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PERFORMANCE ANALYSIS AND COMPARISON OF LOCAL AREA NETWORKS (LANS)

Iowa State University PH.D. 1985

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Performance analysis and comparison of Local Area Networks (LANs)

by

Dennis Shin Tao Mok

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1985

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NOTATION

θ - the average throughput of a system (used in Heyman's model).

λ_{node} - the average message arrival rate to a node (overall).

λ'_{node} - the average message arrival rate to a node (during the cycle the node has message to transmit).

$\lambda_{station}$ - user data rate (in bits per second) to a PBX station.

λ_{system} - the average arrival rate of packets to a system.

λ_{user} - the average user message rate (can be in bits per second, bytes per second, or packets per second).

τ - the worst case one-way signal propagation delay.

b_{ack} - number of acknowledging bits.

b_{byte} - the average number of user data bytes that are transmitted per packet.

$b_{control}$ - number of packet control bits.

N_{data} - number of user data bits.

N_{max} - the maximum number of user bytes allowed in a packet.

N_{min} - the minimum number of bits per packet.

N_{space} - number of spacing bits behind each byte of user data.

N_{set} - number of bits in a free buffer enquiry packet.

N_{token} - number of bits in a token packet.

$D_{message}$ - the average message delay.

L - the server walking time (used in Cheng's model).

L' - the average number of packets waiting for transmission in the system (used in Heyman's model).

L_{net} - network length.

L_{token} - the average token passing distance.

L_{ring} - ring length.

L_{tran} - the average message transmission distance.

N_{buffer} - the average total number of user data bits that are in a node's buffer.

$N_{collisions}$ - average number of packet collisions between consecutive successful transmissions on a saturated network.

$N_{maxnodes}$ - the maximum number of nodes a network can support at network saturation.

N_{nodes} - number of nodes connected to the network.

$N_{passrepeaters}$ - the average number of repeaters a token encountered in the token passing process.

N_{queue} - the average number of user data bits in a node's output queue.

$N_{repeaters}$ - the average number of repeaters a packet will encountered in going from the packet sending node to the receiving node.

N_{rings} - the average number of times a token will have to travel around the logical ring in between a queue's turn to transmit.

$N_{stations}$ - number of stations connected to a PBX network.

N_{trans} - the average number of transmitting nodes on a token cycle around the logical ring.

N_{users} - the average number of users per node.

P_i - the probability that i packets are in a system at any given time.

P(node) - the probability that a node will transmit when it receives a token.

P(user) - the probability that a queue is not empty when its turn to transmit occurs.

R_{byte} - the average data rate (in bytes per second) to a node.

$R_{netpacket}$ - the maximum average network packet rate.

$R_{network}$ - network data rate (in bits per second).

R_{node} - maximum achieveable data rate (in bits per second) per node.

R_{packet} - the maximum node packet rate per second.

$R_{saturate}$ - network saturation message rate to a node.

$R_{station}$ - data rate of a PBX station.

R_{user} - maximum achieveable data rate (in bits per second) per user.

S - the elapsed time involved in the transmission of a packet (used in Heyman's model).

T_{ack} - message acknowledging delay.

$T_{buffchk}$ - the buffer checking time spent by a node in detecting ready messages in its buffers.

$T_{contention}$ - the average time spend in all unsuccessful transmissions and collision recoveries between consecutive successful transmissions on the network.

T_{copy} - interface (message copy) delay incurred by the message receiver of a token ring.

T_{cycle} - network cycle time.

$T_{delivery}$ - message delivery delay from the sending to the receiving node.

T_{detect} - the average elapsed time starting at the instant a node begins its transmission right after the brief interframe delay, to the instant when all contending nodes detect a message collision on the network.

$T_{interface}$ - packet interface (message verification and regeneration) delay at a node.

$T_{interframe}$ - the specified waiting time after the end of a packet transmission.

T_{jam} - the message collision enforcement time.

$T_{message}$ - the transmission time of a message.

T_{packet} - the packet transmission time.

$T_{passprop}$ - the signal propagation delay of the token.

$T_{passrepeat}$ - token signal regeneration delay at repeaters.

T_{prop} - signal propagation delay.

T_{queue} - the message queueing delay.

T_{tran} - signal regeneration delays a packet signal incurred in passing through repeaters.

$T_{repeater}$ - signal regeneration delay of a repeater.

T_{ring} - the token cycle time around a logical ring.

$T_{rotation}$ - the average elapsed time between a queue's turn to transmit.

T_{set} - the average elapsed time involved in the transmission of a free buffer enquiry packet.

T_{switch} - the switching delay at the central control computer of a PBX network.

T_{token} - the average token passing delay.

T_{tran} - the average elapsed time involved in successfully transmitting a packet.

V_{prop} - signal velocity on the medium.

W - the normalized average message waiting time.

CHAPTER I. INTRODUCTION

Local Area Networks (LANs)

Local Area Networks (LANs) are communication systems built for the purpose of transferring data between connecting devices. The common types of device connected to LANs are: computers, terminals, mass storage devices, and printers. Typical characteristics of LANs are:

1. The network serves users concentrated within a limited geographic area.
2. Ownership of the network is by a single organization.
3. The network has a total channel data rate of over one million bits per second.

A variety of different information transmission mediums are used in LANs. The most commonly used are twisted pair wire and coaxial cable. Other less popular mediums include radio, microwave, infrared, and fiber optic systems.

The history of LANs began in the mid '70s. In those early years, a variety of small scale ring and loop networks were built by universities and research laboratories, mostly as part of their experimentations with distributed processing. In 1976, a major advancement in LAN development came about when Xerox Corporation presented in professional literature a description of a LAN called Ethernet. A number of other vendors since then commercially manufactured and marketed Ethernet-like networks to buyers of LANs. In 1980, the joint venture of Xerox-Intel-Dec in announcing a specification for the commercial version of Ethernet generated widespread publicity among data communication vendors, and the talk of adopting Ethernet as an industry standard started to circulate.

As the market for LANs exploded in the early '80s, the need for standards became felt. The establishment of LAN standards benefits both buyers and vendors. For buyers, LAN standards allow equipment manufactured by different vendors to be compatible for connection to the network, thus, allowing buyers more freedom in choosing among vendors. For vendors, LAN standards offer reliable design guidance and more potential buyers for their products.

In December 1980, a committee was formed by the IEEE[1] Computer Society to study the issue of establishing LAN standards. The project, designated Project 802, soon found that a single standard adopting only the Ethernet contention protocol would not be acceptable to all parties. Consequently, a number of other medium access protocols were proposed to become standards. Currently, the IEEE802 standards established or near completion are:

- The CSMA-CD[2] bus medium access protocol.
- The token passing bus medium access protocol.
- The token passing ring medium access protocol.

A detailed description of these protocols are given in Section E of this chapter. It is those networks conforming to the IEEE802 standards that we are concerned with in this study of performance analysis and comparison of LANs.

---

[1] Institute of Electrical and Electronic Engineers.

[2] Carrier Sense Multiple Access with Collision Detection.

Still another class of networks capable of LAN functionings but not covered in the formulations of IEEE802 standards are the PBX[1] networks. PBX networks can provide significant cost savings by making use of existing twisted pair telephone wire as the communication medium. The most technologically advanced PBX products provide extensive call management features, non-blocking switching, and the integration of voice and data traffic for simultaneous transmission through the network. All these make PBX a serious competitor in the LAN market. Therefore, because of its great potential as a networking alternative, the performance analysis of PBX type networks are included in this work.

Statement of Problem and Objectives

Even with the IEEE802 standards in place, LANs in the market still vary in topology, modulation method, bandwidth, connecting medium, range and load limits, and medium access schemes. Thus, the job of selecting a best LAN for any given application is not a trivial task.

For the past several years, numerous articles and papers on the topic of performance analysis and comparison of networking protocols have been published. However, much of the quantitatively oriented work has often been so theoretical as to be of little direct use to those involved in buying LANs.

The intent of this study on network performance analysis is in creating a software tool useful for the practical analysis of and comparison among various networking alternatives. Readers of this work are assumed to have general knowledge of the bases of computer networking and data communications, as well as a basic background in queueing theory and statistics.

---

[1] Private Branch Exchange telephone switching network.

The types of network considered are networks following either the CSMA-CD, token passing bus, token passing ring, or PBX type of medium access protocols. A list of LANs to which the developed software is applicable is given in Table 1. In the next few sections, the key concepts and terms that users must understand, in using the equations and the software tool developed in this study, are discussed.

A node is a device that provides users access to the medium (Figure 1). A typical node has several ports, each connected to a user e.g., by a RS-232 interface (Figure 2). A user sends messages to an assigned output buffer in a node at an average user message rate of λ_{user} (can be quantified in bits per second or bytes per second or packets per second). If the node can not have access to the network when the user message arrives, the message will then be queued in the output buffer until it is transmitted. The average length of a single output buffer queue is called the average user queue length. The average size (in bits) of all the output buffer queues put together is called the average node buffer size. The average arrival rate of messages from users to a node is equal to the sum of the average user message rates from all users of the node. Thus, when λ_{user} is identical for all users,

$$\lambda_{node} = N_{users} \lambda_{user} \qquad (1)$$

where,

λ_{node} is the aggregated average user message rate.

N_{users} is the number of users per node.

λ_{user} is the average user message rate.

Table 1. Local area networks

Access Scheme	Network	Vendor	No. of Packets Transmitted/ Access
CSMA-CD	AppleNet	Apple Computer, Inc.	1
	CIM/NET	Cadlinc, Inc.	1
	DESNET	The Destek Group	1
	Ethernet	Xerox, Intel, DEC Corp.	1
	Etherway	Technology Concepts, Inc.	1
	GEnet	Intersil Systems, Inc.	1
	LocalNet	Sytek, Inc.	1
	Net/One	Ungermann-Bass, Inc.	1
	PCnet	Orchid Technology	1
	PERQ KAB	3 Rivers Computer Corp.	1
Token Passing Bus	ARCNET	Datapoint Corp.	1
	Harris LAN	Harris Corp.	1
	LAN/1	Interactive Systems/3M	1
	Xodiac	Data General Corp.	1
Token Passing Ring	Domain	Apollo Computer, Inc.	1
	IBM Ring	IBM Corp.	1
	MagnaLoop	A.B. Dick Company	1
	Ringnet	Prime Computer, Inc.	1
	ProNET	Proteon, Inc.	1
PBX	CBX	ROLM Corp.	—
	IBX	InteCom, Inc.	—
	SL-1	Northern Telecom, Inc.	—
	System 85	AT&T Corp.	—

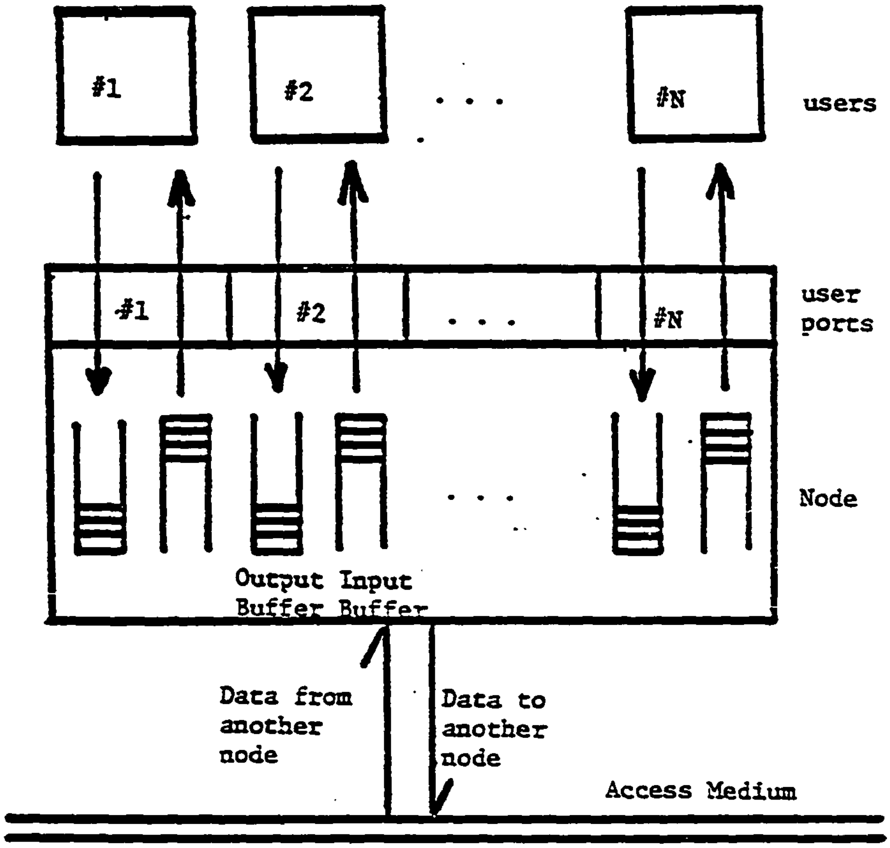

#1
#2
. . .
#N
users
#1
#2
. . .
#N
user ports
. . .
Node
Output Input Buffer Buffer
Data from another node
Data to another node
Access Medium

Figure 1. A node

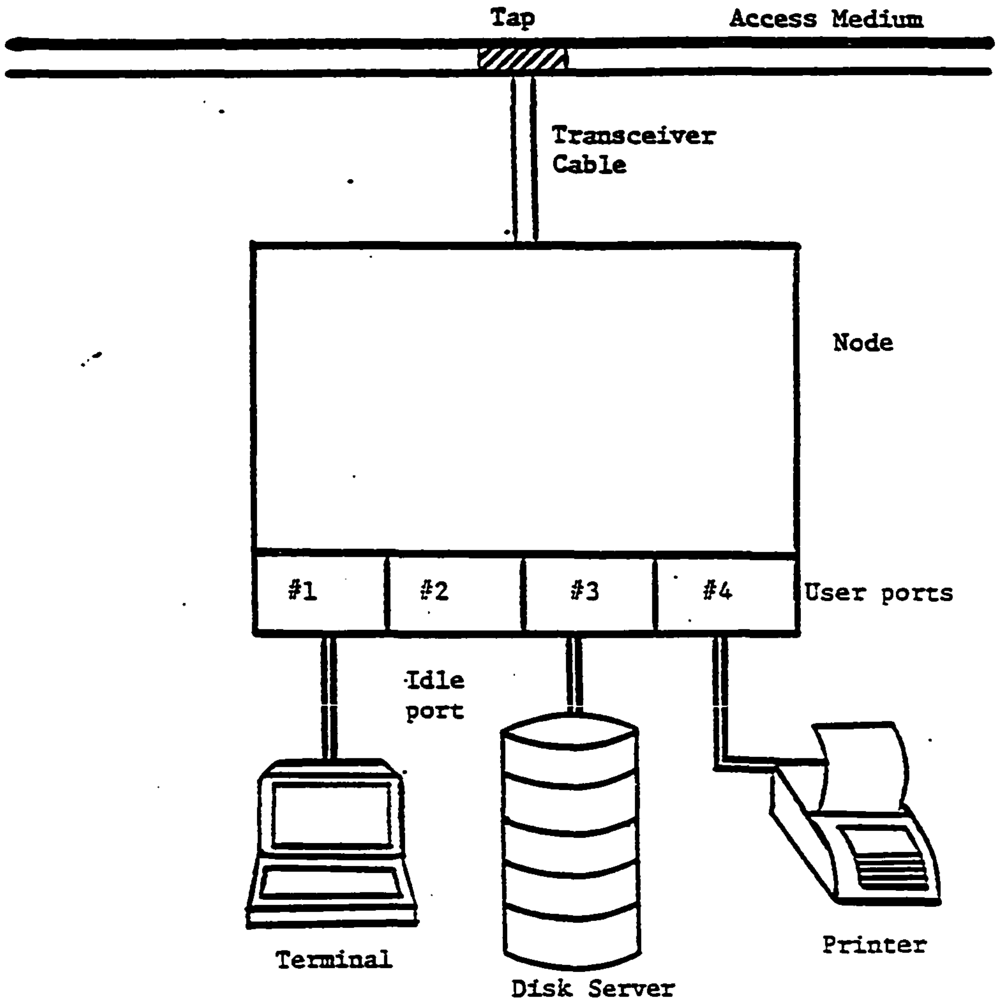

Tap
Access Medium
Transceiver Cable
Node
#1
#2
#3
#4
User ports
Idle port
Terminal
Disk Server
Printer

Figure 2. Physical configuration of a node and its connected peripherals

When a node has access to the network, it will transmit messages from one of its output buffer queues. For token passing networks, user queues are polled in a fixed rotation for message transmission, such that access to the network is balanced among all user queues. When a non-empty queue is polled, the node will either transmit all messages accumulated in the queue (exhaustive service), or will only transmit some of the messages in the queue (non-exhaustive service). Details on how much information a node can transmit from a user queue, each time the node has access to the network, are described later in this chapter.

For this study, performance parameters considered are:

1. Maximum number of nodes the network can support: the maximum number of nodes that can be supported by the network, at a given average message arrival rate to each node, such that the queueing delay of messages in a node's output buffer is not infinite.
2. Maximum achieveable data rate per node: the maximum average user data rate in bits per second at which a node can transmit user data (Figure 3), when all nodes of the network transmit at the maximum packet rate possible (with no idle time on the medium).
3. Average message delay: the average message queueing delay plus average signal propagation delay (Figure 4), incurred in going from the message sending node to the receiving node.
4. Average node buffer size: the average number of user data bits that are in all the output buffers of a node.

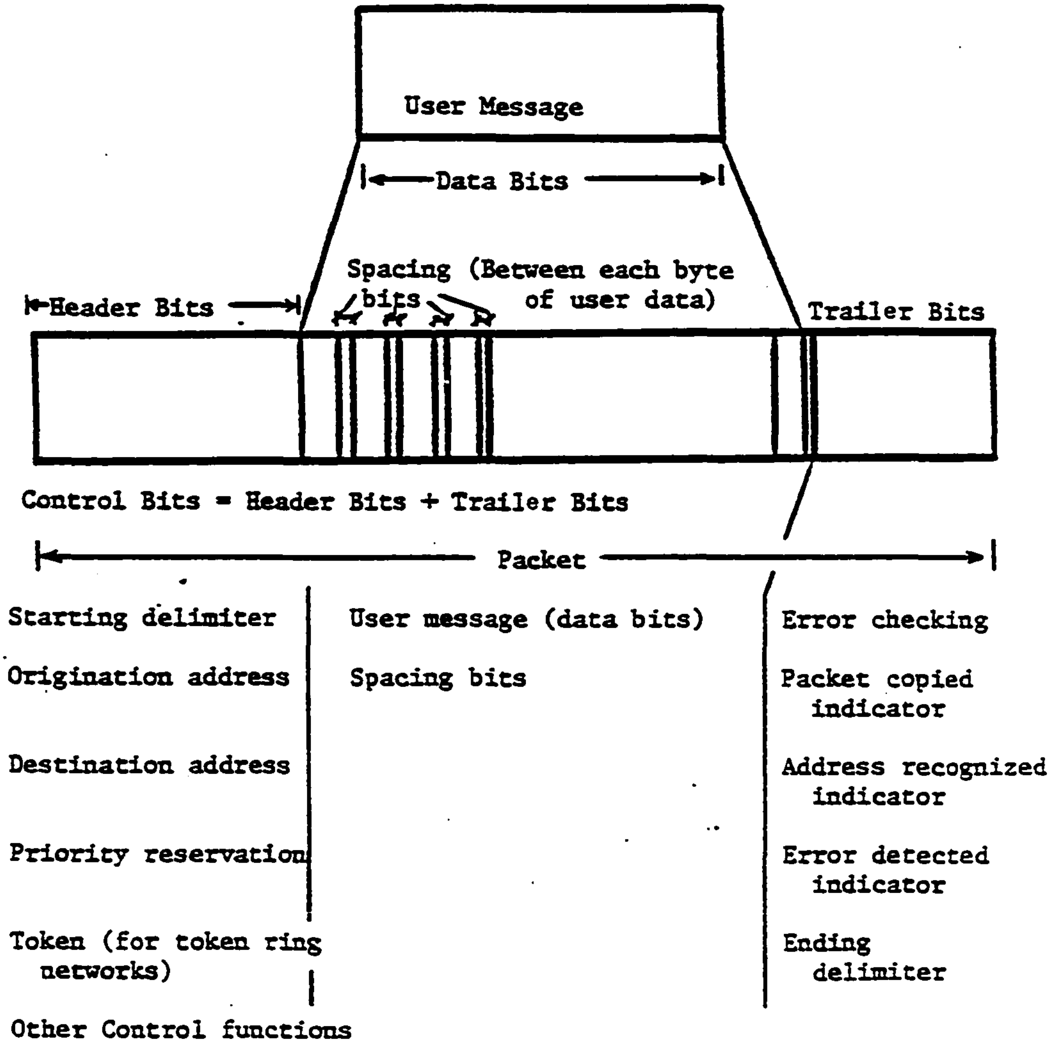

User Message
Data Bits
Spacing (Between each byte
bits
of user data)
Header Bits
Trailer Bits
Control Bits = Header Bits + Trailer Bits
Packet
Starting delimiter
Origination address
Destination address
Priority reservation
Token (for token ring networks)
Other Control functions
User message (data bits)
Spacing bits
Error checking
Packet copied indicator
Address recognized indicator
Error detected indicator
Ending delimiter

Figure 3. Packet format

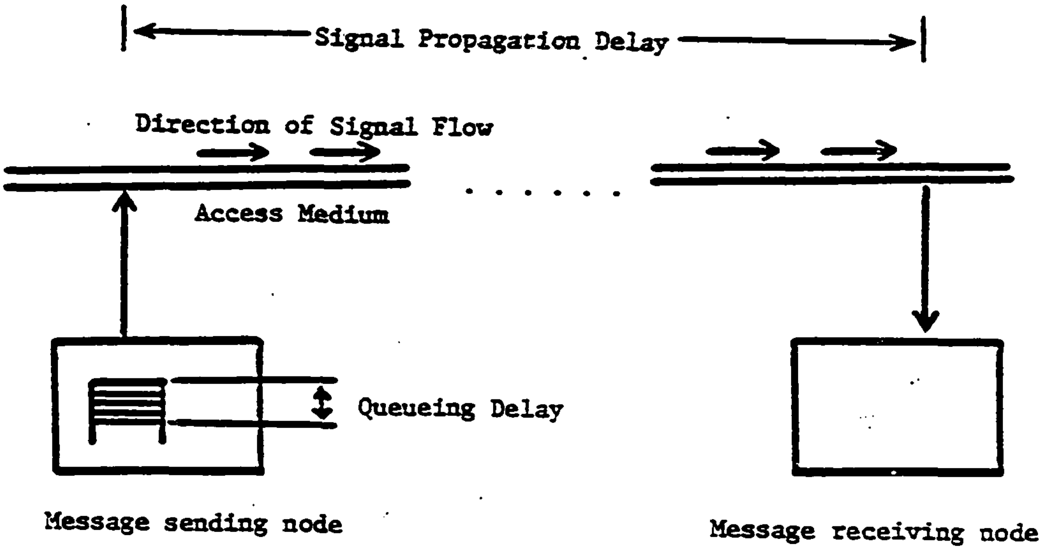

Signal Propagation Delay
Direction of Signal Flow
Access Medium
Queueing Delay
Message sending node
Message receiving node

Figure 4. Message delay

5. Network saturation message rate to a node: the average arrival rate of messages from users to a node that would result in infinite queueing delay of messages in a node's output buffer.

These parameters are evaluated for the different access schemes as functions of:

1. The number of nodes that are connected to the network.
2. The number of data bits that are in each packet.
3. The network length (as defined later in this chapter).
4. The average message transmission distance (as defined later in this chapter).
5. The average user message arrival rate to each node (in bytes per second or packets per second).
6. Signal propagation velocity.
7. Other protocol related features.

Original contributions of this work are:

1. The deriving of analytical models in computing the:
    a. Maximum achieveable data rate to a node (for the CSMA-CD, Token Bus, and Token Ring types of networks).
    b. Average message delay and average node buffer size[1].
    c. Maximum number of nodes the network can support[1].
    d. Network saturation message rate to a node[1].
2. The modification of existing derived models, in computing average message delay and average node buffer size (for

---

[1] for the Token Bus, and Token Ring types of networks following the exhaustive queue service discipline.

the Token Bus and the Token Ring types of networks following the non-exhaustive queue service discipline), such that they conform more closely with the actual working of real systems.

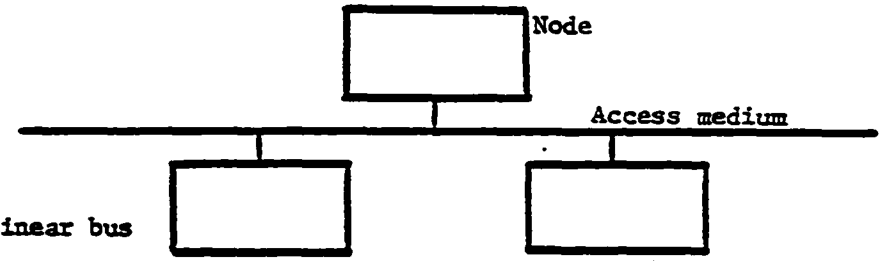
3. The creation of a software tool to facilitate the performance analysis and comparison among real LANs.

Networking Topologies

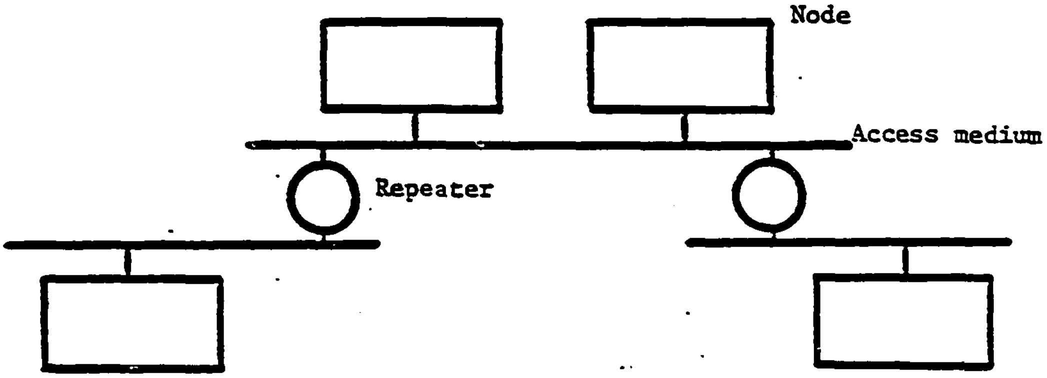
The topology of a network refers to the way in which the nodes are connected. There are three major LAN topologies: broadcast, ring, and star. These topologies are discussed in more detail in the following paragraphs.

Broadcast topology

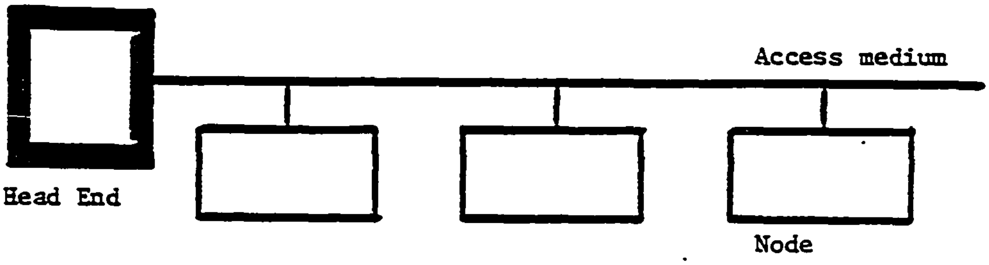
The broadcast topology (Figure 5a) consists of bidirectional broadcast mediums (busses) to which all nodes are attached. Information signals propagate away from the originating node in both directions to the ends of the bus. Multiple busses can be interconnected by repeaters, so long as the signal transmission path on the busses does not form a loop. Thus, a bus network can be viewed as a kind of branching, non-rooted tree (Figure 5b), since there is a unique path from every node to every other node with no central or root node. CATV broadcast systems (Figure 5c) are configured in single or dual trunk configurations (Figures 6a and 6b). In a dual trunk configuration, information signals are transmitted through the forward trunk to a headend network amplifier, where they are retransmitted onto the return trunk to the receiver.


Node
Access medium

a. Linear bus


Node
Access medium
Repeater

b. Non-rooted tree


Access medium
Head End
Node

c. CATV Network

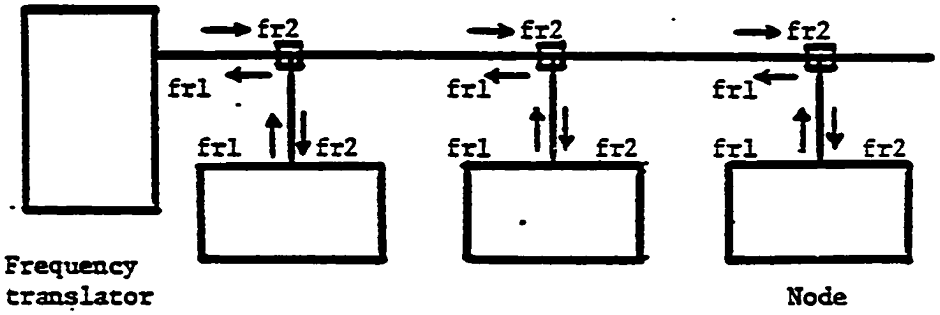
Figure 5. Broadcast networks

Legend

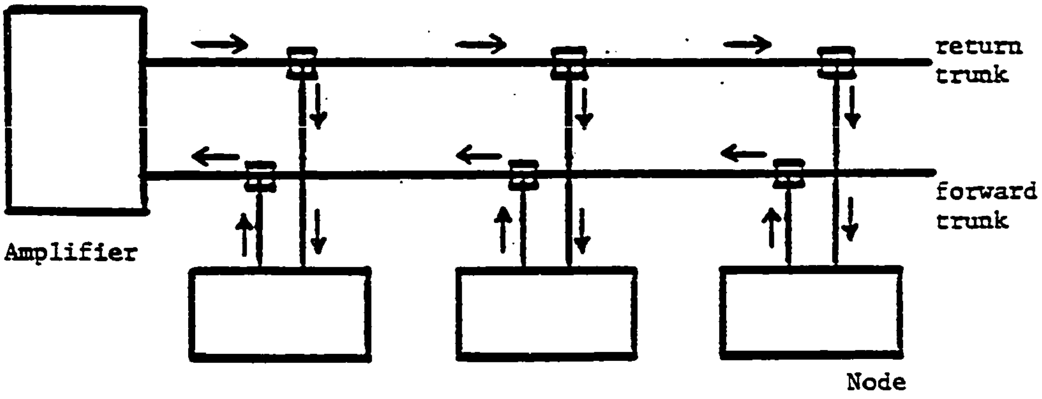
→ Direction of message flows

fr1: forward frequency

fr2: return frequency


fr2
fr1
fr1
fr2
Frequency translator
Node

a. Single trunk CATV Network


return trunk
forward trunk
Amplifier
Node

b. Dual trunk CATV Network

Figure 6. CATV Networks

Thus, a node connected to a dual trunk CATV network transmits messages on one (forward) trunk and receives messages on another (return) trunk. For broadcast networks configured in a single trunk CATV configuration, the bandwidth of the trunk is divided into forwarding and receiving channels. Messages from a node are transmitted through the forwarding channel to the network frequency translator, where the message signals are converged into another (higher or lower) frequency for transmission, through the receiving channel, to the receiver.

Ring topology

The ring topology (Figure 7) connects its nodes by a set of unidirectional transmission links to form a closed loop. Each node on the ring is connected by two links, one link to transmit, another link to receive. Messages are processed and typically repeated at each node of the ring.

Star topology

The star topology (Figure 8) uses a single central node. To transmit, a user (station) will have to send its messages to the central node, from this central node the messages are routed to their destinations.

Network Size Parameters

The three network size parameters used in this study are: the network length, the ring length, and the average message

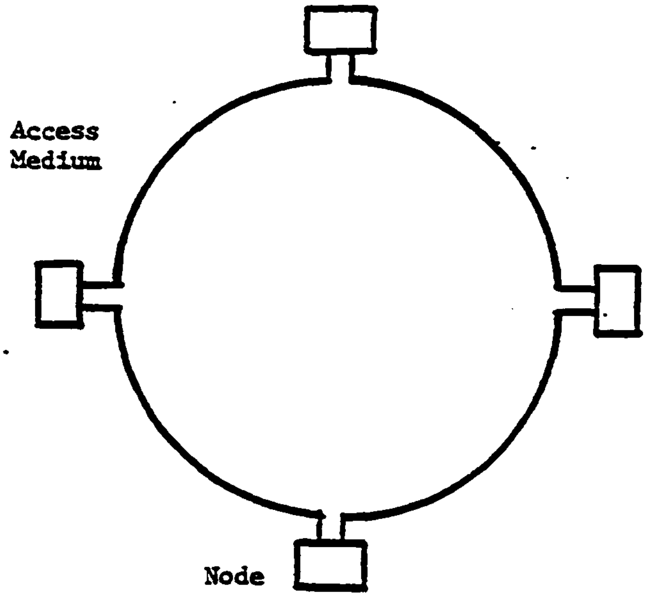

Access
Medium
Node

Figure 7. The Ring Topology

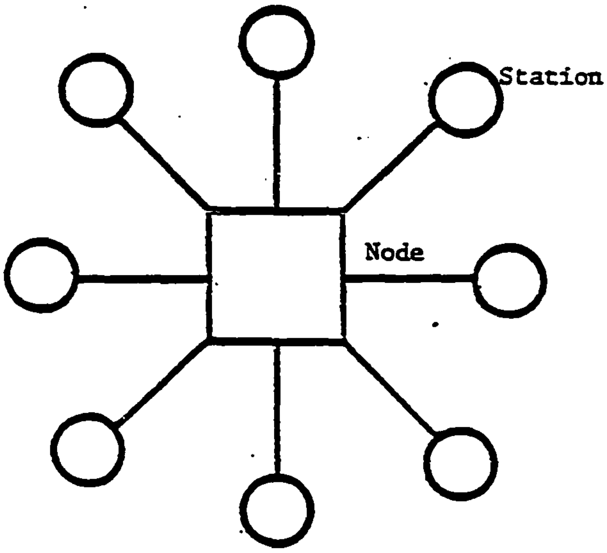
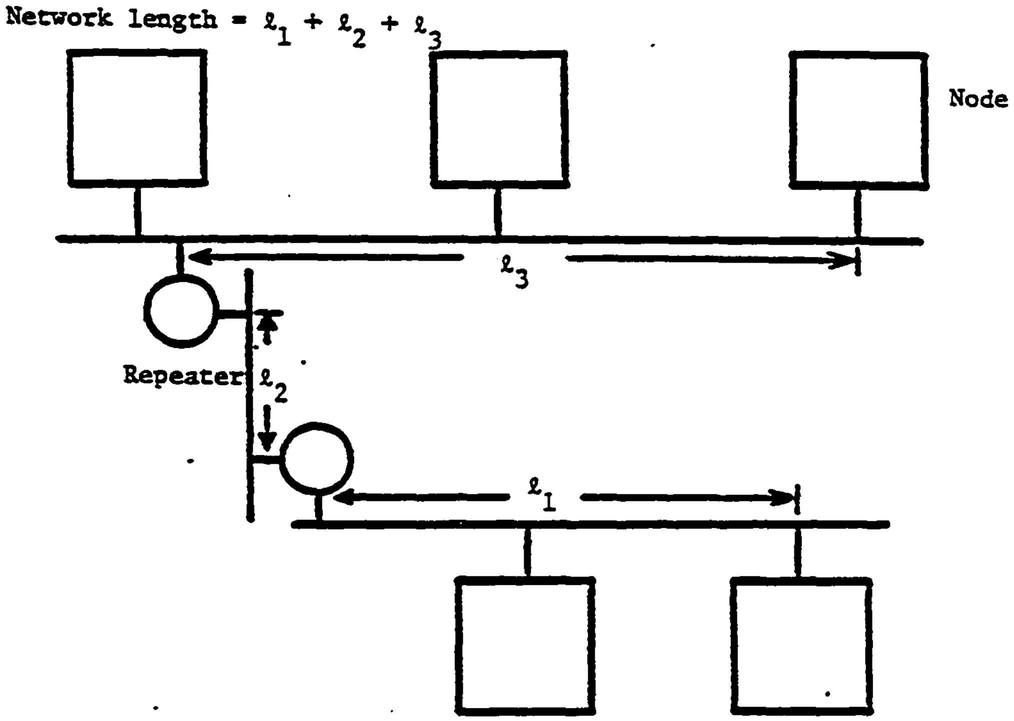
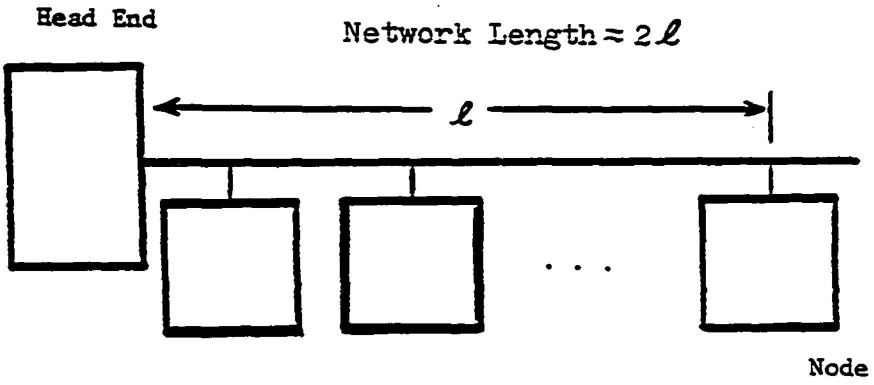

Station
Node

Figure 8. The Star Topology


Network length = $\ell_1 + \ell_2 + \ell_3$
Node
ℓ_3
Repeater
ℓ_2
ℓ_1

a. Tree/Bus Network


Head End
Network Length $\approx 2\ell$
ℓ
. . .
Node

b. CATV Network

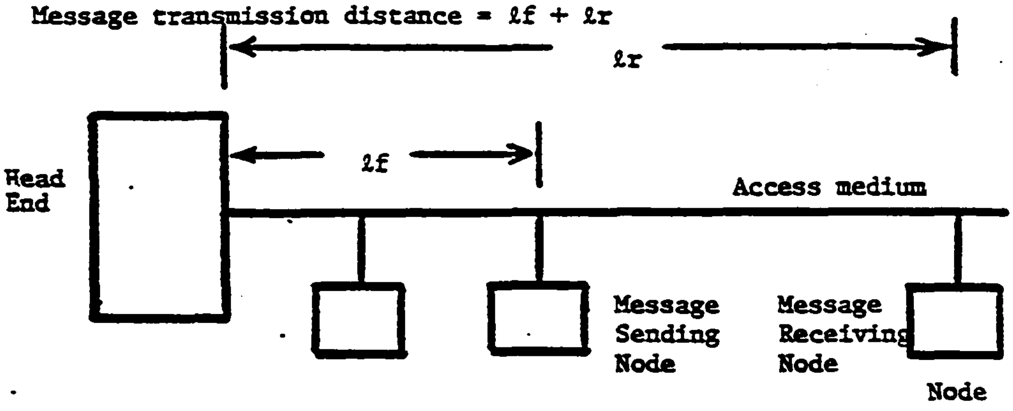
Figure 9. The Network length

transmission distance.

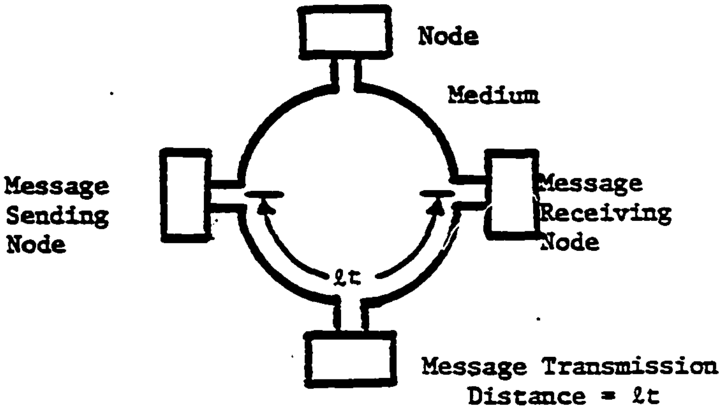
For networks configured in a tree topology, the network length (Figure 9a) is the distance between the two nodes that are placed furthest apart on the network. For CATV networks (Figure 9b), the network length is approximately two times the distance between the head end and the node on the furthest end of the network. The network length parameter is used in this study only in computing the one-way signal propagation delay between the two nodes that are placed furthest apart on a CSMA-CD type network (only the tree and broadcast types of topologies are considered in the sizing of this parameter). The network length for a network configured in a broadcast or tree topology is measured by adding up the lengths of the various trunk segments (dual trunk is treated as a single trunk) separating the two nodes placed furthest apart on the network.

The ring length is used in measuring the total length of a token passing ring. This parameter is used in computing the propagation delay of the packet header in traveling once around the ring. This parameter is measured by adding up the lengths of all cable segments forming the ring.

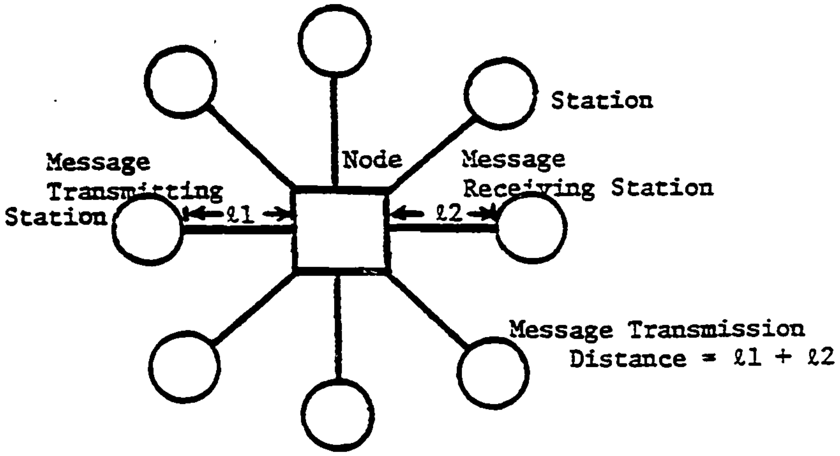
The average message transmission distance is the average propagation distance on the medium that a message will have to travel in going from the message transmitting node to the receiving node. For networks configured in a broadcast CATV topology (Figure 10a), this parameter is measured by adding up the average networking distance between the headend and the message transmitting node and the average


Message transmission distance = ℓf + ℓr
ℓr
ℓf
Head End
Access medium
Message Sending Node
Message Receiving Node
Node

a. Broadcast CATV Network


Node
Medium
Message Sending Node
Message Receiving Node
ℓt
Message Transmission Distance = ℓt

b. Ring Network


Station
Node
Message Transmitting Station
Message Receiving Station
ℓ1
ℓ2
Message Transmission Distance = ℓ1 + ℓ2

c. Star Network

Figure 10. The message transmission distance

networking distance between the headend and the message receiving node. The average message transmission distance for networks configured in a ring topology (Figure 10b), is the average networking distance (along the direction of signal flow on a unidirectional transmission medium) between the message sending node and the receiving node. The average message transmission distance for networks configured in a star topology (Figure 10c), is the average networking distance between the message transmitting station and the receiving station.

Medium Access Protocols

For this study, analytical models are developed according to the exact description outlined in this section for the various medium access protocols.

CSMA-CD

Typical CSMA-CD networks are configured in a broadcast topology [1]. Before a packet's bits are placed on the network by a node, it senses the presence of any carrier on the network and defers to any ongoing transmission. Once transmission stops, the nodes waiting to transmit a packet all defer momentarily (interframe delay) before initiating their own transmission. Once a node's transmission has been in progress for an end-to-end propagation time with no other nodes submitting their packet during that period, the medium is acquired by the transmitting node. The packet will then be transmitted to completion without interference. But there can be circumstances where

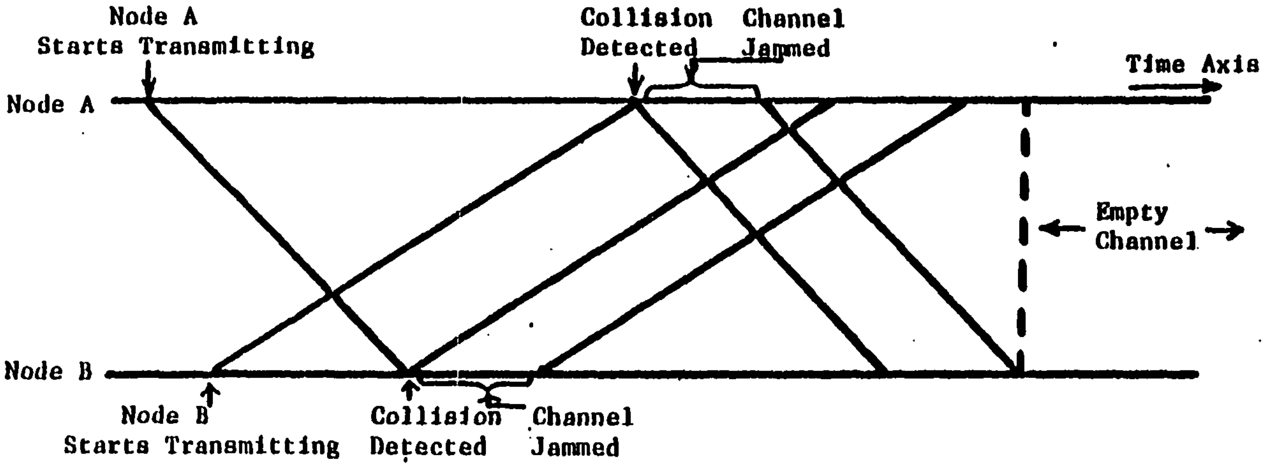

Node A
Starts Transmitting
Collision
Detected
Channel
Jammed
Time Axis
Node A
Empty
Channel
Node B
Node B
Starts Transmitting
Collision
Detected
Channel
Jammed

Figure 11. CSMA-CD collision detection and channel recovery

another node starts transmitting before message signals from the current node reaches it (Figure 11). When this happens, message collision occurs. After detecting a collision, all colliding nodes momentarily jam the medium to ensure that all other nodes stop transmitting. They will then each backoff for a random amount of time, as determined by the binary exponential backoff algorithm [2], before attempting to transmit again. Once a node has completed transmitting a packet, it relinquishes control of the medium, but can still attempt another transmission after the brief interframe delay.

Token passing bus

For token passing bus [3] networks, all nodes "hear" all transmissions on the bus, allowing medium access to be controlled by token passing through a logical ring (Figure 12). The token is a unique bit sequence that bears the address of the next node in a logical sequence, and is passed from node to node without requiring them to be physically adjacent as in a physical-ring topology. Also, unlike a ring, each node interface must receive the full token bit sequence before it can act on the token (either passes the token onto the next node when it has nothing to transmit, or transmits its messages). Only the node holding the token addressed to it can transmit, thus eliminating the possibility for message collision.

Token passing networks follow either one of the following two service schemes (Figure 13) in transmitting messages:

a. Byte scheme- where messages are transmitted to the input

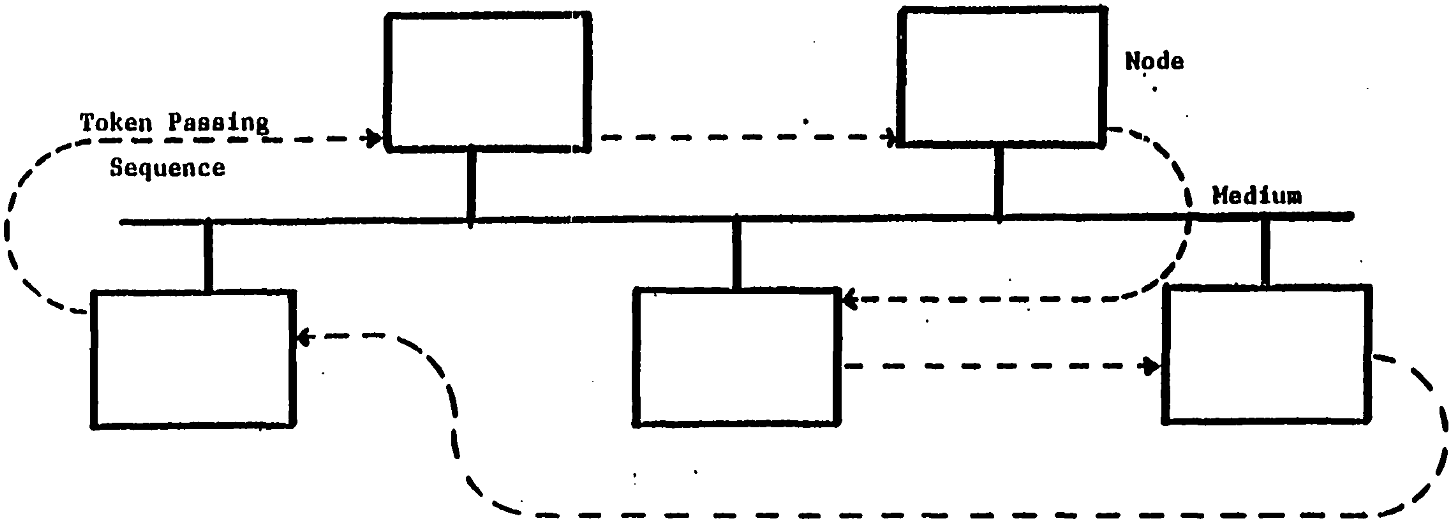
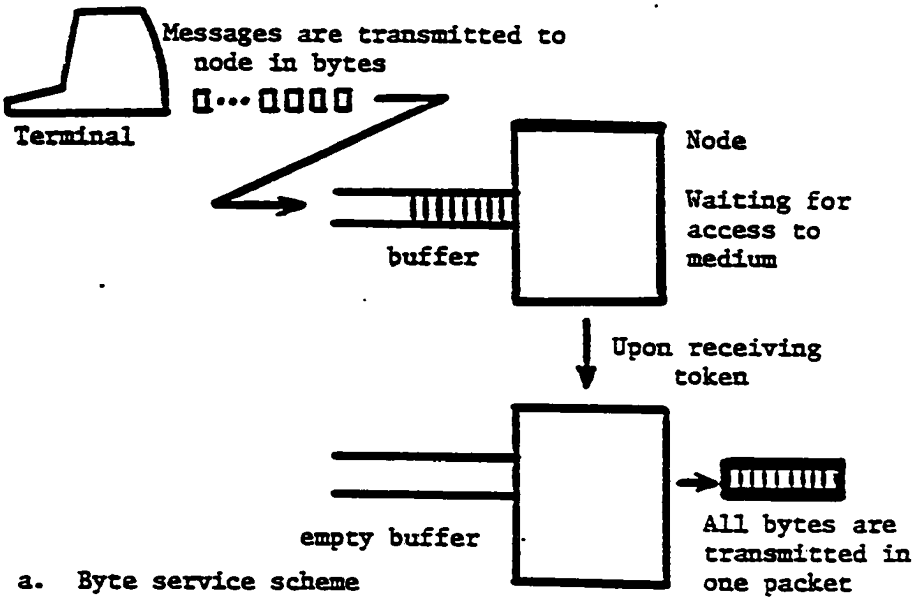
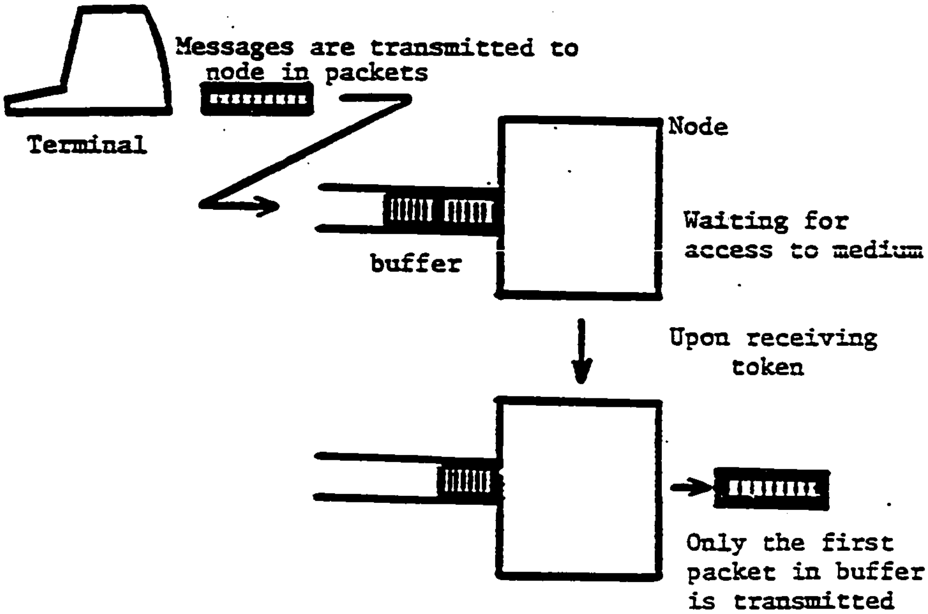

Token Passing
Sequence
Node
Medium

Figure 12. Token passing through a logical ring


Messages are transmitted to node in bytes
Terminal
Node
Waiting for access to medium
buffer
Upon receiving token
empty buffer
All bytes are transmitted in one packet

a. Byte service scheme


Messages are transmitted to node in packets
Terminal
Node
Waiting for access to medium
buffer
Upon receiving token
Only the first packet in buffer is transmitted

b. Packet service scheme

Figure 13. Byte and packet service schemes

buffers of a node in bytes (without first being grouped into packets). When the node has access to the medium, all bytes that are in one of the buffers are transmitted.

b. Packet scheme- where messages are transmitted to the input buffers of a node in packets. When the node has access to the medium, only the first packet at the top of one of the buffers is transmitted.

Depending on the message transmission discipline specified for the network, a node utilizing the packet scheme may have to first send a free buffer enquiry and get a positive response from the destination before it can start transmitting (Figure 14). Also, after the transmission had completed, a node may have to wait for an acknowledgment from the receiver before it relinquishes control of the medium. If the acknowledgment is negative, the node will repeat transmitting the same packet the next time it has access to the medium.

Token passing ring

For token passing ring [4] networks, the medium access control mechanism uses a single token passed sequentially from node to node around the ring. The token is a bit sequence indicating its status (busy or free). A node that has message bits to transmit can capture the free token (Figure 15a), change the token status to busy, and append to it its message bits followed by a frame check sequence for error control. Also, like the token passing bus medium access protocol, a node capturing the token will follow either the byte service scheme or

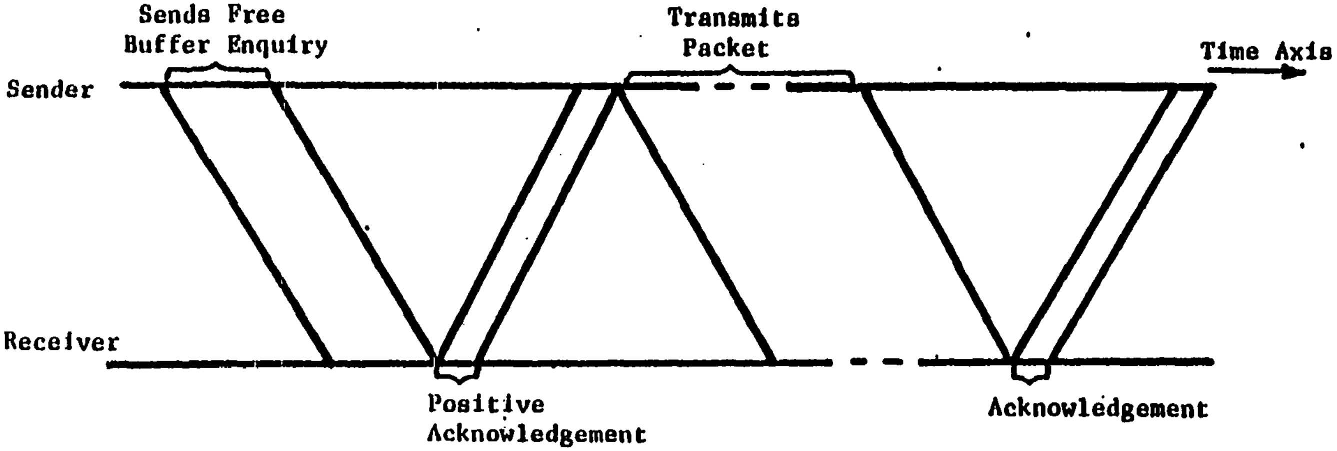
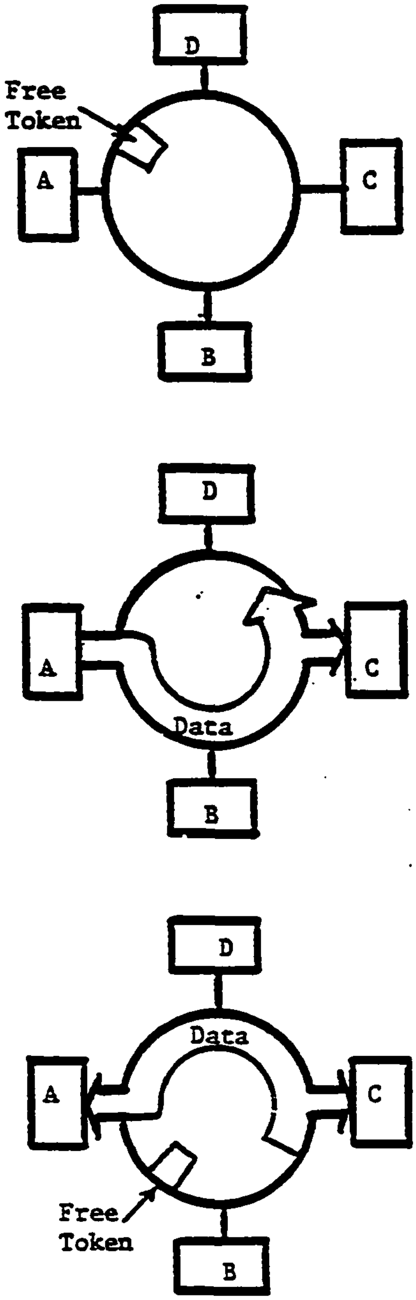

Sends Free
Buffer Enquiry
Transmits
Packet
Time Axis
Sender
Receiver
Positive
Acknowledgement
Acknowledgement

Figure 14. Data communication protocol of a token passing bus network following the packet service scheme


D
Free Token
A
C
B
D
A
C
Data
B
D
Data
A
C
Free Token
B

a. Sender (Node A) waits for free token, changes free token to busy token and appends data

b. Receiver (Node C) copies data addressed to it

c. Sender generates free token upon receipt of physical header (and completion of transmission)

Figure 15. The token passing ring access scheme (Source: Markov and Strole [4])

the packet service scheme in transmitting messages. Each packet transmitted onto the ring passes from node to node and is regenerated as it passes through each node (Figure 15b). Upon receipt of a packet, each node verifies the packet's integrity and address, but will only copy messages that are addressed to it. Only the node that initiates a packet transfer can remove the packet from the ring (Figure 15c) and issue a free token upon receipt of the packet header (and completion of transmission). The free token is passed implicitly to the next node connected to the ring.

PBX

A PBX [5] network is managed by a network control computer (switch), which establishes and maintains circuits among stations. Typically, a PBX network is configured in a star topology , with the central computer directly connected to all users. In order to establish a circuit, a station requests a connection from the control computer (Figure 16). Once a virtual circuit is established between the caller and the receiver by the control computer, the communication line is maintained for them for the whole duration of the communication session as if it were a permanent hardwired connection. Most modern PBX systems are capable of simultaneous voice and data communications through the same station. Typically, two pairs of twisted-pair wiring service each voice/data station. One pair handles voice and dialing, and the other handles the data; one wire to transmit, the other to receive. When a data transmission session is completed, a special signal is transmitted

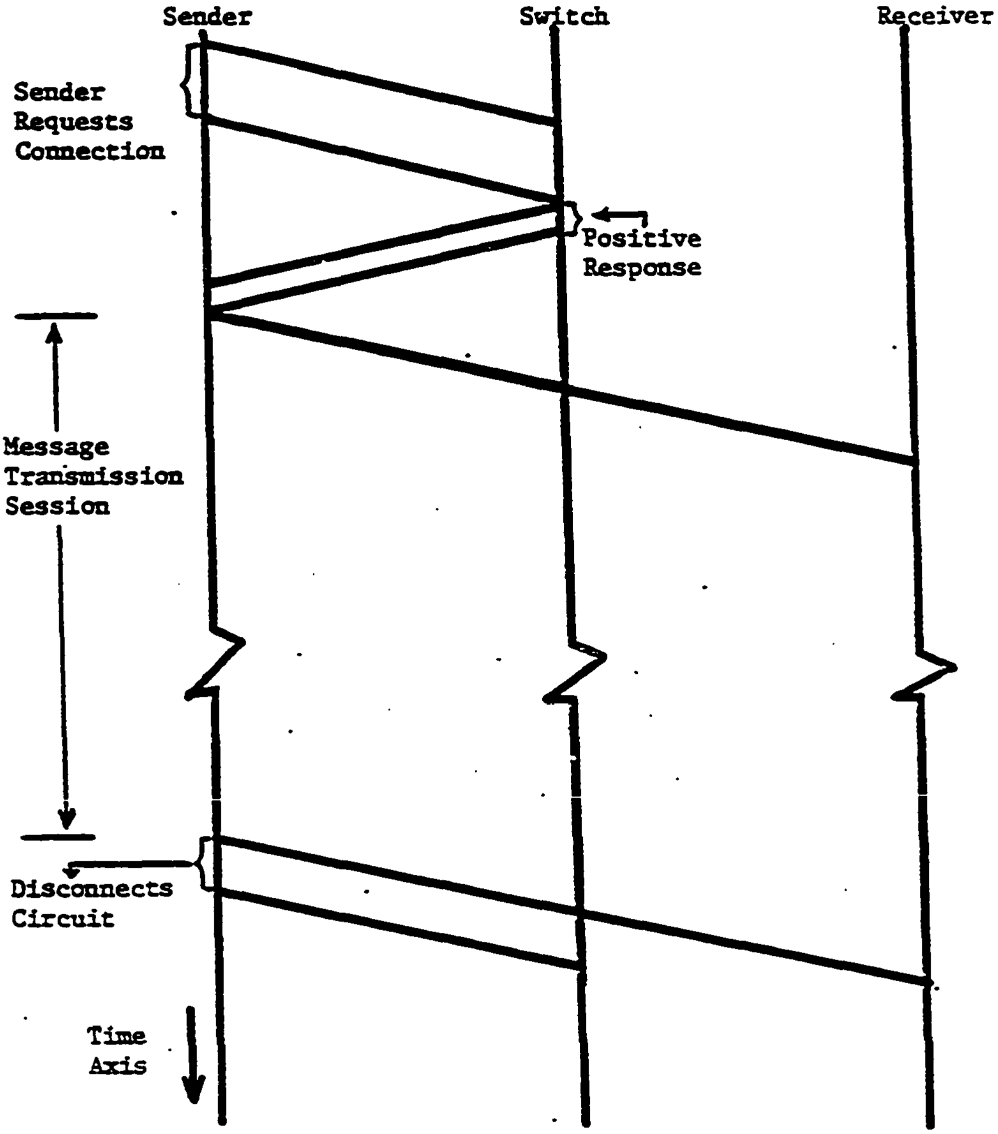

Sender
Switch
Receiver
Sender Requests Connection
Positive Response
Message Transmission Session
Disconnects Circuit
Time Axis

Figure 16. PBX access scheme

from the source to the switch, the switch will then disconnect the circuit.

Thesis Outline

Chapter I introduces this paper. Chapter II presents a survey of the literature dealing with performance analysis of the CSMA-CD and token passing types of protocols. Chapter III details the development of models for performance analysis of CSMA-CD, token passing bus, token passing ring, and PBX type networks. Chapter IV consists of a description of the programming structure of the software tool that is applied in Chapter V for performance evaluation of actual networks in two different scales of actual networking environments:

1. the networking of nodes in a single building.
2. the networking of nodes on a university campus.

Selected networks used in the performance evaluation are those that are representatives of their type. They are: Ethernet (CSMA-CD), Arcnet (token passing bus), Ringnet (token passing ring), and CBX (PBX). In Chapter VI, the analytical results of network performance among the various selected networks are compared. Discussion on the validity of the developed analytical models are included. Comments, recommendations, and the conclusion of this study are presented in Chapter VII. Description of the procedures for using the software, as well as explanation of terms and queries the software uses, are detailed in Appendix A. Flow charts describing the logical structuring of the computer programs are presented in Appendix B. A simulation program of a token passing network following the byte service scheme is presented in Appendix C.

CHAPTER II. LITERATURE REVIEW

Some of the modeling and analysis work in this dissertation has been borrowed from and built on the analytical models of others. A survey of this previous work is presented in this chapter.

CSMA-CD Models

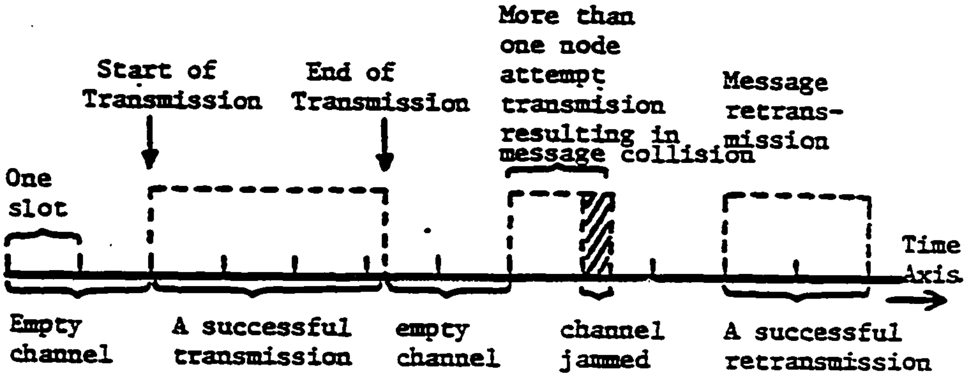
In one of the earliest efforts, Kleinrock and Tobagi [6], [7] studied the performance of the CSMA type of protocols. Their concerns are in analyzing how long a packet will have to wait in a node's buffer before being successfully transmitted under different packet arrival rates (loads). Also, they investigated the effects increasing message load have on network throughput (the percentage of time a CSMA network is involved in successful transmission of user packets). In a later study, Tobagi and Hunt [8] added collision detection to CSMA. Collision detection is a feature through which the source knows of the collision of its message with messages send by other sources soon after the collision occurs. Their analytical results clearly show that for the same amount of message load, CSMA-CD has higher channel throughput than that of CSMA. Also, the average waiting time of packets (queueing delay) in the buffer of a CSMA-CD node is shorter than that of the most efficient CSMA. This fact was further verified by LaBarre [9], whose simulation studies demonstrated that CSMA-CD has a queueing delay less than half that of the CSMA for moderate and high message loads. Under separate investigation, Lam [10] conducted performance analysis of CSMA-CD. His model was derived under the assumption that the system is stabilized by using a suitable adaptive algorithm. Like Tobagi and Hunt's model, a slotted channel (the slotting of the transmission channel in time into small intervals (Figure 17a), that synchronizes all node activities on the network, such that the start of any transmission has to be at the beginning of a slot) was assumed by Lam to ensure analytical tractability. However, this unnatural discretization of the time scale causes some small distortions in the results.

Heyman [11] modeled CSMA-CD using the M/D/1/K type queueing model. The use of the parameter K in specifing the maximum number of packets that may be in the system is deemed necessary by Heyman to ensure that proper limiting probabilities exist. For his model the transmission time of a packet is chosen as the time unit. In his derivations, the channel is not slotted (Figure 17b) in time (such that a transmission can start at anytime on an empty channel). Heyman modeled the channel as a single server serving all connecting nodes for a constant service time. The use of constant service time reflects the assumption that all packets have the same length. In Heyman's model, a Poisson packet arrival process is assumed. Under steady state conditions, all accepted packets eventually depart and the number of packets present in the system is no larger than K. Therefore, the average throughput of the system, θ, is

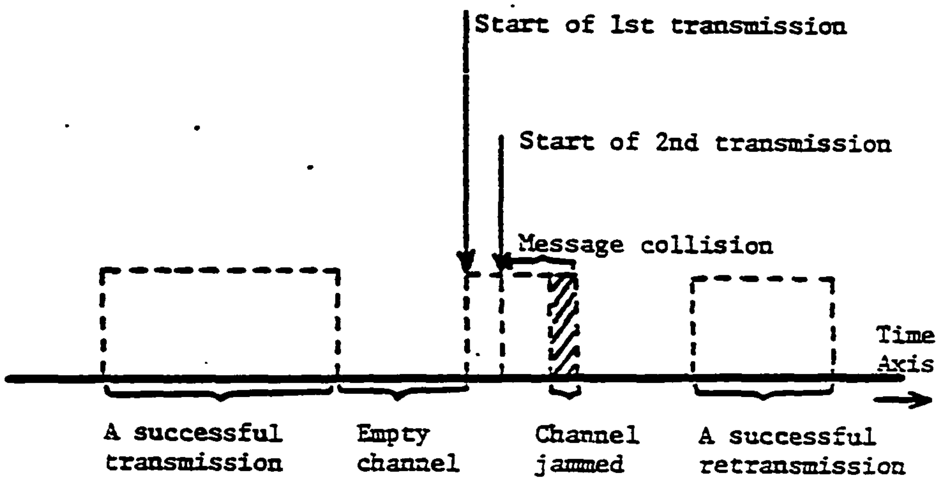
$$\theta = \lambda_{system} \sum_{i=0}^{k-1} P_i \qquad (2)$$

where, λ_{system} is the average arrival rate of packets to the system.

P_i is the probability that i packets are in the system at any given time.


More than one node attempt transmision resulting in message collision
Start of Transmission
End of Transmission
Message retrans-mission
One slot
Time Axis
Empty channel
A successful transmission
empty channel
channel jammed
A successful retransmission

a. Slotted channel


Start of 1st transmission
Start of 2nd transmission
Message collision
Time Axis
A successful transmission
Empty channel
Channel jammed
A successful retransmission

b. Unslotted channel

Figure 17. Slotted and unslotted channels

The average number of packets waiting for transmission is

$$L' = \sum_{i=2}^{k} (i - 1) P_i \qquad (3)$$

Since θ is also the asymptotic rate at which packets are accepted into the system, Little's theorem [12] yields

$$W = L'/\theta \qquad (4)$$

where W is the normalized average waiting time of a packet in the system.

To obtain P_i, Heyman embedded a discrete Markov chain at packet "ejection" epochs (Figure 18). This epoch may be the end of a successful transmission where the packet leaves the system or it may be the end of a collided transmission where the packet rejoins the queue. Doing it this way, analytical tractability is maintained without the unnatural slotting of the channel. Since the actual CSMA-CD systems are unslotted, an unslotted CSMA-CD model should provide better estimates of the average waiting time of a packet in the actual system than that computed with a slotted model. However, the use of the parameter K in Heyman's model means that packets arriving after the system is full (with K packets already in the system), will be cleared and lost. Therefore, in using Heyman's model, an appropriate value for K will have to be chosen, such that the probability of having K packets in the system is almost zero ($P_k \approx 0$).

Arthur's and Stuck's [13] slotted CSMA-CD model for computing the upper bound on packet delay can be used for finding the network

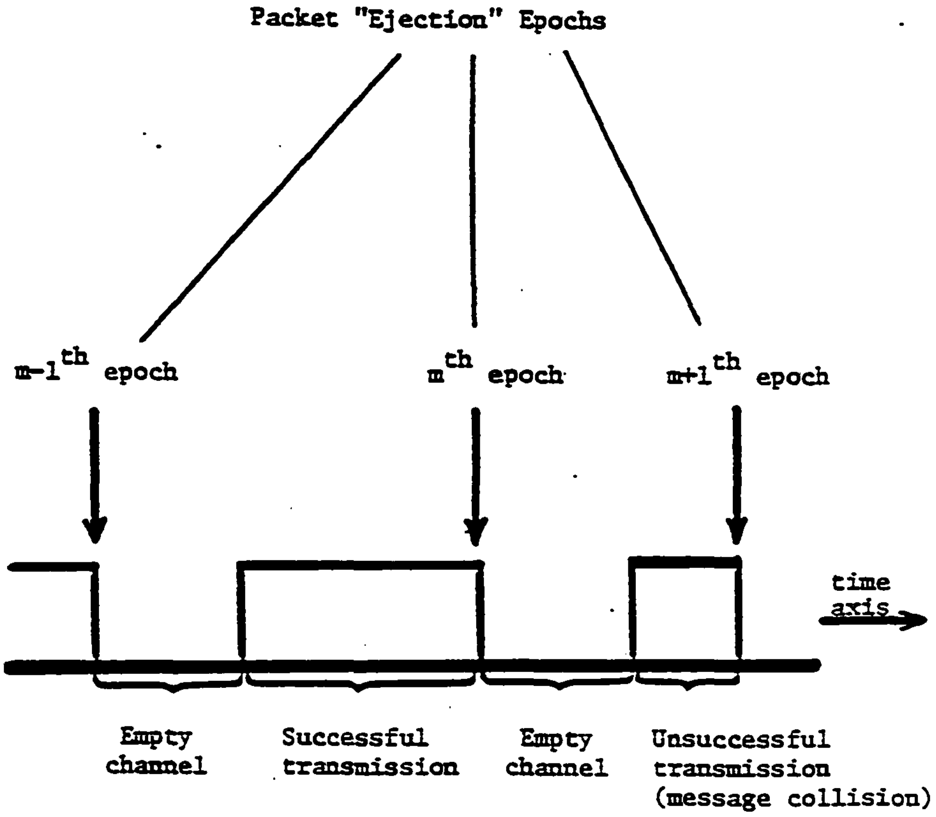

Packet "Ejection" Epochs
m-1th epoch
mth epoch
m+1th epoch
time axis
Empty channel
Successful transmission
Empty channel
Unsuccessful transmission (message collision)

Figure 18. Packet "Ejection" epochs

saturation condition. They have shown in their paper that in order for a network to maintain statistical equilibrium

$$\lambda_{node} \leq 1 \; / \; E(\bar{T}_{message}) \tag{5}$$

where λ_{node} is the mean of an exponentially distributed arrival rate of packets to a node. With

$$E(\bar{T}_{message}) = N \, T_{packet} + \frac{2\tau(1 - N\,Q_N)}{Q_N} \tag{6}$$

where,

$$Q_N = (1/N)(1-(1/N))^{N-1} \tag{7}$$

N is the number of nodes connecting to the network, T_{packet} is the packet transmission time, and τ is the worst case, one-way signal propagation time through the network. The network saturates when the average packet rate per node reaches

$$\lambda_{node} = 1 \; / \; E(\bar{T}_{message}) \tag{8}$$

Also, for N >>1, the network saturates at

$$N = 1/(T_{packet} + 2\tau(e-1))\lambda_{node} \tag{9}$$

Token Passing Models

Two major disciplines can be distinguished with respect to the service policy of token passing networks. They are the exhaustive service discipline (for networks following the byte scheme), and the non-exhaustive service discipline (for networks following the packet scheme). A token passing network following the exhaustive service discipline allows the node possessing the control token to transmit all data messages stored in its output buffer as well as those data which arrive during the transmission process. On the other hand, a token passing network following the non-exhaustive service discipline only allows the node possessing the control token to transmit at most one data packet per access to the network.

The performance of exhaustive service networks has been analyzed by Konheim and Meister [14] under the assumption of equal message arrival rates to all nodes and equal token passing delays. In their model, arrival process of the data messages is assumed to be Poisson and each node is assumed to have infinite storage spaces for data. However, the discrete-time (slotted) assumption used in the model causes distortion in results. Cheng [15] extended the study of Konheim and Meister, and derived a non-discrete time (unslotted) model for computing average message delay and network saturation condition. The model Cheng developed for the non-exhaustive service discipline form the basis for this analysis of token passing network performance.

In Cheng's model, the arrival of message transmission requests at different nodes are assumed to be statistically independent. Within each node, the arrival process of messages is assumed to be Poisson and each node contains infinite buffer spaces. A loop network containing N nodes is modeled as a multiqueue system with the channel envisioned as a server (Figure 19). The server serves the N queues in cyclic order.

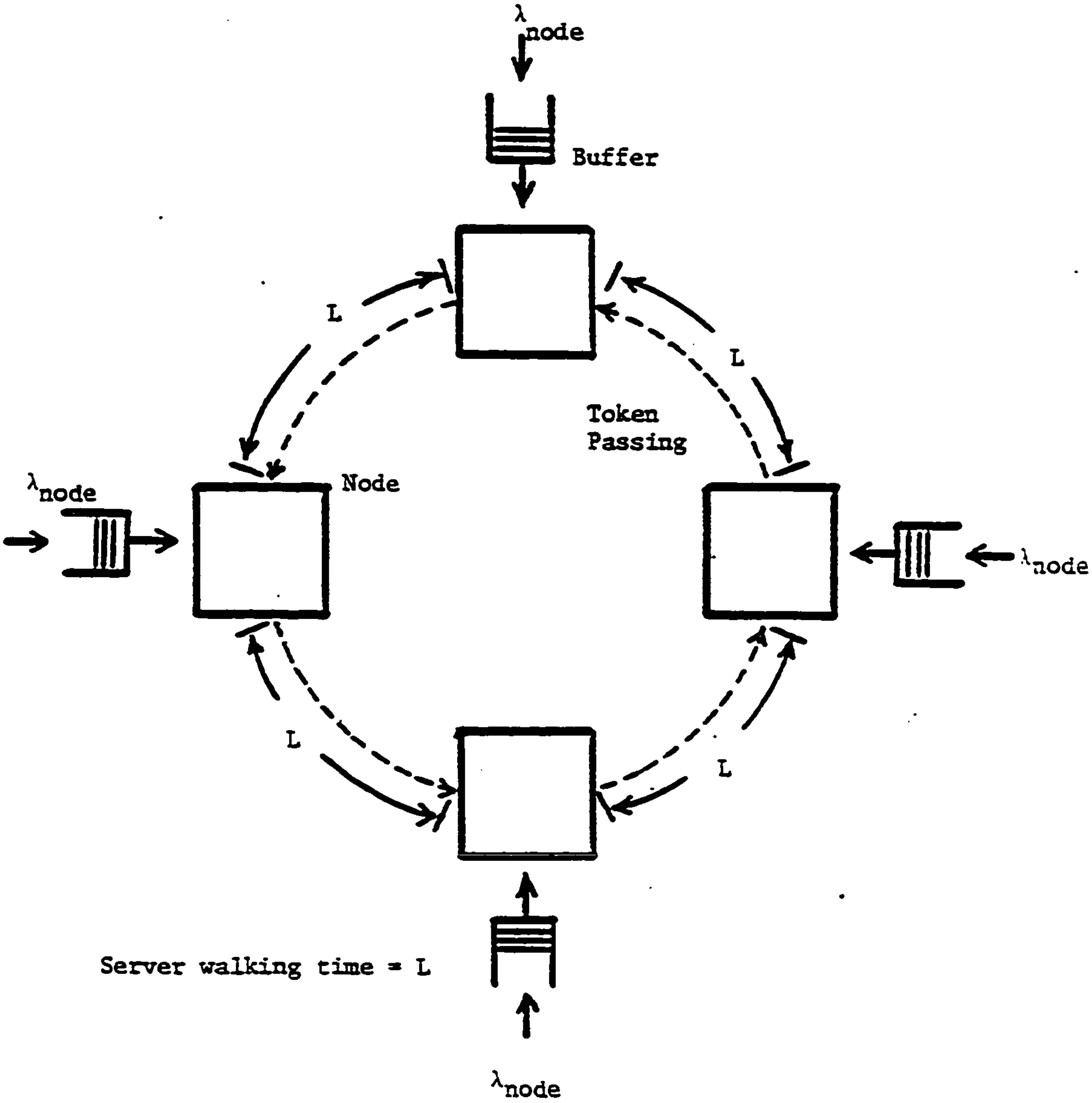

λ_{node}
Buffer
L
L
Token Passing
λ_{node}
Node
λ_{node}
L
L
Server walking time = L
λ_{node}

Figure 19. Token passing network queueing model

The service time is equal to the time interval during which the control token is held up by a node. Because of propagation delay between nodes and the delay inside the nodes, the token passing process will take some finite amount of time. This feature of passing control between nodes is modeled as a server taking a non-zero amount of time to move from one queue to another. Cheng referred to this control passing time as the server walking time between the queues.

In Cheng's analysis for a non-exhaustive service token passing network, the server leaves a queue immediately if the queue is found empty. If the queue is non-empty, one packet from the top of the queue will be transmitted.

The non-exhaustive model developed by Cheng for computing the mean message waiting time in queue is

$$W = \frac{1}{2}\left[\frac{NL\,(1-\rho)}{1-\lambda_{node}NL-N\rho} + \frac{N\lambda_{node}S^2}{1-\lambda_{node}NL-N\rho}\right] \qquad (10)$$

where L is the server walking time, S is the message transmission time (a message can be of arbitrary length), λ_{node} is the mean arrival rate of messages to each node and $\rho = \lambda_{node} S$. The first term in the right hand side of Equation 10 can be interpreted as the average time required for the server to reach the queue where the request to be served next waits. This period of time is equal to one half of the refractory period on the average (the refractory period is the time interval between the instant the server leaves a queue to the instant the server revisits that same queue). The second term of the expression is the mean waiting time in queue. Cheng verified the accuracy of his analytical model with results obtained from simulation studies. He found his model accurately predicted the mean message waiting time in queue.

The saturation condition can be derived from Equations 10. For a non-exhaustive service network, the network saturates at

$$1 - \lambda_{node} N L - N\rho = 0 \qquad (11)$$

Heyman's CSMA-CD model and Cheng's token passing model will be expanded in the next chapter.

CHAPTER III. ANALYTICAL MODELING

In this chapter, analytical models used in the performance analysis of LANs are described. The first section lists the assumptions used in developing the models, and subsequent sections detail their development. These models are later used in creating a software tool (to be described in the next chapter) for the performance evaluation and comparison of LANs.

Modeling Assumptions

1. The network is homogeneous. All nodes connected to the network have the same properties and the same message load.
2. All users of a node have the same average message load.
3. All nodes of the network have the same number of users.
4. The interarrival time of messages from a user to their respective queue in a node follows the exponential distribution.
5. Time of message arrival to individual sending queues (output buffers) are statistically independent.
6. For networks following the packet service discipline, all packets are assumed to be of the same length.
7. A node cannot transmit more than one packet each time it has access to the medium.
8. All models developed assume steady-state operation.
9. All nodes have equal (non-prioritized) access to the network.
10. The transmitting node cannot be the destination of its own

messages.

11. All transient events such as lost token, network reconfiguration, transmission error and recovery etc. are of rare occurrence and are excluded from the analysis.

Analytical Models of Maximum Achievable Data Rate Per Node

The node data rate is the average rate in bits per second at which a node can transmit useful user data bits. This analysis on maximum achievable data rate per node provides estimates on the average amount of user information a node can send per unit time when the use of the network is optimized.

For the various network access schemes, the maximum achievable data rate per node, R_{node}, is the product of the maximum number of packets a node can send per second (when the use of the network is optimized), and the user data size of each packet. Thus,

$$R_{node} = R_{packet}\, b_{data} \tag{12}$$

where,

R_{packet} is the maximum packet rate per node (in packets/second).

b_{data} is the number of user data bits per packet.

Using the assumption of equal user message load for all nodes, the use of the network is optimized if all nodes transmit at the maximum packet rate possible (with no idle time on the medium). Since there are transmission overheads (such as the transmission of packet control information, token passing, or message collision and their recovery), the effective network throughput is less than 100 percent of the vendor quoted network data rate.

When the use of the network is optimized among all nodes, the maximum packet rate per node will then be the reciprocal of the network cycle time, T_{cycle}, which is the total elapsed time for all nodes of the network to transmit one packet plus all intervened token passing or message collision recovery time between successful transmissions (Figure 20). Thus,

$$R_{packet} = \frac{1}{T_{cycle}} \tag{13}$$

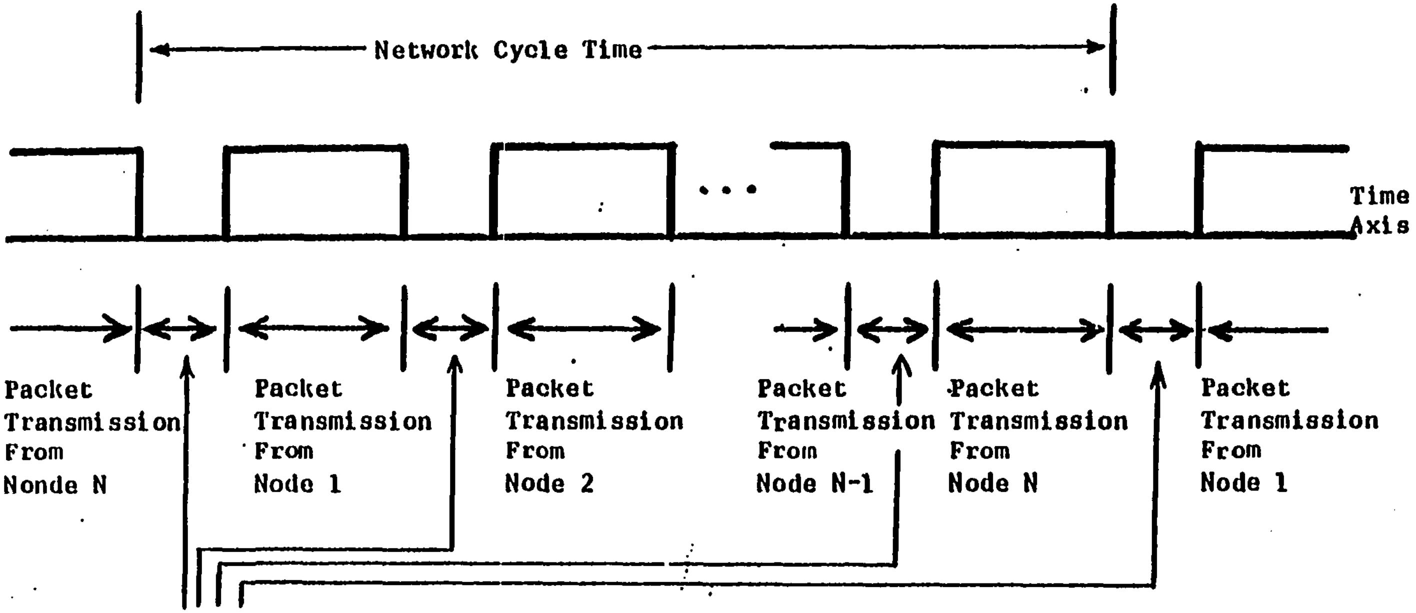
CSMA-CD

When the use of the network is optimized, the network cycle time of a CSMA-CD network (Figure 21) consists of: the total amount of time for all nodes to each successfully transmit one packet; plus all the message contention and collision recovery time after each successful transmission in that cycle. So,

$$T_{cycle} = N_{nodes}(T_{tran} + T_{contention}) \tag{14}$$

where,

N_{nodes}	is the number of nodes connected to the network.
T_{tran}	is the total amount of time involved in the successful transmission of a packet to the message receiver.
$T_{contention}$	is the sum of all the message contention and collision recovery time after each successful transmission in a network transmission cycle.


Network Cycle Time
Time Axis
Packet Transmission From Nonde N
Packet Transmission From Node 1
Packet Transmission From Node 2
Packet Transmission From Node N-1
Packet Transmission From Node N
Packet Transmission From Node 1

Transients: token passing, unsuccessful transmission, message collisions, collision recoveries, etc.

Figure 20. Network cycle time

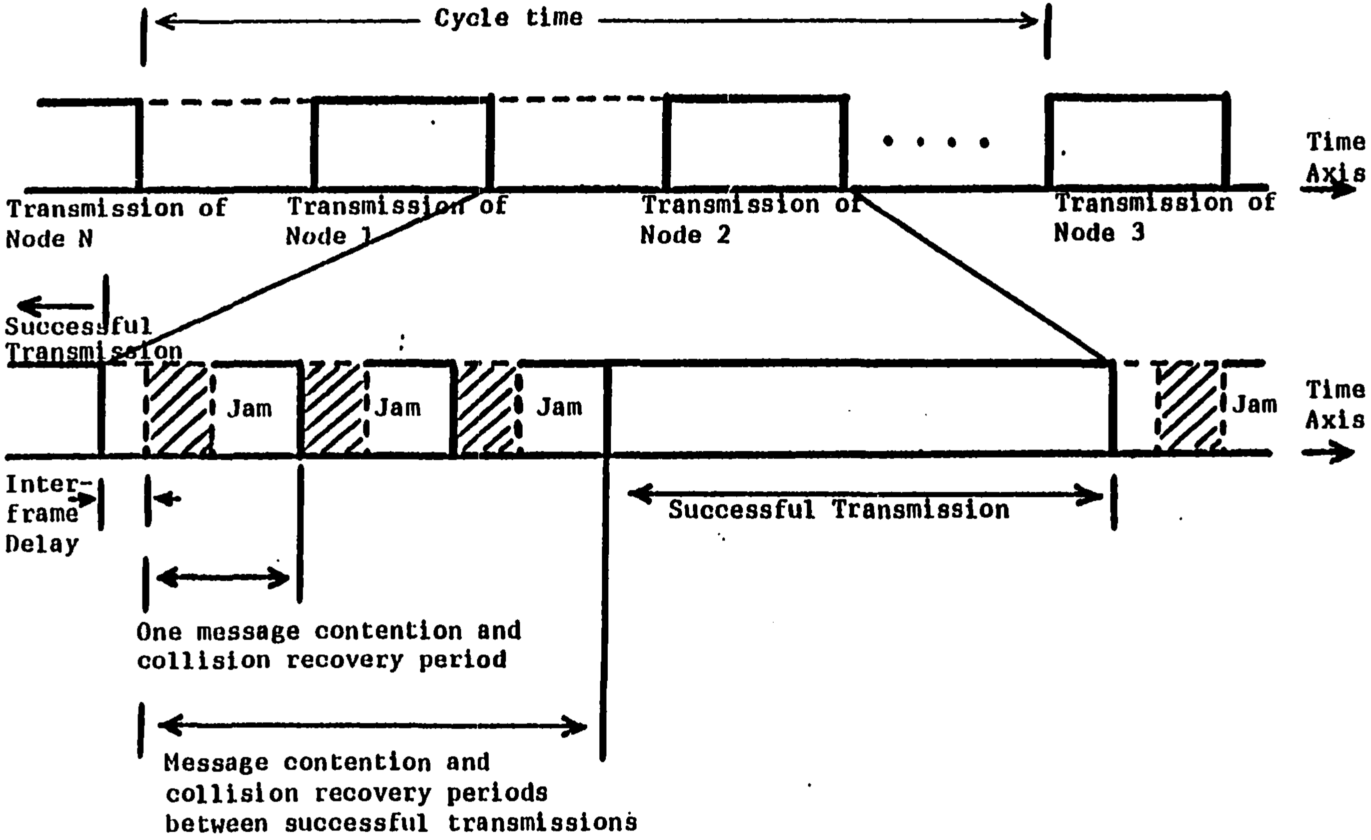

Cycle time
Time Axis
Transmission of Node N
Transmission of Node 1
Transmission of Node 2
Transmission of Node 3
Successful Transmission
Jam
Jam
Jam
Jam
Time Axis
Inter-frame Delay
Successful Transmission
One message contention and collision recovery period
Message contention and collision recovery periods between successful transmissions

Figure 21. Network cycle time of CSMA-DC networks

T_{tran} involves the interframe delay, $T_{interframe}$, plus the actual transmission time of a packet, T_{packet}, plus the average signal propagation delay, T_{prop}, for the signal to go from the message sending node to its destination node; plus the average signal regeneration delay, T_{retran}, the message encounters in passing through repeaters on its way to the destination. Thus,

$$T_{tran} = T_{packet} + T_{prop} + T_{retran} + T_{interframe} \tag{15}$$

The interframe delay, $T_{interframe}$, is as specified by the vendor for its network. The actual packet transmission time, T_{packet}, is the total amount of time the message sending node spends in transmitting packet overhead bits and user data bits. Also, packets transmitted on CSMA-CD networks have to exceed a certain minimum packet length, so as to guarantee that the message transmitting node can detect any message collision that might occur before it completes transmitting its packet. This means that for packets that are shorter than the specified minimum length, filling bits will have to be transmitted. Therefore, the packet size for each packet is the larger of: the packet control bits plus any spacing bits (that may exist behind each byte of user data) plus user data bits; and the minimum specified packet size. The total number of spacing bits per packet is the multiple of the number of user bytes times the number of spacing bits behind each byte. So,

the total number of spacing bits per packet $= (1/8)b_{data}b_{space}$.

The transmission time of a packet is the packet length (in bits) divided by the network data rate (in bits per second), thus

$$T_{packet} = \mathrm{Max}\left[\frac{b_{min}}{R_{network}} , \frac{b_{control} + (\frac{1}{8} b_{data} b_{space}) + b_{data}}{R_{network}} \right] \tag{16}$$

where,

$R_{network}$	is the network data rate.
b_{min}	is the minimum packet length.
$b_{control}$	is the number of packet control bits.
b_{data}	is the number of user data bits.
b_{space}	is the number of spacing bits behind each byte of user data.

The average signal propagation delay between the message sending node and the receiving node is the average message transmission distance divided by the signal velocity. Thus,

$$T_{prop} = \frac{L_{tran}}{V_{prop}} \tag{17}$$

where,

L_{tran}	is the average message transmission distance.
V_{prop}	is the velocity of the signal.

The average signal regeneration delay is the product of the average number of repeaters a packet will encounter in going from the packet sending node to the receiving node, $N_{repeaters}$, and the interfacing delay at a repeater, $T_{repeater}$. Thus,

$$T_{retran} = N_{repeaters} T_{repeater} \tag{18}$$

The average duration of one message contention and collision recovery time period consists of: T_{detect} (the average elapsed time starting at the instant a node begins its transmission right after the brief interframe delay, to the instant when all contending nodes detected a message collision on their packets), and T_{jam} (the collision enforcement time). On the average, the transmission of a node collides with the transmission of another node (in a message collision period) when the leading signal is 3/4 of the way to its destination. It will then take double that time before the colliding signals propagate back to the transmitting node. Therefore, the average elapsed time of a message collision is 3/2 times the average signal propagation delay. Thus, the value of T_{detect} is,

$$T_{detect} = \frac{3}{2} \left(\frac{L_{tran}}{V_{prop}} + T_{retran}\right) \tag{19}$$

T_{jam} is as specified by the vendor for their network. The equation derived by Metcalfe and Boggs [1] for computing the average number of message collisions, $N_{collisions}$, between consecutive successful transmissions on a saturated network is,

$$N_{collisions} = \frac{(1 - A)}{A}$$

where,

$$A = \left(1 - \left(\frac{1}{N_{nodes}}\right)\right)^{N_{nodes}-1} \tag{20}$$

Using Equations 19 and 20, the average duration for one message contention and collision recovery time period is,

$$T_{contention} = N_{collisions}(T_{detect} + \{T_{jam}) \tag{21}$$

where,

$T_{contention}$ is the average message contention and collision resolution time between successful transmissions.

Therefore, using Equations 12-21, the maximum achieveable node data rate, for nodes of a CSMA-CD network, is

$$R_{node} = \frac{b_{data}}{N_{nodes}(T_{tran} + T_{contention})} \tag{22}$$

Also, the maximum achieveable user data rate is,

$$R_{user} = \frac{R_{node}}{N_{users}} \tag{23}$$

Token passing bus

When the use of the network is optimized, the network cycle time of a token passing bus network consists of: the total time spent by all nodes to transmit one packet; plus all intervening token passing time between transmissions. So,

$$T_{cycle} = N_{nodes}(T_{tran} + T_{token}) \tag{24}$$

where,

T_{token} is the average token passing delay.

The average elapsed time involved in transmitting one packet, T_{tran}, consists of: the average transmission set-up time, T_{set}; plus the average elapsed time involved in the transmission of one packet, T_{packet}; plus the average packet acknowledging delay, T_{ack}. Thus,

$$T_{tran} = T_{set} + T_{packet} + T_{ack} \tag{25}$$

The average transmission set-up delay consists of: delays incurred in transmitting the set-up (free buffer enquiry) packet to the receiver; plus the average amount of time the packet sending node spent waiting for a response from the receiver. So,

$$T_{set} = 2(T_{prop} + T_{retran}) + \frac{b_{set} + b_{ack}}{R_{network}} \tag{26}$$

where,

b_{set} is the number of bits in the set-up packet.

b_{ack} is the number of bits in the acknowledgment packet.

T_{prop} is obtained using Equation 17.

The average elapsed time involved in the transmission of one packet consists of: the total amount of time the message sending node spent in transmitting packet overhead bits and user data bits; plus the average signal propagation delay from the message sending node to the receiving node, T_{prop}; plus average repeaters signal retransmission delays, T_{retran}, between packet sender and receiver. Thus,

$$T_{packet} = \frac{b_{control} + (\frac{1}{8}\, b_{data} b_{space}) + b_{data}}{R_{network}} + T_{prop} + T_{retran} \tag{27}$$

The average packet acknowledging delay is the sum of the acknowledgment packet transmission time; plus the average signal propagation delays the acknowledgment encounters in going from the message receiving node back to the sending node. Thus,

$$T_{ack} = \frac{b_{ack}}{R_{network}} + T_{prop} + T_{retran} \tag{28}$$

The average token passing time consists of: the transmission time of the token packet; plus the average signal propagation delays incurred by the token in going from the token passing node to the destination node; plus the interface delay, $T_{interface}$, the destination spends in detecting its token; plus the buffer checking time, $T_{buffchk}$, the token holding node spends checking its buffer for ready messages. Therefore,

$$T_{token} = \frac{b_{token}}{R_{network}} + T_{passprop} + T_{passretran} + T_{interface} + T_{buffchk} \tag{29}$$

$$T_{passprop} = \frac{L_{pass}}{V_{prop}} \tag{30}$$

$$T_{passretran} = N_{passrepeaters}\ T_{repeater} \tag{31}$$

where,

b_{token}	is the number of bits in a token packet.
$N_{passrepeaters}$	is the average number of repeaters a token encountered in the token passing process.

Thus, using Equations 12, 13, and 24-31, the maximum achievable node data rate, for nodes of a token passing bus network, is

$$R_{node} = \frac{b_{data}}{N_{nodes}(T_{tran} + T_{token})} \qquad (32)$$

Also, using Equation 23, R_{user} can be obtained.

Token passing ring

When the use of a network is optimized, the network cycle time of a token passing ring network can also be obtained using Equation 24. However, if the message transmitting node finishes its transmission before the physical header of its packet (which contains the busy token) propagated back to its input port, the node will keep transmitting filling bits to avoid the possibility of having multiple tokens on the ring at any given time. Upon detecting its own busy token, and upon completing its transmission, a node will then pass a free token to its adjacent token receiving node. Therefore, the total transmission time involved in transmitting one packet is the larger of the: average propagation delays of the packet header around the ring, plus the time needed to recover the token; and the actual transmission time of the packet, T_{packet}. So,

$$T_{tran} = \text{Max}[T_{propnet}, T_{packet}] \qquad (33)$$

with,

$$T_{propnet} = \frac{L_{ring}}{V_{prop}} + N_{nodes}T_{interface} + \left(\frac{L_{ring}\ N_{repeaters}\ T_{repeater}}{L_{tran}}\right) + T_{copy} + \frac{b_{token}}{R_{network}} \qquad (34)$$

where,

L_{ring} is the ring length.

$T_{interface}$ is the packet interface delay incurred in passing through an intervening node.

T_{copy} is the interface delay incurred by the message receiver.

The actual transmission time of a packet consists of the: transmission time of packet control bits; plus the transmission time of user data bits; plus the transmission time of any spacing bits, b_{space}, that may exist behind each byte of user data. So,

$$T_{packet} = \frac{b_{control} + (\frac{1}{8} b_{data} b_{space}) + b_{data}}{R_{network}} \qquad (35)$$

The average token passing delay of a token ring can be computed using Equations 29-31. Using Equations 12, 13, 29-31, and 33-35, the maximum achieveable node data rate, for nodes of a token passing ring network, is

$$R_{node} = \frac{b_{data}}{N_{nodes}(Max[T_{propnet}, T_{packet}] + T_{token})} \qquad (36)$$

Also, using Equation 23, R_{user} can be obtained.

PBX

For a PBX network, the data rate per station is specified by the vendor. When

$N_{stations} \leq$ maximum number of stations specified,

$$R_{station} = \text{constant} \qquad (37a)$$

when

$N_{stations} >$ maximum number of stations specified,

$$R_{station} = 0 \tag{37b}$$

Analytical Models on Average Message Delay

Average message delay, $D_{message}$, is a measure of the average queueing delay and average message delivery delay in a successful transmission. So,

$$D_{message} = T_{queue} + T_{delivery} \tag{38}$$

where,

T_{queue}	is the average message queueing delay.
$T_{delivery}$	is the average message delivery delay from sender to receiver.

CSMA-CD

For a CSMA-CD network, T_{queue} can be computed using Heyman's model. Since Heyman uses the packet transmission time as the time unit, his derived average waiting time in queue, W, is normalized with respect to T_{packet}. Thus,

$$T_{queue} = WT_{packet} \tag{39}$$

W	is obtained using Equation 4.
T_{packet}	is obtained using Equation 16.

$T_{delivery}$ is the sum of the average signal propagation delay and the average repeaters signal regeneration delays the packet incurred on its way from the message sending node to the receiving node. So,

$$T_{delivery} = T_{prop} + T_{retran} \tag{40}$$

Substituting Equations 39 and 40 into Equation 38, the average message delay for a CSMA-CD network is,

$$D_{message} = WT_{packet} + T_{prop} + T_{retran} \tag{41}$$

Token passing bus .

For a token passing network, either the packet or the byte service scheme is followed. For token passing bus networks following the packet service scheme, Cheng's non-exhaustive service discipline model on mean message waiting time in queue is used in computing T_{queue}. Also, similar to the CSMA-CD networks, $T_{delivery}$ is the sum of the average signal propagation delay and the average repeaters signal regeneration delays the packet incurred in going from the message transmitting node to the receiving node. So, using Equation 38,

$$D_{message} = W + T_{prop} + T_{retran} \tag{42}$$

where, W is obtained using Equation 10.

In using Equation 10, the parameter L is the average token passing time obtained using Equation 29. The parameter S (the average elapsed time involved in transmitting one packet) is obtained using Equations 25-28. The parameter λ_{node} is the average user packet rate (in packets per second) to a node.

For a token passing bus network following the byte service scheme, a non-empty node will transmit all bytes that are in one of its queues when it has access to the network. So, the average message waiting time in queue is,

$$T_{queue} = \frac{T_{rotation}}{2} \qquad (43)$$

where,

$T_{rotation}$ is the average elapsed time between a queue's turn to transmit.

When a node has access to the medium, it may or may not have a message to transmit. Therefore, the elapsed time between a queue's turn to transmit, $t_{rotation}$, is

$$N_{nodes}T_{token} \leq t_{rotation} \leq N_{users}(N_{nodes}T_{token}) + (N_{users}N_{nodes}-1)T_{tran} \qquad (44)$$

The average elapsed time between a queue's turn to transmit,

$$T_{rotation} = \sum_{t_{rotation} = N_{nodes}T_{token}}^{N_{users}(N_{nodes}T_{token})+(N_{users}N_{nodes}-1)T_{tran}} ((t_{rotation})\ P(t_{rotation}))$$

$$= (t_{rotation} = N_{nodes}T_{token})\ P(t_{rotation} = N_{nodes}T_{token}) + (t_{rotation} = N_{nodes}T_{token}+T_{tran})\ P(t_{rotation} = N_{nodes}T_{token}+T_{tran}) + (t_{rotation} = N_{nodes}T_{token}+2T_{tran})\ P(t_{rotation} = N_{nodes}T_{token}+2T_{tran}) + \cdots + (t_{rotation} = N_{nodes}T_{token}+(N_{nodes}-1)T_{tran})\ P(t_{rotation} = N_{nodes}T_{token}+(N_{nodes}-1)T_{tran}) + (t_{rotation} = 2N_{nodes}T_{token}+T_{tran})\ P(t_{rotation} = 2N_{nodes}T_{token}+T_{tran}) + (t_{rotation} = 2N_{nodes}T_{token}+2T_{tran})\ P(t_{rotation} = 2N_{nodes}T_{token}+2T_{tran}) + \cdots +$$

$$(t_{rotation}= N_{users}(N_{nodes}T_{token})+(N_{users}N_{nodes}-1)T_{tran})$$

$$P(t_{rotation}= N_{users}(N_{nodes}T_{token})+(N_{users}N_{nodes}-1)T_{tran}) \tag{45}$$

For a queue receiving user bytes at a Poisson rate of λ_{user}, the probability that it has one or more bytes when its turn to transmit occurs is:

$$P(user)= 1-e^{-\lambda_{user}t_{rotation}} \tag{46}$$

where,

P(user) is the probability that a queue is not empty when its turn to transmit occurs.

The following is a list of the various $t_{rotation}$ values and their probabilities:

$t_{rotation}$	$P(t_{rotation})$
$N_{nodes}T_{token}$	$(1-P(user))^{N_{users}(N_{nodes}-1)} (1-P(user))^{N_{users}-1}$
$N_{nodes}T_{token}+T_{tran}$	$N_{nodes}-1 \; ^{C} \; N_{nodes}-2$ $(1-P(user))^{N_{users}(N_{nodes}-2)} (1-(1-P(user))^{N_{users}})(1-P(user))^{N_{users}-1}$
$N_{nodes}T_{token}+2T_{tran}$	$N_{nodes}-1 \; ^{C} \; N_{nodes}-3$ $(1-P(user))^{N_{users}(N_{nodes}-3)} (1-(1-P(user))^{N_{users}})^{2} (1-P(user))^{N_{users}-1}$
⋮	⋮

$N_{nodes}T_{token}+(N_{nodes}-1)T_{tran}$	$(1-(1-P(user))^{N_{users}})^{N_{nodes}-1}$ $(1-P(user))^{N_{users}-1}$
$2N_{nodes}T_{token}+T_{tran}$	$(1-P(user))^{N_{users}(2N_{nodes}-2)}$ ${}_{N_{users}-1}C_{N_{users}-2}\,(1-P(user))^{N_{users}-2}\,P(user)$
$2N_{nodes}T_{token}+2T_{tran}$	${}_{2N_{nodes}-2}C_{2N_{nodes}-3}\,(1-P(user))^{N_{users}(2N_{nodes}-3)}$ $(1-(1-P(user))^{N_{users}})$ ${}_{N_{users}-1}C_{N_{users}-2}\,(1-P(user))^{N_{users}-2}\,P(user)$
$\vdots$	$\vdots$

By substituting the above $t_{rotation}$ values and their probabilities into equations 45, the average elapsed time between a queue's turn to transmit is,

$$T_{rotation}=(N_{nodes}T_{token})(1-P(user))^{N_{users}(N_{nodes}-1)}(1-P(user))^{N_{users}-1}$$
$$+(N_{nodes}T_{token}+T_{tran})\ {}_{N_{nodes}-1}C_{N_{nodes}-2}\,(1-P(user))^{N_{users}(N_{nodes}-2)}(1-(1-P(user))^{N_{users}})$$
$$(1-P(user))^{N_{users}-1}\ +(N_{nodes}T_{token}+2T_{tran})\ {}_{N_{nodes}-1}C_{N_{nodes}-3}\,(1-P(user))^{N_{users}(N_{nodes}-3)}$$
$$(1-(1-P(user))^{N_{users}})^{2}\,(1-P(user))^{N_{users}-1})+\cdots+$$
$$(N_{nodes}T_{token}+(N_{nodes}-1)T_{tran})$$

$$((1-(1-P(user))^{N_{users}})^{N_{nodes}-1}(1-P(user))^{N_{users}-1})+$$

$$(2N_{nodes}T_{token}+T_{tran})(1-P(user))^{N_{users}(2N_{nodes}-2)}$$

$${}_{N_{users}-1}C_{N_{users}-2}\,(1-P(user))^{N_{users}-2}P(user)+$$

$$(2N_{nodes}T_{token}+2T_{tran})\;{}_{2N_{nodes}-2}C_{2N_{nodes}-3}$$

$$(1-P(user))^{N_{users}(2N_{nodes}-3)}(1-(1-P(user))^{N_{users}})$$

$${}_{N_{users}-1}C_{N_{users}-2}\,(1-P(user))^{N_{users}-2}P(user)+\cdots$$

$$=\sum_{X=1}^{N_{users}}\;\sum_{Y=X-1}^{XN_{nodes}-1}[(XN_{nodes}T_{token}+YT_{tran})$$

$${}_{X(N_{nodes}-1)}C_{XN_{nodes}-(Y+1)}\,(1-P(user))^{N_{users}(XN_{nodes}-(Y+1))}$$

$$(1-(1-P(user))^{N_{users}})^{Y}\;{}_{N_{users}-1}C_{N_{users}-X}$$

$$(1-P(user))^{N_{users}-X}P(user)^{X-1}] \qquad (47a)$$

Substituting Equation 46 into 47a,

$$T_{rotation}=\sum_{X=1}^{N_{users}}\;\sum_{Y=X-1}^{XN_{nodes}-1}[(XN_{nodes}T_{token}+YT_{tran})$$

$${}_{X(N_{nodes}-1)}C_{XN_{nodes}-(Y+1)}$$

$$(e^{-\lambda_{user}(XN_{nodes}T_{token}+YT_{tran})})^{N_{users}(XN_{nodes}-(Y+1))}$$

$$(1-(e^{-\lambda_{user}(XN_{nodes}T_{token}+YT_{tran})})^{N_{users}})^{Y}$$

$${}_{N_{users}-1}C_{N_{users}-X}$$

$$(e^{-\lambda_{user}(XN_{nodes}T_{token}+YT_{tran})})^{N_{users}-X}$$

$$(1-e^{-\lambda_{user}(XN_{nodes}T_{token}+YT_{tran})})^{X-1}] \qquad (47b)$$

$T_{rotation}$ is obtained by solving Equation 47b. Substituting the value of $T_{rotation}$ into Equation 43, the value of T_{queue} can be obtained.

Similar to the token passing bus networks following the packet service scheme, the average message delivery delay is the sum of the average signal propagation delay and the average signal regeneration delays the signal incurred in going from the message transmitting node to the receiving node. So, using Equations 38 and 43, the average message delay for a network following the byte service scheme is,

$$D_{message} = \frac{T_{rotation}}{2} + T_{prop} + T_{retran} \qquad (48)$$

Token passing ring

Similar to the token passing bus networks, a token ring follows either the packet or byte service scheme. For token passing ring networks following the packet service scheme, T_{queue} is computed using Cheng's nonexhaustive service discipline model (Equation 10). In using this equation, the parameters L and λ_{node} are as defined for the token bus packet service scheme. However, the parameter S is the larger of the: average signal propagation delays of the packet header around the ring, plus the time needed to recover the token; and the packet transmission time. Thus,

$$S = Max[T_{propnet}, T_{packet}] \qquad (49)$$

$T_{delivery}$ is the average signal propagation delays the packet incurred in going from the message sending node to the receiving node, plus average interfacing delays (data verification and retransmission delays) incurred by intervening nodes. Thus,

$$T_{delivery} = T_{prop} + T_{retran} + \frac{T_{interface}L_{tran}N_{nodes}}{L_{ring}} \tag{50}$$

Therefore, for token passing ring networks following the packet service scheme:

$$D_{message} = W + T_{prop} + T_{retran} + \frac{T_{interface}L_{tran}N_{nodes}}{L_{ring}} \tag{51}$$

where, W is obtained using Equation 10.

For token ring networks following the byte service scheme, the average token holding time of a node is the larger of the: average propagation delays of the packet header around the ring, plus time needed to recover the token; and the average transmission time of a packet consisting of data bytes accumulated in a node's queue. So in computing $T_{rotation}$, the algorithm shown in Figure 22 is used. The average message queueing delay is one half of $T_{rotation}$. $T_{delivery}$ is obtained using Equation 50. Using Equation 38, the average message delay for a token passing ring network following the byte service scheme is,

$$D_{message} = \frac{1}{2} T_{rotation} + T_{prop} + T_{retran} + \frac{T_{interface}L_{tran}N_{nodes}}{L_{ring}} \tag{52}$$

where, $T_{rotation}$ is obtained using the algorithm shown in Figure 22.

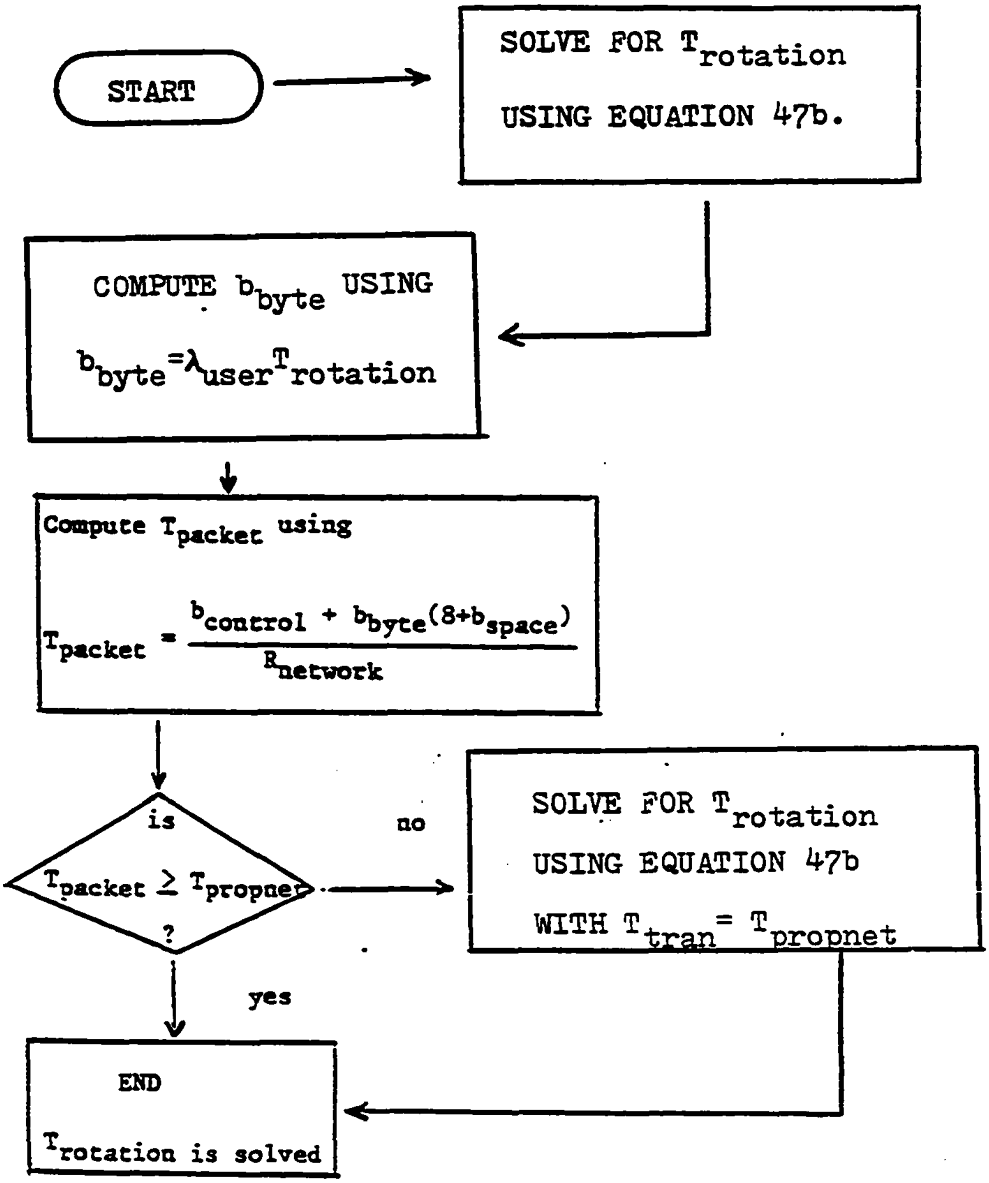

START
SOLVE FOR $T_{rotation}$ USING EQUATION 47b.
COMPUTE b_{byte} USING $b_{byte} = \lambda_{user} T_{rotation}$
Compute T_{packet} using $T_{packet} = \frac{b_{control} + b_{byte}(8+b_{space})}{R_{network}}$
is $T_{packet} \geq T_{propnet}$?
no
SOLVE FOR $T_{rotation}$ USING EQUATION 47b WITH $T_{tran} = T_{propnet}$
yes
END
$T_{rotation}$ is solved

Figure 22. Algorithm for computing $T_{rotation}$ for a token ring network following the byte service scheme

PBX

For a PBX network, messages are not queued inside the station. The user data rate submitted to the station for transmission has to be less than the specified station data rate. Therefore, for

$$\lambda_{station} \leq R_{station}, \qquad T_{queue} = 0 \tag{53}$$

$$\lambda_{station} > R_{station}, \qquad T_{queue} = \infty \tag{54}$$

where,

$\lambda_{station}$ is the average data arrival rate to a station.

$R_{station}$ is the station data rate.

The average message delivery delay, $T_{delivery}$, consists of the average signal propagation delay from the message sending station to the receiving station; plus intervened average repeaters signal regeneration delays; plus switching delay at the switch. Therefore, using Equation 38, for PBX networks with $\lambda_{station} \leq R_{station}$,

$$D_{message} \simeq T_{prop} + T_{retran} + T_{switch} \tag{55}$$

where, T_{switch} is the switching delay at the central node.

Analytical Models on Average Node Buffer Size

Average node buffer size, N_{buffer}, is a measure of the average number of user data bits that are in a node's buffer. By Little's theorem,

$$N_{queue} = T_{queue}\lambda_{user} \tag{56}$$

where,

N_{queue} is the average number of user data bits in a node's queue.

λ_{user} is the average user message arrival rate to a queue (in bits per second or packets per second).

Therefore,

$$N_{buffer} = N_{users}N_{queue} \tag{57}$$

Packet service scheme network

For networks following the packet service scheme,

$$N_{queue} = T_{queue}\lambda_{user}b_{data} \tag{58}$$

where,

λ_{user} is the average user packet rate to a queue.

Thus,

$$N_{buffer} = N_{users}T_{queue}\lambda_{user}b_{data} \tag{59}$$

where,

T_{queue} is obtained using equations derived in the previous section for the various network types.

Byte service scheme networks

For networks following the byte service scheme,

$$N_{queue} = 8T_{queue}\lambda_{user} \tag{60}$$

where,

λ_{user} is the average user byte rate to a queue.

Thus,

$$N_{buffer} = 8N_{users}T_{queue}\lambda_{user} \tag{61}$$

where,

T_{queue} is obtained using equations derived in the previous section for the various network types.

Analytical Models of the Maximum Number of Nodes the Network Can Support

CSMA-CD

For a CSMA-CD network, the maximum number of nodes the network can support, $N_{maxnodes}$, is obtained using Equation 9. So,

$$N_{maxnodes} = ((T_{packet} + 2\tau(e-1))\lambda_{node})^{-1} \tag{62}$$

where,

λ_{node} is the average message arrival rate to a node (in packets per second).

τ is the worst case, one-way signal propagation delay, so

$$\tau = \frac{L_{net}}{V_{prop}} + \frac{T_{repeater}L_{net}N_{repeaters}}{L_{tran}} \tag{63}$$

with L_{net} being the network length.

Token passing bus

For token passing bus networks following the byte service discipline, the network saturates when the average number of user data bytes that are transmitted each packet, b_{byte}, is equal to the maximum number of user bytes that are allowed in a packet, b_{max}. Thus,

$$N_{maxnodes} = \frac{b_{max}}{\lambda_{user}N_{users}(T_{tran} + T_{token})} \tag{64}$$

where,

$$T_{tran} = T_{set} + T_{prop} + T_{retran} + T_{ack} + \frac{b_{control} + (8+b_{space})b_{max}}{R_{network}} \tag{65}$$

For token passing bus networks following the packet service discipline, $N_{maxnodes}$ can be obtained using Equation 11. Thus,

$$N_{maxnodes} = \frac{1}{\lambda_{node}\ (T_{token} + S)} \tag{66}$$

where, S is obtained using Equations 25-28.

Token passing ring

Similar to the token passing bus networks, the maximum number of nodes a token ring following the byte service scheme can support is obtained using Equation 64. However, in using Equation 64, the value for T_{tran} is

$$T_{tran} = \mathrm{Max}\ [T_{propnet}, \frac{b_{control} + (8+b_{space})b_{max}}{R_{network}} \tag{67}$$

To compute $N_{maxnodes}$, first assume $T_{tran} = T_{propnet}$. Let

$$N_{max1} = \frac{b_{max}}{\lambda_{user}N_{users}(T_{propnet} + T_{token})} \tag{68}$$

From Equations 29-31, 34, and 36,

$$N_{maxl} = \frac{b_{max}}{\lambda_{user}N_{users}}[(\frac{L_{ring}}{V_{prop}} + N_{maxl}\ T_{interface} +$$

$$\frac{L_{ring}N_{repeaters}T_{repeater}}{L_{tran}} + T_{copy} + \frac{b_{token}}{R_{network}}) +$$

$$(\frac{b_{token}}{R_{network}} + \frac{L_{pass}}{V_{prop}} + N_{passrepeaters}T_{repeater}$$

$$+ T_{interface} + T_{buffchk})]^{-1} \qquad (69)$$

Rearranging terms in Equation 69,

$$T_{interface}N_{maxl}{}^{2} + (\frac{L_{ring}N_{repeaters}T_{repeater}}{L_{tran}} +$$

$$\frac{L_{ring}}{V_{prop}} + T_{copy} + \frac{2b_{token}}{R_{network}} + T_{interface} + T_{buffchk}$$

$$+ \frac{L_{pass}}{V_{prop}} + N_{passrepeaters}\ T_{repeater})\ N_{maxl}$$

$$- \frac{b_{max}}{\lambda_{user}N_{users}} = 0 \qquad (70)$$

Thus,

$$N_{maxl} = \frac{- B + \sqrt{B^2 - 4AC}}{2A} \qquad (71)$$

where,

$A = T_{interface}$

$$B = \frac{L_{ring}N_{repeaters}T_{repeater}}{L_{tran}} + \frac{L_{ring}}{V_{prop}} + T_{copy} + \frac{2b_{token}}{R_{network}} +$$

$$T_{interface} + T_{buffchk} + \frac{L_{pass}}{V_{prop}} + N_{passrepeaters} + T_{repeater}$$

$$C = \frac{b_{max}}{\lambda_{user}N_{users}}$$

Also, assume $T_{tran} = \dfrac{b_{control} + (8+b_{space})b_{max}}{R_{network}}$. Let

$$N_{max2} = \frac{b_{max}}{\lambda_{user}N_{users}} \left(\frac{b_{control}+(8+b_{space})b_{max}}{R_{network}} + T_{token}\right)^{-1} \quad (72)$$

From Equations 29–31, and 36,

$$N_{max2} = \frac{b_{max}}{\lambda_{user}N_{users}} \left[\left(\frac{b_{control}+(8+b_{space})b_{max}}{R_{network}}\right) + \right.$$

$$\left(\frac{b_{token}}{R_{network}} + \frac{L_{pass}}{V_{prop}} + N_{passrepeaters}T_{repeater}\right.$$

$$\left.\left. + T_{interface} + T_{buffchk}\right)\right]^{-1} \quad (73)$$

Rearranging terms in Equation 73,

$$N_{max2} = \frac{b_{max}}{\lambda_{user}N_{users}} \left[\left(\frac{b_{control}+(8+b_{space})b_{max}+b_{token}}{R_{network}}\right)+\right.$$

$$\frac{L_{pass}}{V_{prop}} + N_{passrepeaters}T_{repeater} + T_{interface} +$$

$$\left.T_{buffchk}\right)\Big]^{-1} \quad (74)$$

Thus, for a token ring following the byte service scheme,

$$N_{maxnodes} = \text{Min}[N_{max1}, N_{max2}] \tag{75}$$

For token ring networks following the packet service scheme, $N_{maxnodes}$ is obtained using Equation 66. The parameter S used in Equation 66 can be computed using Equation 33.

PBX

For PBX networks, $N_{maxnodes}$ is the maximum number of stations specified by the vendor for their PBX.

Analytical Models on Network Saturation Message Rate to a Node

CSMA-CD

For a CSMA-CD network, the network saturation message rate from users to a node, $\lambda_{saturate}$ (in packets per second), is computed using Equations 6-8. Thus,

$$\lambda_{saturate} = \frac{1}{N_{nodes}T_{packet} + \frac{2\tau(1-N_{nodes}Q_N)}{Q_N}} \tag{76}$$

where,

Q_N is obtained using Equation 7.

τ is obtained using Equation 63.

Token passing bus

For token passing bus networks following the byte service discipline, the network saturates when the average number of user data bytes that are transmitted each packet is equal to the maximum number of user bytes that are allowed in a packet. From Equation 64, the network saturates at

$$\lambda_{saturate} = \frac{b_{max}}{N_{nodes}(T_{tran}+T_{token})} \tag{77}$$

where,

$\lambda_{saturate}$ is the network saturation message rate from users to a node (in bytes/second).

For token passing bus networks following the packet service discipline, the network saturation message rate from users to a node, $_{saturate}$ (in packets per second), is computed using Equation 11. Thus,

$$\lambda_{saturate} = \frac{1}{N_{nodes}(T_{token}+S)} \tag{78}$$

where, S is computed using Equation 25.

Token passing ring

Similar to token passing bus networks, the value of $\lambda_{saturate}$ for a token ring following the byte service scheme can be obtained from Equation 77. The value for T_{tran} used in Equation 77 is obtained from Equation 67.

For a token passing ring network following the packet service discipline. $\lambda_{saturate}$ (in packets per second), can be obtained using Equation 78. The parameter S used in Equation 78 is computed using Equation 33.

PBX

For PBX networks, $\lambda_{saturate}$ is the station data rate specified by the vendor for their PBX.

CHAPTER IV. SOFTWARE TOOL

In order to facilitate the use of the network performance evaluation models described in Chapter III, a software tool was developed for the performance analysis and comparison of LANs. The software, which is written in Basic, is made up of twenty-five computer programs stored on a disk. The software is structured into three functional groups of programs (Figures 23-26) whose functions are described in the following sections. Description of the procedures for using the software, as well as explanation of terms and queries the software uses, are detailed in Appendix A. Flow charts describing the logical structuring of the computer programs are presented in Appendix B.

LAN

This program is the starting point of the software. The only function of this program is to display the opening statements and title (Figure 27). Upon completion of its execution by the computer, the program named OPERMENU is automatically accessed.

OPERMENU

This program is the intersecting point of the three software functional groups (the network specification input and performance analysis group; the analytical results retrieval and performance analysis group; and the analytical results retrieval

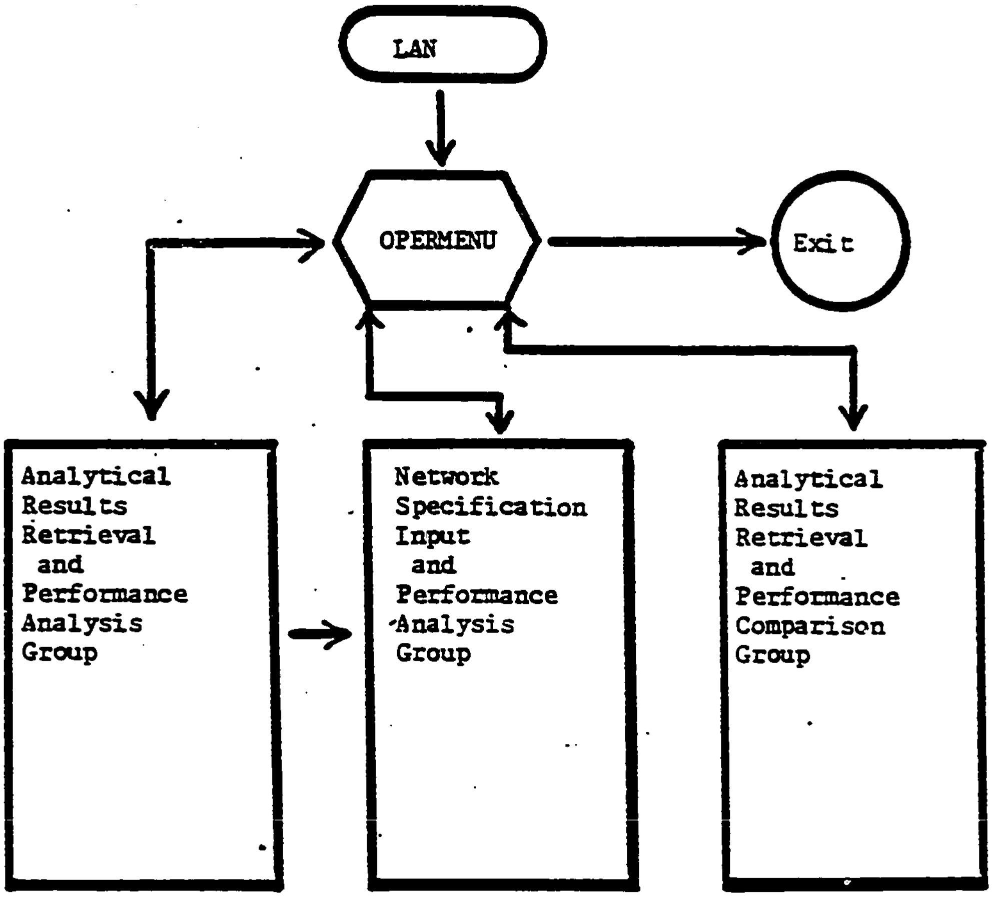
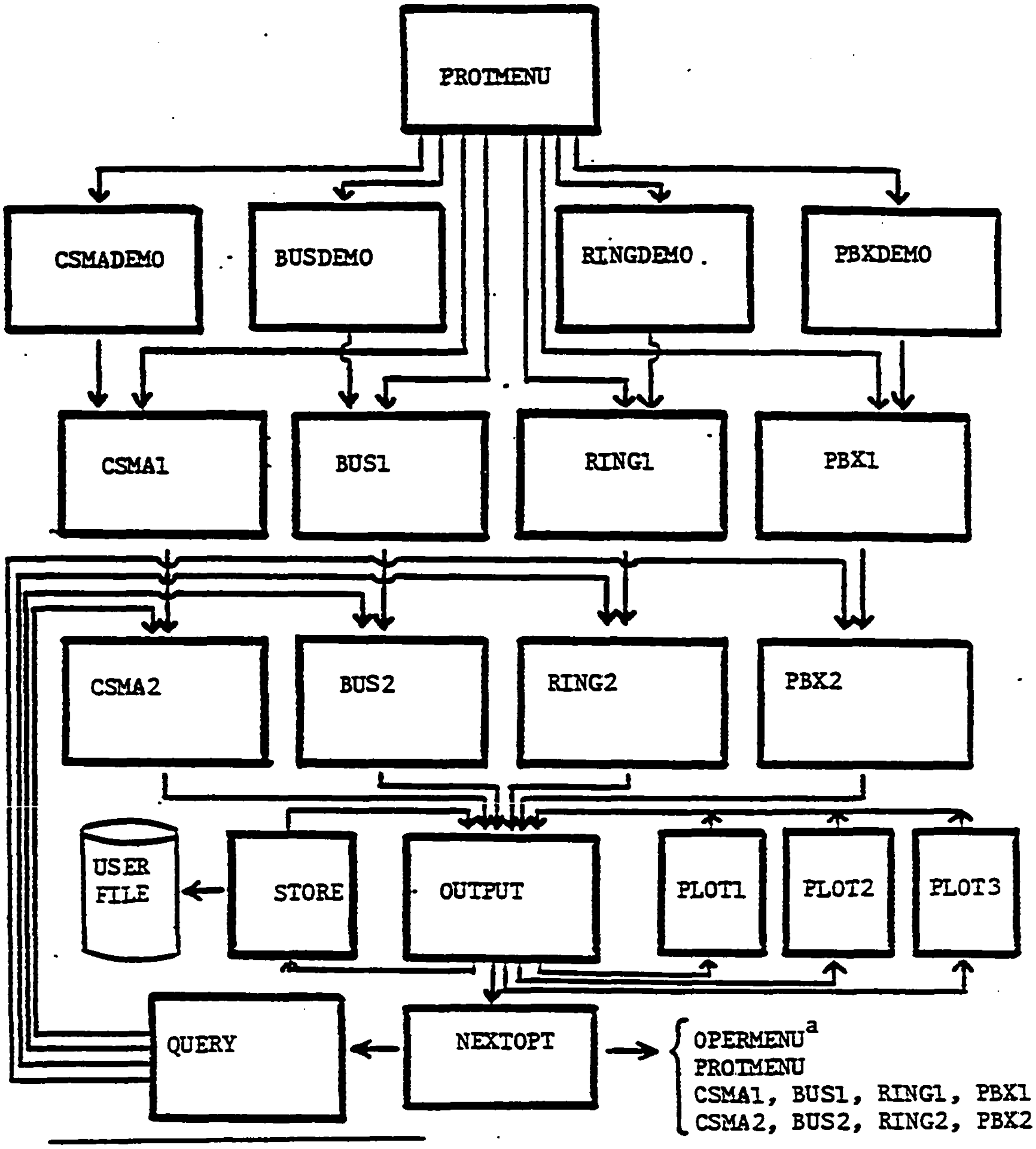

LAN
OPERMENU
Exit
Analytical Results Retrieval and Performance Analysis Group
Network Specification Input and Performance Analysis Group
Analytical Results Retrieval and Performance Comparison Group

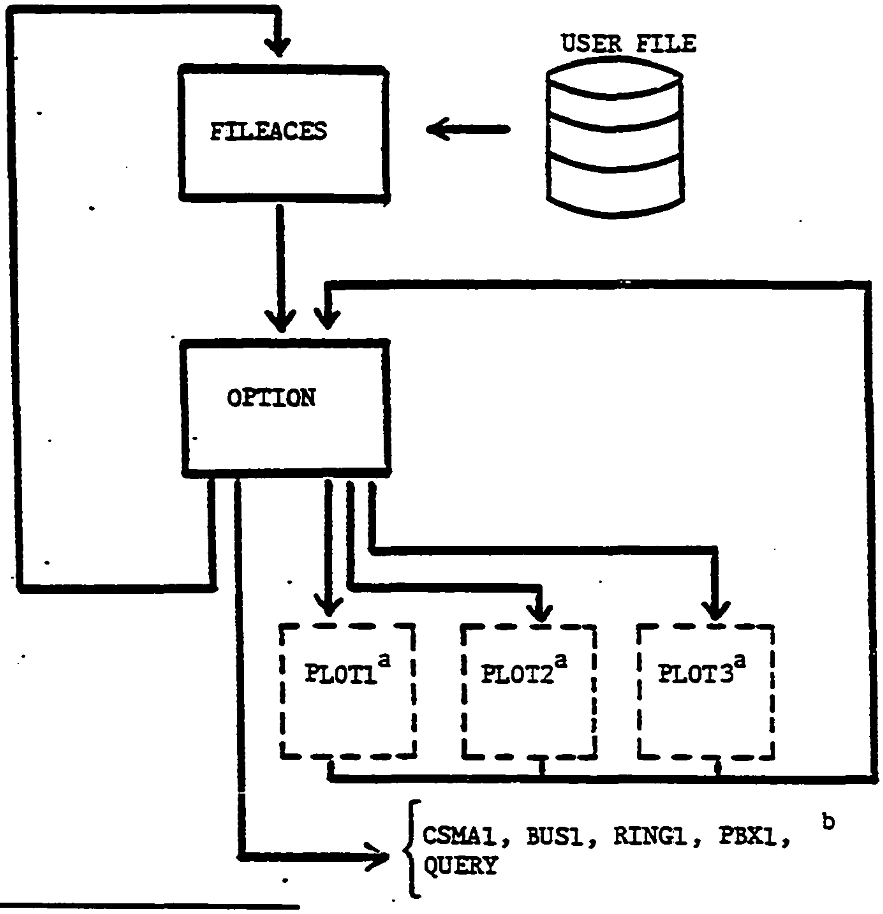
Figure 23. Programming structure


PROTMENU
CSMADEMO
BUSDEMO
RINGDEMO
PBXDEMO
CSMA1
BUS1
RING1
PBX1
CSMA2
BUS2
RING2
PBX2
USER FILE
STORE
OUTPUT
PLOT1
PLOT2
PLOT3
QUERY
NEXTOPT
OPERMENU[a]
PROTMENU
CSMA1, BUS1, RING1, PBX1
CSMA2, BUS2, RING2, PBX2

---

[a] NEXTOPT is the connection to all programs shown in bracket.

Figure 24. Programming structure for the network specification input and performance analysis group of programs

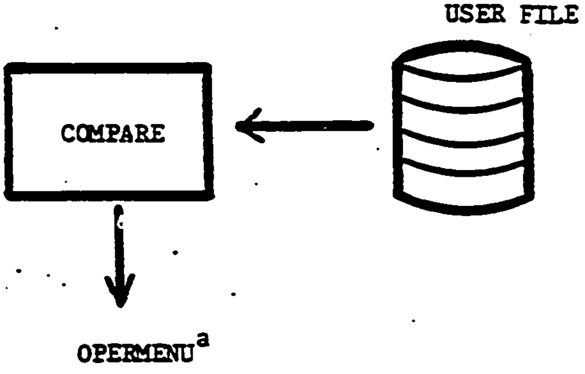

USER FILE
FILEACES
OPTION
PLOT1[a]
PLOT2[a]
PLOT3[a]
CSMA1, BUS1, RING1, PBX1, QUERY
b

---

[a] Program belonging to the Network Specification Input and Performance Analysis Group.

[b] OPTION is the connection to all programs shown in bracket.

Figure 25. Programming structure for the analytical results retrieval and performance analysis group of programs


USER FILE
COMPARE
OPERMENU[a]

---

[a] COMPARE can have direct access to OPERMENU.

Figure 26. Programming structure for the analytical results retrieval and performance comparison group of program

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LANSOFT release 1.0, version 1, 4-2-85

a. OPENING STATEMENTS

PERFORMANCE EVALUATION OF
LOCAL AREA NETWORKS

b. TITLE

Figure 27. Opening display of software

and performance comparison group). The main function of this program is to display to users the Operation Menu (Figure 28). By making the appropriate selection from the four choices listed on the menu, users can have access to programs in anyone of the three functional groups or one can terminate the network performance evaluation session by selecting the EXIT PROGRAM option.

PROTMENU

This program is the main entrance to the network specification input and performance analysis group of programs. Its main function is to present to a user a menu (Figure 29) for their selection in initiating performance analysis of a specific network conforming to either one of the four selected medium access protocols (CSMA-CD, Token Bus, Token Ring, and PBX). Access to programs: CSMADEMO, BUSDEMO, RINGDEMO, PBXDEMO, CSMA1, BUS1, RING1, and PBX1 can be initiated through this program.

CSMADEMO, BUSDEMO, RINGDEMO, and PBXDEMO

Each of these programs present to a user an animated graphical illustration of one of the four selected types of networking protocols. The CSMADEMO program demonstrates the CSMA-CD protocol, the BUSDEMO program demonstrates the token passing bus protocol, the RINGDEMO program demonstrates the token passing ring protocol, and the PBXDEMO program demonstrates the PBX protocol. Written explanations are included with the various

```
PLEASE SELECT ONE OPERATION FROM THE FOLLOWING LIST:


     1.  FIRST TIME EVALUATION OF A NETWORK
     2.  ACCESS FILES OF EVALUATED NETWORKS
     3.  PERFORMANCE COMPARISON OF EVALUATED NETWORKS
     4.  EXIT PROGRAM



                                             PLEASE ENTER
```

Figure 28. Operation menu

```
PLEASE SELECT ONE PROTOCOL FROM THE FOLLOWING LIST:



     1.  CSMA-CD
     2.  TOKEN-PASSING
     3.  TOKEN-PASSING RING
     4.  PBX



                                    PLEASE ENTER



     YOUR SELECTION IS


DO YOU WANT TO SEE A GRAPHICAL DEMONSTRATION OF THE PROTOCOL?

               PLEASE ENTER Y OR N
```

Figure 29. Protocol menu

demonstrations to help viewers to get acquainted with the technical terms that describe the events of the protocols. Upon completion of the demonstration, one of: CSMA1, BUS1, RING1, and PBX1, is accessed.

CSMA1, BUS1, RING1, and PBX1

These programs are where a user enter their inputs regarding the physical and protocol related specification of the network they want to evaluate (Figures 30–33). When the network specification input process is completed, a menu listing the various performance measures the software will generate analytically is presented to the user for his selection on the specific aspect of network performance he is interested in analyzing (Figure 34). Upon completion of program execution, one of: CSMA2, BUS2, RING2, and PBX2, is accessed.

CSMA2, BUS2, RING2, and PBX2

These programs perform the selected analysis of network performance using equations developed in Chapter III. All computed analytical results are tabulated. Upon completion of the computation process, the program named OUTPUT is accessed.

OUTPUT

This program deals with the treatment of analytical results generated by either CSMA2, BUS2, RING2, or PBX2. In this program, a menu listing the options the analytical results can be displayed or recorded, is presented to a user for his selection (Figure 35). Access to

NETWORK SPECIFICATION:

NETWORK NAME:

NETWORK RATE (IN MBPS):

MAXIMUM NUMBER OF NODES PER NETWORK:

NO. OF USERS PER NODE?

- PACKET FORMAT -

NUMBER OF CONTROL BITS:

MINIMUM NUMBER OF BITS PER PACKET:

NUMBER OF SPACING BITS (BEHIND EACH DATA BYTE):

CONDITIONAL SPECIFICATION:

	BEST	EXPECTED	WORST
CABLE SPEED (IN METERS/NANOSECOND):			
INTERFRAME DELAY (IN MICROSECONDS):			
COLLISION JAM TIME (IN MICROSECONDS):			
COLL. SENSING DELAY (IN MICROSECONDS):			
REPEATER DELAY (IN MICROSECONDS):			
AVG. # OF REPEATERS ENCOUNTERED/TRANS.:			
NETWORK LENGTH (METERS):			
AVG. MESSAGE TRANSMISSION DIST. (METERS):			

Figure 30. Networking specifications input for CSMA-CD networks

NETWORK SPECIFICATION

NETWORK NAME:

NETWORK RATE (IN MBPS):

MAXIMUM NUMBER OF NODES PER NETWORK:

NO. OF USERS PER NODE:

- PACKET FORMAT -

NUMBER OF TOKEN BITS:

NUMBER OF ENQUIRY BITS:

NUMBER OF CONTROL BITS:

MAXIMUM NUMBER OF USER DATA BITS PER PACKET:

NUMBER OF ACKNOWLEDGE BITS:

NUMBER OF SPACING BITS (BEHIND EACH DATA BYTE):

CONDITIONAL SPECIFICATION

CABLE SPEED (IN METERS/NANOSECOND):

BUFFER CHECK TIME (IN MICROSECONDS):

MESSAGE CHECK TIME (IN MICROSECONDS):

RESPONSE CHECK TIME (IN MICROSECONDS):

REPEATER DELAY (IN MICROSECONDS):

AVG. # OF REPEATERS ENCOUNTERED/TRANS.:

AVG. # OF REPEATERS ENCOUNTERED/PASS:

AVG. MESSAGE TRANSMISSION DIST. (METERS):

AVG. TOKEN PASSING DIST. (METERS):

Figure 31. Networking specifications input for token passing bus networks

NETWORK SPECIFICATION

NETWORK NAME:

NETWORK RATE (IN MBPS):

MAXIUM NUMBER OF NODES PER NETWORK:

NO. OF USERS PER NODE:

- PACKET FORMAT -

NUMBER OF TOKEN BITS:

NUMBER OF CONTROL BITS:

NUMBER OF SPACING BITS (BEHIND EACH DATA BYTE):

MAXIMUM NUMBER OF USER DATA BITS PER PACKET:

	BEST	EXPECTED	WORST
CABLE SPEED (IN METERS/NANOSECOND):			
BUFFER CHECK TIME (IN MICROSECONDS):			
COPY MESSAGE TIME (IN MICROSECONDS):			
INTERFACE DELAY (IN MICROSECONDS):			
REPEATER DELAY (IN MICROSECONDS):			
AVG. # OF REPEATERS ENCOUNTERED/TRANS.:			
AVG. # OF REPEATERS ENCOUNTERED/PASS:			
RING LENGTH (METERS):			
AVG. MESSAGE TRANSMISSION DIST. (METERS):			
AVG. TOKEN PASSING DISTANCE (METERS):			

Figure 32. Networking specifications input for token passing ring networks

SYSTEM SPECIFICATION

SYSTEM NAME:

DATA RATE PER STATION (IN KBPS):

MAXIMUM NUMBER OF STATIONS PER SYSTEM:

CONDITIONAL SPECIFICATION:

	BEST	EXPECTED	WORST
CABLE SPEED (IN METERS/NANOSECOND):			
SWITCHING DELAY (IN MICROSECONDS):			
REPEATER DELAY (IN MICROSECONDS):			
AVG. # OF REPEATERS ENCOUNTERED/TRANS.:			
AVG. MESSAGE TRANSMISSION DIST. (METERS):			

Figure 33. Networking specifications input for PBX systems

```
SELECT QUERY:

1.  HOW MANY NODES CAN THE NETWORK SUPPORT?

2.  WHAT IS THE MAXIMUM ACHIEVABLE DATA RATE PER NODE?

3.  WHAT IS THE AVERAGE MESSAGE DELAY?

4.  WHAT IS THE AVERAGE NODE BUFFER SIZE?

5.  WHAT IS THE NETWORK SATURATION MESSAGE RATE TO A NODE?

6.  ALL OF THE ABOVE



                                        PLEASE ENTER
```

Figure 34. Performance evaluation menu/query list

```
SELECT ONE OPTION:

    1.  STORE RESULTS ON DISK

        2.  PLOT RESULTS ON SCREEN

            3.  PRINT SPECIFICATION ON PRINTER

                4.  PRINT RESULTS ON PRINTER

                    5.  TABULATE RESULTS ON SCREEN

                        6.  CLEAR RESULTS FROM ACTIVE FILE
```

Figure 35. Output options menu

programs: STORE, PLOT1, PLOT2, PLOT3, and NEXTOPT can be conveniently accessed through this program.

NEXTOPT

This program is accessed at the end of each run through the network performance evaluation process. Here, a user will have to decide on what to do next by selecting from the few choices listed in the Next Operation Menu (Figure 36). Access to programs: OPERMENU, PROTMENU, QUERY, CSMA1, CSMA2, BUS1, BUS2, RING1, RING2, PBX1, and PBX2 can be accessed through this program.

QUERY

This program displays a menu listing the various performance measures on which the software will generate analytical results. The menu is presented to a user for his selection of the specific aspect of network performance he is interested in analyzing (Figure 34). Through this program, the appropriate performance evaluation program (CSMA2, or BUS2, or RING2, or PBX2) is accessed.

STORE

This program is accessed through the program OUTPUT. When called, it will store the most recently generated analytical results (together with the network specification information the results are derived from) in a data file named by the user. Upon completion of its execution, the program OUTPUT is accessed.

PLOT1, PLOT2, and PLOT3

These programs can be accessed through either of the programs: OUTPUT or OPTION. Their function is to display on screen a graph plotted using analytical results generated by either CSMA2, BUS2, RING2, or PBX2. The program PLOT1 presents results on the maximum number of nodes a network can support at network saturation condition versus the number of user data bits per packet; and the maximum number of nodes a network can support at network saturation condition versus the node data rate. The program PLOT2 presents results on the maximum achievable data rate per node versus the number of user data bits per packet; and the network saturation message rate to a node versus the number of nodes. And finally, the program PLOT3 presents results on the average node buffer size versus the node data rate; and the average message delay versus the node data rate. After a user had finished examining a plot, control returns to the program that called for the plot (either OUTPUT or OPTION).

FILEACES

This program is accessed through the program OPERMENU. It is the only entrance to the analytical results retrieval and performance analysis group of programs. Its function is to access user files containing data recorded by the program STORE on a previous analysis of network performance. When a user file is accessed a record showing the network specification used in the analysis of the retrieved results is tabulated and displayed. After a user had finished verifying on whether

```
SELECT NEXT OPERATION:

1.  RETURN TO OPERATION MENU

2.  RETURN TO PROTOCOL MENU

3.  ALTER SPECIFICATION AND RE-EVALUATE

4.  CONTINUE WITH CURRENT TASK

5.  RETURN TO QUERY LIST


                                               PLEASE ENTER
```

Figure 36. Next operation menu

```
SELECT ONE OPTION:

1.  ACCESS ANOTHER FILE

2.  PRINT SPECIFICATION ON PRINTER

3.  PRINT EVALUATION RESULTS ON PRINTER

4.  TABULATE EVALUATION RESULTS ON SCREEN

5.  PLOT EVALUATION RESULTS ON SCREEN

6.  ALTER SPECIFICATION AND RE-EVALUATE

7.  PROCEED TO QUERY LIST

8.  RETURN TO OPERATION MENU

9.  EXIT PROGRAM


                                               PLEASE ENTER
```

Figure 37. Options in dealing with retrieved results

he had retrieved the correct file, the program OPTION is then accessed.

OPTION

The main function of this program is to display a list of options to a user (Figure 37), for his selection on what to do next with the contents of the data file he retrieved. Through this program the contents of the retrieved file can be either tabulated or plotted on screen or printed. Also, the previously recorded network specification can be used to do further analysis of network performance. Through this program the programs: CSMA1, BUS1, RING1, PBX1, QUERY, PLOT1, PLOT2, PLOT3, FILEACES, and OPERMENU can be accessed.

COMPARE

The only access one can have to this program is through the program OPERMENU. This program is the main program of the analytical results retrieval and performance comparison group. The main function of this program is to allow a user to retrieve and have the software plot for him on the screen graphs containing analytical results of previously evaluated networks. These graphs can allow a user to easily compare the network performance of various LANs. The graphs that this program can plot are the same as those that can be plotted by the programs PLOT1, PLOT2, and PLOT3. After a user had completed his performance comparison process, the program OPERMENU is accessed.

CHAPTER V. APPLICATIONS

In this chapter, the LAN software is applied in the performance analysis of several real LANs. Selected networks used in the performance evaluation are those that are representatives of their type. They are: Ethernet (CSMA-CD), Arcnet (token passing bus), Ringnet (token passing ring), and CBX (PBX). The two actual networking environments used in this study are: the networking of nodes in Coover Hall the Electrical and Computer Engineering Building at the Iowa State University, and the networking of nodes on the Iowa State University Main Campus.

Networking of Nodes in A Building

For this study, Coover Hall (the Electrical and Computer Engineering Building at the Iowa State University) is used as the environment for the connection of users by a single network. In evaluating the performance of the selected networks, their configuration in connecting the nodes will first need to be determined such that values for their network size parameters (average message transmission distance, token passing distance for token passing networks, network length for Ethernet, and ring length for Ringnet) can be estimated. The following paragraphs describe the specification that governs the physical configuration of the selected networks. Figure 38 presents a layout of the building indicating where nodes are located. The numbering of nodes (to be used as reference in the computation of network size parameters) are shown in Figure 39. In using Ethernet to

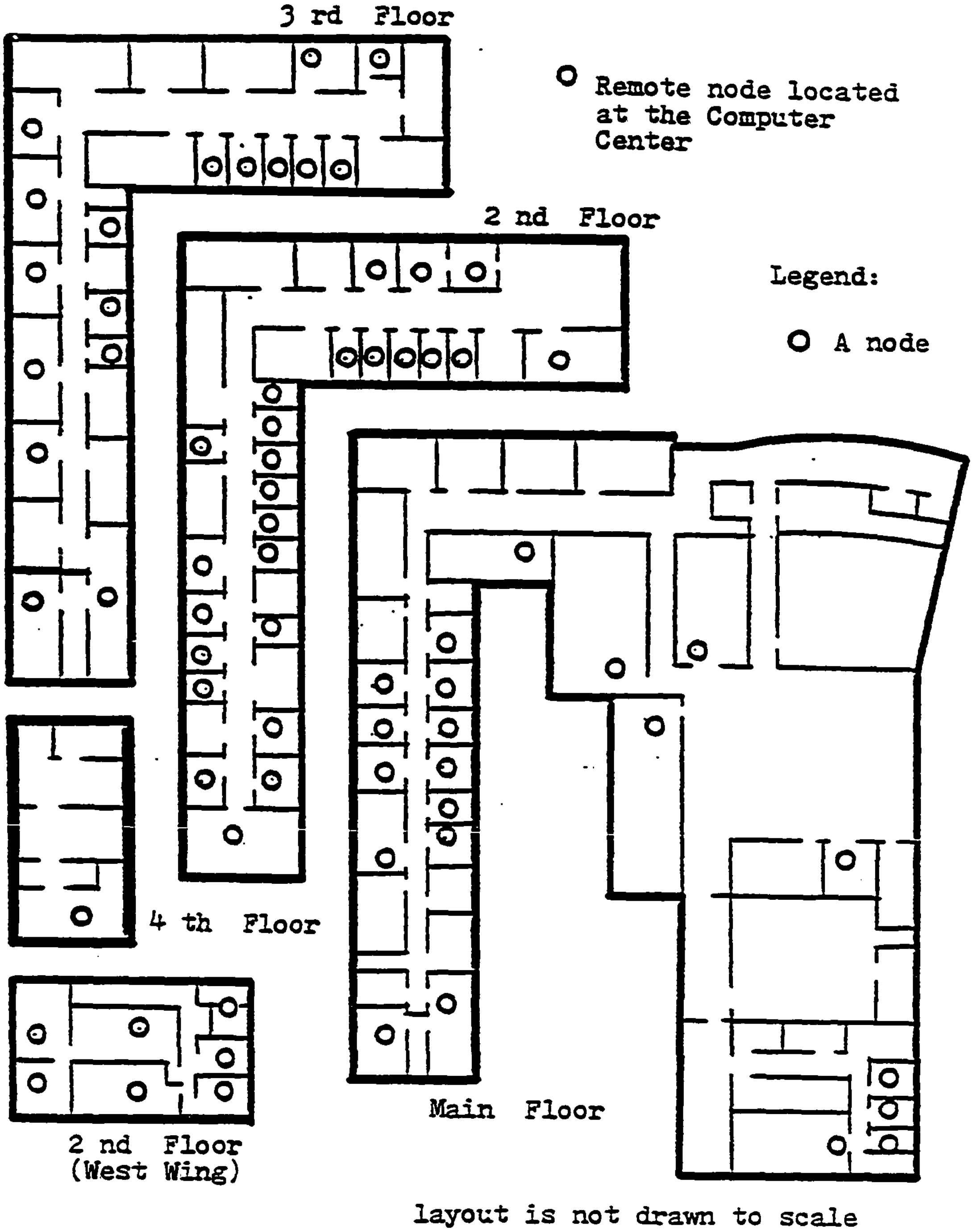
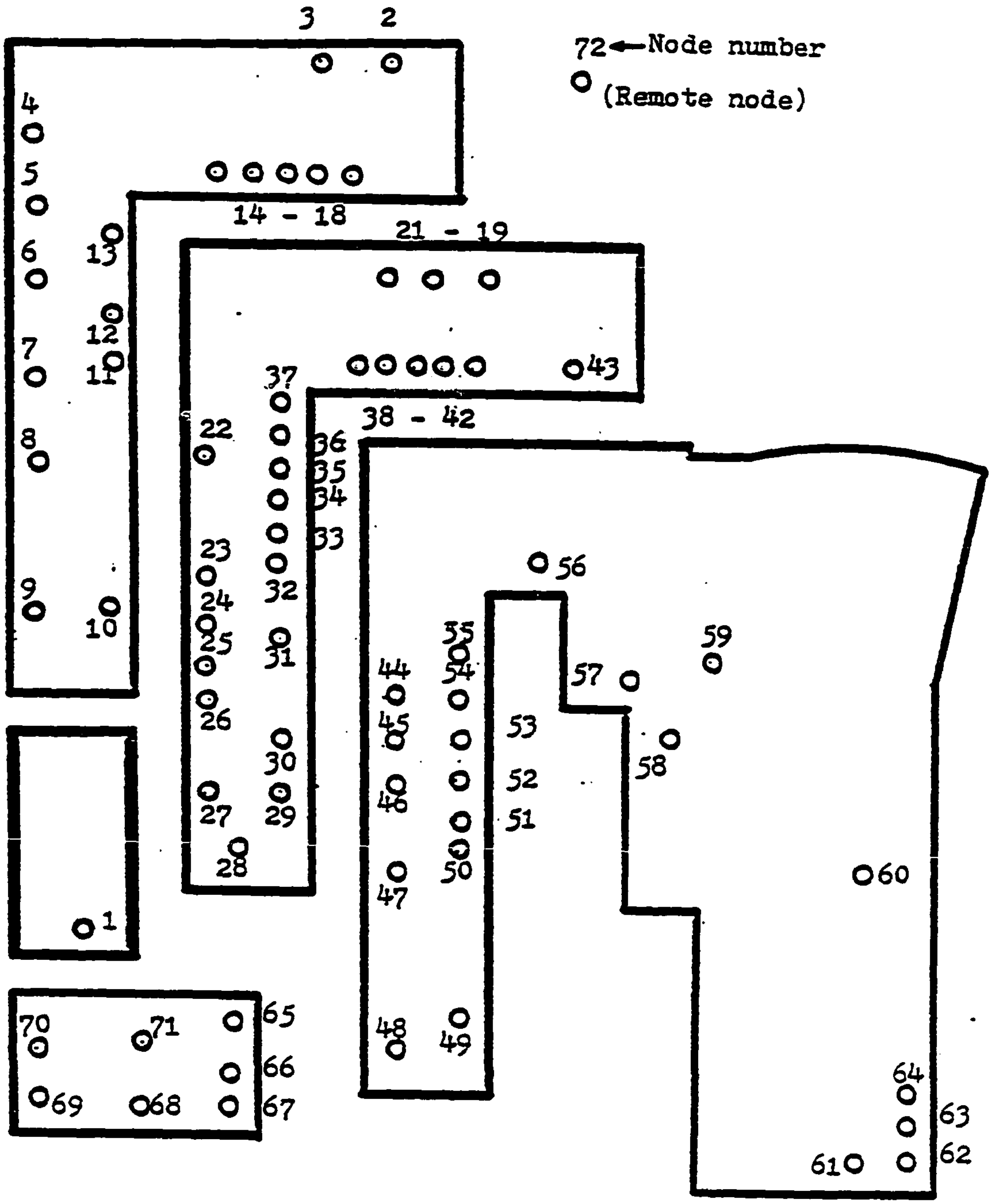

3 rd Floor
Remote node located at the Computer Center
2 nd Floor
Legend:
A node
4 th Floor
2 nd Floor (West Wing)
Main Floor
layout is not drawn to scale

Figure 38. Layout and location of nodes in Coover Hall


72←Node number
(Remote node)
3
2
4
5
6
7
8
9
10
11
12
13
14 - 18
21 - 19
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38 - 42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65
66
67
68
69
70
71
1

Layout is not drawn to scale

Figure 39. Nodes and node numbers

network all nodes (Figure 40), several configurational restrictions are observed:

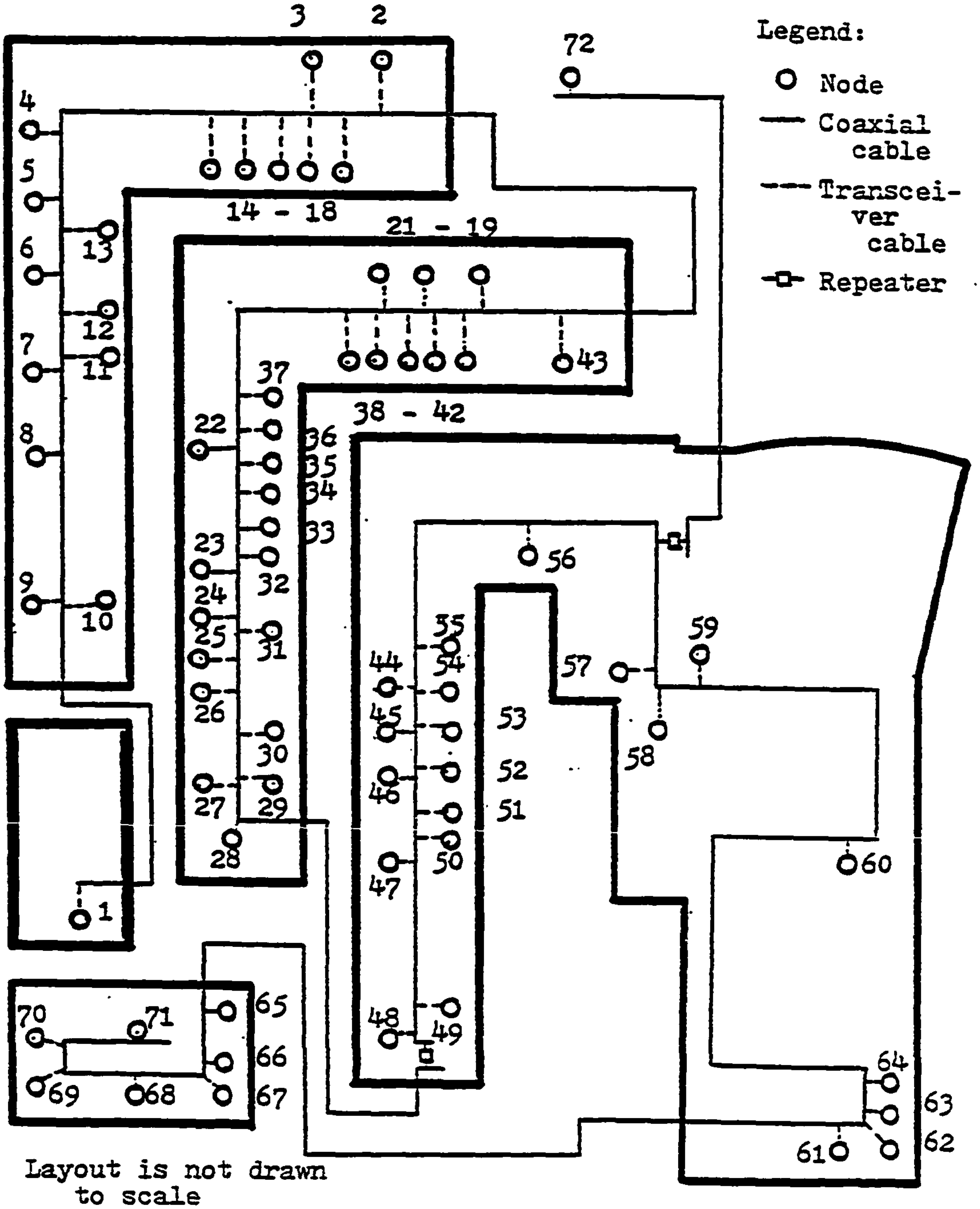
1. A maximum of 1024 nodes may be connected.
2. The maximum network length is 1500 meters.
3. Each cable segment has a maximum length of 500 meters.
4. A maximum of 2 repeaters in the path between any two nodes.

In using Arcnet to network all nodes, each node is connected through a length of coaxial cable to an outlet on a "Hub" (Figure 41). The hubs function as repeaters and network taps. Each outlet of a hub may be connected to a node, to another hub, or to nothing at all. Hubs may be no more than 600 meters apart, although as many as 10 hubs may be cascaded. The maximum network distance between two nodes of the network is 6600 meters. The vendor specified maximum number of nodes is 255.

In using Ringnet to network all nodes, each node is connected through a length of coaxial cable to its adjacent nodes (Figure 42). Two connecting nodes may be no more than 200 meters apart. A maximum of 247 nodes may be connected by a ring. The maximum ring length is 49,400 meters.

In using CBX to network all stations, each station is connected through a length of twisted pair wire to a "Junction" (Figure 43). The junctions are connected by cable trunks to the central switch, which may support a maximum of 10,000 stations. The maximum network distance between a station and the switch is 1,500 meters.

The use of the Coover Hall network is primarily for the transferring of data files between user and the letter quality printer,


3
2
72
Legend:
Node
Coaxial cable
Transceiver cable
Repeater
4
5
6
7
8
9
10
11
12
13
14 - 18
21 - 19
43
37
22
36
35
34
33
23
32
24
25
31
26
30
27
29
28
1
38 - 42
56
55
54
44
45
46
47
48
49
50
51
52
53
57
58
59
60
64
63
62
61
65
66
67
70
71
69
68

Layout is not drawn
to scale

Figure 40. Configuration of Ethernet in Coover Hall

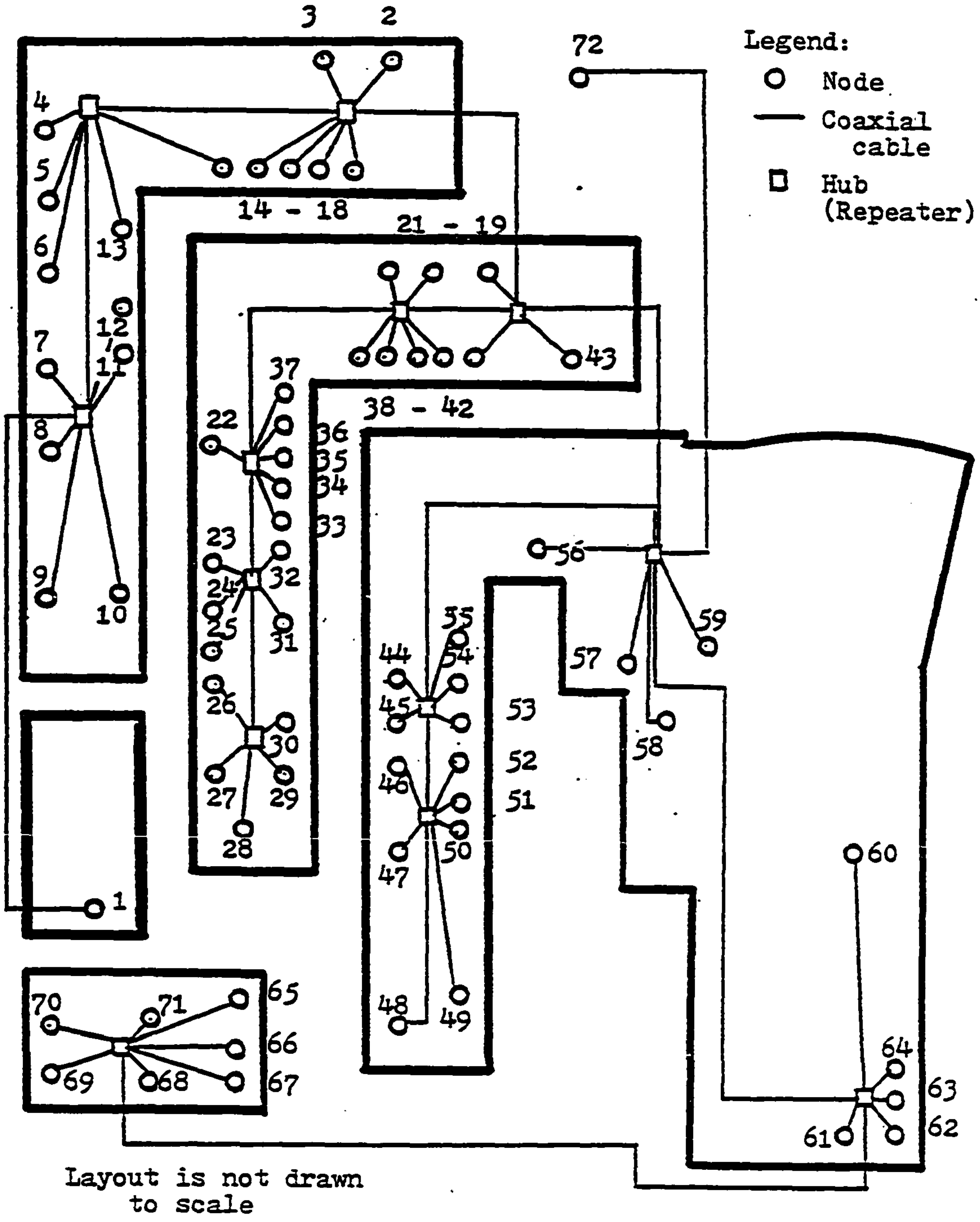
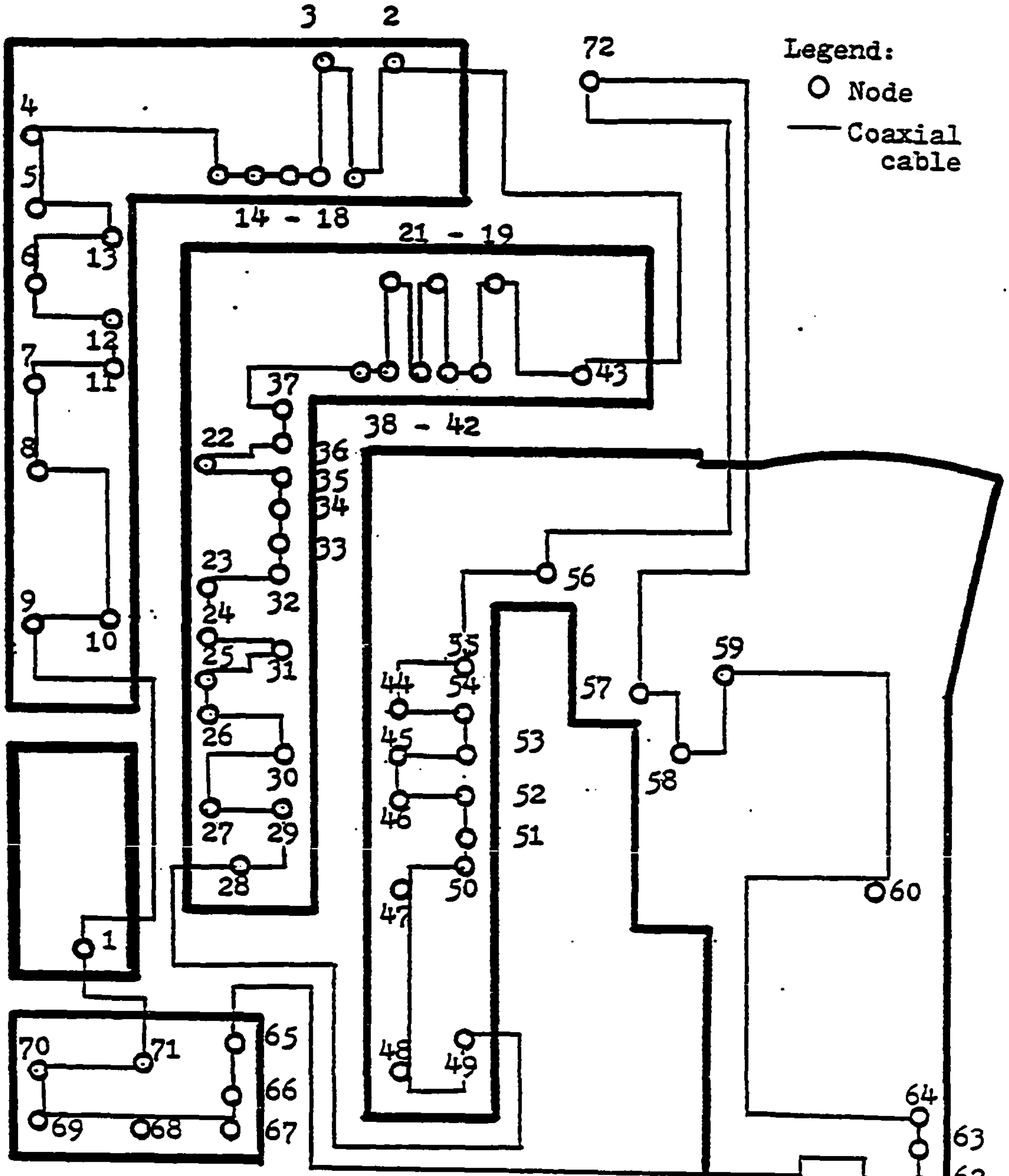
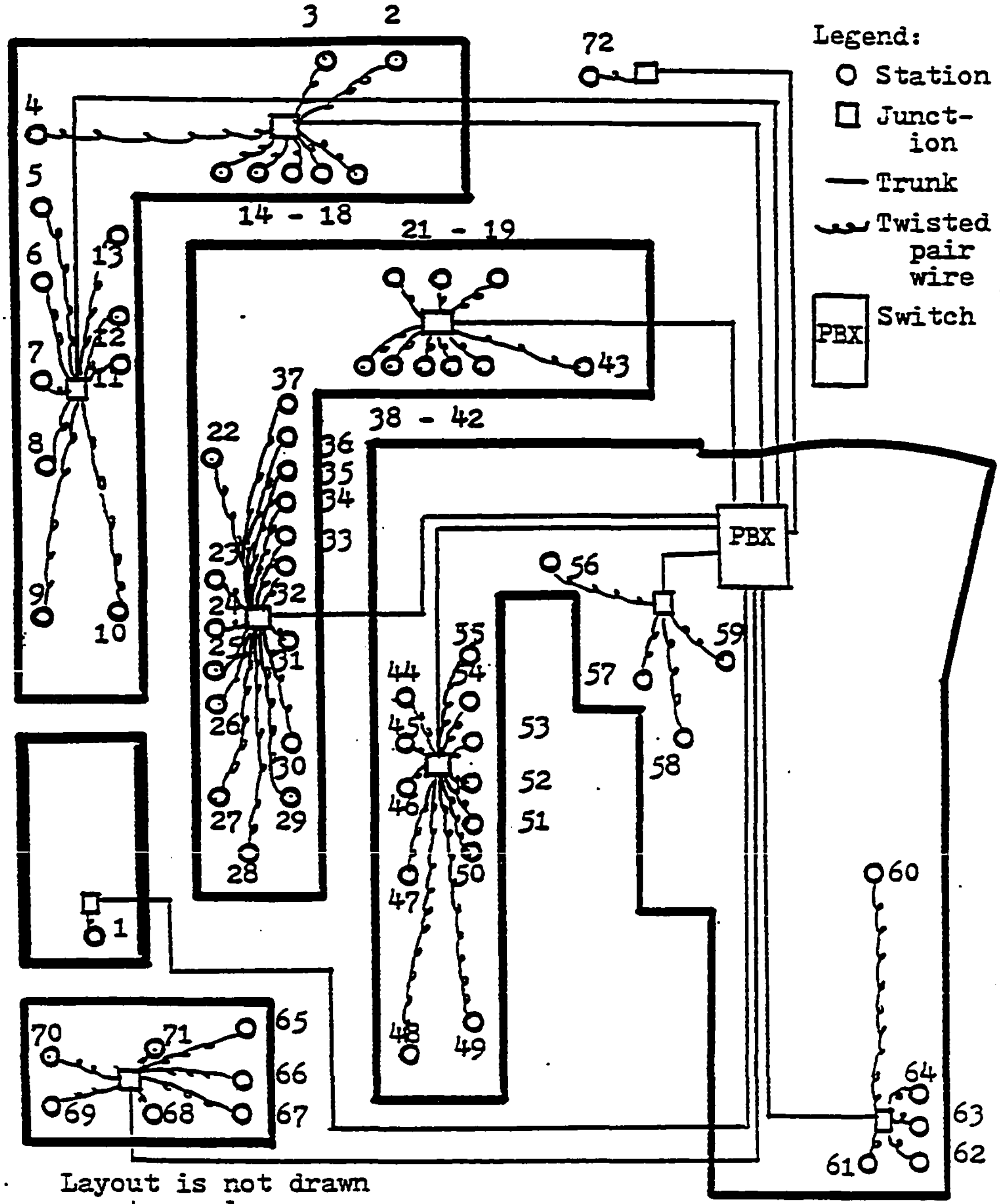

Legend:
Node
Coaxial cable
Hub (Repeater)
3
2
72
4
5
6
13
14 - 18
21 - 19
12
7
11
37
43
38 - 42
22
36
35
34
8
33
23
9
10
24
32
25
31
26
30
27
29
28
1
56
59
57
55
44
54
45
53
58
46
52
51
47
50
60
70
71
65
66
69
68
67
48
49
64
63
61
62
Layout is not drawn to scale

Figure 41. Configuration of Arcnet in Coover Hall


3
2
72
Legend:
Node
Coaxial cable
4
5
14 - 18
21 - 19
6
13
12
7
11
8
9
10
37
43
22
38 - 42
36
35
34
33
23
32
24
25
31
26
30
27
29
28
1
56
55
44
54
45
53
46
52
51
47
50
57
58
59
60
48
49
70
71
65
66
69
68
67
64
63
61
62

Layout is not drawn
to scale

Figure 42. Configuration of Ringnet in Coover Hall


3
2
72
Legend:
Station
Junct-ion
Trunk
Twisted pair wire
PBX
Switch
4
5
6
13
12
7
11
8
9
10
14 - 18
21 - 19
43
37
22
38 - 42
36
35
34
33
23
24
32
25
31
26
30
27
29
28
PBX
56
59
57
58
55
54
44
45
53
46
52
51
47
50
48
49
1
60
70
71
65
66
69
68
67
64
63
61
62

Layout is not drawn
to scale

Figure 43. Configuration of CBX in Coover Hall

which is the remote node located at the Computer Center. Since the remote node does not transmit any messages to other user nodes, and there is no direct data communication among users, the flow of data traffic is many-to-one.

Data used in the computation of the average message transmission distance and the average number of repeaters the message encountered in going to its destination are presented in Tables 2-5. These estimates of network distance are derived from measurements given in the floor plan of the building. To allow for discrepancy in the actual installation of the network, a 10 percent deviation from the expected distance is assumed on both sides (the best and the worst values). Since the system is a one-to-many system, the average message transmission distance is the average of all network distance between a node and the central storage (node 72). The data used in the computation of the average token passing distance and the average number of repeaters the token encountered (for Arcnet and Ringnet) are presented in Tables 6 and 7. For the same reason as discussed earlier, a 10 percent deviation from the mean is again assumed here for the computation of the best and the worst token passing distance. For Arcnet the token passing sequence is as shown in Table 6. For Ringnet the token passing sequence follows a clockwise manner in traveling from a node to its adjacent node on the network. The network length for Ethernet is the network distance between Node 1 and Node 71 (the two nodes that are placed furthest apart on the network). The ring length for Ringnet is the sum of all the cable segments. Network specification

Table 2. Average message transmission distance (Ethernet)

From node #72 ——> From\to
Best/Expected/Worst ——> /

From\to	1	2	3	4	5	6	7	8	9
BEST	335/2	267/2	269/2	287/2	291/2	295/2	302/2	306/2	317/2
EXP.	372/2	297/2	299/2	319/2	323/2	328/2	335/2	340/2	352/2
WORST	409/2	326/2	329/2	351/2	355/2	361/2	369/2	374/2	387/2

From\to	19	20	21	22	23	24	25	26	27
BEST	248/2	245/2	241/2	226/2	217/2	213/2	211/2	208/2	201/2
EXP.	276/2	272/2	268/2	251/2	241/2	237/2	234/2	231/2	223/2
WORST	304/2	299/2	295/2	276/2	265/2	261/2	257/2	254/2	245/2

From\to	37	38	39	40	41	42	43	44	45
BEST	229/2	239/2	240/2	244/2	246/2	248/2	254/2	159/1	163/1
EXP.	254/2	265/2	267/2	271/2	273/2	275/2	282/2	177/1	181/1
WORST	279/2	292/2	294/2	298/2	300/2	303/2	310/2	195/1	199/1

From\to	55	56	57	58	59	60	61	62	63
BEST	158/1	147/1	145/1	152/1	159/1	195/1	250/1	248/1	247/1
EXP.	175/1	163/1	161/1	169/1	177/1	217/1	278/1	276/1	274/1
WORST	193/1	179/1	177/1	186/1	195/1	239/1	306/1	304/1	301/1

Average message transmission distance (meters):

Average number of repeaters encountered/trans.:

<------ Node # (Destination)
<------ Avg. msg. trans. dist. (meters)
Avg. # of repeaters per trans.

10	11	12	13	14	15	16	17	18
315/2	301/2	298/2	293/2	278/2	276/2	275/2	273/2	271/2
350/2	334/2	331/2	325/2	309/2	307/2	305/2	303/2	301/2
385/2	367/2	364/2	358/2	340/2	338/2	336/2	333/2	331/2

28	29	30	31	32	33	34	35	36
198/2	200/2	204/2	212/2	219/2	221/2	222/2	224/2	227/2
220/2	222/2	227/2	236/2	243/2	245/2	247/2	249/2	252/2
242/2	244/2	250/2	260/2	267/2	270/2	272/2	274/2	277/2

46	47	48	49	50	51	52	53	54
166/1	172/1	185/1	183/1	170/1	167/1	165/1	162/1	160/1
184/1	191/1	206/1	203/1	189/1	186/1	183/1	180/1	178/1
202/1	210/1	227/1	223/1	208/1	205/1	201/1	198/1	196/1

64	65	66	67	68	69	70	71	72
245/1	273/1	279/1	281/1	289/1	298/1	300/1	309/1	—
272/1	303/1	310/1	312/1	321/1	331/1	333/1	343/1	—
299/1	333/1	341/1	343/1	353/1	364/1	366/1	377/1	—

Best	Expected	Worst
235	261.5	288
1.6	1.6	1.6

Table 3. Average message transmission distance (Arcnet)

From node #72 ———> From\to
Best/Expected/Worst ———> /

From\to	1	2	3	4	5	6	7	8	9
BEST	233/5	186/3	185/3	194/4	195/4	195/4	208/5	209/5	215/5
EXP.	259/5	207/3	206/3	216/4	217/4	217/4	231/5	232/5	239/5
WORST	285/5	228/3	227/3	238/4	239/4	239/4	254/5	255/5	263/5

From\to	19	20	21	22	23	24	25	26	27
BEST	169/2	173/3	173/3	186/4	195/5	195/5	195/5	205/6	204/6
EXP.	188/2	192/3	192/3	207/4	217/5	217/5	217/5	228/6	227/6
WORST	207/2	211/3	211/3	228/4	239/5	239/5	239/5	251/6	250/6

From\to	37	38	39	40	41	42	43	44	45
BEST	186/4	173/3	173/3	173/3	173/3	171/2	169/2	163/2	163/2
EXP.	207/4	192/3	192/3	192/3	192/3	190/2	188/2	181/2	181/2
WORST	228/4	211/3	211/3	211/3	211/3	209/2	207/2	199/2	199/2

From\to	55	56	57	58	59	60	61	62	63
BEST	163/2	144/1	144/1	146/1	144/1	248/2	210/2	210/2	210/2
EXP.	181/2	160/1	160/1	162/1	160/1	276/2	233/2	233/2	233/2
WORST	199/2	176/1	176/1	178/1	176/1	304/2	256/2	256/2	256/2

Average message transmission distance (meters):

Average number of repeaters encountered/trans.:

<——— Node # (Destination)
<——— Avg. msg.trans. dist. (meters)
Avg. # of repeaters per trans.

10	11	12	13	14	15	16	17	18
215/5	208/5	209/5	195/4	195/4	186/3	185/3	185/3	185/3
239/5	231/5	232/5	217/4	217/4	207/3	206/3	206/3	206/3
263/5	254/5	255/5	239/4	239/4	228/3	227/3	227/3	227/3

28	29	30	31	32	33	34	35	36
205/6	204/6	204/6	195/5	195/5	186/4	186/4	186/4	186/4
228/6	227/6	227/6	217/5	217/5	207/4	207/4	207/4	207/4
251/6	250/6	250/6	239/5	239/5	228/4	228/4	228/4	228/4

46	47	48	49	50	51	52	53	54
171/3	170/3	178/3	177/3	170/3	170/3	170/3	163/2	163/2
190/3	189/3	198/3	197/3	189/3	189/3	189/3	181/2	181/2
209/3	208/3	218/3	217/3	208/3	208/3	208/3	199/2	199/2

64	65	66	67	68	69	70	71	72
210/2	247/3	247/3	247/3	241/3	186/3	186/3	241/3	—
233/2	274/3	274/3	274/3	268/3	270/3	270/3	268/3	—
256/2	301/3	301/3	301/3	295/3	228/3	228/3	295/3	—

Best	Expected	Worst
192.2	213.5	234.9
3.4	3.4	3.4

Table 4. Average message transmission distance (Ringnet)

From node #72 ———> From\to
Best/Expected/Worst ———> /

From\to	1	2	3	4	5	6	7	8	9
BEST	335/0	410/0	404/0	387/0	383/0	378/0	369/0	365/0	353/0
EXP.	372/0	455/0	449/0	430/0	426/0	420/0	410/0	405/0	392/0
WORST	409/0	501/0	494/0	473/0	469/0	462/0	451/0	446/0	431/0

From\to	19	20	21	22	23	24	25	26	27
BEST	428/0	436/0	441/0	461/0	472/0	475/0	481/0	483/0	492/0
EXP.	476/0	484/0	490/0	512/0	524/0	528/0	534/0	537/0	547/0
WORST	524/0	532/0	559/0	563/0	576/0	581/0	587/0	591/0	602/0

From\to	37	38	39	40	41	42	43	44	45
BEST	456/0	446/0	444/0	438/0	433/0	431/0	423/0	544/0	538/0
EXP.	507/0	495/0	493/0	487/0	481/0	479/0	470/0	604/0	598/0
WORST	558/0	545/0	542/0	536/0	529/0	527/0	517/0	664/0	658/0

From\to	55	56	57	58	59	60	61	62	63
BEST	546/0	557/0	144/0	151/0	158/0	194/0	249/0	248/0	246/0
EXP.	607/0	619/0	160/0	168/0	176/0	216/0	277/0	275/0	273/0
WORST	668/0	681/0	176/0	185/0	194/0	238/0	305/0	303/0	300/0

Average message transmission distance (meters):

Average number of repeaters encountered/trans.:

<------ Node # (Destination)
<------ Avg. msg.trans. dist. (meters)
Avg. # of repeaters per trans.

10	11	12	13	14	15	16	17	18
356/0	372/0	374/0	381/0	396/0	398/0	400/0	401/0	407/0
395/0	413/0	416/0	423/0	440/0	442/0	444/0	446/0	452/0
435/0	454/0	458/0	465/0	484/0	486/0	488/0	491/0	497/0

28	29	30	31	32	33	34	35	36
497/0	494/0	488/0	478/0	469/0	467/0	465/0	464/0	458/0
552/0	549/0	542/0	531/0	521/0	519/0	517/0	515/0	509/0
607/0	604/0	596/0	584/0	573/0	571/0	569/0	567/0	560/0

46	47	48	49	50	51	52	53	54
536/0	526/0	514/0	511/0	528/0	531/0	534/0	540/0	542/0
595/0	584/0	571/0	568/0	587/0	590/0	593/0	600/0	602/0
655/0	642/0	628/0	625/0	646/0	649/0	652/0	660/0	662/0

64	65	66	67	68	69	70	71	72
244/0	272/0	278/0	280/0	288/0	297/0	299/0	308/0	—
271/0	302/0	309/0	311/0	320/0	330/0	332/0	342/0	—
298/0	332/0	340/0	342/0	352/0	363/0	365/0	376/0	—

Best	Expected	Worst
408.2	453.6	499
0	0	0

Table 5. Average message transmission distance (CBX)

From node #72 ———> From\to
Best/Expected/Worst ———> /

From\to	1	2	3	4	5	6	7	8	9
BEST	324/0	188/0	187/0	196/0	216/0	212/0	207/0	210/0	215/0
EXP.	360/0	209/0	208/0	218/0	240/0	236/0	230/0	233/0	239/0
WORST	396/0	230/0	229/0	240/0	264/0	260/0	253/0	256/0	263/0

From\to	19	20	21	22	23	24	25	26	27
BEST	174/0	171/0	171/0	189/0	180/0	180/0	181/0	182/0	189/0
EXP.	193/0	190/0	190/0	210/0	200/0	200/0	201/0	202/0	210/0
WORST	212/0	209/0	209/0	231/0	220/0	220/0	221/0	222/0	231/0

From\to	37	38	39	40	41	42	43	44	45
BEST	178/0	171/0	171/0	171/0	171/0	171/0	175/0	175/0	174/0
EXP.	198/0	190/0	190/0	190/0	190/0	190/0	194/0	194/0	193/0
WORST	218/0	209/0	209/0	209/0	209/0	209/0	213/0	213/0	212/0

From\to	55	56	57	58	59	60	61	62	63
BEST	175/0	155/0	155/0	157/0	155/0	255/0	216/0	216/0	216/0
EXP.	194/0	172/0	172/0	174/0	172/0	283/0	240/0	240/0	240/0
WORST	213/0	189/0	189/0	191/0	189/0	311/0	264/0	264/0	264/0

Average message transmission distance (meters):

Average number of repeaters encountered/trans.:

<———— Node # (Destination)
<———— Avg. msg. trans. dist. (meters)
Avg. # of repeaters per trans.

10	11	12	13	14	15	16	17	18
215/0	207/0	208/0	214/0	188/0	187/0	187/0	187/0	187/0
239/0	230/0	231/0	238/0	209/0	208/0	208/0	208/0	208/0
263/0	253/0	254/0	262/0	230/0	229/0	229/0	229/0	229/0

28	29	30	31	32	33	34	35	36
190/0	189/0	185/0	180/0	180/0	183/0	187/0	189/0	181/0
211/0	210/0	206/0	200/0	200/0	203/0	208/0	210/0	201/0
232/0	231/0	227/0	220/0	220/0	223/0	229/0	231/0	221/0

46	47	48	49	50	51	52	53	54
174/0	176/0	185/0	183/0	175/0	174/0	174/0	174/0	175/0
193/0	195/0	205/0	203/0	194/0	193/0	193/0	193/0	194/0
212/0	214/0	226/0	223/0	213/0	212/0	212/0	212/0	213/0

64	65	66	67	68	69	70	71	72
216/0	239/0	239/0	239/0	234/0	236/0	236/0	234/0	—
240/0	266/0	266/0	266/0	260/0	262/0	262/0	260/0	—
264/0	293/0	293/0	293/0	286/0	288/0	288/0	286/0	—

Best	Expected	Worst
193	214.9	236
0	0	0

Table 6. Average token passing distance (ARCNET)

Best/Expected/Worst From\to \
Value ------> /

From\to	1\2	2\3	3\4	4\5	5\6	6\7	7\8	8\9	9\10
BEST	52/3	4.5/1	13/2	4.5/1	12/1	18/1	4.5/1	12/1	18/1
EXP.	58/3	5/1	14/2	5/1	6/1	20/2	5/1	13/1	20/1
WORST	64/0	5.5/1	15/2	5.5/1	6.6/1	22/2	5.5/1	14/1	22/1
From\to	19\20	20\21	21\22	22\23	23\24	24\25	25\26	26\27	27\28
BEST	7.2/2	3.6/1	17/2	13/2	3.6/1	3.6/1	14/2	4.5/1	4.5/1
EXP.	8/2	4/1	19/2	14/2	4/1	4/1	15/2	5/1	5/1
WORST	8.8/2	4.4/1	21/2	15/2	4.4/1	4.5/1	16/2	5.5/1	5.5/1
From\to	37\38	38\39	39\40	40\41	41\42	42\43	43\44	44\45	45\46
BEST	17/2	3.6/1	3.6/1	3.6/1	9/2	5.4/1	51/3	3.6/1	12/2
EXP.	19/2	4/1	4/1	4/1	10/2	6/1	57/3	4/1	13/2
WORST	21/2	4.4/1	4.4/1	4.4/1	11/2	6.6/1	66/3	4.4/1	14/2
From\to	55\56	56\57	57\58	58\59	59\60	60\61	61\62	62\63	63\64
BEST	26/2	7.2/1	9/1	9/1	112/2	42/1	3.6/1	3.6/1	3.6/1
EXP.	29/2	8/1	10/1	10/1	124/2	47/1	4/1	4/1	4/1
WORST	32/2	8.8/1	11/1	11/1	136/2	52/1	4.4/1	4.4/1	4.4/1

Average token passing distance (meters):

Average number of repeaters encountered/pass:

<------ To node # (Destination) \ From node # (Sender)
<------ Avg. token passing dist. (meters)
Avg. # of repeaters per pass

10\11	11\12	12\13	13\14	14\15	15\16	16\17	17\18	18\19
11/1	4.5/2	19/2	5.4/1	14/0	4.5/0	3.6/1	3.6/1	20/1
12/1	5/1	21/2	6/1	16/2	5/1	4/1	4/1	22/2
13/1	5.5/1	23/2	6.6/1	18/2	5.5/1	4.4/1	4.4/1	24/2

28\29	29\30	30\31	31\32	32\33	33\34	34\35	35\36	36\37
4.5/1	3.6/1	13/2	3.6/1	13/2	3.6/1	3.6/1	3.6/1	3.6/1
5/1	4/1	14/2	4/1	14/2	4/1	4/1	4/1	4/1
5.5/1	4.4/1	15/2	4.4/1	15/2	4.4/1	4.4/1	4.4/1	4.4/1

46\47	47\48	48\49	49\50	50\51	51\52	52\53	53\54	54\55
4.5/1	12/1	19/1	11/1	3.6/1	3.6/1	11/2	3.6/1	3.6/1
5/1	13/1	21/1	12/1	4/1	4/1	12/2	4/1	4/1
5.5/1	14/1	23/1	13/1	4.4/1	4.4/1	13/2	4.4/1	4.4/1

64\65	65\66	66\67	67\68	68\69	69\70	70\71	71\72	72\1
41/2	14/1	14/1	9/1	5.4/1	7.2/1	5.4/1	241/3	233/5
45/2	16/1	16/1	10/1	6/1	8/1	6/2	268/3	259/5
50/2	18/1	18/1	11/1	6.6/1	8.8/1	6.6/1	295/3	285/5

Best	Expected	Worst
18.13	20.14	22.15
1.4	1.4	1.4

Table 7. Average token passing distance (Ringnet)

Best/Expected/Worst From\to \
Value ——> /

From\to	1\9	9\10	10\8	8\7	7\11	11\12	12\6	6\13	13\5
BEST	18/0	7.2/1	9/1	9/1	112/2	42/1	3.6/1	3.6/1	3.6/1
EXP.	29/2	8/1	10/1	10/1	124/2	47/1	4/1	4/1	4/1
WORST	32/2	8.8/1	11/1	11/1	136/2	52/1	4.4/1	4.4/1	4.4/1
From\to	43\19	19\42	42\41	41\20	20\40	40\21	21\39	39\38	38\37
BEST	5.4/0	2.7/0	1.8/0	2.7/0	2.7/0	2.7/0	2.7/0	1.8/0	11/0
EXP.	6/0	3/0	2/0	3/0	3/0	3/0	3/0	2/0	12/0
WORST	6.6/0	3.3/0	2.2/0	3.3/0	3.3/0	3.3/0	3.3/0	2.2/0	13/0
From\to	31\25	25\26	26\30	30\27	27\29	29\28	28\49	49\48	48\47
BEST	2.7/0	2.7/0	4.5/0	4.5/0	1.8/0	2.7/0	14/0	2.7/0	12/0
EXP.	3/0	3/0	5/0	5/0	2/0	3/0	16/0	3/0	13/0
WORST	3.3/0	3.3/0	5.5/0	5.5/0	2.2/0	3.3/0	18/0	3.3/0	14/0
From\to	55\56	56\72	72\57	57\58	58\59	59\60	60\64	64\63	63\62
BEST	11/0	149/0	144/0	7.2/0	7.2/0	36/0	50/0	1.8/0	1.8/0
EXP.	12/0	165/0	160/0	8/0	8/0	40/0	55/0	2/0	2/0
WORST	13/0	182/0	176/0	8.8/0	8.8/0	44/0	60/0	2.2/0	2.2/0

Average token passing distance (meters):

Average number of repeaters encountered/pass:

<------ To node # (Destination) \ From node # (Sender)
<------ Avg. token passing dist. (meters)
Avg. # of repeaters per pass

5\4	4\14	14\15	15\16	16\17	17\3	3\18	18\2	2\43
41/2	14/1	14/1	9/1	5.4/1	7.2/1	5.4/1	241/3	233/5
45/2	16/1	16/1	10/1	6/1	8/1	6/2	268/3	259/5
50/2	18/1	18/1	11/1	6.6/1	8.8/1	6.6/1	295/3	285/5

37\36	36\22	22\35	35\34	34\33	33\32	32\23	23\24	24\31
1.8/0	2.7/0	2.7/0	2.7/0	1.8/0	1.8/0	2.7/0	3.6/0	2.4/0
2/0	3/0	3/0	3/0	2/0	2/0	3/0	4/0	3/0
2.2/0	3.3/0	3.3/0	3.3/0	2.2/0	2.2/0	3.3/0	4.4/0	3.3/0

47\50	50\51	51\52	52\46	46\45	45\53	53\54	54\44	44\55
2.7/0	2.7/0	2.7/0	1.8/0	2.7/0	1.8/0	1.8/0	1.8/0	2.7/0
3/0	3/0	3/0	2/0	3/0	2/0	2/0	2/0	3/0
3.3/0	3.3/0	3.3/0	2.2/0	3.3/0	2.2/0	2.2/0	2.2/0	3.3/0

62\61	61\65	65\66	66\67	67\68	68\69	69\70	70\71	71\1
1.8/0	23/0	6.3/0	1.8/0	1.8/0	9/0	1.8/0	9/0	27/0
2/0	25/0	7/0	2/0	9/0	10/0	2/0	10/0	30/0
2.2/0	2.7/0	7.7/0	2.2/0	9.9/0	11/0	2.2/0	11/0	33/0

Best	Expected	Worst
9.8	10.9	12
0	0	0

for the selected networks are presented in Figures 44-47. The values used in the specification are obtained from technical publications as well as from specification manuals published by vendors [2], [16]-[20]. These specifications were used as input to the LAN software in the evaluation of network performance.

Using the LAN software, the message rates (in packets per second, or in bytes per second) over which the performance criteria are evaluated for the selected networks are listed in Table 8. The data shown in the Table are used as input to the software. The number under the heading "Task #" indicate the performance measure for which analytical results are generated. The tasks are numbered as follows:

Task # 1- the maximum number of nodes the network can support.

Task # 2- the maximum node data rate.

Task # 3- the average message delay.

Task # 4- the average node buffer size.

Task # 5- the network saturation message rate to a node.

The analytical results generated using inputs shown in Table 8 are plotted in Figures 48-65.

Figures 48-52 show that the maximum number of nodes a network can support are usually greater than the vendor specified node limit. Only when the user packet rate gets large (over one packet per second), or when the user bit rate (for those following the byte service scheme) gets big (over one hundred bits per second) then the network may not be able to support its specified maximum number of nodes. For CBX the

NETWORK SPECIFICATION

NETWORK NAME: ETHERNET

NETWORK RATE (IN MBPS): 10

MAXIMUM NUMBER OF NODES PER NETWORK: 1024

NUMBER OF USERS PER NODE: 1

- PACKET FORMAT -

NUMBER OF CONTROL BITS: 144

MINIMUM NUMBER OF BITS PER PACKET: 512

NUMBER OF SPACING BITS (BEHIND EACH DATA BYTE): 0

	BEST	EXPECTED	WORST
CABLE SPEED (IN METERS/NANOSECOND):	.23	.21	.19
INTERFRAME DELAY (IN MICROSECONDS):	9.6	10	10.6
COLLISION JAM TIME (IN MICROSECONDS):	3.2	4	4.8
COLLISION SENSING DELAY (IN MICROSECONDS):	.1	.2	.3
REPEATER DELAY (IN MICROSECONDS):	.2	.3	.4
AVERAGE NUMBER OF REPEATERS ENCOUNTERED/TRANS.:	1.6	1.6	1.6
NETWORK LENGTH (METERS):	363	403	443
AVG. MESSAGE TRANSMISSION DIST. (METERS):	235	261.5	288

Figure 44. Network specification of Ethernet

NETWORK SPECIFICATION

NETWORK NAME: ARCNET

NETWORK RATE (IN MBPS): 2.5

MAXIMUM NUMBER OF NODES PER NETWORK: 255

NUMBER OF USERS PER NODE: 1

- PACKET FORMAT -

NUMBER OF TOKEN BITS: 39

NUMBER OF ENQUIRY BITS: 39

NUMBER OF CONTROL BITS: 83

NUMBER OF ACKNOWLEDGE BITS: 17

MAXIMUM NUMBER OF USER DATA BITS PER PACKET: 2024

NUMBER OF SPACING BITS (BEHIND EACH DATA BYTE): 3

	BEST	EXPECTED	WORST
CABLE SPEED (IN METERS/NANOSECOND):	.19	.18	.17
BUFFER CHECK TIME (IN MICROSECONDS):	.1	.2	.3
MESSAGE CHECK TIME (IN MICROSECONDS):	.2	.3	.4
RESPONSE CHECK TIME (IN MICROSECONDS):	.2	.3	.4
REPEATER DELAY (IN MICROSECONDS):	.2	.3	.4
AVERAGE NUMBER OF REPEATERS ENCOUNTERED/TRANS.:	3.4	3.4	3.4
AVERAGE NUMBER OF REPEATERS ENCOUNTERED/PASS:	1.4	1.4	1.4
AVERAGE MESSAGE TRANS. DIST. (METERS):	192.2	213.5	234.9
AVERAGE TOKEN PASSING DIST. (METERS):	18.13	20.14	22.15

Figure 45. Network specification of Arcnet

NETWORK SPECIFICATION

NETWORK NAME: RINGNET

NETWORK RATE (IN MBPS): 8

MAXIMUM NUMBER OF NODES PER NETWORK: 247

NUMBER OF USERS PER NODE: 1

- PACKET FORMAT -

NUMBER OF TOKEN BITS: 32

NUMBER OF CONTROL BITS: 64

MAXIMUM NUMBER OF USER DATA BITS PER PACKET: 16320

NUMBER OF SPACING BITS (BEHIND EACH DATA BYTE): 0

	BEST	EXPECTED	WORST
CABLE SPEED (IN METERS/NANOSECOND):	.19	.18	.17
BUFFER CHECK TIME (IN MICROSECONDS):	.1	.2	.3
COPY MESSAGE TIME (IN MICROSECONDS):	.2	.3	.4
INTERFACE DELAY (IN MICROSECONDS):	.33	.35	.37
REPEATER DELAY (IN MICROSECONDS):	0	0	0
AVERAGE NUMBER OF REPEATERS ENCOUNTERED/TRANS.:	0	0	0
AVERAGE NUMBER OF REPEATERS ENCOUNTERED/PASS:	0	0	0
RING LENGTH (METERS):	706	784	862
AVERAGE MESSAGE TRANS. DIST. (METERS):	408.2	453.6	499
AVERAGE TOKEN PASSING DIST. (METERS):	9.8	10.9	12

Figure 46. Network specification of Ringnet

SYSTEM SPECIFICATION

NETWORK NAME: CBX

DATA RATE PER STATION (IN KBPS): 56

MAXIMUM NUMBER OF STATIONS PER NETWORK: 10000

	BEST	EXPECTED	WORST
CABLE SPEED (IN METERS/NANOSECOND):	.19	.18	.17
SWITCHING DELAY (IN MICROSECONDS):	.2	.3	.4
REPEATER DELAY (IN MICROSECONDS):	0	0	0
AVERAGE NUMBER OF REPEATERS ENCOUNTERED/TRANS.:	0	0	0
AVERAGE MESSAGE TRANS. DIST. (METERS):	193	214.9	236

Figure 47. Network specification of CBX

Table 8. Performance evaluation of LANs

Task #	Network Name	Trans. Scheme	Users /Node	Message Rate /user	Message size (user bits/pac.)	Figure #
1	Ethernet	Packet	1	.1 pac./sec.	10 - 12,000	48
1	Ethernet	Packet	1	1 pac./sec.	10 - 12,000	48
1	Ethernet	Packet	1	10 pac./sec.	10 - 12,000	48
1	Ethernet	Packet	4	.1 pac./sec.	10 - 12,000	48
1	Ethernet	Packet	4	1 pac./sec.	10 - 12,000	48
1	Ethernet	Packet	4	10 pac./sec.	10 - 12,000	48
1	Arcnet	Packet	1	.1 pac./sec.	10 - 2,024	49
1	Arcnet	Packet	1	1 pac./sec.	10 - 2,024	49
1	Arcnet	Packet	1	10 pac./sec.	10 - 2,024	49
1	Arcnet	Packet	4	.1 pac./sec.	10 - 2,024	49
1	Arcnet	Packet	4	1 pac./sec.	10 - 2,024	49
1	Arcnet	Packet	4	10 pac./sec.	10 - 2,024	49
1	Ringnet	Packet	1	.1 pac./sec.	100 - 16,320	50
1	Ringnet	Packet	1	1 pac./sec.	100 - 16,320	50
1	Ringnet	Packet	1	10 pac./sec.	100 - 16,320	50
1	Ringnet	Packet	4	.1 pac./sec.	100 - 16,320	50
1	Ringnet	Packet	4	1 pac./sec.	100 - 16,320	50
1	Ringnet	Packet	4	10 pac./sec.	100 - 16,320	50
1	Arcnet	Byte	1	1-1000 bytes/s	—	51
1	Arcnet	Byte	4	1-1000 bytes/s	—	51
1	Ringnet	Byte	1	1-1000 bytes/s	—	52
1	Ringnet	Byte	4	1-1000 bytes/s	—	52
2	Ethernet	Packet	-	—	10 - 12,000	53
2	Arcnet	Packet	-	—	1 - 2,024	54
2	Ringnet	Packet	-	—	10 - 16,320	55
2	CBX	Packet	-	—	1 - 56,000	56
3	Ethernet	Packet	1	.001-.01 p/s[a]	368	57a
3	Ethernet	Packet	4	.001-.01 p/s	368	57a
3	Ethernet	Packet	1	.001-.01 p/s	12,000	57b
3	Ethernet	Packet	4	.001-.01 p/s	12,000	57b
3	Arcnet	Packet	1	.001- 100 p/s	368	58
3	Arcnet	Packet	4	.001- 100 p/s	368	58
3	Arcnet	Packet	1	.001- 100 p/s	2,024	58
3	Arcnet	Packet	4	.001- 100 p/s	2,024	58
3	Ringnet	Packet	1	.001- 100 p/s	368	59
3	Ringnet	Packet	4	.001- 100 p/s	368	59
3	Ringnet	Packet	1	.001- 100 p/s	16,320	59
3	Ringnet	Packet	4	.001- 100 p/s	16,320	59

---

[a] Packets/second.

Table 8. (continued)

Task #	Network Name	Trans. Scheme	Users /Node	Message Rate /user	Message size (user bits/pac.)	Figure #
3	Arcnet	Byte	1	1-1000 bytes/s	—	60
3	Arcnet	Byte	4	1-1000 bytes/s	—	60
3	Ringnet	Byte	1	1- 300 bytes/s	—	61
3	Ringnet	Byte	4	1- 300 bytes/s	—	61
4	Arcnet	Byte	1	1-4000 bytes/s	—	62
4	Arcnet	Byte	4	1- 400 bytes/s	—	62
5	Ethernet	Packet	-	—	10 - 12,000	63
5	Arcnet	Packet	-	—	1 - 2,024	64
5	Ringnet	Packet	-	—	10 - 16,320	65

number of stations the network can support is always 10,000, the message rate for each station is always 56,000 bits per second (Figure 56). Figures 53-55 show that the maximum node data rate gets large when the number of user bits per packet gets large. Therefore, an efficient way in utilizing most of the capacity offered by the network is to transmit long packets. Figure 57 show that the average message delay of Ethernet is sensitive to variation in network length. For the longer the distance a message signal has to propagate before being detected by all nodes of the network, the larger the collision contention period will become. Therefore in the configuration of Ethernet, the shorter the network length the smaller the average message delay its nodes will get. The average message delay of Arcnet and Ringnet are lower bounded by the propagation time of the token around the logical ring (Figures 58-61). So for Ringnet, the shorter the ring length the smaller its average message delay will become. Whereas for Arcnet, the shorter the average token passing distance the better its delay performance will become. Figure 62 shows the average node buffer size of Arcnet under various user message load. It demonstrates that at user message rates of less than 100 bits/sec. there is no significant amount of data in a node's buffer. For Ethernet and Ringnet the network saturation message rate stays constant when the user bits per packet is small (Figures 63 and 65). This is due to the fact that Ethernet has a specified minimum packet size and the message transmission protocol of Ringnet is such that a node can not pass the token until the recovery of its packet header (if it has completed transmitting before the physical header has propagated once

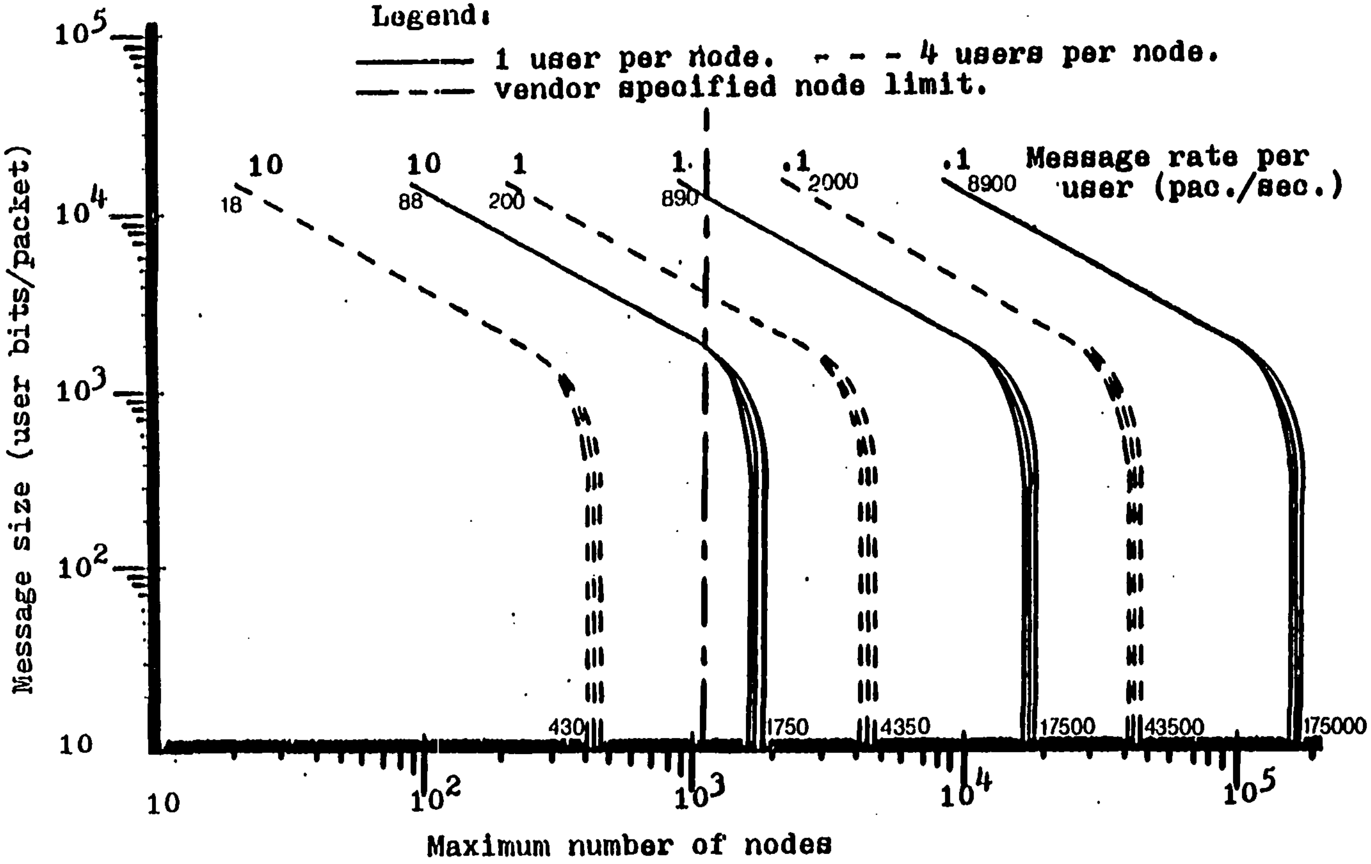


Figure 48. Ethernet - the maximum number of nodes the network can support Vs message size

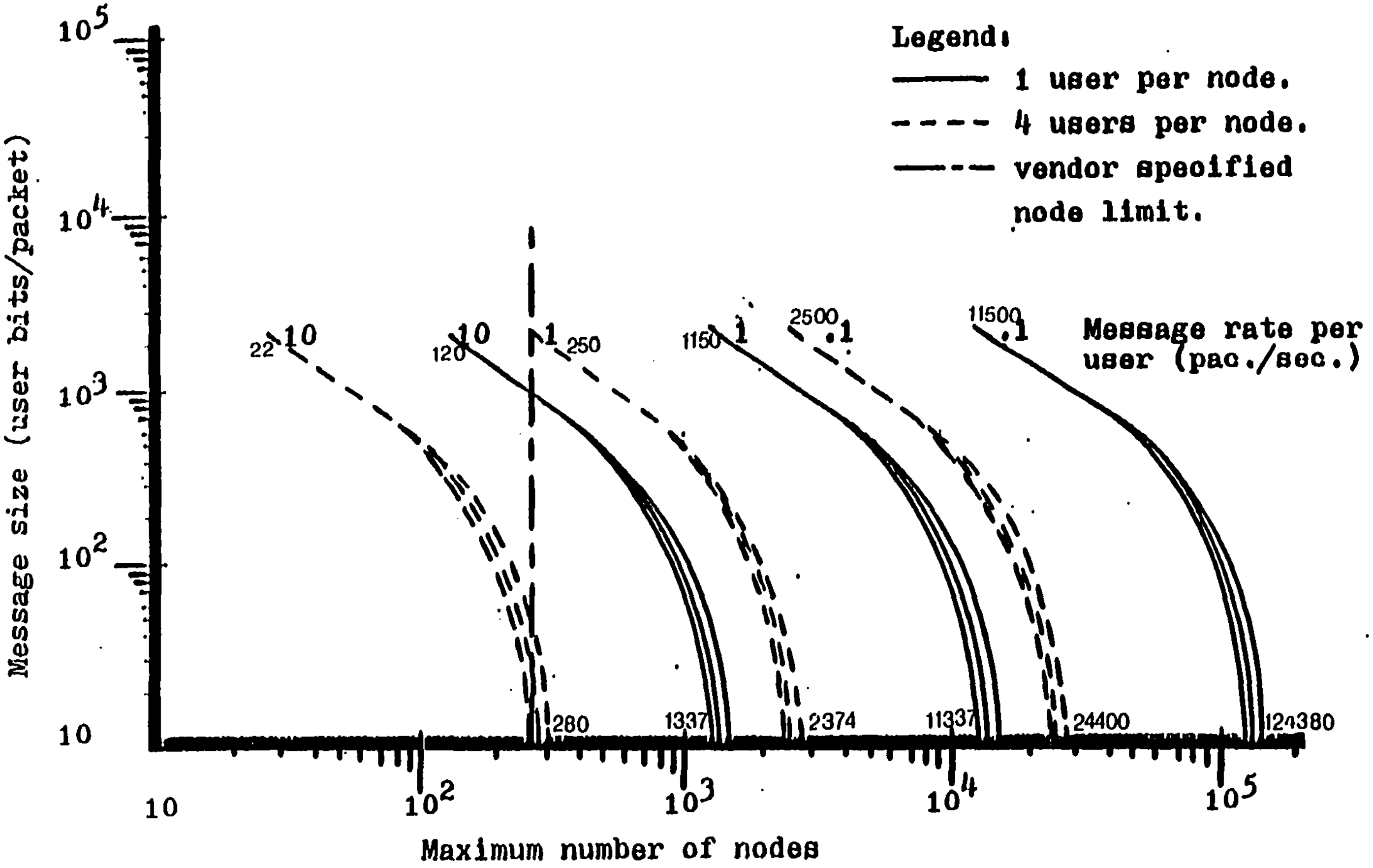


Figure 49. Arcnet - the maximum number of nodes the network can support Vs message size

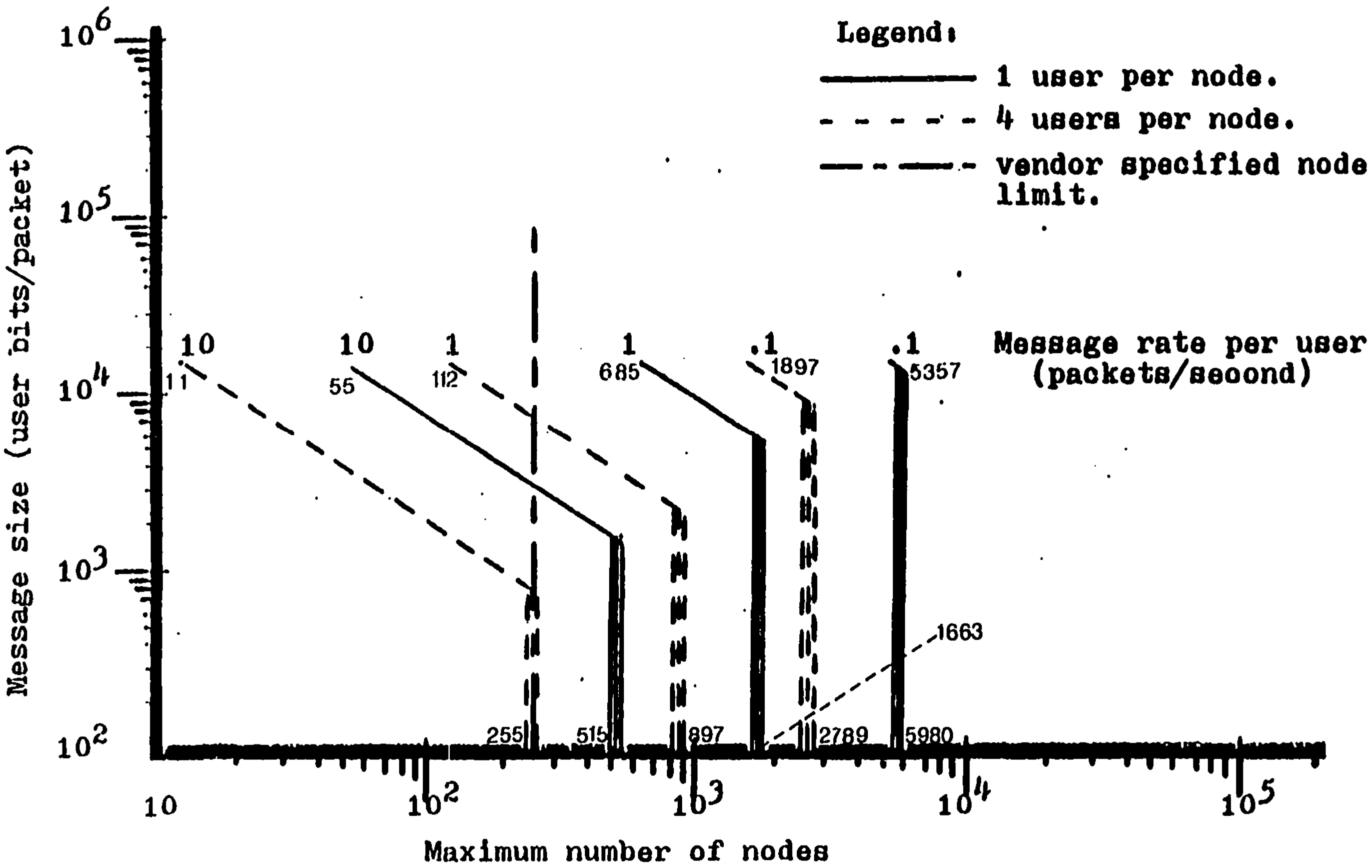


Figure 50. Ringnet - maximum number of nodes the network can support Vs message size

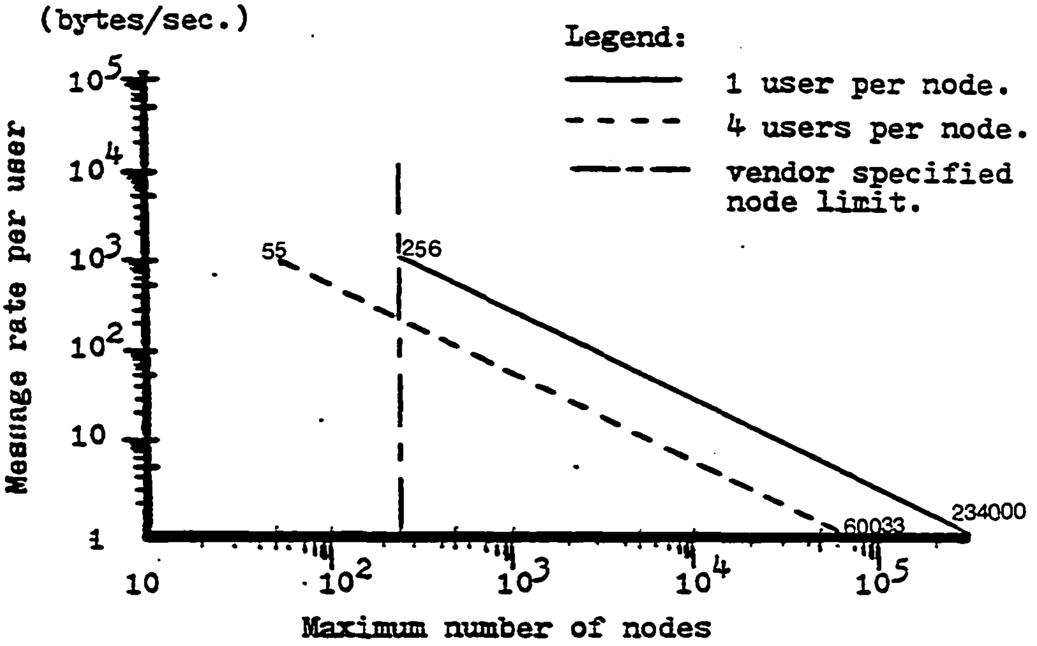


Figure 51. Arcnet - maximum number of nodes Vs user message rate

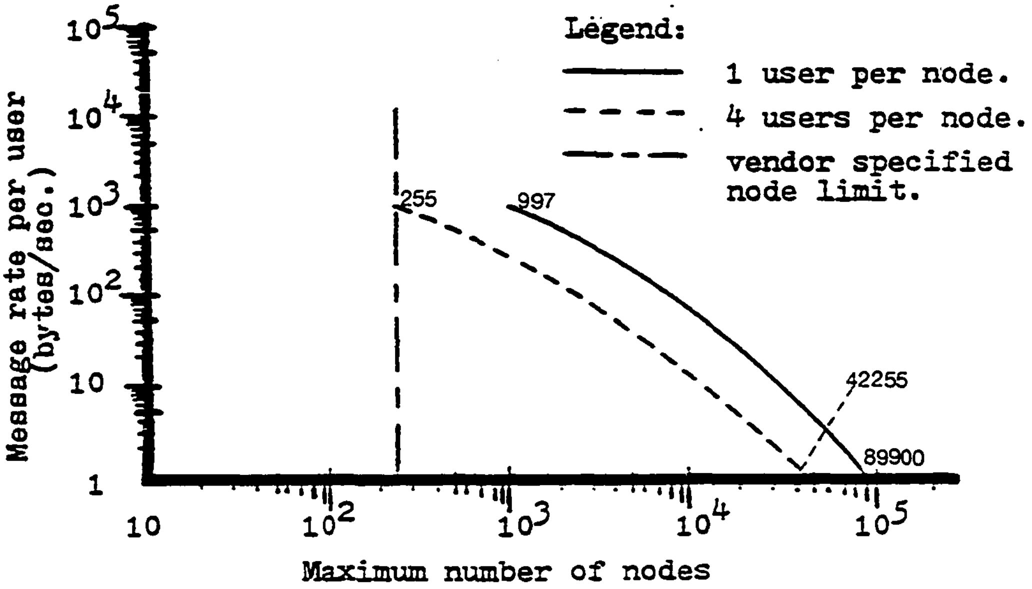


Figure 52. Ringnet - maximum number of nodes Vs user message rate

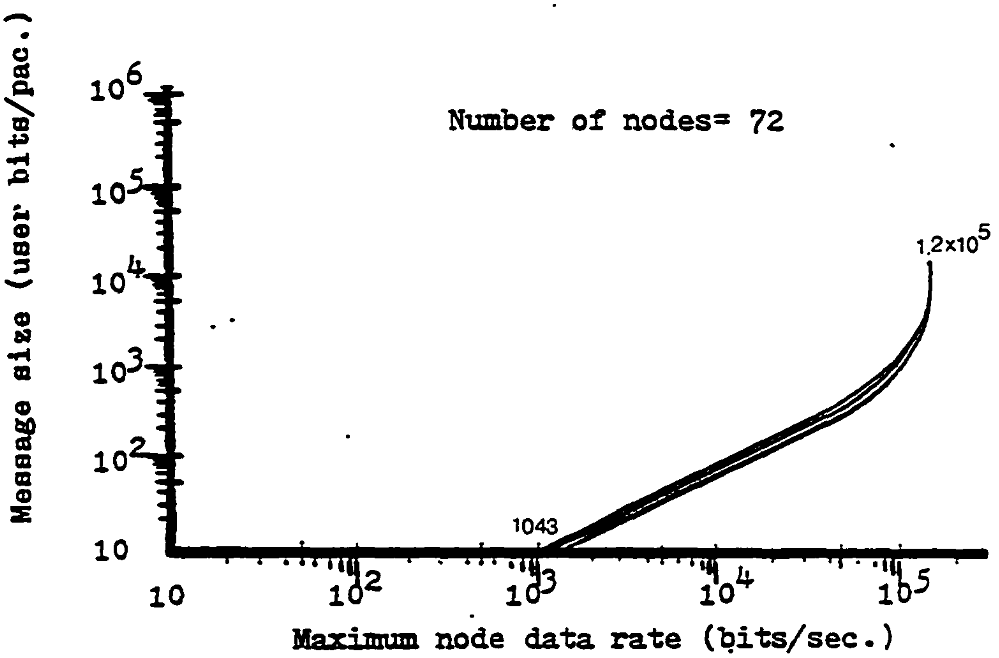


Figure 53. Ethernet - maximum node data rate Vs message size

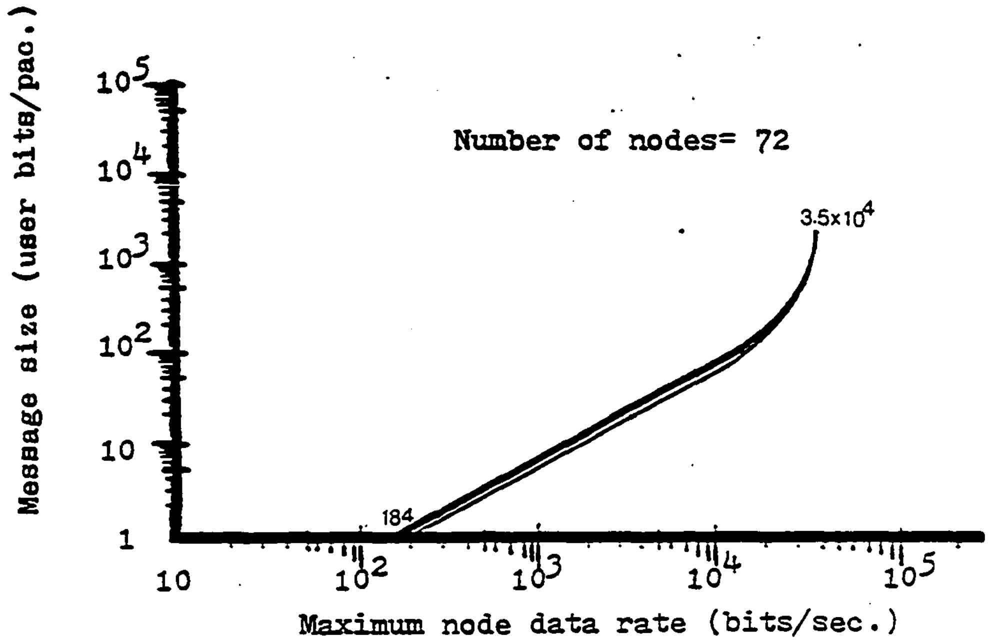


Figure 54. Arcnet - maximum node data rate Vs message size

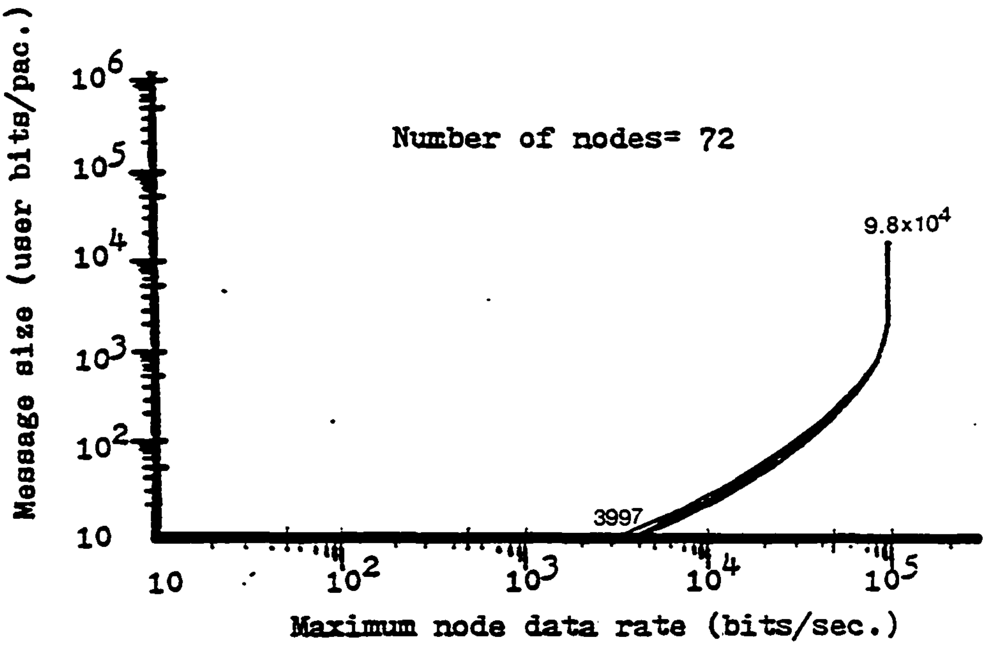


Figure 55. Ringnet - maximum node data rate Vs message size

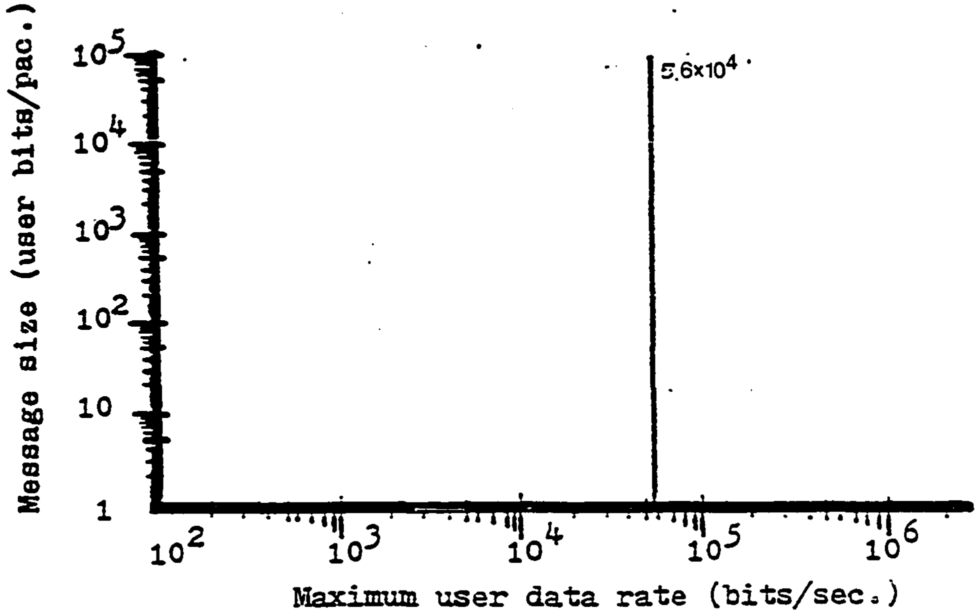


Figure 56. User data rate of CBX

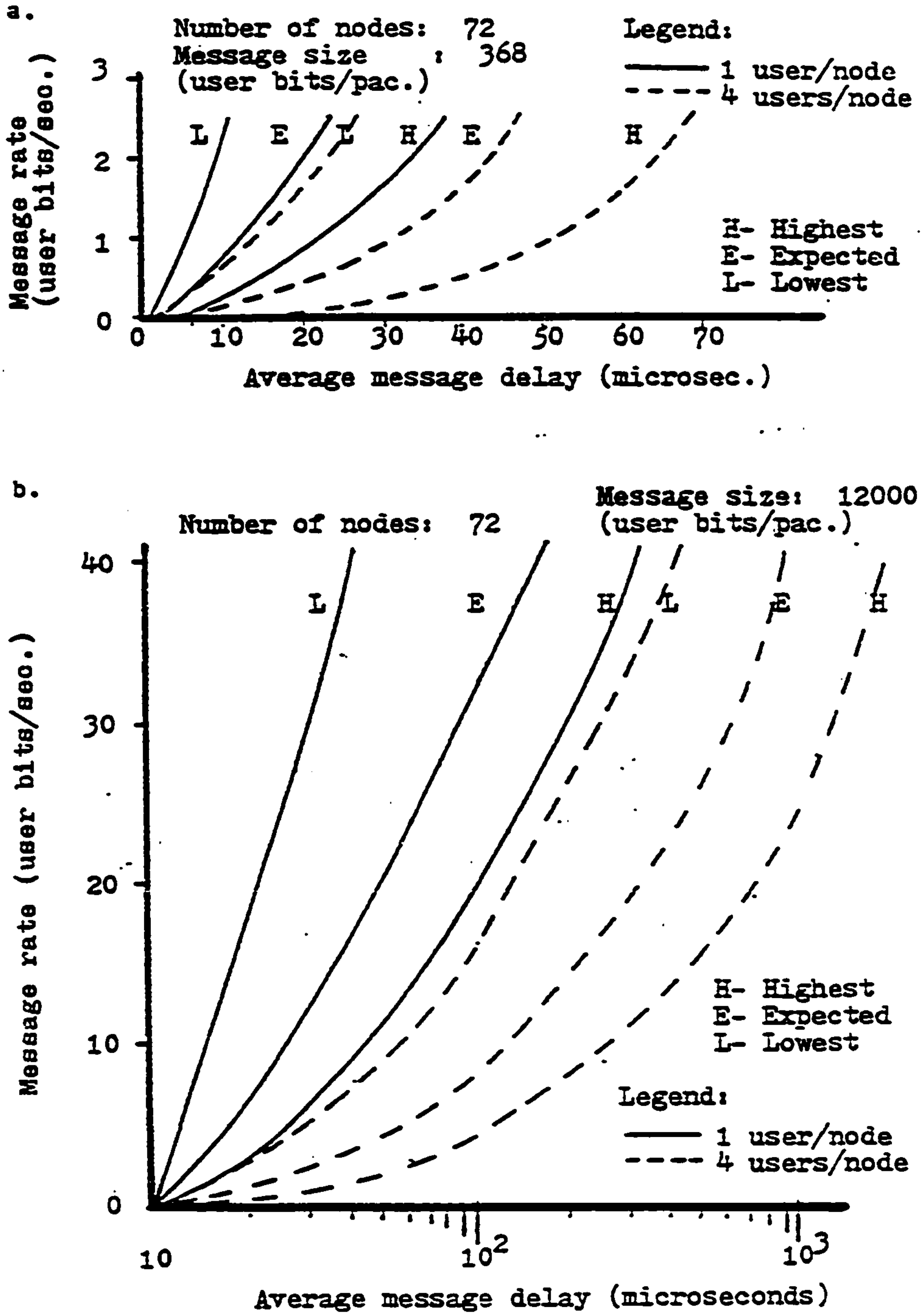


Figure 57. Ethernet - average message delay Vs user message rate
a. Short packet
b. Long packet

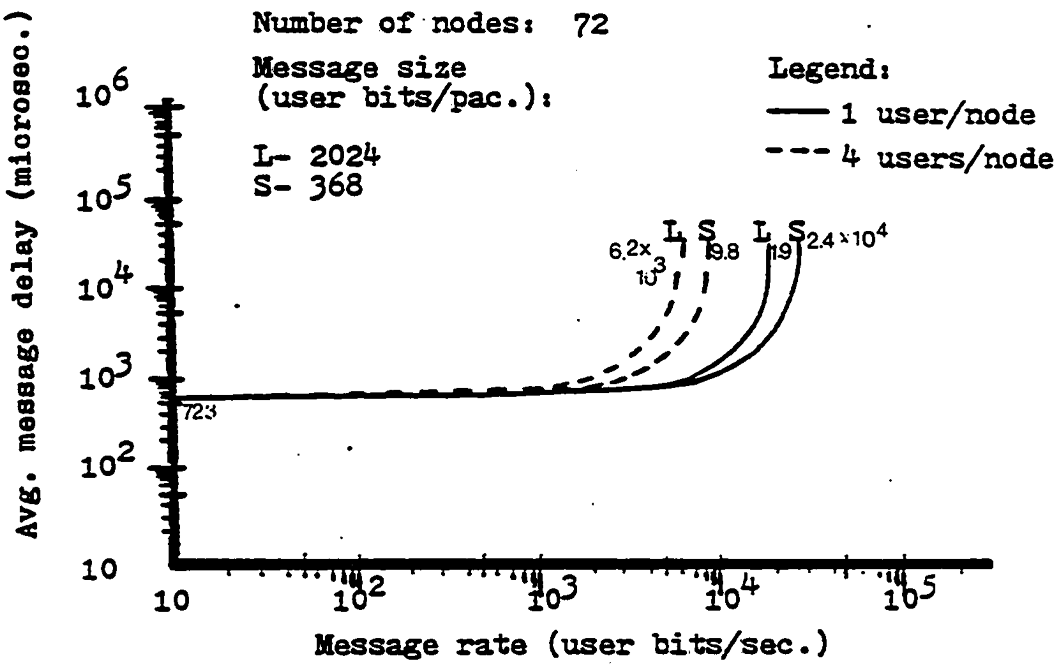


Figure 58. Arcnet - Average message delay Vs user message rate (Packet scheme)

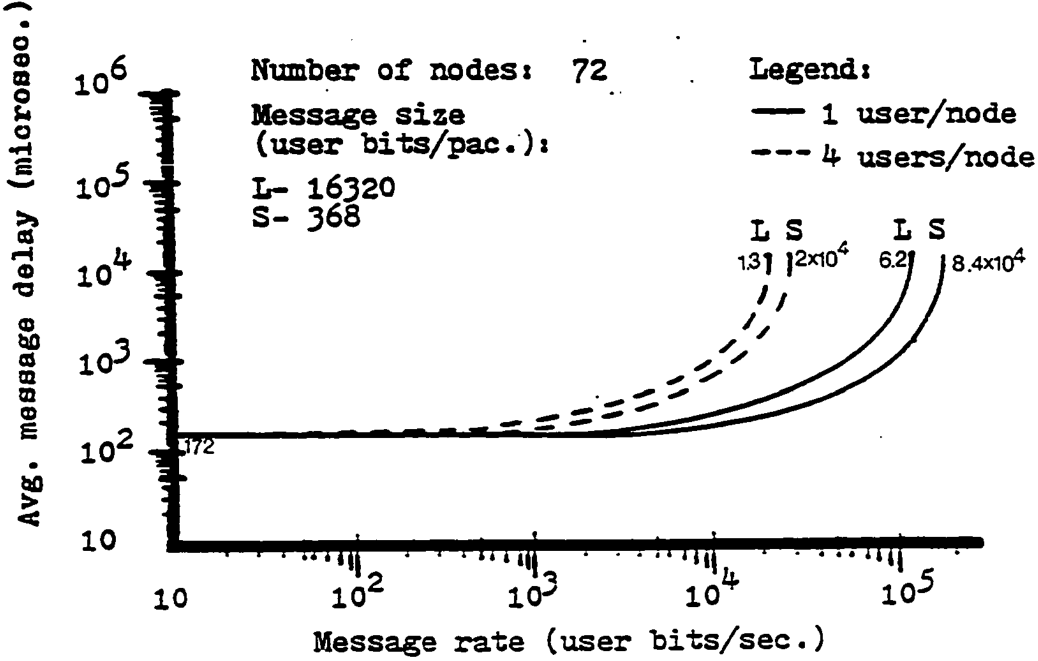


Figure 59. Ringnet - average message delay Vs user message rate (Packet scheme)

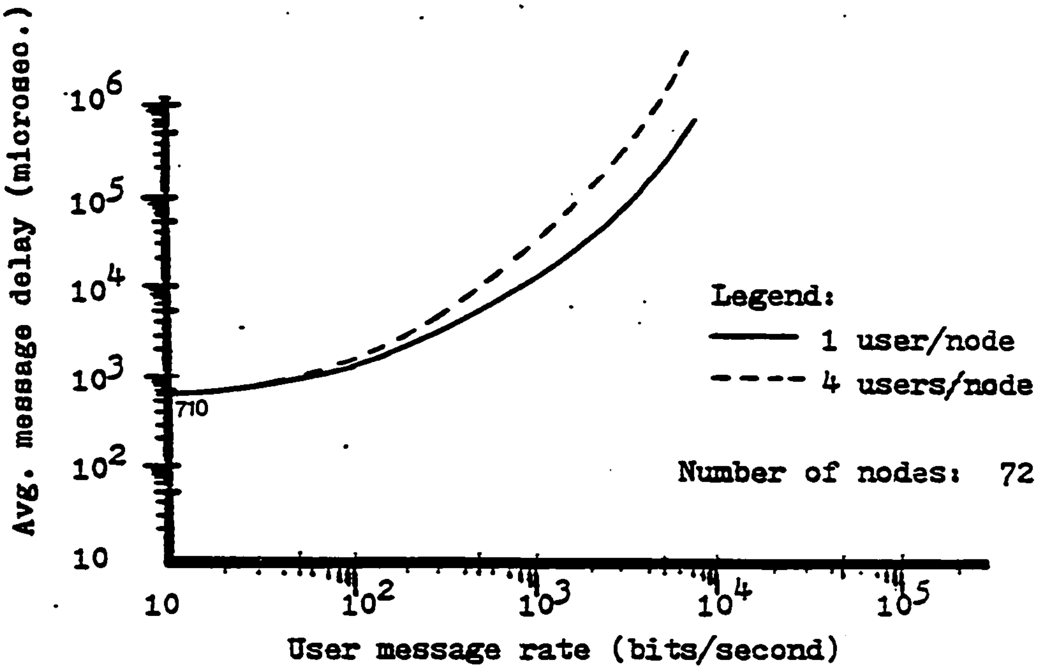


Figure 60. Arcnet - average message delay Vs user message rate (byte scheme)

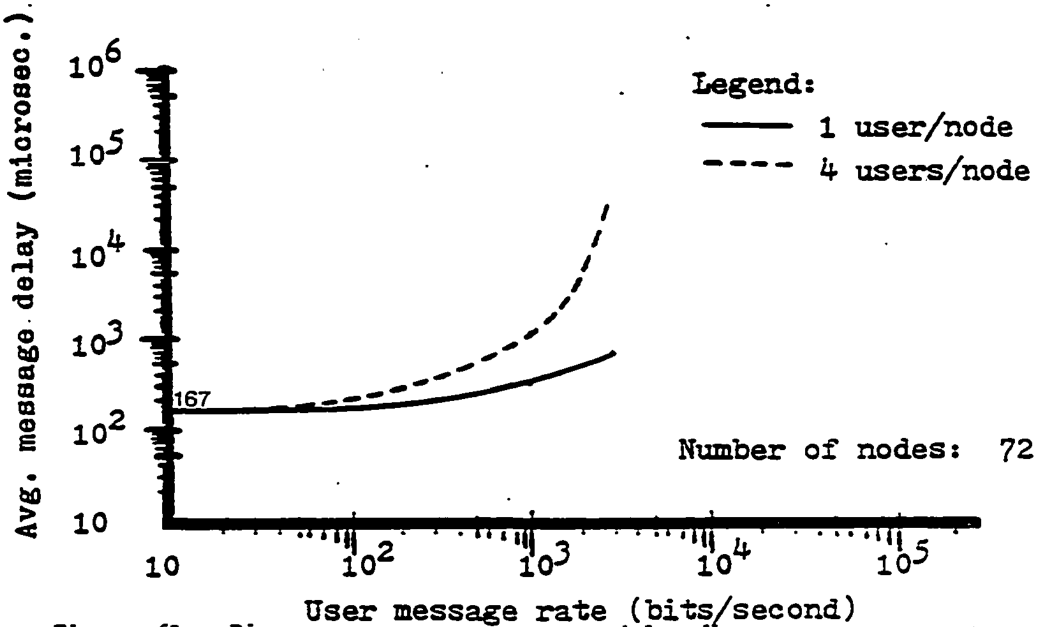


Figure 61. Ringnet - average message delay Vs user message rate (byte scheme)

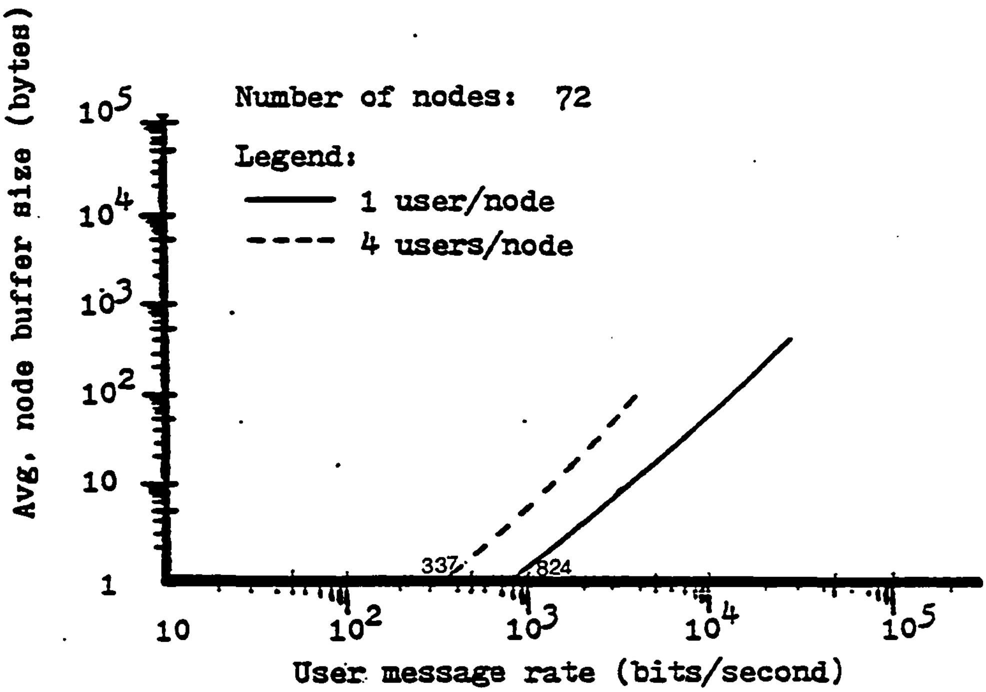


Figure 62. Arcnet - average node buffer size Vs user message rate

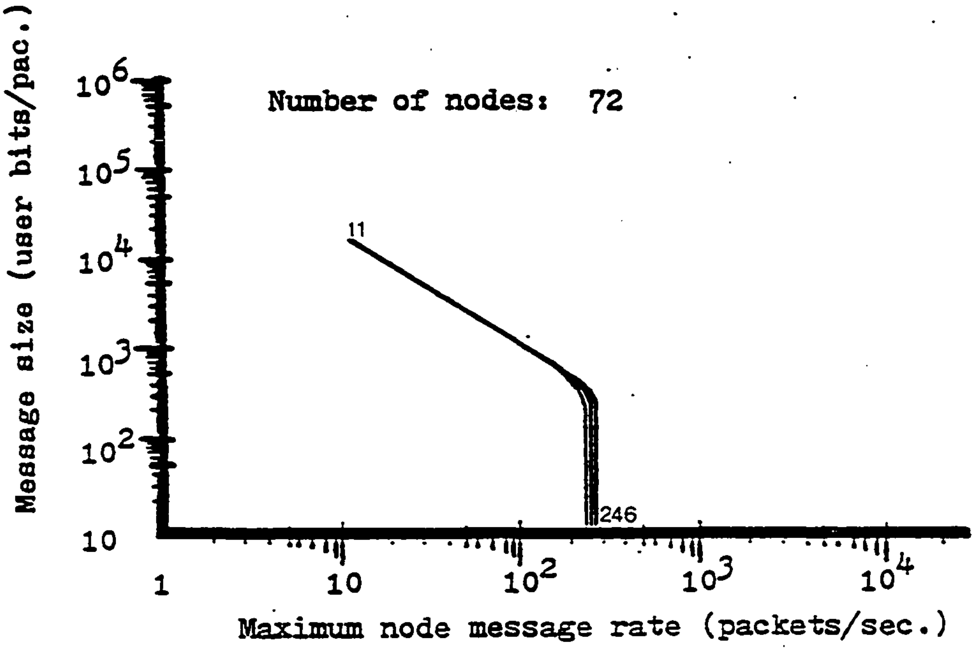


Figure 63. Ethernet - maximum node message rate Vs message size

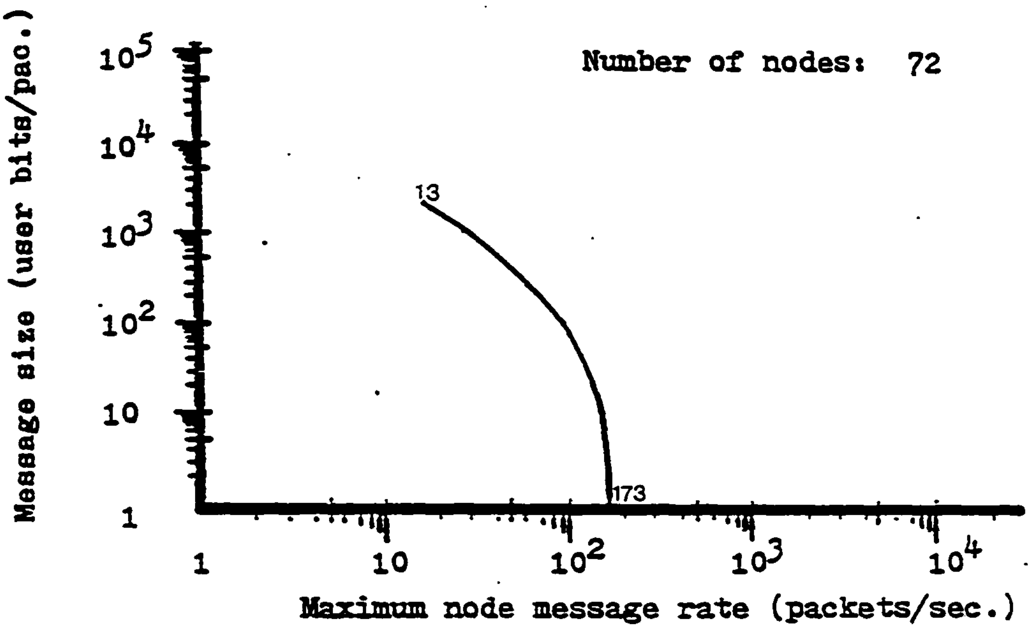


Figure 64. Arcnet - maximum node message rate Vs message size

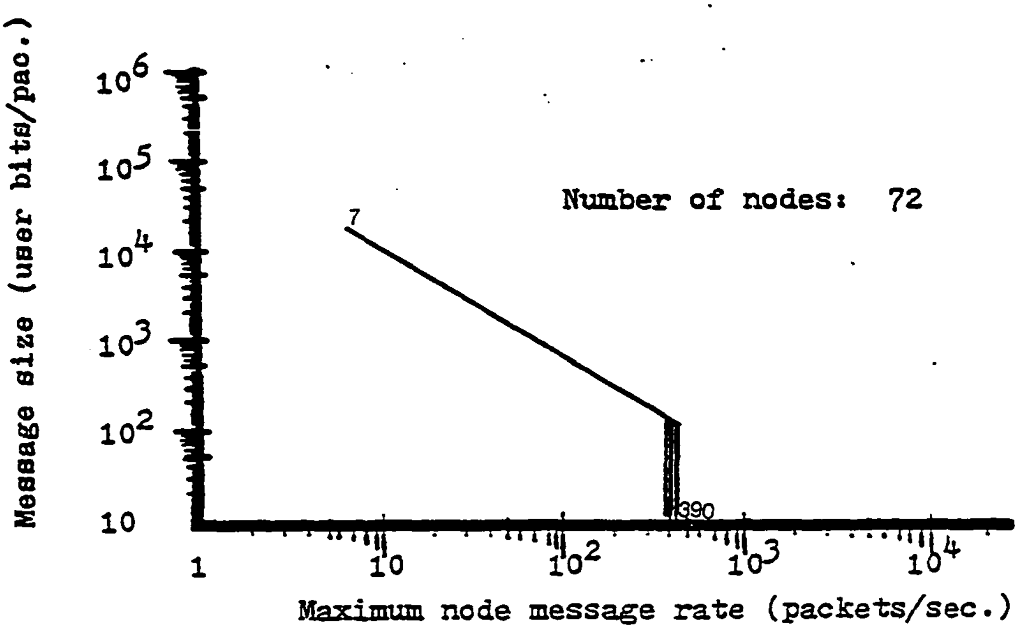


Figure 65. Ringnet - maximum node message rate Vs message size

around the ring). For all networks, the network saturation message rate gets small as the message size gets large (Figures 63-65).

Networking of Nodes on A University Campus

The connection of nodes scattered over the Iowa State University Main Campus (Figure 66) requires internetworking of several networks. For nodes that are located in the same building, a network is installed to network those nodes (like the case of networking nodes in the Electrical and Computer Engineering Building). For each network, one node serves the functions of a "Bridge" (Figure 67) for message communications between nodes of that network with nodes of other networks. A backbone network connects all bridges (Figures 68-71). It serves the functions of a data link in internetworking all networks on campus. Each network operates independently from others. A message that is destined for a node on another network is first transmitted by the sender to a bridge (connected to the same network as the sender). There the message is queued with other packets until its turn for transmission over the backbone to the receiver's bridge, where the message may once again be queued until its turn for transmission to the receiver.

In evaluating network performance, the software tool is applied (using the same procedure shown in the previous section) in measuring performance of individual networks (including the backbone network). The average message delay of messages destined for a node on another network, is the sum of the average message delay for messages transmitted over the

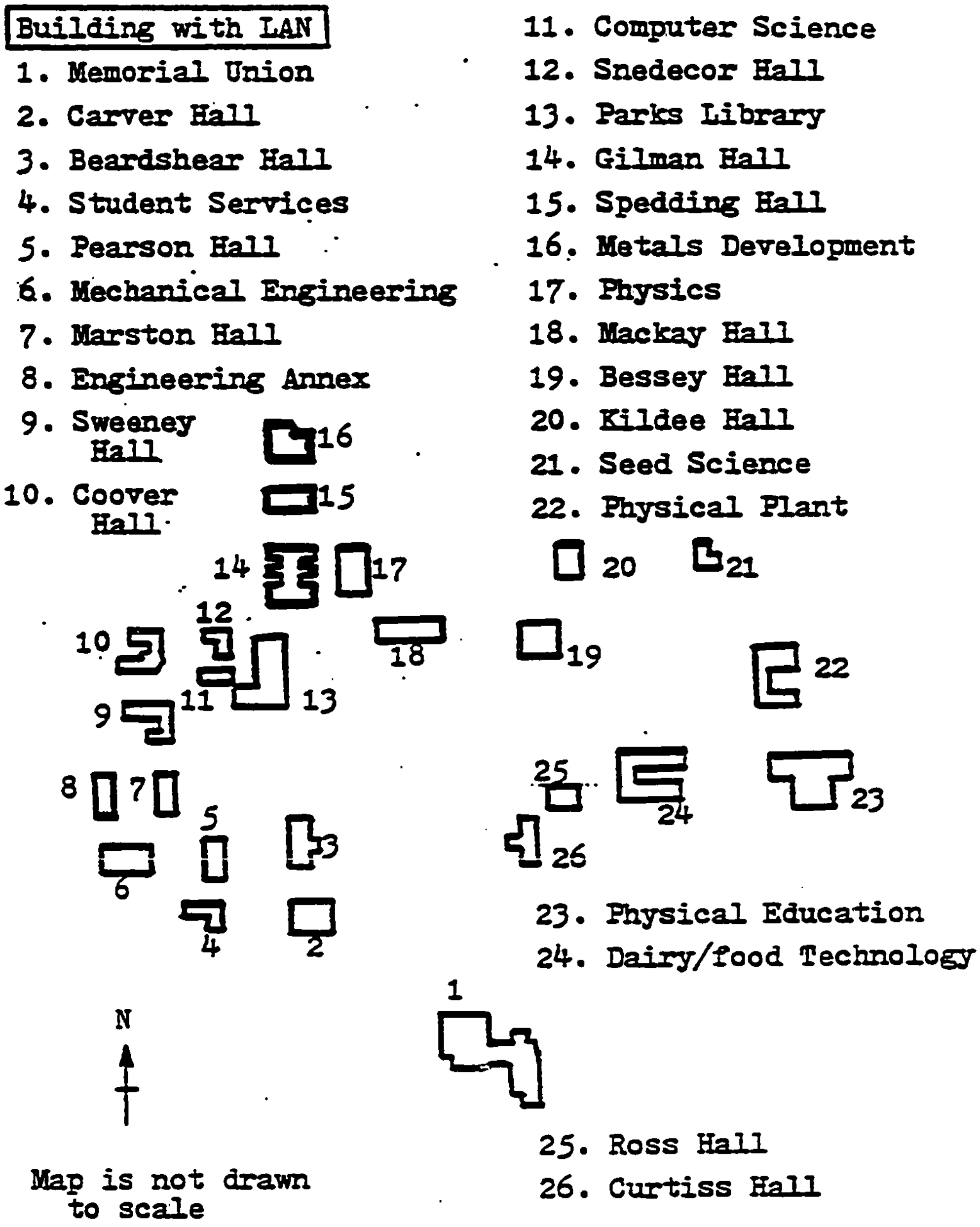

Building with LAN
1. Memorial Union
2. Carver Hall
3. Beardshear Hall
4. Student Services
5. Pearson Hall
6. Mechanical Engineering
7. Marston Hall
8. Engineering Annex
9. Sweeney Hall
10. Coover Hall
11. Computer Science
12. Snedecor Hall
13. Parks Library
14. Gilman Hall
15. Spedding Hall
16. Metals Development
17. Physics
18. Mackay Hall
19. Bessey Hall
20. Kildee Hall
21. Seed Science
22. Physical Plant
23. Physical Education
24. Dairy/food Technology
25. Ross Hall
26. Curtiss Hall
16
15
14
17
20
21
12
10
18
19
22
9
11
13
8
7
25
24
23
5
3
26
6
4
2
1
N
Map is not drawn to scale

Figure 66. Iowa State University campus map

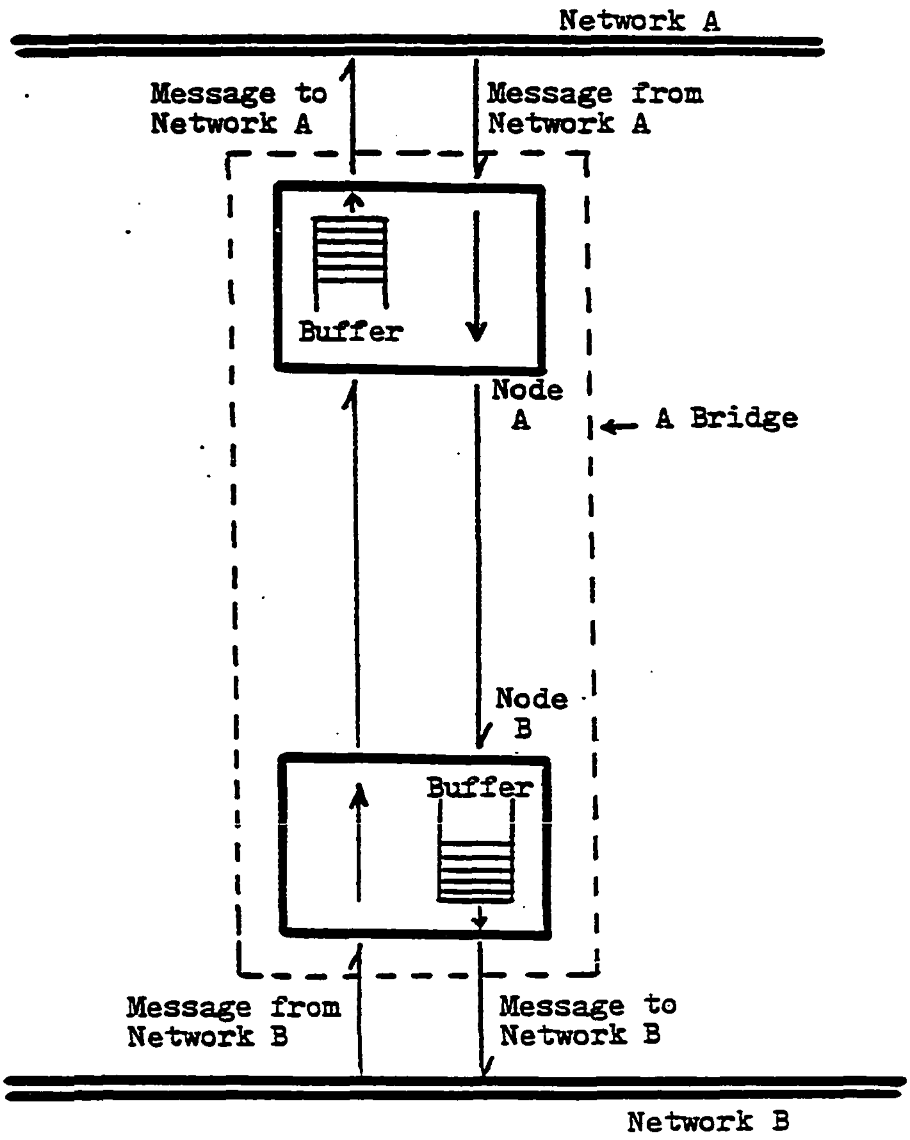
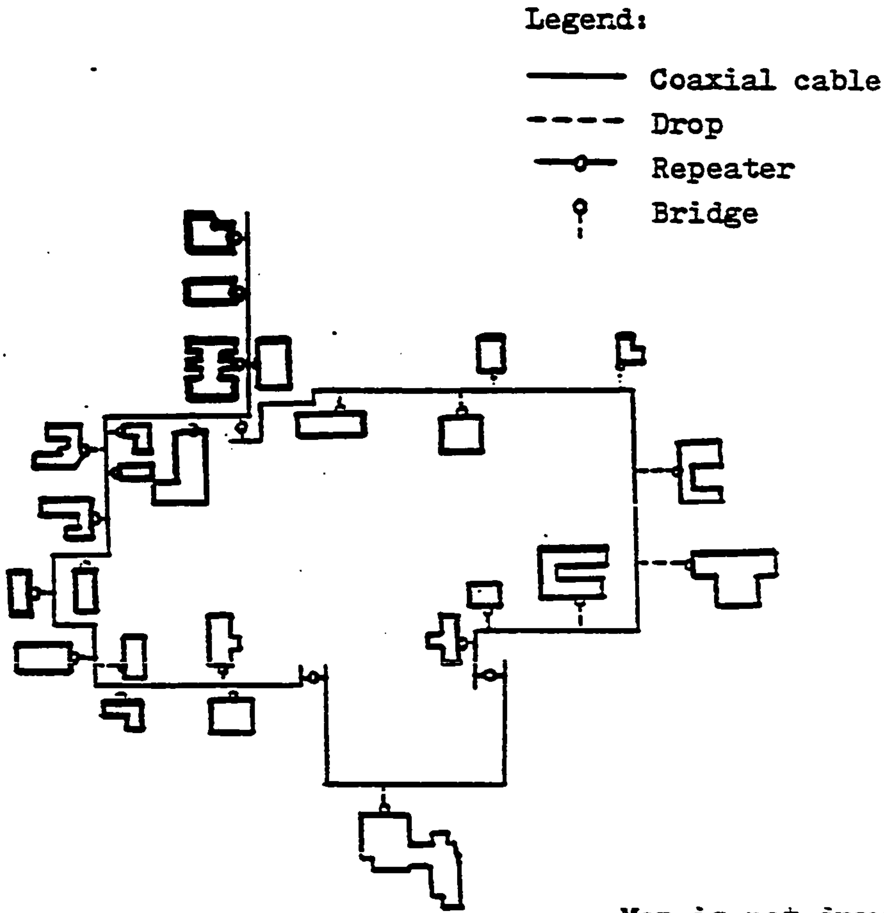

Network A
Message to Network A
Message from Network A
Buffer
Node A
A Bridge
Node B
Buffer
Message from Network B
Message to Network B
Network B

Figure 67. A bridge


Legend:
Coaxial cable
Drop
Repeater
Bridge

Map is not drawn
to scale

Figure 68. Configuration of Ethernet as the backbone network

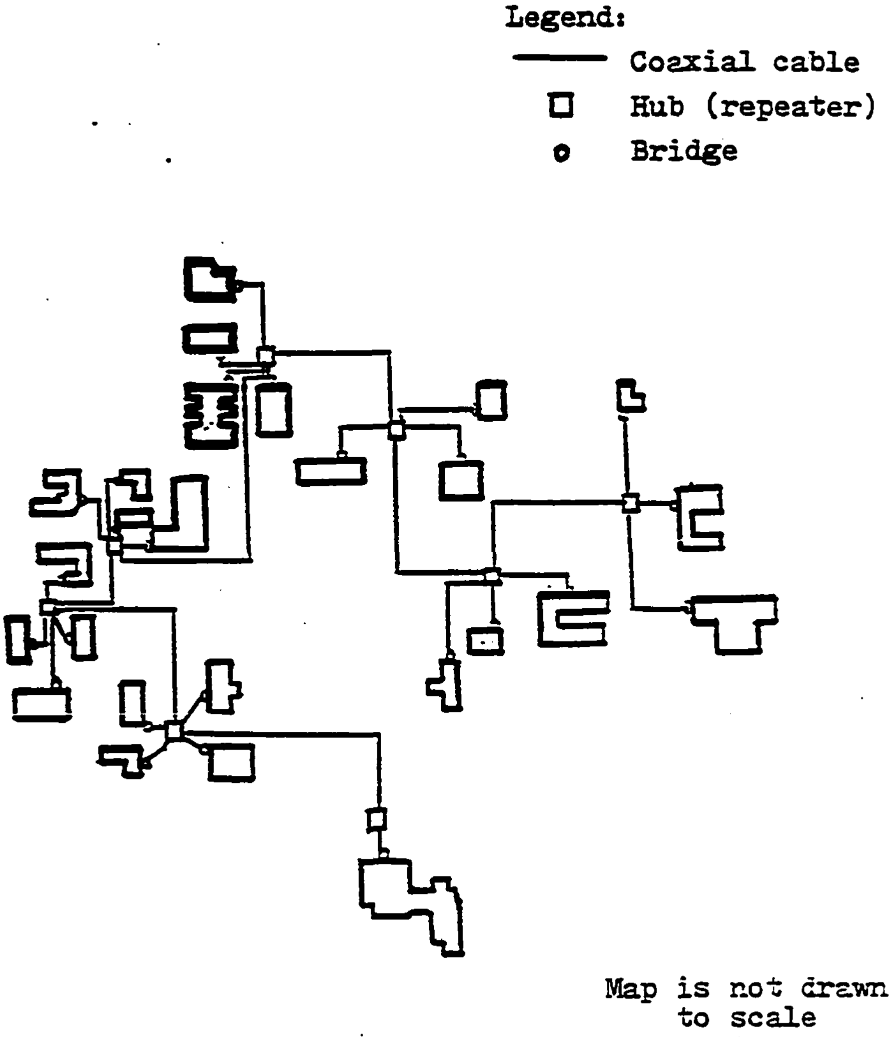
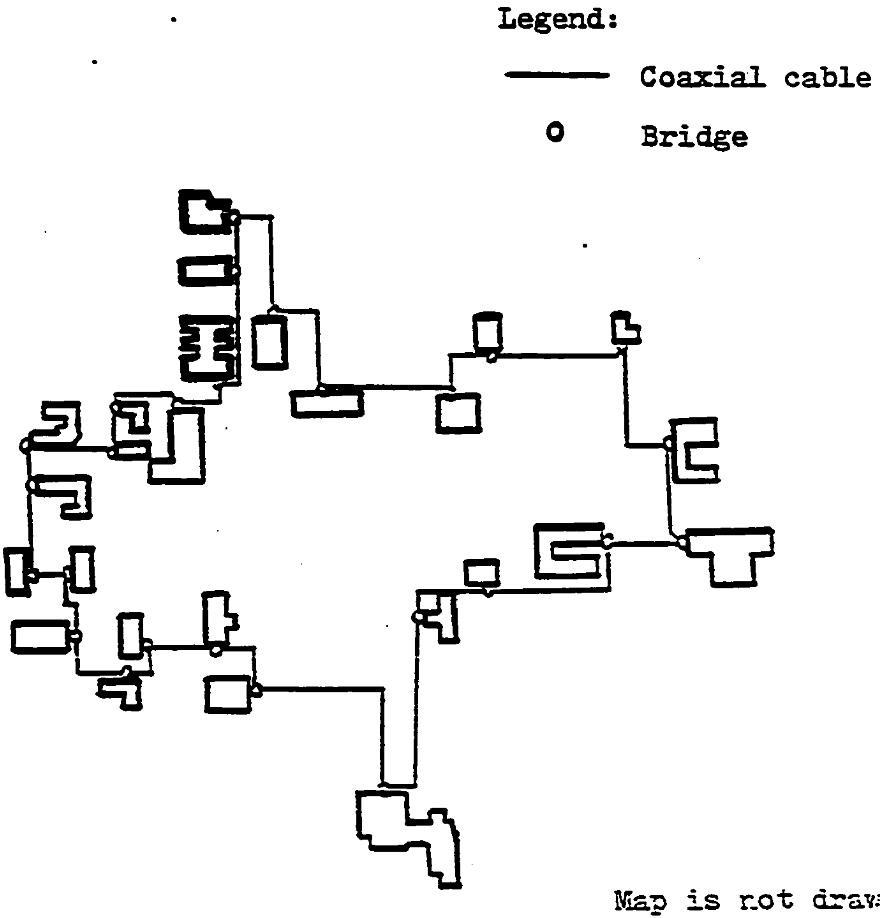

Legend:
Coaxial cable
☐ Hub (repeater)
● Bridge
Map is not drawn to scale

Figure 69. Configuration of Arcnet as the backbone network


Legend:
Coaxial cable
Bridge

Map is not drawn
to scale

Figure 70. Configuration of Ringnet as the backbone network

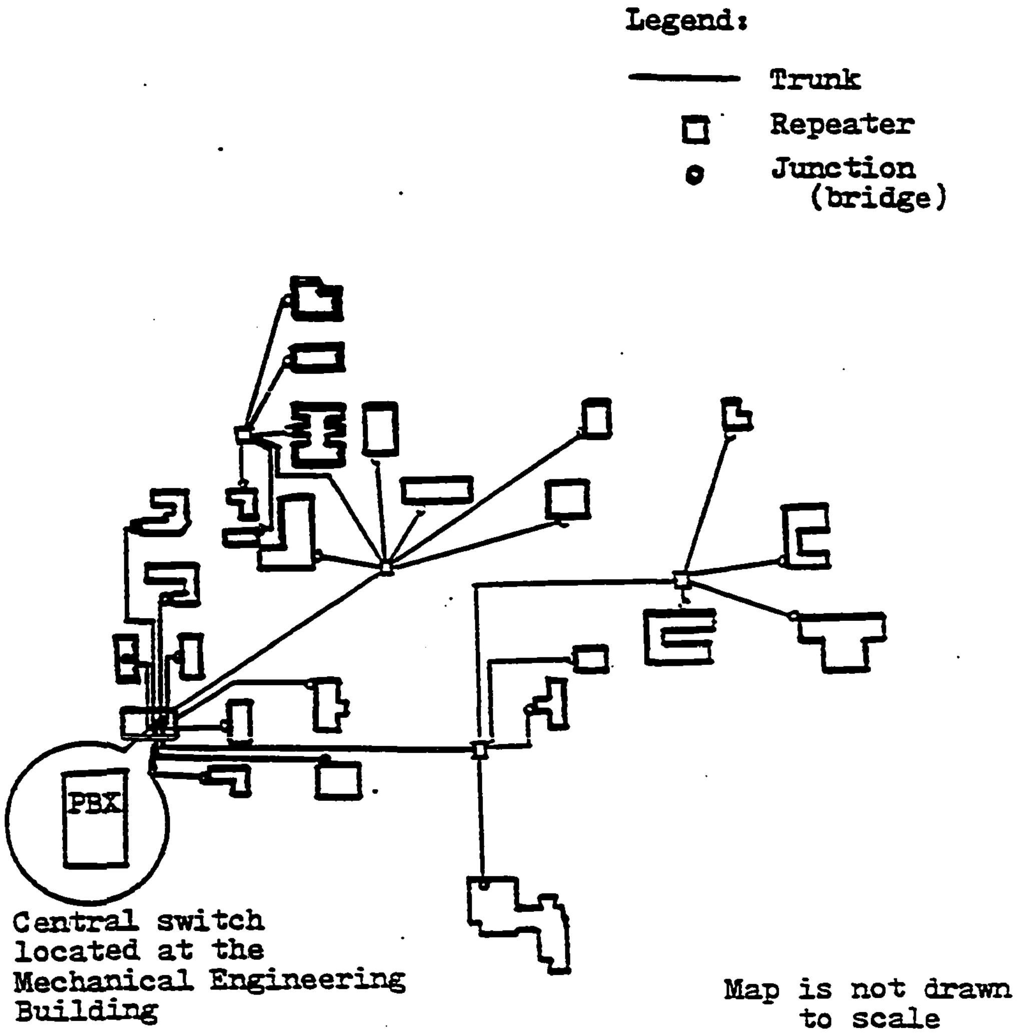

Legend:
Trunk
Repeater
Junction (bridge)
PBX
Central switch located at the Mechanical Engineering Building
Map is not drawn to scale

Figure 71. Configuration of CBX as the backbone network

sender's network, plus the average message delay for messages transmitted over the backbone, plus the average message delay for messages transmitted over the receiver's network (Figure 72). So, for example, if the average message delay on the backbone is double that of the network installed in the various buildings, the overall delay of a message destined to a node in another building is about four times that of a message destined for a node in the same building.

In the next chapter, analytical results that are generated here are used for the performance comparison of the selected networks.

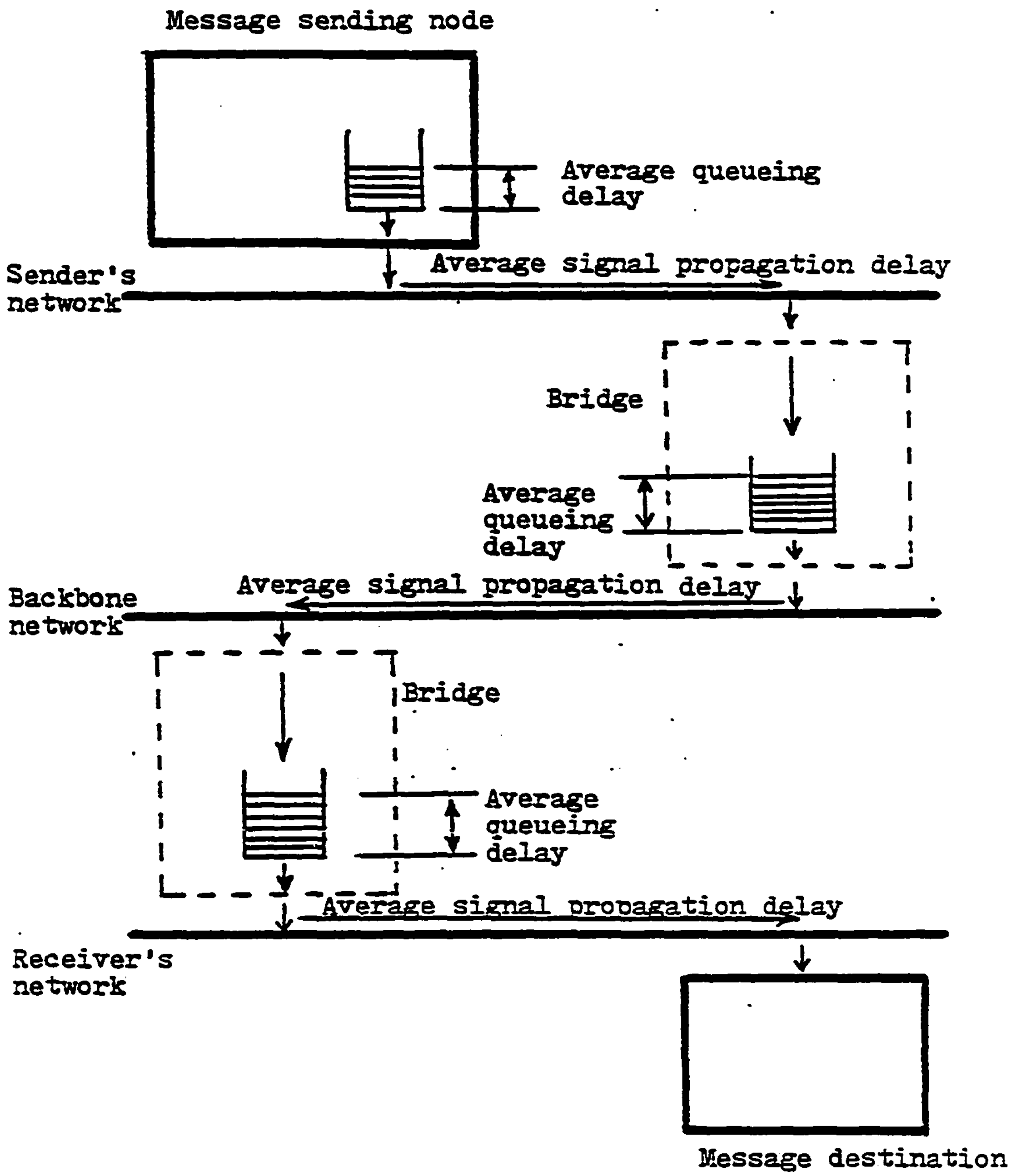

Message sending node
Average queueing delay
Average signal propagation delay
Sender's network
Bridge
Average queueing delay
Average signal propagation delay
Backbone network
Bridge
Average queueing delay
Average signal propagation delay
Receiver's network
Message destination

Figure 72. "Internetworking" average message delay

CHAPTER VI. PERFORMANCE COMPARISON

The analytical results generated in Chapter V for the selected LANs (Ethernet, Arcnet, Ringnet, and CBX) are compared in the first section. The message sizes and rates over which the performance criteria are compared are listed in Table 9. The comparisons are plotted in Figures 73-82. In the second section, the analytical results are compared with either measured or approximated results. The validity of the developed analytical models is discussed.

Performance Comparison of LANs

The data shown in Table 9 are used as input to the LAN software for the generation of analytical results in the comparison among selected LANs. The comparisons are commented as follows:

- Figure 73 demonstrates that at the user packet rate of .1 packets per second, Ethernet supports the most number of nodes at network saturation than Arcnet, CBX, or Ringnet. However, except for CBX, all analytical results on maximum number of nodes the network can support are much greater than the vendor specified node limit. So if the vendor specification is to be strictly followed, CBX will support the most number of nodes. In Figure 74, the user packet rate is 1 packet per second. Analytically, Ethernet supports the most number of nodes when the message size is between 1 to 2100 bits; above this CBX supports the most number of nodes. Again, the analytical

Table 9. Performance Comparison of LANs

Comparison #	Task #	Network Name	Trans. Scheme	Message Rate /User	Message Size (user bits/pac.)	Figure #
1	1	Ethernet	Packet	.1 pac./sec.	10 - 12,000	73
1	1	Arcnet	Packet	.1 pac./sec.	10 - 2,024	73
1	1	Ringnet	Packet	.1 pac./sec.	10 - 16,320	73
1	1	CBX	Packet	.1 pac./sec.	10 - 56,000	73
2	1	Ethernet	Packet	1 pac./sec.	10 - 12,000	74
2	1	Arcnet	Packet	1 pac./sec.	10 - 2,024	74
2	1	Ringnet	Packet	1 pac./sec.	10 - 16,320	74
2	1	CBX	Packet	1 pac./sec.	10 - 56,000	74
3	1	Ethernet	Packet	10 pac./sec.	10 - 12,000	75
3	1	Arcnet	Packet	10 pac./sec.	10 - 2,024	75
3	1	Ringnet	Packet	10 pac./sec.	10 - 16,320	75
3	1	CBX	Packet	10 pac./sec.	10 - 56,000	75
4	1	Arcnet	Byte	1-30000 bytes/s	—	76
4	1	Ringnet	Byte	1-90000 bytes/s	—	76
4	1	CBX	Byte	1- 7000 bytes/s	—	76
5	2	Ethernet	Packet	—	10 - 12,000	77
5	2	Arcnet	Packet	—	10 - 2,024	77
5	2	Ringnet	Packet	—	10 - 16,320	77
5	2	CBX	Packet	—	10 - 56,000	77
6	3	Ethernet	Packet	.001-.01 p/s[a]	2,000	78
6	3	Arcnet	Packet	.001-.01 p/s	2,000	78
6	3	Ringnet	Packet	.001-.01 p/s	2,000	78
7	3	Arcnet	Byte	1- 1000 bytes/s	—	79
7	3	Ringnet	Byte	1- 5000 bytes/s	—	79
7	3	CBX	Byte	1- 7000 bytes/s	—	79
8	4	Arcnet	Byte	1- 4000 bytes/s	—	80
8	4	Ringnet	Byte	1- 6000 bytes/s	—	80
8	4	CBX	Byte	1- 7000 bytes/s	—	80
9	5	Ethernet	Packet	—	1 - 12,000	81
9	5	Arcnet	Packet	—	1 - 2,024	81
9	5	Ringnet	Packet	—	1 - 16,320	81
9	5	CBX	Packet	—	1 - 56,000	81
10	5	Arcnet	Byte	—	—	82
10	5	Ringnet	Byte	—	—	82
10	5	CBX	Byte	—	—	82

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[a] Packets/second.

results are greater than the vendor specified node limit. In Figure 75, the user packet rate is 10 packets per second. CBX now supports the most number of nodes when the message size is less than or equal to 5,600 bits; above this Ethernet supports the most number of nodes. The analyical results indicate that the networks may not be able to support as many nodes as specified when the message size gets large.

- Figure 76 shows that among the selected networks that follow the byte service scheme, CBX supports the most nodes when the user message rate is between 1 to 56,000 bits per second; above this Ringnet supports the most nodes.
- Figure 77 demonstrates that Ethernet provides each node of the network with the highest maximum node data rate at network saturation when the number of user bits per transmission is above 1000 bits. When the number of user bits per transmission is between 210-1000 bits, Ringnet provides the highest maximum node data rate. When the number of user bits per transmission is below 210 bits, CBX provides the highest maximum node data rate.
- Figure 78 presents the average message delay of networks following the packet service scheme, at a user packet rate of .001 to .01 packets/second (with message size of 2000 user bits per packet). At this range of user packet rate, Ethernet has better delay performance than Arcnet and

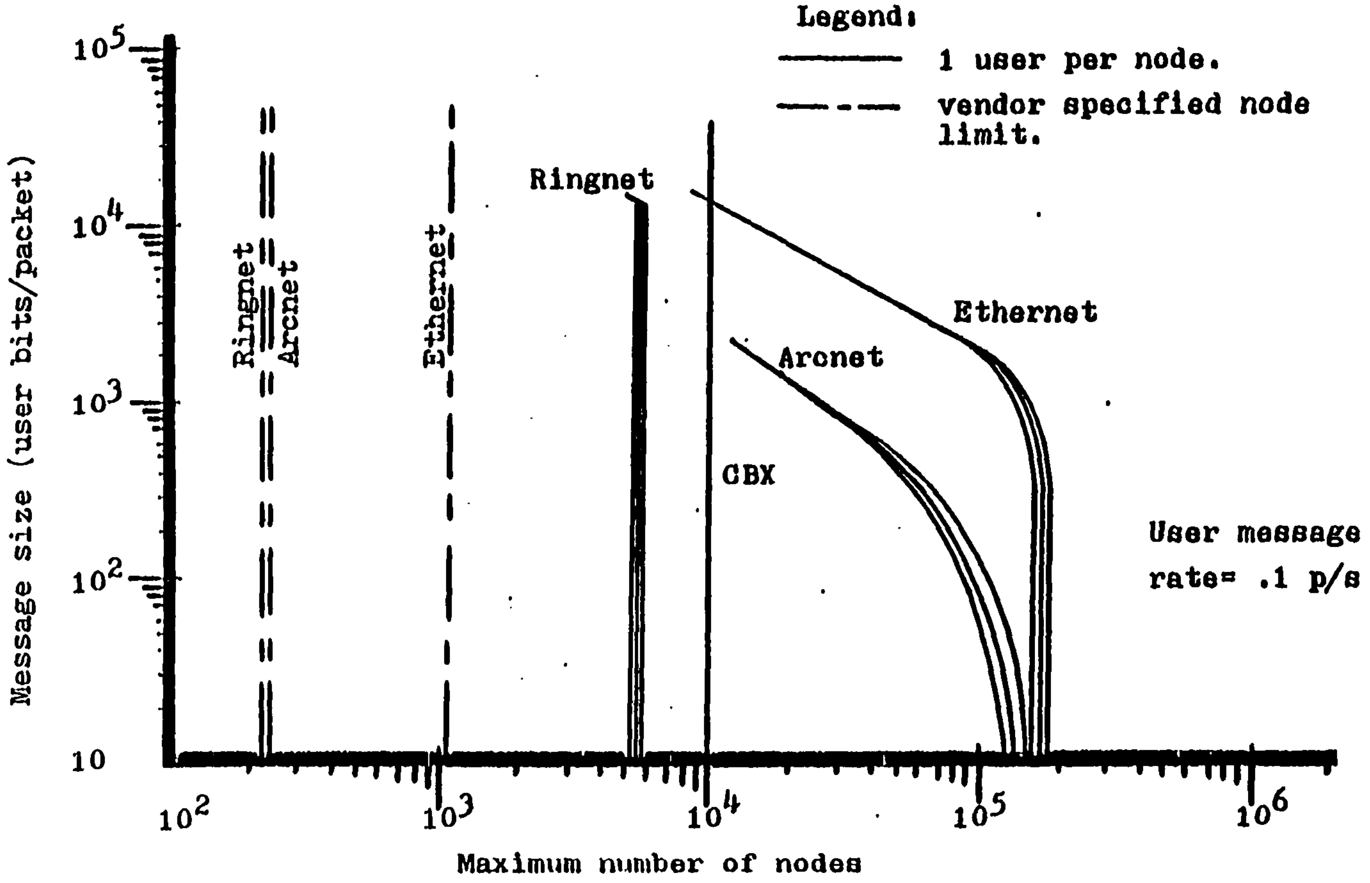

Figure 73. Performance Comparison - maximum number of nodes Vs message size (at user message rate of 0.1 packets per second)

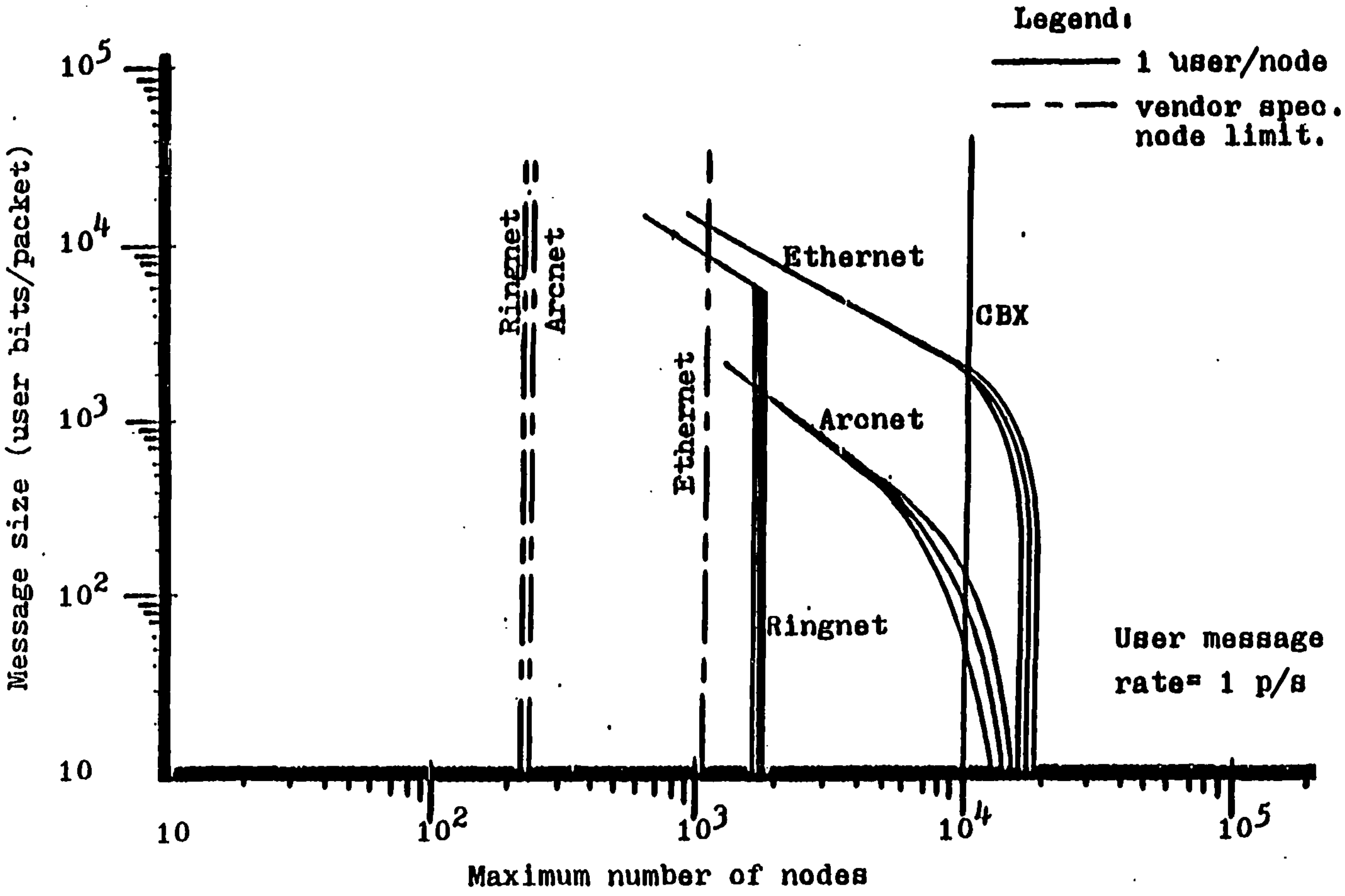

Figure 74. Performance Comparison - maximum number of nodes Vs message size (at user message rate of 1 packet per second)

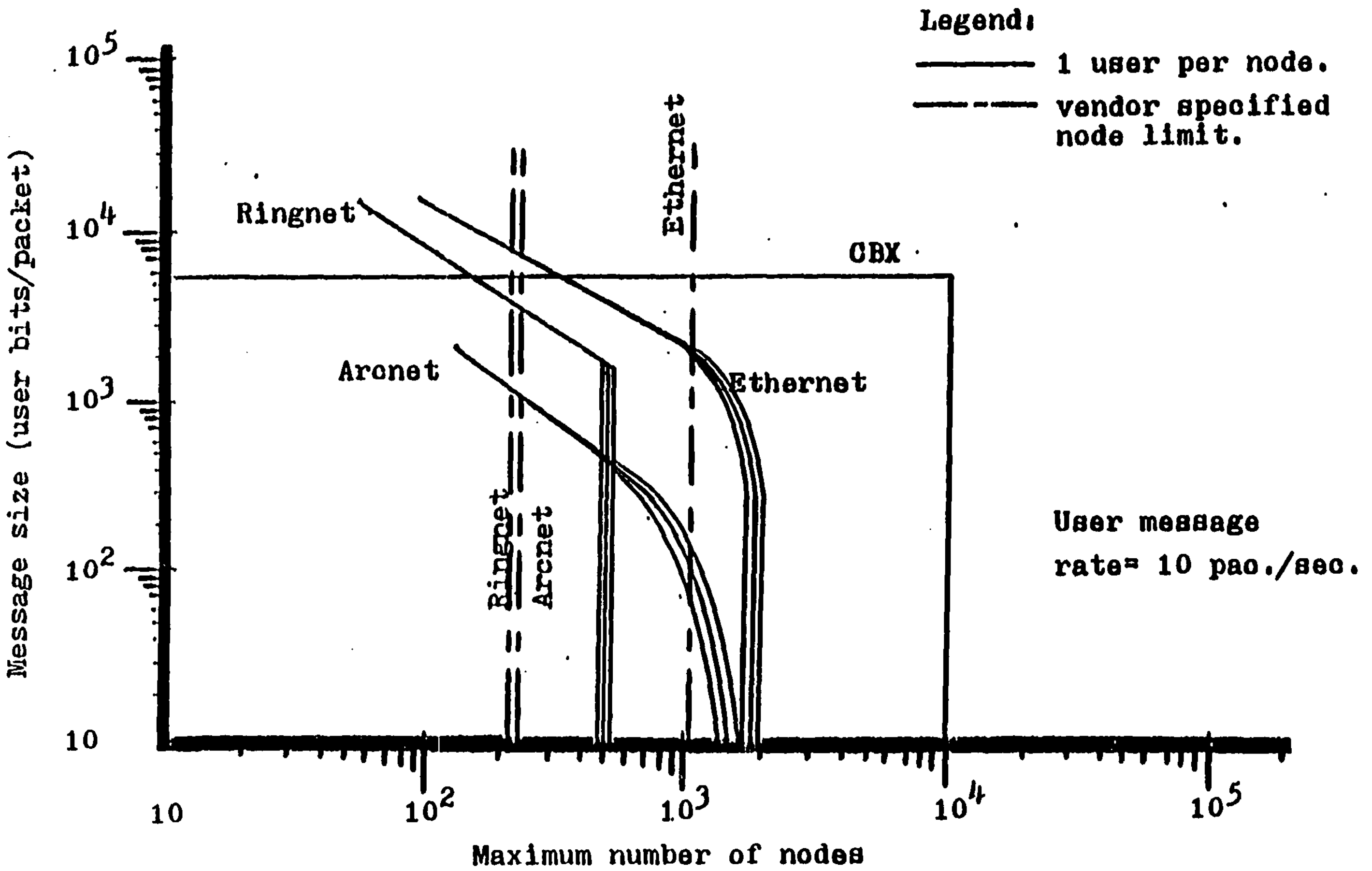

Figure 75. Performance Comparison - maximum number of nodes Vs message size (at user message rate of 10 packets per second)

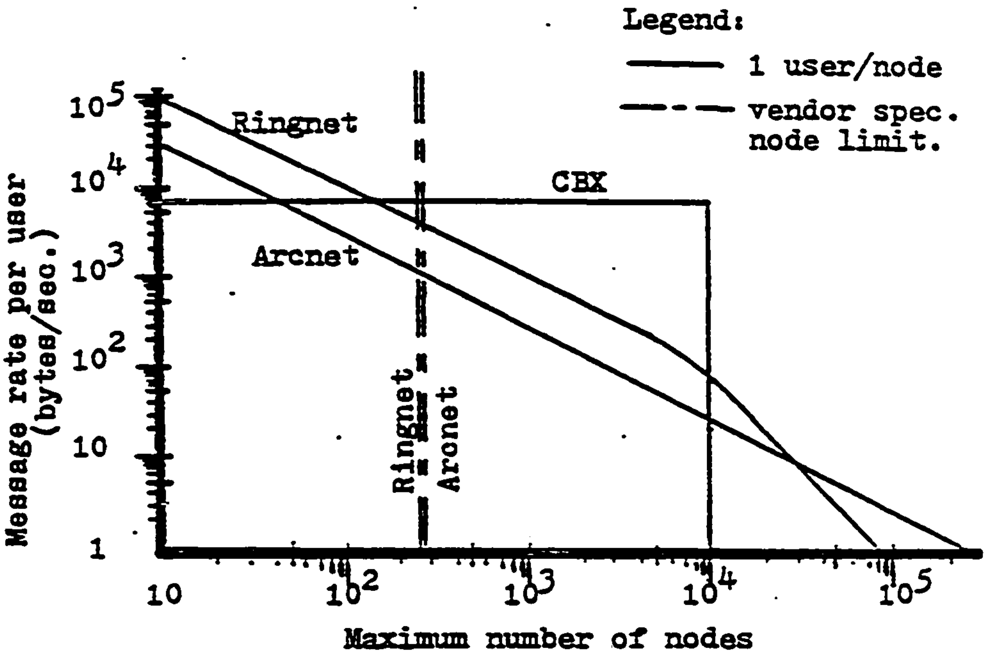

Figure 76. Performance Comparison - maximum number of nodes Vs user byte rate

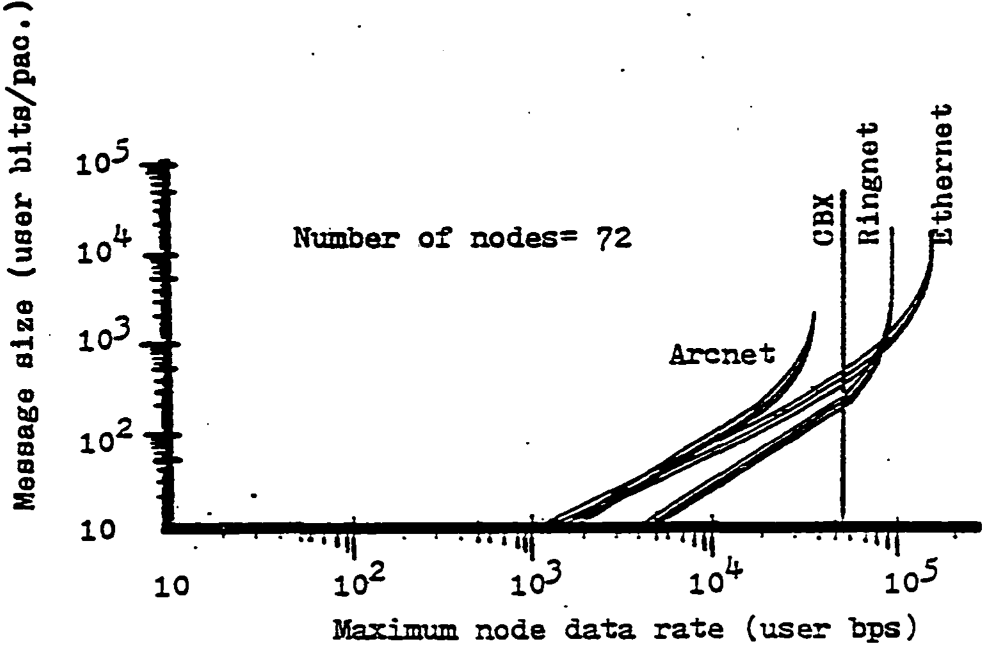

Figure 77. Performance Comparison - maximum node data rate Vs message size

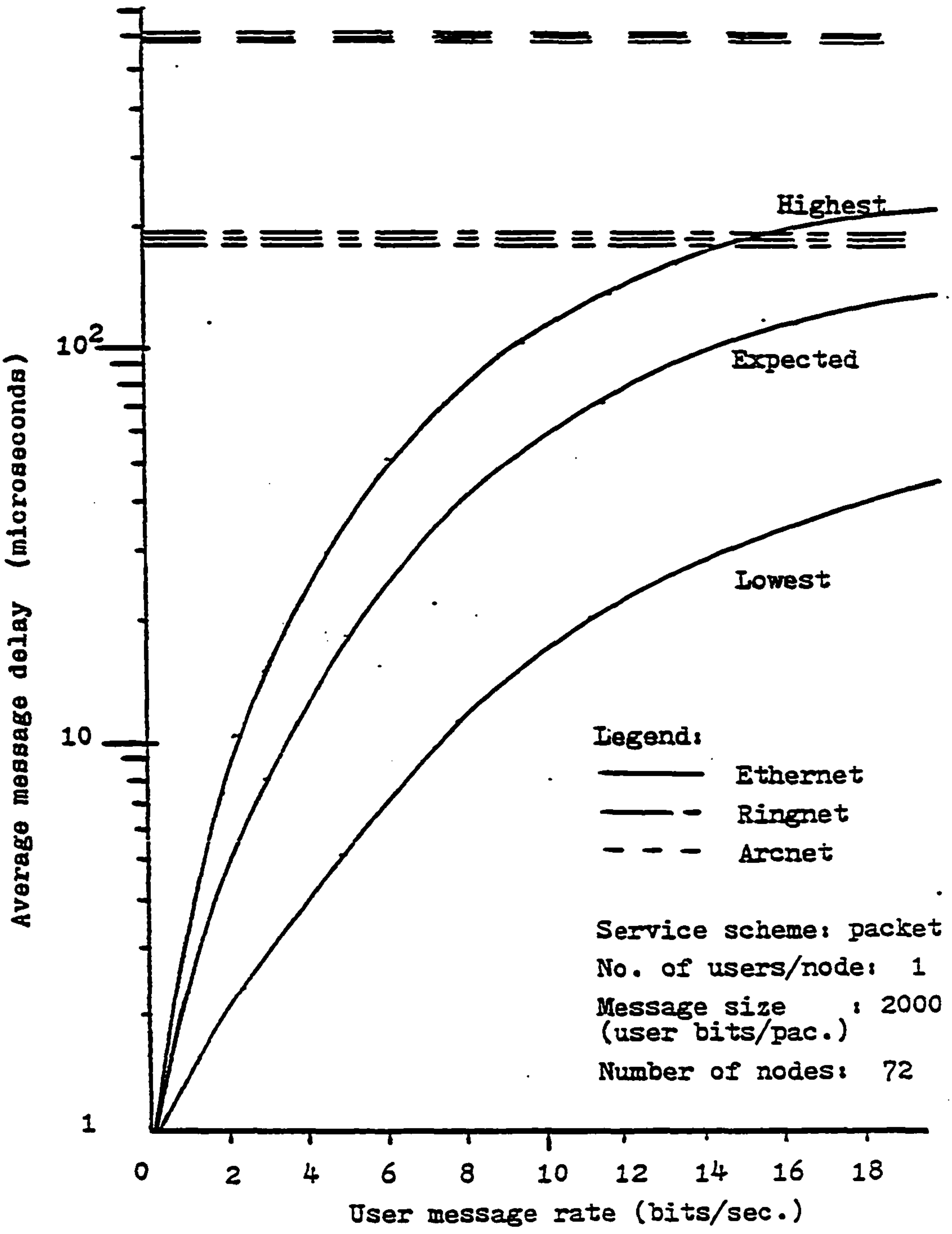

Figure 78. Performance Comparison - average message delay Vs message rate (Packet scheme)

Ringnet (whose average message delays are lower bounded by the token passing process).

- Figures 79 and 80 present the average message delay and average node buffer size performances of networks following the byte service scheme. In order to plot these figures, the LAN software is modified to obtain delay performance results at high user byte rate. In both figures, Ringnet has better delay and node buffer size performances than Arcnet on all user message rates.
- Figure 81 presents the maximum node message rate performance of networks following the packet service scheme. Ethernet provides the highest node message rate at network saturation when the message size is above 210 user bits per packet. For message size of less than or equal to 210 user bits per packet, CBX provides the highest node packet transmission rate.
- Figure 82 presents the maximum node message rate performance of networks following the byte service scheme. Ringnet provides the highest byte transmission rate for each node when the number of connecting nodes is less than or equal to 140; above this CBX provides the highest node message rate.

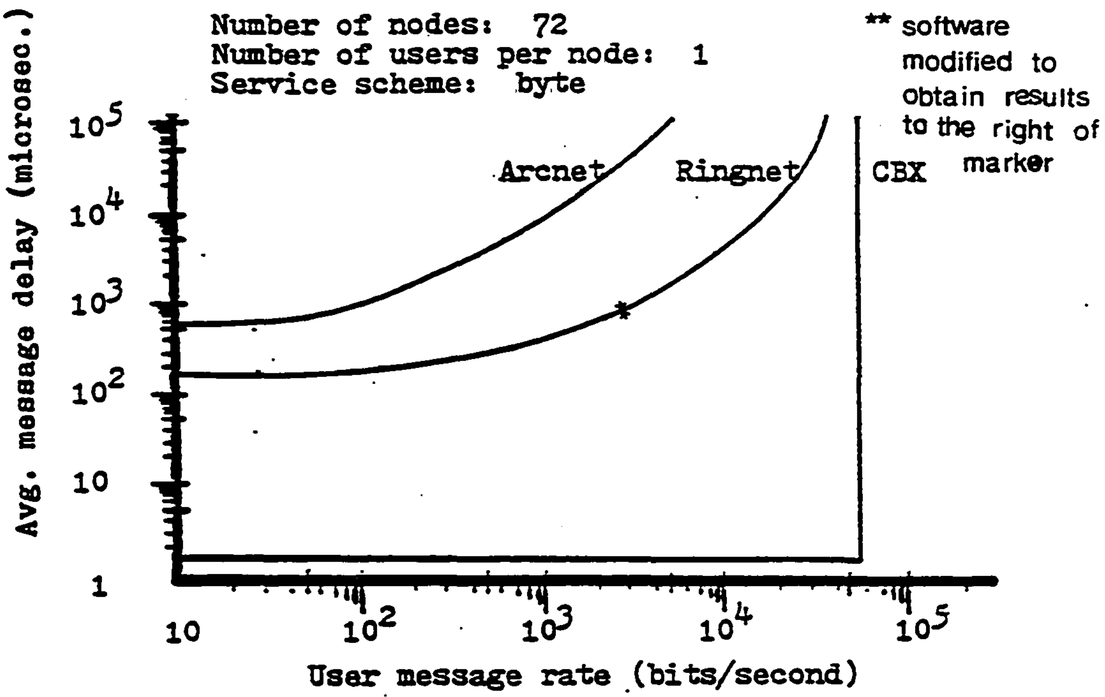

Figure 79. Performance Comparison - average message delay Vs user message rate (Byte scheme)

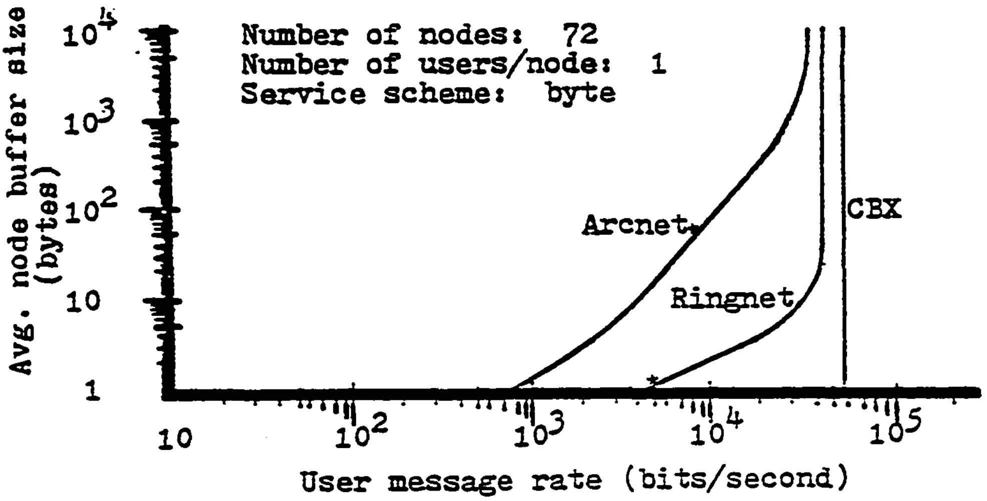

Figure 80. Performance Comparison - average node buffer size Vs user message rate (Byte scheme)

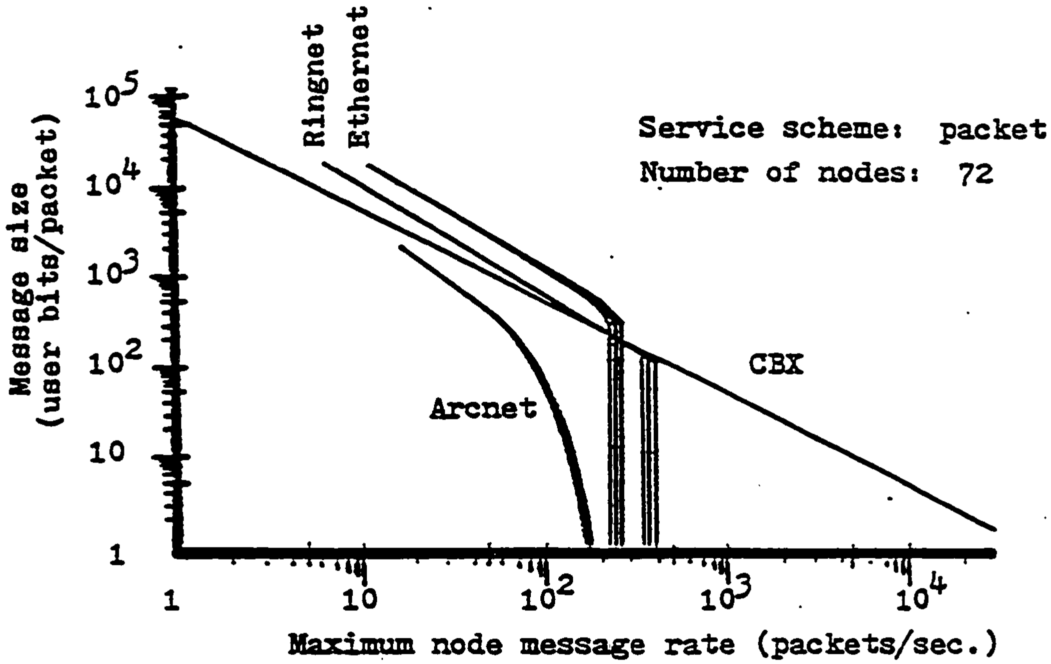

Figure 81. Performance Comparison - maximum node message rate Vs message size (Packet scheme)

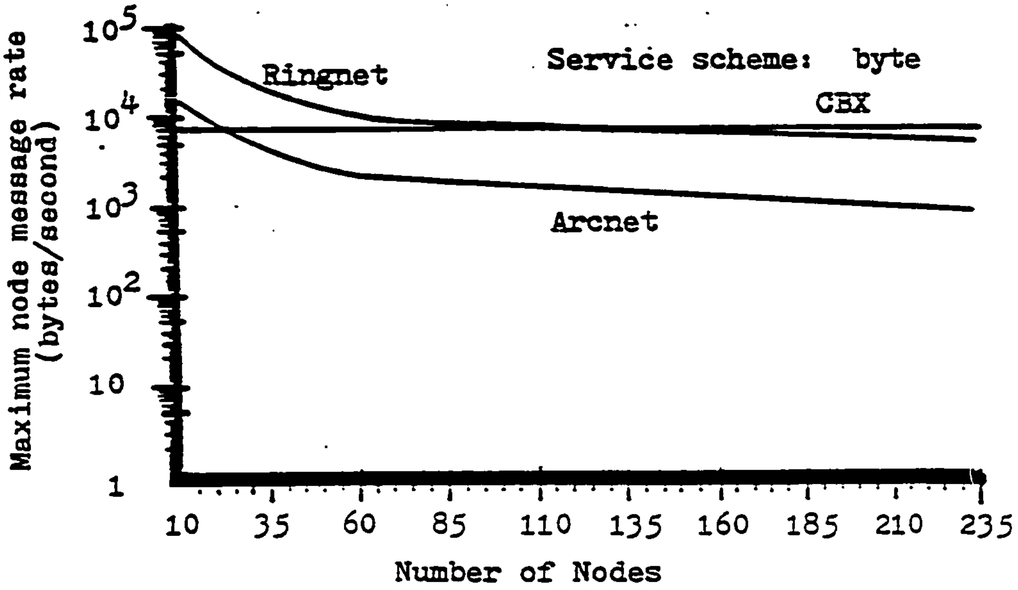

Figure 82. Performance Comparison - maximum node message rate Vs number of nodes (Byte scheme)

Verification of Analytical Results

In this section, results computed using the analytical models are compared with either measured results, or results computed using "back-of-the envelope" analysis. Measured results of network performance are rarely published. The two noted publications of such are the: performance measurement of Ethernet [21], and the performance measurement of NBSNET[1] [22].

In 1979, a prototype of Ethernet was installed at the Xerox Palo Alto Research Center, using regular coaxial cable and running at 2.94 Mbps. It spans about 550 meters and connects over 120 nodes. To conduct the measurements, a series of specialized test and monitoring programs have been built to assess the performance of the network. One of the experiments conducted was to measure the utilization (the percent in time the network is transmitting successfully) of Ethernet at network saturation. To analyze network utilization analytically:

$$\text{Percent Utilization} = \frac{N_{nodes} R_{node}}{R_{network}} \tag{79}$$

where R_{node} is computed using Equation 22 (with $b_{control}=0$). Table 10 shows the comparison between measured and analytical results. At a packet size of 512 bytes, the two results are close (with a discrepancy of 1.7%). At a packet size of 64 bytes (the minimum packet size allowed of Ethernet packets), the maximum discrepancy between measured and analytical results is 7.1% (when the number of connecting nodes is 32). Therefore, in general, the analytical results provide

---

[1] National Bureau of Standard Network.

Table 10. Comparing analytical results and measured results-utilization of Ethernet

# Of Nodes	Packet Length (in bytes)					
	512		128		64	
	Analy. Result	Measured Result	Analy. Result	Measured Result	Analy. Result	Measured Result
5	98.7%	97%	95.1%	95%	90.6%	94%
10	98.7%	97%	94.9%	91%	90.3%	89%
32	98.7%	97%	94.8%	90%	90.1%	83%
64	98.7%	97%	94.8%	92%	90.0%	85%

accurate prediction of actual performance.

The NBSNET is a 1 Mbps CSMA-CD network designed and installed at the National Bureau of Standard's Institute for Computer Sciences and Technology. It spans 30 meters and connects 6 nodes. One node of the network is modified to behave as a network monitor, capturing data from passing packets in the performance analysis of the network. One of the experiments conducted was to measure the average packet delay under different levels of network utilization. Figure 83 shows the comparison between measured and analytical results.

In 1981 a subcommittee of the IEEE Computer Society was formed to study the traffic handling capability of the proposed medium access protocols. The subcommittee held two open meetings, each followed by circulation of a draft report, [13] and [23], for comment. The equations developed at the meetings [24] for rough estimation of the maximum average network packet rate, $R_{netpacket}$, for each of the proposed methods are listed below:

CSMA-CD:

$$R_{netpacket} = (T_{message} + T_{interframe} + (2e-1)(2\tau+T_{interface}+T_{jam}))^{-1} \tag{80}$$

Token Passing Bus:

$$R_{netpacket} = (T_{message} + T_{prop} + T_{interface})^{-1} \tag{81}$$

Token Passing Ring:

$$R_{netpacket} = \left(T_{message} + T_{interface} + \frac{L_{ring}}{V_{prop}N_{nodes}}\right)^{-1} \tag{82}$$

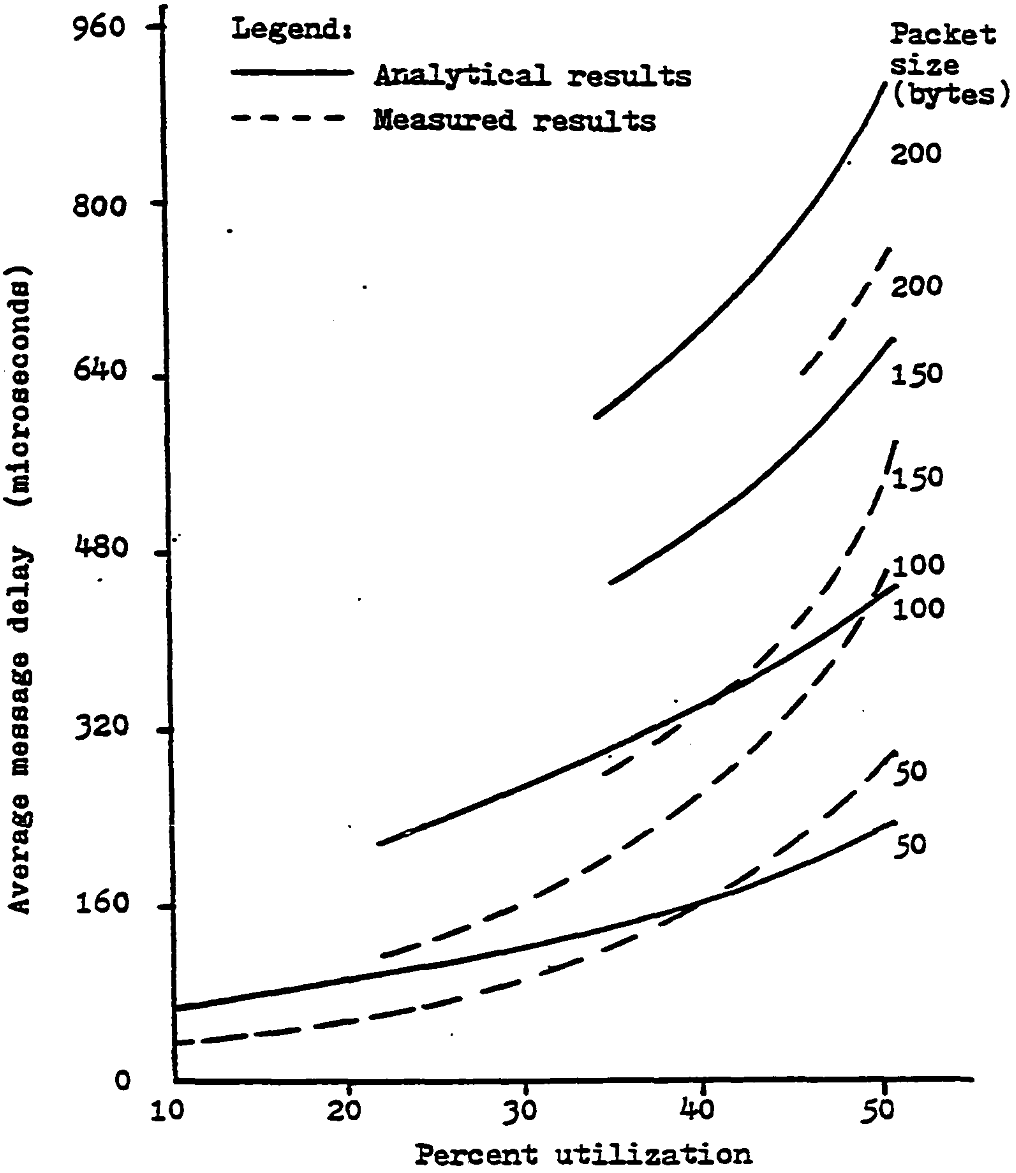

Figure 83. Comparing analytical results with measured results - message delay Vs utilization (CSMA-CD)

For Equations (80)-(82), the transmission time of a message is

$$T_{message} = \frac{b_{control} + b_{data}}{R_{network}} \tag{83}$$

By assuming that each node has one user, and each user submits messages at a rate of one packet per second, the following "back-of-the envelope" equations are derived for computing $N_{maxnodes}$, $\lambda_{saturate}$, and R_{node} for the proposed medium access methods:

$$N_{maxnodes} = R_{netpacket} \tag{84}$$

$$\lambda_{saturate} = R_{netpacket}/N_{nodes} \tag{85}$$

$$R_{node} = R_{netpacket}b_{data}/N_{nodes} \tag{86}$$

Figures 84-95 show the comparison between analytical and approximated results. For Arcnet, two sets of analytical results are computed. One set is obtained by taking into consideration the free buffer enquiry and packet acknowledgment processes with each packet transmission. Another set is obtained without considering such processes. This was done to show the difference between the two sets of analytical results with that of the approximated results (which do not include the free buffer enquiry and packet acknowledgment processes in their computation). The analytical results computed without including the enquiry and acknowledgment processes in their computation match more closely with the approximated results.

For token passing ring networks, the "back-of-the envelope" equations are derived using the assumption that a free token is generated and passed right after a node has completed its transmission (even when it

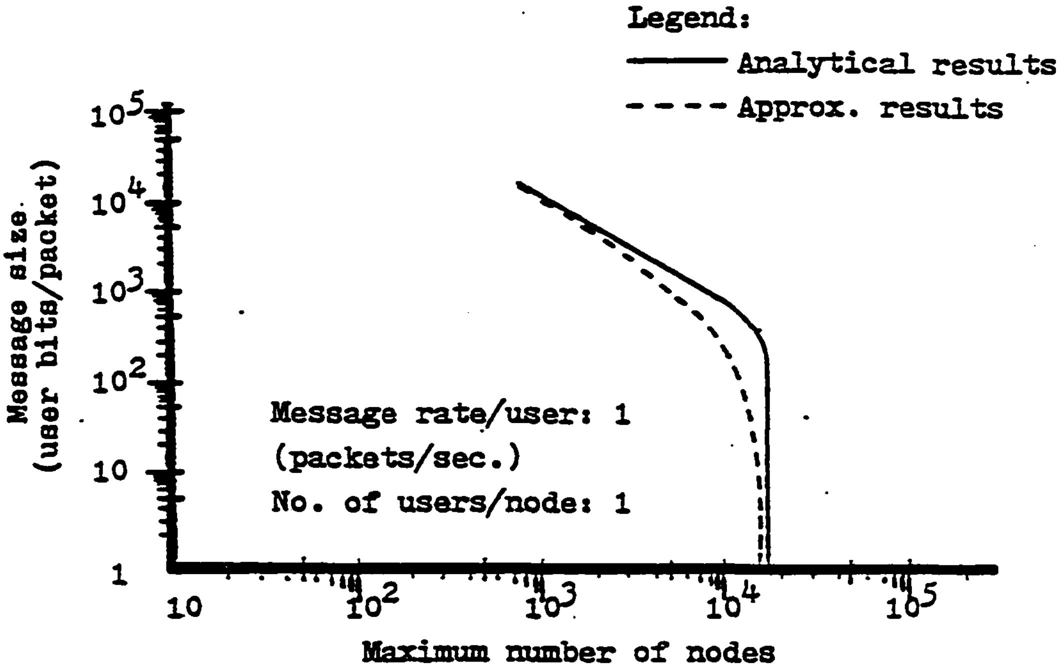

Figure 84. Comparing analytical results with approximate results - message size Vs maximum number of nodes (Ethernet)

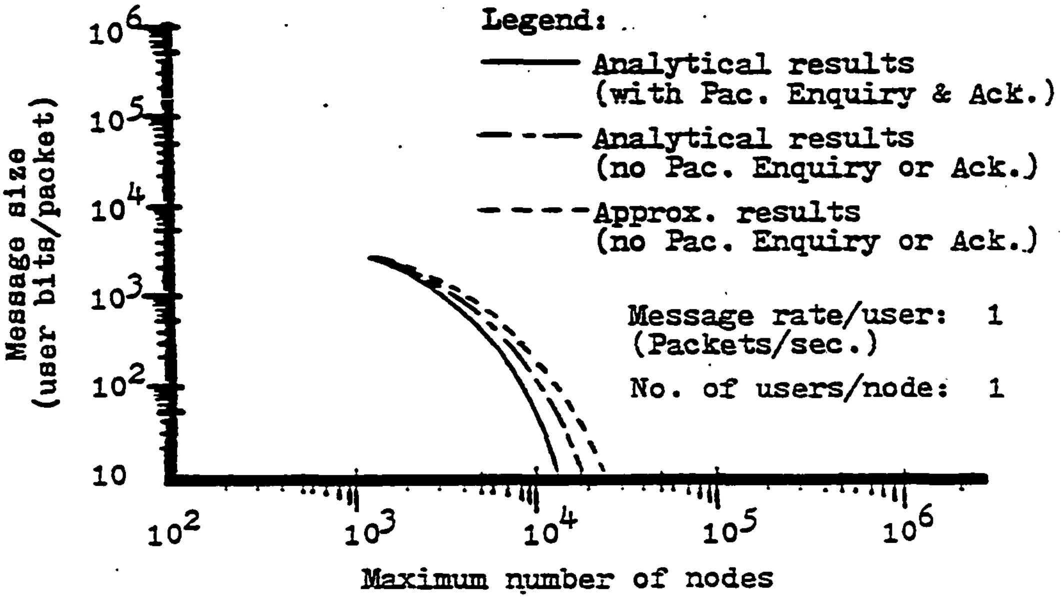

Figure 85. Comparing analytical results with approximate results - message size Vs maximum number of nodes (Arcnet)

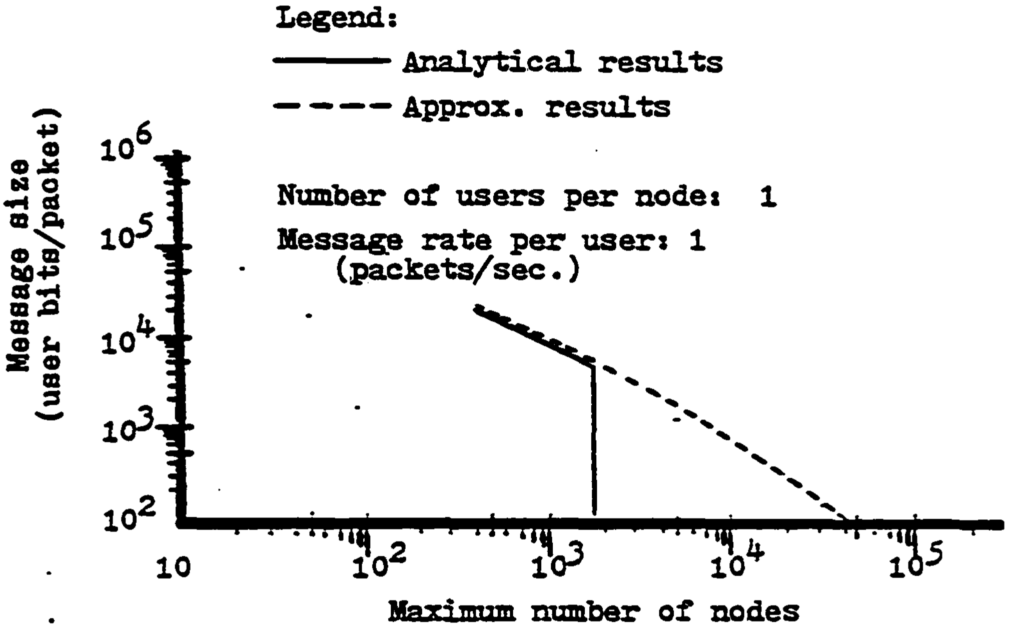

Figure 86. Comparing analytical results with approximate results - message size Vs maximum number of nodes (Ringnet)

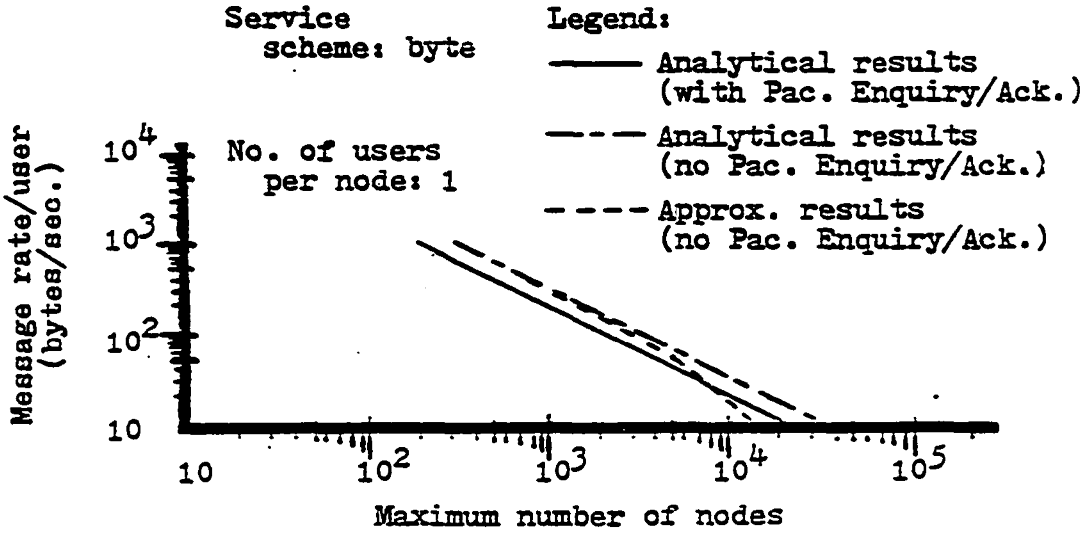

Figure 87. Comparing analytical results with approximate results - user message rate Vs maximum number of nodes (Arcnet)

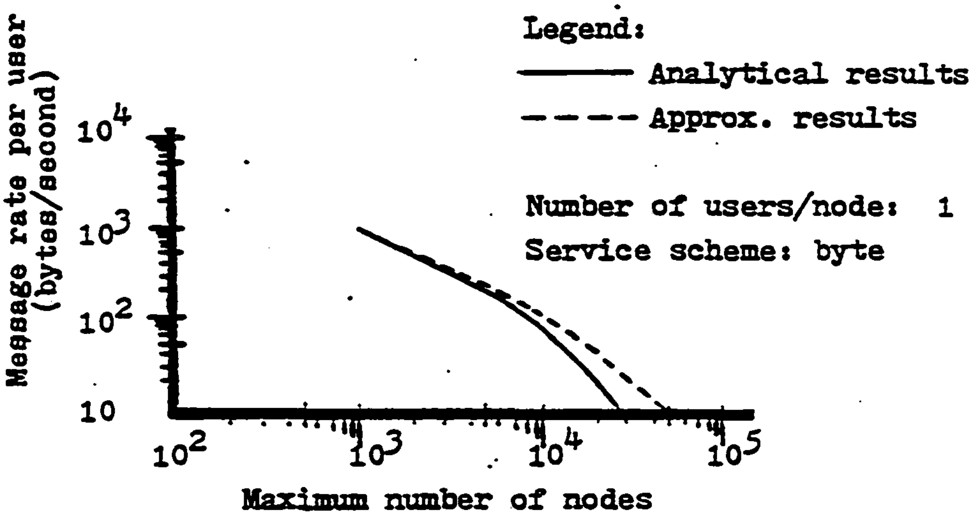

Figure 88. Comparing analytical results with approximate results - user message rate Vs maximum number of nodes (Ringnet)

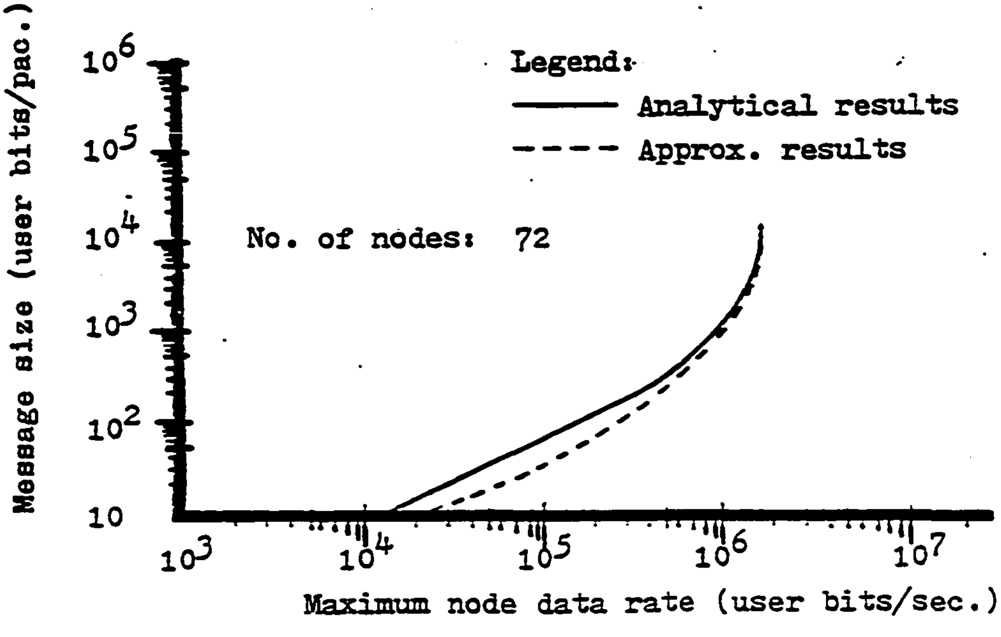

Figure 89. Comparing analytical results with approximate results - maximum node data rate Vs message size (Ethernet)

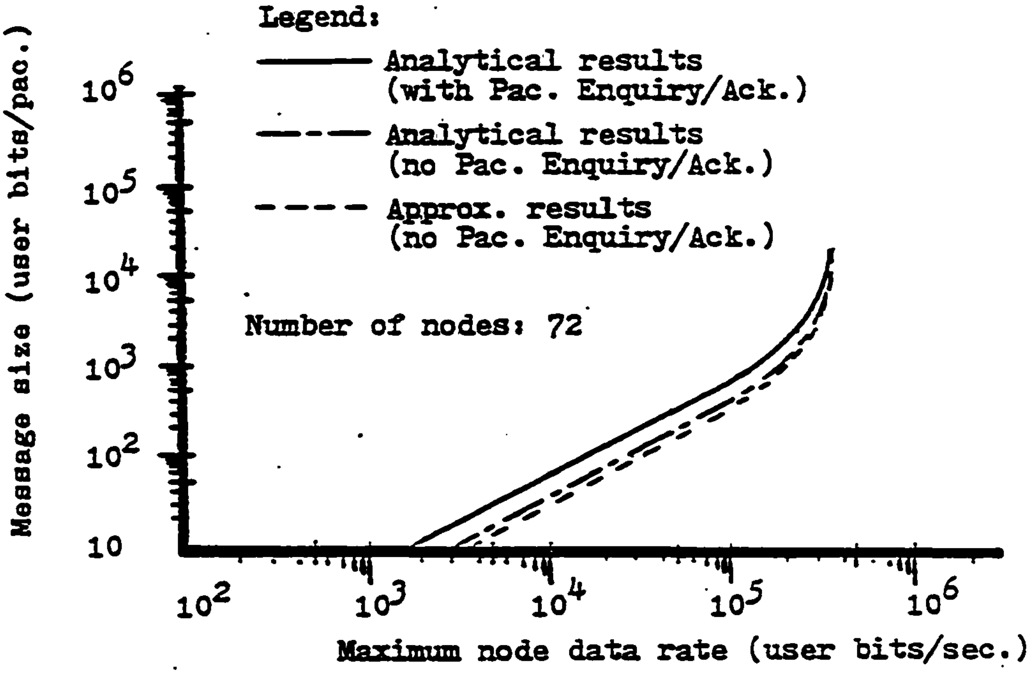

Figure 90. Comparing analytical results with approximate results - maximum node data rate Vs message size (Arcnet)

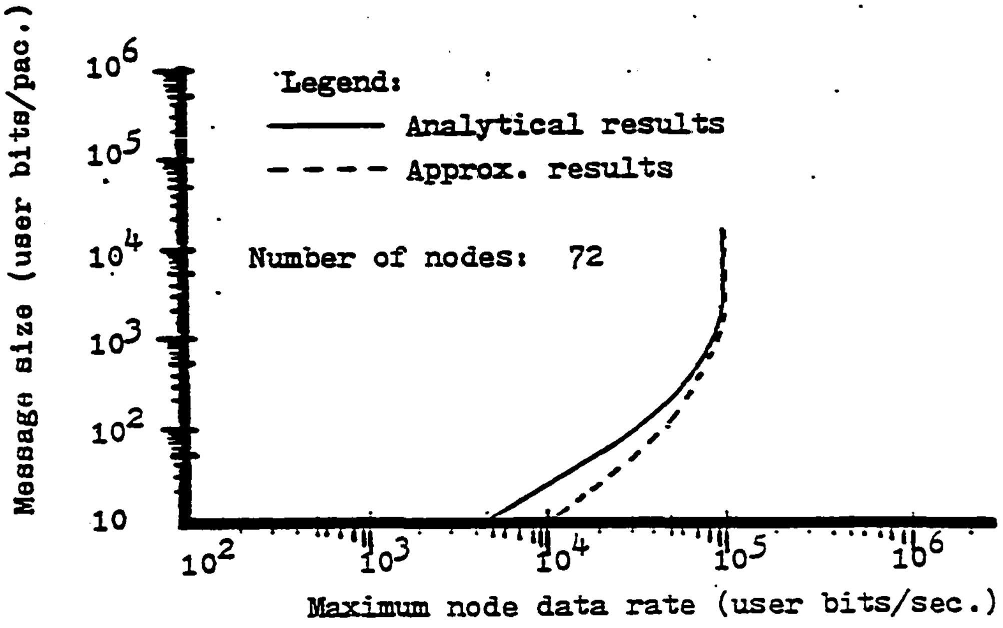

Figure 91. Comparing analytical results with approximate results - maximum node data rate Vs message size (Ringnet)

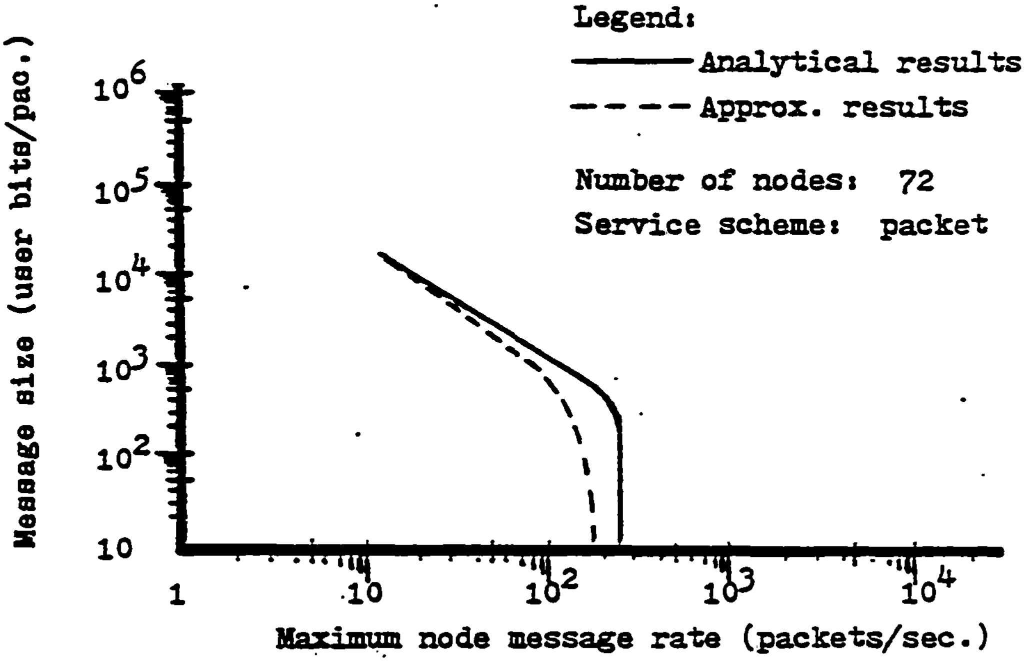

Figure 92. Comparing analytical results with approximate results - maximum node message rate Vs message size (Ethernet)

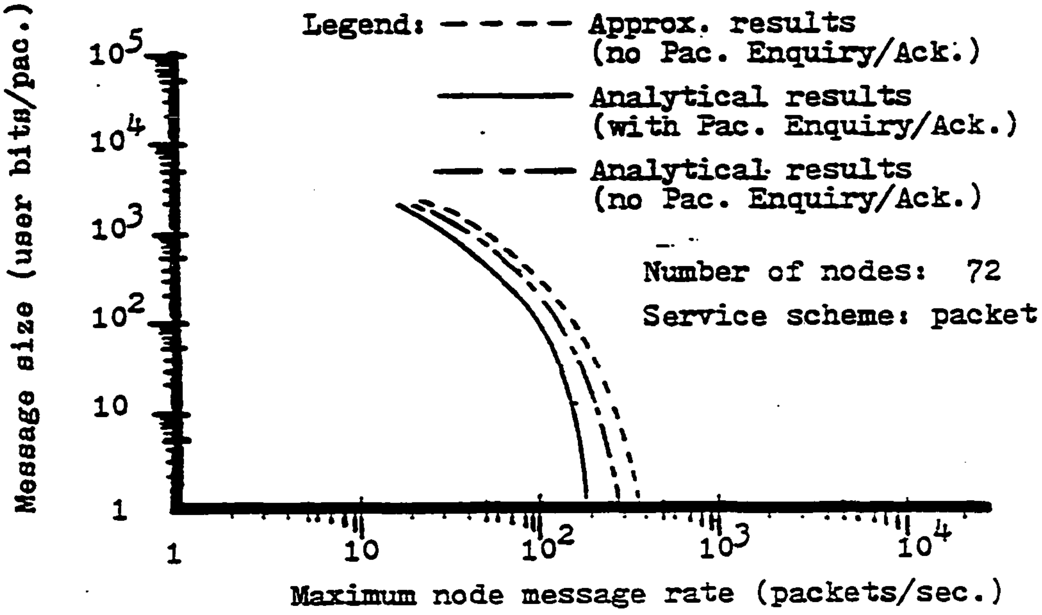

Figure 93. Comparing analytical results with approximate results - maximum node message rate Vs message size (Arcnet)

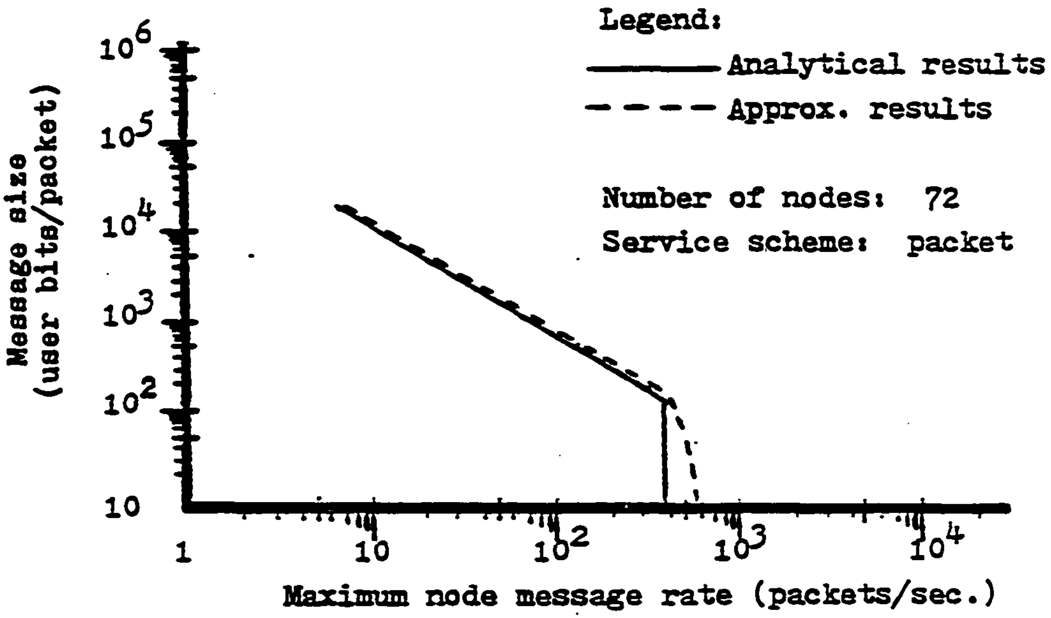

Figure 94. Comparing analytical results with approximate results - maximum node message rate Vs message size (Ringnet)

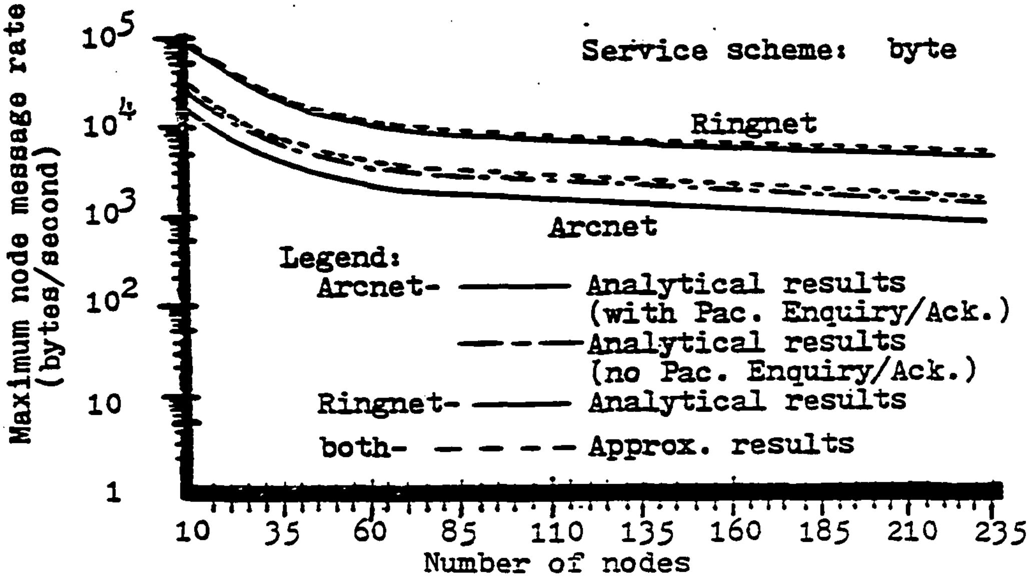

Figure 95. Comparing analytical results with approximate results - maximum node message rate Vs number of nodes (Byte scheme)

has not recovered its packet header). This resulted in a discrepancy between analytical and approximated results at the region of small packet size (such that the transmission time of a packet is less than the header propagation time around the ring). Otherwise, the approximated results provide good estimates.

"Back-of-the envelope" equations are also derived for computing the average message delay of token passing networks. At the region of almost no traffic on the network, the average message delay is one-half of the token rotation time around the logical ring. So, by assuming that each node has only one user, the approximated equations for computing the average message delay are:

Token Passing Bus-

$$D_{message} = \frac{1}{2} N_{nodes} \left(\frac{b_{token}}{R_{network}} + \frac{L_{pass}}{V_{prop}} \right) \tag{87}$$

Token Passing Ring-

$$D_{message} = \frac{1}{2} N_{nodes} \left(\frac{b_{token}}{R_{network}} + \frac{L_{ring}}{V_{prop} N_{nodes}} \right) \tag{88}$$

On the other hand, when the network is near saturation the token rotation time is the sum of the propagation time of the token to travel once around the logical ring, plus the time required of each node to transmit a packet of maximum length. So, by modeling this token rotation time as the average service time of a server serving a M/M/1 queue,

$$D_{message} = \frac{\rho}{\mu(1-\rho)} \tag{89}$$

where, $\rho = 99.9\%$,

$$\mu = (N_{nodes}\,(\frac{b_{control} + b_{data} + b_{token}}{R_{network}} + \frac{L_{pass}}{V_{prop}}))^{-1} \quad \text{(token bus)} \tag{90}$$

$$\mu = (N_{nodes}\,(\frac{(b_{control} + b_{data} + b_{token})}{R_{network}} + \frac{L_{ring}}{V_{prop}N_{nodes}}))^{-1} \quad \text{(token ring)} \tag{91}$$

Table 11 shows the comparison between analytical and approximated results. For both token bus and token ring, the approximated results match closely with the analytical results at the two extreme conditions.

Table 11. Comparing between analytical and approximated results–average packet delay

Network Utilization (ρ)	Network Name	Average Packet Delay (Microseconds)		
		Analytical[a]	Analytical[b]	Approximated
.001	Arcnet	601	584	565
.001	Ringnet	—	165	146
.999	Arcnet	3.066×10^8	9.767×10^7	6.175×10^7
.999	Ringnet	—	1.578×10^7	1.476×10^7

[a] Free buffer enquiry and packet acknowledgment included in computation.

[b] No free buffer enquiry and packet acknowledgment.

CHAPTER VII. CONCLUSIONS

In this dissertation, analytical models were derived for the performance evaluation of real LANs (those conforming to the IEEE 802 Standards) in computing their: maximum achieveable node data rate, average message delay, average node buffer size, maximum number of nodes the network can support, and the network saturation message rate to a node. Performance models were developed for networks following the packet service scheme and for those following the byte service scheme. Also, a user friendly software tool was developed to facilitate the solution of the performance models, as well as the recording and presentation of analytical results using a microcomputer.

The results of this dissertation can be summarized as follows:

- In comparing the performance among Ethernet, Ringnet, Arcnet, and CBX:
  1. Ethernet has the highest maximum node data rate at message size of above 1000 user bits per packet. Also, when compared with Arcnet and Ringnet it supports the most number of nodes and has the lowest average message delay at low user packet rate. It also supports the highest maximum node packet rate at message size of above 210 user bits per packet.
  2. Ringnet has the highest maximum node data rate at message size of between 210-1000 user bits per packet. Other than CBX, it supports the highest node packet transmission rate at message size of less than or equal

to 210 user bits per packet. Also, among networks following the byte service scheme: it has the lowest average message delay at user message rate above 56000 bps, and has the highest byte transmission rate for each node when the number of connecting nodes is less than or equal to 140.

3. Arcnet has a higher maximum node data rate than Ringnet at message size below 30 user bits per packet.
4. CBX has the highest maximum user data rate at message size below 210 user data bits per packet. Among networks following the byte service scheme: it supports the most number of users at user message rate of below 56000 bps, has the highest maximum user byte rate when the number of connecting users is above 140, and has the lowest average message delay when the user message rate is below 56000 bps.

- From Figures 73-76, it is demonstrated that the maximum number of nodes a network can support at saturation usually greatly exceeded the vendor specified maximum node limit.
- For token passing networks, those that follow the packet service scheme have shorter average message delay (until the moment of network saturation) than those that follow the byte service scheme (Figure 96).
- For CSMA-CD networks, the average message delay is

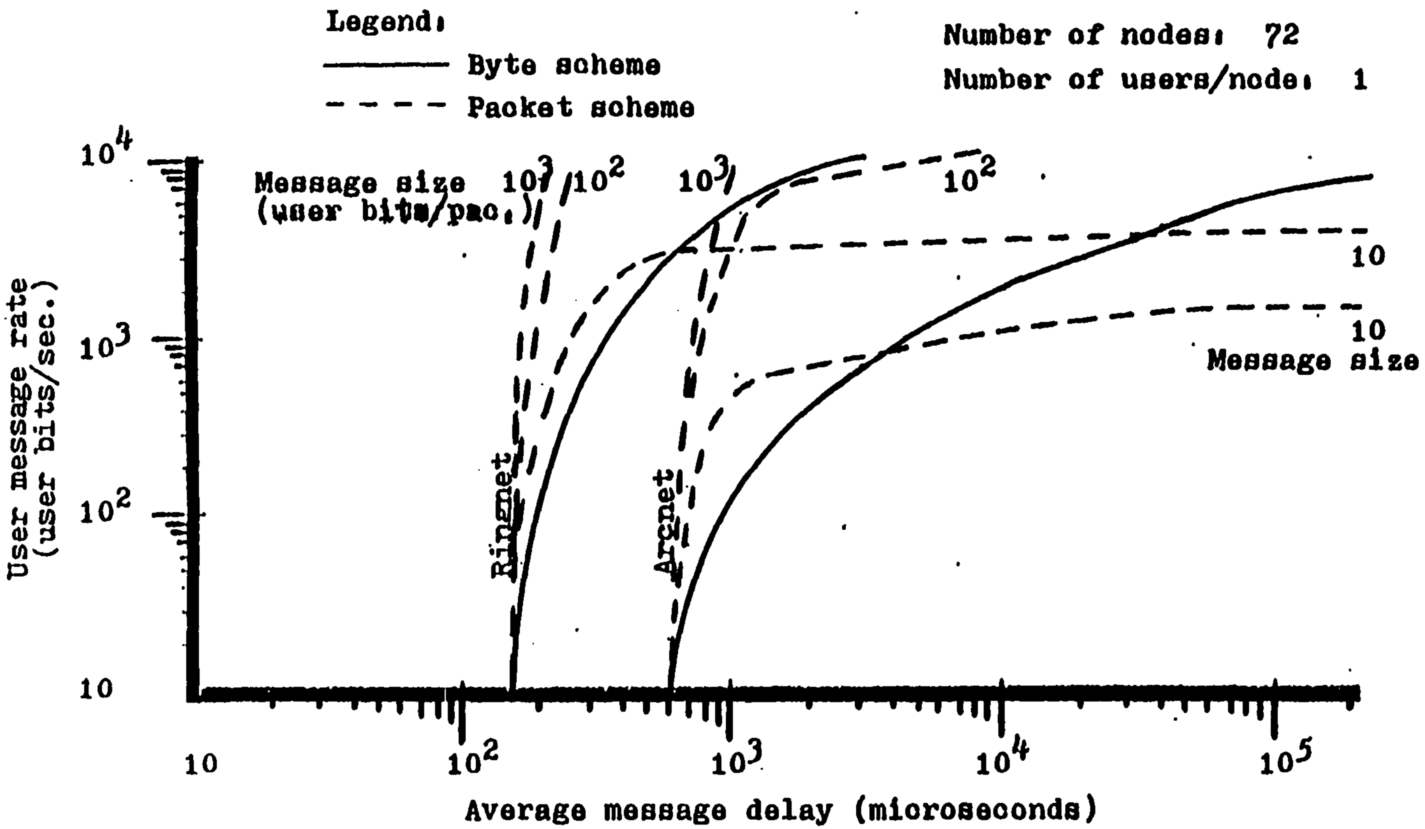

Figure 96. Comparison of byte scheme with packet scheme - average message delay Vs user message rate

sensitive to variation in network length (Figure 57).

- The maximum node data rate gets big when the number of user bits per packet gets large (Figures 53-55).
- For token passing ring network, the shorter the ring length the smaller its average message delay will become.
- For token passing bus networks, the best token passing policy is to pass the token to the nearest node (not including nodes that had received the token in that token passing cycle). This results in shorter average token passing delay.
- The network saturation message rate gets small as the message size gets large (Figure 81).

This dissertation had achieved its goal of providing user tools (models and software) that can be used in performance evaluation and comparison of real LANs. The author, recommends the conducting of real measurements of network performance in future research of LANs to enable their comparison with analytical performance models developed in this study.

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APPENDIX A. USER'S MANUAL

This appendix guides a user in the proper operating procedures for utilizing the software tool for the performance evaluation and comparison of LANs.

Equipment, operating system, and programming language interpreter/compiler requirements

The following items are needed to run the developed software:

a) Equipment:-

One Zenith Z-100 microcomputer (with graphic capability, and 128K memory).

One color monitor.

Two floppy disk drives.

One printer.

b) Operating system:-

Z-DOS/MS-DOS (release 1.0, version 1.2) [25].

c) Programming language interpreter/compiler:-

Z-BASIC (release 1.0) [26].

d) LAN disk (containing programs of the software tool).

e) Formatted storage disks.

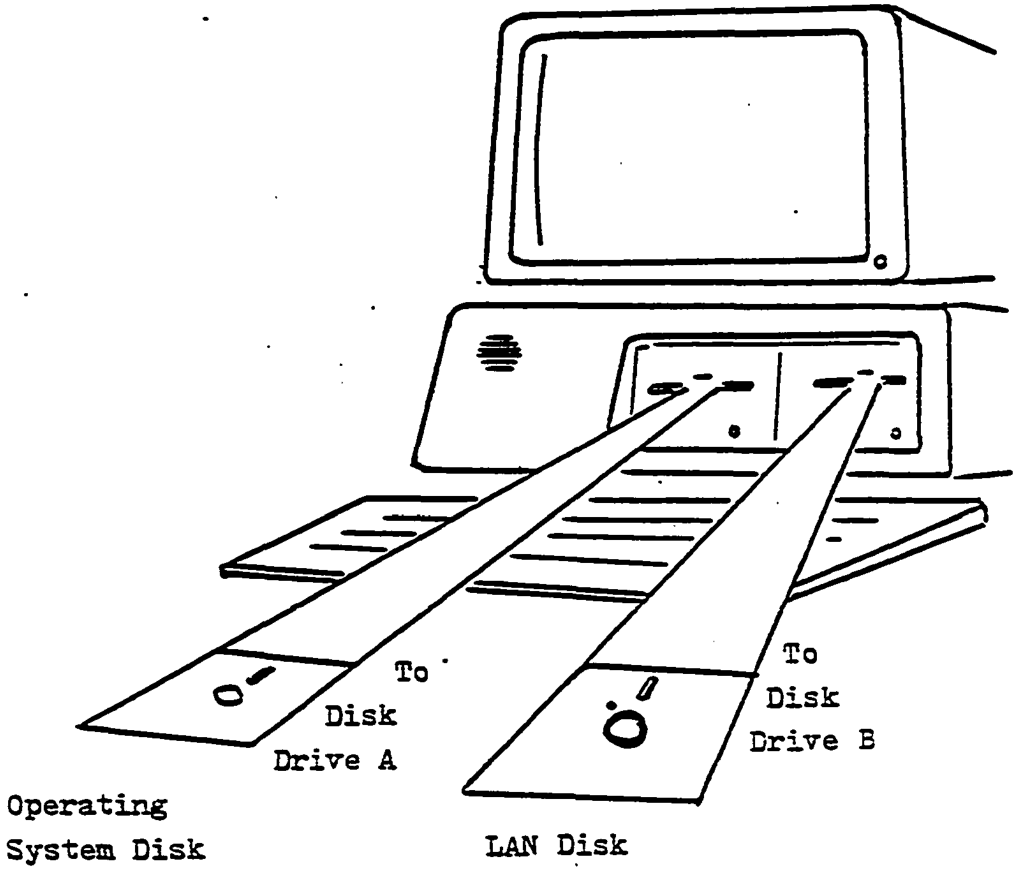

To
Disk
Drive A
Operating
System Disk
LAN Disk
To
Disk
Drive B

Figure 97. Loading operating system disk and LAN disk

Getting started

Insert Operating System Disk into disk drive A, and insert LAN disk into disk drive B (Figure 97). Switch on the computer, and respond to queries concerning the input of new date and time. The boot-up procedure is completed when the prompt A: appears on the screen. Now type in

```
ZBASIC B:LAN
```

and hit <CR> (Carriage Return). The Z-BASIC interpreter will be loaded and the session opening program of the software will be accessed and run. If the screen displays the opening statements and the software title shown in Figure 27, the software is thus properly loaded and accessed. Now remove the Operating System Disk from disk drive A, but keep the Software Disk in disk drive B for the whole networking performance evaluation session. Upon completion of the session opening process, an Operation Menu is presented to users for their selection of what to do next.

Operation Menu

Upon display of the Operation Menu (Figure 28), one can now select among the following options:

1. First time evaluation of a network: this selection is for conducting the network specification input process, as well as for the subsequent analysis of the performance of the network.
2. Access files of evaluated networks: this selection is for the

retrieving of user files containing data on network specification and analytical results of a previously evaluated network.

3. Performance comparison of evaluated networks: this selection is for the retrieving and comparing analytical results previously stored in different user files. Performance data of different networks can be retrieved and plotted on the same graph for easy comparison.
4. Exit program: this selection will cause the network performance evaluation session to be terminated. System control will be transferred back to the Operating System.

First time evaluation of a network

Upon selecting the first option listed on the Operation Menu, a user will be presented with a list of four protocols to select from (Figure 29). Here, one should pick the protocol of the network he wishes to evaluate. Upon making a selection, one will be presented with the opportunity to see a graphical demonstration of the selected protocol. This is for the benefit of first time users to have the opportunity in getting acquainted with terms that are used later in the network specification input process, as well as allowing a user to see the events of the protocol he selected. To read the statements displayed during the demonstration, hold the keys <CTRL> <S> down simultaneously (doing this will pause the demonstration). To continue, hit any key. Upon completion of the graphical demonstration, or immediately if one skips the demonstation, the network specification input queries are presented to the user.

Network specification input process

There are two kinds of network specification:

1. Fixed specification- these are physical and protocol related specifications that can take on only one value (typically as specified by the network vendor) (e.g., network rate, maximum number of connecting nodes, number of packet conrol bits, minimum number of bits per packet etc.).
2. Conditional specification- these are physical and protocol related specifications that can take on a range of values depending on how the network is implemented (e.g., average network length, average message transmission distance, average token passing distance, packet interframe delay, message collision signal sensing delay, repeater signal regeneration delay etc.). For the conditional specifications, three values are input:
    1. Worst case value- this is the worst value the specification will take on with regard to a specific implementation of the network.
    2. Expected value- this is the average value the specification will take on with regard to a specific implementation of the network.
    3. Best case value- this is the most optimistic value the

specification will take on with regard to a specific implementation of the network.

During the network specification input process, a user is queried to enter his input (Figures 30-33). The meaning of the queries is listed below:

1. Fixed specification:

Network/system name- the name of the system or network (e.g., Ethernet, Arcnet, Lan/1 etc.).

Network rate (in megabits per second)- the network data rate. Typically, this value ranges from 1 to 10 megabits per second.

Data rate per station (in kilobits per second)- the data rate of each PBX station. Typically, this value ranges from 9.6 to 64 kilobits per second.

Maximum number of nodes per network- the maximum number of nodes that are allowed to be connected to the network. This input is a number greater than 0.

Maximum number of stations per system- the maximum number of stations supported by a PBX. This input is a number greater than 0.

Number of users per node- the number of users that are connected to each node. Typically, this value ranges from 1 to 8.

Minimum number of bits per packet- the minimum number of bits specified for each packet. This input is a number greater than 0.

Number of control bits- the specified number of control bits (packet header bits plus trailor bits) for a packet (Figure 3). Typically, this value ranges from 32 to 208.

Number of spacing bits- the specified number of spacing bits behind each byte of user data (Figure 3). Typically, this value ranges from 0 to 8.

Number of token bits- the specified number of bits in a token packet. Typically, this value ranges from 32 to 96.

Number of enquiry bits- the specified number of bits in a free buffer enquiry packet. Typically, this value ranges from 24 to 48. If no free buffer enquiry packet is send then input 0.

Number of acknowledge bits- the specified number of bits in a message acknowledgment packet. Typically, this value ranges from 24 to 48.

Maximum number of user data bits per packet- the maximum number of user data bits (Figure 3) that are allowed in each packet. Typically, this value is greater than 1000.

2. Conditional specification:

Cable speed (in meters per nanosecond)- the signal propagation speed on the medium. Typically, this value ranges from .1 to 1 meter per nanosecond.

Switching delay (in microseconds)- the elapsed time of a signal in passing through the central switch (PBX system). Typically, this value ranges from .1 to 1 microsecond.

Repeater delay (in microseconds)- the elapsed time of a signal in passing through a repeater. Typically, this value ranges from .1 to 1 microsecond.

Interframe delay (in microseconds)- the packet interframe delay of the CSMA-CD protocol. Typically, this value ranges from .1 to 1 microsecond.

Collision sensing delay (in microseconds)- the elapsed time of a node in sensing and acting on a message collision signal once the signal arrived at the node. Typically, this value ranges from .1 to 1 microsecond.

Copy message delay (in microseconds)- the elapsed time of a node in copying one bit of passing message. Typically, this value ranges from .1 to 1 microsecond.

Interface delay (in microseconds)- the elapsed time of a node in verifing and retransmitting one bit of passing message. Typically, this value ranges from .1 to 1 microsecond.

Collision jam time (in microseconds)- the collision enforcement delay of the CSMA-CD protocol. Typically, this value ranges from .1 to 1 microsecond.

Response check time (in microseconds)- the elapsed time of a node in checking the contents of an acknowledgment packet. Typically, this value ranges from .1 to 1 microsecond.

Message check time (in microseconds)- the elapsed time of a packet receiving node to check the contents of a message. Typically, this value ranges from .1 to 1 microsecond.

Buffer check time (in microseconds)- the elapsed time of a node in checking its buffer for ready messages. Typically, this value ranges from .1 to 1 microsecond.

Average number of repeaters encountered/transmission- the average number of repeaters a message encountered in traveling from the message sending node to the receiver.

Average number of repeaters encountered/pass- the average number of repeaters a token encountered in traveling from the token passing node to its destination.

Average message transmission distance (in meters)- the average message transmission distance (Figure 10). This input is a number greater than 0.

Average token passing distance (in meters)- the average network distance involved in the token passing process. This input is a number greater than 0.

Network length (in meters)- the networking distance between the two nodes that are placed furthest apart on a CSMA type network (Figure 9). This input is a number greater than 0.

Ring length (in meters)- the total length of a token passing ring. This input is a number greater than 0.

During the network specification input process, there are subroutines that will assist a user in computing the lowest, expected, and highest values of the average message transmission distance and the average token passing distance. In the average message transmission distance subroutine, one will have to determine if the network he is evaluating is a one-to-many or a many-to-many transmission system. A one-to-many transmission system is a system that has a central node (e.g., disk server) which all other nodes communicate with, and there is no communication between all these other nodes. A many-to-many transmission system is a system with no master node, and all nodes communicate directly between themselves. The algorithms used in computing the average message transmission distance or average token passing distance are described in Figures 98-100. Demonstrations in the use of these algorithms are given in Chapter V.

After all network specification values are properly entered, a user will be given the opportunity to have the specification printed. To print, one should:

1. Type <Y> in response to the query "Do you want a printout of the specification? Enter <Y> or <N>".
2. Switch on the printer (make sure that it is properly connected, and the communications ports properly configured with the computer).
3. To proceed with the printing process, type <Y> in response to the query "Printer ready (yes or abort)?". To avoid printing the specifications, type <A>.
4. By entering <Y> in step 3, a user will be queried to enter the date, which will be printed as part of the report. The correct way to input date (numerically) is

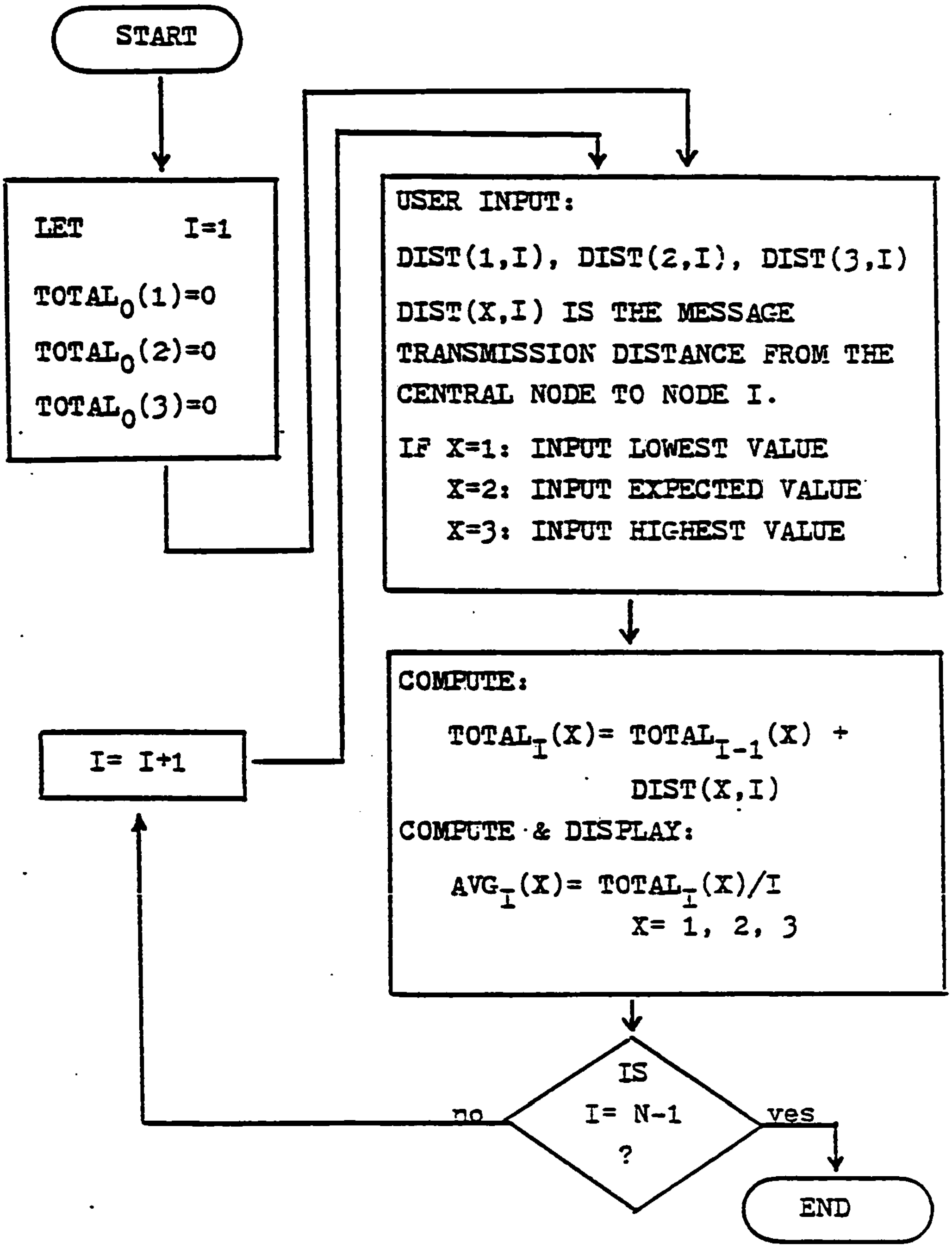

START
LET I=1
$TOTAL_0(1)=0$
$TOTAL_0(2)=0$
$TOTAL_0(3)=0$
USER INPUT:
DIST(1,I), DIST(2,I), DIST(3,I)
DIST(X,I) IS THE MESSAGE TRANSMISSION DISTANCE FROM THE CENTRAL NODE TO NODE I.
IF X=1: INPUT LOWEST VALUE
X=2: INPUT EXPECTED VALUE
X=3: INPUT HIGHEST VALUE
COMPUTE:
$TOTAL_I(X)= TOTAL_{I-1}(X) + DIST(X,I)$
COMPUTE & DISPLAY:
$AVG_I(X)= TOTAL_I(X)/I$
X= 1, 2, 3
I= I+1
IS I= N-1 ?
no
yes
END

Figure 98. Algorithm for computing the average message transmission distance for a one-to-many system

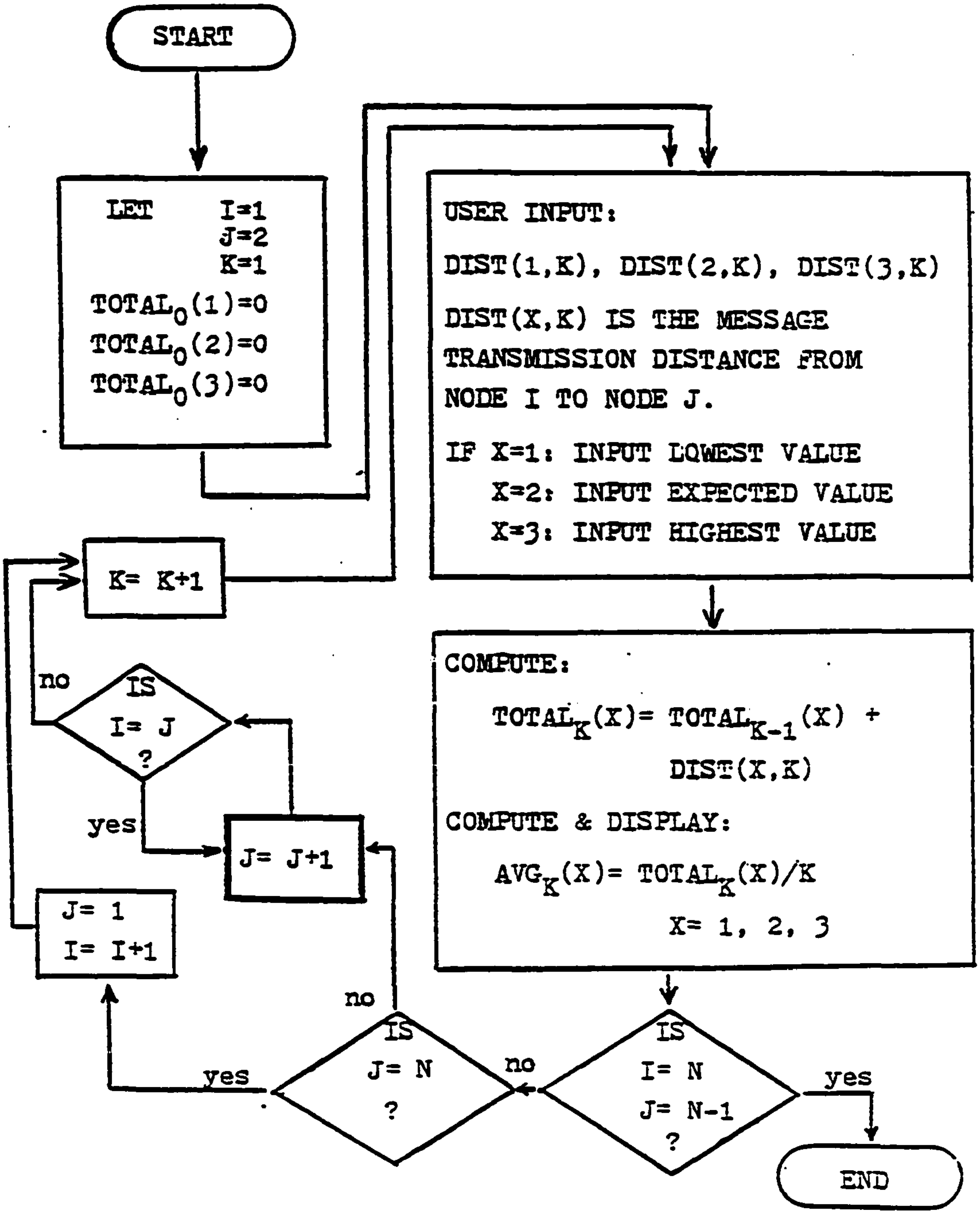

START
LET I=1
J=2
K=1
TOTAL$_0$(1)=0
TOTAL$_0$(2)=0
TOTAL$_0$(3)=0
USER INPUT:
DIST(1,K), DIST(2,K), DIST(3,K)
DIST(X,K) IS THE MESSAGE TRANSMISSION DISTANCE FROM NODE I TO NODE J.
IF X=1: INPUT LOWEST VALUE
X=2: INPUT EXPECTED VALUE
X=3: INPUT HIGHEST VALUE
K= K+1
COMPUTE:
TOTAL$_K$(X)= TOTAL$_{K-1}$(X) + DIST(X,K)
COMPUTE & DISPLAY:
AVG$_K$(X)= TOTAL$_K$(X)/K
X= 1, 2, 3
no
IS I= J ?
yes
J= J+1
J= 1
I= I+1
no
yes
IS J= N ?
no
IS I= N J= N-1 ?
yes
END

Figure 99. Algorithm for computing the average message transmission distance for a many-to-many transmission

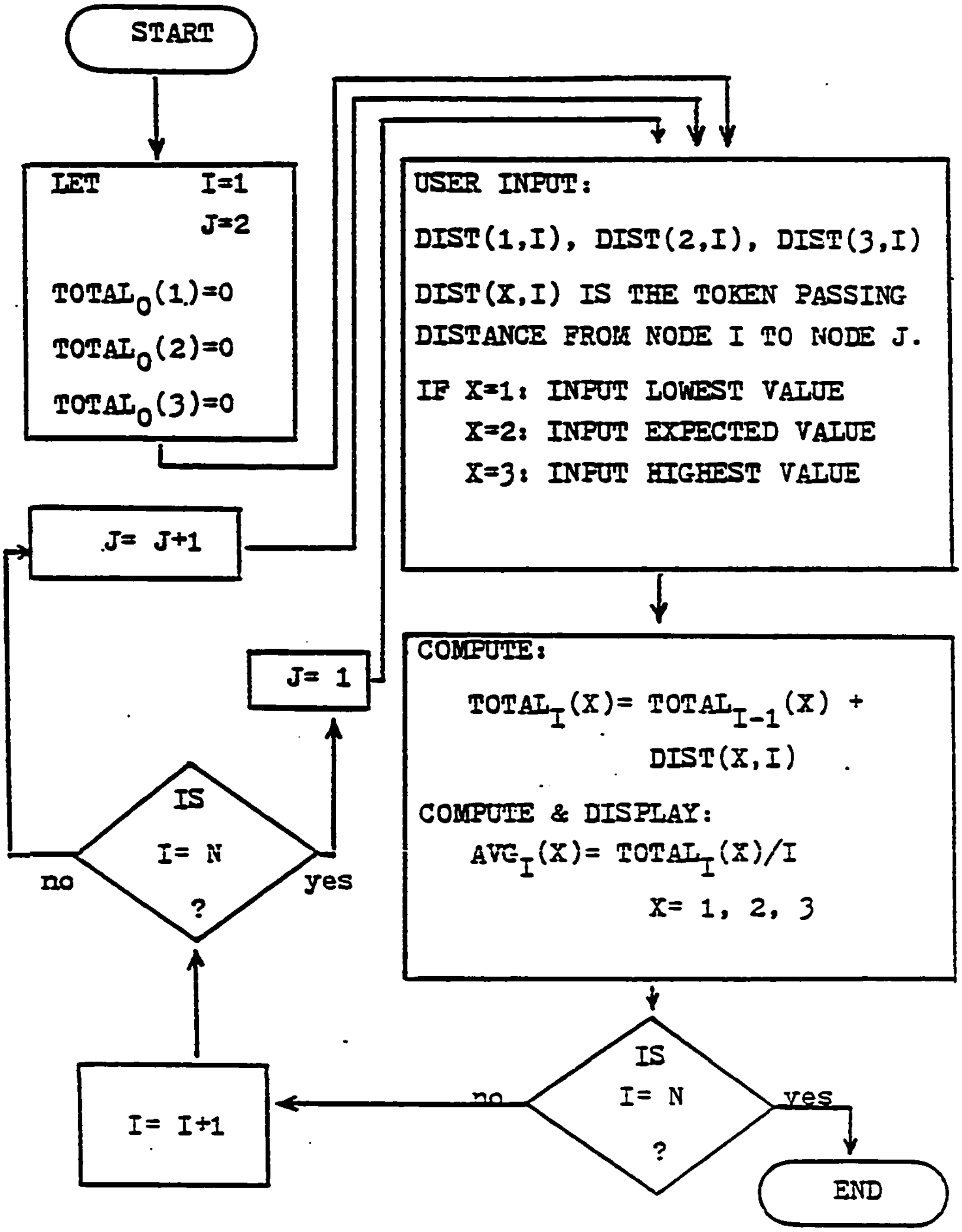

START
LET I=1
J=2
TOTAL$_0$(1)=0
TOTAL$_0$(2)=0
TOTAL$_0$(3)=0
USER INPUT:
DIST(1,I), DIST(2,I), DIST(3,I)
DIST(X,I) IS THE TOKEN PASSING DISTANCE FROM NODE I TO NODE J.
IF X=1: INPUT LOWEST VALUE
X=2: INPUT EXPECTED VALUE
X=3: INPUT HIGHEST VALUE
J= J+1
J= 1
COMPUTE:
TOTAL$_I$(X)= TOTAL$_{I-1}$(X) + DIST(X,I)
COMPUTE & DISPLAY:
AVG$_I$(X)= TOTAL$_I$(X)/I
X= 1, 2, 3
IS I= N ?
no
yes
I= I+1
IS I= N ?
no
yes
END

Figure 100. Algorithm for computing the average token passing distance for token passing networks

xx/yy/zz (e.g., 7/26/85).

where, xx- month, yy- day, zz- year.

To speed up the process, one can also skip inputing date by hitting <CR>.

5. After the date is entered, the printer will generate a report of the specification.

At this point the network specification input process is completed.

Performance evaluation

Upon completion of the network specification input process, a menu listing the various performance measures which the software will generate analytically is presented to the user (Figure 34). After deciding on the aspect of networking performance one wants to evaluate, a user will make his selection by hitting the appropriate key. Upon doing this, one may be queried on the kind of transmission service scheme i.e., byte or packet (Figure 13) that one's network is following. Discussions on the difference between the packet service scheme and the byte service scheme is given in Chapter I.

Before the computer will actually do the computing, a user is queried on the range over which performance evaluation is to be carried out:

Message rate per user (in packets/second)- the arrival rate of packets from a user to its respective output buffer in a node. This input is a number (integer or real) greater than 0.

Message rate per user (in bytes/second)- the arrival rate of bytes from a user to its respective output buffer in a node. This input is a number (integer or real) greater than 0.

Message size (in user bits/packet)- the number of user data bits per packet. This input is a number (integer) greater than 0.

Number of nodes- the number of nodes connected to the network. This input is a number greater than 1.

Due to the highly complexed algorithms that are used by the software in computing the average message delay and the average node buffer size, the following restrictions are imposed in the generation of analytical results:

1. For CSMA-CD networks- the input to the query "Message rate per user (in packets/sec.):" has to be less than or equal to .01.
2. For token passing networks that follow the byte service scheme- the input to the query "Message rate per user (in bytes/sec.):" has to be less than or equal to 1000.

A user will have a choice in the way analytical results are displayed during the evaluation. The options are:

1. On-line printing of results: the printer will print the results line by line as soon as the results are computed.
2. Continuous display of results on screen: analytical results

are continuously displayed on the screen until the end of the performance evaluation process. This option can be used in conjunction with the on-line printing option such that a physical record of the analysis is available at the end of the computation process.

3. Page-by-page display of results on screen: analytical results are displayed until they fill up the screen. At that time program execution will pause and a user will have as much time as he wishes to examine the analytical results. This option is also intended for a user who does not have a printer, so he can select this option to allow himself enough time to copy the results displayed on screen. However, if a user desires, this option can also be used in conjunction with the on-line printing option. To proceed with the computation process, a user will have to type in a <C>, and earlier results will be overwritten.

After all relevant information is collected by the software, the computation process will begin and analytical results presented on the screen. The various table headings for the analytical results are shown in Figure 101. The three columns of results displayed under the headings: highest, expected, and lowest, represent the values computed using the respective best, expected, and worst case values a user inputed earlier in the table of conditional specifications. Upon completion of the evaluation process, a user will have several options in displaying

USER RATE (BYTES/SEC.)	USER RATE (BITS/SEC.)	-- MAX. # OF NODES --		
		HIGHEST	EXPECTED	LOWEST

a. Table heading for the analysis of the maximum number of nodes a network can support (byte scheme)

USER RATE (PAC./SEC.)	MESSAGE SIZE (BITS/PAC.)	-- MAX. # OF NODES --		
		HIGHEST	EXPECTED	LOWEST

b. Table heading for the analysis of the maximum number of nodes a network can support (packet scheme)

# OF NODES	MESSAGE SIZE (BITS/PAC.)	MAX. NODE DATA RATE (BITS/SEC.)		
		HIGHEST	EXPECTED	LOWEST

c. Table heading for the analysis of the maximum achieveable data rate per node

MESSAGE SIZE (BITS/PAC.)=

# OF NODES	USER RATE (BITS/SEC.)	AVG. MESSAGE DELAY (MICROSEC.)		
		LOWEST	EXPECTED	HIGHEST

d. Table heading for the analysis of the average message delay

Figure 101. Table headings used in tabulation of analytical results

MESSAGE SIZE (BITS/PAC.)=

# OF NODES	USER RATE (BITS/SEC.)	AVG. NODE BUFFER SIZE (BYTES)		
		LOWEST	EXPECTED	HIGHEST

e. Table heading for the analysis of the average node buffer size

# OF NODES	MESSAGE SIZE (BITS/PAC.)	MAX. NODE MESSAGE RATE (PAC./SEC.)		
		HIGHEST	EXPECTED	LOWEST

f. Table heading for the analysis of the network saturation packet rate to a node

# OF NODES	----- NODE BYTE RATE (BYTES/SEC.) -----		
	HIGHEST	EXPECTED	LOWEST

g. Table heading for the analysis of the network saturation byte rate to a node

Figure 101. (continued)

and recording the results the software just generated.

Displaying and recording analytical results

The following are options a user has in dealing with the analytical results:

1. Storing results on disk: in selecting this option, a user can have the analytical results stored in a user file on a disk supplied by the user. To store, one should:
   a) Input <1> at the Output Options Menu (Figure 35).
   b) Upon display of the instruction "Insert formatted storage disk into drive A: (Ready or Abort)? Enter <R> or <A>", insert a formatted disk into disk drive A and type <R>.
   c) The software will then query the user for a filename to be used in identifing the user file. The length of the name used should be from 1 to 8 characters long. Both numerical and alphabetical characters can be used. The name should then be followed by a dot and the letters LAN (e.g. IBM1BYTE.LAN) to identify this as a file containing analytical results generated by the software. After entering the full filename, hit <CR>.
   d) The computer will then store the analytical results in a user file. Upon completion of the recording process, remove user disk from drive A, and hit <E> to return to the Output Options Menu.
2. Plot results on screen: after the selection of this option,

analytical results generated are plotted on the screen (Figure 102). In most cases, several sets of data (up to a maximum of 6 sets) are plotted on the same graph. Program execution pauses after the plotting of each set to allow a user time to study the plot. To proceed, one simply needs to type <P>. When the plotting process is completed, a cursor appears on the screen to help a user in reading the coordinates of any points on the plot. To move the cursor, the numeric keys on the right side of the keyboard are used (Figure 103). One should:

Type <8> to move the cursor up.

Type <2> to move the cursor down.

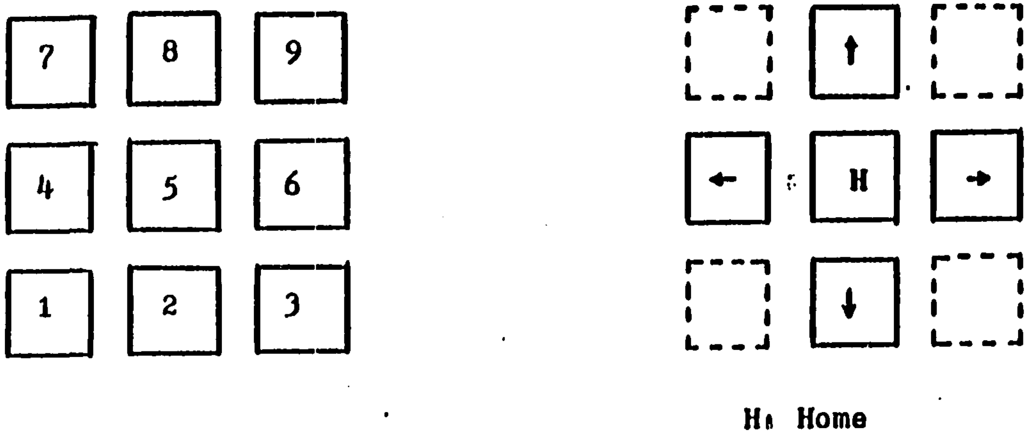
Type <4> to move the cursor to the left.

Type <6> to move the cursor to the right.

Type <5> to move the cursor back to its initial position.

To return to the Output Options Menu, type <C>.

3. Printing specification or analytical results on printer: a report is printed using the same printing process described earlier in this section.
4. Tabulate results on screen: analytical results are tabulated on screen using the page-by-page display mode. After all results are tabulated, one can return to the Output Options Menu by typing <C>.
5. Clear results from memory: all analytical results are deleted from computer memory. Unless they were stored earlier in an


7
8
9
4
5
6
1
2
3
↑
←
H
→
↓
H: Home

a. Numeric keypad layout

b. Directional control

Figure 1.02. Plotting on screen

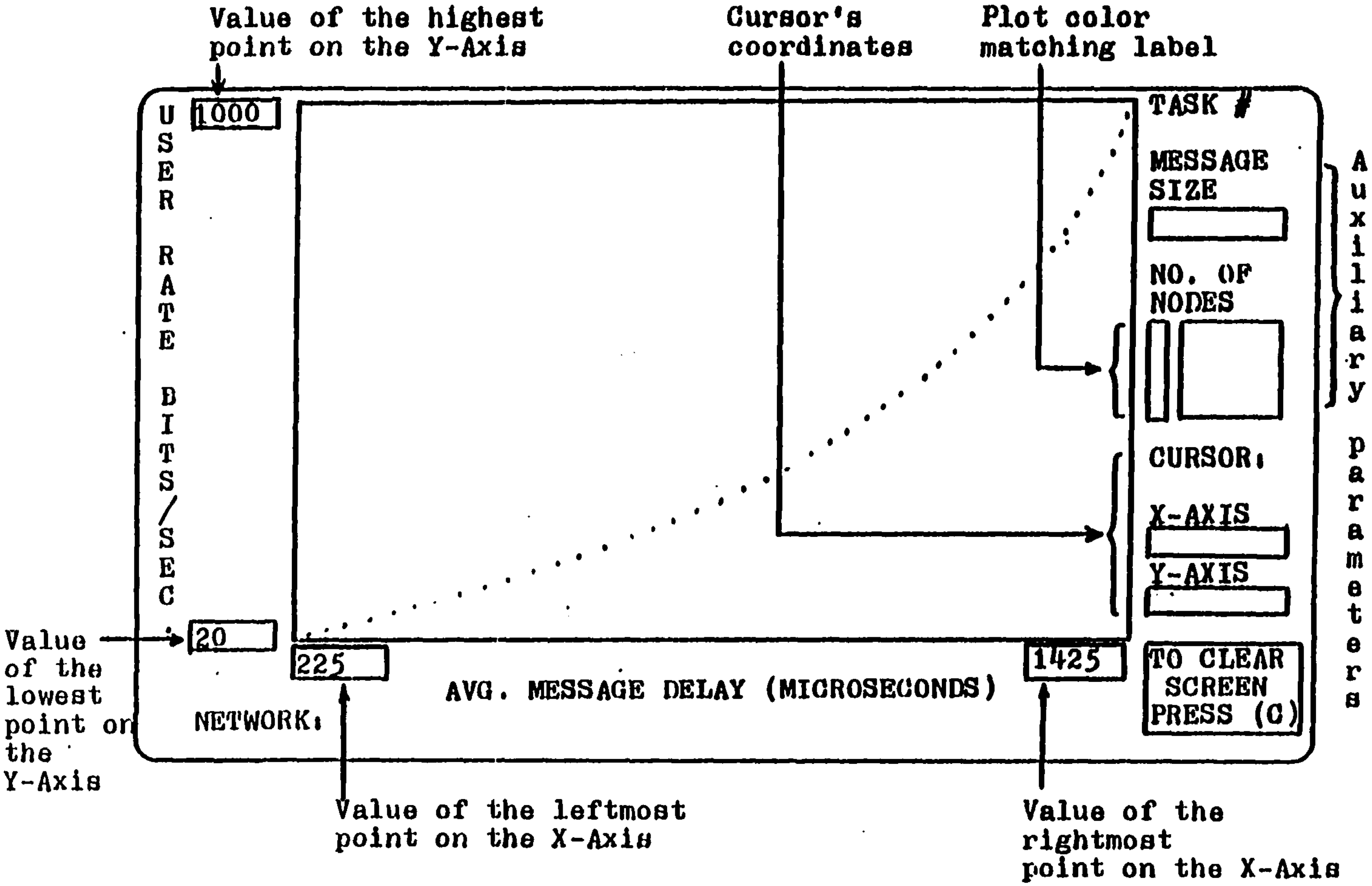

Value of the highest point on the Y-Axis
Cursor's coordinates
Plot color matching label
1000
USER RATE BITS/SEC
TASK #
MESSAGE SIZE
NO. OF NODES
CURSOR:
X-AXIS
Y-AXIS
Auxiliary parameters
Value of the lowest point on the Y-Axis
20
225
1425
AVG. MESSAGE DELAY (MICROSECONDS)
TO CLEAR SCREEN PRESS (C)
NETWORK:
Value of the leftmost point on the X-Axis
Value of the rightmost point on the X-Axis

Figure 103. Cursor control

user file, they will be lost. Therefore, when selecting this option, one should be certain that the results are either stored or are no longer needed. Upon deleting all results, a user is presented with the Next Operation Menu (Figure 36), for his selection on what operation to conduct next.

Access files of evaluated networks

One can retrieve a user file by following these steps:

1. Upon display of the Operation Menu, input <2>.
2. Upon display of the instruction "Insert formatted storage disk into drive A", insert the disk containing the user file one wants to retrieve into disk drive A.
3. Input <R>. Look through the directory of filenames displayed on the lower half of the screen, and make certain that the name of the user file one wants to retrieve is listed.
4. Type in the full filename, and hit <CR>.
5. When the file is accessed, a table summarizing the network specification is displayed.

The contents of the retrieved file can be printed or tabulated or plotted on screen. Also, the network specification can be used for doing further analysis of network performance. To do this, one simply needs to select the option "Proceed to query list" from the displayed menu, and proceed from there as if one is doing a first time evaluation of network performance.

Performance comparison of evaluated networks

To compare the analytical results stored in several user files, one should:

1. Input <3> at the Operation Menu.
2. Upon display of the list of performance measures one can compare on (Figure 104), make the appropriate selection.
3. Access user files the same way as described earlier.
4. For each user file accessed, give it a name (0-8 characters) to be used as label on the plot to be generated later.
5. To plot using data accessed so far, input <N> to the query "Read another file?".
6. Data from a maximum of seven files can be plotted on one graph. To read the coordinates of the plots, simply move the cursor using the method described earlier. The values of the coordinates are shown at the bottom of the screen.

As shown in Chapters V and VI, the developed software was applied in the performance analysis and comparison of several real LANs.

```
PLEASE SPECIFY:-

COMPARISON BASIS:


1.  THE NUMBER OF NODES THE NETWORK CAN SUPPORT.

2.  THE MAXIMUM ACHIEVEABLE DATA RATE PER NODE.

3.  THE AVERAGE MESSAGE DELAY.

4.  THE AVERAGE NODE BUFFER SIZE.

5.  THE NETWORK OR SATURATION MESSAGE RATE TO A NODE.

                       OR

6.  RETURN TO OPERATION MENU.


                                                 PLEASE ENTER
```

Figure 104. Performance comparison menu

APPENDIX B.

FLOW CHARTS OF SOFTWARE PROGRAMS

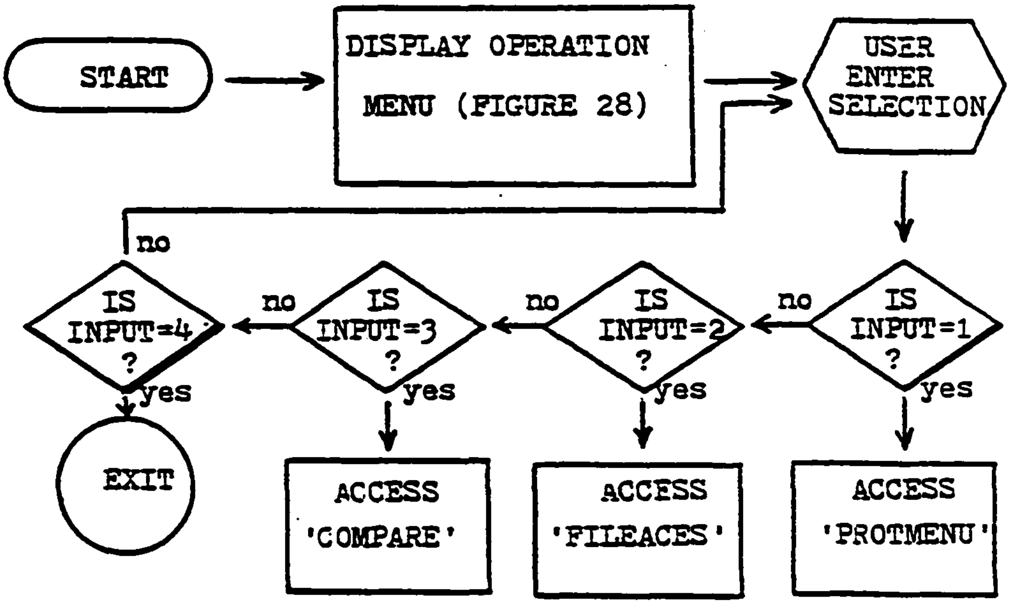

START
DISPLAY OPERATION MENU (FIGURE 28)
USER ENTER SELECTION
IS INPUT=1 ?
yes
no
ACCESS 'PROTMENU'
IS INPUT=2 ?
yes
no
ACCESS 'FILEACES'
IS INPUT=3 ?
yes
no
ACCESS 'COMPARE'
IS INPUT=4 ?
yes
no
EXIT

Figure 105. Flow chart for the program OPERMENU

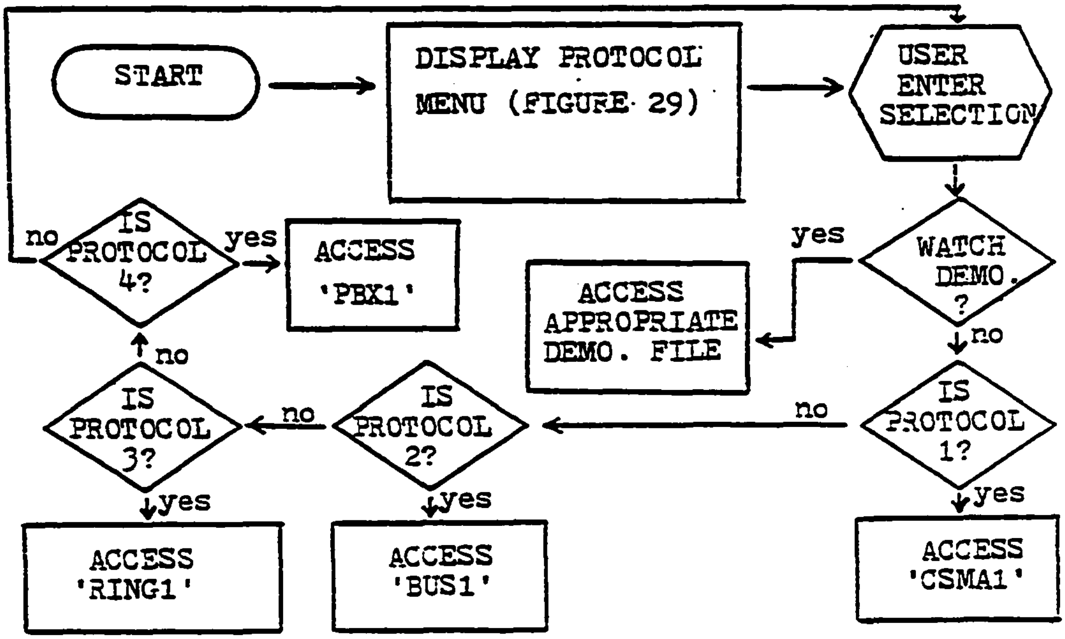

START
DISPLAY PROTOCOL MENU (FIGURE 29)
USER ENTER SELECTION
WATCH DEMO ?
yes
ACCESS APPROPRIATE DEMO. FILE
no
IS PROTOCOL 1?
yes
ACCESS 'CSMA1'
no
IS PROTOCOL 2?
yes
ACCESS 'BUS1'
no
IS PROTOCOL 3?
yes
ACCESS 'RING1'
no
IS PROTOCOL 4?
yes
ACCESS 'PBX1'
no

Figure 106. Flow chart for the program PROTMENU

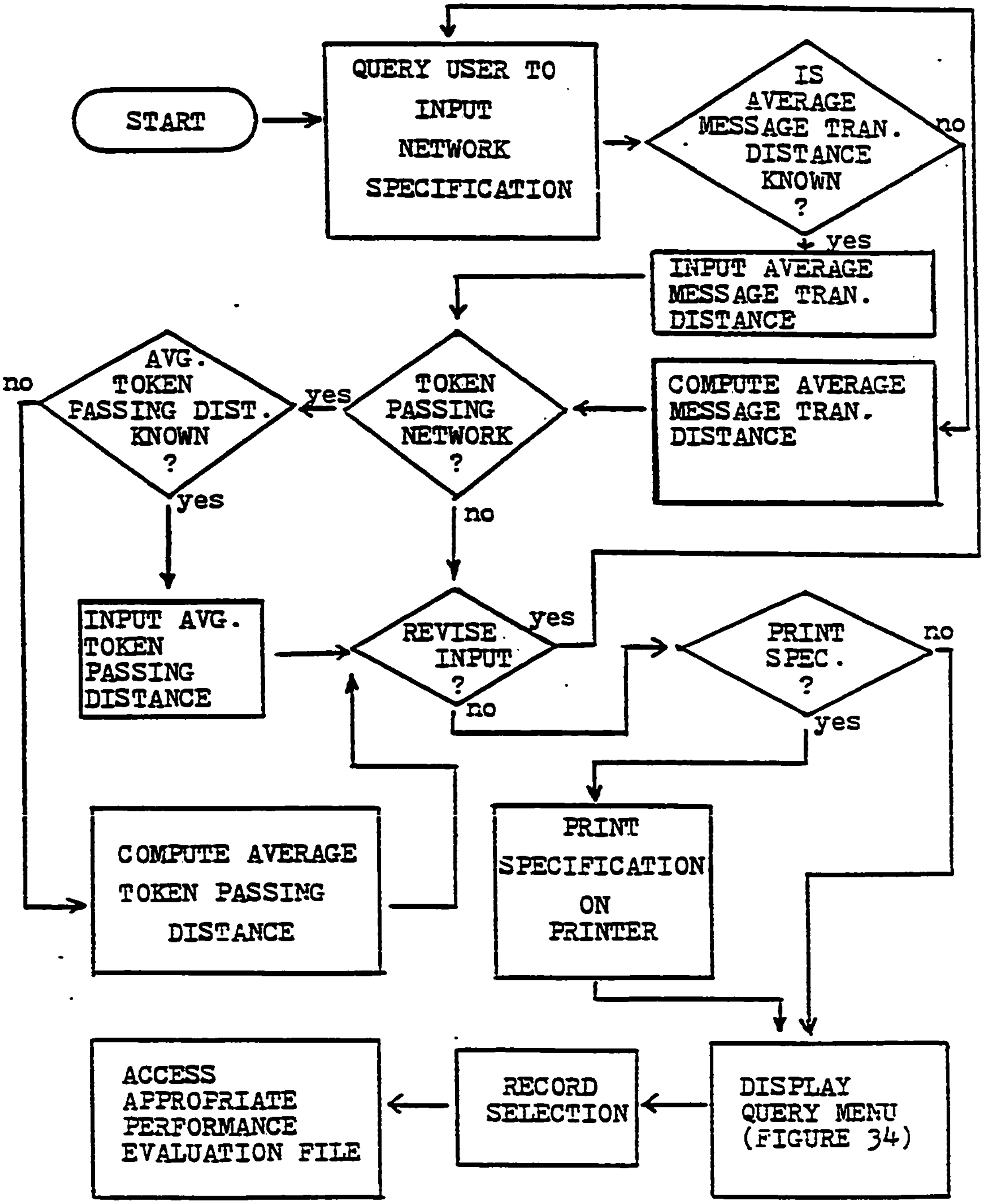

START
QUERY USER TO INPUT NETWORK SPECIFICATION
IS AVERAGE MESSAGE TRAN. DISTANCE KNOWN ?
no
yes
INPUT AVERAGE MESSAGE TRAN. DISTANCE
COMPUTE AVERAGE MESSAGE TRAN. DISTANCE
TOKEN PASSING NETWORK ?
yes
no
AVG. TOKEN PASSING DIST. KNOWN ?
no
yes
INPUT AVG. TOKEN PASSING DISTANCE
REVISE INPUT ?
yes
no
PRINT SPEC. ?
no
yes
COMPUTE AVERAGE TOKEN PASSING DISTANCE
PRINT SPECIFICATION ON PRINTER
ACCESS APPROPRIATE PERFORMANCE EVALUATION FILE
RECORD SELECTION
DISPLAY QUERY MENU (FIGURE 34)

Figure 107. Flow chart for the programs CSMA1, BUS1, RING1, PBX1

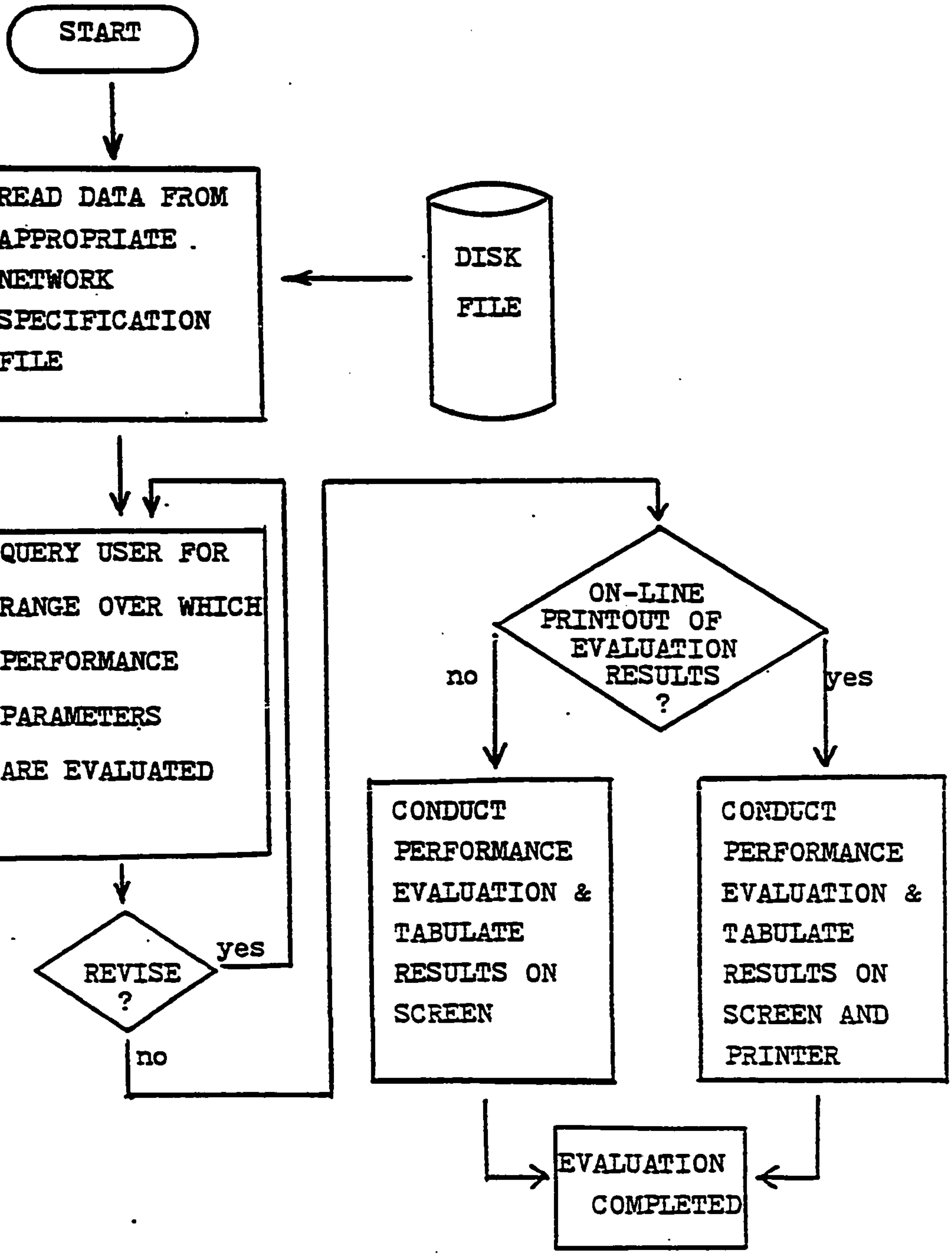

START
READ DATA FROM APPROPRIATE NETWORK SPECIFICATION FILE
DISK FILE
QUERY USER FOR RANGE OVER WHICH PERFORMANCE PARAMETERS ARE EVALUATED
REVISE ?
yes
no
ON-LINE PRINTOUT OF EVALUATION RESULTS ?
no
yes
CONDUCT PERFORMANCE EVALUATION & TABULATE RESULTS ON SCREEN
CONDUCT PERFORMANCE EVALUATION & TABULATE RESULTS ON SCREEN AND PRINTER
EVALUATION COMPLETED

Figure 108. Flow chart for the programs CSMA2, BUS2, RING2, PBX2

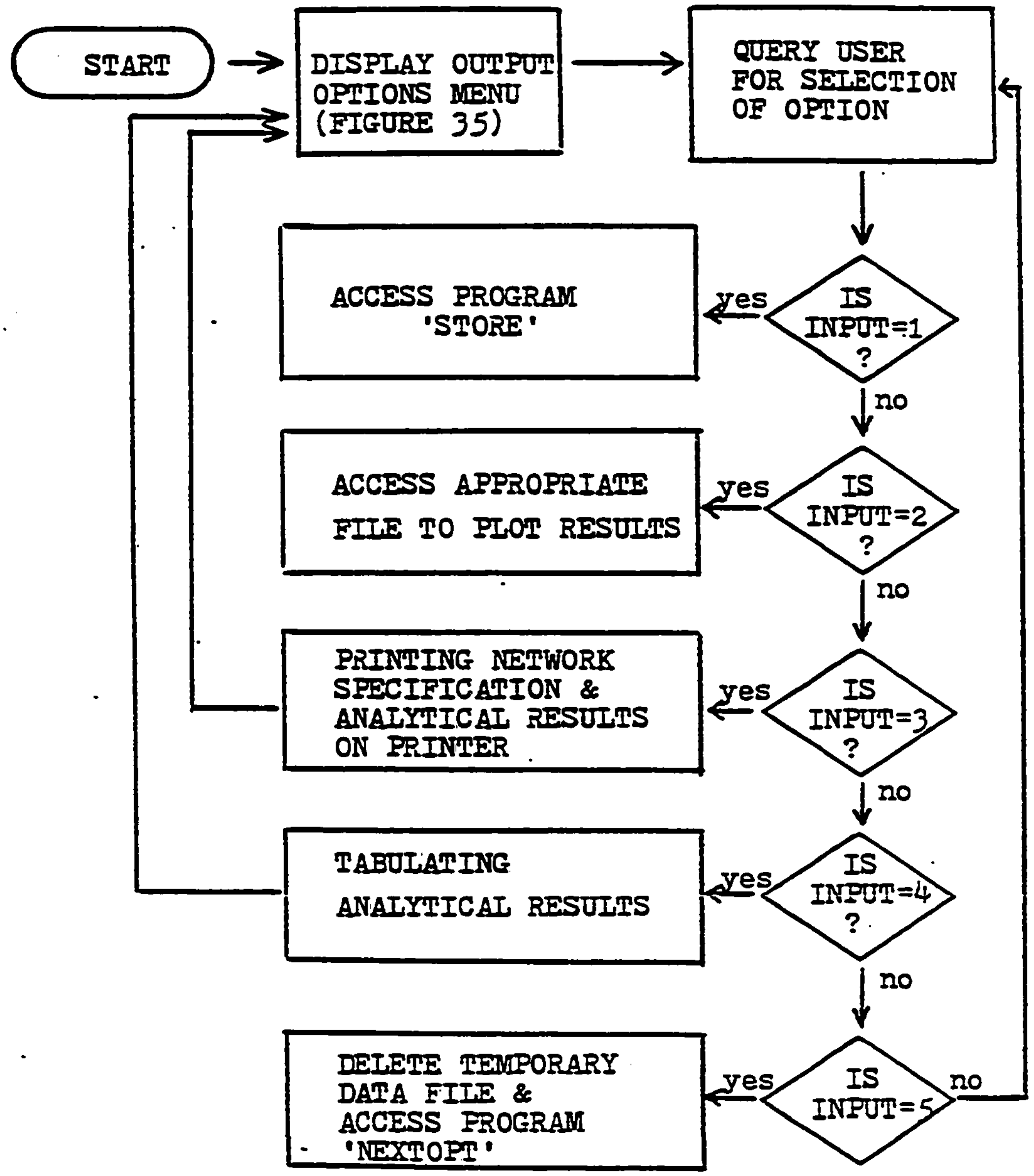

START
DISPLAY OUTPUT OPTIONS MENU (FIGURE 35)
QUERY USER FOR SELECTION OF OPTION
IS INPUT=1 ?
yes
ACCESS PROGRAM 'STORE'
no
IS INPUT=2 ?
yes
ACCESS APPROPRIATE FILE TO PLOT RESULTS
no
IS INPUT=3 ?
yes
PRINTING NETWORK SPECIFICATION & ANALYTICAL RESULTS ON PRINTER
no
IS INPUT=4 ?
yes
TABULATING ANALYTICAL RESULTS
no
IS INPUT=5
yes
DELETE TEMPORARY DATA FILE & ACCESS PROGRAM 'NEXTOPT'
no

Figure 109. Flow chart for the program OUTPUT

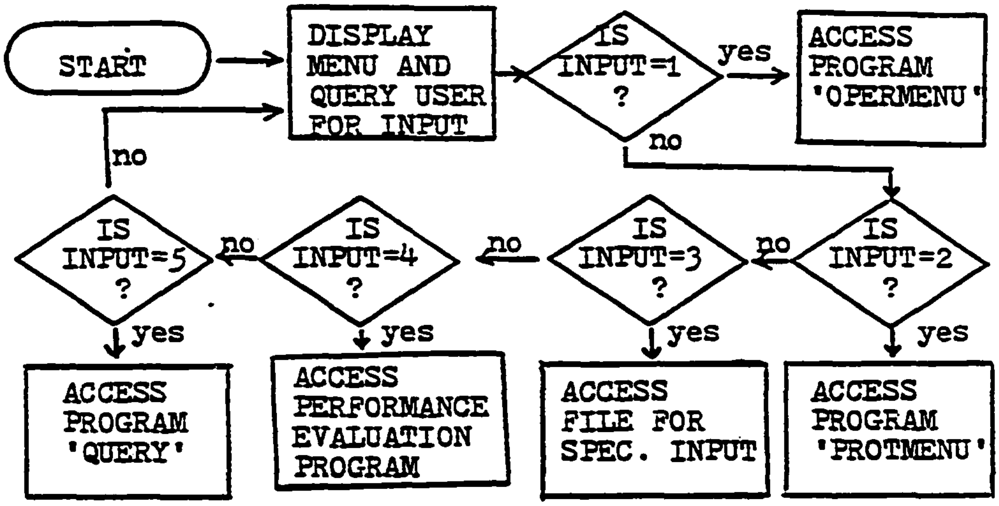

START
DISPLAY MENU AND QUERY USER FOR INPUT
IS INPUT=1 ?
yes
ACCESS PROGRAM 'OPERMENU'
no
IS INPUT=2 ?
yes
ACCESS PROGRAM 'PROTMENU'
no
IS INPUT=3 ?
yes
ACCESS FILE FOR SPEC. INPUT
no
IS INPUT=4 ?
yes
ACCESS PERFORMANCE EVALUATION PROGRAM
no
IS INPUT=5 ?
yes
ACCESS PROGRAM 'QUERY'
no

Figure 110. Flow chart for the program NEXTOPT

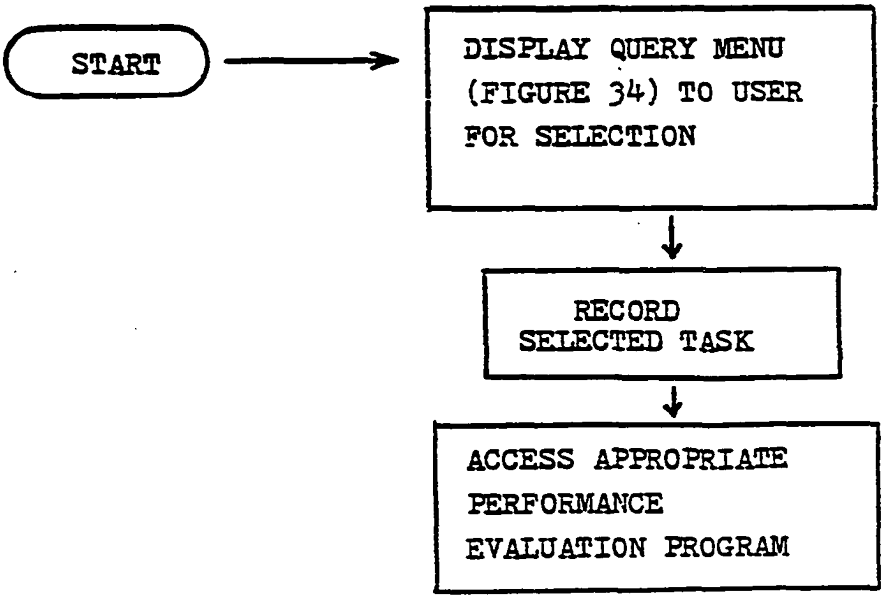

START
DISPLAY QUERY MENU (FIGURE 34) TO USER FOR SELECTION
RECORD SELECTED TASK
ACCESS APPROPRIATE PERFORMANCE EVALUATION PROGRAM

Figure 111. Flow chart for the program QUERY

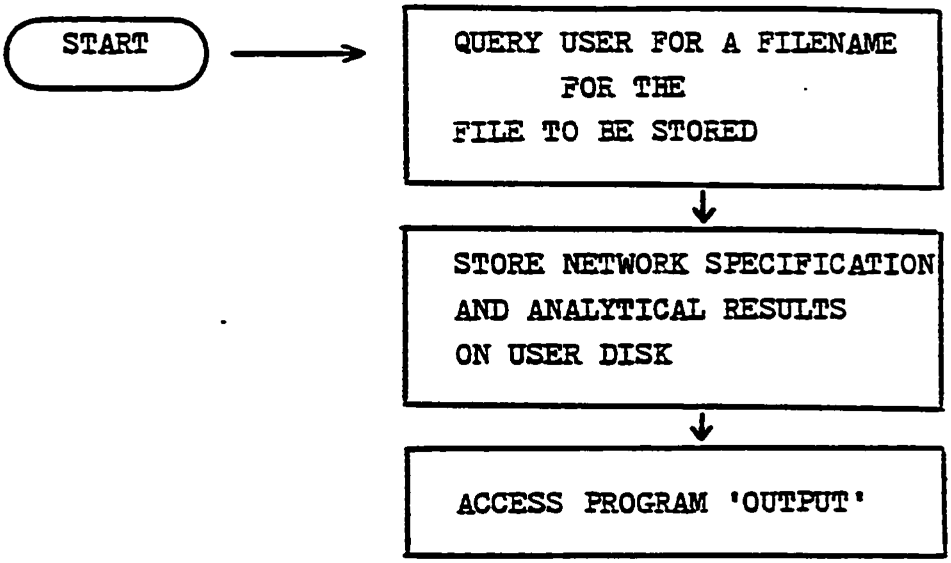

START
QUERY USER FOR A FILENAME FOR THE FILE TO BE STORED
STORE NETWORK SPECIFICATION AND ANALYTICAL RESULTS ON USER DISK
ACCESS PROGRAM 'OUTPUT'

Figure 112. Flow chart for the program STORE

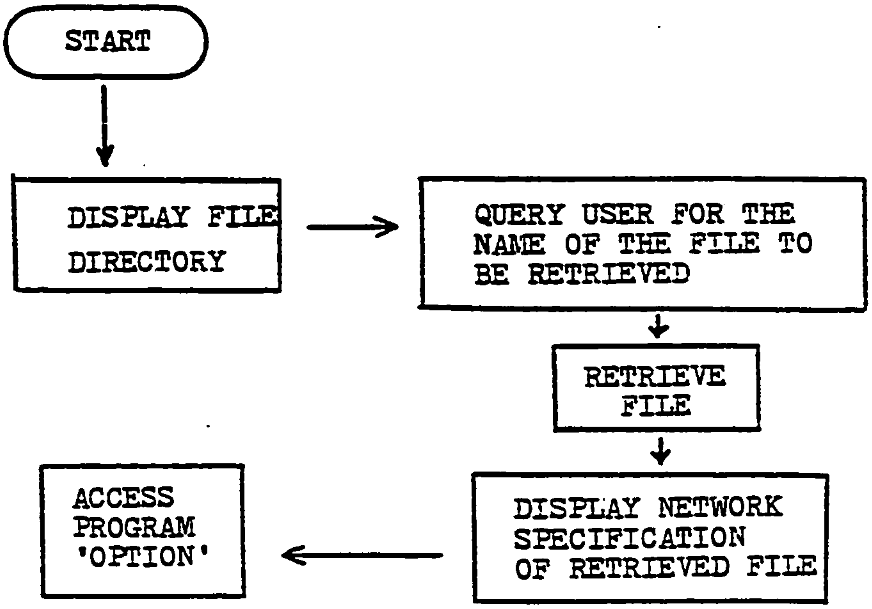

START
DISPLAY FILE DIRECTORY
QUERY USER FOR THE NAME OF THE FILE TO BE RETRIEVED
RETRIEVE FILE
DISPLAY NETWORK SPECIFICATION OF RETRIEVED FILE
ACCESS PROGRAM 'OPTION'

Figure 113. Flow chart for the program FILEACES

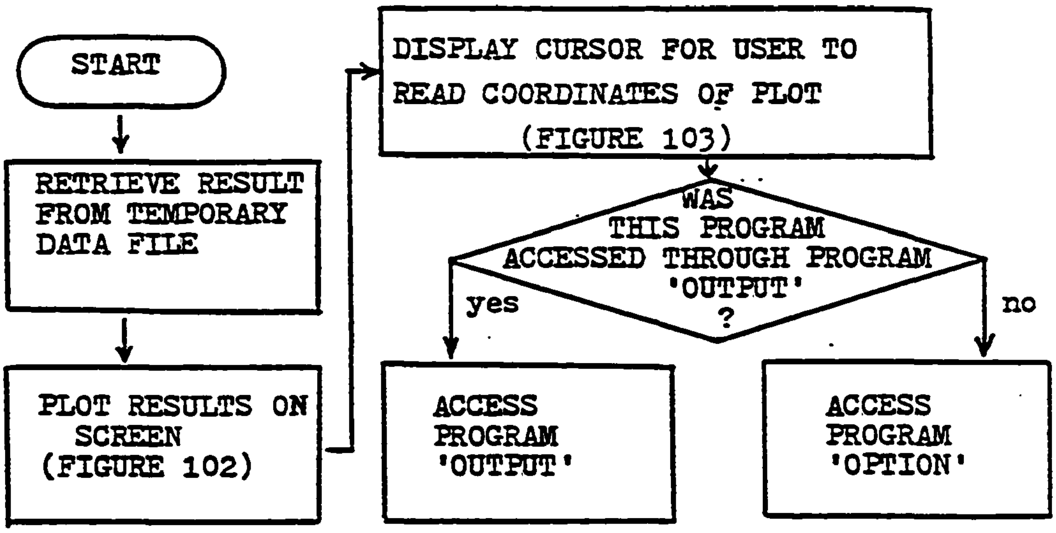

START
RETRIEVE RESULT FROM TEMPORARY DATA FILE
PLOT RESULTS ON SCREEN (FIGURE 102)
DISPLAY CURSOR FOR USER TO READ COORDINATES OF PLOT (FIGURE 103)
WAS THIS PROGRAM ACCESSED THROUGH PROGRAM 'OUTPUT' ?
yes
no
ACCESS PROGRAM 'OUTPUT'
ACCESS PROGRAM 'OPTION'

Figure 114. Flow chart for the programs PLOT1, PLOT2, PLOT3

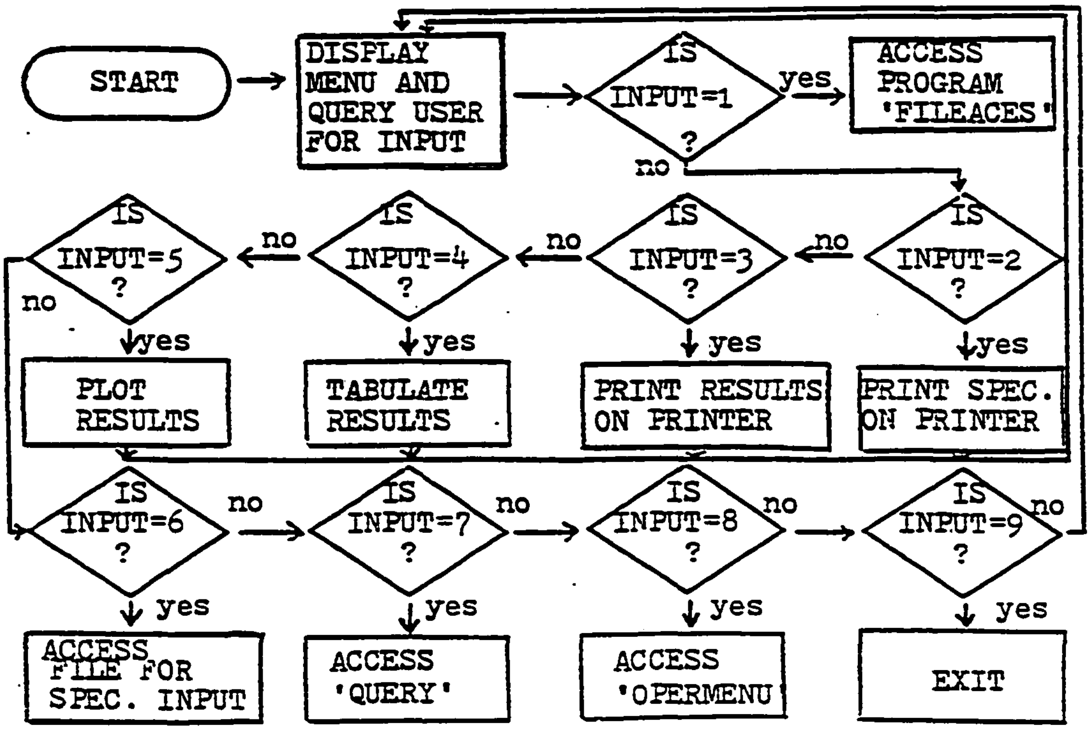

START
DISPLAY MENU AND QUERY USER FOR INPUT
IS INPUT=1 ?
yes
ACCESS PROGRAM 'FILEACES'
no
IS INPUT=2 ?
IS INPUT=3 ?
IS INPUT=4 ?
IS INPUT=5 ?
no
yes
PRINT SPEC. ON PRINTER
PRINT RESULTS ON PRINTER
TABULATE RESULTS
PLOT RESULTS
IS INPUT=6 ?
IS INPUT=7 ?
IS INPUT=8 ?
IS INPUT=9 ?
ACCESS FILE FOR SPEC. INPUT
ACCESS 'QUERY'
ACCESS 'OPERMENU'
EXIT

Figure 115. Flow chart for the program OPTION

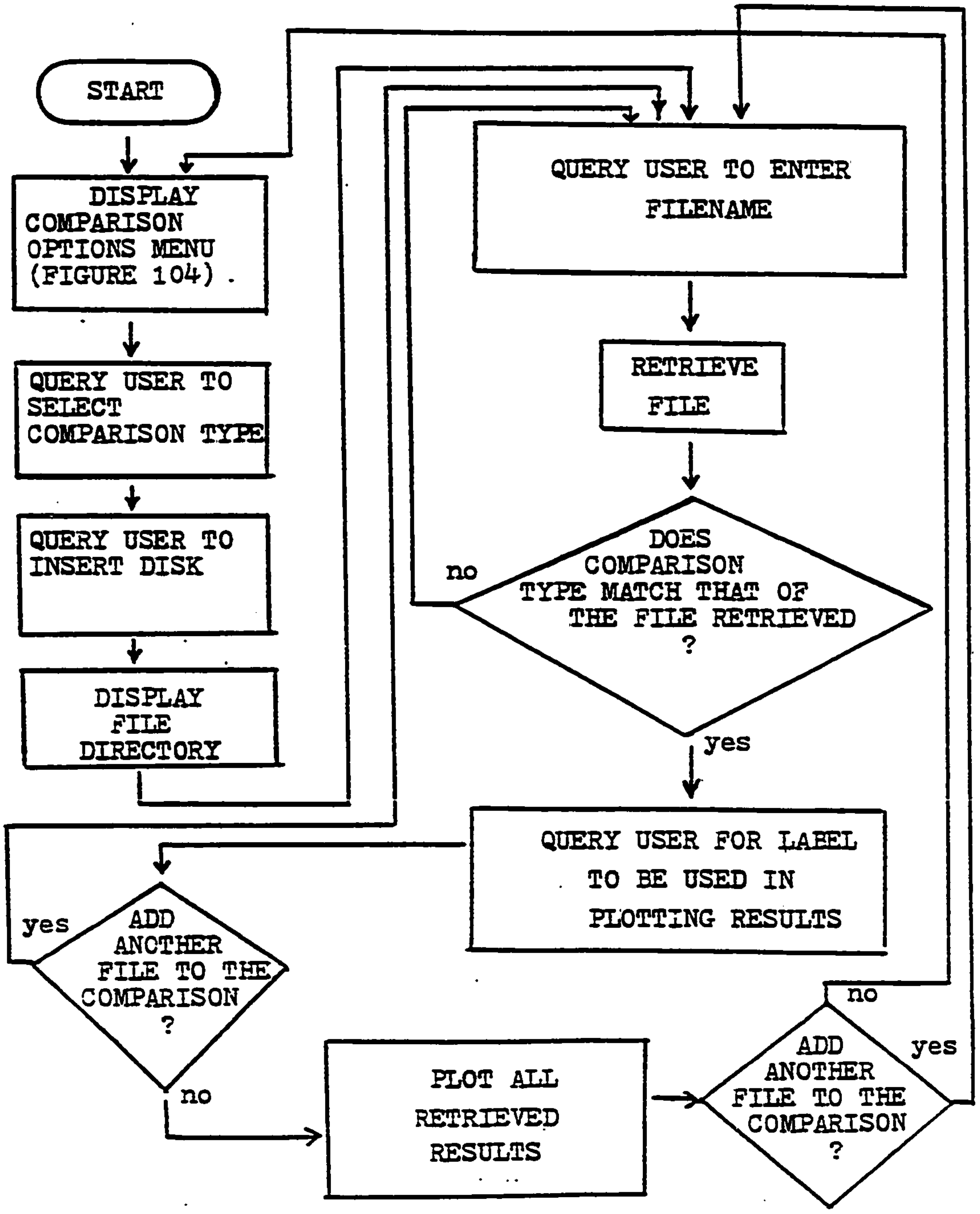

START
DISPLAY COMPARISON OPTIONS MENU (FIGURE 104).
QUERY USER TO SELECT COMPARISON TYPE
QUERY USER TO INSERT DISK
DISPLAY FILE DIRECTORY
QUERY USER TO ENTER FILENAME
RETRIEVE FILE
DOES COMPARISON TYPE MATCH THAT OF THE FILE RETRIEVED ?
no
yes
QUERY USER FOR LABEL TO BE USED IN PLOTTING RESULTS
ADD ANOTHER FILE TO THE COMPARISON ?
yes
no
PLOT ALL RETRIEVED RESULTS
ADD ANOTHER FILE TO THE COMPARISON ?
no
yes

Figure 116. Flow chart for the program COMPARE

APPENDIX C. COMPUTER SIMULATION OF A TOKEN PASSING NETWORK FOLLOWING THE BYTE SERVICE SCHEME

This appendix describes the simulation of a token passing network following the byte service scheme. Results obtained in this simulation are compared with results computed using the analytical models in predicting the average message queueing delay for token passing networks. A flow diagram illustrating the events included in the simulation is presented in Figure 117. In Figure 118, the simulation program written in Basic is listed.

For the simulation, the transmission time of one byte of data is the time unit. Simulation runs are conducted using the network specification of Arcnet. Results of the comparison is listed in Table 10. It indicates that simulation results are reasonably close to what is predicted using the analytical models.

Table 10. Comparing analytical results with simulation results-average message delay of Arcnet (byte scheme). T_{byte}=3.2 microseconds, T_{prop}=2 microseconds.

λ_{user} (bytes/ sec.)	No. of Nodes	Analytical Results	Simulation Results		
		$D_{message}$ (microsec.)	$T_{rotation}$ (norm.)	(μs)	$D_{message}$ (microsec.)
1	10	122	83	266	135
10	10	130	88	282	143
100	10	180	116	370	187
1	30	374	226	723	364
10	30	384	241	771	388
100	30	650	412	1318	661
1	50	620	401	1283	644
10	50	650	417	1334	669
100	50	1732	1073	3434	1719

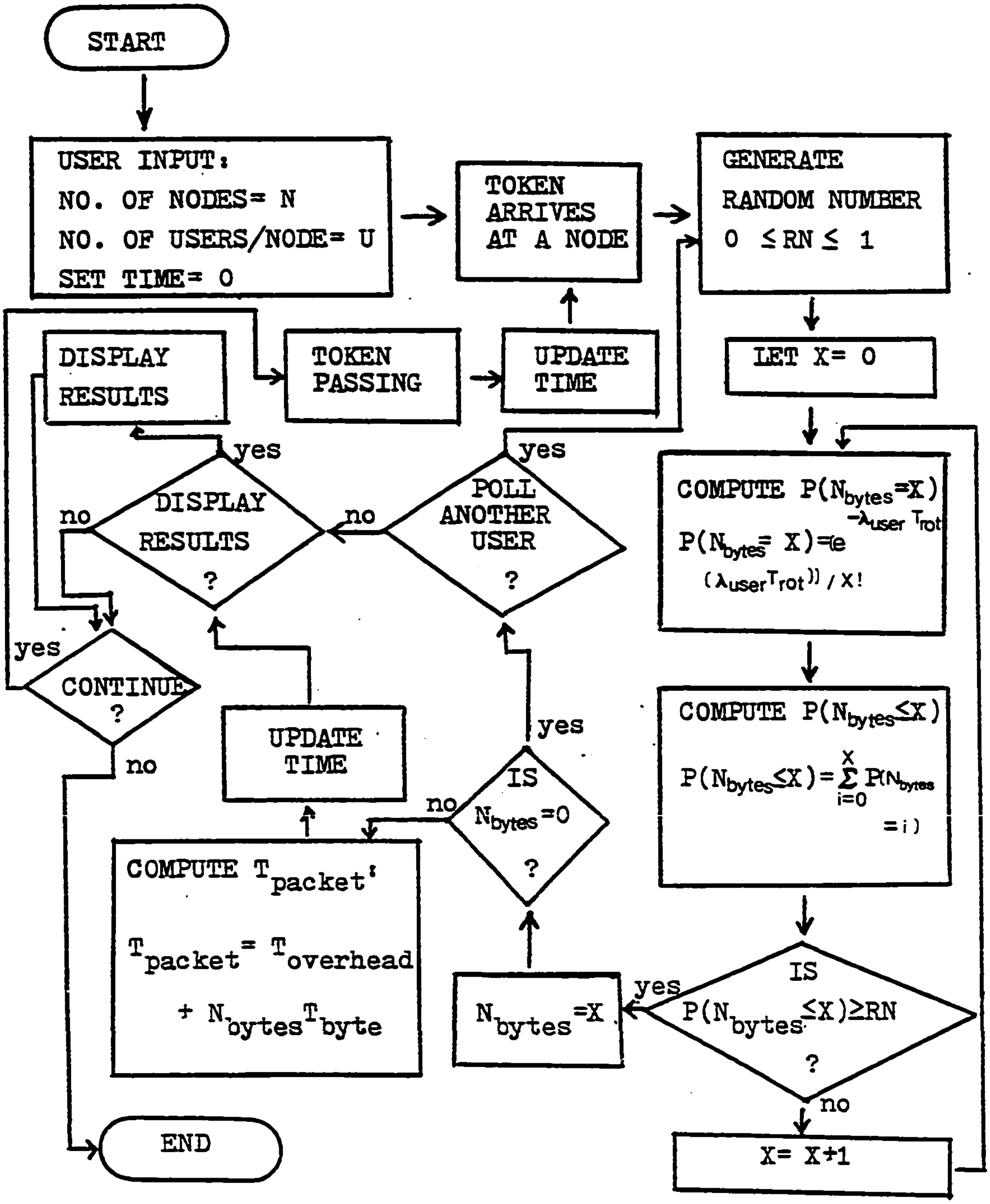

START
USER INPUT:
NO. OF NODES= N
NO. OF USERS/NODE= U
SET TIME= 0
TOKEN ARRIVES AT A NODE
GENERATE RANDOM NUMBER
0 ≤ RN ≤ 1
DISPLAY RESULTS
TOKEN PASSING
UPDATE TIME
LET X= 0
yes
DISPLAY RESULTS ?
no
no
yes
POLL ANOTHER USER ?
COMPUTE P(N_bytes=X)
P(N_bytes= X)=(e^-λuser Trot (λuserTrot)) / X!
yes
CONTINUE ?
no
UPDATE TIME
yes
COMPUTE P(N_bytes≤X)
P(N_bytes≤X)= Σ_(i=0)^X P(N_bytes =i)
no
IS N_bytes=0 ?
COMPUTE T_packet:
T_packet= T_overhead + N_bytes T_byte
N_bytes=X
yes
IS P(N_bytes≤X)≥RN ?
no
END
X= X+1

Figure 117. Simulation model

```
100 REM  TITLE:  COMPUTER SIMULATION OF A TOKEN PASSING NETWORK
110 REM          FOLLOWING THE BYTE SERVICE SCHEME.
120 REM  *******************  USER INPUT  ************************
130 REM  N- NUMBER OF NODES.
140 REM  U- NUMBER OF USERS PER NODE.
150 REM  MEAN- AVERAGE USER BYTE RATE PER TIME UNIT.
160 REM  TOVERHEAD- PACKET TRANSMISSION OVERHEAD DELAY.
170 REM  TBYTE- TRANSMISSION TIME OF ONE DATA BYTE.
180 REM  TTOKEN- TOKEN PASSING DELAY.
190 REM  START- THE TOKEN CYCLE NUMBER AT WHICH THE COLLECTION
200 REM         OF SIMULATION RELATED STATISTIC BEGINS.
210 REM  PRINTER- THE TOKEN CYCLE NUMBER AT WHICH THE
220 REM        .  PRINTING OF SIMULATION RELATED STATISTIC
230 REM           BEGINS.
240 REM  INCRE- THE NUMBER OF TOKEN CYCLES BETWEEN THE
250 REM         PRINTING OF ONE SET OF STATISTICAL RESULTS.
260 REM  LEND- THE TOKEN CYCLE NUMBER AT WHICH THE SIMULATION
270 REM        TERMINATES.
280 REM  ********************************************************
290 N=10: U=1: MEAN=.000001: TOVERHEAD=10: TBYTE=1: TTOKEN=5
300 START=5: PRINTER=10: INCRE=5: LEND=10000
310 PRINT N,U,MEAN,TOVERHEAD,TBYTE,TTOKEN
320 DIM USER(N,U): DIM NODE(N): DIM T(N,U): DIM TL(N,U)
330 I=1: CLS
340 FOR K=1 TO N: NODE(K)=1: NEXT K
350 REM  THE TOKEN ARRIVES AT NODE I, USER J.
360 J=NODE(I): COUNT=1
370 REM  COMPUTE THE ELAPSED TIME SINCE THE USER LAST
380 REM  TRANSMITTED.
390 TELAPSE=TCLOCK-USER(I,J)
400 REM  COMPUTE THE PROBABILITY THAT THE USER QUEUE IS
410 REM  EMPTY.
420 PEMPTY=EXP(-MEAN*TELAPSE)
430 REM  GENERATE A RANDOM NUMBER BETWEEN 0 TO 1.
440 R=RND
450 REM  IS THE USER QUEUE EMPTY?
460 IF R>PEMPTY THEN GOTO 620
470 REM  THE USER QUEUE IS EMPTY.
480 IF TLCOUNT<START THEN GOTO 510
490 GOSUB 850
500 GOSUB 1070
510 T(I,J)=TCLOCK: TL(I,J)=TLCOUNT
520 IF J=U THEN J=1: NODE(I)=1: GOTO 570
530 NODE(I)=J+1
540 REM  THE NODE POLLS ITS NEXT USER QUEUE FOR
550 REM  TRANSMISSION.
```

Figure 118. Program listing of simulation program.

```
560 J=J+1
570 IF COUNT=U THEN GOTO 760
580 COUNT=COUNT+1
590 GOTO 390
600 REM  THE USER QUEUE IS NOT EMPTY.  COMPUTE
610 REM  NUMBER OF DATA BYTES IN QUEUE.
620 GOSUB 1270
630 REM  COMPUTE PACKET TRANSMISSION TIME.
640 TPACKET=INT(TOVERHEAD+(NBYTES*TBYTE))
650 IF TLCOUNT<START THEN GOTO 700
660 GOSUB 850
670 GOSUB 1070
680 GOSUB 1150
690 TTCOUNT=TTCOUNT+1
700 USER(I,J)=TCLOCK:  T(I,J)=TCLOCK:  TL(I,J)=TLCOUNT
710 REM  UPDATE SIMULATION CLOCK.
720 TCLOCK=TCLOCK+TPACKET
730 NODE(I)=J+1
740 IF J=U THEN NODE(I)=1
750 REM  TOKEN PASSING.
760 TCLOCK=TCLOCK+TTOKEN
770 IF I=N THEN I=1:  GOSUB 950:  GOTO 800
780 I=I+1
790 GOTO 360
800 IF TLCOUNT=LEND+1 THEN END
810 GOTO 360
820 REM  ***************  END OF MAIN PROGRAM  *********
830 REM  SUBROUTINE FOR COMPUTING THE AVERAGE TOKEN
840 REM  ROTATION TIME AROUND ALL USER QUEUES.
850 TR=TCLOCK-T(I,J)
860 TRSUM=TR+TRSUM
870 TRCOUNT=TRCOUNT+1
880 TROTATE=TRSUM/TRCOUNT
890 RETURN
900 REM  SUBROUTINE FOR COMPUTING THE:
910 REM  1.  PROBABILITY THAT A NODE TRANSMITS UPON
920 REM      RECEIVING A FREE TOKEN.
930 REM  2.  THE AVERAGE TOKEN CYCLE TIME AROUND THE
940 REM      LOGICAL RING.
950 TL=TCLOCK-TMARK
960 TLSUM=TL+TLSUM
970 TLCOUNT=TLCOUNT+1
980 IF TLCOUNT<START THEN GOTO 1000
990 PNODE=TTCOUNT/((TLCOUNT-(START-1))*N)
```

Figure 118. (continued)

```
1000 IF TLCOUNT=PRINTER THEN GOSUB 1200: PRINTER=PRINTER+INCRE
1010 TRING=TLSUM/TLCOUNT
1020 TMARK=TCLOCK
1030 RETURN
1040 REM  SUBROUTINE FOR COMPUTING THE AVERAGE NUMBER
1050 REM  OF TOKEN CYCLES BETWEEN A USER'S TURN TO
1060 REM  TRANSMIT.
1070 NR=TLCOUNT-TL(I,J)
1080 NRSUM=NR+NRSUM
1090 NRCOUNT=NRCOUNT+1
1100 NRING=NRSUM/NRCOUNT
1110 RETURN
1120 REM  SUBROUTINE FOR COMPUTING THE PROBABILITY
1130 REM  THAT A USER WILL TRANSMIT WHEN ITS TURN
1140 REM  TO TRANSMIT OCCURS.
1150 NTRAN=NTRAN+1
1160 PTRAN=NTRAN/TRCOUNT
1170 RETURN
1180 REM  SUBROUTINE FOR THE PRINTING OF STATISTICAL
1190 REM  RESULTS.
1200 PRINT TLCOUNT, TCLOCK: BEEP
1210 PRINT"TROTATION=";TROTATE
1220 PRINT"TRING=";TRING
1230 PRINT"NRINGS=";NRING
1240 PRINT"PTRANS(USER)=";PTRAN
1250 PRINT"PTRANS(NODE)=";PNODE
1260 RETURN
1270 REM  SUBPROGRAM FOR COMPUTING THE NUMBER OF DATA BYTES
1280 REM  IN QUEUE.
1290 XX=1: PCUM=PEMPTY
1300 FAC=1
1310 FOR II=1 TO XX
1320 FAC=FAC*II
1330 NEXT II
1340 PNBYTES=(EXP(-MEAN*TELAPSE)*((MEAN*TELAPSE)^XX))/FAC
1350 PCUM=PCUM+PNBYTES
1360 IF R>PCUM THEN XX=XX+1: GOTO 1300
1370 NBYTES=XX
1380 RETURN
```

Figure 118. (continued)