Performance Analysis of Deflection Routing in Optical Burst-Switched Networks

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***Abstract*-- This paper concerns itself with the performance of deflection routing in optical burst-switched networks based on Just-Enough-Time (JET) signaling. Generally speaking, buffer requirement is not vital for JET-based optical burst switching (OBS). However, if deflection routing is enabled, optical buffers are necessary to solve the *insufficient offset time* problem. A variant of priority queuing model is proposed to approximate burst loss probability and the results show that the model provides an accurate estimation. We also evaluate the performance of deflection routing in arpanet-2 topology. Simulation results indicate that deflection routing evidently brings significant blocking performance gain, especially with fewer wavelengths and under lighter load. In addition, we notice that excessive deflection will cause longer end-to-end delay and reduce the blocking performance. Therefore, it is necessary to control the maximum allowed deflection occurrences of a burst.**

1. Introduction

The explosive growth of Internet traffic is driving the demand of more and more bandwidth in the network backbone, especially when multimedia services have gradually become the major direction of application development in recent years. With no doubt, fiber is the most promising physical medium to meet such emerging requirements. With the advances in dense wavelength-division multiplexing technology (DWDM), the tremendous deliverable bandwidth of fibers can be exploited more effectively and completely.

Because of the pervasive usage of the Internet Protocol (IP), it has been a crucial issue to provide a reasonable solution of Optical Internet (i.e., IP-over-WDM) which can efficiently and flexibly utilize the huge potential capacity to accommodate the exploding Internet-based applications. As a matter of fact, the core of this issue lies in the design of switching paradigm. In the evolution of optical networking, the most important switching techniques are wavelength routing (optical circuit switching), optical packet switching and optical burst switching (OBS) [15][17][20][26].

Basically, the wavelength routing approach follows the main concepts of traditional circuit-switched networks. Network backbone is constructed by connecting wavelength routers that provide wavelength routing according to the input port and wavelength. To set up a communication channel, a route between the source-destination pair is chosen with appropriate wavelengths allocated on the links along the route. Such channels are usually called lightpaths. If the signaling protocol operates in a distributed mode, it is necessary to initiate a two-way reservation process for lightpath establishment. On any fiber link of the network, no wavelength sharing is allowed between two distinct lightpaths simultaneously although one of them is idle. As a result, such coarse-grained processing makes wavelength routing suffer from low bandwidth utilization.

To overcome the problem of inefficient bandwidth usage of wavelength routing, a technological breakthrough called optical packet switching emerges. The processing unit is a fixed-length and unaligned packet consisting of header and payload. In this way, resources are allocated in an on-demand fashion with finer granularity and consequently bandwidth utilization can be greatly improved. Because of store-and-forward nature inherited from packet switching, packets are temporarily buffered at each intermediate node. At present, using fiber delay lines (FDLs) is the most practicable way to implement optical buffers. To align packets coming from various input ports, synchronizers are also vital components. Roughly speaking, the major problems of optical packet switching include the difficulty of realizing optical packet synchronizer, requirement of optical buffers, and relatively high control overhead resulting from small payloads [15][17][20][26].

In recent years, a novel paradigm, named optical burst switching (OBS), has been proposed [17-19][26]. The incentive of this new idea is to retain advantages of above two approaches while eliminating their shortcomings as possible. The first step is to change the basic block from a fixed-length packet to a burst that is a super packet with variable size. Unlike a packet, a burst is a pure payload. Each burst is associated with a control packet recording related control information of the burst, e.g., burst length and routing information. In this way, the control overhead is alleviated. A control packet goes through O/E/O conversion at each intermediate node for electronically processing while a burst is completely in optical domain along the path without buffering. The bandwidth reservation is a one-way process [17-18][21]. Compared with wavelength routing, the burst starts transmission without waiting for an acknowledgement from destination and the problem of significant signaling delay can be eliminated. In addition, the separation between a control packet and its burst in both time and wavelength domain can avoid buffering as well as synchronization problem in optical packet switching [17].

According to signaling schemes, there can be various OBS protocols, e.g., Just-In-Time (JIT) by opened-ended reservation and Just-Enough-Time (JET) by closed-ended reservation [17-18][20][23-26]. In both protocols, a burst is transmitted after its control packet without waiting for an acknowledgement. In JIT, there are two types of control packets corresponding to a burst: setup packet and release packet. At each intermediate node, the desired bandwidth is reserved from the time at which the setup packet has been processed and relinquished after receiving the related release packet. On the other hand, bandwidth is reserved from the time at which the burst will arrive at the intermediate node in JET and just allocated for the burst duration indicated in the control packet. Since closed-ended reservation gains better resource utilization, we focus on JET-based OBS paradigm in this paper.

Deflection routing provides an alternative to resolve contentions for the same output link other than pure buffering. Nevertheless, it may be implemented with or without output buffers. Hot-potato is the extreme simplification of deflection routing where buffers are not provided at all. In fact, the performance can be significantly improved with a small number of buffers [1-2]. In the past years, the issue of evaluating performance of deflection routing in regular topologies has been extensively studied [1-6][8]. For example, various analytical models for buffered deflection routing were proposed under specific assumptions of network topology or traffic model [1-2][8]. Compared slotted deflection routing with unslotted case, analyses or simulations all indicated that unslotted network should be the better solution to build an optical deflection-routing network [3-4][6]. By exploiting the special topological properties of shufflenet, Chan and Kobayashi derived a simple but accurate closed-form approximation of the deflection probability [5].

For traffic engineering, deflection routing may also be supported on future IP-over-WDM backbone [17]. In this paper, we study the impacts of deflection routing in JET-based OBS networks by analysis and simulation. Since analytical models previously devised for OBS did not take deflection into consideration [18][23-25], we propose a queuing model to estimate burst loss probability. Other important metrics are also measured in simulation. As aforementioned, buffer requirement is not vital for either deflection routing or JET-based OBS [17-18][22-26]. However, if deflection routing is enabled in JET-based OBS networks, optical buffers are necessary to prevent a burst from overtaking its control packet. We will further elaborate on this in later sections.

The rest of this paper is organized as follows. Section 2 introduces possible optical switch architectures supporting deflection routing in JET-based OBS networks. Detailed operations of deflection routing in JET-based OBS networks are described in Section 3. In Section 4, we propose a variant of priority queuing model to approximate burst loss probability. Analytical and simulation results are presented and discussed in Section 5. Finally, we conclude this paper in Section 6.

2. Optical Switch Architecture And FDL Buffer

2.1. *Optical Switch Architecture*

To accommodate optical buffering to optical switches, various architectures have been proposed. In [11], a broadcast-and-select space switch is designed by KEOPS project. The single-stage forward buffering scheme is used for contention resolution. Several architectures using non-blocking space-switch with output-buffered FDL have been investigated in [9]. The FDL buffers can be either shared among the output ports or dedicated to each output port. A similar structure using broadcast and select switch (BSS) to select among the output of space switch and optical buffers to the output port is employed in [21]. For OBS burst buffering, an input-buffered structure is introduced in [24] and each port is equipped with a dedicated FDL buffer.

Fig. 1 illustrates possible output-buffered optical switch architectures[1]. The FDL buffers can be either dedicated to each port (Fig. 1(a)) or shared among the ports (Fig. 1(b)). There are F links in the optical switch and W wavelengths on each fiber. Each FDL buffer contains a set of N delay lines.

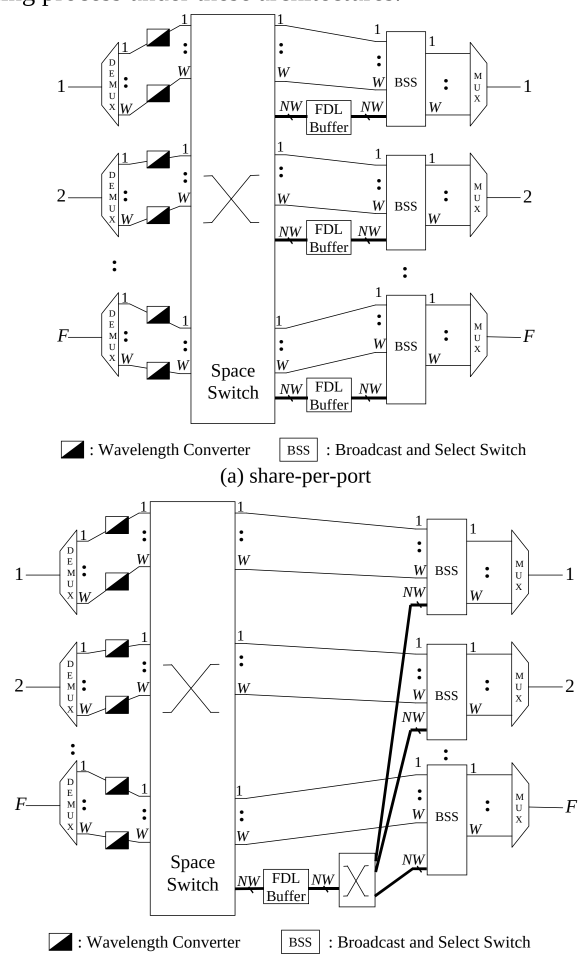
2.1.1. *Share-per-port*

In the share-per-port structure shown in Fig. 1(a), each port is equipped with a FDL buffer with N delay lines, i.e., $N\times W$ channels. The input of each link is de-multiplexed into W wavelengths, which can be converted to different wavelengths if necessary. The non-blocking space-switch is used to direct each burst to its desired outlet. If all W channels of the outlet are in use, the burst will be switched to the appropriate delay line in the FDL buffer. The BSS then selects W channels among the output of space switch and FDL buffer. Finally, the signals are multiplexed and transmitted to the output fiber link.

2.1.2. *Share-per-node*

Fig. 1(b) depicts the share-per-node design. In this system, all the delayed bursts are transmitted to the only one FDL buffer. Hence, an additional space switching is required after the delay process. However, the space-switch size in the first stage can be reduced as compared with share-per-port architecture.

Certainly, both share-per-port and share-per-node have pros and cons and further discussion is beyond the scope of this paper. In the next section, we will investigate the deflection routing process under these architectures.



(a) share-per-port

(b) share-per-node

Figure 1. Optical Switch Architecture

2.2. *FDL Buffer Design*

There are many proposals of FDL buffer design [7][14][16][24]. In this paper, we follow the work in [24], which focuses on burst-switched network carrying variable

[1] The electronic control interfaces and add/drop from local nodes are omitted in Fig. 1.

size bursts asynchronously. We adopt the variable-delay structure introduced in [24] as illustrated in Fig. 2. In this figure, delay time of each delay element is b. The maximum delay time B is equal to $(2^0 + 2^1 + \cdots + 2^n) \times b$. The W input channels are multiplexed into the fiber delay line and de-multiplexed after proper delay time. The output burst can be converted to another wavelength in order to resolve any possible contention. Each FDL buffer consists of N delay lines and its input contention can be resolved by the wavelength converters shown in Fig. 1(a) and (b).

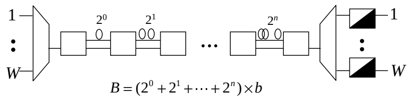


Figure 2. Fiber Delay Line Design

3. Deflection Routing Operations In JET-Based OBS

In this section, we discuss the operations of deflection routing. In JET-based OBS networks, an *offset time T* is necessary between the control packet and data burst [17]. The control packet can employ the *delayed reservation* technique to reserve the bandwidth along the predetermined path. Let (S, D) be the source-destination pair, H be the number of hops between S and D along the predetermined route, and δ be the maximum required processing time for a control packet at each hop. The total delay encountered by control packet is no greater than $\Delta=\delta \times H$ and therefore the offset time T should be at least Δ. For example, Fig. 3(a) depicts a sample OBS network and the predefined path between S and D is *S-A-B-D*, i.e., H=3. Let T=3δ, the burst will arrive at D just after the control packet is processed as illustrated in Fig. 3(b). If the control packet cannot reserve bandwidth at some intermediate hop, say B, it may reserve FDL buffer consequently instead of being blocked directly [18]. However, if all FDL resources have been allocated to other bursts, the burst is blocked and the control packet will not be transmitted to D (Fig. 3(c)).

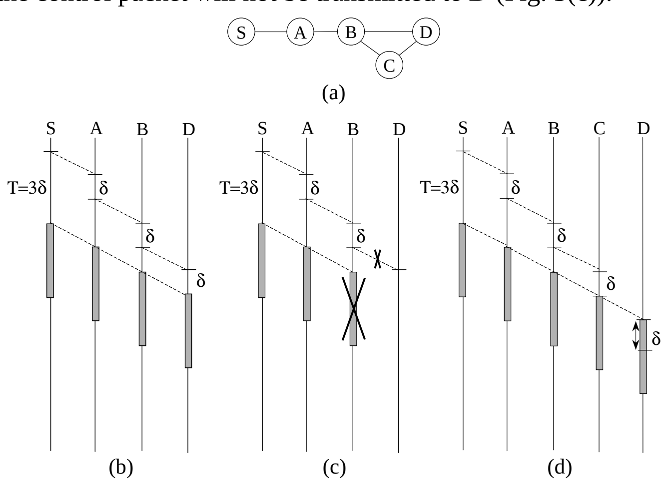


Figure 3. Possible cases of a burst from S to D: (a) a sample network, (b) successful transmission on path *S-A-B-D*, (c) FDL reservation failure at B, and (d) deflection routing is triggered at B

In order to achieve better blocking performance, we may invoke the *deflection routing* at such a congested hop. Unlike the traditional dynamic routing in circuit-switched WDM networks [10][13] where a fixed-alternate or dynamic route is reassigned between (S, D) pair, the deflection route should be chosen between the congested node B and the destination D since the control packet has arrived at B. Due to the nature of burst transmissions, the network state changes rapidly in OBS networks. As a result, it is hard to perform dynamic calculation of deflection route. To predefine deflection routes between each node pair in a fixed table is a more reasonable solution. In the previous example, the burst is blocked at node B. Then the deflection route from B to D is looked up in the table and the burst is forwarded to the new route *B-C-D*.

There is a crucial problem when we redirect the burst to the deflection route: *insufficient offset time*. Let h denote the increased number of hops of deflection route. If the initial offset time $T=\delta \times H$ and $h>0$, the burst will arrive at the destination node D earlier than the control packet is completely processed in D by $\delta \times h$ time units. As shown in Fig. 3(d), the deflection route *B-C-D* has one more hop than the original route *B-D*, i.e., h=1. The burst will reach the destination δ time units before the control packet is processed.

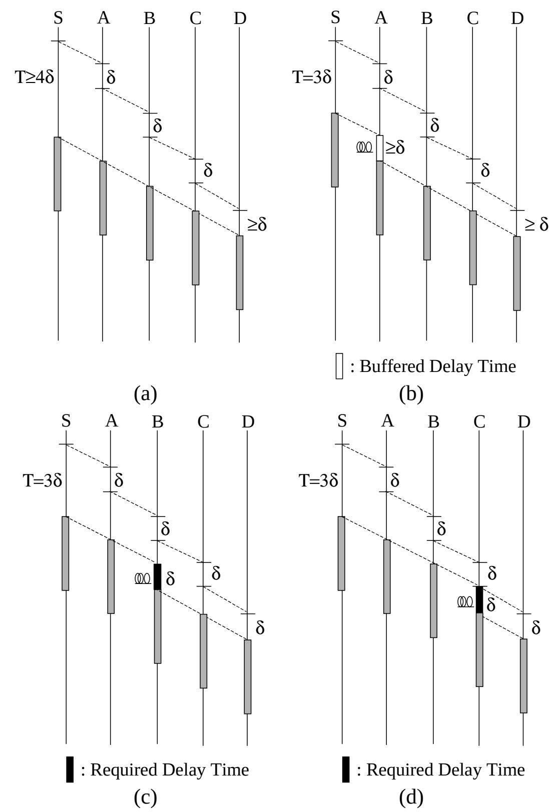


Figure 4. Approaches for keeping offset time sufficient: (a) extra offset time, (b) delayed-at-previous-hops, (c) delayed-at-congested node, and (d) delayed-at-next hop

Therefore, the deflection routing will not succeed without enough offset time or buffered delay. We discuss different possible solutions as follows:

1) Extra offset time

If we provide a sufficient offset time, as $T \geq \delta \times (H+h)$, the burst can be successfully redirected to the deflection route. Continued from previous example, if the offset time is greater than 4δ as shown in Fig. 4(a), the burst will arrive at D after the control packet is processed. However, it is hard to determine extra offset time in the beginning. Without enough extra offset time, the deflection cannot be completed; with huge extra time, the priority of burst will be raised. It means that other bursts may be affected [24]. Thus, this strategy is lack of flexibility and can not be easily implemented.

2) Delayed-at-previous-hops

It may happen that the burst has encountered buffered delay before entering the congested node. There will be no problem if total delayed time is greater than $\delta \times h$. Fig. 4(b) depicts such a situation that the burst has been delayed for more than δ at hop *A*. Nevertheless, this case may not occur each time when deflection routing is required.

3) Delayed-at-congested-node

If the burst does not have sufficient offset time and has not been delayed at previous hops, a buffered delay time $\delta \times h$ is required at the congested hop. In Fig. 4(c), a delay time of δ is enforced at *B* and the redirection can be performed successfully. Under share-per-port architecture described in section 2.1.1, the burst cannot be sent to *D* because both the bandwidth of output port and FDL buffer of the port to *D* are occupied at node *B*. Thus, the control packet will reserve the bandwidth of the FDL buffer at the port to *C* to produce the delay for the deflection route. But under share-per-node architecture, buffered delay cannot be issued due to the sharing of FDL buffer among all of the output ports. Hence, this strategy can be applied only to share-per-port switching architecture.

4) Delayed-at-next-hop

There is a promising solution for both share-per-port and share-per-node architectures: delaying the burst at the next hop of the congested node. Because there is at least one hop between the congested node and the destination node, the burst can be transmitted to the next hop where the delay can be performed without any problem. For example, the burst is congested at node *B* and the required delay is issued at its next hop (node *C*) in Fig. 4(d).

Despite of buffering issue, since deflection routing causes longer end-to-end delay, excessive deflection may reduce the blocking performance. Thus, there should be a limitation on the deflection frequency to avoid such a side effect. Let $f(s)$ denote the deflection frequency of a burst *s*. The deflection frequency limit f_{max} is defined as the maximum allowed deflection occurrence, i.e., $f(s) \le f_{max}$ for any burst *s*.

In the following discussion on deflection routing, we check the delayed time at previous hops. If the total delay is no more than $\delta \times h$, delayed-at-next-hop technique is adopted.

4. ANALYSIS

By extending the model in [24], we propose a queuing model to analyze JET-based OBS scheme in which deflection routing is enabled. Here, the estimated performance metric is the burst loss probability. Under the proposed model, although the result cannot be expressed in a closed-form expression, we can solve it from a set of linear equations.

4.1. Assumptions

- There are *W* wavelengths on each fiber link represented by a set $\Lambda = \{\lambda_1, \lambda_2, ..., \lambda_W\}$.
- The burst length is exponentially distributed with an average of *L*.
- There are *N* physical FDLs in the FDL buffer. For simplicity, among the physical FDLs, N_d FDLs (V_d virtual FDLs) are designated to the deflected bursts and N_q FDLs (V_q virtual FDLs) are for the non-deflected traffic, i.e., $N = N_d + N_q$, $V_d = N_d \times W$, $V_q = N_q \times W$.
- The average number of extra hops of deflected traffic is *h*.
- In order to simplify our analysis, we consider an optical switch with single output link, and assume that the arrivals of deflected and non-deflected bursts are both Poisson processes with mean rate γ_d and γ_q individually. On the other hand, both two types of bursts are serviced with an average rate $\mu = 1/L$.

4.2. The Proposed Queuing Model

As described in the previous section, to prevent bursts from overtaking corresponding control packets, the offset time of deflected bursts has to be lengthened due to extra hop distances as a result of deflection. Consequently, though there exists an available wavelength while the deflected burst coming from some input port enters the output port, it cannot utilize the wavelength before staying in FDL buffer at least for extra offset time. From above observation, we propose a Markovian model composed of two stages with priorities to approximate the behavior of the output port. The queuing system is shown in Fig. 5.

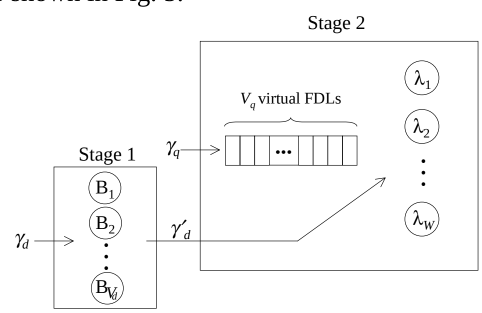


Figure 5. Proposed queueing system

In Fig. 5, the first stage is a *M/M/c/c* model to depict the behavior of deflected bursts in FDLs. B_i denotes *i*-th virtual FDL among those dedicated to deflected bursts, where i=1, 2, ..., V_d. The average service rate of these V_d virtual FDLs is $\mu_d = 1/(\delta \times h)$. Therefore, according to Erlang's loss formula, the loss probability of this stage can be obtained as

$$p_1 = \frac{(\gamma_d/\mu_d)^{V_d}/V_d!}{\sum_{i=0}^{V_d}(\gamma_d/\mu_d)^i/i!} \tag{1}$$

After leaving FDLs, deflected and non-deflected bursts enter stage 2 to contend for free wavelengths on output fiber link. According to the properties of Markovian queues [12], the departure time distribution is identical to the interarrival time distribution if there is no restriction on the system capacity, i.e., $M/M/c/\infty$ queue. For simplicity of our analysis, we assume that the departure from stage 1 is a Poisson process with mean rate γ'_d although there are at most V_d bursts in stage 1 simultaneously, where

$$\gamma'_d = \gamma_d(1 - p_1) \tag{2}$$

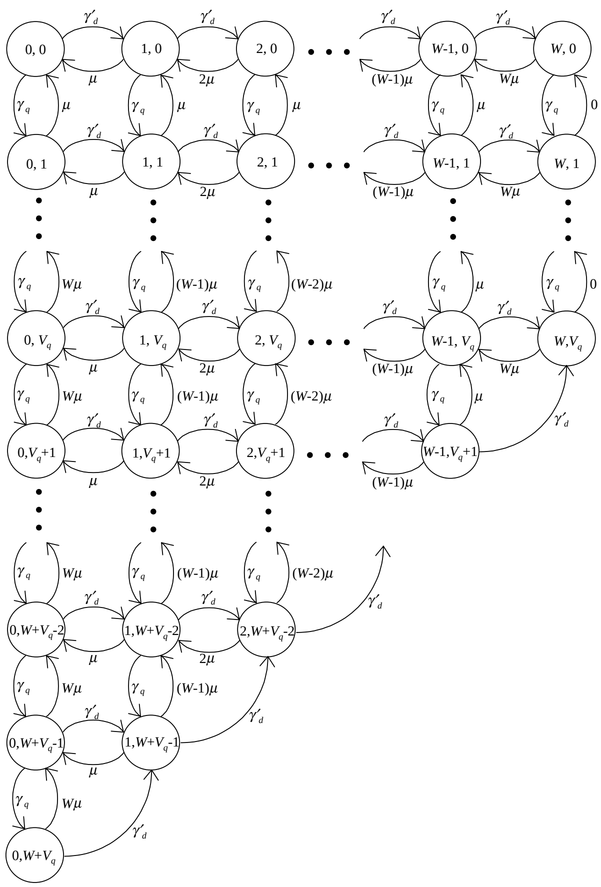


Figure 6. State transition diagram of proposed queueing system

Unlike non-deflected traffic, deflected bursts will not utilize FDLs in stage 2 when there is no available wavelengths temporarily. If the discipline is non-priority, it will be much advantageous to the non-deflected bursts because of the offered waiting queue and the accuracy of the estimation might be worse. Accordingly, we propose a variant of preemptive priority queuing model at this stage and assign higher priority to deflected traffic. Such a policy can compensate the disadvantage of deflected traffic and just slightly affect non-deflected traffic since the latter can enter FDLs after preemption if FDLs are available. Because we assume that service is exponential, whether or not the ejected bursts lose all service performed before preemption is irrelevant in view of memorylessness. The state transition diagram of this priority model with preemption is shown in Fig.6 and the number of states, represented by *nos*, is as follows:

$$\begin{aligned} nos &= \frac{(V_q+1+W+V_q+1)(W+1)}{2} \\ &= (W+1)(V_q+\frac{W}{2}+1) \end{aligned} \qquad (3)$$

In Fig. 6, each state is identified by a 2-tuple notation (i, j); i and j are the number of deflected and non-deflected bursts in stage 2 separately, where $0 \le i \le W$, $0 \le j \le (W+V_q)$, $0 \le (i+j) \le (W+V_q)$. Let p_{ij} denote the steady-state probability that stage 2 is in state (i, j). According to the transition rules defined in Fig. 6, a system of difference equations may be derived for the stationary probabilities as follows:

$$\begin{cases} 0=-(\gamma'_d+\gamma_q)\,p_{00}+\mu p_{10}+\mu p_{01} \\ 0=-(\gamma'_d+W\mu)\,p_{0,W+V_q}+\gamma_q\,p_{0,W+V_q-1} \\ 0=-(\gamma_q+W\mu)\,p_{W0}+\gamma'_d\,p_{W-1,0} \\ 0=-W\mu p_{W,V_q}+\gamma'_d\,(p_{W-1,V_q}+p_{W-1,V_q+1})+\gamma_q\,p_{W,V_q-1} \\ 0=-(\gamma'_d+\gamma_q+m\mu)\,p_{m0}+\gamma'_d\,p_{m-1,0}+(m+1)\mu p_{m+1,0} \\ \quad +\mu p_{m1}\ ,\ 1\le m\le W-1 \\ 0=-(\gamma'_d+\gamma_q+\min(W,n)\mu)\,p_{0n}+\gamma_q\,p_{0,n-1}+\mu p_{1n} \\ \quad +\min(W,n+1)\mu p_{0,n+1}\ ,\ 1\le n\le W+V_q-1 \\ 0=-(\gamma'_d+m\mu+(W-m)\mu)\,p_{m,W+V_q-m}+\gamma'_d\,p_{m-1,W+V_q-m} \\ \quad +\gamma'_d\,p_{m-1,W+V_q-m+1}+\gamma_q\,p_{m,W+V_q-m-1}\ ,\ 1\le m\le W-1 \\ 0=-(\gamma_q+W\mu)\,p_{W,n}+\gamma'_d\,p_{W-1,n}+\gamma_q\,p_{W,n-1}\ ,\ 1\le n\le V_q-1 \\ 0=-(\gamma'_d+\gamma_q+m\mu+\min(W-m,n)\mu)\,p_{mn}+\gamma'_d\,p_{m-1,n} \\ \quad +\gamma_q\,p_{m,n-1}+(m+1)\mu p_{m+1,n}+\min(W-m,n+1)\mu p_{m,n+1}\ , \\ \quad 1\le m\le W-1, 1\le n\le W+V_q-2,\ 2\le m+n\le W+V_q-1 \\ 1=\sum p_{mn}\ ,\ 0\le m\le W\ ,\ 0\le n\le W+V_q\ ,\ 0\le m+n\le W+V_q \end{cases} \qquad (4)$$

To solve the set of linear equations in (4), we can compactly express (4) in the following form.

$$\mathbf{y} = \mathbf{pQ} \qquad (5)$$

Row vector **y** and **p** are composed of *nos* and *nos*+1 elements respectively, and **Q** is a *nos* × (*nos*+1) matrix as respectively defined by (6).

$$\mathbf{y}=[0 \quad 0 \quad \cdots \quad 0 \quad 1],$$

$$\mathbf{p}=[\,p_{00} \quad p_{01} \quad p_{10} \quad \cdots \quad p_{W,V_q}\,],$$

$$\mathbf{Q}=\begin{bmatrix} -(\gamma'_d+\gamma_q) & & 1 \\ \mu & & 1 \\ \mu & \cdots & 1 \\ 0 & & \vdots \\ \vdots & & 1 \\ 0 & & 1 \end{bmatrix} \qquad (6)$$

After the solution of row vector **p** comes out, the loss probability of stage 2, p_2, can be derived by (7)

$$p_2=\frac{\gamma'_d}{\gamma'_d+\gamma_q}\sum_{j=0}^{V_q}p_{W,j}+\frac{\gamma_q}{\gamma'_d+\gamma_q}\sum_{i=0}^{W}p_{i,W+V_q-i} \qquad (7)$$

Finally, we can derive the loss probability of the 2-stage system p_{total} as (8).

$$p_{total}=\frac{\gamma_d}{\gamma_d+\gamma_q}\,p_1+\frac{\gamma'_d+\gamma_q}{\gamma_d+\gamma_q}\,p_2 \qquad (8)$$

5. Numerical Results

We present results from analysis and simulation in this section. All results are divided into two parts. The first part involves simulation and analytical results obtained for a single optical switch with one output link. Arrivals are generated by Poisson model with mean rate γ, where $\gamma = \gamma_d + \gamma_q$. Traffic load of both deflected and non-deflected bursts are $\rho_d = \gamma_d \,/\, (W\mu)$ and $\rho_q = \gamma_q \,/\, (W\mu)$, and total traffic load is $\rho = \rho_d + \rho_q$. On the other hand, the second part includes performance evaluation of deflection routing in a JET-based OBS network by simulation. Bursts are generated according to a Poisson process with a network-wide arrival rate β. The switch architecture is share-per-port. We exploit delayed-at-next-hop strategy to lengthen offset time if necessary.

(A) Accuracy of Analytical Model

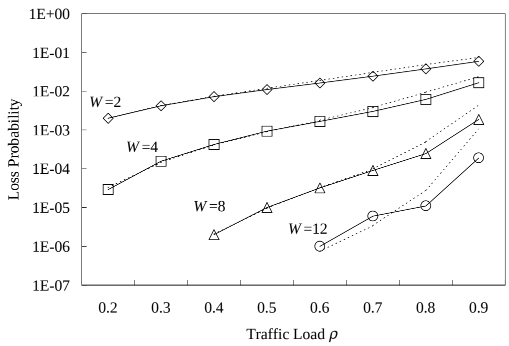


Figure 7. Burst Loss Probability vs. Traffic Load

Fig. 7 shows the relation between burst loss probability and traffic load ρ when $\rho_d = 0.3\rho$, $B = 5L$, $N_d = 1$, $N_q = 3$, $h = 2$, $\delta = 0.1L$, and $W = 2, 4, 8, 12$. Results from analysis and simulation are displayed by dotted lines and solid lines respectively. In general, the accuracy of the proposed model decreases as traffic load rises. The reason is explained as follows. In our model shown in Fig. 5, a high-priority (i.e., deflected) burst will be blocked in stage 2 when all channels are occupied by deflected bursts. On the other hand, low-priority (i.e., non-deflected) bursts can wait for transmission in FDLs. For deflected bursts, such a disadvantage cannot be compensated by assigning higher processing precedence to them. As traffic load rises, the effect is more significant because it is more possible that all channels are occupied by deflected bursts when a deflected burst enters stage 2. However, the two types of bursts are processed equally in simulation. Apparently, the total loss probability will be overestimated when traffic load exceeds some threshold, e.g, ρ = 0.5, 0.6, 0.7, and 0.8 when W = 2, 4, 8, and 12 respectively. In addition, we can also observe that the proposed model is more accurate when W is smaller. As discussed in [24], the behaviors of a FDL and a Markovian queue are distinct. With the increasing of wavelengths, the number of virtual FDLs in the FDL buffers also grows. Thus, the aggregated inaccuracy results in worse approximation. As a whole, the model provides an accurate estimation as the discrepancy is acceptable.

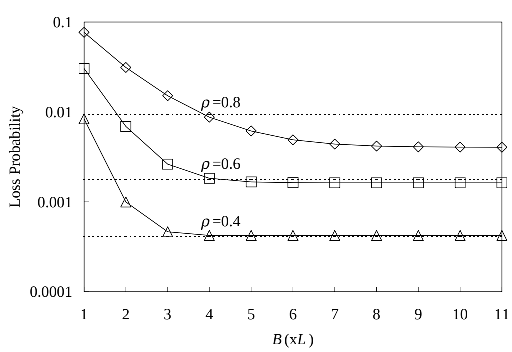


Figure 8. Burst Loss Probability vs. Maximum Delay Time

Fig. 8 plots burst loss probability with various maximum delay times (i.e., B) when $\rho_d = 0.3\rho$, $N_d = 1$, $N_q = 3$, $h = 2$, $\delta = 0.1L$, $W = 4$, and ρ = 0.4, 0.6, and 0.8. Owing to the essential difference between a FDL and a queue in the $M/M/c/K$ model, the model tends to estimate a lower (higher) loss probability than that derived from simulation when B is relatively small (long) compared with L [24]. As aforementioned, our model is composed of a $M/M/c/c$ model in stage 1 and a $M/M/c/K$ model with preemptive priority in the stage 2. From Fig. 8, we know that this phenomenon still exists when deflection is considered and the analytical model is changed to a variant of $M/M/c/K$ model. In addition, although the simulation results indicate that loss probability generally decreases as B gets longer, the reduction saturates when B exceeds some threshold. Longer B can help the output link to accommodate more bursts by deferring their transmission for longer delay time. In other words, the increment of B can improve utilization of output link in terms of time. Nevertheless, there is a limit of utilization of any finite resource. No matter how long a burst stays in a FDL, its transmission to the output link could still be blocked if utilization reaches or approaches the limit. For example, the simulation results saturate at $B = 4L$, $5L$, and $10L$ when ρ = 0.4, 0.6, and 0.8 respectively.

(B) Network Performance

In this subsection, we evaluate performance of deflection routing in a JET-based OBS network by simulation. The considered network topology is arpanet-2 composed of 21 nodes. To distinguish loss probability in *(A)* from the term used here, the rate of transmission failure is called blocking probability in the following discussions. The measured performance metrics include blocking probability, average hop distance per burst and deflection ratio, which is the rate of triggering deflection routing.

Fig. 9, Fig. 10, and Fig. 11 separately demonstrate blocking probability, average hop distance, and deflection ratio as a function of network-wide arrival rate β when $N = 3$, $B = 5L$, $\delta = 0.1L$, W = 4, 8, 16 and f_{max} = 0, 1, 2. Apparently, deflection routing brings great improvement on blocking performance, especially when W is smaller and arrival rate is lower. For example, the improvement is 90% at $\beta = 25$ in Fig. 9(a). In fact, even if W = 8 and 16, the improvement still achieves about 70% at β = 65 and 140 respectively. The rationale behind this is that there is more room for improvement by deflection routing under light load when there are fewer resources (i.e., wavelengths). We also observe that deflection routing with f_{max} = 1 and 2 have similar blocking performance. It reveals that excessive deflection does not always bring performance gain. The reason is that more deflection occurrences will cause longer end-to-end delay, which is equivalent to occupying more resources. Certainly, immoderate usage of resources will reduce blocking performance. Therefore, unlimitedly raising f_{max} is not necessarily. For example, $f_{max} = 1$ is enough in arpanet-2.

As arrival rate rises, blocking probability increases and the improvement is gradually reduced under heavier traffic. In Fig. 9 and Fig. 11, we observe that all blocking curves are very close when deflection ratio is greater than 0.3, e.g., $\beta \geq 45$, 95, and 190 when W = 4, 8, and 16 respectively. The reason is that the utilization of network resources approaches its extremity when deflection ratio increases to some extent. In the meanwhile, deflection routing is not as advantaged as described in last paragraph because its gain is based on extra resources. The whole network can not afford to offer so much demand from deflection under heavy traffic. Therefore, the improvement diminishes as arrival rate increases. As to Fig. 10, because of the fixed routing table, the average hop distance with f_{max} = 0 almost remains stable. Another observation from this figure is that the increment of curves with f_{max} = 1 and 2 is gentler when average hops reaches around 4, i.e., deflection ratio is about 0.3 in Fig. 11. The reason is similar to the explanation of why blocking curves are very close when deflection ratio is greater than 0.3. When utilization of resources nearly saturates, it is more difficult to acquire additional resources for deflection. Consequently, the growth of curves with f_{max} = 1 and 2 in Fig. 10 is not so sharp when deflection ratio is greater than 0.3 in Fig. 11.

In Fig. 12 and Fig.13, related parameters are β = 30, δ = 0.1L, W = 4, and f_{max} = 0, 1, 2. Fig. 12 shows blocking probability versus maximum delay time B when N = 3. Fig. 13 plots the relation between blocking probability and number of FDLs per FDL buffer N with B = 5L. Obviously, as discussed before, the performance with f_{max} = 1 and 2 are indiscernible in both figures and so the following discussions of these two figures focus on curves with f_{max} = 0 and 1. In Fig. 12, it is clear that significant improvement on blocking performance is attained by increasing B with or without deflection routing. For example, taking B = 1L as a basis, blocking probability is improved by three and four order of magnitude when B = 10L and 15L respectively. All curves remain stable when B > 15L. It means that lengthening delay in FDLs is meaningless if network capacity almost saturates, which is consistent with discussions of Fig. 8. On the other hand, curves are steady when N > 3 in Fig. 13. More FDLs can buffer more bursts and therefore should make output links accommodate more transmissions. However, when N increases to some extent, such a benefit diminishes because resources are nearly fully utilized for a certain value of B. What is needed for further improvement is to elongate maximum delay time to allow more requests to defer their desired time. This can explain above phenomenon in Fig. 13.

6. Conclusions

In this paper, we investigate the impacts brought by deflection routing in JET-based OBS networks by both analyses and simulations. Generally speaking, buffer requirement is not vital for either deflection routing or JET-based OBS. However, if deflection routing is enabled, optical buffers are necessary to solve the insufficient offset time problem. We also propose a variant of priority queuing model to approximate burst loss probability. From our observation, the accuracy of the proposed model generally decreases as traffic load rises. It is because that the suppression effect in a priority model is more significant under heavier load. In addition, the model is more accurate when W is smaller and the reason is that larger W will cause the difference between a virtual FDL and a Markovian queue to be magnified. As a whole, the model provides an accurate estimation as the discrepancy is acceptable.

We also evaluate performance of deflection routing in arpanet-2 topology by simulation. Simulation results show that deflection routing evidently brings significant performance gain, especially with fewer wavelengths and under lighter load. Results also reveal that excessive deflection does not always bring performance gain because of immoderate usage of resources. For example, f_{max} = 1 is enough in arpanet-2. Another observation is that the increment of B can significantly improve blocking performance with or without deflection routing. However, the gain reaches a limit when B increases to a certain extent because lengthening delay in FDLs is meaningless if network capacity almost saturates. A similar performance bound exists in the relation between blocking probability and number of FDLs N. What is needed for further improvement is to elongate maximum delay time to allow more requests to defer their desired time. As a future work, we will investigate deflection routing in JET-based OBS networks with QoS consideration.

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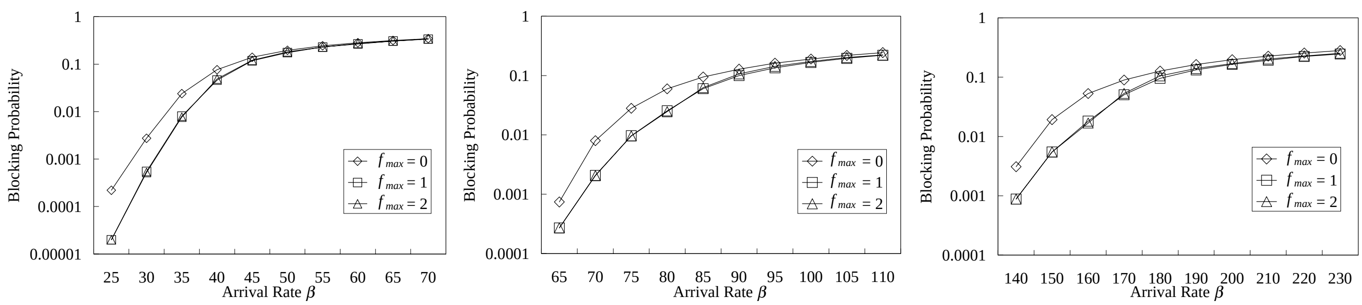
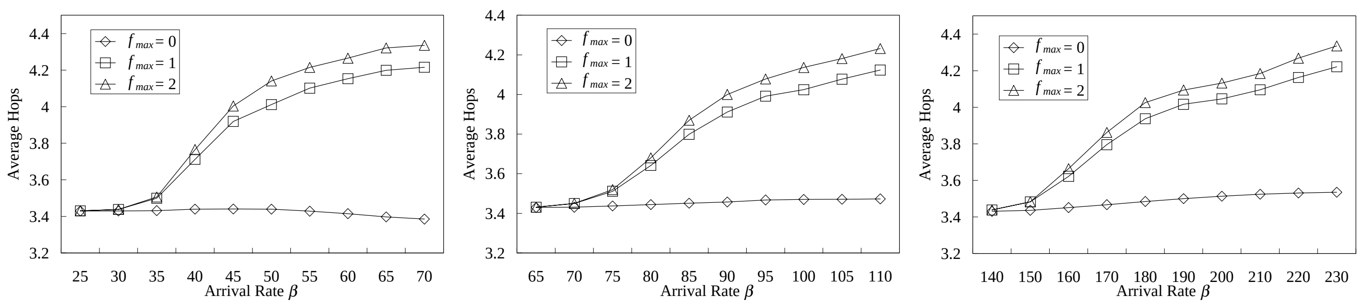


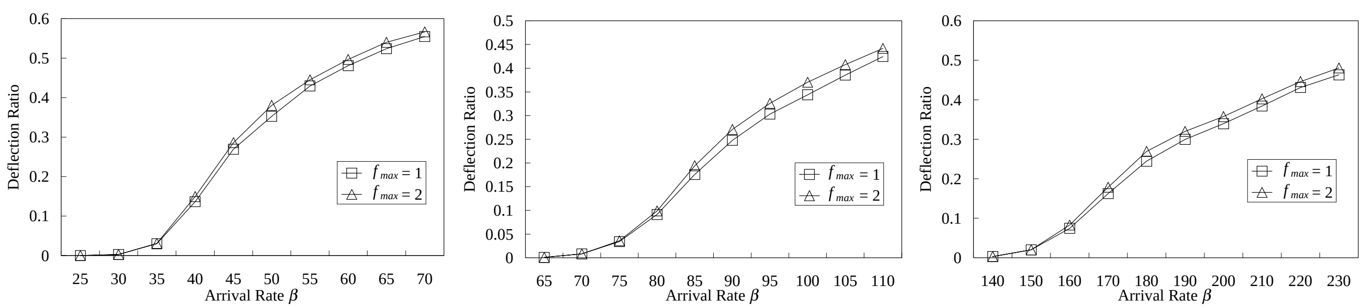
(a) W=4 (b) W=8 (c) W=16

Figure 9. Blocking Probability vs. Arrival Rate in arpanet-2



(a) W=4 (b) W=8 (c) W=16

Figure 10. Average Hops vs. Arrival Rate in arpanet-2



(a) W=4 (b) W=8 (c) W=16

Figure 11. Deflection Ratio vs. Arrival Rate in arpanet-2

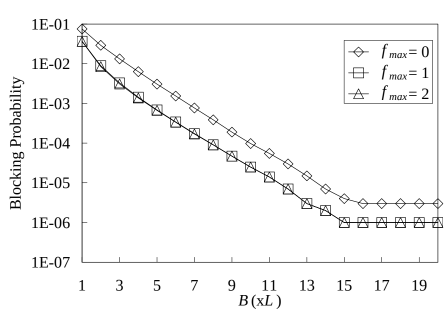


Figure 12. Blocking Probability vs. Maximum Delay Time in arpanet-2

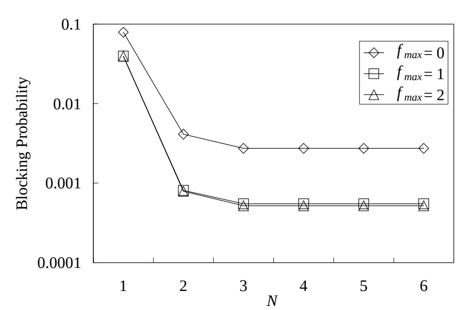


Figure 13. Blocking Probability vs. Number of FDLs in arpanet-2