Performance Study on a WDM Packet Switch With Limited-Range Wavelength Converters

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***Abstract*—We consider a slotted WDM packet switch with limited-range wavelength converters. The performance of this switch is studied using simulations with various types of data traffic. Results show that the slotted WDM packet switch with a small range of wavelength conversion capability can achieve a performance close to that of a switch with the full range of wavelength conversion capability.**

***Index Terms*—All-optical packet switching, cell loss probability, limited-range wavelength conversion, WDM.**

I. INTRODUCTION

ALL-OPTICAL packet switches have been proposed as a promising candidate for next generation high-speed switches. This kind of switch can be implemented purely in the time domain or in a combination of the time domain and the wavelength domain [1]. It can also be implemented in either a time-slotted fashion or in an unslotted fashion [2]. Slotted WDM packet switches function in a combination of the time domain and the wavelength domain such that they reduce the required number of fiber delay-lines by exploiting the wavelength domain. In earlier studies of this kind of switches, various switch architectures have been proposed and their performance were studied based on both analyses and simulations. In [3] and [4], a slotted WDM packet switch using fiber delay-lines as the output buffers had been proposed and analyzed both for the models of uniform traffic and bursty traffic. In [5], a slotted WDM packet switch with shared wavelength converters was also proposed. A slotted WDM packet switch with shared buffering has also been proposed in [6]. These proposed switch architectures share the common feature that the wavelength converters in the switches were assumed to be capable of converting to and from wavelengths over the full range of wavelengths. In practical systems, a wavelength converter normally has a limited range of wavelength conversion capability. Moreover, a wide range wavelength conversion may slow down the switching speed because it would take a longer time to tune a wavelength over a wider range. To better understand the benefit of wavelength conversion for the performance of the slotted WDM packet switch, it is, therefore, important to study the performance of the switch with limited-range wavelength converters. We have selected the switch architecture proposed in [3] to carry out this study and have conducted simulations with various types of data traffic, both uniform and bursty. Note that the other WDM packet switch architectures may also be studied in a similar fashion.may slow down the switching speed because it would take a longer time to tune a wavelength over a wider range. To better understand the benefit of wavelength conversion for the performance of the slotted WDM packet switch, it is, therefore, important to study the performance of the switch with limited-range wavelength converters. The purpose of the study reported here is to study this by studying the effect of limited-range wavelength conversion on the performance of the switch. We have selected the switch architecture proposed in [3] to carry out this study and have conducted simulations with various types of data traffic, both uniform and bursty. Note that the other WDM packet switch architectures may also be studied in a similar fashion.

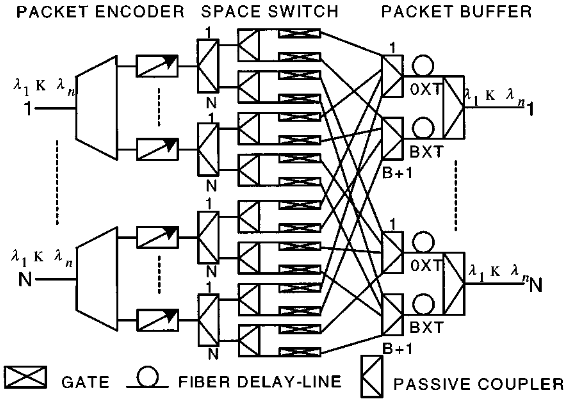

Fig. 1. Slotted WDM packet switch with gates to form a space switch and fiber delay-lines to realize optical buffers.

II. SLOTTED WDM PACKET SWITCH

Fig. 1 illustrates the WDM packet switch architecture proposed in [3]. The switch consists of three blocks: 1) a demultiplexer (DMUX) per inlet fiber, followed by limited-range wavelength converters (LWC) that convert a wavelength within a limited range; 2) a space-switch constructed by passive couplers and gate switches; and 3) output buffers realized by fiber delay-lines.

As shown in Fig. 1, the wavelength of each packet can be converted in a limited fashion to another, say k $(k \leq n)$, wavelength by LWC. This means that each packet is able to access k *output*

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wavelength buffers in its destination outlet port where we define an *output wavelength buffer* as the buffer that stores packets with a certain wavelength at the outlet port. Therefore, an outlet port with n different multiplexed wavelengths will have n such *buffers*. When packet switching is going on, the numbers of packets in the *output wavelength buffers* will change dynamically. For a newly arriving packet, different policies may be applied to select an available *output wavelength buffer* to store the packet. To minimize the packet loss, we use the policy that the switch should store a packet in the *output wavelength buffer* that has the smallest number of packets among the k accessible *output wavelength buffers*. We refer to this *output wavelength buffer* as the *preferred output wavelength buffer*. There may be situations where there are multiple *preferred output wavelength buffers* simultaneously available. If this happens, the switch will randomly select one of the *preferred output wavelength buffers* and will store the packet in it.

The WDM packet switch is assumed to have a limited number of output buffers. Each *output wavelength buffer* is assumed to store up to maximum B cells; the total capacity of the output buffers is therefore nB cells, where n is the number of wavelengths multiplexed in the outlet port. The switch will discard a packet if all of its k accessible *output wavelength buffers* are fully occupied.

III. WAVELENGTH CONVERSION DEGREE AND TRAFFIC DISTRIBUTIONS

A. *Wavelength Conversion Degree*

We propose the term, *wavelength conversion degree* [7], to represent the wavelength conversion capability. A wavelength converter with *conversion degree* d is able to convert a wavelength to any wavelength of its d higher wavelengths and any of its d lower wavelengths. When $d = n$, the limited-range wavelength conversion becomes the same as full-range wavelength conversion.

B. *Traffic Distributions*

Uniform Traffic: This kind of traffic assumes that the probability of a cell arriving at one of the n wavelengths per inlet is given by the time independent load ρ. Traffic on different wavelengths in different inlets are assumed to be uncorrelated. Cells in different time slots are also assumed to be uncorrelated.

On–Off Bursty Traffic With Geometrical Random Distribution [8]: This kind of traffic is modeled as an on–off source. Assume that $p(q)$ is the probability of the event that an active (idle) period will terminate after the current time slot and will be followed by an idle (active) period. The probability that the active period (burst) lasts for a duration of i time slots (consists of i cells) is then

$$P(i) = p(1-p)^{i-1} \quad i \geq 1 \tag{1}$$

with mean *burst length* is $1/p$.

The probability that an idle period lasts for j time slots is

$$Q(j) = q(1-q)^{j-1} \qquad j \geq 1 \tag{2}$$

where the mean idle period is $1/q$.

Note that this assumes that there should be at least one time slot in each active or idle period.

The overall network utilization is—$\rho = (1/p)/(1/p + 1/q)$

Therefore, given p and ρ, q may be expressed as

$$q = p\rho/(1-\rho)\ . \tag{3}$$

From (1) and (2), given a random variable U with uniform distribution on [0, 1], we can use the following transformation to generate the random number P for the number of time slots in the active period and in the idle period.

$$P = [1 + \ln U / \ln(1-x)]^{+}\ . \tag{4}$$

Here $x = p$, if it is in an active period; otherwise, $x = q$. The operator $[*]^{+}$ implements a round-up operation.

On–Off Bursty Traffic With Pareto Distribution [9]: Traffic with the Pareto distribution is used to simulate Internet traffic which tends to have the self-similar feature. Here we also adopt this function to generate the self-similar traffic for our simulations. The duration of each on-off period is assumed to be a random variable $T_i,\ i \in \{\text{on}, \text{off}\}$, with the Pareto distribution, having a cumulative distribution function

$$F_i(t) = 1 - (t_0/t)^{\alpha_i} \tag{5}$$

with mean $E[T_i] = t_0\alpha_i/(\alpha_i - 1)$ when $\alpha_i > 1$. In the simulation we set $t_0 = 1$, so that the active period and the idle period of the bursty traffic can vary from 1 to ∞ time slots.

The overall network utilization may be written as

$$\rho = (E(T_{\text{on}})/(E(T_{\text{on}}) + E(T_{\text{off}})))$$

Therefore, given the utilization ρ and the mean of the active period $E[T_{\text{on}}]$, the α_{off} parameter is obtained as

$$\alpha_{\text{off}} = \frac{(1-\rho)\alpha_{\text{on}}}{(1-\rho)\alpha_{\text{on}} - \rho(\alpha_{\text{on}} - 1)}. \tag{6}$$

Based on (5), given a random variable U with uniform distribution on [0, 1], we use the following transformation to generate the random number P of time slots during the active period and the idle period

$$P = \left[1 \Big/ U^{1/\alpha}\right]^{+} \tag{7}$$

IV. SIMULATION RESULTS

Our simulation experiments measure the cell loss probability of a 16 × 16 WDM packet switch with 8 wavelengths per inlet (outlet) port. The three types of data traffic, which are described in Section III, are studied under different conditions of wavelength conversion capabilities. The statistics of about 100 million packets are collected over all inlet ports of the switch.

Fig. 2 shows the results of cell loss probability versus the number of fiber delay-lines for different *wavelength conversion degrees* (from 0 to full-range wavelength conversion) for uniform data traffic. We find that with the increase in the number of fiber delay-lines, the cell loss probabilities decrease continuously. We therefore conclude that the optical output buffers are important to improve the performance of the slotted WDM packet switches. Fig. 2 also shows that having even a minor wavelength conversion capability can result in a big performance improvement in the WDM packet switch (compare

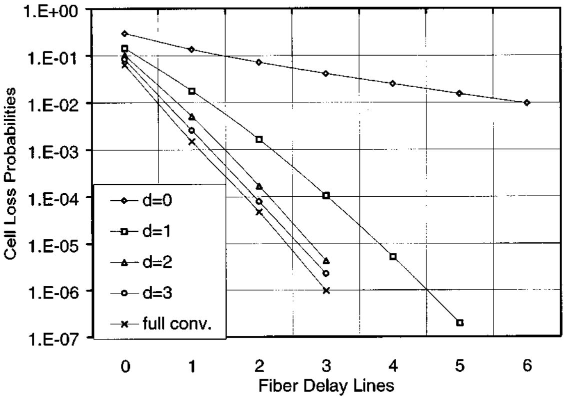

Fig. 2. Cell loss probability versus number of fiber delay-lines with different wavelength conversion capabilities ($d = 0$ to full-range). The traffic load per wavelength $\rho = 0.8$.

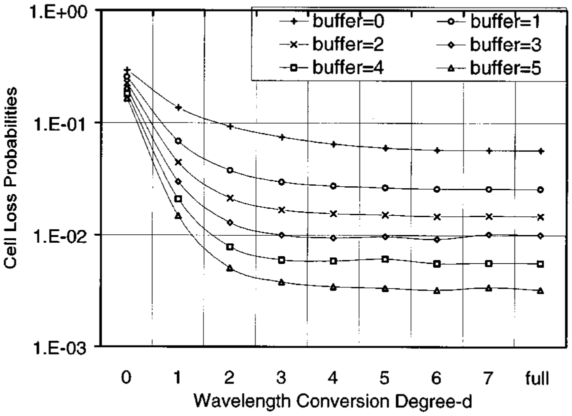

Fig. 3. Cell loss probability versus wavelength conversion degree for bursty traffic with geometrical random distribution. The traffic load per wavelength $\rho = 0.8$, the average bursty length is 5 ($p = 0.2$), and the output buffers range from 0 to 5.

the curve $d = 0$ with the curve $d = 1$). However, when the wavelength conversion capability reaches a certain threshold (here $d = 2$), the performance improvement is marginal if more wavelength conversion capability is subsequently added. From this, we can conclude that while some wavelength conversion is beneficial to improve the performance of a WDM packet switch, full-range wavelength conversion, or even conversion to a high degree, is not actually necessary.

Figs. 3 and 4 show the results of cell loss probability versus wavelength conversion degree for the on-off bursty traffic with a geometrical random distribution ($bursty\ length = 5, p = 0.2, \rho = 0.8$) and a Pareto distribution ($bursty\ length = 5, \alpha_{\mathrm{on}} = 1.25, \rho = 0.8$), respectively. As for the uniform traffic, these two types of traffic are also observed to have a threshold (here $d = 2$, too) of wavelength conversion capability. It is interesting to observe that this threshold seems to be about the same for all three kinds of traffic models.

Finally, we compare the cell loss probabilities of the three types of data traffic. It is found that uniform traffic shows the lowest cell loss probability, while the bursty traffic with geometrical random distribution and Pareto distribution (i.e., self-similar traffic) have much higher cell loss probabilities. This implies that the burstiness of the traffic has a strong negative impact on the switch performance. Therefore improving the switch performance by reducing the data traffic burstness will be significant for WDM packet switches.

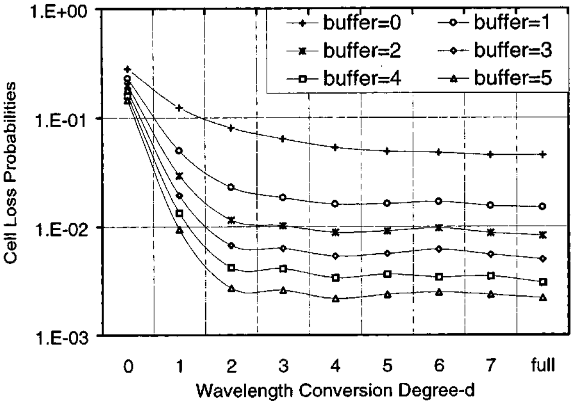

Fig. 4. Cell loss probability versus wavelength conversion degree for bursty traffic with Pareto distribution (self-similar traffic). The traffic load per wavelength $\rho = 0.8$, the average bursty length is 5 ($\alpha_{\mathrm{on}} = 1.25$), and the output buffers range from 0 to 5.

V. CONCLUSIONS

We have studied the impact of wavelength conversion capability on the performance of the WDM packet switch. Through simulations with various types of data traffic, we find that wavelength conversion can lead to significant performance improvement of the WDM packet switch. However, it is also found that a threshold of wavelength conversion exists for the performance improvement of the switch. When the wavelength conversion capability exceeds the threshold, the performance improvement is marginal even if more wavelength conversion capability is added. We conclude from this that, for the WDM packet switch, limited-range wavelength conversion will be sufficient and full conversion would not be necessary.

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