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Performance analysis of two bridged CSMA/CD networks

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This paper analyses the performance of two non-persistent CSMA/CD LANs linked by a bridge. The main function of the bridge is to buffer all internetwork packets and forward them across networks to their destinations. From establishing and solving the main equations governing the behaviour of the bridged networks, the effects of design parameters such as the bridge buffer size and re-transmission backoff delay on the performance of the system are studied. It is shown that if these parameters are chosen properly, better throughput and delay performance can be obtained, when compared with an equivalent CSMA/CD network without using a bridge.

Keywords: CSMA/CD, performance, bridge, throughput

The use of the CSMA/CD protocol in LANs is well known[1,2], and the performance characteristics have been extensively studied using analytical models and computer simulations[3-6]. Favourable performance and protocol simplicity have made the CSMA/CD method an attractive choice in LANs.

To further improve the protocol's performance, variations of the backoff mechanism[7] and transmission attempt strategy[8] of the basic protocol have been proposed. The multi-channel CSMA/CD scheme[9,10] achieves improvement in performance by providing stations in the network with alternative communication channels when one is currently in use. Hybrid token CSMA/CD access protocols[11,12] take advantage of the good performance of the former under heavy loading and the latter under light to medium load. Dynamic segmentation[13] of the CSMA/CD bus has also been proposed to provide for the possibility of having more than one simultaneous successful transmission in the network.

As discussed by Stallings[14], the main advantages of incorporating a bridge are greater geographic coverage, improved performance, reliability and security in the network. Thus, in an organization consisting of a number of distinct departments, it may be better for each department to have their own networks linked together through bridges than to have one large network for all departments.

Because of its importance, the interconnection of LANs with similar MAC protocols (e.g. standard IEEE 802 protocol) has received considerable interest from international standardization bodies, resulting in the formulation of IEEE 802.1 (D)[15] and (M)[16] draft standards. The former describes issues such as transparent bridging, frame forwarding, learning of station addresses and use of the spanning tree algorithm to resolve possible loops in the topology, while the latter describes network management in a number of functional areas. Specifically, the use of management filtering such as dynamic load-balancing of intra- and inter-network traffic to optimize resources throughout the interconnected networks[17], and the use of access control for filtering out packets sent across the network[18] are described.

In parallel with these standardization efforts, several analytical investigations have also been carried out on the interconnection of LANs. Bux and Grillo[19] have investigated flow control issues in LANs consisting of multiple token rings interconnected through bridges. Exlay and Merakos[20] obtained results on performance bounds when two CSMA/CD LANs are interconnected through a bridge link, while Hamilton and Fui[21] investigated the situation where an infinite population of stations and a single gateway share a single asynchronous, non-persistent CSMA/CD channel.

In this paper we investigate the behaviour and performance of finite CSMA/CD networks connected together through bridges by modelling the protocol with a simple finite-state model. For simplicity, only

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the case of two networks communicating through a bridge is studied. Although issues such as management filtering are important, they are primarily concerned with network management and, as with other similar analytical investigations[19-21], they are not investigated here; the paper is concerned primarily with studying the performance of interconnected networks through analytical formulations.

BRIDGED CSMA/CD NETWORKS

Figure 1 shows two CSMA/CD networks connected through a bridge. Network 1 has M_1 stations, network 2 M_2 stations. The non-persistent CSMA/CD protocol is used whenever any station in the two networks tries to send a packet.

Thus, when a station in network i, $i = 1, 2$, has a newly arrived packet to send, the station first senses the channel to determine if it is busy or idle. If the channel is sensed busy, the station waits a random period of time, after which it senses the channel again. Sensing of the channel is repeated in this manner until it is sensed idle, when the station transmits the packet and listens to the transmission to see if collision has occurred. If no collision is detected the packet is transmitted successfully, otherwise the user stops transmission, waits a random period of time, senses the channel, and tries to transmit the packet again. This process is repeated until the packet is successfully transmitted. For simplicity, the random backoff period after sensing an idle channel or detecting a collision will be assumed to have an exponential distribution with the same mean backoff length.

The CSMA/CD protocol described is sufficient for communication between stations belonging to one network. Communication with stations on the other network, however, has to be carried out indirectly through the bridge. First, the station concerned has to send the packet using the CSMA/CD protocol described earlier to the bridge, which stores the packet received in a buffer. By using the non-persistent CSMA/CD protocol with, perhaps, a different mean backoff length as for the stations, the bridge then senses and contends for an idle channel in the destination network. Finally, when the channel has been successfully seized, the bridge transmits all the packets in its buffer one after another in succession. To implement such an exhaustive service, 'filler' packets[20] or programmable VLSI controllers, such as the Intel 802.3 upward compatible 82586 controller[22], can be employed. Since the main implication of such implementations is that a few more bits have to be transmitted by the bridge, and this is small compared with the packet length, the ensuing performance degradation will be negligible. Thus, the issue of implementing exhaustive service is not discussed any further here, and the bridge will be assumed simply to forward packets in succession in the manner outlined.

ANALYTICAL MODEL AND MAIN ASSUMPTIONS

Due to their complicated behaviour, detailed analysis[1, 3] of random access protocols such as CSMA/CD has traditionally been based on a slotted model in which the time axis is slotted so that all the bus activities are, in a certain sense, synchronized. Without dividing the time axis into slots, the performance of the network, which depends not only on the protocol but also on its topology, would be too complicated to be analysed. Essentially, the use of a slotted model reduces the complexity of the network to one which is independent of the topology and whose behaviour can be described by a certain Markov chain. From solving the key equations governing this Markov chain, the various performance characteristics of the protocol can be calculated. Therefore, for mathematical tractability, the analysis to be presented will follow the approach described and will be based on the use of a slotted model.

Suppose a packet transmission is initiated in a network which has an end-to-end delay of τ. It is well known that if no collision is detected in the first 2τ seconds, then the transmission will be successful[2]. If there is a collision, it will occur in this time interval, by the end of which the channel will be silent and ready to be contended for again. From this and the other considerations outlined earlier, the time axis will be divided into slots of size 2τ for analytical purposes. In addition, the following simplifying assumptions regarding the packet arrival, transmission and backing off processes will be made for mathematical tractability and ease of analysis:

(a) The arrival of new packets and the beginning of a packet transmission always occur at the beginning of a slot.

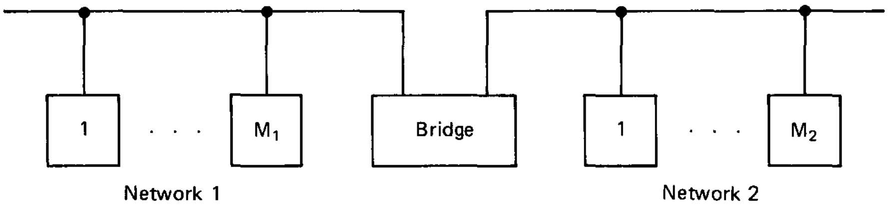

Figure 1 Two CSMA/CD networks connected by a bridge

(b) Each station has a buffer for storing only one packet, whereas the bridge has a buffer which can store up to M_{bi} packets with destinations in the ith network. A newly arrived packet can be accepted by the station or the bridge only if the appropriate buffer is not full.

(c) The packet arrival process for each station in the ith network is Poisson with a mean of σ_i packets per slot.

(d) The arrival of packets to the bridge to be forwarded to the ith network is Poisson with a mean of σ_{bi} packets per slot.

(e) The backoff lengths for the station and the bridge attempting to transmit in the ith network are geometrically distributed with means of $1/p_i$ and $1/p_{bi}$ slots respectively.

(f) The packet lengths are geometrically distributed with a mean of ℓ slots.

(g) After seizing the communication channel in the ith network, the bridge or station will transmit all the packets stored in its buffer until the buffer is empty.

Note that all the assumptions regarding the stations are in line with those frequently used for the analysis of CSMA/CD networks and that assumption (e) on the geometric distribution of the backoff lengths for the station and the bridge is simply the discrete-time case of the analogue exponential distribution of the backoff lengths. The basic thinking behind the various assumptions on the bridge is similar to the corresponding ones for the stations, except perhaps assumption (d) on the Poisson packet arrival process for the bridge. Since packets arriving at the bridge to be forwarded to network 1 actually originate from stations in network 2, the packet arrival process for the bridge in forwarding packets to network 1 should in fact be the same as that for the successful transmission of inter-network packets in network 2. With the former process assumed to be Poisson, the arrival of packets to be forwarded to network 1 becomes dependent only on the parameter σ_{b1}, rather than the instantaneous state of network 2. This parameter is of course still related to the throughput of network 2 through:

$$\ell\sigma_{b1} = e_2T_2 \tag{1a}$$

where e_i is the fraction of inter-network packets and T_i is the throughput, normalized with respect to the channel capacity, due to all the stations in the ith network. However, apart from equation (1a) and a similar equation:

$$\ell\sigma_{b2} = e_1T_1 \tag{1b}$$

on the traffic from network 2 to 1, the two CSMA/CD networks are now 'decoupled' and can be investigated individually. As a result, the number of states for characterizing the entire system is substantially reduced, thereby opening up the possibility for obtaining useful numerical results. In this context, it is probably worth mentioning that a state transition matrix with numbers of elements in the order of $M_1^2M_2^2M_{b1}M_{b2}$ and $M_1^2M_{b1} + M_2^2M_{b2}$ will be necessary to characterize the bridged CSMA/CD system with and without using assumption (d), respectively.

Apart from computational implications, there are some justifications for assuming the arrival of packets to the bridge to be Poisson. First consider the situation when the network is lightly loaded. In this environment, all newly arrived packets will be successfully transmitted almost immediately. Since the packet arrival process for each station is Poisson (assumption (c)), the combined process and so the packet arrival process for the bridge will also be Poisson in nature. In general, because the packet lengths are geometrically distributed (assumption (f)) and the packet arrival process for the stations is Poisson (assumption (c)), it appears intuitively plausible that the actual process governing the arrival of packets to be forwarded by the bridge will also be approximately Poisson. This is indeed the case, as shown later by using some simulation results. Lastly, even though the packet arrival process for the bridge may not be Poisson exactly, the impact on the performance of the system can be envisaged as being small. This is because the bridge has a buffer for storing a number of packets and because there are many other network users in the system.

PERFORMANCE ANALYSIS

With the mathematical model, the main assumptions and their justifications discussed, this section continues the theoretical analysis by formulating the state transition probabilities and the other equations for determining the performance of the bridged system. However, before doing so, the various state variables are first introduced and defined. Note that, as mentioned earlier, apart from the requirements to satisfy equation (1), the two CSMA/CD networks are decoupled. Therefore unless stated otherwise, the formulation and derivation presented will be for the transmission of packets in a particular ith network.

From assumption (a), and that the slot size is 2τ, exactly one slot will be wasted and the channel will be ready for contention again in the next slot in the event of a collision. Also, any packet which has been in continuous transmission for at least 1 slot obviously experiences no collision and will be said to be in 'successful transmission'. Likewise, a packet will be said to be 'blocked' if it has been generated in previous slots but has not successfully contended for an idle channel, and so is not in successful transmission yet. Blocked packets therefore include those currently contending for an idle channel (in transmission but not in successful transmission yet) or those waiting for re-transmission.

Now consider the state of the network stations in the current slot. Firstly, let s_i and m_i denote the numbers of successfully transmitting and blocked stations, respectively, in the ith network. With assumption (b), the number of stations which can accept newly arrived packets in this network is $M_i - s_i - m_i$. From assumptions (a) and (c), the probability for a new packet to arrive at any ith network station in any one slot is constant and is given by σ_i. Thus, the probability for g_i stations to accept new packets and contend for idle channels in the current slot is:

$$G_i(g_i) = \left(\frac{M_i - s_i - m_i}{g_i}\right)\sigma_i^{g_i}(1 - \sigma_i)^{M_i - s_i - m_i - g_i} \quad (2)$$

In addition to these g_i stations attempting to start transmission, some of the m_i blocked stations will also attempt to re-transmit in the current slot. From assumption (e), the probability for any blocked station to sense and contend for idle channels in any slot is always p_i. Thus, the probability for r_i of the m_i blocked stations to attempt re-transmissions in the current slot is:

$$R_i(r_i) = \left(\frac{m_i}{r_i}\right)p_i^{r_i}(1 - p_i)^{m_i - r_i} \quad (3)$$

Likewise, from assumptions (f) and (g), the probability for any successfully transmitting station to finish transmission in the crrent slot is always $1/\ell'$, independent of how long the station has been in transmission.

As outlined in assumptions (a)–(g), the main difference between the bridge and the station is that instead of having a buffer for only 1 packet, the bridge has a buffer which can store up to M_{bi} packets. Thus, following the same arguments as for the stations, the probability for g_{bi} packets to arrive and be accepted by the bridge in the current slot is:

$$G_{bi}(g_{bi}) = \begin{cases} G_{1bi}, & m_{bi} + s_{bi} < M_{bi} \\ G_{2bi}, & m_{bi} + s_{bi} = M_{bi} \end{cases} \quad (4a)$$

where:

$$G_{1bi} = P[g_{bi}/m_{bi} + s_{bi} < M_{bi}] = \begin{cases} \sigma_{bi}, & g_{bi} = 1 \\ 1 - \sigma_{bi}, & g_{bi} = 0 \end{cases} \quad (4b)$$

$$G_{2bi} = P[g_{bi}/m_{bi} + s_{bi} = M_{bi}] = \begin{cases} 1, & g_{bi} = 0 \\ 0, & g_{bi} = 1 \end{cases} \quad (4c)$$

s_{bi} is the number of successfully transmitting packets from the bridge, and m_{bi} is the number of blocked packets in the bridge in the current slot. Similarly, whenever the bridge is not successfully transmitting ($s_{bi} = 0$), the probability for it to attempt a transmission in the current slot is:

$$T_{bi}(g_{bi}) = \begin{cases} T_{1bi}, & m_{bi} > 0 \\ T_{2bi}, & m_{bi} = 0 \end{cases} \quad (5a)$$

where:

$$T_{1bi} = P[t_a/m_{bi} > 0] = \begin{cases} p_{bi}, & t_a = 1 \\ 1 - p_{bi}, & t_a = 0 \end{cases} \quad (5b)$$

$$T_{2bi} = P[t_a/m_{bi} = 0] = \begin{cases} 1, & g_{bi} = 1 \text{ and } t_a = 1 \\ 0, & \text{otherwise} \end{cases} \quad (5c)$$

and:

$$t_a = \begin{cases} 1, & \text{attempt transmission} \\ 0, & \text{does not attempt transmission} \end{cases} \quad (5d)$$

Let the state of the channel in the ith network in the current slot be denoted by c_i, where c_i can be 0, 1s and 1b. $c_i = 0$ indicates that the channel is idle, whereas $c_i = 1\text{s}$ or 1b indicates that the channel is currently carrying a successful transmission from one of the stations or the bridge, respectively. Clearly, s_i and s_{bi} are related to c_i by:

$$s_i = \begin{cases} 1, & c_i = 1\text{s} \\ 0, & \text{elsewhere} \end{cases} \quad (6)$$

and:

$$s_{bi} = \begin{cases} 1, & c_i = 1\text{b} \\ 0, & \text{elsewhere} \end{cases} \quad (7)$$

From the derivation presented above, the acceptance and transmission of newly arrived packets, the re-transmission of blocked packets and the end of a successful transmission in the current slot depend only on the variables s_i, m_i, s_{bi} and m_{bi}. Since s_i and s_{bi} are in turn related to the state of the channel c_i through equations (6) and (7), the state of the ith network can be completely characterized by m_i, m_{bi} and c_i. Specifically, the transition probabilities from m_i, m_{bi} and c_i in the current slot to $\hat{m}_i$, $\hat{m}_{bi}$ and $\hat{c}_i$ in the next slot can be expressed in terms of the probabilities formulated in equations (2)–(5), as shown in Table 1. For example, the transition from $c_i = 1\text{s}$ to $\hat{c}_i = 1\text{s}$ corresponds to the situation when a successfully transmitting station does not finish its transmission in the current slot, and so remains in successful transmission in the next slot. Therefore, if the number of blocked stations increases from m_i to $\hat{m}_i = m_i + \Delta m_i$ at the same time, the implication is that there are $g_i = \Delta m_i$ stations accepting newly arrived packets, attempting to start a transmission and subsequently getting blocked. Likewise, the change from m_{bi} to $\hat{m}_{bi} = m_{bi} + \Delta m_{bi}$ implies that $g_{bi} = \Delta m_{bi}$ new packets have arrived and have been accepted by the bridge. The probability for all these events to occur simultaneously is thus $(1/\ell)G_i(\Delta m_i)G_{bi}(\Delta m_{bi})$, and is equal to the transition probability $P(c_i = 1\text{s},\ m_i,\ m_{bi} \rightarrow c_i = 1\text{s},\ \hat{m}_i = m_i + \Delta m_i,\ \hat{m}_{bi} = m_{bi} + \Delta m_{bi})$ as given by the second entry in Table 1. All the other entries in the table can be obtained in a similar manner.

From the network state transition probabilities, the network equilibrium state probabilities $P(c_i, m_i, m_{bi})$ can be calculated by solving:

Table 1 Tabulation of the transition probability $P(c_i, m_i, m_{bi} \rightarrow \hat{c}_i, \hat{m}_i, \hat{m}_{bi})$

c_i	$\hat{c}_i$	$P(c_i, m_i, m_{bi} \rightarrow \hat{c}_i, \hat{m}_i = m_i + \Delta m_i, \hat{m}_{bi} = m_{bi} + \Delta m_{bi})$
1s	0	$\left(\frac{1}{\ell}\right) G_i(\Delta m_i) G_{bi}(\Delta m_{bi})$
1s	1s	$\left(1 - \frac{1}{\ell}\right) G_i(\Delta m_i) G_{bi}(\Delta m_{bi})$
1s	1b	0
1b	0	$\frac{\delta(m_{bi})\delta(\Delta m_{bi})}{\ell} G_i(\Delta m_i) G_{bi}(\Delta m_{bi})$
1b	1s	0
1b	1b	$G_i(\Delta m_i)\left\{\left(1 - \frac{1}{\ell}\right) G_{bi}(\Delta m_{bi}) + \left(\frac{1}{\ell}\right) G_{bi}(\Delta m_{bi} + 1)\right\}$
0	0	$G_i(\Delta m_i) G_{bi}(\Delta m_{bi}), \Delta m_i > 1$ $G_i(\Delta m_i) G_{bi}(\Delta m_{bi})\{[1 - R_i(0)] + R_i(0) T_{bi}(\Delta m_{bi})\}, \Delta m_i = 1$ $G_i(\Delta m_i) G_{bi}(\Delta m_{bi})\{R_i(0)[1 - T_{bi}(\Delta m_{bi})] + [1 - R_i(0) - R_i(1)] + R_i(1) T_{bi}(\Delta m_{bi})\}, \Delta m_i = 0$
0	1s	$G_{bi}(\Delta m_{bi})[1 - T_{bi}(\Delta m_{bi})] G_i(\Delta m_i + 1)\{\delta(\Delta m_i + 1) R_i(1) + \delta(\Delta m_i) R_i(0)\}$
0	1b	$G_{bi}(\Delta m_{bi} + 1) T_{bi}(\Delta m_{bi} + 1) G_i(\Delta m_i) \delta(\Delta m_i) \mathrm{R}_i(0)$

$$P(\hat{c}_i, \hat{m}_i, \hat{m}_{bi}) = \sum_{c_i} \sum_{m_i} \sum_{m_{bi}} P(c_i, m_i, m_{bi} \rightarrow \hat{c}_i, \hat{m}_i, \hat{m}_{bi}) P(c_i, m_i, m_{bi}) \qquad (8a)$$

together with the constraint:

$$\sum_{c_i} \sum_{m_i} \sum_{m_{bi}} P(c_i, m_i, m_{bi}) = 1 \qquad (8b)$$

From the network state equilibrium probabilities, the average number of blocked stations is:

$$E[m_i] = \sum_{c_i} \sum_{m_i} \sum_{m_{bi}} m_i P(c_i, m_i, m_{bi}) \qquad (9)$$

Likewise, the probability of finding the channel carrying successful transmission from the stations is:

$$T_i = E[s_i] = \sum_{c_i} \sum_{m_i} \sum_{m_{bi}} s_i P(c_i, m_i, m_{bi}) \qquad (10)$$

which is also equal to the normalized throughput of the stations. Therefore, by using Little's result, the average delay experienced by a packet from its arrival to a station to the end of its successful transmission is:

$$D_i = \frac{\ell E[m_i]}{T_i} + \ell \text{ slots} \qquad (11)$$

Note that the first term corresponds to the delay of the packet while being blocked, whereas the second term is the average transmission delay.

By following the same analysis as for the stations, the normalized throughput of the bridge in forwarding packets to the ith network is:

$$T_{bi} = E[s_{bi}] = \sum_{c_i} \sum_{m_i} \sum_{m_{bi}} s_{bi} P(c_i, m_i, m_{bi}) \qquad (12)$$

Since packets to be forwarded are arriving at the rate of σ_{bi} packets per slot and have a length of ℓ slots on average, the fraction of packets which will not be accepted by the bridge is:

$$L_{bi} = 1 - \frac{T_{bi}}{\sigma_{bi}} \ell \qquad (13)$$

Clearly, it is desirable for L_{bi} to be as small as possible, although the size of the buffer in the bridge should not also be excessive. Again, by using Little's result, the average delay experienced by a packet from arriving at the bridge to finishing being transmitted successfully is:

$$D_{bi} = \frac{\ell E[m_{bi}]}{T_{bi}} + \ell$$

$$= \ell + \frac{\ell}{T_{bi}} \sum_{c_i} \sum_{m_i} \sum_{m_{bi}} m_{bi} P(c_i, m_i, m_{bi}) \text{ slots} \qquad (14)$$

As given by equation (10), the throughput of stations in the ith network is a function of the normalized bridge loading $\ell\sigma_{bi}$:

$$T_i = f_i(\ell\sigma_{bi}) \qquad (15)$$

However, as given by equation (1) and discussed earlier, $\ell\sigma_{bi}$ should be equal to the normalized throughput due to inter-network packets sent from stations in the other network. Evidently, equations (1) and (15) give rise to four simultaneous equations from which σ_{b1}, σ_{b2}, T_1 and T_2 can be determined. Once σ_{b1}

and σ_{b2} are found, all the relevant performance measures can be calculated through the use of equations (9)–(14).

NUMERICAL AND SIMULATION RESULTS

Having formulated the various equations governing the behaviour of the bridged CSMA/CD system, this section presents the numerical results calculated from solving these equations. Some simulation results, obtained from simulating the bridged systems without using assumption (d) on the Poisson packet arrival process for the bridge, are also presented to verify the numerical results as well as this particular assumption. Note that unless stated otherwise, the following parameters have been used: $M_1 = M_2 = M = 10$, $\ell_1 = \ell_2 = \ell = 66$ slots, $p_1 = p_2 = p = 1/10$, $e_1 = e_2 = e = 0.5$; $\sigma_1 = \sigma_2 = \sigma$, $M_{b1} = M_{b2} = M_b$ and $p_{b1} = p_{b2} = p_b$. Since the two networks are identical with this set of parameters, $T_1 = T_2 = T$, $\sigma_{b1} = \sigma_{b2} = \sigma_b$, and equations (1) and (15) degenerate to become:

$$T = f(\ell\sigma_b) \tag{16}$$

$$eT = \ell\sigma_b \tag{17}$$

Thus it is necessary to solve only two instead of the original four simultaneous equations in this situation.

First, to investigate the packet arrival process for the bridge, *Figure 2* shows the distribution function of the inter-arrival time of packets arriving at the bridge to be forwarded across networks. The points are obtained from simulating the bridged system specified with $M_b = 4$, $p_b = 0.2$ and the normalized system loading due to all the stations $2M\ell\sigma = 0.8$ and 2. The curves are obtained from using the exponential distribution with mean values chosen to be the same as those for the simulated results. Clearly, as can be seen, the simulated points are very close to the corresponding exponential distribution functions, indicating that the packet arrival process for the bridge is approximately Poisson.

Figure 3 shows the variation of the function $T = f(\ell\sigma_b)$ together with the line corresponding to equation (17) for the situation of *Figure 2* when the normalized system loading $2\ell M\sigma = 0.4$, 1.2, 2 and 2.8. Clearly, as the normalized bridge loading $\ell\sigma_b$ increases, the throughput of the station decreases. This decrease in throughput also becomes more drastic when the loading from the stations is high. The intersection of the curve $T = f(\ell\sigma_b)$ (16) with the line $0.5T = \ell\sigma_b$ (17) gives the throughput T and the normalized bridge loading $\ell\sigma_b$ of the bridged CSMA/CD system. From this, the other performance measures can be calculated as discussed earlier.

Using the procedures described, *Figures 4* and *5* show the variation of the average fraction of packets not accepted by the bridge $L_{b1} = L_{b2} = L_b$ as a function of the normalized system loading. *Figure 4* shows the results obtained when the bridge has a buffer size of four packets and the average backoff re-transmission probabilities vary from 0.1 to 0.4. In *Figure 5*, the backoff re-transmission probability is fixed at 0.2, and the buffer size is varied from 2–8 packets. Note that the points are obtained from simulation, whereas the curves are calculated from the theoretical analysis presented. Comparing the results in the two figures, it is evident that if the number of packets rejected by the bridge due to buffer size limitation is to be negligible, it may not be sufficient to just increase the re-transmission probability without increasing the buffer size, particularly when the system loading is high. To reduce the number of packets rejected by the bridge, it is more effective to increase the buffer size.

Figures 6 and *7* show the throughput and delay characteristics of the bridged CSMA/CD networks as a function of the normalized system loading with $M_b = 4$

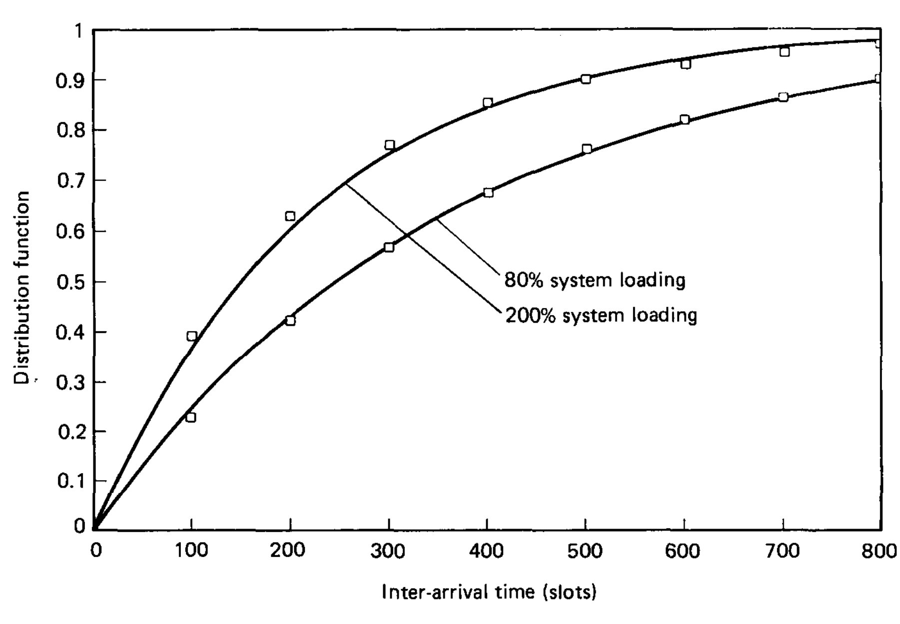

Figure 2 Distribution function of inter-arrival time of packets arriving at the bridge to be followed across networks (network parameters are given in the text)

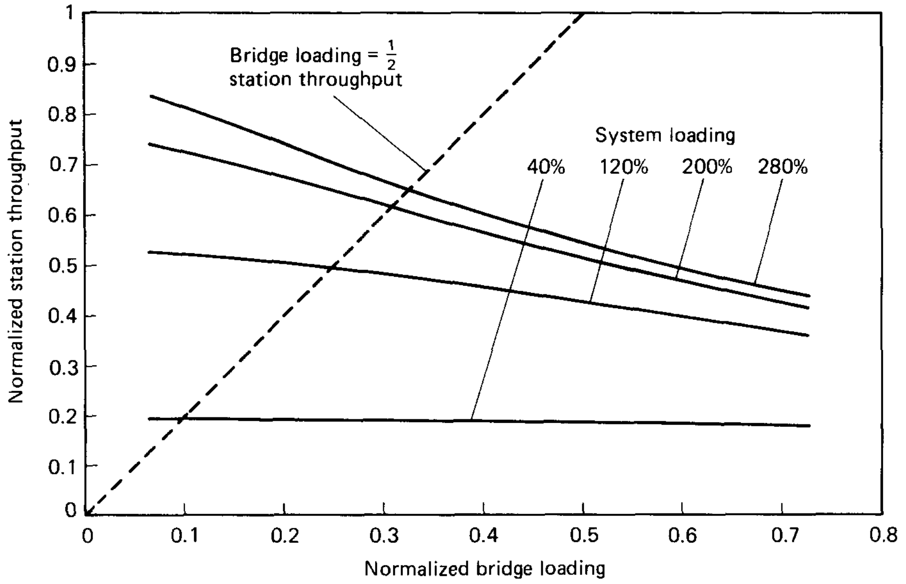

Figure 3 Variation of $f(\ell\sigma_b)$ against normalized bridge loading $\ell\sigma_b$ for the situation of *Figure 2* at various normalized system loading

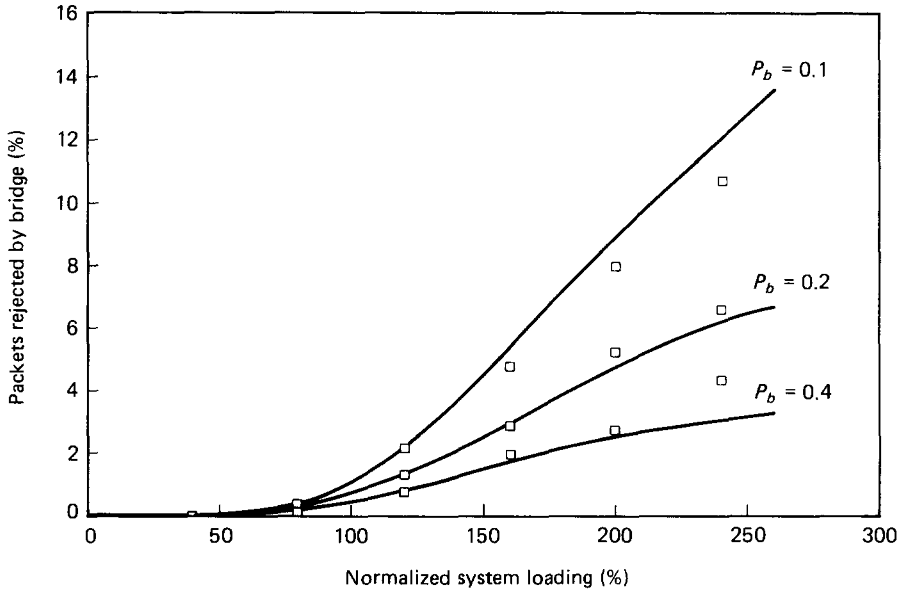

Figure 4 Average fraction of packets not accepted by the bridge against normalized system loading for the situation of *Figure 2* at various values of p_b

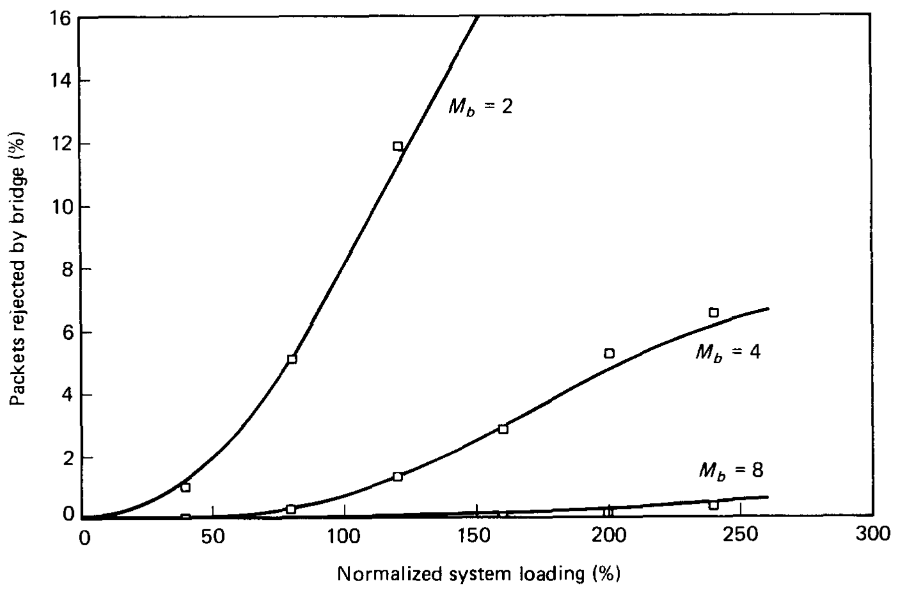

Figure 5 Average fraction of packets not accepted by the bridge against normalized system loading for the situation of *Figure 2* at various values of M_b

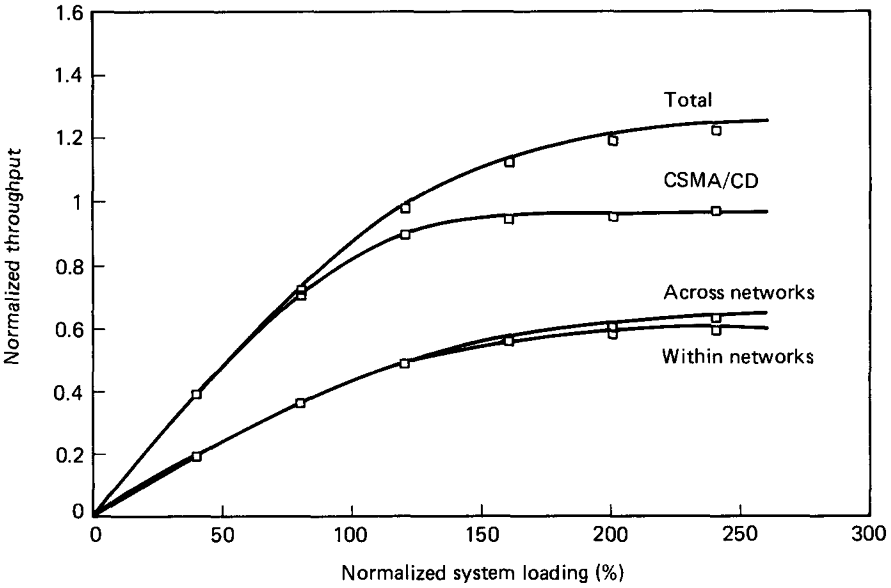

Figure 6 Throughput against normalized system loading for the situation of *Figure 2* with $M_b = 4$ and $p_b = 0.2$

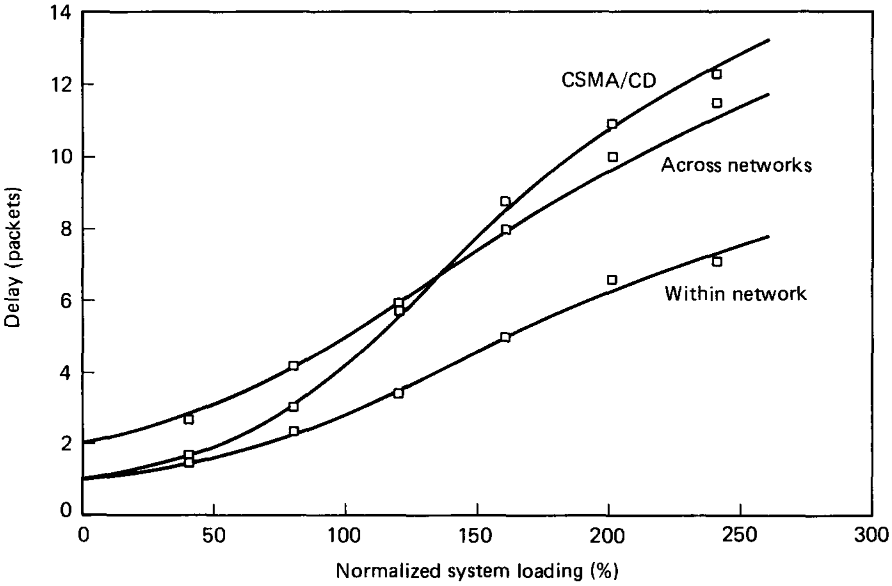

Figure 7 Average delay against normalized system loading for the situation of *Figure 2* with $M_b = 4$ and $p_b = 0.2$

and $p_b = 0.2$. The results from simulation, analysis as well as from an equivalent CSMA/CD system are also shown for comparison. Once again, as in *Figures 2, 4* and *5*, the closeness of the simulated results to the theoretical ones demonstrates the validity of the analytical approach and the Poisson packet arrival assumption for the bridge. Also, from *Figures 6* and *7*, the performance of the bridged system is roughly the same as that of the equivalent CSMA/CD network when the network load is small. However, as the network load increases, both the throughput and delay performance of the bridged network become better than the corresponding performance of the CSMA/CD network. It is particularly interesting that at high network load, the delay experienced by packets destined across networks through the bridge is still smaller than that in the equivalent CSMA/CD network. Also, as two simultaneous successful transmissions are possible in the bridged networks, the throughput of the bridged networks eventually becomes greater than 1 when the network load is high.

Nevertheless, note that even in the ideal situation of no collision, no packet loss due to bridge buffer size limitation and the throughput in each of the two bridged CSMA/CD networks being equal to 1, the total throughput of the entire system will be less than 2. This can be derived as follows. Let the throughputs of the stations and the bridge be equal to $\tilde{T}$ and $\tilde{T}_b$, respectively, in this situation. Clearly:

$$\tilde{T} + \tilde{T}_b = 1 \qquad (18)$$

and for equilibrium, $\tilde{T}_b$ and $\tilde{T}$ must satisfy:

$$\tilde{T}_b = e\tilde{T} \qquad (19)$$

Solving (18) and (19) then leads to:

$$\tilde{T} = \frac{1}{1+e} \tag{20}$$

$$\tilde{T}_b = \frac{e}{1+e} \tag{21}$$

Since a fraction e of the throughput $\tilde{T}$ from stations is destined across networks, the total throughput of the system is:

$$2[\tilde{T}(1-e) + \tilde{T}_b] = \frac{2}{1+e} \tag{22}$$

Thus, if most of the packets are destined within their own networks so that e is small, the total system throughput can be twice that when the bridge is not used. With $e = 0.5$, the maximum throughput is only 4/3, in agreement with the results given in *Figure 6*.

Figures 8 and *9* compare the throughput and delay performance of the bridged CSMA/CD networks as e, the fraction of packets destined across networks, changes. *Figure 8* shows the total throughput of the two networks for $M_b = 4$ and $p_b = 0.4$, whereas *Figure 9* shows the average delay for packets destined across networks for $M_b = 4$ and $p_b = 0.8$. Clearly, as can be intuitively expected, both the throughput and delay performance of the bridged system improve as the traffic becomes more localized within the individual local CSMA/CD networks. The advantages of using bridges will therefore become more prominent in these situations.

CONCLUSIONS

In this paper, the performance of two bridged LANs using the non-persistent CSMA/CD protocol is analysed.

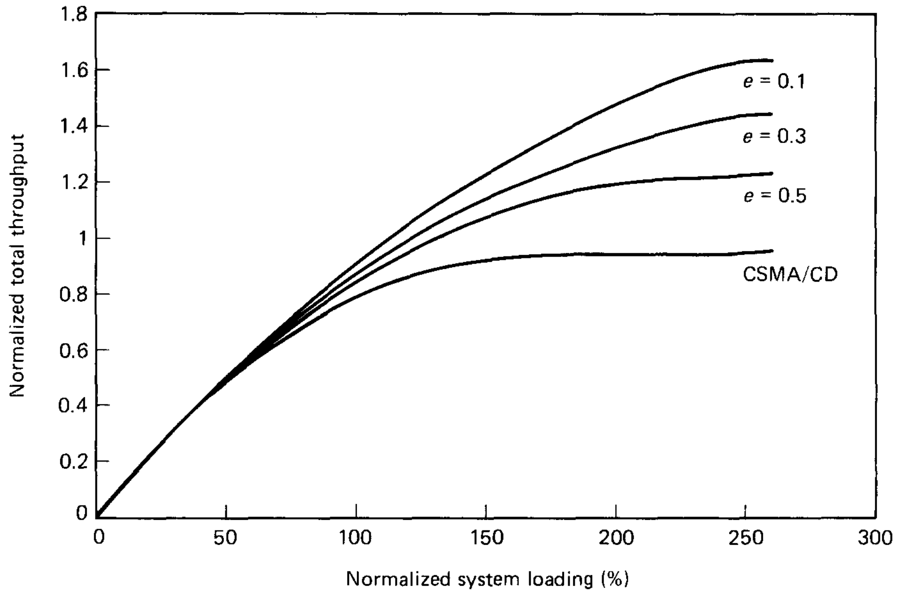

Figure 8 Total throughput against normalized system loading for the situation of *Figure 2* with $M_b = 4$ and $p_b = 0.4$ at various values of e

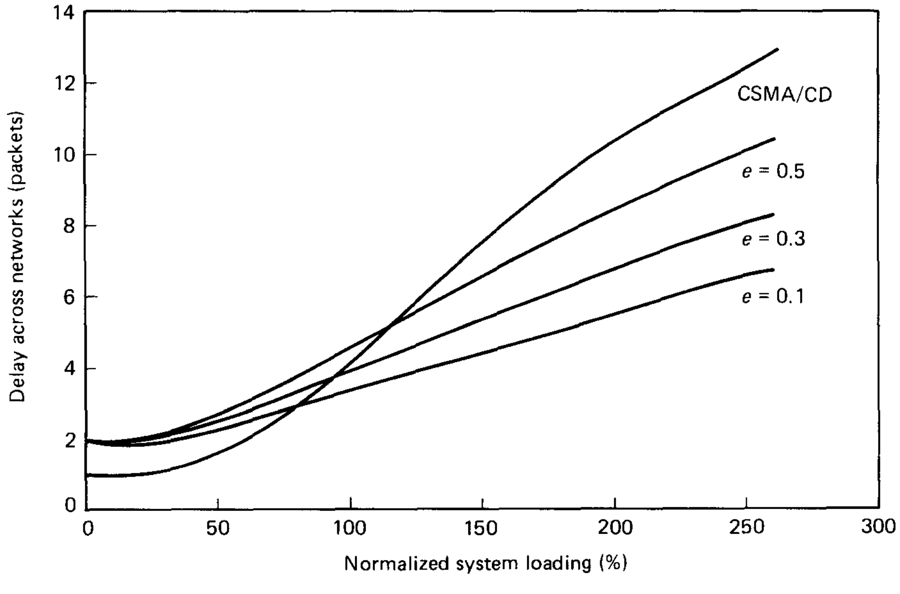

Figure 9 Average total delay for packets destined across networks against normalized system loading for the situation of *Figure 2* with $M_b = 4$ and $p_b = 0.8$ at various values of e

After deriving the main equations characterizing the system behaviour, the effects of design parameters such as bridge buffer size and re-transmission backoff delay are investigated. It is found that if the packet rejection probability due to bridge buffer overflow is to be negligible, it is not sufficient to decrease only the bridge re-transmission backoff delay when the network is heavily loaded. Instead, it is more effective to increase the buffer size in such situations. Nevertheless, if these parameters are chosen properly, significant improvement in throughput and delay can result, when compared with an equivalent CSMA/CD network without using a bridge. In particular, the delay experienced by packets destined across networks is found to be smaller than that in an equivalent CSMA/CD network when the loading is high.

REFERENCES

1 **Kleinrock, L and Tobagi, F A** 'Packet switching in radio channels: Part I – Carrier sense multiple-access modes and their throughput-delay characteristics', *IEEE Trans. Commun.* Vol 23 (December 1975) pp 1400–1416

2 **Tanenbaum, A S** *Computer Networks*, Prentice-Hall, NJ (1981)

3 **Tobagi, F A and Hunt, V B** 'Performance analysis of carrier sense multiple access with collision detection', *Comput. Networks*, Vol 4 (1980) pp 245–259

4 **Lam, S S** 'A carrier-sense multiple-access protocol for local networks', *Comput. Networks*, Vol 4 (1980) pp 21–32

5 **Heyman, D P** 'An analysis of the carrier-sense multiple access protocol', *Bell Syst. Tech. J.*, Vol 61 (October 1982) pp 2023–2051

6 **O'Reilly, P J P and Hammon Jr, J L** 'An efficient simulation technique for performance studies of CSMA/CD local networks', *IEEE J. Selected Areas in Commun.*, Vol 2 (January 1984) pp 238–248

7 **Arthurs, E and Stuck, B W** 'A modified access policy for Ethernet Version 1.0 data link layer', *IEEE Trans. Commun.*, Vol 32 (August 1984) pp 974–977

8 **Tobagi, F** 'Multiaccess protocols in packet communication systems', *IEEE Trans. Commun.*, Vol 28 (April 1980) pp 468–488

9 **Okada, H, Nomura, Y and Nakanishi, Y** 'Multi-channel CSMA/CD method in broadband-bus LAN', *Proc. IEEE GLOBECOM*, USA (November 1984) pp 19.1.1–19.1.6

10 **Ko, C C and Lye, K M** 'A new priority multi-channel CSMA/CD protocol', *Proc. IEEE ICC*, Canada (June 1986) pp 5.2.1–5.2.5

11 **Gopal, P M and Wong, J W** 'Analysis of a hybrid token CSMA/CD protocol for bus networks', *Comput. Networks*, Vol 9 (1985) pp 131–141

12 **Ibe, O C and Chen, P Y** 'Hybrinet: A hybrid bus and token ring network', *Comput. Networks*, Vol 9 (1985) pp 215–221

13 **Chua, K C, Lye, K M and Ko, C C** 'CSMA/CD-based protocol with dynamic segmentation', *Comput. Commun.*, Vol 9 (October 1986) pp 234–240

14 **Stallings, W** *Local Networks*, Macmillan, NY (1984)

15 *IEEE Standards for Local Area Networks: MAC Bridges*, Draft IEEE 802.1 Part D (December 1987)

16 *IEEE Standards for Local Area Networks: Systems Management*, Draft IEEE 802.1 Part M (January 1987)

17 **Hall, J, Renesse, R and Staveren, H** 'Gateways and management in an internet environment', in *Issues in LAN Management* **(I N Dallas and E B Spratt, Eds)**, Elsevier, Amsterdam (1988) pp 77–92

18 **Zielinski, K, Chopping, M, Milway, D, Hopper, A and Robertson, B** 'The Metrobridge a backbone network distributed switch', *Comput. Commun. Rev.*, Vol 21 (July 1991) pp 45–60

19 **Bux, W and Grillo, D** 'Flow control in local area networks of interconnected token rings', *IEEE Trans. Commun.*, Vol 33 (October 1985) pp 1058–1066

20 **Exley, G M and Merakos, L F** 'Throughput-delay performance of interconnected CSMA local area networks', *IEEE J. Selected Area in Commun.*, Vol 5 (December 1987) pp 1380–1390

21 **Hamilton, R L and Fui, J T** 'A matrix-geometric model for a CSMA/CD network with a gateway', *Comput. Networks & ISDN Syst.*, Vol 21 (1991) pp 399–415

22 **Chlamtac, I** 'A programmable VLSI controller for standard and prioritized Ethernet local networks', in *Local Area & Multiple Access Networks* **(R L Pickholtz, Ed.)**, Computer Science Press, NY (1986) pp 69–92