A STUDY OF THE CSMA PROTOCOL IN LOCAL NETWORKS*

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Abstract

A consequence of bursty traffic in computer communications is that among a large population of network users, at any one time only a small number of them have data to send (ready users). In this environment, the performance of an access protocol for a broadcast network depends mainly upon how quickly one of the ready users can be identified and given sole access to the shared channel. The relative merits of the access protocols of polling, probing and carrier sense multiple access (CSMA) with respect to this channel assignment delay in local networks are considered. A central controller is needed for polling and probing while CSMA employs distributed control. A specific CSMA protocol is defined which requires that "collisions" in the channel be detected and that the users involved in a collision abort their transmissions quickly. In addition, it is assumed that the contention algorithm is adaptive and gives rise to a stable channel. An analytic model is developed. Our main result is the moment generating function of the distributed queue size (number of ready users). Mean value formulas for message delay and channel assignment delay are also derived. These results on queue size and delay are the major contribution of this paper, since they are not available in prior CSMA models in closed analytical form. Numerical results are given to illustrate the performance of the CSMA protocol. When the channel utilization is light to moderate, the mean channel assignment delay of the CSMA protocol is significantly less than that of both polling and probing; consequently, the mean message delay is much smaller. It is also shown that when queueing of messages is permitted at individual users, the maximum channel throughput of CSMA approaches unity in the limit of very long queues.

1. INTRODUCTION

Multipoint networks have been widely used in local networking for the interconnection of terminals to a central site: either a central computing facility or a gateway to a resource sharing computer network. The terminals are typically unintelltgent and access to the shared data path (channel) is managed by the central site using a polling protocol [1]. With increasing interest in local networking and the availability

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of inexpensive microprocessors, other interconnection topologies, transmission media and access protocols have been proposed and investigated. They include loop networks with centralized control [2] or distributed control [3], a digital cable network using time-division multiple access [4], the ALOHANET [5] and Packet Radio Network [6], which pioneered the use of radio channels and contention protocols for multiple access. Recently, considerable interest has been revived in multipoint cable networks (based upon CATV technology) employing a variety of multiple access protocols [7-10].

The multiple access problem in multipoint networks is addressed in this paper. A multipoint cable network such as those in [8,9] can be viewed upon as a broadcast channel shared by a population of distributed users. Two major categories of multiple access protocols may be used: polling and contention protocols [11]. Polling protocols require a central controller. On the other hand, with contention protocols each network user makes his own decision according to an algorithm which is driven by observable outcomes in the broadcast channel. We shall consider multipoint networks that have short propagation delays between users relative to the transmission time of a message. In a short propagation delay environment, carrier sense multiple access (CSMA) protocols have been found to be the most efficient among contention protocols [12-15].

Consider a broadcast channel (the multipoint network) shared by a population of N users (terminals, computers, etc.). There are two problems to be addressed by an access protocol: (1) among the N users, identify those with data who desire access to the channel, the ready users, and (2) assign channel access to exactly one of the ready users if at least one exists.

The ready users can be considered as forming a "distributed queue" waiting to use the broadcast channel. We assume that each user generates and holds for transmission at most one message of arbitrary length at a time. (The effect of queuing messages at individual users is discussed in the last section of this paper.) A consequence of the conservation law in queuing theory [12] is that the average message delay performance of an access protocol is independent of the order of service but depends mainly upon the amount of overhead needed for assigning channel access. Thus, when access protocols are compared solely on the basis of average message delay performance for a given channel throughput level, the above two problems reduce to just the following: whenever the channel is free and there are one or more ready users, how quickly can channel access be assigned to a ready user?

In conventional polling protocols [1], the above problem is solved by a central controller that queries the N users one after the other. Let $\bar{w}$ be the average overhead associated with querying one user; $\bar{w}$ includes propagation delay, polling message transmission time etc. To find out who the ready users are, the overhead per polling cycle (querying all N users) is $N\bar{w}$, regardless of the number of ready users present. This overhead is an indirect measure of the responsiveness of the access protocol; Konheim and Meister [16] showed that the mean delay of a polled network is directly proportional to $N\bar{w}$.

Hayes [17] recently proposed and studied the method of probing: polling a group of users all at one. The key idea is as follows. If a group of users is probed and none responds, the whole group can be eliminated. If probing a group produces a positive response, it is subdivided into two groups which are then probed separately. Thus when the network is lightly loaded, with few ready users, significant overhead reduction results through eliminating groups of non-ready users all at once. In the extreme case of only one out of the N users being ready, the number of queries required by probing is $2(\log_2 N) + 1$ instead of N required by polling. However, if all N users are ready, the number of queries required by probing is (N^2-1). (See [17] and [11].) Thus probing is penalized when the channel is heavily utilized. Hayes proposed an adaptive algorithm which optimizes the performance of probing and also avoids the above penalty by reverting to pure polling beyond a certain level of channel utilization.

Unlike polling and probing, which require a central controller and are designed for "passive" users, contention protocols require that each ready user actively seek channel access and make his own decisions in the process. We define below a CSMA protocol and show that the time required by it to assign channel access to a ready user is independent of N. Under this protocol, when there is exactly one ready user and the channel is free, the ready user gets channel access immediately. Thus the average "channel assignment delay" is near zero when the channel is lightly utilized. On the other hand, when the channel is heavily utilized the average channel assignment delay is bounded above by a small constant (see below).

CSMA protocols have been studied extensively in the past within a packet radio network environment by Kleinrock and Tobagi [13, 14] and later by Hansen and Schwartz [15]. Analytic results in these references are mainly concerned with the maximum channel "throughput" achievable by various protocols. Characterization of the number of ready users and message delay is limited to approximate numerical solutions or simulation results.

The main contribution of this paper is an analytic model of a CSMA protocol. The protocol is defined and our assumptions stated in Section 2. In Section 3, the moment generating function of the number of ready users is obtained. Formulas for the average message delay and average channel assignment delay are also derived. In Section 4, numerical results are plotted to illustrate the performance of the CSMA protocol, which is also compared with polling. We conclude by discussing possible extensions of this work in Section 5.

2. THE PROTOCOL AND ASSUMPTIONS

The main difference between the CSMA protocol studied in this paper and the p-persistent CSMA protocol of Kleinrock and Tobagi [13, 14] is as follows. We assume here that collisions in the channel are detected and that users involved in a collision abort their transmissions immediately upon detecting the collision. Mechanisms for detecting collisions and aborting collided transmissions have been implemented in at least two multipoint cable networks [8,9]. However, it appears to be much more difficult to implement a "collision abort" capability in the radio environment of interest in [13, 14].

Like the p-persistent protocol in [13,14] network users are assumed to be time synchronized so that following each successful transmission, the channel is slotted in time. (See Fig. 1.) Users can start transmissions only at the beginning of a time slot. Let τ be the amount of time from the start of transmission by one user to when all users sense the presence of this transmission. It is equal to the maximum propagation delay between two users in the network plus carrier detection time. (The latter depends upon the modulation technique and channel bandwidth. It was considered to be negligible relative to the propagation delay in [14].) In order to implement the collision abort capability described above, the minimum duration of a time slot is $T = 2\tau$, so that within a time slot if a collision is detected and the collided transmissions are aborted immediately, the channel will be free of any transmissions at the beginning of the next time slot.

The slotted channel assumption is made to simplify our analysis. (The practical problem of time synchronizing all users in the network is a classical one and beyond the scope of this paper.) In a real system, either a slotted or unslotted channel may be implemented. We discuss in Section 5 that the performance of an unslotted channel is likely to be approximated by that of the slotted model in this paper.

The CSMA protocol in this paper is defined by the following two possible courses of action for ready users:

(P1) Following a successful transmission, each ready user transmits with probability 1 into the next time slot.

(P2) Upon detection of a collision, each ready user uses an adaptive algorithm for selecting its transmission probability (<1) in the next time slot.

It should be clear at this point that we have effectively reduced the contention problem in CSMA to a slotted ALOHA problem. Slotted ALOHA has been studied extensively in the past [18-25], from which we learned that to prevent channel saturation (with zero probability of a successful transmission), the transmission probability of each ready user must be adaptively adjusted. Various control strategies have been proposed and studied. Experimental results have shown that a slotted ALOHA channel can be adaptively controlled to yield an equilibrium throughput rate S close to the theoretical limit of $1/e$ (=0.368) for a large population of users [21-24]. With an asymmetric strategy, the achievable S will be even higher [25].

For our analysis in the next section, we shall assume that in (P2) a suitable adaptive algorithm is used so that the probability of a successful transmission (slotted ALOHA throughput) in the next time slot is equal to a constant S. This assumption is an approximation but has been found to be a very good one in simulation studies [21-24].

We shall further assume that errors due to random noise are insignificant relative to errors due to collisions and can be neglected. The source of traffic to the broadcast channel consists of an infinite population of users who collectively form an independent Poisson process with an aggregate mean message generation rate of λ messages per second. This approximates a large but finite population in which each user generates messages infrequently; each message can be transmitted in an interval much less than the average time between successive messages generated by a given user. Each user is allowed to store and attempt to transmit at most one message at a time. Thus the generation of a new message is equivalent to increasing the number of ready users by one. The effect of queuing messages at individual users is discussed later.

Finally, the transmission time of each message is an independent identically distributed (i.i.d.) random variable with the probability distribution function (PDF) $\beta(x)$, mean value b_1, second moment b_2 and Laplace transform $\beta^*(s)$.

3. THE ANALYSIS

The ready users can be considered to form a distributed queue with random order of service for the broadcast channel. We are interested in obtaining the equilibrium moment generating function of the distributed queue size. We shall use an imbedded Markov chain analysis. Under the assumptions of Poisson arrivals and that messages arrive and depart one at a time, the moment generating function of queue size obtained for the imbedded points is valid for all points in time.

A snapshot of the channel is illustrated in Fig. 1. We define the following random variables:

q_n = number of ready users left behind by the departure of the n^{th} transmission, C_n

y_{n+1} = time from the departure of C_n to the beginning of the next successful transmission

u_{n+1} = number of new (Poisson) arrivals during y_{n+1}

x_{n+1} = transmission time of C_{n+1}

v_{n+1} = number of new (Poisson) arrivals during $x_{n+1} + \tau$.

We assumed earlier that x_{n+1} has the PDF $\beta(x)$. We shall let $B(x)$ be the PDF of $x_{n+1} + \tau$. The corresponding Laplace transform is thus

$$B^*(s) = \beta^*(s)e^{-s\tau}$$

The random variable y_{n+1} is the sum of two independent random time intervals

$$y_{n+1} = (I_{n+1} + r_{n+1})T$$

where T is the duration of a slot, I_{n+1} is the number of slots in an idle period immediately following the departure of C_n, and r_{n+1} is the number of slots in the contention period following a collision until the next successful transmission. The slot containing the initial collision is included in r_{n+1}. We note that I_{n+1} is nonzero only if $q_n = 0$. Also, if there has been no collision when C_{n+1} begins, $r_{n+1} = 0$.

Let p_j be the probability of j new arrivals (ready users) in a time slot.

$$p_j = \frac{(\lambda T)^j e^{-\lambda T}}{j!} \qquad j = 0,1,2,...$$

At the start of the next time slot, each new arrival executes (P1) or (P2) in exactly the same manner as all other ready users.

Given our earlier assumptions, we have

$$\text{Prob}[I_{n+1} = k/q_n = 0] = (1-p_0)p_0^{k-1} \qquad k = 1,2,...$$

Also,

$$\text{Prob}[r_{n+1} = k/\text{collision occurred}] = S(1-S)^{k-1} \qquad k = 1,2,...$$

From this last result, the Laplace transform of the probability density function (pdf) of a contention period (given a collision occurred) is

$$C^*(s) = \frac{Se^{-sT}}{1-(1-S)e^{-sT}}$$

which has a mean of T/S and a second moment of $T^2(1 + \frac{2(1-S)}{S^2})$.

The following important relationship is evident from Fig. 1.

$$q_{n+1} = q_n + u_{n+1} + v_{n+1} - 1 \qquad (1)$$

where v_{n+1} is an independent random variable with the z-transform $B^*(\lambda-\lambda z)$, while u_{n+1} depends upon q_n in the following manner as a consequence of (P1) and (P2). Given

(1) $q_n = 0$,

$$u_{n+1} = \begin{cases} 1 & \text{with prob. } \frac{p_1}{1-p_0} \\ j + \text{number of arrivals during a contention period} & \text{with prob. } \frac{p_j}{1-p_0} \end{cases}$$

(2) $q_n = 1$, $u_{n+1} = 0$

(3) $q_n \geq 2$, u_{n+1} = number of arrivals during a contention period. (2)

Given the occurrence of a collision, the number of new arrivals during a contention period is an independent random variable with the z-transform $C^*(\lambda-\lambda z)$.

The equilibrium queue length probabilities

$$Q_k = \lim_{n\to\infty} \text{Prob}[q_n = k] \qquad k = 0,1,2,...$$

exist if $\lambda(b_1 + \tau + T/S) < 1$ (see below). Define the z-transform

$$Q(z) = \sum_{k=0}^{\infty} Q_k z^k.$$

By considering Eqs. (1) and (2) and taking the $n \to \infty$ limit, we obtain after some algebraic manipulations the following important result:

$$Q(z) = \frac{B^*(\lambda-\lambda z)\{Q_1 z[1-C^*(\lambda-\lambda z)] + \frac{Q_0}{1-p_0}[p_1 z(1-C^*(\lambda-\lambda z)) - C^*(\lambda-\lambda z)(1-e^{-\lambda T(1-z)})]\}}{z - B^*(\lambda-\lambda z)\, C^*(\lambda-\lambda z)} \tag{3}$$

where

$$Q_0 = \frac{1-\lambda\,(b_1 + \tau + T/S)}{\lambda T[\frac{1}{1-p_0} - \frac{1}{B^*(\lambda)S}]} \tag{4}$$

and

$$Q_1 = \left(\frac{1}{B^*(\lambda)} - \frac{p_1}{1-p_0}\right) Q_0 \tag{5}$$

Using Eqs. (3) - (5), we can obtain the mean queue size. Application of Little's result [12] yields the mean message delay (time of arrival to time of departure) to be

$$D = \bar{x} + \frac{T}{S} + \frac{T}{2} - \frac{1-p_0}{2[B^*(\lambda)S-(1-p_0)]}\left(\frac{2}{\lambda} + ST - 3T\right) + \frac{\lambda[\overline{x^2} + 2\,\bar{x}\,\frac{T}{S} + T^2(1 + 2\,\frac{1-S}{S^2})]}{2[1 - \lambda(\bar{x} + \frac{T}{S})]} \tag{6}$$

where

$$\bar{x} = b_1 + \tau$$

and

$$\overline{x^2} = b_2 + 2b_1\,\tau + \tau^2$$

We next consider the channel assignment delay, that is, given that the channel is free and that there is at least one ready user, we want the pdf of the time from when the above conditions are satisfied to the start of the next successful transmission. Let d_n be a random variable representing the channel assignment delay immediately prior to the n^{th} transmission and

$$d = \lim_{n\to\infty} d_n$$

It can be readily shown that

$$\text{Prob}\,[d = k] = \begin{cases} Q_0 \dfrac{p_1}{1-p_0} + Q_1 & k = 0 \\ \left[Q_0\left(1-\dfrac{p_1}{1-p_0}\right) + \sum\limits_{i=2}^{\infty} Q_i\right] S(1-S)^{k-1} & k = 1,2,\ldots \end{cases} \tag{7}$$

The mean channel assignment delay is thus

$$\bar{d} = \frac{1}{S}\left(1 - Q_0 \frac{p_1}{1-p_0} - Q_1\right) \tag{8}$$

Note that $Q_0 \frac{p_1}{1-p_0} + Q_1$ is the fraction of transmissions that incur zero delay in gaining channel access (given that the channel is free).

4. PERFORMANCE OBSERVATIONS

An important performance parameter is the ratio of the carrier sense time τ to the mean message transmission time b_1:

$$\alpha = \frac{\tau}{b_1}$$

The <u>throughput</u> of the CSMA channel is defined to be the fraction of channel time utilized by data messages, which is

$$\rho = \lambda b_1$$

under equilibrium conditions.

In Fig. 2, we show the delay performance of the CSMA channel as a function of α and ρ. The normalized delay D/b_1 is plotted and it is assumed that messages are of constant length. Observe that the delay performance of CSMA improves significantly as α becomes small. A small α may come about either by decreasing the carrier sense time τ or by increasing the duration b_1 of each user transmission.

In these numerical calculations, the probability S of a successful transmission during contention periods is assumed to be 1/e which is the slotted ALOHA throughput rate in an infinite population model. Experience with experimental results [21-25] indicates that S = 1/e is pessimistic when the number of contending ready users is small (small ρ) and optimistic when the number of contending ready users is large (large ρ). Thus the same comments will apply to the CSMA delay results in Fig. 2.

The delay-throughput performance of roll-call polling is also shown using the delay formula in [16]. The delay results shown for polling also assume Poisson message arrivals and constant message length. The ratio of propagation delay to message transmission time is $\alpha = 0.05$. The ratio of data to polling message length is 10. Queuing of messages at individual users is assumed; hence the maximum channel throughput is one. Delay-throughput curves for both 10 users and 100 users are shown. Note that the corresponding delay-throughput performance of CSMA at $\alpha = 0.05$ is independent of the number of users. It also permits no queuing of messages at individual users; hence the maximum throughput is less than 1. We observe that CSMA is superior to polling when the channel throughput is low but becomes inferior when the channel throughput is increased to one. However, if queuing of messages is possible at individual users for CSMA, more than one message may be transmitted every time a user gains channel access. Hence, as the network load ρ is increased from 0 to 1, the delay performance of CSMA is 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 is one in the limit of infinitely long queues at individual users.

In Fig. 3, we show the mean channel assignment delay $\bar{d}$ as a function of α and ρ. Note that $\bar{d}$ decreases to zero when ρ is small. This is because (P1) in the CSMA protocol permits a ready user to access the channel immediately. In Fig. 4 we plot the fraction of transmissions that incur zero delay in gaining channel access given that the channel is free. For comparison, recall that when only one ready user is present, the polling cycle overhead is $N\bar{w}$ for conventional polling and $[2(\log_2 N)+1]\bar{w}$ for probing.

Referring again to Fig. 3, observe that as ρ is increased, $\bar{d}/T$ increases to the maximum value of $1/S$. This desirable property is a consequence of the presence of an adaptive algorithm that we assumed in (P2) which guarantees channel stability during contention periods.

Another advantage that CSMA has over polling protocols is that the time slot duration T is typically much smaller than its counterpart $\bar{w}$ in polling protocols since $\bar{w}$ must include the transmission time of a polling message.

5. CONCLUSIONS

We considered a CSMA protocol as a distributed control technique for a population of users sharing a multipoint network. The capability of aborting collided transmissions is the main difference between our model and previous models of CSMA. It is also assumed that the channel is stable during contention periods (presence of an adaptive control algorithm). Our main results include the moment generating function of the number of ready users, as well as mean value formulas for message delay and channel assignment delay. These results are new. The modeling of the queue size and message delay has previously been limited to numerical solutions or simulations.

We found that the CSMA protocol as defined in this paper has the desirable property that when the channel is lightly utilized, the channel assignment delay is extremely short. The performance of CSMA when the channel is heavily utilized depends upon the ratio α. We make the following observation. If the number of users is finite and queuing of messages is permitted at individual users, then as $\rho\uparrow 1$, we must have $\alpha\downarrow 0$, since the transmission time of each user increases as a result of long queues. In this case, the maximum channel throughput of CSMA is one (the same as polling with queueing permitted at individual users).

Lastly, we discuss the issue of channel slotting. A slotted channel was assumed in our analysis. In practice, either a slotted or unslotted channel may be implemented. The analysis of an unslotted protocol will be more involved. However, the following observation indicates that the performance of an unslotted protocol should be approximated by our slotted model in this paper. In the analysis of slotted and pure ALOHA [12,18] it was found that the probability of success of a transmission depends mainly upon the duration of its "vulnerable period" to another transmission. The vulnerable period in our slotted CSMA channel is the duration of a time slot T. On the other hand, the vulnerable period in an unslotted version of our CSMA protocol would be 2τ (after a little thought) which is the sames as T. Thus the probability that an attempted transmission is successful during a contention period is approximately the same in both cases.

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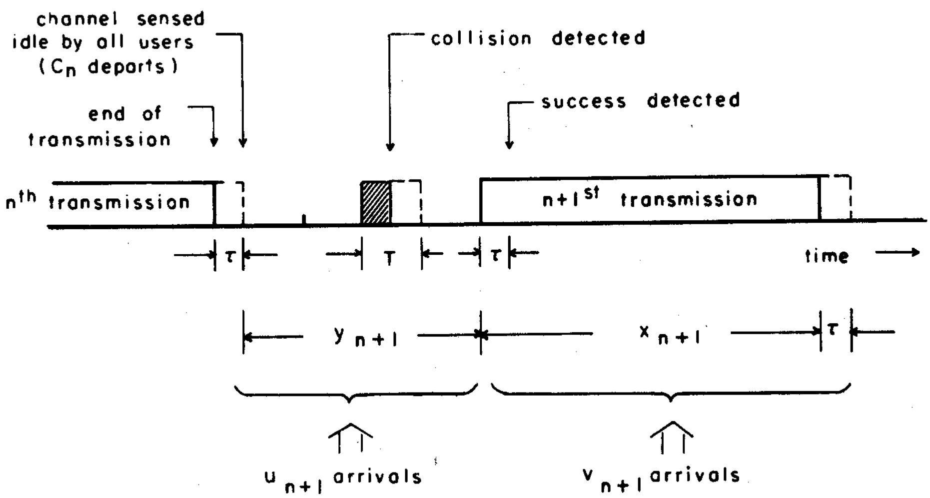

Figure 1. A snapshot of the broadcast channel.

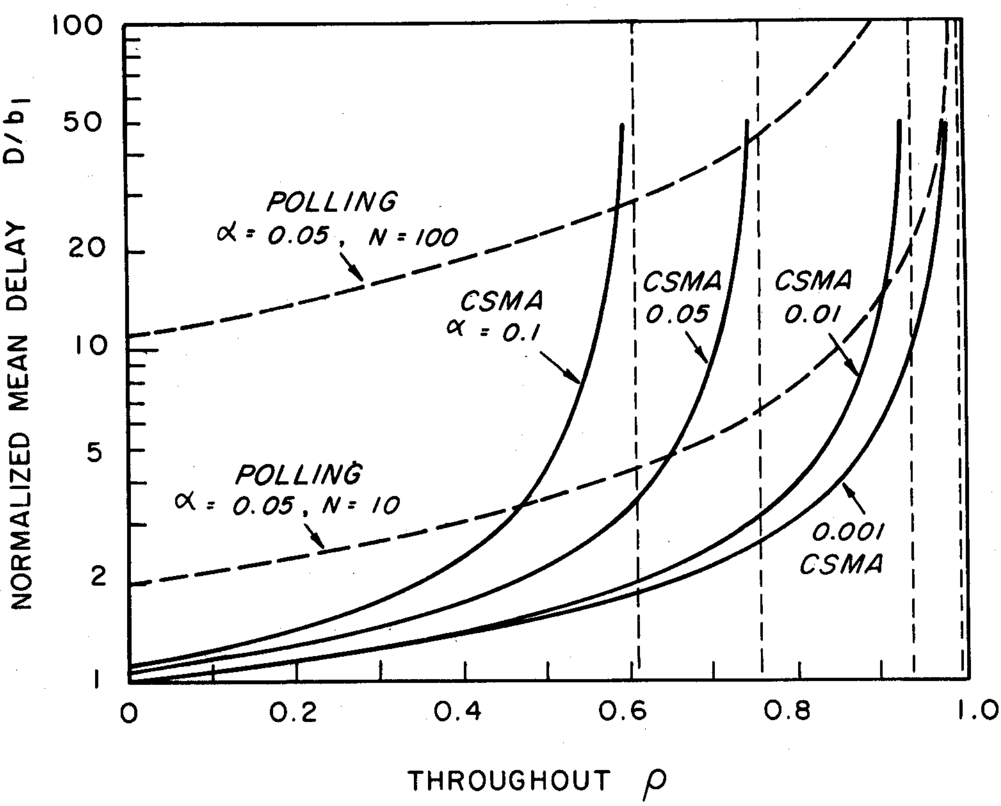

Figure 2. Delay versus throughput.

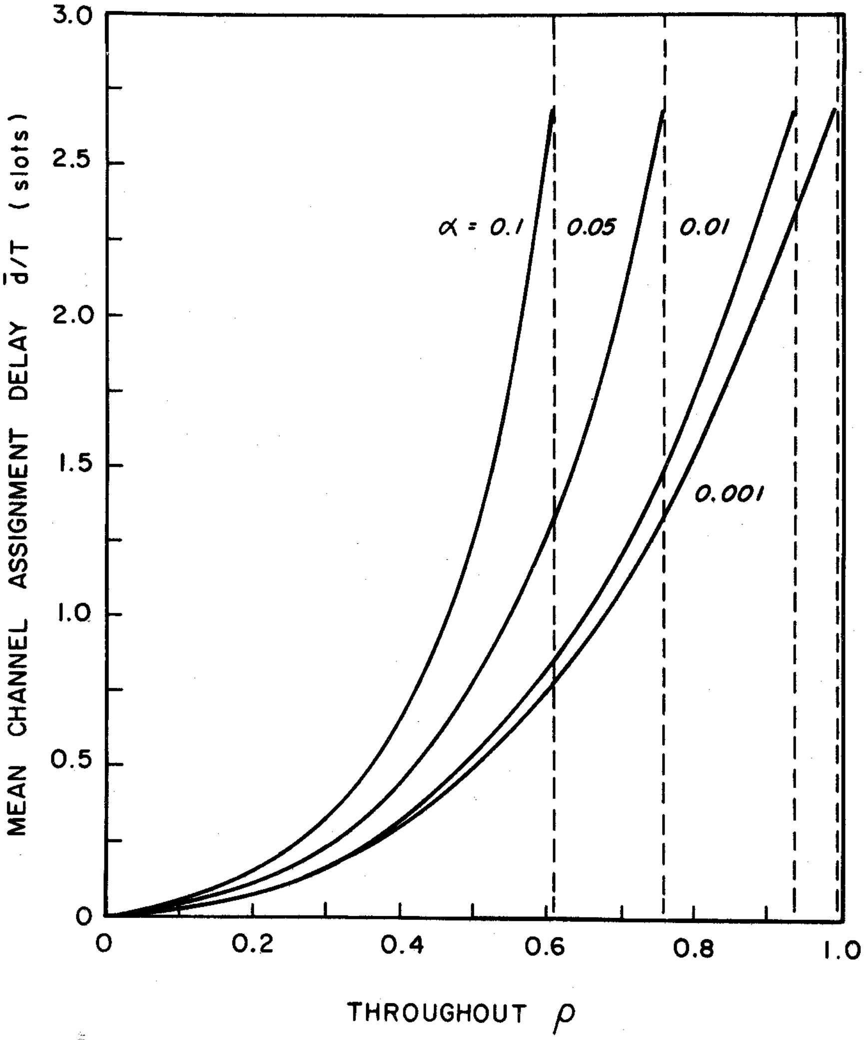

Figure 3. Channel assignment delay versus throughput.

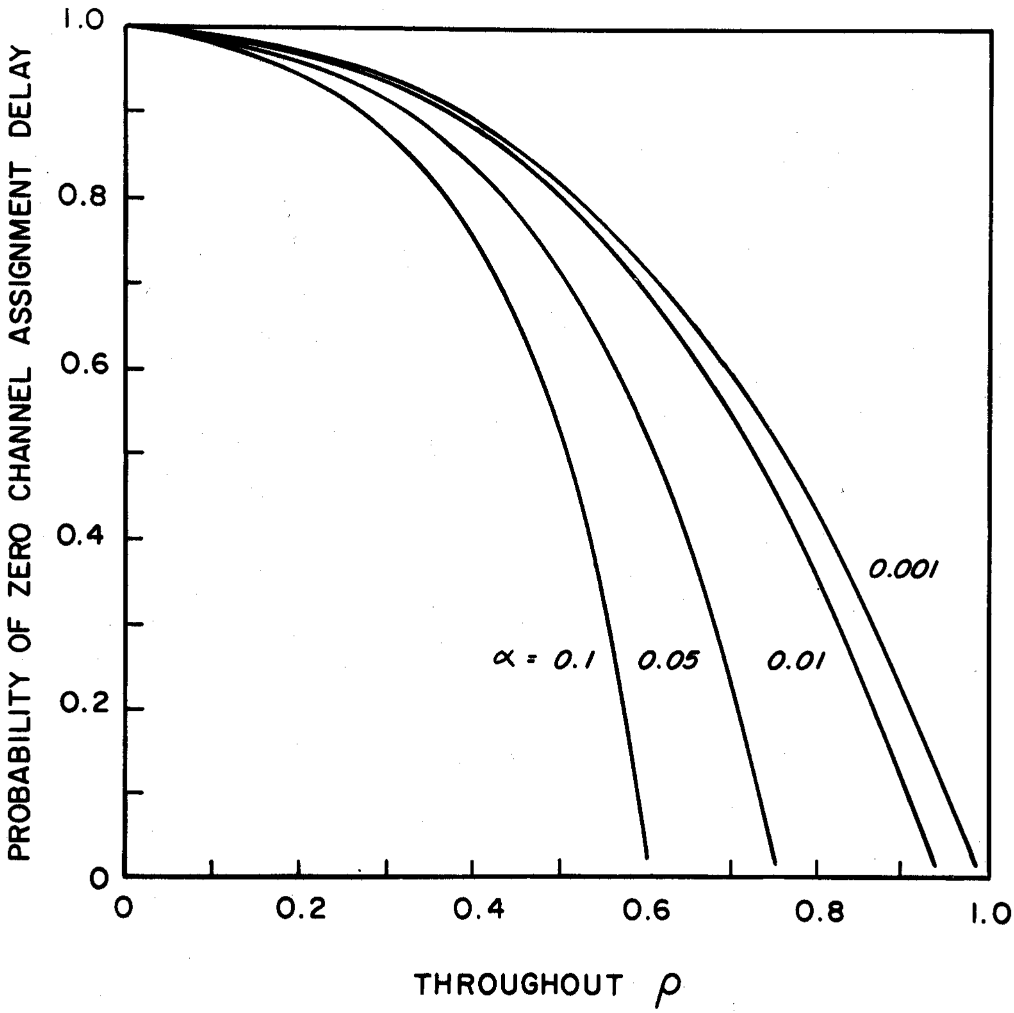

Figure 4. Probability of zero channel assignment delay versus throughput.