WDM Fiber Delay Line Buffer Control for Optical Packet Switching

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ABSTRACT

A high-speed optical packet switching node using the WDM all optical switch structure is studied in this paper. Tele-traffic performance of an optical IP packet router is simulated under the self-similar (bursty) traffic condition. Four different control algorithms are investigated for the performance and complexity. A simple round-robin algorithm cannot attain an acceptable performance. Finding minimum buffer occupancy and sorting the packets by length are methods used to improve the IP router performance.

1. INTRODUCTION

The emergence of applications such as WWW, net conference, video on demand, etc., have created enormous growth in data rate and bandwidth requirements. Research has shown that Internet traffic demand doubles every six months. Wavelength division multiplexing in optical fiber provides huge capacity for the transmission of traffic. However, the circuit switching paradigm is not suitable for the fast Internet traffic because of its low multiplexing gain. The packet switching, such as IP routing, technique first appeared as store-and-forward mode with a powerful computer used as a forward engine. Now the IP routers use both layer two switching and layer three forwarding techniques.^{1,2}

Wavelength division multiplexing (WDM) technique has been deployed for point-to-point transmission in fiber optic networks to increase effective bandwidth and traffic capacity. In order to enhance the throughput and flexibility in a WDM optical network, all-optical switches will be essential building blocks for the optical network.³ Different optical packet switching architectures⁴⁻⁷ have been introduced. In,^{4,5} the tele-traffic performance of the optical packet switch is analyzed for random traffic with fixed-length packets. The packets are synchronously arriving. IP packets, on the other hand, have the property of variable packet lengths and burstiness in arrival time. In both LANs and core networks, IP traffic shows self similar character.^{8,9} These aspects are significant drawbacks in tele-traffic performance for an IP router. In order to keep an acceptable packet loss rate, more buffers are required.

Optical memories are not available for fast packet switching. Fiber delay lines (FDLs) are used in the all-optical packet switches as buffers.^{4,5} Each FDL can hold multiple wavelengths which are used to buffer packets optically inside the router. The wavelengths in the FDLs can form separate logical output queues for every output fiber. The algorithms used for assigning wavelengths to the new packet arrivals affect the probability of packet loss rate (PPL) for an optical IP router. In order to maintain PPL at an acceptable level, the choice of a wavelength assignment algorithm is important.

In this paper, we first present an all-optical IP router architecture and discuss each block of the router function. Second, four different buffer management algorithms are introduced and demonstrated. We then apply the four different algorithms to the router under consideration and investigate the tele-traffic performance under bursty traffic. Other factors that affect router performance, such as burstiness, traffic load and number of wavelengths per fiber, are also studied in this paper.

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2. OPTICAL PACKET SWITCHING NODE ARCHITECTURE

An example of optical packet switching node architecture,^{5,7} is shown in Fig. 1. Inlets and outlets of the IP router are WDM fibers. Each WDM input fiber will be demultiplexed into wavelengths $\lambda_1, \dots, \lambda_n$ for n channels. Each wavelength is reassigned to an internal wavelength and converted by a tunable wavelength converter (TWC). The internal wavelengths serve as intermediate router channels that allow sharing of router switch matrix and FDL resources. The wavelength assignment is determined by the wavelength usage in the buffer and the output fiber. Wavelength domain speed-up is used in this architecture. The total number of wavelengths inside the all-optical packet switching node equals Nn , where N is the total number of fibers at input/output of the router and n is the number of wavelengths inside each fiber. Wavelengths are grouped into different subsets associated with output fibers. Each output fiber is allocated n wavelengths, e.g., λ_1 to λ_n are assigned to output fiber 1, λ_{n+1} to λ_{2n} are assigned to output fiber 2, and so on. For each set of wavelengths, assignment of incoming input packets has the flexibility of choosing any unused one.

After wavelength conversion, space switches are used to route each packet to different FDL buffers. The space switches consist of a matrix of semiconductor optical amplifiers (SOAs), which are used as ON/OFF gate. This space switch fabric structure functions as a cross-bar switch. One set of FDL buffers is used inside the optical router to resolve contention for packets having the same output address. As discussed above, the FDL is shared by all the output fibers and so the wavelengths within FDLs can be considered as logical output queues. The controller will assign wavelength and delay time for each packet to avoid contention. Packets are directed to the proper outputs depending on the wavelength assignments. Another set of wavelength converters are used at the output unit to convert the internal wavelengths into the transmission wavelengths at the output fibers.

The optical IP router has the WDM fiber at both input and output. One set of physical FDLs are shared among all channels to reduce the complexity of the optical buffers. Hence the number of SOA gates in the space switch is reduced. In the space switch block of the optical IP router, the packet will only traverse a single SOA gate. Each SOA gate processes one channel of optical signal. This reduces the signal cross-talk inside SOA gates.

3. CONTROL ALGORITHM FOR OPTICAL PACKET SWITCHES USING FDLs AS OPTICAL BUFFER

As shown in Fig.1, FDL buffers are grouped by wavelengths to form output queues for different output fibers. Each output fiber will use n wavelengths for buffering the packets to resolve contention at the output. Since each FDL can only delay a packet for a fixed time, once a packet is assigned a wavelength and a particular FDL, there is no way to modify its assignment during the delay period. It is important to have an optimal FDL buffer control algorithm for scheduling the packet, so that the wavelength and buffer assignments allow accommodation of packet arrivals at the router inputs.

Four different FDL buffer control algorithms are presented in the following. The packet loss rate associated with each algorithm is simulated in next section. We assume that packets have variable lengths, which are multiple of a basic unit time slot, and new packets arrive only at the beginning of each time slot. There are n wavelengths associated with each output fiber. A queue is formed with variable length packets at each wavelength. We call the total length of each queue the *buffer occupancy* of that wavelength. The incoming packets will be assigned to the FDL buffers by one of the following control algorithms:

- *Case A: Pure round robin.*

This is the simplest control method for the WDM FDL buffer management scheme. Each packet is independently assigned a wavelength by *First Come First Serve* (FCFS) order. The incoming packets are assigned to different wavelength in round robin fashion. The round robin order for the FDL can be written as: $i, i+1, \dots, n, 1, \dots, i-1$. This means that a packet will be assigned to one wavelength in the FDL buffer whether this wavelength is available or not. If the assigned wavelength in FDLs is full, the packet will be dropped. Minimum control complexity is required in this algorithm; however, the packet loss is high due to incomplete utilization of the FDL buffer.

- *Case B: Round robin with memory*

In this case, we add a memory for the FDL buffer to the pure round robin algorithm. This method will track the occupancy of each wavelength. The packets are assigned to wavelengths in round robin fashion. If an

Figure 1. WDM all-optical switch architecture for optical packet switching nodes⁵.

arriving packet is assigned to a wavelength with full occupancy, the algorithm then re-assigns the packet to the next available wavelength. When all the buffer positions are full, the packet is dropped.

- *Case C: Round robin with memory, finding minimum occupancy of the buffer*¹⁰

To reduce the packet loss rate, a modification of *Case B* is added in this algorithm. The occupancy of each wavelength is tracked. When new packets arrive, they will be processed in FCFS fashion. But each time, a packet is assigned to the least occupied wavelength in FDL. In this case, if the least occupied wavelength is full, the packet will be dropped without further process.

- *Case D: Shortest packet first and assign to minimum occupancy buffer*

A further modification can be made to enhance the tele-traffic performance. New arrival packets are sorted according to their length at each time slot. The shortest packet will be assigned to the least occupied wavelength. This algorithm gives a better result in terms of the packet loss rate.

To demonstrate the operation of the preceding algorithms, an example is presented. We assume three wavelengths for each output fiber. At the FDL, each wavelength has a depth of eight time slots to buffer the incoming packets. Buffer occupancy for one output fiber is 6,3 and 5 time slots before the new time slot. New packets with length 2,1,3,4,1,3, and 2 time slots are arriving at the beginning of the time slot to this output fiber. Packets are assigned to different wavelengths in the FDL according to the four algorithms respectively. Algorithms *A – D* are shown in Fig. 2 (a) – (d). As noticed, the first algorithm cannot provide satisfactory performance as it cannot fully utilize FDL resources. In this case, packets with length 4,3, and 2 time slots are dropped, even though there is remaining capacity in the buffers. In algorithm B, C, and D, we add the functionality of tracing the buffer occupancy, finding the minimum occupancy wavelength in the WDM buffer and sorting new arrival packets in each time slot. From Fig. 2, we can find the performance improvement for each case. In case B, the last three packets with length 1,3 and 2 time slots are dropped. In case C, only last one packet with length 2 time slots is dropped. In case D, there is no packet loss. However, the price to pay for this performance improvement is the additional complexity of the FDL buffer control mechanism. In Table 1, we compare the complexity of the four different algorithms for three categories.

	Sorting Packets	Find Buffer minimum	Keep Track of Buffer Occupy
Case A	No	No	No
Case B	No	No	Yes
Case C	No	Yes	Yes
Case D	Yes	Yes	Yes

Table 1. Complexity comparison of the four algorithms.

4. SIMULATION RESULT AND DISCUSSION

We have simulated the tele-traffic performance of the optical IP router under self-similar traffic. The optical router configuration is shown in Fig. 1. The input traffic is generated according to Ref.¹¹ The self-similar traffic is constructed by multiplexing a large set of ON/OFF sources with ON and OFF periods independently but identically distributed according to a Pareto distribution, which has the form

$$F(x) = 1 - \frac{1}{x^\alpha}, \quad 1.0 < \alpha < 2.0 \quad (1)$$

where α is a parameter that determines the heaviness of the distribution tail. This heavy-tail distribution with an infinite number of sources results in self-similar process with Hurst parameter

$$H = (3 - \alpha)/2. \quad (2)$$

The relation between the average packet length and α is given by

$$\bar{L} = \alpha/(\alpha - 1). \quad (3)$$

When a high number of sources is used in simulation, the result is an approximation of self-similar traffic.

(a)

(b)

(c)

(d)

Figure 2. Example of the different FDL buffer control algorithm.

Figure 3. Probability of packet loss for different control Algorithm. Number of fibers for input/output is 16 with 8 wavelengths in each fiber. Load per wavelength is 0.8. $\alpha = 2.0$ for all ON/OFF sources.

A simulation study of a 16×16 WDM optical IP router is presented and characterized. We assume each fiber has 8 wavelengths. The traffic load in each wavelength is 0.8. In Fig. 3, we set $\alpha = 2.0$; according to Eq. 2, input traffic has the Hurst parameter $H = 0.5$ which is the onset for self-similar traffic. From Fig. 3, we find the algorithm A gives us the worst performance in term of the probability of packet loss (PPL). There is a large improvement from algorithm A to B, because the WDM FDL buffer has been fully utilized. Algorithm C improves the performance of PPL by finding minimum buffer occupancy. Sorting the packets by length can further improve the PPL performance. However, when the number of wavelengths is larger, sorting the packets by length in each time slot is time intensive. In algorithm D, the shorter packets are given higher priority than algorithm C. In our simulation, the packet length is an integer multiple of a time slot. If a longer packet is dropped, we lose more information than with the loss of a shorter one. In Fig. 4, we calculate the probability of information loss (PIL). Here, the PIL is defined as following:

$$PIL = \frac{\sum \text{Loss packet length}}{\sum \text{Total packet length}} \quad (4)$$

Comparing with Fig 3, algorithm A still has the worst performance with this measurement. Comparing algorithms C and D, only neglectable difference is observed. However, algorithm D do exhibit a better PPL performance. Hence, algorithm D provides the best buffer control method among the four algorithms.

In addition to the different control algorithms, there are other issues affecting the tele-traffic performance of the optical router using WDM FDL. In Figs. 5 and 6, we study the tele-traffic performance with different *Hurst* parameter, traffic load and number of wavelengths in each fiber. Simulations were run with algorithms where WDM FDLs are fully utilized. In Fig. 5, it is very obvious that lowering the traffic load will improve the packet loss performance. Comparing Figs. 5 and 6, with the same traffic load and number of wavelengths per fiber, the smaller

Figure 4. Probability of information loss for different control algorithms. Number of fibers for input/output is 16 with 8 wavelengths in each fiber. Load per wavelength is 0.8. $\alpha = 2.0$ for all ON/OFF sources.

the degree of self-similarity, the better the performance obtained. For a fixed load and degree of self-similarity, an increase in wavelength number per fiber results in a decrease of packet loss rate. This result is true for all the algorithms. For the same load and self-similarity, we find that if the number of wavelengths is higher, then the packet loss rate will be lower for all the algorithms.

5. CONCLUSION

In this paper, we presented an all-optical router using WDM FDL buffers. Four different buffer control algorithms were proposed. The tele-traffic performance of the router under self-similar traffic was simulated for the proposed algorithms. A good control algorithm can lower the packet loss rate and enhance the performance of the optical IP router. In addition, for the same input connectivity and traffic load, the probability of packet loss decreases as the number of wavelengths used to route the IP packets increases. Also, when the self-similarity of IP traffic is lower, the packet loss will be reduced under the same traffic load.

Figure 5. Probability of packet loss for different control Algorithms under different conditions. $\alpha = 1.2$ (*Hurst* parameter is 0.9), Load is 0.5 and 0.8, wavelengths per fiber are 4 and 8.

Figure 6. PPL for different control algorithms under different conditions. $\alpha = 2.0$ (*Hurst* parameter is 0.5), Load is 0.8 and wavelengths per fiber are 4 and 8.

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