MODELLING OF MULTIMEDIA MAC PROTOCOLS ON WDM OPTICAL NETWORKS

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ABSTRACT

Conventional *Medium Access Control* (MAC) protocols perform quite well for the traffic types they have been designed for, but poorly for other traffic streams with different characteristics. But, the emerging multimedia applications require that the MAC protocol should perform *equally* well for all types of traffic characteristics. In this paper, we propose an integrated MAC protocol (herein termed as *Multimedia Medium Access Control* protocol (*Multimedia*-MAC)) which integrates different MAC protocols into a hybrid protocol to efficiently accommodate various types of multimedia traffic streams with different characteristics and QoS demands. We have applied our *Multimedia*-MAC design approach to *wavelength division multiplexing* (WDM) based optical network. We have developed a mathematical framework for the analysis and performance evaluation of our *Multimedia*-MAC protocol which involves a queueing model with *vacation*.

1. INTRODUCTION

Future generation Local and Metropolitan Area Networks (LANs/MANs) will be required to provide a wide variety of services. To accomplish this, the *Medium Access Control* (MAC) protocol has to be designed in such a way that the integrated services (multimedia) LANs and MANs can support the whole spectrum of the traffic, since in most cases the topology is based on the shared medium technology. Since, all the higher layer services are built on the fundamental packet transfer service which is provided by the MAC sub-layer, the design of MAC protocol remains crucial. A plethora of MAC protocols have been proposed for future generation LAN/MANs [2]. Unfortunately, most of these MAC protocols are not suitable for multimedia applications because they have been designed with one *generic* traffic type in mind. As a result, they perform quite well for the traffic types they have been designed for, but poorly for other traffic streams with different characteristics. This is true for wireline networks (including *wavelength division multiplexing* (WDM) based optical networks) as well as wireless networks.

The objective of this paper is to propose a methodology and framework for integrating different MAC protocols into an hybrid protocol to efficiently accommodate various types of multimedia traffic streams with different characteristics and QoS demands. The proposed integrated MAC protocol is termed *Multimedia Medium Access Control* (*Multimedia*-MAC) protocol. We use queueing with vacation for the analysis and performance evaluation of *Multimedia*-MAC protocol. This paper is organized as follows. Section 2 introduces our *Multimedia*-MAC protocol. We present the application of Multimedia-MAC protocol for WDM networks and the related performance studies in Section 3. Finally, Section 4 concludes the paper.

2. THE *MULTIMEDIA*-MAC PROTOCOL

The *Multimedia*-MAC protocol consists of three *sub-protocols* - namely, pre-allocation (wherein nodes access the shared medium in a predetermined way), reservation (wherein the nodes reserve one or more time slots within a frame before the actual packet transmission starts) and contention protocols (wherein the nodes access the shared medium with no coordination between them) - each of which serves a certain type of traffic (see Figure 1).Note that the video/audio data (basically constant-bit-rate) streams are best served by allocation based protocols (denoted by TDM). Similarly, the bursty (VBR) traffic is served best by reservation based MAC protocols (denoted by RSV) and finally the urgent messages are best handled by contention based (denoted by CNT) protocols. Obviously, the integration of these three protocols would serve the multimedia traffic streams.

A time division multiplexing scheme controls the three different access strategies into a single protocol. Whenever a protocol uses the medium, the medium access is con-

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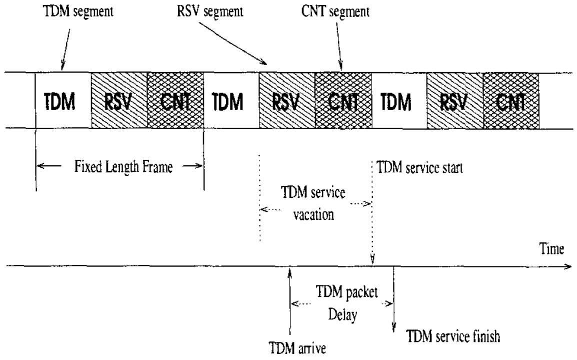

Figure 1: *Multimedia*-MAC protocol construction.

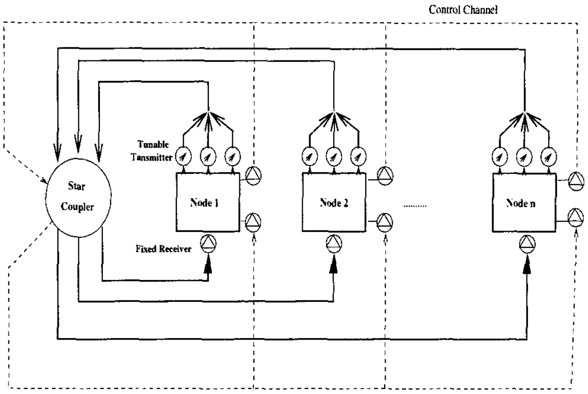

Figure 2: A M-WDMA network architecture.

trolled according to the discipline of that protocol. A cycle in a *Multimedia*-MAC consists of a *fixed time frame* (of length L_{frame} slots) which consists of three segments namely TDM segment (of length L_{TDM} slots), RSV segment (of length L_{RSV} slots) and CNT segment (of length L_{CNT} slots) in that order (see Figure 1).

3. THE APPLICATION OF *MULTIMEDIA*-MAC ON WDM NETWORKS

The *Multimedia*-MAC design presented in the previous section can be applied to a wide variety of shared medium networks [4, 5]. Here, we apply the *Multimedia*-MAC to WDM networks (called M-WDMA protocol) and its analytical modeling. We consider the single-hop topology where a WDM optical network is configured as a broadcast-and-select network in which all the inputs from the various nodes are combined in a passive star coupler, and the mixed optical information is broadcast to all destinations. The nodes in a WDM network can transmit and receive messages on any of the available channels by using and tuning one or more tunable transmitter(s) and/or tunable receiver(s).

3.1. The M-WDMA Architecture

Consider a M-WDMA network with N nodes which are connected by a star-coupler and having C channels as shown in Figure 2. Each node has a fixed channel (*home channel*) with wave-length λ_i ($i = 1, 2, .., C$). The home channels are intended for the destination nodes to receive packets. In case, the number of available channels $C < N$, several nodes ($\lceil \frac{N}{C} \rceil$) may share one single home channel. The destination nodes can then accept or discard the packets by checking the addresses associated with these packets.

In our M-WDMA protocol, each node has three tunable transmitters. The three tunable transmitters are used to serve three different classes of traffic streams according to the corresponding *sub-protocols*. In a M-WDMA network, the transmitters have to tune to the home channel of the destination node before the transmission takes place. If more than one transmitter send data to the same receiver, it would produce *receiver collision*. When two or more receivers share the same wave-length (the case when $N > C$), only one of them can be active during the communication, otherwise, it may cause *channel collision*. Finally, if at a pre-scheduled transmission time, the transmitter is occupied by another transmission at the same node, this may result in a *transmitter collision*. Consequently, with the occurrence of any of the above collisions, the transmission would be a failure. The major function of the MAC protocol is to properly avoid these collisions.

The three transmitters of a M-WDMA network can operate in a *pipeline* fashion. That is, when one transmitter is transmitting a packet, the other transmitters tune to the next channel. As a result, the three types of transmissions (TDM, CNT, and RSV) from a node cannot take place simultaneously. A transmission example of our M-WDMA MAC protocol is illustrated in Figure 4. In this figure, the X-axis denotes time-slot and the Y-axis denotes spatial location of the back-logged nodes. The white segments denote the TDM segments, the light-shaded segments are the RSV segments and the dark segments are the CNT segments. The numbers in the TDM segments identify the home channel number that the underlying TDM segment ties to, according to the TDM protocol. The data transmission format in M-MAC WDM network is illustrated in Figure (3). Note that in the TDM and RSV sub-protocols, only a single node can access a channel *at a time* since they are all protocols based on preallocation and reservation in advance. But, in the CNT sub-protocol, multiple nodes can access the same channel *at the same time*.

The tuning time (Γ) satisfies the following relationships: $L_{TDM} + L_{RSV} > \Gamma$, $L_{TDM} + L_{CNT} > \Gamma$ and $L_{CNT} +$

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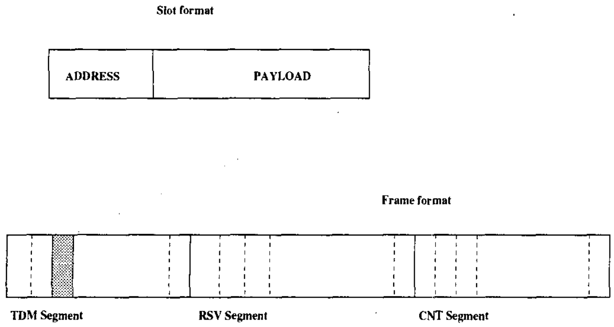
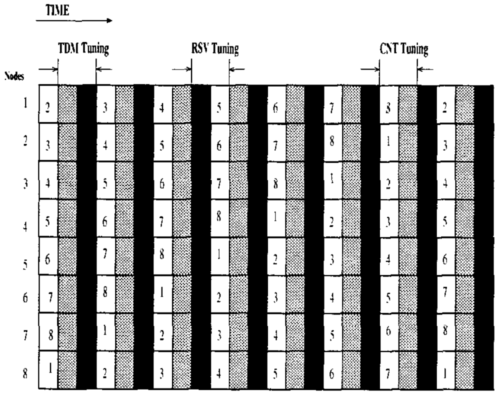


Figure 3: A M-WDMA frame and slot formats.



Nodes								
1	2	3	4	5	6	7	8	2
2	3	4	5	6	7	8	1	3
3	4	5	6	7	8	1	2	4
4	5	6	7	8	1	2	3	5
5	6	7	8	1	2	3	4	6
6	7	8	1	2	3	4	5	7
7	8	1	2	3	4	5	6	8
8	1	2	3	4	5	6	7	1

Figure 4: A M-WDMA transmission schedule example.

$L_{RSV} > \Gamma$. It follows that $L_{frame} > 3\Gamma/2$. In particular, the length of the frame directly affects the bandwidth allocated to TDM segments. Hence, the total TDM bandwidth is given by: $B_{TDM} = \frac{L_{TDM}R}{L_{frame}(N-1)}$ where R is the channel bandwidth.

Control Channel Configuration The control channel operates in a TDMA manner independent of the data transmission (and is coincident). One cycle consists of N *mini-slots*, each of which is designated to a node. Based on the broadcast information over the control channel (of cycle length T_{cntrl}) all the control procedures can be done by the nodes locally and network-wide synchronously. The control messages include: 1) reservation requests which are used by the reservation sub-protocol; and 2) collision acknowledgments in the CNT sub-protocol. For the reservation of RSV protocol we use a bit map to represent the reservation request, each node taking a bit ("1" to denote that the node wants to transmit and "0" to denote that there are no transmission requests). Similarly, we use the bit map (of length L_{cnt} slots corresponding to the number of slots in the data channel) to indicate the success (denoted by 1) or failure (denoted by 0) during the contention in a CNT sub-protocol. Note that the length of a mini-slot is $N + L_{cnt}$. Hence, the cycle time $T_{ctrl} = \frac{N(N+L_{cnt})}{R}$ where R is the channel bit rate. To realize the frame-by-frame reservation and collision detection, the control cycle has to complete within a frame time, that is, $\frac{N(N+L_{cnt})}{l_{slot}} < L_{frame}$ where l_{slot} is the slot length in bits.

3.2. Modeling of the M-WDMA network

This section investigates the performance of the M-WDMA MAC protocol analytically and through simulations. In a M-WDMA MAC protocol, three sub-protocols operate independently and one can think of these protocols operating in three different networks. These three virtual networks have bandwidth equal to the bandwidth allocated to that sub-protocol in a M-WDMA network. This is reasonable under the assumption that the three classes of traffic are independent of each other (called as *protocol independent assumption*). With this assumption, the three sub-protocols can be studied independently. One can think of a (transmitting) node (logically) consists of $N-1$ queues each corresponding to $N-1$ receivers (apart from itself). The transmitter polls one queue at a time to serve (transmit) a packet. Also, since a particular sub-protocol is active in its own segment, these logical queues can be modeled using a queue with vacation.

We assume that all the nodes in the M-WDMA network are statistically identical, i.e. arrival and service process of packets have identical distributions (and thus the system is *symmetric*). Let λ be the network normalized traffic load, then λ_{TDM}, λ_{RSV}, and λ_{CNT} are the mean traffic loads for the individual segments of the respective sub-protocols. Then, $\lambda_i = \frac{L_i}{L_{frame}}\lambda$ where i can be TDM, RSV or CNT.

We consider a system of N nodes and C channels. Logically, each node has $3C$ queues corresponding to C channels and the three types of traffic. We assume each queue has infinite capacity and uses FCFS discipline. Let $B(x)$ be the distribution function for the service time, with $1/\mu$ being its mean and $B^*(s)$ being its Laplace-Stieltjes Transform (LST). We denote the random variable of vacation length (in terms of slot time) as V, its LST as $V^*(s)$ and its mean as $E[V]$. By applying the analytical results of suitable queueing models with vacation for the queue encountered by the packets belonging to different traffic streams, we obtain the performance measure namely, the mean delay of packets. In particular, we model the queue encountered by the packets belonging to the traffic stream served by TDM protocol by D/D/1 queue with vacation. Similarly, we use $M^{(x)}/G/1$ queue with vacation to model the queue

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corresponding to RSV sub-protocol and $M/G/1$ queue with vacation to model the queue corresponding to CNT sub-protocol. Due to space constraints, we give only the results here. (See [6] for details).

The TDM Sub-protocol Model: The operation of the TDM sub-protocol within our M-WDMA network is basically an *interleaved TDMA* MAC protocol [3]. The only difference between our TDM sub-protocol and ITDMA are that in a M-WDMA network we take tuning time into consideration. Using the M-WDMA protocol, at the boarder between a TDM segment and a RSV segment, the TDM transmitter starts to tune to the next channel.

According to a TDM sub-protocol, node i gets a chance to transmit L_{tdm} packets to node j in every $N-1$ frames. Hence the vacation length in the (logical) queue (at node i) of packets destined to node j is given by $v_j = (N-1)L_{frame}T_{slot}$. By traffic independent assumption and statistical similarity of nodes, this queue (corresponding to jth adjacent node) is generic with vacation period given by, $V = (N-2)L_{frame}T_{slot} + (L_{frame} - L_{TDM})T_{slot}$. The vacation period ($L_v$) is given by $L_v = (N-2)L_{frame} + (L_{TDM} - L_{frame})$. Noting that $\mu = R$ (where R is the channel bandwidth), the delay (waiting time plus the service time) distribution is given by,

$$W^*_{TDM}(s) = \frac{(1-e^{-\lambda L_v s})e^{-s/\mu}}{s - L_v\lambda} \qquad (1)$$

Further the numerical evaluation method presented in [6] allows one to compute the mean delay which is the performance measure studied here. Figure 5 presents the results corresponding to the mean delay of packets (served by TDM sub-protocol) computed by the analytical model and the discrete event simulation. As one can see from the Figure, the results obtained by simulations agree very well with the analytical results confirming the accuracy of our analytical model.

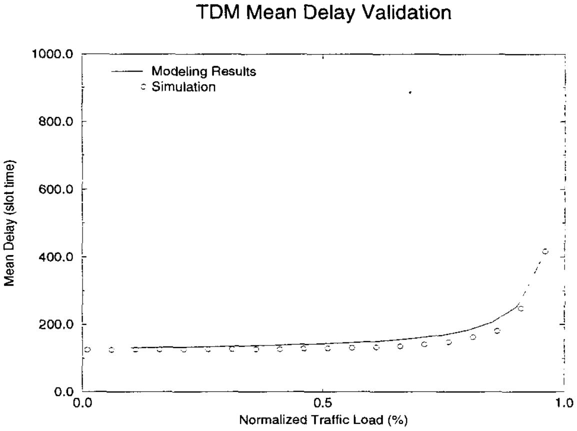

Figure 5: TDM model validation in terms of mean delay.

The RSV Sub-protocol Model In a M-WDMA MAC protocol, the RSV packet transmission is controlled using a *multiple token* method [1]. Once a node i gets a token corresponding to the destination (or channel) j, when logical queue corresponding to jth destination node will be served until the queue is empty or the number of packets transmitted exceeds L_{RSV}. This is implemented by *token rotation algorithm*. Thus, the vacation time is the time that the token is rotated through all other backlogged nodes. Note that here, we assume bulk arrivals with a arrival mean λ_{RSV} and the bulk size is *geometrically* distributed with mean g, i.e., $G(z) = \frac{1}{g(g+1-z)}$. The service time for a packet is deterministic (we ignore the packet length variations) and hence the LST of the service time distribution ($B^*(s)$) is given by $B^*(s) = e^{-s/\mu}$. Note that the service time for a given message (composed of packets) depends on the bulk size (number of packets). Hence the number of frames a node takes to transmit a message depends on the size of the bulk (G). The LST of the delay of a packet ($W^*_{RSV}(s)$) in the RSV protocol model can be obtained using the following equation:

$$W^*(s) = \frac{(1-\rho)}{s-\lambda+\lambda G[B^*(s)]}\,\frac{(1-G[B^*(s)])}{g[1-B^*(s)]} \qquad (2)$$

(Note that the parameter T_r can be obtained from $1/\mu$ and the distribution of G). Figure 6 shows both the results from our simulations of CNT protocol and analytical results of our model corresponding to the performance measure of mean delay. The result shows that the proposed model is reasonably accurate.

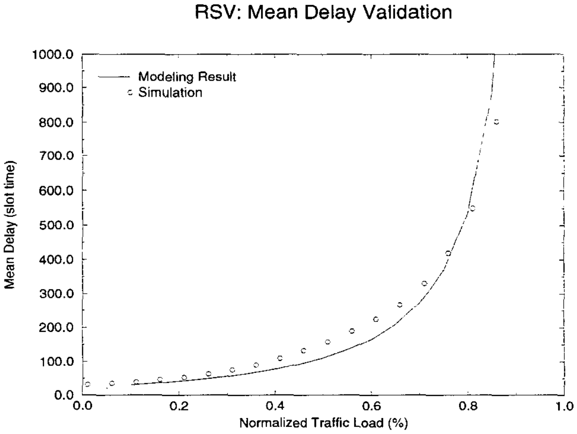

Figure 6: RSV model validation in terms of mean delay.

CNT Sub-protocol Model: The CNT sub-protocol of our

M-WDMA MAC protocol is similar to the *interleaved slotted ALOHA* [3]. The active nodes compete for the slots in the current CNT segment. In case there is a collision, retransmission is scheduled after a random number of slots. The collided packets have to be retransmitted *within* the current CNT segment, otherwise it will collide with the other types of transmissions. Hence, when a node encounters the last slot of a CNT segment its CNT segment counter stops counting. When the first slot of a CNT segment arrives, the counter starts to tick again. In this way, the retransmission can be carried out across frames. For the collision notification, the control channel is used (at each node, there are two receivers corresponding to the home channel and the control channel).

For analysis, we use the bufferless model (owing to the low arrival rate, this is justified) and the M/G/1 queue with vacation (similar to the conventional analysis of slotted ALOHA) and the LST of the delay is given by,

$$W^*_{CNT}(s) = \frac{s(1-\rho)}{s-\lambda+\lambda B^*_{CNT}(s)} B^*_{CNT}(s) \frac{1}{s-\lambda L_v} \qquad (3)$$

where $\rho = \frac{\lambda}{B^{*'}_{CNT}(0)}$ and $B^*_{CNT}(s) = \frac{p}{(1-p)e^{-s}-1}$ where again, $p = \left[\frac{(m-n)q_a}{1-q_a} + \frac{nq_r}{1-q_r}\right](1-q_a)^{m-n}(1-q_r)^n$, where, q_a is the probability that un-backlogged nodes transmit packets in a given slot and q_r is the probability of transmission of a packet in a given slot. Also note that the notation $B^{*'}_{CNT}(s)$ is used to denote $\frac{d(B^*_{CNT}(s)}{ds}$.

By choosing the exact parameters for both modeling and simulation, we validate the CNT model in Figure 7 corresponding to the mean delay. As we can see, again the results are reasonably close to each other.

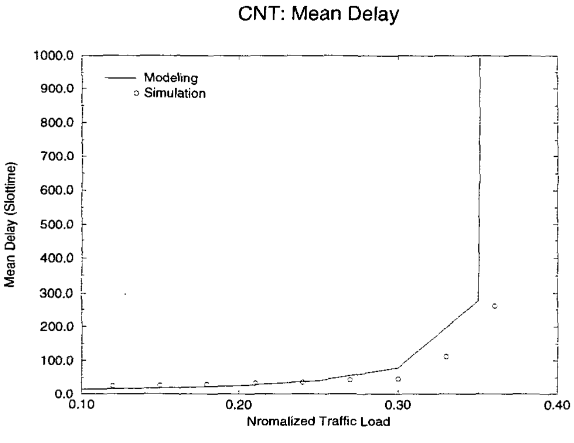

Figure 7: CNT model validation in terms of mean delay.

4. CONCLUSION

This paper introduces a new methodology that combines different types of MAC protocols into a single shared medium network to better serve a wide variety of multimedia applications. Some of the goals of this approach are: 1) To keep the advantages of the individual MAC protocols with respect to specific types of traffic streams; 2) To efficiently support a large range of traffic streams with different characteristics and QoS requirements in a single shared medium network; and 3) to be applied to wide variety of shared medium networks. We have successfully applied our MAC protocol to a wavelength division multiplexing network. We have used the queueing system with vacation to model the queue encountered by packets served by various sub-protocols. We believe our framework can be applied to many other types of shared medium networks, especially in the next generation of networks where the integrated or multimedia services are provided in a single physical network.

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