users to choose an infinite dimensional address during the execution of the algorithm. In this case, the binary tree is infinite whether the user population is finite or infinite. If the user population is infinite (Poisson source) then the deterministic and random addressing schemes are identical. Note that the statistics of the contending users are the same under both schemes. In one case, the contending users randomly choose their addresses. In the other case the addresses are preassigned but the users are chosen randomly.

For the Poisson source model, Capetanakis [CAPE 77] showed that the tree which minimizes the number of time slots to process η packets, where η is a Poisson random variable, is binary everywhere except for the root node. The optimum degree d_0^* of the root node depends upon the mean value of η.

An adaptive version of the tree algorithm (analogous to adaptive polling) can be designed to dynamically adjust the degree of the root node at the beginning of each epoch as a function of the mean number of accumulated packets λh where h is the number of time slots in the previous epoch and λ is the Poisson source rate. The optimum degree of the root node is

$$d_0^* = \begin{cases} 1 & \lambda h \leq 1.70 \\ n & 1.70+1.15(n-2) < h \leq 1.70+1.15(n-1) \end{cases}$$

The adaptive tree algorithm has a maximum channel throughput of 0.430 packets/slot and guarantees channel stability of $\lambda<0.430$ packets/slot.

The tree algorithm can be used for contention resolution in CSMA instead of adaptively controlled random retransmission delays for ready users. The tradeoff is the tree algorithm's requirement for time slotting; time synchronizing distributed user to achieve small time slots is a nontrivial problem [ELLI 73, GARD 80].

Concluding remark

In this section, we began with pure contention protocols (ALOHA, slotted ALOHA) and then moved on to more sophisticated contention-based protocols (R-ALOHA, CSMA,URN) with improved delay-throughput performance. A tree algorithm for contention resolution was also shown. These protocols all have distributed control. Each user makes his own decision regarding channel access based solely upon observable outcomes in the broadcast channel. In the URN protocol implementation however, a reservation subchannel is provided for users to communicate with each other in a limited fashion. In Section 3.2, we describe reservation protocols that require users to cooperate with each other to avoid collisions entirely through use of a reservation subchannel.

3.2 Reservation Protocols

The objective of reservation protocols is to avoid collisions entirely. Since users are distributed, a reservation subchannel is necessary for users to communicate with each other. There are two key problems to be solved for most reservation protocols: (1) implementation of the reservation subchannel, and (2) implementation of a queue for the entire population of distributed users (distributed global queue). We shall also examine some protocols for a short propagation delay environment which do not require a global queue.

The reservation channel

The original broadcast channel can be either time or frequency multiplexed into a reservation channel and a data channel. An advantage of time multiplexed channels is that the partition may be variable. With a variable partition, the maximum throughput of data messages can be made very close to one under a heavy network load when users have long queues.

With a fixed partition, the overhead lost to the reservation channel is a fixed fraction of the original channel capacity.

With a global queue, there is no conflict in the use of the data channel. However, the multiple access problem of the distributed users has not disappeared. It exists now in the access of the reservation channel. Any of the previously described multiple access protocols can be used. However, for simplicity, most proposed reservation protocols adopt either a fixed assigned TDMA protocol or some version of the slotted ALOHA protocol. We are faced with the same tradeoff as before. A TDMA protocol performs poorly for a large population of bursty users. On the other hand, a slotted ALOHA protocol is independent of N but needs to be adaptively controlled for stable operation.

The high achievable channel throughput of reservation protocols (relative to pure contention) comes about from substantially reducing the volume of traffic requiring conflict resolution, and the concomitant overhead; the reduction is from the totality of data messages to just one short reservation packet per data message (or less). Note that R-ALOHA and CSMA described earlier derive their efficiency from essentially the same principle.

Part of the price that one pays for the gain in channel throughput of reservation protocols over contention protocols is an increase in message delay. The minimum delay incurred by a message, excluding message transmission time, is more than twice the channel propagation time. This consideration is important for satellite channels. The minimum delay can be reduced, however, if one can anticipate future arrivals and make reservations in advance! One possible example is packetized digital speech traffic.

The distributed global queue

There are two approaches to implement a global queue of requests for a population of distributed users. One is to employ a central controller which tells the ready users when to access the channel; an additional subchannel for controller-to-user traffic is typically required. On the other hand, a distributed control implemenation is more interesting and probably more desirable. In this approach, each user maintains information on the status of the global queue and makes his own decision on when is his turn to access the channel. An important problem here is the synchronization of queue status information of all users. This means that reservation packets broadcasted in the reservation channel need to be received correctly by all users. In the event of an error, an individual user must be able to detect the presence of error in his queue status information. Any such user who is out of synchronization as well as new users who have just joined the network must be able to acquire queue synchronization from observing the reservation and data channels within a reasonable duration of time.

Various queue disciplines may be used for the global queue e.g. random selection, first-in-first-out (FIFO), round-robin, priority based upon type or delay constraint etc. The processing requirement of a sophisticated scheduling algorithm may be quite substantial.

A protocol with distributed control [ROBE 73]

The ideas of a reservation subchannel and a distributed global queue were first proposed by Roberts [ROBE 73]. A satellite channel was considered; the reservation protocol proposed, however, is applicable to other broadcast media. It is assumed that the channel is time slotted and time slots are organized into frames. Each frame consists of a data subframe and a reservation subframe; each slot in the reservation subframe is further subdivided into V smaller slots. The small slots are for reservation packets, as well as possibly positive acknowledgment packets and small data packets, to be used on a contention basis with the slotted ALOHA protocol.*

Roberts' protocol makes use of the broadcast capability of the channel; a reservation packet successfully transmitted with no interference is received by all users. Each reservation request is for a position in the global queue for a group of packets. The queue discipline proposed by Roberts is FIFO according to the order reservation requests are received. We shall refer to this as the FIFO protocol. Each user maintains his copy of the queue status information. It is sufficient for each user to record only the queue length (in number of packets) as well as the queue positions of his own reservations.

For a currently inactive user who wants to join the queue, it is necessary for him to acquire queue synchronization. In this protocol, the queue length information may be supplied in the header of each data packet transmitted. Alternatively, it may be announced periodically by a "master" controller. Note that such queue length information is one propagation delay old when received. To acquire queue synchronization, a user must update the queue length information so received with reservation requests received within a channel propagation time just prior to receiving the queue length information.

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* Our description varies slightly from the reference. In Roberts' original proposal, each reservation subframe is just one data slot long. He also considered a technique for adaptively changing the ratio of the subframe sizes as a function of traffic load. When the total reservation count is zero, the whole frame is used for making reservations.

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

As a result of the distributed nature of queue management, the impact of an error in a user's queue status is to cause some collisions in data slots and to delay some data packets momentarily. However, no catastrophic failure occurs. Users involved in such collisions must declare themselves to be out of synchronization. A user who recieves a reservation packet with unrecoverable error must also do the same. Users who are out of synchronization discard their acquired reservations and reacquire queue synchronization in the same fashion as newly activated users described above.

Maximum channel throughput

The maximum channel throughput of a reservation protocol is $1-\gamma$, where γ is the minimum fraction of the original channel capacity needed to accommodate the reservation request traffic. Consider the FIFO protocol above. Let L be the average number of data packets per reservation request. Since there are V small slots in a data slot, the ratio of data bits to reservation request bits transmitted is equal to

$$\bar{v} = VL$$

Suppose that the reservation channel is used by reservation packets only (excluding acknowledgment and small data packets mentioned above) and its maximum channel throughput is C_{SA} under the slotted ALOHA protocol. It can be easily shown that in this case

$$\gamma = \frac{1}{1 + C_{SA}\bar{v}} \tag{17}$$

The maximum channel throughput of the reservation protocol is $1 - \gamma$. We make several observations. First, the maximum throughput expression is the same as that for R-ALOHA with just a slightly different interpretation for $\bar{v}$. Second, it is independent of N. Third, $\bar{v}$ is assumed to be a fixed parameter; thus the maximum channel throughput value is fixed and strictly less than one.

Now suppose the partition between data and reservation slots in a frame can be dynamically varied. Also, reservation requests can be piggybacked in the header of scheduled data packets. In this case, when the network is heavily loaded with long message queues at individual users, $\bar{v}$ will become very large; the maximum channel throughput becomes one in the $\bar{v} \to \infty$ limit.

Alternatively, if the frame is fixed partitioned and a fixed assignment TDMA protocol is used for the reservation subchannel, we have

$$\gamma = \frac{N}{MV} \tag{18}$$

where N is the number of users and M is the number of data slots in a frame.

A fixed assignment TDMA protocol is sometimes preferable to slotted ALOHA for the reservation subchannel since it is simple to implement; unlike slotted ALOHA adaptive control is not needed. However, Eq. (18) shows that it is applicable only for a small user population. One can always increase M to increase channel throughput; a large M is undesirable, however, since the delay of reservation packets becomes large and hence the message delay as well.

The maximum throughput $1 - \gamma$ is plotted in Fig. 12 versus N for the two cases given by Eqs. (17) and (18).

Other protocols with distributed control

Another reservation protocol with distributed control was proposed by Binder [BIND 75b]. The channel is divided into time slots which are organized into frames. Let M be the number of slots in a frame. The frame duration is required to be larger than the channel 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 and sends information concerning his current queue length in the header of each data packet that he transmits into his fixed assigned slot. Note that this is equivalent to a fixed assigned TDMA reservation subchannel.

The global queue is implemented via distributed control. The global queue status consists of the queue lengths of all ready users (those with nonempty queues). Each user exercises the following rules for channel access. A user may send data in his fixed assigned slot at any time. Any unassigned as well as unused slots (assigned to currently idle users) within a frame are used by the ready users in a round-robin fashion. A user who has been idle can transmit in his fixed assigned (owned) slot to deliberately generate a collision. Such a collision is noted by all users. Another rule dictates that following a collision, only the owner of the slot can use it in the next frame. Thus a special feature of this protocol is that even if a user is in the process of acquiring queue synchronization, he still has the use of a fixed assigned TDMA channel. A disadvantage is that the number of users N must be less than M. The problems of maintaining and acquiring queue synchronization are similar to those of the FIFO protocol above.

Recently the PODA (Priority-Oriented Demand Assignment) protocol was proposed and implemented in SATNET, a prototype packet satellite network [JACO 77, JACO 78, WEIS 78]. Logically, PODA is an extension of Roberts' FIFO protocol with a much more sophisticated scheduling algorithm designed to handle the requirements of a general purpose packet satellite network. These requirements include: multiple delay constraints, multiple priority levels, variable message length, fairness, efficient message acknowledgments, and the accommodation of "stream traffic." Stream traffic denotes a class of traffic sources typified by digital voice. Each such traffic source generates a stream of messages with a small interarrival time variance. Also, the maximum acceptable delay for each message is only slightly larger than the channel propagation time. These characteristics are quite different from what we have considered so far. Thus stream traffic requires special handling apart from individual data messages (datagrams).

Like the FIFO protocol, PODA divides channel time into frames. Each frame consists of an information subframe and a reservation subframe. If slotted ALOHA is used for multiple access in the reservation subframe, the protocol is said to be contention-based and is called CPODA; if fixed assignment TDMA is used, the protocol is called FPODA. In addition to using the reservation subframe, a reservation request can also be piggybacked into the header of a scheduled message. While the total frame size is fixed, the reservation subframe is allowed to grow or shrink according to network loading. If the global queue is empty, the reservation subframe occupies the entire frame. The two types of traffic are distinguished when reservations are made. An explicit reservation is sent for each datagram while a reservation is sent only once for all messages of a particular stream. Each stream reservation contains information defining the stream repetition interval, desired maximum delay relative to this interval, and priority. Whenever the interval starting time is near, a reservation is automatically created and entered into the scheduling queue. The scheduling discipline of the global queue is very elaborate and depends upon both explicit priority, urgency and fairness. Some measurement and simulation performance results of CPODA are reported in [GERL 77b, CHU 78]. Queue synchronization is addressed in [HSU 78, WEIS 78]. More on reservation protocols can be found in [BALA 79, BORG 77, BORG 78].

Short propagation delay environment

The reservation protocols described above all maintain a global queue of reservations, one reservation for a group of packets, for channel access. Consider now networks with a very short propagation delay, relative to the transmission time of a packet. Instead of a global queue, the following approach for conflict resolution has been proposed for a ground radio network environment by Kleinrock and Scholl [KLEI 77].

The broadcast channel is divided into minislots interleaved with data slots. Each data slot is preceded by N minislots where N is the user population size. We shall refer to this class of protocols as the Minislotted protocols. Before the start of every data slot, a priority ordering exists among the N users. Three priority disciplines were considered in the reference (Alternating Priorities, Round Robin and Random Order). The priority ordering determines the assignment of minislots; one per user. Ready users make their presence known by transmitting (carrier only) into their assigned minislots while idle users keep quiet. The first ready user appearing in a minislot gets the following data slot. Since there are N minislots associated with every data slot the maximum channel throughput is

$$\frac{1}{1 + N\alpha}$$

where α is the ratio of minislot to data slot duration. Obviously, the performance of this class of protocols is acceptable only if $N\alpha \ll 1$. The delay-throughput performance of Minislotted protocols was found to be inferior to roll-call polling in many cases [KLEI 77].

To reduce the number of minislots needed for each data slot the MSAP protocol was proposed. At the end of a packet transmission, the protocol operates as follows:

(1) The user who transmitted the last packet is given priority.

(2) The priority user can transmit immediately; other users defer via carrier sensing.

(3) If the priority user is sensed idle, then one minislot later, access priority is passed on to the next user in sequence, and steps (2) and (3) are repeated.

The number of minislots in between contiguous packet transmissions ranges from 0 to N-1. It should be clear that MSAP is analogous to conventional polling in its scheduling discipline but has distributed control and active users instead of centralized control and passive users. Furthermore, a minislot of duration τ (same as that in CSMA) in MSAP is typically much smaller than the corresponding average walk time $\bar{w}$ in polling. This is because the transmission time of a polling message needs to be included in $\bar{w}$ but no corresponding overhead is needed in τ. The delay-throughput performance of MSAP was found to be better than roll-call polling in all cases considered in [KLEI 77]. However, MSAP requires the nontrivial task of time synchronizing users to implement minislots.

Independently, a similar idea was explored by Rothhauser and Wild [ROTH 76] for a bit-synchronous broadcast channel (e.g. a data bus). As a result of bit synchronism, a single bit is sufficient for a user to indicate his status (ready or idle). With a population of N users, N bits are sufficient for identifying all ready users immediately preceding each data transfer phase using the "one-out-of-N" code. During the data transfer phase, ready users can transmit according to a priority sequence known to all users. A multi-level code structure was also proposed in [ROTH 76] that can substantially reduce the number of bits for identifying ready users (to a minimum of $\ell n(N)$ bits when only one ready user is present). This protocol is called multi-level multiple access (MLMA). A closer look shows that the multi-level code structure is based upon the same "tree search" idea as Hayes' algorithm and the tree algorithm described earlier.

No provision for traffic adaptivity was mentioned in the MLMA proposal. Traffic adaptivity was found to be necessary for efficiency in times of heavy traffic in the other two algorithms.

Protocols with centralized control

The presence of a central controller eliminates the queue synchronization problem discussed earlier for distributed control protocols. Instead, the central controller manages the global queue, accepts reservations and informs users of when to access the channel. An additional subchannel is typically required for controller-to-user traffic. Since the multiple access problem of the reservation subchannel remains essentially the same as discussed in the above for distributed control protocols, we will not describe specific protocols.

Protocols with centralized control have been proposed and studied by Tobagi and Kleinrock for radio networks [TOBA 76], by Mark for a data bus [MARK 78], and by Ng and Mark for a satellite network with on-board processing that serves as the central controller [NG 77]. Recently, Mark and Ng proposed a coding scheme, called CMAP, that offers significant overhead reduction over the one-out-of-N code for identifying ready users [MARK 79]

4. PERFORMANCE COMPARISONS

Our focus in this chapter is mainly on the sharing and conflict resolution aspect of the multiple access problem. A broadcast channel of C bps is assumed. The performance criteria of interest are channel throughput and message delay. Engineering considerations such as modulation, clock synchronization, coding, random noise errors, etc. are not within the scope of this chapter. Different broadcast media are differentiated mainly by the effect of their channel propagation delay on an MA protocol's delay-throughput performance. (We note, however, that some protocols do have special requirements and can be implemented in some broadcast media but not others.)

Even within our limited scope of performance it should be clear to the reader by now that there is no single protocol that is optimum. The performance of a multiple access protocol is strongly dependent upon the traffic model and network loading. In general, some traffic characteristics do favor one class of protocols more than others. We list some of them below.

Traffic model	Multiple access protocols favored
nonbursty users	fixed assigned channels (TDMA, FDMA)
bursty users, short messages	pure contention
bursty users, long messages, large N	reservation protocols with contention reservation channel
bursty users, long messages, small N	reservation protocols with fixed TDMA reservation channel

For traffic models which are a fixed or time-varying combination of the above models, "mixed" protocols (such as R-ALOHA, CSMA) and adaptive protocols (such as URN, adaptive polling) may be suitable. To illustrate some of the above observations, we show the delay-throughput performance of representatives of the different classes of protocols under various specific traffic assumptions.

In Figures 13-15, four protocols are considered: (1) fixed assigned TDMA channels, (2) slotted ALOHA, (3) FIFO modified to use a fixed TDMA reservation channel, and (4) FIFO with a slotted ALOHA reservation channel; they are labeled as TDMA, ALOHA, FIFO and FIFO^* respectively in the figures. Delay formulas for TDMA and slotted ALOHA from [LAM 77b, KLEI 73] are used. The expected delay of a message for the reservation protocols is taken to be the sum of the expected delay D_1 incurred by the reservation request and the expected delay D_2 incurred by the message itself after the reservation has been made. To calculate D_1 and D_2, we shall regard the original broadcast channel at C bps to be split up into two separate channels: a data channel at $(1-\gamma)C$ bps and a reservation channel at γC bps. D_1 and D_2 are then calculated separately.

In Fig. 13, we show results obtained assuming 10 users sharing a 50 KBPS satellite channel with a propagation delay of 0.27 second.

All messages consist of single packets of 1125 bits each. In the case of FIFO, a frame size $M = 12$ is assumed with $V = 5$ and $\gamma = 1/6$. Observe that the performance of fixed assigned TDMA is the best for this traffic model except when the channel throughput is less than 0.2 where slotted ALOHA gives a smaller delay.

Now suppose we consider a larger population of more bursty users than the above traffic model. Let N be increased from 10 to 50 (so that the bursty factor of each user is now 1/5 of that of the above model). Fig. 14 shows that TDMA has the worst performance for this new traffic model. FIFO, with $M = 24$ and $\gamma = 5/12$, also has poor performance due to the large reservation channel overhead needed for 50 users. FIFO^*, with $\gamma = 0.4$ assuming $C_{SA} = 0.3$, has better performance than FIFO but the reservation channel overhead is still quite large since each message consists of a single packet only. The delay-throughput performance of slotted ALOHA is independent of the change from the first to the second traffic model and appears to be the most suitable protocol for the second traffic model, provided a channel throughput of about 0.3 or less is acceptable. If a channel throughput of more than 0.3 is desired, then FIFO^* should be employed.

Now suppose we are back to having 10 users but the data traffic consists of long messages (8 packets each) as well as short messages (one packet each) in equal number. The average message length L is increased from 1 to 4.5 packets. Delay-throughput results for the four protocols are shown in Fig. 15. The delay curve for slotted ALOHA is plotted using the delay formula for multipacket messages in [LAM 74]. For this traffic model, the reservation protocols have the best performance except at a channel throughput of less than 0.2 where slotted ALOHA is better. Slotted ALOHA, as we know, was not designed to take advantage of the presence of multipacket messages. Simulations also showed that when a large number of multipacket messages are present in the input traffic, the slotted ALOHA channel becomes more unstable [LAM 74].

Some protocols are designed to take advantage of a short propagation delay environment. They include CSMA protocols which are contention-based, the reservation protocols MSAP and MLMA as well as polling protocols. Reservation protocols that are not contention-based and polling protocols have similar delay-throughput characteristics since the conflict resolution overhead in each case is proportional to N, the number of users. In particular, MSAP and polling are characterized by essentially the same delay formula; any difference in performance is just a consequence of different values for the minislot duration τ in MSAP and the corresponding average walk time $\bar{w}$ in polling [KLEI 77]. There are, of course, differences that do not show up explicitly in the delay-throughput performance, such as: distributed control in MSAP versus centralized control in polling, and the need for time synchronizing distributed users in MSAP but not in polling.

The delay-throughput performance of CSMA and roll-call polling are compared in Fig. 16 using the CSMA delay formula from [LAM 79b] and polling delay formula from [KONH 74]. The delay results shown for polling assume Poisson message arrivals and one packet per message. The ratio of propagation delay to the packet transmission time is $\alpha = 0.05$. The ratio of data to polling message length is $\bar{v} = 10$. Queueing of messages at individual users is assumed; hence the channel throughput approaches one when queues become very long under heavy traffic. Delay-throughput curves for both 10 users and 100 users are shown. The corresponding delay-throughput performance of CSMA at $\alpha = 0.05$ is independent of the number of users. Since the analysis in [LAM 79b] assumes that individual users handle one packet at a time, the maximum channel throughput is less than 1. As before, we observe that CSMA being a contention-based protocol is superior to polling when the channel throughput is low but becomes inferior when the channel throughput is increased to near one. However, if queueing of messages is possible at individual users for CSMA, more than one message may be transmitted every time a user gains channel access; the amount of overhead per message is reduced. Hence, as the network load is increased from 0 to 1, the delay performance of CSMA if first given by the $\alpha = 0.05$ curve at a small channel throughput but switches to the $\alpha = 0.01$ curve and then the $\alpha = 0.001$ curve and so on as the channel throughput increases and queues become long. The channel throughput of CSMA approaches one in the limit of infinitely long queues at individual users.

5. FUTURE DIRECTION

We considered the problem of interconnecting distributed users via a broadcast channel and surveyed a wide class of multiple access protocols. The throughput-delay performance characteristics of these protocols were examined and compared. Our emphasis has been on packet-oriented protocols. Channel-oriented protocols however are currently prevalent in existing systems and are in many cases more cost effective than packet protocols. Specifically, in broadcast networks with a large population of users, the total user interface cost, proportional to N, tends to dominate the network cost. Packet protocols become important only when the cost of user interface to a (shared) wideband broadcast medium is reduced to the point that a large population of users can be economically interconnected directly via the broadcast medium i.e. without the user of a traffic multiplexor/concentrator to justify the cost of an interface. Trends in the costs of electronics and computing seem to be most encouraging towards packet protocols in the forseeable future. Some specific observations follow.

With the current cost ($\geq$ \$100k) and size (antenna size $\geq$ 5 meters) of satellite earth stations, it would not be economical to install a separate earth station at a packet network node unless it has a substantial amount of traffic (100 Kbps or more [ROBE 78]). At such a traffic level, traditional channel-oriented multiple access protocols will perform very well; there will be no need for the more complex packet protocols. However, the advent of satellite systems at the higher frequencies (e.g. 14/12, 30/20 GHz) than currently available, will facilitate the development of small inexpensive earth stations (say, 1-3 meter antenna size) that can be sited almost anywhere for low-rate users. The packet protocols described herein will be very important in this new environment. Other developments in satellite communications that will impact the development of multiple access protocols include: multibeam satellites (thus the broadcast network assumption in this paper needs to be modified) and the availability of on-board processing capability [PRIT 77, JACO 78].

In recent years, packet communication has made significant advances to reduce the cost of long distance backbone networks. Local distribution and collection of data (between a central site and a population of terminals) however remains by far the most expensive portion of many communication networks. We are addressing local area networks which, though outside the computer room, are confined to local environments, such as office complexes and manufacturing plants, without the use of common carrier facilities. Local area networks serve several functions: for local interconnection, for access to local computing facilities, for access to a gateway into a backbone network and so on. The broadcast media of interest here include CATV, optical fiber and radio. All of these are currently under intensive research and development. In this environment, packet protocols will again be important in networks that can economically interconnect a large population of users. With the availability of inexpensive microprocessors, the key to implementing such packet broadcast networks reduces to the development of inexpensive transceivers for the specific broadcast medium. The economic viability of packet broadcast networks using CATV-based technology has already been demonstrated at data rates of several Mbps [DEMA 76, METC 76, CLAR 78, WEST 78].

In conclusion, we have examined the basic principles and performance tradeoffs of multiple access protocols for broadcast networks. For the sake of clarity, we have often omitted specific implementation details. Therefore, the protocols described herein form the basic elements of more sophisticated operational protocols. In the future, more flexible and reliable protocols will be needed to accommodate the increasing volume and diversity of data traffic, including digital voice, facsimile, word processing systems, in addition to the present transaction-based terminal and file transfer traffic.

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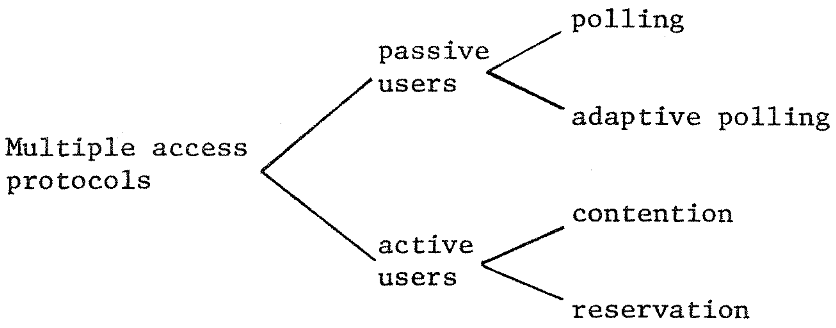


Fig. 1. A classification of multiple access protocols.

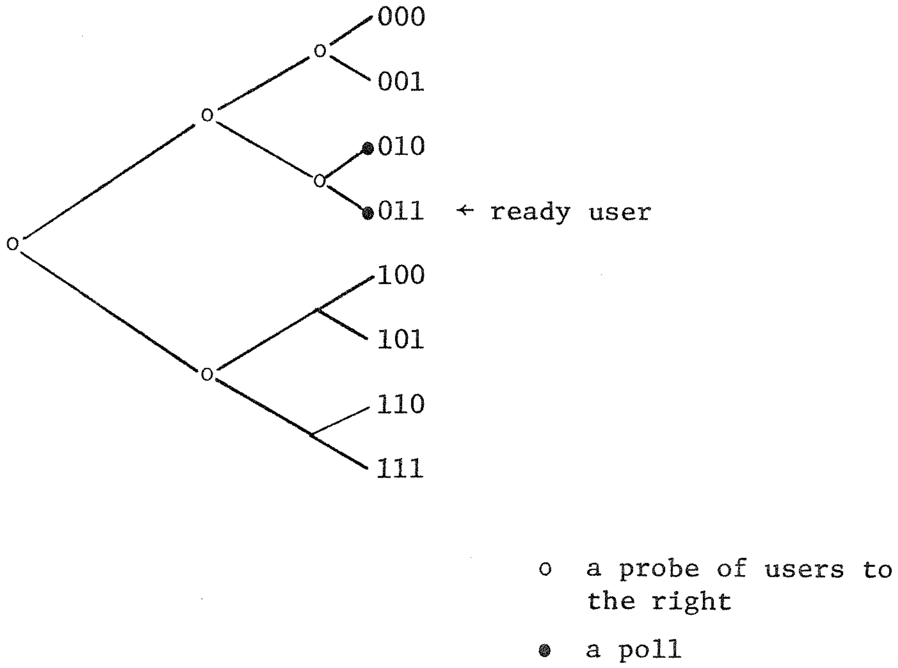


Fig. 2. Inquiries (probe or poll) needed in an example of eight users.

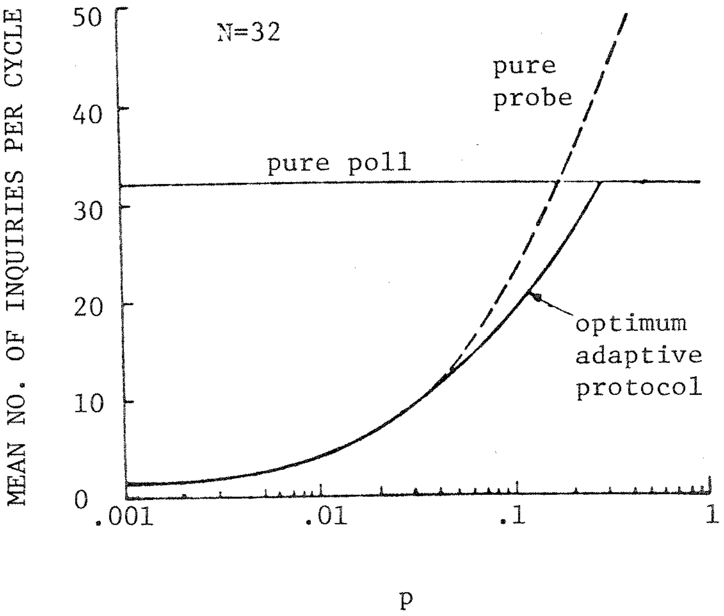


Fig. 3. Performance of adaptive polling.

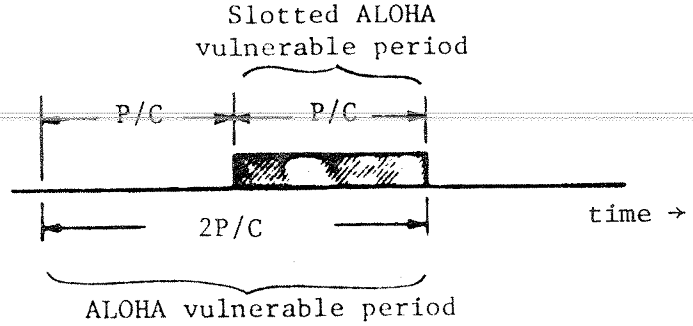
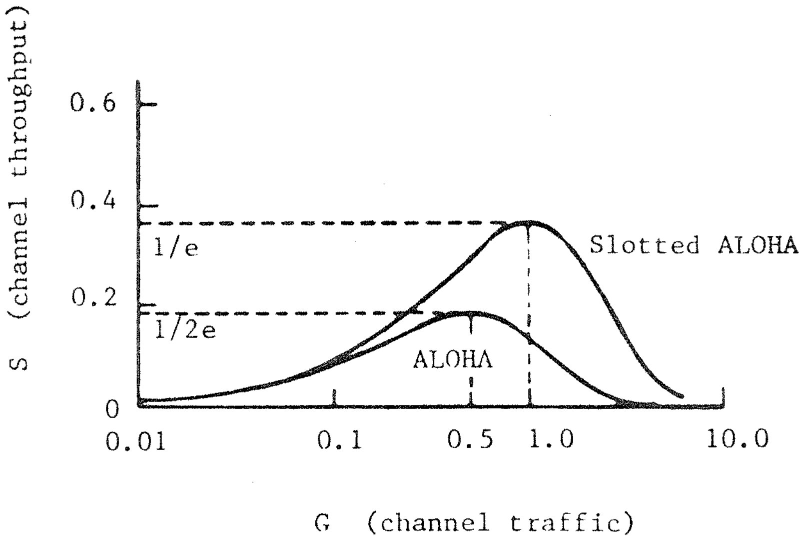


Fig. 4. ALOHA and slotted ALOHA vulnerable periods of a transmitted packet.



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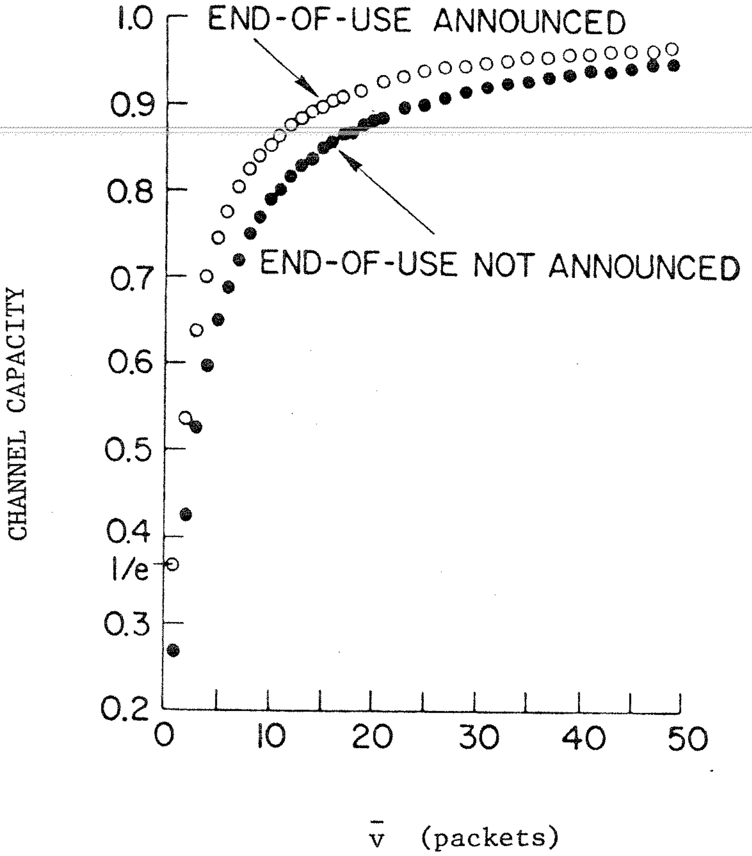

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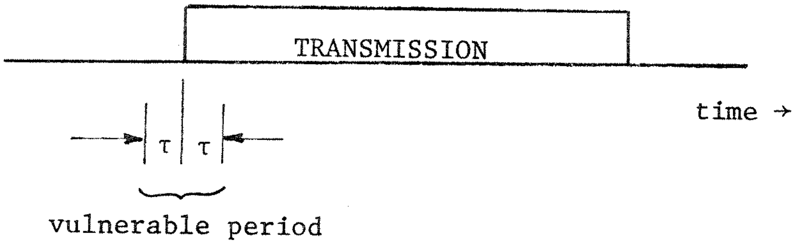

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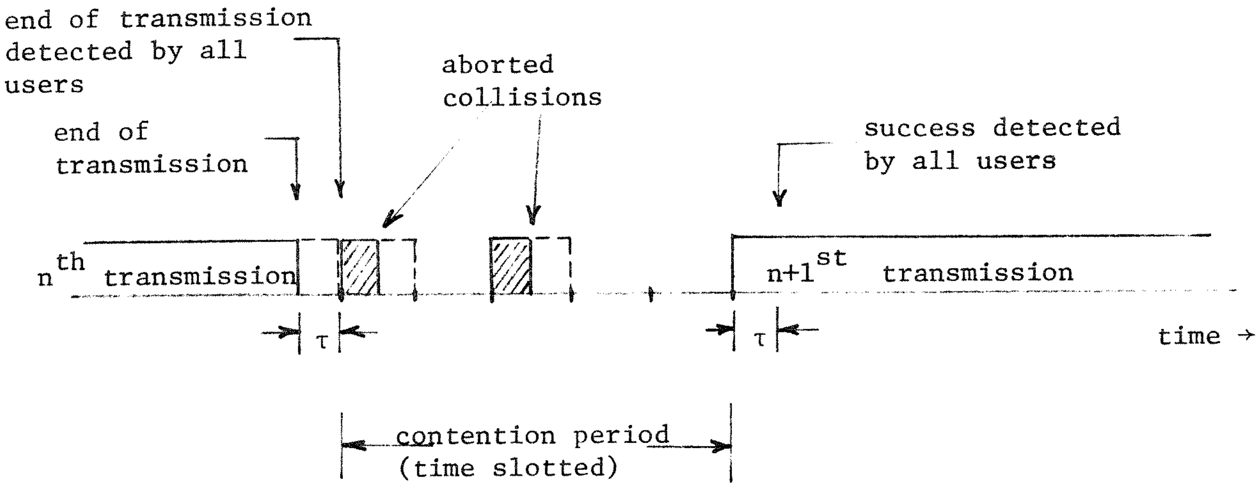

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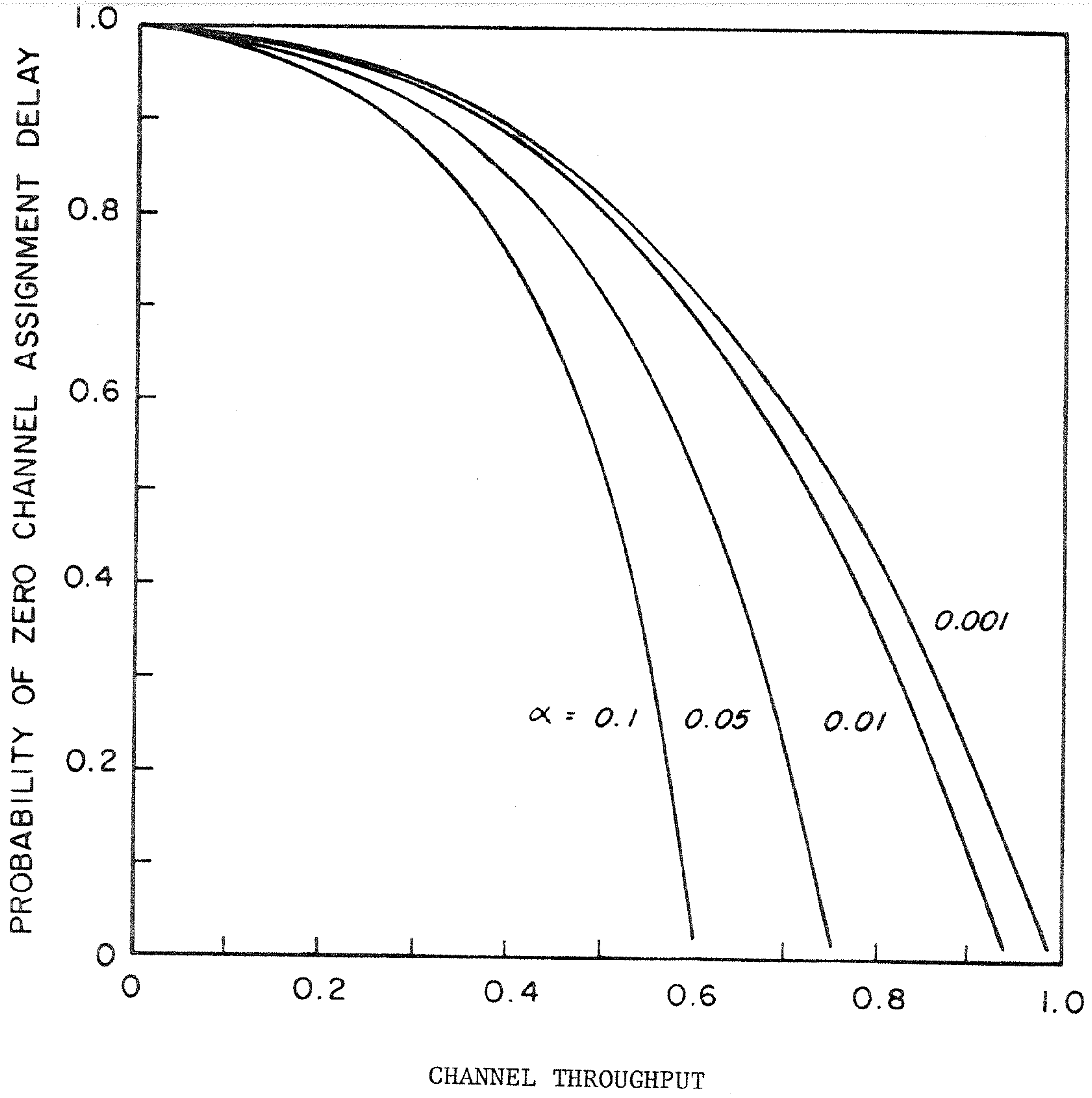

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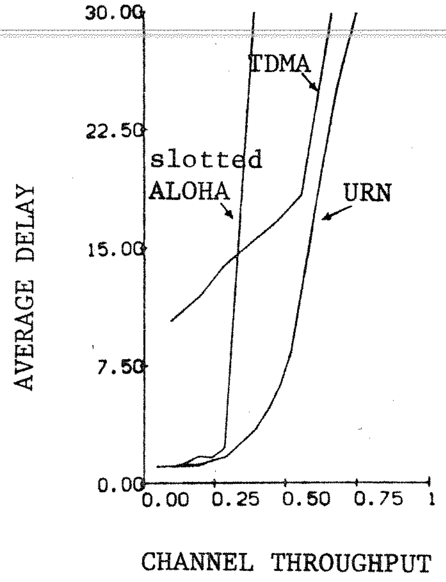

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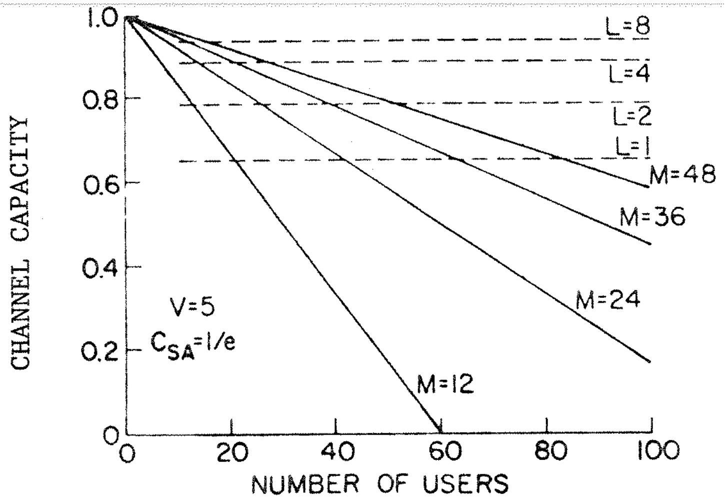

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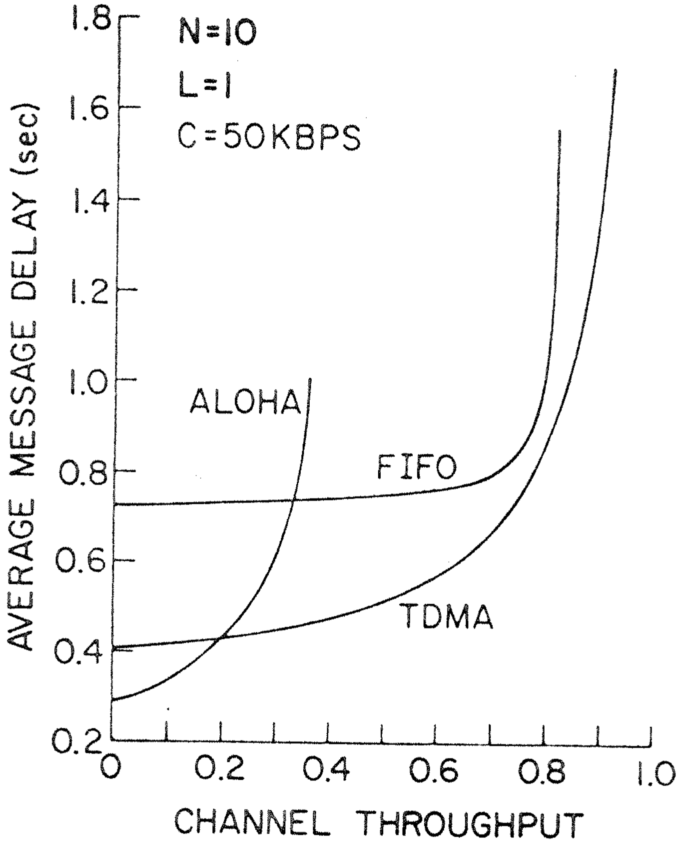

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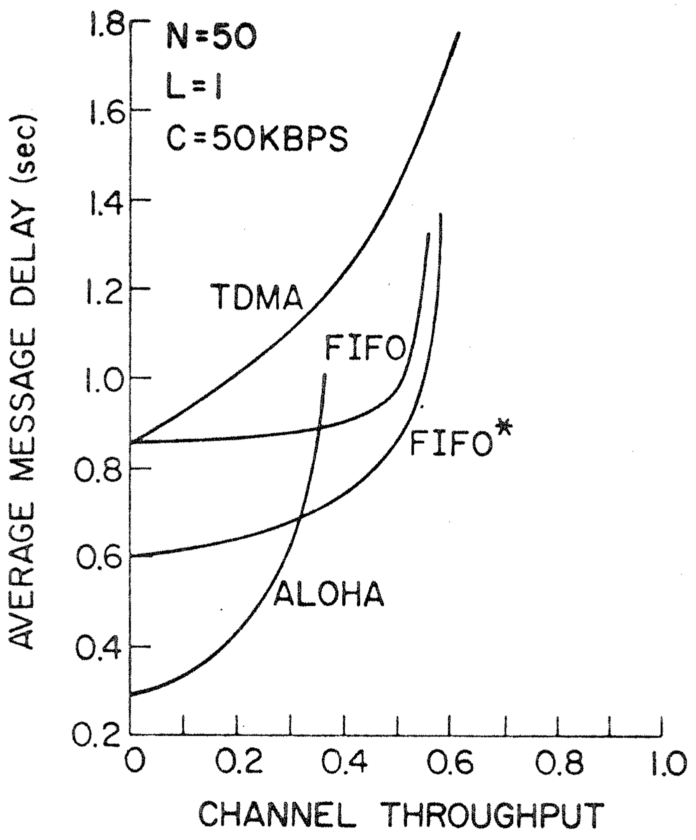

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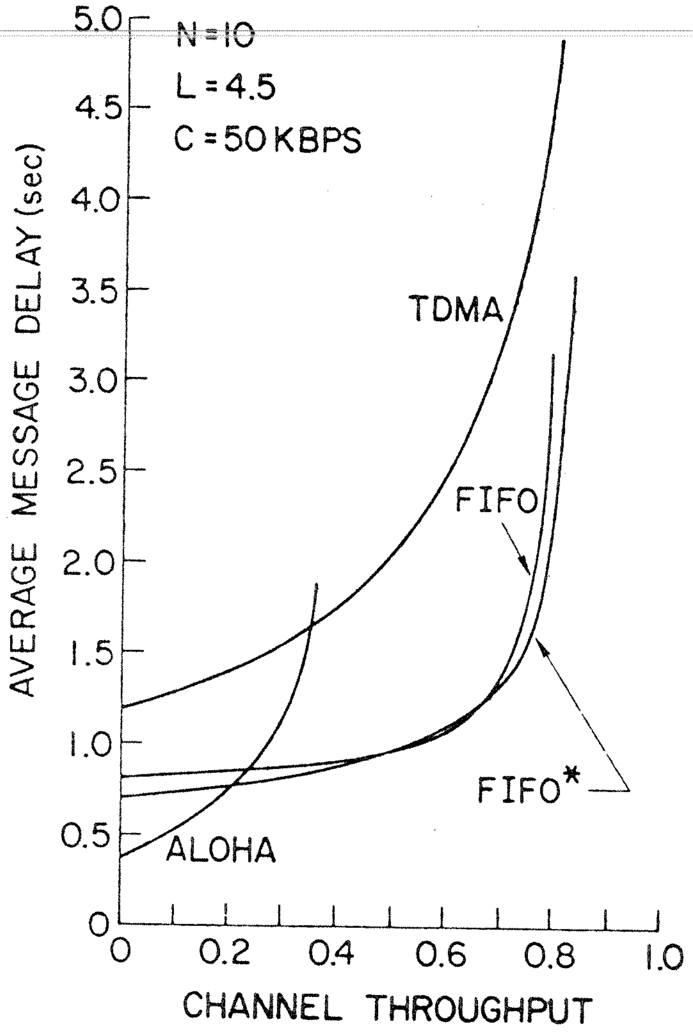

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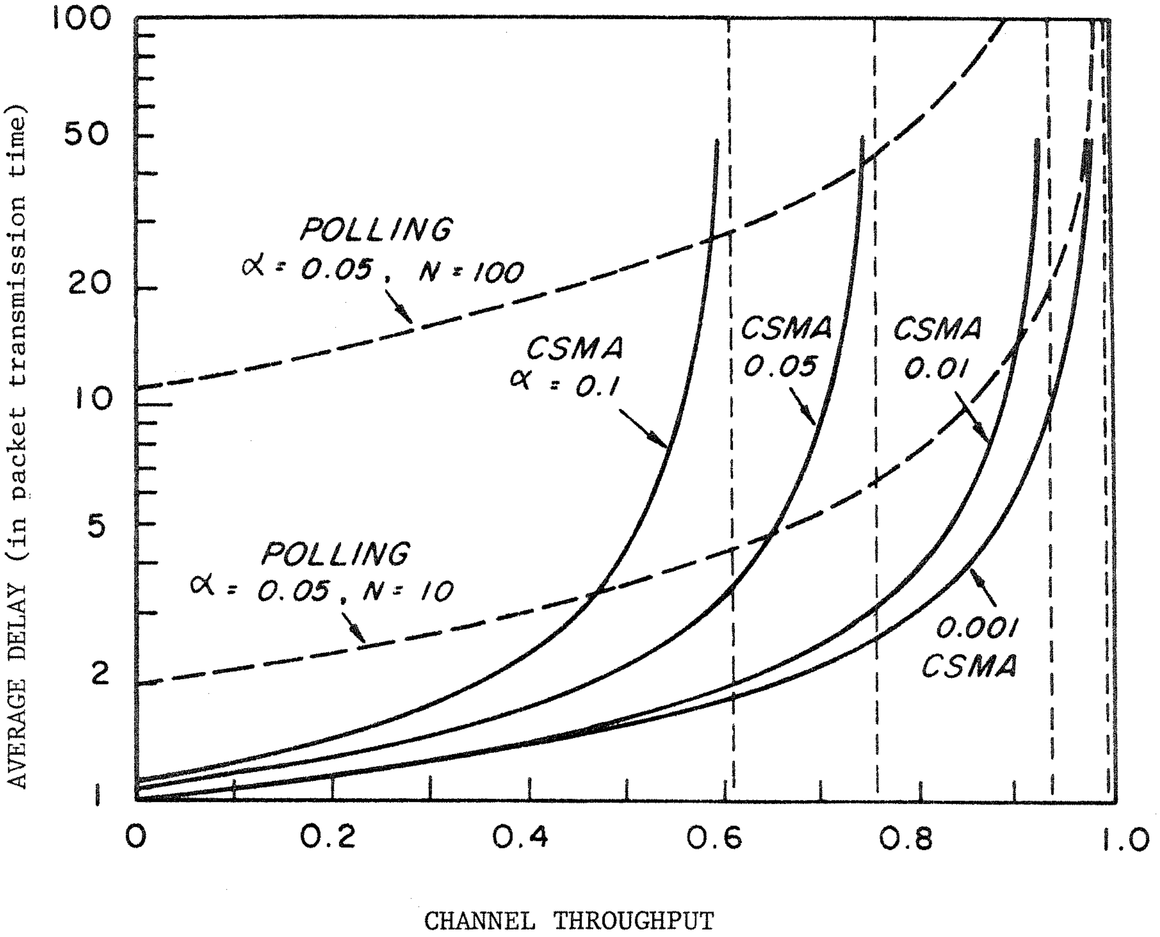

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