Performance Analysis of an OBS Edge Router

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***Abstract*—We consider optical burst switching with acknowledgment in an edge router served by a limited number of wavelength channels. We approximate the latency of an arbitrary packet and derive exact expressions for the mean burst size and stationary burst blocking probability, which are insensitive to the traffic distribution.**

***Index Terms*—Burst blocking, optical burst switching (OBS).**

I. Introduction

A BROAD range of experimental switching technologies are available to support Internet Protocol (IP) over wavelength-division multiplexing (WDM) in future terabit optical telecommunications networks. The concept of optical burst switching (OBS) [3], [5] refers to a group of such switching technologies. The most viable of such switching technologies is still rather unclear. To assist vendors and telecommunications providers in making informed business decisions on the viability of experimental switching technologies, performance evaluation methodologies are needed.

Underpinning OBS is the idea of sending large assemblies of IP packets, known as *bursts*, by way of temporary lightpaths. Pioneering OBS proposals, such as just-enough-time (JET) [3] and just-in-time (JIT) [5], operate *without* acknowledgment, i.e., one-way reservation. For example, in JET, IP packets, with a common destination and a common quality of service (QoS), arriving at an edge router are assembled to form a burst. Since burst assembly times typically span only a few hundred microseconds, rather than delaying the burst by possibly several milliseconds for a lightpath reservation acknowledgment to propagate, it is considered viable to send the burst without acknowledgment. However, without acknowledgment, bursts may be blocked at the WDM layer due to wavelength channel contention at intermediate optical cross-connects, and QoS may not be guaranteed for mission-critical and real-time applications.

OBS with acknowledgment (OBS/A), an OBS switching paradigm *with* two-way reservation, which is a version of wavelength-routed OBS [1], [2], has been proposed to facilitate QoS support for IP at the WDM layer. Unlike JET and JIT, acknowledgment is considered feasible for OBS/A where burst assembly times span at least several milliseconds, which is the same order as propagation delay. At some point during the burst assembly phase, the edge router sends a *control packet* toward the destination router. The control packet traverses the WDM layer, link-by-link, in an attempt to reserve an end-to-end lightpath for the burst currently being assembled. If a lightpath is reserved, an acknowledgment is returned to the edge router and the burst is sent via the reserved lightpath. Once the burst is sent, the edge router sends a *trailer packet* to tear-down the used lightpath so that it can be reserved for subsequent bursts.

In this letter, we present new analysis to assist in the design and performance evaluation of OBS/A networks. Features of our analysis, such as quantifying the burst blocking probability and the packet delay achievable for a given OBS/A network, may be utilized by vendors to determine the viability of deploying OBS/A. Our analysis includes two important aspects that are not considered in [1] and [2]. New aspects are as follows.

1) Given an edge router served by a limited number of wavelength channels, we derive the probability of a burst blocking at the edge router due to wavelength channel unavailability. We assume that bursts blocked at the edge router are lost and not electronically buffered for sending at a later time. The analysis of [1] and [2] assumes a sufficient number of wavelength channels are available to prevent burst blocking at edge routers.
2) To prevent the loss of packets at the edge router due to a burst size limit, as in [1] and [2], and to reduce switching overheads, we propose sending a trailer packet once the buffer is empty. Thus, from the point in time when a burst is sent, further packets may arrive, be assembled into the same burst and be sent as part of that burst.

II. Edge Router Model and Analysis

We consider an edge router served by K wavelength channels, herein referred to as channels. As shown in Fig. 1, packets arriving at the edge router are aggregated into separate electronic buffers according to their destination and QoS. Let M be the number of buffers. We assume the capacity of each buffer is sufficient to prevent overflow. Packets in the same buffer are assembled to form bursts and then scheduled for transmission on one of the K channels. In this way, the output of the buffers is the input to the K channels. By considering the buffers as sources, we have here a K server loss model with M sources.

Although more efficient active queue management (AQM) [6] schemes may be considered, for simplicity, we assume that if an assembled burst is ready to go and none of the K channels are available, it will be blocked and lost. Let t_{edge} denote the maximum total latency (delay) a packet can withstand to satisfy QoS

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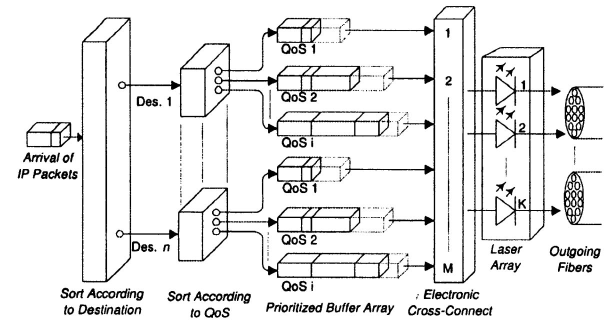

Fig. 1. OBS/A edge router with $M = n \cdot i$ buffers. All outgoing fibers terminate at a single optical cross-connect of the WDM core network.

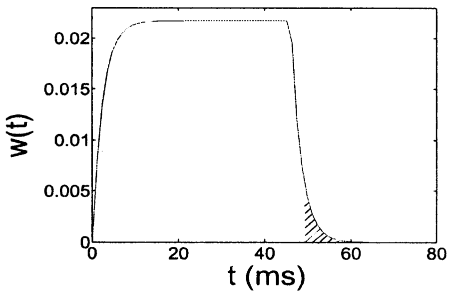

Fig. 2. PDF of the latency of an arbitrary packet.

requirements. Note that $t_{\rm edge}$ may be different for each buffer. Latency encompasses burst assembly delay, queueing delay, and transmission time.

When a packet arrives at an empty buffer, after a time interval $t_{\rm wait}$, a control packet is sent to reserve one of the K channels for the burst currently being assembled. The time interval $t_{\rm wait}$ is a design parameter controlling the burst assembly delay. If a channel is reserved, an acknowledgment is received by the edge router after a further round-trip propagation delay $t_{\rm RTP}$ and the burst is sent via the channel. Only when the buffer is empty, a trailer packet is sent to release the reserved channel. Then, after sometime, another packet may arrive and the assembly of a new burst will commence.

Each packet may be subject to one or more of the following three delays.

1) *Assembly delay*: This is the time a packet spends in the buffer, from the time of its arrival to the time an acknowledgment is received. The assembly delay is zero for a packet arriving after an acknowledgment.
2) *Queueing delay*: For a packet that arrives during the assembly phase, this is the time from the moment an acknowledgment is received to the time the transmission of the packet commences, and for a packet that arrives after the assembly phase, this is the time from the moment of its arrival to the time its transmission commences.
3) *Transmission time*: This is the time required for a packet to traverse its allocated channel. We assume that once the first packet arrives, it can be extracted from the burst and processed.

We assume each buffer generates output traffic with a peak transmission rate $R_{\rm out}$ of one channel. For stability, it is necessary that the mean input rate $R_{\rm in}$ for each buffer does not exceed $R_{\rm out}$. For each packet q, let $t_{\rm as}(q)$, $t_{\rm que}(q)$, and $t_{\rm tr}(q)$ denote the burst assembly delay, queuing delay, and packet transmission time, respectively. Thus, for each buffer, the inequality

$$t_{\rm edge} \geq t_{\rm as}(q) + t_{\rm que}(q) + t_{\rm tr}(q) \tag{1}$$

must hold for all q. Since $R_{\rm in} \leq R_{\rm out}$, it may be reasonable to approximate (1) with

$$t_{\rm edge} \gtrapprox t_{\rm wait} + t_{\rm RTP} + E(T_{\rm tr}) + C, \tag{2}$$

where $T_{\rm tr}$ is a nonnegative random variable representing the packet transmission time, and C is a parameter chosen to control the probability p that (2) holds but (1) does not. Note that if $C = 0$, the right hand side of (2) is the mean total latency of the first arriving packet in a burst. To reduce signalling overheads, it is desirable to maximize the length of the burst assembly phase, subject to (2). Accordingly, we set the design parameter $t_{\rm wait}$ by considering (2) at equality; that is, $t_{\rm wait} := t_{\rm edge} - t_{\rm RTP} - E(T_{\rm tr}) - C$.

Let us now determine C in the case of Poisson packet arrivals and exponentially distributed transmission times. For each buffer, let $1/\mu$ and $1/\lambda$ denote the mean packet length (in units of time) and the mean packet interarrival time, respectively. By an embedded Markov chain approach [4], it can be shown that the generating function $\Pi(z) \triangleq \sum_{n=0}^{\infty} \pi_n z^n$ of the stationary distribution $\{\pi_n | n = 0, 1, \ldots\}$ for the number of packets left behind in a buffer by a departing packet is given by

$$\Pi(z) = \frac{(\eta - \lambda) \cdot (1 - z \cdot e^{\lambda \cdot (t_{\rm wait} + t_{\rm RTP}) \cdot (z-1)})}{(1 + \lambda \cdot (t_{\rm wait} + t_{\rm RTP})) \cdot (\lambda \cdot z^2 - \lambda \cdot z + \eta - \eta \cdot z)},$$

where $\eta \triangleq (R_{\rm out}/R_{\rm in}) \cdot \mu$. The packets that a departing packet leaves behind in a buffer are precisely those packets that arrived while the departing packet was in the buffer or being transmitted. Thus, the Laplace transform $W(s)$ of the probability density function (pdf) for the total latency (i.e., assembly delay, queuing delay, and transmission time) of an arbitrary packet satisfies $W(\lambda - \lambda \cdot z) = \Pi(z)$[4]. By integrating, we can invert $W(s)$ to yield the required pdf $w(t)$, which is given by

$$w(t) = \frac{\lambda \cdot (1 - e^{(-\Delta \cdot t)})}{1 + \lambda \cdot t_{\rm as}} - \frac{H(t - t_{\rm as}) \cdot (\eta \cdot e^{-\Delta \cdot (t - t_{\rm as})} - \lambda)}{1 + \lambda \cdot t_{\rm as}} \tag{3}$$

where $\Delta \triangleq \eta - \lambda$, $t_{\rm as} \triangleq t_{\rm wait} + t_{\rm RTP}$, and $H(t)$ is the Heaviside function. It follows that $p \triangleq \int_{t_{\rm edge}}^{\infty} w(\xi) d\xi$, and thus

$$p = \frac{\lambda \cdot e^{(\lambda - \eta) \cdot t_{\rm edge}} - \eta \cdot e^{(\lambda - \eta) \cdot (E(T_{\rm tr}) + C)}}{(\lambda - \eta) \cdot [1 + \lambda \cdot (t_{\rm edge} - E(T_{\rm tr}) - C)]}. \tag{4}$$

Given a desired probability p, a suitable numerical method can be applied to solve (4) for the required value of C. For example, suppose $t_{\rm edge} = 50$ ms, $t_{\rm RTP} = 10$ ms, $1/\lambda = 1/312$ ms, $R_{\rm out} = 1$ Gb/s, and $R_{\rm in}/\mu = 400$ B. For $p = 0.01$, we solve (4) to determine $C = 3.98$, and then by considering (2) at equality, we set $t_{\rm wait} = 35.98$ ms. Fig. 2 shows the pdf of the latency of an arbitrary packet; the hatched region represents the probability $p = 0.01$.

We now derive the mean burst size $L_{\rm burst}$. For simplicity, assume $R_{\rm in} = R_{\rm out}$. Let I and B denote the mean idle and busy periods for the output of each buffer, respectively. The proportion of time that the output of a buffer is busy is given by

$B/(B+I)$, which is also equal to $\lambda/(\lambda+\mu)$, the proportion of time that packets are entering the buffer. Combining the two and noting that $I = 1/\lambda + t_{\text{wait}} + t_{\text{RTP}}$, we have

$$\frac{B}{B+\frac{1}{\lambda}+t_{\text{wait}}+t_{\text{RTP}}} = \frac{\lambda}{\lambda+\mu} \tag{5}$$

or

$$B = \frac{1}{\mu} + \left(\frac{\lambda}{\mu}\right)\cdot(t_{\text{wait}}+t_{\text{RTP}}). \tag{6}$$

Since $L_{\text{burst}} = R_{\text{out}} \cdot B$, we have

$$L_{\text{burst}} = \frac{R_{\text{out}}\cdot(1+\lambda\cdot t_{\text{wait}}+\lambda\cdot t_{\text{RTP}})}{\mu}. \tag{7}$$

We continue by deriving the stationary burst blocking probability. Let $\overline{T}_{\text{tr}}$ denote the random variable representing the burst transmission time. (Recall that T_{tr} denotes the random variable representing the packet transmission time.) Note that $E(\overline{T}_{\text{tr}}) = B$. As in [1] and [2], the effective channel holding time for a burst is given by the random quantity $t_{\text{RTP}} + \overline{T}_{\text{tr}}$, with mean $t_{\text{RTP}} + B$.

Our limited source K server loss model with M sources is equivalent to an Engset model with mean on and off times $t_{\text{RTP}} + B$ and $1/\lambda + t_{\text{wait}}$, respectively. An appealing feature of the Engset model is its insensitivity to both the on-time and off-time distributions. It can be shown that the stationary probabilities $\{\alpha_k | k = 0, 1, \ldots, K\}$ for the number of busy channels is given by

$$\alpha_k = \frac{\binom{M}{k}\cdot\rho^k}{\sum\limits_{q=0}^{K}\binom{M}{q}\cdot\rho^q} \tag{8}$$

where $\rho \triangleq (t_{\text{RTP}}+B)/(1/\lambda+t_{\text{wait}})$. The offered burst load T_o is given by $T_o = \rho\sum_{k=0}^{K}(M-k)\cdot\alpha_k$, and the carried burst load T_c is given by $T_c = \sum_{k=0}^{K} k\cdot\alpha_k$. And thus, the stationary burst blocking probability B_{burst} is given by $B_{\text{burst}} = (T_o - T_c)/T_o$.

III. Numerical Evaluation

We set the mean packet size to 400 B; i.e., $R_{\text{in}}/\mu = 400$ B. We also set $R_{\text{out}} = 1$ Gb/s. Furthermore, we assume that $M = 120$ and $K = 80$. To gain insight into the performance of the OBS/A edge router, in Figs. 3 and 4, we plot the stationary burst blocking probability B_{burst} against t_{wait}, for $t_{\text{RTP}} = 5, 10, 15$ ms and $1/\lambda = 2, 4, 6$ μs, respectively. This represents a variety of path lengths and network loads.

In Fig. 3, observe that B_{burst} increases with t_{RTP} as the effective channel holding time is prolonged. Thus, networks of large diameter may expect an increase in blocking probability and packet latency. Fig. 3 quantifies the burst blocking probability and the packet delay achievable for an OBS/A network of given diameter. For example, under the assumptions of our model, to achieve a burst blocking probability of 0.001 in a network of diameter 1000 km, t_{wait} must be set to at least 48 ms. For $C = 0$, $t_{\text{wait}} = 48$ ms is commensurate to a packet delay $t_{\text{edge}} = 58$ ms.

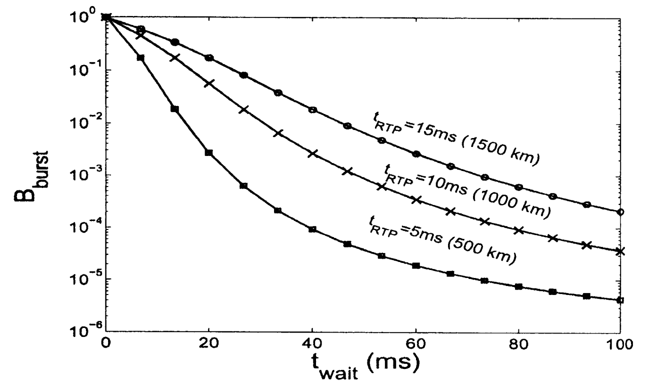

Fig. 3. Burst blocking probability B_{burst} for $t_{\text{RTP}} = 5, 10, 15$ ms with $1/\lambda = 4$ μs and $R_{\text{in}}/\mu = 400$ B. Commensurate network diameter is shown in parentheses.

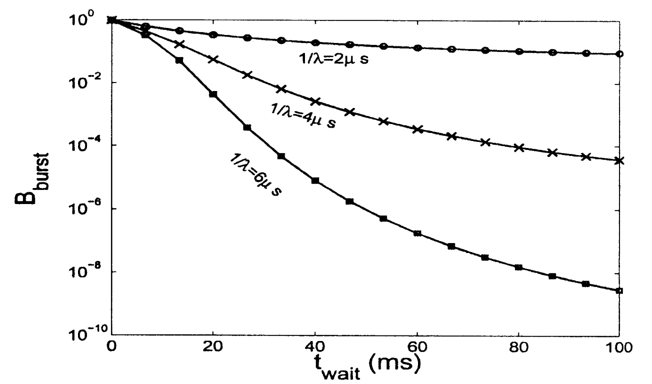

Fig. 4. Burst blocking probability B_{burst} for $1/\lambda = 2, 4, 6$ μs with $t_{\text{RTP}} = 10$ ms and $R_{\text{in}}/\mu = 400$ B.

IV. Conclusion

We have approximated the latency of an arbitrary packet and derived exact expressions for the mean burst size and the stationary burst blocking probability for an OBS/A edge router. By adjusting the burst assembly delay, we were able to design for a desired blocking probability and, with a high probability, satisfy the latency requirements of packets. Future research may extend our analysis to a network, and consider heterogeneous sources and various AQM options.

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