Evaluation of Burst Retransmission in Optical Burst-Switched Networks

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Abstract— **In this paper, we evaluate the performance of a burst retransmission scheme in which the bursts lost due to contentions in an OBS network are retransmitted at the OBS layer. The retransmission scheme aims to reduce burst loss probability in OBS networks. We develop an analytical model for obtaining the burst loss probability over an OBS network that uses the retransmission scheme. We also compare the performance of the burst retransmission scheme with the deflection scheme. Simulation results also show that at a moderate traffic load, the retransmission scheme provides an improvement of up to four times the burst loss probability with the deflection scheme. Results also show that the retransmission scheme significantly improves the burst loss probability compared to an OBS network without the retransmission scheme.**

I. INTRODUCTION

Optical Burst Switching (OBS) [1] is a promising switching technology that efficiently utilizes the raw bandwidth provided by dense wavelength division multiplexing (DWDM), and at the same time, avoids the need for optical buffering while handling bursty traffic. OBS is expected to support the dramatically increasing bandwidth demands of the Internet backbone. In an OBS network, a data burst consisting of multiple IP packets is switched through the network all-optically. A *Burst Header Packet* (BHP) is transmitted ahead of the burst in order to reserve the data channel and configure the switches along the burst's route. In the *Just-Enough-Time* (JET) signaling scheme [1], the burst transmission follows an out-of-band BHP after a predetermined offset time. The offset time allows the BHP to be processed before the burst arrives at the intermediate nodes; thus, the burst does not need to be delayed at the intermediate nodes. The BHP also specifies the duration of the burst in order to let a node know when it may reconfigure its switch for the next arriving burst. Also, other OBS signaling techniques, such as just-in-time (JIT) [2], [3] are implemented in a one-way unacknowledged manner.

Due to the bufferless nature of OBS core network and the one-way based signaling scheme, the OBS network suffers from random burst losses due to contention, even at low traffic loads. In the OBS literature, there are many contention resolution schemes that can reduce random burst loss. These schemes include fiber delay line buffering [4], wavelength conversion [5], segmentation [6], and deflection [7]. The network performance of these schemes have been evaluated in [6], [8], [9].

In this paper, we evaluate an edge-based burst retransmission scheme to handle burst contentions in the OBS core network. In the following discussions, we refer to the burst which fails to make a successful channel reservation due to contention at a core node as the *contending burst*. In the *burst retransmission* scheme, contending bursts are retransmitted by their source OBS nodes, thereby reducing burst loss probability in the OBS network. In the retransmission scheme, when a burst encounters a contention at a core node, the core node sends an *Automatic Retransmission Request* (ARQ) back to the ingress node. Once the ingress node is notified of the burst contention, the ingress node retransmits a duplicate of the contending burst. The retransmission scheme may retransmit the burst multiple times until either the burst reaches the egress node, or the burst retransmission process exceeds a delay constraint. Hence, the retransmission scheme will increase traffic load in the network due to the retransmitted bursts, leading to higher burst contention probability. During retransmission of the burst if the delay constraint is exceeded, then the burst will simply be dropped.

In this paper, we develop an analytical model for the retransmission scheme, and we also compare the performance of the retransmission scheme with the performance of the deflection scheme. One of the reasons to compare retransmission with deflection is that both these schemes resolve contentions at the cost of increased burst contention probability than a barebone OBS network. Note that the retransmission scheme can also be used in conjunction with other contention resolution schemes in order to further improve the burst loss probability.

The remainder of the paper is organized as follows. Section II describes the retransmission scheme and the deflection scheme in OBS networks. Section III presents an analytical model evaluating the burst loss probability for the retransmission scheme. Section IV presents numerical results from the analysis and simulation, and also compares the performance of the retransmission scheme with the deflection scheme. Section V concludes the paper.

II. RETRANSMISSION AND DEFLECTION

In this section, we describe the retransmission scheme and the deflection scheme in OBS networks. We also discuss certain potential issues in the retransmission scheme and the deflection scheme.

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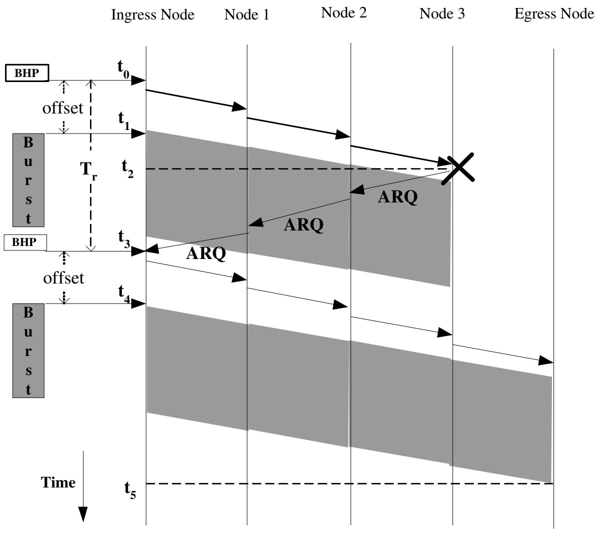


Fig. 1. OBS retransmission scheme.

A. *Retransmission Scheme*

The basic idea of retransmission is to allow contending bursts to be retransmitted in the OBS layer. In this scheme, BHPs are sent out prior to data burst transmission in order to reserve resources. After an offset time, the burst is transmitted into the core. At the same time, the ingress node stores a copy of the transmitted burst for possible retransmissions. As the BHP traverses through the core nodes, if the channel reservation fails due to burst contention, the core node will send an explicit ARQ to the ingress node in order to report the reservation failure. Upon receiving an ARQ, the ingress node retransmits a duplicate of the requested contending burst preceded by the corresponding BHP. In order to uniquely identify the contending burst which needs to be retransmitted, each data burst should be assigned a unique *burst id* (sequence number).

We illustrate a retransmission scenario in Fig. 1. In this figure, the BHP is transmitted at time t_0, while the burst is duplicated and stored at the ingress node before being transmitted. The burst is transmitted at time t_1 after some offset time. At t_2, the burst reservation fails at Node 3, triggering Node 3 to send an ARQ back to the ingress node. The ingress node receives the ARQ at t_3, then sends a new BHP and retransmits a duplicate burst at t_4 after some offset time. Assuming the second transmission is successful, at t_5 the burst arrives at the egress node. A burst duplicate may be retransmitted multiple times until the burst successfully reaches the egress node. Note that along with each duplicate data burst stored, we could also store the corresponding BHP in the edge buffer. So that in the case of a retransmission, we could avoid creating another BHP for each duplicate at a low additional cost of storing the corresponding BHP.

We observe from Fig. 1 that the retransmission scheme results in an extra delay, T_r, referred to as *retransmission delay*. The retransmission delay is the time elapsed between the initial BHP transmission of a burst and the last ARQ receipt for the corresponding burst, i.e., $t_3 - t_0$. The retransmission delay can be bounded by a delay constraint, notated as δ. δ can be chosen based on the delay requirement of application layer, as in [10]. Once the ingress node receives an ARQ for the contending burst, the ingress node calculates T_r for the contending burst and decides if it is necessary to retransmit the burst. If $T_r \geq \delta$, the ingress node ignores the ARQ and does not retransmit the contending burst.

If the network is lightly loaded, the retransmission scheme has a good chance of successfully retransmitting contending bursts. If the network is heavily loaded, the retransmitted bursts have a lower probability of being successfully received. The ingress node can continue to attempt retransmission until the retransmission delay exceeds the delay constraint, in which case the burst is dropped and no longer retransmitted when a contention occurs. Compared to an OBS network without retransmission, an OBS network with retransmissions will have a higher traffic load in the network, leading to higher burst contention probability. However, the burst is allowed to experience multiple contentions, which leads to a lower burst loss probability, particularly at lower loads.

In the retransmission scheme, each ingress node must store a copy of each burst for possible retransmission, prior to transmitting the burst. Therefore, electronic buffering at each ingress node is necessary. The size of the buffer can be determined by the delay constraint and the burst arrival rate. If an arriving burst can not be stored due to lack of buffers, the burst will not be retransmitted. In order to satisfy a certain probability that an arriving burst can not be stored at the ingress node, we must estimate the required buffer size. Since the retransmission scheme only reports contention but not the successful receipt of the bursts, the ingress node can purge the bursts that have been in the buffer for δ units of time, where δ is a given delay constraint. Hence, if we assume that the duration of the burst staying in the retransmission buffer is δ and that the buffer can store k bursts, we can model the retransmission buffer as a $M/G/k/k$ queuing system. Let P_b be the buffer blocking probability, or the probability that a burst could not be stored in the buffer, and let *buffer capacity*, k, be the number of bursts that the buffer needs to store in order to satisfy a given buffer blocking probability. Using the Erlang-B formula, we can obtain the relationship between k and P_b, and can estimate the required buffer capacity for a certain buffer blocking probability.

B. *Deflection Scheme*

In the deflection scheme, bursts are initially routed through their primary (shortest) paths. A contending burst will be redirected to an alternative path at the core node where the burst encounters a contention. The deflection scheme will increase traffic load in the network since the deflected bursts may traverse additional hops, which result in higher burst contention probability.

The deflection scheme suffers from potential looping [9] and *insufficient offset time* [11]. The potential looping problem is caused by rerouting a deflected burst back to nodes that have already been visited. The potential looping problem can be solved by setting a delay constraint for the deflected burst or by implementing a loopless deflection scheme [12]. The insufficient offset time is caused when a deflected burst traverses more hops along the alternative path than the primary path. Since the offset time between the deflected burst and its BHP is initially determined for the primary path, the deflected burst may lack sufficient offset time, thereby leading to the burst being dropped. One approach to solve the insufficient offset time problem is to introduce additional offset time at the ingress node. However, it may be difficult to predetermine the additional offset time at the ingress node. Another solution is to have optical buffers at core nodes in order to delay the deflected burst for the additional offset time introduced by deflection.

Several works have analyzed the burst loss probability in an OBS network with deflection [11], [13], [14]. In the next section, we will analyze the burst loss probability in an OBS network with retransmission.

III. PERFORMANCE ANALYSIS OF THE RETRANSMISSION SCHEME

In this section, we develop an analytical model for evaluating the average end-to-end burst loss probability for OBS networks with retransmission.

We define burst loss probability as the probability that a burst does not successfully reach its destination, even after possible retransmissions. We assume that the new burst arrival between each ingress-egress pair (s, d) is Poisson with rate λ_{sd}, which does not include the arrivals of retransmitted bursts. Let retransmission buffer blocking probability be P_b. Since bursts that are blocked by the retransmission buffer are unable to be retransmitted, the arrival rate of bursts that are unable to be retransmitted is $P_b \lambda_{sd}$ and the arrival rate of bursts that are able to be retransmitted is $(1 - P_b)\lambda_{sd}$.

Since a delay constraint is associated with the propagation delay of an ingress-egress pair (s, d), let the delay constraint for ingress-egress pair (s, d) be δ_{sd}, and the propagation delay for an ingress-egress pair (s, d) be $T_{p_{sd}}$. We assume that each retransmission takes an average time of $T_{p_{sd}}$. We can then approximate the maximum number of retransmissions for a burst that is able to be retransmitted as:

$$r_{sd} = \lfloor \frac{\delta_{sd}}{T_{p_{sd}}} \rfloor. \tag{1}$$

Let p_{sd} be the steady-state end-to-end burst contention probability between the ingress node s and egress node d. We define burst contention probability as the probability that a burst is dropped due to contention at an intermediate node. For each ingress-egress pair (s, d), all dropped bursts that are able to be retransmitted along the route can be retransmitted a maximum of r_{sd} times by the corresponding ingress node. In the worst case, when a burst is retransmitted the maximum number of times, the total burst arrival rate of the ingress-egress pair (s, d) which includes the arrivals of retransmitted bursts, is given by:

$$\Lambda_{sd} = \lambda_{sd} P_b + \sum_{k=0}^{r_{sd}} (\lambda_{sd}(1 - P_b) p_{sd}^k). \tag{2}$$

In order to obtain the end-to-end burst contention probability p_{sd}, we compute the burst contention probability on each link by using the Erlang-B formula. Let the burst contention probability at steady state on link l_{ij} be p_{ij}. We assume that the burst length is exponentially distributed with an average burst length of $1/\mu$ time units. We denote the Erlang-B formula as $ErlangB(\rho, m)$, where ρ is the traffic load and m is the number of wavelengths on a fiber link. Given the routes of the ingress-egress pairs, $route(s, d)$, the total arrival rate Λ_{ij} on link l_{ij} is given by:

$$\Lambda_{ij} = \sum_{\{\forall (s,d) | l_{ij} \in route(s,d)\}} \Lambda_{sd}. \tag{3}$$

Hence, the burst contention probability on link l_{ij} is given by:

$$p_{ij} = ErlangB(\frac{\Lambda_{ij}}{\mu}, m). \tag{4}$$

We can then obtain the average end-to-end burst contention probability of every ingress-egress pair (s, d) based on the burst contention probability on each link. We have:

$$p'_{sd} = 1 - \prod_{\{\forall (i,j) | l_{ij} \in route(s,d)\}} (1 - p_{ij}). \tag{5}$$

We iterate until p_{sd} and p'_{sd} converge.

Since a burst that is able to be retransmitted is lost only if the $r_{sd}th$ retransmission fails in the retransmission scheme, and a burst that is unable to be retransmitted is lost with probability p_{sd}, the average end-to-end burst loss probability for an ingress-egress pair (s, d) at steady state is:

$$P_{sd} = p_{sd} P_b + (1 - P_b)(p_{sd})^{r_{sd}}, \tag{6}$$

and the average end-to-end burst loss probability over an entire network is:

$$p = \frac{\sum_{\forall (s,d)} \lambda_{sd} P_{sd}}{\sum_{\forall (s,d)} \lambda_{sd}}. \tag{7}$$

From the analytical model, we can see that, for a given burst arrival rate, the end-to-end burst loss probability can be calculated based on three parameters: buffer capacity, delay constraint, and buffer blocking probability. One possible approach to calculate the end-to-end burst blocking probability is to set a fixed buffer capacity and a fixed delay constraint. Then we can obtain the buffer blocking probability by the Erlang-B formula and the end-to-end burst blocking probability using the analytical model. Using this approach, we can obtain an optimal value of delay constraint, δ, for a certain buffer capacity such that the network has the least average end-to-end burst loss probability.

Another approach is to set a fixed buffer blocking probability and a fixed delay constraint. Then, we can obtain the end-to-end burst blocking probability using the analytical model and obtain the buffer capacity that is required to satisfy the buffer blocking probability by the Erlang-B formula. In our simulation, we adopt the this approach.

IV. NUMERICAL RESULTS

We develop simulations in order to verify the analytical results and to evaluate the performance of the retransmission scheme.

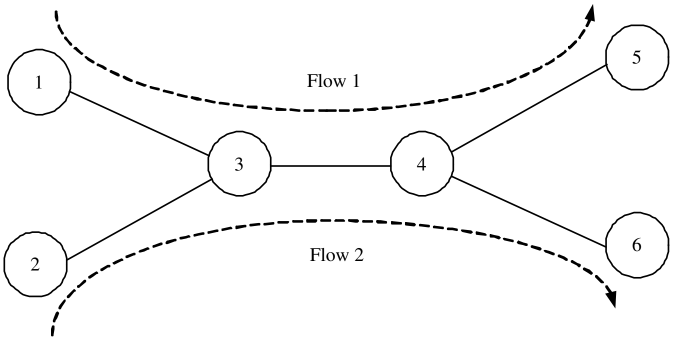


Fig. 2. Two-flow OBS network for analysis.

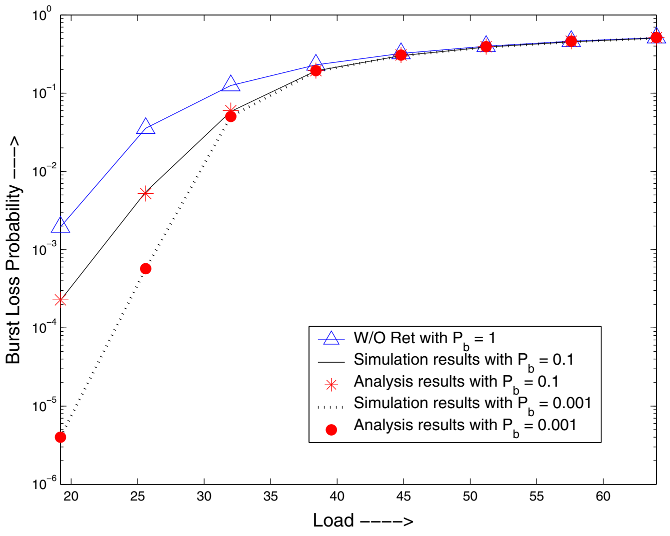


Fig. 3. Burst loss probability versus load for analysis and simulation results.

A. Analytical and Simulation Results for Retransmission

In this section, we verify the analytical model for burst loss probability over an OBS network with the retransmission scheme. We simulate a network as shown in Fig. 2, in which the number of wavelengths on each link is 32 and the transmission rate on a wavelength is 10 Gb/s. We assume that the burst arrival is Poisson and is uniformly distributed between Flow 1 and Flow 2. The burst length is exponentially distributed with an average burst length of 100 μs. In the simulation, we set the delay constraint of retransmission as two times of the propagation delay for an ingress-egress pair, i.e. $2T_p$. In this case, the delay constraints for different ingress-egress pairs may be different. We set the retransmission buffer blocking probability to be 0.1 and 0.001, respectively.

Fig. 3 shows the average burst loss probability over the OBS network obtained by the analytical model and simulation. We see that the simulation results and the analytical results perfectly match with each other, thereby validating our analytical model.

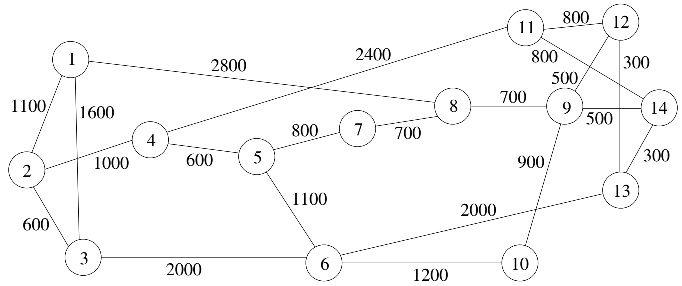


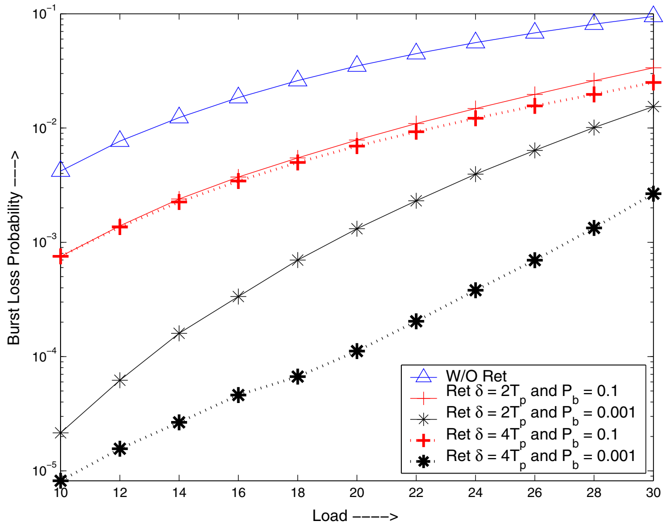
Fig. 4. NSF network.

B. Simulation Results for an OBS Network with and without Retransmission

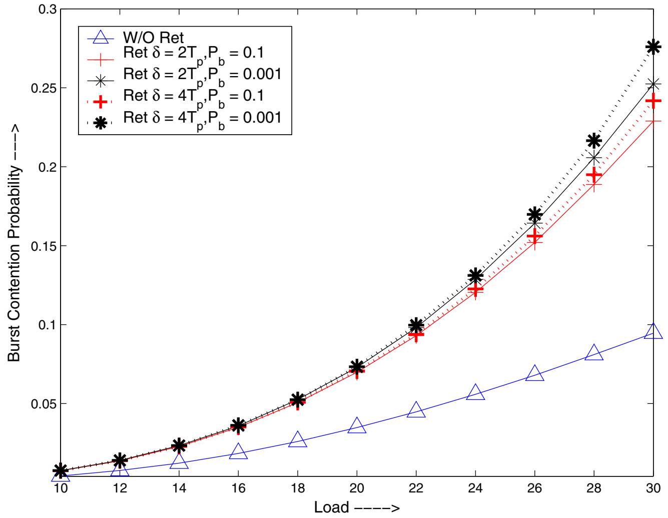
In this section, we develop a network-wide simulation model in order to evaluate the performance over an OBS network with and without retransmission. We simulate the NSF network as shown in Fig. 4. The distances shown are in km. The network diameter, i.e., the maximum number of hops along the any of the shortest paths between in the network is three. The number of wavelengths on each link is four and the transmission rate on a wavelength is 10 Gb/s. We assume that the core node has full wavelength conversion capability. Burst arrivals follow a Poisson process and are uniformly distributed among the ingress-egress pairs in the network. The burst lengths are exponentially distributed with an average burst length of 100 μs. The load in each figure is the original input traffic load to the entire network in Erlang.

Fig. 5 plots the average burst loss probability and burst contention probability versus load for the OBS network with and without retransmission. The different delay constraints are $2T_p$ and $4T_p$, and the different retransmission buffer blocking probabilities are 0.1 and 0.001. We can see from Fig. 5 (a) that the burst loss probability with retransmission is much lower than without retransmission. For instance, at a load of 20 Erlang, the retransmission scheme has 4 times lower burst loss probability for the case when $\delta = 2T_p$ and $P_b = 0.1$ and 300 times lower burst loss probability for the case when $\delta = 4T_p$ and $P_b = 0.001$, than the burst loss probability without retransmission. We can also see that, given the same delay constraint, having a higher retransmission buffer blocking probability results in higher burst loss probability since more bursts are unable to be retransmitted. Also, given the same buffer blocking probability, having higher delay constraints results in lower burst loss probability since bursts are allowed more retransmissions. Fig. 5 (b) shows that the burst contention probability with retransmission is higher than without retransmission. This is due to the added traffic load by the retransmitted bursts.

Fig. 6 plots average buffer capacity on each port of an ingress node versus load. We observe that the required buffer capacity for $\delta = 2T_p$ and $P_b = 0.001$ is much lower than the case $\delta = 4T_p$ and $P_b = 0.1$, while from Fig. 5 (a), the burst loss probability for the case $\delta = 2T_p$ and $P_b = 0.001$ is much lower than the case in which $\delta = 4T_p$ and $P_b = 0.1$. For instance, at a load of 20 Erlang, for the case $\delta = 2T_p$ and $P_b = 0.001$, the burst loss probability is 1.32×10^{-3} and the required buffer capacity



(a) Burst loss probability versus load



(b) Burst contention probability versus load

Fig. 5. Burst loss probability and burst contention probability versus load for the OBS network with and without retransmission.

is 139, while for the case $\delta = 4T_p$ and $P_b = 0.1$, the burst loss probability is 6.94×10^{-3} and the required buffer capacity is 206. This is because the number of bursts that are unable to be retransmitted is relatively high in the case $\delta = 4T_p$ and $P_b = 0.1$ compared to the case $\delta = 2T_p$ and $P_b = 0.001$. Hence, we can see that higher buffer capacity does not always lead to lower burst loss probability.

Fig. 7 shows average burst delay versus load. We see that the average burst delay for the network with retransmission is higher than without retransmission. Also, the average burst delay without retransmission decreases with increasing load. This is because bursts traversing fewer hops have a higher probability of reaching their egress nodes when the load increases. We can also see that, given the same delay constraint, having a higher retransmission buffer blocking probability results in lower burst delay since fewer bursts suffer from the retransmission delay. We also observe that

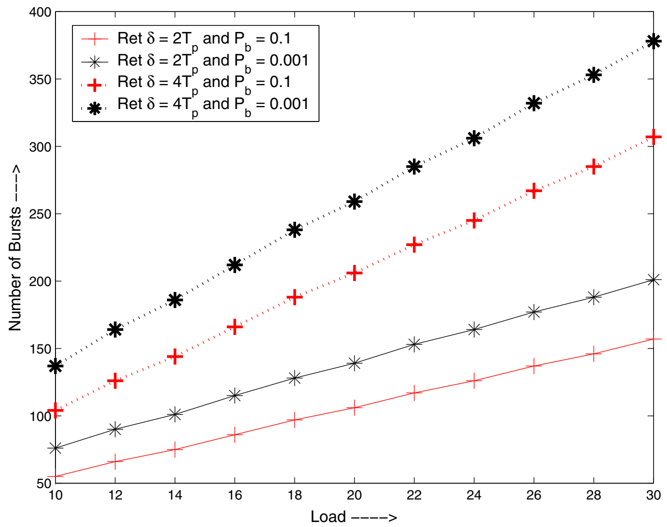


Fig. 6. Buffer capacity versus load.

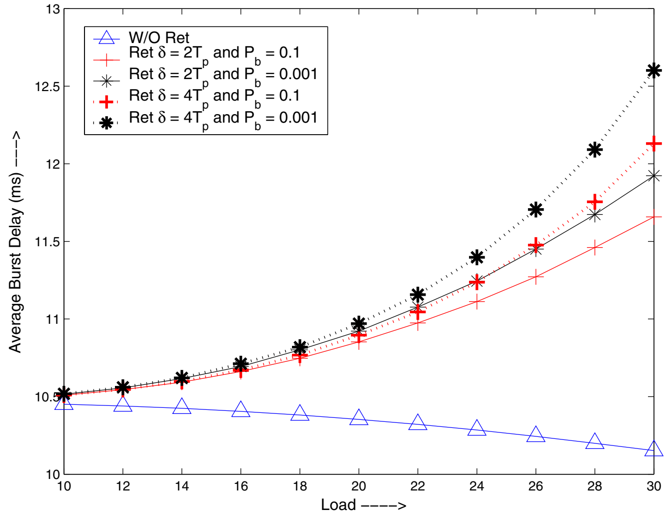
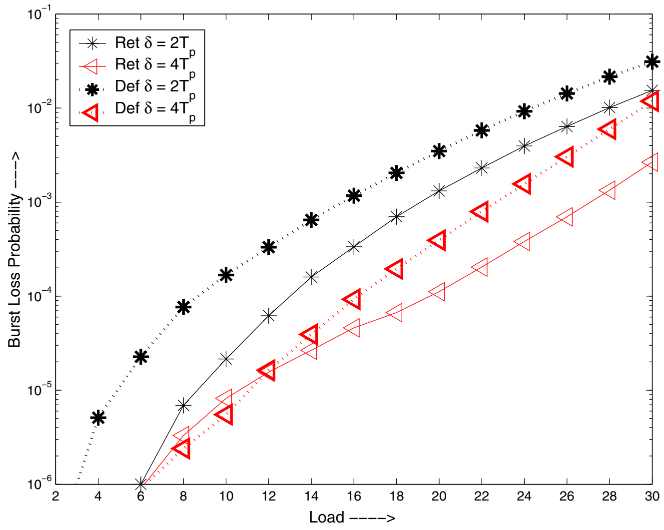


Fig. 7. Burst delay versus load for the OBS network with and without retransmission.

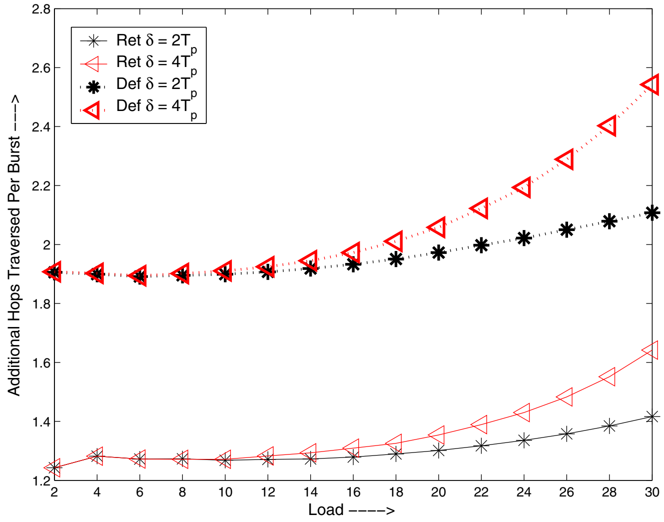
there is a crossover between the case $\delta = 2T_p$ and $P_b = 0.001$ and the case $\delta = 4T_p$ and $P_b = 0.1$. At a load below 24 Erlang, the retransmission delay for a successfully retransmitted burst is low due to relatively low burst loss probability, hence the delay constraint for retransmission has less impact on the average burst delay than the buffer blocking probability. Therefore, the average delay for the case $\delta = 4T_p$ and $P_b = 0.1$ is lower than the case $\delta = 2T_p$ and $P_b = 0.001$. On the other hand, at a load higher than 24 Erlang, the delay constraint for retransmission has a greater impact on the average burst delay than the buffer blocking probability, hence the average delay for the case $\delta = 4T_p$ and $P_b = 0.1$ is higher than the case $\delta = 2T_p$ and $P_b = 0.001$.

C. *Comparison of Retransmission and Deflection*

In this section, we compare the simulation results of the retransmission scheme and the deflection scheme based on the



(a) Burst loss probability versus load



(b) Additional hops traversed per burst versus load.

Fig. 8. Burst loss probability and additional hops traversed per burst versus load for the retransmission scheme and the deflection scheme.

network-wide simulation model in the previous subsection. In the comparison, we set the retransmission buffer blocking probability to be 0.001. For the deflection scheme, we assume that there are sufficient optical buffers at core nodes for avoiding the insufficient offset time problem. We pre-define all the deflection paths for each node pair in the network. Since the maximum nodal degree of the network shown in Fig. 4 is four, the maximum number of alternative deflection paths is three.

We set the same delay constraints for the retransmission scheme and the deflection scheme, such that if the end-to-end delay of a burst exceeds the delay constraint, the burst will be dropped. Note that the performance of the retransmission scheme and the deflection scheme depends heavily on the network topology. Here, we discuss the performance of both schemes based only on the NSF network shown in Fig. 4.

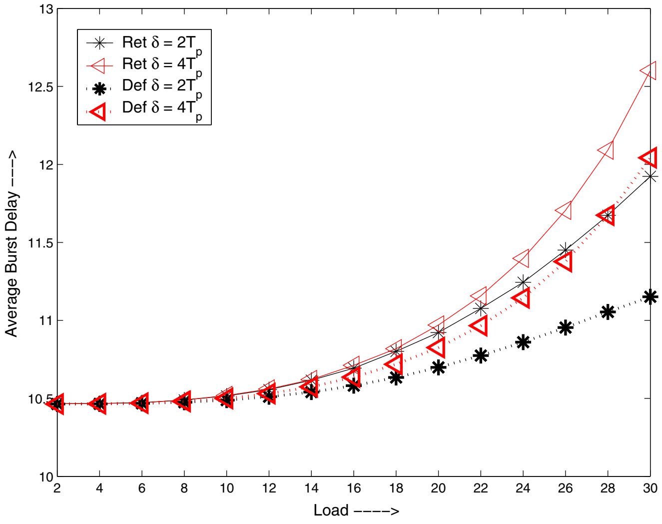


Fig. 9. Average burst delay versus load for the retransmission scheme and the deflection scheme.

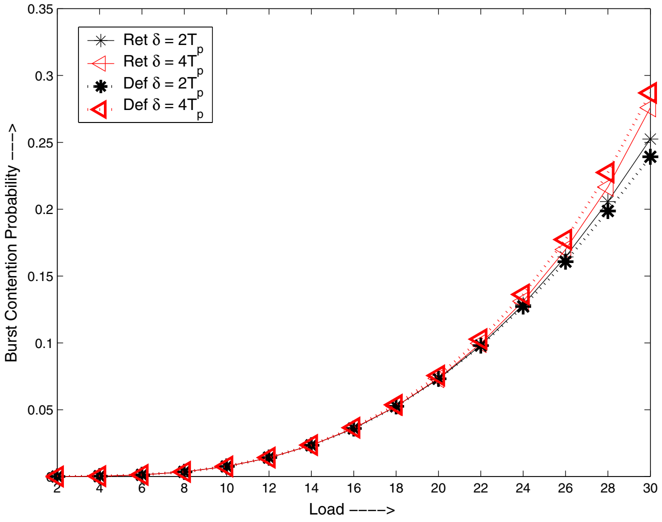


Fig. 10. Burst contention probability versus load for the retransmission scheme and the deflection scheme.

Fig. 8 plots the burst loss probability and the additional hops traversed per burst versus load for the retransmission scheme and the deflection scheme. When $\delta = 2T_p$, the retransmission scheme has much lower burst loss probability than the deflection scheme. This result shows that the delay constraint, $\delta = 2T_p$, is more restrictive for the deflection scheme than for the retransmission scheme. When $\delta = 4T_p$, at a load below 12 Erlang, the deflection scheme has slightly lower burst loss probability than the retransmission scheme, although bursts in the deflection scheme traverse more hops than the retransmission scheme from Fig. 8 (b). This is because the deflection scheme balances the network load by rerouting around the relatively congested links, while the retransmission scheme always sends retransmitted bursts through the same shortest paths. At a load higher than 12 Erlang, the deflection scheme has higher burst loss probability than the retransmission scheme. For instance, at a load of 20 Erlang, the burst loss probability in the retransmission scheme is 4 times lower than the burst loss probability in the deflection scheme. This is because the deflected bursts traverse much more hops than the retransmitted bursts at high loads, as shown in Fig. 8 (b), and the burst loss probability increases with the number of hops.

Fig. 9 plots the average burst delay versus load for both schemes. We see that, given the same delay constraint, the retransmission scheme has longer burst delay than the deflection scheme. This is due to the additional delay required in the retransmission scheme to notify the source that the burst has been dropped.

Fig. 10 shows the burst contention probability versus load for the retransmission scheme and the deflection scheme. We see that, at low traffic loads, both schemes have similar burst contention probability. At high traffic loads, when $\delta = 2T_p$, although bursts in the deflection scheme traverse more hops, the deflection scheme has slightly lower burst contention probability than the retransmission scheme. This is because the deflection scheme has much higher burst loss probability and drops more bursts, leading to lower overall traffic load in the network. When $\delta = 4T_p$, the deflection scheme has slightly higher burst contention probability than the retransmission scheme. This is because, at high loads, the additional number of hops traversed per burst has a greater impact on the burst contention probability compared to the burst loss probability.

V. CONCLUSION

In this paper, we evaluated the performance of a retransmission scheme through simulation results and developed an analytical model for the retransmission scheme. We also compare the performance of the retransmission scheme with the deflection scheme in the NSF network. Our simulation results show that both schemes will generate additional traffic load into the network, thereby increasing burst contention probability in the network. At low traffic loads, the deflection scheme has lower burst loss probability since the deflection scheme reroutes contending bursts, thereby balancing the network load. At high traffic loads, the retransmission scheme has much lower burst loss probability since bursts in the deflection scheme traverse more hops than the retransmission scheme. The simulation results also show that the burst delay in the retransmission scheme is higher than the deflection scheme. This is due to the additional delay required in the retransmission scheme to notify the source that the burst has been dropped.

In our current retransmission scheme, the retransmitted bursts follow the same route as the contending bursts. Possible future work is to have alternate routes for the retransmitted bursts, such that the network load can be well-balanced. Another very important area of future work is to evaluate the effect of the retransmission scheme on different TCP flavors at the higher layer, such as TCP Reno[15], TCP NewReno[16], TCP SACK[17], HighSpeed TCP [18], Fast TCP [19], and XCP [20].

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