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On Performance of Optical Buffers With Specific Number of Circulations

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***Abstract*—Deployment of fiber delay lines (FDLs) as a means of contention resolution is analytically studied. We consider a single-wavelength optical link equipped with a single FDL and assume that packets of fixed length arrive to the link asynchronously. The results obtained include accurate equations to calculate the congestion rate for different reservation scenarios including a prereservation scheme as well as a postreservation scheme with a specific number of circulations. Accuracy of the proposed model is validated through simulation.**

***Index Terms*—Fiber delay line (FDL), loss rate, optical burst switching (OBS), optical packet switching, queuing system.**

I. Introduction

CONTENTION resolution and congestion control of all-optical networks (AONs) have attracted much attention recently. Since there is no equivalent of electronic random access memory (RAM) in the optical domain, use of fiber delay lines (FDLs) is proposed [1], [2] to handle the need of buffering in AONs. However, unlike electronic RAMs, FDL buffers merely provide discrete time delays. Thus, designing and dimensioning FDLs forms an important aspect of an optical router design. While many works have considered the performance of different FDL buffer architectures, only a few analytical studies in this direction exist. For example, an approximate analysis is presented for degenerate buffers in [3]. Performance of the same architecture in a slotted synchronous system is provided in [4]. Also, a method of calculating the drop rate of the degenerate model for a single-channel link under asynchronous arrivals is presented in [5]. However, this model is valid only if the total offered load is below a specific value. To address these shortcomings in existing literature, we provide a study of the performance of a single-wavelength link equipped with an FDL buffer under asynchronous fixed length packet traffic, which has important applications in optical burst switching (OBS) and optical packet switching networks. Throughout this letter, the terms FDL and buffer are used interchangeably.

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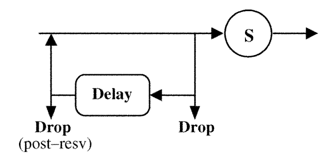

Fig. 1. Queuing model of the system.

II. System Model

Consider a single-channel output link of an optical node modeled as a single server queuing system as in Fig. 1. We assume that fixed length packets arrive asynchronously from different input links to the node. While the statistics of assembled burst in OBS networks is still under debate, the assumption of fixed packet lengths is justified by noticing that, in a heavily loaded burst assembler, 99.9% of the assembled bursts will have the average burst length [6], and in a light load situation, this decreases to 76.9%. When a packet arrives, a) if it finds the node idle, it undergoes service immediately. Otherwise, b) it checks the buffer; if the buffer is empty, then it goes through a fixed delay. c) A packet that undergoes through the FDL may try to reserve the node in two different ways [7]: c1) In the prereservation (PRR) scheme, it may reserve the node in advance and before entering the buffer; or alternatively, c2) in the postreservation (POR) scheme, it may try to access the node when it leaves the buffer. Note that, in the PRR scheme, the node is regarded as busy even when no packet is being served but a packet is in the buffer. Thus, in this scheme, transmission of every packet that enters the buffer is guaranteed. This is, however, not true for the POR case, where a packet leaving the buffer still might find the node busy. In such a situation, the packet may re-enter the buffer, i.e., recirculation process, or it may simply be dropped. In practice, in order to keep the optical signal quality above a desired level, the total number of times a packet may undergo through the FDL is limited. In the following, performance of both the PRR and POR scheme with a specific number of circulations is studied.

III. Performance Evaluation

Let requests for service at a node arrive according to a Poisson process with rate λ, and let b be the service time for a packet (constant for all packets). It was shown in [8] that the optimum performance in this case, in terms of loss rate, is achieved when the delay provided by the single FDL is equal to b. In the following, we first mention the results of [8] for PRR scheme.

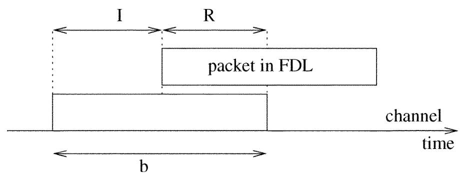

Fig. 2. Forward recurrence time of a packet in service as seen by a packet which enters the buffer.

A. PRR Scheme

In this scheme, it can be shown that a packet gets lost only if it arrives during the periods which FDL is busy. According to the PASTA (Poisson Arrivals See Time Average) property of arrivals, the probability that a channel is found busy by an arrival would be equal to the link utilization that is given by $u = \rho(1 - P_D)$, where $\rho = \lambda b$ is the total offered load to the link, and P_D is the packet loss rate. In [8], it is shown that the average drop rate is given by

$$P_{D,\text{PRR}} = \frac{\rho(1-e^{-\rho})}{1+\rho(1-e^{-\rho})}. \quad (1)$$

B. POR Scheme

In the POR scheme, a packet that goes through the buffer postpones the reservation process until the time instant it leaves the buffer. Therefore, a packet leaving the buffer may be blocked by the channel again, and thus, it may re-enter the FDL. We assume that the maximum number of allowable circulations for a packet is limited to L. That is, a packet may use the buffer L times at most. If it is not accepted after L circulations, it is simply dropped. First, we calculate the probability that a packet in the buffer seize the channel after k circulations, P_k for $1 \le k \le L$. For $k = 1$, this can be evaluated as the probability that no new packet arrives during the gap after the channel has become idle and before the packet being delayed begins to leave the buffer. This probability can be written as $e^{-\lambda(b-r)}$, in which $(b-r)$ is the gap duration, and r, which is represented by random variable R [see Fig. 2], is the forward recurrence time of the packet in service as seen by the packet in the buffer at its arrival time instant. Note that $R + I = b$, where I represents the interarrival time between two packets. Therefore, we can write

$$\begin{aligned} Pr.\{(I \le b-r)|(I \le b)\} &= \frac{Pr.\{(I \le b-r) \cap (I \le b)\}}{Pr.\{I \le b\}} \\ &= \frac{Pr.\{I \le b-r\}}{Pr.\{I \le b\}} = \frac{1-e^{-\lambda(b-r)}}{1-e^{-\lambda b}} \end{aligned} \quad (2)$$

and the conditional probability density function (pdf) of $b - r$ for a given b is given by

$$f_{b-r|b} = \frac{\lambda e^{-\lambda(b-r)}}{1-e^{-\lambda b}} \quad (0 \le r \le b). \quad (3)$$

Averaging $P_{1|r}$ with respect to r, we have

$$P_1 = \int_0^b e^{-\lambda(b-r)} \frac{\lambda e^{-\lambda(b-r)}}{1-e^{-\lambda b}}\, dr = \frac{1-e^{-2\rho}}{2(1-e^{-\rho})}. \quad (4)$$

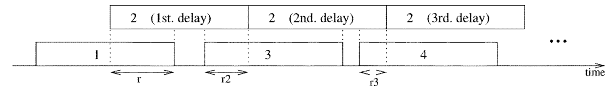

Fig. 3. Packet 2 recirculates because of arrival of Packets 3 and 4.

Then, we calculate the density function of random variable R

$$\begin{aligned} \text{Pr.}\{R \le r\} &= \text{Pr.}\{b - I \le r\} \\ &= 1 - \text{Pr.}\{(I < b-r)|(I < b)\} = \frac{e^{-\lambda b}(e^{\lambda r}-1)}{1-e^{-\lambda b}}. \end{aligned} \quad (5)$$

The pdf of the random variable R is

$$f_R(r) = \frac{\lambda e^{-\rho}}{1-e^{-\rho}} e^{\lambda r}. \quad (6)$$

Therefore, its mean value is given by

$$\overline{R} = \int_0^b r f_R(r)\, dr = \frac{\rho - 1 + e^{-\rho}}{\lambda(1-e^{-\rho})}. \quad (7)$$

According to Fig. 3, to calculate P_k $(k \ge 2)$ we can write

$$P_{k|r_k} = \left(1 - \sum_{i=1}^{k-1} P_i\right) e^{-\lambda r_k} \quad (k \ge 2) \quad (8)$$

where r_k is the forward recurrence time of r_{k-1}. For the sake of simplicity, in calculating P_k, we assume that r_{k-1} is a fixed value represented by its mean value $\overline{r}_{k-1}$. Then, it can be shown that the density function of r_k is given by $1/\overline{r}_{k-1}$. P_k $(k \ge 2)$ is, thus, given by

$$P_k = \left(1 - \sum_{i=1}^{k-1} P_i\right) \frac{1-e^{-\lambda \overline{r}_{k-1}}}{\lambda \overline{r}_{k-1}} \quad (k \ge 2) \quad (9)$$

where

$$\overline{r}_k = \frac{b - \overline{R}}{2^{k-1}} \quad (k \ge 1). \quad (10)$$

Next, we calculate the expected value of number of circulations of a packet in the buffer $E[k]$ before it is either accepted or dropped as follows:

$$E[k] = \sum_{i=1}^{L-1} i P_i + L\left(1 - \sum_{i=1}^{L-1} P_i\right). \quad (11)$$

Thanks to PASTA, the drop rate for a given L is

$$\begin{aligned} P_{D,L} = {} & \text{Pr.}\{(\text{channel busy}) \cap (\text{FDL busy})\} \\ & + \text{Pr.}\{(\text{channel busy}) \cap (\text{FDL free})\}\, P_d \end{aligned} \quad (12)$$

where $P_d = 1 - \sum_{i=1}^{L} P_i$ represents the probability that an accepted packet to the buffer is dropped after L circulations. The first term in the right-hand side of (12) represents the joint probability that both the channel and the buffer are busy and can be calculated as

$$P_{\text{Ch}\cap\text{FDL}} = P_{\text{Ch}|\text{FDL}} P_{\text{FDL}} \quad (13)$$

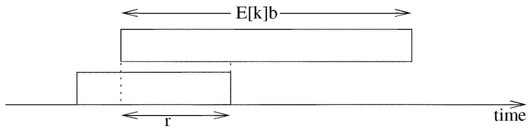

Fig. 4. Simple model to calculate the conditional probability that channel is busy given that FDL is busy.

where P_{FDL} gives the probability that FDL is busy, and $P_{\mathrm{Ch|FDL}}$ is the conditional probability that channel is busy given that FDL is busy. For $L = 1$, it is given by

$$P_{\mathrm{Ch|FDL}} = \frac{\overline{R}}{b} + \left(1 - \frac{\overline{R}}{b}\right)(1 - P_1). \tag{14}$$

For L greater than one, according to Fig. 4, this probability can be approximated by

$$P_{\mathrm{Ch|FDL}} \approx \frac{r}{E[k]b} + \left(1 - \frac{r}{E[k]b}\right)(1 - e^{-\lambda(E[k]b - r)}). \tag{15}$$

Therefore, we can write

$$\begin{aligned} P_{\mathrm{Ch|FDL}} &= \int_0^b P_{\mathrm{Ch|FDL}} f_R(r) dr \\ &\approx 1 - \frac{e^{-(E[k]+1)\rho}(e^{2\rho} - 1)}{2(1 - e^{-\rho})} \\ &\quad + \frac{e^{-(E[k]+1)\rho}(e^{2\rho}(2\rho - 1) + 1)}{4E[k]\rho(1 - e^{-\rho})}. \end{aligned} \tag{16}$$

Moreover, due to the recirculation process, each packet that enters the buffer stays there for the duration of $E[k]b$, on average. Accordingly, the probability that the FDL is busy can be evaluated as $E[k]$ times the fraction of load that enters the buffer. That is

$$\begin{aligned} P_{\mathrm{FDL}} &= \frac{\text{load carried through FDL}}{1 - P_d} E[k] \\ &= \frac{\rho((1 - P_{D,L}) - (1 - u))}{\sum_{i=1}^{L} P_i} E[k] \\ &= \frac{E[k]\rho(\rho - (1 + \rho)P_{D,L})}{\sum_{i=1}^{L} P_i}. \end{aligned} \tag{17}$$

In order to calculate the joint probability that the channel is busy and the buffer is idle $P_{\mathrm{Ch} \cap \overline{\mathrm{FDL}}}$, we can write

$$\begin{aligned} P_{\mathrm{Ch} \cap \overline{\mathrm{FDL}}} &= P_{\overline{\mathrm{FDL}}|\mathrm{Ch}} P_{\mathrm{Ch}} \\ &= \left(1 - \frac{P_{\mathrm{Ch} \cap \mathrm{FDL}}}{P_{\mathrm{Ch}}}\right) P_{\mathrm{Ch}} = u - P_{\mathrm{Ch|FDL}} P_{\mathrm{FDL}}. \end{aligned} \tag{18}$$

Substituting the results into (12), $P_{D,L}$ can be derived as

$$P_{D,L} = \frac{E[k]\rho^2 P_{\mathrm{Ch|FDL}} + \rho\left(1 - \sum_{i=1}^{L} P_i\right)}{1 + E[k]\rho(1 + \rho)P_{\mathrm{Ch|FDL}} + \rho\left(1 - \sum_{i=1}^{L} P_i\right)}. \tag{19}$$

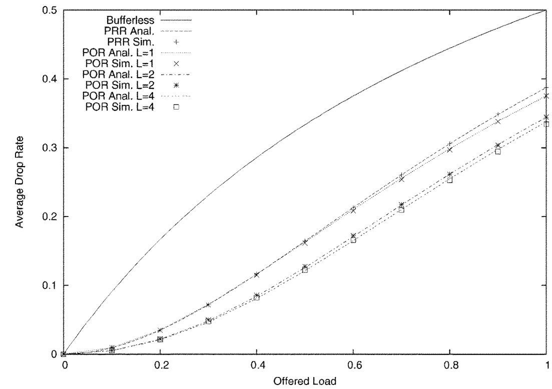

Fig. 5. Average drop rate versus offered load.

IV. Numerical Results

Analytical results for the drop rate for different scenarios are compared with the simulation results and plotted in Fig. 5. A discrete event simulator is used for this purpose, and each simulation point is run for 10 000 000 packets to generate confident results. It is seen that the analytical results closely match the simulation results. We also observe that using a single buffer results in a much improved performance compared to that of a bufferless node. It can also be noted that the POR scheme performs better than the PRR scheme. This is due to the fact that, in the PRR scheme, in a fraction of time the node remains unused. Another important observation is that increasing L from one to two has a great impact on the performance. However, $L > 2$ does not have any remarkable effect, and $L > 4$ does not lead to any improvement since P_d approaches zero. It can be further shown that the value of $E[k]$ is always less than 1.5, which validates the approximation used in (15).

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