Performance Evaluation of Transmission Algorithms for CSMA/ID WDM Ring Networks

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Abstract—**As data traffic increase rapidly, IP over WDM (Wavelength Division Multiplexing) transport will replace conventional SONET transport in current metropolitan area networks. Such networks will require new MAC protocols to efficiently share network bandwidth among multiple network nodes. This research project describes and evaluates a novel Carrier Sense Multiple Access with Idle Detection (CSMA/ID) MAC protocols for IP over WDM ring networks. The paper focuses on the influence of performance for the packet scheduling algorithms included FIFO, OPF_CA and OPF_CF. An analytical model is developed to evaluate the performance of the protocol, with simulation results showing good network efficiency and will be an excellent candidate for next-generation metro networks.**

Index Terms— **IP over WDM, CSMA/ID, FIFO, OPF_CA, OPF_CF, Analytical Model and Simulation**

I. INTRODUCTION

In the past decade years, there has been an enormous increase in the bandwidth requirements of the explosion of information traffic due to the Internet application such as electronic commerce, multi-media, voice over IP; the need for a transmission medium with the bandwidth capabilities for handling such a vast amount of information is paramount. Recently, advances in solid-state and photonic technologies; the Wavelength Division Multiplexing (WDM) has been emerging as the technology of choice for increasing the transmission capacity of carrier networks. Bit rate in a wavelength can reach more than 40 Gbps and SMF (Single Mode Fiber) is a transmission medium that permits light to travel through it without amplification for hundreds of kilometer. Furthermore, researches have demonstrated that the number of wavelengths in a fiber could increase to more than 1000, and this clearly is not a limitation [1]. DWDM technology indeed now offers a solution for bandwidth insatiability, hence backbone area network can support up to several Tb/s by using WDM technology [2]. The more interested study now is the access area that connects the customer premise network to Internet backbone network, and the most of access networks are T1~T3 line today. Therefore upgrading this area is very urgent issue [3].

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. This extended network stack results in high overhead, complicates the system infrastructure, and increases cost; the redundancy has become an important research issue [4]. In addition, many WDM systems have been deployed in Wide Area Networks (WANs), so the bottleneck of communications will be pushed ahead from backbone networks to local access networks. In the state, Metro network plays a critical role in the overall expansion of network services. They do not only provide for services within individual metropolitan areas, but they also serve as the gateways for wide-area-national and international-scale-networks [5]; as a result, applying WDM to LANs and MANs gains much research interests [6-14]. Although most of the researches had interested in start and mesh WDM architectures, but there has been an increased attention focused on the WDM ring networks in the past few years. There are two major research fields in the WDM ring network: slotted and unslotted; the former is used for fixed packet length and the latter is suited to variable packet length. For example, Metro Ring, Hornet, and so on [6-10] adopted the slotted WDM ring architecture; the literatures in [11-14] adopted the unslotted WDM ring architecture which definitely matches better with IP traffic. Besides, the packet switching is also an important topic in optical network, and it can be divided into Optical Circuits Switching (OCS), Optical Burst Switching (OBS), and Optical Packet Switching (OPS). OCS is a coarse switching technology; the number of the available wavelength is constrained and the wavelength routing is not the ideal switching paradigm to realize All Optical Networks (AON). OBS aggregates a lot of asynchronous packets into a synchronous burst packet and increases the end-to-end delay. Recently the study on packet switching is focused on OPS and OBS. This paper will propose a novel transmission scheduling algorithm to handle the variable size IP packet over the unslotted WDM Metro ring network. In this paper, the WDM ring

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network architecture, CSMA/ID protocol, and three transmission algorithms are presented in Section 2. Analytical models for evaluating the average packet delay performance are developed in Section 3. Then, Section 4 validates the accuracy of the proposed model by comparing the analytical results with those obtained using simulations. Finally, Section 5 contains the conclusion.

II. NETWORK ARCHITECTURE AND CSMA/ID MAC PROTOCOL

A. *The Network Architecture*

The network architecture used in this paper is a single, unidirectional fiber ring network, which connects an *N* number of nodes. The optical fiber is composed of *W* data channels (λ_1, λ_2, λ_3,…, λ_w), as shown in Figure 1. The network scope is assumed to cover a metropolitan area (i.e., a ring circumference of about 100 km), so the system is referred to as a WDM metro ring. The Access Points (APs) connect LANs to the MAN ring network, while PoP connects the MAN to the WAN. Each data channel makes use of one specific wavelength to convey the optical signal. Therefore, using WDM technology, channels can work independently without interfering with each other. Logically, the network can be treated as a multi-ring network.

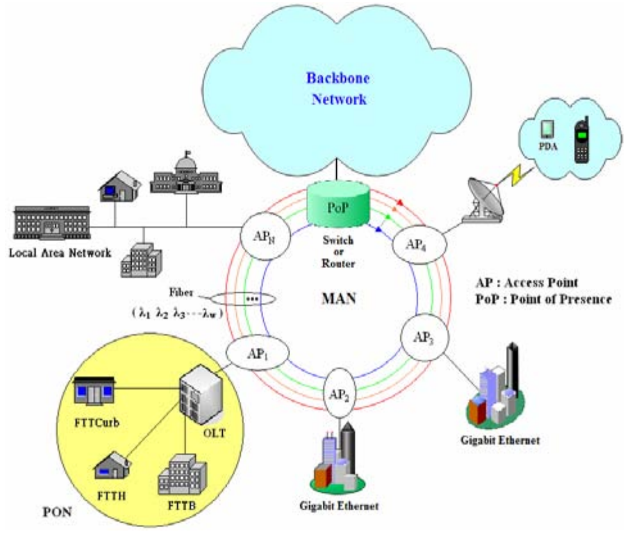

Figure 1. Architecture of a Metro WDM ring

The node structure of the network is shown in Figure 2. Each node has one tunable transmitter and *W* fixed receivers, 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 opening of the on-off switch for the corresponding data channel in order to remove the received packet carried in the major portion of the optical signal through the delay line. If the node is not the packet's destination, the detected packet is ignored and the process of scanning the next packet is started.

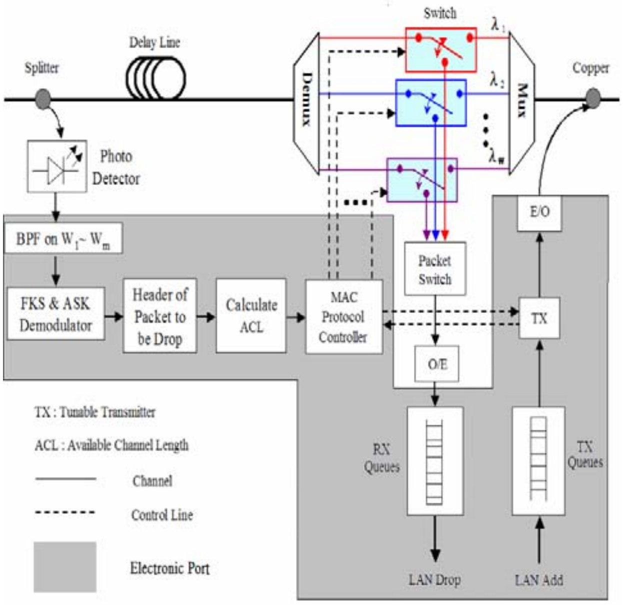

Figure 2. The node structure of the network

B. *CSMA/ID MAC Protocol*

The downstream access point recognizes the incomplete IP packet by the presence of the sub-carrier signal and pulls it off the ring. The carrier-sense can check the ACL (available channel length) to notify the Tx transmit the packet to the queue packet. Based on the protocol, each node monitors the wavelengths and detects the corresponding ACL provided that there are IP packets for transmission. Given that an IP packet is being transmitted to a target channel while the node is detecting another IP packet arriving on the same channel at its input, a dilemma of ring access (an access collision) will occur. Such collisions are due to the fact that the node cannot know if the opening is long enough to accommodate the packet. With the carrier access scheme, to guarantee the correctness of the protocol operations, the delay line inside the nodes must be used to delay the incoming packet. In addition, the delay line should be long enough to cover the maximum IP packet length (1500bytes) so that unnecessary fragmentation can be avoiding along with packet collision and thus improve the utilization of the bandwidth. Furthermore, the fiber delay line inside the AP is responsible for processing IP packets time. Fig.3. shows the CSMA/ID MAC protocol flowchart. The MAC protocol decides whether packet in the queue can transmit or not according to idle channel messages, transmit packet lengths and the transmission algorithms. There are three features in this protocol. First, it is a fully distributed, asynchronous protocol that does not need a centralized controller or a separate control channel to harmonize and synchronize the operations of

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nodes. Second, the transmitting packet will not happen collide with incoming packet on same wavelength, because the FDL length is opening enough. Third, it supports variable-length IP packets without complicated segmentation and reassembly, which becomes harder as the line speed of optical wavelengths increases.

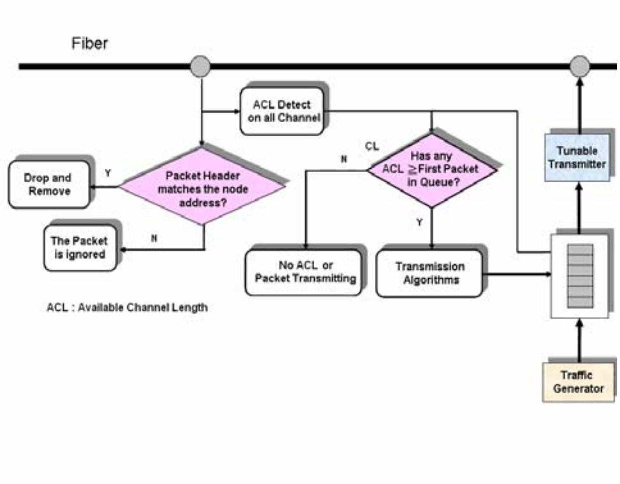

Figure 3. The CSMA/ID MAC Protocol Flow Chart

C. Three Transmission algorithms for CSMA/ID MAC Protocol

(1). First in First out Queueing (FIFO) Scheduling

In FIFO queue architecture, the packet that first arrived will be first service. The MAC controller monitors all channels to get the information of ACL, which is larger or equal than the length of the first packet in FIFO queue. If ACLs more than one then select among based on the ACL algorithms and transmit the first packet on the ACL by selected; otherwise, the first packet has to remain in the buffer (electronic memory) of the TX-queue until a sufficient ACL is arrived. By this way, the packet collision can be avoided but the Head-of-Line (HoL) will pull the throughput down.

(2). OPF_CA Scheduling Scheduling

In order to solve the HoL of FIFO scheduling, this paper proposes a scheduling algorithm OPF_CA (Optimal Packet First based on Carrier Avoidance) to increase the system throughput. In the algorithm, the MAC controller picks up a packet which length approaches the M-ACL when the HoL was happen; afterward the packet will be transmitted on the M-ACL space. However, if all packets in the queue are bigger than the M-ACL, the MAC controller will not put any packet on the M-ACL space. Fig.4 illustrates a 512-byte packet transmits onto the M-ACL space. Although the algorithm overcomes the HoL problem, it requires more operations to maintain the status information of packets in queue.

(3). OPF_CF Scheduling Scheduling Scheduling

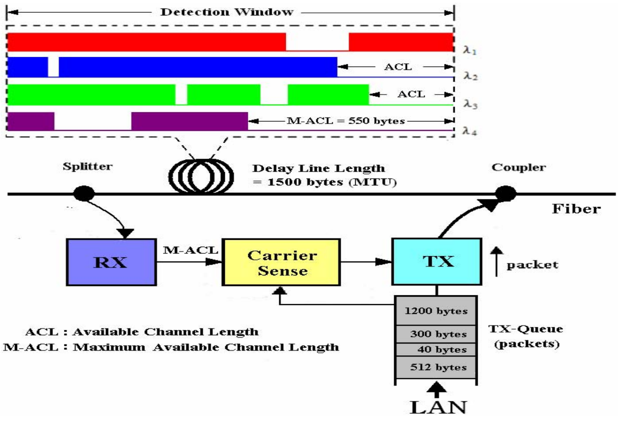

Figure 4. An Example for OPF_CA Scheduling

This proposed scheduling algorithm OPF_CF (Optimal Packet First based on Carrier Fragment) is similar to CSMA/CP protocol [18]. While the length of the packet on the header of TX-queue is too long for transmitting on the M-ACL space, the MAC controller picks up a packet which length approaches the M-ACL to transmit; however, if all packets in the queue are longer than the M-ACL, the MAC controller will fragment the packet on the queue header into two packets. The length of former fragmented packet is equal to the M-ACL, and the packet will be transmitted onto the M-ACL space; the latter fragmented packet will be remained in the TX-queue waiting for transmitting. Fig. 5 illustrates this scenario; there is no packet in TX-queue smaller than the M-ACL space, so the MAC controller fragments the first packet of TX-queue into 550 and 650 bytes packets. Afterward, the former packet is transmitted onto the M-ACL space and the latter packet is remained in queue.

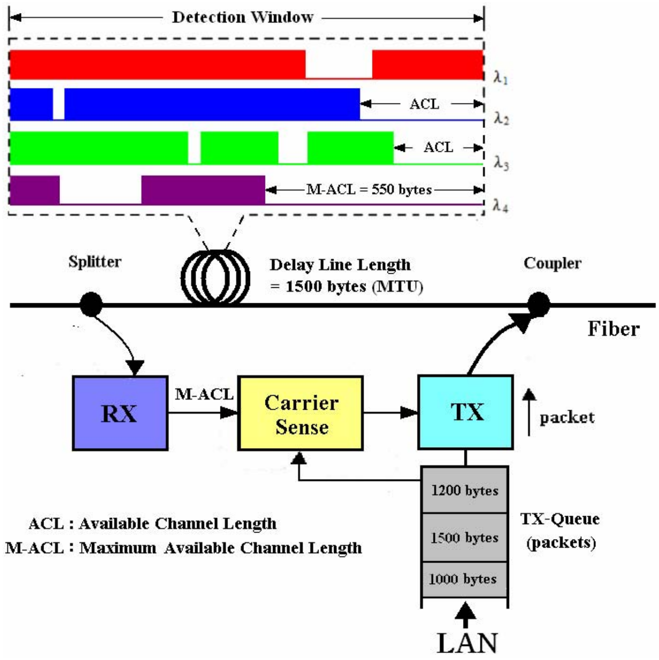

Figure 5. An Example for OPF_CF Scheduling

D. The Frame Format

To support the carrier access scheme, the frame format adopted is shown in Figure 6. The carrier sensing mechanism for finding transmitted packets in an optical fiber can be based on sub-carrier signaling [15] 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 they not economical to manufacture, but a cheaper process may be realized later. The start delimiter (SD) and the end delimiter (ED) mark a physical data frame conveyed in data channels for packets. The source address (SA) and the destination address (DA) serve as the address information in the network. To prevent possible transmission errors midway, the cyclic redundancy check (CRC) is employed. The flag (FG) field is reserved for extended protocol functions.

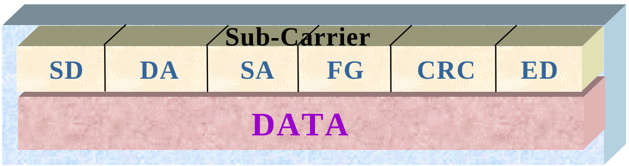

Figure 6. The frame format

III. PERFORMANCE EVALUATION

A. Approximate Analytical Models

The transfer delay of a packet measured from when the packet is completely stored in the source node queue until that packet has been completely received by the destination node. This delay consists of queuing delay, transmission delay and propagation delay. The queuing delay of a packet is measured from when a packet is fully stored in a queue of the source node to the time the source node was last selected by the queue before successful transmission. Meanwhile, in this investigation, the transmission delay is defined as the interval between the source node selecting the queue to transmit the packet successfully and the time the source node last selected the queue before transmitting the packet successfully. Finally, the propagation delay of a packet is the interval between the time that the last bit of the packet reaches the destination and the moment that the last bit of the packet was transmitted. From the behavior of the expected queuing delay for the *i*th packet, the model can be categorized as an M/G/1 queue with vacations model [16]. Clearly, the queuing delay captures the effect of contention and is dependent on traffic density. In order to present expressions for packet transfer delay at a node on multi-rings using an M/G/1 vacation model, we first present some assumptions and the general notation to be used in various subsections.

(1). Assumptions. For simplicity, the following assumptions are made:

1. The number of WDM channels is W.
2. The total propagation delay of the WDM ring is τ seconds, and the distances between the nodes are equal.
3. Packets which arrive are 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 $\lambda = \sum_{i=0}^{N-1} \lambda_i$.
4. The arrival stream of packets at node i destined for node $i \oplus j$ is a Poisson process with rate of $\lambda_{i,i\oplus j}$, where $\oplus$ indicates addition modulo N; thus $\lambda_i = \sum_{j=1}^{N-1} \lambda_{i,i\oplus j}$. In the case of uniform and symmetric traffic on the ring, it indicates 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 $0 \le i \le N-1, 1 \le j \le N-1$
5. The 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 [11] $P_r(M = k) = \beta \cdot (1-\beta)^k, k = 0,1,2,\ldots$ where $\beta = \frac{1}{1 + E[M]}$.
6. The WDM ring channel bit rate is R (bps) and the packet transmission time is X (= M/R) seconds.
7. Define MTU (maximum transfer unit) as equal to the delay line (L=1500bytes) with $T_i = L/R$ seconds to transmit the MTU.

(2). Notations. The following notations are used in the analytical formulas below:

D	average packet transfer delay
TQ_i	queue-waiting delay of packet i
TQ	average packet queue-waiting delay
α_i	residual time of packet i
α	packet residual time
V_i	duration of all the whole vacation intervals for which packet i must wait before being transmitted
V	steady-state duration of all whole vacation intervals
S	average transmission delay

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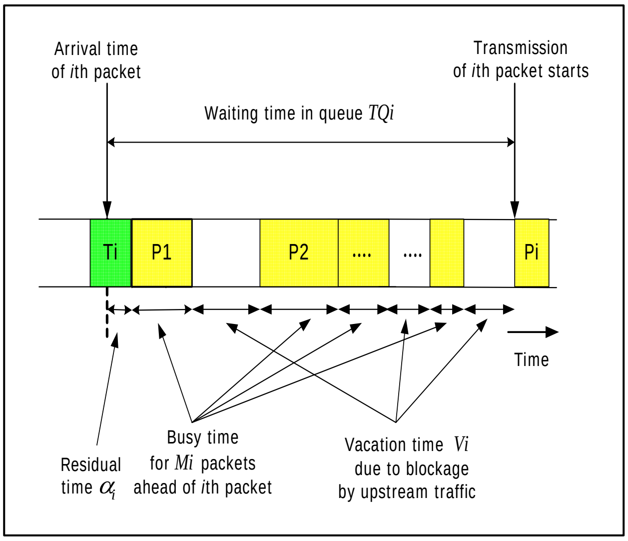

Figure 7. Calculation of the average waiting time in M/G/1 system with vacations. The average waiting time E[TQ_i] of the ith packet is E[TQ_i] = E[α_i] + E[M_i]E[X] + E[V_i].

B. Analysis of the single-ring case

With the above assumptions, we model the queuing and transmission delay using a M/G/1 queue with vacations as illustrated in Figure 7. The average queuing delay, TQ_i, for the ith packet is given by

$$\mathrm{E}[TQ_i] = \mathrm{E}[\alpha_i] + \mathrm{E}[M_i]\mathrm{E}[X] + \mathrm{E}[V_i] \tag{2}$$

The queuing delay and transmission delay capture the effect of contention and upstream traffic dependence. Thus we consider the delay line (or MTU) as a slot unit, so the dependence is when the full slots are uniformly and independently distributed on a single ring. Since the arrival process is assumed to be Poisson, this residual time α can be considered to be uniformly distributed between 0 and L/R. Therefore, the mean packet residual time is simply

$$E[\alpha] = \frac{L}{2 \times R} \tag{3}$$

By Little's formula, the value of $\lim_{i\to\infty} \mathrm{E}[M_i]\mathrm{E}[X]$ is $\lambda_i TQ\,\mathrm{E}[X]$. Letting $V = \lim_{i\to\infty} \mathrm{E}[V_i]$, we can thus write the steady-state version of equation (2):

$$TQ = \mathrm{E}[\alpha] + \lambda_i TQ\,\mathrm{E}[X] + V \tag{4}$$

Next we calculate approximation V by multi-channel slotted ring networks. Packets sent by an upstream source use node i as a bridge to reach their destinations, and this bridge has an average traffic load of $\rho_{Bi} = \sum_{k=2}^{N-1} \sum_{j=N-k+1}^{N-1} \lambda_{i\oplus k, i\oplus k\oplus j} E[X_j] \cdot$

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

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

With this assumption, the average density ρ_{Bi} can be viewed as the probability of MTU is full on the ring. The probability that a packet has to wait i more MTU before it can be transmitted is $\rho_{Bi}{}^{i}(1-\rho_{Bi})$. The mean waiting time $E[d]$ to find an empty MTU can be expressed as

$$E[d] = \sum_{i=0}^{\infty} i\frac{L}{R}\rho_{Bi}{}^{i}(1-\rho_{Bi}) = \frac{L \cdot \rho_{Bi}}{R(1-\rho_{Bi})} \tag{6}$$

The steady-state duration of all the whole vacation intervals V is equal to $\lambda_i TQ \cdot \mathrm{E}[d]$, and combining equations (3) and (6) we obtain the average queuing delay

$$\begin{aligned} TQ &= E[\alpha] + \lambda_i TQE[X] + \lambda_i TQE[d] \\ &= \frac{L}{2 \cdot R} + \lambda_i TQE[X] + \lambda_i TQ \frac{L \cdot \rho_{Bi}}{R \cdot (1-\rho_{Bi})} \end{aligned} \tag{7}$$

which can be reduced to

$$TQ = \frac{L}{2 \cdot R \cdot (1 - \lambda_i E[X] - \lambda_i \frac{L \cdot \rho_{Bi}}{R \cdot (1-\rho_{Bi})})} \tag{8}$$

Because the packet transfer delay is comprised of the queuing delay, transmission delay and propagation delay, the average packet transfer delay is

$$D = TQ + S + \tau' \tag{9}$$

where τ' is the average propagation delay from a source node to a destination node, which is often expressed as $\tau/2$. The average transmission delay is

$$\begin{aligned} S &= E[X] + E[d] \\ &= E[X] + \frac{L \cdot \rho_{Bi}}{R \cdot (1-\rho_{Bi})} \end{aligned} \tag{10}$$

Thus, the average transfer delay is given by

$$D = TQ + S + \tau/2 \tag{11}$$

C. Analysis of the multi-ring (WDM ring) case

In order to analyze the multiple WDM ring networks, it is assumed that the bridge traffic load from the upstream source is equally distributed among W rings. To simplify the analysis, let the circulation of slots on W rings be synchronized [17-18]. That is, a node can observe W MTU on different rings at the same time. Since the bridge traffic load from the upstream source is uniformly distributed among the W rings, the average bridge traffic load of each ring, ρ_B, can be expressed as

$$\rho_B = \rho_{Bi} / W \tag{12}$$

The probability that the packet at the head of a queue cannot get an empty MTU among the currently passing W MTUs is $(\rho_B)^W$. Therefore, the probability that the packet has to wait i MTUs before it can be sent out is $(\rho_B)^{W \cdot i}(1-(\rho_B)^W)$.

Similar to subsection III.B, let $E[d_B]$ be the average time required to find the arrival of an empty MTU, then we have

$$E[d_B] = \sum_{i=0}^{\infty} i\frac{L}{R}(\rho_B)^{W \cdot i}(1-(\rho_B)^W) = \frac{L \cdot (\rho_B)^W}{R \cdot (1-(\rho_B)^W)} \tag{13}$$

Since for each packet in the queue the arriving packet has to wait for L/R, the average queuing delay in the queue faced by an arriving packet is

$$TQ = E[\alpha] + \lambda_i TQE[X] + \lambda_i TQE[d_B] \tag{14}$$

Therefore, we have

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$$TQ = \frac{E[\alpha]}{1 - \lambda_i E[X] - \lambda_i E[d_B]} \tag{15}$$

The average transmission delay is

$$\begin{aligned} S &= E[X] + E[d_B] \\ &= E[X] + \frac{L \cdot (\rho_B)^W}{R \cdot (1 - (\rho_B)^W)} \end{aligned} \tag{16}$$

Thus, the average transfer delay is given by

$$D = TQ + S + \tau / 2 \tag{17}$$

IV. SIMULATIONS AND RESULTS

This section describes the results of the discrete event simulations under IP packets were generated with packet size distribution matching that of a measurement trace from one of MCIs backbone OC-3 links. In the simulation, packets are generated by the packet generator both Poisson process and Interrupted Poisson Process (IPP), however this paper will give only the results based on Poisson process because of paper space limitation. In addition, all simulations were run for a time long enough to reach the confidence; in general, each node transmits more than 2 million packets in a simulation.

The simulation experiments are based on the codes by SIMSCRIPT II and are replicated corresponding to variance reduction technique with different sequences for pseudo random numbers. The results are obtained with 95% confidence level.

TABLE I. THE SIMULATION PARAMETERS

Architecture : TT-FR^W	
Number of nodes	16 (Fixed)
Number of channels	8, 4
Light velocity in fiber	$2 \times 10^8\, m/s$
Ring network length	100 km
Channel speed	10 Gb/s (OC-192)
Size of the delay line	1500 Bytes (240 meters)
packet range	OC-3 Traffic Distribution and Poisson Process
Average Packets	353 Bytes

The parameters of the network are shown in Table I. Figure 8 presents the simulated and analytical results of the average packet transfer delay in this network. The curves demonstrate that a high node offer load can be achieved with low transfer delay when the number of channels is large. The agreement between the simulation results and the analytical results is excellent. Figure 9 plots the packet transmission delay versus the offered load per node. We observe that the delay characteristics of the designed CSMA/ID protocol are better than that of the Hornet (TT-FR architecture) protocol [8] when the number of channels is equal to 8.

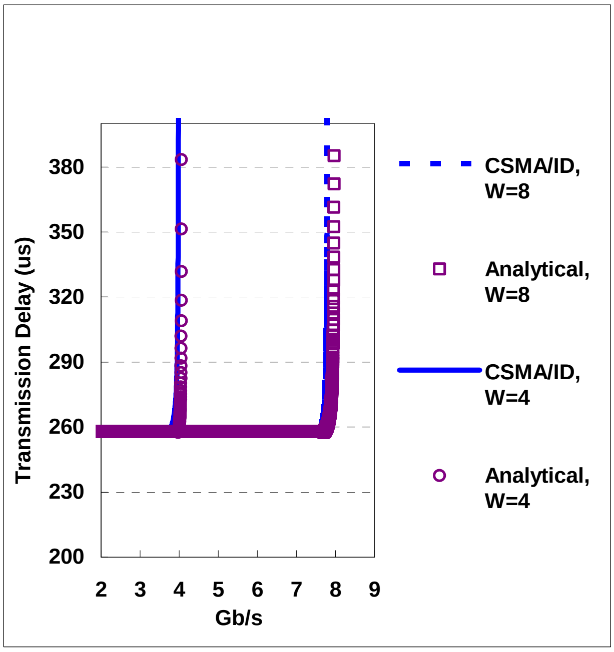

Figure 8. Average transfer delay versus offered load per node, when the number of channels equals 4 and 8.

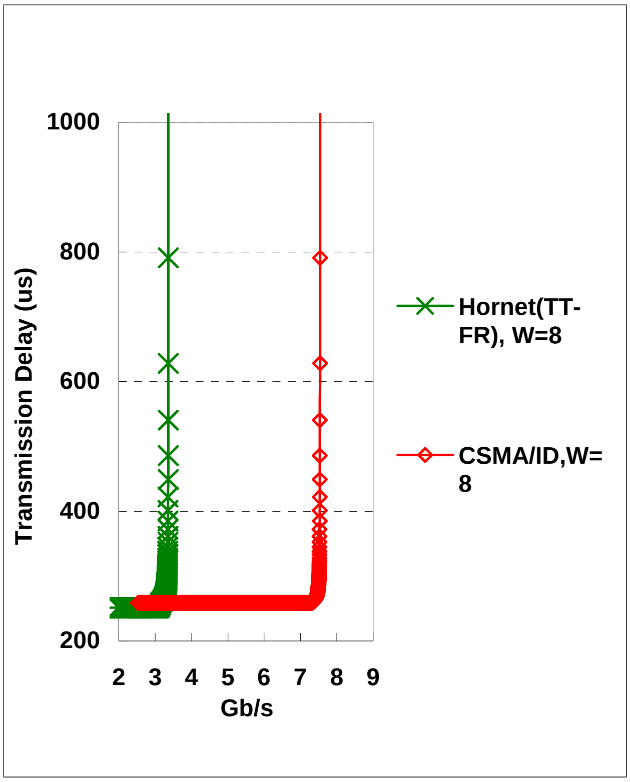

Figure 9. Comparing CSMA/ID and Hornet: average transmission delay when the number of channels equals 8.

The simulation results in throughput per node of FIFO and OPF scheduling algorithms by increasing the number of channels are shown in Fig. 10 and 11. In terms of performance, the fragmented packet scheme (FIFO_AP or OPF_CF) has higher performance than the complete packet scheme (FIFO_CA or OPF_CA). Fig. 12 and 13 illustrate the simulation results the performance of the complete packet scheme and the fragmented packet scheme in FIFO or OPF scheduling algorithm. From the simulation results, it shows that the network performance of OPF_CA has better network efficiency in the complete packet scheme and the superiority is obvious when increasing the number of channels, but the superiority is not obvious in the fragmented packet scheme. Fig. 14 indicates that the improvement in fragmented times between OPF_CF and FIFO_CP. The simulation result shows it is a very attractive scalability feature that the fragment time of each packet is decreased about 40% in the OPF_CF scheduling algorithm.

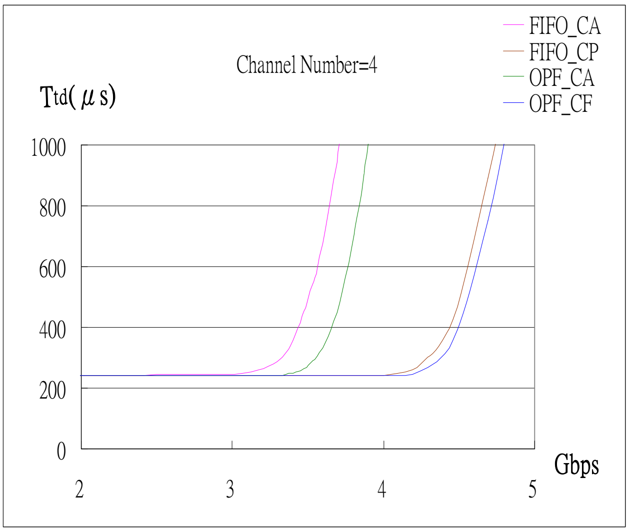

Figure 10. Throughput per Node with Channel Number=4

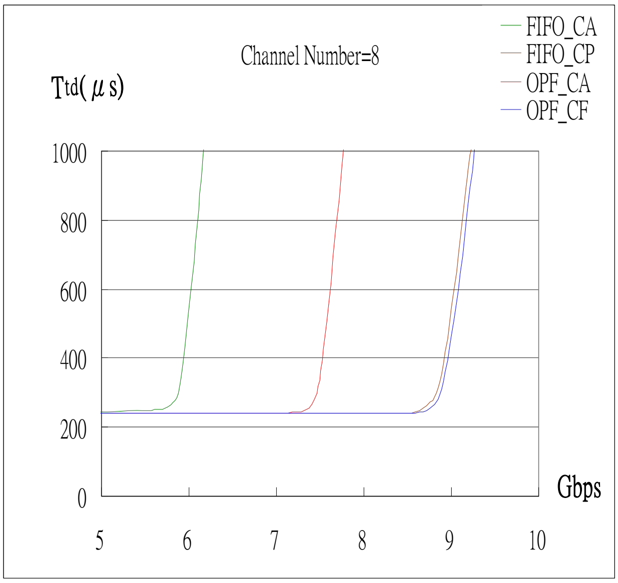

Figure 11. Throughput per Node with Channel Number =8

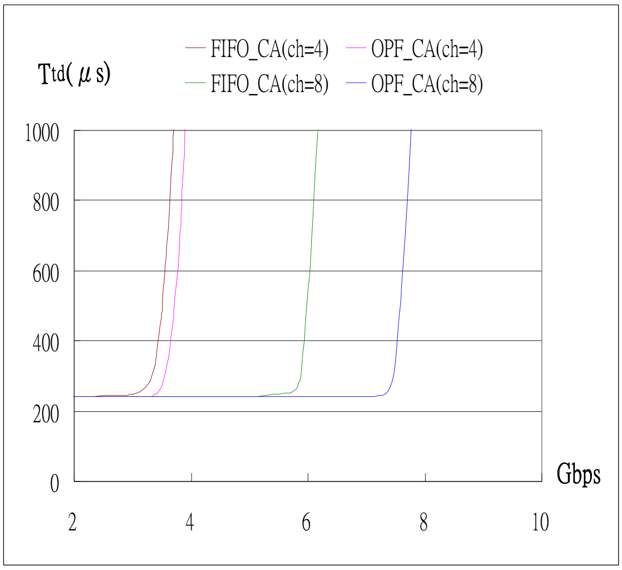

Figure 12. Compare OPF with FIFO Scheduling Algorithm

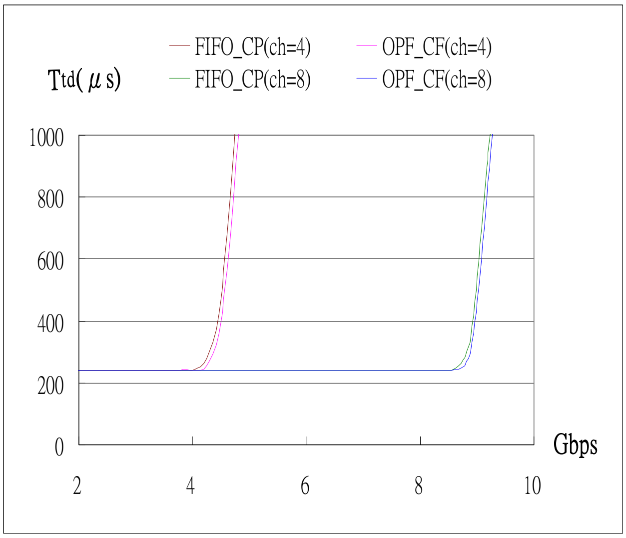

Figure 13. Compare OPF with FIFO Scheduling Algorithm

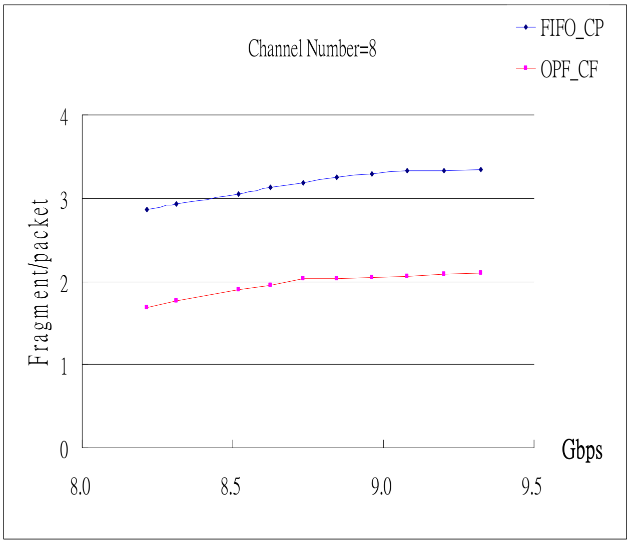

Figure 14. Compare OPF with FIFO Scheduling Algorithm for the Number of Fragments

V. CONCLUSION

In summary, in this paper we have investigated a novel MAC protocol for all optical WDM ring networks. The protocol supports the transmission of IP packets directly over WDM from LAN to MAN. 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. There are three packet scheduling algorithms are discussed and analyzed. For verification, a simulation program obtains simulated results for the network, and the simulated results closely resemble the analytical values, and this demonstrates the performance of the network. The throughput of the fragmented packet scheme is better than that of the complete packet scheme. It is also observed that the throughput characteristic of the network is almost proportional to the number of channels in the network. With regards to the utilization of bandwidth of all the optical ring networks, our protocol displays the excellent characteristics of high throughput and low delay for all optical communications.

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