# A Comparative Study of Contention Resolution Policies in Optical Burst Switched WDM Networks *

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## ABSTRACT

The offset-time-based QoS scheme has been proposed for the next generation Optical Internet as a way to improve current IP's best effort service. For a single node, it has been shown that the offset-time-based scheme efficiently achieves service differentiation without requiring any buffer at the WDM layer. In this paper, the offset-time-based scheme is applied to the multi-hop case. To this end, we consider various policies to handle blocked bursts such as drop, retransmission, deflection routing and buffering in the multi-hop very high performance Backbone Network Service (vBNS), and compare their performance in terms of the average wavelength utilization, the average wavelength efficiency and the average end-to-end extra delay. It is shown that the buffering policy is useful with scarce network resources (e.g., bandwidth), but the dropping policy in conjunction with the offset-time-based scheme is good enough with abundant resources.

**Keywords:** Optical Internet, drop, retransmission, deflection routing, FDL buffer, priority, QoS, performance.

## 1. INTRODUCTION

IP over WDM has received a considerable amount of attention as a way of building the next generation Optical Internet. It appears to be an efficient and economical approach to transporting the ever-growing Internet traffic since it can eliminate shortcomings associated with ATM and IP [1]. As current IP provides only best effort service, one has to address how Quality of Service (QoS) can be supported in the Optical Internet. In particular, considering unique features of WDM layer (all-optical networks), a novel QoS scheme is necessary to provide the future multimedia applications with satisfactory services. Previously, based on optical burst switching (OBS) [2], we have proposed a novel QoS scheme for the Optical Internet, which is called the offset-time-based scheme. By virtue of the "extra offset time", it can efficiently differentiate the arbitrary number of services at the WDM layer. It differs from the existing QoS schemes, which are buffer-based, in that the offset-time-based scheme does not mandate the use of buffer at the WDM layer. This makes the offset-time-based scheme suitable for the all-Optical Internet. For a single WDM switch node, we have quantified the extra offset time required for the class isolation, and have analyzed the burst blocking (loss) probability of each class. In particular, the case when a WDM switch does not have any fiber delay lines (FDLs) was studied in [3, 4] and the case when a WDM switch has FDLs was studied in [5, 6].

Although it is easier to analyze the performance of offset-time-based scheme in the single node model, the result cannot provide the end-to-end network performance such as end-to-end blocking probability and end-to-end delay, which are important parameters when dimensioning network resources. In this paper, we extend our previous work on the offset-time-based scheme, and evaluate its QoS performance in a multi-hop mesh-connected network. To this end, we use the topology of the very high performance Backbone Network Service (vBNS) [7–10], which has been built as a part of the Next Generation Internet (NGI) and Internet 2 [11].

One of the important performance issues is to reduce the blocking (and loss) probability. A request (and its corresponding data burst) is said to be blocked when the network resources (e.g., bandwidth) are unavailable for reservation. Depending on how the WDM switch node deals with the blocked request, policies can be classified into four categories such as drop and discard (or simply drop), drop and retransmission (or simply retransmission), deflection routing [12–15] and buffering [5, 6, 16–19]. Under these policies, QoS performance of the offset-time-based scheme will be evaluated for the vBNS in this paper. The QoS performance will be presented in terms of the average wavelength utilization, the average wavelength efficiency and the average end-to-end extra delay. The performance of various policies under consideration will be compared in order to determine the

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most efficient policy for the offset-time-based scheme. Our results show that the buffering (with limited FDLs) policy is the most effective for real-time applications, the dropping policy is good enough otherwise. In addition, the service differentiation (and class isolation) is still valid for the multi-hop case.

The rest of paper is organized as follows. Section 2 describes the vBNS and IP/WDM switch node under consideration. Section 3 reviews the concept of class isolation using an extra offset time for both cases without and with FDLs. In section 4, we will describe each policy and the QoS performance metrics to be used. Section 5 presents the simulation results with discussions. Finally, Section 6 concludes the paper.

## 2. VBNS AND IP/WDM SWITCH NODE

The origin of the Internet can be traced back to ARPAnet in ’70s and ’80s, which was build as a part of Department of Defense project. During late ’80s and early ’90s, National Science Foundation (NSF) built NSFnet, which provided the foundation of today’s Internet. In 1995, vBNS, which is as a part of the effort building Next Generation Internet (NGI) and Internet 2, took over NSFnet, and since then it has provided high speed data connectivity. Currently, vBNS is implemented as an IP over ATM over WDM network. However, in this paper, we assume that vBNS (or a network with the same topology) can support IP directly over WDM network. vBNS has 12 points of presence (POPs) connecting more than 100 institutions, and its geographical map is shown in Figure 1.

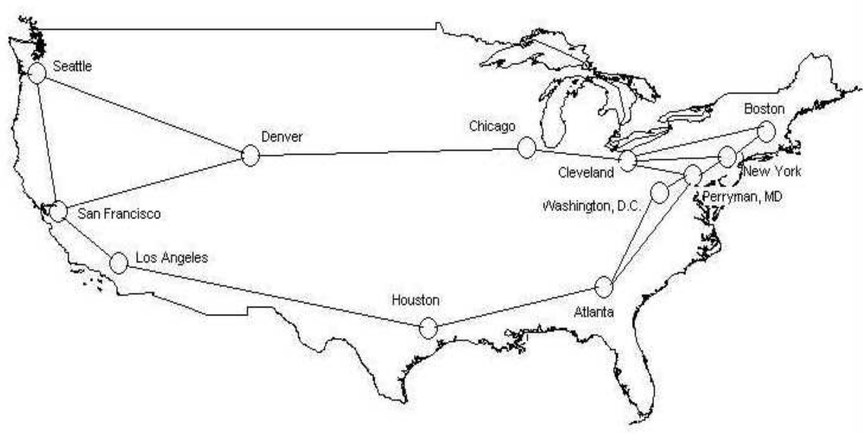

**Figure 1.** Topology of the vBNS

In Figure 1, each node (POP) corresponds to WDM switch node that is vertically interconnected with IP edge router. We consider two different types of WDM switch node, namely one without FDLs (when the drop, retransmission and deflection routing policies are applied) and the other with FDLs (when the buffering policy is applied). Both types of switch are assumed to have wavelength conversion capability. Each WDM switch node is interconnected with its neighboring WDM switch nodes through two separate fiber links (i.e., the fiber links for the incoming direction and the fiber links for the outgoing direction). It is assumed that each link has $k$ wavelengths for transmitting the data burst and one (or more) wavelength for transmitting the control packets. Note that a link may consist of multiple $f$ fibers. However, due to wavelength conversion capability assumed at the WDM switch, the link having multiple fibers, each consisting of $k/f$ wavelengths, can be treated same as a single fiber link with $k$ wavelengths. In addition, the bit rate at which a data burst is transmitted on each wavelength is assumed to be 10 Gbps, which is fully used to transmit a single data burst.

Each source WDM switch node receives the source traffic from IP edge router(s), and then forms a burst for transmission. To send a burst, a control packet is generated according to Poisson process. To route the control packet, we consider the distributed control and shortest path routing. Upon arrival of control packet, a WDM switch node decides the next node based on its own routing table, which shows the remaining number of hops to its destination among other information. When multiple shortest paths exist, the fair coin toss rule is used to decide one of them. The control packet carries the information such as the destination address, the burst length, and the offset time. The offset time is the sum of ”base” and ”extra offset” time. To determine the destination address, we use the uniform distribution. Note that since vBNS has an irregular topology, the uniformly distributed destination does not distribute the load evenly among the links. It is also assumed that the average size of a data burst is 1 Mbits, which corresponds to 0.1 $msec$ transmission time over a single wavelength operating at 10 Gbps. To calculate the inter-node propagation delay, the inter-node distance is divided by the speed of light inside the fiber, which is $2 \times 10^8 m/sec$. The specific inter-node propagation delays are shown in Table 1, where only one-hop propagation delays are shown. These propagation delays will be used to calculate the extra delay caused by the retransmission and the deflection routing.

**Table 1.** Inter-node propagation delay ($msec$)

| prop delay | Atl | Bos | Chi | Cle | Den | Hou | LA | NY | Per | Sea | SF | DC |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Atlanta | - | - | - | - | - | 5.64 | - | - | 4.84 | - | - | 4.38 |
| Boston | - | - | - | 4.44 | - | - | - | 1.53 | - | - | - | - |
| Chicago | - | - | - | 2.51 | 7.33 | - | - | - | - | - | - | - |
| Cleveland | - | 4.44 | 2.51 | - | - | - | - | 3.28 | 2.57 | - | - | - |
| Denver | - | - | 7.33 | - | - | - | - | - | - | 8.26 | 7.74 | - |
| Houston | 5.64 | - | - | - | - | - | 10.1 | - | - | - | - | - |
| Los Angeles | - | - | - | - | - | 10.1 | - | - | - | - | 2.77 | - |
| New York | - | 1.53 | - | 3.28 | - | - | - | - | 1.17 | - | - | - |
| Perryman, MD | 4.84 | - | - | 2.57 | - | - | - | 1.17 | - | - | - | 0.47 |
| Seattle | - | - | - | - | 8.26 | - | - | - | - | - | 5.46 | - |
| San Francisco | - | - | - | - | 7.74 | - | 2.77 | - | - | 5.46 | - | - |
| Washington DC | 4.38 | - | - | - | - | - | - | - | 0.47 | - | - | - |

## 3. CLASS ISOLATION USING OFFSET TIME

We now explain how class isolation (or service differentiation) can be achieved by using an "extra" offset time in both cases without and with fiber delay lines (FDLs) at a switch. One may distinguish the following two different types of contention in reserving resources (wavelengths and FDLs): the intra-class contentions caused by requests belonging to the same class, and the inter-class contentions caused by requests belonging to different classes. In what follows, we will focus on how to resolve inter-class contentions using the extra offset time. For simplicity, we assume that there are only two classes of (OBS) services: namely class 0 and class 1, where class 1 has priority over class 0. In the offset-time-based QoS scheme, to give class 1 a higher priority for resource reservation, an extra offset time, denoted by $t_o^1$, is given to class 1 traffic (but not to class 0, i.e., $t_o^0 = 0$). In addition, we will refer to the extra offset time as simply the offset time hereafter if stated otherwise. Finally, without loss of generality, we also assume that a link has only one wavelength for data (and an additional wavelength for control).

### 3.1. The case without FDLs

In the following discussion, let $t_a^i$ and $t_s^i$ be the arriving time and the service-start time for a class $i$ request denoted by $req(i)$, respectively, and let $l_i$ be the burst length requested by $req(i)$, where $i = 0, 1$. Fig. 2 illustrates why a class 1 request that is assigned an (extra) offset time obtains a higher priority for wavelength reservation than a class 0 request. We assume that there is no burst (arrived earlier) in service when the first request arrives. Consider the following two situations where contentions among two classes of traffic are possible.

In the first case as illustrated in Fig. 2(a), $req(1)$ comes first and reserves wavelength using delayed reservation [2], and $req(0)$ comes afterwards. Clearly, $req(1)$ will succeed, but $req(0)$ will be blocked if $t_a^0 < t_s^1$ but $t_a^0 + l_0 > t_s^1$, or if $t_s^1 < t_a^0 < t_s^1 + l_1$.

In the second case, $req(0)$ arrives first, followed by $req(1)$ as shown in Fig. 2(b). When $t_a^1 < t_a^0 + l_0$, $req(1)$ would be blocked *had* no offset time been assigned to $req(1)$ (i.e., $t_o^1 = 0$). However, such a blocking can be avoided by using a large enough offset time so that $t_s^1 = t_a^1 + t_o^1 > t_a^0 + l_0$. Given that $t_a^1$ may only be slightly behind $t_a^0$, $t_o^1$ needs to be larger than the maximum burst length over all bursts in class 0 in order for $req(1)$ to completely avoid being blocked by $req(0)$. With that much offset time, the blocking probability of (the bursts in) class 1 becomes only a function of the offered load belonging to class 1, that is, independent of the offered load belonging to class 0. On the other hand, the blocking probability of class 0 will be determined by the offered load belonging to both classes.

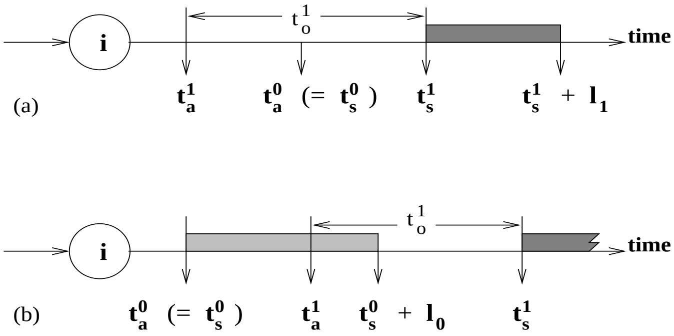

**Figure 2.** Class isolation at an optical switch without FDLs

### 3.2. The case with FDLs

Although the offset-time-based QoS scheme does not mandate the use of FDLs, its QoS performance can be significantly improved even with limited FDLs so as to resolve contention for bandwidth among multiple bursts. For the case with FDLs, the variable $B$ will be used to denote the maximum delay that a burst can go through at each switch.

Fig. 3 (a) and (b) illustrate class isolation at a switch equipped with FDLs where contention for both wavelength and FDL reservation may occur. In Fig. 3 (a), let us assume that when $req(0)$ arrives at $t_a^0$ $(= t_s^0)$, the wavelength is in use by a burst that arrived earlier. Thus, the burst corresponding to $req(0)$ has to be delayed (blocked) for $t_b^0$ units. Accordingly, if $t_b^0 < B$, the FDL is reserved for a class 0 burst as shown in Fig. 3 (b) (the burst will be dropped if $t_b^0$ exceeds $B$), and the wavelength will be reserved from $t_s^0 + t_b^0$ to $t_s^0 + t_b^0 + l_0$ as shown in Fig. 3 (a). Now assume that $req(1)$ arrives later at $t_a^1$ (where $t_a^1 > t_a^0$) and tries to reserve the wavelength. $req(1)$ will succeed in reserving the wavelength as long as the offset time, $t_o^1$, is so long that $t_s^1 = t_a^1 + t_o^1 > t_a^0 + t_b^0 + l_0$. Note that had $req(1)$ arrived earlier than $req(0)$ in Fig. 3 (a), it is obvious that $req(1)$ would not have inter-class contention caused by $req(0)$. This illustrated that class 1 can be isolated from class 0 when reserving wavelength because of the offset time. Of course, without the offset time ($t_o^1 = 0$, and thus $t_a^1 = t_s^1$), $req(1)$ would be blocked for $t_a^0 + t_b^0 + l_0 - t_a^1$, and it would be entirely up to the use of FDLs to resolve this inter-class contention.

Similarly, Fig. 3 (b) illustrates class isolation in FDL reservation. More specifically, let us assume that $req(0)$ has reserved the FDLs as described earlier, and because $t_o^1$ is not long enough, $req(1)$ would be blocked in wavelength reservation and thus needs to reserve the FDLs. In such a case, $req(1)$ will successfully reserve the FDLs if the offset time is still long enough to have $t_s^1 = t_a^1 + t_o^1 > t_a^0 + l_0$. Otherwise (i.e., if $t_s^1 < t_a^0 + l_0$), $req(1)$ would contend with $req(0)$ in reserving the FDL and would be dropped.

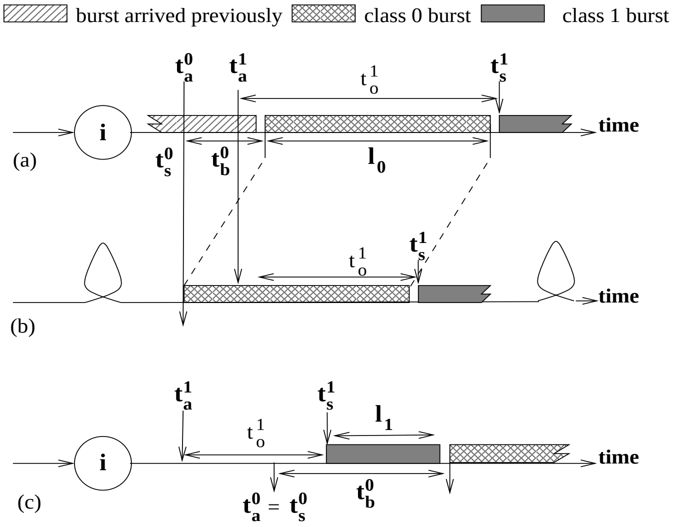

**Figure 3.** Class isolation at an optical switch with FDLs

As shown in Fig. 3 (c), if $req(1)$ comes first and reserves the wavelength based on $t_o^1$ and delayed reservation, and $req(0)$ comes afterwards, $req(1)$ is not affected by $req(0)$. However, $req(0)$ will be blocked either when $t_a^1 < t_a^0 < t_s^1$ but $t_a^0 + l_0 > t_s^1$, or when $t_s^1 < t_a^0 < t_s^1 + l_1$. Similarly, if $req(1)$ arrives first, it can reserve the FDL first regardless of whether $req(0)$ succeeds in reserving the FDL. As mentioned earlier, this implies that class 1 can be isolated from class 0 in reserving both wavelength and FDL by using an appropriate offset time, which explicitly gives class 1 a higher priority over class 0. As a result of having a low priority on resource reservation class 0 bursts will have a relatively high blocking and loss probability.

### 3.3. Class isolation in the multi-hop case

In the previous discussions, we have illustrated that for a single WDM switch node, the use of extra offset time isolates high priority traffic from low priority traffic. In such a single node case, the number of service classes can be generalized to an arbitrary number ($> 2$), and the degree of isolation for a given extra offset time can also be obtained [4,6]. We now consider the multi-hop case, where a control packet (and its corresponding data burst) needs to go through more than one WDM switch node.

When a source edge router has a burst to send, two offset times, namely the base offset time and extra offset time, are assigned, which are carried by the control packet. The base offset time is calculated based on the total processing time to be encountered by a control packet on its way to the destination edge router. As a control packet goes through each hop, the base offset time decreases accordingly [2]. Unlike the base offset time, the extra offset time, which is determined according to a burst's service priority class, remains the same all the way to the destination edge router. This means that the class isolation achieved by the extra offset time for a single node case is still valid to the multi-hop case. Thus, once the extra offset time is given for a burst according to its service class, the same degree of isolation is maintained at all the intermediate nodes.

## 4. POLICIES AND PERFORMANCE METRICS

### 4.1. Policies

When evaluating the QoS performance, four policies are considered depending on how the WDM switch node deals with the blocked request: drop, retransmission, deflection routing, and buffering.

Using the drop policy, a blocked request is simply dropped and discarded. A WDM switch node that discards a request will send a negative acknowledgement back to the source WDM switch node, which then notifies the source IP router. The source WDM switch node does not retransmit. The retransmission of the discarded request is entirely up to the source IP router (or application that generated the request that was discarded).

When the retransmission policy is used, it is similar to the drop policy except that the retransmission is done at the WDM layer. In other words, upon receiving the negative acknowledgement, the source WDM switch node retransmits the discarded request without notifying the source IP router. To alleviate the immediate and recurrent blocking, the source WDM switch node waits for the backoff time before each retransmission. In addition, a simple admission control scheme running at each WDM switch node is required otherwise the offered load might increase indefinitely due to retransmissions, resulting in constant congestion and performance deterioration. Specifically, an admission control scheme maintains a threshold of the offered load, which is set to a certain value (e.g., 0.9), and each WDM switch node keeps track of the current average load offered for a given period of time. When receiving a request for retransmission, the source WDM switch node will send it if the current offered load is lower than the threshold value, otherwise it will discard. Accordingly, the retransmission policy does not guarantee lossless transport at the WDM layer.

Using the deflection routing policy, a blocked request will be deflected to another link. Unlike other policies where only one selected link leading to the shortest path is tried for resource reservation, the deflection routing tries all the links that a given node is interconnected with neighboring nodes. When selecting the link for deflection, the "shortest path (to the destination) first" rule is applied. When none of these links is available, a blocked burst is discarded as in the drop policy. Therefore, deflection routing cannot guarantee lossless transport at the WDM layer either.

The three policies mentioned above are applied to a WDM switch without FDLs. On the other hand, the buffering policy is applied to the WDM switch with FDLs. Using the buffering policy, a blocked request will reserve a FDL (and a wavelength), for the following data burst. Although a large electronic buffer (RAM) may increase the queuing delay and is susceptible to congestion, the use of FDL buffer has a great potential in improving network performance without suffering such disadvantages. More specifically, unlike the electronic buffer which can store a blocked data burst for infinite period of time (infinite queuing delay), the FDL buffer has a maximum allowable queuing delay, which is determined by the length of the FDLs. When a blocked request needs a delay which is longer than the maximum delay that can be provided by the FDL buffer, it will be discarded.

### 4.2. Performance metrics

When presenting the simulation results in the next section, we will consider two OBS protocols, namely the classless OBS and the prioritized OBS. In the classless OBS, there is no distinction between classes, and all classes have the same network performance such as blocking probability and delay. On the other hand, in the prioritized OBS where the offset-time-based scheme is used to differentiate services, there is a clear distinction between classes, and each class expects different quality of service according to its priority. For simplicity, two classes are considered, class 0 and class 1, where class 1 has high priority over class 0. For example, the class 0 corresponds to non-real-time applications, while the class 1 corresponds to real-time applications. When applying the policies such as retransmission, deflection routing, and buffering, we assume that class 1 traffic is also subject to be retransmitted, deflected or buffered in addition to class 0 traffic, although class 1 traffic requires a strict delay bound. Accordingly, we measure the additional delay for class 1 caused by such policies and determine whether the resulting delay is acceptable for the real-time applications.

Before presenting the simulation results, we need to define the following performance metrics. The average wavelength (channel) utilization is the percentage of a single wavelength that has been utilized to successfully deliver data bursts.

The average wavelength efficiency is the percentage of the average offered load per wavelength that has been successfully contributed to the average wavelength utilization. It is a ratio of the average wavelength utilization over the average wavelength offered load. In other words, the average wavelength efficiency shows the successful transmission rate. To obtain the average wavelength offered load, one needs to consider all traffic offered to network such as the source traffic generated from edge router, the through-traffic from neighboring WDM switch nodes, and the traffic from retransmission or deflection routing, which is averaged over the total number of wavelengths in the network.

The average end-to-end extra delay is the cumulative delay from source to destination, which excludes the one-way propagation delay traversing the shortest path. The sum of end-to-end extra delay that has been experienced by each data burst is averaged by the number of data bursts received at the destination. Note that the drop policy does not result in the extra delay, instead it will result in a low utilization (high loss probability). On the other hand, both retransmission and deflection routing are expected to result in the extra delay due to extra propagation delay under such policies. Under the buffering policy, the end-to-end extra delay corresponds to the end-to-end queuing delay.

## 5. RESULTS AND DISCUSSION

In this section, we present the simulation results and compare the QoS performance. The first subsection presents the comparison between classless OBS and prioritized OBS to show the service differentiation achieved by the offset-time-based scheme. The second subsection compares the policies under consideration in terms of the QoS performance metrics described in the previous section.

### 5.1. Service differentiation under the drop and buffering policies

#### 5.1.1. Drop policy

Figure 4 (a) and (b) show the wavelength utilization and wavelength efficiency as a function of the number of wavelengths, respectively, when the drop policy is applied to the bufferless WDM switch. Each WDM switch receives a source traffic load from the edge router, which is 0.8 per wavelength [†]. The offset time difference is set to $3L$, where $L$ is the average burst length. As can be seen in Figure 4 (a), the service differentiation can be observed in the multi-hop case in that class 1 achieves a better wavelength utilization than the classless OBS (and class 0). In addition, the conservation law still holds in the multi-hop case in that the overall wavelength utilization of the prioritized OBS (sum of class 1 and class 0) is equal to that of the classless OBS. Figure 4 (b) shows that only 80 % of the offered load is contributed to the wavelength utilization even when $k = 32$. In other words, the successful delivery rate for a given offered load is at most 0.8. However, class 1 comes close to having a reliable transmission (100 % success rate) when $k = 32$. Thus, the prioritized OBS requires much fewer number of wavelengths than the classless OBS in providing a reliable service to high priority class (class 1).

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[†] 0.8 is the default value of offered load used in all other simulations in this section.

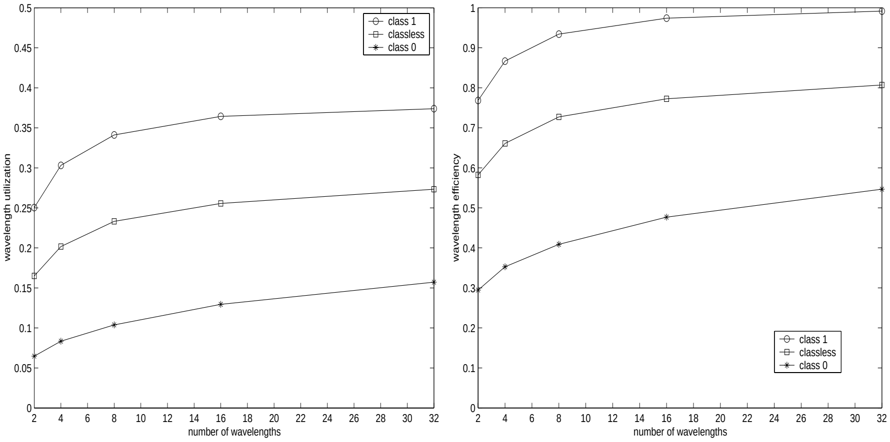

**Figure 4.** Drop policy (a) wavelength utilization (b) wavelength efficiency

### 5.1.2. Buffering policy

The network performance can be improved with the FDL buffer although this will introduce queuing delay. Figure 5 shows the wavelength utilization and the wavelength efficiency as a function of the number of wavelengths. Each link has a dedicated FDL buffer, which has a single FDL inside whose maximum delay time is $3L$. By comparing with the drop policy as in Figure 4, the FDL buffer significantly improves the wavelength utilization and the wavelength efficiency. In particular, the wavelength efficiency of class 1 approaches to a quite reliable transmission level when $k > 8$. The subsection 5.2 will cover the comparison between policies in more detail.

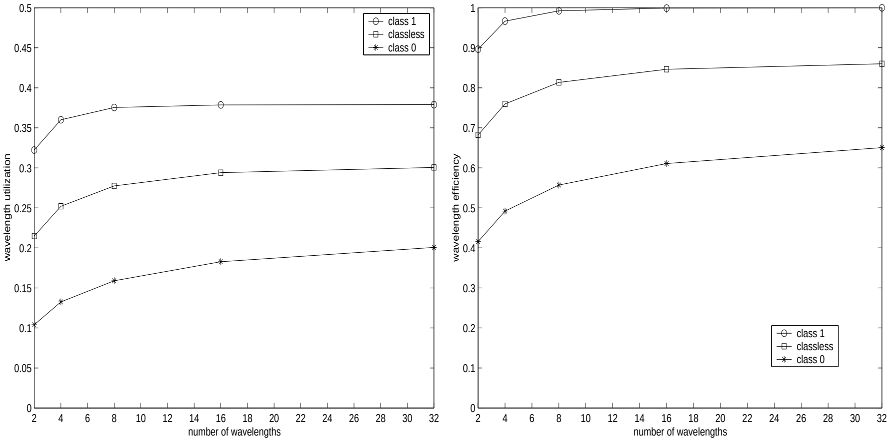

**Figure 5.** Buffering policy (a) wavelength utilization (b) wavelength efficiency

As the buffering policy incurs a queuing delay, Figure 6 plots the end-to-end queuing delay as a function of the number of wavelengths. Throughout this paper, the delay is indicated in unit of $L$ (which is $0.1msec$). As can be seen, the queuing delay of class 1 tends to decrease with $k$, whereas those of class 0 and classless tend to increase with $k$. This can be explained by Figure 5 (b). Since the wavelength efficiency of class 1 is close to 1.0 when $k$ is larger than 8, it implies that most class 1 data bursts are successfully delivered without being blocked (i.e., having to go through the FDL buffer), and therefore the queuing delay decreases. On the other hand, both classless and class 0 experience a longer queuing delays because the blocking probabilities are still high even with a large $k$. For these classes, FDL buffer can improve the performance further, but need a longer length of FDL as the expected blocking time increases. The comparison of the end-to-end extra delay between policies will be covered in subsection 5.2.

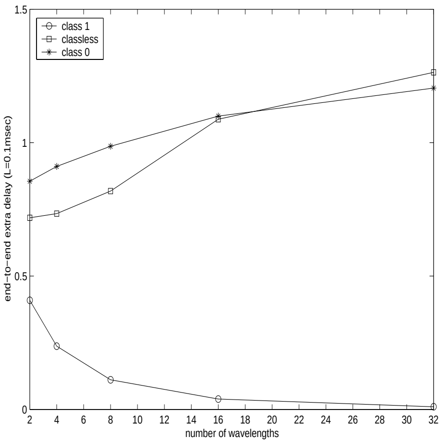

**Figure 6.** End-to-end extra delay under buffering policy

### 5.1.3. Effect of FDL buffer size

Both Figure 7 and Figure 8 show the effect of FDL buffer size on the performance improvement. The number of FDLs $N$ increases up to 4. Note that the number of virtual FDLs $d$ increases with $k$ (i.e., $d = N \cdot k$). When $N = 4$, the smallest unit of FDL is $L$ and the longest unit is $4L$, which is the maximum delay time $B$. The offset time difference is set to $3L + B$.

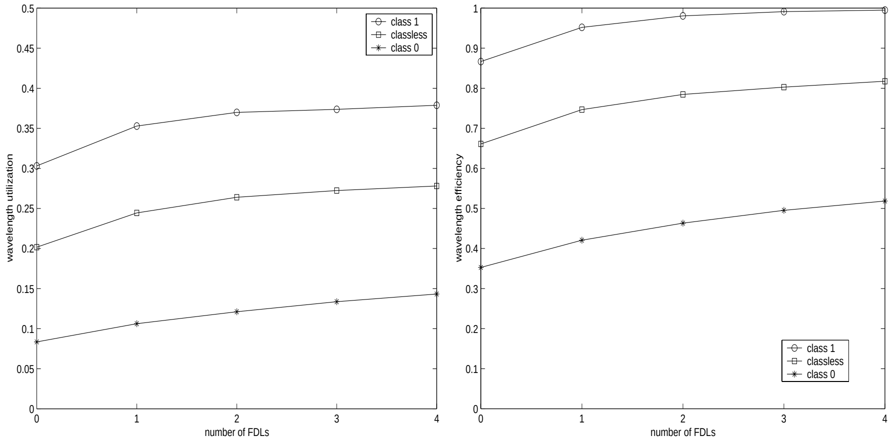

**Figure 7.** Effect of the number of FDLs on (a) wavelength utilization (b) wavelength efficiency

Figures 7 and 8 correspond to the case when $k = 4$ in Figure 4. As $N$ increases, both the wavelength utilization and the wavelength efficiency increase, but not significantly after $N = 2$. This implies that a blocked burst tends to have a long blocking time. Thus, if $N$ increases beyond 4, which increases $B$ as well, FDL buffer can accommodate more blocked bursts with long blocking time, but the queuing delay increases indefinitely as well. This tendency is shown in Figure 8, where the queuing delays keep increasing rapidly, resulting in an insignificant improvement on utilization and efficiency as shown in Figure 7. Note that the classless OBS has a longer queuing delay than the class 0 because class 0 bursts usually encounter a longer blocking time than the bursts in classless OBS, where a burst is dropped when blocking time exceeds $B$. This is why class 0 has a lower utilization than the classless OBS. The advantage of prioritized OBS is that class 1 (high priority class) can achieve a reliable transmission with less resources (wavelength and FDL buffer). As can be seen in Figure 7 (b), the wavelength efficiency of class 1 comes close to 1.0 with $N = 4$ even when $k$ is as small as $4$.

## 5.2. Comparison between policies

In this subsection, we will compare the performances under various policies as a function of the number of wavelengths. The comparisons are made in terms of overall performance (classless OBS) and high priority class (class 1). The policies such as

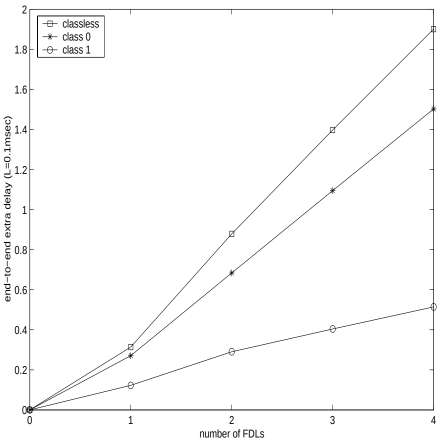

**Figure 8.** Effect of the number of FDLs on end-to-end extra delay

drop, retransmission and deflection routing are applied to the bufferless WDM switch, where the offset time difference is set to $3L$ for the prioritized OBS. The buffering policy is applied to WDM switches with FDL buffer, where each FDL buffer has a single physical FDL ($N = 1$) whose the length is set to $3L$, and the offset time difference is set to $6L$ for the prioritized OBS.

### 5.2.1. Overall (classless OBS) performance comparison

Figure 9 (a) plots the average wavelength utilization. The preferred choice for wavelength utilization is deflection routing, buffering, retransmission and drop in the descending order. The deflection routing results in the best wavelength utilization because some blocked bursts are deflected and successfully delivered to their destination, which effectively increases the number of hops traversed and the number of wavelengths utilized. The deflection routing becomes more effective with $k$ because a deflected burst is more likely to succeed in finding a wavelength among all links that a given node is attached to and ultimately to reach its destination. The buffering policy is the next best policy, which improves the utilization by delaying a blocked burst for a blocking time instead of dropping it. It is expected that increasing $N$ up to certain point improves utilization further as explained in Figure 7. The retransmission policy results in a small improvement on utilization as compared to the drop policy, which can be explained as follows. The average offered load per wavelength without retransmission is fairly high enough to cause many bursts to be blocked and retransmitted. The resulting retransmission increases the average offered load and blocking probability further, which results in a chain reaction. Since the threshold value is set to 0.95 of the average offered load per wavelength using a simple admission control, the network always has a high offered load and suffers a constant congestion due to retransmission. It is expected that the retransmission policy performs better with the reduced threshold value. The admission control with more elaborate schemes could play an important role in the retransmission policy.

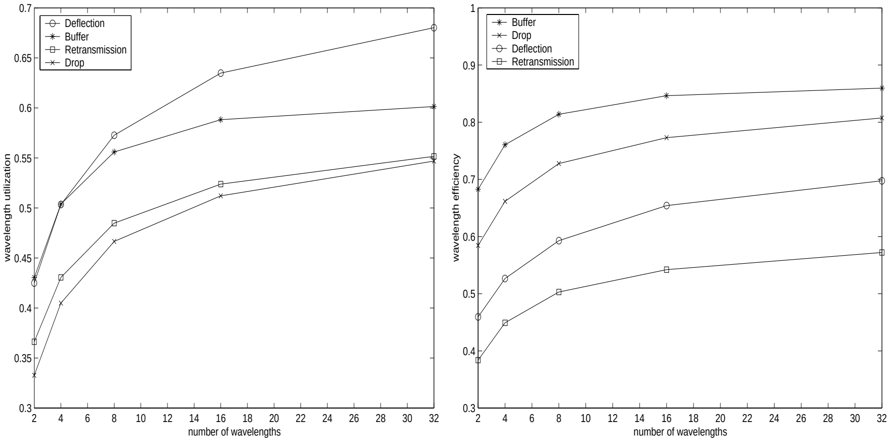

**Figure 9.** Policy comparison on overall performance (a) wavelength utilization (b) wavelength efficiency

For the wavelength efficiency in Figure 9 (b), the preferred policy is buffering, drop, deflection routing and retransmission in the descending order. Although deflection routing achieves the best wavelength utilization, it is in the third place when it comes to the wavelength efficiency. This is because the deflected bursts, which are going through more hops than the shortest path, increase the overall network offered load. Since wavelength efficiency is the ratio of average wavelength utilization over average wavelength offered load, if the increased amount of offered load exceeds the amount of successful delivery, the average wavelength efficiency will decrease. The deflection routing helps increase the wavelength utilization through distributing the offered load to the less congested part of network (especially in the irregular topology), but it is not enough to provide a reliable transmission by itself. Similarly, the retransmission policy suffers a high offered load and a high loss probability, which is worse than the deflection routing policy. The buffering policy achieves the best wavelength efficiency by effectively reducing the loss probability through the FDL buffer and discarding only the blocked burst whose the blocking time exceeds $B$.

Figure 10 compares the end-to-end extra delays for each policy. As can be seen, the deflection routing and retransmission policies result in a relatively long extra delays which are mainly caused by the inter-node propagation delay where the values are shown in Table 1. The extra delay caused by the deflection routing policy decreases with $k$ and becomes lower than that of the retransmission policy. This is because the probability of deflection decreases with $k$, while the probability of retransmission remains high due to a high offered load from the retransmission [‡]. The buffering policy results in a negligible extra (queuing) delay as compared to the deflection routing and retransmission policies. This is because there is a few tens of difference in units between maximum delay time of FDL (in the unit of $L$) and inter-node propagation delay (in the unit of few tens of $L$).

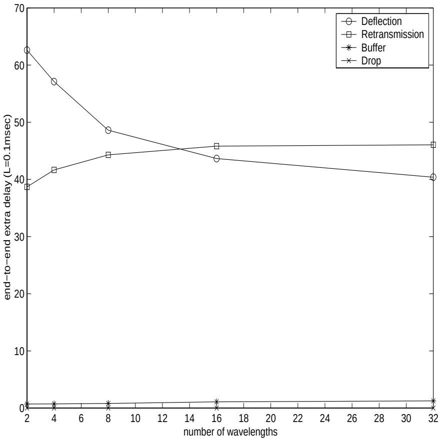

**Figure 10.** Policy comparison on overall extra delay

From the overall performance results discussed above, one can conclude that the buffering policy is the best policy choice for WDM layer that provides a long-haul transport service. The performance of buffering policy can be improved further with increasing $N$ and/or adaptive routing, which distributes the offered load evenly throughout the network.

### 5.2.2. High priority class (class 1) performance comparison

Since the performance of high priority class (class 1) is a major factor when provisioning QoS, it is necessary to compare the performance of various policies from the class 1's perspective. Figure 11 (a) shows that four policies come in the same order as that in Figure 9 (a). However, the curves have different patterns. In the deflection routing, the wavelength utilization decreases with $k$ because the blocking probability (deflection probability) decreases as well, which effectively reduces the number of hops traversing. Similarly, as $k$ increases, the performance improvement under other policies decreases. Due to service differentiation made by the prioritized OBS (the offset-time-based scheme), class 1 has a negligible blocking probability when $k > 32$, which makes policies such as buffering, retransmission and deflection routing less effective.

A similar pattern to Figure 11 (a) can be found in Figure 11 (b), where all curves converge into one point when $k > 32$. Unlike in Figure 9 (b), the deflection routing policy is in the second place for the wavelength efficiency. This is because of the reduced deflection probability of class 1, which in turn decreases the offered load as compared to the case in Figure 9 and thus relatively increases wavelength efficiency.

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[‡] Since source traffic load (0.8) is per wavelength, increasing $k$ does not mean that traffic load reduces accordingly.

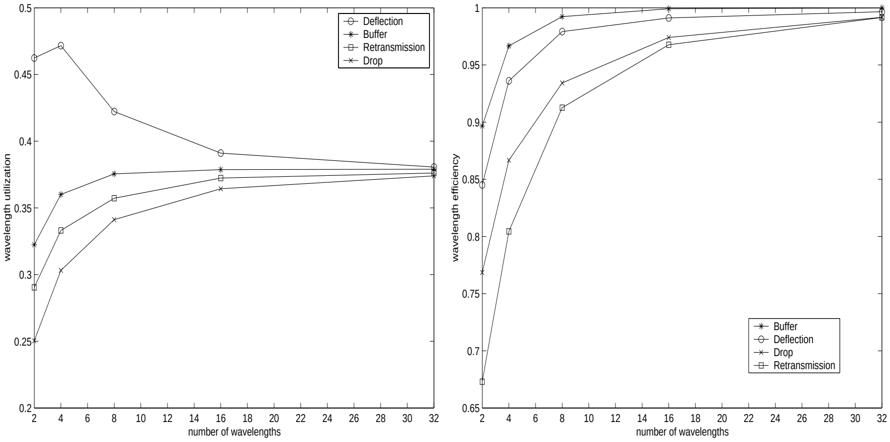

**Figure 11.** Policy comparison on class 1 performance (a) wavelength utilization (b) wavelength efficiency

Figure 12 plots the end-to-end extra delay of class 1, where a similar converging curve pattern is shown. It is noted that the extra delay of the buffering policy becomes more negligible as compared to the overall extra delay shown in Figure 10. It is also shown that the retransmission policy has less extra delay than the deflection routing policy when $k < 16$. This is because the probability of retransmission increases the offered load of class 1 (although it is far less than classless OBS and class 0), which leads to a higher loss probability than the deflection routing, which otherwise might significantly increase the extra delay.

From the above results, one can conclude that due to the service differentiation in prioritized OBS, which reduces blocking probability of class 1 significantly when $k$ is large, the policies under consideration becomes less effective on the performance improvement. In other words, the drop policy, which is the simplest to implement and where the processing time of control packets at WDM switch can be very small [§], is enough for high priority class due to the dominance of service differentiation. Nevertheless, when network resources are scarce, the policies such as buffering or deflection routing can play an important role in providing more reliable service to class 1.

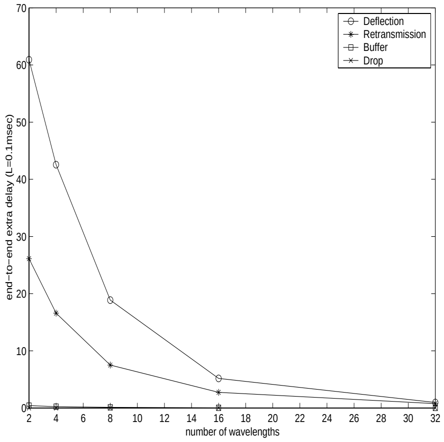

**Figure 12.** Policy comparison on extra delay of class 1

## 6. CONCLUSION

In this paper, we have described the offset-time-based QoS scheme for the multi-hop case. In particular, the performance of the offset-time-based QoS scheme has been evaluated through simulations of the vBNS network. Four different burst contention resolution policies such as drop, retransmission, deflection routing and buffering have been discussed. The QoS performance metrics used are the average wavelength utilization, the average wavelength efficiency, and the average end-to-end extra delay.

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[§] Buffering through FDL and deflection routing require quite complex operations and take longer processing delay than drop policy.

We have compared the policies under consideration in terms of such QoS performance metrics. It has been shown that the dropping policy used in conjunction with the offset-time-based scheme is good enough with abundant resources. Nevertheless, the use of limited FDL buffer can greatly improve the QoS performance of real-time applications with scarce network resources.

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