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Satellite Multiaccess Schemes for Data Traffic*

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Abstract: Satellite systems have traditionally been designed for voice traffic. In this paper, satellite multiaccess schemes for data traffic are considered. Three general categories of schemes are identified and described: channel reservation schemes, random access schemes and packet reservation schemes. Bounds on achievable channel throughput are presented for the three classes of schemes. Finally, numerical examples are used to compare the delay-throughput performance of several specific schemes for a variety of data traffic environments.

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1. INTRODUCTION

We are witnessing two rapidly growing fields in the world of communications: distributed computer networks and satellite communications. The growth in computer data traffic is evidenced by the development of packet-oriented public data networks in several countries [1]. The pace of development of communication satellite systems has accelerated markedly and satellite system costs have come down significantly [2]. In addition to potential cost reductions, satellites offer special capabilities which may be used to great advantage by communication users, in particular, data communication users.

Computer data traffic has more diverse characteristics and transmission requirements than voice traffic. The purpose of this paper is to present a taxonomy of satellite multiaccess schemes and examine their delay-throughput performance. We begin by reviewing some unique satellite characteristics. A model and a new measure for characterizing computer data traffic are then given. Next, three categories of satellite multiaccess schemes (channel reservation schemes, random access schemes and packet reservation schemes) are identified and described. Bounds on achievable channel throughput are then given. The delay-throughput performance of these schemes are compared for a variety of data traffic environments.

2. SATELLITE CHARACTERISTICS

Satellites have special capabilities which can be used to great advantage in a computer communication network. A satellite can receive signals from any earth station (multiaccess) and transmit signals to all earth stations (broadcast) in its antenna pattern. This allows implementation of schemes for dynamic allocation of the satellite transmission capacity, thus achieving statistical averaging of traffic loads over a large number of users who are geographically distributed. The multiaccess capability is especially beneficial to computer data traffic sources which are typically much more "bursty" than voice traffic. The broadcast capability also permits routing via a destination address in each transmission burst. This would result in a fully interconnected network with direct "logical" connections between all earth station pairs.

On the other hand, the satellite channel propagation delay of approximately 0.27 second will impact the computer-communication network environment in many ways. It will require modifications in error and flow control protocols at the link level, the source-to-destination level as well as any intermediate level requiring these protocols. It will increase buffer requirements not only at the two nodes connected by a satellite link but also throughout the computer-communication network. Some of these issues are discussed in [3].

The throughput of a satellite channel is defined as follows. Let C be the channel transmission rate in bits per second (bps) and let there be on the average P bits in a transmitted data block. The *channel throughput* is then defined to be the ratio of the rate of successfully transmitted data blocks multiplied by P to the rate C. Note that this definition includes as useful throughput all overhead bits in a data block as well as any unused bits in fixed length blocks (packets) obtained from segmenting variable length messages. The *channel capacity* is defined to be the maximum possible channel throughput.

We note that although channel throughput is an important factor in determining the satellite cost per unit of transmitted data, it is by no means the only criterion for evaluating a satellite multiaccess scheme. (In fact, for a power-limited FDMA satellite system, such as SPADE [4], it may be possible to take advantage of the knowledge of a low channel activity factor to increase the effective transponder capacity, in number of channels.) Since an overriding objective is to minimize the total system cost, other factors such as earth station cost and the satellite system's impact on the overall computer-communication network environment, are important and should also be considered.

3. DATA TRAFFIC CHARACTERISTICS

Data traffic streams generated in data processing applications (time-sharing, data base inquiry-response, etc.) typically have large variability in their transmission requirements. The length of messages ranges from a single byte to thousands of bytes. One such message is often made available instantly by some control signal (e.g., carriage return of a terminal) and must be transported from source to destination within a specified delay constraint.

A Model

The following model will be used to represent the traffic characteristics and transmission requirements of a computer-communication network. Consider a finite number of data traffic sources in the network. Each source is modeled as a point process with instants of message "arrivals" being the points of interest. Each message may be segmented into one or more fixed size blocks called packets. Messages generated by a traffic source may belong to one or more classes with different message interarrival time and message length (number of packets) statistics. Source-destination delay constraints are specified for individual classes of messages. Only average delay constraints are considered in the following.

How Bursty is Data Traffic?

Computer data traffic sources are often described to be "bursty." A quantitative measure of how bursty a given data traffic source is, called *bursty factor*, is presented below [5].

The bursty nature of a data traffic source stems from more than just the randomness in message generation time and size. User-specified message delay constraints to be met for these traffic sources are actually the single most important factor in determining if data traffic sources behave in a bursty manner. Suppose we are given a data traffic source with

T = average interarrival time between messages

and

δ = average message delay constraint (excluding channel propagation delays).

The bursty factor β of the traffic source is defined to be

$$\beta = \delta / T \qquad (1)$$

Note that, unlike usual measures, such as the ratio of peak-to-average data rates (PAR), this new measure is not dependent upon a specific design. It also exposes the role played by the delay constraint explicitly. Now consider a traffic source which is formed by merging together N sources with different statistics and delay constraints. The bursty factor of the aggregate source is defined to be the sum of the bursty factors of the individual sources, namely

$$\beta = \beta_1 + \beta_2 + \dots + \beta_N \qquad (2)$$

The usefulness of β is due to the following results. Suppose a channel is fixed assigned to a data traffic source with bursty factor β and all delay constraints are met. Then the resulting peak-to-average ratio satisfies

$$\text{PAR} \geq 1/\beta \qquad (3)$$

and the channel throughput S satisfies

$$S \leq \beta \qquad (4)$$

In other words, the bursty factor gives an upper bound on the "duty cycle" of a traffic source.

4. SATELLITE MULTIACCESS SCHEMES

For purposes of this paper, satellite multiaccess schemes for data traffic can be classified into three general categories:
(1) channel reservation schemes,
(2) random access schemes,
(3) packet reservation schemes.
All of the above are based upon a satellite channelization using FDMA or TDMA techniques. Other techniques such as code division and space division multiple access are not considered. The three categories of schemes are described below.

4.1 Channel Reservation Schemes

Included in this category are conventional satellite multiaccess schemes (for voice traffic). The satellite transponder is channelized using FDMA, TDMA or a combination FDMA-TDMA technique. The channels (forming a common pool) can then be either fixed assigned for periods of hours/days or demand assigned for periods of seconds/minutes. The traffic sources may represent individual data ports within earth stations or entire earth stations acting as data concentrators. Channels may be assigned between source-destination pairs of users as well as to traffic sources which can send packets to different destinations by attaching a destination address to each packet.

Typically, a channel is set aside for signalling among the earth stations. Access to the signalling channel can be achieved by having time slots (within a frame) fixed assigned to earth stations. Demand assignment can then be accomplished with a central controller at a master earth station or with decentralized controllers at all earth stations (e.g., SPADE [4]).

Channel reservation schemes are very efficient for voice traffic since voice conversations typically are several minutes long. The total allocation-deallocation time overhead for circuit-switching is on the order of one second---an insignificant fraction of the connect time.

The efficiency of channel reservation schemes for data depends upon the specific traffic environment. Three channel reservation schemes are distinguished for data traffic:
(1). FA -- channels are fixed assigned to traffic sources
(2) DA/Session -- channels are demand assigned for each "computer session"
(3) DA/Message -- channels are demand assigned for each message.

We next consider upper bounds on channel throughput for the three channel reservation schemes. For the scheme DA/Session, the allocation-deallocation time overhead is typically insignificant compared to the channel connect time for a session and can be ignored. For purposes of this paper, no distinction will be made between FA and DA/Session. For these schemes, the channel throughput is bounded above by the bursty factor of the given traffic source. Thus

$$S \leq \beta = \delta/T \qquad (5)$$

For the scheme DA/Message, suppose the average channel allocation and deallocation times are t_a and t_d seconds, respectively. Assume that during allocation and deallocation times the channel is idle. Let t be the average channel transmission time for a message. The channel throughput S must then satisfy

$$S \leq t/(t + t_a + t_d)$$

The message delay (assuming zero blocking probability for allocation requests) is $t+t_a$ and must satisfy

$$t + t_a \leq \delta$$

From the above two inequalities, we get the following bound

$$S \leq (\delta - t_a)/(\delta + t_d) \tag{6}$$

The above bounds on channel throughput are plotted in Fig. 1 as a function of δ and for different values of T, t_a and t_d.

Note that Eq. (6) does not depend on the average message interarrival time T. Therefore, summing traffic sources into a single stream has no effect on the throughput bound of DA/Message. On the other hand, FA (and also DA/Session) will have a very low channel throughput if T is large compared to the delay constraint δ. In such case, the channel throughput can be improved by merging many traffic sources into the same channel.

The curves in Fig. 1 represent upper bounds on channel throughput. The actual throughput at the system design point must be smaller due to (1) queueing delays, and (2) the fact that channel speeds are available only at certain discrete values. For a demand assigned system, the difference between the actual throughput and the upper bound also depends upon the blocking probability that can be tolerated for allocation requests.

Formulas for the average message delay of FIFO and priority disciplines using a fixed assigned channel are given in [6].

4.2 Random Access Schemes

Multiaccess schemes included in this category are: (1) ALOHA, which had its origin in the ALOHA System at the University of Hawaii [7], (2) slotted ALOHA and (3) Reservation-ALOHA [8]. It is assumed that a common FDMA satellite channel is shared by a population of users (earth stations). Whenever packet transmissions from different users overlap in time at the satellite, it is assumed that neither one can be correctly received (destructive interference).

ALOHA

In the ALOHA scheme, channel users are not synchronized in any way. Each user transmits a packet whenever one is ready. Each packet contains parity bits for error detection. Since a satellite channel has the broadcast capability, a user can actually monitor his own packet transmissions on the down link. If he receives a correct copy of a previously transmitted packet, he can assume that the intended receiver has also received it correctly (given that the channel has a very low error rate). At the same time, a positive acknowledgment scheme can also be used for the detection of transmission errors. In the event that two or more packets interfere with each other at the satellite (a collision), each of the users involved will detect the collision. Each will then retransmit the packet involved in the collision after a randomized delay. This randomization procedure turns out to be crucial to the throughput, delay and stability performance of such random access channels [9-11].

In [7], Abramson first derived the capacity of an ALOHA channel shared by a large number N of low-rate users (very bursty). All messages are assumed to consist of single packets only. In the limit of an infinite user population ($N \rightarrow \infty$ and for each user $\beta \rightarrow 0$), the packet birth process is a Poisson process. Abramson then made the assumption that the sum of new transmissions and retransmissions in the channel (called *channel traffic*) can be approximated by a Poisson process, which gives rise to the following relationship

$$S = Ge^{-2G} \tag{7}$$

where

S = aggregate channel throughput in packets/packet time

G = aggregate channel traffic in packets/packet time.

From the above equation, the maximum possible ALOHA channel throughput (under the above assumptions) is obtained at $G = 0.5$. Thus the ALOHA channel capacity for an infinite population model is

$$C_A = 1/e = 0.184$$

Slotted ALOHA

The slotted ALOHA scheme was first proposed and studied by Roberts [12]. In this case, channel users are required to synchronize their packet transmissions into fixed length channel time slots. The protocols of slotted ALOHA are just like ALOHA. However, by requiring synchronization of packet start times, packet collisions due to partial overlaps are avoided. Under the same assumptions given above for ALOHA, the relationship between channel throughput and channel traffic is given by

$$S = Ge^{-G} \tag{8}$$

where S is maximized at $G = 1$. The resulting slotted ALOHA channel capacity for an infinite population model is twice that of the unslotted case, namely

$$C_{SA} = 1/e = 0.368$$

In [11], it was shown via simulations that the above equation is quite accurate for as few as 10 users with balanced traffic. When the traffic distribution is unbalanced with a combination of high-rate and low-rate users, the channel throughput can be considerably improved [13].

Reservation-ALOHA

The traffic environment suitable for ALOHA and slotted ALOHA is that of a large population of low-rate bursty users and short messages (single packets). The Reservation ALOHA scheme was proposed by Crowther et al. [8] for less bursty users. In addition to time slotting, the slots are organized into frames. The duration of a frame is assumed to be greater than the satellite channel propagation delay so that each user is aware of the usage status (mine, others', unused) of time slots one frame ago. A slot is unused if it is empty or contains a collision. Those slots in the last frame which were unused are available for random access by all users just as in slotted ALOHA. A slot which had a successful transmission by user X in the last frame is off limits to everyone except user X. However, if user X fails to use it in the current frame, then that slot becomes available again for general contention in the next frame. Thus we see that this scheme will achieve very good channel throughput for users with long messages or steady arrival streams.

Under the assumption of equilibrium conditions, the throughput S_{RA} of a Reservation-ALOHA channel can be expressed in terms of the slotted ALOHA throughput S_{SA} for the contention portion of the channel [14]

$$S_{RA} = S_{SA}/(S_{SA} + 1/L) \tag{9}$$

where L = average number of packets transmitted before a user releases his "captured" slot. The above equation is derived in [14] under certain assumptions. An example that satisfies these assumptions is an infinite population model with geometrically distributed message length (in number of packets). From Eq. (9), the capacity of a Reservation-ALOHA channel is

$$C_{RA} = C_{SA}/(C_{SA} + 1/L) \tag{10}$$

For an infinite population model such that $C_{SA}=1/e$, we then have

$$C_{RA} = 1/(1 + e/L) \qquad (11)$$

which gives

$$1/(1+e) \leq C_{RA} \leq 1$$

for L ranging from 1 to ∞ .

Note that in the worst case, the Reservation-ALOHA channel capacity is actually less than than of slotted ALOHA. This deficiency can be remedied if an end-of-use flag is included in the last packet before a user stops using his captured slot. Slots containing packets with end-of-use flags can then be treated as if they are unused and are available for general contention in the next frame. In this case, the Reservation-ALOHA channel throughput is [14]

$$S_{RA} = S_{SA}/(S_{SA} + (1-S_{SA})/L) \qquad (12)$$

We then have

$$C_{RA} = C_{SA}/(C_{SA} + (1-C_{SA})/L) \qquad (13)$$

and

$$C_{SA} \leq C_{RA} \leq 1$$

The channel capacity of Reservation-ALOHA is shown in Fig. 2 for the infinite population model with and without employing end-of-use flags.

Other Performance Criteria

Apart from channel capacity, it is necessary to characterize the delay performance of any given multiaccess scheme. In addition, all random access schemes suffer from potential instability behavior and may require some form of adaptive control.

For slotted ALOHA, the delay-throughput tradeoff was first shown by Kleinrock and Lam [9]. A theory and a stability definition for characterizing stable and unstable channels for a finite population of users is given in [10] where a measure of instability for unstable channels is also introduced. A comprehensive theoretical treatment of adaptive control using a Markov decision model is given in [15]. Various heuristic schemes and their performance are presented in [16].

For Reservation-ALOHA, the tradeoff between average message delay and channel throughput is treated in [14].

4.3 Packet Reservation Schemes

Packet reservation schemes, like random access schemes, are intended for sharing a single multiaccess channel among a population of geographically distributed users (earth stations). In packet reservation schemes, the channel transmission capacity is demand assigned to individual packets or groups of packets. Because of demand assignment, a disadvantage of such schemes is that the average message delay is at least twice the satellite channel propagation delay ($\geq$ 0.54 second).

Packet reservation schemes typically require mechanisms for making reservations and queue management, as well as protocols for error control and recovery. Below we describe two packet reservation schemes [17,18] both based upon a distributed queue management method. They serve to illustrate the concepts and protocols involved. The possibility of centralized queue management using an intelligent satellite has been proposed [19] but not considered here.

A FIFO Scheme

We describe below a FIFO scheme first proposed and studied by Roberts [17]. The satellite channel is divided into time slots. For a certain number of slots used for data packets, one slot is subdivided into V small slots. The small slots are for reservation packets (as well as possibly positive acknowledgment and small data packets) to be used on a contention basis with the slotted ALOHA technique.

A single global queue consisting of messages holding reservations is maintained via a distributed queue management method. It makes use of the satellite broadcast capability such that a reservation packet successfully transmitted with no interference can be received by all users. Each user maintains his copy of the global queue status. It is sufficient for each user to record only the queue size and the queue positions of his own reserved messages. The queue discipline proposed by Roberts is FIFO according to the order reservation packets are received.

For a currently inactive user who wants to join the queue, it is necessary for him to first acquire sufficient queue status information (queue synchronization). In this scheme, the current queue length information may be supplied in the header of each data packet transmitted. Alternatively, it may be announced periodically by a master earth station. Note that such queue length information is one propagation delay old when received. In order for a currently inactive user to acquire queue synchronization, he must update the queue length information with reservation packets received within a satellite propagation time just prior to receiving the queue length information.

To maintain coordination between all users, it is necessary and sufficient that each reservation packet which is received correctly by any user is received correctly by all users. This can be assured by properly encoding the reservation requests. A simple strategy proposed by Roberts is to send parity-checked copies of each reservation request in triplicate within a reservation packet.

Due to the decentralized nature of queue management, the impact of any error in a user's queue status information is merely to delay some data packets momentarily. Error recovery can be accomplished by requiring any user who receives a reservation packet with error or who has been involved in a collision in a reserved data slot to discard his acquired reservations and reacquire queue synchronization.

A Round-Robin Scheme

We describe here a round-robin scheme first proposed and studied by Binder [18]. The satellite channel is divided into time slots and organized into frames of M slots each. The frame time is required to be longer than the satellite propagation time. Also, the number N of users is required to be less than or equal to M. Each user is fixed assigned a time slot within the frame. Each user sends information concerning his current queue length in the header of the data packet transmitted into his fixed assigned slot.

Distributed queue management such as described above is assumed. The global queue status consists of the queue lengths of the active users. Any unassigned slots as well as unused slots (assigned to currently inactive users) within a frame are used by the active users in a round-robin fashion.

A user who has been inactive can transmit into his fixed assigned slot to deliberately generate a conflict. Such conflict is detected by all users and the protocol dictates that following a collision only the owner of the slot can use it in the next frame. The queue status is announced by a master earth station at the beginning of each frame. Thus a previously inactive user can acquire queue synchronization by just listening in for one complete frame.

Error control and recovery can be done in a similar fashion as described above. A special feature of this scheme is that even if a user is in the process of acquiring queue synchronization, he can use his fixed assigned slot in the mean time. Thus in the worst case, his throughput is equal to that of a single TDMA channel.

Other Scheduling Disciplines

Apart from the FIFO and round-robin queue disciplines given above, other scheduling disciplines can be used to achieve response time characteristics suitable for a given traffic environment and specific delay requirements. For example, head-of-the-line priority can be imposed to give shorter delays to control and interactive traffic at the expense of longer delays for other messages.

Reservation Overhead

The maximum channel throughput of a packet reservation scheme is $1-\alpha$, where α is the minimum fraction of channel capacity needed to accommodate the reservation request traffic. As illustrated in the above schemes, two methods (slotted ALOHA or fixed assignment) can be employed for accessing the reservation channel. With slotted ALOHA, each message requires one reservation packet. The minimum overhead is thus

$$\alpha = 1/(1+C_{SA}VL) \tag{14}$$

where C_{SA} is the slotted ALOHA channel capacity, V is the ratio of data packet size to reservation packet size and L is the average message length (in number of packets). We make two observations: (1) α decreases as L decreases, and (2) α is independent of the number of users. The first observation says that a slotted ALOHA reservation channel incurs a large overhead when the data traffic consists of mostly short messages (e.g., single packets). The second observation says that it can be used for a very large user population without any performance degradation.

With a fixed assigned reservation channel, the minimum overhead is

$$\alpha = N/(MV) \tag{15}$$

where the number N of users is required to be smaller than the frame size M . Observe that α increases with N but is independent of the average message length. A fixed assigned reservation channel has other advantages over slotted ALOHA. First, the reservation packets suffer no contention delay. Second, unlike slotted ALOHA, adaptive channel control is not required. Equations (14) and (15) are shown in Fig. 3 in which $1-\alpha$ is plotted as a function of the number of users with L and M as parameters.

5. PERFORMANCE COMPARISONS

The applicability of a satellite multiaccess scheme depends upon the particular characteristics and delay requirements of the traffic environment under consideration. In this section, we shall compare, via some numerical examples, the 3 categories of satellite multiaccess schemes for a variety of data traffic environments.

Delay formulas for fixed assigned TDMA and slotted ALOHA are taken from [6] and [9] respectively. The expected delay of a message in a packet reservation scheme is the sum of the expected delay D_1 incurred by its reservation request and the expected delay D_2 incurred by the data message itself after the reservation has been made. To calculate D_1 and D_2, we shall regard the channel (with capacity C bps) to be split up into two channels: a data channel with capacity $C\gamma$ bps and a reservation channel with capacity $C(1-\gamma)$ bps. D_1 and D_2 are then calculated separately.

In Fig. 4, we show the delay-throughput performance of representatives from the three categories of multiaccess schemes: (1) slotted ALOHA, (2) FIFO with a fixed assigned reservation channel, and (3) a fixed assigned TDMA channel; they are labeled as ALOHA, FIFO and TDMA respectively. We assume that there are 10 users sharing a 50 KBPS satellite channel with a channel propagation delay of 0.27 second. All messages consist of single packets of 1125 bits each and in the case of FIFO, a frame size of 12 slots is assumed with $\gamma=1/6$ and $V=5$. In this case, we observe from Fig. 4 that the performance of fixed assigned TDMA is the best, except when the channel throughput is less than 0.2 where slotted ALOHA gives a smaller delay.

In Fig. 5, we show the effect of decreasing the data rate of each user while the number of users is increased to 50 so that the total data rate remains the same as before. Note that the bursty factor of each user is now 1/5 of the bursty factor in the previous case. This predicts the significantly degraded performance of fixed assigned TDMA shown in Fig. 5. FIFO with a fixed assigned reservation channel (frame size = 24, γ = 5/12) also has poor performance due to the large reservation overhead needed for a large number of users. FIFO with a slotted ALOHA reservation channel (labeled as FIFO* in Fig. 5) gives better performance but the reservation overhead is still quite large; $\gamma=0.4$ assuming a value of 0.3 for C_{SA} in Eq. (14). The delay performance of slotted ALOHA is independent of the increase in the number of users and is most suitable for this environment if a throughput of about 0.3 or less is acceptable.

Now suppose we are back to having 10 users but the data traffic consists of single-packet and eight-packet messages in equal number. The average message length L is increased to 4.5 packets. This implies that the bursty factor of each user is 1/4.5 of that in Fig. 4 and predicts the poor performance of TDMA compared to FIFO in Fig. 6. The delay curve for slotted ALOHA is plotted using the delay model for multi-packet messages in [11]. We see that it performs much worse than FIFO in this traffic environment except for a throughput of less than 0.2 . Simulations also seem to indicate that when there are more multi-packet messages in the input traffic, the slotted ALOHA channel becomes more "unstable" [11].

A large disparity in delay requirements which often exists between different classes of messages can be capitalized upon to improve channel throughput through use of an appropriate scheduling discipline in a packet reservation scheme. We shall illustrate this point by considering a traffic environment in which 20 percent of the messages are single packets while messages having 2, 3, 4, 5, 6, 7, 8 or 16 packets make up 10 percent each of the total input. In Fig. 7, we have shown the expected message delay versus message length at a throughput $S=0.2$, 0.6 and 0.8 for two scheduling disciplines: FIFO and shortest-message-first (SMF). Notice that the delay of short messages in SMF is significantly lower than that for FIFO. This is at the expense of a long delay (10 seconds) for messages which are 16 packets long. If a 10 second delay for these long messages is acceptable to the users, then SMF is far superior to FIFO for this traffic environment.

6. CONCLUSIONS

We have identified and described three general categories of satellite multiaccess schemes that can be used for data traffic: channel reservation schemes, random access schemes and packet reservation schemes. A new measure called bursty factor was introduced for characterizing data traffic sources. Bounds on achievable channel throughput were presented for the three classes of schemes. Numerical examples were used to explore the suitability of specific multiaccess schemes in a variety of traffic environments.

It was found that for nonbursty traffic sources (large bursty factor), fixed assigned channels are adequate (see Fig. 4). For bursty traffic sources (small bursty factor), packet reservation schemes are suitable for multi-packet messages (see Fig. 6); slotted ALOHA is suitable for short single-packet messages and is required when the average delay constraint is less than 0.6 second (see Fig. 5). Finally, if the traffic sources are bursty but the average delay constraint is large (several seconds), then the scheme DA/Message is also applicable (see Fig. 1).

Our main emphasis has been the achievable satellite channel throughput. We should, however, keep in mind that although achievable channel throughput is an important factor in determining the satellite cost per unit of data transmitted, it is not the only criterion for evaluating multiaccess schemes. If the total system cost is to be optimized, then factors such as earth station cost (as a function of antenna size, intelligence, and power requirement etc.) and the impact of the multiaccess scheme on the computer-communication network environment should also be evaluated.

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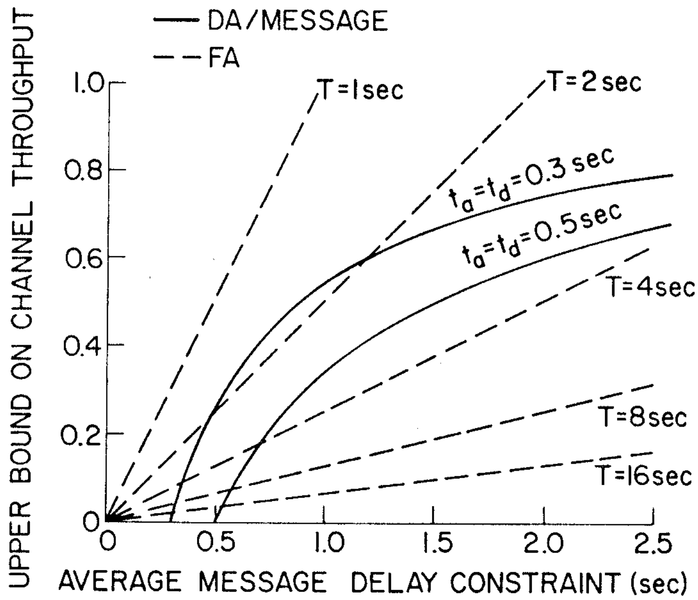

Fig. 1 Upper bounds on channel throughput for channel reservation schemes.

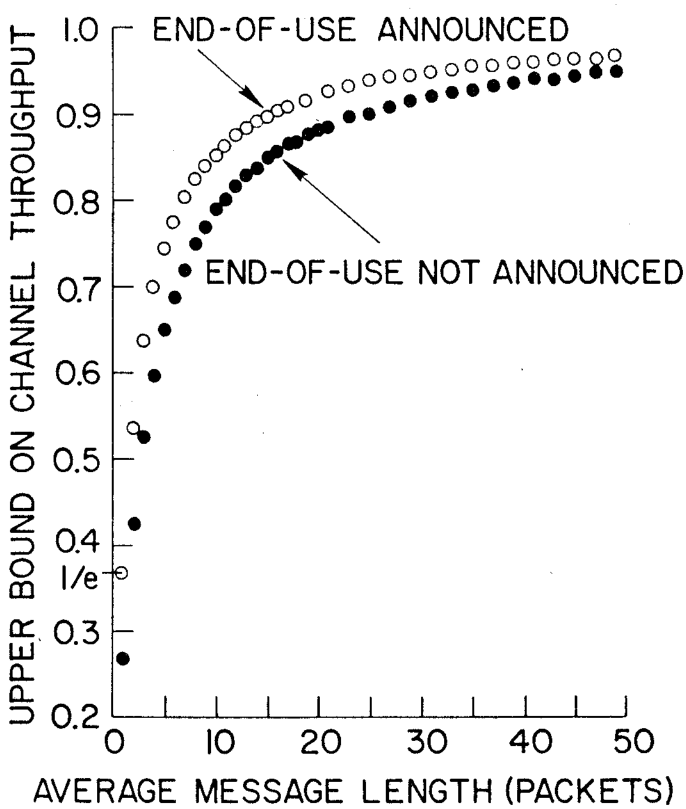

Fig. 2 Upper bounds on channel throughput for Reservation-ALOHA.

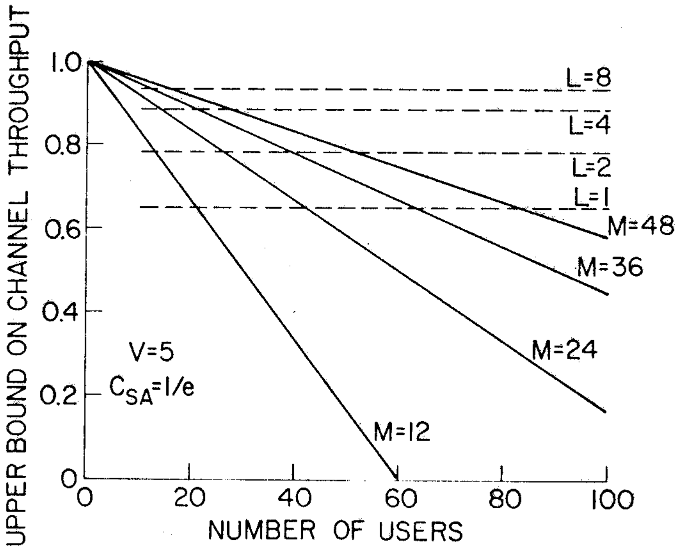

Fig. 3 Upper bounds on channel throughput for packet reservation schemes.

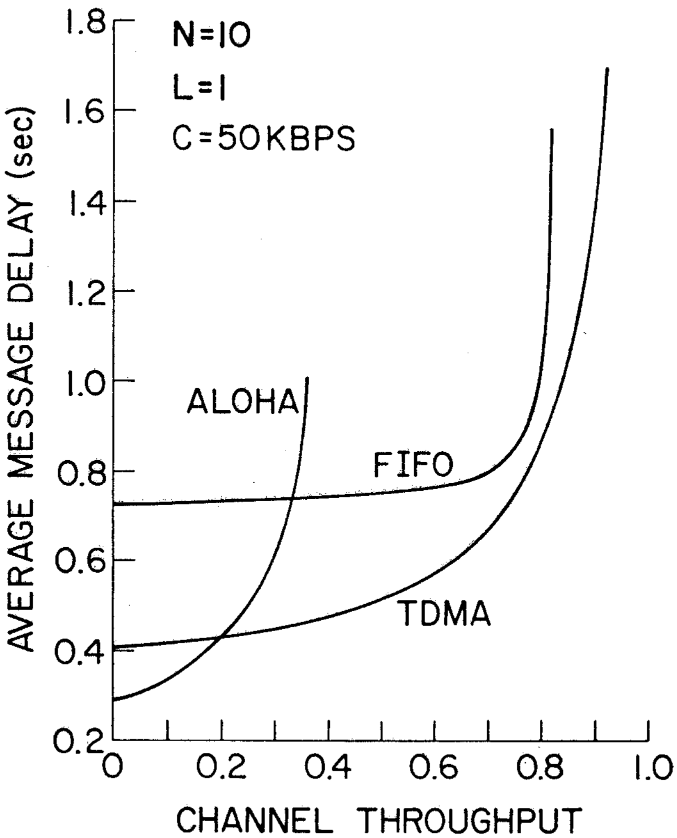

Fig. 4 Delay-throughput tradeoff for 10 users and short messages.

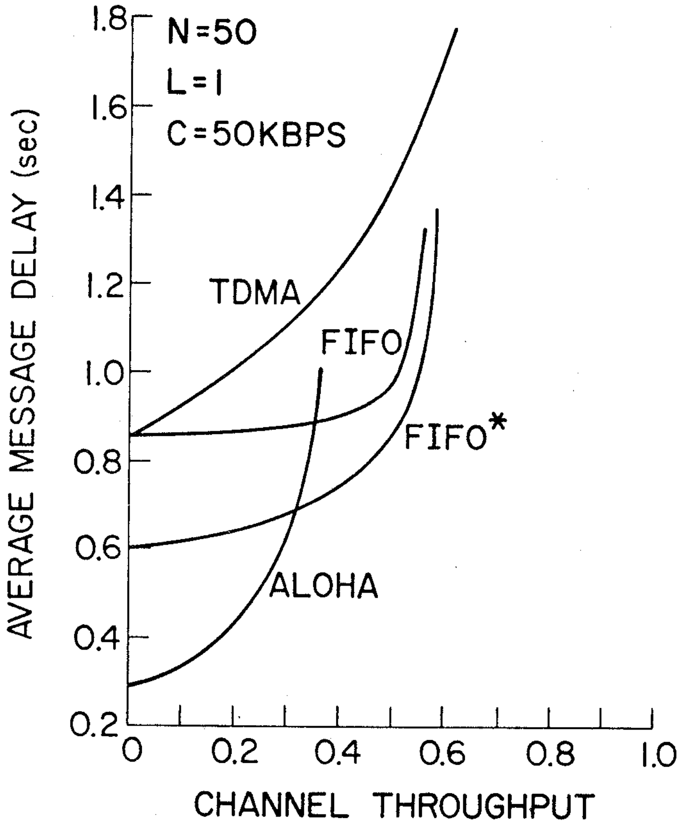

Fig. 5 Delay-throughput tradeoff for 50 users and short messages.

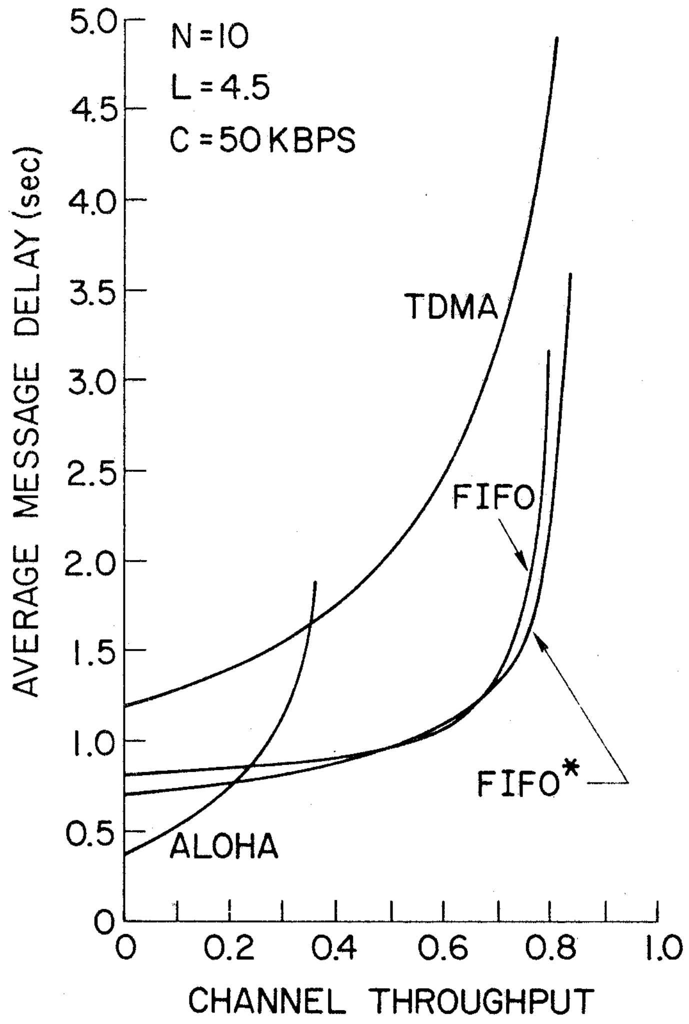

Fig. 6 Delay-throughput tradeoff for 10 users and long messages.

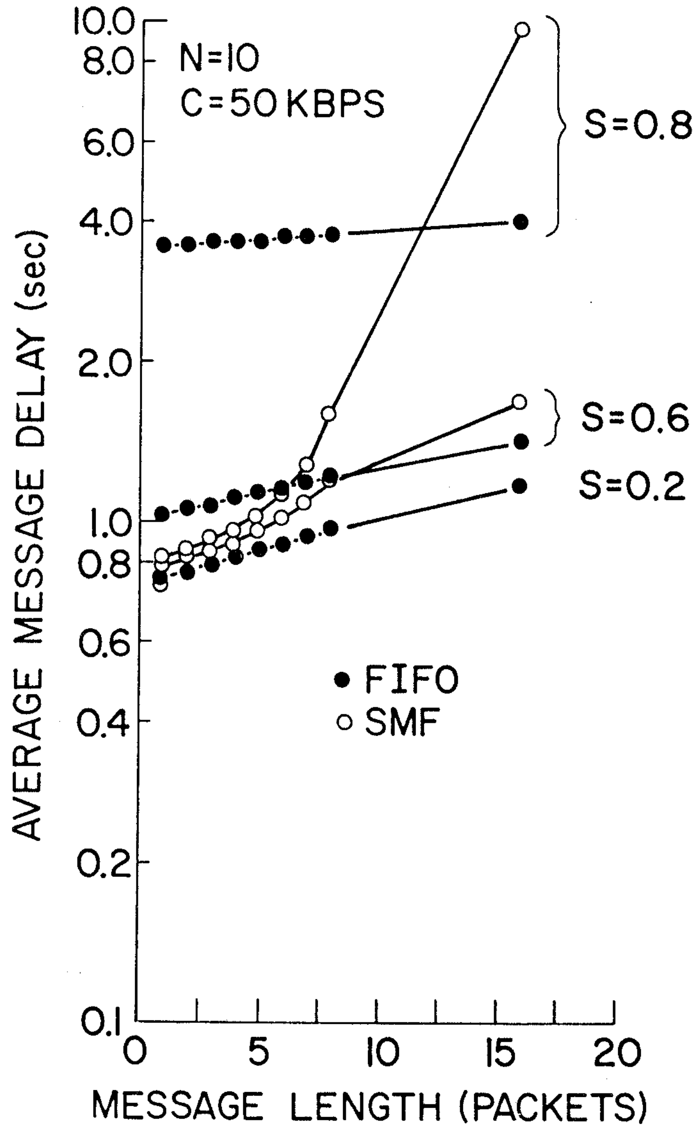

Fig. 7 Delay vs. message length for two scheduling disciplines.