Blocking and Delay Analysis of Single Wavelength Optical Buffer With General Packet Size Distribution

Jianming Liu, Tony Tong Lee, *Fellow, IEEE*, Xiaohong Jiang, and Susumu Horiguchi, *Senior Member, IEEE*

***Abstract*—Buffers are essential components of any packet switch for resolving contentions among arriving packets. Currently, optical buffers are composed of fiber delay lines (FDL), whose blocking and delay behavior differ drastically from that of conventional RAM at least two-fold: 1) only multiples of discrete time delays can be offered to arriving packets; 2) a packet must be dropped if the maximum delay provided by optical buffer is not sufficient to avoid contention, this property is called balking. As a result, optical buffers only have finite time resolution, which may lead to excess load and prolong the packet delay. In this paper, a novel queueing model of optical buffer is proposed, and the closed-form expressions of blocking probability and mean delay are derived to explore the tradeoff between buffer performance and system parameters, such as the length of the optical buffer, the time granularity of FDLs, and to evaluate the overall impact of packet length distribution on the buffer performance.**

***Index Terms*—Blocking and delay performance, optical buffer, optical switching, queueing analysis.**

I. Introduction

THE ADVANCES in dense wavelength division multiplexing (WDM) technology and the emerging all-optical network call for the realization of high-speed optical switches, which serve a heterogeneous population of users who require both guaranteed bandwidth connections and bandwidth on demand services of differing average information rates and burstiness. To serve these users, the switches provide point-to-point and point-to-multipoint services between the access stations. In the face of optical technology evolution, the switch architecture should also seamlessly support the addition of even higher speed stations in the future.

Manuscript received March 16, 2008; revised July 31, 2008. Current version published April 17, 2009. Part of this paper has been presented on the INFOCOM 2007, Anchorage, AK, with the title: Blocking and Delay Analysis of Optical Buffer with General Packet Length Distribution. This work was supported in part by the GCOE project of Tohoku University, JSPS Grant-In-Aid of Scientific Research (C) 19500050, the National Natural Science Foundation of China (60762002) and GuangXi Province (0731024), and GuiJiaoKeYan 2006 (No.26, D200644).

J. Liu is with the Department of Computer Science, Graduate School of Information Sciences, Tohoku University, Sendai 980-8579, Japan and also with the School of Computer and Control, GuiLin University of Electronic Technology, GuiLin 541001, China (e-mail: jmliu@guet.edu.cn; jmliu@ecei.tohoku.ac.jp).

T. T. Lee is with the Department of Information Engineering, Chinese University of Hong Kong, Shatin, NT.

X. Jiang is with the Department of Computer Science, Graduate School of Information Sciences, Tohoku University, Sendai 980-8579, Japan (e-mail: jiang@ecei.tohoku.ac.jp) and also a visiting researcher of the State Key Laboratory for Novel Software Technology, Nanjing University, China.

S. Horiguchi is with the Department of Computer Science, Graduate School of Information Sciences, Tohoku University, Sendai 980-8579, Japan (e-mail: susumu@ecei.tohoku.ac.jp).

Digital Object Identifier 10.1109/JLT.2008.2004951

Optical burst switching (OBS), a hybrid of packet switching and circuit switching, is a promising switching technology for supporting all-optical networks [1]. The basic information unit handled by OBS is the variable-length packet or a "*burst*," which is the aggregation of upper layer data units, transmitted through the wavelength channels in WDM networks. In general, packets arrive at an OBS router asynchronously, two or more packets may contend for a same output port. Buffers, either at input ports or at the output ports, are essential components of packet switches for resolving contention problems. Various optical burst switch architectures employing different buffering strategies have been proposed in [2]–[5]. It has been shown in [5] that the employment of optical buffer at the output port of the OBS switch can reduce the packet loss probability by two to three orders of magnitude.

Currently, optical random access memory (RAM) is unavailable, and the optical buffer is usually composed of a set of fiber delay lines (FDLs). Optical buffers can be either single-stage, which have only one block of FDLs, or multistage, which have several blocks of FDLs cascaded together. We can further classify the optical buffers into feed-forward, feedback, and hybrid architectures [3], [6]. For example, in the feedback architecture, each FDL connects an output port of a switching element at a given stage to an input port of a switching element in the same stage or a previous stage. Furthermore, buffers can be either configured as fixed-delay FDL buffer [2], [8], [14] or variable-delay FDL buffer [2], [3]. The fixed-delay buffer, as illustrated in Fig. 2, is simple in structure and also cost effective, which make it one of the research focuses [10]–[12].

Optical buffer behaves differently from electronic RAM two-folds.

1) The FDLs can only delay the packets for multiples of *discrete* (i.e. constant) amount of time, which is related to the length of the FDL, measured in terms of delay unit, called *time granularity*.
2) The maximum delay that an optical buffer can provide to an input packet is bounded. A packet will be dropped if this maximum delay is not sufficient to avoid contention. This characteristics is referred to as the *balking* property.

Furthermore, a packet can be stored in electronic buffer for arbitrary amount of time and read out whenever necessary. However, due to the *discrete* delay and *balking* property described above, a packet stored in an optical buffer can only be retrieved at the end point of a FDL. Thus, we say that the optical buffer only has *finite time resolution*, while the electronic buffer has *infinite time resolution*. The finite time resolution property will introduce a void period between two successive buffered packets. During this void period, the output channel is standing idle, even if there are packets waiting in the buffer. This non-work conserving property will deteriorate the buffer performance and prolong the delay experienced by input packets. Therefore, key parameters such as the length of optical buffer and the time granularity of FDL should be properly chosen to meet blocking and delay requirements.

The performance evaluation of optical buffer raises some new modelling issues. Attempts have been made in [7]–[9] to approximate the optical buffer behavior by M/M/k/D queue, but they fail to characterize both the *discrete* delay and the *balking* property of optical buffer. An improved approximation is developed in [5], which adopts M/M/k queue to study the impact of optical buffer on the performance of OBS. Some numerical estimations of the blocking of optical buffers are reported in [10]–[12]. An iterative scheme to approximate optical buffer blocking performance is proposed in [10], which assumes that the packet arrival process is Poisson and the packet length is exponentially distributed. This exponential assumption is relaxed in [11], in which an approximation of blocking probability is obtained and the impact of burst distribution on buffer performance is evaluated. A Markovian model to evaluate the buffer performance numerically under arbitrary traffic patterns is presented in [12]. With Poisson arrival process and exponentially distributed packet length assumptions, we derive a simple closed-form expression to approximate the packet blocking probability in [13].

In this paper, taking discrete delays and balking property into consideration, we develop a novel queueing model of optical buffer with Poisson arrival and general packet length distribution. To model the finite time resolution, we treat the void period between two successive buffered packets as the prolonged length of the *real packet*. We analyze the busy period with exceptional first packet to account for the real packet plus the preceded void period, called PACKET. To model the balking property, we first obtain the waiting time distribution for the infinite buffer through busy period analysis, in which the maximum delay provided by optical buffer is assumed to be unbounded and no packets will be blocked. We then analyze the excess load introduced by FDLs and evaluate the impact of finite time resolution property on the offered load. It follows that the closed-form expressions of packet blocking probability and the mean delay can be obtained by a connection of virtual waiting time distributions between infinite and finite optical buffers.

Our analytical results reveal the fact that the finite time resolution property leads to excess offered load to system, and there exists an optimal time granularity of FDLs that minimizes the packet blocking probability. We show that this optimal granularity is not sensitive to packet length distribution; and when buffer length is large, the optimal granularity is also not sensitive to the length of buffer, it is mainly determined by the traffic load.

The remainder of this paper is organized as follows. Section II describes a structure of optical buffer and its finite time resolution property. In Section III, we develop a specific queueing model for infinite optical buffer, analyze the impact of finite time resolution on the offered load to system, and obtain the waiting time distribution. In Section IV, we derive the mean packet delay and packet blocking probability for the finite optical buffer. In Section V, we show how the design parameters will influence the buffer performance. Finally, this paper is concluded in Section VI.

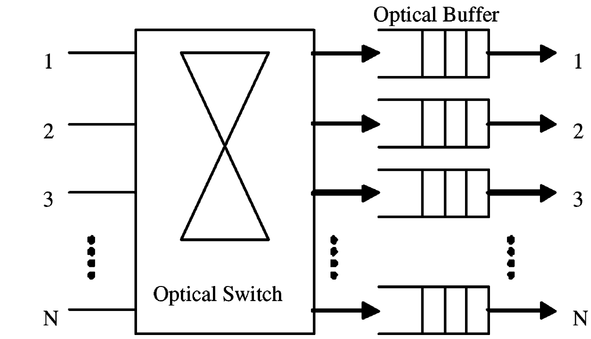

Fig. 1. Optical buffers at the output ports of an optical burst switch.

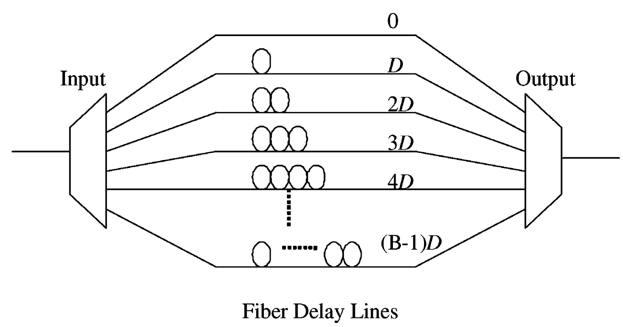

Fig. 2. Optical buffer consists of fiber delay lines.

II. Finite Time Resolution of Optical Buffer

In this section, we will describe the finite time resolution properties, discrete delay and balking, of optical buffer in details to facilitate our analysis in the sequel.

A. Discrete Delay Property

As an example, Fig. 1 shows the basic configuration of the optical buffers at the output ports of a switch. This switch architecture employs the output buffering strategy and each of the output port is equipped with a dedicated buffer, which consists of FDLs.

The fixed-delay FDL buffer is simpler and less costly to implement. In our analysis, we will focus on the fixed-delay buffer. The fixed-delay buffer, as illustrated in Fig. 2, has B FDLs with the ith FDL being able to delay a packet for a *discrete* time $(i-1)D$, $1 \leq i \leq B$, where D is the time *granularity* of the FDLs, and B is the buffer length. Thus, the optical buffer can only provide discrete delays $0, D, 2D, \ldots, T$ of multiples of Ds, where the maximum delay is given by $T = (B-1)D$.

Note that each FDL can accommodate up to k different wavelengths, such that an optical buffer can effectively provide k identical *virtual buffers*. Without loss of generality, we will analyze one of these virtual buffers, and adopt the first-in-first-out (FIFO) policy.

B. Balking and Finite Time Resolution

The characteristics of optical buffer is depicted in Fig. 3, in which we use the black lines with different lengths to denote the different delays realized by the FDLs.

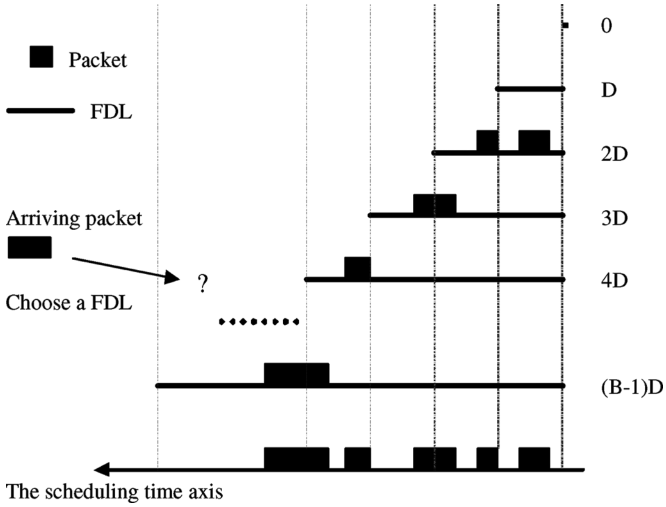

Fig. 3. Time interleave in optical buffer.

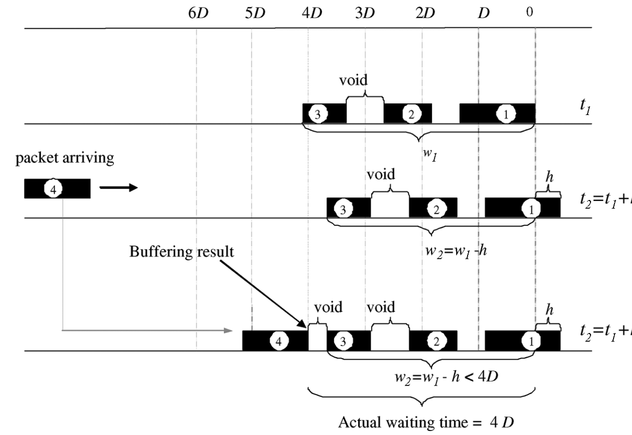

Fig. 4. Packet scheduling in optical buffer.

For the convenience of analysis, the packet length is measured in terms of service time.

In an output queued switch, plural packets with the same wavelength may be switched to the same output port. These packets should be scheduled in time to avoid contentions. As shown in Fig. 3, a newly arrived packet will be transmitted by the output channel immediately if no packets are waiting in the buffer and the output channel is free. Otherwise, the arriving packet will be injected into one of the FDLs to be buffered. The length of a packet is known upon its arrival. The choice of FDL is based on the time needed to process the backlog packets in the buffer. Suppose an arriving packet has to wait for at least w units of time to be served, then two possible scenarios may occur:

1) if $(i-1)D < w \leq iD$, the packet will be switched to $(i+1)$th FDL of the buffer;
2) if $w > (B-1)D$, the packet will be blocked.

Accordingly, services of packets buffered in different FDLs will be scheduled on FIFO basis, as depicted in the bottom of Fig. 3. The buffering process is illustrated by an example displayed in Fig. 4. At time t_1, it takes w_1 units of time to process all three packets in the buffer. The packet 4 arrives after h units of time at $t_2 = t_1 + h$, and the time needed to process all three packets becomes $w_2 = w_1 - h$. Since the output channel is occupied by packet 1, the packet 4 has to wait for at least w_2 units of time to avoid contention. Fig. 4 shows that $3D < w_2 < 4D$, which means the packet 4 will be injected into the 5th FDL according to the above rule, and it will be dropped (blocked) if buffer length $B < 5$, the *balking* property of FDLs.

The discrete delay will introduce void period between consecutive packets. In the schedule given in Fig. 4, the packet 4 will not reach the end point of 5th FDL before time $t_2 + 4D$, however, the services of packets 1,2,3 are completed at time $t_2 + w_2$. The output channel will be standing idle and waiting for packet 4 to come out of the 5th FDL during the time interval $[t_2 + w_2, t_2 + 4D]$, a *void period* of duration $\tau = 4D - w_2$ is introduced.

The output channel is non-work conserving and the service time of buffered packets are prolonged due to the void periods, which introduce *excess load* to the system. In the case that the buffer is empty and the output channel is free upon the arrival of the packet, it can be transmitted immediately and no void period will be introduced. This packet is a *first-arrival-packet*, which initiates a busy period of the system, and all other packets are *non-first-arrival-packet*, e.g. packet 4 in the above example.

In the following analysis, the term '*packet*' denotes the physical (real) packets in the buffer, and the term PACKET is used to indicate the effective service time of a packet. For the first-arrival-packet, the PACKET service time is the real packet length, while the PACKET service time of the non-first-arrival-packet is the sum of real packet length and the duration of preceded void period.

III. Analysis of Infinite Optical Buffer

The waiting time distribution is the core issue of optical buffer analysis, because an arriving packet will choose the FDL according to required waiting time, a constraint imposed by the finite time resolution of optical buffer described in Section II. We first consider the infinite buffer case, $B \to \infty$, in which the buffer can provide infinite long delay and no packet will be lost. Later, this result will be extended to analyze the finite buffer case.

The buffer is modeled as a single server queue with FIFO policy. We assume that the packet arrival is a Poisson process with rate λ, and the packet length s_0 follows a general distribution with probability density function (PDF) $g_0(x)$, with mean $\overline{s}_0$ and cumulative distribution function (CDF) $G_0(x)$. In this section, we will describe the busy period of this single server queue with exceptional service for the first packet.

A. Busy Period With Exceptional Service for the First Packet

The busy period depicted in Fig. 5 starts when a first-arrival-packet arrives at an empty system, and ends when the system becomes empty again. Suppose a non-first-arrival-packet arrives at time t_a and it has to wait for a minimum duration w to avoid contention. The packet would be delayed for a discrete duration

$$\Theta = \left\lceil \frac{w}{D} \right\rceil D = iD \tag{1}$$

and injected into the $(i+1)$th FDL, where $\lceil x \rceil$ indicates the smallest integer greater than x. Consequently, the server is

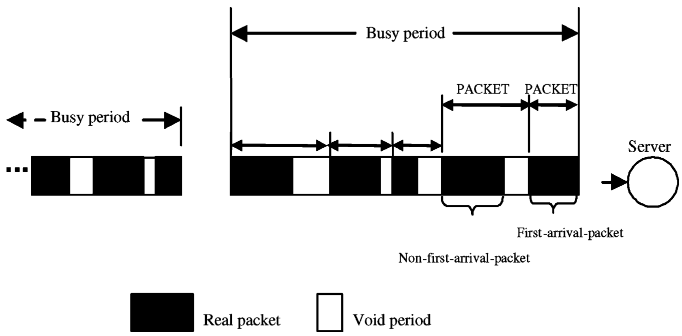

Fig. 5. Queueing process of optical buffer.

standing idle during the interval $[t_a + w, t_a + \Theta]$ with duration $\tau = \Theta - w$, until this packet comes out of the $(i+1)$th FDL to commence the service.

Under the assumptions of Poisson arrivals and independent packet length distribution, in [5], [10], [11] the duration of void period τ is considered to be uniformly distributed over the interval $[0, D]$ with mean $D/2$. Recall that the optical buffer shown in Fig. 5 is modeled as a queueing system with exceptional service for the first packet in each busy period, in which the service time of first PACKET (first-arrival-packet) equals to the real packet length s_0, and the service times of other PACKETs (non-first-arrival-packets) are i.i.d. random variables $s_v = s_0 + \tau$ with the following PDF

$$g(x) = g_0(x) * l(x) \tag{2}$$

where $l(x)$ is the PDF of the void period, '*' is the convolution operation and the CDF of s_v is denoted by $G(x)$.

B. PACKET Waiting Time Analysis

We need the following definitions in conducting the analysis of infinite buffer:

$v(x,t)$	PDF of virtual waiting time x at time t
$v(x)$	steady state PDF of virtual waiting time x;
$V(x)$	steady state CDF of virtual waiting time x;
$Q(t)$	probability of system being empty at time t;
Q	steady probability of system being empty;
$\overline{S}$	expected PACKET service time.

The *virtual waiting time* at time t is the duration x needed by the output channel to clear all backlogged packets in the buffer. In other words, if a packet arrives at time t, it would have to wait for duration x to get service. The Poisson arrival see time average (PASTA) [16] property implies that each arriving packet will see a waiting time distribution that equals to the steady-state virtual waiting time distribution. Thus, the PACKET waiting time distribution can be deduced from the virtual waiting time analysis directly.

The state equation of $v(x,t)$ is gathered from the probability transitions of virtual waiting time into state $x - \Delta$ within an infinitesimal time interval Δ. There are three possible transitions that may occur in the interval $[t, t+\Delta]$:

1) At time t, the virtual waiting time is in state x, and no packet arrived during $[t, t+\Delta]$, the probability of no packet arrival is $1 - \lambda\Delta + o(\Delta)$.
2) At time t, the virtual waiting time is in state ξ, $0 < \xi < x$, and a packet of length $x - \xi$ arrived during $[t, t+\Delta]$ with probability $\lambda\Delta + o(\Delta)$. In this case, the system is not empty at the time of packet arriving. The arrived packet is a non-first-arrival-packet, the PACKET service time follows PDF $g(x)$, and we use the convolution $\int_0^x g(x-\xi)v(\xi,t)d\xi$ to include all the possibilities when $0 < \xi < x$.
3) At time t, the system is empty with probability $Q(t)$ and virtual waiting time $x = 0$, and a packet of length x arrived during $[t, t+\Delta]$ with probability $\lambda\Delta + o(\Delta)$. In this case, the arrived packet is a first-arrival-packet, whose length follows the PDF $g_0(x)$ of real packet.

Collecting above three cases for $t > 0$, we can obtain the first branch of the following:

$$\begin{cases} v(x-\Delta, t+\Delta) = & [1 - \lambda\Delta + o(\Delta)]\, v(x,t) \\ & + [\lambda\Delta + o(\Delta)] \int_0^x g(x-\xi)v(\xi,t)d\xi \\ & + [\lambda\Delta + o(\Delta)]\, Q(t) g_0(x) \\ Q(t+\Delta) = & [1 - \lambda\Delta + o(\Delta)]\, Q(t) \\ & + [1 - \lambda\Delta + o(\Delta)]\, v(\Delta,t)\Delta. \end{cases} \tag{3}$$

In the second branch of (3), there are two possible transitions that may lead to $Q(t+\Delta)$:

1) at time t, the system is empty with probability $Q(t)$, and no packet arrived during $[t, t+\Delta]$ with probability $1 - \lambda\Delta + o(\Delta)$;
2) at time t, the virtual waiting time is in state Δ with probability $v(\Delta, t)\Delta$, and no packet arrived during $[t, t+\Delta]$ with probability $1 - \lambda\Delta + o(\Delta)$.

When $\Delta \to 0$, $o(\Delta)/\Delta \to 0$, standard infinitesimal analysis yields

$$\begin{cases} \frac{\partial v(x,t)}{\partial t} - \frac{\partial v(x,t)}{\partial x} = & -\lambda v(x,t) + \lambda Q(t) g_0(x) \\ & + \lambda \int_0^x g(x-\xi)v(\xi,t)d\xi \\ \frac{dQ(t)}{dt} = & -\lambda Q(t) + v(0,t) \end{cases} \tag{4}$$

where $v(x,t)$ and $Q(t)$ satisfy the following normalization condition

$$1 = Q(t) + \int_{0^+}^{\infty} v(x,t)dx. \tag{5}$$

Let $t \to \infty$, $v(x,t) \to v(x)$, $Q(t) \to Q$, the steady state equations are given as follows:

$$\begin{cases} \frac{dv(x)}{dx} - \lambda v(x) + \lambda \int_0^x g(x-\xi)v(\xi)d\xi + \lambda Q g_0(x) = 0 \\ v(0) = \lambda Q \end{cases} \tag{6}$$

where Q is the probability of an incoming packet will see system empty and not be queued in the buffer. The PDF $g(x)$ given by (2) is quite involved even in the case that the underlying PDF $g_0(x)$ of real packet is exponential. It is rather difficult to derive Q and $v(x)$ analytically from (6). Nevertheless, the probability Q is related to the *equivalent load* ρ_{eq} and the *expected PACKET service time* $\overline{S}$, which includes the void period, as follows:

$$\rho_{eq} = \lambda\overline{S} \tag{7}$$

and

$$Q = 1 - \rho_{eq}. \tag{8}$$

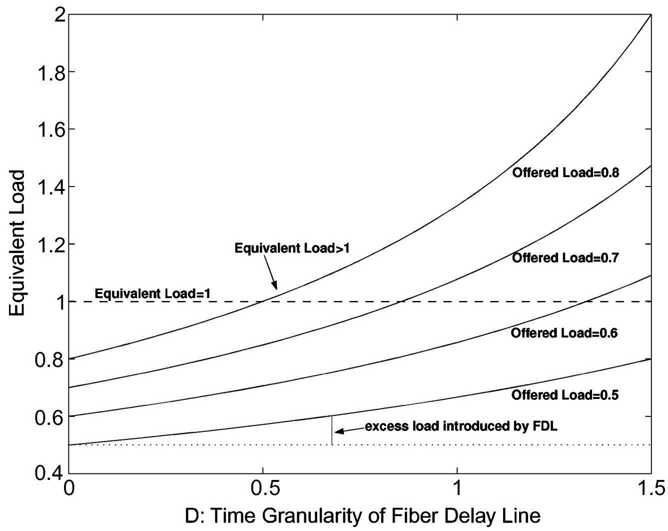

Fig. 6. The impact of FDL time granularity on the traffic load to system.

It is obvious that the packet loss probability of an infinite system is zero, and the probability of an incoming packet being queued is $1-Q$. Given that the service of a queued packet is preceded by a void period with mean duration $D/2$, therefore the expected PACKET service time can be expressed as follows

$$\overline{S}=Q\overline{s}_0+(1-Q)\left(\overline{s}_0+\frac{D}{2}\right)=\overline{s}_0+\rho_{eq}\frac{D}{2}. \tag{9}$$

Combining (7), (8) and (9) yields the following lemma.

Lemma 1: For the given offered load $\rho=\lambda\overline{s}_0$, the equivalent load is

$$\rho_{eq}=\frac{2\rho}{2-\rho\frac{D}{\overline{s}_0}}. \tag{10}$$

The (10) manifests the excess load caused by the finite time resolution property, it is easy to see that $\rho_{eq}>\rho$ whenever $D>0$. The incurred offered load due to void period is illustrated in Fig. 6, which shows that the equivalent load ρ_{eq} is increasing with respect to the time granularity D. Notice that even if the offered load $\rho<1$, it is possible that the equivalent load $\rho_{eq}>1$ and the infinite system will become unstable owing to the excess load.

To ensure $\rho_{eq}<1$, the following upper bound of input traffic can be observed by inserting $\rho=\lambda\overline{s}_0$ into (10)

$$\lambda<\frac{2}{2\overline{s}_0+D} \tag{11}$$

which delineates the stable condition of the system.

With the help of **lemma 1**, the PACKET waiting time distribution for infinite buffer is presented in Theorem 1:

Theorem 1: For the infinite optical buffer with $\rho_{eq}<1$, the Laplace transform of PACKET waiting time PDF $v(x)$ is given by

$$v^*(\theta)=\frac{\lambda Q\left[1-g_0^*(\theta)\right]}{\theta-\lambda\left[1-g^*(\theta)\right]} \tag{12}$$

where $g_0^*(\theta)$ and $g^*(\theta)$ are the Laplace transform of $g_0(x)$ and $g(x)$, respectively.

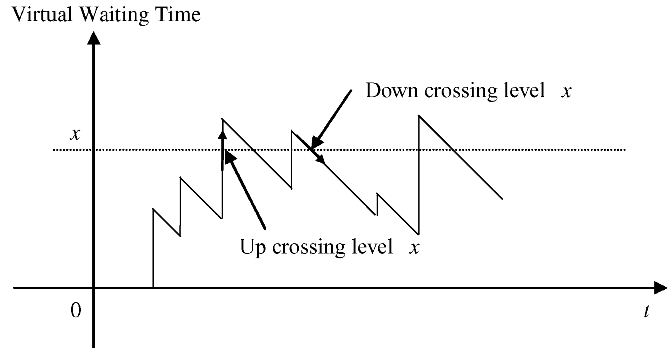

Fig. 7. A realization of virtual waiting time process to illustrate **Theorem 2**.

Proof: We assume that $\rho_{eq}<1$ and the infinite system is stable. The Laplace Transform of (6) is

$$\theta v^*(\theta)-v(0)-\lambda v^*(\theta)+\lambda g^*(\theta)v^*(\theta)+\lambda Qg_0^*(\theta)=0. \tag{13}$$

Note that the Laplace transform of the derivative term $dv(x)/dx$ in (6) is $\theta v^*(\theta)-v(0)$. Rearranging the terms and combining with $v(0)=\lambda Q$ yield (12). $Q.E.D.$

From $v^*(\theta)$ and Q, we can compute the cumulative distribution function $V(x)$ of PACKET waiting time for the infinite buffer.

C. Level Crossing of Virtual Waiting Time

An alternative derivation of the state equation (6) can be conducted by the level crossing of virtual waiting time described in [15].

Considering a single server queue with Poisson arrivals and FIFO service discipline, it is assumed that the stationary virtual waiting time process exists and has a unique distribution.

Fig. 7 is a sample path of the virtual waiting time process, in which the vertical lines represent new arrivals, who may lead the sample path to upcrossing the level x of virtual waiting time. On the other hand, the slope lines indicate the decreasing of virtual waiting time due to the services rendered by server, they may lead the sample path to downcrossing the level x.

Let $H_t(x)$ denotes the number of upcrossings of level x during an arbitrary interval $[0,t]$, then

$$\lim_{t\to\infty}\frac{H_t(x)}{t}=v(x). \tag{14}$$

More precisely, we have the following theorem:

Theorem 2: In a stationary single server queue with Poisson arrivals and FIFO policy, the rate of upcrossing a level x of the virtual waiting time is equal to the rate of downcrossing the level x. In addition, this rate is equal to the probability density function of the virtual waiting time at x.

The proof of this theorem is detailed in [15]. We will show that the state equation (6) can be obtained from this theorem directly.

In the optical buffer with Poisson arrival of rate λ, the rate of upcrossing level x of virtual waiting time from level 0 is equal to $\lambda[1-G_0(x)]$, and the rate of upcrossing the same level x but starting from level $\xi, 0 < \xi \leq x$ is equal to $\lambda[1 - G(x - \xi)]$. A direct consequence of **Theorem 2** is the following equation:

$$v(x) = \lambda\left[1 - G_0(x)\right]V(0) + \lambda \int_0^x \left[1 - G(x - \xi)\right]v(\xi)d\xi \tag{15}$$

where $V(0) = Q$ is the probability of system being empty. Taking the derivative of (15), we obtain

$$\frac{dv(x)}{dx} = -\lambda V(0)g_0(x) + \lambda v(x) - \lambda \int_0^x g(x - \xi)v(\xi)d\xi \tag{16}$$

which is identical to the state equation (6).

In the next section, based on Q and $V(x)$ of the infinite system, the level crossing method can be utilized to calculate the mean packet delay and blocking probability of the finite buffer.

IV. Analysis of Finite Optical Buffer

In the finite buffer, if the required waiting time of an incoming packet is greater than the maximum allowable delay $T = (B - 1)D$, the packet will be blocked. Thus, the key to analyze the finite buffer lies on the evolvement of virtual waiting time process. In Section IV-A, we will derive the PACKET waiting time distribution and the mean packet delay formula. In Section IV-B, the close form of the blocking probability is obtained from the connection between the virtual waiting time distributions of finite and infinite buffers.

We need the following definitions in conducting the analysis of finite buffer:

P_B	packet blocking probability;
W_T	waiting time of admitted PACKETs with CDF $W_T(x)$;
$\overline{w}_T$	mean (real) packet delay.

Note that all variables associated with the finite buffer with maximum allowable delay T are designated by the subscript '$_T$'.

A. PACKET Waiting Time Analysis

Applying **Theorem 2** to the finite buffer based on the same ground for (15), we get

$$v_T(x) = \lambda\left[1 - G_0(x)\right]V_T(0) + \lambda \int_0^x \left[1 - G(x - \xi)\right]v_T(\xi)d\xi \tag{17}$$

for $x \leq T$. Since (17) has the same form as the corresponding (15) of the infinite buffer, therefore, the virtual waiting time distribution $v_T(x)$ for the finite buffer is proportional to that of $v(x)$ for the infinite buffer in the interval $[0, T]$. Actually, we have

$$v_T(x) = \alpha v(x), \quad \alpha > 0, x \in [0, T]. \tag{18}$$

Inserting (18) into (17) yields

$$\begin{aligned} \alpha v(x) &= \lambda\left[1 - G_0(x)\right]V_T(0) \\ &\quad + \lambda \int_0^x \left[1 - G(x - \xi)\right]\alpha v(\xi)d\xi, \\ v(x) &= \lambda\left[1 - G_0(x)\right]\frac{V_T(0)}{\alpha} \\ &\quad + \lambda \int_0^x \left[1 - G(x - \xi)\right]v(\xi)d\xi. \end{aligned} \tag{19}$$

Comparing (19) with (15), we can obtain

$$\alpha = \frac{V_T(0)}{V(0)}. \tag{20}$$

Hence

$$v_T(x) = \frac{V_T(0)}{V(0)}v(x) \quad x \leq T, \tag{21}$$

$$V_T(x) = \frac{V_T(0)}{V(0)}V(x) \quad x \leq T. \tag{22}$$

It is important to note that $V_T(x)$ is the virtual waiting time distribution seen by all arriving packets. For finite buffer, the mean packet delay offered in the following theorem is focused on the waiting time distribution experienced only by those packets admitted into the buffer.

Theorem 3: The mean packet delay of finite optical buffer with $\rho_{eq} < 1$ is given by

$$\overline{w}_T = T - \int_0^T \frac{V(x)}{V(T)}dx + \frac{D}{2}\left[1 - \frac{Q}{V(T)}\right] \tag{23}$$

where $V(x)$ is the CDF of PACKET waiting time in the corresponding infinite buffer.

Proof:

1) Mean PACKET delay.
The condition $\rho_{eq} < 1$ ensures that the corresponding infinite system is stable. For $x \leq T$, the CDF of admitted PACKET waiting time $W_T(x)$ can be written down as (24), shown at the bottom of the next page. Now combining with (22), we obtain

$$W_T(x) = \begin{cases} \frac{V(x)}{V(T)}, & x < T \\ 1, & x \geq T. \end{cases} \tag{25}$$

It follows that the mean delay of admitted PACKETs in the finite buffer is given by

$$\overline{W}_T = \int_0^T x dW_T(x) = T - \int_0^T \frac{V(x)}{V(T)}dx. \tag{26}$$

2) Mean packet delay.

The PACKET waiting time distribution (26) immediately gives rise to the probability of an admitted packet finding system empty as follows:

$$P(\text{packet finding system empty}|\text{packet is admitted}) = W_T(0) = \frac{Q}{V(T)}, \quad (27)$$

which means with probability $Q/V(T)$, an admitted packet is a first-arrival-packet, and it can enter the server directly. It also means that an admitted packet is a non-first-arrival-packet with probability $1-(Q/V(T))$, and it has to wait for an additional void period with mean duration $D/2$ to get service due to the finite time resolution illustrated in Fig. 5. Now, we can calculated the mean packet delay as follows:

$$\begin{aligned}\overline{w}_T &= \overline{W}_T + \frac{D}{2}[1 - P(\text{packet finding system}\\ &\qquad\qquad \text{empty}|\text{packet is admitted})]\\ &= T - \int_0^T \frac{V(x)}{V(T)}dx + \frac{D}{2}\left[1 - \frac{Q}{V(T)}\right]. \end{aligned} \quad (28)$$

$Q.E.D.$

Example 1: If we set $B=1$, which means the optical buffer only consists of one single FDL with zero delay, then $T|_{B=1}=0$, $V(T)|_{T=0}=Q$, it follows from the mean delay formula (28) that $\overline{w}_T = 0$. In this case, the arriving packet can be admitted only when the output channel is free, and the admitted packet can be served directly.

B. Packet Blocking Probability

The packet blocking probability of finite optical buffer is presented in the following theorem.

Theorem 4: For a finite optical buffer with maximum delay $T=(B-1)D$ and $\rho_{eq}<1$, the packet blocking probability is given by

$$P_B = 1 - \frac{V(T)}{Q + \lambda \overline{S}_T V(T)}. \quad (29)$$

The probability of system being empty is

$$Q_T = \frac{Q}{Q + \lambda \overline{S}_T V(T)} \quad (30)$$

where $V(x)$ is the CDF of PACKET waiting time in the corresponding infinite buffer, $Q=V(0)=1-\rho_{eq}$, and

$$\overline{S}_T = \overline{s}_0 + \frac{D}{2}\left[1 - \frac{Q}{V(T)}\right] = \overline{S} + \frac{D}{2}\left[Q - \frac{Q}{V(T)}\right] \quad (31)$$

is the expected service time of the admitted PACKETs.

Proof: Since the derivation of packet blocking probability of the finite buffer is relying upon its corresponding infinite buffer, the condition $\rho_{eq}<1$ is required to ensure the underlying infinite system is stable.

In the finite buffer, blocking occurs when the virtual waiting time seen by the incoming packet is larger than the maximum allowable delay T, which implies

$$P_B = 1 - V_T(T). \quad (32)$$

Since $V_T(x)$ is related to $V(x)$ in (22), and $V(x)$ is given by (12) in **Theorem 1**, it remains to derive $V_T(0)$ in order to determine $V_T(x)$. By the definition of virtual waiting time, the steady state probability Q_T that the finite buffer is empty should be equal to the steady state probability that the virtual waiting time V_T is zero, that is

$$Q_T = V_T(0). \quad (33)$$

From Little's law [16], we have

$$1 - Q_T = (1 - P_B)\lambda \overline{S}_T \quad (34)$$

$$\begin{aligned} W_T(x) &= P(W_T \le x|\text{the arriving packet is admitted})\\ &= \frac{P(W_T \le x, \text{the arriving packet is admitted})}{P(\text{the arriving packet is admitted})}\\ &= \frac{\int_0^x P(W_T \le x, \text{the arriving packet is admitted}|V_T = y)dV_T(y)}{P(\text{the arriving packet is admitted})}\\ &= \int_0^x \frac{dV_T(y)}{V_T(T)}\\ &= \frac{V_T(x)}{V_T(T)}. \end{aligned} \quad (24)$$

where $\overline{S}_T$ is the expected PACKET service time in the finite buffer. Recall that the admitted PACKETs include both first-arrival-packets and non-first-arrival-packets, we have

$$\begin{aligned}\overline{S}_T =& \overline{s}_0 P(\text{packet finding system empty}|\text{packet is admitted}) \\ &+ \left(\overline{s}_0 + \frac{D}{2}\right)[1 - P(\text{packet finding system empty}|\text{packet is admitted})] \\ =& \overline{s}_0 + \frac{D}{2}\left[1 - \frac{Q}{V(T)}\right]\end{aligned}$$

which can be written as

$$\overline{S}_T = \overline{s}_0 + \frac{D}{2}(\rho_{eq} + Q) - \frac{D}{2}\frac{Q}{V(T)} = \overline{S} + \frac{D}{2}\left[Q - \frac{Q}{V(T)}\right]. \quad (35)$$

Combining (32), (33), and (34) yields

$$V_T(T) = \frac{1 - V_T(0)}{\lambda \overline{S}_T} \quad (36)$$

from (22) and (36), we have

$$\frac{V_T(0)}{V(0)} V(T) = \frac{1 - V_T(0)}{\lambda \overline{S}_T}. \quad (37)$$

Hence

$$Q_T = V_T(0) = \frac{V(0)}{V(0) + \lambda \overline{S}_T V(T)} = \frac{Q}{Q + \lambda \overline{S}_T V(T)}. \quad (38)$$

Inserting (38) into (22), we obtain the CDF of virtual waiting time of finite buffer as follows:

$$V_T(x) = \frac{V(x)}{Q + \lambda \overline{S}_T V(T)} \quad x \le T \quad (39)$$

which shows that $V_T(x)$ is a compressed version of $V(x)$ in the interval $[0, T]$. In particular, we have

$$V_T(T) = \frac{V(T)}{Q + \lambda \overline{S}_T V(T)}. \quad (40)$$

Thus, the packet blocking probability of finite optical buffer is readily obtained from (32) as follows:

$$P_B = 1 - V_T(T) = 1 - \frac{V(T)}{Q + \lambda \overline{S}_T V(T)}. \quad (41)$$

Q.E.D.

Notice that the equivalent load is required to be less than 1 in both Theorem 3 and Theorem 4, which imposes the additional constraint (11) on the offered load. Actually, to get the analytical blocking formula under any offered load, we need to first derive the analytical virtual waiting time (VWT) distribution for an optical buffer with maximum delay T. This problem is equivalent to the analytical VWT analysis of an $M/G/1$ queue with bounded waiting time T, where the VWT can be infinite and which makes it infeasible to get a steady state equation like (6) and thus an analytical result on its VWT distribution. That is why the widely adopted approach now is to get the VWT distribution of the above finite queue through analyzing its corresponding infinite queue counterpart without waiting time limit [17]–[20], which results in the offered load constraint of (11) for the stability guarantee of the infinite queue.

1) Examples:

Example 2

In the blocking formula (41), when $\lambda = 0$, no packet arrives, no blocking occurs. In fact, we have $\rho = \lambda \overline{s}_0 = 0$ and $\rho_{eq} = 0$, it follows that $Q = 1$ and $Q_T = 1$, both finite and infinite buffers are empty with probability 1. It also follows that $V(T) = 1$ in the infinite buffer. So, for the finite buffer, the blocking probability is

$$P_B = 1 - \frac{V(T)}{Q + \lambda \overline{S}_T V(T)} = 1 - \frac{1}{1+0} = 0. \quad (42)$$

Example 3

Due to the finite time resolution property, the expected PACKET service times in finite buffer, $\overline{S}_T$ (see (35)), and infinite buffer, $\overline{S}$ (see (9)), are different. In the case when $B \to \infty$, $T|_{B=\infty} = \infty$, the finite optical buffer will become an infinite system and $V(T)|_{T=\infty} = V(\infty) = 1$, and the PACKET service time (35) becomes

$$\overline{S}_T = \overline{S} + \frac{D}{2}(Q - Q) = \overline{S} \quad (43)$$

which means $\overline{S}_T \to \overline{S}$ as $T \to \infty$, and

$$\lambda \overline{S}_T = \lambda \overline{S} = \rho_{eq}. \quad (44)$$

It is obvious that the infinite optical buffer has zero blocking probability, which agrees with the blocking formula (41). Indeed, as $T \to \infty$, we have

$$P_B = 1 - \frac{1}{Q + \rho_{eq}} = 1 - \frac{1}{1} = 0. \quad (45)$$

Example 4

In this example, we consider another extreme case when $T = 0$, which can be either:

1) $B = 1$, the optical buffer only consists of one single FDL with zero delay; or
2) $D = 0$, FDLs do not offer any delay to incoming packets.

In both cases, all packets will be switched to the output channel directly, and they will be blocked if the output channel is occupied. In both scenarios, $V(T)|_{T=0} = V(0) = Q$, and the expected PACKET service time (35) becomes

$$\overline{S}_T = \overline{s}_0 + \frac{D}{2}(1 - 1) = \overline{s}_0. \quad (46)$$

That is, $\overline{S}_T = \overline{s}_0$ as $T = 0$, the mean PACKET service time is equal to real packet mean length $\overline{s}_0$, and then

$$\lambda \overline{S}_T = \lambda \overline{s}_0 = \rho. \quad (47)$$

It is simply because no packets will be buffered and no void periods (excess load) will be introduced. It follows from (29) and (30) that

$$P_B = 1 - \frac{Q}{Q + \rho Q} = \frac{\rho}{1 + \rho} \quad (48)$$

and

$$Q_T = \frac{Q}{Q + \rho Q} = \frac{1}{1 + \rho}. \quad (49)$$

It is interesting to note that the blocking probability given in (48) is the same as that of $M/G/1/1$ queue [21].

2) Discussions: In fact, the blocking formula (29) can be rewritten as

$$P_B = \frac{Q-(1-\lambda\overline{S}_T)V(T)}{Q+\lambda\overline{S}_T V(T)} = \frac{(1-\rho_{eq})-(1-\lambda\overline{S}_T)V(T)}{(1-\rho_{eq})+\lambda\overline{S}_T V(T)} \tag{50}$$

where $T=(B-1)D$ can be any positive constant, then in the case that $D \to 0$, $B \to \infty$ at the same time and the expected PACKET service time (35) becomes

$$\overline{S}_T = \overline{s}_0 + \frac{0}{2}\left[Q - \frac{Q}{V(T)}\right] = \overline{s}_0. \tag{51}$$

That is, $\overline{S}_T \to \overline{s}_0$ as $D \to 0$, which means when the FDLs' granularity approaches to zero, no void period (excess load) is introduced and the mean PACKET service time is equal to the mean length $\overline{s}_0$ of real packet. Then

$$\lambda\overline{S}_T = \lambda\overline{s}_0 = \rho. \tag{52}$$

From (10), $D \to 0$ also yields

$$\rho_{eq} = \rho. \tag{53}$$

Substituting (52) and (53) into (50) yields

$$P_B = \frac{(1-\rho)\left[1-V(T)\right]}{1-\rho\left[1-V(T)\right]}. \tag{54}$$

This is the formula for a physically degenerate optical buffer with infinite time resolution that can not be realized by FDLs. However, the (54) can be considered as the blocking probability of an $M/G/1$ queue in which blocking occurs if the waiting time seen by incoming packets is greater than the constant T. For the sake of comparison, we found that the (54) is similar to the following blocking formula of the $M/G/1/K$ queue given in [21]

$$P_K = \frac{(1-\rho)\sum_{i=K}^{\infty}\pi_i}{1-\rho\sum_{i=K}^{\infty}\pi_i} \tag{55}$$

where $\{\pi_i\}$ $(i=0,1,2,\ldots)$ is the steady queue length distribution in the corresponding infinite $M/G/1$ queue. The difference of these two blocking probabilities is that the blocking in (54) is constrained by the virtual waiting time, in terms of the tail distribution $1-V(T)$, while the blocking in (55) is constrained by waiting space, in terms of the tail distribution of queue length $\sum_{i=K}^{\infty}\pi_i$.

V. Buffer Performance Evaluation

In this section, we analyze the characteristics of optical buffer that can determine the buffer performance.

There are many parameters that will influence the buffer performance: the offered load ρ, the length B of optical buffer, the time granularity D of the FDLs, and the distribution of the packet length. In our analysis, we will focus on the following packet length distributions: *exponential*, *uniform* and *deterministic*, and times are normalized by mean packet length such that $\lambda=\rho$. We have studied eight cases to explore the buffer performances under different packet length distributions and design parameters. In all figures displayed in the sequel, simulation results are marked by diamond ($\diamond$) symbols and analytical results are designated by solid or dash lines.

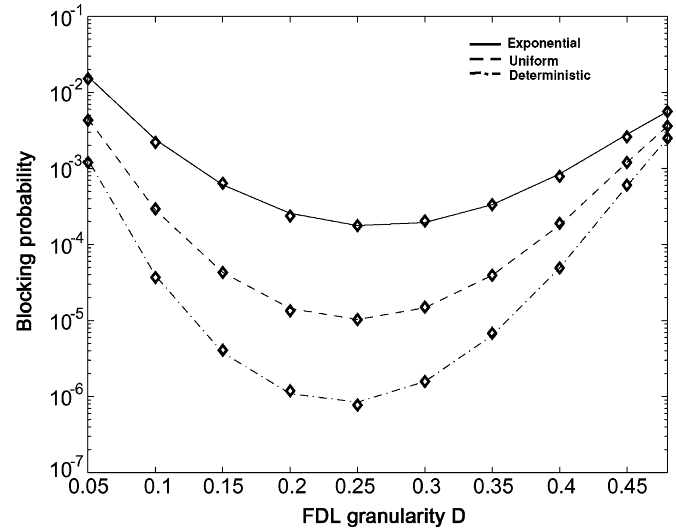

Fig. 8. Packet blocking probability versus FDL granularity D when $\rho=0.8$, $B=256$, under different packet length distributions.

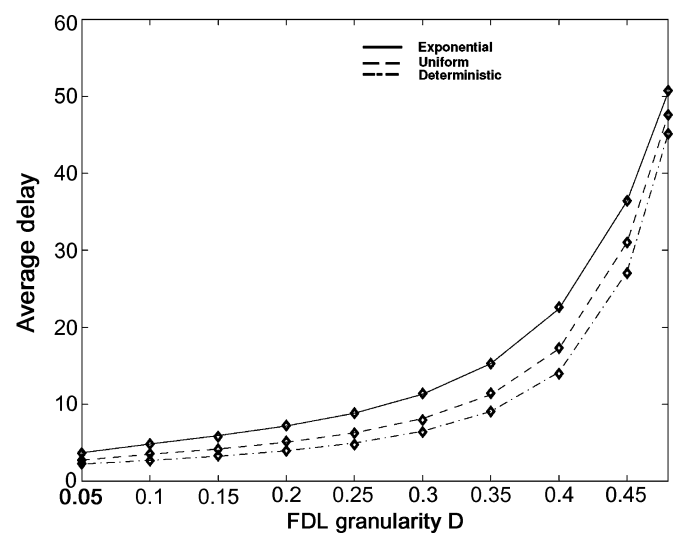

Fig. 9. Mean packet delay versus FDL granularity D when $\rho=0.8, B=256$, under different packet length distributions.

Figs. 8 and 9 compare the blocking probabilities and mean delays calculated from (29) and (23), respectively, with the simulation results of the three packet length distributions mentioned above. The results are obtained for a buffer with $B=256$, $\rho=0.8$, and the FDL granularity D varying from 0.05 to 0.48.

Figs. 10 and 11 illustrate the blocking probabilities and mean delays for a buffer with length $B=32$, fixed granularity $D=0.3$, and the offered load ρ ranging from 0.3 to 0.8.

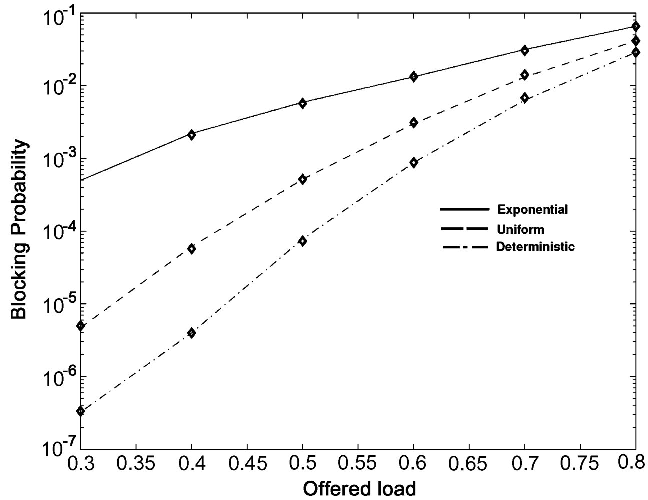

Fig. 10. Packet blocking probability versus Offered load ρ when $B = 32$, $D = 0.3$ under different packet length distributions.

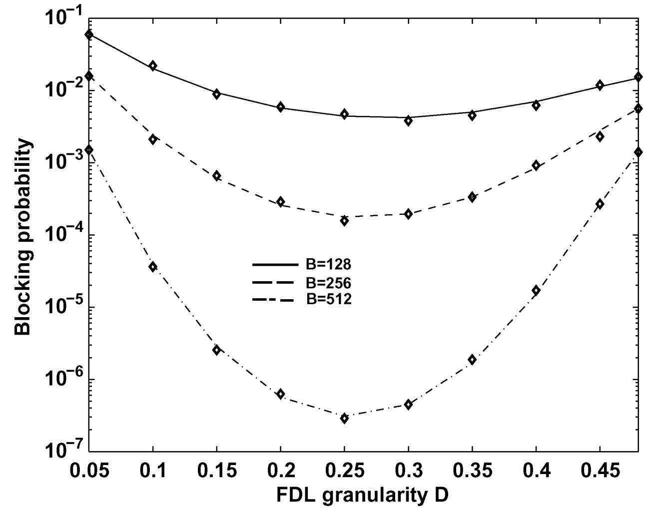

Fig. 12. Packet blocking probability versus FDL granularity D when $\rho = 0.8$ under different buffer length.

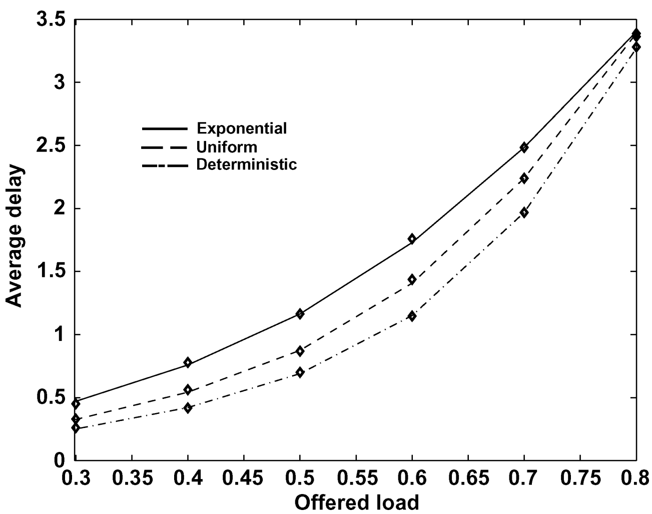

Fig. 11. Mean packet delay versus Offered load ρ when $B = 32, D = 0.3$ under different packet length distributions.

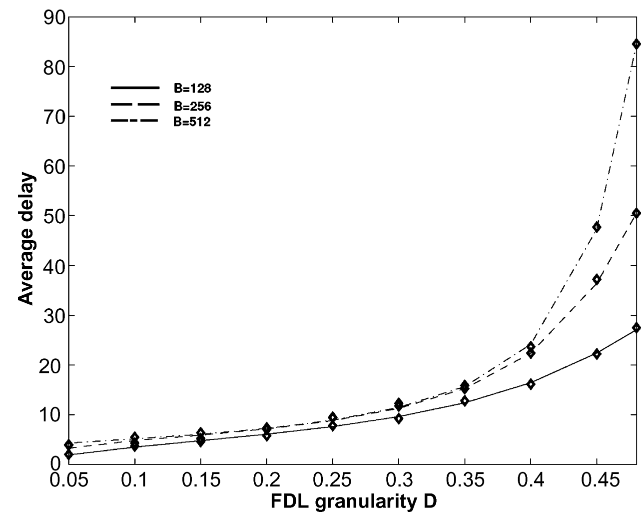

Fig. 13. Mean packet delay versus FDL granularity D when $\rho = 0.8$ under different buffer length.

In Figs. 12 and 13, we investigate the impact of buffer length B and time granularity D on the buffer performance with offered load $\rho = 0.8$ and exponentially distributed packet length. We have observed in Figs. 8 and 12 that when D increases from 0 to about 0.25, the blocking probability will decrease. However, if the time granularity D keeps on increasing, the blocking probability will stop decreasing and become bigger and bigger. The existence of optimal time granularity D that minimizes the blocking probability is reasoned below:

1) *For small time granularity D, the blocking probability is decreasing with respect to increasing D.* To avoid contentions, incoming packets are scheduled by the optical buffer. The incoming packet will be blocked if the required delay is greater than the maximum allowable delay $T = (B-1)D$. Thus, the blocking probability can be reduced by increasing T, which can be realized either by increasing B or D. As shown in Fig. 12, if we increase B, the buffer length, blocking probability will decrease accordingly. When D is small, beefing up the maximum delay T to reduce the blocking probability can also be effectively achieved by expanding the time granularity D.
2) *For large time granularity D, the blocking probability is increasing with respect to increasing D.* From preceding discussions, in particular **Lemma 1** and Fig. 6, we know that the time granularity D will introduce excess load, which becomes the dominating factor of blocking when D is large.

In Fig. 8 and Fig. 12, we note that the optimal granularity $D_{\rm opt} \approx 0.25$ is not sensitive to the packet length distributions; when buffer length is large (e.g. $B = 128$, 256, 512), $D_{\rm opt}$ is also not sensitive to B. In fact, $D_{\rm opt}$ is mainly determined by the traffic load as shown in Fig. 14. The impact of traffic load on the packet blocking probability and mean delay is demonstrated in Fig. 14 and Fig. 15, where the buffer length $B = 32$ and packet length is exponentially distributed. We see that $D_{\rm opt} \approx 0.45$ when $\rho = 0.8$, and the $D_{\rm opt}$ is around 0.7 and 1.4 respect to $\rho = 0.6$ and $\rho = 0.4$. It is clear that the traffic load has significant influence on $D_{\rm opt}$. It is also obvious that the mean

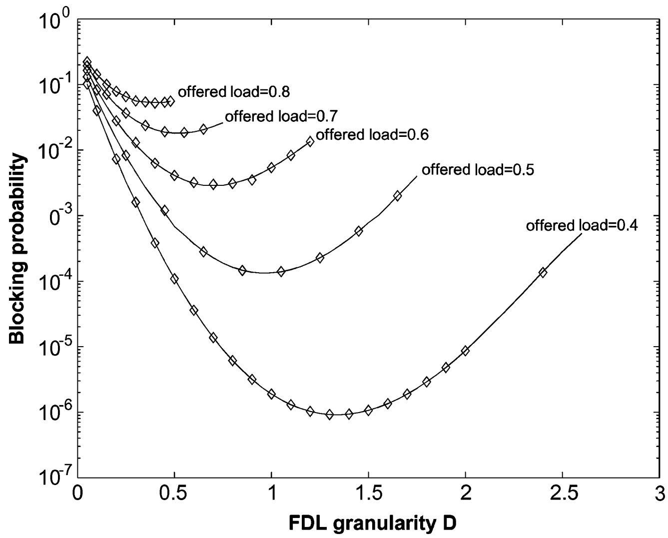

Fig. 14. Packet blocking probability versus FDL granularity D under different offered load when $B = 32$, exponential distributed packet length.

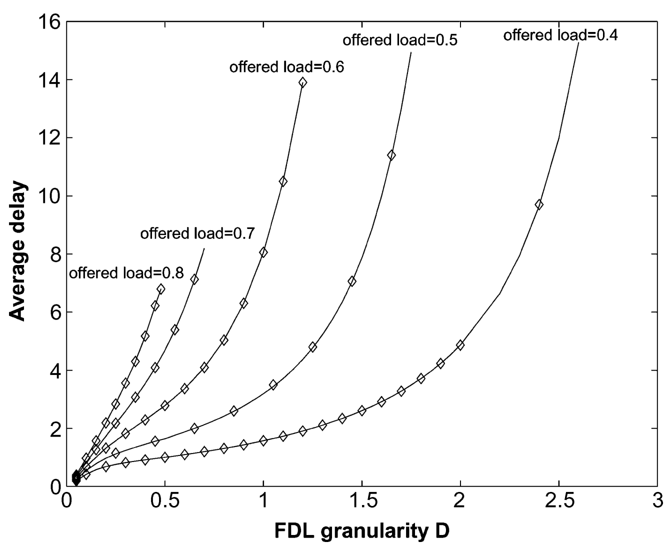

Fig. 15. Mean packet delay versus FDL granularity D under different offered load when $B = 32$, exponential distributed packet length.

delay is uniformly increasing, as shown in Figs. 9, 11, 13, 15, with respect to the increasing of time granularity D.

For one specific network with a given traffic load, our model can be directly applied to determine an optimal granularity corresponding to this load. For a network with variable traffic loads, however, it is impossible for us to find one FDL granularity that is optimal for all possible traffic loads.

VI. Conclusion and Future Work

This paper developed a novel queueing model to analyze the blocking and delay performance of optical buffer under generic packet size pattern. Our model captures both the deterministic and balking property of optical buffer. We have derived the waiting time distribution in the infinite buffer and analyzed the impact of finite time resolution property on the offered load to system. We present an interesting connection of virtual waiting time distribution between the infinite and finite optical buffer. Based on this connection, we derived the closed-form formulas of blocking probability and mean delay.

Our analysis results reveal that there exists an optimal time granularity of FDL that can minimize the packet blocking probability. This optimal granularity is not sensitive to different packet length distributions. When buffer length is large, the optimal granularity is also not sensitive to the length of buffer, it is mainly determined by the traffic load.

Notice that the offered load in our model cannot be too high to ensure the equivalent load is below 1, so one future research is to extend our analytical framework to cover the analysis of finite buffer under any offered load. Since the model in this paper was developed only for the single wavelength scenario, so another future work is to extend this model to the more realistic multi-wavelengths case.

References

[1] C. Qiao and M. Yoo, "Optical burst switching (OBS)-a new paradigm for an optical Internet," *J. High Speed Netw.*, vol. 8, no. 1, pp. 69–84, Feb. 1999.

[2] Y. Xiong, M. Vandenhoute, and H. C. Cankaya, "Control architecture in optical burst-switched WDM networks," *IEEE J. Sele Areas Commun.*, vol. 18, no. 10, pp. 1838–1851, Oct. 2000.

[3] D. K. Hunter, M. C. Chia, and I. Andonovic, "Buffering in optical packet switches," *J. Lightw. Technol.*, vol. 16, no. 12, pp. 2081–2094, Dec. 1998.

[4] L. Xu, H. G. Perros, and G. Rouskas, "Techniques for optical packet switching and optical burst switching," *IEEE Commun. Mag.*, vol. 39, no. 1, pp. 136–142, Jan. 2001.

[5] X. Lu and B. L. Mark, "Performance modeling of optical-burst switching with fiber delay lines," *IEEE Trans. Commun.*, vol. 52, no. 12, pp. 2175–2183, Dec. 2004.

[6] M. C. Chia, D. K. Hunter, I. Andonovic, P. Ball, I. Wright, S. P. Ferguson, K. M. Guild, and M. J. OMahony, "Packet loss and delay performance of feedback and feed-forward arrayed-waveguide gratings-based optical packet switches with WDM inputs-outputs," *J. Lightw. Technol.*, vol. 19, no. 9, pp. 1241–1254, Sep. 2001.

[7] J. Turner, "Terabit burst switching," *J. High Speed Netw.*, vol. 8, pp. 3–16, Jan. 1999.

[8] M. Yoo, C. Qiao, and S. Dixit, "QoS performance of optical burst switching in IP over WDM networks," *IEEE J. Sel. Areas Commun.*, vol. 18, no. 10, pp. 2062–2071, Oct. 2000.

[9] P. Fan, C. Feng, Y. Wang, and N. Ge, "Investigation of the time-offset-based QoS support with optical burst switching in WDM networks," in *Proc. IEEE Int. Conf. Commun.*, 2002, vol. 5, pp. 2682–2686.

[10] F. Callegati, "Optical buffers for variable length packets," *IEEE Commun. Lett.*, vol. 4, no. 9, pp. 292–294, Sep. 2000.

[11] K. Laevens and H. Bruneel, "Analysis of a single-wavelength optical buffer," in *Proc. IEEE INFOCOM 2003*, April 2003, pp. 2262–2267.

[12] R. C. Almeida, Jr., J. U. Pelegrini, and H. Waldman, "Optical buffer modeling for performance evaluation considering any packet inter-arrival time distribution," in *Proc. IEEE Int. Conf. Commun. 2004*, Jun. 2004, vol. 3, pp. 20–24.

[13] J. Liu and T. T. Lee, "Performance modeling of optical buffers supporting variable length packets," in *IEEE Workshop on High Perf. Switching Rout.*, Hong Kong, 2005, pp. 535–538.

[14] L. Tancevski, L. Tamil, and F. Callegati, "Nondegenerate buffers: An approach for building large optical memories," *IEEE Photon. Technol. Lett.*, vol. 11, no. 8, pp. 1072–1074, Aug. 1999.

[15] P. H. Brill and J. M. Posner, "Level crossing in point processes applied to queues: Single server case," *Oper. Res.*, vol. 25, Jul.–Aug. 1977.

[16] D. Gross and C. M. Harris*, Fundamentals of Queueing Theroy*. New York: Wiley, 1998.

[17] T. Takine and T. Hasegawa, "A note on $M/G/1$ vacation systems with waiting time limits," *Adv. Appl. Prob.*, vol. 22, pp. 513–518, 1990.

[18] I. Rubin and M. Ouaily, "Performance analysis of message delay limited synchronous communication and queueing systems," in *Proc. IEEE INFOCOM*, 1989, pp. 51–58.

[19] H. Schulzrinne, J. F. Kurose, and D. Towsley, "Congestion control for real-time traffic in high-speed networks," in *Proc. IEEE INFOCOM*, 1990, pp. 543–550.

[20] A. R. Swensen, "On a $GI/M/C$ queue with bounded waiting times," *Oper. Res.*, vol. 34, no. 6, pp. 895–908, 1986.

[21] H. Takagi, "Queueing analysis: A foundation of performance evaluation," in *Finite System*. New York: North-Holland, 1993, vol. 2.

Jianming Liu received the B.Eng., B.B.A., and M.Eng. degrees from the University of Science and Technology of China, Hefei, China, in 1999 and 2002, respectively, and the Ph.D. degree in information engineering from the Chinese University of Hong Kong, Hong Kong, in 2006.

Currently, he is an Associate Professor of GuiLin University of Electronic Technology, GuangXi, China.

Dr. Liu is also a GCOE Research Fellow of Tohoku University, Sendai, Japan.

Tony Tong Lee (SM'99–F'05) received the B.S.E.E. degree from National Cheng Kung University, Tainan, Taiwan, R.O.C., in 1971 and the M. S. and Ph.D. degrees in electrical engineering from Polytechnic University, Brooklyn, NY, in 1976 and 1977, respectively.

Currently, he is a Professor of Information Engineering with Chinese University of Hong Kong, Shatin, Hong Kong, and an adjunct Professor with the Institute of Applied Mathematics, Chinese Academy of Science, Beijing. From 1991 to 1993, he was a Professor of electrical engineering with Polytechnic University. From 1977 to 1983, he was with AT&T Bell Laboratories, Holmdel, NJ, and, from 1983 to 1993, with Bellcore, currently Telcordia Technologies, Morristown, NJ.

Dr. Lee is a fellow of the Hong Kong Institute of Engineers. He is now serving as an Editor of the IEEE TRANSACTIONS ON COMMUNICATIONS and an area Editor of the Journal of Communication Networks. He is a recipient of 1999 National Natural Science Award, which is China's most prestigious award that recognizes achievements in various fields of natural science that bring significant advancement in scientific knowledge, for his contribution to high speed broadband packet switches. He also received Outstanding Paper Award from the IEICE of Japan in 1999, the Leonard G. Abraham Prize Paper Award from the IEEE Communication Society in 1988, and the Distinguished Member of Professional Staff Award from Bellcore in 1988.

Xiaohong Jiang received the B.S., M.S., and Ph.D. degrees in 1989, 1992, and 1999 respectively, all from Xidian University, Xi'an, China.

He is currently an Associate Professor in the Department of Computer Science, Graduate School of Information Science, Tohoku University, Japan. Before joining Tohoku University, Dr. Jiang was an Assistant Professor in the Graduate School of Information Science, Japan Advanced Institute of Science and Technology (JAIST), from October 2001 to January 2005. He was a JSPS (Japan Society for the Promotion of Science) Postdoctoral Research Fellow at JAIST from 1999 to 2001. He was a Research Associate in the Department of Electronics and Electrical Engineering, the University of Edinburgh, from March 1999 to October 1999. His research interests include optical switching networks, routers, network coding, WDM networks, VoIP, interconnection networks, clock distribution and fault-tolerant technologies for VLSI/WSI. He has published over 120 referred technical papers in these areas.

Susumu Horiguchi (M'81-SM'95) received the B.Eng., M.Eng., and Ph.D. degrees from Tohoku University, Sendai, Japan, in 1976, 1978, and 1981, respectively.

He is currently a Full Professor in the Graduate School of Information Sciences, Tohoku University. He was a Visiting Scientist at the IBM Thomas J. Watson Research Center from 1986 to 1987. He was also a Professor in the Graduate School of Information Science, Japan Advanced Institute of Science and Technology (JAIST). He has been involved in organizing international workshops, symposia and conferences sponsored by the IEEE, IEICE, IASTED, and IPS. He has published over 150 papers technical papers on optical networks, interconnection networks, parallel algorithms, high performance computer architectures and VLSI/WSI architectures.

Prof. Horiguchi is a member of IEICE, IPS and IASTED.