Approximate Modeling of Optical Buffers for Variable Length Packets

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Abstract. This paper addresses the problem of dimensioning buffers realized by means of fiber delay lines in optical routers able to switch packets that have variable length and are sent asynchronously on the optical links.

The optical buffer is analyzed focusing on the different behavior of a delay buffer and an electronic memory. The role of the time unit of the fiber delay lines is discussed, showing that it is a crucial parameter to determine the queueing performance.

The paper presents two approximate analytical models that can be used both for analysis and engineering of the optical buffer and in particular to dimension the buffer time unit in an way that is optimal with respect to packet loss probability. The first model is based on an infinite queueing approximation. It is not very accurate and is valid for a limited set of values of the traffic load, but is extremely simple. The second model is based on a finite queueing approximation. It is more complex but more accurate and is valid for any value of traffic load.

The accuracy of the models is compared with simulation and their range of applicability purposes is discussed.

Keywords: optical packet switching, fiber delay line buffers, optical internet, queueing systems

1 Introduction

The explosion of the Internet, with the exponential increase of traffic in the national and international backbones, requires powerful, very flexible and scalable networks. The optical technology is able to meet these requests providing a very high bandwidth and a good flexibility as well as scalability with the introduction of dense wavelength division multiplexing (DWDM) systems.

Optical packet switching is poised to be the next step towards the fulfillment of the aforementioned needs, making available the optical resource on a per packet basis, and several network and switching fabric architectures for optical packet switching have been investigated recently (see, for instance, Yao et al. [1] for a survey).

In this paper, the focus is placed on optical buffers, that are an integral part of any optical packet switch. Up to now, the most common way to realize an optical buffer has been by means of fiber delay lines (FDLs). Since the purpose of the FDLs is to delay a packet, their length is measured in terms of delay units, called $D$ in this paper. In a network with synchronous fixed length packets it is natural to choose $D$ equal to the length of the packets. In this case, the optical buffer is equivalent to a normal queue and the teletraffic performance is related to the buffer occupancy, namely the number of packets in the buffer. Dimensioning of FDL buffers as well as congestion resolution techniques tailored to this scenario has been widely studied in the last few years [2–5].

On the other hand, in the case of asynchronous variable length packets the behavior of the delay buffer is different from that of a normal queue, as pointed out in Tancévski et al. [6] and Callegati [7]. At the same time, the problem is extremely up to date since the proposals for optical packet switching to support Internet traffic goes into the direction of the so-called “optical burst switching”, where packets have variable length [8,9].

This paper presents and compares two approximate analytical models that can be used to engineer an optical buffer in this case. The models were originally presented separately in Callegati [7, 10]. Here they are reviewed in a uniform perspective and compared in terms of performance and accuracy. The models are not tailored to a specific switching matrix, and only assume output queuing and a first-come-first-served scheduling policy. The focus is on a single output buffer, seen as a stand-alone queuing system. In a real implementation, it is very unlikely that an optical packet switch will be equipped with a set of FDLs per output port. Usually a switching matrix is equipped-
with a single set of delay lines, shared in WDM among all input and output pairs [11]. In spite of the physical sharing, the logical behavior depends on the switch control. In general, the control is simpler and easier to implement when each output queue behaves independently, as if there was a dedicated set of delay lines for each output, and this is the case considered in this paper.

It is also assumed that the buffer is degenerate, following the definition by Tancévski [12], meaning that the FDLs introduce delays that are consecutive multiples of $D$. The first delay is equal to 0, the second to $D$, the third to $2D$ and the maximum delay is equal to $D_M = MD$. If $B$ is the number of FDLs, the maximum delay in a feed-forward architecture is $D_M = (B-1)D$. In a feedback architecture it is $D_M = RB - 1)D$ where $R$ is the maximum number of times a packet can be fed back into the buffer. In order to keep the presentation as general as possible, it will be assumed that $D_M = MD$ in the following, where $M$ depends on the switching architecture.

In case the input/output links are operated in WDM, a wavelength circuit multiplexing scheme is assumed in this paper, according to the definition in Guillemot et al. [5]. This is also called shared wavelength path (SHWP) multiplexing scheme in Hunter et al. [13]. In this scheme, each end-to-end connection or packet flow is assigned a particular wavelength on any fiber and many connections share the same wavelength. In practice, each wavelength operates like a single link and there is no statistical multiplexing of packets belonging to the same connection on the wavelengths.

The paper is structured as follows. In Section 2, a discussion on the functional behavior of the FDL buffer is presented outlining the difference with respect to a normal electronic buffer and intuitively explaining the role of $D$. In Section 3, the approximate models are briefly reviewed, followed, in Section 4, by numerical results and discussion. In Section 5, some conclusions are drawn.

2 FDL Buffers and Variable Length Packets

If in the optical switching matrix a packet arrives and the assigned wavelength on the output fiber is idle, it is served immediately. If the wavelength is busy, the packet is delayed up to the time the output will be free. Calling $t$ the time of the arrival and $t_f$ the time at which the output wavelength will be free the packet should be delayed of an amount $t_f - t$. On the contrary, as shown with an example in Fig. 1 the new packet is going to be delayed of an amount

$$\Delta = \left\lceil \frac{t_f - t}{D} \right\rceil D$$

where $\lceil x \rceil$ indicates the smallest integer greater than or equal to $x$.

As a result, for the time interval $\tau = \Delta - t_f + t \geq 0$ (shaded in Fig. 1), the output line is not used while there would be a packet to transmit. Thus, it may be that there is a packet queued even if the server is idle. This happens when one packet has been served and there is another packet queued that can not be served yet since its delay has not expired. This vacation of the

![Fig. 1. Example of queuing in a FDL buffer.](image-url)