A New Performance Model of Optical Burst Switching with Fiber Delay Lines

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***Abstract*— We present a new performance model for a prioritized optical burst switch architecture employing fiber delay lines (FDLs) as optical buffers to reduce the burst loss probability. The performance of such an architecture cannot be captured accurately using traditional queueing models since FDLs behave fundamentally differently from conventional electronic buffers. We formulate a Markovian model to evaluate the system performance when the burst arrival process is Poisson and the burst lengths are exponentially distributed. Both the balking and bounded delay characteristics of FDLs are captured in the model. A conservation law is used to extend the analysis to a system implementing differentiated services with two prioritized traffic classes. The extended model captures the system dynamics for high priority traffic and yields a good approximation for low priority traffic. We also find that the previously developed models are approximations of our general model in the regimes of short and long FDLs. Our numerical results validate the accuracy of our modeling approach and demonstrate significant performance gains when FDLs are employed as optical buffers.**

I. Introduction

Optical burst switching has been recently proposed as a suitable switching paradigm in the optical domain (cf. [1], [2]). In optical burst switching, the data burst (DB) and the burst head packet (BHP) are transmitted over separate channels and a one-way reservation scheme is used to reserve wavelength channels dynamically for the DB on a link-by-link basis. By properly choosing an offset time between the BHP and the DB, a scheduling algorithm can guarantee that the light path has been set up by the time the DB arrives at an intermediate switch node. In the one-way reservation scheme, the end-to-end latency for burst transmission is approximately one round-trip time less than in optical circuit switching.

Design and performance evaluation of optical burst switches have been active topics of research in the last few years, e.g., [1], [2], [3], [4], [5]. Various scheduling algorithms for assigning DBs to wavelengths have been proposed. Xiong et al. [4] describe two such algorithms: Latest Available Unscheduled Channel (LAUC) and Latest Available unused Channel with Void Filling (LAVF). Yoo et al. [3] proposed a scheme to provide prioritized quality-of-service (QoS) in optical burst switching by employing extra offset times between the BHP and the DB for higher priority traffic classes.

The unique characteristics of FDLs impose extra challenges on the performance modeling. Assume that the maximum delay of an FDL is B seconds. Unlike conventional electronic buffers, the amount of time that an optical burst can stay is constrained to be less than B. We call this phenomenon *buffering with bounded delay*. In addition, unlike electronic buffers, where a packet can use a buffer as long as it is available, an optical burst can occupy an FDL only if the FDL is idle and the requested delay is less than B. We call this phenomenon *balking*.

Based on the $M/M/k/D$ queueing model, Yoo et al. [3] obtained upper and lower bounds of the burst loss probability for their proposed architecture. However, their model (and also that of [1]) does not capture the unique balking and buffering characteristics of FDLs. Rather, the behavior of FDLs is approximated by that of conventional buffers. The investigation of the performance impact of FDLs in [3] was mainly carried out via simulations. More recently, Fan et al. [6] proposed a queueing-based model to improve upon the lower bound of [3]. However, their model fails to capture the balking property of FDLs, i.e., a burst must be discarded if its expected waiting time is longer than the maximum delay provided by all available FDLs. Based on a queueing model with balking, we obtained an approximate analytical model of optical burst switches with FDLs [7] that provided more accurate performance results, particularly for the case of short FDLs where the balking phenomenon dominates. However, the queueing model with balking does not fully capture the delay properties of FDLs, leading to inaccuracies for longer FDLs when the effect of balking is diminished.

In the present paper, we propose a new stochastic model for optical burst switches that captures both the *bounded delay* and *balking* properties of FDLs. Our performance model is directly applicable to the prioritized optical switch architecture with FDLs proposed by Yoo et al. [3]. The model is very accurate for the case of classless traffic and improves on earlier approximate models for the case of two prioritized traffic classes. The two-class model retains high accuracy for high priority traffic and yields a less accurate, though reasonably good approximation for low priority traffic. We also develop asymptotic approximations for burst loss probabilities that are accurate in the regimes of short and long FDLs.

As in the earlier work in this area [1], [3], [6], [7], we assume that the burst arrival processes are Poisson and the burst lengths are exponentially distributed. It is well known that Poisson/exponential assumptions may break down in modeling

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broadband networks. Nevertheless, we feel that our model provides valuable insight into the performance characteristics of optical burst switching with FDLs and provides a solid basis for further investigations using more realistic arrival process models and burst length distributions.

II. Optical Burst Switching with FDLs

A. OBS Architecture

We assume an output queued $N \times N$ optical burst switch architecture. Assuming that the incoming traffic is uniformly distributed, one only needs to investigate the performance of a typical output port. In optical burst switching, the BHPs and DBs travel in the control plane and data plane, respectively. The BHPs experience O-E-O conversions at each intermediate switch node, setting up light paths for the ensuing DBs, which stay exclusively in the optical domain.

In the data plane, each output port has k wavelengths for transmitting DBs. Optical buffering in the form of F FDLs is associated with each output port. Each FDL is capable of providing a continuous-valued variable delay of up to B time units. The physical design of variable length FDLs is discussed in [8]. The assumption that the delay value can assume a continuous value is an idealization, but is found to be a reasonable one. Assuming that each FDL can also support k wavelengths, the total number of *virtual optical buffers* is $m = Fk$. In the control plane, a BHP is transmitted δ seconds ahead of the ensuing DB, and tries to reserve a wavelength for the DB. The time value δ is called the *base offset* time.

The reservation scheme consists of two phases: *wavelength reservation* in the output port and *FDL reservation* in the optical buffer. During the wavelength reservation phase, the scheduler checks the k wavelengths in the output port first. If there is one wavelength that will be idle at $t + \delta$ and the idle duration is long enough to accommodate the DB, this wavelength will be reserved immediately; otherwise, the minimum waiting time W among all k wavelengths is computed. If $W > B$, the DB has to be discarded, since no FDL can provide such a delay. In the case of $W < B$, the FDL reservation is performed. If there exists a wavelength in the FDLs, which will be idle at $t + \delta$ and the idle duration is longer than the DB duration, both the wavelength and the FDL will be reserved. Otherwise, the DB has to be dropped. A flowchart diagram of the wavelength and FDL reservation scheme is given in Figure 1. In the reservation scheme, we assume full wavelength conversion capability, i.e., the DBs blocked during the wavelength reservation phase can use any of the available wavelengths among the FDL buffers.

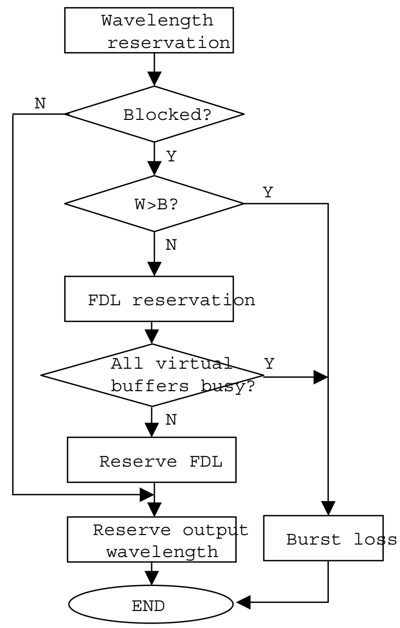

Fig. 1. A generic wavelength reservation scheme in OBS with FDLs.

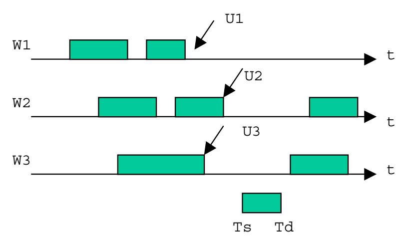

Fig. 2. An example of LAUC and LAVF scheduling algorithm

B. Signaling Protocol and Scheduling Algorithms

We assume the Just-Enough-Time (JET) signaling protocol introduced in [2]. As a result, both the arrival and the departure times of a DB are known. By reserving a specified wavelength only for the duration for the incoming burst, the wavelength utilization is higher for JET than for other protocols [5].

Of the two classes of wavelength scheduling algorithms mentioned earlier, LAUC is easier to implement, while LAVC can achieve better performance. In LAVF the scheduler must maintain a record of all the reserved time slots for each wavelength, whereas in LAUC the scheduler maintains only the completion time of the last scheduled burst. As an example of the LAVF and LAUC algorithms, Figure 2 shows a fiber with three wavelengths. For the arriving DB characterized by the interval $[T_s, T_d]$, the unscheduled/unused times of the three wavelengths are U_1, U_2, and U_3, respectively. Under LAUC, wavelength 1 will be chosen, while wavelength 2 will be chosen under LAVF. The detailed operations of the LAUC and LAVF scheduling algorithms are described in [4].

C. Extra offset-time-based QoS Scheme

Yoo et al. [3] proposed an *extra offset-time*-based quality-of-service (QoS) scheme for the OBS architecture. Assume that the maximum delay of an FDL is B seconds, the average burst duration is L seconds, and that the extra offset time is Δ. The actual offset time between the BHP and the DB is $\delta + \Delta$. By choosing $\Delta = B + 3L$, the authors showed that the system can achieve 95% isolation between high and low traffic classes and that the high priority traffic can attain much lower burst loss probabilities.

III. Analysis

The modeling assumptions in our analysis of OBS with FDLs are summarized below:

1) Output queued optical burst switch with uniform traffic distribution.
2) k wavelengths in each output port and m virtual optical buffers, each of which can provide a variable delay of up to B seconds. Full-range wavelength conversion capability is assumed.
3) JET signaling and LAUC wavelength scheduling[1].
4) Bursts arrive according to a Poisson process with a mean rate of λ bursts/second. The burst duration is exponentially distributed with a mean of $1/\mu$ seconds.

A. Stochastic model for classless traffic

1) Stochastic representation of wavelength reservation: Based on the wavelength reservation and the FDL reservation mechanisms using LAVF (see Figure 1), the scheduler computes the minimum waiting time W for the blocked DB during the wavelength reservation phase. If $W < B$ and there is a virtual buffer available to hold the DB, both the FDL and the wavelength will be reserved. In addition, the waiting time of the DB is equal to the residual busy time of the wavelength, i.e., the sum of the residual service time of the burst currently in service and the durations of all other bursts that have already been scheduled.

Now suppose that j bursts have reserved the wavelength at time $t+\delta$ and that their durations are $X_1, \cdots, X_j$, respectively. Let R_0 denote the residual service time of the burst in service at $t+\delta$. Then the probability that a DB arriving at time t will be discarded is given by

$$E_j = \Pr\left\{R_0 + \sum_{i=1}^{j-1} X_i > B\right\}. \quad (1)$$

Using the memoryless property of exponentially distributed random variables, the above blocking probability is equivalent to

$$E_j = \Pr\left\{\sum_{i=0}^{j-1} X_i > B\right\}, \quad (2)$$

which can be expressed as

$$E_j = e^{-\mu B} \sum_{n=0}^{j-1} \frac{(\mu B)^n}{n!}. \quad (3)$$

We next define a function F_{ij}, $i, j \geq 0$, that will be used in our subsequent analysis:

$$F_{ij} = \Pr\left\{\sum_{l=1}^{i} X_l < \sum_{l=1}^{j} Y_l\right\}, \quad (4)$$

[1]In the classless traffic case, LAVF and LAUC are identical if the base offset time is constant among all bursts.

where X_l and Y_l are $i.i.d.$ exponentially distributed random variables with parameter μ. Here, i and j refer to the number of residual stages on the two wavelengths and F_{ij} is the probability that the waiting time on one wavelength is shorter than that on another one. It can be shown that

$$F_{ij} = \sum_{n=0}^{j-1} \binom{n+i-1}{n} \frac{1}{2^{n+i}} \quad (5)$$

2) Markovian model: We model the overall system as a multi-dimensional continuous-time Markovian chain (CTMC). For ease of presentation we assume that $k = 2$. The derivation for $k > 2$ is straightforward and is not presented. Define the current state to be (n_1, n_2, s), where n_1 and n_2 are the number of residual Erlang stages and s is the number of busy FDLs at $t + \Delta$. The ranges of these state variables are $n_1, n_2 \geq 0$ and $0 \leq s \leq m$. We compute the state transition rates as follows.

Two types of transitions are possible for the system to leave a given state: λ-type transitions and μ-type transitions. The λ-type transitions occur when a data burst arrives at the switch. The μ-type transitions are due to data burst departures from the virtual buffer or the output port. To make the problem tractable, we assume that the μ-type transitions due to DB departures from the FDLs are independent of the μ-type transitions due to the DB departures from the output port. According to the values of n_1 and n_2, we distinguish four cases:

- $n_1 = 0, n_2 = 0$. In this state, there is no burst loss since the two wavelengths are idle. Therefore, λ-type transitions may lead to the next state of $(1, 0, s)$ or $(0, 1, s)$ with rate $\lambda/2$. We assume that the two types of transitions are equally probable. When $s > 0$ the μ-type transition rate to state $(0, 0, s-1)$ is $s\mu$.
- $n_1 = 0, n_2 > 0$. In this case no blocking occurs. The next state due to a λ-type transition is $(1, n_2, s)$, since the first wavelength is idle. The transition rate is λ. The μ-type transitions can lead the system to state $(0, n_2 - 1, s)$ or $(0, n_2, s-1)$ (if $s > 0$). The transition rates to these states are μ and $s\mu$, respectively.
- $n_1 > 0, n_2 = 0$. Similar to the previous case, λ-type transitions lead to state $(n_1, 1, s)$ with rate λ and μ-type transitions go to state $(n_1 - 1, 0, s)$ or $(n_1, 0, s-1)$ (if $s > 0$), with rate μ and $s\mu$, respectively.
- $n_1 > 0, n_2 > 0$.

In the last case, the arriving data burst will be blocked in the wavelength reservation phase, since both wavelengths are busy. The μ-type transitions can lead to states $(n_1 - 1, n_2, s)$, $(n_1, n_2 - 1, s)$, and $(n_1, n_2, s-1)$ (if $s > 0$), with rates of μ, μ, and $s\mu$, respectively. The next possible states due to λ-type transition are $(n_1+1, n_2, s+1)$ and $(n_1, n_2+1, s+1)$, depending on which wavelength is used. Their transition rates are computed as follows. Denote the blocking times on the two wavelengths as B_1 and B_2, respectively. According to the scheduling algorithm, the next state due to a λ-type transition is $(n_1+1, n_2, s+1)$, if the blocking time B_1 satisfies $B_1 < B$ and $B_1 < B_2$, and $s < m$. Therefore, the transition rate to state $(n_1+1, n_2, s+1)$ when $s < m$ is

$$\begin{aligned} g_1(n_1, n_2) &= \lambda[\mathrm{P}\{B_1 < B_2 < B\} + \mathrm{P}\{B_1 < B < B_2\}] \\ &= \lambda(1 - E_{n_1})[(1 - E_{n_2})F_{n_1,n_2} + E_{n_2}]. \end{aligned}$$

Similarly, the transition rate to state $(n_1, n_2+1, s+1)$ is

$$g_2(n_1, n_2) = \lambda(1 - E_{n_2})[(1 - E_{n_1})F_{n_2,n_1} + E_{n_1}].$$

This completes the formulation of the basic Markovian model characterizing the dynamics of OBS with FDLs.

Let us denote the steady-state probability that the system is in state (i, j, l) by π_{ijl} and the corresponding burst loss probability by p_{ijl}, where[2]

$$\begin{aligned} p_{ijl} &= \mathrm{P}\{B_1 > B \,\text{and}\, B_2 > B\} + \\ &\quad \mathrm{P}\{B_1 \le B \,\text{or}\, B_2 \le B\} I_{\{l=m\}} \\ &= E_i E_j + (1 - E_i E_j) I_{\{l=m\}}. \end{aligned}$$

The mean burst loss probability can then be computed as

$$\beta = \sum_{i=1}^{\infty} \sum_{j=1}^{\infty} \sum_{l=0}^{m} \pi_{ijl} p_{ijl}. \qquad (6)$$

B. Extension to two priority classes

We now extend the above model to the case of two prioritized traffic classes: high (class-H) and low (class-L). We assume that the probability that the incoming DB is of class-H is $\alpha, 0 < \alpha \le 1$. The extra offset time for the class-H traffic is given by $\Delta = B + 3/\mu$ seconds. We ignore the small base offset time δ.

It was verified in [3] via simulations that a conservation law among multiple prioritized traffic classes applies when the traffic intensity is high, e.g., $\rho > 0.8$. Our own numerical experiments have confirmed the validity of the conservation law at high traffic intensities. In the special case of two traffic classes, the conservation law expresses the overall burst loss probability via the law of total probability and is valid regardless of the traffic intensity. We denote the burst loss probabilities for class-H, class-L, and the overall traffic are β_H, β_L, and β, respectively. The *conservation law* is given by

$$\beta = \alpha \beta_H + (1 - \alpha) \beta_L. \qquad (7)$$

The class-H burst loss probability, β_H, can be derived using the analysis described above for the classless case. An *approximation* for the overall burst loss probability, β, can be obtained by treating the class-H and class-L bursts as an aggregate traffic stream. Finally, given values for β_H and β, the class-L burst loss probability β_L can be obtained from the conservation law (7).

IV. Approximate Models

In this section, we note that the models derived in [3] and [7] can be treated as asymptotic approximations of our more general model in the regimes of long and short FDLs, respectively. Let A_W be the event that a DB is blocked in

[2] I_A denotes the indicator function on the set A.

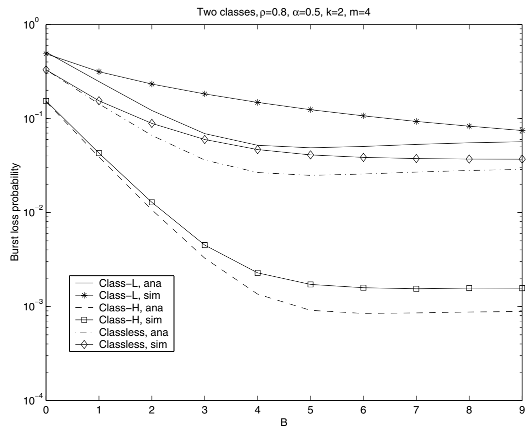

Fig. 3. Prioritized OBS, two classes, ρ=0.8, α=0.5, $k = 2$, $m = 4$.

the wavelength reservation phase, W be the waiting time, and A_F be the event that the DB is blocked in the FDL reservation phase. The burst loss probability during the wavelength reservation phase is given by $\beta_W = \Pr\{A_W, W > B\}$. The loss probability of the burst during the FDL reservation phase is $\beta_F = \Pr\{A_W, W \le B, A_F\}$. The burst loss probability is simply given by

$$\beta = \beta_W + \beta_F. \qquad (8)$$

When B is close to zero, we would expect that $\beta_F \ll \beta_W$, since in this case it is unlikely for a blocked burst to find an available FDL capable of providing a sufficiently long delay. As a result, burst losses during the wavelength reservation phase play the main role and for small B we have $\beta \approx \beta_W$. In this case, the *balking* property of the FDLs play the dominant role. Thus the model in [7] applies.

When $B \to \infty$ and $m > k$, we expect that $\beta_W \ll \beta_F$, since almost all blocked bursts can obtain an available FDL. Therefore, for large B we have $\beta \approx \beta_F$. In this case, the *buffering* characteristic of FDLs dominates. As a result, the FDLs can be approximately treated as electronic buffers and the $M/M/k/D$ queueing model proposed in [3] is applicable.

V. Numerical Results

We constructed a discrete event-driven simulator based on DaSSF [9] to verify the accuracy of our analytical results.

In Figure 3, we show the burst loss probabilities for an OBS fed with two-priority traffic. The number of wavelengths in the output port is $k = 2$. The number of virtual buffers in the optical buffer is $m = 4$. The overall traffic intensity is $\rho = 0.8$. The fraction of class-H traffic is 30% ($\alpha = 0.5$). The mean burst duration is $\mu = 1$. We plot the burst loss probability versus the maximum delay B that can be provided by a virtual buffer. Also plotted is the classless case with the same traffic intensity of $\rho = 0.8$. We can see from this plot that the analytical model quite accurately predicts the performance of class-H traffic, especially for short FDLs. In all cases the model slightly underestimates the burst loss probabilities. From this plot we can also see that when there is a small

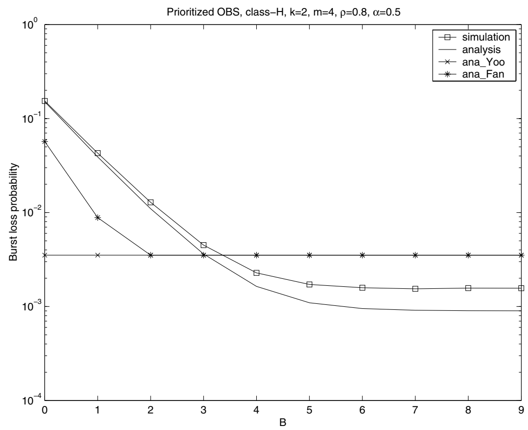

Fig. 4. Prioritized OBS, class-H, $\rho = 0.8$, α=0.5, $k = 2$, $m = 4$.

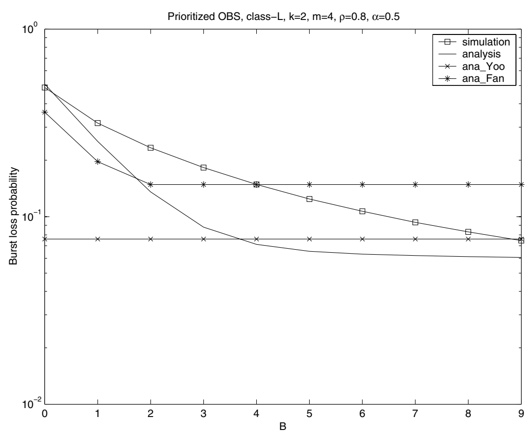

Fig. 5. Prioritized OBS, class-H, $\rho = 0.8$, α=0.5, $k = 2$, $m = 4$.

portion of high priority traffic, the performance of class-L traffic is close to the classless case. However, the performance of high priority traffic is significantly better, especially with longer FDLs. Also, observe that adding extremely long FDLs does not help the system performance. In this example, the system performance does not improve when $B > 6L$, where $L = 1$ is the mean burst duration.

To compare our model with those obtained in [3] and [6], we plot in Figure 4 the performance of class-H traffic. The parameters of the OBS are chosen as $k = 2, m = 4, \rho = 0.8, \alpha = 0.5$. We can see in this case that neither Yoo's model [3] nor Fan's model [6] can provide a lower bound of the system performance. When the maximum delay B of FDLs is small, Yoo's model is not applicable, while Fan's model can only provide a loose lower bound. By considering the behavior of FDLs, our model provides accurate results for small B, and a tight lower bound for large B.

In Figure 5, we plot the performance of class-L traffic under the same set of parameters. In this case we observe that Yoo's result provides a slightly better lower bound than ours when B is large. However, our analysis provides a better lower bound when B is small. Figure 6 shows the burst loss probability

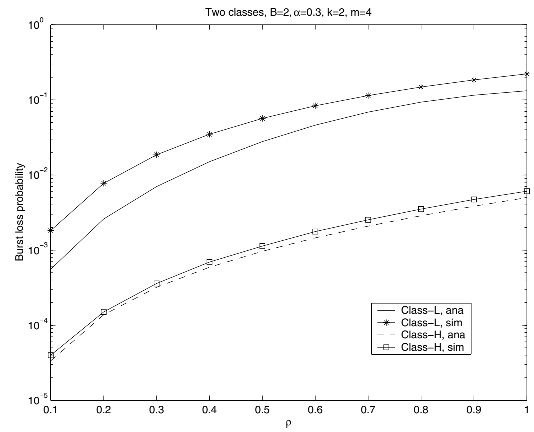

Fig. 6. Prioritized OBS, two classes, $B = 2$, α=0.3, $k = 2$, $m = 4$.

for fixed $B = 2$ with the remaining parameters specified as follows: $k = 2, m = 4$, and $\alpha = 0.3$. From the figure, one can see that our analysis provides lower bounds for both class-L and class-H traffic across all traffic loads.

VI. Conclusion

We developed a new analytical model to evaluate the performance of an optical burst switching with fiber delay lines. The model takes the form of a multi-dimensional Markov chain and captures the unique buffering and balking characteristics of FDLs. We analyzed the conditions under which the previously developed models become the approximate asymptotic cases of the new general Markovian model. We also extended the model to the case of two prioritized traffic classes by means of a conservation law following the approach of Yoo et al. [3].

Acknowledgment

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