A Carrier Fragmentation Aware CSMA/ID MAC Protocol for IP over WDM Ring Networks

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Abstract: - In this paper, a packet pre-classification MAC protocol based on Carrier Sense Multiple Access with Idle Detection (CSMA/ID) with carrier fragmentation aware scheme has been investigated for completely transporting IP packets over the all-optical WDM ring networks. In order to improve the utilization of the network, the packets are first pre-classified into various class queues of access point (AP) according their length. 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 available channel length (ACL) to notify the transmission queues transmit the packet. This protocol avoids packet collision and uses carrier fragmentation when finding no appropriate ACL. An analytical model has had been developed to evaluate the performance of the protocol, and the simulation results show good network efficiency.

Key-Words: - CSMA/ID, Carrier fragmentation, Available channel length, Analytical model and simulation

1 Introduction

In the past few years, there has been an enormous increase in the bandwidth requirements by the explosion of information traffic due to the Internet, electronic commerce, computer networks, voice, data, and video. Therefore, the need of a transmission medium with the bandwidth capabilities to handle such a vast amount of information is very crucial. Recently, the advance in solid-state and photonic technologies is very fast; hence the technology of wavelength division multiplexing (WDM) has been emerging as the choice for increasing transmission capacity of carrier networks. In the technology, the transmission rate of a wavelength can reach about 40 Gb/s and a glass fiber can permit light travel through it without amplification for hundreds of kilometer. Presently many researches exhibit the total bandwidth of an optical fiber can reach more than 10Tbps [1]. Furthermore, the research [2] has demonstrated the number of wavelengths per fiber could increase to more than 1000, and it clearly is not a limitation. DWDM technology indeed now offers a solution for insufficient bandwidth.

Due to the widespread services and tremendous user population in the Internet, the IP packet traffic dominates the most utilization of data networks. However, the traffic now is transferred, switched, and manipulated through the complex protocol stacks, such as IP/ATM/SONET/WDM, IP/ HDLC/SONET/WDM, and so on. The topic how to merge and collapse the middle layers to reduce cost, complexity, and redundancy has became to an important research issue [3]. Additionally, many WDM systems have been deployed in Wide Area Networks (WANs), so the bottleneck of data communications will be pushed ahead from backbone networks to local access networks; hence applying WDM to LANs/MANs increases much research interests [4-8]. The research of WDM architectures has been focused an increased attention on the WDM ring networks in the past few years because of a number of advantages associated with ring networks [9]. In the paper [10], Lee et al. had outlined the main advantages of the ring topology: simple routing policy, simple control and management of network resources, simple hardware system, and simple protection from network failures. Moreover, ring networks are predominant in the current MANs market; WDM rings are also expected to appear as the next-generation access networks in the MAN area. In addition, ring topology can be designed as wavelength routing or broadcast-and-select networks; in last few years there have been a number of proposed broadcast-and-select ring architectures. Presently, the progress achieved in optical amplifiers has provided the compensation of insertion losses at intermediate nodes; it is the main disadvantage of ring topology than star topology.

A number of papers have examined 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 [11]. To achieve all optical communications, MTIT adopts the source removal policy [10] for dropping packets from networks to prevent packet re-circulation. Shrikhande et al. developed HORNET as a testbed for a packet-over-WDM ring MAN [12]. To facilitate signal regeneration and destination removal, HORNET utilizes opto-electronic and electro-optic conversion, which may constrain the transmission rate of the network. Although the IP standard allows a packet length of between 40 and 64k bytes, a measurement trace from one of MCIs backbone OC-3 links shows a discrete packet-size distribution, from 40 bytes to 1500 bytes [11]. Jih-Hsin Ho et al. proposed an CSMA/CP MAC protocol based on avoiding packet collision using a fragment packet scheme for all optical WDM multi-rings with a tunable transmitter and fixed receiver (TT-FR) [13]. In this paper the WDM ring network architecture are presented in section 2 and CSMA/ID protocol with carrier fragmentation are presented in section 3. Analytical models for evaluating the average packet delay performance are developed in section 4. Then, section 5, validates the accuracy of the proposed model by comparing the analytical results with those obtained by means of simulations. Finally, a few remarks are given in the conclusion.

2 Network Architecture

The backbone ring is a shared medium, so it requires a media access control (MAC) protocol to manage the network operations. This paper uses a CSMA/ID MAC protocol with carrier fragmentation that will be described in next section. To illustrate the node architecture of the network, let us firstly consider a single and unidirectional fiber ring network which connects a number of nodes; the ring network is composed of N data channels as shown in figure 1. The access points (APs) connects LANs to the ring network, while the POP connects the MAN to the WAN. 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-channel ring network.

The node structure of the network is shown in figure 3. In order to avoid the use of expensive wide-band WDM equipment and improve scalability, multiple APs share the same drop wavelength, instead of dropping a unique wavelength. Each node has one tunable transmitter and fixed receiver (i.e. TT-FR[1] system). 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 receiver. The 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 FBG Filter 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.

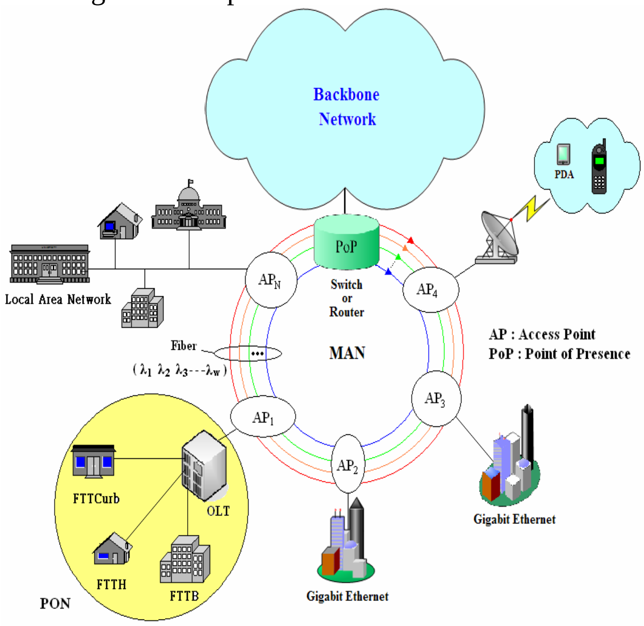

Figure 1.Logical architecture of a WDM ring

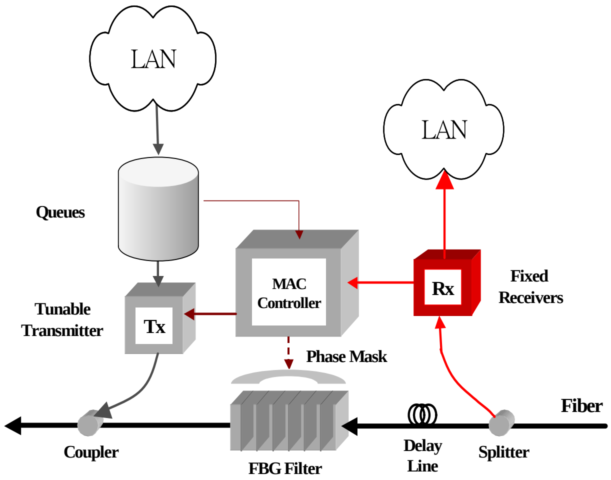

Figure 2. The node structure with the IP packet size (no pre-classification scheme)

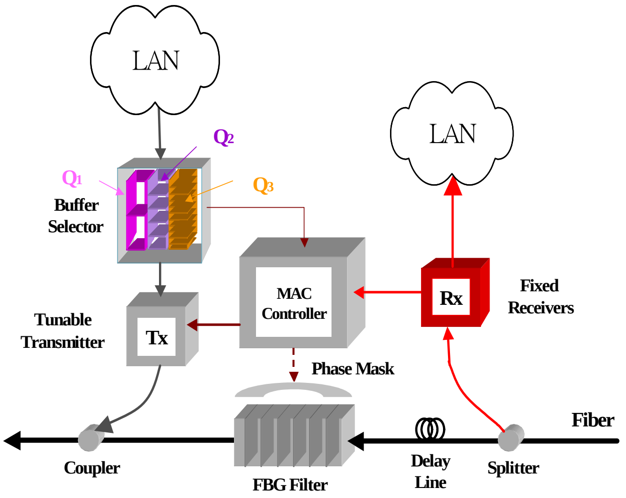

Figure 3. The node structure with the IP packet size pre-classification scheme.

Furthermore, although the IP standard allows a packet length between 40 bytes and 64k bytes, a measurement trace from one of MCIs backbone OC-3 links shows a discrete packet-size distribution, from 40 bytes to 1500 bytes. According to the discrete packet-size distribution, we proposed design another node structure of the network is shown in figure 3. This node structure will have been better network efficiency compare with the no pre-classified scheme.

3 CSMA/ID MAC Protocol with Carrier Fragmentation

3.1 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. Figure 4. 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 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.

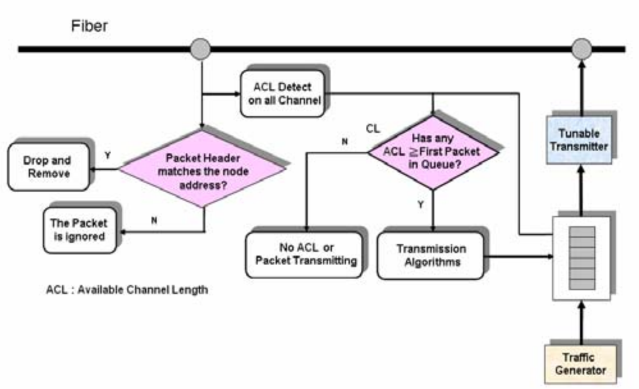

Figure 4. The CSMA/ID MAC Protocol Flow Chart

3.2 CSMA/ID MAC Protocol with Carrier Fragmentation

The CSMA/ID Protocol with carrier fragmentation processes are as follows:

(1) IP packets are pre-classified to three kinds of different queues (Q_1, Q_2, and Q_3) with the buffer selector. The three kinds of queues are for storage of 553~1500 bytes, 41~552 bytes, and 40 bytes, respectively. The MAC controller reads the IP packets size storage message and sends it to the appropriate queue.

(2) Since each node is equipped with a receiver for corresponding data channel, an IP packet can be transmitted via a corresponding available data channel to its destination node. The receiver is responsible for checking the destination address of incoming IP packets and detecting available channels to notify the MAC controller.

(3) According the information in(1) and (2), the MAC controller then delivers a message to the active buffer selector to transmit the Q_1, Q_2, or Q_3 buffers packet. Figure 5 illustrates the MAC controller model flowchart and Figure 6 illustrates an example of the MAC controller scheme. If the maximum available channel length (M-ACL) is 550 bytes and the three kinds of different queue storage for the first IP packet are 1200 bytes, 300 bytes, 40 bytes and 512 bytes respectively then the MAC controller transmits a message to tunable transmitter which transmits the Q_2 buffer's packet.

(4) 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. Figure 7 illustrates this scenario; there is no packet in TX-queue smaller than the M-ACL space, so the MAC controller fragments the Q_1 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.

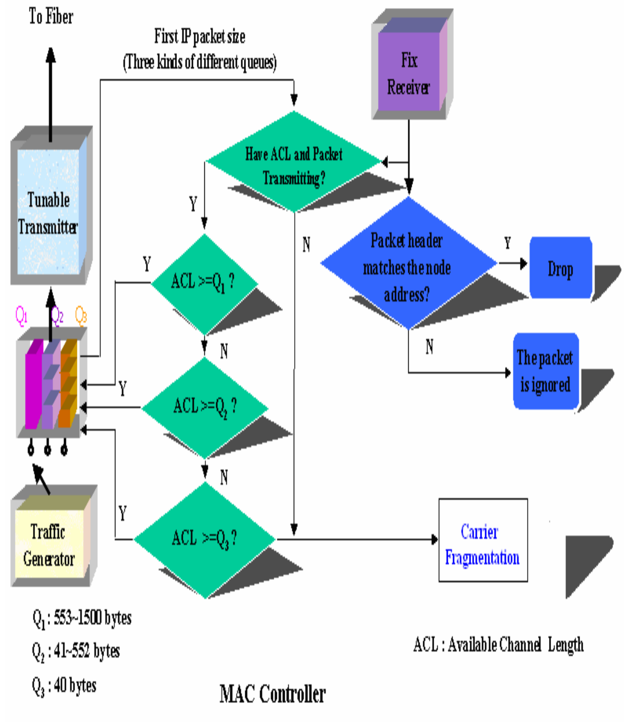

Figure 5. The CSMA/ID with Carrier Fragmentation MAC controller model flowchart

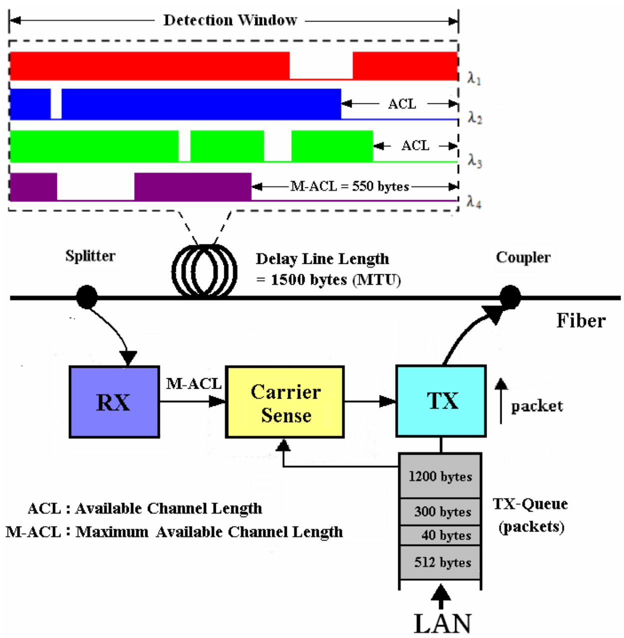

Figure 6. An Example for CSMA/ID

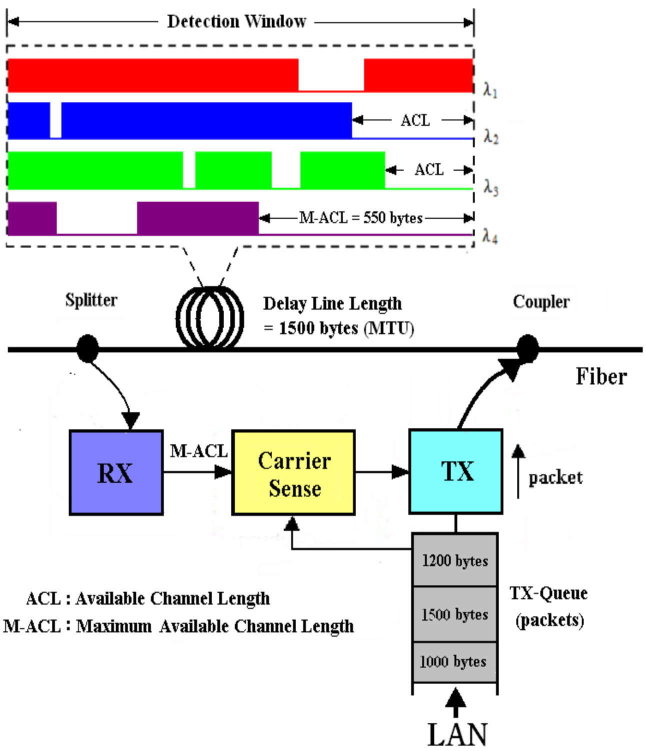

Figure 7. An Example for CSMA/ID with Carrier Fragmentation

3.3 The Frame Format

To support the carrier fragmentation scheme, a frame format is designed, as shown in Figure 8, to solve the addressing capabilities and fragmentation mechanisms. Basically, this consists of a start delimiter (SD), which labels the data frame that is conveyed in the data channel either as packets or fragments. The destinations address (DA) and the source address (SA) fields record the address information in the network. The sequence number (SN) expresses the serial number in a sequence of fragments, and the end fragment (EF) field is used to indicate the last fragment. Finally, the flag field (FG) is reserved for extended protocol functions, such as defining different service classes for the data payload. The frame length (FL) indicates the length of frame, when the frame is fragmented. Finally, the end delimiter (ED) determines the frame termination. The frame header is composed of SD, DA, SA, SN, EF, FG fields, and the frame trailer is composed of FL, ED fields. To demonstrate the action of packet fragmentation, a collided packet is fragmented into two fragments, as depicted in Figure 9. The front fragment that has just been transmitted is appended into a frame trailer and the rear fragment for later transmission is inserted into a frame header.

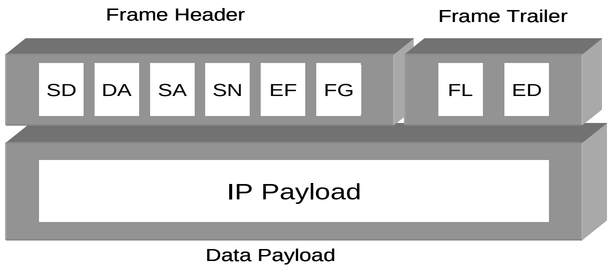

Figure 8. The frame format

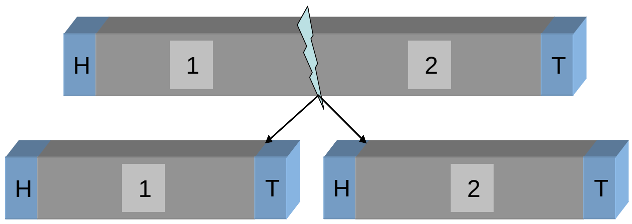

Figure 9. Fragmentation of data frame.

4 Analytic Models

The transfer delay of a packet measured from 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 queue-waiting delay, transmission delay and propagation delay. The queue-waiting 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.

Figure 10 illustrates the timing diagram of a specific node on one channel, considering the *i*th packet (P*i*) arrival into a node transmission queue. This packet must wait in queue for the residual time α_i until the end of the current packet transmission or vacation interval. It must also wait for the transmission of the M_i packets currently in the queue. This queue includes M_i packets, which would be fragmented by upstream traffic as in Figure 10, and when packet P1 arrivals, it is fragmented into P11 and P12. Finally, the packet must wait during the vacation time V_i because some M_i packets are blocked by upstream traffic. As described above, the expected queue-waiting delay for this packet consists of three items: first, the mean residual time for the packet; second, the expected waiting time for packets ahead of *i*th packet; and third, the expected vacation times due to blockage by upstream traffic.

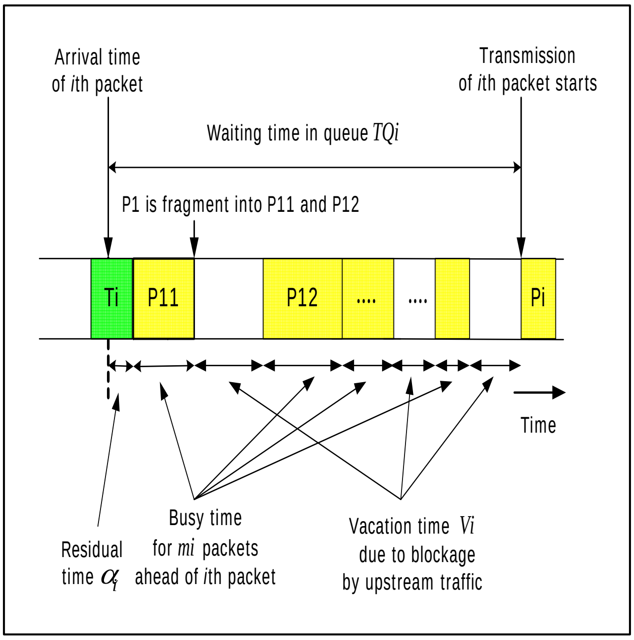

Figure 10. Calculation of the average waiting time in M/G/1 system with vacations. The average waiting time E[TQi] of the ith packet is E[TQi] = E[αi] + E[mi]E[x] + E[Vi]

From the behavior of the expected queue-waiting delay for the *i*th packet, the model can be categorized as M/G/1 queue with vacations model [14]. Clearly, the queue-waiting 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.

4.1 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 an 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 a rate of $\lambda_{i,i\oplus j}$, where ⊕ 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, identical and geometrically distributed random variables (denoted by the r.v. M(bits)) with mean E[M] and probability mass function [15] $P_r(M=k) = \beta \cdot (1-\beta)^k, k = 0,1,2,..$ where $\beta = \frac{1}{1+E[M]}$.
6. The WDM ring channel bit rate is R (bps) and the packet transmission time without considering vacations is X (= M/R) seconds.
7. The data packet of Length M would be fragmented into a sequence of n_G consecutive mTUs (minimum transfer unit) ignoring the header and trailer length, and assume that $P_r(n_G = k), k = 0,1,2,\ldots$ denotes the probability that $n_G = k$.
$$P_r(n_G = 0) = 0,$$
$$P_r(n_G = 1) = \sum_{M=0}^{mTU} \beta (1-\beta)^M = 1 - (1-\beta)^{mTU+1},$$
and, $k = 2,3,\ldots$ $P_r(n_G = k) = P_r[(k-1) \cdot mTU < M \le k \cdot mTU]$
$$= [1-(1-\beta)^{mTU}](1-\beta)^{(k-1) \cdot mTU+1}$$

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

8. The fiber delay line is defined as *L*, where
$$L = \text{mTU} + \text{Tg and } L \ge \text{Tg} \qquad (3)$$

4.2 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
m_i number of fragmented packets that must be transmitted before packet *i*
x fragmented packet transmission time
α_I residual time of packet *i*

V_i duration of all the vacation intervals for which packet i must wait before being transmitted

V steady-state duration of all the vacation intervals

S average transmission delay

4.3 Analysis of CSMA/ID with Carrier Fragmentation for single-ring case

With the above assumptions, we model the queue-waiting and transmission delay using an M/G/1 queue with vacations. The average queue-waiting delay, TQ_i, for the ith packet is given by

$$\mathrm{E}[TQ_i] = \mathrm{E}[\alpha_i] + \mathrm{E}[m_i]\mathrm{E}[x] + \mathrm{E}[V_i] \qquad (4)$$

The queue-waiting delay and transmission delay capture the effect of contention and upstream traffic dependence. Thus we consider the delay line as a slot unit, so the dependence is when the full slots are uniformly and independently distributed on a single ring. Our analytical average queue-waiting delay approximations can be obtained by redrawing the timing diagram shown in figure 11. Figure 11 illustrates the calculation of the average queue-waiting time in a specific node using the aggregation of busy time and vacation time. 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

$$E[\alpha] = \frac{L}{2 \times R} \qquad (5)$$

The number of fragmented packets m_i that packet i must wait for is equal to the number aggregation of full packets in the queue. The value of $\lim_{i\to\infty} \mathrm{E}[m_i]\mathrm{E}[x]$ is equal to $\lim_{i\to\infty} \mathrm{E}[M_i]\mathrm{E}[X]$ and 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 (4):

$$TQ = \mathrm{E}[\alpha] + \lambda_i\, TQ\, \mathrm{E}[X] + V \qquad (6)$$

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 $\rho_{Bi} = \sum_{k=2}^{N-1}\sum_{j=N-k+1}^{N-1} \lambda_{i\oplus k, i\oplus k\oplus j} E[X_j]$.

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

$$\begin{aligned}\rho_{Bi} &= \sum_{k=2}^{N-1}\sum_{j=N-k+1}^{N-1} \lambda_{i\oplus k, i\oplus k\oplus j} E[X_j] \\ &= \frac{(N-1)(N-2)}{2} \times \frac{\lambda}{N(N-1)} \times \frac{E[M]}{R} \\ &= \frac{(N-2)\times \lambda_i \times E[M]}{2\times R} \\ &= \frac{(N-2)\times \lambda \times E[M]}{2\times N \times R}\end{aligned} \qquad (7)$$

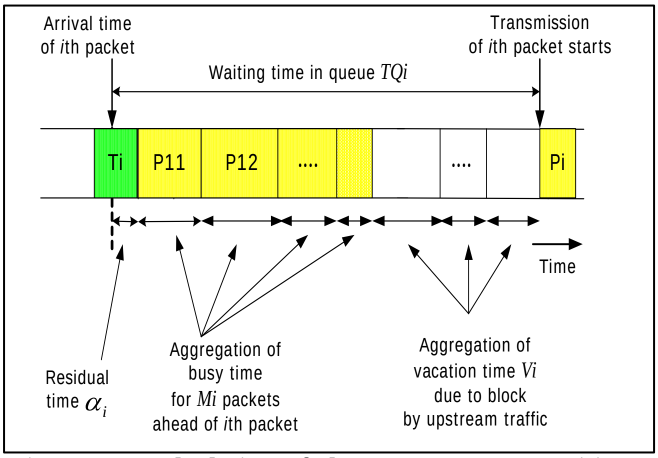

Figure 11. Calculation of the average queue-waiting time in a specific node using aggregation of busy time and vacation time. The average waiting time E[TQ_i] of the ith packet is E[TQ_i] = E[α_i] + E[M_i]E[X] + E[V_i].

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

$$E[d] = \sum_{i=0}^{\infty} i \frac{L}{R} \rho_{Bi}{}^i (1-\rho_{Bi}) = \frac{L\cdot \rho_{Bi}}{R(1-\rho_{Bi})} \qquad (8)$$

When a new packet arrives, it must wait $n_G\cdot d$ seconds for each item ahead of it and wait $n_G\cdot d$ more for its own service. The steady-state duration of all the whole vacation intervals V is equal to $\lambda_i TQ\mathrm{E}[n_G]\mathrm{E}[d]$, and combining equations (5) and (8) we obtain the average queue-waiting delay

$$\begin{aligned}TQ &= E[\alpha] + \lambda_i TQ E[X] + \lambda_i TQ E[n_G] E[d] \\ &= \frac{L}{2\cdot R} + \lambda_i TQ E[X] + \lambda_i TQ E[n_G] \frac{L\cdot\rho_{Bi}}{R\cdot(1-\rho_{Bi})}\end{aligned} \qquad (9)$$

which can be reduced to

$$TQ = \frac{L}{2\cdot R\cdot\left(1 - \lambda_i E[X] - \lambda_i E[n_G]\dfrac{L\cdot\rho_{Bi}}{R\cdot(1-\rho_{Bi})}\right)} \qquad (10)$$

Because the packet transfer delay is comprised of the queue-waiting delay, transmission delay and propagation delay, the average packet transfer delay is

$$D = TQ + S + \tau' \qquad (11)$$

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

$$S = E[X] + E[n_G]E[d] = E[X] + \frac{E[n_G] \cdot L \cdot \rho_{Bi}}{R \cdot (1 - \rho_{Bi})} \quad (12)$$

Thus, the average transfer delay is given by

$$D = TQ + S + \tau / 2 \quad (13)$$

4.4 Analysis of CSMA/ID with Carrier Fragmentation for multi-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 [16-17]. That is, a node can observe W delay line L 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

$$\rho_B = \rho_{Bi} / W \quad (14)$$

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

Similar to subsection 4.3, let E[d_B] be the average time required to find the arrival of an empty L, then we have

$$E[d_B] = \sum_{i=0}^{\infty} i \frac{L}{R} (\rho_B)^{W \cdot i}(1-(\rho_B)^W) = \frac{L \cdot (\rho_B)^W}{R \cdot (1-(\rho_B)^W)} \quad (15)$$

Since for each packet in the queue the arriving packet has to wait for L/R + d_B times, the average queue-waiting delay faced by arriving packet is

$$TQ = E[\alpha] + \lambda_i TQE[X] + \lambda_i TQE[n_G]E[d_B] \quad (16)$$

Therefore, we have

$$TQ = \frac{E[\alpha]}{1 - \lambda_i E[X] - \lambda_i E[n_G]E[d_B]} \quad (17)$$

The average transmission delay is

$$S = E[X] + E[n_G]E[d_B] = E[X] + \frac{E[n_G] \cdot L \cdot (\rho_B)^W}{R \cdot (1 - (\rho_B)^W)} \quad (18)$$

Thus, the average transfer delay is given by

$$D = TQ + S + \tau / 2 \quad (19)$$

5 Numerical Results

Several simulated and analytical results are conducted in order to evaluate the performance of proposed carrier fragmentation aware CSMA/ID MAC protocol in this study. This section presents the simulated and analytical results for CSMA/ID and carrier fragmentation aware CSMA/ID. The CASI SIMSCRIPT II.5 simulation tool is used to simulate the network model. Here, the behavior of every node is assumed to be the same, and all channels are unidirectional and synchronized in the network. Meanwhile, the packet arrival rate distribution of every node is the same, and the destination of all packets is assigned randomly. Therefore, packets are evenly distributed to all nodes except for their generators. The packet arrival distribution of every node is a Poisson distribution. For a WDM ring with the destination removal policy, each node has one tunable transmitter and W fixed receivers dedicated to their particular data channel. We present some numerical examples to show the correctness of our analyses for average transfer delay. The parameters of the network are shown in Table 1.

Table 1 Network parameters

Number of nodes (*N*)	16
Number of channels (*W*)	1, 2, 4, 8
Ring distance	30Km, 50 Km, 100Km
Propagation delay of the fiber	5 μs / Km
Channel speed	OC-192 (10 Gbps)
Size of the delay line	1500 bytes
Average IP packet size	512 bytes

Figure 12 presents the simulated and analytical results of average packet transfer delay in carrier fragmentation aware CSMA/ID. The curves demonstrate that a high node offer load can be achieved with low transfer delay when the number of channels is large. When there are 1, 2, 4, and 8 channels, the heaviest offered load (packets / μs) per node is 0.2, 0.5, 1.0 and 2.0. The agreement between the simulation results and the analytical results is excellent.

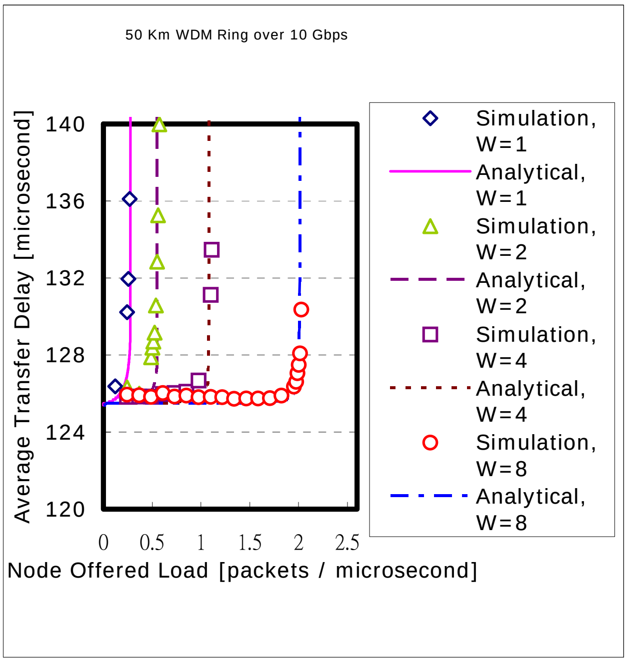

Figure 12. Average transfer delay versus offered load per node, when the number of channels equals 1,2,4 and 8.

The simulation results in throughput per node of CSMA/ID and carrier fragmentation aware CSMA/ID by increasing the number of channels are shown in Figure 13 and 14. In terms of performance, the scheme with carrier fragmentation has higher performance than the scheme without carrier fragmentation scheme. From the simulation results, it shows that the network performance of the carrier fragmentation aware scheme has better network efficiency in the scheme without carrier fragmentation.

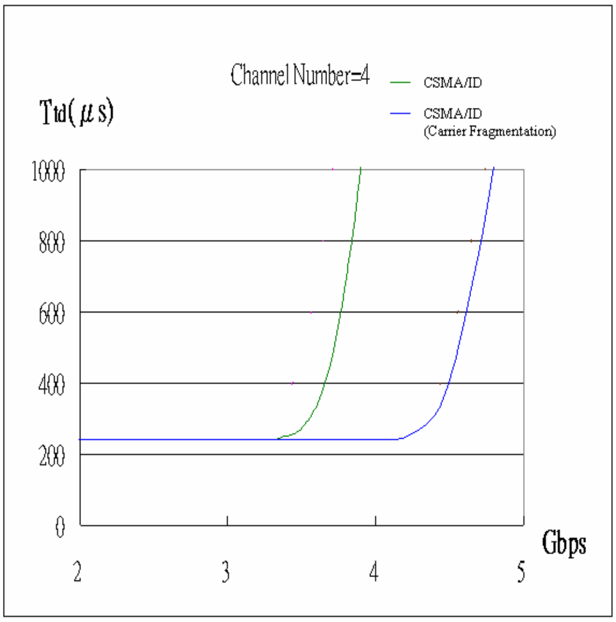

Figure 13. Throughput per Node with Channel Number=4

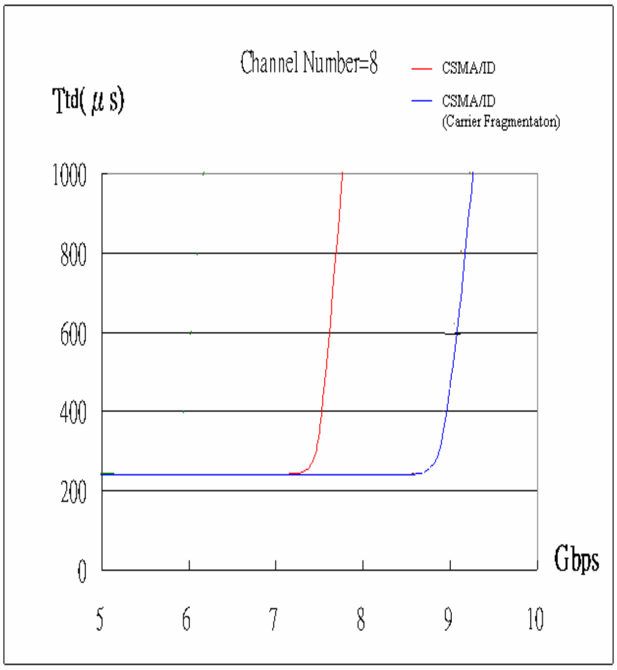

Figure 14. Throughput per Node with Channel Number=8

6 Conclusion

In this chapter, novel techniques have been devised to analyze the average transfer delay of a packet in the CSMA/ID and carrier fragmentation aware CSMA/ID networks respectively. For verification, we also simulate the networks using CASI Simscript II.5 and obtain the simulation results. 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. From simulated results, the throughput of the proposed carrier fragmentation aware CSMA/ID MAC protocol has better performance than the CSMA/ID MAC protocol.

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