IEEE Pacific Rim Conference on Communications, Computers and Signal Processing
June 1st - 2nd, 1989

Performance Evaluation of Prioritized Collision-Avoidance Star Local Area Networks

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Abstract

In this paper, we propose and analyze a two-class prioritized Collision-Avoidance Star Local Area Network (CASLAN) protocol. The retry time of a node is used for priority assignment. A 3-dimensional Markovian chain is used to model the CASLAN which is represented by a polling system in which the central node chooses at random one of the idle or ready nodes. We present numerical results from our analytical model and compare these results to results from a simulation model.

1. Introduction

Star shaped Networks are one of the oldest used communication networks [1]. They have many advantages over networks with other topologies. Theses advantages include high utilization, high data rates and simple node access protocols. However, due to the centralized nature of star networks, they have the disadvantage of having a complex central node.

Collision-Avoidance Star Local Area Networks (CASLANS) overcome this disadvantage by reducing the complex central node to a simple controller. The function of the controller is to choose at random one of the packets delivered to it and broadcast this packet to all nodes. CASLANS were discovered independently by Closs and Lee [1], Albanese [2], and Lee and Boulton [3]. The access protocol for CASLANS is described in the following section.

Many attempts have been made to model the single-class CASLAN protocol [5-9]. In this paper we introduce and analyze a two-class prioritized CASLAN protocol. This protocol is described in section 2. In sections 3 and 4, we introduce the model and analysis of the protocol. In section 5, numerical results are shown and compared to simulation results. Finally, in section 6, we present the conclusions drawn from this work.

2. CASLANS Protocol

2.1 Basic Protocol:

The access protocol for CASLANS is based on repeated attempts by nodes to acquire the hub. Nodes are either idle (have no packets to transmit) or ready (have a packet but have not acquired the hub yet).

As soon as an idle node receives a packet, it forwards that packet to the hub (central node). A packet transmitted by a node acquires the hub if the hub is free, upon the packet arrival at the hub, otherwise, the packet is blocked. If a node does not sense its own packet after the round trip propagation delay between the node and the hub, it retries transmission immediately until successful (the propagation delay of a node is thus called its retry time).

The hub protocol is as follows. If a packet arrives at the hub and the hub is free, the packet acquires the hub instantaneously. Once a Packet acquires the hub , the packet is transmitted on all outgoing links. If two or more packets arrive at the hub at the same time, one of them is chosen at random and the other packets are blocked. Thus, collisions never occur in such networks.

It should be noted that, even though this protocol is collision free, and hence achieves very high utilization, it does not prevent unbounded delays. Indeed, depending on the offered load, it is possible for a particular packet to always encounter a busy hub, thus resulting in an infinite delay.

This research was supported in part by NSERC (Canada) grant OGP-9187.

2.2 Prioritized protocol:

In the prioritized protocol, the retry time of a node is used for priority assignment. Since the greater the retry time the more time it takes a packet to reach the hub, assigning a higher retry time to a certain class of users would mean less contention from the users of this class at the hub. Thus other classes would have better delay. In other words, retry times are artificially increased to force lower priority access.

Since we consider only two classes of nodes, only two different values of retry time are assigned, τ_1 and τ_2 for classes 1 and 2, respectively.

3. The Model

The model used in this paper is an approximate model which is an extension of an earlier model for the single class case [9]. The system is modeled as a polling system where the central hub chooses a node at random from the idle or ready nodes. Packet generation time at nodes is modified to be an exponential plus constant process, rather than an exponential only, in order to reflect the effect of the propagation delay.

Let C_1 and C_2 be the two classes considered in the model. Let $N_1(N_2)$, $T_1(T_2)$, $\lambda_1(\lambda_2)$ and $\tau_1(\tau_2)$ be the number of nodes, packet length, arrival rate per time unit and the retry time for $C_1(C_2)$. We assume that $\tau_1 \le \tau 2$, thus giving higher priority to C_1 users. We also assume that $\mathrm{Min}(T_1,T_2) \ge \mathrm{Max}(\tau_1,\tau_2)$.

As in [9], ready nodes are modeled to obey a uniform distribution, where the arrival instant at the hub of the start of a packet transmission is chosen randomly from the period $(0, \tau_1(\tau_2)]$ for $C_1(C_2)$ nodes, following the end of a transmission. An implied assumption here is that a retry attempt does not depend on the original arrival time of the packet nor on previous retries. In actual CASLANS protocols, this is not the case.

The status of the central node is either serving a node (a packet transmission) or waiting for a packet. The latter state is called the waiting period. Because of the retry nature of the protocol at hand, the waiting period is no more than τ_1 if at least one node of C_1 is ready, no more than τ_2 if at least one node of C_2 is ready, and unbounded if there are no ready nodes.

A three-dimensional embedded Markovian chain is used to represent the polling system. The first two dimensions are the number of ready users in each class, i_1 and i_2, respectively, while the third is the last class to release the hub, i.e. last from $C_1(C_2)$.

The need to know the class that released the hub last follows from the fact that it is essential to know the retry time of the last packet to release the hub. This is because it takes time τ ($\frac{\tau}{2}$ after the hub release to the node, and $\frac{\tau}{2}$ before hub acquisition from the node to the hub) for the last node to release the hub to be able to acquire it again, where τ is $\tau_1(\tau_2)$ if last was from $C_1(C_2)$. Since τ_1 is different from τ_2, the third dimension representing the last class to release the hub is essential. If l_k denotes last from class k (where k = 1(2) for $C_1(C_2)$, then the state space could be represented by (i_1, i_2, l_k). One could then obtain the transition probabilities $P(j_1, j_2, l_m \mid i_1, i_2, l_k)$ from state (i_1, i_2, l_k) to state (j_1, j_2, l_m).

To keep notations compact, we define the following for either class.

- $$P_{tx}(M,m,T,\lambda) = \begin{cases} \binom{M}{m} (1-e^{-\lambda T})^m (e^{-\lambda T})^{M-m} & 0 \le m \le M \\ 0 & otherwise \end{cases}$$

  This is the probability of m transmissions of M idle nodes during the transmission time (T) at arrival rate λ.

- $$P_{\bar{L}}(\tau,T,t,\lambda) = \begin{cases} e^{-\lambda(t+T-\tau)} & 0<t\le\tau \\ e^{-\lambda T} & t>\tau \end{cases}$$

  This is the probability that the last node to acquire the hub will transmit during the next acquisition given that it occured at time t.

- $$P_L(\tau,T,t,\lambda) = 1 - P_{\bar{L}}(\tau,T,t,\lambda)$$

- $$f(i,\tau,t) = \frac{i\,(\tau-t)^{i-1}}{\tau^i}$$

  This is the probability that one of i ready nodes would acquire the hub at exactly time t.

- $$1-F(i,\tau,t) = \frac{(\tau-t)^i}{\tau^i}$$

  This is the probability that none of the i ready nodes would acquire the hub before time t.

- $$P_s(M,t,\lambda) = \lambda M e^{-\lambda M t}$$

  This is the probability that one out of M idle nodes acquires the hub at time t.

- $$P_{\bar{s}}(M,t,\lambda) = e^{-\lambda M t}$$

  This is the probability that none of the M idle nodes acquires the hub before time t.

We also define,

- $$P_{s'}(M,\tau,t,\lambda) = \begin{cases} P_s(M-1,t,\lambda) & 0<t\le\tau \\ P_s(M-1,t,\lambda)\cdot e^{-\lambda(t-\tau)} + P_{\bar{s}}(M-1,t,\lambda)\cdot\lambda e^{-\lambda(t-\tau)} & t>\tau \end{cases}$$

  &

- $$P_{\bar{s}'}(M,\tau,t,\lambda) = \begin{cases} P_{\bar{s}}(M-1,t,\lambda) & 0<t\le\tau \\ P_{\bar{s}}(M-1,t,\lambda)\cdot e^{-\lambda(t-\tau)} & t>\tau \end{cases}$$

Note that all of the above probabilities are joint on t, the overhead or waiting time. Since t is dependent on the number of ready users in the system, we must first obtain the joint transition probabilities $P^{(t)}(j_1,j_2,l_k \mid i_1,i_2,l_m)$ then integrate over t. We distinguish four different cases of transition probabilities depending on the class of the last user to acquire the hub.

case $l_1 \to l_1$:

$$P^{(t)}(j_1,j_2,l_1 \mid i_1,i_2,l_1) = P_{\bar{s}}(N_2-i_2,t,\lambda_2)\cdot(1-F(i_2,\tau_2,t))\cdot P_{tx}(N_2-i_2,j_2-i_2,T_1,\lambda_2)$$

$$\cdot\Bigg\{P_{\bar{s}'}(N_1-i_1,\tau_1,t,\lambda_1)\cdot f(i_1,\tau_1,t)\cdot\begin{bmatrix} P_{\bar{L}}(\tau_1,T_1,t,\lambda_1)\cdot P_{tx}(N_1-i_1-1,j_1-i_1+1,T_1,\lambda_1)+ \\ P_L(\tau_1,T_1,t,\lambda_1)\cdot P_{tx}(N_1-i_1-1,j_1-i_1,T_1,\lambda_1) \end{bmatrix}$$

$$+ P_{s'}(N_1-i_1,\tau_1,t,\lambda_1)\cdot(1-F(i_1,\tau_1,t))$$

$$\cdot\begin{bmatrix} P_{\bar{L}}(\tau_1,T_1,t,\lambda_1)\cdot P_{tx}(N_1-i_1-2,j_1-i_1,T_1,\lambda_1)+ \\ P_L(\tau_1,T_1,t,\lambda_1)\cdot P_{tx}(N_1-i_1-2,j_1-i_1-1,T_1,\lambda_1) \end{bmatrix}\Bigg\} \qquad (1)$$

The common multiplier outside the curly brackets in equation (1) above is the probability that none of C_2 users acquires the hub and that j_2-i_2 idle users from C_2 become ready during T_1. The term inside the curly bracket is the probability that a user from C_1 acquires the hub and that the number of ready users from C_1 by the end of the transmission is equal to j_1.

case $l_2 \to l_1$:

$$P^{(t)}(j_1,j_2,l_1 \mid i_1,i_2,l_2) = P_{\bar{s}'}(N_2-i_2,t,\lambda_2)\cdot(1-F(i_2,\tau_2,t))$$

$$\times\begin{bmatrix} P_{\bar{L}}(\tau_2,T_1,t,\lambda_2)\cdot P_{tx}(N_2-i_2-1,j_2-i_2,T_1,\lambda_2)+ \\ P_L(\tau_2,T_1,t,\lambda_2)\cdot P_{tx}(N_2-i_2-1,j_2-i_2-1,T_1,\lambda_2) \end{bmatrix}$$

$$\times\begin{bmatrix} P_{\bar{s}}(N_1-i_1,\tau_1,t,\lambda_1)\cdot f(i_1,\tau_1,t)\cdot P_{tx}(N_1-i_1,j_1-i_1+1,T_1,\lambda_1)+ \\ P_s(N_1-i_1,\tau_1,t,\lambda_1)\cdot(1-F(i_1,\tau_1,t))\cdot P_{tx}(N_1-i_1,j_1-i_1,T_1,\lambda_1) \end{bmatrix} \quad (2)$$

The first term of equation (2) above is the probability that none of C_2 users acquires the hub. The second term is the probability that j_2-i_2 idle users from C_2 become ready during T_1. While the third term is the probability that a user from C_1 acquires the hub and that the number of ready users from C_1 by the end of the transmission is equal to j_1.

case $l_1 \to l_2$:

This case is similar to the $l_2 \to l_1$ case with all the information for C_1 and C_2 interchanged.

$$P^{(t)}(j_1,j_2,l_2 \mid i_1,i_2,l_1) = P_{\bar{s}'}(N_1-i_1,t,\lambda_1)\cdot(1-F(i_1,\tau_1,t))$$

$$\times\begin{bmatrix} P_{\bar{L}}(\tau_1,T_2,t,\lambda_1)\cdot P_{tx}(N_1-i_1-1,j_1-i_1,T_2,\lambda_1)+ \\ P_L(\tau_1,T_2,t,\lambda_1)\cdot P_{tx}(N_1-i_1-1,j_1-i_1-1,T_2,\lambda_1) \end{bmatrix}$$

$$\times\begin{bmatrix} P_{\bar{s}}(N_2-i_2,\tau_2,t,\lambda_2)\cdot f(i_2,\tau_2,t)\cdot P_{tx}(N_2-i_2,j_2-i_2+1,T_2,\lambda_2)+ \\ P_s(N_2-i_2,\tau_2,t,\lambda_2)\cdot(1-F(i_2,\tau_2,t))\cdot P_{tx}(N_2-i_2,j_2-i_2,T_2,\lambda_2) \end{bmatrix} \quad (3)$$

case $l_2 \to l_2$:

This case is similar to the $l_1 \to l_1$ case with all the information for C_1 and C_2 interchanged.

$$P^{(t)}(j_1,j_2,l_2 \mid i_1,i_2,l_2) = P_{\bar{s}}(N_1-i_1,t,\lambda_1)\cdot(1-F(i_1,\tau_1,t))\cdot P_{tx}(N_1-i_1,j_1-i_1,T_2,\lambda_1)$$

$$\cdot\Bigg\{P_{\bar{s}'}(N_2-i_2,\tau_2,t,\lambda_2)\cdot f(i_2,\tau_2,t)\cdot\begin{bmatrix} P_{\bar{L}}(\tau_2,T_2,t,\lambda_2)\cdot P_{tx}(N_2-i_2-1,j_2-i_2+1,T_2,\lambda_2)+ \\ P_L(\tau_2,T_2,t,\lambda_2)\cdot P_{tx}(N_2-i_2-1,j_2-i_2,T_2,\lambda_2) \end{bmatrix}$$

$$+ P_{s'}(N_2-i_2,\tau_2,t,\lambda_2)\cdot(1-F(i_2,\tau_2,t))$$

$$\cdot\begin{bmatrix} P_{\bar{L}}(\tau_2,T_2,t,\lambda_2)\cdot P_{tx}(N_2-i_2-2,j_2-i_2,T_2,\lambda_2)+ \\ P_L(\tau_2,T_2,t,\lambda_2)\cdot P_{tx}(N_2-i_2-2,j_2-i_2-1,T_2,\lambda_2) \end{bmatrix}\Bigg\} \qquad (4)$$

To obtain the steady state probabilities, a transformation from the three dimensional state space to a one dimensional state space may be employed. In such a transformation, a state $(i_1,i_2,l_1(l_2))$ would be mapped to state $m_1(m_2)$, where $m_1 = i_1\cdot N_1 + i_2$ and $m_2 = N_1\cdot(N_2+1) + i_1\cdot N_1 + i_2$. Note that the state space would consist of $N_1\cdot(N_2+1) + (N_1+1)\cdot N_2$ states, i.e. $O(N_1\cdot N_2)$.

The steady state probabilities can be obtained by solving the set of equations in (5) below

$$\vec{\pi} = \vec{\pi}\cdot P$$

and

$$\vec{\pi}\cdot\vec{1} = 1 \qquad (5)$$

Where P is the one-dimensional transition probability matrix and $\vec{\pi}$ is the row vector containing the steady state probabilities, and $\vec{1}$ represents a column vector of 1 elements.

4. Throughput and Average Delay

To obtain the throughput and average delay for each class, the regenerative nature of Markovian chains is used. The entrance to any state, say state $(0,0,l_1)$, is a regenerative process. Let R_{i_1,i_2,l_k} denote the expected time to reach state $(0,0,l_1)$ for the first time from state (i_1,i_2,l_k), and let $TX1_{i_1,i_2,l_k}$ and $TX2_{i_1,i_2,l_k}$ respectively denote the number of successful transmissions of class 1 and class 2 during R_{i_1,i_2,l_k}. If X_1 and X_2 respectively represent the throughput per time unit for class 1 and class 2, then X_1 and X_2 are given by equations (6) and (7) below.

$$X_1 = \frac{TX\,1_{0,0,l_1}}{R_{0,0,l_1}} \tag{6}$$

$$X_2 = \frac{TX\,2_{0,0,l_1}}{R_{0,0,l_1}} \tag{7}$$

The average delays for classes 1 and 2, D_1 and D_2, are respectively given by equations (8) and (9).

$$D_1 = \frac{N_1}{X_1} - \frac{1}{\lambda_1} \tag{8}$$

$$D_2 = \frac{N_2}{X_2} - \frac{1}{\lambda_2} \tag{9}$$

Now, $TX\,1_{0,0,l_1}$, $TX\,2_{0,0,l_1}$ and $R_{0,0,l_1}$ can be obtained by solving the set of simultaneous equations in (10), (11) and (12) below.

$$TX\,1_{0,0,l_1} = \sum_{i_1=0}^{N_1-1}\sum_{i_2=0}^{N_2} P(i_1,i_2,l_1|0,0,l_1)\cdot(1+TX\,1_{i_1,i_2,l_1}) + \sum_{i_1=0}^{N_1}\sum_{i_2=0}^{N_2-1} P(i_1,i_2,l_2|0,0,l_1)\cdot(0+TX\,1_{i_1,i_2,l_2}) - TX\,1_{0,0,l_1}\cdot P(0,0,l_1|0,0,l_1) \tag{10a}$$

$$TX\,1_{i_1,i_2,l_1} = \sum_{j_1=0}^{N_1-1}\sum_{j_2=0}^{N_2} P(j_1,j_2,l_1|i_1,i_2,l_1)\cdot(1+TX\,1_{j_1,j_2,l_1}) + \sum_{j_1=0}^{N_1}\sum_{j_2=0}^{N_2-1} P(j_1,j_2,l_2|i_1,i_2,l_1)\cdot(0+TX\,1_{j_1,j_2,l_2}) - TX\,1_{0,0,l_1}\cdot P(0,0,l_1|i_1,i_2,l_1) \tag{10b}$$

$$TX\,1_{i_1,i_2,l_2} = \sum_{j_1=0}^{N_1-1}\sum_{j_2=0}^{N_2} P(j_1,j_2,l_1|i_1,i_2,l_2)\cdot(1+TX\,1_{j_1,j_2,l_1}) + \sum_{j_1=0}^{N_1}\sum_{j_2=0}^{N_2-1} P(j_1,j_2,l_2|i_1,i_2,l_2)\cdot(0+TX\,1_{j_1,j_2,l_2}) - TX\,1_{0,0,l_1}\cdot P(0,0,l_1|i_1,i_2,l_2) \tag{10c}$$

$$TX\,2_{0,0,l_1} = \sum_{i_1=0}^{N_1-1}\sum_{i_2=0}^{N_2} P(i_1,i_2,l_1|0,0,l_1)\cdot(0+TX\,2_{i_1,i_2,l_1}) + \sum_{j_1=0}^{N_1}\sum_{j_2=0}^{N_2-1} P(j_1,j_2,l_2|0,0,l_1)\cdot(1+TX\,2_{i_1,i_2,l_2}) - TX\,2_{0,0,l_1}\cdot P(0,0,l_1|0,0,l_1) \tag{11a}$$

$$TX\,2_{i_1,i_2,l_1} = \sum_{j_1=0}^{N_1-1}\sum_{j_2=0}^{N_2} P(j_1,j_2,l_1|i_1,i_2,l_1)\cdot(0+TX\,2_{j_1,j_2,l_1}) + \sum_{j_1=0}^{N_1}\sum_{j_2=0}^{N_2-1} P(j_1,j_2,l_2|i_1,i_2,l_1)\cdot(1+TX\,2_{j_1,j_2,l_2}) - TX\,2_{0,0,l_1}\cdot P(0,0,l_1|i_1,i_2,l_1) \tag{11b}$$

$$TX\,2_{i_1,i_2,l_2} = \sum_{j_1=0}^{N_1-1}\sum_{j_2=0}^{N_2} P(j_1,j_2,l_1|i_1,i_2,l_2)\cdot(0+TX\,2_{j_1,j_2,l_1}) + \sum_{j_1=0}^{N_1}\sum_{j_2=0}^{N_2-1} P(j_1,j_2,l_2|i_1,i_2,l_2)\cdot(1+TX\,2_{j_1,j_2,l_2}) - TX\,2_{0,0,l_1}\cdot P(0,0,l_1|i_1,i_2,l_2) \tag{11c}$$

$$R_{0,0,l_1} = \sum_{i_1=0}^{N_1-1}\sum_{i_2=0}^{N_2} P(i_1,i_2,l_1|0,0,l_1)\cdot(T_1+R_{i_1,i_2,l_1}) + \sum_{i_1=0}^{N_1}\sum_{i_2=0}^{N_2-1} P(i_1,i_2,l_2|0,0,l_1)\cdot(T_2+R_{i_1,i_2,l_2}) - R_{0,0,l_1}\cdot P(0,0,l_1|0,0,l_1) + \overline{W}_{0,0,l_1} \tag{12a}$$

$$R_{i_1,i_2,l_1} = \sum_{j_1=0}^{N_1-1}\sum_{j_2=0}^{N_2} P(j_1,j_2,l_1|i_1,i_2,l_1)\cdot(T_1+R_{j_1,j_2,l_1}) + \sum_{j_1=0}^{N_1}\sum_{j_2=0}^{N_2-1} P(j_1,j_2,l_2|i_1,i_2,l_1)\cdot(T_2+R_{j_1,j_2,l_2}) - R_{0,0,l_1}\cdot P(0,0,l_1|i_1,i_2,l_1) + \overline{W}_{i_1,i_2,l_1} \tag{12b}$$

$$R_{i_1,i_2,l_2} = \sum_{j_1=0}^{N_1-1}\sum_{j_2=0}^{N_2} P(j_1,j_2,l_1|i_1,i_2,l_2)\cdot(T_1+R_{j_1,j_2,l_1}) + \sum_{j_1=0}^{N_1}\sum_{j_2=0}^{N_2-1} P(j_1,j_2,l_2|i_1,i_2,l_2)\cdot(T_2+R_{j_1,j_2,l_2}) - R_{0,0,l_1}\cdot P(0,0,l_1|i_1,i_2,l_2) + \overline{W}_{i_1,i_2,l_2} \tag{12c}$$

Where, $\overline{W}_{i_1,i_2,l_1}(\overline{W}_{i_1,i_2,l_2})$ is the average waiting period if the last to release the hub is from $C_1(C_2)$, with i_1 ready users of C_1 and i_2 ready users of C_2. Expressions for the waiting period are not shown here due to lack of space, however, they are not very difficult to obtain.

5. Numerical results

In this section we show results obtained from the analysis in sections 2 and 3. In addition, we show simulation results.

Figures 1 and 2 show the average delay of C_1 and C_2 users as a function of τ_2 for a 4 node and a 20 node systems respectively. Note that increasing the retry time results in an increase in average delay associated with a decrease in throughput. Moreover, by fixing τ_1 and increasing τ_2, the delay for class 1 packets decreases even though τ_1 did not decrease. This is because class 1 packets will face less contention at the central hub as τ_2 increases. The above phenomenon is even more apparent at relatively high load. For instance, in figure 2, a decrease of 42.7% in average delay for class 1 is observed if τ_2 is to be increased form 120 to 480 (bits) at an arrival rate of 0.0004, while a decrease of only 3% is observed at an arrival rate of 0.00004.

Figure 3 shows the average delay of C_1 and C_2 users versus τ_2 in a 4 node and a 12 node systems under heavy traffic with $T_2 = 2 \cdot T_1$. By increasing τ_2 priority is given to C_1 users, i.e. priority is for short packets. Note the sharp decrease in average delay for C_1 users with the increase of τ_2 (54.4% over the range 120-480 for the 12 node system).

Simulation results show that the model yields very accurate results at light to medium offered load. At heavy load, however, there exists some points where the analytical results are not as accurate, see figures 1 and 2. These instances seem to show that, in contrast to what was believed earlier [4-9], increasing the retry time does not necessarily mean an increase in average delay. For instance, at $\tau_2 = 240$, D_2 is less than that at $\tau_2 = 200$ in both figure 1 and figure 2. The authors are currently conducting research involving an in-depth study of CASLANS and in particular the effect of the retry time on the performance of such networks [10].

6. Conclusion

In this paper, a two-class prioritized CASLAN protocol was introduced and analyzed. Analytical results show that by increasing the retry time of one class the delay of the other class is improved. The model yields excellent results at light to medium offered load. At heavy load, however, there exists some points where the model is not as accurate.

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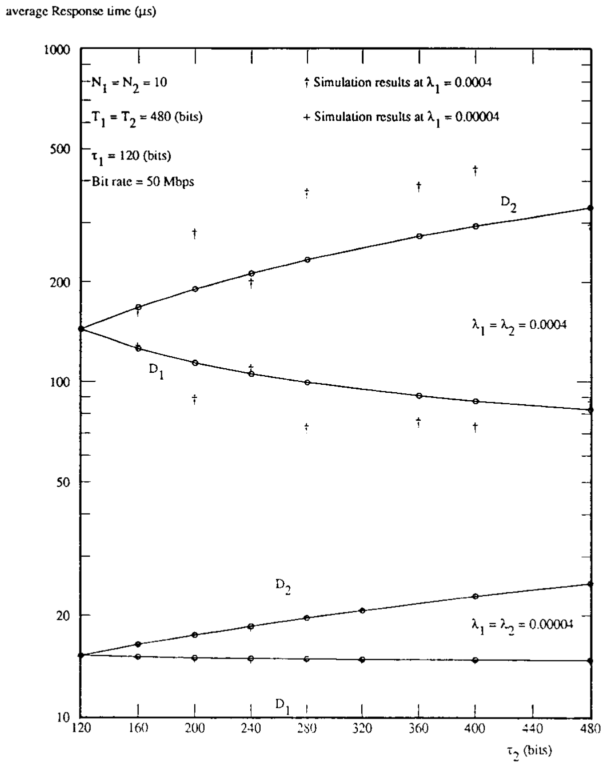

Figure 2: Response time at different values of τ_2 in a 20 node system.

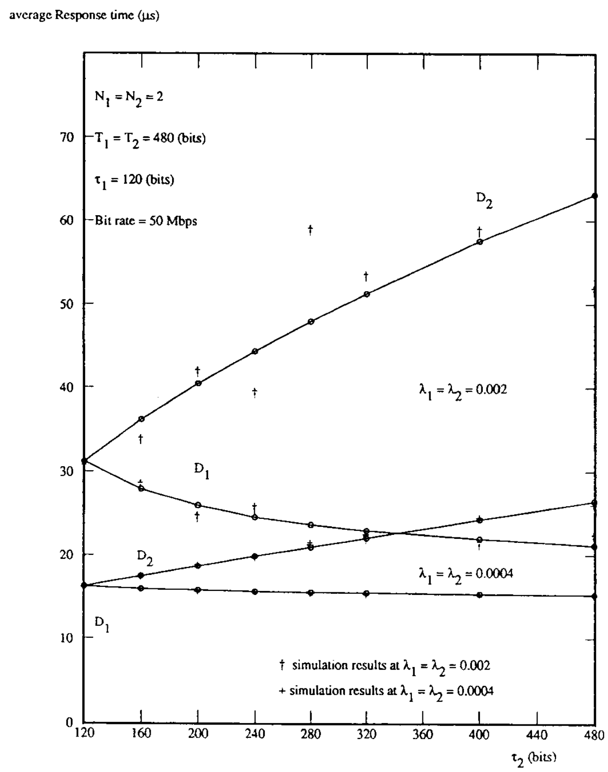

Figure 1: Response time at different values of τ_2 in a 4 node system.

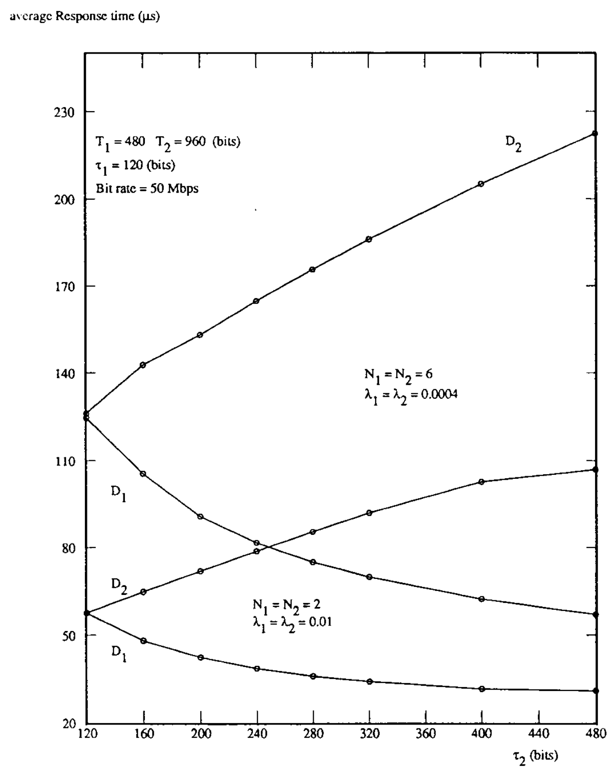

Figure 3: Response time at different values of τ_2 with $T_2 = 2T_1$.