Analysis of Multimedia Access Protocols for Shared Medium Networks

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Abstract—

The objective of this paper is to propose a methodology and framework for integrating different MAC protocols into a single shared medium network to efficiently accommodate various types of multimedia traffic streams with different characteristics and QoS demands. In particular, we propose an integrated MAC protocol which is termed *Multimedia Medium Access Control* (*Multimedia*-MAC) protocol that can efficiently and simultaneously serve three types of multimedia traffic streams: A constant-bit-rate (CBR) traffic and two classes of variable-bit-rate (VBR) traffic.

We have developed a queuing system with *vacation* model and multiple priority queuing system to establish a mathematical framework for the analysis and performance evaluation of our *Multimedia*-MAC protocol besides using extensive computer simulations. The main purpose of our performance analysis and evaluation is to assess our *Multimedia*-MAC protocol in its provision of QoS guarantees under a variety of realistic traffic and networking parameters.

More importantly, our theoretical analysis results in an efficient approach to estimate the QoS of a shared medium network for given dead-line missing rate (DMR) vs network traffic load, that leads to more accurate admission control and higher network utilization in multimedia communication. The simulation results show that our approach can have accurate estimation in a wide range of taffic load and deadline requirement.

I. INTRODUCTION

A plethora of MAC protocols have been proposed for future generation LANs / MANs. 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 observation is true for MAC protocols for wireline networks as well as wireless networks.

These different traffic streams are better served by different MAC protocols. Video/audio data streams and other constant bit rate (CBR) traffic streams benefit best from pre-scheduled MAC protocols since they can guarantee that each node has a cyclic and fixed available bandwidth. On the other hand, reservation-based MAC protocols are very well suited for applications where the traffic streams are bursty or the traffic load of each node is unbalanced, since reservation-based MAC protocols schedule the transmission according to a particular transmission request. The disadvantages are that the reservation mechanism requires extra bandwidth and time to exchange the request and the acknowledgment information [1], [2], [3], [4]. The random access MAC protocols usually do not consider the status of the channels or the destination nodes. The source node starts the transmission almost immediately. This, however, leads to potential collision between packets. But when the traffic load gets high, then packet collisions start to occur more frequently, and the performance become quite poor.

As we can see, none of these MAC protocols serves all types of traffic well although each one of them is ideal for certain types of traffic streams. When these types of traffic are simultaneously loaded on a single network, no single protocol can efficiently deal with all traffic types.

With this observation, we propose an efficient access scheme for shared medium networks that: Integrates different types of MAC protocols into a single MAC protocol; Efficiently supports different type of traffic; Can be widely applied into various kinds of shared medium networks.

We term this protocol as *multimedia medium access control* (*Multimedia*-MAC) protocol for shared medium networks. With the improvement on the bandwidth allocation strategy, the *Multimedia*-MAC become *Multimedia*-MAC+ [5], [6]. In this paper, we focus on the newer version.

The objective of this paper is to propose a methodology and framework for integrating different MAC protocols into a single shared medium network to efficiently accommodate various types of multimedia traffic streams with different characteristics and QoS demands. We also develop efficient methodologies, using both analytical modeling and computer simulations, for the performance evaluation of our MAC protocols applied in different traffic and networking environments.

More importantly, the analysis results in a meaningful expression of the QoS: the relation between dead-line missing rate (DMR) and traffic dead-line requirement as well as network traffic load. All possible values of the relation form an *admissible region* with which the QoS can be estimated for given traffic dead-line requirement and current network traffic status.

This paper is organized as follows: Section 2 illustrates the modeling approach for *Multimedia*-MAC protocol and its evaluation method ;Section 3 shows the results of simulation study and modeling analysis ; section 4 concludes this paper.

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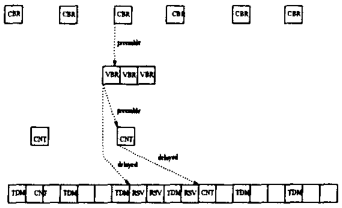

Fig. 1. The principle of *Multimedia-MAC+*.

II. PRIORITY QUEUING MODEL OF MULTIMEDIA-MAC+ PROTOCOLS

The Multimedia-MAC+ consists of three sub-protocols correspondingly to handle the traffic of CBR, burst-VBR and VBR, named, in turn, TDM, RSV and CNT. The detailed operation can be found in [5], [6] and the idea is shown in Figure 1. In the figure, The transmission are organized in form of fixed-length frame. the CNT service can be preempted by RSV process once it occures without TDM services active. The TDM service can interrupt the RSV service because it has higher priority. Since the *Multimedia-MAC+* has fixed frame-length, the frame timing is the most domainant events. It should preempt any transmission services.

This preembling process gives us a heitarics to model the *Multmedia*-MAC protocol by queuing model with priority.

A. Multiple Class Queue with priority and without vacation

We assume a symetric system, that is, all nodes are loaded statistically identically with all classes of traffic streams. Let us start from very general case: The total number of traffic classes is P. The traffic load of *priority class* $p \in P$ is λ_p. Then accumulated arrival of priority messages $1, 2, ..., p$ is $\lambda_p^+ = \sum_{k=1}^{+} \lambda_k$ corresponding server utilization is $\rho_p^+ = \sum_{k=1}^{p} \rho_k$

The LST of density function of the accumulate messages is $B_p^+(s) = \frac{1}{\lambda_p^+} \sum_{k=1}^{p} \lambda_k B_k^*(s)$ where $B_k^*(s)$ is the LST of service distribution for messages in class k.

We can also represent load of ordinary messages which have lower priority than the class p messages as

$\lambda_p^- = \sum_{k=p+1}^{P} \lambda_k$

The service utilization is correspondingly

$\rho_p^- = \sum_{k=p+1}^{P} \rho_k$

and the LST of service time distribution is $B_p^-(s) = \frac{1}{\lambda_p^-} \sum_{k=1}^{p} \lambda_k B_k^*(s)$

When a higher priority message arrives, it preempt the transmission of lower priority message, and the lower priority message is delayed. During the time when the lower priority message transmission suspends, the probability that kth priority messages arrive during the service time of a priority message is denoted as $a_p^+(k)$ where

$$a_p^+(k) = \int_0^\infty \frac{(\lambda_p^+ x)^k}{k!} e^{-\lambda_p^+} dB_p^+(x)$$

and its PGF form is:

$$A_p^+(z) = \sum_{k=0}^{\infty} a_p^+(k) z^k = B_p^+(\lambda_p^+ - \lambda_p^+ z)$$

Similarly, the probability that kth priority messages arrive during the service time of a ordinary message is:

$$a_p^-(k) = \int_0^\infty \frac{(\lambda_p^- x)^k}{k!} e^{-\lambda_p^-} dB_p^-(x)$$

and its PGF form is:

$$A_p^-(z) = \sum_{k=0}^{\infty} a_p^-(k) z^k = B_p^-(\lambda_p^- - \lambda_p^- z)$$

Take L_n as the number of priority messages in the system, immediately aft the nth departure time of both priority and ordinary messages. We can construct an Markov Chain with system state being $L_n; n = 1, 2, ...$

The state transition probabilities p_{jk} are given in three cases:

1. If $L_n = j = 0$ and there are ordinary messages in the system, then the $n+1$th service is given to an ordinary message, thus we have:
$$p_{0k} = a_p^-(k) \tag{1}$$
with probability $\pi_0 - P_0$
2. If $L_n = j = 0$ and there are no ordinary messages in the system, the the system will serve whichever message comes first. Since the probability that a priority message arrives to a empty system is λ_p^+/λ, and the probability that a ordinary message comes to a empty system is λ_p^-/λ, then
$$p_{0k} = \frac{\lambda_p^+}{\lambda} a_p^+(k) + \frac{\lambda_p^-}{\lambda} a_p^-(k) \tag{2}$$
3. If $L_n = j \geq 1$, the $n+1$th service is given to a priority messages, thus
$$p_{jk} = a_p^+(k), k \geq j - 1 \geq 0 \tag{3}$$

By intensive mathematical performance, we can obtain:

$$W_p^+(s) = \frac{(1-\rho)s + \lambda_p^+[1 - B_p^+(s)]}{s - \lambda_p^+ + \lambda_p^+ B_p^+(s)} \tag{4}$$

Because $W_p^+(s)$ includes the delay of all the priority messages of class $1, 2, ...p-1$ and class p. So the LST of delay distribution of class p messages is

$$W_p^*(s) = W_p^+[s + \lambda_{p-1}^+ - \lambda_p^+ \Theta_{p-1}^+(s)] \tag{5}$$

where Θ_{p-1}^+ is the *busy period* generated by higher priority messages of class $1, 2, ...p-1$, and obtained by solving

$$\Theta_{p-1}^+(s) = B_{p-1}^+[s + \lambda_p^+ - \lambda_p^+ \Theta_{p-1}^+(s)] \tag{6}$$

Let $\Theta_{p-1}^+ = \sigma_{p-1}$, we can obtain

$$W_p^*(s) = \frac{(1-\rho)\sigma_{p-1} + \sum_{k=p+1}^{P} \lambda_k [1 - B_k^*(\sigma_{p-1})]}{s - \lambda_p + \lambda_p B_p^*(\sigma_{p-1})} \tag{7}$$

which is the LST of class p message waiting time distribution.

B. Vacation of the multi-class queue with priority

In the *Multimedia-MAC+*, in the point view of RSV or CNT sub-protocol, the server is not available only when the TDM sub-protocol is in service. When the TDM service time is over, i.e., the RSV or CNT service is resumed from 'vacation', the server will idle if there is no RSV or CNT messages in their buffer. Thus, it is *single mode vacation.*

The system is in one of the following states: an idle period with probability P_0, in length V vacation with probability P_v, the priority message service with probability P_{p-1}^{+}, the service for class p with probability P_p, and the ordinary message service with probability P_p^{-}. Then we have

$$P_0 + P_v + P_{p-1}^{+} + P_p + P_p^{-} = 1 \tag{8}$$

Suppose LST of vacation is $V^*(s)$, and mean vacation length is $E[V]$, and mean length of the interval between two successive *regeneration points* [7] is given by

$$V^*(\lambda)\left[\frac{1}{\lambda} + \frac{\sum_{k=1}^{P}(\lambda_k/\lambda)b_k}{1-\rho}\right] + E[V] = \frac{V^*(\lambda) + \lambda E[V]}{\lambda(1-\rho)} \tag{9}$$

Then P_0 is the probability that system is idle which form the regeneration point. P_v is the probability that all the priority message (including class p) is on vacation.

From all above, we can obtain:

$$\begin{aligned} W_p^*(s) &= \frac{(1-\rho)\{V^*(\lambda)\sigma_{p-1} + \lambda[1 - V^*(\sigma_{p-1}]\}}{(V^*(\lambda) + \lambda E[V])[s - \lambda_p + \lambda_p B_p^*(\sigma_{p-1})]} \qquad (10) \\ &+ \frac{\sum_{k=p+1}^{P} \lambda_k[1 - B_k^*(\sigma_{p-1})]}{s - \lambda_p + \lambda_p B_p^*(\sigma_{p-1})} \end{aligned}$$

According to *stochastic decomposition principle* [], we can easily get the LST of the waiting time distribution of class-p message based the waiting time distribution (LST) of the priority queue with and without vacation, as:

C. Numerical Evaluation of the model

We have got the waiting time distribution (LST form) of the different sub-protocols within the framework of the *Multimedia*-MAC+. However, directly inverting from the LST form to their PGF is very difficult [8], [9] Fortunately, a Fourier-series method that can numerically invert the Laplace transforms and generating functions by a numerical method [9], [10], [8], [11] which gives following formula to calculate the moments of given LST form of distribution, and the error associated.

$$\begin{aligned} \mu_n &= n!\omega_{nn}/\alpha_n^n \\ &= \frac{n!}{2nlr_n^n\alpha_n^n}\{W_n(r_n) + (-1)^n W_n(-r_n) + \\ &\quad 2\sum_{j=1}^{nl-1} Re(W_n(r_n e^{\pi ij/nl})e^{-\pi ij/l})\} - \bar{e} \qquad (11) \\ \bar{e} &= \sum_{j=1}^{\infty} \alpha_n^{2ljn} \frac{n!}{(n+2ljn)!}\mu_{n+2ljn} 10^{-\gamma j} \qquad (12) \end{aligned}$$

By knowing the *cumulative density function* (CDF) of distribution of the waiting time, which is determined by all its moments, $W_{cdf}(x) = Pr\{w \leq x\}$, the probability distribution that the waiting time exceeds a given deadline D is $F_{DMR} = Pr\{d = D\} = Pr\{w > D\} = 1 - W_{cdf}(x)$. It is equivalent to computing the *tail probability* of $W(t, D)$ which is the waiting time distribution. However, an arbitrarily given deadline causes computing of the W_{cdf} quite difficult because the number of moments required to produce the adequately accurate results is unknown, although we can get quite a number of moments with enough accuracy by the method we discussed in the previous subsection. Therefore, we need to find an approximation to obtain the tail probability. Chudhury proposed an approximation for this purpose [11] which is in the following form:

$$F_{DMR}(x) \approx Ae^{-\eta x} \tag{13}$$

where $\eta = \lim_{n\to\infty}\eta_n$ and $\eta_n = n\mu_{n-1}/\mu_n$. Whereas, $A = \lim_{n\to\infty} A_n$ and $A_n = \eta_n^n \mu_n/n!$.

With this calculation, we can obtain the deadline-missing rate(DMR) of an arbitrarily given deadline.

D. Admissible Region

As we can see from above discussion, the DMR depends on a given deadline, D, and the network traffic load (e.g., the distribution of the arrival and its mean λ), service discipline (e.g., $B^*(s)$) and the vacation regulation (e.g., $V^*(s)$). Thus, the DMR not only reflects the requirement of the traffic to be transmitted (i.e., the deadline D), but also the current network status and operation situation. The significance to evaluate the DMR is that it can *estimate* the QoS of the network. That is, by knowing the $F_{DMR}^{t}(t)(x)$ which is the DMR at time t, we can estimate the DMR $F_{DMR}^{t+}(x+)$ when a new traffic arrives, which is associated with the arrival distribution, amount of load, deadline requirement $(x+)$ and expected DMR, Ψ. If $F_{DMR}^{t+}(x+) > \Psi$, this traffic QoS requirement can not be satisfied, otherwise, the traffic can be admitted safely. Note that after a new traffic is admitted in, the network state is changed. If a new traffic arrives, the estimation should be performed based on the latest network states, i.e., the $F_{DMR}(x)$ should be re-evaluated.

More precisely, within each of the sets, the parameters are only the traffic load λ and a given deadline D for the evaluation of the $F_{DMR}(x, d)$. Therefore the relation between the DMR and the mean traffic load λ and the given deadline D can be illustrated in a three-dimensional graph as shown in Figure 2. As we can see, the space is divided by a surface. The points on the surface indicate the critical state at which, for the corresponding traffic load and deadline, the *minimum deadline missing rate*, denoted by $\mathcal{F}$, can be achieved. So at this point, if the required DMR is above $\mathcal{F}$, this traffic can be safely admitted. Therefore, we call the region that is above the surface as ***admissible region.***

Walking on the surface, we can see that when the deadline requirement is not strict, then more traffic can be

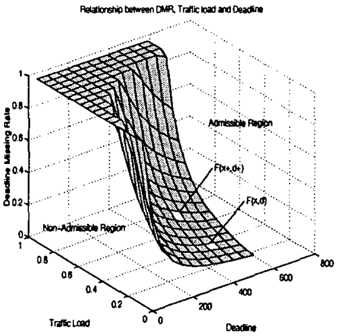

Fig. 2. Admissible Region as a function of DMR, deadline, and traffic load.

loaded. Also, when the traffic load is low, more tight deadline requirement traffic can be admitted in.

For a given traffic distribution, service distribution and vacation discipline, the admissible region is relatively stable. Thus it is significant in practice to quickly estimate the QoS, by possibly constructing a lookup table, or by approximately computing the surface.

III. PERFORMANCE MODEL OF MULTIMEDIA-MAC+

We can view the process of the *Multimedia-MAC+* as multi-class priority queue. This point can be shown in Figure 1, where the three types of traffic streams can be treated as three classes of the queues in priority order of the TDM, RSV, CNT. we can think the frame flows as a special kind of deterministic traffic stream although they do not really generate load or thoughput on the network. We refer this type of supplimentory traffic stream as *dummy traffic*. In fact the vocation process can be thought as a dummy traffic stream, however, because it will cause impact to the decipline of the priority order, the vocation process, such as token-passing process, will be embeded in RSV service, as show in later description of this sub-section. With this observation, we can model the *Multimedia-MAC+* in *four-classes* queuing with priorities as sumerized in Table 1.

More precisely, the TDM sub-protocol has highest priority. However, because it is of non-M/G/1 queue properties, it can not be directly applied in the results we have derived in previous sub-section. Fortunately we can treat the TDM sub-protocol operation as *vacation* process because once TDM traffic appear, it will preempt all other traffic streams, that is, other sub-protocols are in vacation. Since the CBR traffic appears deterministically and cyclically, the 'vacation' can be model as a deterministic vacation, that is,

$$V^*(s) = B^*_{TDM}(s) = e^{\mu_T DM/s} \qquad (14)$$

where $\mu_{TDM} = \lambda_{TDM} l_{TDM} / l_{frame}$. The l_{TDM} is a control parameter which avoids the TDM bandwidth allocation from starvation.

In *Multimedia-MAC+*, the RSV sub-protocol is a token-passing protocol. Each node gets a fair chance to sustain a rotated token for certain time (in frame time). When a token was catched by a node, this node starts to transmit if there are pending packets, other nodes are in vacation. In other words, the vacation time is equal to the time for a token go through all other nodes in the network. Therefore, the vacation time, in the view point of a node, can be considered as consisting of a number of stages, each of the stages takes a exponential elapse time. Obviously, the vacation time can be modeled as a $Erlang - n$ process [12], where n is equal to the number of the subscribed nodes excluding the underlying node. However, the vacation time can not be included into the priority queues for it may cause contradiction on our service discipline. When a RSV message arrive, the if the server is in vacation, the message can not be served. So the vacation preempts the RSV message transmission. It seems reasonable to put the RSV vacation as a *dummy* traffic with higher priority than the RSV transmission. But this arrangement may cause the RSV vacation stops the transmission of CNT transmission because the RSV transmission is of higher priority than that of the CNT traffic streams. Our solution is to ignore the RSV vacation in modeling with priority queues, and get the LST of $W^*_{RSV}(s)$ by (7). The vacation effects can be reflected in the appended model of RSV performance by applying *stochastic decomposition* principle (as discussed in previous section).

Classes	Traffic Streams	Arrival and Service
1	Frame Timing	Deterministic
2	CBR	D/D/1 (TDM)
3	VBR	M/G/1 (RSV)
4	CNT	M/M/1 (CNT)

TABLE I

PRIORITIES OF THE SERVICES IN *Multimedia-MAC+*

Because the CNT transmission can be always interrupted by other two sub-protocols and frame timing, the CNT sub-protocol can be simply model as the lowest priority class in the multiple-class queuing with priority which has been derived in (7).

With typical parameters of *Multimedia*-MAC+, we evaluate the model both in numerical method and simulation. To show the tightiness of the estimation of the DMR, we compare the result with that using upper bound analysis [6] in figure 3-5. As we can see the estimation is far tighty than the upperbound analysis and much closer to the simulation results.

IV. CONCLUSION

We observe that different traffic streams are best served by certain protocols but none of the protocols can serve best all types of traffic. Therefore, we propose a integrated protocol that integrate three types of protocols within the same framework, each of them serve for corresponding types of traffic. Because there are multiple type of services existing in the same network, the mul-

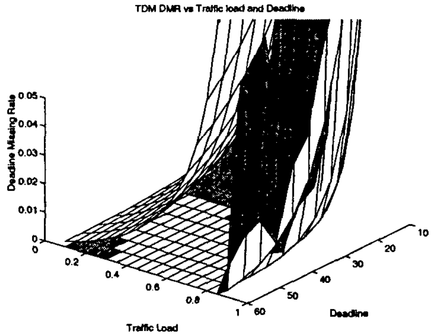

Fig. 3. Admissible Region for CBR traffic.

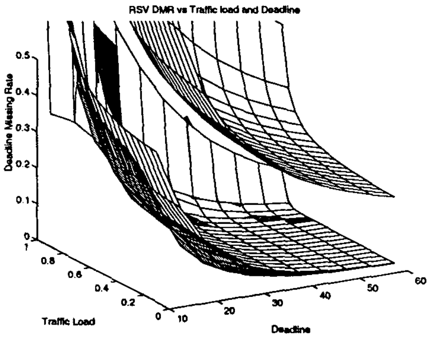

Fig. 4. Admissible Region for RSV traffic.

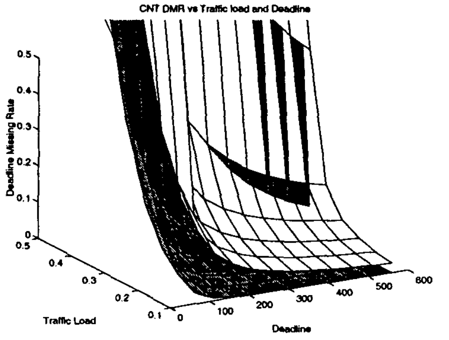

Fig. 5. Admissible Region for CNT traffic.

timedia traffic streams are conveniently supported. We apply a queuing system with a vacation model to study the *Multimedia*-MAC+ performance analytically, based on which we propose a general approach to estimate the QoS of the *Multimedia*-MAC+ network. That is, by theoretical analysis, we can obtain the relationship between *deadline missing rate* (DMR) and a given deadline by the particular traffic as well as other traffic parameters (traffic load, burstiness, etc). Based on the relationship, we can obtain the *admissible region* for each particular sub-protocol. The admissible region supplies the information of current QoS state of the network, and thus, can be used to estimate the QoS if a newly arrived traffic stream was admitted. It can be exacted to be a practical, efficient admission method if the admissible region is calculated using some simple approximation or directly constructed in a lookup table.

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 supplied in a single physical network. At the same time, we believe there are many new issues that will be raised when the framework is further studied.

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