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CARRIER SENSE MULTIPLE ACCESS FOR PACKET SWITCHED RADIO CHANNELS*

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ABSTRACT

Radio communication is considered as a method for providing remote terminal access to computers. Digital byte streams are partitioned into packets (blocks) and transmitted in a burst mode over a shared radio channel. When many terminals operate in this fashion, transmissions may conflict with and destroy each other. A means for controlling this is for the terminal to sense the presence of other transmissions; this leads to the Carrier Sense Multiple Access (CSMA) method for multiplexing in a packet radio environment. Three protocols are described for CSMA and their throughput-delay characteristics are given.

1. INTRODUCTION

Large computer installations, enormous data banks, and extensive national computer networks are now becoming available. They constitute large expensive resources which must be utilized in a cost/effective fashion. The constantly growing number of computer applications and their diversity render the problem of accessing these large resources a rather fundamental one. Prior to 1970, wire connections were the principal means for communication among computers and between users and computers. The reasons were simple: dial-up and leased telephone lines were available and could provide inexpensive and reasonably reliable communications for short distances, using a readily available and widespread technology. It was long recognized that this technology was inadequate for the needs of a computer-communication system which is required to handle bursty traffic (i.e., large peak to average data rates). For example, the inadequacies included the long dial-up and connect time, the minimum three-minute tariff structure, the fixed and limited data rates, etc. However, it was not until 1969 that the cost to switch communication bandwidth dropped below the cost of the bandwidth being switched.[1] At that time, the new technology of packet-switched computer networks emerged and developed a cost/effective means for connecting computers together over long distance, high speed lines. However, these networks did not solve the local interconnection problem; namely, how can one efficiently provide access from the user to the network itself? Certainly, one solution is to use wire connections here also. An alternate solution is the subject of this paper; namely, ground radio packet switching.

Thus, we wish to consider radio communications as an alternative for computer and user communications. The ALOHA System[2] appears to have been the first such system to employ wireless communications. The advantages in using broadcast radio communications are many: easy access to central computer installations and computer networks, collection and dissemination of data over large distributed geographical areas independent of the availability of preexisting (telephone) wire networks, the suitability of wireless connections for communications with and among mobile users (a constantly growing area of interest and applications), easily bypassed hostile terrain, etc. Perhaps, the broadcast property is one of the most important.

Consider now an environment consisting of a number of (possibly mobile) users in line-of-sight and within range of each other, all communicating over a (broadcast) radio channel. The classical approach for satisfying the requirement of two users who need to communicate is to provide a communication channel for their use so long as their need continues (line-switching). However, the measurements of Jackson and Stubbs[3] show that such allocation of scarce communication resources is extremely wasteful. Rather than providing channels on a user-pair basis, we much prefer to provide a single high-speed channel to a large number of users which can be shared in some fashion. This, then, allows us to take advantage of the powerful "large number laws" which state that with very high probability, the demand at any instant will be approximately equal to the sum of the average demands of that population. We wish to take advantage of these gains due to resource sharing.

Of interest to this paper is the consideration of radio channels for packet switching (also called Packet Radio Channels). A packet is merely a package of data prepared by one user for transmission to some other user in the system. As soon as we deal with shared channels in a packet-switching mode, then we must be prepared to resolve conflicts which arise when more than one demand is simultaneously placed upon the channel. In packet radio channels, whenever a portion of one user's transmission overlaps with another user's transmission, the two collide and "destroy" each other. The existence of some acknowledgement scheme permits the transmitter to determine if his transmission was successful or not. The problem we are faced with is how to control the access to the channel in a fashion which produces, under the physical constraints of simplicity and hardware implementation, an acceptable level of performance. The difficulty in controlling a channel which must carry its own control information gives rise to the so-called random access modes. A simple scheme, known as "pure ALOHA", permits users to transmit any time they desire. If, within some appropriate time-out period, they receive an acknowledgement from the destination, then they know that no conflicts occurred. Otherwise, they assume a collision occurred and they must retransmit. To avoid continuously repeated conflicts, some scheme must be devised for introducing a random retransmission delay, spreading the conflicting packets over time. A second method for using the radio channel is to modify the completely unsynchronized use of the ALOHA channel by "slotting" time into segments whose duration is exactly equal to the transmission time of a single packet (assuming constant length packets). If we require each user to start his packets only at the beginning of a slot, then when two packets conflict, they will overlap completely rather than partially, providing an increase in channel efficiency. This method is referred to as "slotted ALOHA".[4,5]

The radio channel as considered in this paper is characterized as a high-speed capacity channel with a propagation delay between any source-destination pair which is very small compared to the packet transmission time.* This suggests a third approach for using the

*This research was supported by the Advanced Research Projects Agency of the Department of Defense under Contract No. DAHC15-73-C-0368.

*Consider, for example, 1000 bit packets transmitted over a channel operating at a speed of 100 Kb/s. The transmission time of a packet is then 10 mseconds. If the maximum distance between the source and the destination is 10 miles, then the (continued on next sheet)

channel; namely, the Carrier-Sense Multiple Access (CSMA) mode. In this scheme one attempts to avoid collisions by listening to (i.e., "sensing") the carrier due to another user's transmission. Based on this information about the state of the channel, one may think of various actions to be taken by the terminal. Three protocols will be described and analyzed which we call "persistent" CSMA protocols: the 1-Persistent, the non-Persistent, and the p-Persistent CSMA. Below, we present the protocols, discuss the assumptions, and finally display the throughput-delay performance for each.

2. TRANSMISSION PROTOCOLS AND SYSTEM ASSUMPTIONS

The various protocols considered differ by the action (pertaining to packet transmission) that a terminal takes after sensing the channel. When a terminal learns that its transmission was unsuccessful, it reschedules the transmission of the packet according to a randomly distributed transmission delay. At this new point in time, the transmitter senses the channel and repeats the algorithm dictated by the protocol. At any instant a terminal is called a ready terminal if it has a packet ready for transmission at this instant (either a new packet just generated or a previously conflicted packet rescheduled for transmission at this instant).

A terminal may, at any one time, either be transmitting or receiving (but not both simultaneously). However, the delay incurred to switch from one mode to the other is negligible. All packets are of constant length and are transmitted over an assumed noiseless channel (i.e., the errors in packet reception caused by random noise are not considered to be a serious problem and are neglected in comparison with errors caused by overlap interference). The system assumes non-capture (i.e., the overlap of any fraction of two packets results in destructive interference and both packets must be retransmitted). We further simplify the problem by assuming the propagation delay (small compared to the packet transmission time) to be identical* for all source-destination pairs.

The 1-Persistent CSMA protocol is devised in order to (presumably) achieve acceptable throughput by never letting the channel go idle if some ready terminal is available. More precisely, a ready terminal senses the channel and operates as follows:

- If the channel is sensed idle, it transmits the packet with probability one.
- If the channel is sensed busy, it waits until the channel goes idle (i.e., persisting on transmitting) and only then transmits the packet (with probability one -- hence, the name, 1-Persistent).

A slotted version of the 1-Persistent CSMA can be considered in which the time axis is slotted and the slot size is τ seconds (the propagation delay). All terminals are synchronized and are forced to start transmission only at the beginning of a slot. When a packet's arrival occurs during a slot, the terminal senses the channel at the beginning of the next slot and operates according to the protocol described above.

We next consider the non-Persistent CSMA (or carrier sense with randomized resensing delay). While the previous protocol was meant to make "full" use of the channel, the idea here is to limit the interference among packets by always rescheduling a packet which finds the channel busy upon arrival. However, this scheme may introduce idle periods between two consecutive non-overlapped transmissions. More precisely, a ready terminal senses the channel and operates as follows:

- If the channel is sensed idle, it transmits the packet.
- If the channel is sensed busy, then the terminal schedules the retransmission of the packet to some later time according to the retransmission delay distribution. At this new point in time, it senses the channel and repeats the algorithm described.

Last, we consider the p-Persistent CSMA (or carrier sense with initial random transmission delay). The two previous protocols differ by the probability (one or zero) of not rescheduling a packet which upon arrival finds the channel busy. In the case of a 1-Persistent CSMA, we note that whenever two or more terminals become ready during a transmission period, they wait for the channel to become idle (at the end of that transmission) and then they all transmit with probability one. A conflict will also occur with probability one! The idea of randomizing the starting times of transmission of packets accumulating at the end of a transmission period suggests itself for interference reduction and throughput improvement. The scheme consists of including an additional parameter p, the probability that a ready packet persists (1-p being the probability of delaying transmission by τ seconds). The parameter p will be chosen so as to reduce the level of interference while keeping the idle periods between any two consecutive non-overlapped transmissions as small as possible.

More precisely, the protocol consists of the following: the time axis is slotted where the slot size is τ seconds. For simplicity of analysis, we consider the system to be synchronized such that all packets begin their transmission at the beginning of a slot.

Consider a ready terminal:

- If the channel is sensed idle, then
  - with probability p, the terminal transmits the packet.
  - with probability 1-p, the terminal delays the transmission of the packet by τ seconds (i.e., one slot). If at this new point in time, the channel is still detected idle, the same process above is repeated; otherwise, some packet must have started transmission, and our terminal schedules the retransmission of the packet according to the retransmission delay distribution (i.e., acts as if it had conflicted and learned about the conflict).
- If the ready terminal senses the channel busy, it waits until it becomes idle (at the end of the current transmission) and then operates as above.

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*By considering this constant propagation delay equal to the largest possible, one gets lower (i.e., pessimistic) bounds on performance.

(cont'd from preceding sheet) (speed of light) packet propagation delay is of the order of 54 µseconds. Thus the propagation delay constitutes only a very small fraction (a = .005) of the transmission time of a packet.

3. TRAFFIC MODEL: ASSUMPTIONS AND NOTATION

In the previous section, we identified the system protocols, operating procedure and assumptions. Here we characterize the traffic source and its underlying assumptions.

We assume that our traffic source consists of an infinite number of users who collectively form an independent Poisson source with an aggregate mean packet generation rate of λ packets/second. This implies that each user will generate packets infrequently and each packet can be successfully transmitted in a time interval much less than the average time between successive packets generated by a given user. Thus, each user in the infinite population will have at most one packet requiring transmission at any time (including any previously blocked packet).

In addition, we characterize the traffic as follows. We have assumed that each packet is of constant length requiring T seconds for transmission. Let $S = \lambda T$. S is the average number of packets generated per transmission time, i.e., the input rate normalized with respect to T. If we were able to perfectly schedule the packets into the available channel space with absolutely no overlap or space between the packets, we would have $S = 1$; therefore, we also refer to S as the channel utilization, or throughput. The maximum achievable throughput for an access mode is called the capacity of the channel under that mode.

Since conflicts can occur, some acknowledgement scheme is necessary to inform the transmitter of its success or failure. We assume a positive acknowledgement scheme*: If within some specified delay (an appropriate time-out period) after the transmission of a packet, a user does not receive an acknowledgement, he knows he has conflicted. If now he retransmits immediately, and if all users behave likewise, then he will definitely be interfered with again (and forever!). Consequently, each user delays the transmission of a previously collided packet by some random time whose mean is $\bar{X}$ (chosen, for example, uniformly between 0 and $X_{max} = 2\bar{X}$). As a result, the traffic offered to the channel from our collection of users will now consist of new packets and previously collided packets. This increases the mean offered traffic rate to G packets per transmission time T, where $G \geq S$.

Our two further assumptions are:

(A1) The average retransmission delay $\bar{X}$ is large compared to T.

(A2) The interarrival times of the point process defined by the start times of all the packets plus retransmissions are independent and exponentially distributed.

We wish to solve for the channel capacity of the system using various access protocols. This we do in section 4 by solving for S in terms of G (as well as the other system parameters). The channel capacity is then found by maximizing S with respect to G. From the (S, G) relationship, we have S/G which is merely the probability of a successful transmission and G/S which is the average number of times a packet must be transmitted (or scheduled) until success. Furthermore, in section 5, we discuss delay and give the throughput-delay tradeoff for these protocols.

So far, we have defined the following important system variables: S, G, T, $\bar{X}$, τ, and p. Without loss of generality, we choose $T = 1$. This is equivalent to expressing time in units of T. We may express $\bar{X}$ and τ in these normalized time units as $\delta = \bar{X}/T$ and $a = \tau/T$.

*The channel for acknowledgement is assumed to be separate from the channel we are studying (i.e., acknowledgements arrive reliably and at no cost).

4. THROUGHPUT ANALYSIS

4.1 ALOHA Channels. In the pure ALOHA access mode, each terminal transmits its packet over the data channel in a completely unsynchronized manner. Under the system and model assumptions, we can calculate the probability that a given packet interferes with another packet as follows. A given packet will overlap with another packet if there exists at least one start of transmission within T seconds before or after the start time of the given packet. Since the traffic is Poisson, we have[2]

$$S = Ge^{-2G} \tag{1}$$

which also shows that pure ALOHA achieves a maximum throughput of $1/(2e) = .184$ (at $G = 1/2$).

In slotted ALOHA, if two packets conflict, they will overlap completely rather than partially. The throughput equation becomes

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

and was first obtained by Roberts[5] who extended Abramson's result in Eq. (1). The maximum throughput is increased to $1/e = .368$ (at $G = 1$). Below, in Fig. 4, we plot the throughput S versus G for these and the following systems.

4.2 1-Persistent CSMA. The arrival of any packet, new or rescheduled, in 1-Persistent CSMA, as in the ALOHA systems, results in an actual transmission. Again, G is the measure of total channel traffic. For the analysis, we identify the busy and idle periods (see Fig. 1)

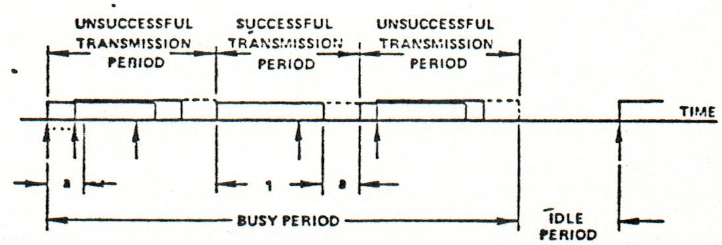

Fig. 1. 1-Persistent CSMA

as well as the condition for success over a transmission period as shown in Fig. 1; in this and succeeding figures, the vertical arrow (↑) indicates the event of a terminal becoming ready. We have shown[6,7] that the throughput is given by

$$S = \frac{G[1 + G + aG(1 + G + aG/2)]e^{-G(1+2a)}}{G(1 + 2a) - (1 - e^{-aG}) + (1 + aG)e^{-G(1+a)}} \tag{3}$$

Note that by using an upper bound on the propagation delay, we get a pessimistic expression for channel utilization. Similarly, for the slotted 1-Persistent CSMA the throughput equation is given by

$$S = \frac{Ge^{-G(1+a)}\left[1 + a - e^{-aG}\right]}{(1 + a)\left(1 - e^{-aG}\right) + ae^{-G(1+a)}} \tag{4}$$

The ultimate performance in the ideal case ($a = 0$), for both slotted and unslotted versions, is

$$S = \frac{Ge^{-G}(1 + G)}{G + e^{-G}} \tag{5}$$

For any value of a, the maximum throughput S will occur at an optimum value of G. Below, in Fig. 4, we show S versus G for the non-slotted version when $a = 0.01$.

4.3 Non-Persistent CSMA Again, we let G denote the arrival rate of new and rescheduled packets. All arrivals, in this case, do not necessarily result in actual transmissions (a packet which finds the channel in a busy state is rescheduled without being transmitted). Thus, G constitutes the "offered" channel traffic and only a fraction of it constitutes the channel traffic itself. Let us develop the throughput equation for this (simple) case. Consider the time axis (see Fig. 2) and let t be the time of arrival of a packet (packet 0) which finds both that the channel is idle and that no other terminal has undertaken transmission. Any packet arriving between t and $t + a$ will find (sense) the channel as unused, will transmit, and hence, will cause a conflict. If no other terminals transmit a packet during these a seconds (the "vulnerable" period), then packet 0 will be successful. The probability that no terminal transmits during these a seconds is e^{-aG}.

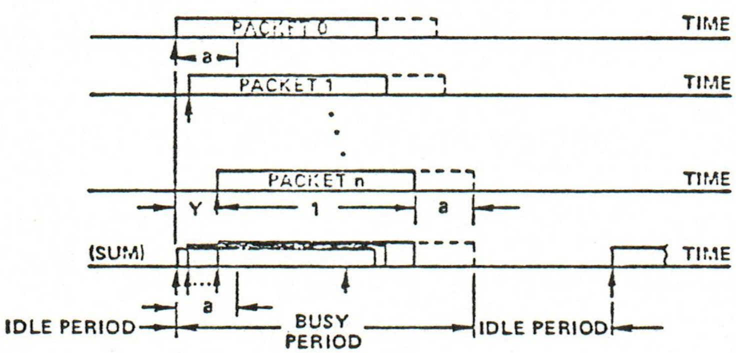

Fig. 2. Non-Persistent CSMA

Let $t + Y$ be the time of occurrence of the last packet arriving between t and $t + a$. The transmission of all packets arriving in $(t, t + Y)$ will be completed at $t + Y + 1$. Only a seconds later will the channel be sensed unused. Now, any terminal becoming ready between $t + a$ and $t + Y + 1 + a$ will sense the channel busy and, hence, will reschedule its packet. It is clear that the distribution function for Y is

$$\Pr\{Y \leq y\} = e^{-G(a-y)} \tag{6}$$

which gives an average

$$\overline{Y} = a - \frac{1}{G}\left(1-e^{-aG}\right) \tag{7}$$

The average duration of a busy interval is $1 + \overline{Y} + a$. The average duration of an idle period is simply $1/G$. Thus, the average cycle is $1 + \overline{Y} + a + 1/G$. The expected time during a cycle that the channel is used without conflicts is e^{-aG}. This divided by the average cycle time is therefore S, the average throughput in packets/transmission time. Using Eq. (7) we have

$$S = \frac{Ge^{-aG}}{G(1 + 2a) + e^{-aG}} \tag{8}$$

Note that $\lim_{a \to 0} S = G/(1 + G)$; this shows that when $a = 0$, a throughput of 1 can be theoretically attained for an offered channel traffic equal to infinity. S versus G for $a = 0.01$ is plotted in Fig. 4.

4.4 p-Persistent CSMA Consider a transmission period during which some packets arrive (See Fig. 3). The

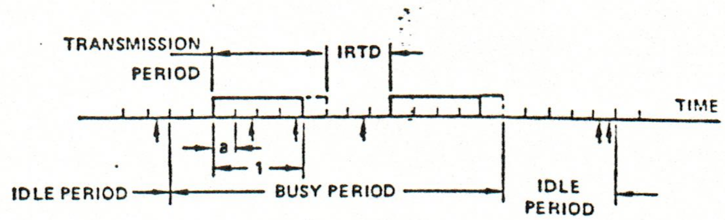

Fig. 3. p-Persistent CSMA

packets, having sensed the channel busy, accumulate at the end of the transmission period, and then randomize the starting times of their transmission according to the randomizing process described in section 2. This randomization creates a random delay before a transmission period starts, called the initial random transmission delay (IRTD), during which the channel is "wasted." If, at the start of a new transmission period, two or more terminals decide to transmit, then a conflict will certainly occur. All other packets which have delayed their transmissions by τ seconds will then sense the channel busy and will have to be rescheduled for transmission by incurring a retransmission delay. Thus, at the expense of creating this initial random transmission delay, we greatly improve the probability of success over a transmission period.

The approach for analysis consists, as above, of identifying the busy and idle periods and the wasted time created by the initial random transmission delay, and of determining the condition for success over a transmission period.

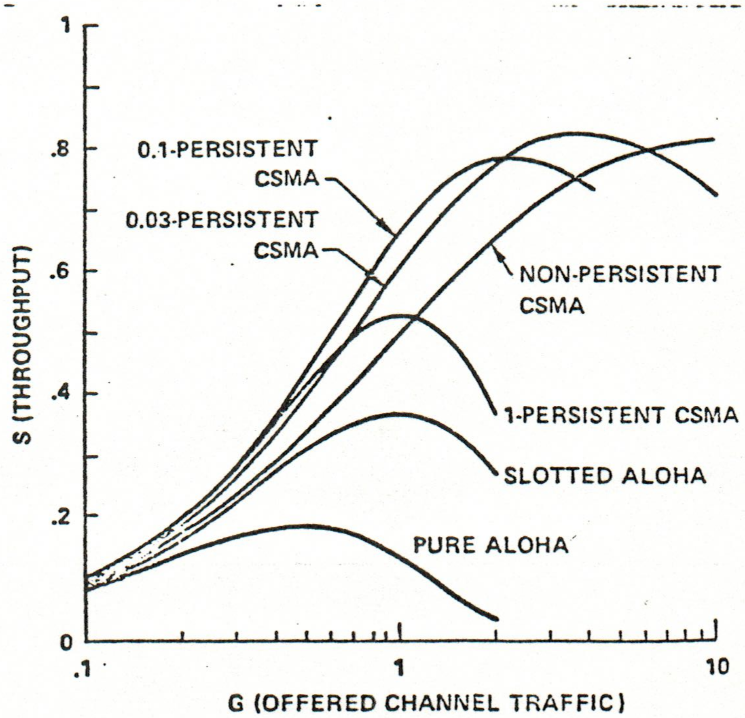

Fig. 4. Channel Throughput (a = 0.01)

For a given offered traffic G and a given value of the parameter p , we can then determine[6,7] the throughput S . When p = 1 , the (slotted) p-Persistent CSMA actually reduces to the slotted 1-Persistent CSMA. We also note that for a = 0 , the limit as $p \to 0$ and $G \to \infty$ will give S = 1 (its maximum possible value).

For each value of a , one can plot a family of curves S versus G with parameter p . The capacity (maximum throughput) for each value of p can be numerically determined at an optimum value of G . The capacity is not very sensitive to small variations of p ; for a = 0.01 , it reaches its highest value (i.e., the channel capacity for this protocol) at a value $p \approx .03$. In Fig. 4, we plot S versus G for a = 0.01 and for p = 0.03 and 0.1 .

Variation of Capacity with the Parameter a. While the capacity of ALOHA channels does not depend on the propagation delay, the capacity of a CSMA channel does. An increase in a increases the vulnerable period of a packet. This also results in "older" state channel information from sensing.

In Fig. 5, we plot, versus a , the channel capacity for all of the above random access modes. We note that the capacity loss for non-Persistent and p-Persistent CSMA is more sensitive to increases in a as compared to the 1-Persistent scheme. Non-Persistent CSMA drops below 1-Persistent for larger a . Also, for large a , slotted ALOHA is superior to any CSMA mode since decisions based on partially obsolete data are deleterious; this effect is due in part to our assumptions about the constant propagation delay. (For p-Persistent, numerical results are shown only for $a \le 0.1$. Clearly, for larger a , optimum p-Persistent is lower-bounded by 1-Persistent.)

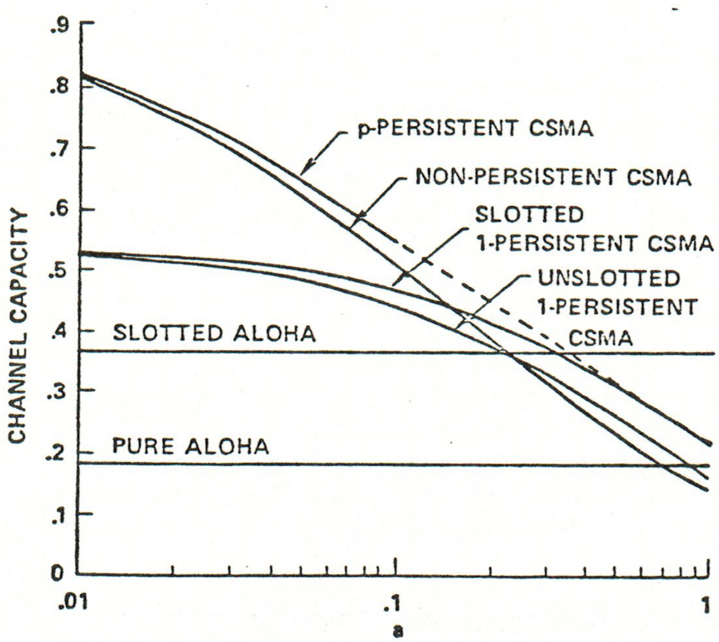

Fig. 5. Effect of Propagation Delay on Channel Capacity

5. DELAY CONSIDERATIONS

5.1 Delay Model. In the previous section, we analyzed the performance of Carrier Sense Multiple Access modes in terms of maximum achievable throughput. We introduce at this point the expected packet delay D defined as average time from when a packet is generated until it is successfully received.

Our principal concern in this section is to investigate the trade-off between the average delay D and the throughput S .

As we have already stated that for the correct operation of the system, a positive acknowledgement scheme is needed such that if an acknowledgement is not received by the sender of a packet within a specified period of time, then the packet is retransmitted incurring the random retransmission delay S , introduced to avoid repeated conflicts. For the present study, it is assumed that

(A3) the acknowledgement packets are always correctly received with probability one.

The simplest way to accomplish this is to create a separate channel* to handle acknowledgement traffic. If sufficient bandwidth is provided, overlaps between acknowledgement packets are avoided, since a positive acknowledgement packet is created only when a packet is correctly received, and there will be at most one such packet at any given time. Thus, if T_a denotes the transmission time of the acknowledgement packet on the separate channel, then the time-out for receiving a positive acknowledgement is $T + \tau + T_a + \tau$, provided that we make the following assumption:

(A4) The processing time needed to perform the sumcheck and to generate the acknowledgement packet is negligible.

Assumption (A2) further simplifies our delay model by implicitly assuming that the probability of a packet's success is the same whether the packet is new or has been blocked, or interfered with any number of times before; this probability is given by the throughput equation, i.e.,

$$P_s = \frac{S}{G} = \frac{\text{throughput}}{\text{offered traffic}}$$

Let $\alpha = T_a/T$. As an example, let us focus on the non-Persistent CSMA mode. In order to treat all packet arrivals in a uniform manner, we assume, in this case, that when a packet is blocked, it behaves as if it could transmit, and learned about its blocking only T_a seconds after the end of its "virtual" transmission. With this simplification, the delay equation is

$$D(S) = \left(\frac{G}{S} - 1\right)(2a + 1 + \alpha + \delta(S)) + 1 + a \tag{9}$$

where $\frac{G}{S} = 1 + G(1+2a)e^{aG}$ from Eq. (8). Similar equations can be written for all other access modes[6,7].

Some comments are in order concerning these delay equations. First, G/S as obtained from the throughput equations rests on two important and strong assumptions (A1) and (A2); namely, that δ is infinite, or large compared to the transmission time (in which case delays are also large and unacceptable); this gives us our needed independence assumptions. On the other hand, δ cannot be arbitrarily small. It is intuitively clear that when a certain backlog of packets is present, the smaller δ is, the higher is the level of interference and, hence, the larger is the offered channel traffic G . Thus, $G = G(S, \delta)$ is a decreasing function of δ such that the average number of transmissions per packet, $\frac{G(S, \delta)}{S}$, decreases with increasing values of δ, and reaches the asymptotic value predicted by the throughput equation. Thus, for each S , a minimum

*assumed to be available

delay can be achieved by choosing an optimal δ . Such an optimization problem is difficult to solve analytically, and simulation techniques have been employed in order to study the effect δ has on throughput and delay.[6,7]

Before we proceed with the discussion of simulation results, we compare the various access modes in terms of the average number of transmissions (or average number of schedulings*) G/S . For this purpose, we plot G/S versus S in Fig. 6 for the ALOHA and CSMA modes, when a = 0.01 . Note that CSMA modes provide lower values for G/S than the ALOHA modes. Furthermore, for each value of the throughput, there exists a value of p such that p-Persistent is optimal. For small values of S , p = 1 (i.e., 1-Persistent) is optimal. As S increases, the optimum p decreases.

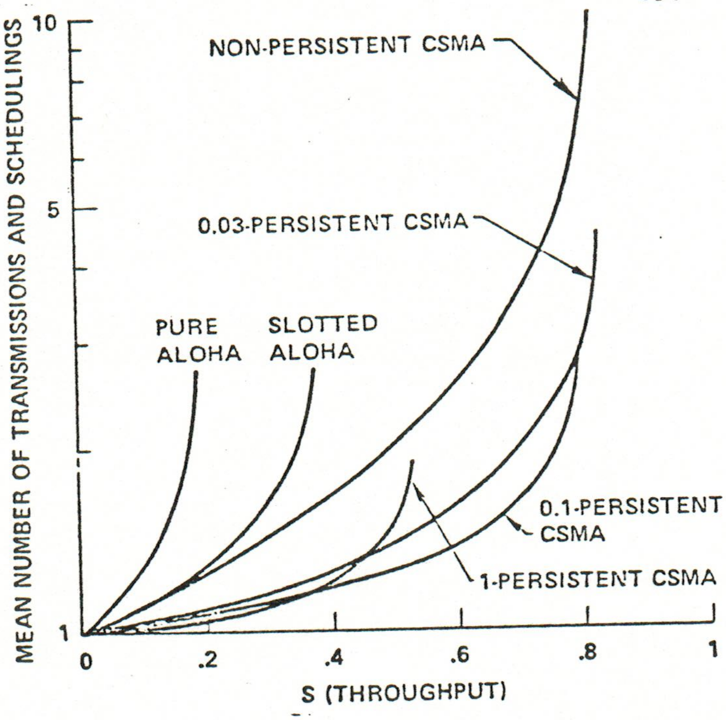

Fig. 6. G/S Versus Throughput (a = 0.01)

5.2 Simulation Results. The simulation model is based on all system assumptions presented in section 2. However, we relax assumptions (A1) and (A2) concerning the retransmission delay and the independence of arrivals for the offered channel traffic. That is, in the simulation model, only the newly generated packets are derived independently from a Poisson distribution; any collisions or random retransmissions are accounted for without further assumptions.

In general, our simulation results indicate the following:

1) For each value of the input rate S , there is a minimum value δ for the average retransmission delay variable, such that below that value, it is impossible to achieve a throughput equal to the input rate.* The higher S is, the larger δ must be to prevent a constantly increasing backlog, i.e., to prevent the channel from saturating. In other words, the maximum achievable throughput (under stable conditions) is a function of δ , and the larger δ is, the higher is the maximum throughput.

2) Recall that the throughput equations were based on the assumption that δ is infinitely large compared to T = 1 . Simulation shows that for finite values of δ, $\delta > \delta_o$, but not too large compared to 1 , the system already "reaches" the asymptotic results ($\delta \to \infty$). That is, for some finite values of δ, assumption (A2) is satisfied and delays are acceptable. Simulation experiments were conducted to find the optimal delay; that is, the value of $\delta(S)$ which allows one to achieve the indicated throughput with the minimum delay.

Finally, in Fig. 7, we give the throughput-minimum delay trade-off for the three Carrier Sense Multiple Access modes and a = 0.01 . This is the basic performance curve. (For the non-Persistent CSMA, lower packet delays can be achieved if a blocked packet does not incur the "forced" delay of its "virtual" transmission time and the corresponding time-out, as indicated in section 5.1 prior to Eq. (9).) We conclude that the optimum p-Persistent CSMA provides us with the best performance (and, in fact, the p = 0.1 curve shown is quite close to the lower envelope over all p for the case a = 0.01).

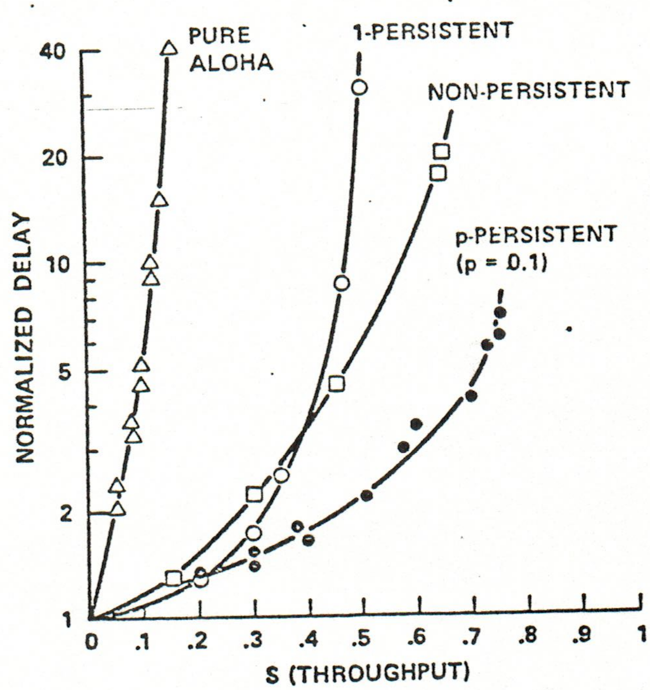

Fig. 7. Throughput-Delay Trade-offs (a = 0.01)

6. SUMMARY AND DISCUSSION

We have introduced the Carrier Sense Multiple Access mode which is an efficient means for randomly accessing packet switched radio channels. Just like

*For the non-Persistent and p-Persistent CSMA, G measures the offered channel traffic and not the actual channel traffic. G/S represents, then, the average number of times a packet was scheduled for transmission before success.

*Such behavior is characteristic of random multiple access modes. Similar results were already encountered by Kleinrock and Lam[8] when studying slotted ALOHA in the context of a satellite channel.

most "contention" systems, these random multi-access broadcast channels (ALOHA, CSMA) are characterized by the fact that the throughput goes to zero for large values of channel traffic. At an optimum traffic level, we achieve a maximum throughput which we define to be the system capacity. This and the throughput-delay performance were obtained by a steady-state analysis under the assumption of equilibrium conditions.

These channels present unstable behavior at most input loads as shown by Kleinrock and Lam.[9] In this last reference, the dynamic behavior and stability of an ALOHA channel is considered; quantitative estimates for the relative stability of the channel are given, indicating the need for special control procedures to avoid a collapse.

Throughout the paper, it was assumed that all terminals are within range and in line-of-sight of each other. A common situation consists of a population of terminals, all within range and communicating with a single "station" (computer center, gate to a network, etc.) in line-of-sight of all terminals. Each terminal, however, may not be able to hear all the other terminals' traffic. This gives rise to what is called the "hidden terminals" problem. The latter badly degrades the performance of CSMA. Fortunately, in a single station environment, the hidden terminal problem can be eliminated by dividing the available bandwidth into two separate channels: a busy tone channel and a message channel. As long as the station is receiving a signal on the message channel, it transmits a busy tone signal on the busy tone channel (which terminals sense for channel state information). The CSMA with a busy tone under a non-Persistent protocol has been analyzed.[6,7] It is shown to provide a maximum channel capacity of approximately 0.65 when $a = 0.01$ for a channel bandwidth A of 100 KHz (modulated at 1 Bit/Hz); when $W = 1$ MHz and $a = 0.01$, the channel capacity is 0.71.

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