Latency Evaluation of WDM-based Packet/Path Integrated Networks

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***Abstract*—Wavelength Division Multiplexing (WDM) technology multiplexes optical signals that take different wavelengths into the optical fiber, and offers a high bandwidth transmission. As an application of the WDM technology to the Internet, several network architectures have been discussed; packet-based architecture such as IP over WDM and path-based architecture that establishes a lightpath between nodes on-demand basis. In this paper, we consider a packet/path integration for WDM-based optical networks. The main advantage of the packet/path integration is to enjoy strengths of both packet switching paradigm and circuit switching paradigm. We evaluate the performance of packet/path integrated network via computer simulations with respect to the latency, which is defined from when a data transfer request arises to when the data transfer completes. We first show that the latency much depends on the amount of wavelength resources allocated to the packet switched network. We therefore develop a wavelength allocation algorithm that determines the amount of wavelength resources based on the queue length of buffers in packet switched network. Computer simulations show that our algorithm lowers the latency of the packet/path integrated network even when the arrival rate of data transfer requests drastically changes.**

***Index Terms*—packet/path integration, IP over WDM, circuit switching, wavelength routing, Transmission Control Protocol (TCP), latency**

I. Introduction

A Wavelength Division Multiplexing (WDM) technology [1] multiplexes optical signals that take different wavelengths into the optical fiber. It offers a high bandwidth transmission.

One of approaches that utilize WDM networks is to transfer the data based on the circuit switching paradigm. That is, when a data transfer request arises at a source node, a wavelength is dynamically reserved between the source and destination nodes, and a lightpath is configured. Then, the data is transferred using the allocated wavelength channel. After the data transmission using the lightpath, the lightpath is immediately torn down (i.e., the wavelength is released). In this case, the request solely uses and enjoys the wavelength channel, so congestion avoidance mechanism is no longer necessary. That is, any transport protocols other than TCP can be used for the data transfer. One of examples for a transport protocol that effectively utilizes the wavelength channel is investigated in Ref. [2]. This is a great feature to support applications that require high reliability and large bandwidth. The drawbacks of circuit-switching approach are the lightpath setup delay, defined from when data transfer request arises to time when data transfer starts and blocking during the lightpath establishment.

Another approach is called IP-over-WDM [3], [4] where virtual network topology (VNT) is constructed on top of the physical topology. In this approach, each node consists of IP router and OXC (Optical Cross Connect) that binds an input wavelength channel to a specified output wavelength channel. Then, lightpaths are established by configuring OXCs between two IP routers. A lightpath behaves as the virtual link from viewpoint of IP networks. That is, a data transfer is made based on the packet switching paradigm.

The current Internet is mainly based on the packet switching paradigm. However, many problems arise with increasing traffic demand and advances of related technologies and services. For example, the packet drop rate and packet delay increases due to congestion caused by other user traffic [5], which is a serial problem when applications requiring high reliability and large bandwidth such as grid services or digital cinemas emerged. Thus, it is important to separate traffic which requires high reliability and large bandwidth from other traffic. Other examples are 1) to ensure QoS to some extent, over-provisioning of link capacity and router's processing capability is necessary. However, the over-provisioning is eventually difficult because of technological constraints or power-consumption perspective, 2) as the link capacity increases, speed of packet processing must be higher, which leads to high-cost interfaces. Although more advances of technology may resolve the above-mentioned problems, these problems are essential for the packet-switching paradigm.

Both the packet switched network and circuit switched network have strengths and weaknesses. Therefore to construct only packet switched or circuit switched network cannot meet the various requirements of users. Thus, an integration of packet switched network and circuit switched network is required to enjoy strength of both packet-switching paradigm and circuit-switching paradigm. One possible approach to fulfill this is to use WDM technology where it can split wavelengths and allocate different architecture to each wavelength.

In this paper, we investigate the performance of packet/path integrated network. Here, the integration is made by allocating a part of wavelengths to the packet switched network and the rest of wavelengths to the circuit switched network. The paper [6] evaluates the performance of packet/path integrated network with approximation analysis method based on M/M/1/K

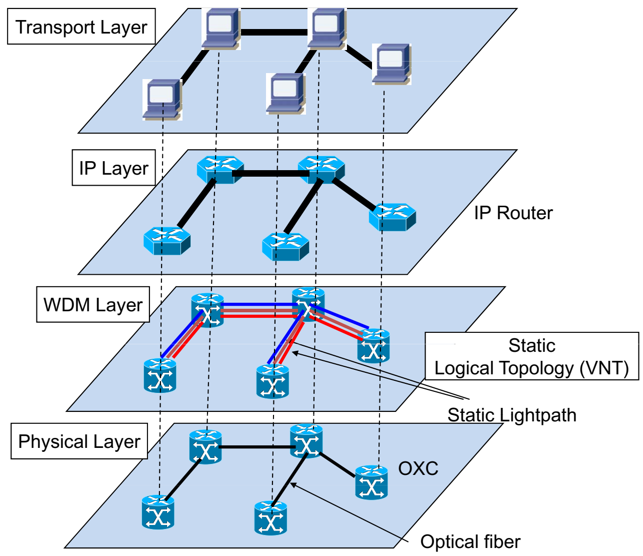


Fig. 1. Network architecture (packet switched network)

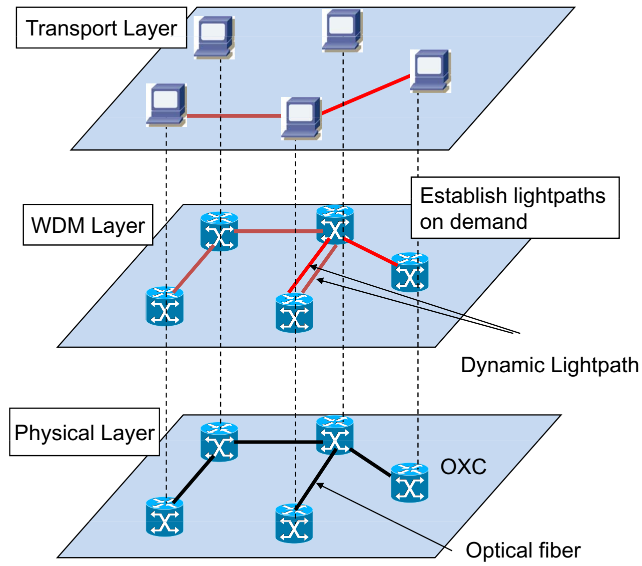


Fig. 2. Network architecture (circuit switched network)

queuing system and iterative calculation. It verifies the accuracy of approximation analysis method. It also evaluates packet/path integrated network with respect to the throughput and packet loss rates. However, [6] evaluates packet/path integrated network with respect to only average throughput, and did not show the performance of packet/path integrated network from the viewpoint of user.

In this paper, we evaluate the performance of packet/path integrated network with respect to the latency, which is defined from when a data transfer request arises to when the data transfer completes. We first evaluate the latency via computer simulations with static wavelength allocation method that allocates a pre-specified number of wavelengths to each network. Numerical results show that packet/path integrated network actually decreases the latency. However, the optimal number of wavelengths allocated to packet/path integrated network depends on traffic load. Therefore, we next develop dynamic wavelength allocation method that dynamically changes the number of allocated wavelengths for achieving minimum latency on various traffic load. Our method is based on a queue length of buffer in packet switched network. Our results show that the latency is decreased even when traffic load is changed.

The rest of paper is organized as follows. In Section 2, we introduce the network architecture of packet/path integrated network. In Section 3, we evaluate the performance of packet/path integrated network with the static wavelength allocation. In Section 4, we evaluate the performance of packet/path integrated network by using dynamic wavelength allocation method. The enabling architecture is also presented. Section 5 concludes this paper.

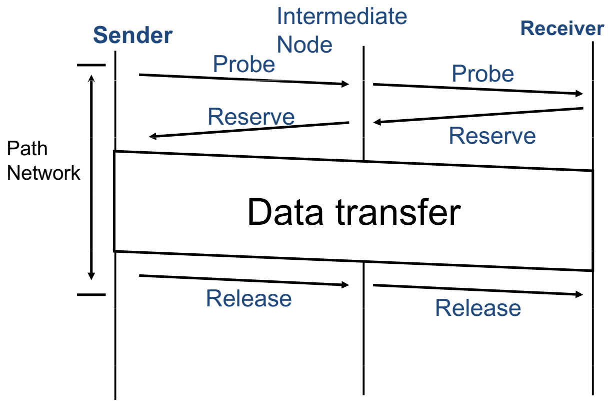
II. A MODEL OF PACKET/PATH INTEGRATED NETWORK

Each node in packet/path integrated network consists of IP router and OXC. OXCs are connected with optical fiber. The packet/path integrated network provides a packet switched network and a circuit switched network by allocating wavelengths for each network. Each end-host connecting with the node has two network interfaces; one for forwarding IP packet via packet switched network and one for establishing a lightpath between two end-hosts. When the data transfer request arises, the end-host selects the packet switched network or the circuit switched network to transfer the data (Figure 1, 2).

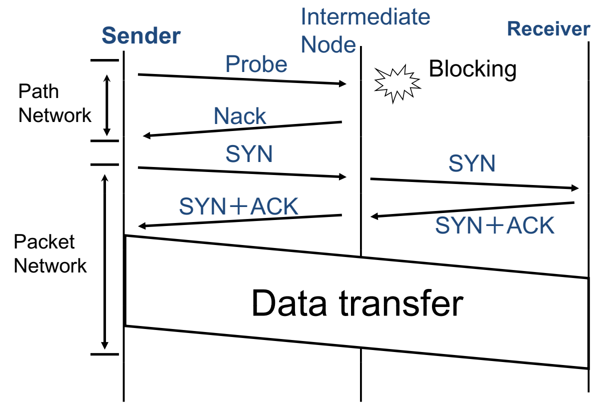
For the packet switched network, the virtual network topology is constructed by pre-configuring a set of lightpaths. When a packet arrives at a node, the packet is forwarded to the next node in the VNT. In the circuit switched network, when a data transfer request arises, lightpaths are established between source and destination nodes on-demand basis. RSVP-based wavelength reservation protocol is used in this paper.

The end-host has two network interfaces. Thus, the end-host can select the packet or circuit switched network to transfer the data. Various strategies to select the network can be considered. We believe that the optimal strategy highly depends on the traffic characteristics, so the highly sophisticated strategy may be necessary. Instead of chasing the sophisticated strategy, we take a simple strategy to select the network because our primary concern of the current paper is to show whether the packet/path integrated network lowers the latency or not.

Our simple strategy to select the network is as follows. When the data transfer request arises, the sender host first tries to transfer the data in circuit switched network. When the lightpath establishment succeeds, the sender host transfers the data using the maximum bandwidth of wavelengths. When the lightpath establishment fails, the sender host gives up transferring the data via circuit switched network and transfers the data via the packet switched network. In this case, the sender host uses TCP protocols during the data transfer. Figure 3 illustrates control messages that are exchanged for a data



(a) The case when the circuit switched network is used



(b) The case when the packet switched network is used

Fig. 3. Control messages exchanged for a data transfer in packet/path integrated network

TABLE I
SIMULATION PARAMETERS

Topology	Dumbbell
OD pairs	120
OXC configuration delay	0 ms
Link propagation delay	10 ms
Arrival process	Poisson
Amount of data	exponential distribution with mean 1 Gbit
Bandwidth of a wavelength	10 Gbps
Number of wavelengths	8
Buffer size at IP routers	256 MB

transfer.

III. Latency of Packet/Path Integrated Network – Static Wavelength Allocation –

A. Simulation parameters

For our evaluation, we use the dumbbell network shown in Figure 4. The network has sender hosts and receiver hosts equipped with two network interfaces. Nodes, each having IP router and OXC, are connected with hosts via the network interfaces, and are also connected with each other via WDM transmission link. The number of wavelengths multiplexed between nodes is eight, and the buffer size of each IP router is 256MB. In this evaluation, we assume that the bandwidth of links between sender hosts and nodes is enough not to be a bottleneck of packet/path integrated network.

In the packet switched network, the packet is processed based on the FIFO (First-in First-out) drop-tail discipline. The sender host employs TCP Tahoe when the data is transferred via the packet switched network. When the circuit switched network is used, the sender host transfers the data with the maximum bandwidth of wavelengths since the sender host exclusively uses the lightpath. The other simulation parameters are summarized in Table I .

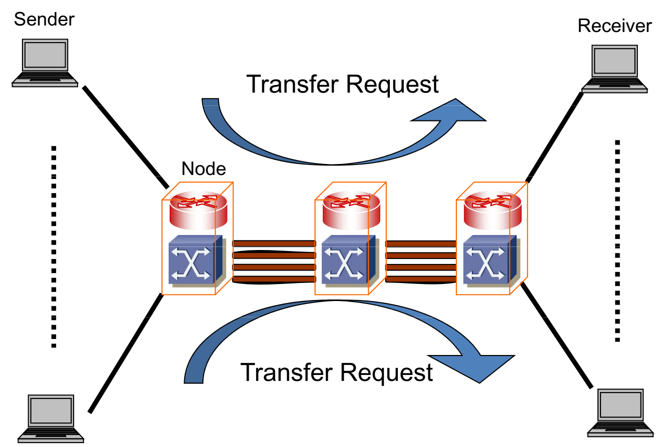


Fig. 4. Dumbbell network

B. Latency

The performance metric used in this paper is the average latency. We define latency as the time from when a data transfer request arises to when the data transfer completes. The formal definition of the average latency is

$$(\sum_{i=1}^{n_c} P_i + \sum_{k=1}^{n_p} B_k + \sum_{k=1}^{n_p} T_k)/(n_c + n_p), \tag{1}$$

where n_c is the number of data transfers completed by using the circuit switched network and n_p is the number of data transfers completed by using the packet switched network. P_i represents the latency of the i-th request among the n_c requests. For the k-th request among the n_p requests, we define B_k as the time consumed for exchanging the control messages to establish a lightpath and define T_k as the time from when a TCP session starts to when the data transfer completes.

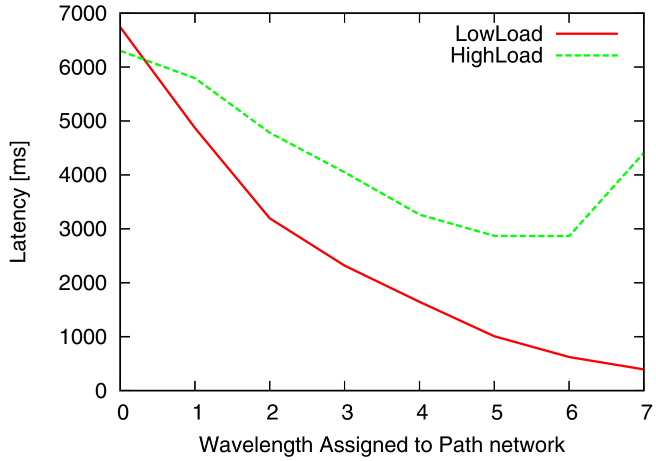


Fig. 5. Average latency of packet/path integrated network

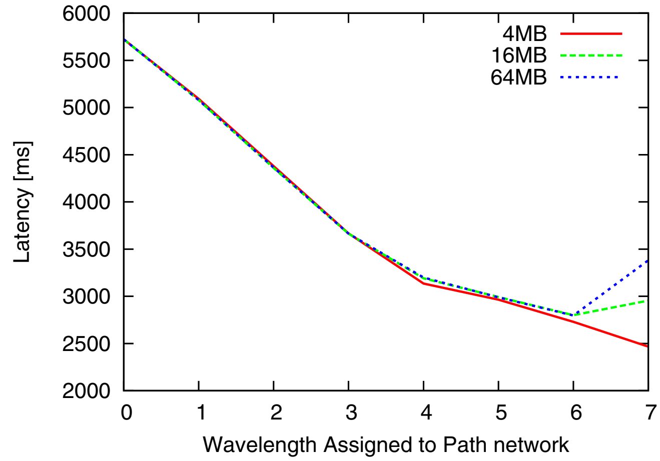


Fig. 6. Latency variation when buffer size is changed

C. Simulation results

An average latency of packet/path integrated network is shown in Figure 5. In the figure, the x-axis represents the number of wavelengths allocated to the circuit switched network. The WDM link has eight wavelengths, so the rest of wavelengths are used for the packet switched network. Note that we statically allocate the number of wavelengths allocated to the circuit/packet switched network in the current evaluation. We show the average latency when the arrival rates of data transfer request at bottleneck link are 9.6 requests/s ("LowLoad" in the figure), and 28.8 requests/s ("HighLoad" in the figure). In the case of "LowLoad", the latency decreases as the number of wavelengths allocated to the circuit switched network increases. This is because more requests are accommodated in the circuit switched network. In the case of "HighLoad", the lowest average latency is achieved when the number of wavelengths allocated to the circuit switched network is five or six wavelengths. The reason is as follows. The latency of the circuit switched network eventually decreases as the number of wavelengths allocated to the circuit switched network increases. However, as the number of wavelengths allocated to the circuit switched network increases, the bandwidth allocated for the packet switched network becomes narrow, which leads to the increase of the average latency. We realized that an optimal number of wavelengths allocated to each network depends the traffic load and traffic characteristics. In the next section, we will discuss the dynamic wavelength allocation method.

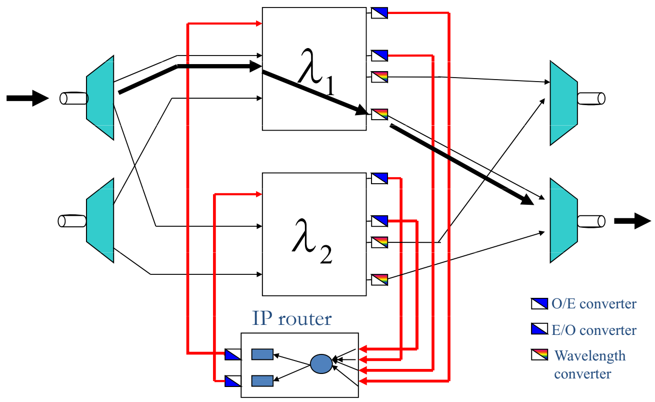
We next show the average latency of packet/path integrated network when the buffer size of routers are changed. Figure 6 show the average latency depends on the number of wavelengths allocated to the circuit switched network. The arrival rate of data transfer request at the bottleneck link is set to 38.4 requests/s. In the figure, we show the results when the buffer sizes of routers are 4MB, 16MB, and 64MB. We observe that the latency of packet/path integrated network decreases to around 25% of the latency in packet switched network. That is, the packet/path integrated network is effective with regard to the reduction of buffer size in the router. Note that we can see the latency in packet switched network for looking at the value when x-axis is 0 in Figure 6. The minimum latency is achieved when the buffer size is small due to the lower queuing delay in the buffer.

IV. Latency of packet/path integrated network – dynamic wavelength allocation –

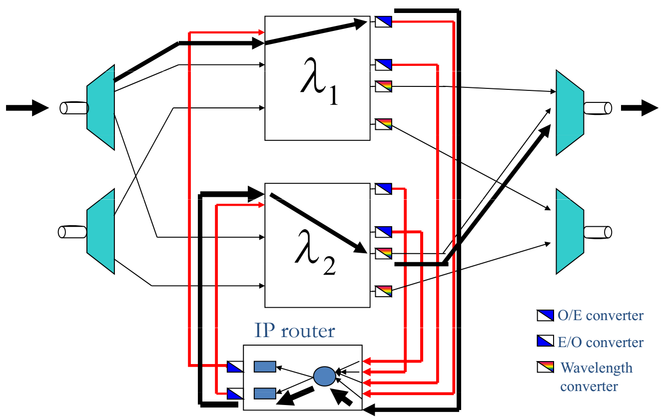
In previous section, we show the latency of packet/path integrated network when wavelengths are statically allocated to packet switched network and circuit switched network. The results show that optimal wavelength allocation depends on the traffic load. In this section, we develop dynamic wavelength allocation method that dynamically changes the number of allocated wavelengths for achieving minimum latency on various traffic load.

A. Enabling architecture

To perform the dynamic wavelength allocation, each node must have an ability to dynamically switch data flows to packet switched network or circuit switched network. In this section, we show the enabling node architecture. Figure 7 illustrates the node architecture in the case of two input/output links and two wavelengths multiplexed on a link. The node consists of one IP router and two OXCs, one for λ_1 and one for λ_2. When λ_1 is allocated to the circuit switched network (Figure 7(a)), packets on lightpaths are not processed by IP router. Thus, the incoming (optical) signal is directly forwarded to the output port. When λ_1 is allocated to the packet switched network (Figure 7(b)), each packet arriving at λ_1 in input ports is converted from the optical signal to an electronic signal, and is directed to the IP router. The packet is then processed by the IP router for routing, and then stored in the buffer prepared for each output port. The packet is again converted from the electronic signal to optical signal and is forwarded to the output port. There is an controller to manage the configuration of OXCs and observe the buffer utilization in the IP router. The controller uses the information of buffer utilization to determine the amount of wavelengths allocated



(a) The case when λ_1 is used for circuit switched network



(b) The case when λ_1 is used for packet switched network

Fig. 7. Node architecture

to circuit/packet switched network. Note that we can consider various kinds of node architectures that dynamically switch data flows to each network. Our node architecture used in this paper requires lots of ports for IP router and OXCs. Further investigation is left to the node architectures.

B. Dynamic wavelength allocation method

We use the average queue length of IP router as the sign of redundancy / shortage of wavelength resources. When the average queue length is long, too many packets are transferred in the packet switched network. Therefore, the number of wavelengths allocated to the packet switched network must be increased. When the average queue length is short, it means that less congestion for the packet switched network. In this case, the number of wavelengths allocated to packet switched network is decreased to reduce the overall latency via the circuit switched paradigm. Based on this observation, we introduce the following dynamic wavelength allocation method to nodes.

Step. 1: The controller in the node measures queue length and calculates the average queue length periodically

Step. 2: When the average queue length exceeds 60% of buffer size, go to Step. 3. When the average queue length is less than 30% of buffer size, go to Step 4. Otherwise go back to Step. 1

Step. 3: Increase the number of wavelengths allocated to the packet switched network by one. Consequently, the number of wavelengths allocated to the circuit switched network decreases by one. Go back to Step. 1

Step. 4: Decrease the number of wavelengths allocated to the packet switched network by one. Consequently, the number of wavelengths allocated to the circuit switched network increases by one. Go back to Step. 1

C. Simulation results

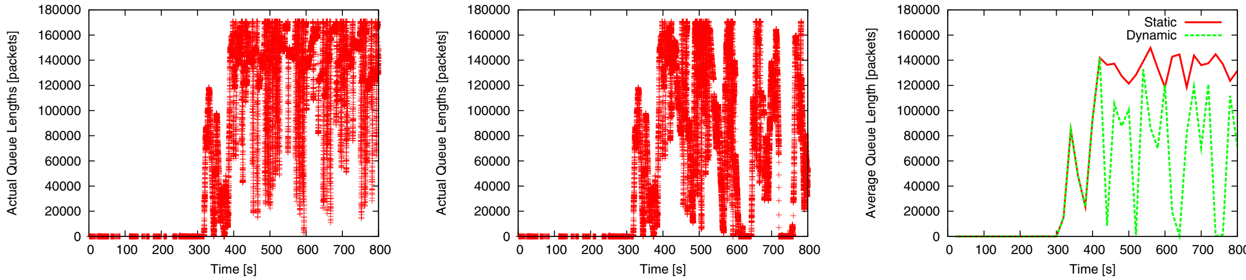
We evaluate the effect of dynamic wavelength allocation method via computer simulation. The simulation parameters used here are the same as the section III-A except that the arrival rate varies with time.

Figure 8(a) and 8(b) shows the actual queue length of the buffer in the IP router (the left router in Fig. 4). We can observe that the queue length with dynamic wavelength allocation method is less than that with static wavelength allocation method. Figure 8(c) shows the average queue length of the buffer in the IP router (the left router in Fig. 4). In obtaining this figure, we set the arrival rate of data transfer request to be 13.2 request/s for [0s-300s], and increase the arrival rate to be 39.6 requests/s for [300s -]. The average queue length is calculated at every 20 [s]. For comparison purpose, we prepare "Static" in Figure 8(c) where one wavelength is allocated to the packet switched network and the remaining seven wavelengths are allocated to the circuit switched network at the beginning of the simulation, and never be changed during the simulation, i.e., the static wavelength allocation. At the time 300s, the arrival rate of data transfer requests increase. Therefore the average queue length increases in the case of the static wavelength allocation. However, when dynamic wavelength allocation method is applied, after the increase of average queue length, the number of wavelengths is changed. Then the average queue decreased (see Figure 8(c)).

Figure 9 shows the latency for every TCP connection to convey the data via the packet switched network. Since the dynamic wavelength allocation method decreases the average queue length during the higher arrival rate, the latency of TCP connection is greatly reduced, which in turn decreases the average latency in packet/path integrated network.

V. Conclusion

In this paper, we evaluate the performance of packet/path integrated network. We first show that the latency is decreased

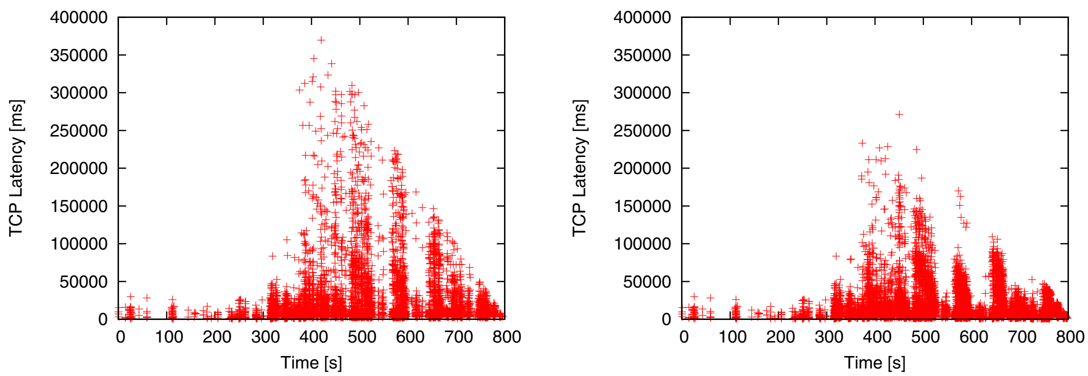


(a) The case of static wavelength allocation

(b) The case of dynamic wavelength allocation

(c) Average queue length

Fig. 8. Time variation of queue length



(a) Static wavelength allocation

(b) Dynamic wavelength allocation

Fig. 9. Latency of TCP connection

to about 25% of the latency in packet switched network when the number of wavelengths is statically allocated. We next show the dynamic wavelength allocation method based on queue lengths of buffer to decrease the latency on various traffic load. Our results indicate our method decreases the latency effectively. In this paper, we evaluate the performance in a dumbbell topology network. In the future, we evaluate the dynamic wavelength allocation method for larger topologies.

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REFERENCES

[1] C. S. R. Murthy and M. Gurusamy, *WDM OPTICAL NETWORKS*. PRENTICE HALL, 2002.

[2] M. Veeraraghavan, X. Zheng, W. chun Feng, H. Lee, E. K. Chong, and H. Li, "Scheduling and transport for file transfers on high-speed optical circuits," *Journal of Grid Computing*, vol. 1, pp. 395–405, Dec. 2003.

[3] M. Kodialanm and T. V. Lakshman, "Intergrated dynamic IP and wavelength routing in IP over WDM networks," in *Proceedings of IEEE INFOCOM*, pp. 358–366, Apr. 2001.

[4] R. Ramaswami and K. N. Sivarajan, "Design of logical topologies for wavelength-routed optical networks," *IEEE Journal on Selected Areas in Communications*, vol. 14, pp. 840–851, June 1996.

[5] S. Lin and N. McKeown, "A simulation study of IP switching," in *Proceedings of ACM SIGMCOM1997*, pp. 15–24, Sept. 1997.

[6] M. Ohashi, S. Arakawa, and M. Murata, "Performance evaluation of optical packet / path integrated architecture on wdm-based networks," Master's thesis, Graduate School of Information Science and Technology, Osaka University, Feb. 2008.