

ADVANCED SOLID ROCKET MOTOR (ASRM) COMMUNICATIONS NETWORK ANALYSIS

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ABSTRACT

This paper describes the simulation of a proposed campus-wide network for a new manufacturing facility. The proposed network consists of five carrier sense multiple access with collision detection (CSMA/CD) networks connected to five ports of a VAX cluster. In Section 1 the system configuration, the projected traffic pattern, and the proposed protocols are presented. Section 2 describes the models used in constructing the network simulation, while Section 3 contains the results and an analysis of the simulations. The simulations are compared to a mathematical model in Section 4. Some conclusions are drawn in Section 5.

1.0. THE ADVANCED SOLID ROCKET MOTOR FACILITY

The Advanced Solid Rocket Motor (ASRM) facility is part of a National Aeronautics and Space Administration (NASA) program to develop new solid rocket motors for the Space Shuttle. Five major manufacturing endeavors -- case preparation, propellant mixing, core stripping, core preparation, and motor assembly -- will be performed at the facility, which will be automated using the latest technology. A primary objective of this project is to provide a safe and paperless environment. The facility will consist of several buildings spread over a large area. Critical manufacturing will take place in four separate buildings on the site. A Local Area Network (LAN) will be required to provide communication for the manufacturing process, as well as to carry control and managerial information. The network should be reliable, secure, and provide enough bandwidth to carry all the information [1].

1.1. The ASRM System Configuration

The network consists of five CSMA/CD LANs attached to a 4-node VAX cluster (two VAX 4300s and two VAX 6500s) via five separate CSMA/CD controllers. The VAX cluster is called the Operations Information System (OIS).

1.1.1. Operations Information System (OIS) The OIS is to provide an efficient means to plan and control the manufacturing of solid rocket motors for the ASRM project. Most nodes talk only to the OIS; there is little peer-to-peer communication. The OIS is also the link between the business functions and the manufacturing functions of the facility. Scheduling, shop floor control, and data collection will be performed by the OIS; these functions will be provided by commercial software packages [1].

1.1.2. Medium The transmission media will be fiber optics which requires a fiber for receiving and a fiber for transmitting. In each of the CSMA/CD LANs, optical hubs will connect the nodes together. Each receiving port of the hub retransmits the signal to all transmitting ports. Fiber optics was chosen because of its immunity to electromagnetic interference (EMI), because of the long runs, and to allow the network to upgrade easily to FDDI in the future if the need arises.

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1.2. ASRM Traffic Analysis

All nodes will communicate with the OIS. There will be three main types of nodes [1]:

- Workstations
- Workcells
- Area Supervisory Computers (ASC).

There will be several workstations throughout the facility available to the shop floor managers for entering and retrieving data during manufacturing. There will also be terminals in workcells. Each workcell has a specific job such as a vapor degreaser or a pattern cutting station. Some areas will have an ASC to archive data from several smaller nodes during manufacturing. This information will then be transferred to the OIS. The ASC must store the information in the event of a failed link to the OIS. After the link is restored, information must then be uploaded to the OIS.

1.2.1. Automotive Control and User Response Time Since control of the manufacturing will be accomplished over the LAN via Automated Process Instructions (APIs), the network should be reliable and have redundant links in case a link is lost. Also, the user response time is important because the user will be getting instructions from the OIS. The delay of information on the LAN for a given load is therefore an important consideration.

1.2.2. Data Collection Large amounts of data must be stored because of the critical nature of the solid rocket motors in the Space Shuttle program. It is crucial that none of this data is corrupted or lost. Therefore, the network should be reliable, robust, and have redundant links.

1.3. Protocols

The protocols for the manufacturing data network should adhere to industry standards. The Institute of Electrical and Electronics Engineers (IEEE) 802.3 CSMA/CD protocol was specified. All of the fibers installed in the system will be 62.5 micron fibers to easily migrate to a Fiber Distributed Data Interface (FDDI) system, if the need arises.

1.4. Research Objective

The objective of the research is to analyze the manufacturing network to determine its performance at different loads. The two evaluation parameters used to judge the network are throughput and delay. The throughput is the effective bit rate of the system in bits per second (bps). It does not include the overhead bits used by the protocol or the packets that had to be transmitted again. The delay in a LAN is judged by the mean delay per packet. This mean delay per packet will be used to calculate the time to transmit a graphics page. This user delay is important since workers will be receiving graphical instructions from the OIS.

2.0. SIMULATION WITH BONES

The commercial software package BONEs [2] -- Block Oriented Network Simulator -- was used for simulating the network. The software is written in LISP and allows the user to graphically piece together blocks to model various networks such as FDDI, CSMA/CD, and X.25. For each part of the model it generates C source code. During a simulation, it links the code together and creates an executable to do the simulation.

Models of CSMA/CD nodes, FDDI nodes, and bridges are included in the BONEs library. Also, an example of a campus-wide network is included in version 1.5.1 of BONEs [2]. These models were used to simulate the ASRM network.

2.1. CSMA/CD Workstation Model

BONEs comes with a complete model for a CSMA/CD workstation which includes the carrier sense, collision detection, exponential backoff, attempt limit, slot time, and the interframe gap. The parameters were set to the IEEE 802.3 CSMA/CD standards.

2.2. Optical Hub Model

Optical hubs are required for implementing CSMA/CD over fiber. The model of the optical hub passes all frames that are received on the receive fiber to all transmitting ports with delay. This delay is caused by the light-to-electrical and electrical-to-light conversion.

2.3. Traffic Source Model

A model to send a set number of packets randomly at Poisson intervals was developed. Once triggered by the Poisson generator the traffic source model sends a set number of packets as fast as possible. In other words, another packet is sent as soon as a packet is sent successfully. The parameters for the traffic source model are the interarrival mean of the blocks and the number of packets to be sent. The interarrival mean of the blocks is the mean time in seconds between the blocks of packets.

3.0. MANUFACTURING NETWORK

The manufacturing network at the ASRM facility was analyzed by using the simulation program BONEs. The traffic parameters were varied and statistics were collected during each iteration. Each of the five networks were modeled for a worst-case analysis. The parameters for each node were generalized to speed the simulation time required to model the networks.

3.1. Simulations

The VAX has six CSMA/CD ports, five are used to connect to the five manufacturing links and one is used to communicate with the Business Information System (BIS). Analysis of the BIS link was outside the scope of this work. It was assumed in the simulations that each port could handle a full speed of 10 Mbps CSMA/CD. Therefore, each port of the OIS was treated as a separate CSMA/CD node and five separate simulations were run to simulate the five different links. These five links constitute the manufacturing LAN. In the simulations, all nodes sent packets to the OIS per the ASRM communication model. The OIS randomly picked one of the nodes in the link and sent a packet to it. Each node had an equal opportunity of being picked. The delays of commercial transceivers and optical hubs were used in the simulation [3-5].

3.1.1. Parameters The delay of the CSMA/CD transceiver and the propagation delay caused by the optical fiber cable connecting the node to the network were combined into one total delay per node. The worst-case collision detection time of a typical commercial transceiver was found to be 900 nanoseconds [3-4]. The total delay per node was set to two microseconds. The extra 1.1 microseconds added to the transceiver delay accounts for the propagation delay caused by approximately 181 meters (594 feet) of optical fiber cable.

The worst-case packet delay of a typical commercial optical hub was found to be 630 nanoseconds [5]. This delay is caused of the light-to-electrical and electrical-to-light conversion. Therefore, the optical hub delay was set to 630 nanoseconds during the simulation.

The packet size was set to the smallest possible size of 64 bytes for a worst-case analysis. A benefit of fixing the packet length is a decrease in the simulation runtime. The smaller the packet transmission time with respect to the propagation delay the more collisions occur [6].

3.1.2. Probes Probes were placed in the network to gather statistics during each simulation. The mean delay per packet, received throughput, transmitted throughput, and the number of completed packets were collected for each separate link. Each iteration interval was divided into ten batches to collect these statistics.

These statistics were collected by placing a Generic Probe on the Media Access Control (MAC) Statistics module in each link. The MAC Statistics module was used to measure the delay and throughput for all CSMA/CD workstation models in one link. All CSMA/CD workstation model MAC instances share the same memory. Therefore, all the CSMA/CD workstation models write the delay and throughput into one memory. These statistics are then made available to the Post Processor in BONEs by placing a Generic Probe on the MAC Statistics Compute module.

3.1.3. Iterations The load of each of the networks was varied from 1 Mbps to 10 Mbps in eight steps. The simulation time was set to vary with the load so that approximately 1000 packets were sent during each iteration. The actual computer time to do each simulation was two to five hours on a Sun Sparcstation II GX with 16 Megabytes (MB) of memory.

3.2. Analysis and Results

The statistics collected with the probes during each of the five simulations were plotted to judge the performance of the network. The mean delay per packet and mean throughput were plotted versus the normalized offered traffic intensity. Also, the number of completed packets was plotted versus the normalized offered traffic intensity. These plots were created using the Post Processor in BONEs and show the performance of the networks at each iteration of the traffic intensity during the simulations.

3.2.1. Delay per Packet The mean delay per packet was collected during each iteration for all five links. The mean delay per packet versus the normalized traffic intensity was plotted for each of the links on one plot and is shown in Figure 1. As the offered traffic intensity increases, the mean delay per packet increases.

3.2.2. Transmitted Throughput The mean transmitted throughput was collected during each iteration for all five links. The mean transmitted throughput versus the normalized offered traffic intensity was plotted for each of the links on one plot and is shown in Figure 2. The curves in Figure 2 show the throughput increasing linearly with the offered traffic intensity. However, the analysis of the mean delay per packet shows that the mean packet delays for each link begin to increase as the offered traffic intensity is increased. What is happening in the simulation is that only a few nodes are able to transmit and all others cannot.

3.2.3. Number of Completed Packets The number of completed packets was collected during each iteration for all five links. The number of completed packets versus the normalized offered traffic intensity was plotted for each of the links on one plot and is shown in Figure 3. The curves show that the number of completed packets decreases as the offered traffic intensity was increased. Increasing the traffic causes more collisions and longer delays for the nodes to access the network. Therefore, fewer packets are transmitted successfully.

3.2.4. Delay per Graphics Page The mean delay per packet at an offered traffic intensity of 3 Mbps from Figure 1 was used to calculate the delay to send one graphics page. The mean delay per packet at 3 Mbps was used because experiments have shown that a CSMA/CD network is overloaded between three and five Mbps [7]. A page of graphics was assumed to be 640 pixels by 480 lines with 16 colors. This is equal to 153.6 kilobytes of data to be transmitted. The number of packets required to send 153.6 kilobytes was calculated using 64-byte packets. The delay per graphics page was calculated by multiplying the number of packets by the mean delay per packet. The results are summarized in Table 1.

3.3. Conclusions

The simulations show the mean delay per graphics page to be on the order of 300 milliseconds at an offered traffic intensity of 3 Mbps. The largest mean delay of 317 milliseconds per graphics page occurred in the Mix Cast link which has the largest number of nodes (40 nodes). Final Assembly has the second highest delay of 307 milliseconds even though it has only fifteen nodes. Notice that the long length of fiber (approximately 3200 feet) causes a large propagation delay when compared to the other links. Also, it has three cascaded optical hubs. This shows that the ratio of the propagation delay to the transmission time of a packet is an important factor in the success of the CSMA/CD protocol [6].

The packet size in the simulations was set to the smallest packet size of 64 bytes which is a worst-case condition. Larger packet sizes would cause the delays to decrease [8]. The optical hubs should be arranged to cascade as few as possible to avoid large propagation delays. In fact, one commercially available optical hub specifies that each additional hub in a path reduces that path by 180 meters (590 feet) [9].

4.0. VERIFICATION OF THE CSMA/CD MODEL

The CSMA/CD model was verified by using an analytical model developed by Lam [6]. In Lam's paper, the analytical model was developed under a CSMA protocol that detected collisions and aborted the transmissions. The main assumption in the paper was the presence of an adaptive control algorithm for contention. In Lam's paper, an equation was developed for the mean delay per packet in a CSMA network that detected collisions. This equation was used to verify the BONEs simulations.

4.1. Lam's Analysis

In the analysis by Lam, the mean value of the transmission time of each message is assumed to be a random variable with a probability distribution function of $\beta(x)$, a mean value of b_1 , a second moment of b_2 , and a Laplace transform of $\beta^*(x)$. The amount of time from the start of the transmission by one user to when all users sense the presence of the transmission is denoted as τ . This includes delays of the transceiver, software, optical hubs, and the propagation delay. The maximum end-to-end delay is used to calculate τ to give the worst-case condition. This assumes that the delay from any one node to another is the maximum end-to-end delay.

It is assumed that the channel is slotted in time and users can only begin transmission at the beginning of a slot. The minimum slot time is $T = 2\tau$ so that collisions can be aborted and the next slot will be free. The probability of a successful transmission in the next slot is defined as S . The assumption of slotted time is used to simplify the analysis of a CSMA network with a contention algorithm.

The traffic source is assumed to be an infinite population of users that form a Poisson distribution of messages with a mean message generation rate of λ messages per second. The probability of j new arrivals in a time slot is given by Lam as:

$$p_j = \frac{(\lambda T)^j e^{-\lambda T}}{j!}, \quad j = 0, 1, 2, \dots$$

Lam's expression for the mean delay per packet, D , is shown in equation 1.

$$D = x + \frac{T}{S} + \frac{T}{2} - \frac{1 - p_0}{2[\beta^*(\lambda)S - (1 - p_0)]} \left(\frac{2}{\lambda} + ST - 3T \right) + \frac{\lambda[x^2 + 2x(T/S) + T^2(1 + 2(1 - S)/S^2)]}{2[1 - \lambda(x + T/S)]} \quad (1)$$

where

$$x = b_1 + \tau$$

and

$$x^2 = b_2 + 2b_1\tau + \tau^2$$

The probability distribution function of x_{n+1} is $\beta(x)$. Let the probability distribution function of $x_{n+1} + \tau$ be $B(x)$. Therefore, the Laplace transform is:

$$B^*(s) = \beta^*(\lambda)e^{-s\tau}$$

4.2. Delay per Packet

The mean delay per packet versus the normalized throughput was calculated using equation 1 for each of the links in the ASRM network. A program written in the programming language C was written to implement equation 1.

The packet size was assumed to be the minimum packet size of an IEEE 802.3 packet of 64 bytes. It was also assumed that the packet size was a constant. Variable packet sizes were not allowed. Therefore, the mean transmission time of a packet, b_1 , was calculated by dividing the packet size by the transmission rate.

$$b_1 = \frac{(64 \text{ bytes})(8 \text{ bits/byte})}{(10 \times 10^6 \text{ bits/second})} = 512 \times 10^{-7} \text{ seconds}$$

The probability distribution function of the transmission time of each packet, $\beta(x)$, is an impulse of height one centered at b_1 since the packet size was assumed to be a constant. The Laplace transform of $\beta(x)$, $\beta^*(x)$, is therefore equal to one.

The maximum end-to-end propagation delay, τ , was calculated for each of the links. This included the propagation delay from the OIS to the first building in each of the networks, the transceiver delay, and the optical hub delay. The propagation delay was calculated by dividing the distance from the OIS to the first building in the network by the speed at which light travels down an optical fiber. The transceiver delay was doubled to include the total transceiver delay between two computers. The optical hub delay was calculated by assuming that every packet had to pass through all hubs that were in the link. All three delays were added together to give the worst-case delay of the network.

The probability of a successful transmission, S , in the calculations was assumed to be $1/e$. Lam explains that this is the optimum slotted ALOHA throughput rate of a network with an infinite number of users.

The normalized throughput of the channel, ρ , is equal to the number of messages per second, λ , times the mean transmission time per packet, b_1 . The normalized throughput of the channel was varied from 0 to 1 and the mean delay per packet, D , was calculated at each point for each of the links. The mean delay per packet versus normalized throughput is shown in Figure 4.

Lam's model shows all five links in the ASRM network being overloaded between thirty and fifty percent of the transmission rate (between 3 Mbps and 5 Mbps) as seen in Figure 4. All five links show a knee at a particular throughput rate where the mean delay per packet approaches infinity. The longer the end-to-end delay the lower the maximum throughput.

4.3. Comparison of Lam's Model and the BONEs Simulations

The mean delay per packet versus throughput obtained from the BONEs CSMA/CD simulations was compared to the theoretical mean delay per packet versus throughput obtained from Lam's model. Data points were taken off the BONEs plots shown in Figure 1 for Storage and Support and plotted on the same plot with the mean delays calculated using Lam's model. This plot is shown in Figure 5.

Lam's theoretical model and the simulation results are close at throughputs less than approximately 3 Mbps. The simulated mean delay per packet is slightly higher than the theoretical mean delay per packet at these lower throughputs. The simulation accounts for the overhead bits in a packet frame, such as the header and the CRC, that are transmitted but do not contain the original information. The theoretical model presented by Lam does not include overhead bits. Lam assumed that all the bits in a packet were information bits. Therefore, the mean delay per packet for the theoretical model is less than the simulated delay at throughputs less than approximately 3 Mbps.

Lam's theoretical model shows each of the networks overloading (mean delay per packet increasing without bound) at a lower throughput than the simulations. All five networks overload between 3 Mbps and 5 Mbps. There are three reasons to explain this difference. First, the simulation only calculates the delay per packet for packets that are transmitted successfully. The delays for packets that are rejected because of the excessive traffic are not included in the calculation of the mean delay per packet. Also, the theoretical model was calculated with the maximum end-to-end delay. It was assumed that the delay between

every node is the maximum end-to-end delay which is a very pessimistic view. Finally, Lam's model assumes an infinite number of users. The simulation has a finite number of users.

5.0. CONCLUSIONS FOR THE MANUFACTURING NETWORK

The ASRM manufacturing network configuration and the traffic analysis were discussed in Section 1. The BONEs models used to simulate the ASRM network were discussed in Section 2. The simulations of the five networks at the ASRM facility were analyzed in Section 3. The delay per graphic page at a throughput rate of 3 Mbps was found to be on the order of 300 milliseconds. In Section 4 the BONEs simulations were verified using a mathematical model presented by Lam [6].

The BONEs software allows the user to graphically build a network. The ASRM simulation was built using several components from the BONEs library. BONEs also allows the user to build his own modules. A very detailed simulation can be accomplished with BONEs. However, this also means that building a simulation can be a complex task and the actual time to do the simulations can be very long.

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Table 1 Delay per Graphics Page

Link	Number of nodes	Link delay	Maximum number of cascaded hubs	Mean delay per packet at 3 Mbps	Delay per graphics page
				micro-seconds	millisec-onds
Storage and Support	34	1.82	3	109	262
Final Assembly	15	4.85	3	128	307
Propellant	12	0.758	2	109	262
Case Preparation	27	1.52	5	114	274
Mix Cast	40	5.46	4	132	317

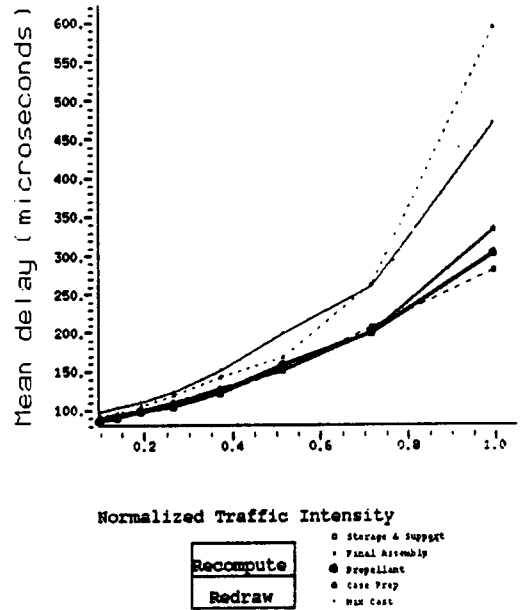


Figure 1. Mean Delay per Packet versus Traffic Intensity

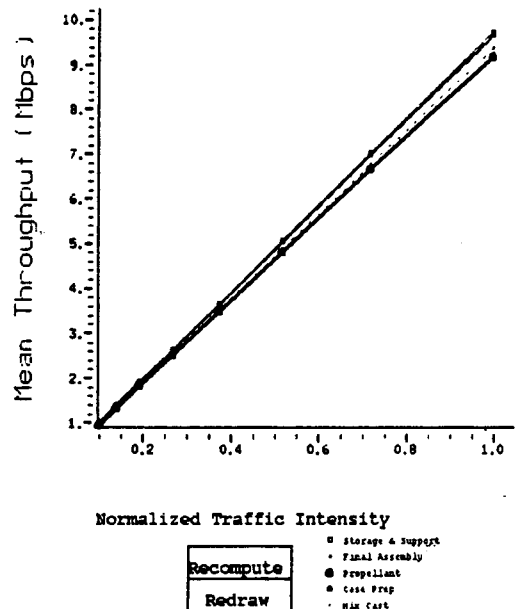


Figure 2. Transmitted Throughput versus Traffic Intensity

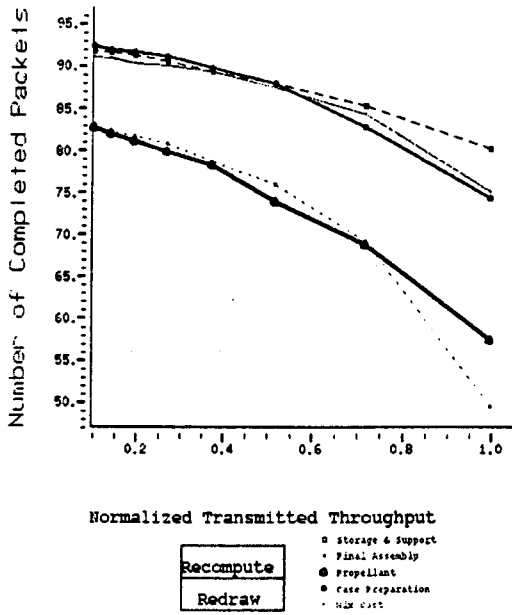


Figure 3. Number of Completed Packets versus Traffic Intensity

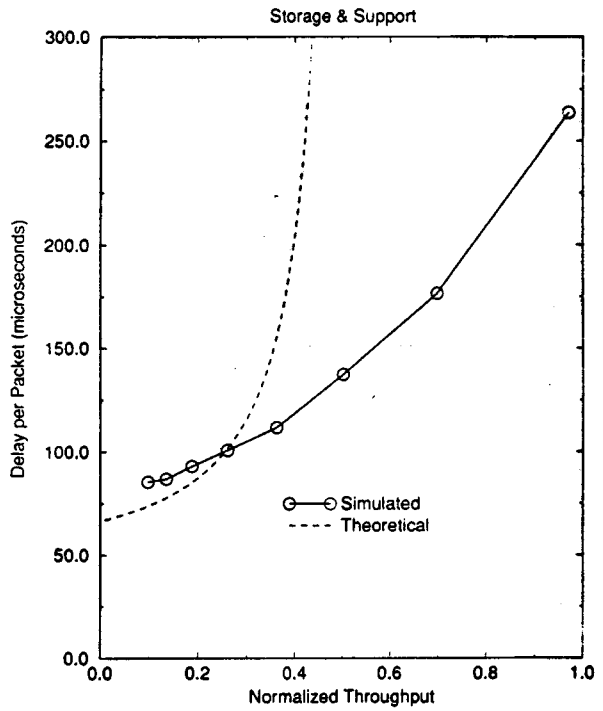


Figure 5. Storage and Support Simulated and Theoretical Delays per Packet

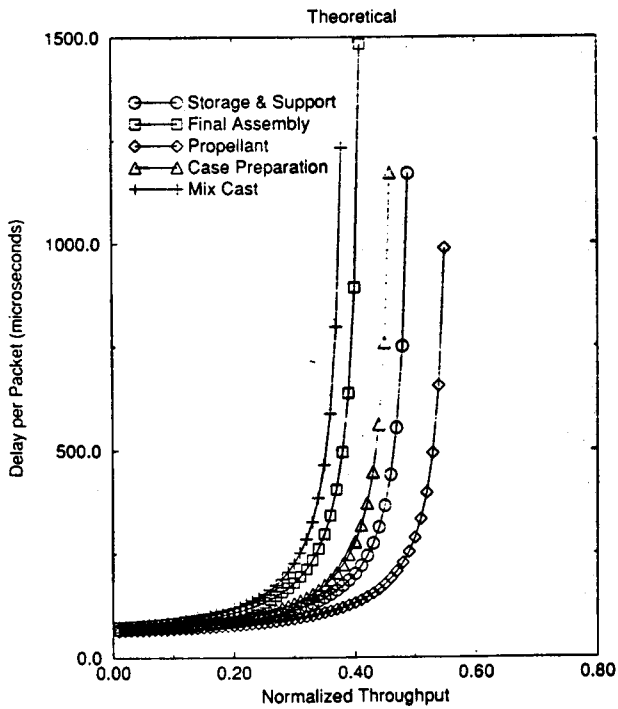


Figure 4. Delay per Packet versus Throughput using Lam's Model