A COMBINATIONAL MEDIA ACCESS PROTOCOL FOR MULTICAST TRAFFIC IN SINGLE-HOP WDM LANS[†]

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ABSTRACT

Multicast transmissions over single-hop WDM LANs have become much more important with several evolving applications. This paper presents a combinational media access protocol which can provide an efficient mechanism for scheduling multicast traffic. The protocol is originated from the unicast-based protocol, which is a pre-allocation-based protocol with tunability at the receiving end. The MSR (Multicast Slot Reservation) reserves slots for the multicast packets and modifies the allocation map derived from the unicast-based protocol. Each node accesses the control channel with the CMS (Combinational Multicast Schedule) algorithm. A multicast packet is verified by the multicast distance in order to determine whether it should be treated as a multicast packet or not. The protocol is simple to implement, and the simulation results suggest that a protocol with the proper multicast distance would result in better performance tradeoffs between unicast traffic and multicast traffic.

I. INTRODUCTION

With the huge bandwidth of optical fibers, the network deployment has migrated from the electronic backbones into the optical backbones. In order to overcome the speed mismatch between the electronic end-user side and the optical backbone side, the wavelength division multiplexing (WDM) technique has been proposed and extensively studied to divide the enormous information-carrying capacity of a single mode fiber into several concurrent channels [1-3]. Accompanied with the advent of computer applications and communication services such as distributed data processing, broadcasting systems, and teleconferencing, WDM LANs require specific transmission mechanisms to schedule and manage the multicast traffic [4,5]. The multicasting mechanisms in multi-hop WDM LANs [7] have been discussed thoroughly with the construction of minimal Steiner tree [8,9]. Those in single-hop WDM LANs, however, have received comparatively less attention because such networks broadcast information on the identified channel to the nodes that tune their receivers to that channel; this seems to support multicast transmission easily [6].

In addition to involving the operations of the protocols for unicast transmission to coordinate transmissions and to eliminate collisions in single-hop WDM LANs [10,11], the media access protocols for multicast transmission induce different issues in spite of the characteristic described above. For instance, the reservation-based multicast protocol results in insufficient network throughput because the receivers of the multicast group may not become available at the same time [12]. This may be resolved by partitioning the multicast group into a number of smaller subgroups and re-transmitting multicast packets several times to the subgroups [13]. The other is the pre-allocation-based multicast protocol over the network [14]. The transmission schedule is composed of the unicast slot, the multicast slot, and the broadcast slot. Nodes tune their receivers to the wavelength of the multicast source node to monitor multicast transmission at the synchronization slot. The protocol, however, might result in large packet delay with the complex operations among three different time slots.

In this paper we propose a combinational media access protocol for multicast traffic in single-hop WDM LANs. The protocol combines the unicast-based protocol and the Multicast Slot Reservation (MSR) to schedule the overall traffic, while the allocation map is for the data wavelength/tuning receiver wavelength. Each node contains one pair of FT-FR to collect the status of multicast traffic over the entire network, and one pair of FT-TR to access data channels. The control channel is via round-robin TDMA according to the Combinational Multicast Schedule (CMS) algorithm. After receiving all control information, MSR checks receiver availability of the multicast group and modifies the allocation map. The protocol would result in better performance tradeoffs in packet delay and network throughput compared with the protocols described above.

The outline of the paper is as follows. In Section II we introduce the architecture of single-hop WDM LANs for the protocol and describe the characteristics of multicast traffic. The definition of multicast distance M_d is also developed in this section. The combinational media access protocol for multicast traffic is presented in Section III. The Combinational Multicast Schedule (CMS) is shown in Section IV. Simulation results for different M_d are depicted in Section V and conclusions are given in Section VI.

II. ARCHITECTURE AND MULTICAST TRAFFIC

A. Architecture of Single-Hop WDM Networks

The architectures for the single-hop WDM LANs use the passive star coupler to connect N nodes. The passive star coupler is an $N \times N$ broadcast-and-select device interconnected through the optical fibers. The number of wavelengths supported by most WDM systems is significantly less than the number of nodes in anything but a trivial network. Thus the medium is assumed to support $\Omega \leq N$ data wavelengths, $\omega_0, \omega_1, ..., \omega_{\Omega-1}$ and the control wavelength ω_Ω; the system is also called a wavelength-limited system. Each node contains at least one pair of transmitter and receiver to establish a connection between two nodes. In order to implement the pre-allocation-based protocol, either the TT-FR architecture (one tunable transmitter and one fixed receiver) or the FT-TR architecture (one fixed transmitter and on tunable

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[†] This research was supported by the National Science Council, Taiwan, R. O. C., under the Grant NSC 87-2213-E259-007.

receiver) would be selected. In this paper we select the FT-TR architecture to access the data wavelengths ω_0, ω_1, ..., $\omega_{\Omega-1}$ for the pre-allocation-based protocol of unicast traffic because the FT-TR architecture can support multicast transmission much easier than the TT-FR architecture can. The tunable receiver at node i, i = 0, 1, ..., N - 1, can tune to the data wavelength γ_i to listen to packets based on the data wavelength/tuning receiver wavelength allocation map. The fixed transmitter at node i is assigned one data wavelength τ_i as the home channel. In addition, the FT-FR architecture is also equipped to broadcast the transmission and multicast status of the overall network on the control channel ω_Ω in the reservation-based fashion.

The network is packet-switched with fixed-size packets and operates in a slot mode without any packet loss, while the time slot is equal to the packet transmission time plus the latency of the tunable receiver with the *normalized tuning latency* $\delta << 1$. The network is assumed that each node is equally distant from the passive star coupler, which induces the same propagation delay between all node pairs. When two or more fixed transmitters access the same wavelength at the same time slot, also called a *collision*, packet loss is avoided with the arbitration procedure of the protocol. The *destination conflict*, two or more source nodes transmit data to the same node on different channels at the same time slot, will never occur because the wavelength/tuning receiver wavelength allocation map ensures that only one node is allowed to receive on the allocated channel. Besides, all nodes are synchronized to slot boundaries to transmit packets. The buffer at each node is assumed to be infinite and uses link-list addressing to allocate N-1 queues, one dedicated queue per node, and to allocate one queue for multicast transmission [15]. This eliminates the head-of-line blocking effect observed in [11], and results in good network throughput and packet delay.

B. Multicast Traffic

Multicast traffic can be modeled with the multicast session length S and the multicast group $\boldsymbol{G}$. The size of the multicast group is noted as $|\boldsymbol{G}|$. As defined in [14], multicast traffic can be classified into three types according to S and $|\boldsymbol{G}|$. As shown in Fig. 1, TYPE 1 is with small S and large $|\boldsymbol{G}|$, TYPE 2 is with small S and small $|\boldsymbol{G}|$, and TYPE 3 is with large S. However, S and $|\boldsymbol{G}|$ are not quantitatively defined to distinguish these three types from each other. Apart from the discussion of multicast traffic in [14], we define *multicast distance* M_d to classify multicast traffic into two categories. According to M_d the protocol can determine the processing methodologies for the multicast packet. Let M be the distance of S and $|\boldsymbol{G}|$; that is,

$$M = \sqrt{S^2 + |\boldsymbol{G}|^2}\ .$$

Each multicast packet has its own value of M. If $M > M_\text{d}$, outside the shaded curve as shown in Fig. 1, the packet is treated as the multicast packet and the protocol schedules the packet immediately to perform multicast transmission. If $M \leq M_\text{d}$, inside the shaded curve as shown in Fig. 1, the packet is treated as the unicast packet. The protocol replicates the packet to transmit from the multicast source node to members of the multicast group individually.

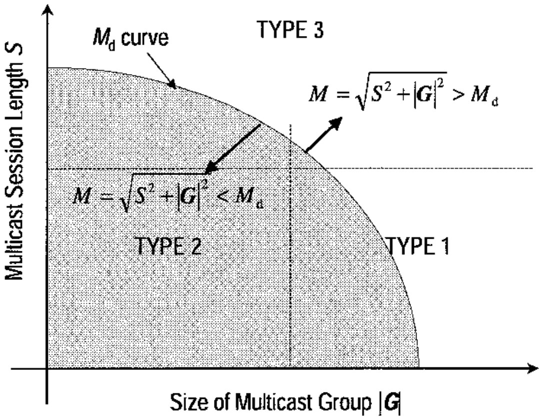


Fig. 1. Two classifications for multicast traffic.

Multicast session length S and the size of multicast group $|\boldsymbol{G}|$ can be identified in terms of network size N, but M_d can not be determined by simple observations. S is intuitively no less than 1, and assumed to be no larger than N. In fact a multicast packet with S larger than N may exist with much smaller probability, and the packet is assumed to be divided into several multicast packets with S no larger than N before entering the network. Because the members of a multicast group contain the multicast source node and at least two destination nodes, $|\boldsymbol{G}|$ is no less than 3 and no larger than N. Moreover, M_d is a network-wide constant to represent the bandwidth requirement of the multicast packet. M_d can be determined with great detail, which is not discussed in this paper.

III. THE COMBINATIONAL PROTOCOL FOR MULTICAST TRAFFIC

The combinational media access protocol combines the unicast-based protocol and the Multicast Slot Reservation (MSR) for multicast traffic to schedule the overall traffic with the FT-TR architecture. Home channel assignment and the wavelength/receiving node allocation map are constructed in the unicast-based protocol, and the CMS manipulates multicast traffic with M_d. In order to provide the transmission and multicast status to execute the arbitration procedure and the CMS, the format of the control packet and the access scheme of the control channel with the FT-FR architecture are also necessary to be derived.

A. The Unicast-Based Protocol

The combinational multicast protocol is originated from the unicast-based protocol. The protocol is pre-allocation-based with FT-TR architecture discussed in Section II to avoid the architectural requirement of both a tunable transmitter and a tunable receiver. The protocol allocates one channel to node i as the home channel τ_i for the fixed transmitter, while the destination node tunes the receiver to τ_i to receive packets if the packet is transmitted from node i. The home channel τ_i at node i could be assigned by interleaved allocation or neighbor allocation to provide almost equal amount of bandwidth utilization:

$\tau_i = \omega_{i \bmod \Omega}$ for interleaved allocation.

$\tau_i = \omega_{\lfloor i/\lceil N/\Omega \rceil \rfloor}$ for neighbor allocation.

If the bandwidth requirement of the traffic is asymmetric, the policy could be modified to provide suitable allocation to achieve better utilization. Because the network is the wavelength-limited system with $\Omega \le N$, some nodes may be assigned to the same home channel and collisions have to be avoided.

In order to connect the transmission from the fixed transmitter of the source node to the tunable receiver of the destination node, data wavelength/tuning receiver wavelength allocation map is derived to decide the tuning wavelengths for Ω nodes at each time slot. The wavelength γ_i for the tunable receiver of node i at the time slot t is determined according to the following simple equation:

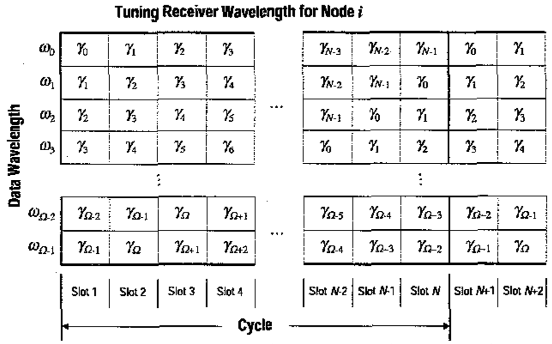
$$c_i = (i - t + 1) \bmod N \quad i = 0, 1, \ldots, N-1 .$$

$$\gamma_i = \begin{cases} \omega_{c_i}, & 0 \le c_i \le \Omega - 1 \\ \phi, & c_i \ge \Omega \end{cases} .$$

$\gamma_i = \phi$ means that the receiver is idle. As shown in Fig. 2, each node is assigned Ω slots per cycle and idle for the remaining N-Ω slots. The cycle length is N slots to achieve self-routing. However, the source node has to request the access privilege of the home channel to complete the transmission with the FT-TR architecture. The access requests of the home channels are collected through the control channel ω_Ω and arbitrated in the arbitration procedure.

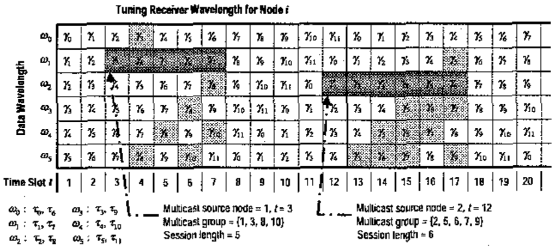
B. Multicast Slot Reservation

The Multicast Slot Reservation (MSR) examines the multicast packet, makes a reservation of the channel for the packet, and modifies the allocation map of the unicast-based protocol on each node. When the node receives a multicast packet with the multicast session length S and the multicast group $\boldsymbol{G}$ (with the size $|\boldsymbol{G}|$), the MSR examines first if the packet is qualified to make the reservation according to M (the product of S and $|\boldsymbol{G}|$) and M_d. If $M \le M_d$, the packet is viewed as the unicast packet. The MSR replicates the packet and transmits the replicated packets from the multicast source node to members of the multicast group individually. If $M > M_d$, the packet is viewed as the multicast packet. Then the MSR makes the reservation of the home channel of the multicast source node. The MSR informs the arbitration procedure to reserve the channel preemptively. The number of time slots reserved for the packet is equal to the multicast session length S.



	Slot 1	Slot 2	Slot 3	Slot 4		Slot *N*-2	Slot *N*-1	Slot *N*	Slot *N*+1	Slot *N*+2
ω_0	γ_0	γ_1	γ_2	γ_3		γ_{N-3}	γ_{N-2}	γ_{N-1}	γ_0	γ_1
ω_1	γ_1	γ_2	γ_3	γ_4		γ_{N-2}	γ_{N-1}	γ_0	γ_1	γ_2
ω_2	γ_2	γ_3	γ_4	γ_5	...	γ_{N-1}	γ_0	γ_1	γ_2	γ_3
ω_3	γ_3	γ_4	γ_5	γ_6		γ_0	γ_1	γ_2	γ_3	γ_4
			⋮				⋮			
$\omega_{\Omega-2}$	$\gamma_{\Omega-2}$	$\gamma_{\Omega-1}$	γ_Ω	$\gamma_{\Omega+1}$		$\gamma_{\Omega-5}$	$\gamma_{\Omega-4}$	$\gamma_{\Omega-3}$	$\gamma_{\Omega-2}$	$\gamma_{\Omega-1}$
$\omega_{\Omega-1}$	$\gamma_{\Omega-1}$	γ_Ω	$\gamma_{\Omega+1}$	$\gamma_{\Omega+2}$	...	$\gamma_{\Omega-4}$	$\gamma_{\Omega-3}$	$\gamma_{\Omega-2}$	$\gamma_{\Omega-1}$	γ_Ω

Fig. 2. Data wavelength/tuning receiver wavelength allocation map for the unicast-based protocol.



Time Slot *t*	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
ω_0	γ_0	γ_1	γ_2	γ_3	γ_4	γ_5	γ_6	γ_7	γ_8	γ_9	γ_{10}	γ_{11}	γ_0	γ_1	γ_2	γ_3	γ_4	γ_5	γ_6	γ_7
ω_1	γ_1	γ_2	γ_3	γ_4	γ_5	γ_6	γ_7	γ_8	γ_9	γ_{10}	γ_{11}	γ_0	γ_1	γ_2	γ_3	γ_4	γ_5	γ_6	γ_7	γ_8
ω_2	γ_2	γ_3	γ_4	γ_5	γ_6	γ_7	γ_8	γ_9	γ_{10}	γ_{11}	γ_0	γ_1	γ_2	γ_3	γ_4	γ_5	γ_6	γ_7	γ_8	γ_9
ω_3	γ_3	γ_4	γ_5	γ_6	γ_7	γ_8	γ_9	γ_{10}	γ_{11}	γ_0	γ_1	γ_2	γ_3	γ_4	γ_5	γ_6	γ_7	γ_8	γ_9	γ_{10}
ω_4	γ_4	γ_5	γ_6	γ_7	γ_8	γ_9	γ_{10}	γ_{11}	γ_0	γ_1	γ_2	γ_3	γ_4	γ_5	γ_6	γ_7	γ_8	γ_9	γ_{10}	γ_{11}
ω_5	γ_5	γ_6	γ_7	γ_8	γ_9	γ_{10}	γ_{11}	γ_0	γ_1	γ_2	γ_3	γ_4	γ_5	γ_6	γ_7	γ_8	γ_9	γ_{10}	γ_{11}	γ_0

ω_0 : τ_0, τ_6 ω_3 : τ_3, τ_9
ω_1 : τ_1, τ_7 ω_4 : τ_4, τ_{10}
ω_2 : τ_2, τ_8 ω_5 : τ_5, τ_{11}

Multicast source node = 1, $t = 3$
Multicast group = {1, 3, 8, 10}
Session length = 5

Multicast source node = 2, $t = 12$
Multicast group = {2, 5, 6, 7, 9}
Session length = 6

Fig. 3. The MSR manipulates two qualified multicast packets at different time slots.

After reserving the home channel, the MSR examines receiver availability of the multicast group. If all of them are available, the MSR deletes the slots pre-allocated for the receivers in the multicast group during the multicast session. The slots pre-allocated for the receivers not included in the multicast group still follows the original unicast-based protocol. As shown in Fig. 3 for instance, the MSR manipulates two qualified multicast packets at different time slots. For the packet at the time slot 3, the MSR reserves ω_1 from the time slot 3 to the time slot 7 as shown in the gradient area. Then the MSR deletes 7 slots as shown in the shaded areas during the multicast session from the time slot 3 to the time slot 7. This means that no other transmissions to the receivers of node 3, 8, and 10 could be accomplished during the multicast session. The MSR also reserves ω_2 and deletes 11 slots from the time slot 12 to the time slot 17 for the packet at the time slot 12. The number of slots deleted by the MSR during the multicast session might be related to S, $|\boldsymbol{G}|$, and the time slot t.

C. The Arbitration Procedure and the Control Channel Access

The arbitration procedure determines which node owns the access privilege of the home channel at the specific time slot. The request of the home channel is issued through the control channel ω_Ω, and the arbitration is determined by priorities generated from the traffic type and the queue length. The request for multicast transmission has the higher priority to reserve the home channel and can be issued at any time slot. The request for unicast transmission has the lower priority to reserve the channel and be issued according to the unicast protocol. If the priorities of the requests are the same, the procedure arbitrates the access privilege according to M (the distance of S and $|\boldsymbol{G}|$) for multicast transmission and the queue length of the destination node for unicast transmission. For multicast transmission, the procedure selects the node with larger M. If the active nodes have the multicast packets with the same M, the procedure would randomly select the node. For unicast transmission, the procedure selects the node with the longest queue length for the destination node. The queue lengths of the destination node in the nodes with the same home channel are also transmitted through the control channel ω_Ω. If the queue lengths of the active nodes are zero, the procedure

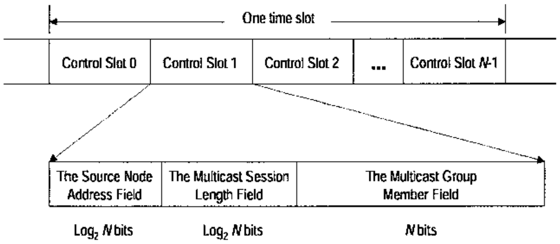


Fig. 4. Control channel access via round-robin TDMA.

would randomly select the node to own the access privilege of the home channel. Therefore, the arbitration procedure can determine the access privilege of the wavelength according to the traffic type and the queue length.

The control channel ω_Ω, which is used for network management, scheduling of wavelengths and time slots, and clock distribution in the conventional WDM LANs, also collects broadcast transmission and multicast status among nodes for the unicast-based protocol and the MSR. As shown in Fig. 4, each node transmits a control packet on the control channel ω_Ω via the round-robin TDMA to schedule the transmission of the data packet at the head of the queue. The control packet consists of the source node address field, the multicast session length field, and the multicast group member field. The source node address field encodes the node's identity in $\log_2 N$ bits. The multicast session length field represents S with binary coding in $\log_2 N$ bits, while S is assumed to be no larger than N. If the control packet is for unicast transmission, the multicast session length field represents the queue length for the destination nodes. The multicast group member field is of N bits such that the jth bit of the field is set if node j is one of the destination nodes. The multicast group member field also indicates if the packet is a unicast packet or the multicast packet. If only one bit of the field is set, the packet is the unicast packet. Otherwise the packet is a multicast packet. Thus the control packet length is equal to $N + 2\log_2 N$ bits, which is the length of the control slot. After all control packets are received simultaneously by each node, data transmissions can be scheduled deterministically.

IV. THE COMBINATIONAL MULTICAST SCHEDULE (CMS)

After receiving the control packet from the control channel ω_Ω, all nodes execute the Combinational Multicast Schedule (CMS) at each time slot to accomplish the unicast-based protocol, the MSR, and the arbitration procedure in the distributed fashion. Each node retains the variables and arrays described in Table 1. The CMS uses interleaved allocation to specify the home channel. In order to meet the requirement of the format for the control packet, the array C_Packet[i,1] denotes the multicast group member field and C_Packet[i,2] denotes the multicast session length field. T_Node[ω] and R_Node[ω,t] denotes the access privilege of the channel ω at the time slot t. The CMS is described as follows.

Table 1. Arrays retained in Combinational Multicast Schedule.

Arrays	Range	Description
C_Packet[i,j]	$0 \le i \le N-1$ $1 \le j \le 2$	C_Packet[i,1] = multicast traffic or unicast traffic C_Packet[i,2] = multicast session length or the queue length
T_Node[ω]	$0 \le \omega \le \Omega - 1$	T_Node[ω] = node arbitrated to access ω
R_Node[ω,t]	$0 \le \omega \le \Omega - 1$ $0 \le t < N$	R_Node[ω,t] = node with the receiver tuned to ω at t relative to TIME, followed the unicast-based protocol

```
1. Procedure CMS
2. for i=0 to Ω-1
3.   M_d=0
4.   Q_t=∞
5.   for j=0 to ceiling(N/Ω)
6.     group=C_Packet[j*Ω+i,1]
7.     length=C_Packet[j*Ω+i,2]
8.     if group=multicast traffic then
9.       if group*length>M_d then
10.        Check receiver availability
11.        if receivers not available
12.          Resolve receiver availability
13.      else
14.        T_Node[i]=j*Ω+i
15.        M_d=group
16.        Q_t=0
17.    else
18.      if length<Q_t then
19.        T_Node[i]=j*Ω+i
20.        Q_t=length
21. for i=0 to Ω-1
22.   group=C_Packet[Trans_Node[i],1]
23.   length=C_Packet[Trans_Node[i],2]
24.   if group=unicast traffic then
25.     Schedule with Rec_Node[i,0]
26.   else
27.     for j=0 to length-1
28.       R_Node[i,j]=T_Node[i]
29.       for k=0 to Ω-1
30.         if R_Node[k,j]=multicast member
31.           R_Node[k,j]=-1
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The CMS is executed on each node at the time slot TIME. TIME is a variable increased automatically by the global clock. The slot reservation status denoted as R_Node[w,t] indicates the slot relative to TIME. The details of the procedure CMS are described as follow. Line 2-30 execute the arbitration procedure for the nodes that want to own the access privilege of the home channel. Line 11 checks the multicast status first to keep multicast transmission preemptive. Line 13-15 resolve the receiver availability problem by two approaches discussed in Section III.B. Line 31-46 schedule the transmission status with the unicast-based protocol and the MSR. Line 38-45 execute the MSR to reserve the slots for multicast traffic. After executing the CMS, the transmission schedule of unicast traffic and multicast traffic is completed and all the packets could be transmitted; in addition, network throughput will be enhanced and packet delay will not suffer a lot.

V. SIMULATION RESULTS

The goal of the simulation experiment is to investigate the impact of the combinational protocol for multicast traffic behaves on the packet delay and the network throughput. The parameters are described as follows: N = 50 network nodes, Ω = 25 wavelengths. The buffer size of the dedicated queue per node is 100 to represent the infinite buffer size. $|G|$ has the normal distribution with a mean of 5 nodes in the multicast group, and the lexis ratio $\tau_g = 1$. The nodes in the multicast group G are randomly chosen from the uniform distribution $[0,N\text{-}1]$. S also has the normal distribution with a mean length of 5 and the lexis ratio $\tau_s = 1$. The simulation experiment generates two kinds of traffic and measures the performance. Packet generation follows the Poisson arrival process with the parameter q = 0.1. In addition, the packet type follows the bernoulli process with multicast ratio p, while the multicast packet with probability p and the unicast packet with probability 1-p.

The experiment simulates five values of M_d to compare the performance tradeoffs of the protocols. M_d = 0 means that the protocol manipulates the multicast packet with the MSR as long as the packet is generated. M_d = 100 means that the protocol manipulates the multicast packet with the conventional approach; that is, the multicast packets are all replicated to several copies of the unicast packets and transmitted with the pre-allocation-based protocol. M_d = 5, M_d = 7, and M_d = 10 mean that the protocol compares the distance of the multicast packet with M_d, as defined in Section II.B. Therefore, the influence of M_d could be examined clearly.

The simulation experiment measures both the packet delay and the network throughput. Packet delay is defined as the number of time slots elapsed from the slot entering the network to the slot leaving the network. Network throughput is defined as the expected number of transmitted packets per time slot over the entire network. The second approach in MSR as shown in Section III.B, which partitions the multicast group into the ready subgroup and the delayed subgroup if the receivers of the members are not ready yet, may mis-treat a multicast packet as two unicast packets. This will confound the performance evaluation of M_d. Therefore, only the first approach is simulated.

Fig. 5 and Fig. 6 depict the network throughput versus the multicast ratio p for unicast traffic and multicast traffic, respectively. For unicast traffic as shown in Fig. 5, the curve for M_d = 100 slightly increases as p increases because the MSR replicates all of the multicast packets as the unicast packets; this increases the number of unicast packets. The curves for M_d = 10, M_d = 7, M_d = 5, and M_d = 0 decrease as p increase because the MSR limits unicast transmission and enhances multicast transmission. In addition, the larger the M_d, the larger the network throughput for unicast traffic because the number of unicast packets increases. For multicast traffic as shown in Fig. 6, the curve for M_d = 100 remains 0 as p increases because no multicast packets are qualified to start the MSR. The curves for M_d = 0, M_d = 5, M_d = 7, and M_d = 10 slightly increase as p increases; in addition, the larger the value of M_d, the smaller the network throughput for multicast traffic because M_d limits the number of multicast packets. That is to say, if the value of M_d is properly chosen, the protocol may result in little degradation in network throughput for unicast traffic, and good network throughput for multicast traffic.

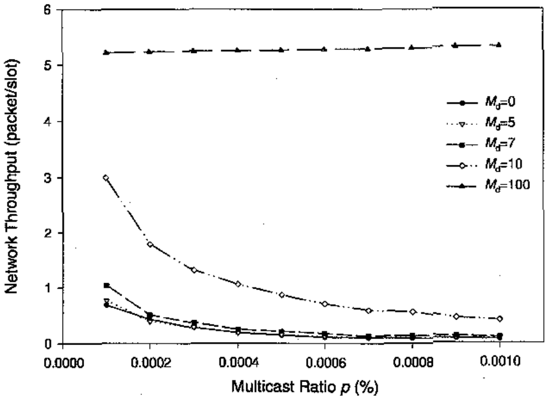

Fig. 5. Network throughput versus multicast ratio for unicast traffic.

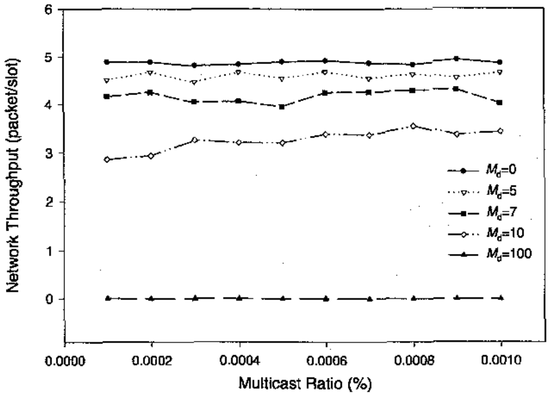

Fig. 6. Network throughput versus multicast ratio for multicast traffic.

Fig. 7 and Fig. 8 depict the packet delay versus the multicast ratio p for unicast traffic and multicast traffic, respectively. For unicast traffic as shown in Fig. 7, the curve for M_d=100 slightly increases as p increases. This curve is lowest because no slots are deleted in the wavelength allocation map. The curves for M_d = 0, M_d = 5, M_d = 7, and M_d = 10 decrease as p increases. From the system's point of view, when the unicast packet enters the network, the number of packets in the system queue virtually remains the same as p increases with the same q. Because the multicast packet is preemptively manipulated, the packet delay is generated from the unicast packets in the system queue. Hence the curves decrease as p increases. In addition, the larger the M_d, the larger the packet delay because the MSR generates more unicast packets for large M_d.

For multicast traffic as shown in Fig. 8, the curves for all values of M_d almost remain zero because the protocol schedules the multicast packets preemptively. The curve

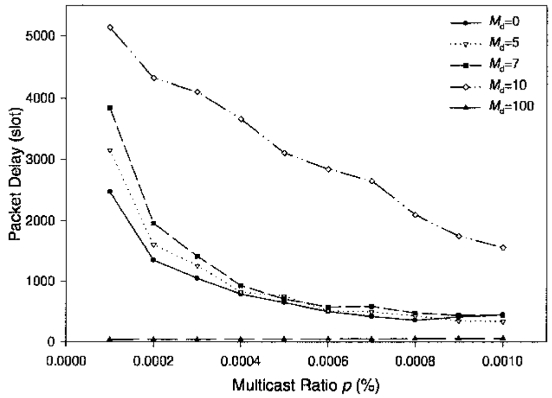

Fig. 7. Packet delay versus multicast ratio for unicast traffic.

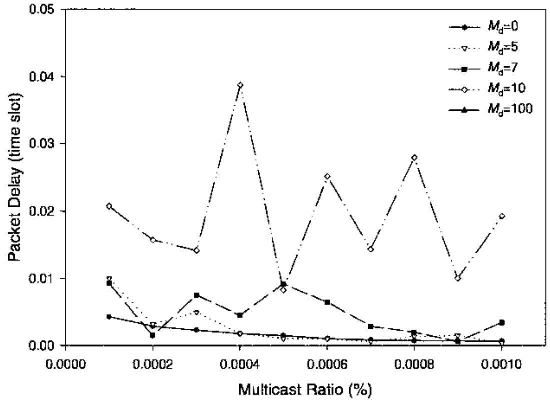

Fig. 8. Packet delay versus multicast ratio for multicast traffic.

for M_d = 100 remains zero because no multicast packets are transmitted. However, the packet delay approximately increases as M_d increases because the receiver avalibility problem may be serious for large M_d. Therefore, the protocol would result in better performance tradeoffs in packet delay and network throughput if M_d is properly chosen.

VI. CONCLUSIONS

We have proposed a combinational media access protocol for multicast traffic in single-hop WDM LANs. The protocol uses the allocation map derived from the unicast-based protocol, which is a pre-allocation-based protocol with tunability at the receiving end. The Multicast Slot Reservation (MSR) is adopted in the protocol to reserve the slots of the home channel for the multicast packets and to modify the allocation map. In order to support the MSR operations, the network architecture combines the pre-allocation-based architecture and the additional control channel. Each node executes the Combinational Multicast Schedule (CMS) algorithm to access the control channel and to perform the protocol distributedly. Simulation results show that the protocol would result in better performance tradeoffs between unicast traffic and multicast traffic in packet delay and network throughput over the conventional ones.

We also define the multicast distance M_d to determine the processing methodologies with multicast traffic. Compared with the distance of the multicast session length S and the size of the multicast group $|G|$, the protocol may perform the MSR to schedule the multicast packet, or treat the packet as the unicast packet to replicate several copies. However, M_d needs to be analyzed in detail to optimize the performance of the protocol.

REFERENCES

[1] C. A. Brackett, "Dense Wavelength Division Multiplexing Networks: Principles and Applications," *IEEE J. Select. Areas Commun.*, vol. 8, pp. 948-964, Oct. 1987.

[2] M. H. Ammar and G. N. Rouskas, "On the Performance of Protocols for Collecting Responses Over a Multiple-Access Channel," *IEEE J. Commun.*, vol. 43, pp. 412-420, Feb. 1995.

[3] P. E. Green Jr., "Optical Networking Update," *IEEE J. Select. Areas Commun.*, vol. 14, no. 5, pp. 764-779, June 1996.

[4] J. S. Turner, "The Challenge of Multipoint Communication," *in Proceedins of 5th ITC Seminar*, pp. 263-279, May 1987.

[5] M. Ammar, G. Polyzos, and S. Tripathi (Eds.), Special Issue on Network Support for Multipoint Communication, *IEEE J. Select. Areas Commun.*, vol.15, no. 3, Apr. 1997.

[6] B. Mukherjee, "WDM-Based Local Lightwave Networks Part I: Single-Hop Systems," *IEEE Network Mag.*, pp. 12-27, May 1992.

[7] B. Mukherjee, "WDM-Based Local Lightwave Networks Part II: Multihop Systems," *IEEE Network Mag.*, pp. 20-32, Jul. 1992.

[8] P. Winter, "Steiner Probelm in Networks: A Survey," *Networks*, vol. 17, no. 2, pp. 129-167, Summer 1987.

[9] S. Ramanathan, "An Algorithm for Multicast Tree Generation in Networks with Asymmetric Links," *IEEE/ACM Transactions on Networking*, vol. 4, no. 4, pp. 558-568, Aug. 1996.

[10] K. M. Sivalingam, K. Bogineni, and P. W. Dowd, "Pre-Allocation Media Access Control Protocols for Multiple Access WDM Photonic Networks," *ACM SIGCOMM'92*, pp. 235-246, Aug. 1992.

[11] K. Bogineni, K. M. Sivalingham, and P. W. Dowd, "Low-Complexity Multiple Access Protocols for Wavelength-Division Multiplexed Photonic Networks," *IEEE J. Select. Areas Commun.*, vol. 11, pp. 590-604, May 1993.

[12] M. S. Borella and B. Mukherjee, "A Reservation-Based Multicasting Protocol for WDM Local Lightwave Networks," *ICC'95*, pp. 1277-1281, 1995.

[13] J. P. Jue and B. Mukherjee, "The Advantages of Partitioning Multicast Transmissions in a Single-Hop Optical WDM Network," *ICC'97*, pp. 427-431, 1997.

[14] G. N. Rouskas and M. H. Ammar, "Multidestination Communication Over Tunable-Receiver Single-Hop WDM Networks," *IEEE J. Select. Areas Commun.*, vol. 15, no. 3, pp. 501-511, Apr. 1997.

[15] T. Kozaki, *et al.*, "32 × 32 Shared Buffer Type ATM Switch VLSIs for B-ISDNs," *IEEE J. Select. Area Commun.*, vol. 9, pp. 1239-1247, Oct. 1991.