JOURNAL OF INFORMATION SCIENCE AND ENGINEERING 23, 259-270 (2007)

Short Paper

Modeling IP Packets over WDM Ring Network with One Tunable Transmitter and Multiple Fixed Receivers (TT-FRs)*

WEN-SHYANG HWANG, JIH-HSIN HO+ AND CE-KUEN SHIEH+
Department of Electrical Engineering
National Kaohsiung University of Applied Sciences
Kaohsiung 807, Taiwan
+*Department of Electrical Engineering*
National Cheng Kung University
Tainan 701, Taiwan

This paper presents an optical network architecture for supporting the Internet protocol (IP) packets directly over the wavelength division multiplexing (WDM) ring with one tunable transmitter and multiple fixed receivers (TT-FRs). A well-known access scheme based on carrier sense is adopted in this paper for all optical networks. An approximate analysis, base on the M/G/1 queuing model, has been developed to evaluate the performance of the network. The analytical results show an excellent agreement with simulation results over a broad range of parameters. The results show that major part of the packet transfer delay is coming from the propagation delay from a source to a destination. It is also observed that the throughput characteristic of the network depends upon the aggregated transmission capacity of the network. Both throughput and transfer delay improve with the number of wavelengths used in the ring, that proportional to the current escalation of WDM technology.

Keywords: optical network, IP over WDM ring, carrier sense, performance analysis, simulation

1. INTRODUCTION

With the explosion of information traffic due to the Internet, electronic commerce, computer networks, voice, data, and video, the need for a transmission medium with the bandwidth capabilities for handling such a vast amount of information is paramount. Recently, the channel bandwidth of commercial WDM (Wavelength Division Multiplexing) communication systems has reached to OC-192 (10 Gbps), and the total bandwidth of an optical fiber exceeds 1 Tbps. This indicates that WDM is the solution for bandwidth insatiability.

Due to the widespread services and tremendous user population on Internet, the traffic of IP packets dominates the utilization of data networks. However, they are now

---

Received November 1, 2004; revised February 16, 2005; accepted April 18, 2005.
Communicated by David H. C. Du.

* This paper was partially supported by the National Science Council of Taiwan, R.O.C., under grand No. 90-2213-E-151-014.

transferred, switched, and manipulated through complex protocol stacks, such as IP/ATM/SONET/WDM, IP/HDLC/SONET/WDM, and so on. How to merge and collapse the middle layers to reduce cost, complexity, and redundancy has become an important research issue [1]. Additionally, since many WDM systems have been deployed in wide area networks (WANs), the bottleneck of communications will be pushed ahead from backbone networks to local access networks. As a result, applying WDM to local and metropolitan area networks (LANs/MANs) gains much research interests [2-7].

In the literature, a number of research works were done for WDM ring networks. Cai et al. proposed the MTIT access protocol for supporting variable size packets over WDM ring networks based on fixed transmitters and fixed receivers (FTs-FRs) architecture [2]. Shrikhande *et al.* developed HORNET as a testbed for a packet-over-WDM ring MAN [3-5]. To facilitate signal regeneration and destination removal, HORNET utilizes optic-electronic and electro-optic conversion, which may constrain the transmission rate of the network.

Logically, the WDM ring network can be treated as a multi-channel ring network. There are many papers present the analytical models about slotted ring networks. In [8-11], the performance analytical models of single slotted ring network are presented. In [8, 9], the analytical models of multi-channel slotted ring networks are presented. In these analytical models about multi-channel slotted rings, the assumption that nodes are equipped with one transmitter and one receiver for each channel is adapted. The above analytical models are not appropriate to analyze the IP packets over WDM ring networks.

To support IP packets directly over WDM ring networks and satisfy the all optical communications and spatial reuse requirements, a well-known access scheme based on carrier sense is adopted. The access mechanism for the protocol uses the architecture of one tunable transmitter and multiple fixed receivers (TT-FRs). This study utilizes the ‘M/G/1 queuing model’ [12] for constructing the analytical model for IP packets over WDM networks. In subsequent descriptions, the WDM ring network architecture for carrier sense protocol is presented in section 2. To evaluate the performance of the protocol, the performance analysis is described in section 3. In section 4, the simulation results are compared with the analytical results over a broad range of parameters. Finally, a few remarks are given in the conclusions.

2. NETWORK ARCHITECTURE

Let us consider a single and unidirectional fiber ring network, which connects a number of nodes. The ring network is composed of B data channels as shown in Fig. 1.

2.1 Network Logical Architecture

Each data channel makes use of one specific wavelength to convey optical signal. Therefore, based on the WDM technology, channels can work independently without mutual interference to each other. Logically, the network can be treated as a multi-ring network. The node structure of the network is shown in Fig. 2.

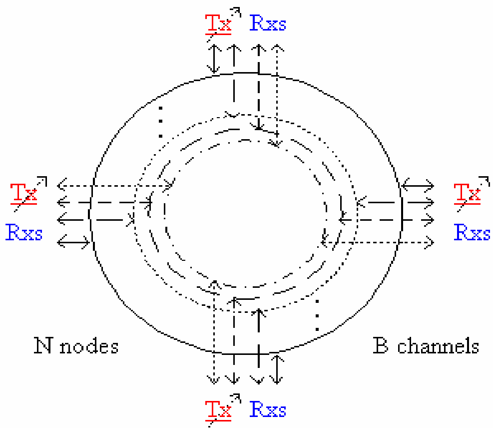

Fig. 1. Logical architecture.

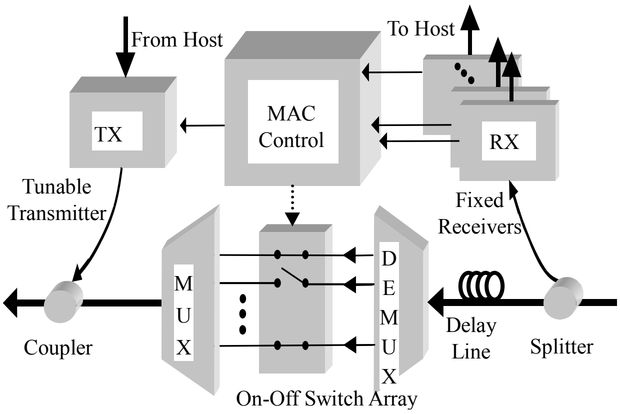

Fig. 2. The node structure.

2.2 Network Hardware Architecture

Each node has one tunable transmitter and B fixed receivers with one for each data channel. For the optical signal sent from upstream nodes, a splitter is used to tap off a small portion of the optical power from the ring to the receivers. Every receiver detects the optical signal carried in its corresponding wavelength within the output branch from the splitter for node address identification. If the destination address in the incoming packet header matches the node address, the packet data is sent to the host. Meanwhile, the MAC control scheme is signaled to activate the open of the on-off switch for the corresponding data channel to remove the received packet carried in the major portion of the optical signal through the delay line. If the destination address is irrelevant to the node address, the detected packet is ignored and the process of scanning next new packet is started.

As for the portion of optical signal through the delay line, optical carriers will be delayed a period of delay time for the operation time of address recognition, MAC control scheme, and on/off switching to remove received packets. After through the delay line, the optical signal will be de-multiplexed by the DEMUX (see Fig. 2) into B data channels according to their separate wavelength. The output of the DEMUX is connected to an on-off switch array with B input ports and B output ports. If a switch for one specific channel is opened, it means that the node is ready to remove the packet in that channel from the ring to prevent the re-circulation of packets. Otherwise, optical signal flows through the closed switches directly to the MUX. The MUX of nodes is used to multiplex the separate wavelength into its output fiber link. With the combination of a delay line, a DEMUX, an on-off switch array, and a MUX in nodes, the destination removal policy can be realized in our ring network.

The packets ready to be transmitted are placed in the transmission queues of a node transmitter before sending. In order to avoid the head of line (HOL) blocking problem occurred in the mechanism of single transmission queue for ordinary packet transmissions, the transmission mechanism with multiple queues is adopted in the transmitter of nodes, where one queue is used for each destination node. When the receivers detect a few idle data channels, the tunable transmitter that is signaled can tune to the transmission wavelength corresponding to a data channel, pick a packet from a transmission queue according to some transmission selection strategies, and then send the packet onto the target channel. Since each node is equipped with a receiver for each data channel, a packet can be transmitted via any available data channel to its corresponding destination node. As a packet has been transmitted onto an available data channel, the optical carrier of the packet is then coupled with the optical carriers from the MUX by the coupler. The integrated carriers are then sent to the downstream nodes. For the transmission selection strategies, they are part of the MAC control scheme and will be discussed in the later section.

2.3 Access Control Protocol

In the network architecture of TT-FRs, each node has the ability to transmit on any usable wavelength and receives on any wavelength at the same time.

Since multiple nodes can transmit on the same network wavelength, a MAC control scheme is necessary to govern to the wavelength and detect or avoid collisions between nodes.

Here we refer a well-known access control scheme based on carrier sense. In this protocol, the access node listens to all wavelengths by monitoring sub-carriers. When a packet is ready for transmission, the access node checks the occupancy of the target wavelength. If it is free at that instant, the access node begins to transmit the packet. However, since the access node cannot know if the opening is long enough to accommodate the entire packets, it continues to monitor the wavelength. If it detects a packet arriving on the same wavelength at its input, it immediately ends the packet transmission and sends a jamming signal like in Ethernet. The delay line structure shown in Fig. 2, which allows the node to terminate its transmission before the packet interfere s with the packet already on the ring. The downstream access node recognizes the incomplete packet by the presence of the jamming signal and pulls it off the ring. The access node can retransmit the packet for a later time.

3. PERFORANCE ANALYSIS

3.1 Assumptions and Notations

For simplicity, some assumptions and notations are given as follows:

1. Packets arrive according to independent, identically distributed (i.i.d.) Poisson process with rate λ_i (packets/second) at each of the N nodes on the ring and with aggregate arrival rate for the network of $\lambda = \sum_{i=0}^{N-1} \lambda_i$.
2. We also assume that the arrival stream of packets at node i destined for node $i \oplus j$ is Poisson process with rate $\lambda_{i,\, i \oplus j}$ shown in Fig. 3, where $\oplus$ indicates addition modulo N; thus $\lambda_i = \sum_{j=1}^{N-1} \lambda_{i,i\oplus j}$. In case of uniform and symmetric traffic on the ring, it means that the mean packet generation for all nodes is equal and each source sends equal traffic to all destinations.

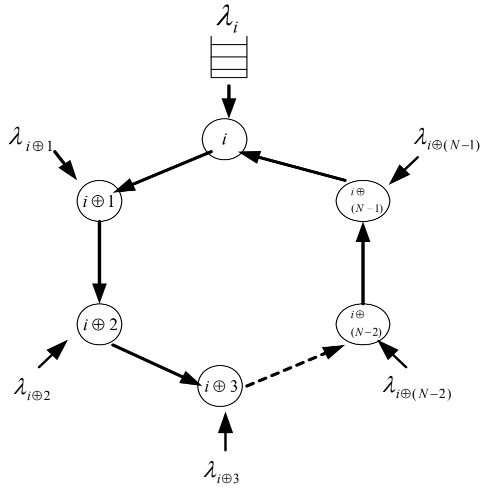

Fig. 3. The diagram of N-node WDM ring.

$$\lambda_i = \lambda / N, \lambda_{i,i\oplus j} = \frac{\lambda_i}{N-1} = \frac{\lambda}{N(N-1)} \tag{1}$$

$\lambda_{i,i} = 0$, for $0 \le i \le N-1$, $1 \le j \le N-1$

3. We assume that packets have random lengths determined at each node as independent, identically and geometrically distributed random variables (denoted by the r.v. M (bits)) with mean $E[M]$ and probability mass function

$$P_r(M = k) = \beta \cdot (1-\beta)^k,\ k = 0, 1, 2, \ldots \text{ where } \beta = \frac{1}{1+E[M]}.$$

4. We assume the WDM ring channel bit rate (speed) is R bps and the packet service time is x (= M/R) seconds with mean $E[x]$ and probability density function $b(x)$.
5. In a destination-packet-remove strategy, the node determines whether they remove the packet or not after checking out within a delay line. Therefore the node latency is equal to delay line.
6. The total WDM ring latency (the propagation delay of the WDM ring + the sum of node latencies) is τ seconds.
7. The number of WDM channels in the ring is B.
8. The distances between the nodes are equal in the WDM ring.

3.2 Analysis of Single WDM Ring Network

Because the transfer delays at all FIFO queues on its entire path from source station to destination, the transfer delay consists of queue-waiting delay, packet service time and propagation delay.

In the queue-waiting delay captures the effect of contention and upstream traffic dependence. With the above assumption, we model the contention in queue-waiting delay using M/G/1 queuing model [12]. The transfer delay, D, is defined as

$$D = W + x + \tau' \tag{2}$$

where τ' is the average propagation delay from a source node to a destination node which often expressed as $\tau/2$. W is queue-waiting delay that can be analyzed approximately using an imbedded Markov chain.

The probability of having j packets generated in a packet service time is denoted with A_j which is a Poisson distribution with mean λ.

$$A_j = \int_0^\infty \frac{(\lambda \cdot x)^j}{j!} \cdot e^{-\lambda x} \cdot b(x)dx \tag{3}$$

In the following we define as each node transmitter state S_i at the departure of ith packet from service, the number of packets stored in the transmission buffer. Following this approach, the system behavior can be described using a imbedded Markov chain.

Packets sent by an upstream source that use node i as a bridge to reach their destinations, and this bridge has average traffic load $\rho_{Bi} = \sum_{k=2}^{N-1} \sum_{j=N-k+1}^{N-1} \lambda_{i\oplus k, i\oplus k\oplus j} E[x_j]$.

These upstream traffic blocks the head of queue packet at the node i. Substitution of above assumptions into ρ_{Bi} given an expression as follows:

$$\begin{aligned}\rho_{Bi} &= \sum_{k=2}^{N-1} \sum_{j=N-k+1}^{N-1} \lambda_{i\oplus k, i\oplus k\oplus j} E[x_j] \\ &= \frac{(N-1)(N-2)}{2} \times \frac{\lambda}{N(N-1)} \times E[x] \\ &= \frac{(N-2) \times \lambda_i \times E[x]}{2}.\end{aligned} \tag{4}$$

With this assumption, the average density ρ_{Bi} can be viewed as the probability (= *Pb*) that upstream traffic may block the node *i*. Let *Pb* denote the probability of interfering with the packet already on the ring at the departure of a packet from service. If $S_i = k$ and in the *i*th packet departure time *j* new arrivals ($j \geq 0$) occur, then

(i) $S_{i+1} = k + j$ with probability *Pb*; and
(ii) $S_{i+1} = k + j - 1$ with probability $(1 - Pb)$.

In this case, the transition probabilities for the imbedded Markov chain generic state *k* are shown in Fig. 4.

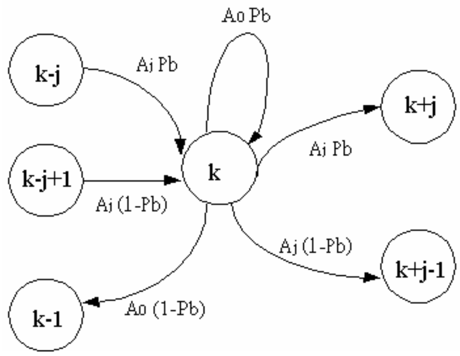

Fig. 4. Transition probabilities for the imbedded Markov chain generic state k.

Let P_{ij} is the one-step transition probability from state *i* to state *j*, we have

$$P_{ij} = P_i(A_{j-i} \cdot Pb + A_{j-i+1} \cdot (1 - Pb)). \tag{5}$$

Let P_j denote the probabilty that the system is in the stat *j*, thus

$$P_j = \lim_{n\to\infty} P[X_n = j];\ j = 0,\ 1,\ \ldots$$

$$P_j = \sum_{i=0}^{\infty} P_i \cdot P_{ij} = P_0 A_j + \sum_{j=1}^{j+1} (P_i(A_{j-i} \cdot Pb + A_{j-i+1} \cdot (1 - Pb)) \tag{6}$$

$$\sum^{\infty} P_j = 1.$$

Finally, the average queue-waiting delay approximately is given by

$$\begin{aligned} E(W) &\cong \frac{(1-\rho_i)(1-Pb)(\lambda_i \overline{b^2} + 3\bar{b}Pb)}{2(1-\lambda_i \bar{b} - Pb)^2} \cong \frac{(1-\rho_i)(1-Pb)(\lambda_i \overline{b^2} + 3\bar{b}Pb)}{2(1-\rho_i - Pb)^2} \\ &\cong \frac{\lambda_i \overline{b^2} + 3\bar{b}Pb}{2 \cdot \frac{1-\rho_i-Pb}{1-\rho_i} \cdot \frac{1-\rho_i-Pb}{1-Pb}} \cong \frac{\lambda_i \overline{b^2} + 3\bar{b}Pb}{2(1-\frac{Pb}{1-\rho_i})(1-\frac{\rho_i}{1-Pb})} \end{aligned} \tag{7}$$

where $\overline{b}$ and $\overline{b}^2$ are the first moment and second moment of packet service time x, and fractional network load in each node i is defined $\rho_i = \lambda_i \cdot \overline{b}$, $\rho_i < 1$. Consider the particular case when the packet service time is exponential distribution, that is the M/M/1 queue. Thus we are here assuming $\overline{b} = 1/\mu$, $\overline{b}^2 = 2/\mu^2$, where μ is the mean packet service rate. From Eq. (7) we have

$$\begin{aligned} E(W) &= \frac{\lambda_i \cdot \frac{2}{\mu^2} + 3\frac{1}{\mu}Pb}{2(1-\frac{Pb}{1-\rho_i})(1-\frac{\rho_i}{1-Pb})} = \frac{\frac{2\lambda_i+3\mu Pb}{\mu^2}}{2(1-\frac{Pb}{1-\rho_i})(1-\frac{\rho_i}{1-Pb})} = \frac{\frac{2\lambda_i+3\mu Pb}{2\mu^2}}{(1-\frac{Pb}{1-\rho_i})(1-\frac{\rho_i}{1-Pb})} \\ &= \frac{\frac{\rho_i+\frac{3}{2}Pb}{\mu}}{(1-\frac{Pb}{1-\rho_i})(1-\frac{\rho_i}{1-Pb})} = \frac{\rho_i+\frac{3}{2}Pb}{\mu(1-\frac{Pb}{1-\rho_i})(1-\frac{\rho_i}{1-Pb})}. \end{aligned} \tag{8}$$

In Eq. (8) we can observe that both each node network load ρ_i and the probability of interfering with the packet already on the ring Pb approach unity, the average queue-waiting delay grows in an unbounded fashion.

3.3 Analysis of Multiple WDM Ring Network

In order to analyze the multiple WDM ring networks, it is assumed that the bridge traffic load by upstream source is equally distributed among B rings. To simplify the analysis, we further assume that the circulation of slots on B rings is synchronized. That is, a node can observe B slots on different rings at the same time. Since the bridge traffic load by upstream source is uniformly distributed among the B rings, the probability of interfering with the packet already on the multiple rings can be expressed as

$$Pb_m = \frac{Pb}{B} = \frac{(N-2)\times\lambda_i\times E[x]}{2\times B}. \tag{9}$$

Similar to section 3.2, the transfer delay is given by $D = W + x + \tau'$. We can obtain the solution for average queue-waiting delay by substituting Pb_m for Pb to Eqs. (7)-(8).

4. SIMULATION AND RESULTS

In this section, we will present the analytical and simulation results of packet transfer delay of the network. To evaluate the performance of the WDM ring network, the following parameters have been listed below.

Number of nodes	16
Number of channels	1, 2, 4, 8
Network distance	30km, 50km, 100km
Channel speed	1.22 Gbps, 2.5 Gbps, 10Gbps
Average IP packet size	512 bytes (β = 0.000244)
Propagation delay of the fiber	5 microsecond/km

The WDM ring distance was assumed to be a choice of 30 km, 50 km, or 100 km. Some of the typical results are shown in Figs. 6-9. Fig. 6 charts the average transfer delay versus the number of packets per node in a 10 Gbps four-channel WDM ring. Fig. 7 plots the average transfer delay for various ring distances and for various channel speed. Average transfer delays for the number of channels are shown in Fig. 8. Parts of Fig. 9 are enlarged in Fig. 8 in order to observe the detailed differences among the curves.

From the above analysis, the following results were observed:

(1) Under the steady state network condition, the higher the number of channel in the WDM ring, the higher the node throughput (see Fig. 5). This means the throughput characteristic of the network depends on the aggregated transmission capacity of the network, *e.g.*, the performance of the network that has eight-channel 10 Gbps is superior to than four-channel 10 Gbps.

(2) Under the steady state network condition, the average transfer delay characteristic of the network with a shorter distance is better than that of a long distance WDM ring network (see Fig. 6).

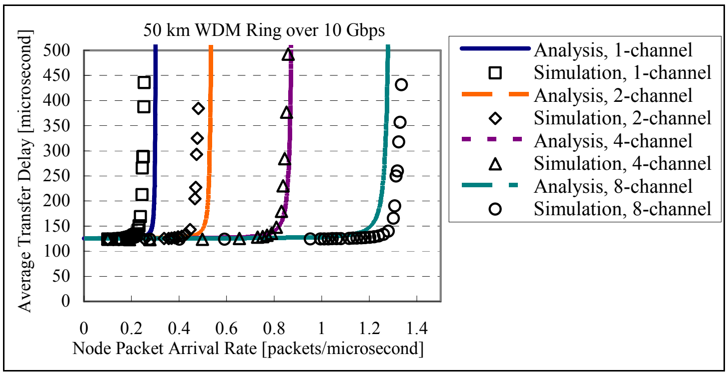

Fig. 5. Average transfer delay for various the number of channels in *a* 50km distance 10 Gbps WDM ring.

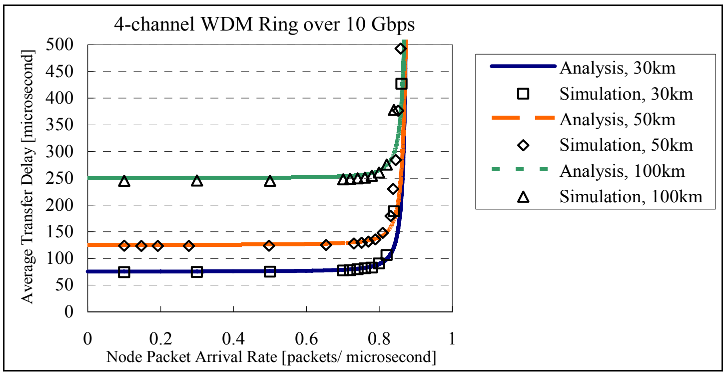

Fig. 6. Average transfer delay for various WDM ring distances in a four-channel 10 Gbps WDM ring.

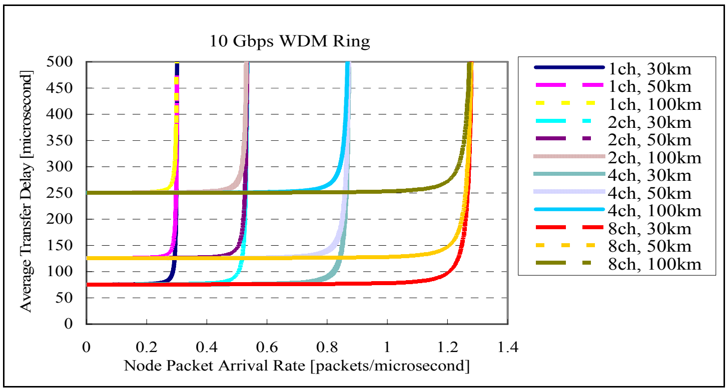

Fig. 7. Average transfer delay for various WDM ring distances and number of channels in a 10 Gbps WDM ring.

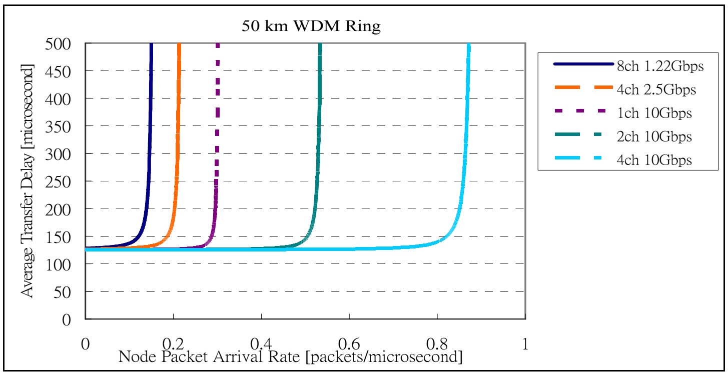

Fig. 8. Average transfer delay for various channel speeds and the number of channels in a 50 km WDM ring.

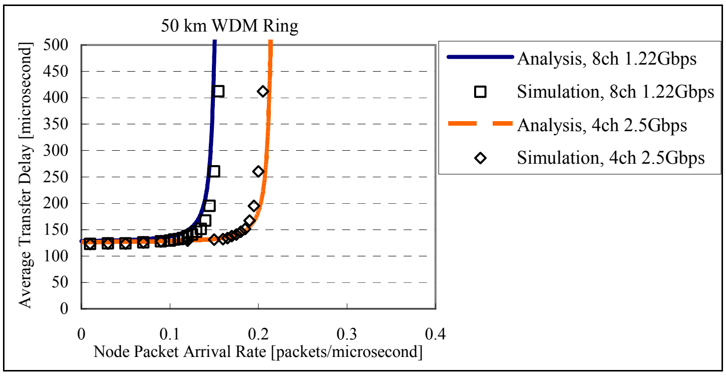

Fig. 9. Some part of detailed observations of average transfer delay for various channel speeds and the number of cannels in a 50km WDM ring.

(3) Under the steady state network condition, the average transfer delay characteristics of the networks with equal ring distances are almost equivalent in all cases (see Figs. 7 and 8). This means that the major factor in transfer delay is neither the transmission delay nor the queue-waiting delay, but the propagation delay from a source node to a destination node.

(4) Even through the WDM ring distance and the aggregated transmission capacity of the WDM rings are the same, there is small difference in the average transfer delay between the networks (for example, see the curves for a eight-channel of 1.22 Gbps WDM ring and a four-channel of 2.5 Gbps WDM ring in Fig. 9). This is coming from the differences of node latency in the WDM ring since each node only has a tunable transmitter. In other word, the node latency in the four-channel 2.5 Gbps WDM ring is shorter than that of an eight-channel 1.22 Gbps WDM ring.

5. CONCLUSIONS

In summary, we have proposed IP packets over WDM ring network with one tunable transmitter and multiple fixed receivers. Meanwhile, we adopt the CSMA/CA as the medium access control protocol. The proposed architecture and this protocol are good candidates for designing IP over WDM networks for local and metropolitan areas.

A novel technique has been devised to analyze the average transfer delay of a packet in the WDM ring network. For verification, we also simulate the network using CASI Simscript II.5 and obtain the simulation result. The analytical results show an excellent agreement with the simulation results over a broad range of parameters. The results show that the major part of the packet transfer delay is coming from the propagation delay from a source to a destination. It is also observed that the throughput characteristic of the network is almost proportional to the aggregated transmission capacity of the network. Both throughput and transfer delay improve with the number of wavelengths used in the ring, that proportional to the today's WDM technology trends.

REFERENCES

1. N. Ghani, S. Dixit, and T. S. Wang, "On IP-over-WDM integration," *IEEE Communications Magazine*, Vol. 38, 2000, pp. 72-84.
2. J. Cai, A. Fumaaglli, and I. Chlamtac, "The multitoken interarrival time (MTIT) access protocol for supporting variable size packets over WDM ring network," *IEEE Journal on Selected Areas in Communications*, Vol. 18, 2000, pp. 2094-2104.
3. K. V. Shrikhande, *et al.*, "HORNET: a packet-over-WDM multiple access metropolitan area ring network," *IEEE Journal on Selected Areas in Communications*, Vol. 18, 2000, pp. 2004-2016.
4. K. Shrikhande, *et al.*, "CSMA/CA MAC protocols for IP-HORNET: An IP over WDM metropolitan area ring network," in *Proceedings of Global Telecommunications Conference 2000*, Vol. 2, 2000, pp. 1303-1307.
5. I. White, M. Rogge, K. Shrikhande, and L. Kazovsky, "A summary of HORNET project: a next-generation metropolitan area network," *IEEE Journal on Selected Areas in Communications*, Vol. 21, 2003, pp. 1478-1494.

6. W. S. Hwang, J. H. Ho, and C. K. Shieh, "Performance analysis of IP packets over WDM ring networks," in *Proceedings of the 14th IASTED Conference on Parallel and Distributed Computing and Systems*, 2002, pp. 816-821.
7. J. H. Ho, W. S. Hwang, and C. K. Shieh, "Analytical model for an IP over WDM ring network," in *Proceedings of the 10th International Conference on Telecommunications*, 2003, pp. 182-187.
8. N. Bhuyan, D. Ghosal, and Q. Yang, "Approximate analysis of single and multiple ring networks," *IEEE Transactions on Computers*, Vol. 38, 1989, pp. 1027-1040.
9. C. S. Kang, B. S. Park, and I. K. Rhee, "Performance comparison of a class of slotted ring networks," in *Proceedings of the International Conference on Communications*, 1995, pp. 220-226.
10. M. Zafiovic-Vukotic and I. G. Niemegeers, "Performance modeling of the Cambridge fast ring protocol," *Digital Communications: Mapping New Applications onto New Technology*, 1988, pp. F2.1-F2.8.
11. A. E. Kamal and V. C. Hamacher, "Approximate analysis of non-exhaustive multiserver polling systems with applications to local area networks," *Computer Networks and ISDN Systems*, Vol. 17, 1989, pp. 15-27.
12. D. Bertsekas and R. Gallager, *Data Network*s, 2nd ed., Prentice-Hall, 1991

Wen-Shyang Hwang (黃文祥) received the B.S., M.S., and Ph.D. degrees in Electrical Engineering from National Cheng Kung University, Taiwan, in 1984, 1990 and 1996, respectively. He is an Associate Professor of Electrical Engineering, National Kaohsiung University of Applied Sciences,Taiwan. His current research interests include multi -channel WDM networks, performance evaluation, QoS, RSVP, WWW database applications.

Jih-Hsin Ho (何日新) is currently a Ph.D. candidate studying at Department of Electrical Engineering, National Cheng Kung University, Tainan, Taiwan. Ho received his B.S. degree from Tatung University in 1993 and M.S. degree from National Cheng Kung University in 1998. His current research interests include performance evaluation, multichannel WDM networks, QoS.

Ce-Kuen Shieh (謝錫堃) is currently a Professor teaching at the Department of Electrical Engineering, National Cheng Kung University. He received his Ph.D., M.S., and B.S. degrees from Electrical Engineering Department of National Cheng Kung University, Tainan, Taiwan. His current research interests include distributed and parallel processing systems, computer networking, and operating systems.