ABSTRACT

PERFORMANCE EVALUATION OF CEBUS POWER LINE COMMUNICATION IN THE PRESENCE OF X-10 MODULE SIGNALING

by
Nashwa F. Kamel

A power line of CEBus has great potential towards inexpensive home automation. Both PLBus and X-10 uses bursts of 120 KHz signals to transmit bits of information on the power line. However, these two systems are completely incompatible and can conflict with each other. This thesis presents the first performance evaluation of Power Line CEBus communication in the presence of X-10 module signaling. The evaluation included simulation experiments measuring packet delays, message delays, message throughput, channel throughput and the percentage of messages received in error verses different loads. Network performance has been confirmed to function well in terms of delays and throughputs over the practical range of normalized offered load. Also the percentage of CEBus messages received in error due to a collision with X-10 signals did not exceed 2% in all our cases.

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by
Nashwa F. Kamel

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APPROVAL PAGE

PERFORMANCE EVALUATION OF CEBUS POWER LINE IN THE PRESENCE OF X-10 MODULES

Nashwa F. Kamel

Dr. Constantine N. Manikopoulos, Thesis Advisor — Date
Associate Professor of Electrical and Computer Engineering
New Jersey Institute of Technology

Dr. Yun-qing Shi, Committee Member — Date
Associate Professor of Electrical and Computer Engineering
New Jersey Institute of Technology

Dr. Zoran Siveski, Committee Member — Date
Assistant Professor of Electrical and Computer Engineering
New Jersey Institute of Technology

BIOGRAPHICAL SKETCH

Author:	Nashwa F. Kamel
Degree:	Mater of Science in Electrical Engineering
Date:	January 1997

Undergraduate and Graduate Education:

- Master of Science in Electrical Engineering
  New Jersey Institute of Technology, Newark, NJ, 1997
- Bachelor of Science in Electrical Engineering
  Cairo University, Egypt, 1989

Major: Electrical Engineering

To my beloved family

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CHAPTER 1

INTRODUCTION

Over the past ten years a new industry called "home automation" has been developing. This industry will create the next generation of consumer appliances. Not only is modern housing becoming more convenient to live in and more energy efficient, but also the primary value added by home automation is the integration of products and services for household use.

In America, several groups have attempted to develop home automation standards. The most focused of these are CEBus, X-10, Smart House, and Echelon.

The EIA (Electronic Industries Association) has taken the lead with the development of the CEBus, the Consumer Electronic Bus. In 1984, a committee was made up of such major companies as Sony, Philips, Panasonic, General instruments, Mitsubishi, RCA, and Johnson Controls to develop a standard to facilitate communication between home appliances over various media. The primary goals of the CEBus are : It is retrofittable which makes it low cost, expandable, ease of operation, use distributed intelligence (have no central computer in order to operate), have an open architecture which means that any product manufacture may produce compatible devices on their own. It follows the ISO/OSI seven layer network model [1].

X-10 was introduced in 1978. It uses power line carrier transmission for system control. It is a one-way open loop system with limited potential for intelligent home control [2].

Echelon is similar to CEBus concept. It produced a specialized computer chip called "LON" which allows multiple devices to communicate through any medium. However, the primary difference is such issues as protocol, language and the proprietary standards (i.e. it is not an open architecture and is owned by the manufacturer) [3].

Smart House is developed by the National Association of Home Builders (NAHB). It is specially for new houses where a three multiconductor cable are installed during original construction in place of conventional house wiring. This cabling system combines power, control, telephone and coaxial conductors and provides a dedicated six-wire bus throughout the house [4].

Table 1.1 shows the major characteristic comparison of home automation groups in the United States.

Table 1.1 Major Characteristic Comparisons of the Home Automation Groups

ITEM	CEBus	X-10	Smart House	ECHELON
Communication	Two-way	One-way	One-way	Two-way
Control Method	Distributed	Distributed	Centralized	Distributed
Standards	Open (OSI)	Proprietary	Proprietary	Proprietary
Cost	May low or not	Low	High	Low or not
Simplicity	May not simple	Simple in design and functionality	Simple	May not simple
Installation	Easy	Special wiring not required	Special wiring required	Easy
Flexibility	Easy to control channels (control and data) as well volume control	No changing channels and no volume control	Not a do-it-yourself system at this time	Easy to control channels (control and data) as well volume control

CHAPTER 2

CEBUS ARCHITECTURE AND PROTOCOLS

2.1 CEBus Architecture

CEBus follows the ISO/OSI seven layer network model with some layers being null as shown in Figure 2.1. Each layer is responsible for one aspect of network communication, with each layer only able to talk to the layers directly above and below it. By breaking the model into well defined pieces, implementation and support are greatly simplified.

2.1.1 Application Layer

The highest level is the application layer and is responsible for what the end user ultimately sees. In the case of CEBus, the highest level defined isn't what the end user will see, (because in many cases, operation will be transparent or part of the device's existing functionality), but what the programmer sees. Application layer will also provide the capability to segment long messages into a sequence of shorter packets, and to guarantee end-to-end message delivery. These packets are handed down to the lower layers for transmission. EIA has defined CAL, Common Application Language, to allow devices to communicate intelligently with each other. The main use of CAL initially will be for control. The language has numerous commands defined for turning devices on and off, dimming up and down, opening and closing, plus more complicated actions such as setting VCR presets or responding to telephone commands. It is actually table driven. There are tables of constants which have been defined to represent device categories, commands, action and responses. As new devices are developed by manufactures, the tables will be expanded (under EIA's control) to include those devices and any new functions associated with them [5]. There is a header that is added to the front of the

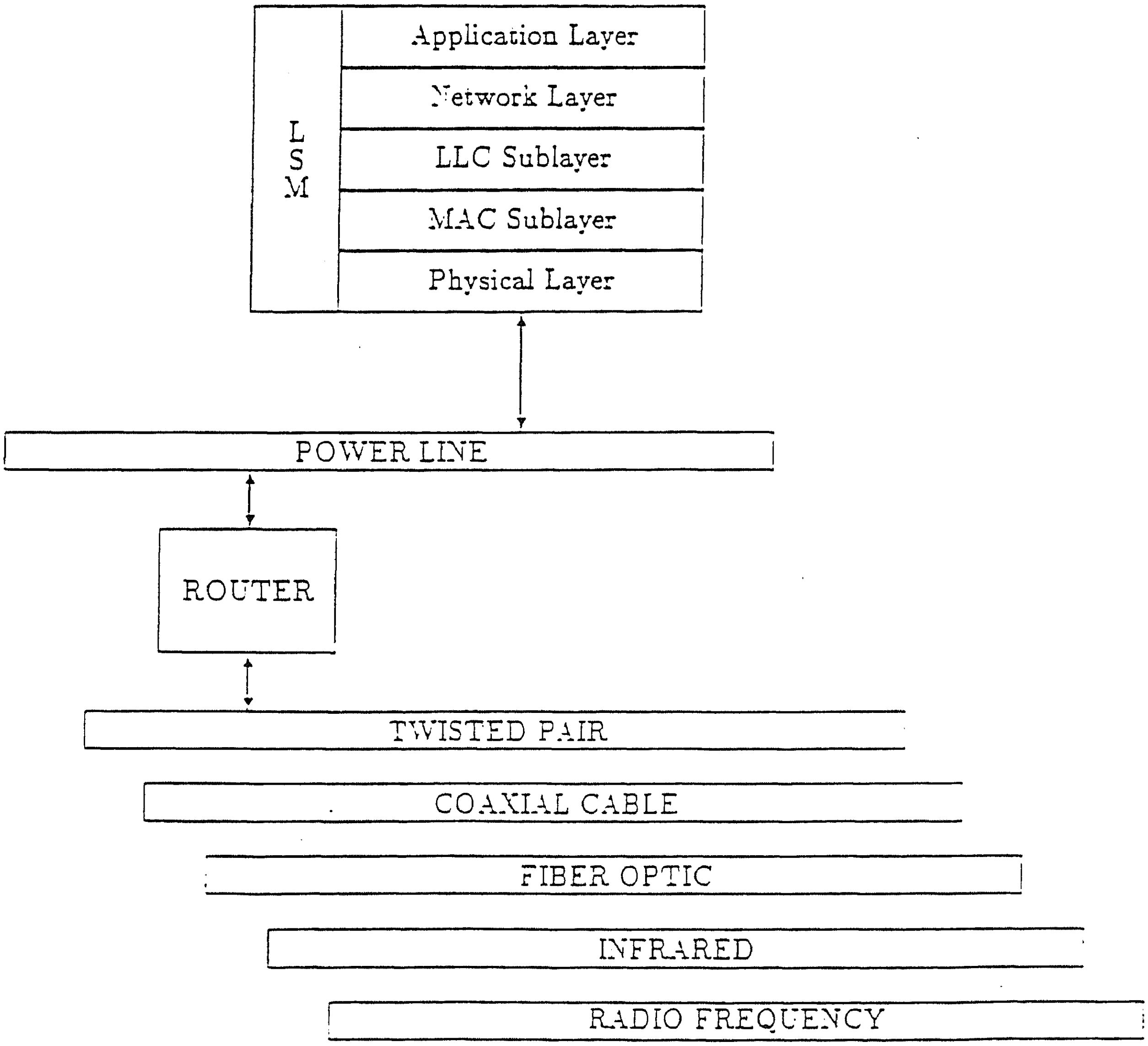


Figure 2.1 - Organization of the CEBus

CAL command to create the Application Protocol Data Unit (APDU), which is then passed to the network layer.(Figure 2.2)

2.1.2 Transport, Session and Presentation Layers

In the CEBus, the transport, session and presentation layers have been omitted to minimize packet length and device complexity. Some of their functions are handled by the application, network and data link layers.

2.1.3 Network Layer

The network layer is responsible for all the functions described in the OSI reference model except for segmentation and network connections, where segmentation takes place in the application layer and the flow control of the segments is handled by the network layer. The Network Protocol Data Unit (NPDU) is added to the front of the information field passed down by the application level and is shown in Figure 2.2. It performs routing of NPDU between different media through routers. There are six bits to determine which media is to receive the packet. Setting a bit in the field results in the corresponding medium receiving the packet (assuming proper bridge is present to transfer packets across media). The last two bits determine whether the packet is to be sent using flood routing, directly routing, or directory routing with a request for a return ID. In flood routing, the packet is sent to every medium specified in the rest of the field. In directory routing, the packet is only sent to the medium which hosts the destination node.

2.1.4 Data Link Layer

The function of the data link layer (DLL) is divided into two sublayers : the Medium Access Control (MAC) Sublayer and the Logical Link Control (LLC) Sublayer.

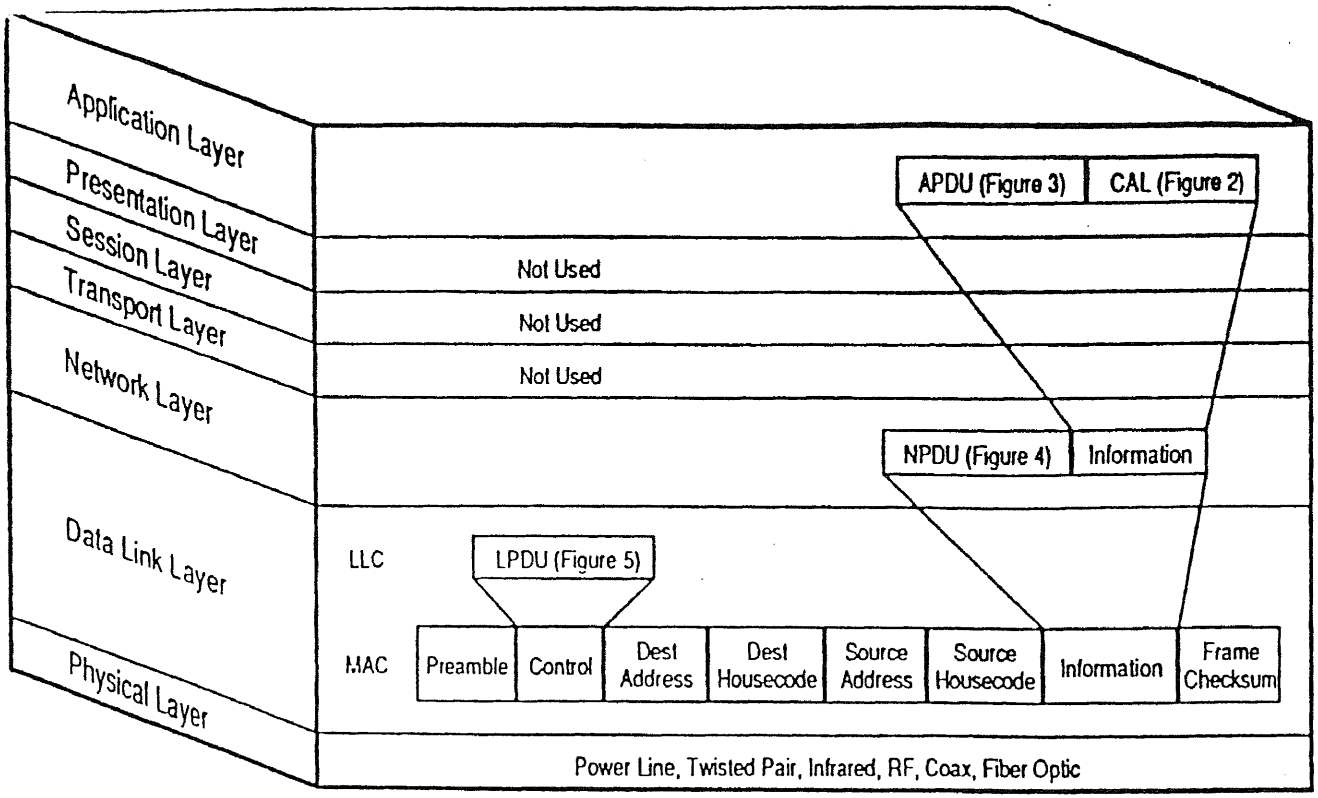


Figure 2.2 - CEBus is based on the ISO/OSI seven-layer network model.Within that model, a network is broken into seven functional pieces, each having responsibility for one part of the network communication.

Logical Link Control Sublayer (LLC)

The LLC Sublayer provides the interface to the Network Layer, and administers the transmission and reception of NPDUs. It receives NPDUs where again, a header is added. The LPDU has a fixed format, and may be of two types of services, unacknowledged or acknowledged connectionless services. In unacknowledged service, a packet is sent blindly in the hopes that it makes it to the destination. Acknowledge services makes use of an IACK and retransmission mechanisms. To transmit a packet, a Logical Link Control Sublayer Data Unit (LPDU) is generated and passed down to MAC Sublayer, with its associated control parameters. If acknowledge service is used, the LLC Sublayer waits for the reception of an IACK and if none arrives in 4 unit symbol time, it initiates a retransmission of the MAC frame. When a frame is received by the MAC Sublayer, the LPDU is removed and passed to the LLC Sublayer. The LLC header is then removed from he LPDU and the remaining NPDU is passed up to the Network Layer.

Medium Access Control Sublayer(MAC)

The LPDU is passed down from the LLC to the MAC Sublayer, where the MAC adds some more information onto the packet to create the MAC frame. Figure 2.2 shows the final frame format. The basis in channel access in the CEBus is CSMA/CD (Carrier Sense Multiple access with collision detection). Before transmitting, each node listens to the network to determine if anyone else is already transmitting. When the network is free, the node waits a certain amount of time before trying to transmit to avoid collision. Node start by sending out a preamble. If the preamble survives intact, the rest of the packet is sent. If a collision is detected, transmission is aborted and the process starts again.

2.1.5 Physical Layer

At the lowest level is the physical layer. It is divided into 2 sublayers: Symbol Encoding Sublayer and the physical sublayer. This is where CEBus's greatest strength lie since several different media are defined in the specification, with the choice of which medium to use up to the appliance designer. A separate Physical Layer specification exists for each different medium. All the layers above the physical layer are identical regardless of medium, so the network is medium independent. Signaling is done on most of the media by switching between a SUPERIOR and INFERIOR state. Times between changes determined the information being conveyed. “One” bits last one “Unit Symbol Time” (UST), “zero” bits last two USTs, end-of-field last three USTs and end-of -packet last four USTs. Exactly what defines the superior and inferior states depends on the medium. Also, since characterizing communication speed for a medium in bits per second is meaningless since one bits and zero bits are of different duration, data rates are usually defined in terms of “one bits per second” Statistically, the overall throughput in bits per second is around two-thirds the value of one bits per second.

Table 2.1 Symbol Duration for PL

Symbol	Transmission Time
ONE	100μs ± 100ms = 1UST
ZERO	200μs ± 200ms = 2UST
EOF	300μs ± 300ms = 3UST
EOP	400μs ± 400ms = 4UST

The CEBus specification defines six media which may be used to carry the signal: power line, twisted pair, fiber optic, coaxial cable, radio frequency, and infrared.

The Symbol encoding sublayer represents necessary interface to the Medium Access Control (MAC) Layer and the physical layer of the medium. The symbols of a frame are given serially to the SE Sublayer for transmission , and also error detection takes place in this sublayer.

Power Line (PL)

It is likely to be the medium of choice for most appliances meant for retrofit installations since almost every house and business in the world is wired for electricity. Since power line is such a harsh environment, with noise and transients the norm, this is the slowest of all media, but still able to attain a data rate of 10,000 one bits per second with a UST of 100μs. Transmission use a 120 kHz carrier to denote a superior state and the lack of a signal for an inferior state. Unlike X-10 systems which transmits only at the 60 Hz zero crossing, PLBus transmits regardless of the state of the AC power on the line. As a result, transmission can still take place even if power isn't present, something that can't be done with X-10.

Infrared or Single-Room Bus (SRBus)

SRBus is an attempt to have a single hand-held remote that transmits all valid CEBus commands. Not only the VCR or TV in the same room, but with the proper bridge in place to transmit the SRBus signals onto PLBus or one of other media it should be able to control any CEBus-compatible device, including lights all over the house or the door opener out in the garage. SRBus uses a 100-kHz infrared carrier and pulse-position signaling to attain a data rate of 10,000 one bits per second. A 50μs burst of IR is used to indicate a transition from superior to inferior. By using just short pulses, the hand held remote's life is extend.

Radio Frequency Bus (RFBus)

Currently used predominantly in the security industry, RF is another medium that would work well in retrofits. FCC regulations limit the strength of RF transmission, so whole house coverage may be possible without interfering with the neighbors' CEBus appliances.

Twisted Pair (TPBus)

TPBus promises to be the most useful high speed medium in the majority of installations. While most houses don't have an abundance of spare twisted-pair wire running room to room, some may have extra telephone pairs that could be used in retrofits. TPBus runs at a data rate of 10,000 one bits per second and uses a ± 125mv peak to peak signal. Similar to SRBus, TPBus uses 50-μs pulses to indicate transition from superior to inferior and vice versa.

Coax Cable (CXBus)

With the spread of cable TV, many houses are being wired with coax cable for television distribution. Since, within the house the TV signal isn't using the entire bandwidth of the cable, there is plenty of room for adding control information plus high-quality audio and Video to the same cable. CXBus uses the same pulse width modulation used by PLBus, with a UST of 100 μs, providing a data rate of 10,000 one bit per second.

Fiber Optics (FOBus)

Fiber Optics are becoming the medium of choice where high data transmission rates and low noise pickup are important. While some provisions have been made for this medium in the CEBus protocol definition, very little work has been done on the physical details.

2.1.6 Layer System Management (LSM)

Layer System Management (LSM) is the entity responsible for initializing variables and processes and for keeping and reporting network status information. The LSM initializes and maintains peer-to-peer protocol of each layer and provides an interface mechanism between non-adjacent layers [1]. The layer System Management is conceptually adjacent to each of the layers and performs various network administrative functions, i.e.,

- Resetting Layer entity to a known state.
- Reading and setting parameter values indifferent sublayer.
- Notifying different sublayers of significant events in the Layer System Management or in the other layer of the node.

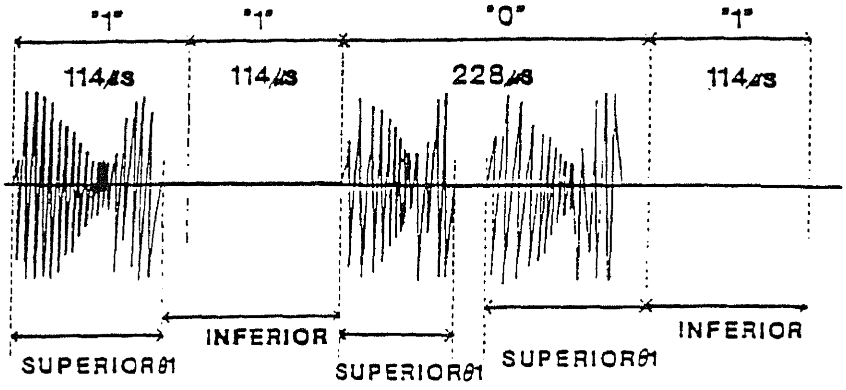
2.2 Control Channel Signal Encoding

The signal encoding for the PL control channel will be Non Return to Zero (NRZ), Pulse Width Encoding using the symbols "1", "0", "EOF", "EOP". These symbols are encoded using a swept frequency carrier coupled to the power line.

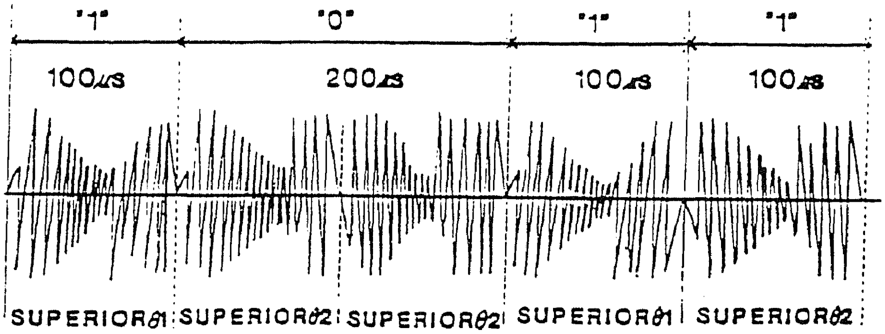
The carrier will consist of a sinusoidal waveform that is swept linearly from 203 KHz to 400 KHz for 19 cycles, back to 100 KHz in one cycle, then back to 203 KHz in 5 cycles during a 100μsec interval (Figure 2.3 a). This carrier sweep period represents the shortest symbol time ("1", or unit symbol time). During longer symbol times, the carrier sweep repeats for a multiple of the unit symbol time[1].

The encoding of the symbols will be performed using the SUPERIOR and INFERIOR states on the PL medium. During the preamble portion of the CEBus message, the presence of the frequency swept carrier on the PL will represent the SUPERIOR state, and the absence of the carrier will represent the INFERIOR state.

During the non-preamble portion of the message, the frequency swept carrier continually transmitted and encodes the different symbols by reversing the phase of the carrier sweep. This can be seen clearly in Figure 2.3 b. If SUPERIOR$\theta 1$ and SUPERIOR$\theta 2$ are used to denote different phase versions of the SUPERIOR state, then they are opposite in phase, regardless of the value of the phase. In the Figure SUPERIOR $\theta 1$ will be used to denote the phase of the carrier transmitted during preamble.



(a). Preamble Encoding Example



(b). Non-preamble Encoding Example

Figure 2.3 - Power Line (PL) Control Channel

2.3 The CEBus Channel Access

The CEBus channel access protocol is a carrier sense multiple access with contention detection and contention resolution CSMA/CDCR. The protocol attempts to avoid contention by delaying a random amount of time after the end of the previous transmission before attempting channel access. This random wait is based on these factors:

1. Deference to other channel traffic in SUPERIOR STATE.
2. Prioritization
3. Round-robin queuing
4. Random start.

2.3.1 Superior State Deference

A node, while transmitting as SUPERIOR state on the medium, will dominate any attempt for the transmission by any other transmitting node in the INFERIOR state. A node with a frame to transmit will defer its transmission till EOP symbol and a minimum of 10 unit symbol times. This mandatory channel quiet time allows an immediate acknowledge or a retransmission be sent without conflict for the channel.

2.3.2 Prioritization

Figure 2.4 illustrates the priority and round-robin queuing delays. The EOP symbols defines the end of a previous transmission. 10 unit symbol times must follow each EOP before any new transmission can begin. Following these 10 unit symbol times is a slot of eight unit symbol times for high priority transmissions. Overlapping with the last four unit symbol times of that slot is a slot reserved for standard priority transmissions. Finally, overlapping with the standard priority is a slot reserved for deferred priority. This scheme allows nodes with higher priority frames to seize the channel before nodes with lower priority frames.

2.3.3 Queuing and Round-robin Scheduling

The use of the round-robin scheme within the same priority level ensures that the contenting nodes have equal opportunity to access the channel. Within each of the eight unit symbol time priority slots are two subdivisions, four unit symbol times each, for unqueued and queued transmissions.

Queued State

Once a transmitting node completes a transmission successfully. the node will be placed in the queued state from an unqueued state . The effect of being in the queuing state is to repeatedly defer channel access to all unqueued nodes at the same priority level which have hot yet been able to transmit a message. If the queued node confirms that no other unqueued nodes attempt to send a message during the 4 UST of its queued state's delay, it may attempt to send a message, as needed.

Unqueued State

This state occurs in one of the following two circumstances:

1. If it has no message to send and the medium is sensed idle for the maximum channel access time (26 USTs).
2. If none of the queued nodes complete a transmission during the following 4 UST slots.

2.3.4 Randomization

Because more than one node may be in the same priority level and queuing state, the probability of contention still exists. A random delay of either 0, 1, 2, or 3 USTs is used for the control of each node's transmission start time, which results in reduction of contention probability during each of the priority queuing time slots (Figure 2.4 b). By this method, the channel throughput can be improved significantly.

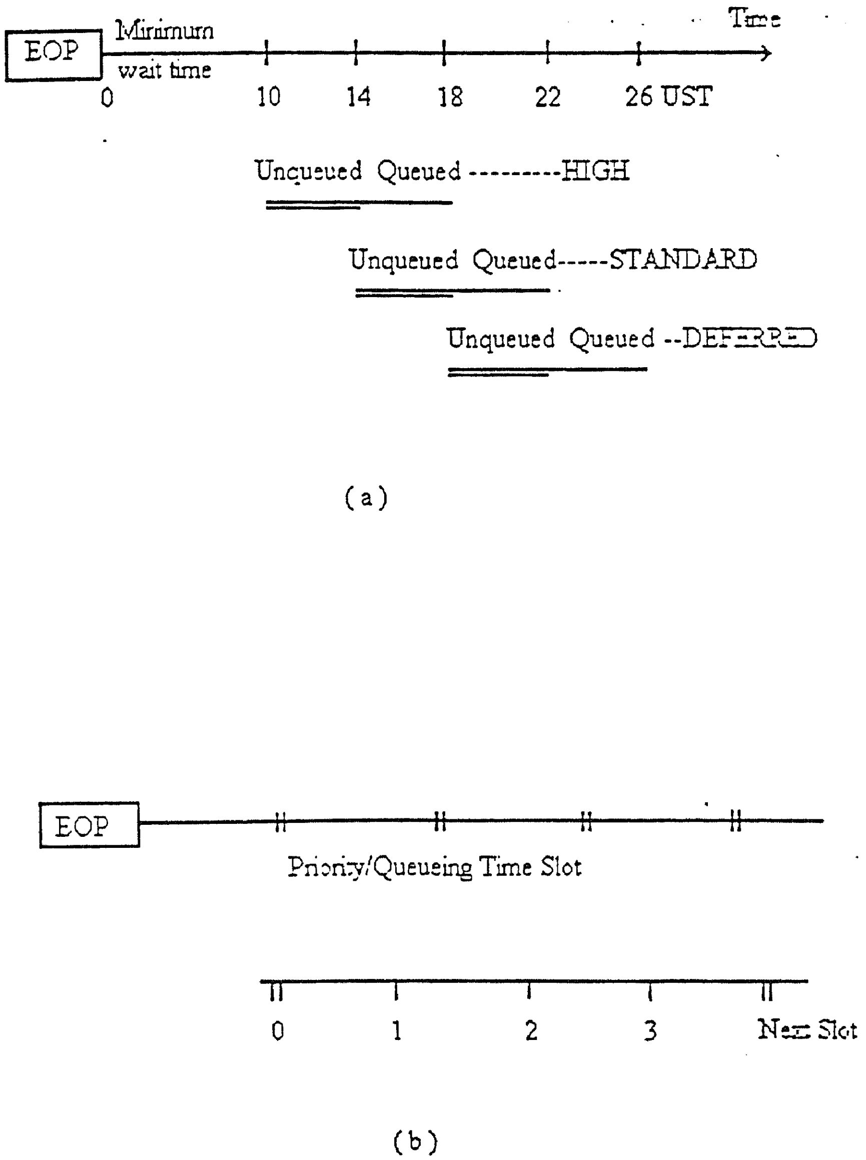


Figure 2.4 - (a) Priority queuing, (b) Random access time

2.4 Contention Detection and Resolution

In the earlier section, steps taken to avoid contention were discussed. However, two or more nodes may still attempt to transmit a frame during the same time interval. To ensure reliable communication between Data Link Layers, a means of detecting contention and resolving in favor of one node is still required.

The use of SUPERIOR and INFERIOR states on the transmission medium enables contention detection. Any node which senses a SUPERIOR state while sending an INFERIOR state, will defer its transmission. It becomes aware of the presence of one or more other transmitting nodes.

Contention will normally occur at the beginning of the transmission. Therefore, the Preamble, positioned at the beginning of the frame, serves to provide signal pattern and to shield the information from being lost during contention. The Preamble field is made up of a random sequence of bits, which is usually a function of the node address and the number of ONE symbols already transmitted by the node [1].

Contention resolution involves the simultaneous transmission of more than one Preamble. Since the node which drops into the INFERIOR state first is removed from contention, the wining node is able to transmit free of contention. That is, contention has to be resolved during the Preamble. Because the Preamble carries no information and its bits are not included in the calculation of the checksum delivery of the frame will be successful.

A collision refers to overlapping transmissions after the Preamble. Although conflict over the channel during any part of the frame after the Preamble constitutes a breakdown of the channel access method, a sending node will abort its transmission and defer during any part of its frame. This will result in the reception of a bad packet. Therefore, a retransmission will be required.

2.5 Message Failure and Retransmission

Message failure occurs when the received frame does not appear to be valid to the receiving node. If all required fields of the frame are not received properly, the frame will be rejected as being a fragment. Also a packet could be rejected if the checksum performed at the receiving node indicates faulty data. Noise on the channel and conflicting node transmissions could cause these message failures. Therefore a retransmission may be needed to guarantee a successful delivery. To increase the reliability of the network, an Immediate Acknowledgment (IACK) and retransmission mechanism could be used.

2.5.1 Immediate Acknowledgment (IACK)

The Immediate Acknowledgment mechanism enables the transmitting node to determine the success or failure across a single medium. It is invoked when the Network Layer requests acknowledged connectionless service.

When a message is received without errors, and an acknowledgment is requested, the receiving node forms an IACK frame. The IACK frame is sent out onto the local medium within 2 USTs of the end of the EOP symbol of the originating frame. By immediately responding within the minimum channel access time (10 UST), the receiving node is assured of sending the IACK without having to contend for the channel.

2.5.2 Retransmission

If a negative acknowledgment is received, or if no IACK is received within 6 USTs at the originating node, then the originating node will begin a retransmission. Immediate channel access is achieved by beginning the retransmission before the minimum channel access time elapsed. All nodes counting the minimum wait time will hear the retransmission and defer to it.

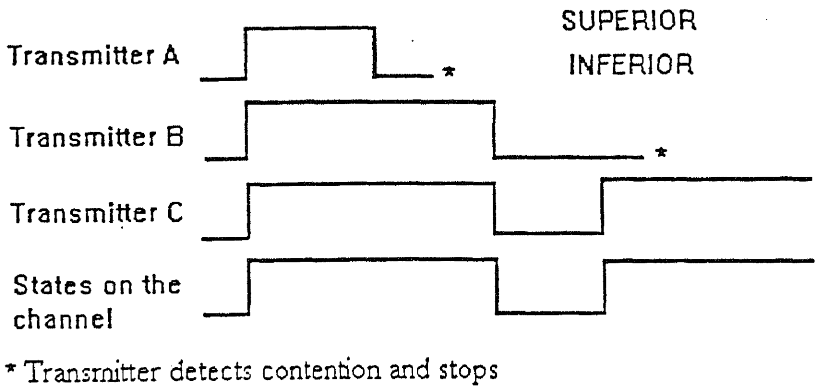


Figure 2.5 - Resolving Contention with SUPERIOR and INFERIOR states

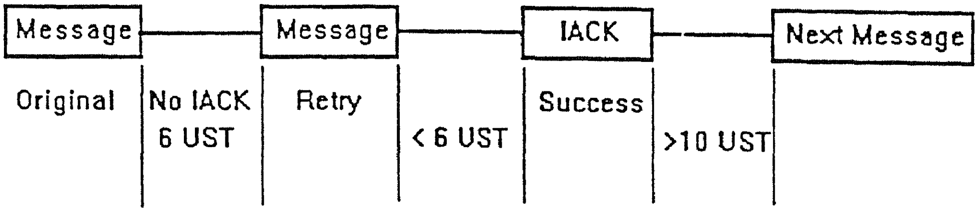


Figure 2.6 - Immediate Retry Timming

CHAPTER 3

X-10

X-10 was introduced in 1978. It uses power line carrier transmission for system control. It is primitive and doesn't provide integrated network. Its products do not communicate on a 2-way basis. It presently focuses as modular add-on type devices which are designed to offer functions of on/off, and level control for resistive and reactive loads.

The X-10 operation is based on 16 letter codes and 32 number codes that are combined into a single command packet. Of the 32 number codes, 16 represents unit address and the remaining 16 represents commands like: on, off, ect. A letter code is used to identify which group of units will receive commands. Combining a letter code with a unit address results in a total of 256 possible addresses for X-10 units. The structure of the code is simple. The letter code precedes the number code, which makes nine bits, plus a start sequence of two bits for a total of eleven bits [6].(Figure 3.1)

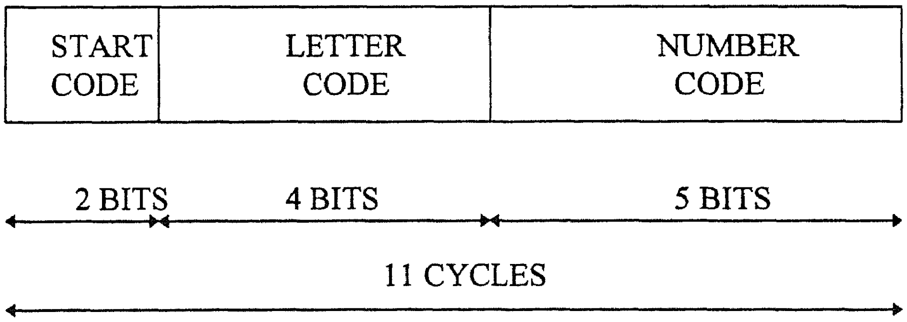


Figure 3.1- X-10 Message Format

The units are first addressed by sending the letter code and unit code. The operation tells the units to expect a command. Several units on the same letter code can be addressed simultaneously by sending multiple unit addresses before one command. Next a command or series of commands are send to the units. The units remember that they have been selected even after receiving a command, so as long as no new addresses are send the same units will receive and carry out subsequent commands.

3.1 X-10 Signal Encoding

X-10 transmission denotes "1" bits with three 1-ms burst of 120-KHz signal and "0" bits with the lack of this signal. One bit is transmitted at each zero crossing of the 60 Hz power line frequency. Each bit is transmitted plus its complement side by side. This aspect is true for all letter code and unit code data bits. The start code uses a different format. It is always the same two cycles sequence 1110. The transmitter releases a burst at its own zero crossing, then sends it again 60° later; the second burst coincides with the zero crossing of the third phase. Then another burst is sent 120° from the first, which corresponds with the zero crossing of the second phase. This is shown in Figure 3.2.

3.2 Theory of Operation

All receivers are looking for a "start code" before anything else. This start code is defined as 1110. For the receiver to consider accepting a full transmission it must first receive the 1110 in 4 adjoining, consecutive zero crossings. Once the start code has been received, the next four true bits of data are compared to the letter code of the receiver's address. Should the letter code not match, all further data will be ignored until the receiver detects another start code. If the letter code match, the next five true bits of data are compared to the number code. When both the letter and number codes match, the receiver will await a function code. Time wise, this sequence, so far takes 11 cycles as shown in Figure 3.3 [6]. For reliable transmission this series is sent twice.

The data string for the command portion of the transmission also begins with a start code. After that, the code is again checked for true complement relationships and

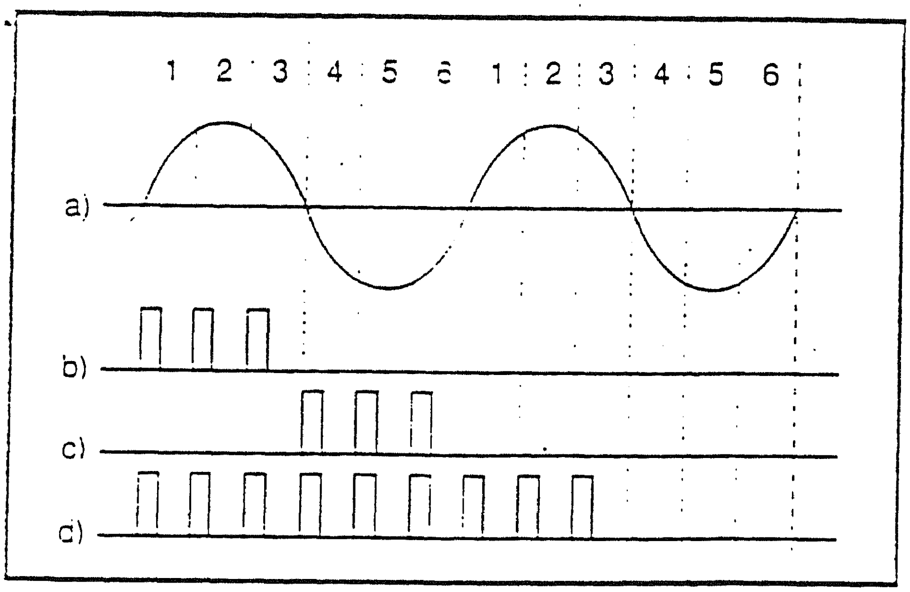


Figure 3.2 - a) X-10 transmissions are synchronized to the power line zero crossings. b) A 1 data bit is represented by three 1-ms bursts of 120 Khz signals, followed by silence during the next half cycle. c) A 0 bit is the opposite, with the bursts occuring during the second half of the cycle. d) Every transmission begins with a unique start code, which lasts two full AC cycles.

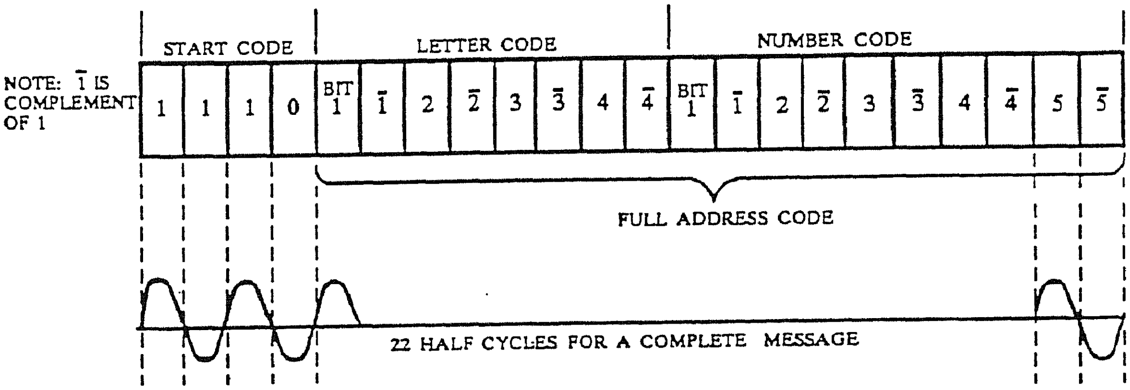


Figure 3.3 - X-10 Message takes 11 cycles

letter code comparison, and if the next 5 bits indicate that this code is the command for "ON", then the receiver will switch on. A pause of 3 power line cycles is inserted between the identification data and function data. This means that a full and complete transmission consists of 47 cycles, or .7833 seconds [7]. (Figure 3.4)

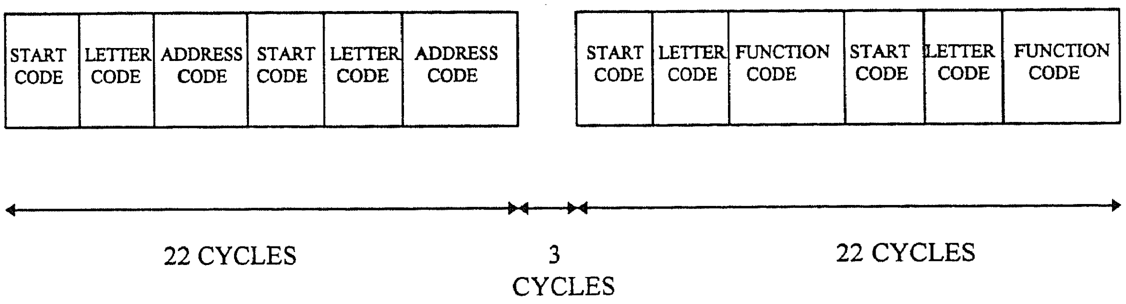


Figure 3.4 - X-10 Full Packet

CHAPTER 4

SIMULATION MODEL

4.1 The Simulator

The simulator is briefly described in this chapter. The definitions which govern the analysis and discussion of the simulation results are introduced here.

The simulator for the system and protocol model for the experiment was written in C language using C Library functions provided by LANSF [8]. LANSF is a configurable simulator designed to model communication networks. It can be modified to simulate the CEBus architecture proposed in the EIA standard released in October 1992 [1], and the X-10 architecture. The attributes of a communication network specified by LANSF can be divided into two categories. The first category contains static elements, for example, system architecture and topology. The second category contains dynamic attributes that describe the temporal behavior of the modeled system, for example, traffic patterns and performance measures. The simulation involves two tasks, system and protocol modeling and network configuration. There are four program files needed to interface LANSF and the CEBus network. They are *protocol.c, protocol.h, options.h,* and the input data file.

The *protocol.c* file specifies the executable part of the protocol specification and functions which represent protocol process executed by stations (nodes). It also contains two other subroutines that must be included with the protocol module. The first *in_protocol* which initialize the simulator and reads the values of the global protocol_specific parameters. The second *out_protocol* which contains the output results and the protocol-specific input parameters.

The definitions of protocol-specific symbolic constants and the declarations of non-standard station attributes are found in the *protocol.h* file.

The options.h file contains the local options such as precision of numbers, the type of port variables representing port transmission rates, the length of additional information carried by messages and packets, the type of transmission link, and the number of moments to be calculated for standard statistics.

The input data file contains the time section and the configuration section which define the backbone of the network. It contains the number of stations, the number of ports per station, the link number and type, the total number of ports and their transmission rates, the distance matrix describing the distance between the nodes, the number of messages, the message length, the mean interarrival time, the number of senders and receivers, and optional flood group or broadcast type messages. The final segment consists of the exit conditions, namely, the total number of messages to be generated, the simulation time, and the CPU time limit.

4.2 Network Model and Traffic Patterns

The Power Line (PL) for CEBus operates at a data rate of 10Kb/s. The assumptions used to develop the model are as follows:

- Independent Poisson arrival process at each node with rate l packets/sec;
- The packet length for CEBUS are exponentially distributed with mean L bits.
- The end-to-end propagation delay is ignored, since it is much smaller than the packet transmission time;
- The bit rate on the channel is c = 10,000 ONE bits/sec.
- There are M nodes on the network.

The total number of nodes, M, utilized in the simulation is 18. There are 9 nodes for X-10 and 9 nodes for CEBus of which three nodes each for HIGH, STANDARD, and DEFERRED priority classes. All CEBus generated messages are symmetric for each priority class, thus each of the 9 nodes employ the same rates(e.g. same arrival time) to get access to the medium. The CEBus normalized offered load G, which is defined as the total offered load normalized by the channel capacity C, is calculated using the following relationship:

$$G = \frac{\lambda_H L_H + \lambda_S L_S + \lambda_D L_D}{C}$$

where λ_i's and L_i's (i=H, S, D, X, for HIGH, STANDARD, and DEFERRED messages respectively) stand for the arriving rate of packet and packet length for the three types of messages, respectively. In this simulation study packet length of 300 bits have been considered for the CEBus packets. The packet arrival rates for all three priorities are equal. Furthermore, the following studies involve equal message and packet length to reveal the queuing time effect. The X-10 normalized offered load is calculated using the following relationship:

$$G= \frac{\lambda_X L_X}{C_x}$$

where λ_X stands for the arriving rate of packets, L_x is the packet length and is equal to 44 bits, and C_x is the bit rate on the channel and is equal to of 60 bits/sec. All the simulations were run for a total of 5,000 messages.

4.3 Relation between CEBus and X-10 Transmission

CEBus power line uses bursts of 120 KHz signal, know as the SUPERIOR state to send bits of information, similar to the way X-10 works. CEBus uses a swept frequency carrier coupled to the power line. The carrier will consists of a sinusoidal waveform that will be swept linearly from 203 KHz to 400 KHz for 19 cycles, back to 100 KHz in one cycle, then back to 203 KHz in 5 cycles during a 100µsec interval. The relation between time and frequency during one UST is shown in Figure 4.1.

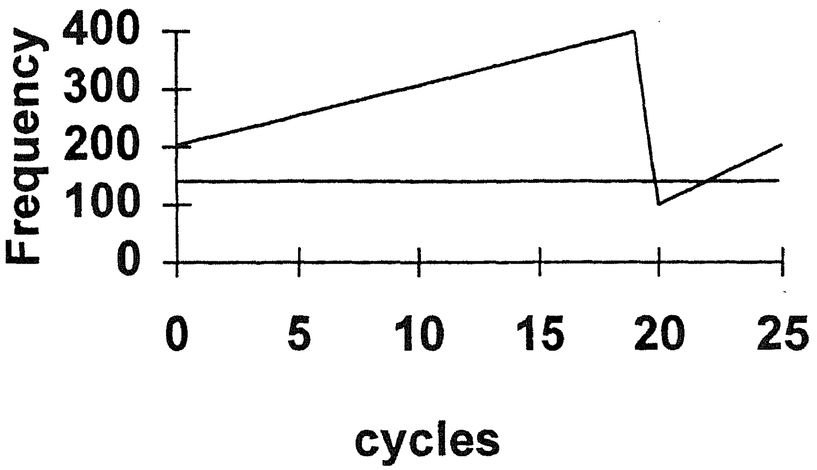


Figure 4.1 - Relation between Frequency and Time for 1 UST

In an effort to estimate the probability of interference, p, between CEBus and X-10 during one UST, we assumed the following:

- The presence of a filter of Q = 5. Then the probability of frequency being in the range of 120 KHz + 12 KHz during one UST is calculated as:

$$p = \frac{24*5/(203-100) + 24*1/(400-100)}{25} = 0.049$$

- The presence of the filter will degrade this calculated probability of interference.
- The robustness of spread spectrum which allows considerable degradation before an error is declared. So we assumed it to be in the order of 10^{-3}.

In our experiment we used a CEBus packet of 300 USTs. Since one UST takes 100μsec, then the whole packet will take 30msec. During this 30msec X-10 transmits 6 1-ms bursts of 120 KHz. In one millisecond CEBus transmits 10 USTs. This is shown if Figure 4.2.

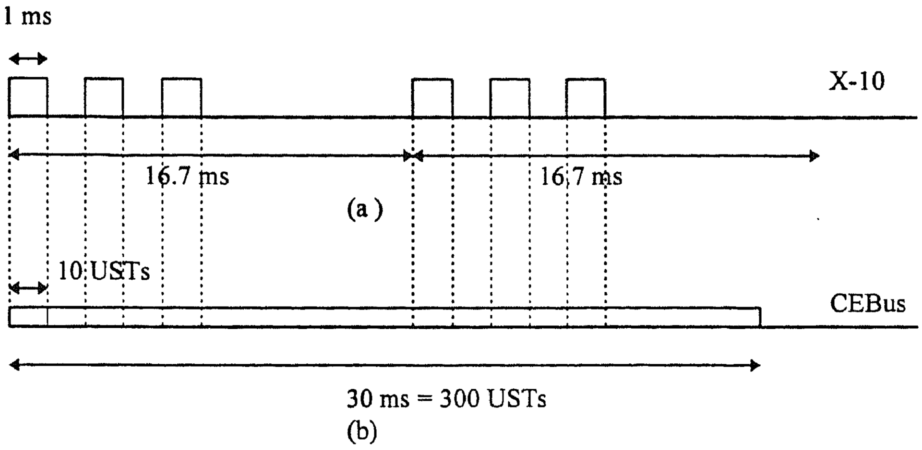


Figure 4.2 - (a) X-10 Transmits 3 1-ms Bursts of 120 Khz Every Power Line Cycle or every 16.7 ms (b) CEBus TransmitsUSTs each of 100μsec Continuously

To estimate the probability of error, POE, in case of a collision between CEBus and X-10 packets, we may write POE = 1 - PNE, where PNE is the probability of no error.

$$PNE = (1-p)^n$$

where n is the number of USTs that collides with the 120 KHz bursts of X-10, n = 6 bursts * 10 USTs per burst = 60, and p is the probability of interference, which was assumed 10^{-3}.

$$PNE = (1-p)^n = (1 - 0.001)^{60} = (1 - 0.001*60) = 0.94$$

$$POE = 1 - PNE = 1 - 0.94 = 0.06$$

Therefore the probability of error in CEBus packet in case of collision with X-10 packet is taken as 6% in our experiments.

4.4 Performance Measure and Definitions

The traffic generator in LANSF generates the packets and places them in station's queue. Once a packet is in a queue it waits until it reaches the top of the queue [9]. When a packet is on top of its queue it is ready to be transmitted. The time spent in the queue awaiting transmission is called the queuing time.

The most important measures of network performance are delay of signal transmission and throughput of the channel. There are two types of delays. They are message delay and packet delay. Also we can consider two different types of throughput. Namely, channel throughput and message throughput.

- ***Message Delay*** which was measured as the time elapsing from the moment the message was queued at the sending node to the moment the entire message is successfully received at the destination (including the message queuing time) [10].

- ***Packet Delay*** was measured as the time elapsing from the time the packet became ready to be transmitted to the moment it is successfully received at its destination [10].

- ***Message Throughput*** was calculated as the ratio of the total number of bits received at the destination address to the number of bits generated at the source.

- ***Channel Throughput*** was measured as the ratio of the total number of information bits successfully transmitted through the link to the simulation time. This sometimes is also referred to as effective throughput of a link, in that it includes not only the bits that were received on the link, but also the bits that were successfully relayed to some other link.

4.5 Analysis and Discussion of Simulation Results

4.5.1 CEBus Performance in the Presence of X-10 Modules

(a) Message Delay vs. Load

The message delay vs load at different loads of X-10, namely 0.1, 0.2 and 0.5 normalized load, are shown in Figure 4.3, 4.4 and Figure 4.5. It is seen in Figure 4.3 that at low CEBus loads the message delay experience slightly higher delays than in the absence of X-10 signals. This is due to the fact that at low loads X-10 modules have high chance to content for the channel and transmit packets which results in some delays in the CEBus packets. As the load increases, the X-10 have little chance to content for the channel and their message throughput decreases. The message delay for HIGH priority packets start to increase rapidly when the normalized offered load reaches around 2.0. For the STANDARD priority a similar trend is observed when the normalized is greater than 0.85, and for DEFERRED priority it is around 0.6.

Similar behavior is seen in Figure 4.4 and Figure 4.5 when the X-10 load is increased to 0.2 and 0.5. At low loads the delays are higher in the second case, as compared to the first case, i.e at higher X-10 loads, message delay were higher. However, at high loads, both cases give similar results.

(b) Packet Delay vs. Load

Packet delay only includes the channel access plus transmitting time, unlike message delay which also include the queuing time. Therefore for HIGH priority packets, packet delay remains small and bounded as observed in previous studies [9]. The packet delay seems to reach a point of saturation. The saturation occurs when the message throughput for STANDARD and DEFERRED priorities already reaches zero, and only HIGH priorities transmit over the channel. After the load reaches the limit for optimum channel throughput, then further increases in load does not have any effect. This is specially true for the packet delay, since it indicates the service time. No matter how large the queue, the service time remains approximately the same after passing its threshold. However, as load increases the time spent in the queue increases. Thus, message delay rises with increases load.

(c) Message Throughput vs. Load

The message throughput for the HIGH, STANDARD and DEFERRED priorities are shown in Figure 4.11. It is clearly seen that the throughput starts to decrease when the load rises to 2, 0.85, and 0.6 for the HIGH, STANDARD and DEFERRED priorities respectively, in agreement with the corresponding observations for message delays.

(d) Channel Throughput vs. Load

The channel throughput vs. normalized offered load in shown in Figure 4.14. It is seen the channel throughput increases as the load increase, until it reaches a maximum of 0.6, 0.81, and 0.88 for 100 USTs, 300 USTs, and 540 USTs, respectively.

(e) Number of Packets Received in Error

The number of packets received in error increases as the number of X-10 packets transmitted on the channel increases. However, the percentage of CEBus messages received in error due to a collision with X-10 signals did not exceed 2% in all our cases.

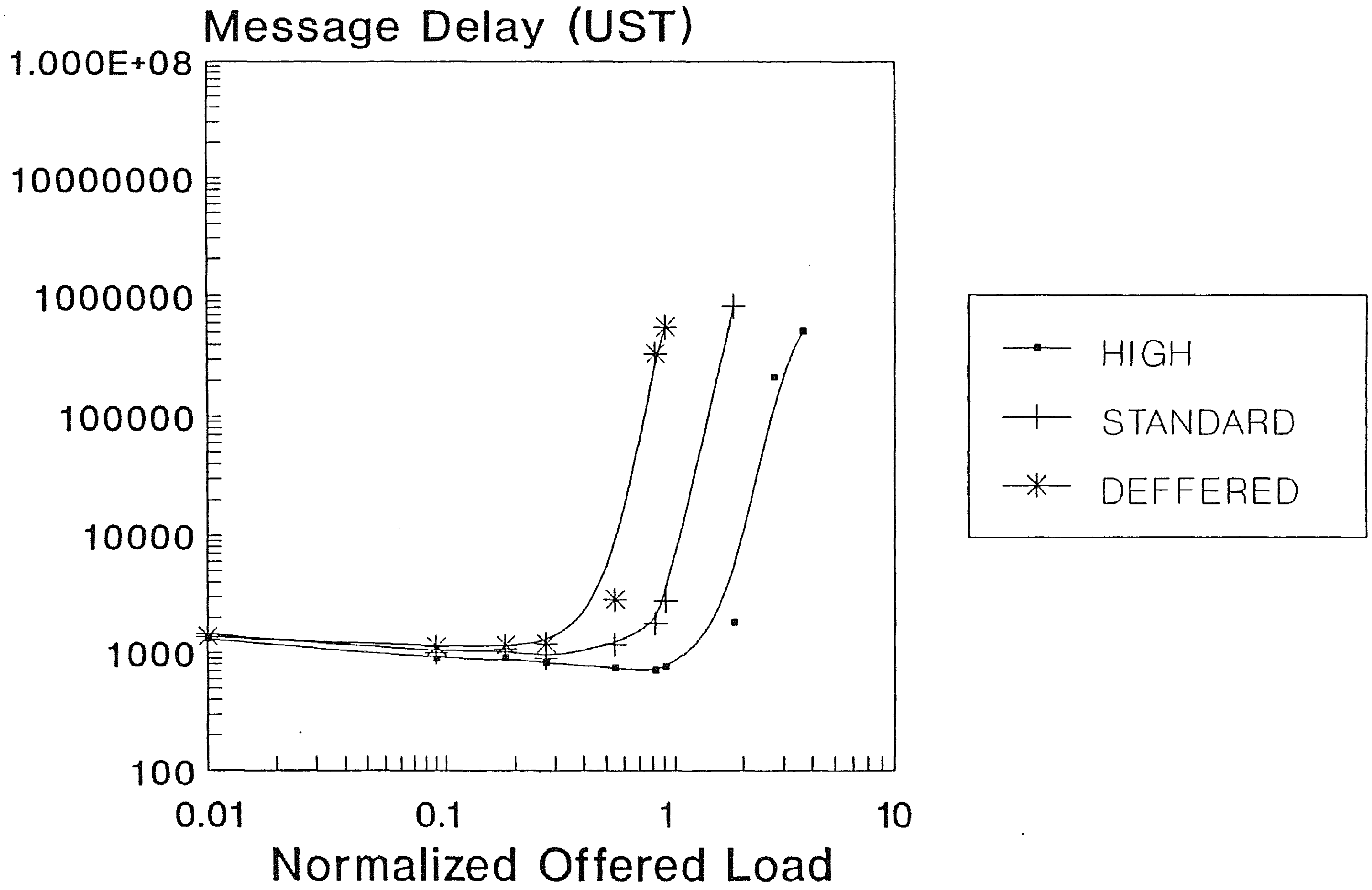


Figure 4.3 Message Delay vs. Normalized Offered Load for X-10 Load of 0.1

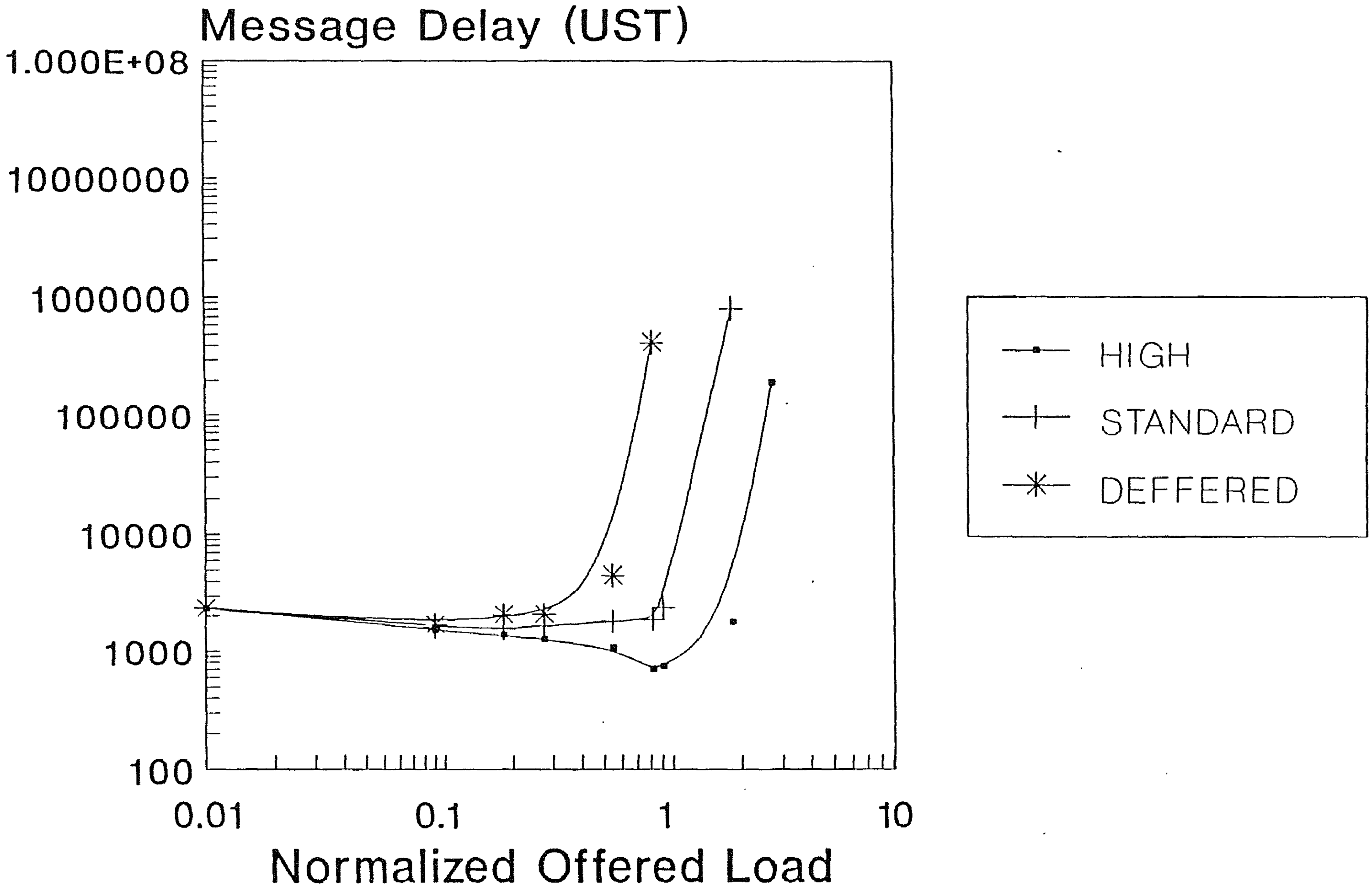


Figure 4.4 Message Delay vs. Normalized Offered Load for X-10 load of 0.2

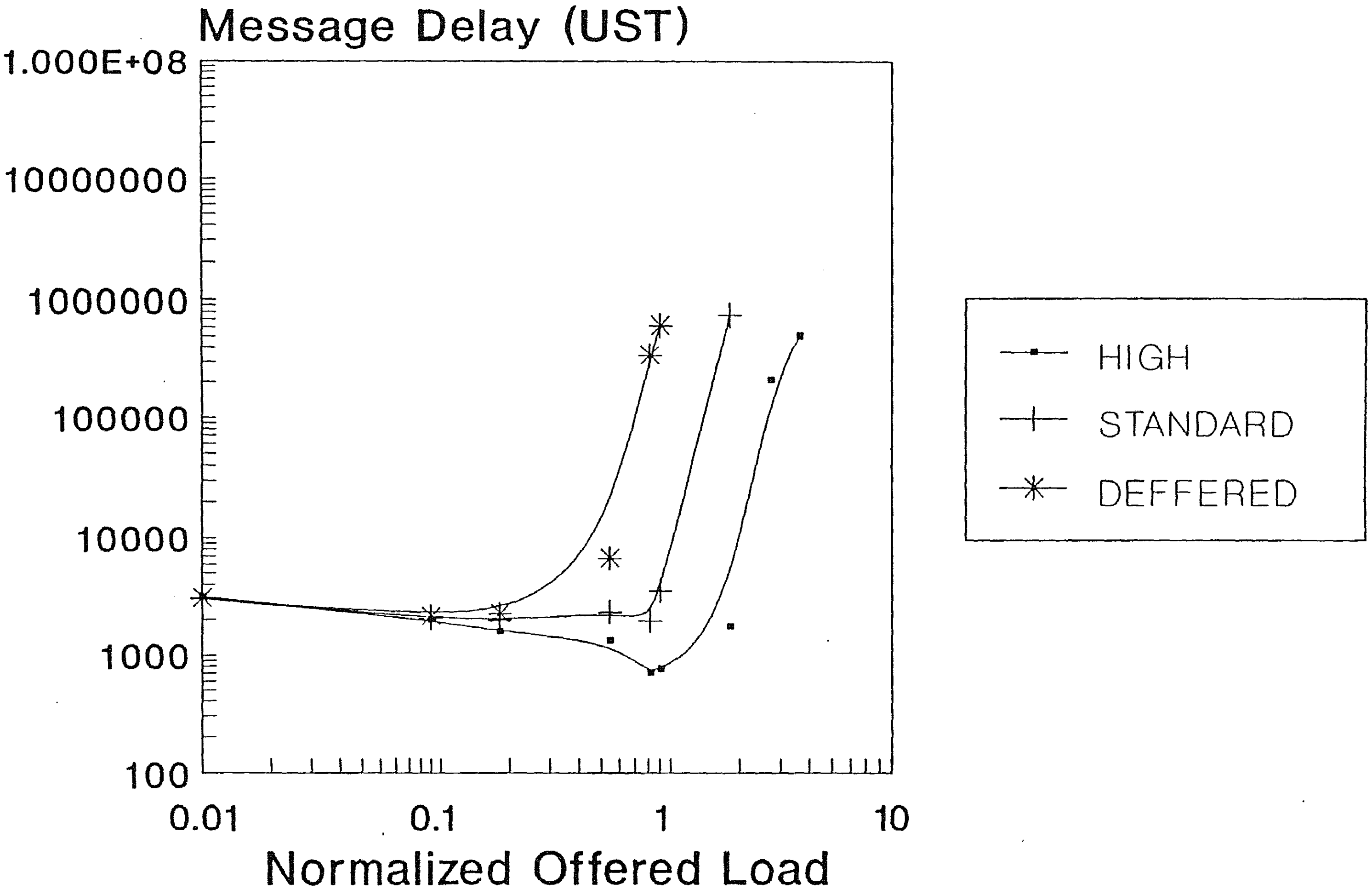


Figure 4.5 Message Delay vs. Normalized Offered Load for X-10 Load of 0.5

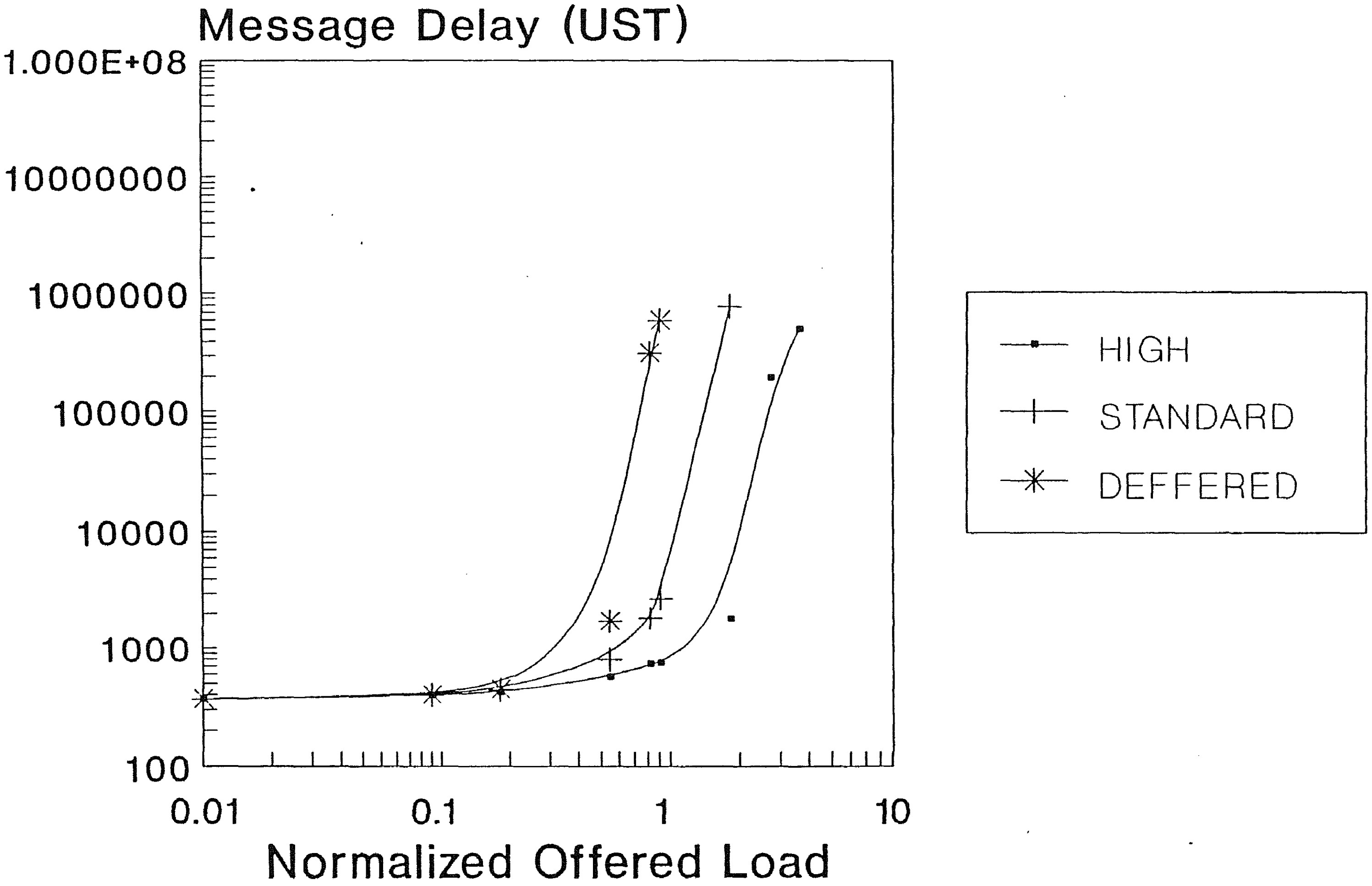


Figure 4.6 Message Delay vs. Normalized Offered Load in Absence of X-10

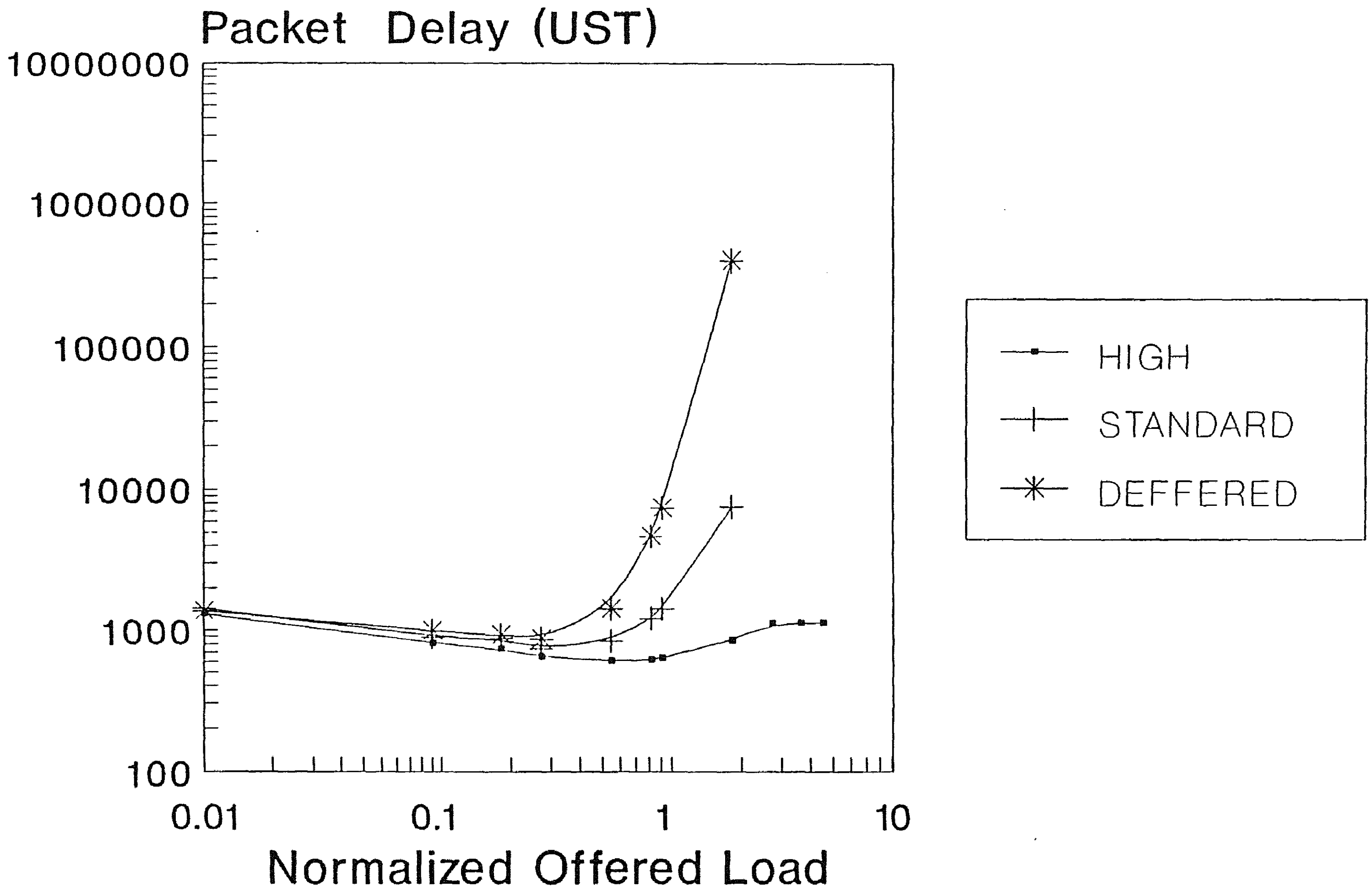


Figure 4.7 Packet Delay vs. Normalized Offered Load for X-10 Load of 0.1

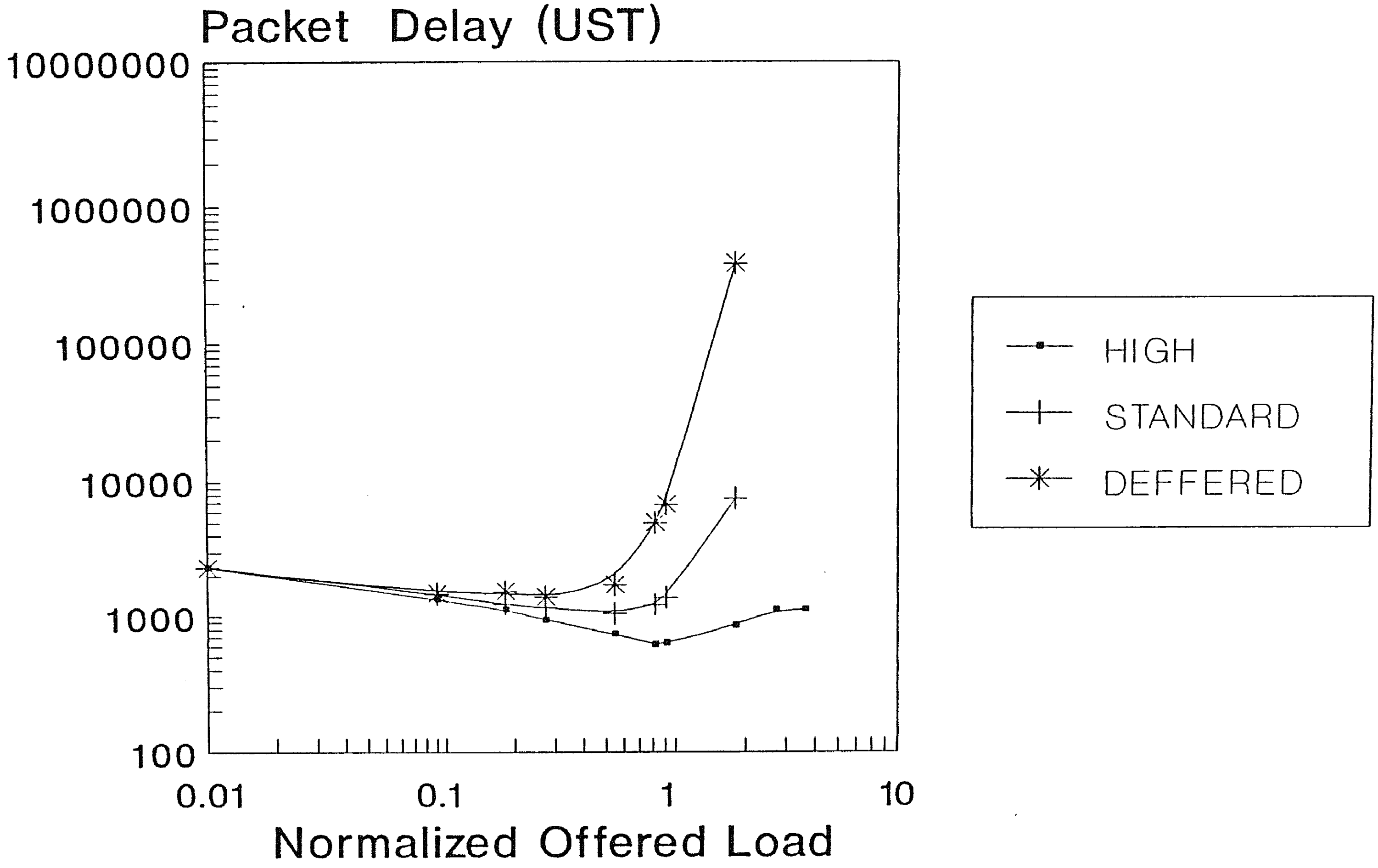


Figure 4.8 Packet Delay vs. Normalized Offered Load for X-10 Load of 0.2

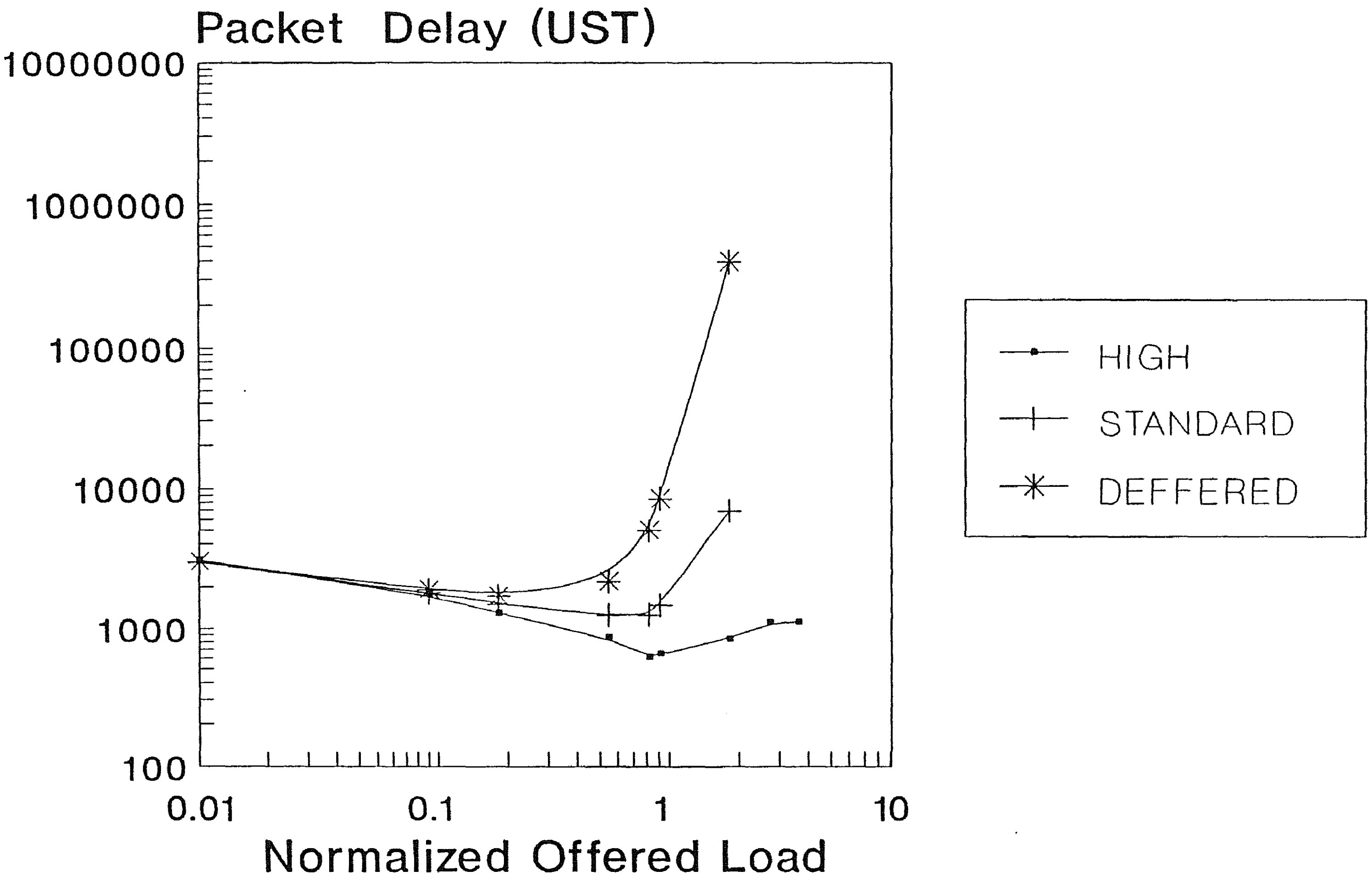


Figure 4.9 Packet Delay vs. Normalized Offered Load for X-10 Load of 0.5

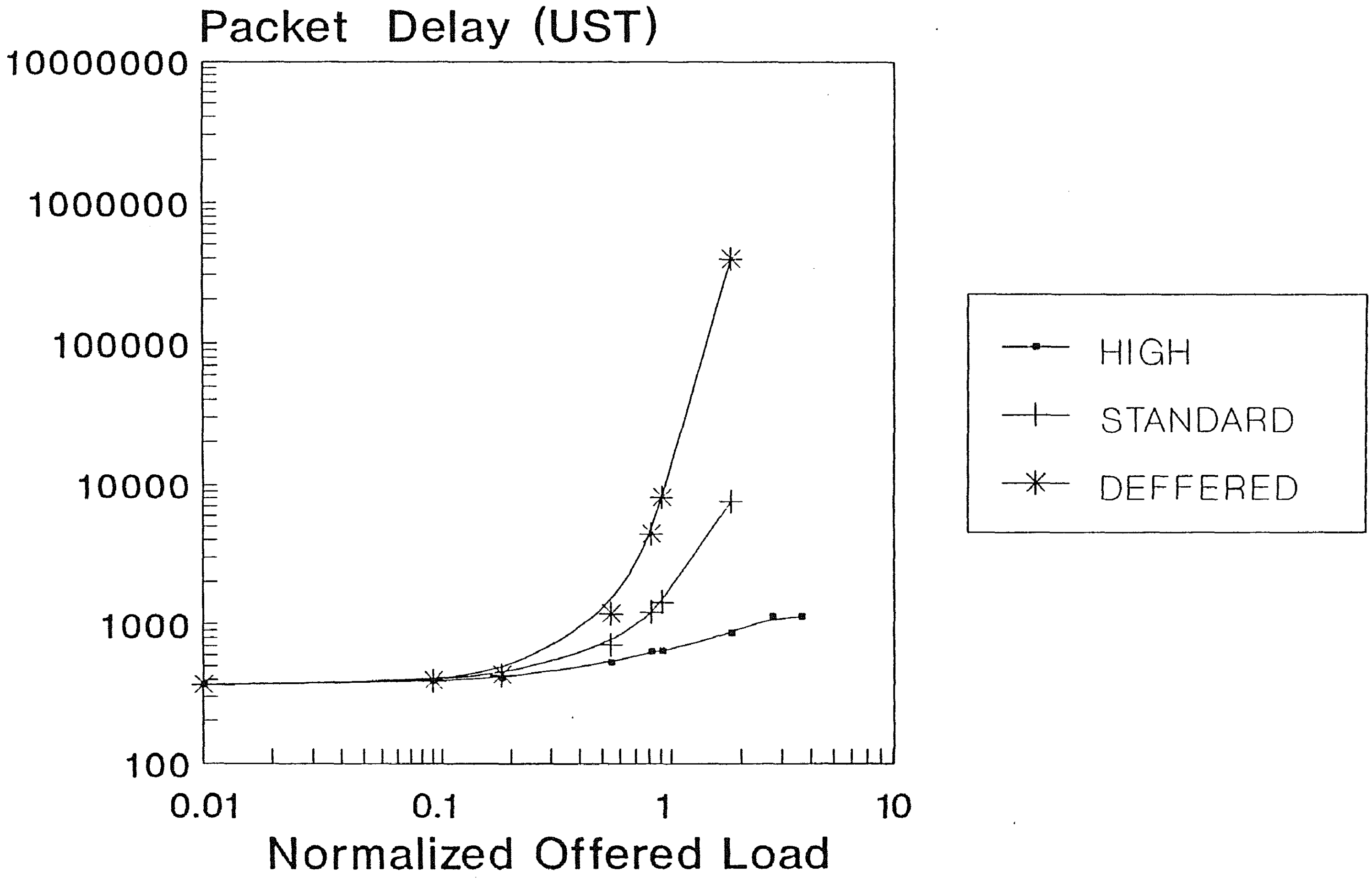


Figure 4.10 Packet Delay vs. Normalized Offered Load in Absence of X-10

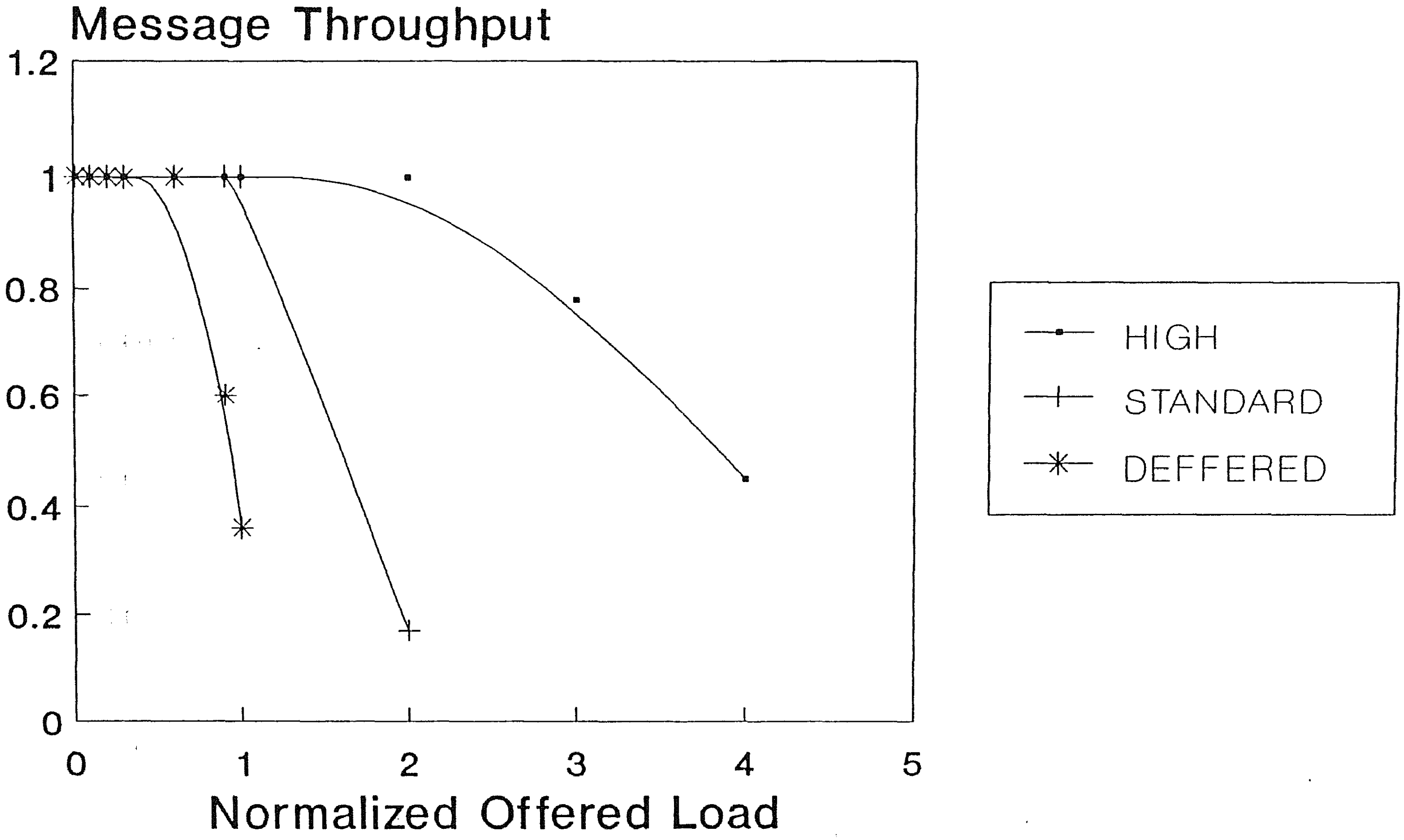


Figure 4.11 Message Throughput vs.
Normalized Offered Load for X-10
Load of 0.1

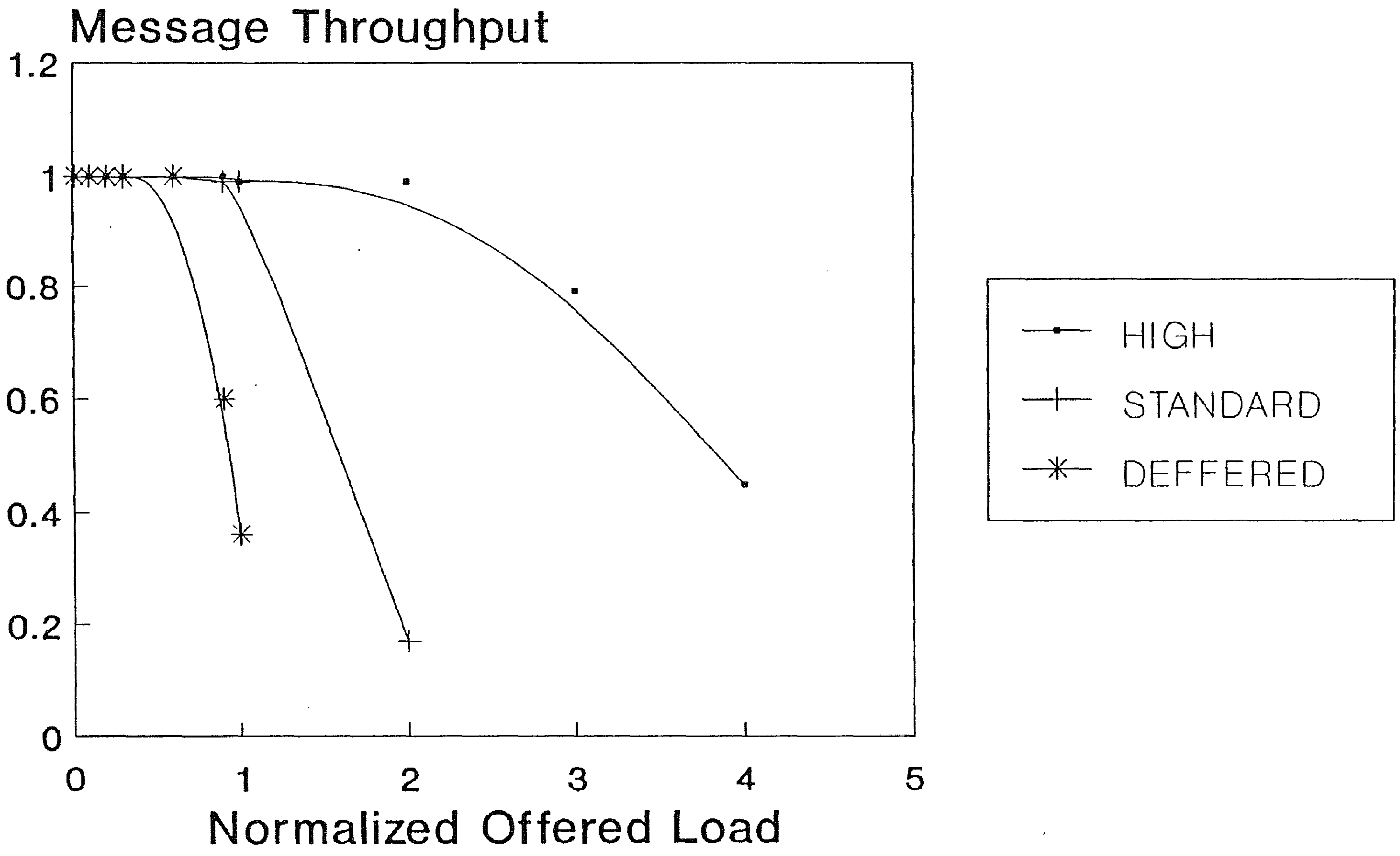


Figure 4.12 Message Throughput vs.
Normalized Offered Load for X-10
Load of 0.2

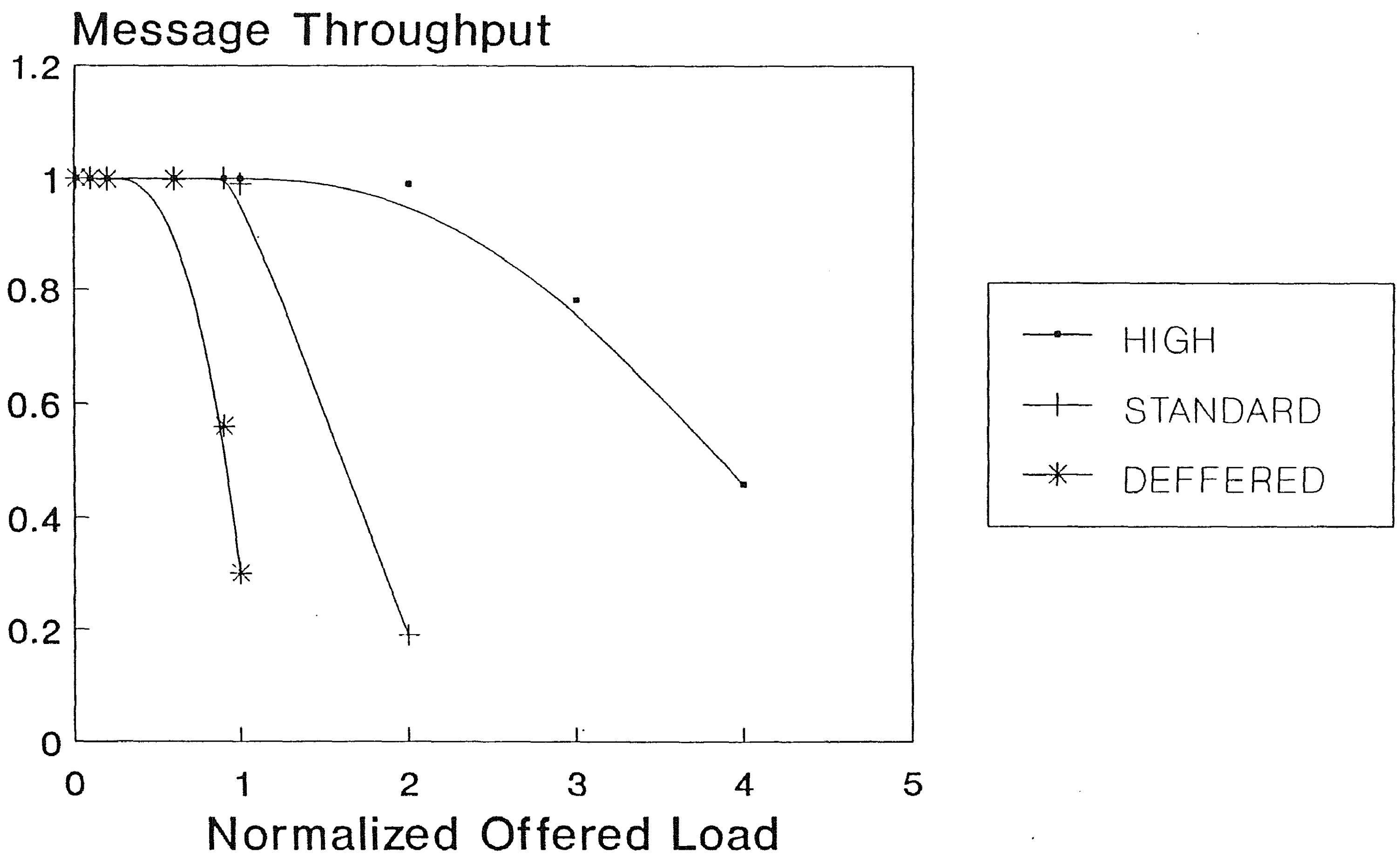


Figure 4.13 Message Throughput vs.
Normalized Offered Load for X-10
Load of 0.5

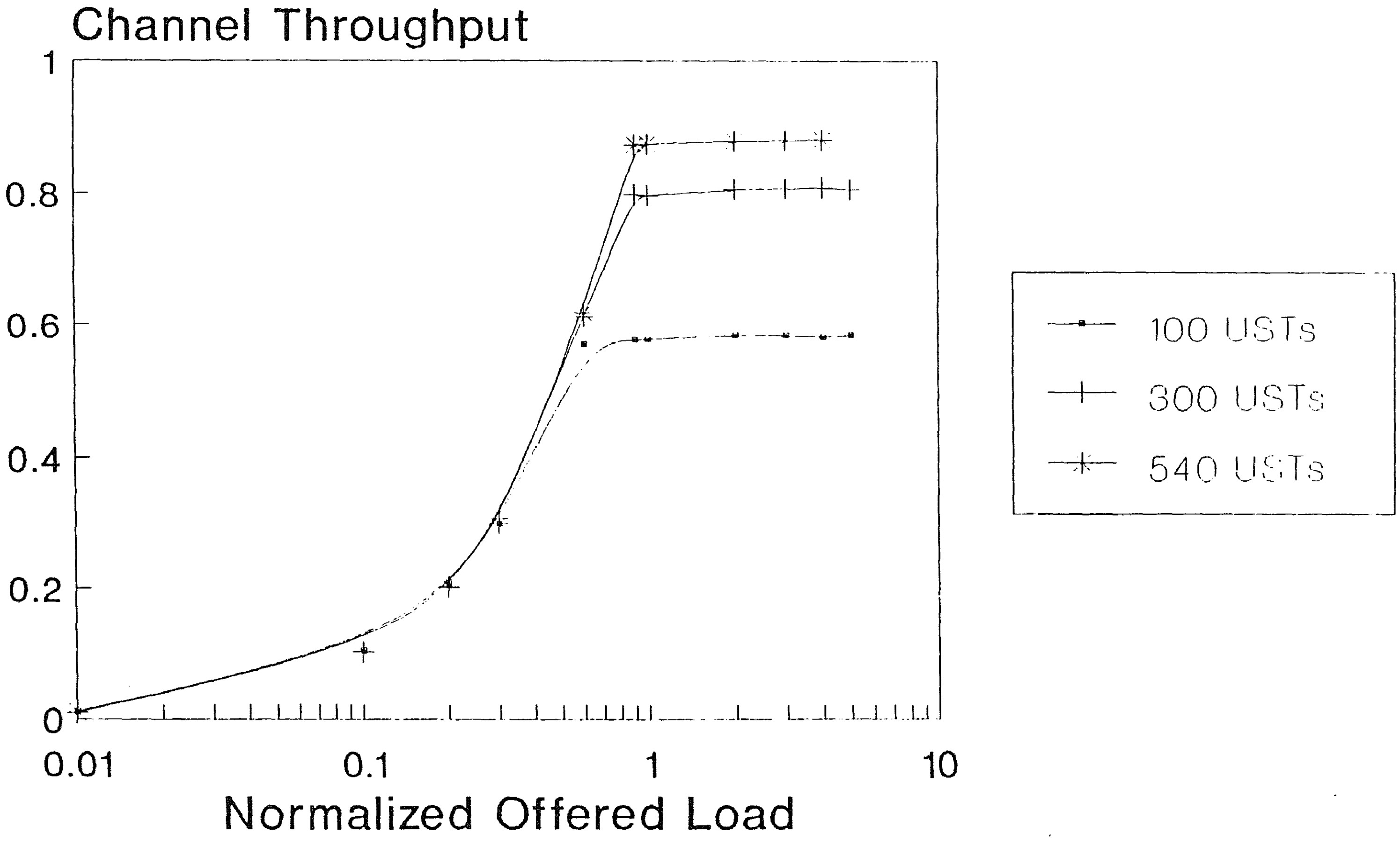


Figure 4.14 Channel Throughput vs. Normalized Offered Load for Packet length of 100,300, and 540 USTs

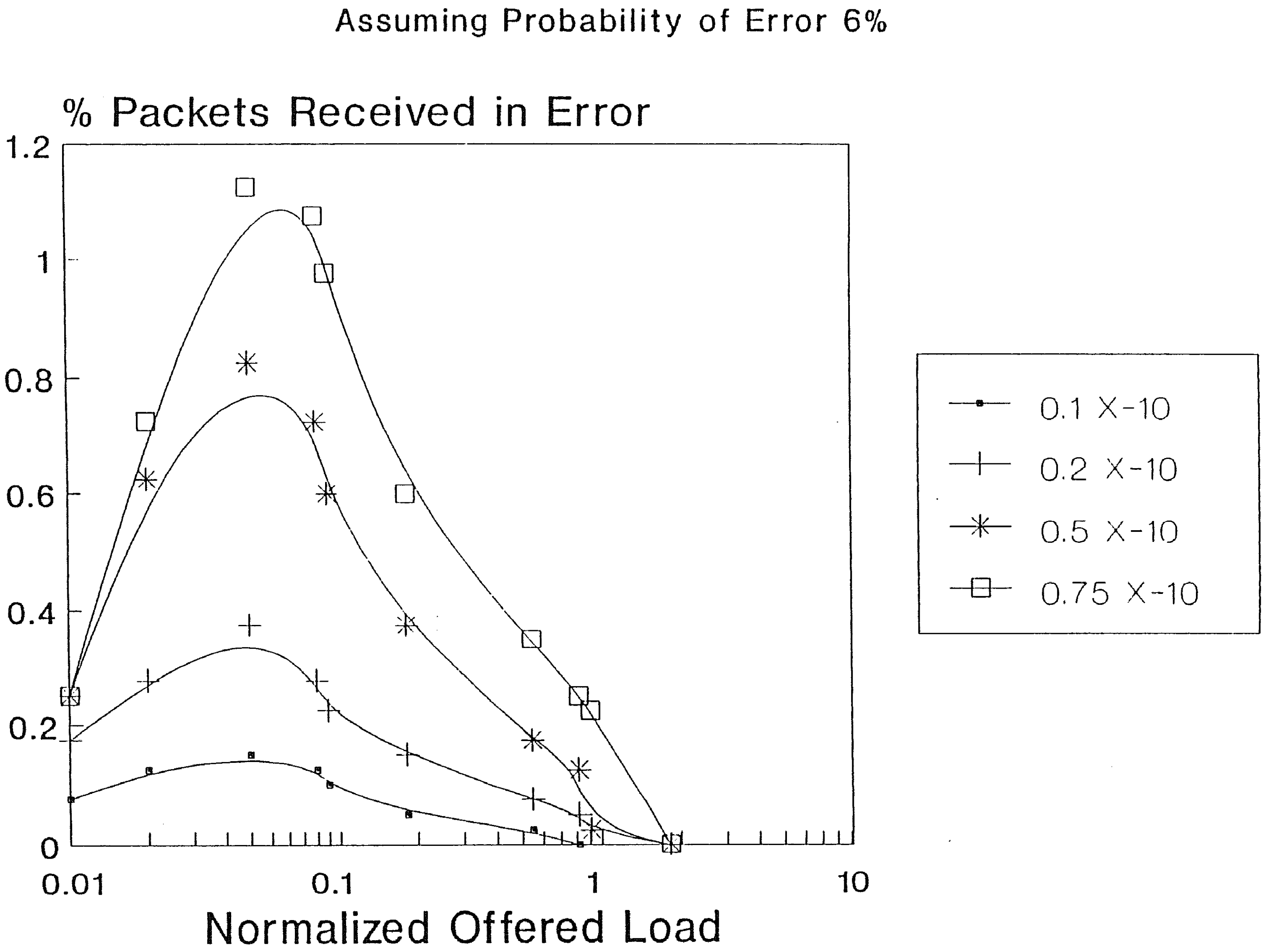


Figure 4.15 Packets received in error
vs Normalized Offered Load

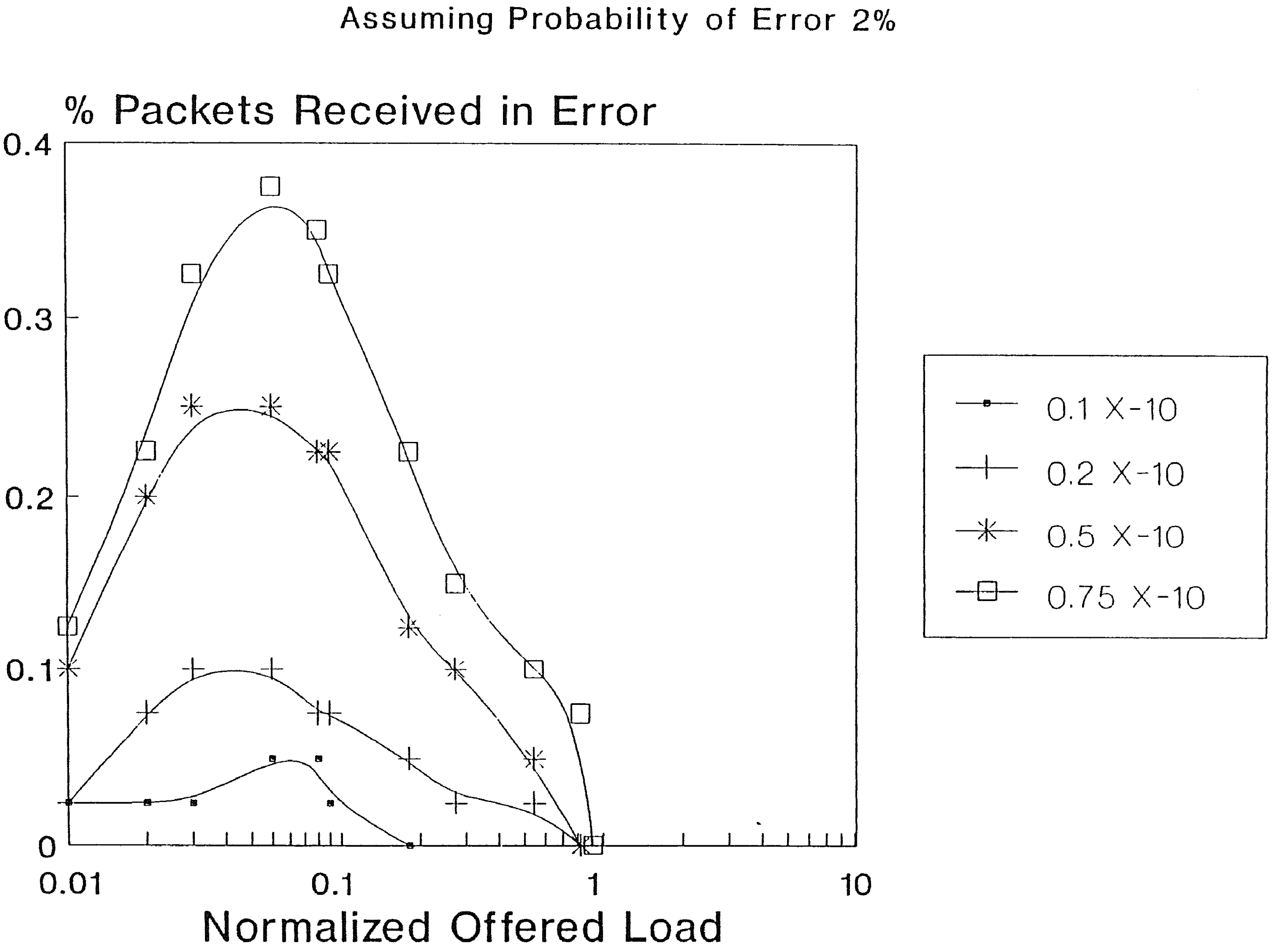


Figure 4.16 Packets received in error
vs Normalized Offered Load

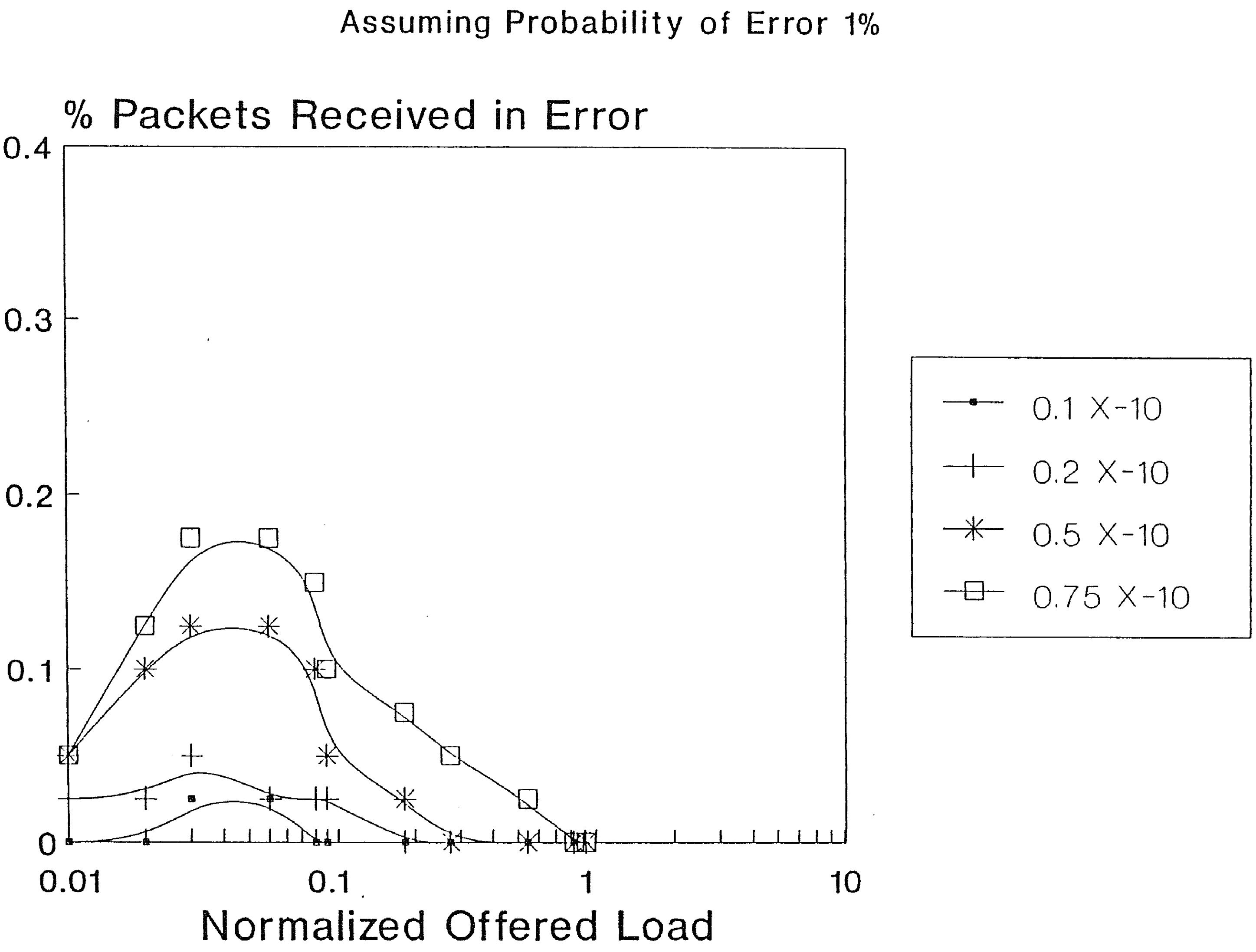


Figure 4.17 Packets received in error
vs Normalized Offered Load

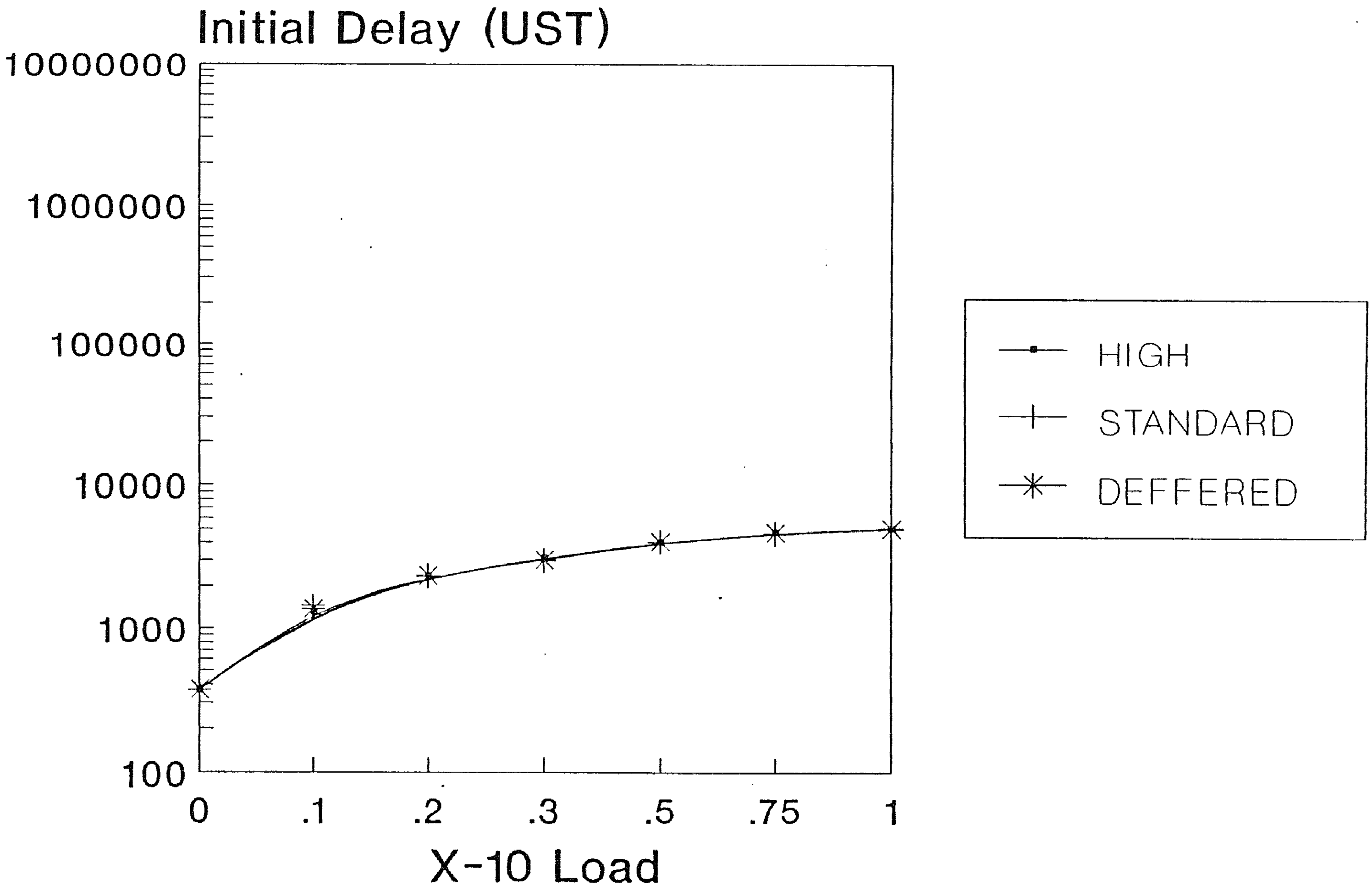


Figure 4.18 The Initial Shift of CEBus Message Delay vs. X-10 load

CHAPTER 5

CONCLUSIONS

Computer simulation experiments have been carried out to evaluate the performance of the Power Line CEBus communication in the presence of X-10 module signaling.

In conclusion, a system of 18 nodes with 9 for X-10 modules and 9 for CEBus, 3 for each of the three message priorities, namely, HIGH, STANDARD, and DEFERRED has been investigated. All the simulation results are a statistical average of 5,000 messages. Performance parameters have been measured, including message delay, packet delay, message throughput, channel throughput, and packets received in error, all as a function of the normalized offered load over a wide range of the normalized offered load.

The message delays vs. load in the presence of X-10 modules is compared in 3 cases, namely, 0.1, 0.2 and 0.5 X-10 loads. It is seen that, at low loads, CEBus messages experience delays. These delays were highest in the third case, i.e. as X-10 load increases the CEBus message delays were higher. This is due to the fact that X-10 are much slower than CEBus. CEBus transmit at rates of 10,000 one bits per second while X-10 transmits at rate of one bit at each zero crossing of the 60 Hz power line frequency. However, at high CEBus loads, the number of X-10 signals transmitted on the channel are very small compared to the CEBus messages, and their effect on the CEBus performance is unnoticeable.

Overall, CEBus network has been confirmed to perform well in terms of delays and message throughput in the presence of X-10 modules over the practical range of normalized offered load. Also, the percentage of CEBus messages received in error due to a collision with X-10 signals has found to be less than 2% in all our cases. However, at high loads, substantial performance differences may occur, especially for DEFERRED messages where their message throughput approaches zero, and only HIGH priority packets get a chance to transmit.

APPENDIX

SIMULATION RESULTS FOR DIFFERENT PACKET LENGTH

In accordance with the thesis format, most of the figures from the simulations are included in Appendix A. Namely, figures illustrating different performance measures for different CEBus packet length have been included.

100 USTs Packets

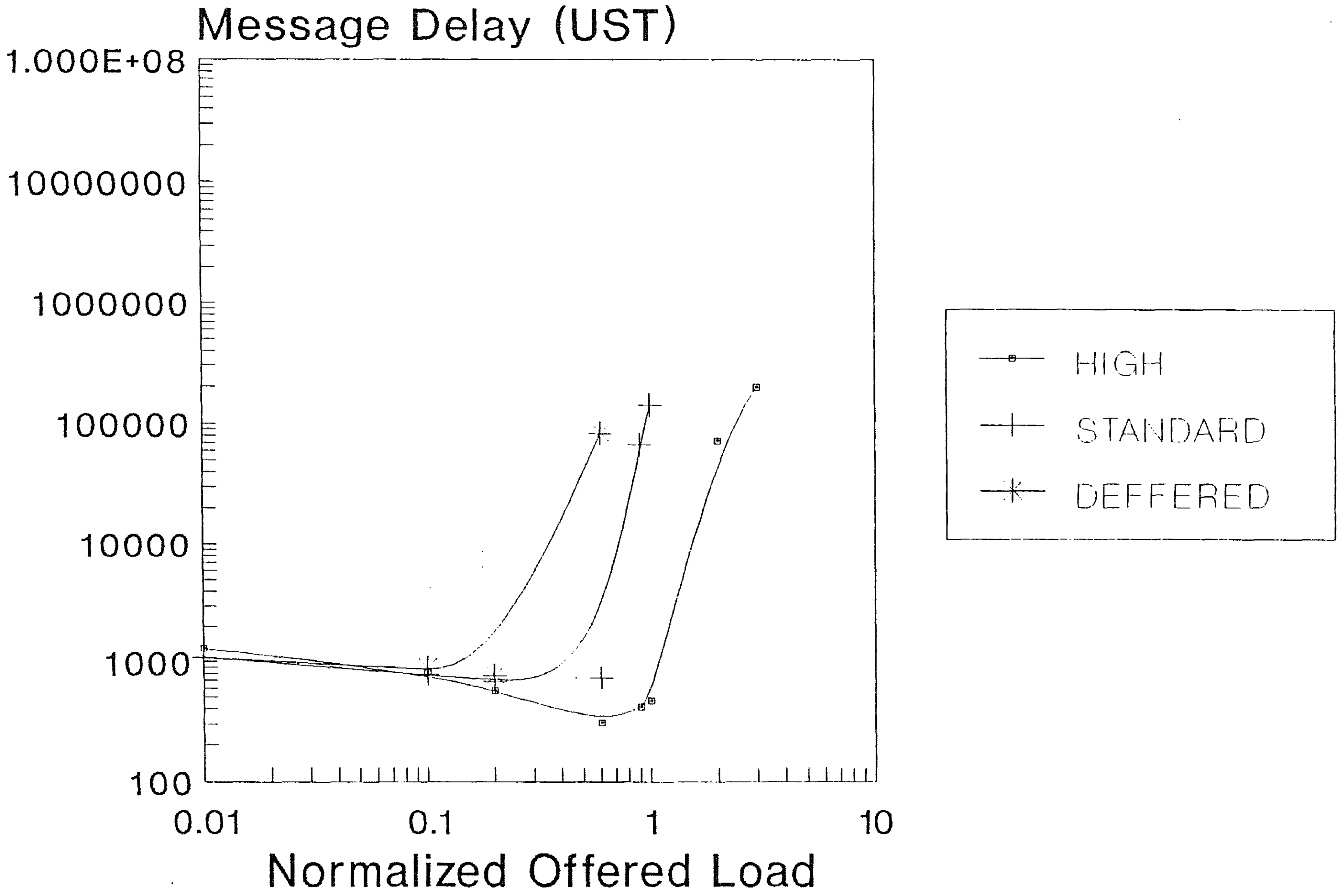


Figure A.1 Message Delay vs. Normalized Offered Load for X-10 Load of 0.1

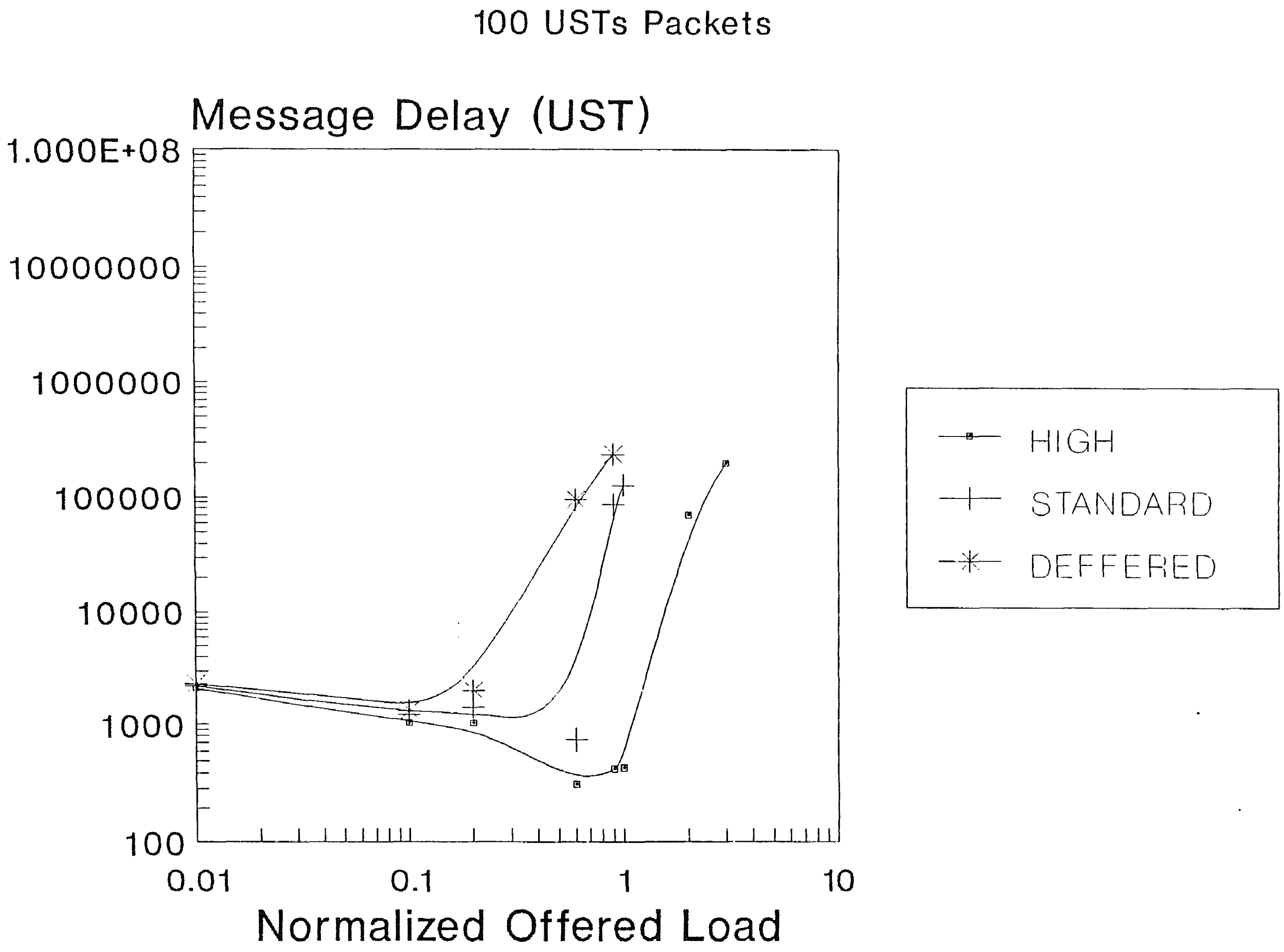


Figure A.2 Message Delay vs. Normalized Offered Load for X-10 Load of 0.2

100 USTs Packets

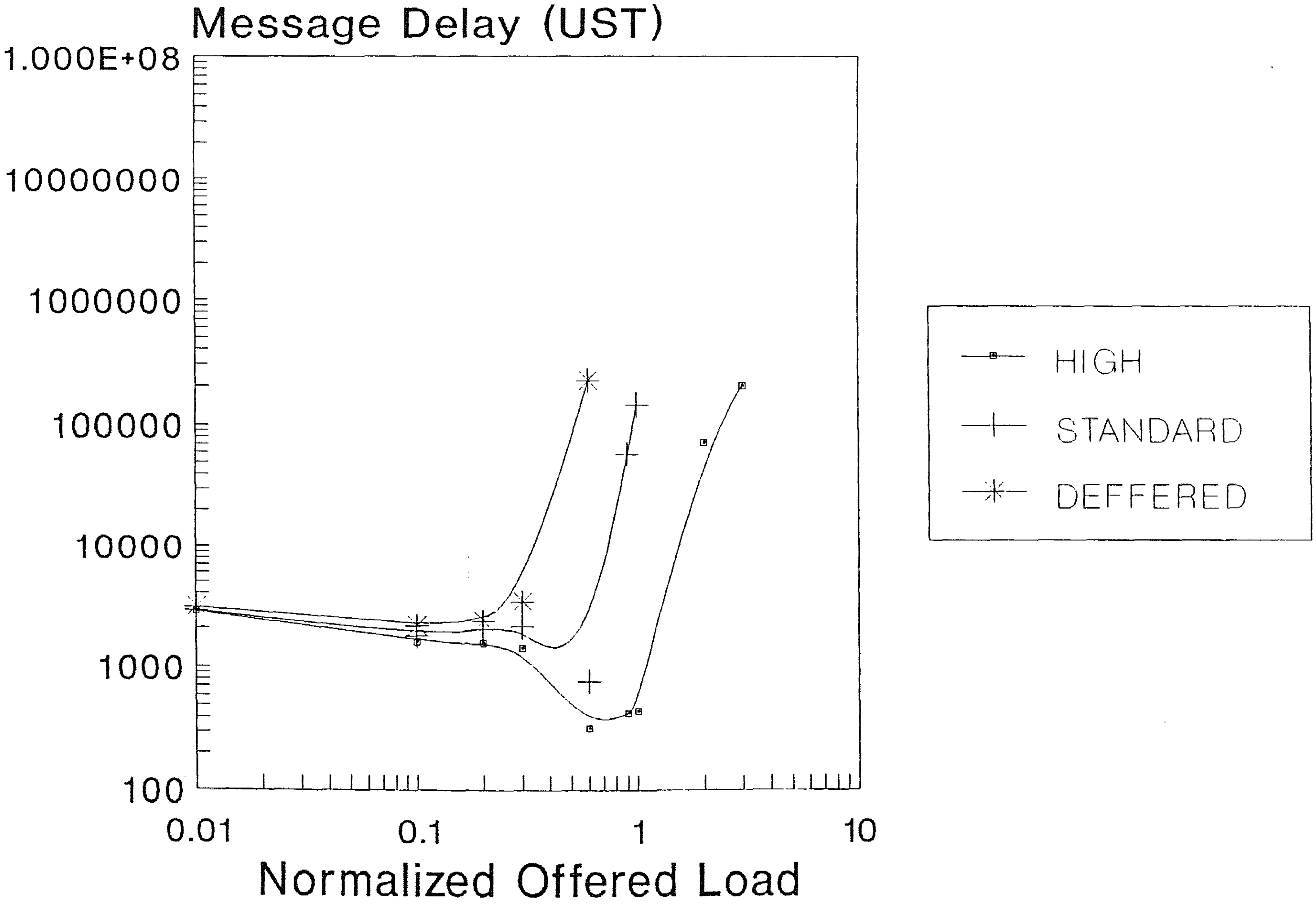


Figure A.3 Message Delay vs. Normalized
Offered Load for X-10 Load of 0.5

100 USTs Packets

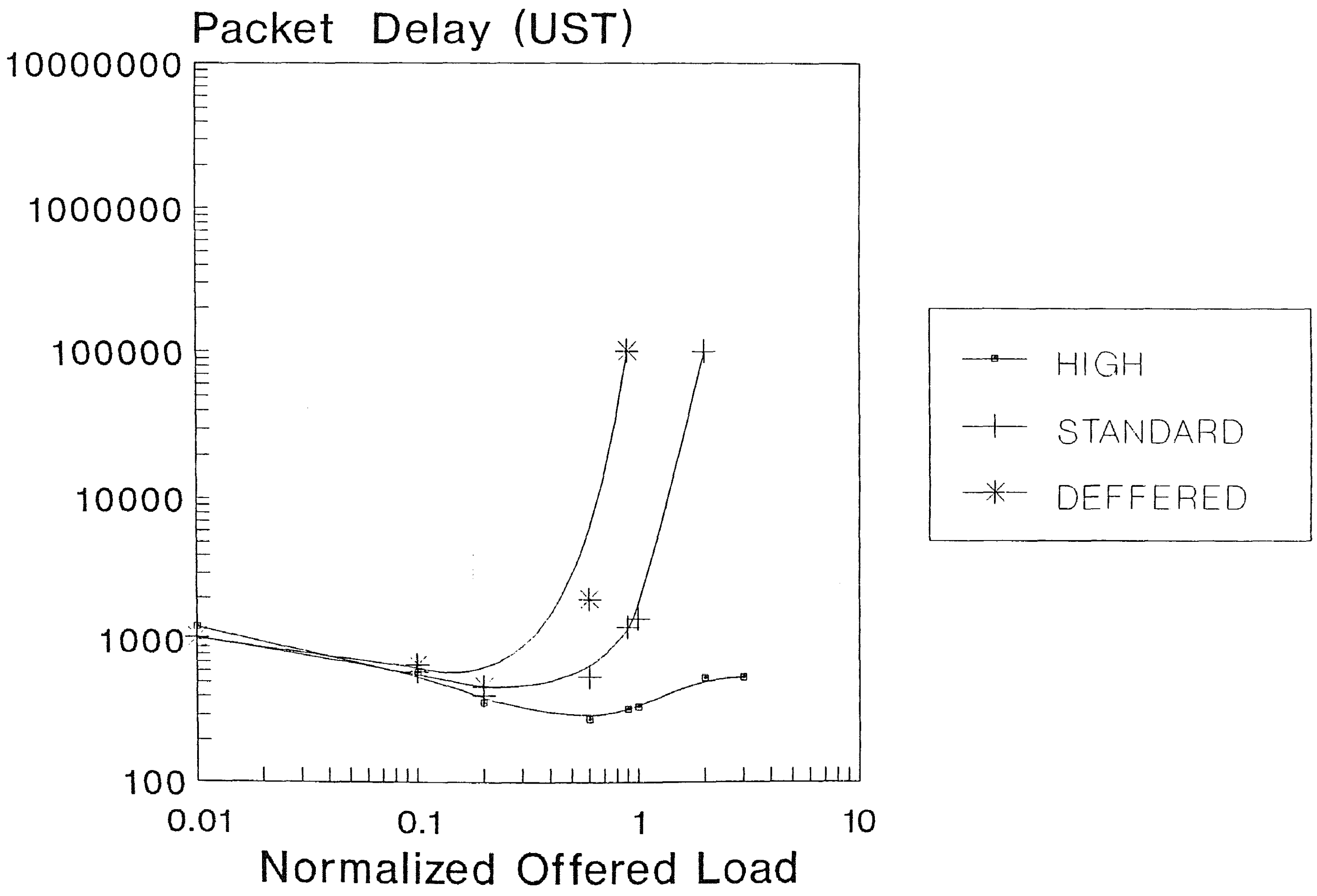


Figure A.4 Packet Delay vs. Normalized Offered Load for X-10 Load of 0.1

100 USTs Packets

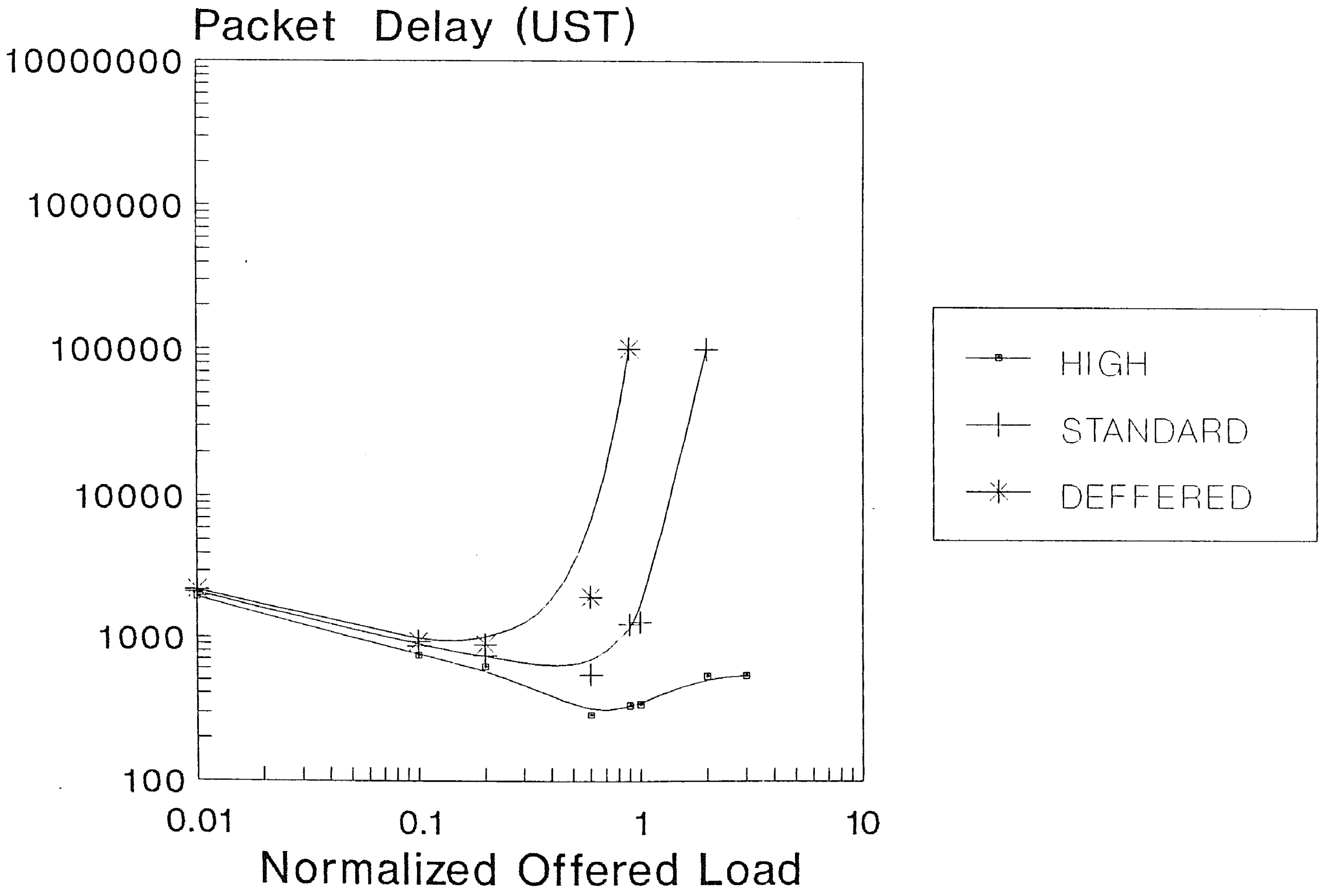


Figure A.5 Packet Delay vs. Normalized
Offered Load for X-10 Load of 0.2

100 USTs Packets

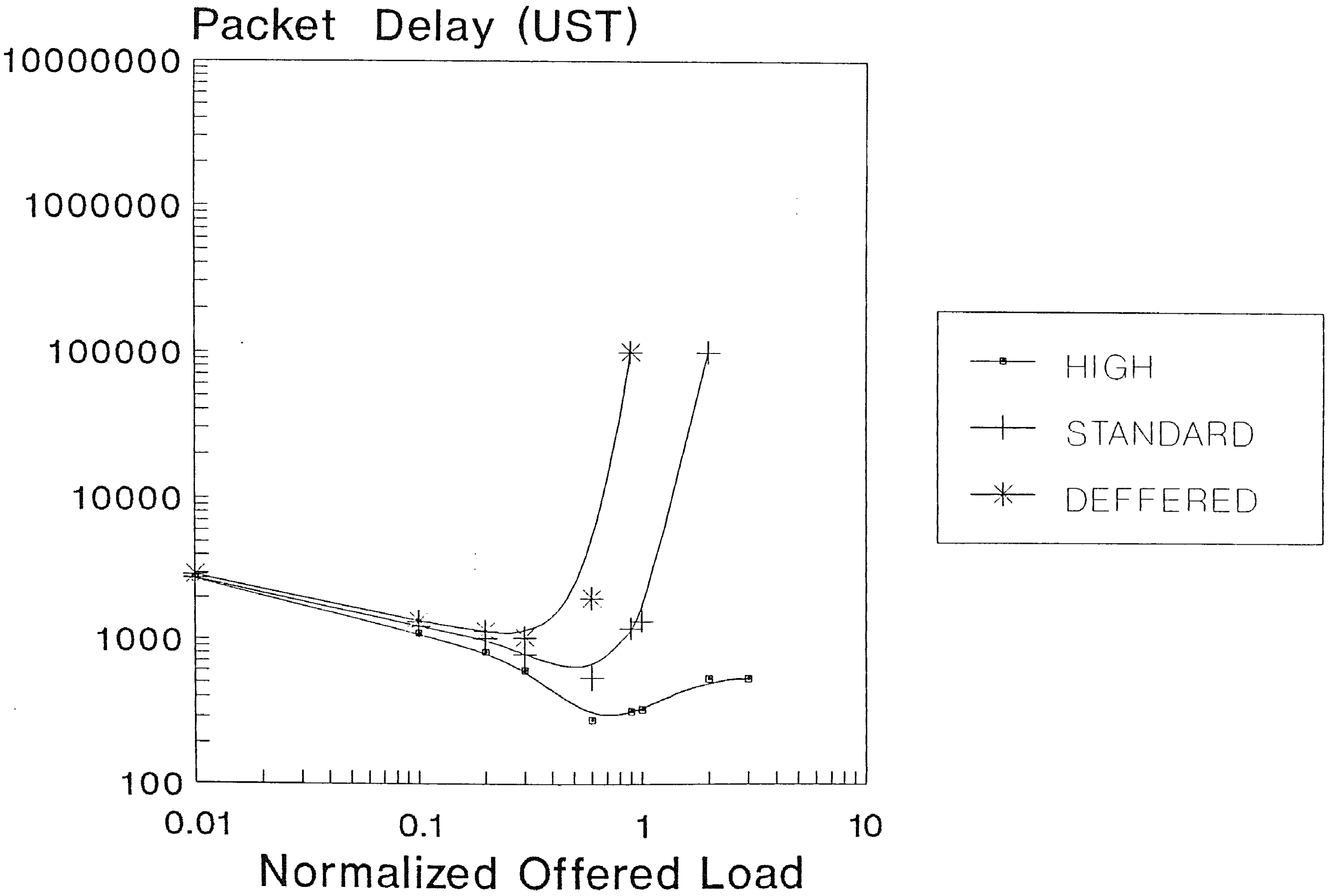


Figure A.6 Packet Delay vs. Normalized
Offered Load for X-10 Load of 0.5

100 USTs Packets

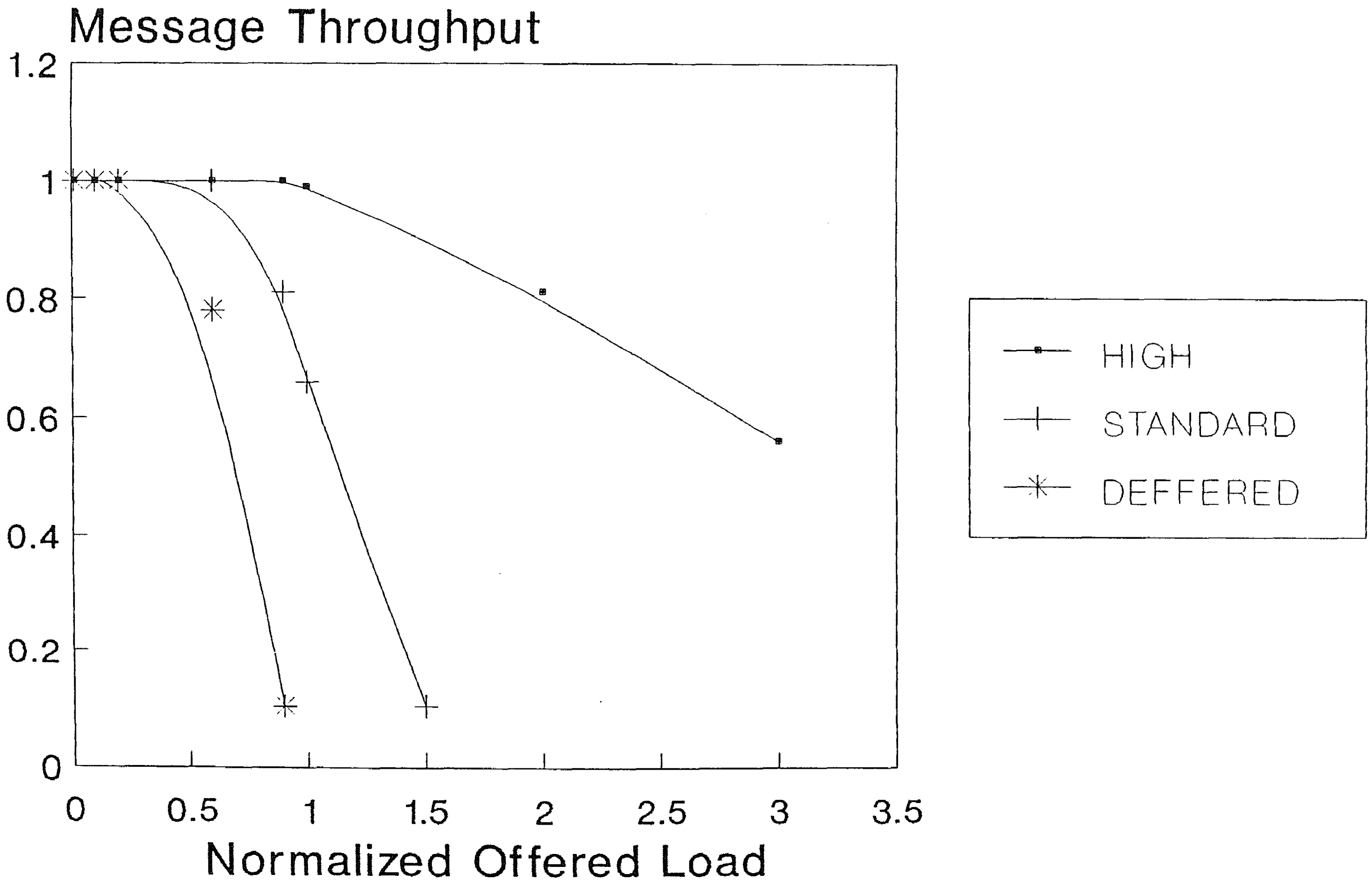


Figure A.7 Message Throughput vs. Normalized Offered Load for .1 x-10 Load

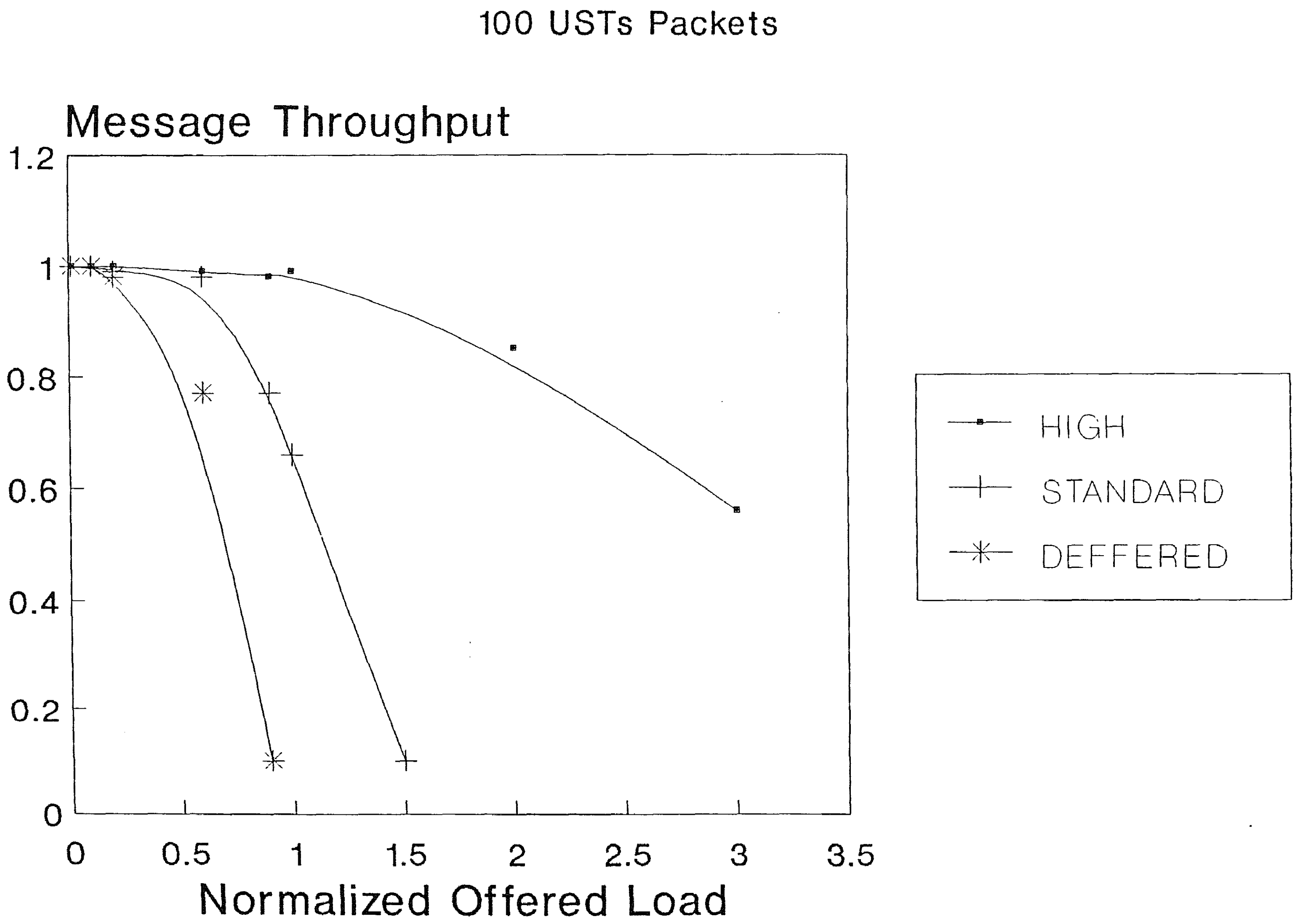


Figure A.8 Message Throughput vs. Normalized Offered Load for .2 X-10 Load

100 USTs Packets

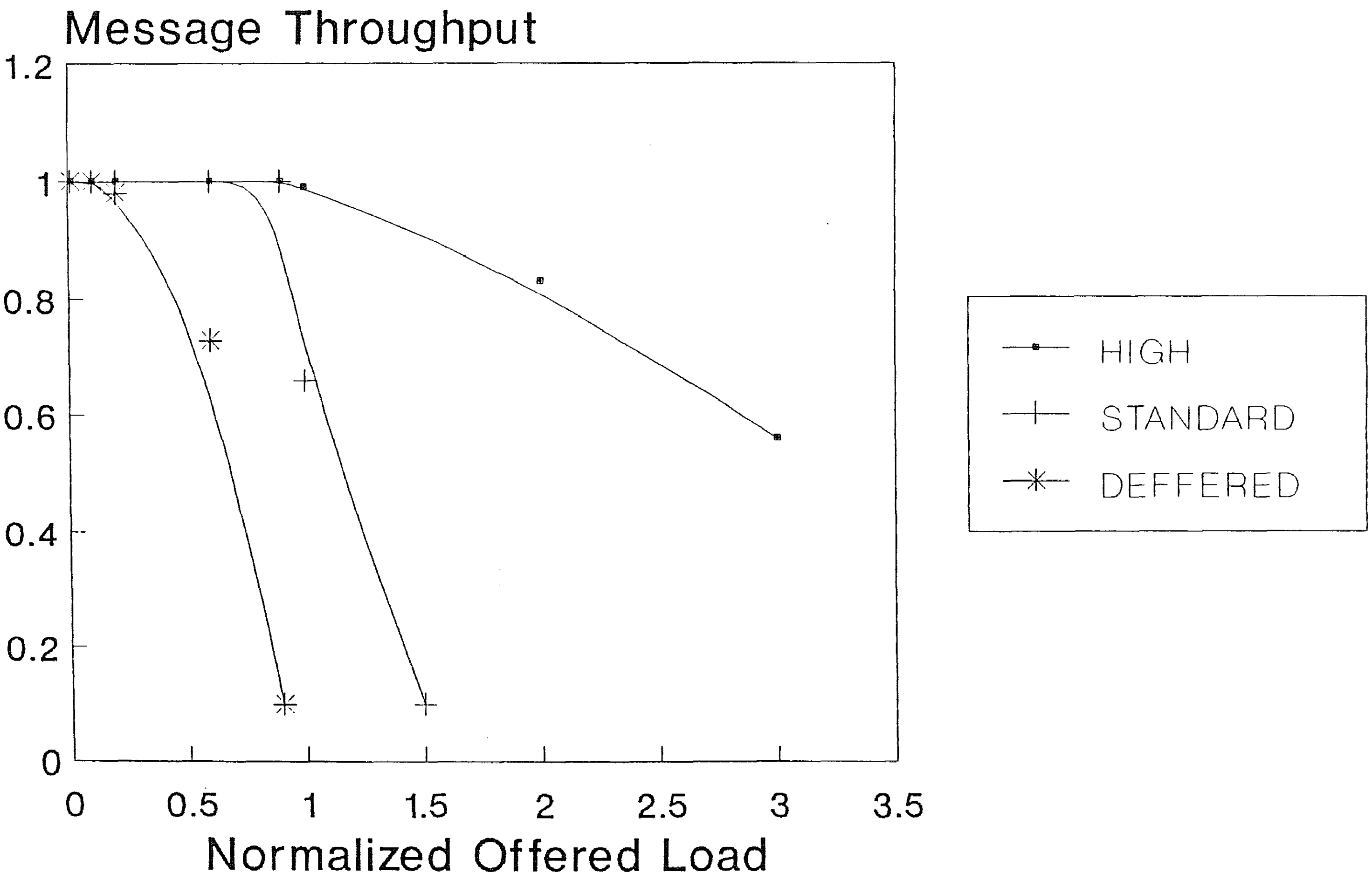


Figure A.9 Message Throughput vs. Normalized Offered Load for .5 X-10 Load

540 USTs Packets

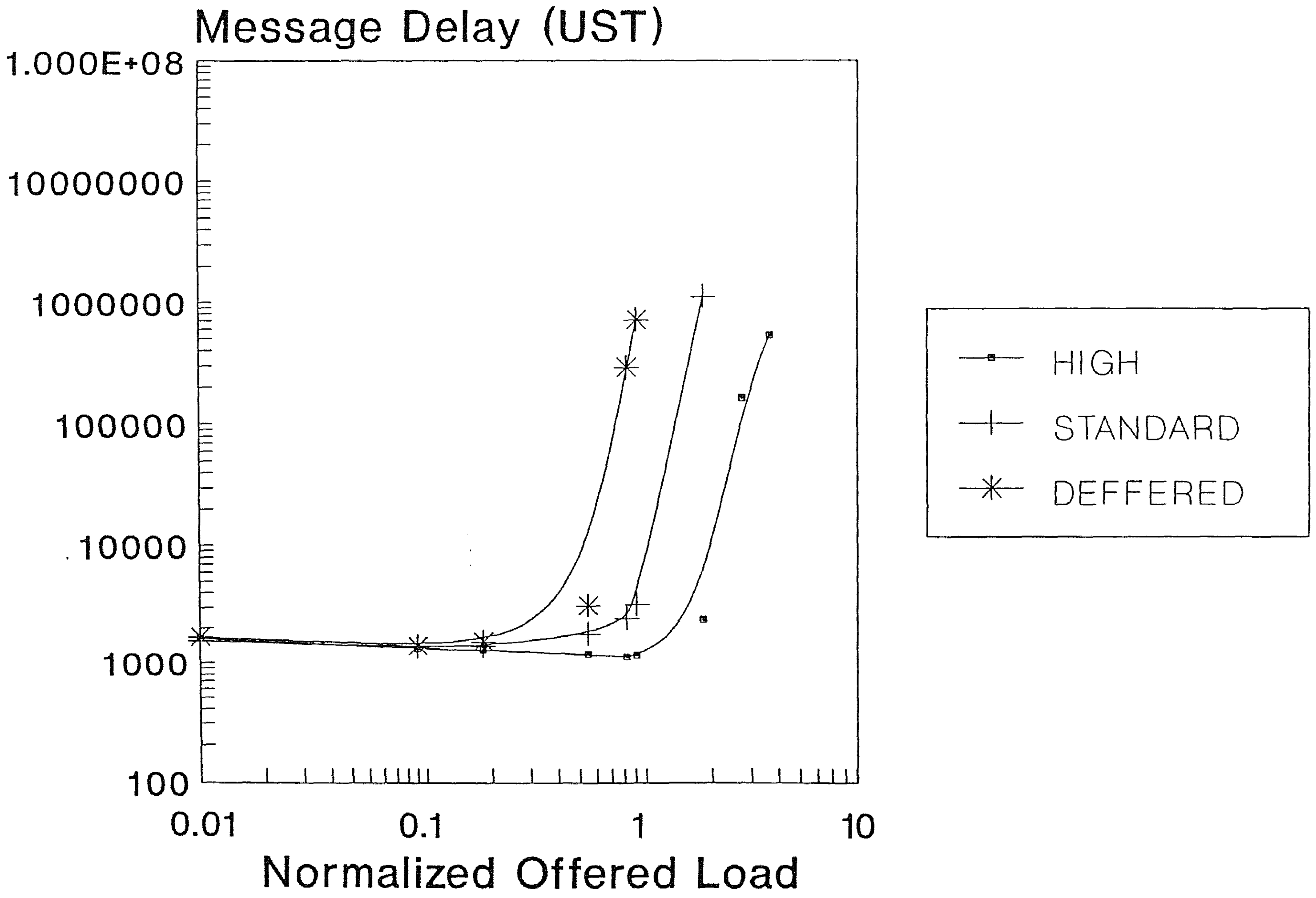


Figure A.10 Message Delay vs. Normalized Offered Load for X-10 Load of 0.1

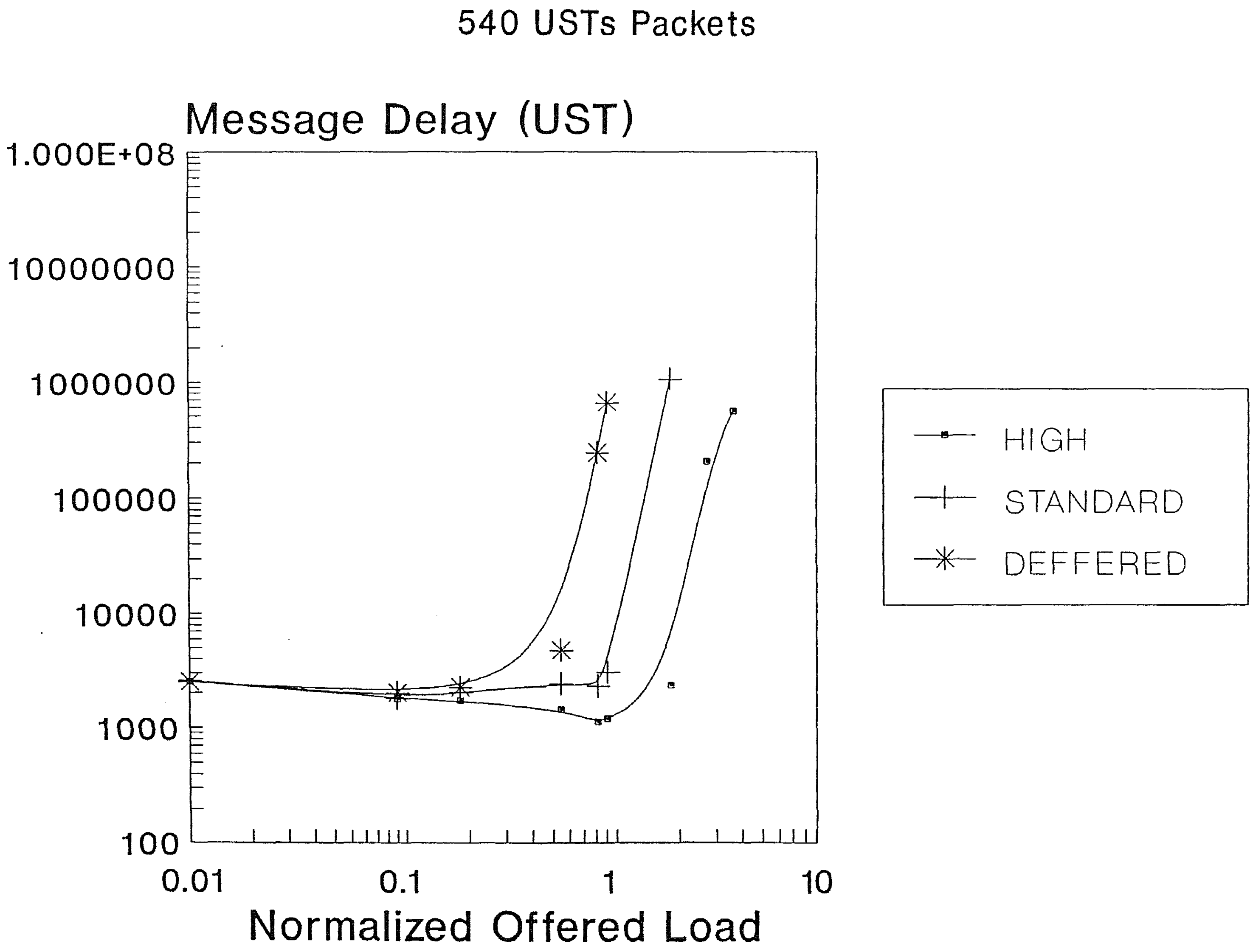


Figure A.11 Message Delay vs. Normalized Offered Load for X-10 Load of 0.2

540 USTs Packets

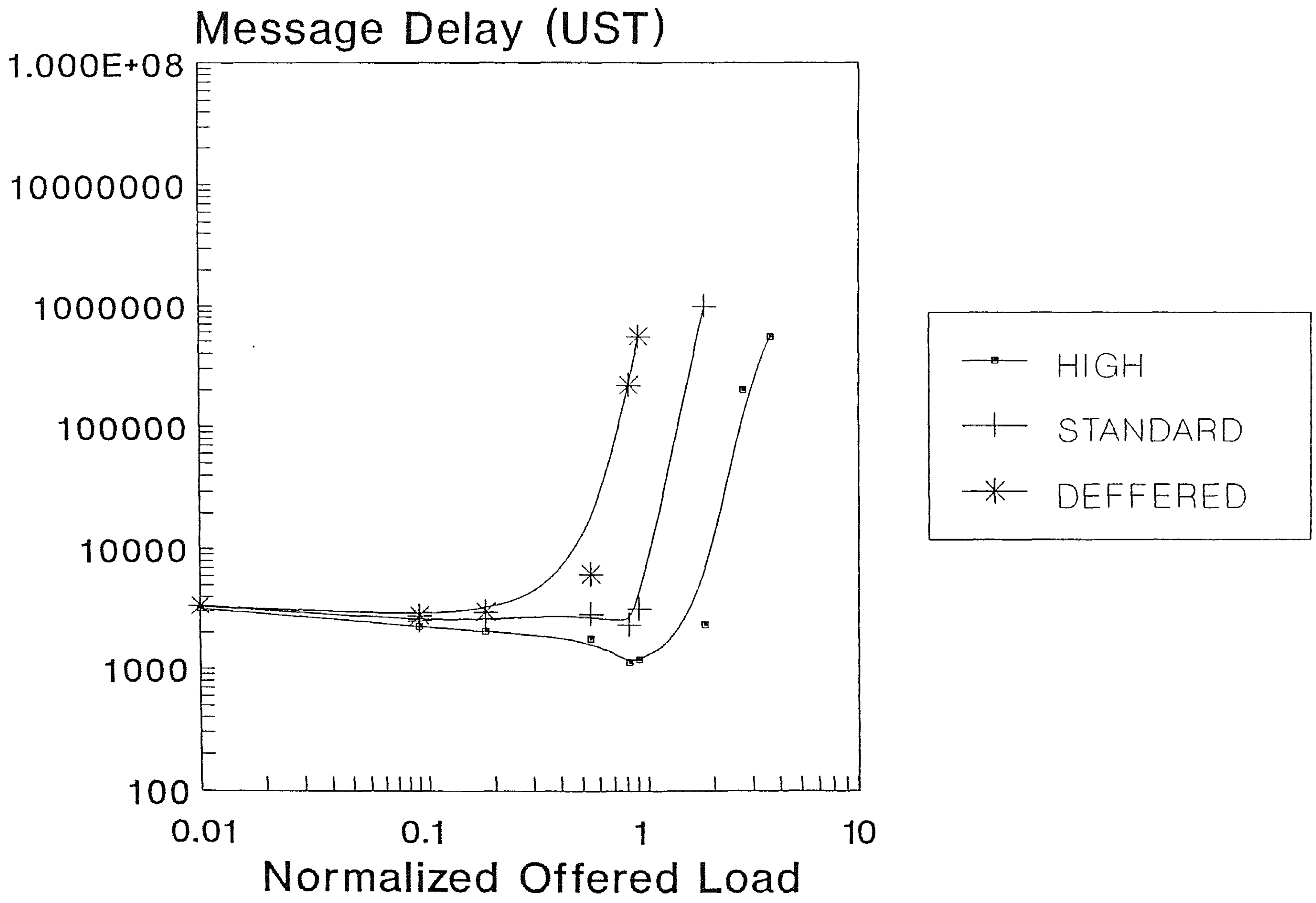


Figure A.12 Message Delay vs. Normalized Offered Load for X-10 Load of 0.5

540 USTs Packets

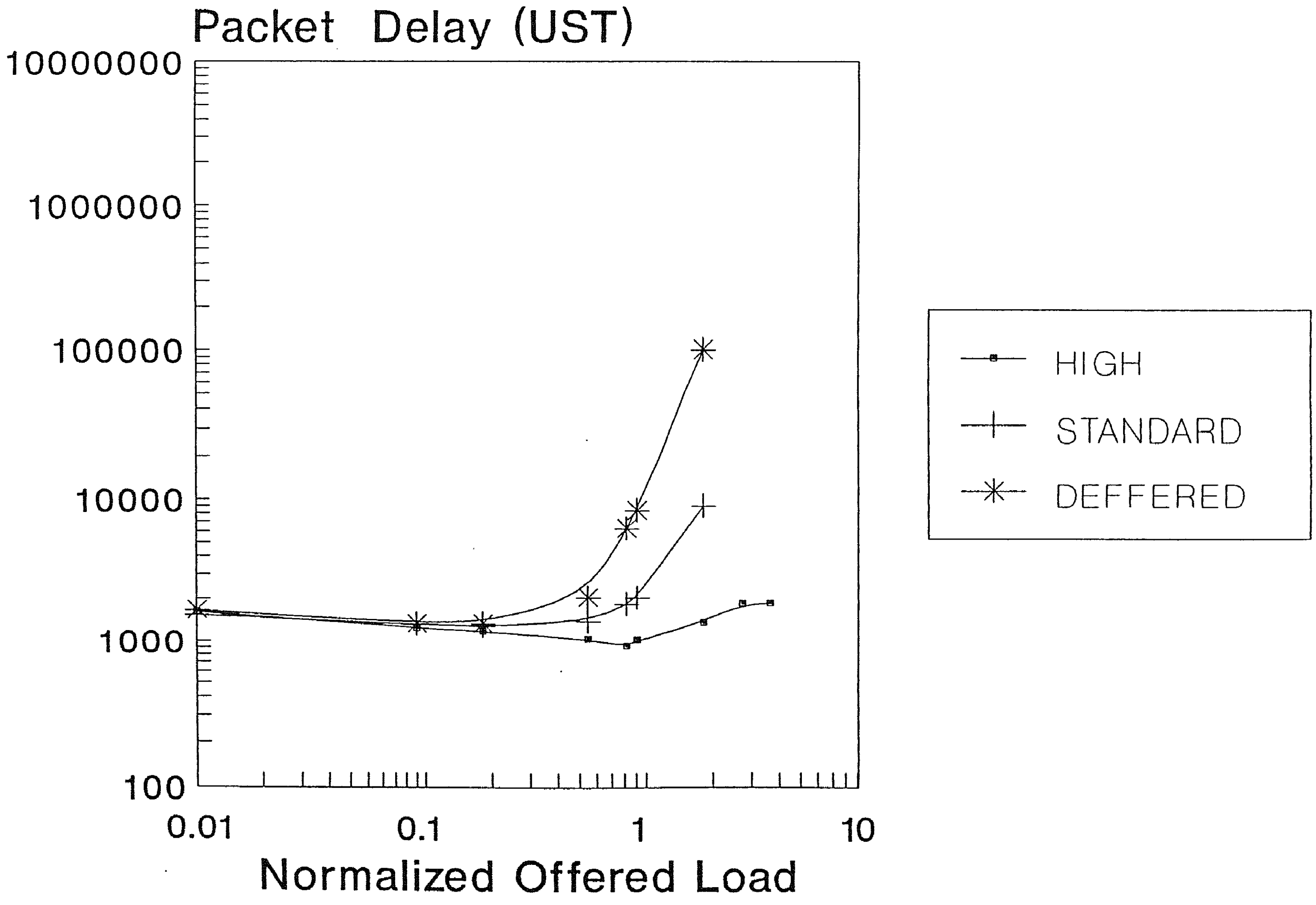
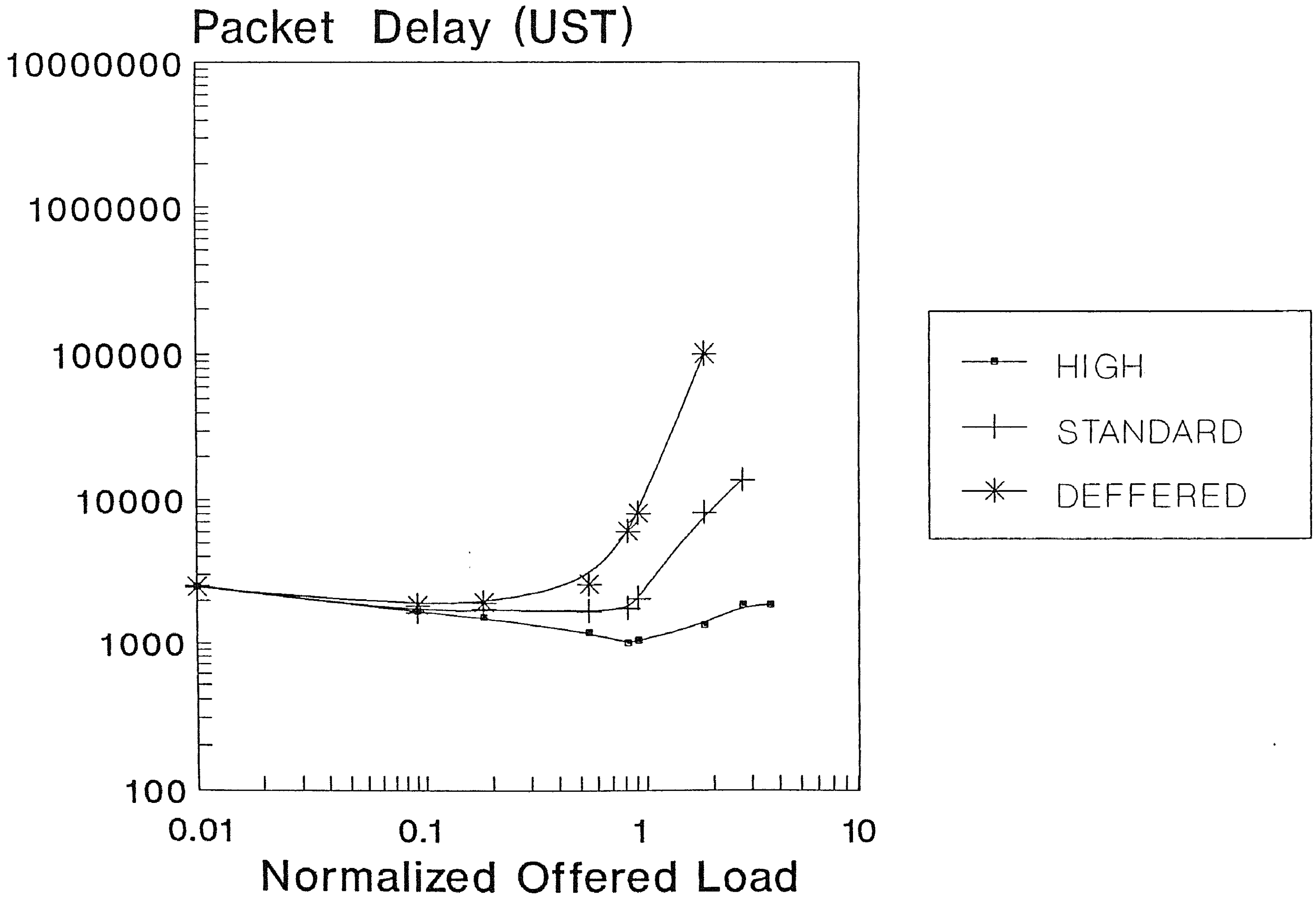


Figure A.13 Packet Delay vs. Normalized Offered Load for X-10 Load of 0.1



540 USTs Packets

Figure A.14 Packet Delay vs. Normalized Offered Load for X-10 Load of 0.2

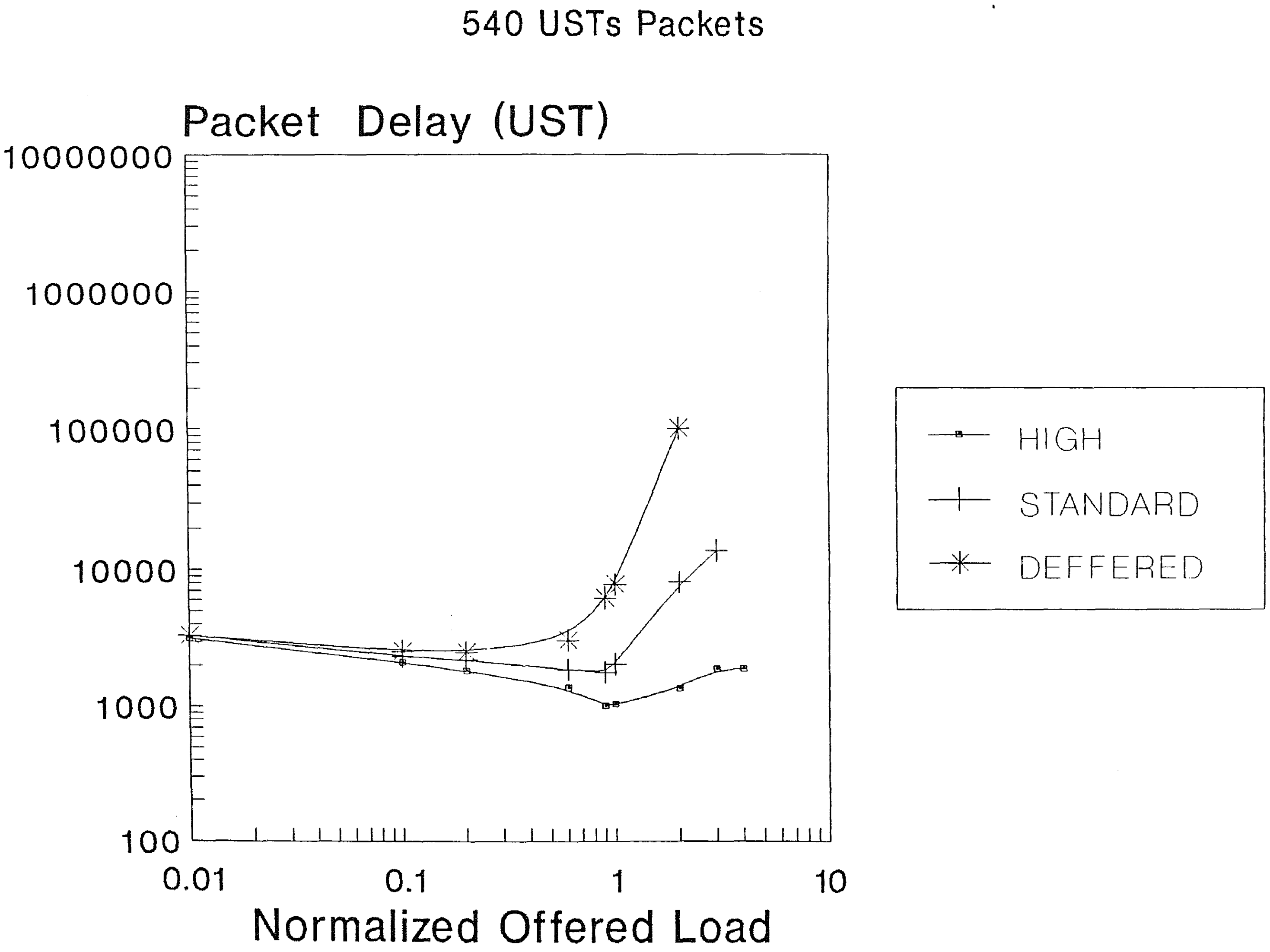


Figure A.15 Packet Delay vs. Normalized Offered Load for X-10 Load of 0.5

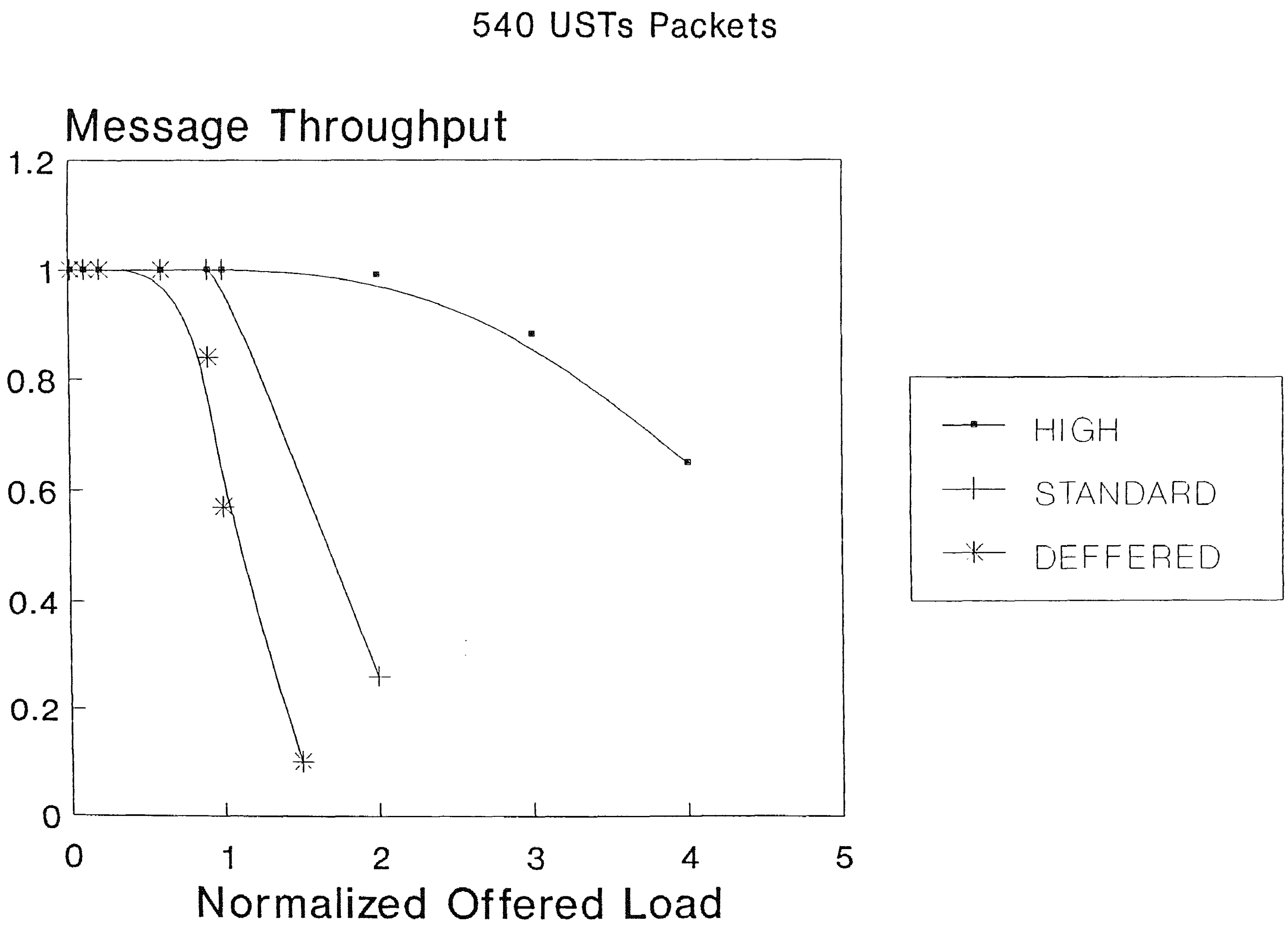


Figure A.16 Message Throughput vs.
Normalized Offered Load for .1 x-10
Load

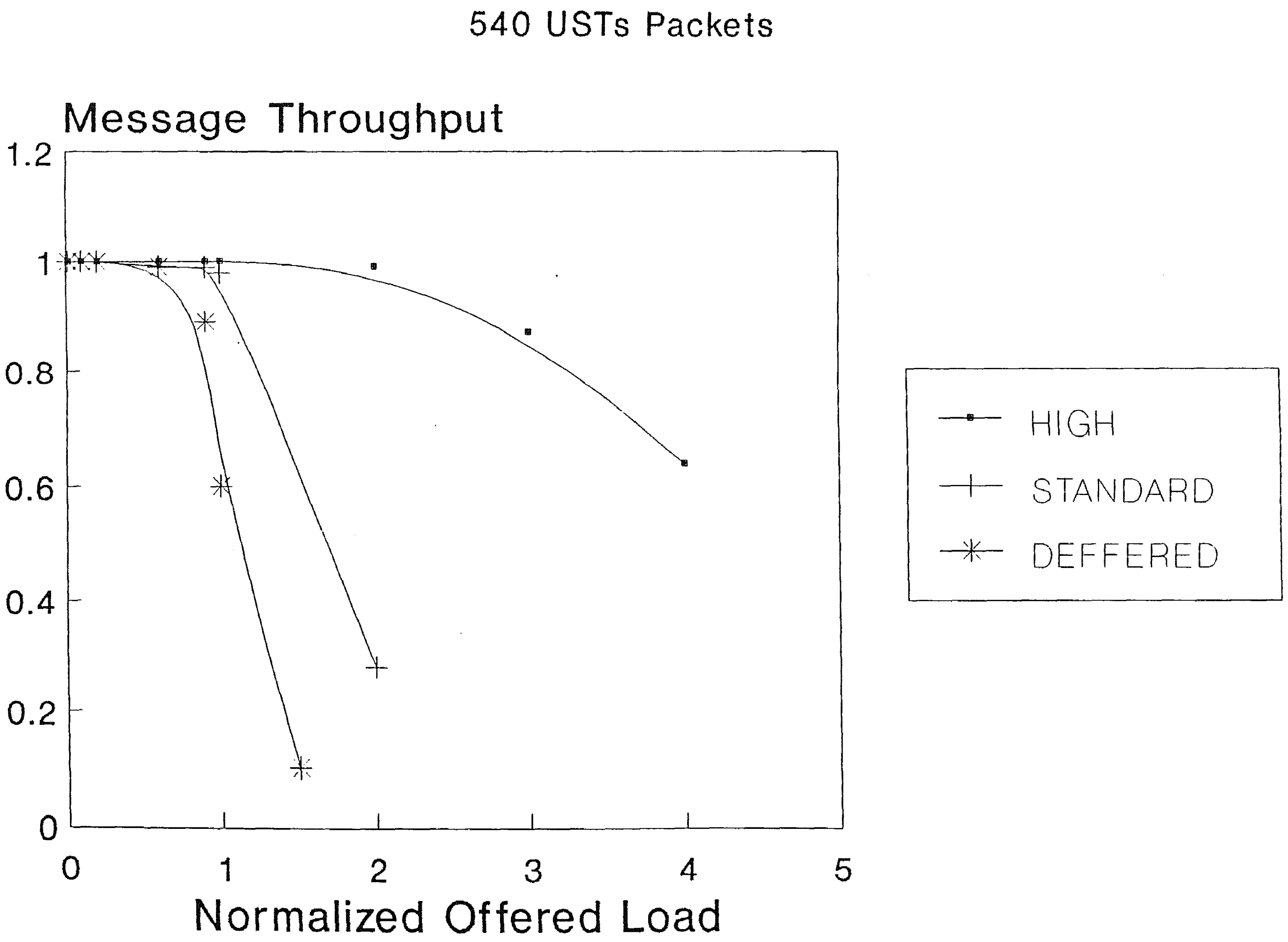


Figure A.17 Message Throughput vs. Normalized Offered Load for .2 X-10 Load

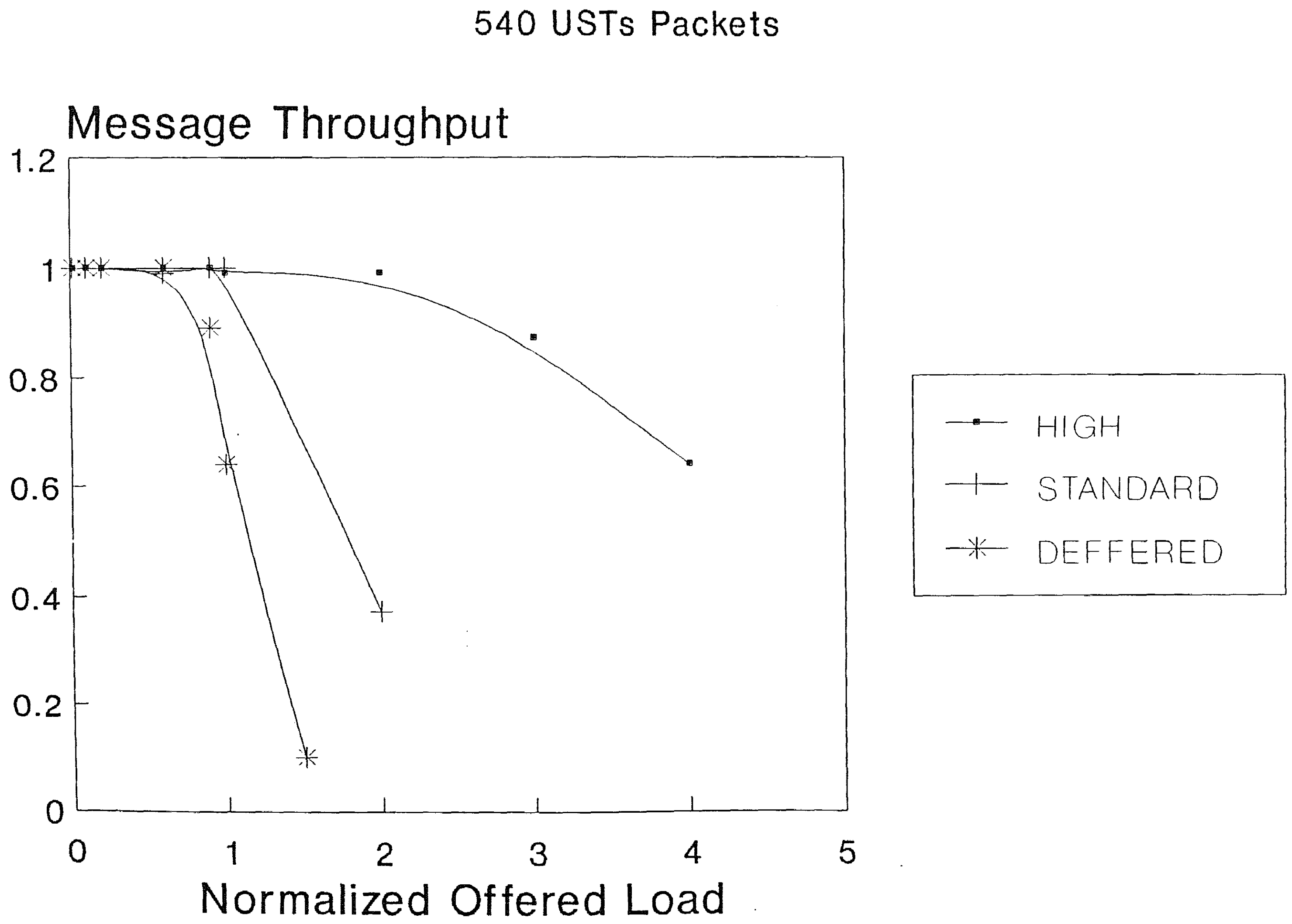


Figure A.18 Message Throughput vs.
Normalized Offered Load for .5 X-10
Load

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