Local Network Performance

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Significant factors in determining local network performance based on recent studies

In recent years, there has been a proliferation of local network products and an intensification of local network R&D activity. Nevertheless, the vast majority of systems conforms to one of two topologies and one of a handful of medium-access control protocols:[1]

- Bus Topology
  ..CSMA/CD
  ..Token Bus
- Ring Topology
  ..Token Ring
  ..Slotted Ring
  ..Register Insertion

Because the number of truly different local network configurations is manageably small, a comparative analysis of local network performance is possible.

The question of performance is of concern in the design or selection of a local network for a specific application. Given a certain collection of devices, with certain traffic characteristics, a fundamental requirement is that the local network has adequate capacity for the expected load. Table I, based on studies by the IEEE 802 Local Network Standards Committee, indicates the type of load that may be offered to a local network by various devices. We would like the local network to be able to sustain a throughput that keeps up with the load, and does so without undue delays.

This paper aims to show which factors are significant in determining local network performance and to summarize recent comparative studies. The first section below shows that two basic characteristics of a local network, propagation delay and data rate, set an upper bound on performance independent of the medium-access control protocol. Next, some simple models are developed for comparing three protocols: CSMA/CD, token bus, and token ring. These are protocols for which standards have been developed [2], and it is likely that most local network products will use a variant of one of them. Finally, some comparative studies are summarized. The results cover CSMA/CD, token bus, and token ring, as well as two other ring protocols — slotted ring and register insertion.

The Effect of Propagation Delay and Transmission Rate

In analyzing local network performance, the two most useful parameters are the data rate (R) of the medium, and the average signal propagation delay (D) between stations on the network. The propagation delay reflects the length of the medium and, in the case of the ring, the number of repeaters and their delay characteristics. In fact, it is the product of these two terms, $R \times D$, that is the single most important parameter for determining the

[1]For the unacquainted reader, these topologies and protocols are defined briefly in an appendix; further details can be found in Stallings [1].

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TABLE I*
WORKLOAD GENERATED FROM EACH SOURCE TYPE

Type of Source	Peak Data Rate (kb/s)	Duty Factor (%)
Heat/Vent/Air Conditioning/Alarm/Security	0.1	100
Line Printer	19.2	50-90
File Server/Block Transfer	20 000	0.1
File Server/File Transfer	100	10-30
Mail Server	100	30-50
Information Server/Calendar	9.6	1.5
Information Server/Decision Support	56	20-40
Word Processor	9.6	1-5
Data Entry Terminal	9.6	0.1-1.0
Data Enquiry Terminal	64	10-30
Program Development	9.6	5-20
Laser Printer	256	20-50
Facsimile	9.6	5-20
Voice/Immediate	64	20-40
Voice/Store and Forward	32	30-50
Video/Noncompressed	30 000	50-90
Video/Freeze Frame	64	50-90
Video/Compressed	400	20-40
Graphics/Noncompressed	256	1-10
Graphics/Compressed	64	10-30
Optical Character Reader	2.4	50-90
Gateway	1000	0.1-1.0
Host/0.5 MIPS	128	20-40
Host/5 MIPS	1000	20-30

*In Stallings [1].

performance of a local network. Other things being equal, a network's performance will be the same, for example, for both a 50-Mb/s, 1-km bus and a 10-Mb/s, 5-km bus. It will be seen that many widely-used metrics of LAN protocol performance, such as channel utilization and normalized service times, will remain constant if the $R \times D$ product is held constant.

Note that the data rate times the delay product is equal to the length of the transmission medium in bits, that is, the number of bits that may be in transit between two nodes at any snapshot in time. Several examples: assuming a velocity of propagation of 2×10^8 m/s, a 500-m Ethernet system (10 Mb/s) has a bit length of 25; both a 1-km HYPERchannel (50 Mb/s) and a typical 5-km broadband local network (5 Mb/s) run about 250 bits.

A useful way of viewing this is to consider the length of the medium as compared to the typical packet transmitted. This allows one to distinguish protocols geared for a local network from those designed for a multiprocessor backplane bus, which needs to accommodate a maximum of a few bits in transit; and from those for a satellite link, which should accommodate several entire packets in transit. Intuitively, it can be seen that this will make a difference. Compare local networks to multiprocessor computers. Relatively speaking, things happen almost simultaneously in a multiprocessor system; when one component begins to transmit, the others know it almost immediately. For local networks, the relative time gap leads to the need for a complex medium-access control protocol. Compare local networks to satellite links. To have any hope of efficiency, the satellite link must allow multiple packets to be in transit simultaneously. This places specific requirements on the link layer protocol, which must deal with a sequence of outstanding packets waiting to be acknowledged. Local network protocols generally allow only one packet at a time to be in transit, or, at the most, a few for some ring protocols. Again, this affects the access protocol.

The length of the medium, expressed in bits, compared to the length of the typical packet is usually denoted by a:

$$a = \frac{\text{Length of Data Path in Bits}}{\text{Length of Packet}}$$

$$a = \frac{RD}{L}$$

where L is the length of the packet. But D is the propagation time on the medium (worst case), and L/R is the time it takes a transmitter to get an entire packet out onto the medium. So,

$$a = \frac{\text{Propagation Time}}{\text{Transmission Time}}$$

Typical values of a range from about 0.01 to 0.1. Table II gives some sample values for a bus topology. In computing a for ring networks, repeater delays must be included in propagation time.

The parameter a determines an upper bound on the utilization of a local network. Consider a perfectly efficient access mechanism that allows only one transmission at a time. As soon as one transmission is over, another node begins transmitting. Furthermore, the transmission is pure data — no overhead bits. What is the maximum possible utilization of the network? It can be expressed as the ratio of total throughput of the system to the capacity or bandwidth:

TABLE II
VALUES OF a

Data Rate	Packet Size	Cable Length	a
1 Mb/s	100 bits	1 km	0.05
1 Mb/s	1000 bits	10 km	0.05
1 Mb/s	100 bits	10 km	0.5
10 Mb/s	100 bits	1 km	0.5
10 Mb/s	1000 bits	1 km	0.05
10 Mb/s	1000 bits	10 km	0.5
10 Mb/s	10 000 bits	10 km	0.05
50 Mb/s	10 000 bits	1 km	0.025
50 Mb/s	100 bits	1 km	2.5

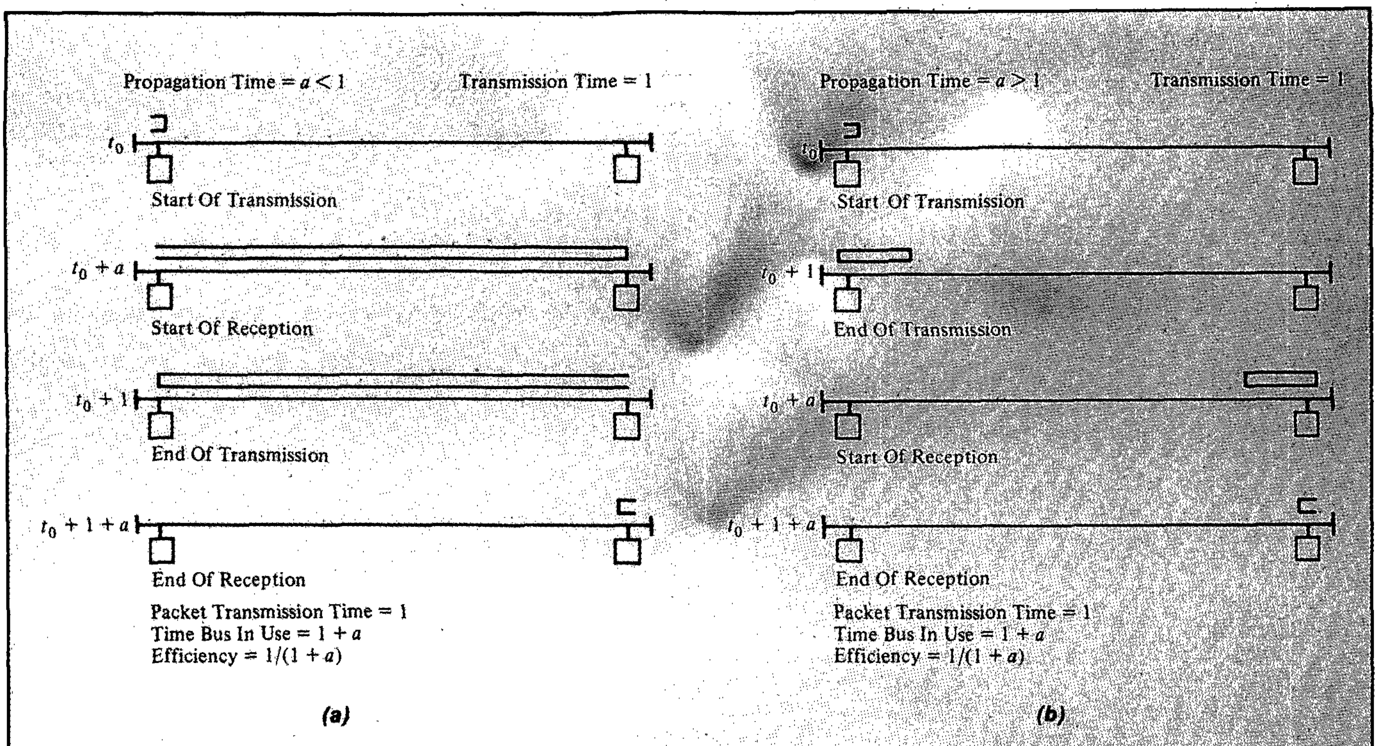


Fig. 1. The effect of a on utilization: bus.

$$U = \text{Throughput}/R$$
$$= \frac{L/(\text{Propagation} + \text{Transmission Time})}{R}$$
$$= \frac{L/(D + L/R)}{R}$$
$$= \frac{1}{1 + a} \qquad (1)$$

So, utilization varies inversely with a. This can be grasped intuitively by studying Fig. 1; this shows a baseband bus with two stations as far apart as possible (worst case) that take turns sending packets. If we normalize the packet transmission time to equal one, then the sequence of events can be expressed as follows.

1) A station begins transmission at t_0
2) Reception begins at $t_0 + a$
3) Transmission is completed at $t_0 + 1$
4) Reception ends at $t_0 + 1 + a$
5) The other station begins transmitting

Event 2 occurs *after* event 3 if $a > 1.0$. In any case, the total time for one "turn" is $1 + a$, but the transmission time is only 1, for a utilization of $1/(1 + a)$.

The same effect can be seen to apply to a ring network in Fig. 2. Here we assume that one station transmits and then waits to receive its own transmission before any other station transmits. The identical sequence of events outlined above applies.

The implication of (1) for performance is shown in Fig. 3. The axes of the plot are:

- S, the throughput or total rate of data being transmitted on the medium, normalized to the bandwidth of the medium.
- G, the offered load to the local network; the total rate of data presented for transmission, also normalized.

The ideal case is $a = 0$, which allows 100% utilization. It can be seen that, as offered load increases, throughput remains equal to offered load up to the full capacity of the system ($S = G = 1$) and then remains at $S = 1$. At any positive value of a, the system saturates at $S = 1/(1 + a)$.

So we can say that an upper bound on utilization or efficiency is $1/(1 + a)$, regardless of the medium-access protocol used. Two caveats: First, this assumes that the maximum propagation time is incurred on each transmission. Second, it assumes that only one transmission may occur at a time. These assumptions are not always true; nevertheless, the formula $1/(1 + a)$ is almost always a valid upper bound, because the overhead of the medium access protocol more than makes up for the lack of validity of these assumptions.

The overhead is unavoidable. Packets must include address and synchronization bits. There is administrative overhead for controlling the protocol. In addition, there are forms of overhead peculiar to one or more of the protocols. We highlight these briefly:

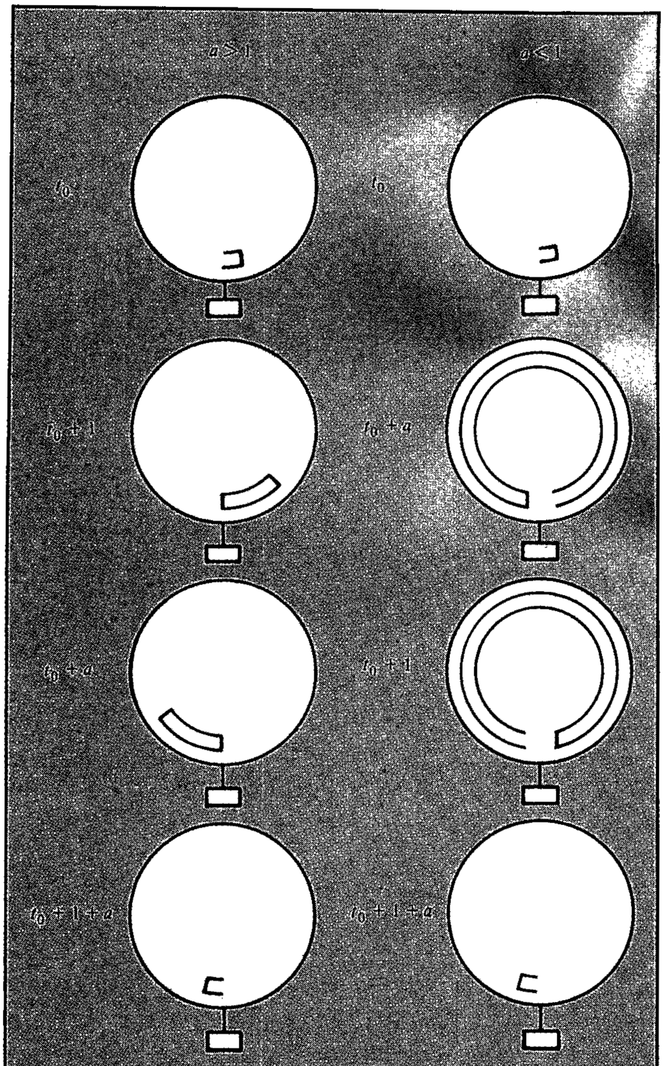


Fig. 2. The effect of *a* on utilization: ring.

- CSMA/CD — Time wasted due to collisions; need for acknowledgment packets.[2]
- Token bus — Token transmission; acknowledgment packets.
- Token ring — Time waiting for token if intervening stations have no data to send.
- Slotted ring — Time waiting for empty slot if intervening stations have no data to send.
- Register insertion — Delay at each node of time equal to address length; from the point of view of a single station, the propagation time, and hence *a*, may increase due to insertion of registers on the ring.

There are two distinct effects here. One is that the efficiency or utilization of a channel decreases as *a* increases. This, of course, affects throughput. The other effect is that the overhead attributable to a protocol wastes bandwidth and hence reduces effective utilization and effective throughput. For the most part, we can think of these two effects as independent and additive. However, we shall see that, for CSMA/CD, there is a strong interaction such that the overhead of the protocol increases as a function of *a*.

In any case, it would seem desirable to keep *a* as low as possible. Referring back to the defining formula, for a fixed network, *a* can be reduced by increasing packet size. This will only be useful if the length of messages produced by a station is an integral multiple of the packet size (excluding overhead bits). Otherwise, the large packet size is itself a source of waste. Furthermore, a large packet size increases the delay for other stations. Of course, variable-length packets may be used; in that case, performance tends to reflect average packet length [3].

[2]Strictly speaking, acknowledgments are not part of the access protocol but of a higher-level link protocol. However, the ring protocols under discussion allow for acknowledgment by having the sender remove its own packet from the ring. Thus this overhead is avoided.

Simple Performance Models of Token-Passing and CSMA/CD

In this section, we will give some insight into the relative performance of the most important LAN protocols — CSMA/CD, token bus, and token ring — by developing two simple performance models. It is hoped this will aid in understanding the results of more rigorous analyses to be presented later.

For these models, we assume a local network with N active stations, and a maximum normalized propagation delay of a. To simplify the analysis, we assume that each station is always prepared to transmit a packet. This allows us to develop an expression for maximum achievable throughput (S). While this should not be construed as the sole figure of merit for a local network, it is the single most analyzed one, and does permit useful performance comparisons.

First, let us consider token ring. Time on the ring will alternate between data packet transmission and token passing. Refer to a single instance of a data packet followed by a token as a cycle and define:

C = average time for one cycle
T_1 = average time to transmit a data packet
T_2 = average time to pass a token.

It should be clear that the average cycle rate is just $1/C = 1/(T_1 + T_2)$. Intuitively,

$$S = \frac{T_1}{T_1 + T_2} \tag{2}$$

That is, the throughput, normalized to system capacity, is just the fraction of time that is spent transmitting data.

Refer now to Fig. 2; time is normalized such that packet transmission time equals 1 and propagation time equals a. For the case of $a < 1$, a station transmits a packet at time t_0, receives the leading edge of its own packet at $t_0 + a$, and completes transmission at $t_0 + 1$. The station then emits a token, which takes an average time

a/N to reach the next station. Thus, one cycle takes $1 + a/N$ and the transmission time is 1. So, $S = 1/(1 + a/N)$.

For $a > 1$, the reasoning is slightly different. A station transmits at t_0, completes transmission at $t_0 + 1$, and receives the leading edge of its frame at $t_0 + a$. At that point, it is free to emit a token, which takes an average time a/N to reach the next station.[3] The cycle time is therefore $a + a/N$ and $S = 1/(a\,(1 + 1/N))$. Summarizing,

$$\text{Token } S = \begin{cases} \dfrac{1}{1 + a/N} & a < 1 \\ \dfrac{1}{a(1 + 1/N)} & a > 1 \end{cases} \tag{3}$$

The above reasoning applies equally well to token bus where we assume that the logical ordering is the same as the physical ordering and that token-passing time is therefore a/N.

For CSMA/CD, we base our approach on a derivation in Metcalfe [4]. Consider time on the medium to be organized into slots whose length is twice the end-to-end propagation delay. This is a convenient way to view the activity on the medium; the slot time is the maximum time, from the start of transmission, required to detect a collision. Again, assume that there are N active stations. Clearly, if each station always has a packet to transmit, and does so, there will be nothing but collisions on the line. Therefore we assume that each station restrains itself to transmitting during an available slot with probability P.

Time on the medium consists of two types of intervals. First is a transmission interval, which lasts $1/2a$ slots. Second is a contention interval, which is a sequence of slots with either a collision or no transmission in each slot. The throughput is just the proportion of time spent in transmission intervals (similar to the reasoning for (2)).

To determine the average length of a contention interval, we begin by computing A, the probability that exactly one station attempts a transmission in a slot and therefore acquires the medium. This is just the binomial probability that any one station attempts to transmit and the others do not:

$$A = \binom{N}{1} P^1(1 - P)^{N-1}$$
$$A = NP(1 - P)^{N-1}$$

This function takes on a maximum over P when $P = 1/N$:

$$A = (1 - 1/N)^{N-1}$$

Why are we interested in the maximum? Because we want to calculate the maximum throughput of the medium. It should be clear that this will be achieved if we maximize the probability of successful seizure of the medium. This says that the following rule should be enforced: During periods of heavy usage, a station should restrain its offered load to $1/N$. (This assumes that each station knows the value of N. In order to derive an expression for maximum possible throughput, we live with this assumption.) On the other hand, during periods of light usage, maximum utilization cannot be achieved because G is too low; this region is not of interest here.

[3]The station could transmit at $t_0 + 1$ (tailgating). This is not allowed in the IEEE 802 Standard to simplify control.

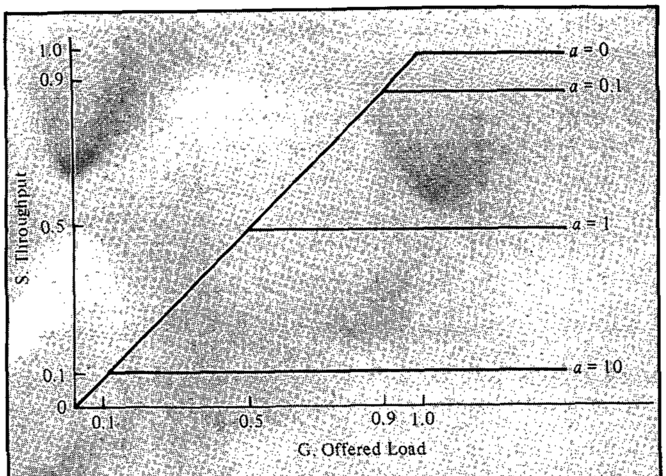


Fig. 3. Throughput versus offered load as a function of a.

Now we can estimate the mean length of a contention interval, w, in slots:

$$E[w] = \sum_{i=1}^{\infty} i\,Pr[i \text{ slots in a row with a collision or no transmission followed by a slot with one transmission}]$$

$$= \sum_{i=1}^{\infty} i(1 - A)^i A$$

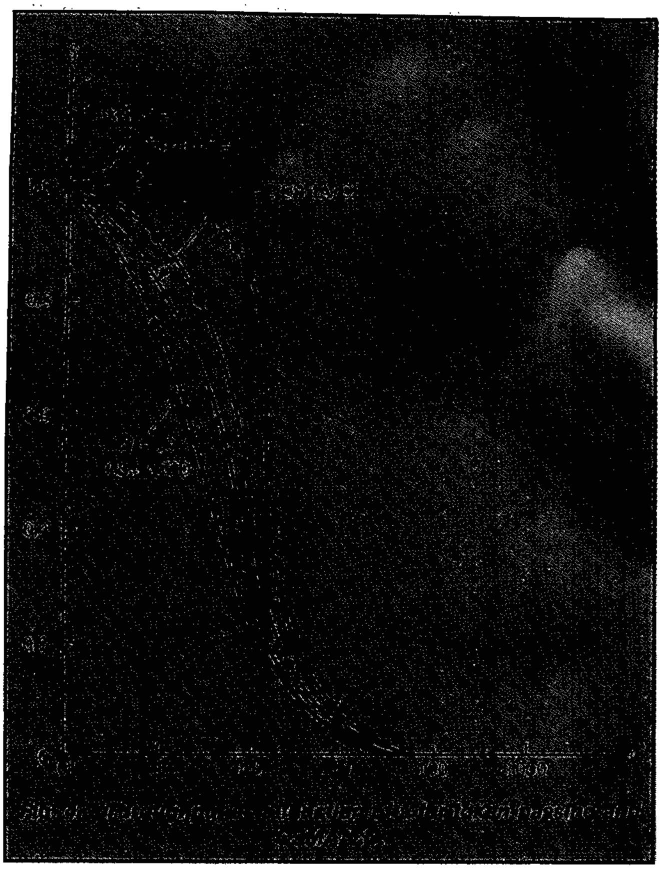
The summation converges to

$$E[w] = \frac{1 - A}{A}$$

We can now determine the maximum utilization, which is just the length of a transmission interval as a proportion of a cycle consisting of a transmission and a contention interval:

$$\text{CSMA/CD } S = \frac{\frac{1}{2}a}{\frac{1}{2}a + \dfrac{1 - A}{A}} = \frac{1}{1 + 2a\,\dfrac{1 - A}{A}} \tag{4}$$

Figure 4 shows normalized throughput as a function of a for various values of N and for both token-passing and CSMA/CD. For both protocols, throughput declines as a increases. This is to be expected; but the dramatic difference between the two protocols is seen in Fig. 5, which shows throughput as a function of N. Token-passing performance actually improves as a function of N, because less time is spent in token-passing. Conversely, the performance of CSMA/CD decreases be-



cause of the increased likelihood of collision or no transmission.

It is interesting to note the asymptotic value of S as N increases. For token:

$$\text{Token} \lim_{N\to\infty} S = \begin{cases} 1 & a < 1 \\ 1/a & a > 1 \end{cases} \tag{5}$$

For CSMA/CD, we need to know that $\lim_{N\to\infty} (1 - 1/N)^{N-1} = 1/e$. Then

$$\text{CSMA/CD} \lim_{N\to\infty} S = \frac{1}{1 + 3.44a} \tag{6}$$

Comparative Results from Analytic and Simulation Models

Although there have been a number of performance studies focusing on a single protocol, there have been few systematic attempts to analyze the relative performance of the various local network protocols. In what follows, we look at the results of several carefully-done studies that have produced comparative results.

CSMA/CD, Token Bus, and Token Ring

The first study was done by a group at Bell Labs, under the sponsorship of the IEEE 802 Local Network Standards Committee [5]. Naturally enough, the study analyzed the three protocols being standardized by IEEE 802: CSMA/CD, token bus, and token ring. The analysis is based on considering not only mean values but second moments of delay and message length. Two cases of message arrival statistics are employed. In the first, only one station out of one hundred has messages to transmit, and is always ready to transmit. In such a case, one would hope that the network would not be the bottleneck, but could easily keep up with one station. In the second case, 100 stations out of 100 always have messages to transmit. This represents an extreme of congestion and one would expect that the network may be a bottleneck. In the two cases, the one station or one hundred stations provide enough input to fully utilize the network. Hence, the results are a measure of maximum potential utilization.

The results are shown in Fig. 6. It shows the actual data transmission rate versus the transmission speed of the medium for the two cases and two packet sizes. Note that the abscissa is not offered load but the actual capacity of the medium. Three systems are examined: token ring with a one-bit latency per station, token bus, and CSMA/CD. The analysis yields the following conclusions:

- For the given parameters, the smaller the mean packet length, the greater the difference in maximum mean throughput rate between token-passing and CSMA/CD. This reflects the strong dependence of CSMA/CD on a.
- Token ring is the least sensitive to workload.
- CSMA/CD offers the shortest delay under light load, while it is most sensitive under heavy load to the workload.

Note also that in the case of a single station transmitting, token bus is significantly less efficient

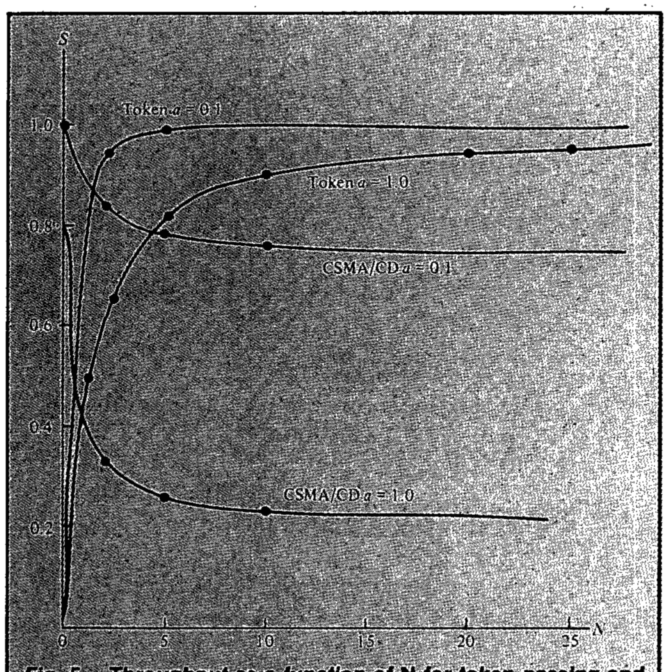
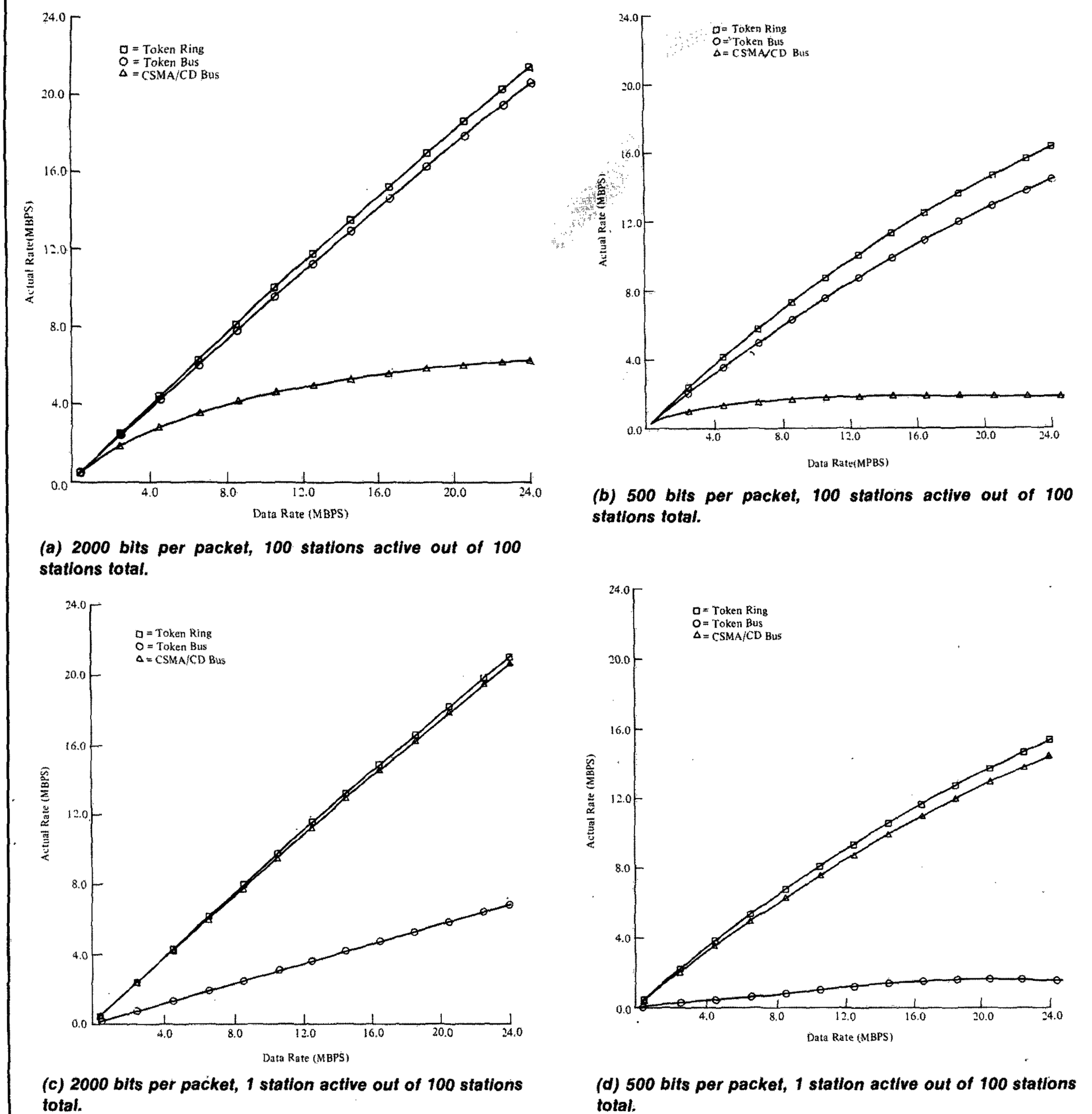


Fig. 5. Throughput as a function of N for token-passing and CSMA/CD.



(a) 2000 bits per packet, 100 stations active out of 100 stations total.

(b) 500 bits per packet, 100 stations active out of 100 stations total.

(c) 2000 bits per packet, 1 station active out of 100 stations total.

(d) 500 bits per packet, 1 station active out of 100 stations total.

Fig. 6. Maximum potential data rate for LAN protocols.

than the other two protocols. This is so because the assumption is made that token-passing time equals the propagation delay, and that the delay in token processing is greater than for token ring.

Another phenomenon of interest is seen most clearly in Fig. 6(b). For a CSMA/CD system under these conditions, the maximum effective throughput at 5 Mb/s is only about 1.25 Mb/s. If expected load is, say, 0.75 Mb/s, this configuration may be perfectly adequate. If, however, the load is expected to grow to 2 Mb/s, raising the network data rate to 10 Mb/s or even 20 Mb/s will not accommodate the increase. The same conclusion, less precisely, can be drawn from the simple model presented earlier.

The reason for this disparity between CSMA/CD and token-passing (bus or ring) under heavy load has to do with the instability of CSMA/CD. As offered load increases, so does throughput until, beyond its maxi-

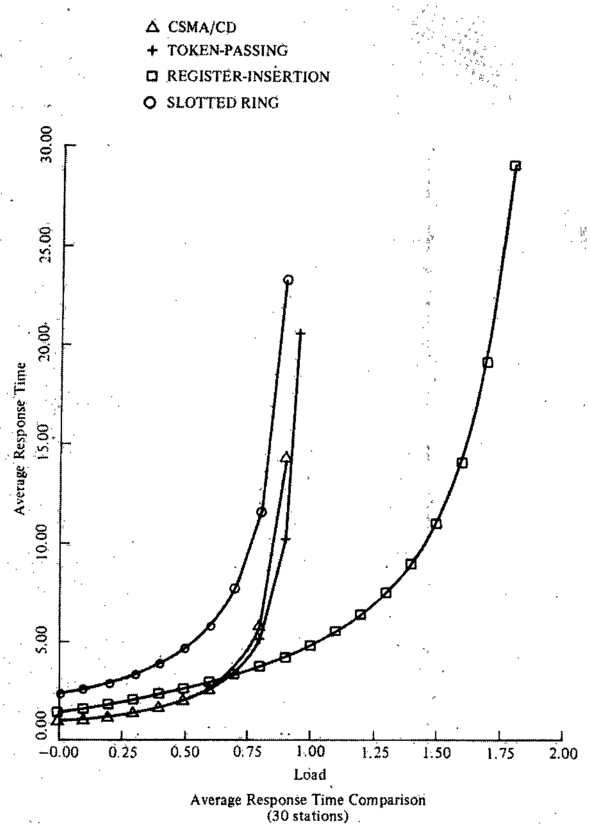


Fig. 7. **Delay for various ring protocols and CSMA/CD.**

mum value, throughput actually declines as G increases. This is because there is an increased frequency of collisions: more packets are offered, but fewer successfully escape collision. Worse, this situation may persist even if the input to the system drops to zero. Consider: for high G, virtually all offered packets are retransmissions and virtually none get through. So, even if no new packets are generated, the system will remain occupied in an unsuccessful attempt to clear the backlog; the effective capacity of the system is virtually zero. Thus, even in a moderately loaded system, a temporary burst of work could move the network permanently into the high-collision region. This type of instability is not possible with the other protocols.

CSMA/CD and Ring Protocols

It is far more difficult to do a comparative performance of the three major ring protocols than to do a comparison of bus and token-ring protocols. The results depend critically on a number of parameters unique to each protocol. For example:

- Token Ring — size of token, token processing time
- Slotted Ring — slot size, overhead bits per slot
- Register Insertion — register size

Thus it is difficult to do a comparison, and although there have been a number of studies on each one of the techniques, few have attempted pairwise comparisons, much less a three-way analysis. The most systematic work in this area has been done by Liu and his associates [6]. Liu made comparisons based on analytic models developed by others for token ring, slotted ring, and CSMA/CD, plus his own formulations for register insertion. He then obtained very good corroboration from simulation studies.

Figure 7 summarizes the results. They are based on the assumption that $a = 0.005$ and that register insertion ring packets are removed by the destination station, whereas slotted-ring and token-ring packets are removed by the source station. This is clearly an unfair comparison since register insertion, under this scheme, does not include acknowledgments, but token ring and slotted ring do. The figure does show that slotted ring is the poorest performer, and that register insertion can carry a load greater than 1.0. This is because the protocol permits multiple packets to circulate.

Bux [7] performed an analysis comparing token ring, slotted ring, and CSMA/CD. This careful analysis produced several important conclusions (see Fig. 8). First, the delay-throughput performance of token ring vs. CSMA/CD confirms our earlier discussion. That is, token ring suffers greater delay than CSMA/CD at light load but less delay and stable throughput at heavy loads. Further, token ring has superior delay characteristics to slotted ring. The poorer performance of slotted ring seems to have two causes: 1) the relative overhead in the small slots of a local-area ring is very high, and 2) the time needed to pass empty slots around the ring to guarantee fair bandwidth is significant. Bux also reports several positive features of slotted ring: 1) the expected delay for a message is proportional to length (that is, shorter packets get better service than long ones), and 2) overall mean delay is independent of packet length distribution type. Bux has recently extended his analysis to include register insertion [8], achieving results comparable to Liu's.

It is difficult to draw conclusions from the efforts made so far. The slotted ring seems to be the least desirable over a broad range of parameter values, owing to the considerable overhead associated with each small packet. For example, the Cambridge ring, which is the most widely commercially-available ring in Europe, uses a 37-bit slot with only 16 data bits!

As between token ring and register insertion, the evidence suggests that, at least for some sets of parameter values, register insertion gives superior delay performance. Interestingly, there seems to be no commercially-available register insertion product, with the exception of the IBM Series 1 loop, where performance is not an issue. On the other hand, token ring in the United States, with a boost from the IEEE 802 Standard and IBM, and slotted ring in Europe, where many firms have licensed the Cambridge slotted ring, seem destined to dominate the ring marketplace.

The primary advantage of register insertion is the

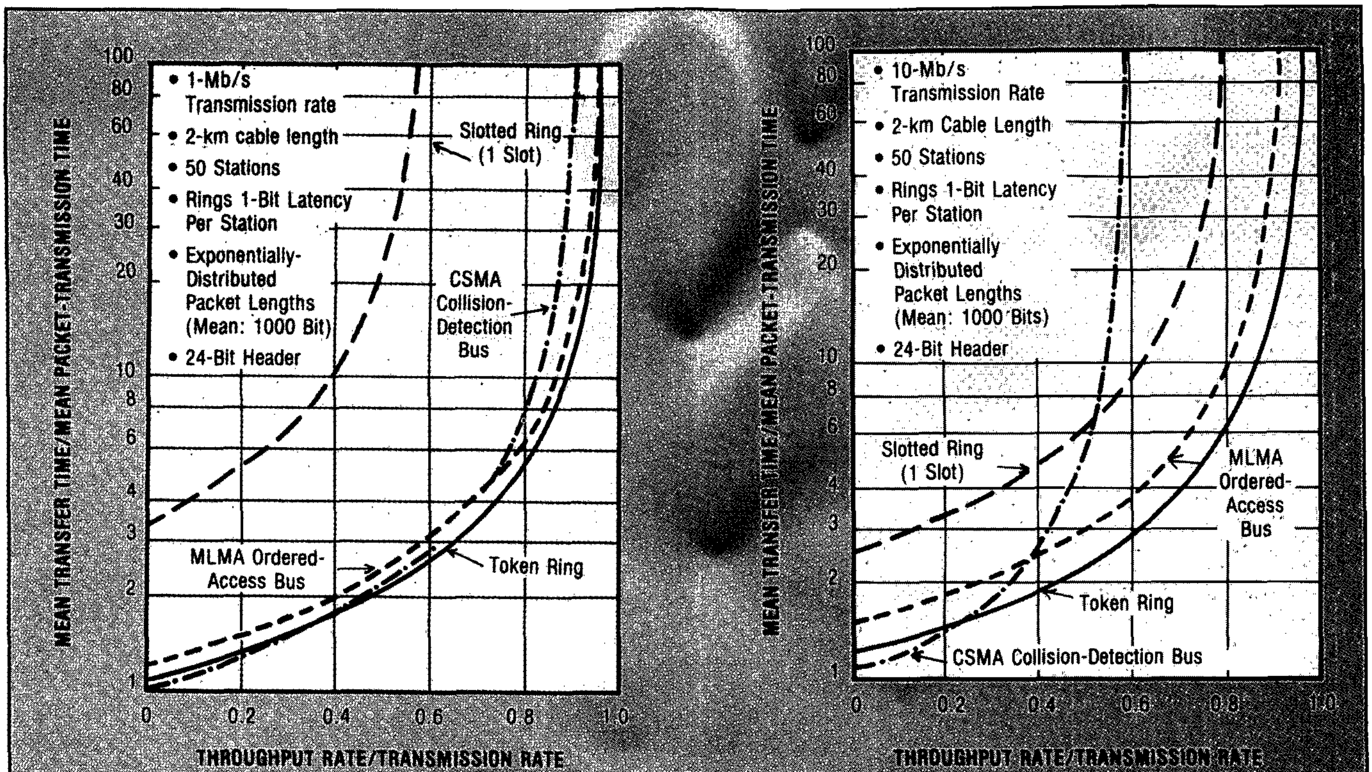


Fig. 8(a). Transfer delay-throughput characteristics of the four subnetworks at 1 Mb/s.

Fig. 8(b). Transfer delay-throughput characteristics of the four subnetworks at 10 Mb/s.

Fig. 8. Delay-throughput performance of various protocols.

potentially high utilization it can achieve. In contrast with token ring, multiple stations can transmit at one time. Further, a station can transmit as soon as a gap opens up on the ring; it need not wait for a token. On the other hand, the propagation time around the ring is not constant, but depends on the amount of traffic.

A final point in comparing token ring and register insertion: Under light loads, register insertion operates more efficiently, resulting in slightly less delay. However, both systems perform adequately. Our real interest is under heavy load. A typical local network will have $a < 1$, usually $a << 1$, so that a transmitting station on a token ring will append a token to the end of its packet. Under heavy load, a nearby station will be able to use the token. Thus almost 100% utilization is achieved, and there is no particular advantage to register insertion.

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Appendix — Local Network Terms

Bus — The common name for a local network with a linear or tree topology, in which stations are attached to a shared transmission medium. Transmissions propagate the length of the linear medium or throughout all the branches of the tree, and may be received by all stations.

Ring — A local network in which stations are attached to repeaters connected in a closed loop. Data are transmitted in one direction around the ring, and can be read by all attached stations.

Medium Access Control Technique — A distributed control technique, shared by stations attached to a local network, that determines which device may transmit on the medium at any time.

CSMA/CD — Carrier Sense Multiple Access with Collision Detection. A medium access control technique for bus local networks. A station wishing to transmit first senses the medium and transmits only if the medium is idle. The station continues to sense the medium during transmission and ceases transmission if it detects a collision.

Token Bus — A medium-access control technique for bus local networks. Stations form a logical ring, around which a token is passed. A station receiving the token may transmit data, and then must pass the token to the next station in logical order.

Token Ring — A medium-access control technique for ring local networks. A token circulates around the ring. A station may transmit by removing the token, inserting a packet onto the ring, and then retransmitting the token.

Register Insertion — A medium access control technique for ring local networks. Each station contains a register that can temporarily hold a circulating packet. A station may transmit whenever there is a gap on the ring and, if necessary, hold an oncoming packet until it has completed transmission.

Slotted Ring — A medium access control technique for ring local networks. The ring is divided into circulating slots, which may be designated empty or full. A station may transmit whenever an empty slot goes by, by marking it full and inserting a packet into the slot.

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