A Controlled Multiaccess Protocol for Packet Satellite Communication

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***Abstract*—A controlled multiaccess protocol for packet satellite communication is introduced and analyzed in this paper. This protocol is fully distributed and no on-board processing is required for the satellite. A control parameter f is used to adaptively control the packet transmission rate such that maximum system capacity can be attained and the average delay is always minimized for a given throughput. The controlled protocol is found to give a smaller average delay than slotted ALOHA even when the throughput is as low as 0.05. On the other hand, under heavy traffic conditions, it can provide a throughput close to unity and an average delay not much more than one round-trip propagation delay. The system performance is also robust, in the sense that a 15% error in throughput estimation results in no more than a 3% increase of the overall average packet delay. Since this protocol degenerates to the reservation ALOHA under heavy traffic, it is equally stable and similar channel control methods are applicable.**

I. Introduction

SINCE the introduction of the ALOHA system [1], research in multiaccess protocols has flourished. For a channel with very low propagation delay, the series of carrier-sensing protocols [2] can give maximum throughput close to unity. But for a satellite channel with a large propagation delay, efficient protocols are more difficult to design. One class of techniques makes use of the reservation principle. These techniques can attain a channel capacity close to unity. But they also have in common a delay overhead of one round-trip propagation time for exchanging reservation information. Some protocols in this class [3] have contention-based reservation, so that not all reservations are successful on the first attempt.

For networks with bursty traffic, random-access techniques can offer more satisfactory delay performance. The familiar tree-algorithm protocol [4] and its derivatives [5], [6] are an improvement of the slotted ALOHA in that the probability of a collision is reduced for successive retransmissions. Maximum throughput in the range of 0.4 to 0.5 can be achieved as compared to 0.37 for slotted ALOHA. To further increase the channel capacity, Raychaudhuri [7] proposed the announced retransmission random-access (ARRA) protocol. ARRA makes use of a low-rate subchannel to announce the packet retransmission times so that conflicts between new and retransmitted packets are prevented. It was shown that the extended ARRA could achieve a capacity close to 0.6, assuming zero overhead.

Yum [8] found that further improvement is possible by avoiding the interslot reservation collision. The improved protocol is called the scheduled retransmission multiaccess (SRMA) protocol. In contrast to ARRA, the common minislot pool at the beginning of each frame is not needed for SRMA. Two versions of SRMA are described and analyzed in Yum's paper. The fixed frame version (SRMA/FF) can give a maximum throughput of 0.65 and the dynamic frame version (SRMA/DF) can attain a maximum throughput of 0.89 assuming 3% of the channel capacity is used for retransmission reservation. Moreover, the average delay for both versions is considerably lower than that for slotted ALOHA.

At about the same time, another group of researchers has made improvements to the reservation-based protocols to accommodate bursty traffic. Bose and Rappaport [9] proposed the idea of trailer transmissions, Chang and Lu [10] proposed the use of multiple request channels, and Lee and Mark [11] proposed the combined random/reservation multiaccess (CRRMA) scheme. The CRRMA protocol requires a packet to make a simultaneous "spare" reservation on the "contention slots" or to make a reservation before transmission on the "reserved slots." It exhibits good delay-throughput performance.

To achieve very low delay under light traffic conditions and high throughput and acceptable delay under heavy traffic conditions, we must have a control parameter on the stations indicating when they should transmit their packets and when they should merely make transmission reservations. In order to minimize the average packet delay, a well-calculated balance must be achieved between the volumes of packets transmitted immediately and those which make reservations. This paper introduces the controlled multiaccess protocol, a fully distributed protocol, which requires no on-board processing and satisfies the above requirements.

II. The Controlled Protocol

Let the packet satellite channel be divided into frames of K slots with all slots equal to one time unit. Let each frame be divided into an ALOHA subframe and a reserved subframe and each slot be divided into a header and a body [Fig. 1(a)]. The header consists of M minislots. Each minislot is long enough such that the three state information: "idle," "success," and "collision" can be distinguished. The body can accommodate one packet. For each new or retrying packet (i.e., those which were not successfully sent on the previous try) transmitted in an ALOHA slot, one of the M minislots in the header is randomly selected and marked by a series of bits

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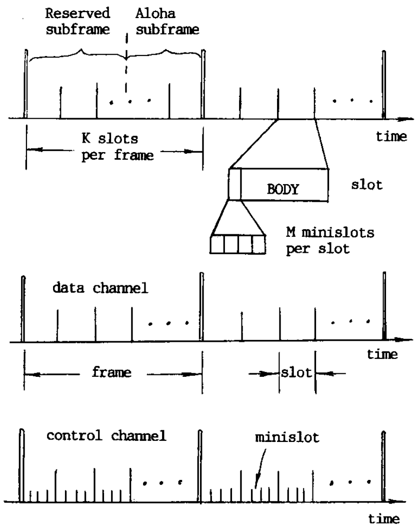

Fig. 1. Frames, subframe, slots, and minislots in the controlled protocol. (a) Common channel arrangement. (b) Separate channel arrangement.

for retransmission scheduling purposes in case of a collision. (Guard times are needed between frames, slots, and minislots to assure synchronization. A discussion on this appears in [12]. Alternatively, a separate control channel can be used to accommodate the reservation information. Fig. 1(b) shows such an arrangement. Since the control channel has a very low bit rate, synchronization of minislots can easily be maintained [13].)

If a station transmits a packet on an ALOHA slot, then after a round-trip propagation delay (equal to R frames), the station will learn on the downlink channel whether the transmission and retransmission reservations were successful or not. For a successful transmission on an ALOHA slot, its corresponding "spare" reservation is ignored. An unsuccessful transmission will either be assigned a dedicated slot (details to follow) for retransmission if the reservation is successful, or will reattempt to transmit after a random delay if the reservation is also unsuccessful (details to follow). Note that a successful reservation means:

1) no collision on the chosen minislot; and
2) the reservation is not rejected due to overflow (since at most K reservations can be accepted per frame).

Similarly, if a station makes only a transmission reservation on the header of the reserved slot (by randomly marking one of the minislots in the header), it will also be assigned a dedicated slot or be asked to retry depending on whether or not the reservation is successful. The collection of all these dedicated slots in a frame constitutes the reserved subframe, while the remaining slots constitute the ALOHA subframe.

We now digress to discuss the assignment of reserved slots to packets with reservations. Since there is no central controller, all stations must use the same algorithm to do scheduling based on the same information from the downlink broadcasting channel. Let $x \in \{1, 2, \cdots, K\}$ and $y \in \{1, 2, \cdots, M\}$ be the slot and the minislot positions where the reservations are made. After a frame of packets is received, all stations perform the following scheduling procedure.

1) Discard all collided reservations.

   Remark: Since the (x, y) values are used for scheduling the retransmission orders, two reservations with the same (x, y) values cannot be differentiated, and therefore cannot be scheduled unambiguously.

2) Discard all spare reservations that correspond to successful transmissions on the ALOHA slots.

3) Collect the remaining reservations and arrange them in order as follows. Arrange the set of vectors into subsets $X_1, X_2, \cdots, X_K$ where $X_i = \{(x, y) | x = i\}$. Each X_i is then sorted into ascending order by its y value.

   Remark: These are the noncollided reservations on the reserved slots and the noncollided spare reservations of those collided packets on the ALOHA slots.

4) If the number of vectors is larger than K, truncate it to K.

   Remark: The retransmission frame can accommodate at most K packets. The truncation is according to a pseudorandom sequence so that all stations discard the same set of reservations.

5) If a station finds its own vector at position b, transmit its packet at the bth slot of the next frame.

   Remark: The ordering of the vector is the order in which packets with successful reservations are to be transmitted.

For satellites with on-board processing, the bookkeeping can be done on-board and the ordered set of "successful" vectors (one per frame) can be broadcasted to all stations. Also, with on-board processing, the uplink traffic may include packet destined for other stations in different "zones" served by different transponders. If that is the case, explicit acknowledgment of a successfully received packet by the satellite is necessary since that packet may not be destined to the same zone from which it originated.

To ensure optimum channel performance under all traffic conditions, we need to control the relative rates of packet traffic and reservation traffic. This could be done by using a control parameter $f \epsilon [-1, 1]$ which specifies the amount of traffic to be relegated from the ALOHA subframe to the reserved subframe or vice versa. When $f = 0$, all packets arriving in the reserved subframe make *reservations* only in the minislot headers of the reserved slots and all packets arriving in the ALOHA subframe are *transmitted* immediately while at the same time making a spare reservation. When f is negative, a fraction $|f|$ of the traffic (or choose each packet concerned with probability $|f|$) arriving in the reserved subframes is to be transmitted in a slot selected randomly from among one of the U upcoming ALOHA slots. (The rest are treated according to the $f = 0$ case.) On the other hand, when f is positive, a fraction f of the traffic arriving in the ALOHA subframes will only make reservations in the header of a slot chosen randomly from among the V upcoming reserved slots. Note that the SRMA protocol in [8] is just the $f = -1$ case and the UCA in [11] is similar to the $f = 0$ case. For all values

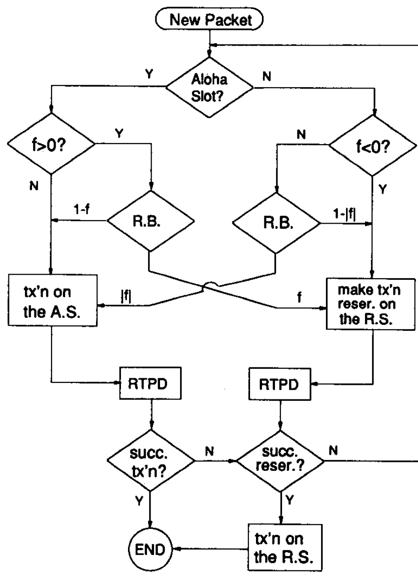

Fig. 2. The controlled protocol.

of f, packets that have the following:

1) unsuccessful transmission reservations on the reserved subframe; or
2) unsuccessful transmission and unsuccessful retransmission reservations on the ALOHA subframe

are scheduled to arrive anew at one of the K upcoming slots at random where K is the frame size in slots. Fig. 2 summarizes the controlled protocol in a flowchart.

In practice, the optimum values of f for minimum average packet delay are predetermined for various values of channel throughput S, and are stored in each station. Whenever there is a significant change in the estimate of S (from the down link), f is updated. Alternatively, S and f can be determined by the satellite on-board processor and broadcasted to the stations. Numerical results show that as S increases from zero to $S_{\max}$, f increases from -1 to 1. An example is shown in Fig. 6. Numerical results also show that a 15% error in throughput estimation results in no more than a 3% increase in the overall average packet delay.

As we have mentioned before, this protocol degenerates to the reservation ALOHA under heavy traffic. Therefore, it is equally stable and similar channel control methods are applicable. A simulation study on this was done and the above claim was verified.

III. Throughput Analysis

Collided packets in frame I will be retransmitted after R frames if they are successfully scheduled. Consider that a subchannel consists of frames I, $I+(R+1)$, $I+2(R+1)$, $I+3(R+1)$, etc., and let us rename these frames as i, $i+1$, $i+2$, $i+3$, etc. We shall evaluate the throughput of the subchannel and argue that since all subchannels are statistically similar, the channel throughput is simply $R+1$ times the subchannel throughput.

Let the combined arrivals of new and aborted packets to the ALOHA subframes be given by a Poisson process with rate g_a packets/slot. (This assumption is valid when the arrival of new packets is Poisson and K, U, V are not very small so that the arrivals of retrying and diverted packets are sufficiently random.) Consider the jth slot of the ALOHA subframe. Let N_a packets be transmitted in that slot. Among the N_a packets, let $L_a(j)$ be the number of successful reservations from the collided packets. Then

$$\begin{aligned}P[L_a(j) = r|N_a = n] &= P[r \text{ out of } n \text{ packets in the } j\text{th ALOHA slot have}\\ &\qquad \text{their reservations not in conflict with others}].\end{aligned}$$

For $n=0$, it is readily seen that $P[L_a(j)=0|N_a=0]=1$. For $n=1$, the only packet transmitted must be successful. Therefore, its retransmission reservation is ignored and we have $P[L_a(j)=0|N_a=1]=1$. For $n=2,3,4,\cdots$, we use the result in [14] to obtain

$$\begin{aligned}&P[L_a(j) = r|N_a = n]\\ &= P[r \text{ cells have exactly one ball given that } n \text{ balls are tossed in } M \text{ cells}].\\ &= \frac{(-1)^r M!\, n!}{r!\, M^n} \sum_{k=r}^{\min(M,n)} (-1)^k \frac{(M-k)^{n-k}}{(k-r)!\,(M-k)!\,(n-k)!}.\end{aligned} \tag{1}$$

As all other cases are impossible, their probability is zero. Since N_a is Poisson distributed, we have

$$P[L_a(j)=r] = \sum_{n=0}^{\infty} \frac{(g_a)^n \exp(-g_a)}{n!} P[L_a(j)=r|N_a=n] \qquad r=0,1,2,\cdots,M. \tag{2}$$

Next, consider the jth slot of the reserved subframe. Through reservation, that slot carries a successful packet transmission. The protocol allows the minislot header (which would not be used otherwise) to carry reservation information. Let N_r be the total number of reservation requests in the minislot header of that slot. Among the N_r reservations, let $L_r(j)$ of them be successful. In a similar manner, $P[L_r(j)=r|N_r=n](n=0,1,\cdots)$ and $P[L_r(j)=r](r=0,1,\cdots M)$ are given by (1) and (2) after changing subscripts from "a" to "r" except when $P[L_r(j)=1|N_r=1]=1$.

Let random variables X_i and Y_i denote the lengths (in slots) of the ith reserved subframe and the ith ALOHA subframe, respectively. Let W_i be the total number of successful reservations in frame i before reservation truncation. Then

$$W_i = L_r(1) + L_r(2) + \cdots + L_r(X_i) + L_a(1) + L_a(2) + \cdots + L_a(Y_i) \tag{3}$$

$\{L_r(j)\}$ and $\{L_a(j)\}$ in (3) are each independent, identically distributed sets of random variables because, first of all, retries randomly select one of the K slots, and second for $f \neq 0$, the selection of a future slot to transmit is random for all diverted packets. The generating function of W_i is therefore

$$G_{W_i}(z) = \sum_{k=0}^{K} [G_{L_a}(z)]^k [G_{L_r}(z)]^{K-k} P[Y_i = k]. \quad (4)$$

Due to the truncation of overflowed reservations, the length of the ith reserved subframe must be $X_i = \min[W_{i-1}, K]$. Its distribution is

$$P[X_i = j] = \begin{cases} P[W_{i-1} = j] & j = 0, 1, \cdots, K-1 \\ \sum_{k=K}^{MK} P[W_{i-1} = k] & j = K. \end{cases} \quad (5)$$

Also, since $X_i + Y_i = K$,

$$P[Y_i = k] = P[X_i = K - k]. \quad (6)$$

In steady state, $\{W_i\}$ has distribution independent of i. Substituting (5) into (6) and then into (4), and expressing the right-hand side of (4) in two terms, the first for $k = 0$ and the second for $k = 1, \cdots, K$, we have

$$\begin{aligned} \sum_{j=0}^{MK} P[W = j] z^j = & \left\{ \sum_{m=0}^{M} P[L_a = m] z^m \right\}^K \\ & \cdot \left\{ \sum_{n=K}^{MK} P[W = n] \right\} \\ & + \sum_{k=1}^{K} \left\{ \sum_{m=0}^{M} P[L_a = m] z^m \right\}^k \\ & \cdot \left\{ \sum_{m=0}^{M} P[L_r = m] z^m \right\}^{K-k} \\ & \cdot P[W = K - k]. \end{aligned}$$

Equating the coefficients of z^j, we arrive at a set of homogeneous linear algebraic equations. Together with the probability normalization equation, we can solve for $\{P[W = j]\}$ and then $\{P[X = j]\}$.

Let $E[X]$ be the mean of X. Then $E[Y] = K - E[X]$. The probability of exactly one packet arriving in an ALOHA slot is $g_a \exp(-g_a)$. Hence, the average number of successful packet transmissions in an ALOHA subframe is $E[Y] g_a \exp(-g_a)$. Let h be the length of a minislot. Then hM is the control overhead per packet. The packet size excluding overhead is therefore $1 - hM$. The channel throughput S is, therefore,

$$S = \frac{E[X] + E[Y] g_a \exp(-g_a)}{K} (1 - hM). \quad (7)$$

Numerical results show that as traffic increases, $E[X]$ approaches K. Hence, $E[Y]$ approaches zero and S approaches $(1 - hM)$. Therefore, under heavy loading conditions the protocol gives the same throughput as the conventional reservation protocols. On the other hand, under very light traffic conditions, most transmissions are successful on their first trial. Therefore, $E[X]$ approaches zero and S approaches the slotted ALOHA throughput $g_a e^{-g_a}$ if we neglect the overhead factor $(1 - hM)$.

IV. Delay Analysis

We first derive the average contention delay D as a function of S and f and then minimize $D(S, f)$ with respect to f to obtain $D(S)$. The expression for $D(S, f)$ is slightly different for negative and positive values of f. Note that the overall average delay including contention, propagation, transmission, and synchronization delays is just $D + R + 1.5$.

A. For $f < 0$

Consider the arrival of a tagged packet to the channel. It will hit the ALOHA subframe with probability $q = E[Y]/K$ and the reserved subframe with the remaining probability $1 - q$.

1) If the tagged packet arrives in the ALOHA subframe, it will be transmitted immediately. Depending on whether the transmission and retransmission reservations are successful or not, the delays are as follows.

i) Successful transmission

$$D_1 = 0. \quad (8a)$$

ii) Unsuccessful transmission, but successful reservation

$$D_2 = E[Y]/2 + RK + E[X]/2 = (R + 1/2)K. \quad (8b)$$

iii) Unsuccessful transmission and unsuccessful retransmission reservation

$$D_3 = E[Y]/2 + (R + 1/2)K + D(S, f \mid f < 0) \quad (8c)$$

where $D(S, f \mid f < 0)$ is the average packet delay when $f < 0$ and is to be derived. Let p_1, p_2, and p_3 denote the probabilities of occurrence for i), ii), and iii), respectively [see (8d) below and (8e) on the following page]

$$p_1 = \exp(-g_a). \quad (8d)$$

$$p_2 = \frac{\text{[average number of successful reservations from the ALOHA subframe]}}{\text{[traffic rate to the ALOHA subframe]}} = \frac{E[X]\delta}{E[Y]g_a} \tag{8e}$$

where δ is the probability that a successful reservation is from the ALOHA subframe. Since all reservations are equally likely to be discarded due to overflow,

$$\delta = \frac{E[Y]E[L_a]}{E[X]E[L_r] + E[Y]E[L_a]}.$$

And finally,

$$p_3 = 1 - p_1 - p_2.$$

The average delay in this case is

$$D|_{\text{ASF}} = p_1 D_1 + p_2 D_2 + p_3 D_3. \tag{9}$$

2) If the tagged packet arrives at the reserved subframe:

i) there is a probability $|f|$ that it will be transmitted in one of the U upcoming ALOHA slots. The delay is

$$D_{(i)} = [U/(2E[Y])]K + D|_{\text{ASF}}$$

ii) alternatively, it will make a reservation on the reserved subframe with probability $1 - |f|$. Depending on whether the reservation is successful or not, the delays are as follows.

a) Successful reservation

$$D_4 = E[X]/2 + E[Y] + RK + E[X]/2 = (1 + R)K. \tag{10}$$

b) Unsuccessful reservation

$$D_5 = E[X]/2 + E[Y] + (R + 1/2)K + D(S, f|f < 0). \tag{11}$$

Case a) occurs with probability as follows in (12) below and case b) occurs with the remaining probability $1 - p_4$. The mean delay in case ii) is therefore

$$D_{(ii)} = p_4 D_4 + (1 - p_4) D_5.$$

Combining the results of cases i) and ii), the mean delay of the tagged packet arriving at the reserved subframe is

$$D|_{\text{RSF}} = |f| D_{(i)} + (1 - |f|) D_{(ii)}.$$

The average delay for f negative, therefore, is

$$D(S, f|f < 0) = qD|_{\text{ASF}} + (1 - q)D|_{\text{RSF}}. \tag{13}$$

Upon substituting and solving, we arrive at (14) below of which

$$C_1 = [U/(2E[Y])]K$$
$$C_2 = E[Y]/2 + (R + 1/2)K$$
$$C_3 = (p_2 D_2 + p_3 C_2)/(1 - qp_3)$$
$$C_4 = p_3(1 - q)/(1 - qp_3).$$

We note that $D(S, f|f < 0)$ is also a function of g_a and g_r via the p_i's.

B. For $f \geq 0$

When $f \geq 0$, we again consider the following two cases.

1) If the tagged packet arrives at the ALOHA subframe, there is a probability f that it will make a *reservation only*

$$p_4 = \frac{\text{[average number of successful reservations from the reserved subframe]}}{\text{[traffic rate to the reserved subframe]}} = \frac{E[X](1 - \delta)}{E[X]g_r} = \frac{1 - \delta}{g_r} \tag{12}$$

$$D(S, f|f < 0) = \frac{|f|(C_1 + C_3) + (1 - |f|)[p_4 D_4 + (1 - p_4)(K/2 + C_2 + qC_3)]}{1 - |f|C_4 - (1 - |f|)(1 - p_4)(1 - q + qC_4)} \tag{14}$$

at one of the V upcoming reserved slots. The average delay in this case is

$$D_{(i)} = [V/(2E[X])]K + D|_{\text{RSF}} \quad (15)$$

where $D|_{\text{RSF}}$ is the mean delay of a packet arriving at the reserved subframe. Alternatively, the tagged packet will be transmitted on the ALOHA subframe with the remaining probability $1 - f$. Following the derivation of the $f < 0$ case in Section V-A, the average delay in this case is

$$D_{(ii)} = p_1 D_1 + p_2 D_2 + p_3 D_3 \quad (16)$$

where D_1, D_2, D_3, p_1, p_2, and p_3 are the same as that given in (8a) to (8e). Combining the results in (15) and (16), we obtain the mean delay on the ALOHA subframe as

$$D|_{\text{ASF}} = fD_{(i)} + (1 - f)D_{(ii)}. \quad (17)$$

2) If the tagged packet arrives at the reserved subframe, it makes a transmission reservation on the minislot header of the current reserved slot. Depending on whether the reservation is successful or not, the delays D_4, D_5 and their corresponding probabilities of occurrence are given by (10)–(12). The mean delay in this case is

$$D|_{\text{RSF}} = p_4 D_4 + (1 - p_4)D_5.$$

Finally,

$$D(S, f|f \geq 0) = qD|_{\text{ASF}} + (1 - q)D|_{\text{RSF}}.$$

Upon substituting and solving, we arrive at

$$D(S, f|f \geq 0) = \frac{f(C_5 + C_6) + (1 - f)\{p_2 D_2 + p_3[C_2 + (1 - q)C_6]\}}{1 - fC_7 - (1 - f)p_3[q + (1 - q)C_7]} \quad (18)$$

of which

$$C_5 = [V/(2E[X])]K$$
$$C_6 = \frac{p_4 D_4 + (1 - p_4)(K/2 + C_2)}{1 - (1 - q)(1 - p_4)}$$
$$C_7 = \frac{(1 - p_4)q}{1 - (1 - q)(1 - p_4)}.$$

Note that $D(S, f|f \geq 0)$ is also a function of g_a and g_r (via the p_i's).

We now derive several relationships among g_a, g_r, S, and f that allow us to express D as a function of S and f only. First, note that the system throughput S as given in (7) is a function of g_a and g_r. Thus, for any given value of S, a relation ϕ_1 between g_a and g_r can be tabulated

$$g_a = \phi_1(g_r, S). \quad (19)$$

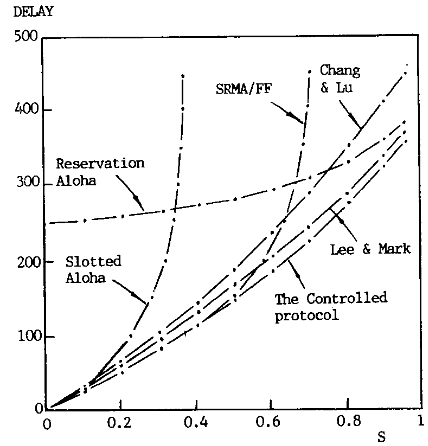

Fig. 3. Delay comparisons (RTPD = 250, $h = 0.001$, and $K = 20$).

When $f < 0$, a fraction $(1 - |f|)$ of the arrivals at the reserved slots will only make reservations. Therefore,

$$g_r = (1 - |f|)(g_a E[Y] + g_r E[X])/K. \quad (20)$$

Solving for g_r, we have

$$g_r = \frac{(1 - |f|)g_a E[Y]}{E[Y] + |f|E[X]}. \quad (21)$$

Equations (19) and (21) can be solved simultaneously for g_a and g_r as functions of f and S. Upon substituting into (14), $D(S, f|f < 0)$ can be tabulated as a function of f and S.

Similarly, when $f \geq 0$, $g_a = (1 - f)(g_a E[Y] + g_r E[X])/K$ or

$$g_r = \frac{g_a(E[X] + fE[Y])}{(1 - f)E[X]}. \quad (22)$$

Together with (19), g_a and g_r can similarly be tabulated as functions of f and S. Substitute into (18), $D(S, f|f \geq 0)$ can be determined from f and S only.

Next, we minimize $D(S, f)$ with respect to f using the bisection method. The average delay of the controlled protocol is therefore $D(S) = D(S, f^*)$ where f^* is the optimum f value.

V. Performance Comparison

Fig. 3 compares the average contention delays of six protocols. A round-trip propagation delay of 250 slots and 8 minislots per slot ($M = 8$) is assumed. The slotted ALOHA delay performance is well known. For SRMA/FF, $K = 20$, $M = 8$, $U = 10$, and $V = 10$ are assumed. For the reservation ALOHA protocol [3], we assume there are 20 slots and 160 minislots in a frame and a uniform retransmission delay interval of 10 slots. It can be seen from the figure that the maximum throughput of SRMA/FF is 0.64 while the Chang

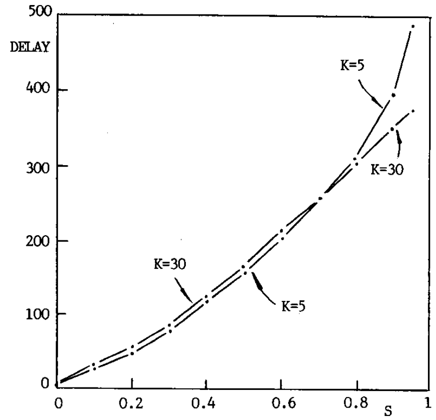

Fig. 4. Delay of the controlled protocol as a function of throughput for $M = 5$, $K = 5$, 30, and $h = 0.001$.

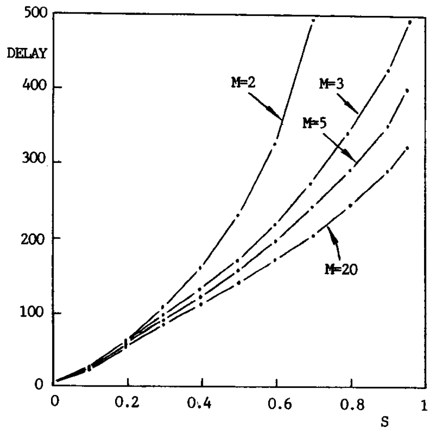

Fig. 5. Delay of the controlled protocol as a function of throughput for $K = 10$, $M = 2, 3, 5, 20$, and $h = 0.001$.

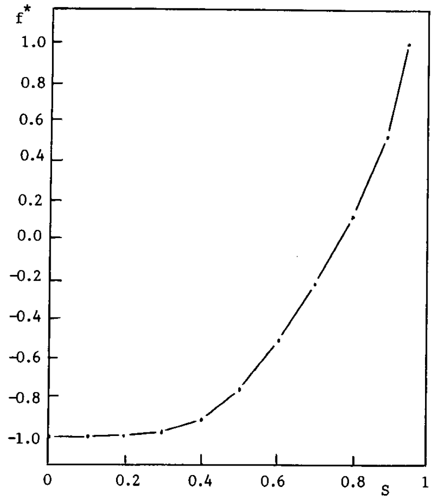

Fig. 6. The optimum control parameter f for the controlled protocol as a function of throughput for $M = 5$, $K = 5$, and $h = 0.001$.

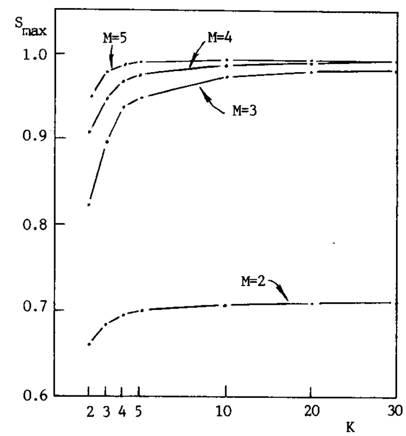

Fig. 7. Maximum throughput of the controlled protocol as a function of K for $M = 2, 3, 4, 5$ and $h = 0.001$.

and Lu, Lee and Mark, controlled and reservation ALOHA protocols give a maximum throughput near one.

Fig. 4 shows the delay throughput characteristics of the controlled protocol for $K = 5$ and 30. $M = 5$ and $h = 0.001$ are assumed for both cases. We see that very little delay reduction and throughput increase can be obtained by increasing K from 5 to 30.

In Fig. 5, we investigate the effect of M on the delay-throughput characteristics of the controlled protocol. We see that very good throughput-delay performance is obtained even for $M = 3$ and very little delay reduction can be obtained by increasing M from 5 to 20.

Fig. 6 shows the optimum control parameter f of the controlled protocol as a function of throughput S with $M = 5$, $K = 20$, and $h = 0.001$. It can be seen that f increases steadily from -1 to 1 as S increases from 0 to $S_{\max}$. In other words, under light traffic conditions, all packets are transmitted on the ALOHA subframes. Under intermediate traffic conditions, some packets will make transmission reservations on the reserved subframes without attempting to transmit on the ALOHA subframes. Under heavy traffic conditions, most of the packets will only make transmission reservations on the reserved subframes.

Fig. 7 shows the maximum throughput achievable by the controlled protocol as a function of K and M. We see that for $M \geq 5$ and $K \geq 10$, the increase in maximum throughput is insignificant. In fact, for $M = 3$ and $K = 5$, the maximum throughput already reaches 0.95.

Fig. 8 shows the maximum throughput $S_{\max}$ of the controlled protocol as a function of M for various h values. We see that initially $S_{\max}$ increases with M as expected. But as M increases beyond some critical value (depending on h), the reservation overhead gets so large that $S_{\max}$ starts to drop. Thus, for a given value of h, there exists an M that maximizes the throughput. In general, if h is not too large, the throughput

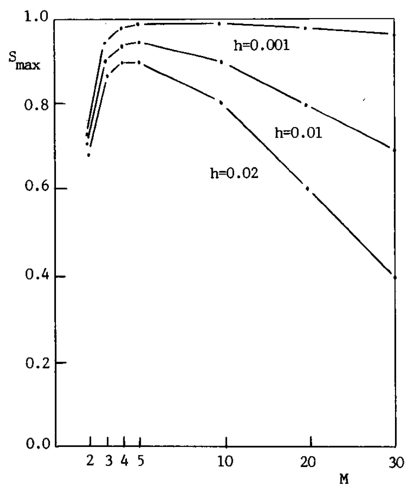

Fig. 8. Maximum throughput of the controlled protocol as a function of M and h for $K = 10$.

remains at its maximum value over a broad range of M. For h equal to 0.1% of the packet size (or the packet size equal to 1000 times the minislot size), and $M = 5$, the maximum throughput is already 0.99.

VI. Conclusion

The above analysis shows that the controlled protocol can give very good throughput-delay performance on the multiaccess channel. This improved performance is due to the self-adjustment of the traffic rates to the ALOHA and reserved subframes. Moreover, the system is robust. Compared to SRMA, the controlled protocol requires very small minislot overhead to achieve a high throughput. This means that even if the minislot size is not very small, a very high effective throughput is possible. The protocol is also fully distributed, requiring no on-board processing. Note that f can be varied for different message types to achieve different delay-throughput characteristics. A preliminary study on the prioritized version of this protocol is in [15].

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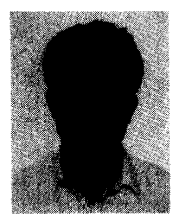

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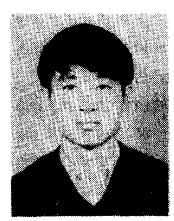

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