Service differentiation using hybrid shared optical buffers in transparent optical networks

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Abstract: This paper proposes a novel service differentiation mechanism utilizing optical buffers in transparent optical networks. We first introduce fiber delay line (FDL)-based optical buffers and propose a hybrid shared optical buffered node. Based on the proposed buffer, diverse service requirements can be satisfied by assigning different priorities on accessing the buffer. Since the blocking performance is affected by the basic delay unit of FDL represented by a ratio of the burst length, this paper also takes into account the effect of the burst assembly process on the buffer performance. By dynamically adjusting the burst length under the changing traffic load, optimal performance of the proposed optical buffer can be achieved. Our simulation results show that diverse service requirements can be satisfied in terms of burst blocking probability and buffering delay time.

OCIS codes: (060.4250) Network; (060.4510) Optical communications

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1. Introduction

Optical burst switching technology have been actively studied to construct transparent optical networks which can transmit huge amounts of data traffic over a much longer distance with less data processing at intermediate nodes [1, 2, 3, 4]. In order to improve transmission efficiency, traffic aggregation is performed at an ingress edge node [5]. Input traffic belonging to the same destination and with the same level of service quality is aggregated to a data burst. The node then attempts to provision the resource for the data transmission toward an egress edge node. This enables the data burst to be switched and forwarded to the next node without optical-electrical-optical conversion or buffering for extracting routing information from the burst.

Burst contention resolution is one of the key issues in transparent optical networks [2, 6, 7, 8, 9]. The burst contention occurs when more than two data bursts attempt to access the same output resource simultaneously. There have been proposed several contention resolution technique, such as the use of wavelength converters [6], optical buffers using fiber delay lines [6, 7], deflection routing [8], burst segmentation [9], and so on. Among these techniques, optical buffer provides a more appropriate method to reduce high burst loss rate since it fundamentally resolves contention by intentionally delaying the blocked burst during the contending time as in conventional networks.

Supporting prioritized service is essential to satisfy diverse customer demands [2, 9, 10, 11]. Data burst is transparently transmitted without any processing at intermediate nodes so that the transmission delay time is not the key performance measure. Instead, the burst blocking probability is usually regarded as a main performance measure. In [2], the higher prioritized data burst could reserve resource earlier than the lower one and receives lower loss rate thanks to longer offset time at the expense of longer latency. In [9], the burst assembler locates input traffic at a specific position in a burst based on its priority. When burst contention occurs, the part at which the lower priority packet is located is segmented, but the part with higher priority packets can be successfully delivered. In [10], the burst which violates the proportionally predefined loss rate for each class is dropped to allow for higher priority burst to have more chances of transmission. This scheme provides proportional service differentiation, but results in high loss and low utilization. In [11], by dynamically managing the number of wavelengths belonging to each class group, higher priority burst can secure more output resources for transmission.

However, the previously proposed schemes provide service differentiation by dividing the same resource to each class. Thus, total blocking performance does not improve very much due to the conservation law [2, 11]. This paper proposes a hybrid shared optical buffer and a suitable resource access mechanism for supporting the service differentiation while improving overall blocking performance. In addition, we take into account the impact of the burst assembly process on the buffer performance for achieving the optimal performance of the proposed buffer by dynamically adjusting the burst length under changing traffic conditions.

The remainder of this paper is organized as follows. Section 2 introduces optical buffers using fiber delay lines and resource reservation mechanisms. Section 3 proposes an optical switching system with hybrid shared optical buffers by combining the advantages of two shared buffers. A novel service differentiation scheme utilizing the proposed buffer is introduced in Section 4. Section 5 presents an optimization method of buffer performance using the burst assembly process. Section 6 presents our performance evaluation results showing the achieved service differentiation. And finally, Section 7 concludes this paper.

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2. Optical buffers using fiber delay lines

Optical buffer is an inevitable element to resolve burst contention. Random access memory (RAM)-like optical memory is currently available not yet for optical switching systems. The only way to avoid burst contention is to forward the contending burst to a long enough fiber delay line (FDL) during the contending time. The optical buffer is implemented as a set of fiber delay lines which have different delay time. The length of the ith FDL is $L_i = i \cdot D$, where D is the basic delay unit of FDL, the so-called *granularity*, and $1 \leq i \leq B$, B is the number of delay lines. The following section introduces different types of FDL buffers and resource reservation mechanisms.

2.1. Classification of FDL buffers

Basically FDL buffers can be categorized into two types: 1) *the feed-forward*-type (FF) buffer [12, 13] and 2) *the feedback* (or *recirculation*)-type (FB) buffer [6, 7]. In the FF buffer, the contending burst is forwarded to a pre-fixed length delay line and then it leaves the buffer regardless of its success or failure in accessing the output resource. There is only one chance to access the buffer. On the other hand, in the FB buffer, even though an attempt to access the output resource fails after buffering, the burst can be further recirculated in the buffer until the burst transport succeeds or the maximum number of recirculations has been reached. Thus, this buffer provides more chances to access the output resource, but the burst leads to longer buffering delay and different signal degradation.

According to the position of buffers, they can be further classified into 1) *the dedicated to wavelength* type [12], 2) *the shared per port* type [13], and 3) *the shared per node* type [7]. In a buffer dedicated to a single output wavelength, more than two bursts attempting to access the same wavelength can be delayed during the contending time. Although this may give lower blocking probability, it requires more buffers and large switch fabric. In the shared buffer at a port, contending bursts for the destination port can be buffered at any available delay lines. In the shared buffer at a node, contending bursts at any output ports can access the buffer. Since the amount of FDLs directly affects the blocking performance, the buffer structure should be carefully designed in consideration of switch scalability and blocking performance. Table 1 compares the features of each buffer.

Table 1. Features of optical buffers using fiber delay lines (M: number of ports, W: number of wavelengths in a port, B: number of FDLs, R: maximum allowable number of recirculations, and D: granularity of FDLs)

Architecture	feed-forward (FF)			feedback (FB)	
	dedicated to wavelength	shared		shared	
		per port	per node	per port	per node
Switch architecture	$MW*$ $M(W+WB)$	$MW*$ $M(W+B)$	$MW*$ $(MW+B)$	$M(W+B)*$ $M(W+B)$	$(MW+B)*$ $(MW+B)$
♯ of FDLs	MWB	MB	B	MB	B
Max Buffering Delay	BD	BD	BD	RBD	RBD
Advantages	low buffering delay equal signal degradation			priority support variable buffering time	
Disadvantages	no priority support fixed buffering time			accumulated signal noise large-sized switch fabric	

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2.2. *Resource reservation schemes*

Contending data burst can reserve output resource at the beginning of buffering (*pre-reservation, PreRes*) or at the departing time from the buffer (*post-reservation, PostRes*) [14]. If the burst reserves output resource at the beginning of buffering, it is surely transmitted to the output port. If the burst fails to find an available buffer, it is directly discarded before attempting to access the buffer. On the other hand, in PostRes, the buffered burst can access output resource when it leaves the buffer. Since the buffered burst does not preempt the output resource, other bursts can access the output resource before the buffering burst attempts to access it. These resource reservation schemes affect the performances of the feed-forward and feedback buffers so that a suitable reservation scheme should be applied for each buffer type.

Interest in the usage of FDL buffer is in the fact that there exists an optimal granularity which can produce the lowest blocking probability at a given traffic load. With small granularity, finer buffering time can be achieved, but it inversely has smaller buffering capability. Thus, as the granularity increases, the blocking performance can be improved. On the other hand, large granularity may provide unnecessarily longer delay and may prohibits another burst from accessing the output resource. Especially, in the PreRes, this phenomenon is more serious. Thus, the decision on the granularity of FDL is a critical issue.

3. Hybrid shared optical buffer supporting differentiated service

As we will see in Section 6.1, two combinations of buffers and their reservation mechanisms are suggested as the best. The FF buffer with PreRes outperforms PostRes at the optimal granularity of FDL in terms of burst blocking. It does, however, show worse performance when the granularity is close to the average burst length. The FB buffer with PostRes outperforms PostRes over the entire range of the granularity, but it experiences longer buffering delay time than the FF buffer due to recirculation.

By combining the features of the two buffer combinations, we propose a hybrid shared optical buffer enabling service differentiation as shown in Fig. 1. Since the FF buffer allows one buffering chance it needs more delay lines in order to maintain satisfactory blocking performance. Thus, an FF buffer is located at each output port. On the other hand, the FB buffer is shared at the node because the FB buffer allowing many recirculations can provide as good

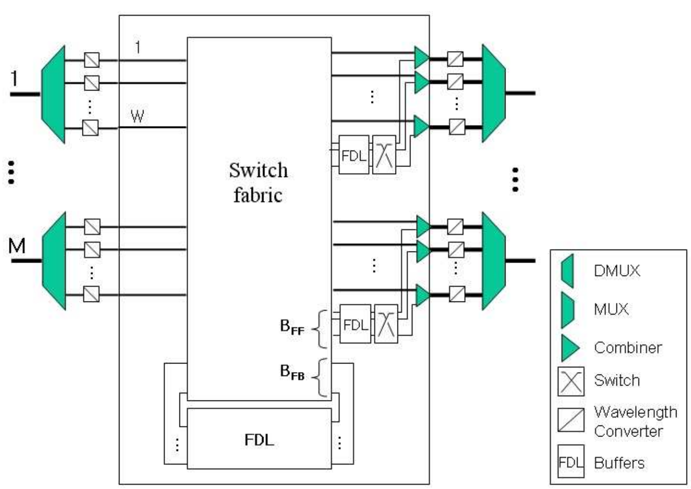

Fig. 1. A hybrid shared optical buffered optical switching system

performance as the FF buffer shared per port. Different buffering time makes the buffers transport different applications requiring diverse target performance. The FF buffer is suitable for delay-sensitive traffic and the FB for delay-insensitive traffic. Based on these buffer features, the following section introduces a differentiated service supporting mechanism.

4. The proposed service differentiation mechanism

Four service classes with different target performances are considered as shown in Table 2. The delay sensitive class 1 and 2 burst exclusively use the FF buffer shared per port and the delay insensitive class 3 and 4 exclusively use the FB buffer shared per node. In addition, the blocking sensitive class 1 and 3 bursts can preempt the buffers being used by the blocking insensitive class 2 and 4 bursts.

Table 2. Four service classes and their applications

Service Level	Target Performance	Applications	Buffers
Class 1	blocking & delay	video conference, video phone	Feed-forward
Class 2	delay	VoIP	Feed-forward
Class 3	blocking	ftp	Feedback
Class 4	best effort	web-traffic, e-mail	Feedback

Now we introduce a novel service differentiation mechanism based on the hybrid shared optical buffer for satisfying the four service requirements. When a burst contends the output resource with an already scheduled burst, the delay-sensitive class 1 and 2 burst attempt to use the FF buffer at the destination output port, of which maximum buffering delay is limited by *BD*. The blocking-sensitive class 1 burst has higher priority on the class 2 burst in usage of buffers. When the class 1 burst gets blocked at the output port and all buffers are busy, the burst attempts to find any buffers carrying class 2 burst. If there are buffers having class 2 burst, the class 1 burst preempts the buffer and can be successfully transmitted. However, the buffered class 2 burst simply gets discarded.

On the other hand, the class 3 and 4 burst support delay insensitive service so that the FB buffer is allocated for them. Since the class 3 burst is blocking sensitive, it has higher priority than the class 4 burst in the use of buffer. When the first attempt of buffering does not allow access to the output resource, the buffered burst can be further delayed at the buffer until the transmission succeeds or the maximum number of recirculations is reached. If the maximum recirculation does not allow the class 3 burst to use the output resource, it can preempt the buffer containing the class 4 burst. This service differentiation mechanism is illustrated in Fig. 2.

5. The impact of the burst assembly process on optimal buffer performance

Once an optical switching system has been manufactured and deployed, it is not easy to upgrade system elements so that the node should be carefully designed in consideration of the performance measure and system requirements. For example, since the FDL granularity considerably affects the blocking performance, the decision on granularity is a critical issue [12, 13, 14].

Note that the burst assembly process has a mechanism to control the length of generated burst [15]. Since the optimal granularity is closely related to the burst length, if we carefully manipulate the burst assembler to adjust the burst length according to network status, the prefixed

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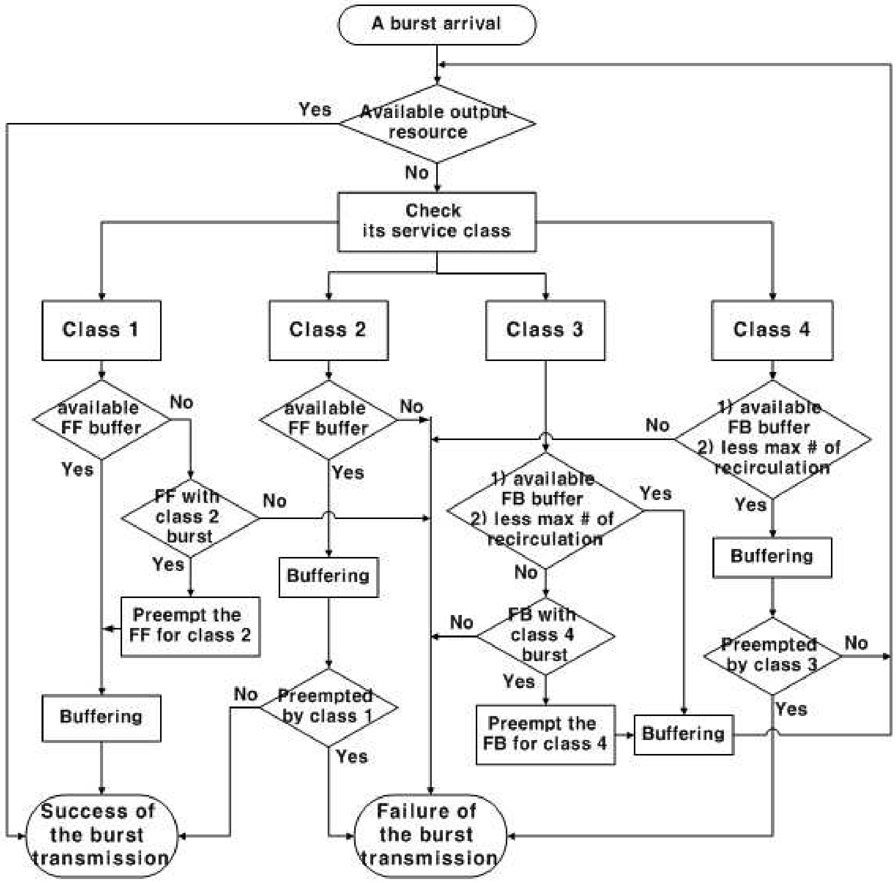

Fig. 2. Procedure of the proposed service differentiation mechanism

buffer can produce its best performance as if it works at the optimal granularity. For achieving the optimum performance of the FDL buffer under various traffic load, this paper proposes a dynamic burst length adjustment mechanism.

5.1. Dynamic adjustment of the burst length

This section first explains how the data burst is generated using a threshold-based burst assembler which can control the burst length [15]. When the total length of waiting input traffic at the assembly queue arrives at the predefined *threshold* value (T_H), a new burst is generated. The last input packet, which arrives with Poisson process and exponentially distributed length (L_P in mean value), enables the queue length to reach the threshold value. Thus, the generated burst length (L_B) is $T_H + L_P$ [15]. Importantly, manipulating the threshold value for adjusting the burst length keeps the offered load identical [15]. That is, the dynamic adjustment of the burst length does not affect the original traffic load.

Now, let us explain how the burst length adjustment can emulate the prefixed buffer to behave at its optimal granularity. For example, let us assume that in a specific buffer structure, the optimal granularity is 0.3 at an offered load of 0.5, and 0.5 at a load of 0.8, respectively. If we design the buffer with granularity 0.3, the buffer produces its best performance at an offered load of 0.5, but not other loads. Note that the granularity is represented as a ratio of the burst length. If we assume the burst length is 100KByte, the granularity 0.3 implies that the basic delay unit is 30KByte. When the traffic load changes from 0.5 to 0.8, if we adjust the burst length to 60KByte, the prefixed buffer can behave at a granularity of 0.5, which is optimal. The newly demanded burst length ($\hat{L_B}$) can be obtained from

$$\hat{L_B} = L_B * \frac{D_F}{D_O} \quad (1)$$

where D_F is the prefixed granularity and D_O is the optimal granularity at the changed traffic load. Supposing that the input packet size is much smaller than the threshold value, the newly required burst length can be set at the threshold value. The decision of optimal granularity in a dedicated buffer to a single output wavelength or a shared buffer for an output port can be referred to in [12] and [13], respectively.

6. Performance evaluation

This section first presents the performances of the feed-forward buffer and the feedback buffer, respectively. The proposed hybrid shared optical buffer is then evaluated for its effectiveness for the service differentiation. We finally present the optimum performance of the buffer by applying the burst length adjustment mechanism.

6.1. Performance evaluation of FDL buffers

We assume the following simulation parameters: number of ports 4, number of wavelengths per port 4, number of delay lines per port or node 8, number of recirculations 5, bandwidth of wavelength 2.5Gbps, full wavelength conversion, the average burst size 100Kbyte with exponential distribution, and the arrival rate of burst with Poisson process is normalized to ensure that the burst offered load (ρ_B) at output wavelength is zero to one. The burst scheduler chooses the earliest available output wavelength for the incoming burst by keeping and updating the last available time of each output wavelength [4]. In the figures, the granularity of FDL is normalized to the mean burst size. For example, the granularity of FDL 0.1 implies that the smallest delay unit is 1/10 of the burst size and the size of the other FDL increases to 0.1 times of the burst size. Thus, the largest granularity is equal to the mean burst size.

6.1.1. Blocking probability

Figure 3 presents the burst blocking probabilities for the shared type optical buffers using PreRes (a zero FDL granularity implies no buffers used). The burst blocking probability varies depending on the granularity of FDL. As mentioned in Section 2, there exists an optimal granularity (around 0.1 to 0.4) to produce the lowest blocking probability, while the optimal value varies depending on the structure and burst offered load (ρ_B). Over the optimal granularity, the burst blocking probability comes to increase and becomes even larger than that without FDL buffer. This is because when a new burst arrives and gets blocked just after the previous burst is buffered, it needs to be buffered at longer FDL than that of the previous one. As the granularity increases, this phenomenon grows more serious. As a result, there is no large enough buffer for the contending burst. The need for larger buffering time is more serious in the FB buffer where the recirculation of the blocked buffer is allowed. Thus, the blocking performance of the FB buffer is worse than the FF buffer at both the optimal granularity and the above.

Blocking performance with PostRes is presented in Fig. 4. The blocked burst is just buffered without reserving the output resource so that the new arriving burst can access the output resource before the buffered burst is transmitted. The FF buffer has only one change of buffering so that the performance enhancement is not high. The FB buffer, on the other hand, can attempt to access the output resource many times thanks to recirculations and its performance is highly

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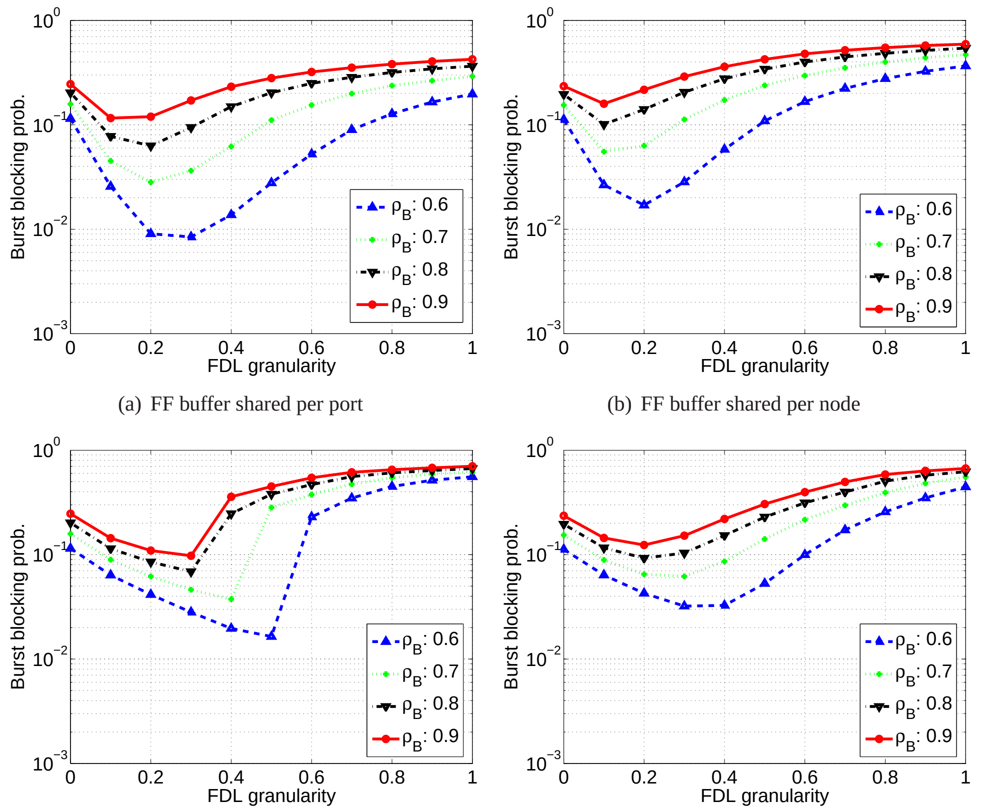

(a) FF buffer shared per port (b) FF buffer shared per node

(c) FB buffer shared per port (d) FB buffer shared per node

Fig. 3. Burst blocking probability for optical buffers with PreRes

enhanced at optimal granularity. Contrary to PreRes, the blocking performance is not much deteriorated at large granularity above the optimal point. This is because the blocked burst does not pre-reserve the output resource so that the late arrived burst just demands as much buffer size as the contending time.

In addition, the increment of the number of recirculations helps improve the blocking performance which is not shown in the graphs. The performance enhancement of recirculation is mostly observed in PostRes, but there is a limitation of enhancement. Signal degradation should also be taken into account for the maximum number of recirculations.

In summary, the blocking performance varies depending on the buffer structures, resource reservation mechanisms, the granularity of FDL and traffic load. PreRes outperforms with the small granulated feed-forward FDL buffer. PostRes can also be used for all ranges of granularity in the feedback buffer. The buffer shared per port outperforms the shared per node buffer because it simply has more delay lines. The linear increment of delay lines for the shared per port buffer does not guarantee linear enhancement of blocking performance for the shared per node buffer. There is an algorithmic benefit for the shared per node. Therefore, the choice of the shared buffer is a problem of the tradeoff between switch scalability and performance guarantee.

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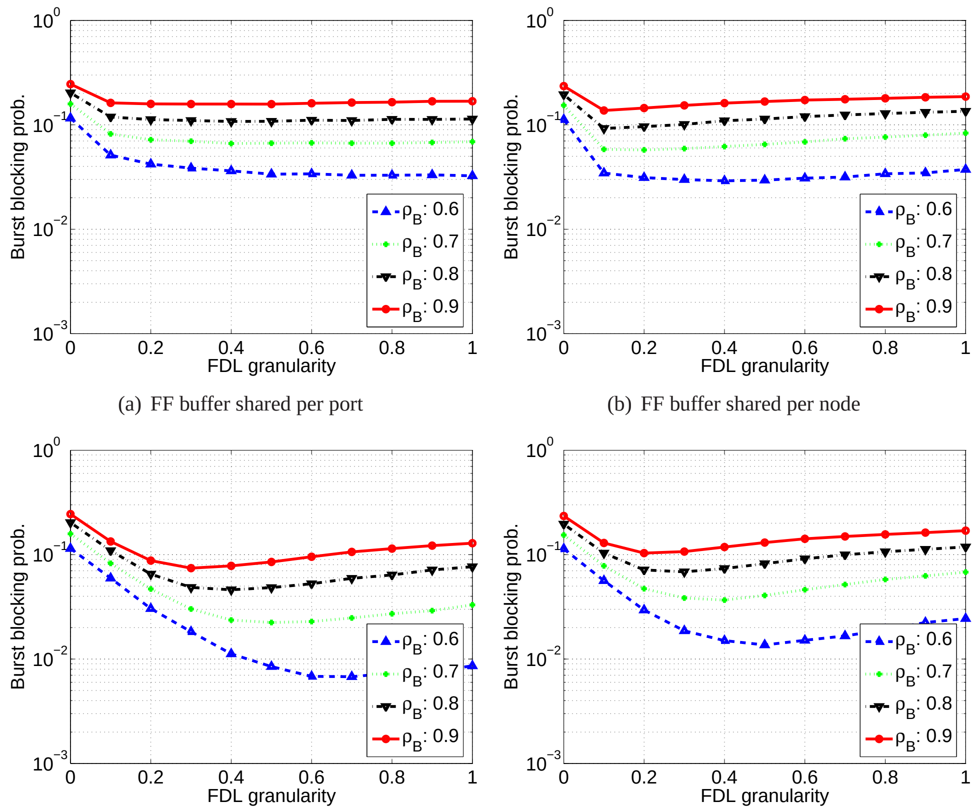


(a) FF buffer shared per port

(b) FF buffer shared per node

(c) FB buffer shared per port

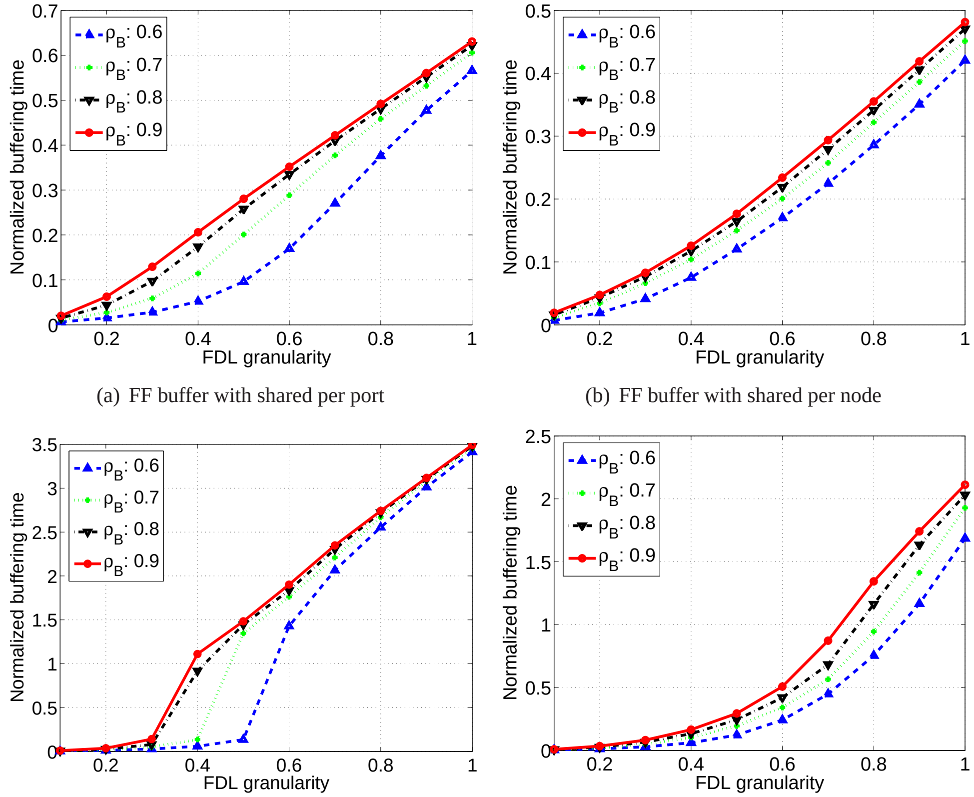
(d) FB buffer shared per node

Fig. 4. Burst blocking probability for optical buffers with PostRes

6.1.2. Buffering delay

Figures 5 and 6 present the buffering delay time (normalized to the burst service time) of optical buffers when PreRes and PostRes are applied, respectively. As the burst offered load and the granularity increase, the buffering delay increases. The use of PreRes produces longer delay time than that of PostRes. The feedback type buffer produces longer delay time than the feed-forward type buffer, especially for PreRes. The reason that PreRes yields longer delay is explained as follows. The blocked burst reserves output resources before entering the buffer. The next blocked burst should thus use a longer delay line than the previous one used. Consequently, as the granularity increases, the usage frequency of longer FDLs increases and then the buffering delay comes to increase. This phenomenon does not happen with PostRes.

On the other hand, the buffer shared per port (shown in Figs. 5(a), 5(c), 6(a), and 6(c)) presents longer buffer delay than the buffer shared per node (shown in Figs. 5(b), 5(d), 6(b), and 6(d)). In the buffer shared per port, the blocked bursts attempt to use as many buffers as possible to resolve burst contention and have more chances to use buffers than the buffer shared per node due to having a higher quantity of buffers. Consequently, the buffer shared per node is superior to the buffer shared per port in terms of buffering delay.



(a) FF buffer with shared per port

(b) FF buffer with shared per node

(c) FB buffer with shared per port

(d) FB buffer with shared per node

Fig. 5. Buffering delay time of optical buffers with PreRes

6.2. Service differentiation using the proposed buffer

Thus far, the performance of each buffer has been evaluated with different resource reservation mechanisms. The distinctive features of each buffer with their suitable resource reservation mechanisms gives a baseline for supporting service differentiation and the hybrid shared optical buffer. For obtaining the evaluation results, let us assume that the number of FF buffer is (B_{FF}) per port 4, the number of FB buffer is (B_{FB}) per node 8, the maximum allowable number of recirculations is 10 and the amount of each class traffic is identical, the destination port for each class is uniformly distributed, and other assumptions as shown in Section 6.1.

Figure 7(a) shows the burst blocking probability according to the granularity of buffer for each class at the burst offered load per wavelength (ρ_B) 0.5. Due to the different usage of buffers and resource reservation mechanisms, the blocking performance for the four classes shows different optimal granularity. This implies that the prefixed granularity may produce unsatisfactory results for each class when traffic load changes. For example, the granularity 0.8 provides satisfactorily good performance for class 1 to 3, but not class 4, because the optimal granularity of class 4 is 0.5. This phenomenon can be improved by using the dynamic burst length adjustment mechanism. Before examining the mechanism, let us observe the buffering delay time for the four classes shown in Fig. 7(b) which are well differentiated according to the service requirement for each class. The reason that the delay time of class 4 is lower than that of class 3 is because not many class 4 bursts can be buffered due to lower priority on accessing

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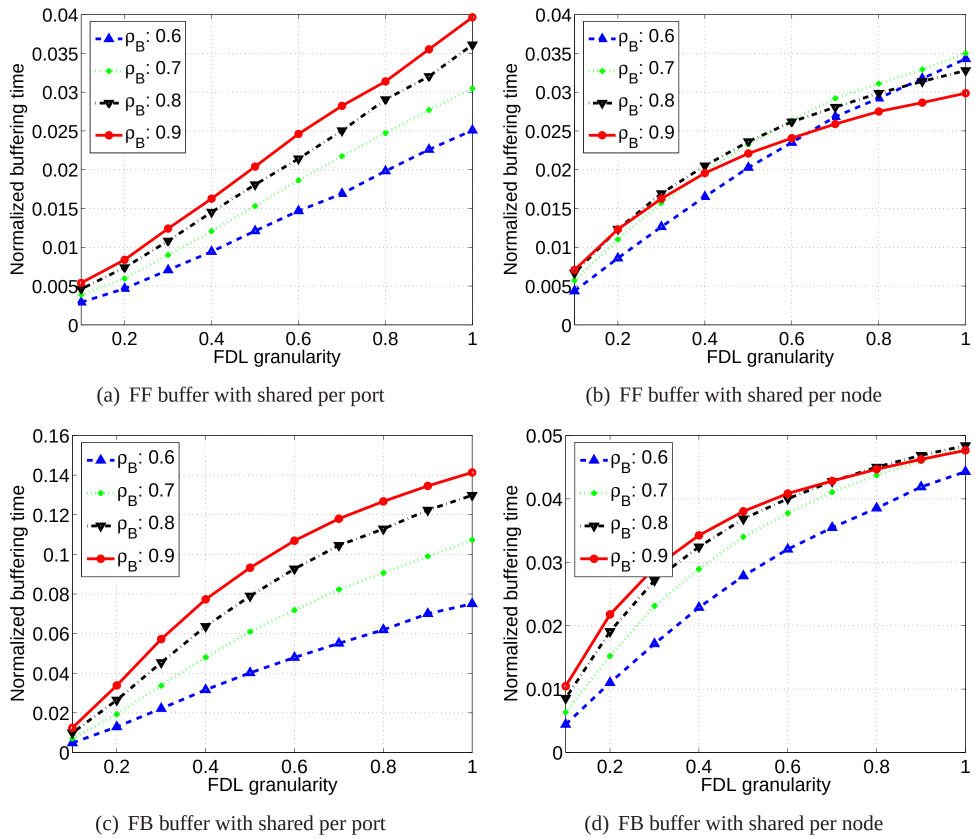


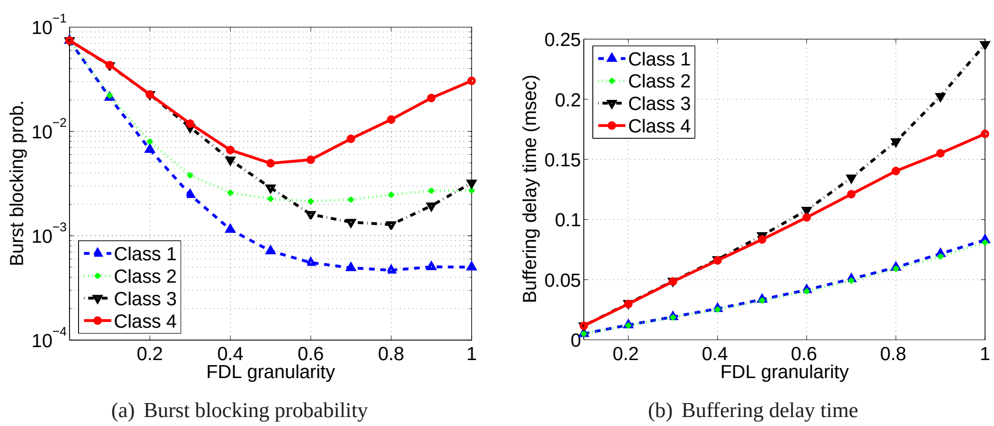
(a) FF buffer with shared per port

(b) FF buffer with shared per node

(c) FB buffer with shared per port

(d) FB buffer with shared per node

Fig. 6. Buffering delay time of optical buffers with PostRes



(a) Burst blocking probability

(b) Buffering delay time

Fig. 7. Results of service differentiation at offered load 0.5

the buffer than class 3.

Now, let us apply the dynamic burst length adjustment mechanism for the service differentiation. From the simulation results and Eq. 1, the optimal FDL granularity (D_O) and the adjusted

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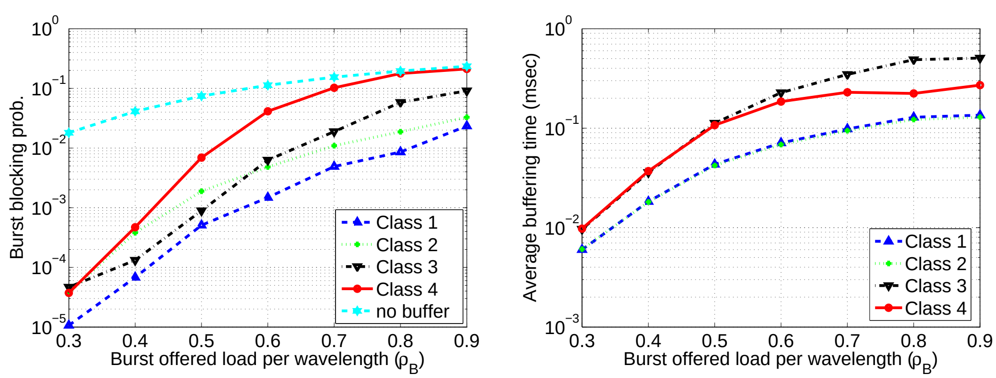
Table 3. Adjusted burst length reflecting the optimal granularity at different offered load

ρ_B		0.3	0.4	0.5	0.6	0.7	0.8	0.9
Class 1	D_O	0.7	0.7	0.7	0.7	0.6	0.5	0.5
	$\hat{L_B}$	71K	71K	71K	71K	83K	100K	100K
Class 2	D_O	0.8	0.8	0.6	0.5	0.4	0.4	0.3
	$\hat{L_B}$	63K	63K	83K	100K	125K	125K	167K
Class 3	D_O	0.8	0.8	0.7	0.5	0.4	0.3	0.2
	$\hat{L_B}$	63K	63K	71K	100K	125K	167K	250K
Class 4	D_O	0.8	0.7	0.5	0.3	0.2	0.2	0.1
	$\hat{L_B}$	63K	71K	100K	167K	250K	250K	500K

burst length ($\hat{L_B}$) at each traffic load with prefixed granularity (D_F) 0.5 are obtained in Table 3. As the load increases, the optimal granularity decreases, especially for the lower classes. This is because the greediness of class 1 and 2 for resource occupancy mainly affects the decision of optimal granularity of class 3 and 4. Since class 3 and 4 support delay-insensitive service, the burst assembly time for generating large burst may not be critical.

Figure 8(a) shows the burst blocking probability according to the burst offered load with the adjusted burst length. As compared with Fig. 7(a), the adjusted burst length helps improve the blocking performance for all classes as well as adapt traffic load. Class 1 supporting blocking sensitive service shows the lowest blocking probability. Class 3 also shows satisfactorily low blocking probability. Class 2 shows better blocking performance than class 3 at high offered load. This is because class 2 has inherently higher priority to occupy output resource due to pre-reservation than class 3 at high load. Notably, the use of buffer much improves the blocking performance regardless of offered load.

Figure 8(b) shows the buffering delay time for the four classes. As the offered load increases, the delay time increases and reaches a saturation point at high load regardless of classes. This is because the maximum buffering delay time is limited to the maximum buffer length (for class 1 and 2), and the multiplication of the maximum buffer lengths and the maximum allowable number of recirculations (for class 3 and 4) at even high load. As shown in the figure, class 1



(a) Burst blocking probability (b) Buffering delay time

Fig. 8. Results of service differentiation with the burst length adjustment

and 2 supporting delay sensitive services show lower delay time than that of class 3 and 4. The delay time for class 1 and 2 is less than 0.1ms over the entire range of offered load so that the total delay time through the network can be surely satisfied for delay-critical applications. Class 4 peculiarly shows lower delay than class 3 and this is because class 4 has lower priority than class 3 when competing to reserve buffer so that it usually gets discarded, not being buffered at the buffer.

7. Conclusion

Optical buffer is an inevitable element to resolve high burst contention. In the design of optical buffers, there is a tradeoff between the buffer size constrained by the switch fabric manufacture and the blocking performance requiring more buffers. Therefore, this paper proposed a cost-effective shared buffer taking into account buffer scalability and performance. The proposed buffer is a hybrid type which pursues advantages of both the feed-forward and feedback buffers. By assigning different priorities to access the buffer and output resource, diverse service requirements could be satisfied in terms of burst blocking probability and buffering delay time. In addition, for achieving the optimal performance of FDL buffers which are affected by the traffic load and the granularity, we proposed a dynamic burst length adjustment mechanism. With prefixed granularity, optimum performance could be accomplished under a diverse network environment by controlling the burst assembly process for adapting the burst length.

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