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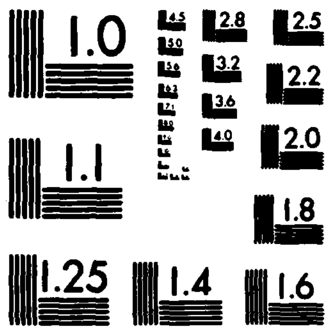
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A PERFORMANCE ANALYSIS OF A CSMA/CD PROTOCOL

Yih-Chiao Liu
Department of Electrical and Computer Engineering
University of Texas at Austin
Austin, Texas 78712

Gary L. Wise
Departments of Electrical and Computer Engineering and Mathematics
University of Texas at Austin
Austin, Texas 78712

ABSTRACT

An analysis of some performance characteristics of a CSMA/CD computer network protocol is presented. The analysis is based on the Enet II protocol which is designed to effectively resolve collisions in the network. In this paper we derive an expression for the average time to resolve a collision involving a given number of stations. We also give an expression for the average time until a packet involved in a collision is successfully transmitted.

INTRODUCTION

Recently there has been a great deal of interest in the subject of local area computer networks. This subject is concerned with interconnecting in an effective manner different types of work stations and/or microcomputers within a limited environment. Packet broadcast random access local computer networks have become commercially available in the last few years. A typical example of such networks is the Ethernet developed by Xerox [1], which was designed based on the concept of carrier sense multiple access with collision detection (CSMA/CD). The basic Ethernet protocol is described in the IEEE standard 802.3, where a station among a number of users sharing a common broadcast channel will listen before transmitting, and defer if the channel is busy. Stations experiencing simultaneous transmissions, which we call collisions, are rescheduled according to the Ethernet protocol until a randomized waiting period. Thus packets involved in a collision may incur excessive delay due to waiting and abortion of transmission.

The Enet II protocol was introduced by Molloy [2] as a candidate for the second generation of Ethernet. This protocol is designed to address the problem of effectively resolving collisions in a multiple access network such as Ethernet. According to the Enet II protocol, the stations of the network are in one of the three states: inactive, active, or deferred. Inactive stations either do not have anything to send or have just finished sending something. Active stations are trying to send a packet (which might be a new message or might be a message involved in a previous collision). Deferred stations have attempted to transmit but are waiting for the active stations to leave the active state. Before describing the protocol we will assume that the "diameter" of the network is given, that is, the maximum propagation delay between any two stations in the network. We will let r denote twice the diameter of the network. Any station listening to the channel for an interval of r units of time after transmitting would be guaranteed to hear something if anyone else was attempting to use the channel during that interval of time. A collision occurs when two or more stations attempt to transmit within an interval of r/2 units of time. Now we will describe the protocol in the following procedure:

<u>Inactive stations</u>

- Follow CSMA (i.e. check channel before trying).
- If channel is idle, wait for 3r units of time, then transmit.
- If channel is busy, wait until it is idle for 3r units of time. Then transmit, and the station goes to the active state.

<u>Active stations</u>

- If transmission is successful, station goes to the inactive state.
- If a collision occurs, all participants in that collision generate a Bernoulli trial (i.e. flip a coin) with "success" or "head" probability p.
  - If "success" appears, the station tries to transmit again.
  - If "failure" appears, the station monitors the channel passively:
    - if the station sees the channel idle for r units of time, transmit;
    - if the station sees a successful transmission, wait for the end of it and then transmit;

(Let $\mu_0=0$ and $\mu_j, j\geq 1$, be the average time until the first of j stations sees end of transmission.)

    - if the station sees a collision, change to the deferred state.

(A later restriction on packet length will guarantee that time needed to witness collision is less than time needed to resolve collision.)

<u>Deferred stations</u>

- Passively monitor the channel.
- If the station sees the channel idle for an interval of 2r units of time, it transmits and then returns to the active state.
- If the station sees the channel as not idle in an interval of 2r units of time, it remains in the deferred state.

The Enet II protocol is simple and needs no extensive support, such as clocks, addresses, current load estimates, or preassigned orderings, as compared with some other contention resolution

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protocols. This protocol is characterized by the introduction of a "gate" for new arrivals such that stations have to wait for the channel to be idle for a period of 3r units of time before transmitting a new packet. Therefore, stations need not monitor the channel when they have nothing to send. All new arrivals must stay behind that gate until all active or deferred users, if any, are finished. Similarly, the deferred users must stay behind their gate for a period of 2r units of time until the active users are finished. Assuming at least one success and at least one failure among the Bernoulli trials generated by the active users, the random test mechanism will decrease the number of active users participating in a collision by successfully transmitting some or having them move to a deferred state in the case that it is known that two or more stations are still in the active state. Active stations which experienced "failure" in their random tests still transmit after the channel is free for r units of time, effectively announcing their presence to keep deferred stations from erroneously concluding that all active stations are done. When all of the active stations transmit successfully, all of the deferred stations will change to the active state.

PERFORMANCE ANALYSIS

In this section, we will investigate the performance of the Enet II protocol by assuming a simplified model of n stations. In this model all packets transmitted in the channel are assumed to be of equal length, and it takes τ ($> r/4$) seconds to transmit a packet. Upon generating a packet, a station tries to transmit the packet by accessing the channel according to the Enet II protocol. If several stations try to transmit their messages within the same interval of r/2 units of time, they are said to be colliding with each other. A collision can be detected and transmission of all colliding stations will be aborted. In the case of a collision, let the random variable Z denote the time between when the first packet was sent and the time when the colliding stations acknowledge the collision and flip their coins. Let $\delta = E\{Z\}$. We note that in [3] it is assumed that δ is a constant equal to r, while in [4] δ is taken to be at least 2r. Let $S = (i,j,k)$ be the status of the network where i is the number of active stations ready to transmit their messages, j is the number of active stations flipping "tail" after a collision and are passively monitoring the channel, and k is the number of stations in deferred states. Let C(S) be the average time to "resolve" an S status. For $(j,k) \neq (0,0)$, C(i,j,k) is the average time from the moment the status (i,j,k) is obtained in executing the Enet II protocol until the last contending packet is sent. Let $C(1,0,0)=\tau$. For $k \geq 2$, C(k,0,0) is the average time between when the first packet is sent but ends up in a k-way collision and when the very last packet in this collision is successfully transmitted. For simplicity we will denote C(k,0,0) as C_k. Using the law of total probability, we have the following set of recursive equations for the C(i,j,k)'s:

$$C(0,0,0) \triangleq 0,$$

$$C(0,j,k) = r + C(j,0,k), \quad \text{for } j,k \geq 1, \tag{1}$$

$$C(0,0,k) = 2r + C(k,0,0) + \mu_k, \quad \text{for } k \geq 1, \text{ and} \tag{2}$$

$$C(1,j,k) = \tau + C(j,0,k) + \mu_j. \tag{3}$$

For $i \geq 2$,

$$C(i,0,k) = [\delta + \sum_{\ell=1}^{i-1} \binom{i}{\ell} p^{\ell}(1-p)^{i-\ell} C(\ell,i-\ell,k) + r(1-p)^i]/[1-p^i-(1-p)^i], \tag{4}$$

$$C(i,j,k) = \delta + \sum_{\ell=0}^{i} \binom{i}{\ell} p^{\ell}(1-p)^{i-\ell} C(\ell,i-\ell,j+k) \tag{5}$$

$$= \delta + \sum_{\ell=1}^{i-1} \binom{i}{\ell} p^{\ell}(1-p)^{i-\ell} C(\ell,i-\ell,j+k) + [p^i + (1-p)^i]\, C(i,0,j+k) + r(1-p)^i.$$

Equation (1) is due to the fact that when the channel is free, the j stations who had flipped "tails" wait r units of time and then try to access the channel again. Equation (2) is due to the fact that the k stations in the deferred states wait 2r units of time to return to the active states. Equation (3) represents the situation where one packet being transmitted experiences no competition for the channel and after it finishes in τ units of time, the j stations who had flipped "tails" immediately move into competition to gain access to the channel; the k deferred stations remain in the deferred state. Equation (5) is obtained in the following manner: the first term δ is the average time to detect the collision of the i transmitting stations, and the rest of the terms in the sum are given by considering the outcomes of the coin flipping and multiplying the respective binomial probability by the average time to resolve each possible outcome. Equation (4) is a special case of equation (5) obtained by setting j=0.

From equations (1)-(5) we can obtain C_k, $1 \leq k \leq n$. For example, $C_1=\tau$ and $C_2=\mu_1+2\tau+[\delta+r(1-p)^2]/[2p(1-p)]$. For $k \geq 3$, the C_k's can be calculated recursively by aid of a computer. By the recursive nature of equations (1)-(5), we observe that C_k, $2 \leq k \leq n$, is a positive continuous function of p in the open interval (0,1). Also, C_k is $+\infty$ when p is equal to 0 or 1 since in either case a k-way collision can never be resolved. By a limiting argument, C_k approaches $+\infty$ as p approaches 0 or 1. Thus C_k has a minimum and can be minimized by choice of p. Note also that C_k is always lower bounded by $k\tau$ which is the overall time required to sequentially transmit k packets. We will call $C_k-k\tau$ the average collision resolution time since the extra time is not accounted for in the actual transmission but rather in resolving the collision. Since $C_2-2\tau$ is independent of τ, it follows from the recursive nature of equations (1)-(5) and an induction argument that the average collision resolution time $C_k-k\tau$ for $k \geq 2$ is independent of τ. Hence C_k is a sum of two terms: the overall time to transmit k packets sequentially, and the average collision resolution time. In Fig. 1, we present a plot for the average collision resolution time for various values of k. In this figure, the minimizing p for each $C_k - k\tau$ is numerically different and is not 1/2 for any k. Note that this plot for average collision resolution time is independent of the value of τ.

Consider a k-way collision ($k \geq 2$). Let L_k be the average time from when the first packet involved in this collision was sent until when a particular packet is successfully sent. Then by the use of the law of total probability and a similar argument used in obtaining C_k, L_k, $2 \leq k \leq n$, is given by

$$L_k = L(\underline{k},0,0),$$

where $L(\underline{k},0,0)$ satisfies the following recursive equations:

$$L(0,0,0) = 0,$$

$$L(0,0,\underline{k}) = 2r + L(\underline{k},0,0) + \mu_k, \text{ for } k \geq 1,$$

$$L(\underline{1},j,k) = \tau,$$

$$L(1,\underline{j},k) = \tau + L(\underline{j},0,k) + \mu_j, \text{ for } j \geq 1,$$

$$L(1,j,\underline{k}) = \tau + L(j,0,\underline{k}) + \mu_j, \text{ for } k \geq 1,$$

where for $i \geq 2$,

$$L(\underline{i},j,k) = \delta + L(\underline{i},0,j+k),$$

$$L(i,\underline{j},k) = \delta + L(i,0,\underline{j+k}),$$

$$L(\underline{i},0,k) = \{\delta + \sum_{\ell=1}^{i-1} p^{\ell}(1-p)^{i-\ell}[\binom{i-1}{\ell-1}L(\underline{\ell},i-\ell,k) + \binom{i-1}{\ell}L(\ell,\underline{i-\ell},k)] + r(1-p)^{i}\}/[1-p^{i}-(1-p)^{i}],$$

$$L(i,0,\underline{k}) = \{\delta + \sum_{\ell=1}^{i-1} \binom{i}{p} p^{\ell}(1-p)^{i-\ell} L(\ell,0,\underline{i-\ell+k})\} / [1-p^{i}-(1-p)^{i}].$$

In the above recursive equations, we use an *under*line to represent where the station with the packet of interest lies among the three classes of packets consisting of those who are competing to transmit, those who had flipped "tails" and are passively monitoring the channel, and those who are in the deferred state. In the above recursive equations, $(\underline{i},j,k)$ denotes that the station with the packet of interest is in the active state and is transmitting the packet. The notation $(i,\underline{j},k)$ denotes that the station with the packet of interest had flipped a "tail", and it is passively monitoring the channel until it can retransmit again or until it moves to the deferred state. The notation $(i,j,\underline{k})$ denotes that the station with the packet of interest is in the deferred state.

Similar observations and arguments in obtaining the C_k's can be applied to the recursive equations of $L_k = L(\underline{k},0,0)$. One can thus show that L_k is also a continuous function of p in the open interval (0,1), and $L_k = +\infty$ when p is either 0 or 1. Also, L_k approaches ∞ as p approaches 0 or 1. Hence a minimum of L_k, $2 \leq k \leq n$ exists. Similar to the fact that $C_k - k\tau$ is independent of τ, $L_k - (k+1)\tau/2$ is independent of τ. Consider k packets transmitted sequentially; then $(k+1)\tau/2$ is the average time until a packet randomly chosen from among these k packets is transmitted. That is, $(k+1)\tau/2$ is the L_k in an ideal situation. Thus L_k is always lower bounded by $(k+1)\tau/2$, and we can interpret $L_k - (k+1)\tau/2$ as the average delay time experienced by the packet of interest in a k-way collision. In Fig. 2, we present a plot for $L_k - (k+1)\tau/2$ for different values of k.

We earlier noted the precise relation between C_2 and δ. In Fig. 3 we present plots of $C_3 - 3\tau$ versus p for various values of δ. We note that it follows from the preceding recursive equations that for a fixed p, C_k is an affine function of δ for $k \geq 1$.

CONCLUSION

In this paper we have presented equations for the C_k's and L_k's. These results allow us to determine some of the statistical aspects of the collision resolution performance of the Enet II protocol. This analysis is not dependent upon a statistical characterization of the packet arrivals. In particular, a value of p, depending on the number of contenders, can be determined which will minimize the overall average collision resolution time.

ACKNOWLEDGEMENT

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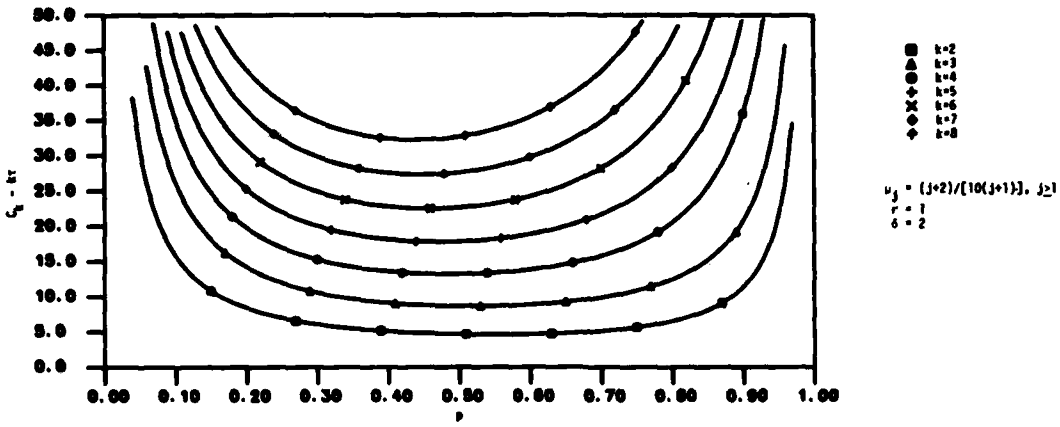

Fig. 1 Average Collision Resolution Time for Various Values of k.

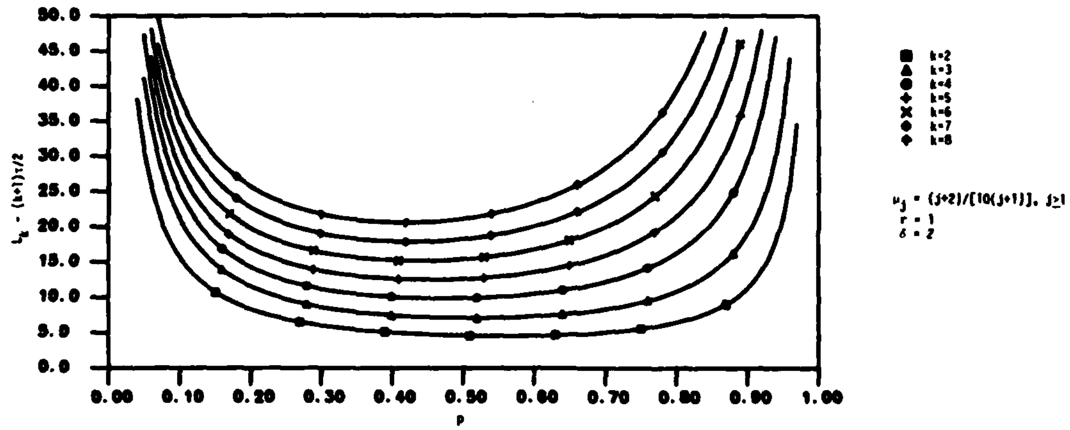

Fig. 2 Average Delay Time Experienced by the Packet of Interest.

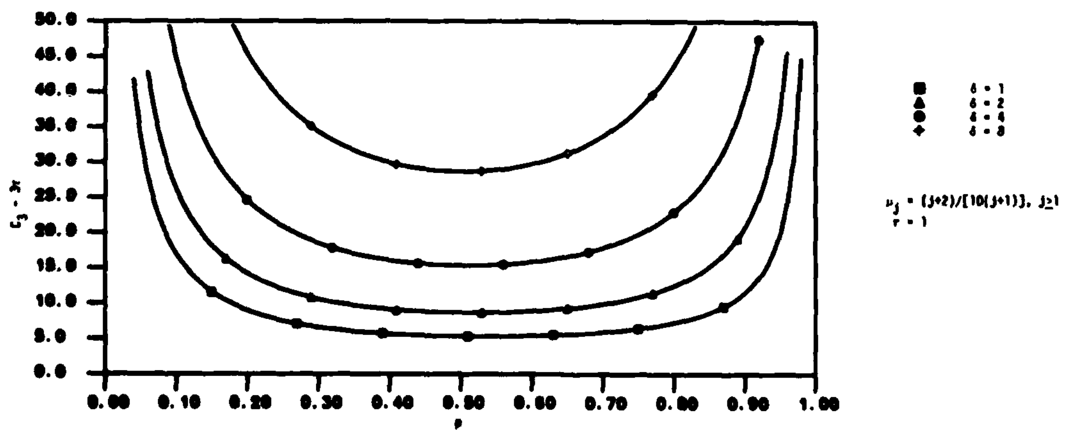

Fig. 3 Average 3-way Collision Resolution Time.

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