Analytical Model for an IP over WDM Ring Network

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***Abstract* — In this paper, a carrier preemption access control protocol based on carrier sense multiple access schemes has been investigated for supporting IP packets over all optical WDM ring networks. The intention of our protocol design is to reduce the communication overhead of IP packets over optical networks for local/metropolitan area. To facilitate spatial reuse on the bandwidth of all optical ring networks, a special design is made for the carrier preemption scheme. We develop an analytical model to approximate the average transsfer delay for our protocol. We validate our model via simulation and show an excellent agreement with simulation results over a broad range of parameters. The results show that the proposed protocol can achieve higher bandwidth efficiency and lower access delay.**

***Index Terms* — Optical network, IP over WDM ring, performance analysis, simulation.**

I. 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 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.

In the literature, a number of research works were done for WDM ring networks. Shrikhande et al. developed HORNET as a testbed for a packet-over-WDM ring MAN [2]. They adopt carrier sense multiple access with collision avoidance (CSMA/CA) MAC protocols [3] for IP over WDM ring networks.

To support IP packets directly over WDM ring networks and satisfy the all optical communications and spatial reuse requirements, we investigate a carrier preemption access control protocol based on carrier sense multiple access (CSMA/CP) schemes. The access mechanism for the protocol uses the architecture of one tunable transmitter and multiple fixed receivers (TT-FRs). In subsequent descriptions, the WDM ring network architecture for CSMA/CP protocol is presented in Section II. To evaluate the performance of the protocol, the analytical model is described in Section III. In Section IV, the analytical and simulation results show our CSMA/CP protocol has better performance than previous proposed CSMA/CA protocol. Finally, a few remarks are given in the conclusions.

II. 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 Figure1.

A. 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 Figure 2.

B. 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 opticalsignal through the delay line. If the destination address is irrelevant to the node address, the detected packet is

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ignored and the process of scanning next new packet is started.

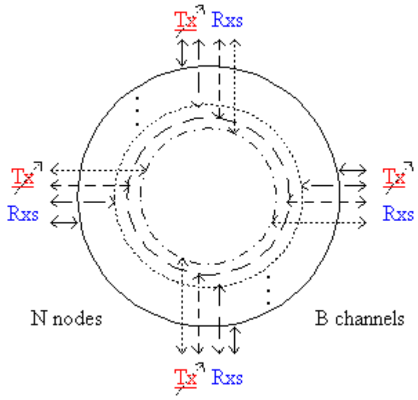

Figure 1. *Logical Architecture*

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 Figure 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.

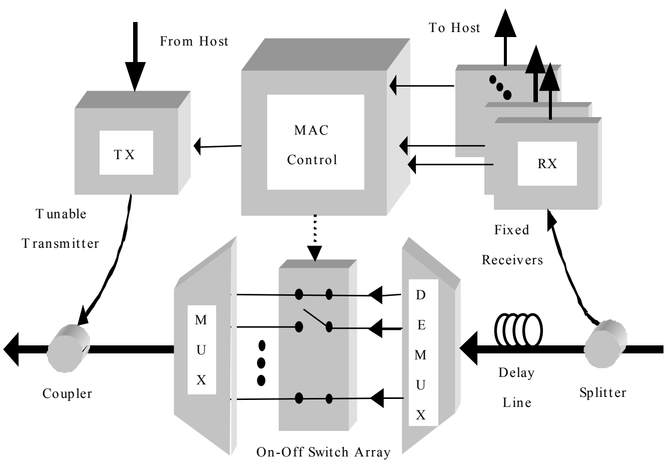

Figure 2. *The node structure*

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.

C. CSMA/CP Access Control Protocol

The carrier sensing mechanism for finding transmitted packets in optical fiber can be based on sub-carrier signaling or receiver monitoring. For sub-carrier signaling, each wavelength is associated with a sub-carrier frequency. When a node transmits a packet, it multiplexes the corresponding sub-carrier frequency. The nodes determine the occupancy of all wavelengths in parallel by monitoring the sub-carriers in the RF domain. In addition, since each receiver extracts the optical signals from the corresponding data channel (or wavelength), receiver monitoring can be another approach to determine the occupancy of all wavelengths. It seems natural that the receivers are associated with the auxiliary function to monitor the status of the optical ring network. Nowadays, the cost of such receivers is still so high that is not economical to manufacture, but it may be realized later.

To resolve the access collisions in our network, a carrier preemption access scheme is proposed in conjunction with the carrier sense multiple access mechanism to form our MAC protocol, which is called the Carrier Sense Multiple Access with Carrier Preemption (CSMA/CP) protocol. Based on the protocol, each node monitors the wavelengths and tries to find an opening on channels provided that there are packets for transmission. Given that a packet is being transmitted onto a target channel while the node detecting another packet arriving on the same channel at its input, a dilemma of ring access (an access collision) has occurred. The cause for access collisions is due to the fact that the node cannot know if the opening is long enough to accommodate the packet.

By the carrier preemption scheme, a collided packet is immediately fragmented into two parts: one for already transmitted and the other one for still in queue. For the fragment of already transmitted, a data frame trailer is appended to its back at once. For the fragment of still in queue, it will be transmitted later on the same channel or on other available channels. To guarantee the correctness of the protocol operations, the delay line inside nodes must be used to delay the incoming packet and to sustain the time for packet fragmentation. In addition, the delay line should be long enough to cover minimum packet length so that unnecessary fragmentation can be avoided.

To support the carrier preemption scheme, the frame format adopted is shown in Figure 3. For the start delimiter (SD) and the end delimiter (ED), they mark a physical data frame conveyed in data channels for packets or fragments. The source address (SA) and the destination address (DA) serve as the address information in the network. The sequence number (SN) is used to record the serial number in a sequence of fragments and the end fragment (EF) is used to indicate the last fragment. To prevent the possible transmission errors in midway, the cyclic redundancy check (CRC) is employed. The flag (FG) field is reserved for extended protocol functions. To demonstrate the action of packet fragmentation, a collided packet is fragmented into two fragments as depicted in Figure 4. The front fragment that has just been transmitted is appended a frame trailer and the rear fragment for later transmission is inserted a frame header.

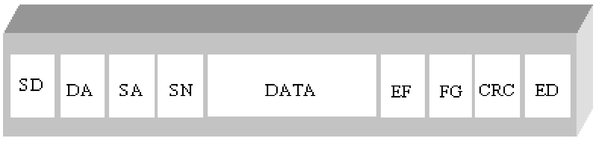

Figure 3. *The frame format*

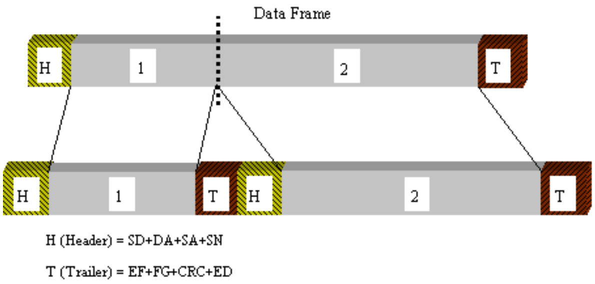

Figure 4. *The data frame fragmentation*

III. PERFORANCE EVALUATION

A. 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 Figure 5., 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.

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

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

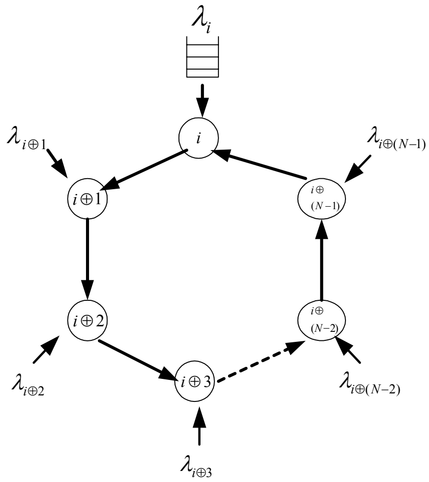

Figure 5. *The diagram of N-node WDM ring*

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 $P_r(M=k) = \beta \cdot (1-\beta)^k, k = 0,1,2,\ldots$ where $\beta = \dfrac{1}{1+E[M]}$.
4. We assume the WDM ring channel bit rate (speed) is R bps and the packet transmission time without considering vacations is X (= M/R) seconds.
5. We define that mTU(minimum transfer unit) is equal to the delay line (L) with L/R seconds to transmit a mTU.
6. We fragment the data packet of Length M sent by node i into a sequence of n_G consecutive mTUs ignored the header and trailer length, and we assume that $P_r(n_G = k), k = 0,1,2,\ldots$ denote the probability that n_G=k.

$$P_r(n_G = 0) = 0,$$

$$P_r(n_G = 1) = \sum_{M=0}^{L} \beta(1-\beta)^M = 1-(1-\beta)^{L+1},$$

For k=2,3,…,

$$P_r = (n_G = k) = P_r[(k-1)L < M \le kL] = [1-(1-\beta)^L](1-\beta)^{(k-1)L+1}$$

Thus, $$E(n_G) = \frac{[1-(1-\beta)^L + (1-\beta)^{L+1}]}{[1-(1-\beta)^L]} \qquad (2)$$

7. 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.
8. The total WDM ring latency (the propagation delay of the WDM ring + the sum of node latencies) is τ seconds.
9. The number of WDM channels in the ring is B.

10. The distances between the nodes are equal in the WDM ring.

B. 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, transmission delay and propagation delay.

In the queue-waiting delay and transmission delay capture the effect of contention and upstream traffic dependence. We consider delay line (or mTU) of our protocol as a slot unit, so the dependence known as the full slots being uniformly and independently distributed on the WDM ring. With the above assumption, we model the contention in queue-waiting and transmission delay using M/G/1 queuing model [4]. The transfer delay, D, is defined as

$$D = W + S + \tau' \quad (3)$$

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 has two components: the residual slot time α and the transmission of packets ahead in the queue shown in Figure 6.

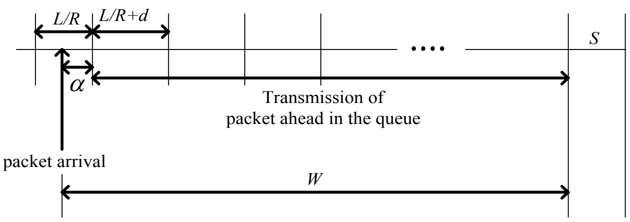

Figure 6. *Delay faced by an arriving packet in slot ring*

Since the arrival process is assumed to be Poisson, this residual slot time α can be considered to be uniformly distributed between 0 and L/R. Therefore, the mean residual slot time is simply

$$E(\alpha) = \frac{L}{2 \times R} \quad (4)$$

Next, the arriving packet has to wait for transmission of other packets ahead of it in the queue. By Little's formula, the average number of packets in the queue seen by an arriving packet is average queue length is given by $\lambda \cdot W$.

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

$$\begin{aligned}\rho_{Bi} &= \sum_{k=2}^{N-1} \sum_{j=N-k+1}^{N-1} \lambda_{i\oplus k, i\oplus k \oplus j} E[X_j] \\ &= \frac{(N-1)(N-2)}{2} \times \frac{\lambda}{N(N-1)} \times E(n_G) \times \frac{L}{R} \\ &= \frac{(N-2) \times \lambda_i \times E(n_G) \times L}{2 \times R} \\ &= \frac{(N-2) \times \lambda \times E(n_G) \times L}{2 \times N \times R}\end{aligned} \quad (5)$$

With this assumption, the average density ρ_{Bi} can be viewed as the probability (=U) that a slot is full and continuing past the current point. Then slot access time for the HOL packet is U, the probability that a packet has to wait i more slots before it can be transmitted is $U^i(1-U)$. The mean of waiting time $E(d)$ to find an empty slot can be expressed as

$$E(d) = \sum_{i=0}^{\infty} i \frac{L}{R} U^i (1-U) = \frac{L \cdot U}{R(1-U)} \quad \text{,where } U < 1 \quad (6)$$

When a new packet arrives, it must wait $n_G \cdot d$ (sec) for each item ahead of it and wait $n_G \cdot d$ more for its own service. Because of the memoryless property of stochastic process, we have

$$W = E(\alpha) + \lambda_i W E(X) + \lambda_i W E(n_G) E(d) \quad (7)$$

which can be reduced to

$$W = \frac{E(\alpha)}{1 - \lambda_i E(X) - \lambda_i E(n_G) E(d)} \quad (8)$$

,where $\lambda_i (E(X) + E(n_G) \cdot E(d)) < 1$

We assume general transmission delay included some vacations is S seconds,

$$S = E(X) + E(n_G) E(d) \quad (9)$$

Thus, the average transfer delay is given by

$$E(D) = E(W) + E(S) + \tau / 2 \quad (10)$$

C. 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 average bridge traffic load of each ring, U_b, can be expressed as

$$U_b = U / B \quad (11)$$

The probability that the packet at the head of a queue cannot get an empty slot among the currently passing B slots in $(U_b)^B$. Therefore, the probability that the packet has to wait i slot times before it can be sent out is $(U_b)^{Bi}(1-(U_b)^B)$.

Similar to section IV-B, let $E(d_B)$ be the average time required to find the arrival of an empty slot, then we have

$$E(d_B) = \sum_{i=0}^{\infty} i \frac{L}{R} (U_b)^{Bi} (1 - (U_b)^B) = \frac{L \cdot (U_b)^B}{R(1 - (U_b)^B)} \quad (12)$$

, where $(U_b)^B < 1$

Since for each packet in the queue the arriving packet has to wait for $L/R+d_B$ times, the total waiting time in the queue faced by arriving packet is

$$W = E(\alpha) + \lambda_i W E(X) + \lambda_i W E(n_G) E(d_B) \quad (13)$$

Therefore, we have

$$W = \frac{E(\alpha)}{1 - \lambda_i E(X) - \lambda_i E(n_G) E(d_B)} \quad (14)$$

,where $\lambda_i (E(X) + E(n_G) \cdot E(d_B)) < 1$

We assume general transmission delay included some vacations is S seconds,

$$S = E(X) + E(n_G)E(d_B) \quad (15)$$

Thus, the average transfer delay is given by

$$E(D) = E(W) + E(S) + \tau / 2 \quad (16)$$

IV. NUMERICAL RESULTS AND SIMULATIONS

In this section, we will compare the analytical and simulation results of packet transfer delay for both the CSMA/CP and CSMA/CA protocol. 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 comparing CSMA/CP and CSMA/CA protocol are shown in Figure 7-10. Figure 8 charts the average transfer delay versus the number of packets per node in a 10 Gbps four-channel WDM ring. Figure 9 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 Figure 10.

From the above analysis, the following results were observed:

(1) Under the steady state network condition, the higher the number of channels in the WDM ring, the higher the node throughput (See Figure 7). This means the throughput characteristic of the network depends on the aggregated transmission capacity of the network. The CSMA/CP protocol has better thoughput. In the 8-channel case, each node can achieve throughput of 2.5 packets/microsecond with the CSMA/CP protocol. On the other hand, each node only achieve throughput of 1.3 packets/microsecond with the CSMA/CA protocol.

(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 Figure 8). In this scenario, our protocol can reach higher throughput of 1.2 packets/microsecond than 0.8 packets/microsecond with the CSMA/CA protocol.

(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 Figure 9 and 10). 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. We compare the throughput between the CSMA/CP and CSMA/CA protocol. The throughput of CSMA/CP protocol is much higher than the CSMA/CA protocol.

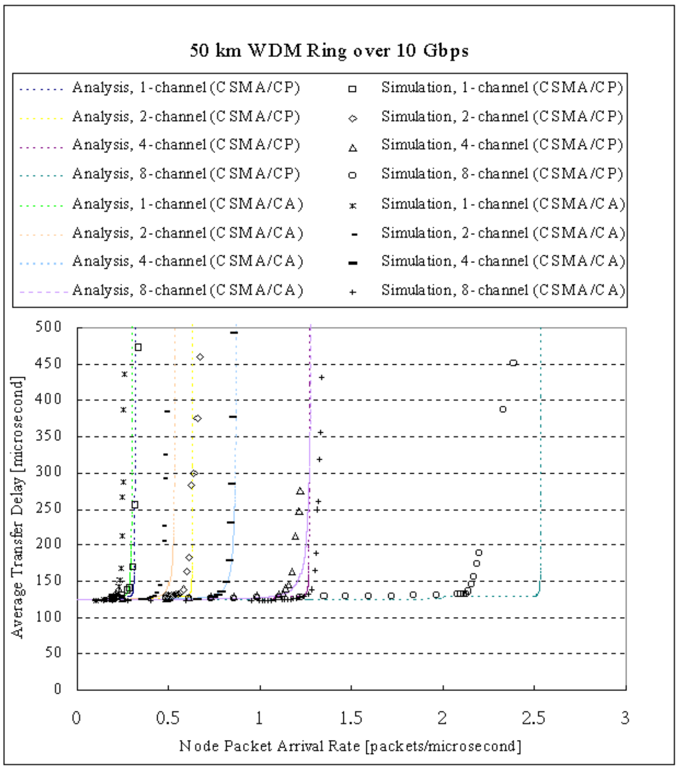

Figure 7. *Comparing CSMA/CP and CSMA/CA : Average transfer delay for various the number of channels in a 50 km distance 10 Gbps WDM ring.*

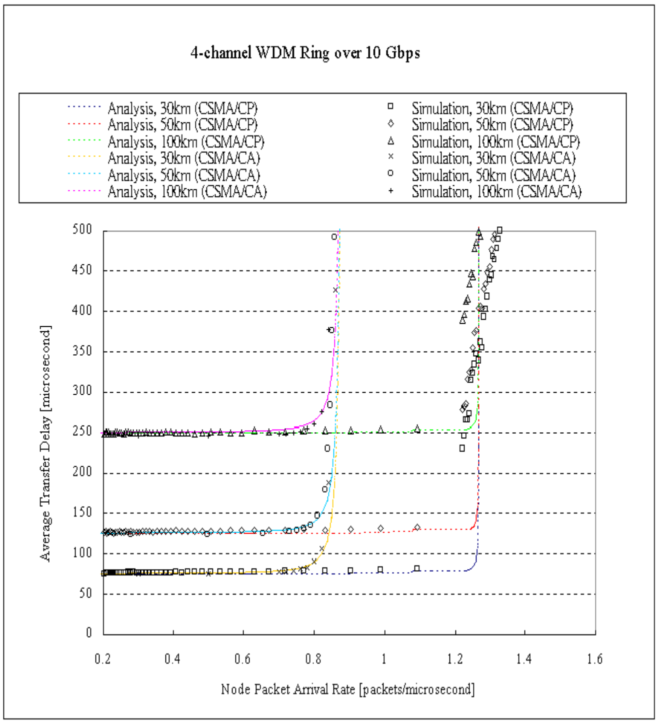

Figure 8. *Comparing CSMA/CP and CSMA/CA : Average transfer delay for various WDM ring distances in a four-channel 10 Gbps WDM ring*

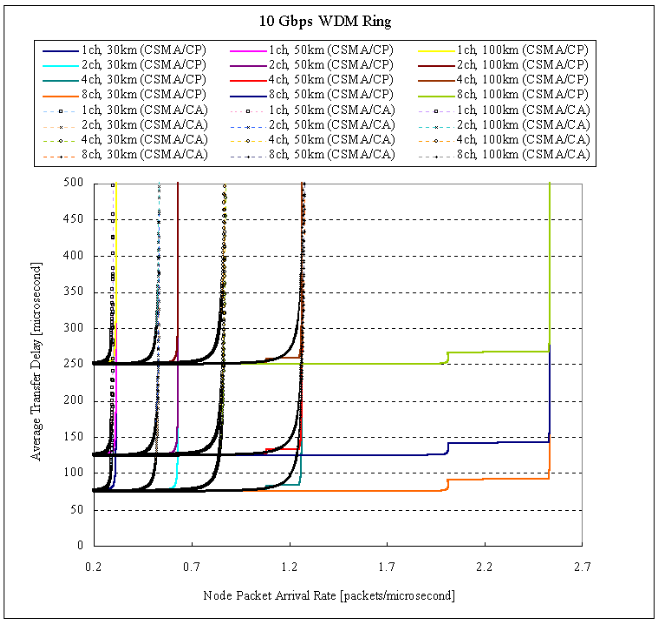

Figure 9. *Comparing CSMA/CP and CSMA/CA : Average transfer delay for various WDM ring distances and number of channels in a 10 Gbps WDM ring*

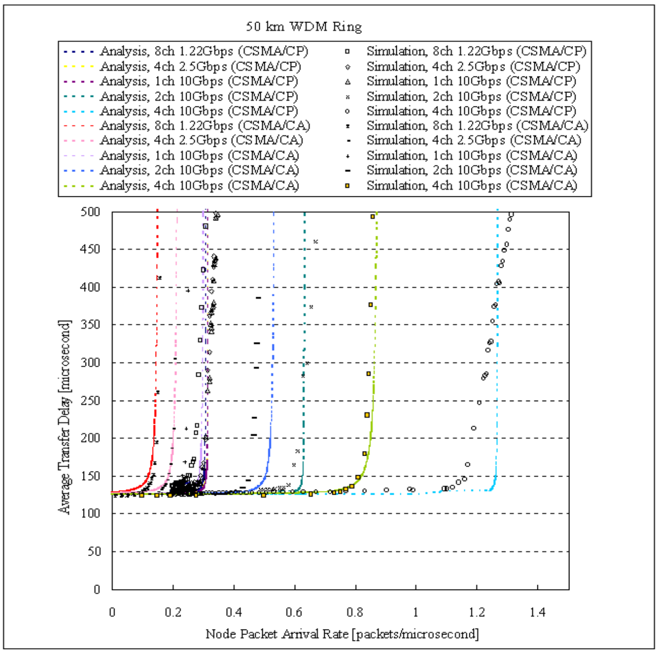

Figure 10. *Comparing CSMA/CP and CSMA/CA : Average transfer delay for various channel speeds and the number of channels in a 50 km WDM ring*

(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 CSMA/CP and CSMA/CA protocol respectively for a eight-channel of 1.22 Gbps WDM ring, a four-channel of 2.5 Gbps WDM ring and a single-channel 10 Gbps WDM ring in Figure 10). 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 10 Gbps WDM ring is shorter than that of a eight-channel 1.22 Gbps WDM ring and a four-channel 2.5 Gbps WDM ring. Consequently, the average transfer delay characteristic of the 10 Gbps WDM ring is better than the other cases. As expected, we see that the CSMA/CP protocol has higher throughput.

V. CONCLUSIONS

In summary, we have investigated a novel MAC protocol for all optical WDM ring networks. The protocol supports the transmission of IP packets directly over WDM. Meanwhile, the investigation has been made about how to merge and collapse the middle layers between IP and WDM for next generation optical LANs/MANs. On facilitating spatial reuse of network bandwidth, our protocol displays the excellent characteristics of high throughput and low delay in the way of all optical communications.

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 for both protocol. 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. The throughput of the proposed CSMA/CP protocol has better performance than the CSMA/CA protocol. Both throughput and transfer delay improve with the number of wavelengths used in the ring, that proportional to the today's WDM technology trends.

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