Abstract This paper presents a comparative performance evaluation of medium-access control (MAC) protocols in LANs. This paper deals with three representative MAC protocols; Token-ring, Token-bus, and CSMA/CD. First, this paper defines a unit-period as the time basis for analysis and obtains the probability distribution on the length of this unit-period. By considering the beginning of this unit-period as the imbedded Markov point, this paper makes it possible to analyze the network performance of the three MAC protocols, stochastically. Then, this paper analyzes the results to verify the validity of the analysis. Finally, this paper shows the performance comparison among the three MAC protocols for various kinds of LAN configurations and discusses the suitable situations of them.

1. Introduction

There have been the increasing needs for local area networks (LANs) in the computer communications environment including office automation, factory automation and so on. A great number of LANs with various configuration schemes have been developed and also developing. These numerous LANs are generally classified by the medium access control (MAC) protocol. Three major schemes of them are Token-ring, Token-bus and CSMA/CD. These three schemes already have been treated for the standardization of LAN by several standard organizations.

When users construct LANs, they must select the eligible schemes for their own environment from at least the three standardized schemes. So, it is necessary to present the comparative evaluation of manifold features of LAN configurations from various points of view at the initial stage. Further, it is also necessary to present the detail performance analysis for the selected configuration scheme of LAN at the designing stage. Hence, in the further researches of LANs, one of the most important problems is to evaluate and compare the performance of these network schemes.

Up to now, a number of works for evaluating and comparing the network performance of LANs have been presented [1,2,3,4,5]. Stuck[1] evaluated the throughput characteristics with some simple network models. While the computation of this evaluation is simple enough, there are some problems on the accuracy of the analysis. Bux[2], Cherukuri et al [3] presented detail analyses on the performance evaluation of networks. However, these papers quoted some results on the network analysis from other papers and applied them to suitable MAC protocols. They adopt the results of Kohnheim and Meiser[6] to Token-ring and the results of Lam[7] to CSMA/CD. Thus, the differences in the analytical methods are left as problems.

The objective of this paper is to present a comparative performance evaluation of the representative MAC protocols in LANs, i.e. Token-ring, Token-bus, and CSMA/CD by an identical analysis. This paper defines a unit-period consisting of an access time and a packet transmission time as the time basis for analysis. This paper derives the probability distribution on the length of this unit-period for the three MAC protocols. Especially, for CSMA/CD, the back-off behavior depending on the number of packet collisions is taken into consideration. By considering the beginning of the unit-period as the imbedded Markov point and introducing some approximation, this paper makes it possible to obtain the throughput-delay performance of the three MAC protocols.

Further, this paper shows some quantitative characteristics of the three MAC protocols on typical network configurations by numerical analysis. First, this paper compares the analytical results to the simulation results to verify the validity of the approximated analysis. Secondly, this paper compares the three MAC protocols from various points of view including channel capacity, network distance, number of nodes and so on, and discusses the suitable situations of the three MAC protocols and their potential features. By extending the analytical method presented in this paper, we can obtain the performance of various kinds of LAN schemes including hybrid schemes of Token-passing and CSMA/CD, some schemes with transmission priorities, and so on.

2. Model

A model of LANs for analysis is described in this section. The model consists of four parts. The first part (1)-(4) is the network configuration and the input traffic property in LANs. This is common to all MAC protocols. The second part 5.1)- 5.6), the third part 6.1)- 6.6), and the fourth part 7.1)- 7.5) are specific properties of Token-ring, Token-bus, and CSMA/CD, respectively.

(1) The network configuration channel capacity $C$ bps
number of nodes \( N \)

maximum distance (or cable length) \( D \) km

buffer size in each node \( 1 \)

(2) In analysis, the time axis is divided into slots with a constant length \( \tau \). The slot length depends on the MAC protocol.

(3) The packet arrival process has the Poisson distribution. The arrival rate per sec is \( \lambda \).

Thus, the arrival rate per slot is \( \frac{\lambda}{\tau} \).

(4) Packets have a constant length, \( Lp \) bits. Then, the packet length per slot \( Lps \) is

\[ Lps = \left\lceil \frac{Lp}{\frac{\lambda}{\tau}} \right\rceil \]

Where, the operator \( \left\lceil \right\rceil \) means the minimum integer that is greater than or equal to the content.

(5) Token-ring

5.1) The distance between any adjacent nodes is identical to \( D / N \) km.

5.2) The repeat delay at each node is \( B \) bits.

5.3) The length of the free-token is \( Hr \) bits.

5.4) The position of the free-token in the network is considered to be probabilistic.

5.5) The slot length of Token-ring \( \tau \) is defined as the propagation delay between adjacent nodes.

It includes the repeat delay \( B \).

\[ \tau = \frac{D}{2 \times 10^5 N} + \frac{B}{C} \quad (1) \]

5.6) The state of the network is expressed by the number of ready nodes. Here, a ready node means a node ready to transmit a packet.

(6) Token-bus

6.1) The distance between any adjacent nodes is identical to \( D / (N-1) \) km.

6.2) The order of passing the free-token (explicit token) is a count-up scheme of the node index, except the node \( N \). That is, \((1)-(2)-(3)-\ldots-(N-1)-(N)-(1)\) as shown in Fig.1. This is the best case of token passing situations in Token-bus.

6.3) The position of the free-token in the network is considered to be probabilistic.

6.4) The switch time from receiving mode to transmitting mode is \( t \) sec.

6.5) The length of the free-token is \( Hb \) bits. Thus, the length per slot \( Hbs \) is \( \left\lceil \frac{Hb}{\frac{\lambda}{\tau}} \right\rceil \).

6.6) The slot length of token-bus \( \tau \) is defined as the average propagation delay of the free-token.

It includes the switch time \( t \).

\[ \tau = \frac{1}{N} \left( \frac{(N-1)D}{2 \times 10^5} + \frac{D}{2 \times 10^5} \right) + \frac{Hb}{C} + t \]

\[ = \frac{D}{10^5 N} + \frac{Hb}{C} + t \quad (2) \]

(7) CSMA/CD

7.1) The slot length of CSMA/CD \( \tau \) is defined as the propagation delay from end to end in the network.

\[ \tau = \frac{D}{2 \times 10^5} \quad (3) \]

7.2) The state of the network is expressed by 2-tuple vector \((i,m)\), where \( i \) is the number of ready nodes and \( m \) is the number of packet collisions.

7.3) When a packet collision occurs, the confusing status on the channel due to the packet collision is dissolved in a slot.

7.4) The number of packet collisions \( m \) coordinates to each node and is updated as follows;

a) to add 1 whenever a packet collision is observed in the network, and

b) to reset 0 whenever a successful transmission of packet is observed in the network.

7.5) If a ready node senses the channel idle at the state \((i,m)\), then this node transmits a packet with probability \( Pd(i,m) \).

\[ Pd(i,m) = \frac{1}{(2 - 2^{m-1})} \quad (4) \]

3. Analysis

First, we define a unit-period as the time-basis for analysis (it is depicted in Fig.2).

[ Definition ] A unit-period is a time interval between a pair of the end times of successively transmitted packets, except the interval when there is no ready node in the network.

Here, the meaning of the end time depends on the network topology and so depends on MAC protocol. In a bus network (CSMA/CD or Token-bus), the end time means the time when the end of the transmitted packet propagates to the far end of the network. The darken triangle in Fig.2 shows the propagation of the last bit of a transmitted packet. On the other hand, in a ring network, the propagation of the end of packet transmission and the starting of the next packet transmission may simultaneously occurs for some specific situations. We can not identify these two events clearly on the time axis. So, we consider the time of releasing the free-token as the end of the packet transmission in Token-ring.

Generally, a unit-period consists of an access time and an packet transmission time as shown in Fig.2. Here, an access time is an interval from the end of the latest packet transmission to the start of the following packet transmission. We exclude the time duration when there is no ready node in the network from the access time. We call this time as a null time. Thus, an access time includes the token-passing time for both Token-ring and Token-bus, and includes some idle times, collision times and the subsequent times to recover the channel from the collision state for CSMA/CD. In other words, it is a time required for some specific node to get the right to transmit a packet on the channel. A packet transmission time is a time to transmit a packet.

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completely to transmission medium. A packet transmission time includes a propagation time in Token-bus and CSMA/CD. In Token-ring, it includes a time required to release the free-token.

The analysis for evaluating the performances of LANs is divided into two parts. In the first part, we obtain the probability distributions on the access time and the packet transmission time for the three MAC protocols. In the second part, we develop a Markov analysis by considering the beginning of the unit-period as the imbedded Markov point. Further, we derive some basic characteristics (average values on throughput, number of ready nodes, and delay) from this Markov analysis.

3.1 Probability distribution on length of unit-period

The unit-period consists of two, i.e. the access time and the packet transmission time. Here, we define three probabilities \( \text{Punit}(k/i) \), \( \text{Pacc}(k/i) \), and \( \text{Ppt}(k/i) \), under the condition that the state of the network just before the beginning of the unit-period is \( i \) (we call this condition simply the condition \( O(i/1) \)).

\( \text{Punit}(k/i) \); probability that a unit-period is \( k \) slots.

\( \text{Pacc}(k/i) \); probability that an access time is \( k \) slots.

\( \text{Ppt}(k/i) \); probability that a packet transmission time is \( k \).

Further, we define the probability generating functions of them \( \text{Gunit}(z/i) \), \( \text{Gacc}(z/i) \), and \( \text{Gpt}(z/i) \), respectively.

The access time is substantially depending on MAC protocols. On the other hand, the packet transmission time is almost identical for all protocols. The access time and the packet transmission time are independent of each other.

\[ \text{Gunit}(z/i) = \text{Gacc}(z/i) \cdot \text{Gpt}(z/i) \] (5)

Then, we derive all of them for the three MAC protocols.

(1) Token-ring

In this MAC protocol, there is only one node that has the transmission right (the free-token) and can transmit a packet in the contention-free scheme. When he completely transmits his packet, he releases the free-token and a unit-period ceases. If there are some ready nodes in the network, a new unit-period begins successively. Otherwise, the next unit-period will begin when there occur some ready nodes in the network.

So, we can consider that the access time is the time interval from the very beginning of the new unit-period to the instant that a node acquires the free-token. From the model 5-4 mentioned before, \( \text{Pacc}(k/i) \) is derived combinatorially.

\[ \text{Pacc}(k/i) = \frac{\text{N-k-1} 
\times \text{i-1}}{\text{N-1}} \quad (i \neq 0) \] (6)

Further, we define the probability generating functions of the receiving packet.

\[ \text{Gacc}(z/i) = \frac{\text{N-i}}{z} \times \sum_{k=1}^{\text{N-i}} \text{Pacc}(k/i) \cdot z^k \quad (i \neq 0) \] (7)

The packet transmission time is depending on both the packet length and the control scheme to release the free-token. In this paper, we only deal with a constant packet-length and the single-token scheme.*1)

In the single-token scheme, a node with the token releases it when the following two conditions are satisfied.

1) The node transmits his packet completely to the transmission medium.

2) The node receives a part of its packet from the receiving port after a ring propagation latency and confirms its address in the source address field of the receiving packet.

Then, the probability generating function on the packet-transmission time is

\[ \text{Gpt}(z/i) = \left\{ \begin{array}{ll} \text{N}^z & \text{Hrs + Lps} \leq \text{N} \\ \text{z} \cdot (\text{Hrs} + \text{Lps}) & \text{Hrs + Lps} > \text{N} \end{array} \right. \] (8)

In this equation, the propagation delay from the sending node to the destination node does not included. Thus, the following correction term should be added to the delay performance of Token-ring in the next subsection (Eq.(3l)).

\[ D_c = \text{N} / \text{Lps} \quad \text{Hrs + Lps} \leq \text{N} \]

\[ D_c = \text{Hrs + Lps} \quad \text{Hrs + Lps} > \text{N} \] (9)

(2) Token-bus

In Token-bus, a logical ring is composed in a bus network and the control token is passed on the node-by-node basis. So, the control scheme of Token-bus is almost similar to Token-ring.

In this analysis, the difference between them is included in the definition of each slot. Hence, \( \text{Pacc}(k/i) \) and \( \text{Gacc}(z/i) \) of Token-bus is the same as those of Token-ring. \( \text{Gpt}(z/i) \) is the following.

\[ \text{Gpt}(z/i) = \frac{\text{Lps} \cdot \text{Cp}}{\text{Lps} + \text{Cp}} \] (10)

In this equation, \( \text{Cp} \) is the maximum propagation time of the end of packet. So, Token-bus does not need the correction term.

(3) CSMA/CD

In this MAC protocol, the state of the network is described as \( (i,m) \), where \( i \) is the number of ready nodes and \( m \) is the number of the packet collisions, as mentioned in the Model. First, we define four probabilities to deal with the channel situation. Under the condition that the state of the network is \( (i,m) \), the probability \( \text{Pa}(i,m) \) that a node successfully transmits a packet in a slot, the probability \( \text{Pi}(i,m) \) that the channel is idle in a slot, the probability \( \text{Pc}(i,m) \) that there is a packet collision on the channel in a slot, and the probability \( \text{Ps}(i,m) \) that there is a new arrival in a slot are, respectively.

\[ \text{Ps}(i,m) = 1 - \text{Pd}(i,m) \left\{ 1 - \text{Pd}(i,m) \right\}^{i-1} \] (11)

\[ \text{Pi}(i,m) = \left\{ 1 - \text{Pd}(i,m) \right\}^i \] (12)

\[ \text{Pc}(i,m) = 1 - \text{Pa}(i,m) - \text{Pi}(i,m) \] (13)

\[ \text{Pa}(i,m) = 1 - e^{-(N-1) \cdot \sigma} \] (14)

Let the probability that an access time is just \( k \) slots, on condition that the state of network is \( (i,m) \), be \( \text{Pacc}(k/i,m) \). Then \( \text{Pacc}(k/i,m) \) satisfies the following Proposition.

*1) Generally, token-passing control schemes are classified into three, multi-token, single-token (single-token multi-packet), and single-packet (single-token single packet). IEEE 802 committee recommends the single-token scheme.

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Gacc(z,i,m) has the following boundary condition. difference equation. function of Pacc(k/i,m) satisfies the following correlation between the probabilistic behavior of the first and the second slots of the unit-period. Here, we omit the proof of this Proposition. Then, the probability generating function of Pacc(k,i,m) satisfies the following difference equation.

\[ Gacc(z,i,m) = \frac{1-P_i(i,m)}{z} \times [P_i(i,m)Pacc(z/i+1,m) + P_0(i,m)Pacc(z/i,m+1)] \]

\[ Gacc(z,i,m) \]

\[ k \geq 2 \]

(15)

The above difference equation gives the correlation between the probabilistic behavior of the first and the second slots of the unit-period. Here, we omit the proof of this Proposition. Then, the probability generating function of Pacc(k,i,m) satisfies the following difference equation.

\[ Gacc(z,i,m) = \frac{1-P_i(i,m)}{z} \times [P_i(i,m)Pacc(z/i+1,m) + P_0(i,m)Pacc(z/i,m+1)] \]

Gacc(z,i,m) has the following boundary condition. difference equation.

1) \( i > N \) \( Gacc(z,i,m) = 0 \)

2) \( m > M \) \( Gacc(z,i,m) = Gacc(z,i,M) \)

Where \( N \) is the maximum number of collisions for increasing the back-off interval at the packet collision in CSMA/CD. From these conditions above, \( Gacc(z,i,m) \) is recursively obtained for any values of \( i \) and \( m \). The probability generating function of the packet-transmission time \( Gpt(z,i,m) \) is

\[ Gpt(z,i,m) = \left[ Gacc(z,i,m) + \frac{1}{z} \times (1-P_i(i,m)) \times Pacc(z/i,m+1) \right] \]

From the Model 6-3), we assume the initial value of \( m \) at the beginning of each unit-period be 0. Hereafter, we will express the functions \( Gacc(z,i,0) \) and \( Gpt(z,i,0) \) of CSMA/CD simply as \( Gacc(z,i) \) and \( Gpt(z,i) \), respectively.

3.2 Markov analysis

In this subsection, a Markov analysis is developed to obtain the network performance of the three MAC protocols. Let us consider the beginning of the unit-period as the imbedded Markov point and the number of ready nodes in the network at this point as the state of the network. Further, the following approximation is introduced.

[ Approximation ] The state transition in the unit-period depends on only the length of the unit-period and the packet arrival rate.

Thus, the analytical procedure of this second part is not depending on MAC control protocol but on the length of the unit-period. If the unit-period begins with the state \( i \) and has the length of \( k \) slots, then the conditional one step state transition probability \( P_t(j/i,k) \) that the state at the beginning of the next unit-period is \( j \), is

\[ P_t(j/i,k) = \begin{cases} 0 & (0 \leq j \leq i-2) \\ N^{-1}c_{j-i+1} (1-e^{-\sigma}) (j-i+1) e^{-\sigma(N-j-1)} & (i-1 \leq j \leq N, i \times 0) \\ P_t(j/i,k) & (i = 0) \end{cases} \]

(19)

Where \( N \) is the total number of nodes in the network and \( \sigma \) is the packet arrival rate per slot-node. As mentioned at the definition, the null times when there is no ready node in the network are excluded from the unit-period. Thus, \( P_t(i/0,k) = P_t(i/1,k) \).

Then the one step state transition probability \( P_t(j/i,k) \) that the state of the next unit-period is \( j \), on the condition \( C(i) \) \(( 0 < i, j < N-1 )\), is obtained as follows.

\[ P_t(j/i,k) = \begin{cases} 0 & (0 \leq j \leq i-2) \\ N^{-1}c_{j-i+1} \sum_{r=0}^{j-i} (j-i+1)! \times Guni(t)(e^{-\sigma(N-r-j-1)/i}) (1-1_{j<i}) & (1 \leq j < N, i = 0) \\ P_t(j/i) & (i = 0) \end{cases} \]

(20)

The state sequence consists of an aperiodic Markov chain with finite states. Thus, the steady state probability distribution \( \Pi = (\pi(i)) \) \((i = 0, 1, 2, ..., N-1) \) exists. \( \Pi = \Pi \cdot P_t \)

(21)

Where \( P_t \) is the one-step state transition probability matrix. Here, we obtain the average length of the unit-period with the initial state \( i \), \( Tunit(i) \), and the average of \( Tunit(i) \) on \( i \), \( Tunit(i) \)

\[ Tunit(i) = \lim_{z \to 1} Guni(t)(z/i) \]

(22)

\[ Tunit(i) = \sum_{i=0}^{N-1} \pi(i) \cdot Tunit(i) \]

(23)

Then, the throughput \( S \) is obtained by

\[ S = \frac{Lps}{(Tunit + \pi(0) \cdot \frac{1}{1-e^{-\sigma(N-1)}})} \]

(24)

Now, we obtain the average number of ready nodes \( Q \) in the network at an arbitrary time instant. As described above, we have the steady state probability distribution \( \pi(i) \). However, this probability is concerned to only the imbedded Markov points. So, the expectation of \( \pi(i) \) is not equal to \( Q \). In the following part of this chapter, we will derive \( Q \).

First, we define the conditional probability \( P(m,n/1,k,j) \) that there is \( m \) ready nodes at the \( n \)-th slot in the unit-period, on condition that the state just before the beginning of the unit-period is \( i \), the length of the unit-period is \( k \) slots, and the state just after the end of the unit-period is \( j \) (hereafter, we call this condition simply the condition \( C(i,k,j) \)). Then, \( P(m,n/1,k,j) \) is as follows.

\[ P(m,n/1,k,j) = \begin{cases} N^{-1}c_{j-i+1} (1-e^{-\sigma}) (j-i+1) e^{-\sigma(N-j-1)} & (0 \leq j \leq i-2) \\ N^{-1}c_{j-i+1} (1-e^{-\sigma}) (j-i+1) e^{-\sigma(N-j-1)} & (i-1 \leq j \leq N, i \times 0) \\ P_t(i/1,k) & (i = 0) \end{cases} \]

(25)
Then, under the condition $C(i,k,j)$, the average number of ready nodes at the $n$-th slot in the unit-period $Q(n,i,k,j)$ is

$$Q(n,i,j,k) = \sum_{m} m \cdot P(m,n/i,k,j) = 1 + (j-i+1) \cdot \frac{1-e^{-\sigma}}{1-e^{-\sigma_k}}$$

Under the condition $C(i,k,j)$, the average accumulated number of ready nodes in the unit-period $A(i,k,j)$ is

$$A(i,k,j) = \sum_{n=1}^{N \cdot \text{Tunit}} Q(n,i,k,j) = k \cdot i + (N-1) \cdot \frac{1}{1-e^{-\sigma}} - \frac{1}{1-e^{-\sigma_k}}$$

Hence, under the condition $C(i,k)$, the average accumulated number of ready nodes in the unit-period $A(i,k)$ is as follows.

$$A(i,k) = \sum_{j=1}^{N \cdot \text{Tunit}} P(j/i,k) \cdot A(i,k,j) = k \cdot i + (N-1) \cdot \frac{1}{1-e^{-\sigma}} - \frac{1}{1-e^{-\sigma_k}}$$

From the definition of the unit-period, it is easily shown that $A(0) = A(i)$. Hence, the average number of ready nodes $Q$ is

$$Q = \frac{\sum_{i=1}^{N} \pi(i) \cdot A(i)}{\text{Tunit} \cdot p(O) \cdot \frac{1}{1-e^{-\sigma}}}$$

Finally, the packet delay (normalized by one packet transmission time without any overheads) $D_p$ is obtained from Eqs(24) and (30) by applying the Little's Formula, as follows.

$$D_p = \frac{Q}{S}$$

It should be noted that the correction term $D_c$ (Eq.(9)) must be added to the above equation (31), in Token-ring.

4. Numerical analysis

We show numerical results for typical LAN configurations. We consider the basic parameters for the network configuration and MAC protocols as follows;

1) network parameter
   - channel capacity $C = 5$ Mbps
   - number of nodes $N = 100$
   - maximum distance $D = 1$ Km
   - packet length $L_p = 2000$ bits

2) Token-ring (Single token)
   - token header length $H_r = 24$ bits
   - repeat delay at node $B = 8$ bits

3) Token-bus
   - token length $H_b = 96$ bits
   - switch delay $t = 50$ nsec

4) CSMA/CD (BEB Back-off Protocol)
   - maximum length of contention to control $M = 10$

First, we compare the analytical results to the results of the computer simulation to check the validity of the approximated analysis. The simulation is a continuous-time event-to-event typed simulation and so it does not introduce the concept of the time slot (Model 2). Additionally, the assumption 7.4) and 7.5) of the model is released and the Ethernet-like scheme is introduced for the back-off control of CSMA/CD. The computer simulation is performed by the single-run-method [12], where the number of sample packets at each run is 10000 except the initial run and every 500 packets composes one sample point for 95% confidence interval.

Fig.3 shows the comparison of the results by the analysis and the simulation. Here, we only deal with Token-ring and CSMA/CD. The delay performance is normalized by one packet transmission time $L_p/C$. We can see that both results for two MAC protocols coordinate each other for lightly loaded and moderately loaded situations. In heavily loaded situation (almost saturated area), there is a slight difference between two results. However, the analytical results are included in the 95% confidence intervals of the simulation results for these saturated area. Hence, we can conclude that the approximated analysis presented in this paper is valid for almost all loaded situations of the typical LAN configuration.

Then, we show the performance comparison among the three MAC protocols for various kinds of LAN configurations. Fig.4 shows the comparison on the throughput-delay characteristics for three cases of the channel capacity, $C = 1, 5, 20$ Mbps. First, we consider the case of $C = 5$ Mbps as the basic situation. In lightly and moderately loaded situations, CSMA/CD is the most desirable on the delay. On the contrary, Token-ring is preferable on both the delay and the throughput (the maximum throughput) to the others in heavily loaded situation. The performances of Token-ring...
and CSMA/CD are crossing around the heavily loaded situation. The critical point for the superiority on the performance fundamentally depends on the network configurations. Token-bus has the worst performance for almost all situations, especially on the delay. This is due to the overhead for passing the explicit token.

Now, we consider the other cases of the channel capacity. While the performance of both Token-ring and Token-bus are hardly affected by the variation of the channel capacity C, CSMA/CD is quite sensitive to the variation of C. For the small value of the channel capacity (C = 1 MBps), CSMA/CD is entirely superior to Token-ring and also Token-bus. For the large value of the channel capacity (C = 20 Mbps), Token-ring relatively becomes to be preferable to CSMA/CD, because CSMA/CD inherently has the capacity limit due to the Carrier Sense effect. When we consider the larger capacity than 20 Mbps, this tendency will become more notable.

Here, we have to note on the value of the packet delay. As mentioned before, the packet delay is measured on the time basis normalized by one packet transmission time Lp/C. The one packet transmission time depends on the packet length and the channel capacity. Hence, it should be noted that when we consider the absolute value of delay, the unit delay (Dp = 1) for some value of the channel capacity C is not equal to the one for another value of C. For instance, Dp = 1 means 2 msec in the case of C = 1 Mbps and Lp = 2000 bits, while Dp = 1 means 0.4 msec in the case of C = 5 Mbps and Lp = 2000 bits.

Fig.5 shows the performance comparison on the throughput-delay characteristics for the three cases of the network distance D, D = 0.1, 1, 10 Km. When the network distance increases from 1 Km to 10 Km, it is observed that the performance of CSMA/CD is drastically degraded. The maximum throughput of CSMA/CD for D = 10 Km is only 40% of the channel capacity. On the other hand, when the network distance decreases to 0.1 Km, the performance of CSMA/CD is improved to almost the perfect scheduling scheme. However, the variation of the network distance hardly affects to the performance of Token-ring and Token-bus. The reasons of this insensitiveness are different from each other for two schemes. In Token-ring, when the network distance increases and one round-trip propagation delay becomes larger than the one packet transmission time, the performance will be degraded, significantly. Until the network distance is less than the critical value, the performance is almost insensitive to the variation of the distance. In Token-bus, the overhead due to the explicit token is substantially large and so the overhead due to the network distance is almost negligible.

Fig.6 shows the performance comparison on the throughput-delay characteristics for three cases of the number of nodes N, N = 10, 100, 200. As far as the traffic intensity and/or traffic load is kept the same, CSMA/CD shows almost the equivalent performance for the increasing the number of nodes from 100 to 200. This tendency will be preserved for larger values of N. However, the performances of Token-ring and
Token-bus are significantly degraded by increasing the number of nodes from 100 to 200 due to the overhead to pass the token. For the small size network (N = 10), the three schemes show almost similar characteristics on the throughput-delay. Token-ring is a little preferable to the others for the maximum throughput ability.

Fig.7 shows the performance comparison on the throughput-delay characteristics for three cases of the packet length Lp. Lp = 500, 2000, 10000. When the packet length increases, the performances of the three protocols are improved. For the case of Lp = 10000, there is scarcely any difference on the throughput-delay performance between Token-ring and CSMA/CD. For the case of Lp = 500, the performance of all schemes are degraded. Especially, the performance of Token-ring is drastically degraded, comparing to the other schemes. This is due to the reason that the round-trip propagation delay becomes larger than the packet transmission delay.

As a result, we can describe as follows.

1) Token-ring As far as the round-trip propagation delay on the ring network is smaller than the one packet transmission time, Token-ring shows the excellent performance on the throughput-delay. This scheme is the most suitable to large channel capacity, large network distance, and small user size.

2) Token-bus From the viewpoint of the network performance, Token-bus has the least potential. This scheme has some advantageous features which can not be evaluated quantitatively, e.g. to utilize off-the-shelf CATV facility, to be easily adaptable to broadband situations, and so on. Thus, this scheme will be adopted to such specific environment.

3) CSMA/CD This scheme shows the low delay ability for lightly and moderately loaded situations. This scheme is suitable to networks with large user size where the aggregate traffic load is not so high. When the network distance is small enough, this scheme shows the notable performance almost similar to the perfect schedule.

5. Conclusion

The performance evaluation of various LAN schemes is one of the most important problems in the researches of LAN. The objective of this paper is to present an analytical method for evaluating three MAC protocols of LANs, Token-ring, Token-bus, and CSMA/CD. This paper introduced the concept of the unit-period that consists of an access time and one packet transmission time. By using some approximation, this paper has developed the imbedded Markov analysis on the basis of the unit-period. In order to verify the validity of the approximation, this paper compared the analytical results to the simulation results.

This paper has shown the performance comparison among the three MAC protocols for typical network configurations. By the numerical analysis, this paper has discussed the suitable situations for each medium-access control protocols in the LAN environment. We can easily obtain the competitive boundary on the network performance for various kinds of LAN configurations. Further, by extending the analytical method, we can obtain the performance of various kinds of LAN schemes including hybrid schemes of Token-passing and CSMA/CD, some schemes with transmission priorities, and so on.

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