A Carrier Sensed Multiple Access Protocol for High Data Rate Ring Networks*

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Abstract

This paper presents the results of the study of a simple but effective media access protocol for high data rate networks. The protocol is based on the fact that at high data rates networks can contain multiple messages simultaneously over their span, and that in a ring, nodes need to detect the presence of a message arriving from the immediate up stream neighbor. When an incoming signal is detected, the node must either abort or truncate a message it is presently sending. Thus, the protocol with local carrier sensing and multiple access is designated CSMA/RN.

The performance of CSMA/RN with "attempt and truncate" is studied in this paper using analytic and simulation models. Three performance factors, wait or access time, service time and response or end-to-end travel time are presented. The service time is basically a function of the network rate; it changes by a factor of 1 between no load and full load. Wait time, which is zero for no load, remains small for load factors up to 70% of full load. Response time, which adds travel time while on the network to wait and service time, is mainly a function of network length, especially for longer distance networks.

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Simulation results are shown for CSMA/RN where messages are removed at the destination. *Destination removal on an average increases* network load capacity by a factor of 2, i.e., a 1 Gbps network can handle a 2 Gbps load. A wide range of local and metropolitan area network parameters including variations in message size, network length and node count are studied. In all cases performance is excellent, and message fracture usually remains less than a factor of 4. Throughput, even at overload conditions, remains high for the protocol. The nominal network rate is 1 Gbps; however, performance remains good for data rates as low as 200 Mbps. Finally, a scaling factor based upon the ratio of message to network length demonstrates that the results of this paper, and hence, the CSMA/RN protocol, are applicable to wide area networks.

1 Introduction

Networks must provide intelligent access for nodes to share the communications resources. During the last eight years, more than sixty different media access protocols for networks operating in the range of 50 to 5000 Mbps have been reported [1]. At 100 Mbps and above, most local area [LAN] and metropolitan area networks [MAN] use optical media because of the signal attenuation advantage and the higher data rate capability. Because of the inability to construct low loss taps, fiber optics systems are usually point-to-point. One of the most straight forward access protocols provides each node with a separate frequency by using wavelength division multiplexing (WDM) either with passive or active star couplers [2],[3]. These systems provide excellent capacity but limit the number of nodes which can be supported since each node must have its own broadcast wavelength. In passive star couplers, the division of signal strength also limits the number of nodes. To overcome these limitations, multi-hop techniques can be used to increase the nodes available but at the expense of slower signal travel time due to staging [4].

In the range of 100 Mbps - 1Gbps, the demand access class of protocols use some form of token, slot or reservation system. Protocol schemes like FDDI [5] use a token, which when received, permits the node to transmit information. Waiting for the token to rotate can cause slow access especially in longer and higher data rate rings. Local sensing of the presence of data or an empty slot is used in slotted and reservation systems. In Expressnet [6], a few bits in the preamble are available to be corrupted if a packet arrives when another packet is being sent by the station. Expressnet however, has separate transmit and receive sections on the bus and therefore, extends the length of the network by a factor of 2 or 3. Other systems like Fastnet [6] and DQDB [7], [8] (formerly QPSX) provide a pair of unidirectional busses to link the nodes. Fastnet provides a train-like operation started at the master stations at the end of the bus, while DQDB provides a empty/full slot indicator. A slot reservation system is used in DQDB so that down stream nodes have a chance at an empty slot. Recent studies indicate that DQDB have fairness difficulties when servicing nodes at the ends of the bus under high load conditions [9]. Slotted ring access protocols work similar to those of dual bus systems but in a ring configuration. Cambridge-like rings [10] can operate with either master assignment or and empty/full access control mechanism. Finally, some systems have used a delay line [11] or a buffer, like the register-insertion system [12], [13], for alleviating the corruption of data because of simultaneous access.

Broadcast or shared channel communication systems, like Ethernet, use information (carrier) sensing to alleviate the damaging effects of col lisions. However, as bandwidth increases and the message size spans a smaller portion of the global bus length, the network throughput is reduced [14]. As the frequency goes up and effective bandwidth increases, the round trip propagation time as measured in terms of packet lengths increases and a larger percentage of the packet or even a number of packets can exist simultaneously over the network span [15]. A resulting collision over the network span wastes time causing lower throughput. Thus, global carrier sensing even with collision detection loses effectiveness. This, coupled with the fact that optical broadcast systems have a difficult time building effective low loss taps, makes global sensing impractical for high speed networks.

As noted above, the amount of space occupied by a packet decreases as network rate increases. For example, at 100 Mbps, a 2K bit packet occupies a space of approximately 4 km along the network ring; at 1 Gbps, this space is reduced to .4 km. Thus, a 1 Gbps, 10 km network can potentially have 25 separate 2K bit packets simultaneously in existence over its span. Ring and dual bus systems realize this sharing of physical network space by having multiple trains or slots distributed along the network length. These blocks can be treated independently and locally, if at any access point :

1. the system can sense and operate on the existence of a data packet or TTcarrier" *at that point*; and

2. packets, once on the net, are not corrupted by collision with incoming packets during their passage through the node.

In a ring network, packets propagate unidirectionally and synchronously. If each node is able to sense the information or TTcarrier" in its locality, i.e., in the concept of TTsense and take action", then the control actions that *occur locally and independently can* provide an effective means for media access.

In this paper, we investigate the concept of local sensing and control as a means to access a ring network with out corrupting the incoming signal. The system is called Carrier Sensed Multiple Access - Ring Network, CSMA/RN. The paper first describes how carrier sensing can be implemented operationally and some of the possible features which can be used to control the node/network operation. Next, we present an analytical model based on queuing theory to describes the fundamental operational parameters which influence CSMA/RN. We then briefly describe a simulator which has been used to verify the analytical model and to study the network protocol capabilities. Finally, we present results which demonstrate CSMA/RN's ability to provide excellent operational features over a wide range of network conditions and indicate the direction for future work.

2 Carrier Sensing and Control in Optical Ring Networks

Local carrier sensing and collision avoidance using a delay line or buffer have been *considered for a tree LAN optical* network operating in the Gbps range [11]. This network has transmitting and receiving nodes at the leaves and junction points of the tree. Groups of nodes are clustered into collision avoidance broadcast units. Each unit has a selector system to choose only one packet from the group of nodes for further propagation. The packet that wins the contention continues to propagate to the broadcast link or to the next higher junction if the tree is multi-level. The key to sensing selection is based on a delay line that gives the switch advanced warning as to the future arrival of packets and hence, a chance to exercise intelligence to select a single incoming line and avoid a collision before the packets arrives. This same form of advanced information detection is the key to a collision avoidance and control scheme for the ring network.

2.1 Basic Carrier Sensed Multiple Access Ring Network-(CSMA/RN) Operation

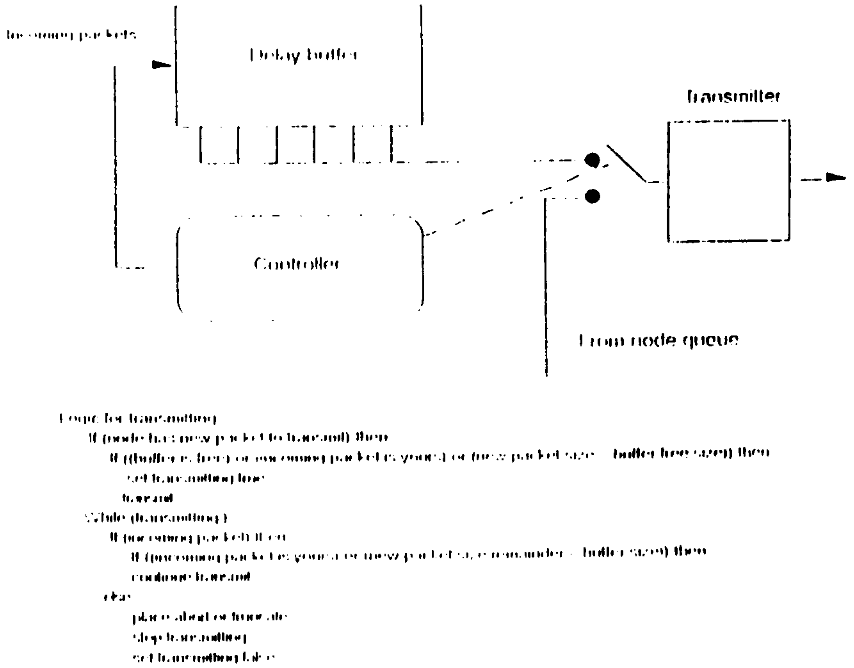

Figure 1: CSMA/RN Logic Operation

Figure 1 illustrates the characteristics of a node in the carrier sensed ring network. The incoming signal is split into two streams, one through a delay line or buffer. A buffer is illustrated here instead of a delay line as used in [11], because it allows greater operational and control flexibility. Note that the delay can be relatively short if high speed logic is used in the controller system. For example, a 100 bit delay at 1 Gbps is approximately a 20 meter piece of fiber and creates a 100 nanosecond delay. The node controller, based upon information accumulated in the buffer, is required to make a number of decisions. First, it must detect the presence of incoming data; if its exists, the node must always propagate incoming information as the outgoing signal to the next node on the ring because it would be impossible to recreate the packet unless sufficient storage is provided. If no incoming packet exists, the node is free to place its own data on the ring if its queue is not empty. However, during the time this latter data is being transmitted, if an incoming packet arrives, then the node, within the time limits dictated by its buffer size, must discontinue its transmission and handle the incoming packet. Hence, packets once on the ring take precedence over the insertion of new packets.

Packets are tested at each node to determine if the incoming packet is destined for this node and should be copied to its incoming data buffer (not shown in Figure 1). In addition, in order to make room for new packets, old packets must not be allowed to circulate continuously. At the very least, after one revolution of the ring, the source node should delete its packet. Alternatively, the destination node can sense the arrival of information and remove the packet as has been done in some slotted and the register-insertion rings[13].

These controller functions will dictate the buffer delay length and to some extent the packet structure. There must be sufficient delay and logic in the unit, Figure 1, to determine the address of the arriving packets prior to the need to send it on to the next node. The logic is no more difficult for either source or destination removal, but it does dictate to some extent the information structure of the packet header; i.e., the addresses should be placed as near the front in the packet header structure as possible. With high speed GaS logic, it seems reasonable that 100 bit delay buffers at each node would be reasonable as a base line design [1].

2.2 Additional Control Features in a CSMA/RN

Additional operational features can be built in to the buffer control system to assist in network regulation and control. First, if the minimum size information packet is N bits long, then it is always possible to place a message on the system if the node's buffer has N bits of empty space and it does not sense an incoming signal at the time it starts transmitting. Second, if a node is sending a long message and an incoming signal occurs, the node has the option either to abort the entire packet or to truncate and continue the message later. Both these actions are interesting from a network control standpoint. For:

1. abort - the operation is similar to T'Tattempt and defer" mechanisms used in many demand access protocols [1], [6], [10], [15], [16]. However, in the case of CSMA/RN, a considerable portion of the message may already have been transmitted and the resource would be wasted as it travels the ring [15]. Hence, the node should place an abort byte at

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[1] In addition, there is another delay caused by the transmitter triggering. Using electro-optical computer components, this delay should only be a few bits.

the end of the packet. To recover the resources, a node receiving the packet could detect the abort signal and eliminate part or all of the packet by removing that part still in its buffer. If a part of the message had already been transmitted, the node can place an abort byte at the new end point. This would allow subsequent nodes to remove further portions of the packet until it was completely eliminated from the system. Hence,the network can recover at least some of the capacity otherwise wasted by aborted packets.

2. truncate - the operation would cause message breakup similar to most slotted systems except that slots here are variable length. The node would continue the message in the next free block. The node could place a unique identifier at the end of the packet, so that the receiving node would be alerted to look for subsequent, correlated packets in order to accumulate the total message. This latter mode is the condition studied in this paper.

Packet removal provides interesting opportunities for enhancing network operation [10], [13]. When a node has packets queued for transmission, the detection of an incoming packet destined for that node is an excellent time to start transmitting a queued packet. Implemented at the destination the scheme allows two nodes to communicate, thus establishing a fixed bandwidth, full duplex circuit. More important, however, is that destination removal can increases the effective network capacity by a factor of 2 or better depending on the message origin and destination patterns [13]. In the interest of fairness, this logic may not be desirable especially when done at the source node, since under heavy loads, once a node captured a slot, it would tend to keep it and not give other nodes fair access. Additional logic schemes would allow nodes to cooperate in the use and control of free blocks on the ring [10].

For synchronous or isochronous traffic on the network, a circulating frame system is used in order to guarantee a node sufficient bandwidth to handle its data [10], [17]. In CSMA/RN, this can be accomplished by a node attaining sufficient data blocks with source removal. Upon receiving the return block, the node would replace it with the newly generated information. Thus, a node, over a time period, could accumulate sufficient data blocks to provide both the timing and the bandwidth to handle its required periodic traffic load. As noted above, some restrictions, such as a master controller assignment for blocks [10], [17] could be used so that node do not accumulate a share of ‘T'locked-in frames" sufficient to make the remainder of the ring's operation unacceptable.

3 Comparison to Other Ring Access Protocol Systems

CSMA/RN has features which make it very similar to slotted ring [10], [14] and register-insertion protocols [12], [13], [18]. With regard to slotted rings, it can be considered to be a ring with a slot size of one bit, although slots this small are unusable by CSMA/RN and are passed on as empty. However, since its slot size is variable, CSMA/RN can take advantage of sending large messages without arbitrarily having to break them into smaller blocks. Conversely, it can send small messages without wasting part of a large slot. However, in fixed size slotted rings, the number of blocks needed for a message is known but can not be determined apriori in CSMA/RN. Finally, it does not need to wait for the head of an empty slot, potentially giving better access. Here, CSMA/RN acts more like a random assignment or contention protocol than a demand assignment system [1]. Hence, it should be more efficient and adaptable to a wider range of network conditions than slotted systems.

With its buffer and controller system, CSMA/RN could be modeled to behave identically to the register-insertion (RI) system studied primarily at Ohio State University [12], [13], [18]. First, the idea of message removal at the destination is adapted from the RI system as it provides a factor of 2 improvement in throughput. The RI system gives non-preemptive priority to the locally generated message with the incoming message delayed. Conversely, in CSMA/RN, the buffer is strictly a delay line, in order to enable truncation or aborting of the outgoing message and to enable detection of incoming messages destined for the node. Thus, packets experience predicable delays when traversing the ring, i.e., message travel time is a fixed, predicable quantity. In doing so, CSMA/RN suffers from the fact that packet sizes on the ring may vary and that unpredictable message fracturing can occur. For low data rate networks, where registers are necessary for RI to operate at all, message fracturing is a significant problem. At high data rates, where the ring can contain many messages simultaneously and large blocks of empty space may be available, reasonable message fracturing should not severely hamper ring operations.

A hybrid media access protocol which senses a carrier is presented in reference [15]. This system operates in two modes, multiple train mode which is very similar to CSMA/RN but where TTattempt and abort" without recovery is used. At high loads, throughput is greatly reduced because of collision, so the network transfers to a single train mode of operation to avoid collisions.

In all cases, CSMA/RN differs in that it uses the concept of TTattempt and truncate" instead of TTattempt & defer" used in demand access protocols or TTattempt and abort" used in the hybrid ring.

4 Access Analysis

A study was conducted to build an analytical model for CSMA/RN operation. The analysis considers only the basic CSMA/RN system without the additional control or abort features. In doing so, a number of analysis configurations were examined including those which were used to model the register-insertion ring [12], [18], [19] and others

based upon priority and preemptive queuing models [20]. After examining these, it was found that a relatively simple queuing theory model can provide acceptable results.

Only a single node need be modeled since logic operations at each node are independent. The message traffic is represented by a Poisson arrival process based on the network load. The analysis evaluates the capability of the node to insert its fixed length message into the ring data stream. The insertion of the total message is defined as the service time for the node. The service time includes the condition where a message may be delayed several times for packets on the ring arriving at the node. Thus, the task is to define a model for calculating service time versus message load based upon the expected arrival of empty packets and to determine what effect the fracturing of packets will have on the service time.

To simplify the analysis, the ring is assumed to be large enough so that an TTinfinite" number of packets the size of the message can be place upon the ring. The probability of an available packet arriving at the node is:

$$Pr(x = available) = p = (1 - lf(n-1)/n + lf(n-1)/n^2) \qquad (1)$$

where lf= $loadfactor$; > n= $numberofnodes$; and

where an available packet is describe as one which is either empty or one whose destination is the node under consideration.

Considering each packet condition to be statistically independent, the probability that the kth packet is the first one available is:

$$Pr(t_k) = (1 - p)^{k-1} p \tag{2}$$

As load increases the empty space on the ring tends to fracture. This can further increase the service time, since now more than a single packet is needed to service the message. Packet fracturing is modeled by assuming a statistical distribution of packet size. It is based upon observations made during the simulation runs (to be discussed in greater detail later) that a portion of the packets have sizes which are uniformly distributed up to the message length and that the remainder have sizes equal to or greater than the message length. Thus, the probability density of packet size is model as:

$$p(s) = \begin{cases} k_u + k_m \delta(s_m) & \text{for } 0 < s \leq s_m \\ 0 & \text{for } s > s_m \end{cases} \tag{3}$$

where > s = packet size, and
> s_m = message size, and
> δ is the dirac delta function.

The values of k_u and k_m are interrelated, by $\int_0^{s_m} p(s)ds = 1$ so that: $k_u = (1 - k_m)/s_m$.

It was observed in the simulator runs that k_m varied as load changed; at low loads, $k_m \rightarrow 1$; at high loads, $k_m \rightarrow 0$. A simple linear equations representing these conditions is:

$$k_m = \begin{cases} (1 - lf) & \text{if } 0 \leq \text{lf} \leq 1 \\ 0 & \text{elsewhere} \end{cases}$$

The service time is:

$$S = S_{nl} E\{t_k\} / E\{s\}(4) \tag{4}$$

where S_{nl} = no load service time. > $E\{t_k\}$ = expected arrival time for an empty packet, an

The value for $E\{S\}$ in equation (4) was calculated both with $E\{S\}$ based on equation (3) and with $E\{S\} = 1$ and compared to simulator runs. Figure 2 shows the comparison for the condition $E\{S\} = 1$ which provided superior results.

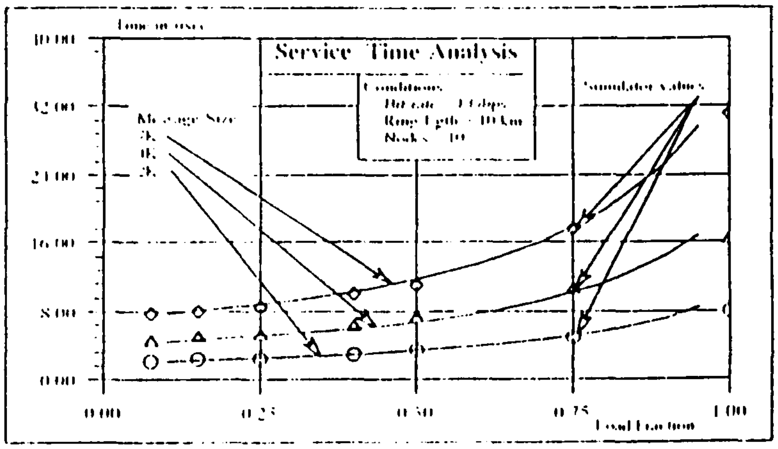

Figure 2: Service Time Comparison Between Analytical and Simulator Models

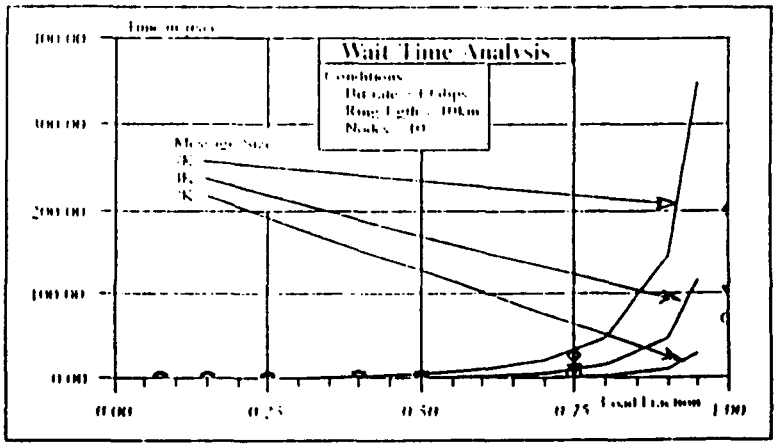

Figure 3: Wait Time Comparison Between Analytical and Simulation Models

Figure 2 demonstrates that service time can be simply and accurately estimated for CSMA/RN by a model which takes into account no load service time and the expected arrival time for empty packets. While packet fracturing may be a factor in service time, it is effectively compensated for by the fact that as packets fracture and become smaller they tend to arrive at the node more rapidly. Hence, in a ring where the message size is small in comparison to ring size, node performance can be modeled by expected available packet arrival.

Based on the service time analysis, the expected wait time for a message is calculated using the Pollaczek-Kintchine formula [20]:

$$E\{w\} = \lambda E\{S^2\}/2(1 - \rho) \tag{5}$$

where $\rho = \lambda E\{S\}$. The calculated values for $E\{S\}$ and $E\{S^2\}$ were taken from equation (4) and by calculating $E\{t_k^2\}$ from the distribution given in Equation (2), respectively. The comparison between calculated and simulated results is shown in Figure 3.

In Figure 3, we have plotted the calculated value of wait time only up to 0.95 load fraction since the value goes unstable for load fractions that approach $\rho = 1.0$. For these conditions, the calculated results accurately represent those obtained from the simulations runs. Hence, we can with confidence model CSMA/RN as an available packet arrival queuing system for those conditions where packet length is small in comparison to ring length.

The response time is defined as the time from message arrival at the source until the time the message reaches the destination. Hence, the expected response time is given by:

$$E\{R\} = E\{w\} + E\{S\} + E\{T\} = E\{w\} + E\{S\} + L/2 \tag{6}$$

where T = travel time of the message on the ring, and
L = travel time to complete one cycle of the ring.

$E\{T\} = L/2$ assumes uniform selection of destinations amongst the nodes. Simulation results presented later will illustrate that equation (6) accurately models the response time, especially for large size rings and low to medium loads, where the response time is primarily the travel time for a message.

5 Simulation System

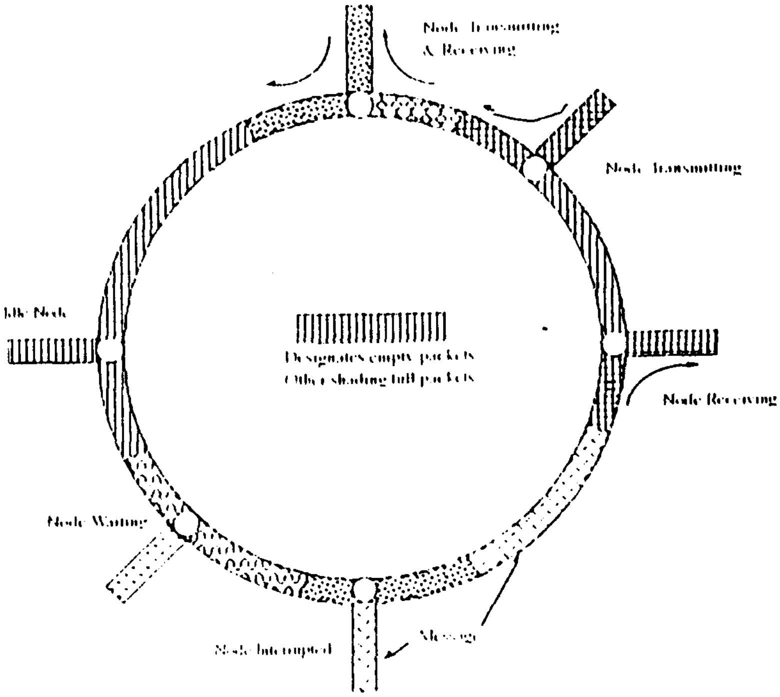

Figure 4: Illustration of Network Operational Conditions

In order to determine the capability of CSMA/RN as an access protocol, a discrete event simulation model was built. This model is designed to enable the rapid determination and handling of the events that can occur at each node based upon the travel of empty and full packets of data around the ring as time progresses. The events are those which can occur at a node by the arrival of a message, by the condition that an empty packet is passing the node when a message arrives, by the arrival of an empty packet at a node which has a queued up message, by the arrival of a packet destined for a node and by interrupting a node which is transmitting. The set of conditions which create events on the ring is illustrated in Figure 4. It is interesting to note that, although the logic conditions at each node are simple, the logic conditions for the ring become quite complex when it contains a large number of nodes and the decisions at a node eventually influence other nodes on the ring.

In the simulation, the ring is modeled as a linked list of packets; each packet containing information on its length, its location conditions, etc. Thus, the condition of each bit of the ring based upon the network bit rate, length and propagation speed are embodied in the ring data. Events are formulated by examining the condition of each node, as noted in Figure 4, to determine the time that the node should transmit based upon its ready condition and the condition of packets approaching its location. Once a packet is placed by the node, its travel time is known so that the event related to its arrival can be calculated at placement time. A time ordered list of events is maintained. Time increments are related to bit size; for each new event, all packet locations on the ring list is incremented and the new event processed to change ring state. Nodes are modeled as fixed data structures and maintain the information as to their present status and their past message handling events.

In conducting simulation runs, questions arose as to how long the simulation runs should be in order that conditions on the ring had stabilized to steady state conditions and that sufficient time elapsed so that statistical data collected was reasonably accurate. A series of tests were conducted to assess the confidence which could be placed on the data collected during a simulation run.

Figure 5 illustrates the type of runs made to study simulator confidence. Data were collected for intervals during a run and compared as to their variability and to the mean of all data collected for the run. In Figure 5, we have plotted wait time, the most sensitive of the variables, taken at the end 10 intervals, and the cumulative average taken of the active period of the run. Load fractions of 1.0 and 1.5 were used since at the higher loads, fluctuations tend to be greater. First, it was found that the ring tended to reach steady state values rather quickly, but that it results still varied considerably between interval. It was found that in order to obtain data with a reasonable confidence in the mean accuracy, the ring had to cycle a number of times, where a cycle is the time for information to completely traverse the ring. In general, about 1000 - 5000 cycles was found to be sufficient elasped time.

Still at the 1.5 load condition, results may vary considerably because of the sensitivity of wait time to load and service time variations.

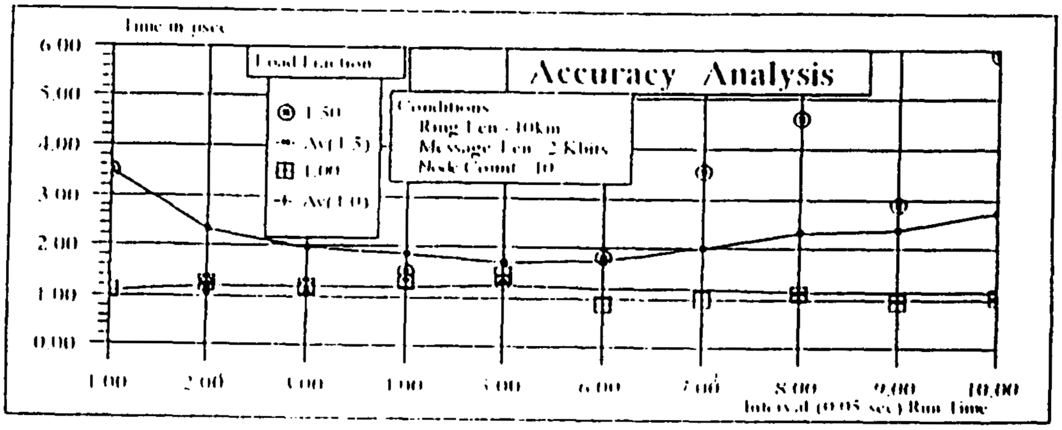

Figure 5: Simulator Run Convergence and Variations

6 Protocol Performance and Operational Features

The simulation system was used to study and document the access performance of the CSMA/RN system. The basic performance measures which were obtained from the runs are wait, service and response time as defined in Section 4.0. In addition, message fracture was obtained in order to estimate the conditions under which fragmentation of the ring could be found to occur. In addition, the ability to handle overloads without degradation in throughput, is critical for network performance. Specific runs were made to study throughput at high loads. Finally, runs were made to determine conditions under which the results can be scaled to related but unstudied conditions.

General conditions for all simulator runs include:

1. packets were removed at the destination and the empty space used by the node to send queued messages,

2. additional header bits required because of packet fracture were not added to the message.

3. nodes are uniformly spaced around the ring.

4. all message arrivals are uniformly distributed among the nodes,

5. all message destination addresses are uniformly distribute among the nodes other than the source node, and

6. all messages are fixed length.

The analysis results, Figures 2 and 3, indicate that under nominal conditions CSMA/RN can provide excellent performance as an access protocol. *First*, access or wait time approaches zero at no load and remains relatively flat until the load approaches 70% of the network load. As load increases, wait time, which is dependent upon service time, becomes unstable as ρ — 1. Service time is close to the minimal, no load service time throughout most of the load range; it remains within a factor of 2 for load levels up to 60% network load and with a factor of 4 for loads up to 95%. Finally, since travel time for a message on the ring is fixed by the media propagation speed, the total response time is dependent upon ring length in MAN and larger LAN networks. In any case, the CSMA/RN access protocol does not slow the travel time, so that a message, once on the network will move as quickly as possible to the destination.

The simulation studies were done to determine its performance under a range of system parameters. Three conditions are of major interest: message length, ring length and the number of nodes in the system. Three sets of runs were made to examine the effects of these variations.

Figures 6a - 6d present data for a 1 Gbps, 10km, 10 node ring for message lengths ranging from 2K to 20K bits. As noted previously, one of the best performance features of the CSMA/RN is immediately apparent in this and all subsequent figures -- the 1Gbps network is capable of handling up to 2 Gbps without saturating, because, on an average, messages travel only half way around the ring. Thus, load performance for CSMA/RN and other destination removal networks systems like register-insertion [13] is at least double the basic net speed bandwidth. We see from Figures 6 that average performance characteristics for CSMA/RN are not detrimentally altered by message length. First, mean wait time is very consistent with that predicted by the analysis.

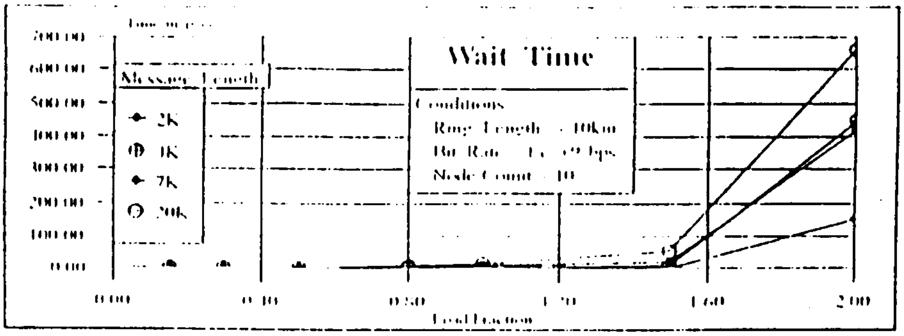

Figure 6a: Wait Time for Various Message Lengths

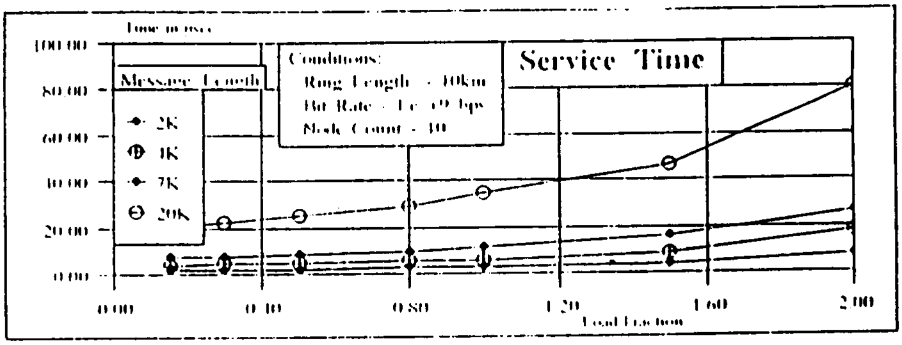

Figure 6b: Service Time for Various Message Lengths

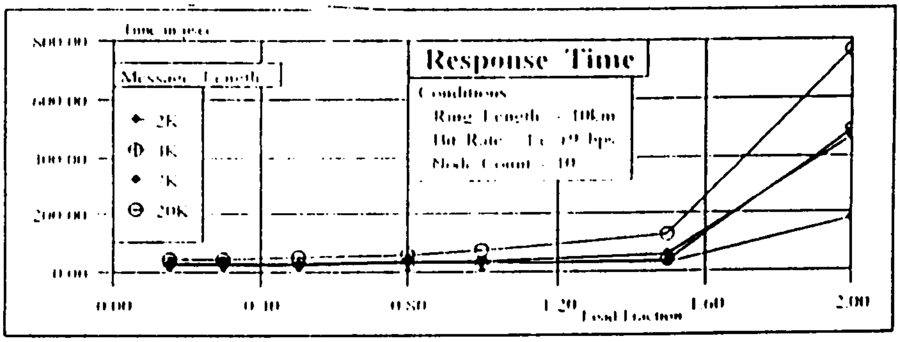

Figure 6c: Response Time for Various Message Lengths

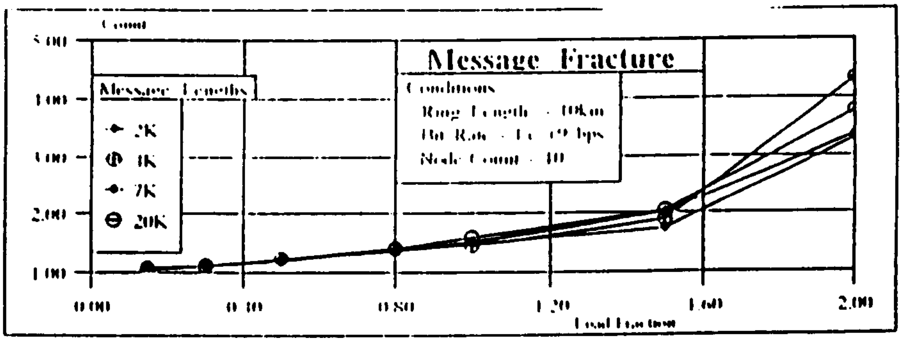

Figure 6d: Message Fracture for Various Message Lengths

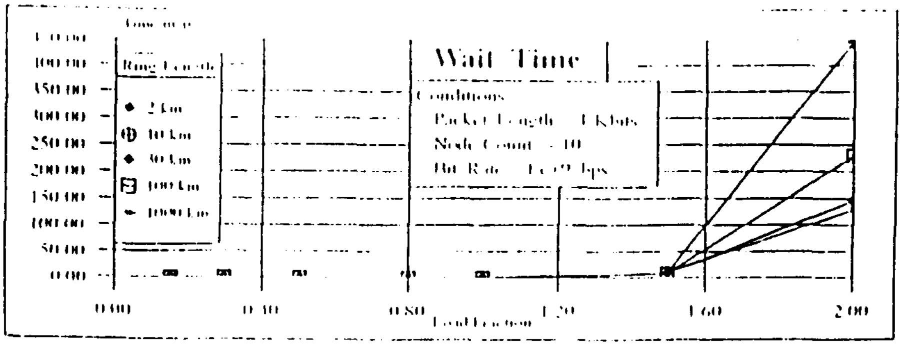

Figure 7a: Wait Time for Various Ring Lengths

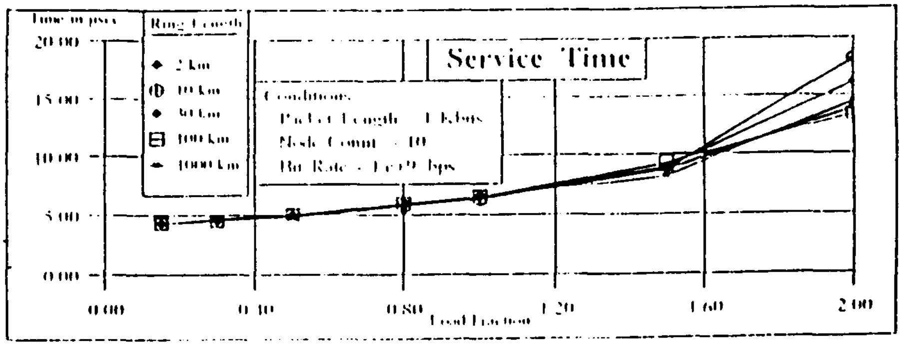

Figure 7b: Service Time for Various Ring Lengths

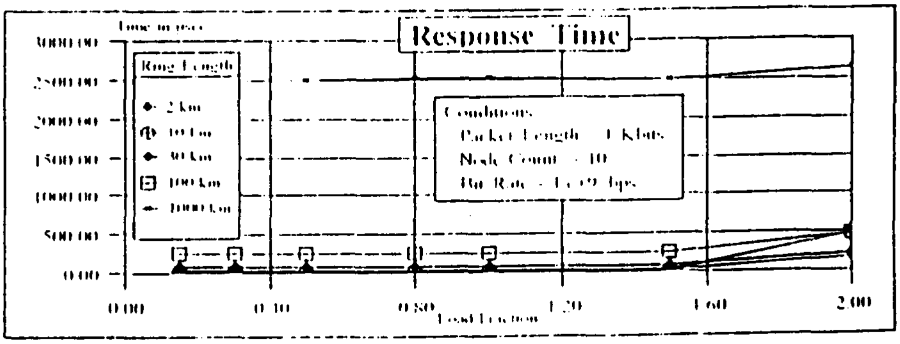

Figure 7c: Response Time for Various Ring Lengths

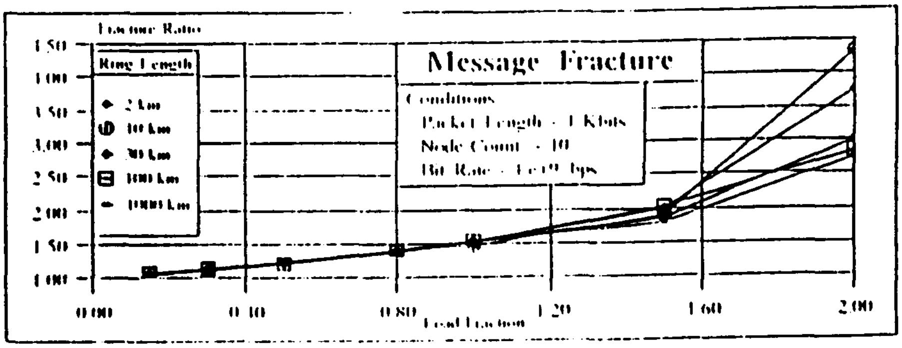

Figure 7d: Message Fracture for Various Ring Lengths

As in the analysis, no load service time is a function of packet length but the shape of each curve is similar to that predicted by the analysis results. Mean response time is greater for the larger packets, primarily because service time is greater. Finally average message fracture ratio does not change significantly as packet length increases, indicating that message fracturing does not materially increase, at least when all messages are of the same size and nodes are uniformly distributed around the ring.

A similar set of curves is plotted in Figures 7a - 7d to show the effect of ring lengths. Here, rings lengths range from 2 km to 1000 km. In all cases, ring length affects mean wait time only after the load has reached 80%. After this point, wait time does not seem to have a consistent variation with ring length. The differences are probably due to the variances in random load generation and the sensitivity of wait time to service time in this region which can cause the system to become unstable. The average service time shows little difference for the wide range of ring lengths. In general length should not have much effect as the service time is mainly dependent on the existence of arriving available packets. Response time shows significant dependence upon ring length, mainly due to the travel time necessary from source to destination. In the case of the longer length rings, this factor dominates, so service and wait time become insignificant. It is only at the lower lengths, 2 km and 10 km, that other ring factors make any difference. Finally, packet fracturing is not affected by ring length in any significant fashion, illustrating, at least, for the uniform ring loads and node locations that the CSMA/RN protocol provides excellent operations over a range of conditions.

Figures 8a - 8d show the simulation results when node count is varied from 10 to 200 nodes for a 50 km ring; node spacing range from 0.25 km to 5 km. Message length for these runs is set at 2 Kbits. For the ranges considered, the operation of CSMA/RN is very good. Mean wait and response times correspond to the previous runs and to the analytical results. At a large node count and high load factor both service time and message fracture show a definite increase. Under these conditions, the CSMA/RN protocol would have it worst operational problems as the packets on the ring would have the greatest tendency to fracture and subsequently increase service time.

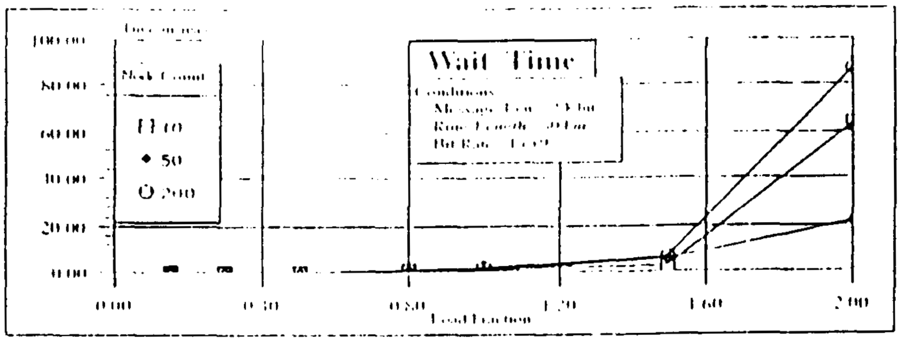

Figure 8a: Wait Time for Various Node Counts

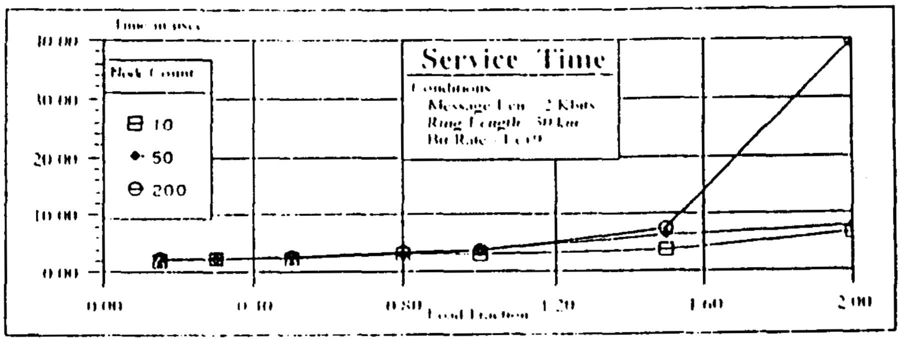

Figure 8b: Service Time for Various Node Counts

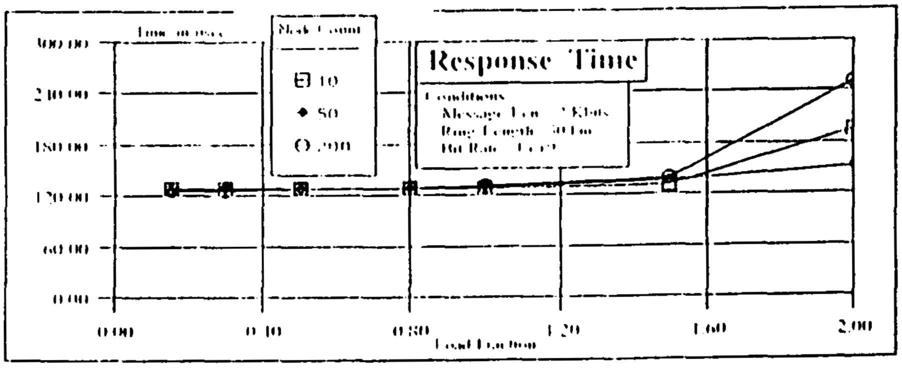

Figure 8c: Response Time for Various Node Counts

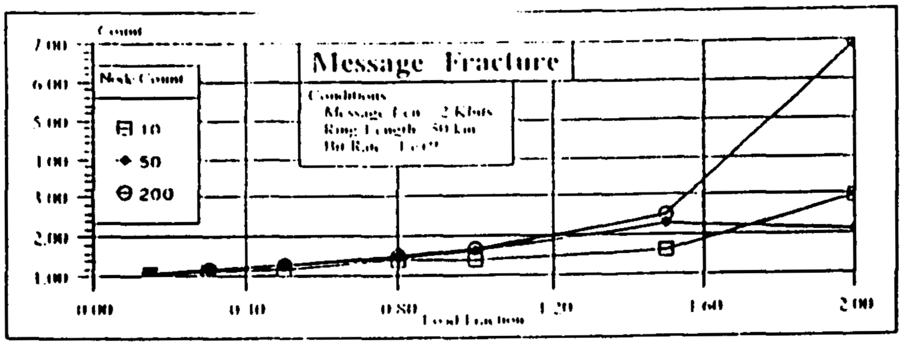

Figure 8d: Message Fracture for Various Node Counts

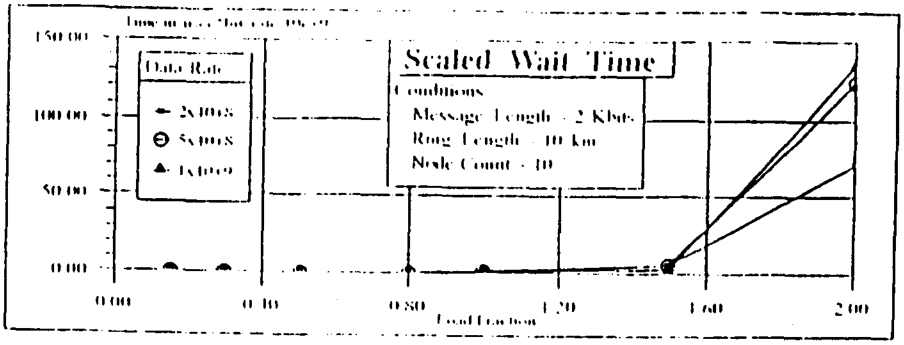

Figure 9a: Scaled Wait Time for Various Data Rates

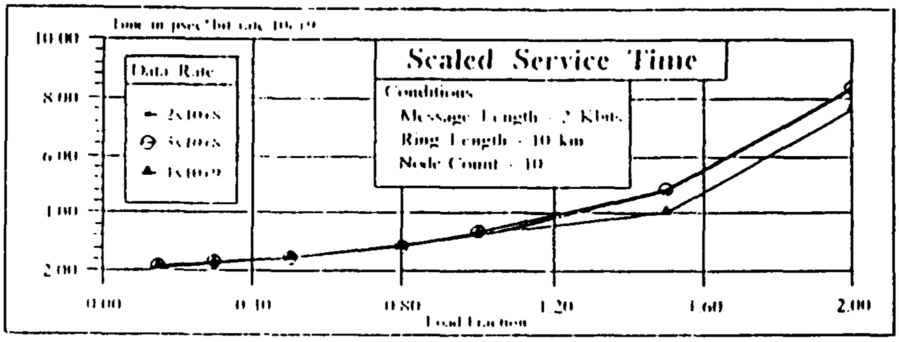

Figure 9b: Scaled Service Time for Various Data Rates

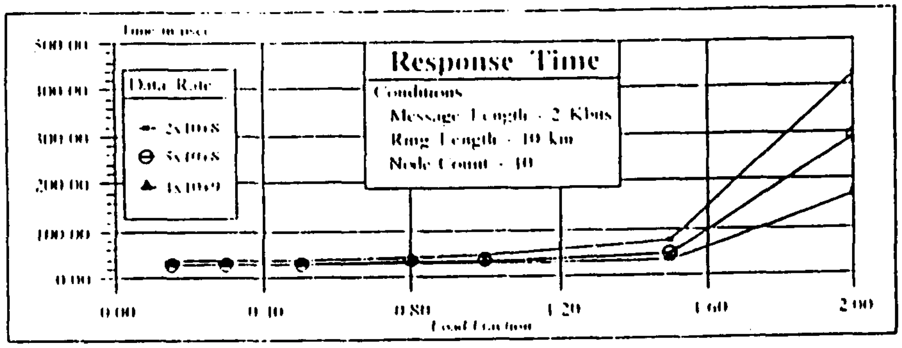

Figure 9c: Response Time for Various Data Rates

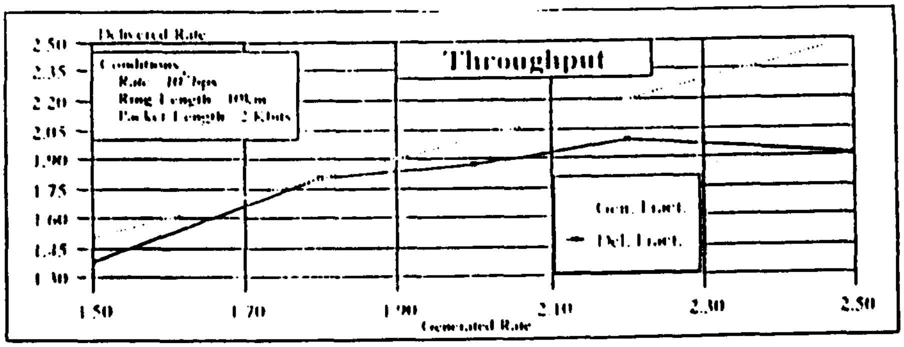

Figure 10: Throughput at High Load Fractions

A set of simulator runs were made to document the performance for network data rates ranging from 2.0 x 10+8 to 1.0 x 10+9. Network conditions are 10 nodes, 10 km and 2 Kbit messages. Figures 9a and 9b show scaled wait and service times, respectively. The scaling has been used to remove the effect of bit rate to demonstrate that the operational characteristics of the CSMA/RN system are independent of bit rate over the range of high data rate networks. Figure 9c shows response time as unscaled to illustrate the advantage available in CSMA/RN as bit rate increases. At low load fractions, most of the response time is caused by network travel time which is independent of bit rate; the secondary factor being service time to get the message on the network. At high load fractions, delay due to wait time tend to predominate, so the higher bit rate for CSMA/RN provides a definite improvement. However, the network performance is very adequate for all conditions considered.

The ability of an access protocol to maintain good throughput under saturated conditions is critical. Runs, shown in Figure 10, were made to examine throughput for loads between 1.5 and 2.5 load fraction. We see that bits delivered is maintained up to the ring saturation limit and remains approximately at the maximum condition as input load is increased further.

The simulation results, Figures 2 - 10, demonstrate very acceptable performance; a high data rate network using CSMA/RN access protocol operates effectively over a wide range of LAN and MAN conditions.

In developing the simulation, the question arose as to whether it was necessary to model the ring at the bit level, i.e., to be able to account for the condition of every bit in the network, or whether larger blocks, at least for modelling performance studies, could be considered inseparable. This lead to the postulation that one can scale the simulation results by treating each bit as a block in an TTup-sized" ring. Thus, a bit in a 10 km, 10 node ring with 2 Kbits messages would scale to represent 10 bits in 100 km, 10node ring with 20 Kbit messages. Scaling is equivalent to the network parameter, a , the round trip propagation time measured in message units. The question is whether the statistical performance of the ring would be affected by the separation of the block into bits, where in the scaled model, a block would be inseparable. It would seem unlikely that block size effects this small would have any appreciable influence on nominal ring operations.

To verify the scaling capability of CSMA/RN, a series of 4 runs were made. The 10 node, 10 km, 2 Kbit rings was compared to a 100 km, 20 Kbit; a 1000 km, 200 Kbit; and a 10000 km, 2 Mbit rings. Three performance factors were considered, the normalized service time, the message fracture ratio and a histogram of empty packet lengths available to nodes when they place a message on the ring. The histogram counts empty block in 11 intervals related to message size. Of these the histogram is considered the best measure of whether bits can be used to represent blocks. If nodes see empty blocks in the ratio equivalent to the scaled bit size then the scaling factor is a very acceptable means to extrapolate CSMA/RN performance.

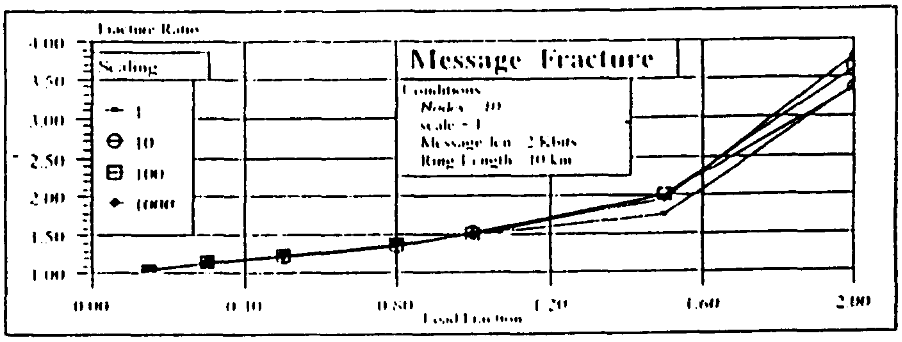

Figure 11a: Message Fracture for Scaled Runs

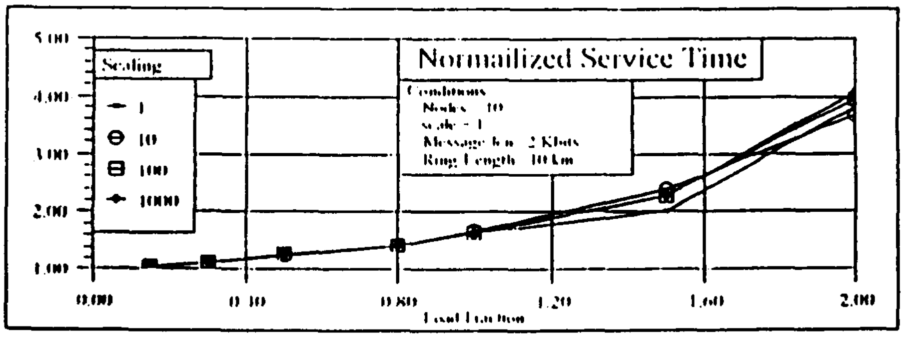

Figure 11b: Normalized Service Time for Scaled Runs

Figure 11a presents message fracture ratios for the 4 runs, above, for load fractions from 15% - 200%; Figure 11b presents the normalized service time based upon message length. Both figures illustrate that scaled conditions are nearly identical. Table 1 presents data based upon the histograms for empty packets. The histogram groups empty packets into the 11 intervals related to message size; i.e., the empty blocks are separated into equal size groups: the first group is packets which are <10% of message size; the second group, packets between 10% - 20% of message size, etc.; the last group, packets >100% of message size. The results are presented as the percentage of packets in a group to the total number of empty packets arriving at the nodes.

The four sets of data in Table 1 are the four run conditions stated above. If we compare identical entries for the four conditions, we see very little difference at the higher load fractions and no difference at lower loads. Thus, for each condition the ring scales nearly identical, i.e., a bit in the lowest size ring is equivalent to a block of 1000 bits in the largest ring. As a result we are very confident CSMA/RM results can be effectively scaled from the bit to the block level over a wide range of conditions.

Note that the scaling studies for CSMA/RN modelled a wide area network (WAN) with a gigabit rate and megabit message transfers. Performance of this network is excellent; it handles up to 2 gigabits/sec of data. Access and service times are excellent and since travel time is based upon the speed of light in the medium, the response time is strictly a function of separation distance between communicating nodes. In fact, it appears that CSMA/RN operational features provide a asynchronous data WAN which is as good as can be expected and should be a suitable access protocol for a National Research and Education Network [21].

7 Conclusions

CSMA/RN operates under conditions where a ring can contain a number of messages simultaneously. It is based upon TTattempt and truncate" for a node transmitting if an incoming carrier is detected on the ring. In this respect it differs from other access protocols which defer or abort transmission when a collision can occur. The results demonstrate that CSMA/RN is a viable protocol for a wide range of ring parameters and conditions. Service and wait times are excellent for a large range of load conditions and a simple analytical model is available to estimate operations. Message fracture does not appear to be a serious a problem for rings which can contain an fairly large number of messages, i.e., where $a >> 1$. Throughput remains high under overload conditions A scaling parameter exists based upon a which allows the estimation of ring performance for WANs. Here, CSMA/RN performance is excellent access and suitable for a future national network system.

To date, CSMA/RN studies have been limited to simple asynchronous data operational conditions. Additional study is required to document its performance for messages with variable lengths, for non-uniform load conditions, for conditions where ring domination by a few nodes can occur, and for large node count conditions where message fracture is most likely. Protocol procedures must be developed and studies must be done for CSMA/RN to effectively handle integrated traffic, i.e., synchronous traffic consisting of voice and video data in conjunction with asynchronous messages.

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