A study of the length effect of fiber delay line based on CSMA/CP optical packet switching

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\textbf{Abstract}

This paper proposes a novel MAC (media access control) protocol named CSMA/CP for a metropolitan area network for the next generation Internet, which is an OPS (optical packet switch) network that all-optically and directly transfers IP packets over a WDM (wavelength division multiplexing) ring network. The proposed protocol uses the concepts of CSMA (carrier sense multiple access) and CP (carrier preemption) to all-optically transfer the IP packets of the nodes in the WDM ring networks. This paper studies the length effect of FDL (fiber delay line) in each node to support variable packet transmission, and develops an analytical model to analyze and simulate the packet delay and throughput.

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1. Introduction

Wavelength division multiplexing (WDM)\cite{1,6}, first developed during the late 1980s, provides tremendous bandwidth, up to OC-192 (10 Gb/s), and has a total bandwidth of an optical fiber exceeding 20 Tbps. WDM-based solutions are therefore expected to appear in the next generation of access networks in metropolitan areas. However, harnessing this unprecedented bandwidth in a metropolitan network environment will require a WDM transmission protocol to efficiently transport IP packets across the data centric WDM-based MANs.

Due to the rapidly increasing services and user population on the Internet, IP packet traffic dominates the utilization of data networks. However, such packets are now transferred, switched, and manipulated through complex protocol stacks, such as IP/ATM/SONET/WDM and IP/HDLC/SONET/WDM. Thus, the goal of merging and collapsing the middle layers of these stacks to reduce cost, complexity, and redundancy has become an important research issue\cite{7}. In order to minimize the layering complexity and overhead of SONET/SDH and ATM, packet-based network traffic should be accommodated directly on the WDM network, which would be an efficient and economical way to implement the next generation of the Internet. In this way, both the equipment cost and the management complexity related to electronic multi-layer solutions can be significantly reduced in all-optical IP-over-WDM networks\cite{2}. Additionally, since many WDM systems have already been deployed in metropolitan area networks (MANs), the bottleneck of communications has been pushed from backbone networks to local access networks. As a result, applying WDM to local area networks (LANs) has attracted a lot of research interest.
Optical packet switching (OPS) networks are an optical switching technique [17]. Although synchronization of packets and hardware cost are the major drawbacks of OPS networks, these can be addressed by transmitting high-speed optical base-band data with a sub-carrier header. The sub-carrier can be used to tag the high-speed base-band data payload with low-speed switching control information, so inexpensive and readily available low-speed electronics can be used at network nodes where high-speed data payload detection is unnecessary. In such a WDM network, one of the essential components is the all-optical wavelength filter, such as a semiconductor optical amplifier (SOA) filter [21]. The SOA filter is split into two output paths, one for control detection, where a low-pass-high-pass filter cascade passes only the sub-carrier; and the other for base-band detection, where a low-pass filter allows only the base-band data payload to pass. Due to the lack of optical random access memory, optical fiber delay line (FDL) is currently the only way to implement optical buffering. Feed-forward and feedback are two kinds of FDL structures used in optical buffering.

The ring topology is chosen as an all-optical metropolitan backbone [22]. In addition to avoiding transmission collisions among nodes attempting to use the same network wavelength, a MAC protocol is necessary to arbitrate access to the wavelengths and detect or avoid collision between nodes. The multi-token inter-arrival time (MTIT) access protocol was proposed in 1999 to support variable size IP packets over a WDM ring network whose architecture is implemented with fixed transmitters and fixed receivers [5]. To achieve all-optical communication, MTIT adopts a source removal policy for dropping packets from networks to prevent packet re-circulation. In 1999, Stanford University’s Optical Communication Research Laboratory (OCRL) proposed the hybrid optoelectronic ring network (HORNET) using carrier sense multiple access with a collision avoidance (CSMA/CA) protocol [8,13,15,23,24,26]. HORNET utilizes optical–electronic (O/E) and electronic–optical (E/O) conversion to retransmit bypassed packets back into the channel received, and employs a jamming signal mechanism to resolve optical packet collisions. Its data packets’ regeneration can minimize the number of erbium-doped fiber amplifiers (ED-FAs) and reduces accumulations of amplifier noise; however, the O/E/O conversion constrains its transmission rate in the WDM backbone network. Marsan [19,20] proposed the Static Round-Robin (SRR), which is an almost optimal MAC protocol based on the time division multiplex (TDM) technique. The SRR architecture has all-optical WDM multiple rings with tunable transmitters and fixed receivers. Due to the strict TDM design, the packet transmission to a node is constrained to using a particular fixed size slot. The destination removal scheme is adopted to free the channel bandwidth for other nodes. In order to facilitate spatial reuse on the bandwidth of all-optical ring networks, a carrier preemption access control protocol was first proposed by Hwang et al. To avoid access collisions and to use bandwidth more efficiently, they proposed a novel MAC protocol that is based on the carrier sense multiple access and carrier preemption (CSMA/CP) schemes. An analytical model has also been developed to approximate the average transfer delay for the CSMA/CP MAC protocol [11,12].

This paper proposes a novel MAC protocol, named CSMA/CP, for a metropolitan area network for the next generation Internet, which is an OPS network that all-optically and directly transfers IP packets over a WDM ring network. The proposed protocol uses the concepts of CSMA (carrier sense multiple access) and CP (carrier preemption) to all-optically transfer IP packets of the nodes in the WDM ring networks. This paper also studies the length effect of FDL (fiber delay line) in optical switching nodes to support variable packet transmission. The rest of this paper is organized as follows. The WDM ring network architecture, CSMA/CP MAC protocol, and the FDL interval effective in the optical switching node are presented in Section 2. Analytical models for evaluating the average packet delay performance of each ring node, when guard-time is considered, are developed in Section 3. Section 4 validates the accuracy of the proposed model by comparing the analytical results with those obtained using simulations. Finally, concluding remarks are made in Section 5.

2. Network architecture and MAC protocol

2.1. The network architecture

The network architecture can be described as a single, unidirectional fiber ring network, which connects \( N \) number of nodes. The optical fiber is composed of \( W \) data channels \((\lambda_1, \lambda_2, \lambda_3, \ldots, \lambda_W)\), as shown in Fig. 1. Furthermore, the network scope is assumed to cover a metropolitan area (i.e., a ring circumference of about 100 km), thus, the system is referred to as a WDM Metro ring. The access points (APs) connect the LAN to the MAN ring network, while PoP connects the MAN to the WAN. Each data channel makes use of one specific wavelength to convey optical signals. Therefore, based on the WDM technology, channels can work independently without mutual interference. Logically, the network can be treated as a multi-ring network.

In the architecture, each network node is equipped with one tunable transmitter (TT) and \( N \) fixed receivers, with one for each data channel (i.e., the TT–FR\(^w\) system). In general, a node equipped with one fixed receiver in the multichannel network can solve unfair access and packet loss issues. Since the transmission and reception of data packets are performed optically, the nodes can be considered as the optical add/drop multiplexers (OADM)s and used to connect a LAN, Gigabit Ethernet (GbE), passive optical networks (PONs), or wireless LAN to the ring network. Each node may send or receive packets on any one of the available data channels in the network. In the network, the number of network nodes can be more than or equal to the number of channels, i.e. \( N \geq W \); that is say, the number of nodes \((N)\) is not necessarily an integer multiple of the number of data channels \((W)\) for symmetry considerations.

The node architecture of the network is shown in Fig. 2. 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 semiconductor optical amplifier (SOA) switch array 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 the next new packet is started. After going through the fiber delay line (FDL), the optical signal is de-multiplexed by the DEMUX into $W$ data channels according to their separate wavelengths. The FDL will be delayed for a fixed interval for address recognition, and then dropped by adjusting the SOA switch array if necessary. The guard-time ($T_g$) interval between two neighboring packets should be long enough to cover the maximum photo detector time ($T_{PD}$), switching time ($T_s$) of the SOA, MAC con-

Fig. 1. Architecture of the WDM metro ring.

Fig. 2. Structure of access node.
Controller time ($T_{MAC}$) and wavelength converting time ($T_W$) [4] of the tunable transmitter to avoid packet collisions or loss when a packet is added to the fiber or dropped at its destination node. Since $T_{PD}$ and $T_{MAC}$ are smaller than the other cases, the guard-time can be reduced to:

$$T_g = \text{Max}(T_{PD}, T_S, T_{MAC}, T_W) \approx \text{Max}(T_S, T_W)$$  \hspace{1cm} (1)$$

The output of the DEMUX is connected to the SOA switch array with $W$ input ports and $W$ output ports. If a switch for one specific channel is opened, the node is ready to remove the packet in that channel from the ring to prevent the re-circulation of packets. Otherwise, an optical signal flows through the closed switches directly to the MUX. The MUX of nodes is used to multiplex the separate wavelengths into its output fiber link. The combination of a delay line, a DEMUX, an SOA switch array, and a MUX in nodes is used to realize the destination removal policy in our ring network.

The packets ready to be transmitted are placed in the transmission queues of a node transmitter before being sent. In order to avoid the head of line (HOL) blocking problem that occurs in the mechanism of a single transmission queue for ordinary packet transmissions, a 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. When a packet has been transmitted onto an available data channel, the optical carrier of the packet is coupled with the optical carriers from the MUX by the coupler. The integrated carriers are then sent to the downstream nodes.

### 2.2. CSMA/CP MAC protocol

To avoid packet collisions and to use bandwidth more efficiently, this paper proposes a novel medium access control (MAC) protocol, named CSMA/CP [11,12], that is based on the carrier sense multiple access and carrier preemption schemes. The carrier sensing scheme is used by the receiver to inspect the sub-carrier signaling of the transmitted packets in an optical fiber. Each wavelength is associated with a sub-carrier frequency; nodes detect the availability of wavelengths by monitoring the sub-carrier in the RF domain [14,18,28].

Each node monitors wavelengths under the carrier sensing scheme, as shown in Fig. 3, and tries to find an opening on channels for packet transmission. It is possible that a packet (called a carrier) from an upstream node arrives on the same channel when the node is still transmitting its packet, creating a collision. The reason for the collision is that the node does not have enough information to know whether the opening on the channel is long enough to accommodate the transmitted packet.

![Fig. 3. Carrier sense (channel i).](image-url)
packet. Under the carrier preemption scheme, the transmission of a packet that might cause a collision is immediately fragmented into two parts: one will be continuously transmitted and the other is added to a queue, as shown in Fig. 4. The transmitter can continue to transmit the former when the arrival carrier passes into the delay line. It should be noted that the CSMA/CP scheme is run in the electrical domain of the node, but the data packet is transmitted in the all-optical domain of the network. The carrier passes through the delay line after $T_{\text{ns}}$ (nanosecond), just as the transmitter finishes the former transmission. The queued fragment will be transmitted later on the same or another available channel. In this protocol, a small FDL will increase the number of packet fragmentations and thus increase the redundant overhead by the guard-time. On the other hand, a large FDL will increase the end-to-end delay and worsen performance, but the number of fragments will be reduced. If the FDL length is equal to 1,500 bytes plus the guard-time distance, the packet will not be fragmented. Therefore, designing the appropriate length of FDL in the optical switching node of CSMA/CP network is a very important issue. This protocol takes the effect of guard-time distance into consideration by using simulations over a broad range of parameters, as shown in Section 4. From the results, bandwidth efficiency and the access delay of the network system have been found to be influenced by different channels and guard-time distance. This paper also provides an appropriate FDL in the optical switching node of a CSMA/CP network to achieve higher throughput and lower delay.

To support the carrier preemption scheme, a frame format is designed, as shown in Fig. 5, to implement the addressing capabilities and fragmentation mechanisms. A start delimiter (SD) labels the data frame that is conveyed in the data channel either as packets or data frame label 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 reserve field (RF) is reserved for extended protocol functions, such as defining different service classes for the data payload. The frame length (FL) indicates the length of the 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, and RF fields, and the frame trailer is composed of FL and ED fields. To demonstrate the action of packet fragmentation, a packet that might cause a collision is fragmented into two fragments, as depicted in Fig. 6. 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.

3. Approximate analytical models

The transfer delay of a packet measured from the packet is stored in the source node queue until that packet has been completely received by the destination node. This delay consists of the queue-waiting delay, the transmission delay, and the 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 that the source node was last selected by the queue before a successful transmission. 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.

Fig. 7 illustrates the timing diagram of a specific node on one channel, considering the ith packet \( P_i \) arrival into a node transmission queue. This packet must wait in the queue for the residual time \( \alpha_i \) 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 Fig. 7. When packet \( P_1 \) arrives, it is fragmented into \( P_{11} \) and \( P_{12} \).

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 terms: 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.

Fig. 7. Calculation of the average waiting time in M/G/1 system with vacations. The average waiting time \( E[TQ_i] \) of the \( i \)th packet is \( E[TQ_i] = E[\alpha_i] + E[M_i|E[x]| + E[V_i]].\)
From the behavior of the expected queue-waiting delay for the ith packet, the model can be categorized as an M/G/1 queue with vacations model [3]. Clearly, the queue-waiting delay captures the effect of contention and depends on traffic density. In order to present expressions for the packet transfer delay at a node on multi-rings using the M/G/1 vacation model, we first present some assumptions and the general notations used in the following subsections.

3.1. 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 \( \tau \) s, and the distances between the nodes are equal.
3. Packets which arrive are independent, in an identically distributed (i.i.d.) Poisson process with rate \( \lambda_i \) (packets/s) 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 \( \oplus \) indicates addition modulo \( N \); thus \( \lambda_i = \sum_{j=1}^{N} \lambda_{i,i\oplus j} \). In the case of uniform and symmetric traffic on the ring, the mean packet generation for all nodes is equal and each source sends equal traffic to all destinations.

\[
\dot{\lambda}_i = \frac{\lambda}{N}, \quad \dot{\lambda}_{i,i\oplus j} = \frac{\lambda}{N(N-1)}
\]  

(2) and \( \dot{\lambda}_i = 0 \), for \( 0 \leq i \leq N-1 \), \( 1 \leq j \leq N-1 \)

5. The packets have random lengths determined at each node as independent, identical, and geometrically distributed random variables (denoted by r.v. \( M(\text{bits}) \)) with mean \( E[M] \) and probability mass function [9] \( P_r(M = k) = \beta \cdot (1 - \beta)^k \), \( k = 0,1,2,\ldots \) where \( \beta = \frac{1}{1+s} \).

6. The WDM ring channel bit rate is \( R \) (bps) and the packet transmission time without considering vacations is \( X = M/R \) s.

7. The data packet of length \( M \) is fragmented into a sequence of \( n_c \) consecutive mTUs (minimum transfer unit) ignoring the header and trailer length. Assume that \( P_r(n_c = k) \), \( k = 0,1,2,\ldots \) denotes the probability that \( n_c = k \).

\[
P_r(n_c = 1) = \sum_{M=0}^{\text{mTU}} \beta(1 - \beta)^M = 1 - (1 - \beta)^\text{mTU+1}
\]

and \( k = 2,3,\ldots \), \( P_r(n_c = k) = P_r([k-1] \cdot \text{mTU} < M \leq k \cdot \text{mTU}] = [1 - (1 - \beta)^{k-1} \cdot \text{mTU}] [1 - (1 - \beta)^{k-1} \cdot \text{mTU}] \]

Thus,

\[
E(n_c) = \frac{[1 - (1 - \beta)^\text{mTU} + (1 - \beta)^{\text{mTU}+1}]}{[1 - (1 - \beta)^\text{mTU}]}
\]

(3) and \( E(n_c) \) is the expected length expressed in mTUs.

8. The fiber delay line is defined as \( L \), where

\[
L = \text{mTU} + T_8 \text{ and } L \geq T_8
\]

(4)

3.2. 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
\( x_i \) residual time of packet \( i \)
\( V_i \) duration of all the whole vacation intervals for which packet \( i \) must wait before being transmitted
\( V \) steady-state duration of all the whole vacation intervals
\( S \) average transmission delay

3.3. Analysis of CSMA/CP for a 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:
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 $\lim_{n \to \infty} E[m_i | E[x]]$ is equal to $\lim_{n \to \infty} E[M_i | E[X]]$, and by Little’s formula the value of $\lim_{n \to \infty} E[M_i | E[X]]$ is $\lambda_i TQ E[X]$. Letting $V = \lim_{n \to \infty} E[V_i]$, we can thus write the steady-state version of Eq. (5):

$$TQ = E[x] + \lambda_i TQ E[X] + V$$ (7)

Next we calculate approximation $V$ using 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 $\rho_{bi}$. Thus we consider the delay line as a slot unit, so the dependence occurs 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 Fig. 8, which 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 $\hat{x}$ can be considered to be uniformly distributed between 0 and $L/R$.

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 $\lim_{n \to \infty} E[m_i | E[x]]$ is equal to $\lim_{n \to \infty} E[M_i | E[X]]$, and by Little’s formula the value of $\lim_{n \to \infty} E[M_i | E[X]]$ is $\lambda_i TQ E[X]$. Letting $V = \lim_{n \to \infty} E[V_i]$, we can thus write the steady-state version of Eq. (5):

$$TQ = E[x] + \lambda_i TQ E[X] + V$$ (7)

Next we calculate approximation $V$ using 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 $\rho_{bi}$. This upstream traffic blocks the head of the queue packet at node $i$. Substituting the above assumptions into $\rho_{bi}$ gives the following expression:

$$\rho_{bi} = \sum_{k=2}^{N-1} \frac{\lambda_i}{N} E[X_j] = \frac{(N-1)(N-2)}{2} \times \frac{\lambda_i}{N(N-1)} \times \frac{E[M]}{E}[X] = \frac{(N-2) \times \hat{x} \times E[M]}{2 \times N \times R}$$ (8)

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

$$E[d] = \sum_{i=0}^{\infty} \frac{L}{R} \rho_{bi}(1 - \rho_{bi}) = \frac{L \cdot \rho_{bi}}{R(1 - \rho_{bi})}$$ (9)

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

$$TQ = E[x] + \lambda_i TQ E[X] + n_c TQ E[n_c] E[d] = \frac{L}{2 \times R} + \frac{\hat{x} \times TQ E[X]}{L \cdot \rho_{bi} R}$$ (10)

which can be reduced to:

$$TQ = \frac{L}{2 \cdot R \cdot (1 - \hat{x} \cdot E[X] - \hat{x} \cdot E[n_c] E[d] \cdot L \cdot \rho_{bi})}$$ (11)

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

Fig. 8. Calculation of the average queue-waiting time in a specific node using the aggregation of busy time and vacation time. The average waiting time $E[TQ_i]$ of the $i$th packet is $E[TQ_i] = E[x] + E[M_i | E[X]] + E[V_i]$. 

\[ E[TQ_i] = E[x] + E[m_i] E[x] + E[V_i] \] (5)
\[ D = \text{TQ} + S + \tau' \]  
(12)  

where \( \tau' \) 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:

\[ S = E[X] + E[n_c]E[d] = E[X] + \frac{E[n_c] \cdot L \cdot \rho_b}{R \cdot (1 - \rho_b)} \]  
(13)

Thus, the average transfer delay is given by

\[ D = \text{TQ} + S + \tau/2 \]  
(14)

3.4. Analysis of CSMA/CP for multi-ring case

In order to analyze 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 \([4,16]\). 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, \( \rho_b \), can be expressed as:

\[ \rho_b = \frac{\rho_b}{W} \]  
(15)

The probability that the packet at the head of a queue cannot get an empty slot is \((\rho_b)^W\). Therefore, the probability that the packet \( i \) has to wait for \( L \) before it can be sent out is \((\rho_b)^W(1 - (\rho_b)^W)\).

Similar to Section 3.3, let \( E[d_b] \) be the average time required to find the arrival of an empty \( L \). Then, we have:

\[ E[d_b] = \sum_{i=0}^{\infty} \frac{L}{i} (\rho_b)^W(1 - (\rho_b)^W) = \frac{L \cdot (\rho_b)^W}{R \cdot (1 - (\rho_b)^W)} \]  
(16)

Since for each packet in the queue the arriving packet has to wait \( L/R + d_b \) time, the average queue-waiting delay faced by the arriving packet is:

\[ \text{TQ} = E[X] + \lambda_i \cdot \text{TQE}[X] + \lambda_i \cdot \text{TQE}[n_c]E[d_b] \]  
(17)

Therefore, we have:

\[ \text{TQ} = \frac{E[X]}{1 - \lambda_i E[X] - \lambda_i E[n_c]E[d_b]} \]  
(18)

The average transmission delay is:

\[ S = E[X] + E[n_c]E[d_b] = E[X] + \frac{E[n_c] \cdot L \cdot (\rho_b)^W}{R \cdot (1 - (\rho_b)^W)} \]  
(19)

Thus, the average transfer delay is given by

\[ D = \text{TQ} + S + \tau/2 \]  
(20)

4. Performance evaluation and numerical results

This section describes the results of the discrete event simulations in which IP packets were generated with packet size distributions matching those of a measurement trace from one of MCI’s backbone OC-3 links \([27]\), as shown in Fig. 9. In the simulation, packets were generated by the packet generator using both the Poisson process and the interrupted Poisson process (IPP). In addition, all simulations were run for a time long enough to reach a reliable conclusion; in general, each node transmitted more than two million packets in the simulation. The CASI SIMSCRIPT II.5 simulation tool was used to simulate the network model. Here, the behavior of every node was assumed to be the same, and all channels were unidirectional and synchronized in the network. The packet arrival rate distribution of every node was the same, and the destination of all packets was assigned randomly. For a WDM ring with the destination removal policy, each node had one tunable transmitter and \( W \) fixed receivers dedicated to the receivers’ particular data channel. We present some numerical examples for the CSMA/CP MAC protocol without considering FDL in Section 4.1.

We explain the appropriateness of the FDL interval and provide an appropriate FDL interval using simulation in Section 4.2. We also present some numerical examples to show the correctness of our analyses of the average transfer delay in Section 4.3.

4.1. Numerical results for CSMA/CP MAC protocol without considering FDL

The parameters of the network are shown in Table 1. Fig. 10 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 performance metric using average transfer delay in comparison with the CSMA/CA MAC protocol is shown in Fig. 11.

4.2. Simulation for finding appropriate FDL

Simulations were performed using the SIMSCRIPT II codes. Each experiment value was calculated using the variance reduction technique and there were 30 replicated simulations using different seeds. The parameters of the simulation are listed in Table 2. The network throughput is calculated using the total traffic that left all nodes in the ring network.

The simulation results presented in Figs. 12 and 13 show the throughput per node of different $T_g$ values under a fixed load created by increasing FDL lengths. According to the simulation results, the appropriate length of FDL in four channels and

![Fig. 9. Simulated OC3 traffic distribution.](image-url)

**Table 1**

<table>
<thead>
<tr>
<th>Network parameters</th>
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<tbody>
<tr>
<td>Number of nodes ($N$)</td>
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<tr>
<td>Number of channels ($W$)</td>
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<tr>
<td>Ring distance</td>
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<tr>
<td>Propagation delay of the fiber</td>
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<tr>
<td>Channel speed</td>
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<tr>
<td>Size of the delay line</td>
</tr>
<tr>
<td>Average IP packet size</td>
</tr>
</tbody>
</table>

![Fig. 10. Average transfer delay versus offered load per node, when the number of channels equals 1, 2, 4, and 8.](image-url)
eight channels approaches 140 bytes. Figs. 14 and 15 illustrate the simulation results for the transmission delay of the different $T_g$ values created by increasing the FDL lengths. They show that the simulation has a lower transmission delay when FDL length is about 140 bytes. Thus, the appropriate length of FDL is equal to 140 bytes, and it is used as a simulation parameter in Section 4.3.

In general, the switching time of SOA is about $200 \text{ ps} \sim 2 \text{ ns}$ [10] and according to the HORNET architecture, the Altitun laser (GCSR laser) turns from one wavelength to the adjacent wavelength in approximately $10 \text{ ns}$ (about 12.5 bytes in 10 Gb/s) [25]. Therefore, the guard-time distance is:

$$T_g = \text{Max}(2 \text{ ns}, 10 \text{ ns}) = 10 \text{ ns} (12.5 \text{ bytes}).$$

<table>
<thead>
<tr>
<th>Architecture: TT–FRW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of nodes ($N$)</td>
</tr>
<tr>
<td>Number of channels ($W$)</td>
</tr>
<tr>
<td>Light velocity</td>
</tr>
<tr>
<td>Ring network length</td>
</tr>
<tr>
<td>Channel speed</td>
</tr>
<tr>
<td>Guard-time distance ($T_g$)</td>
</tr>
<tr>
<td>FDL length ($L$)</td>
</tr>
<tr>
<td>Packet range</td>
</tr>
<tr>
<td>Average packet length</td>
</tr>
</tbody>
</table>

Fig. 11. Comparing CSMA/CP and CSMA/CA: average transfer delay versus offered load per node, when the numbers of channels equals 1, 2, 4, and 8.

Table 2
The simulation parameters

Fig. 12. Comparing throughput with $T_g$ length in four channels under load = 6.89 Gb/s.
4.3. Simulation for verifying the performance analysis considering FDL

The parameters of the network are shown in Table 3. Fig. 16 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.

Fig. 13. Comparing throughput with $T_g$ length in eight channels under load = 3.63 Gb/s.

Fig. 14. Comparing transmission delay with $T_g$ length in four channels under load = 6.89 Gb/s.

Fig. 15. Comparing transmission delay with $T_g$ length in eight channels under load = 3.63 Gb/s.

Fig. 16. Combining simulated and analytical results of average packet transfer delay in this network.
delay when the number of channels is large. The agreement between the simulation results and the analytical results is excellent.

5. Conclusions

This investigation describes a novel MAC scheme that is applicable to all-optical WDM ring networks. By facilitating spatial reuse of network bandwidth, the CSMA/CP MAC protocol displays excellent characteristics of high throughput and low delay for all-optical communications. For verification, a simulation was performed, and the results closely resemble the analytical values, demonstrating the good performance of the network. It is also observed that the throughput characteristic of the network is almost proportional to the number of channels in the network. From the simulation results, the throughput of the proposed CSMA/CP MAC protocol has better performance than that of the CSMA/CA MAC protocol. The approximate equations for the average packet transfer delay for WDM ring networks with the CSMA/CP MAC protocol were also derived. From the simulation, the bandwidth efficiency and access delay of the network system were influenced by different channels and guard-time distances. We provide an appropriate FDL interval in the optical switching node of CSMA/CP networks that achieves a higher throughput and a lower delay. The transfer delay improves with the number of wavelengths used in the ring, which is consistent with current WDM technology trends.

References


