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Wavelength Converter and Fiber Delay-line Sharing in WDM Optical Packet Switches: Dimensioning and Performance Issues*

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Abstract Two novel switch models: MOD1 and MOD2, which employ nondegenerate fiber delay-lines (FDLs) and degenerate FDLs plus wavelength converters shared among the input lines, respectively, are presented to resolve contention. For non-bursty traffic, a very small number of FDLs is sufficient to obtain a reasonable packet loss probability for both models, and in this case, MOD1 is more cost effective than MOD2. While for bursty traffic, given that the total number of FDLs used for MOD1 equals to those of the FDLs and converters used for MOD2, MOD2 performs much better than MOD1 even if no converter is used. With the increase of the average burst length, the number of converters required by MOD2 needs to be increased so as to maintain a reasonable packet loss probability. However, even for the traffic with high degree of burstiness, MOD2 is still a cost effective and robust solution.

Keywords Optical packet switch; Wavelength converters; Fiber delay-lines; Packet loss probability
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0 Introduction

In an optical packet-switched network, it is extremely important to ensure a low packet-loss probability while achieving a relatively high throughput. This can be achieved by incorporating a large buffering capacity, which usually means a large fiber delay-lines (FDLs) and a large stages of switches. To overcome this problem, in ref. [1], a network solution is proposed that combine with the use of wavelength dimension for contention resolution, optical buffers can be avoided when more than 11 WDM channels are used for transmitting data in the optical domain. However, it implies a high number of tunable wavelength converters (TWCs). In ref. [2], Eramo et al. propose a switch model in which the TWCs are shared among the input channels and their number is minimized so that only those TWCs strictly needed to achieve given performance requirements are employed. Numerical results signify that the saving of converters, with respect to the architecture proposed in ref. [1], can reach about 95%. Although the TWCs required in this case can be greatly reduced, the TWCs, which need to be tuned quickly in the whole waveband, are still dominant in the cost.

This paper investigates the somewhat untraditional approach to resolve contention, two WDM-based optical packet switch models, namely, MOD1, employs nondegenerate[3] FDLs shared among the input lines, and MOD2, employs degenerate FDLs and TWCs shared among the input lines, are proposed to handle contention. For a given packet loss probability constraints, we demonstrate that the proposed models are more flexible and cost effective than the traditional methods introduced in the literatures.

1 Proposed architectures and operations

The developed switch architecture consists of three blocks (Fig. 1): 1) Input stage, where a demultiplexer selects the packet arriving on W wavelength channels, $\lambda_1, \cdots, \lambda_W$, on each of the N input fibers; 2) Switch stage, a space switch directs the arriving packets to the appropriate output ports, or to the contention resolution module if contention occurs; 3) Output stage, where a multiplexer multiplexes the packet arriving on W wavelength channels to the output fiber. We assume that packets have fixed size and their arrivals on each wavelength are synchronized on a time-slot basis, and a time slot, T, is the time needed to transmit a single packet. Without loss of generality, assume that each FDL delays packets for one slot, i. e., time is divided into equally long time slots, each is able to hold one

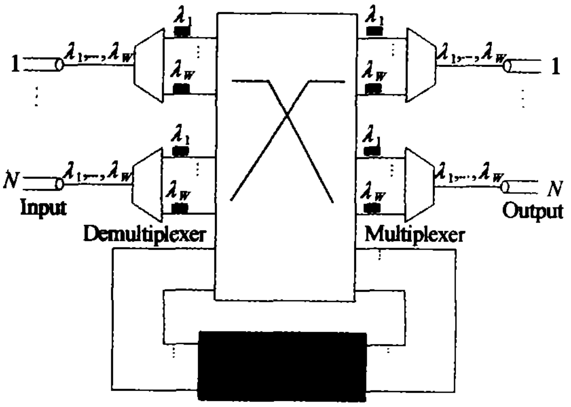

Fig. 1 Structure of the WDM-based switch architecture

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packet of fixed length.

1.1 MOD1 architecture

Contention resolution module of MOD1 is shown in Fig. 2, in which the contentions are resolved by FDLs. Note that, although the delays achieved by FDLs cover the entire range of buffer depth, i. e., from T to LT, the FDLs are arranged in nondegenerate form, wherein the number of FDLs that have l time slots of buffering capacity is M_l, $l = \{1,2,\cdots,L\}$, $M = \sum_l M_l$, $M_1 \geqslant M_2 \geqslant \cdots \geqslant M_L$.

Once contention occurs, switch scheduler searches the free buffers in increasing order of the FDLs' length and first-fit strategy, is used, i. e., first searches FDLs among M_1 FDLs that have one unit of buffering capacity, and stops the searching procedure if one free FDL is found. If no free buffers are found among M_1 FDLs, the scheduler continues searching the free buffers among M_2 FDLs with two units of buffering capacity, etc. Note that for MOD1, the outgoing packets of the FDLs can be re-circulated, this is especially useful to resolve the contention occurred among the outputs of the FDLs.

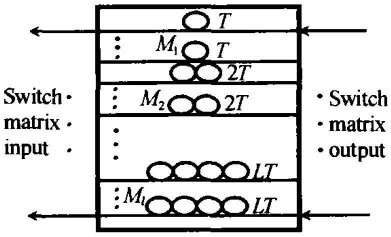

Fig. 2 Contention resolution module of MOD1 architecture

The MOD1 shown in Fig. 2 implies that FDLs with one unit of buffering capacity will be most often used, and, most contentions can be resolved just by one unit length of FDLs. Therefore, for a given number of the FDLs, and especially for a large value of M_1, the total length of FDLs in Fig. 2 will be much fewer than that of a degenerate counterpart. Simulation results shown in the next Section proves that for non-bursty traffic, the developed MOD1 is very effective to reduce the switch size, and thus reduce the switch cost.

1.2 MOD2 architecture

In Fig. 3, we show another switch architecture proposed in this paper, i. e., MOD2, in which the contentions are resolved by shared FDLs and TWCs. In this scenario, the FDLs are arranged in degenerate form, i. e., the delays achieved by FDLs uniformly cover the entire range of buffer depth, i. e., from T to LT, with increments of one unit.

In the figure, R and M denote the number of TWCs and FDLs respectively. Once contention occurs, switch control system can either schedule the contending packets into FDLs (in increasing order of the FDLs' length) so that the packet can be transmitted in future time slot, or, by using TWCs, to tune the wavelength of the arriving packet to another wavelength that is free in the contending output fiber. Obviously, regarding the TWCs as the top-priority is helpful to increase the switch throughput.

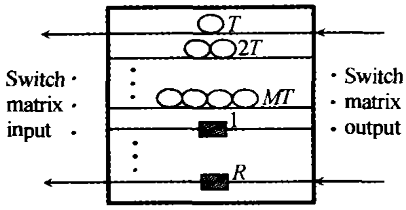

Fig. 3 Contention resolution module of MOD2 architecture

Note that for MOD2, if new contention occurs among the outputs of the FDLs, besides the above mentioned methods introduced for MOD1, i. e., re-circulating the contending packets, contention can also be resolved by selecting the free TWCs.

Let $G = R + M$, denote the total number of TWCs and FDLs shared among the input wavelength channels. We will demonstrate in the next Section that for non-bursty traffic, if $(R,M) = (G,0)$ can satisfy the requirement of the packet loss probability, the configuration of $(R,M) = (x,G\text{-}x)$ $(x \leqslant G)$ can also satisfy the requirement. So, we will determine the packet loss probability with the configuration of $(R,M) = (G,0)$. Assume that the probability of a packet arriving on one of the $N \cdot W$ input channels is given by the channel load, ρ_w, and that the input processes have the same statistic and an arriving packet has the same probability $(1/N)$ to be directed to any output channel. Thus the packet loss probability of the switch is equal to the packet loss probability of a single output fiber. Let $p(h)$ be the probability that h packets are destined for the output considered, we have

$$p(h) = \binom{NW}{h}\left(\frac{\rho_w}{N}\right)^h\left(1 - \frac{\rho_w}{N}\right)^{NW-h} \tag{1}$$

To have an equivalent packet loss probability to the architecture that provides TWCs for each input wavelength channel, e. g., [1], the maximum number of TWCs needed by the developed architecture can be determined as follows:

Theorem: For MOD2 with $(R,M) = (G,0)$, to obtain an equivalent packet loss probability to the method that provides TWCs for each input wavelength channel, the maximum number of TWCs needed is $G = G_{\mathrm{opt}} = WN - W - N + GCD(W,N)$, wherein $GCD(x,y)$ is the greatest common divisor of x and y.

Alike to the share-per-node wavelength convertible switch architecture, the theorem can be proved by Minimum Cost Grouping Problem, the readers with interest are referred to [4] for further details. In fact, as shown in the next Section, much fewer TWCs than the maximum number of TWCs are sufficient to obtain a feasible packet loss probability.

For $(R, M) = (G, 0)$, packet loss may be resulted from two aspects: 1) insufficient TWCs are used for the switch architecture; 2) over W packets are destined for an output line simultaneously. Suppose that G_{opt} TWCs are used for the switch architecture, the packet loss probability can then be found as

$$PLR = P(h > W) = \sum_{h=W+1}^{NW} \binom{NW}{h} \left(\frac{\rho_w}{N}\right)^h \cdot \left(1 - \frac{\rho_w}{N}\right)^{NW-h} \qquad (2)$$

2 Numerical results

We assume that the total load offered to each input line equals to ρ and hence, we have an offered load per wavelength $\rho_w = \rho/W$. This position analogous to that assumed in ref. [1], [2], [6] is consistent with the goal of using wavelength dimension as a mean to exclusively solve contention. Moreover, we also assume that: 1) $N = 16$, $\rho = 0.8$; 2) 8 FDLs/(FDLs and TWCs) are used for MOD1 and MOD2 respectively; 3) 10^8 packet arrivals are simulated for each data point; 4) Non-bursty traffic is generated using the model of random traffic; 5) Bursty traffic is generated using the method introduced in ref. [5], [7]. In the following, we will use notation l to denote the average burst length.

2.1 Simulation results for MOD1

We will compare the performance of MOD1 with the degenerate buffer architecture.

The simulation results for non-bursty traffic are plotted in Fig. 4. We can see that with the increase of the total buffering capacity, the packet loss probability will gradually decrease, while, even with the configuration of $M_1 = 8$, i. e., minimum buffering capacity is configured for MOD1, the difference of the packet loss probability between two architectures is still small, and, the packet loss probability is at an acceptable level when $W \geq 5$. Note that for $M_1 = 8$, the total buffering capacity for MOD1 is $8T$, while the degenerate architecture, $36T$. This means that for non-bursty traffic, MOD1 can significantly decrease the total FDLs' length used for buffering, and thus save the switch size.

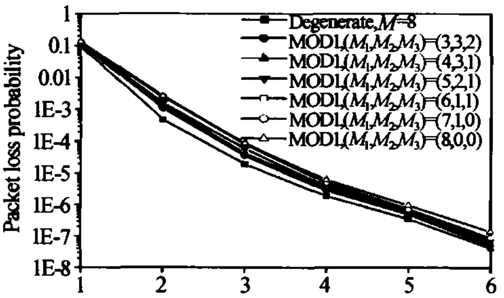

Fig. 4　Packet loss probability under non-bursty traffic for MOD1 and degenerate buffer architectures

For bursty traffic, the corresponding simulation results for traffic with medium degree of burstiness ($l = 5$) are plotted in Fig. 5.

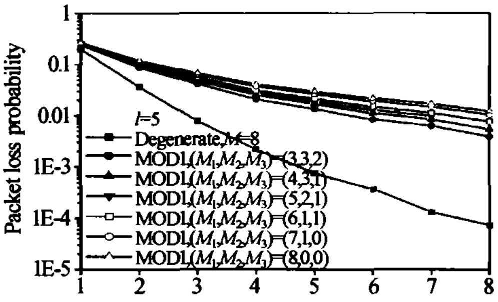

Fig. 5　Packet loss probability under burst traffic for MOD1 and degenerate buffer architectures($l = 5$)

We can see that even for the traffic with medium degree of burstiness, the difference of the packet loss probability between two architectures is much larger than that of the non-bursty traffic counterpart. That is to say, for bursty traffic, the total buffering capacity, i. e., the total length of FDLs, has a more important effect on the packet loss probability than that of the non-bursty traffic. From Fig. 5, we can also deduce that with the increase of the average burst length, i. e., an increasing burstiness, the packet loss probability will increase sharply. For example, for $(M_1, M_2, M_3) = (3, 3, 2)$ and $W = 8$, the minimum packet loss probability for $l = 2$ is 5×10^{-5} (not shown in this paper), while for $l = 5$, the value increases to 0.004. Moreover, even for degenerate architecture, the packet loss probability for $l \geq 5$ is larger than 10^{-4}. Therefore, MOD1 may not be a good choice for bursty traffic.

2.2 Simulation results for MOD2

Simulation results for non-bursty traffic are plotted in Fig. 6. We can see that 1) For a given total number of FDLs and TWCs, increasing the number of FDLs is helpful to improve the packet loss probability; 2) for $M = 0$, a very small number of TWCs can also obtain a good packet loss probability, and the simulation results are very good agreement with analytical results, e. g., for $W = 8$, 8 TWCs are sufficient to obtain equivalent packet loss probability of $G_{opt} = WN - W - N + GCD(N, W) = 112$ TWCs, note that in ref. [1], 128 TWCs are needed; 3) MOD1 is more cost effective than MOD 2; 4) For a given total number of FDLs and

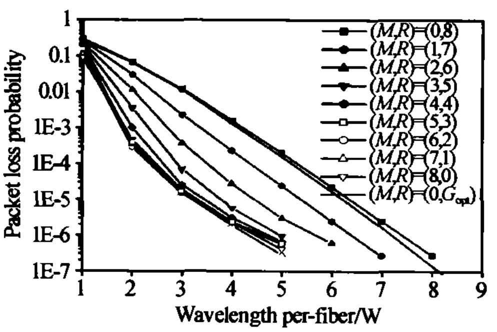

Fig. 6　Packet loss probability under non-bursty traffic for MOD2

TWCs, say, $M+R=8$, and for $W \geqslant 8$, packet loss probability is always at an acceptable level ($<10^{-6}$). In other words, we can arbitrarily configure the number of FDLs (or TWCs).

For bursty traffic, the simulation results that are not completely given in this paper show that 1) For $l=2$, i. e., a small average burst length, the packet loss probability for different configuration of the number of FDLs (TWCs) are very close to that of the non-burst traffic; 2) With the increase of the average burst length, increasing the number of TWCs is an efficient way to decrease the packet loss probability, while, the most efficient and cost effective way to decrease the packet loss probability is with the combined use of FDLs and TWCs, e. g., for $2 < l \leqslant 5$, $W \geqslant 8$, configuring $(M,R)=(5,3)$ is a good choice to obtain a reasonable packet loss probability, and a reasonable cost, while for $5 < l \leqslant 10$, $W \geqslant 8$, the TWCs needed will (gradually) increase to 6 so as to maintain a reasonable packet loss probability. This condition is shown in Fig. 7 with average burst length $l=10$.

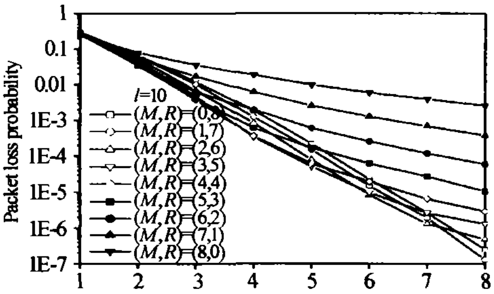

Fig. 7 Packet loss probability under bursty traffic for MOD2 ($l=10$)

3 Closing remarks

In this paper, two switch models, namely, MOD1, in which the contention is resolved by a set of nondegenerate fiber delay lines shared among the input lines, and MOD2, in which the contention is resolved by a set of degenerate fiber delay lines and wavelength converters shared among the input lines, are proposed. Simulation results have shown that by distributing the traffic to more than 8 wavelength channels, both models (especially MOD1) are cost effective solutions against non-bursty traffic, and, MOD2 is also a robust solution against bursty traffic. With the increase of the number of wavelengths per fiber, the total number of FDLs (for MOD1) or FDLs and TWCs (for MOD2) needed by the proposed architectures can, different from the traditional design, gradually decrease.

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波长转换器和光纤延迟线在 WDM 光分组交换中的结构设计和性能研究

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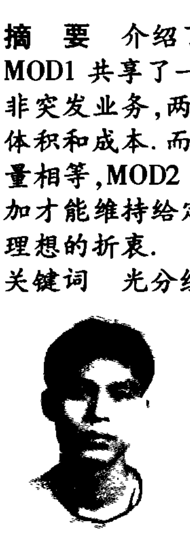
摘　要　介绍了两种新颖的光分组交换结构——MOD1 和 MOD2，用于解决分组冲突问题. 其特点在于，MOD1 共享了一组非简并的延迟线，而 MOD2 则是共享了一组简并的延迟线和波长转换器. 研究表明，对于非突发业务，两种结构都只需要少量的延迟线即可获得理想的性能. 此时，MOD1 比 MOD2 更加能降低系统体积和成本. 而对于突发业务，如果 MOD1 所共享的延迟线数量和 MOD2 所共享的延迟线和转换器的总数量相等，MOD2 的分组丢弃率要远远低于 MOD1. 随着业务突发程度的增加，MOD2 中的转换器数量也需要增加才能维持给定的分组丢弃率，但即使业务突发程度很高，MOD2 在体积、成本和性能等三方面均可取得较理想的折衷.

关键词　光分组交换；波长转换器；光纤延迟线；分组丢弃率



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