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Single-wavelength optical buffers with general burst size distribution: Blocking probability and mean delay☆

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ABSTRACT

As an emerging novel technology, optical buffering via fiber delay lines (FDLs) is adopted in optical burst switching (OBS) networks for contention resolution. In this paper, we study the blocking probability and the mean delay of an asynchronous single-wavelength optical buffer, where the burst arrival process is Poisson and burst-length distribution is general. With the aid of Level Crossing (LC) method, we first derive the integral equations to model the dynamics of the buffer. We then propose a method to solve these equations. Finally we present the mathematical expressions of blocking probabilities and the mean delays for the optical buffer with general burst size distribution. Numerical examples are provided to validate our results, and some interesting observations from the numerical examples are highlighted.

1. Introduction

Optical Burst Switching (OBS) is a promising network technology for the future all-optical networks. Performing wavelength division multiplexing (WDM), optical links in the network have the capacity of multiple parallel transmission channels so as to achieve high overall data rate.

However, blocking of burst will inevitably be resulted from contention in the switches, in the situation where two or more bursts arrive at an OBS router simultaneously and contend for the same output. To resolve the contention problem the optical buffering technique (see, *e.g.* [1,2], and [3]) is proposed. Optical buffer usually consists of a set of fiber delay lines (FDLs), which is used to set upon different delays to the accepted burst. It has been shown in [4] that the application of optical buffer at the output port in an OBS switch is effective, but the additional cost of FDLs will arise.

Regarding the blocking and queueing behavior of an optical buffer there have been a number of analytical models being developed so far. In [5] and [6], the author investigates an asynchronous optical buffer with Poisson arrivals and exponential burst lengths. Overflow analysis of an OBS with FDLs is given in [7]. In [8], the authors develop an analytic model for optical delay line buffer and consider special impatience features with the assumption that the packet lengths are exponentially distributed random variables. They show that the developed model with impatience features can decrease burst loss probability and they claim that shared buffer architecture with optical buffer achieves lower burst loss probability. In [9], based on the multi-regime Markov fluid queues theorem, the authors suggest an algorithm to obtain the exact solutions of the blocking probability. In this work, the packet size is assumed to follow phase-type (*PH*) distribution, which is constructed by a convolution or mixture of exponential distributions [10]. The paper [11] presents numerical results for the exponentially distributed burst length based on the closed-form expression. However, these studies consider the blocking probability under the assumption that the burst size follows some particular distributions.

In [12], the exponential assumption has been lifted, and the author thereby obtains an approximation expression for the blocking probability. Using a probability generating function approach, the authors in [13] consider synchronous FDL buffers. A multi-channel FDL, that is in non-shared status with Bernoulli arrivals, is discussed in [14], and [15], the authors obtain some approximate results to the performance metrics of the optical buffers. The work [16] investigates the blocking probabilities of the optical buffers for a generally distributed packet length even when the offered load is extremely low. However, the blocking probability given in these literatures is only in approximate expressions. In [17], the authors establish the blocking probability and

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mean delay expressions for the case, where the packet-length follows a general distribution. However, during solving the system, some additional assumption is added, *e.g.* the void period is assumed to be uniformly distributed. Furthermore, these solutions are given with the Laplace transformation form being involved. One has to solve the inverse Laplace transformation to obtain the numerical results.

In practice, on one hand, different burst size distributions may arise from the different burst assembly algorithms, the burst size cannot be simply regarded as some particular distribution. On other hand, in some scenario, the blocking probabilities are very sensitive to the burst length distribution (see Section 4). In this case, neglecting the difference between the burst size distributions will bring a drawback to those models and algorithms and make them be impractical in the design, development and optimization of optical buffers.

Motivated by the practical application of OBS networks, in this paper we study an asynchronous single-wavelength optical buffer when burst sizes possess general distributions. Our main objective is to investigate the blocking probability and mean delay time of an asynchronous single-wavelength optical buffer. We present a novel method to derive the exact blocking probabilities and the mean delays of the bursts. The main differences between our current paper and the afore-mentioned papers, *i.e.,* the main contributions of our paper, are given as follows. Firstly, we will relax this constraint on the burst size, and consider the burst with arbitrary size distribution. Secondly, we do not simply extend the currently results in the literature and the references therein. Instead, we propose a novel approach by using the Level Crossing (LC) theory [18,19], to obtain the integral equations of the model system of the optical buffer. Without additional assumption, we give the exact expressions of the blocking probability and the mean delay.

The remaining parts of the paper are structured as follows. We start by describing the established model in Section 2. In Section 3, we briefly describe the LC method and derive our detailed solution procedures. Numerical examples are given in Section 4 that serve as illustrations. Finally, we summarize the main results in Section 5.

2. System model

We consider a single outgoing channel and assume that the contention is resolved by means of an fixed-delay FDL buffer. Unlike the contention buffers, the FDL buffer cannot delay bursts for an arbitrary period of time, but only for multiples of a time granularity D. Buffers of this type are referred to as degenerate. The degenerated optical buffer is composed of $N+1$ FDLs. The i-th FDL is able to delay the arrived burst for iD time units, for some $i = 0, 1, \ldots, N$. The maximum delay of the optical buffer is ND, which means that bursts with a delay time longer than ND are dropped. We assume that bursts are served under the first-come first-served (FCFS) rule. For the convenience of the representation, let $D_0 = 0$, $D_1 = D$, $\ldots, D_N = ND$.

We assume that the incoming burst arrival adheres to a Poisson process, in which the rate is assumed to be λ. We let L denote the burst size, which can be measured using service time. Throughout the paper, the burst-length is assumed to be a random variable, and it can follow an arbitrary distribution. The cumulative distribution function (cdf) and the mean size of the burst are denoted by $S(x) = P(L \le x)$ and $E[L]$, respectively. Besides the above, we do not introduce any other assumption in our following up analysis. We denote the tailed distribution by $\bar{S}(x) = 1 - S(x)$ and the offer load of the optical buffer by $\rho = \lambda E[L]$.

In order to show in detail how the optical buffer works, we first define $\{H(t), t \ge 0\}$ as the channel horizon process. The component $H(t)$ stands for the unfinished work at time epoch t. With reference to Fig. 1, if an optical burst arrives at time epoch t, there are following manipulations taken by the link regarding this specific time epoch:

- If the link is free, *i.e.*, $H(t) = 0$, this burst is immediately accepted and further it is forwarded over the link. In this case, we have $H(t+) = L$.
- If $H(t) > D_N$, then the burst will be blocked due to the fact that, the delays generated by delay lines are not significantly larger than that can avoid the contention.
- If $0 < H(t) \le D_N$, the arriving burst will be injected into the delay line to avoid contention. The burst would be delayed for the time duration given by

$$D\left\lceil \frac{H(t)}{D} \right\rceil,$$

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

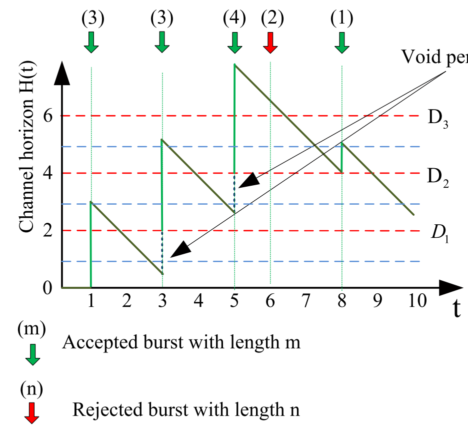

Fig. 1. The channel horizon process sample when $D = 2$ and $N + 1 = 3$. Bursts with the sizes 3, 3, 4, 2, and 1 arrive at time epochs t = 1, 3, 5, 6, and 8, respectively. The burst arriving at $t = 6$ is blocked due to $H(6) > D_3$, and all other bursts are admitted into the buffer.

In the last case, the horizon level subsequently becomes

$$H(t+) = D\left\lceil \frac{H(t)}{D} \right\rceil + L.$$

During other time interval, since the packet length is measured in terms of the service time, the horizon level decreases at rate of 1 until it becomes zero. It remains at level zero until a new burst arrives the buffer.

According to the description, we obtain a new workload dependent balking queue, which operation is described as follows.

The customer arrives in a Poisson process with rate λ. Let $\{H(t), t \ge 0\}$ be the workload process, and we have the following workload dependent balking rule: there are N nonnegative constant thresholds, which are written as $D_0, D_1, \ldots, D_N$. The customer arrives the system at time epoch t, there are three cases:

- if $H(t) = 0$, the customer joins the queue, the service requirement is L;
- if $D_{i-1} < H(t) \le D_i$, $1 \le i \le N$, the service requirement is $D_i - H(t) + L$;
- if $D_N > H(t)$, the customer is blocked.

To further our analysis, we first give the following definition.

Definition 1.

1. The stationary accumulate distribution function: $F(x) = lim_{t\to\infty} P(H(t) \le x)$;
2. The stationary probability density function: $f(x) = \frac{d}{dx}F(x)$;
3. The probability mass at zero: $P_0 = F(0)$.Throughout the paper, in order to simplify the notations, for $i = 0, 1, \ldots, N$, $k = 1, 2, \ldots, N$, and $x \ge 0$, we denote: