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On Performance of Optical Buffers with Fixed Length Packets

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***Abstract*— In this paper, we analytically study the performance of fiber delay line as a means of contention resolution in optical routers. We consider asynchronous arrival of fixed length packets to a single-channel optical link equipped with a single delay line, and investigate the effectiveness of using delay line in improving the loss performance. The results include accurate equations for congestion rate and queuing delay, which are validated through simulation.**

I. Introduction

In recent decade IP-over WDM (Wavelength Division Multiplexing) has become an attractive research area and a lot of effort has been put into devising new techniques in order to deploy the huge capacity available over WDM links at the so-called sub-wavelength granularity. In other words, given the fact that advances in optics has provided a huge bandwidth available for data transmission, the current debate is which networking architecture, ranging from optical circuit switching (OCS) to pure optical packet switching (OPS), can utilize the available capacity in an efficient manner. Despite the fact that optical circuit switching is easy to implement, it fails to efficiently utilize the resources due to the bursty nature of IP traffic. On the other side of the spectrum, there is packet switching which its ability to fully utilize the network capacity has already been proven. However, there is still a big question whether or not the packet switching can be implemented in the optical domain due to lack of randomly accessed memories in optic. That is, a challenging issue in packet switched all-optical networks is congestion control at the core nodes. Accordingly, different variations of optical packet switching, such as optical burst switching (OBS) [1], have been proposed and studied. Nevertheless, contention resolution in all proposed architectures is still an important issue which greatly affects the overall network performance [6].

One of the available solutions is deployment of fiber delay lines (FDL) in order to locally delay contending packets [3]. FDLs merely provide fixed delays which are proportional to their lengths. The effectiveness of FDL buffers for contention resolution has been studied through simulation in [2] and [4], and it can be observed that FDL dimensioning is a crucial task since it has a great impact on the performance. Also, another important issue is that FDL dimensioning is highly dependent on the underlying switching technique. Variations of optical packet switching techniques can be categorized in two ways. First, switching can be performed in a synchronized or asynchronous manner. Second, data packets may have fixed or variable lengths. FDL buffer dimensioning is much simpler for the case of synchronized switching with fixed length packets compared to that of asynchronous switching, since in the former one the exact amount of delay required to resolve the contention is a priori known. According to [3], FDL buffers may be deployed in two different ways, namely feedforward or feedback configuration. In the feedforward configuration, optical buffer feeds forward to the next stage of the switch, while in the feedback configuration packets are sent back to the input of the same stage using FDLs.

In this paper, we develop an accurate queuing model to evaluate performance of a single-wavelength optical link which uses FDL for contention resolution under the assumption of fixed length asynchronous arrivals. Despite we limit our study to the case with fixed packet length, in practice it covers a broad range of architectures from OPS to OBS networks. We should mention here that, statistics of assembled bursts in OBS architecture is still under debate, and while many analytical studies assume exponential burst length distribution, some others have shown that burst length follows a very narrow Gaussian distribution. On the other hand, Yu et al. in [5] report that in a heavily loaded burst assembler, 99.99 per cent of generated bursts will have the average burst length, and in light load situation this decreases to 76.9 per cent. Another motivation for fixed length packets assumption, on the other hand, is that results achieved from related works show that the achieved gain, in terms of loss performance, using FDL buffers is very sensitive to the packet length statistics. Therefore, switching techniques based on fixed packet lengths can be an option since dynamic FDL provisioning is not possible. Throughout this paper, terms FDL and buffer are

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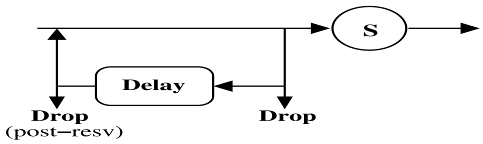

Fig. 1. Queuing model of WDM channel comprising a single server and delay line

used interchangeably.

The rest of this paper is organized as follows. In Section II, we introduce the system model and then in Section III FDL dimensioning is studied. In Section IV, we provide the performance analysis of the system. Section V provides numerical results including those obtained by means of simulation. Finally, we conclude the work in Section VI.

II. System Model

Consider an output WDM channel of an optical core node which is equipped with a single FDL to mitigate short term congestion as modeled in Fig. 1. Packets of the same length arrive to the channel from different input ports. Each arrival blocked by the channel, examines the buffer and joins it if it is available, otherwise, it is simply dropped. Note that each packet that enters FDL may reserve the channel in two different ways depending on the time of reservation. Namely, the packet may reserve the channel before entering FDL, *Pre-reservation* scheme, or alternatively, it can postpone the reservation process until the time instant it leaves the buffer, known as *Post-reservation* scheme [4]. This implies that, transmission of the packet being delayed in the buffer in pre-reservation scheme is always guaranteed. However, this in not the case for post-reservation because a third packet may arrive in the gap between the first packet leaves the channel and the packet in the buffer gets ready for transmission. We assume that in such a situation the packet in the buffer will be dropped. That is, each packet is allowed to use the buffer only once.

III. FDL Dimensioning

As mentioned before, FDL dimensioning is an important task in optical router design. In this section, we investigate the effect of FDL length for the system described in Section II. The objective of FDL dimensioning is *"to find the length of FDL for which the optimum performance, in terms of packet drop rate, is achieved."* Here, we consider both reservation schemes and show that the lowest drop rate is achieved when delay provided by the single FDL is equal to the packet length, i.e. the time required to transmit a packet over the channel.

We have assumed that horizon scheduling algorithm without void filling [2] is used to schedule arriving packets over the channel and FDL buffer. That is, for channel a time horizon is maintained, beyond which channel is not scheduled and thus, is available. When a request arrives to the system, arrival time of the packet is compared to the channel horizon and if channel horizon is before the arrival time, the packet is admitted and the channel horizon is updated to the time the packet will leave the channel. In case a packet fails to directly use the channel, buffer is examined as described in the last section. In a similar way, a time horizon has to be kept for the buffer.

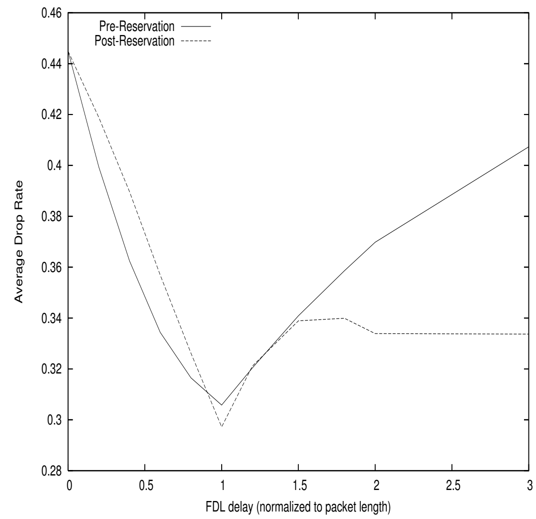

Fig. 2. FDL Dimensioning

Fig. 2, shows the effect of varying the FDL delay on the drop rate performance, obtained by means of simulation. We observe that an FDL delay equal to the packet length gives the lowest drop rate. Also, for small values of FDL delay drop rate of pre-reservation is better than that of post-reservation, however this does not hold when FDL delay increases. This is due to the fact that increasing the delay in pre-reservation translates to wider gaps (voids) over the channel which are not utilized.

IV. Performance Evaluation

In this section, we develop an accurate model to calculate the loss and delay performance of the system described in Section II.

Let requests for the channel arrive according to a Poisson process with rate λ, and service time of all requests be equal to fixed value b. According to the result obtained in Section III, we further assume that delay provided by FDL is equal to b. In the following we first develop a model for pre-reservation scheme.

A. Pre-reservation Scheme

In this scheme, a packet gets lost only when it arrives during the periods which FDL is busy. Note that when FDL is busy channel is also not accessible to a new arrival even if it is idle. Consider the example in Fig. 3, in which packet 2 arrives at time t_1 when channel is busy and FDL is idle. Then, packet 2 reserves the channel from $t_1 + b$ until $t_1 + 2b$ and joins the buffer. Note that, any packet arrives during interval $(t_1, t_1 + b)$ will be dropped in this example. Also, during interval $(t_2, t_1 + b)$ channel cannot be used by any packet. According to the PASTA (Poisson Arrivals See Time Average)

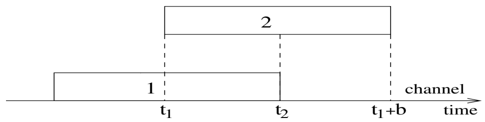

Fig. 3. Packet 1 is being transmitted over the channel when packet 2 arrives

property of arrivals, probability that channel is found busy by an arrival would be equal to the link utilization which is given by

$$u = \rho(1 - P_D) \tag{1}$$

where ρ is total offered load to the channel and P_D is packet drop rate. Average drop rate, thus, can be calculated as

$$P_{D,PreResv} = P(FDL\ \ Busy) = u(1 - e^{-\lambda b}) \tag{2}$$

where considering the exponential inter-arrival times, $(1 - e^{-\lambda b})$ represents probability that at least a new request arrives while channel is busy, and thus makes FDL busy. Substituting (1) in (2) and solving it for $P_{D,PreResv}$, we will have

$$P_{D,PreResv} = \frac{\rho(1 - e^{-\rho})}{1 + \rho(1 - e^{-\rho})} \tag{3}$$

where $\rho = \lambda b$. In the following we calculate the average queuing delay of this scheme. Note that, the fraction of accepted load which doesn't enter the buffer experiences no delay. The remaining part of accepted load, however, experiences fixed delay b. Thus,

$$\begin{aligned} D_{PreResv} &= \frac{carried\ \ load\ \ through\ \ FDL}{total\ \ carried\ \ load} b \\ &= \frac{u(1 - e^{-\rho})}{u} b \\ &= (1 - e^{-\rho})b. \end{aligned} \tag{4}$$

Note that according to definition of u, it gives total fraction of load carried. In addition, $u(1-e^{-\rho})$ represents the fraction of accepeted load which arrives when channel is busy, and hence uses the buffer.

B. Post-reservation Scheme

In this scheme we have to notice that an accepted packet to the buffer is still likely to be dropped if a third packet arrives in the time interval between channel becomes idle and the packet in the buffer comes out. Again consider example in Fig. 3, since packet 2 arriving at t_1 postpones the reservation until $t_1 + b$, any packet who arrives during interval $(t_2, t_1 + b)$ will cause packet 2 to be dropped. For the sake of simplicity we first calculate complementary drop rate $P^c_{D,PostResv} = 1 - P_{D,PostResv}$. Remembering the PASTA,

$$\begin{aligned} P^c_{D,PostResv} &= P(channel\ \ free) \\ &+ P(channel\ \ busy\ \ \cap\ \ FDL\ \ free).P_a. \end{aligned} \tag{5}$$

Obviously probability of channel being free is equal to $(1-u)$. Also, the second term in (5) represents that part of accepted packets arriving when channel is busy but FDL is idle. Therefore, P_a is probability that a packet in the buffer is not dropped. We can write

$$\begin{aligned} & P(channel\, busy \cap FDL\, free) \\ &= P(FDL\, free\, |channel\, busy).P(channel\ \ busy) \\ &\approx e^{-\lambda(b-l)}u. \end{aligned} \tag{6}$$

Given that channel is busy, $e^{-\lambda(b-l)}$ represents the approximate probability that no request arrives while channel is in use. More specifically, when a packet starts receiving service by the channel it may find FDL busy at the beginning, which this length is represented by l and can be approximated by forward recurrence time of a packet in service as seen by a new arrival. Therefore, $(b - l)$ would be fraction of the packet during which FDL is free. Since packet length always assumes fixed value b, probability density function of l is given by

$$f_L(l) = \begin{cases} \frac{1}{b} & (0 \le l \le b) \\ 0 & (elsewhere) \end{cases} \tag{7}$$

Therefore, averaging (6) with respect to l we have

$$\int_0^b e^{-\lambda(b-l)} u \frac{1}{b}\, dl = u \frac{1 - e^{-\rho}}{\rho}. \tag{8}$$

Also, P_a can be determined as the probability that no request arrives in the gap between channel becomes idle and the packet in FDL starts receiving service, which approximately equals $e^{-\lambda(b-l)}$, and thus can be calculated in the same way as in (8). Substituting the results into (5) and solving it for $P_{D,PostResv}$, we will have

$$P_{D,PostResv} \approx \frac{\rho(1 - (\frac{1-e^{-\rho}}{\rho})^2)}{1 + \rho(1 - (\frac{1-e^{-\rho}}{\rho})^2)}. \tag{9}$$

Finally, we study the average queuing delay of the scheme in the same way as in pre-reservation scheme. In this case that part of the carried load which goes through delay is given by $u - \rho(1 - u)$, where the second term is carried load that finds channel idle, and thus doesn't use FDL. Thus,

$$\begin{aligned} D_{PostResv} &= \frac{u - \rho(1 - u)}{u} b \\ &= \frac{\rho - (1 + \rho)P_{D,PostResv}}{1 - P_{D,PostResv}} b. \end{aligned} \tag{10}$$

V. Numerical Results

Results of applying the proposed model to a single WDM channel are presented and compared with those obtained by means of simulation. Fig. 4, represents the average drop rate for different scenarios against load including bufferless case. Note that the average drop rate for bufferless case is simply equal to u. According to the figure, analytical results match the simulation ones very closely. We further observe that the drop rate for both schemes are very close to each other and both perform completely better than the bufferless case, as expected. Also, the post-reservation performs slightly better

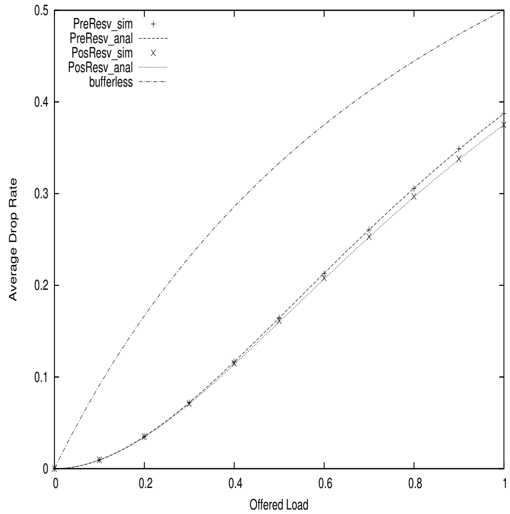

Fig. 4. Average Drop Rate vs. Load

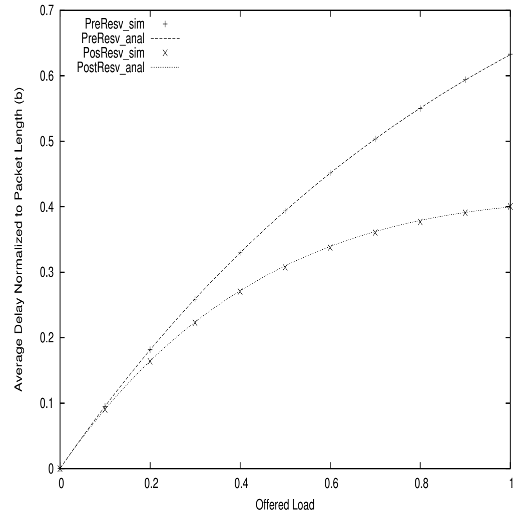

Fig. 5. Average Queuing Delay vs. Load

than pre-reservation. The reason lies in the fact that in pre-reservation scheme a part of capacity remains unused due to voids.

Fig. 5 shows results for average queuing delay. It can be seen that the more the load increases, the more the number of packets which go through delay becomes. Also, by increasing the load beyond 1, though not shown here, we observe that average delay for pre-reservation scheme asymptotically approaches one, however that of post-reservation decays to zero. This can be intuitively understood from the difference in reservation mechanisms of the schemes. Specifically, by increasing the load more packets enter FDL in pre-reservation and since all packets that enter FDL will be transmitted, less packets will be directly accepted by the channel. However, in post-reservation entering the buffer does not necessarily guarantee that packet will not be lost, and the probability that packet in the buffer is dropped increases with load.

VI. Conclusions

We have studied the effectiveness of using FDL for contention resolution in a single-channel optical link with fixed length packets. FDL dimensioning was investigated and it was shown that the optimum loss performance is achieved when an FDL of the length equal to packet length is deployed. Then, we developed an accurate analytical model to evaluate the loss and delay performance of the system using both possible reservation schemes. Accuracy of the presented models has been demonstrated through simulation. We are currently working to extend the model to include a more general case in which a packet is allowed to use FDL more than once in post-reservation scheme.

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