improving prediction. It is the short-term correlation within the structure of a self-similar process rather than the long-term correlation that dominates the performance of the predictors. Therefore, the order of the predictor in LSTP is set to be 4, and step size μ is set by $\mu(n) = L/\sum_{k=0}^{L-1}\left[B_{i,c}^{w}(n-k)\right]^2$ [14].

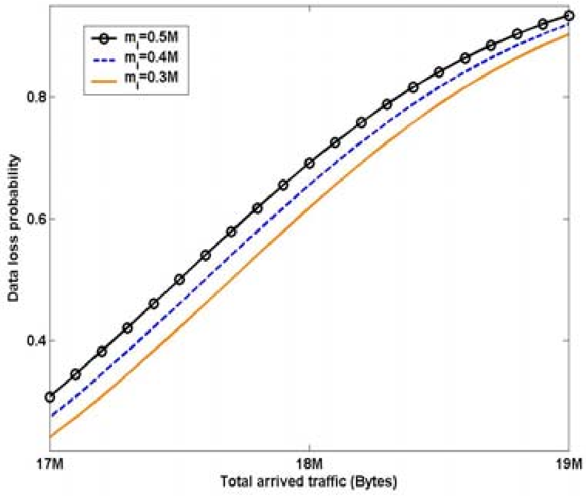

Fig. 6. Data loss versus traffic load $C_i = 20\,\mathrm{M}$ and $m_i = 0.5\,\mathrm{M}$.

The figures of merit are the data delay and data loss. As shown in Fig. 7, FBA experiences the longest delay, which is attributed to the fact that FBA disregards the dynamics of the incoming traffic, and thus, more data are likely deferred to one more extra service interval. LBA alleviates this problem by accommodating the REPORT and the GATE messages to keep track of the incoming traffic. EBR redistributes the underexploited bandwidth of the lightly loaded ONUs among the heavily loaded ones, and thereby alleviates the average data delay.

Figure 8 illustrates the relationship between the data loss probability and the network traffic load. The data loss probability is defined as the number of dropped frames versus the total number of incoming frames. FBA experiences the heaviest frame loss, which is attributed to the fact that FBA disregards the dynamics of the incoming traffic, and thus more frames are likely deferred to one more service interval. Even at the load of 0.4, the frame loss probability is very high (approximately 10%). This is attributed to the traffic burst nature, and most data arrive in bursts. The number of frames in a burst is so large that the local buffer at an ONU overflows, and approximately 10% of the frames is dropped. LBA alleviates this problem by keeping track of the incoming traffic. EBR redistributes the underexploited bandwidth of the lightly loaded ONUs among the heavily loaded ones, and thereby alleviates the frame loss of the heavily loaded ONUs. LSTP outperforms all three of the above mechanisms.

Several points contribute to the performance improvement in LSTP. First, LSTP predicts the traffic arrived during the waiting time, and prereserves bandwidth to transmit them in the next time slot that dramatically reduces the possibility of buffer overflow. Second, LSTP implements the fixed ONU service order instead of the dynamic service order in EBR and reduces the drastic change of the service interval length of an ONU in EBR, thus facilitating the traffic prediction. Third, the OLT responds to each ONU's bandwidth request instantaneously in LSTP. In EBR, the heavily loaded ONUs are always served after the lightly loaded ones, and the deferred service for the heavily loaded ONUs results in a longer delay of the incoming data.

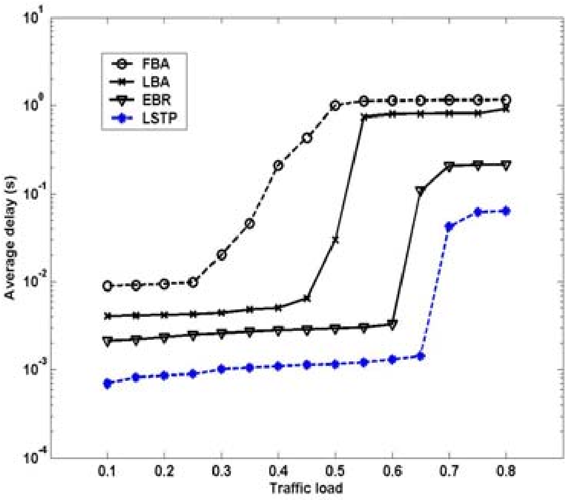

Fig. 7. Simulations on data delay.

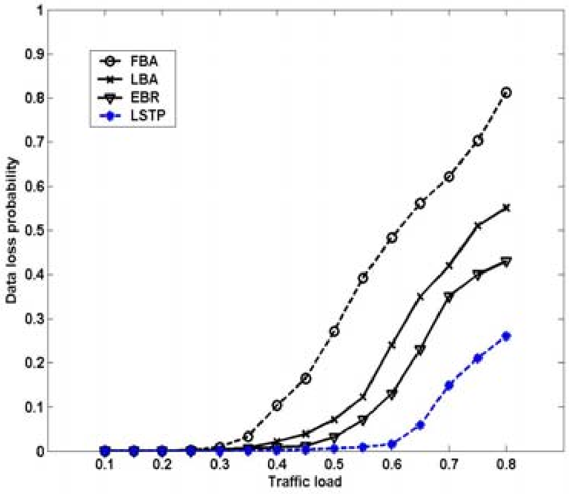

Fig. 8. Simulations on data loss.

5. Conclusions

We have investigated the dynamic bandwidth allocation issue of the upstream channel over EPONs. Our proposed LSTP scheme enhances the upstream bandwidth sharing among ONUs by means of traffic prediction and SLA-based upper-bounded bandwidth allocation. The performance of LSTP has been theoretically analyzed in terms of the prediction success probability, the delay reduction, and the data loss probability. The contributions of employing traffic predictor for QoS provisioning have been justified by the performance improvement. The experimental results also demonstrate that LSTP enhances the accuracy of the prediction of the incoming data during the waiting time, and the improved traffic prediction thus contributes to the reduction of data delay and data loss.

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