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Investigation of CEBus traffic across a router, with and without acknowledgment

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ABSTRACT

INVESTIGATION OF CEBUS TRAFFIC ACROSS A ROUTER, WITH AND WITHOUT ACKNOWLEDGMENT

by
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A power line and twisted pair implementation of the Consumer Electronic Bus(CEBus) has great potential toward inexpensive home automation. Since the introduction of the CEBus Standard, there has been increasing efforts on evaluating its performance. However, most of the work has been performed for unacknowledged networks. Pan[18] was able to implement an acknowledged network for PL CEBus. In this thesis, the acknowledgment process has been taken one step further. The effect of acknowledgment on a Power Line and Twisted Pair CEBus network interconnected by a router is studied. CEBus network performance parameters such as message and packet delays, message throughput, and channel throughput have been evaluated in this simulation for packet lengths of 100, 300, and 600 bits. Acknowledged network performance has been confirmed to function well in terms of the delays and message throughputs over the practical range of the normalized offered load. For larger loads, the acknowledged network provides a more reliable performance, but at the expense of increased delays and reduced throughputs when compared with the unacknowledged network.

INVESTIGATION OF CEBUS TRAFFIC ACROSS A ROUTER, WITH AND WITHOUT ACKNOWLEDGMENT

by
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INVESTIGATION OF CEBUS TRAFFIC ACROSS A ROUTER, WITH AND WITHOUT ACKNOWLEDGMENT

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This thesis is dedicated to my dear parents
and to the memory of my aunt Mayura

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CHAPTER 1

INTRODUCTION

Home automation systems can increase comfort and security around the house and can also provide economic benefits through energy conservation. The concept involves granting the user with complete control over every appliance and electrical equipment in the house, thus relieving him from tasks that require manual control. Several home automation systems were introduced to the market in the late 70s and the 80s, but these manufacturers did not address the problems of cross product compatibility and complete system integration. Hence, a variety of products that can only be controlled individually were introduced. A few of them are energy management units, security systems, lighting controllers, and entertainment systems. In 1983, the Electronic Industries Association(EIA) recognized the need to develop standards covering all aspects of home automation systems communication. After five years of study, the EIA released a home automation system communication standard known as Consumer Electronic Bus.

The Consumer Electronic Bus (CEBus), is a computer network for the intelligent home able to provide a standardized communication interface to 6 different media. They are the PLBus (Power Line Bus), TPBus (Twisted-Pair Bus), CXBus (Coaxial Bus), SRBus (Infrared or Single-Room Bus), RFBus (Radio Frequency Bus) and FOBus (Fiber-Optic Bus). PLBus 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. Also TPBus promises to be the most useful high-speed medium in the majority of installations[2]. The CEBus is intended to support home communication for remote sensing and control, status indication, security monitoring and control, energy management, entertainment facilities, lighting and home appliances.

The CEBus standard, which is continually being updated and which was last released in October 1992, sets out to achieve several objectives. It should be easy to retrofit, and should be able to expand over time as new media and new technologies are adopted. The technical goals are versatility with both distributed and centralized control, simplicity of operation, low cost, compatibility regardless of manufacturer, support of multiple media and media independence. A new language, the Command Application Language (CAL), has been specifically designed for the CEBus for this purpose. It provides compatibility among supported devices and allows for extendibility over time as new features and services are introduced.

The protocol layers of the CEBus follow the Open System Interconnection (OSI) architectural model of the International Organization for Standardization(ISO). By this required specification, the CEBus can be extended and interconnected to various media through a router, a bridge, or a gateway. However, only four of the seven OSI layers are used by CEBus. Some of the functionality associated with the Transport Layer has been built into the CEBus Application and Network Layers. The Session and the Presentation Layers of the OSI model are not required for CEBus. So they have been omitted to reduce both packet length and device complexity.

The architecture of the CEBus routers is layered in the same manner as CEBus nodes. However, in contrast to a CEBus node, a router has two Medium Access Control(MAC) Sublayers and Logical Link Control (LLC) Sublayers - a set for each medium connected to the router[16]. The design of the CEBus router is derived from the requirements for simple, low-cost consumer devices, or nodes, and minimal length packets. The functionality provided by the routers is complex, and would be expensive to include in each individual node in the network. Thus, the functional complexity of determining packet routes and storing information concerning network topology/connectivity is distributed to the routers. In a typical CEBus network, there might be many nodes and only a few routers, justifying the higher complexity and cost.

The CEBus protocol employs Carrier Sense Multiple Access with Contention Detection and Contention Resolution (CSMA/CDCR) for channel access. The channel access delay depends on the packet's priority, the station's queueing state and a random access delay time. Three classes of priority messages HIGH, STANDARD, and DEFERRED are supported in the CEBus protocol. Priority based channel access enables a higher priority message to preempt a lower priority message while the latter is waiting for channel access.

In this thesis, the throughput and delay performance of traffic between the Power Line(PL) and the Twisted Pair(TP) media interconnected by a router is studied. The router is assigned to handle all three priority classes. Simulation results for the throughput and delay behavior are obtained for the acknowledged and unacknowledged cases. Simulation results were obtained by Yang and Manikopoulos[17] for unacknowledged connectionless service across a router which provides an exchange of data between peer Network Layers, but without the acknowledgment mechanism to verify the success of the transmission. Pan[18] developed the acknowledgment mechanism, and investigated the performance of PL CEBus, with and without acknowledgment. The present simulation model includes the acknowledgment mechanism, and successful transmission on the same channel(Local traffic) or successful transmission across the router to another channel(Non-Local traffic) can be verified.

Two of the home automation systems currently available are X-10 and Smart House. X-10 is a one-way open loop system with limited potential for intelligent home control[2]. Smart House is currently aimed at the new construction market. Equipment for retrofits is still being developed[7]. Although EIA has invited both X-10 and Smart House to participate in its standard-setting activities, X-10 has chosen not to, while Smart House is reviewing the EIA standard to ascertain whether portions may be incorporated into Smart House[6].

CHAPTER 2

CEBUS ARCHITECTURE AND PROTOCOL

2.1 CEBus Architecture

The OSI model is utilized in the design of the CEBus. Only four of the seven OSI layers are used in the CEBus as shown in Fig.2.1. The Data Link Layer is divided into the Medium Access Control (MAC) Sublayer and the Logical Link Control (LLC) Sublayer. By enabling different MAC Sublayers to be interchanged with a universal LLC Sublayer, different channel access techniques can be used, thereby increasing the flexibility of the Data Link Layer operation.

2.1.1 Layer System Management

The Layer System Management (LSM) provides an interface mechanism between non-adjacent layers, initializing and maintaining the peer-to-peer protocol of each of the layers or sublayers. In concept, it is adjacent to each of the layers or sublayers, and performs various network administrative functions such as reading and setting parameter values in different sublayers and resetting Layer entity to a known state. It also notifies different layers/sublayers of significant events in the LSM or in the other layers/sublayers of the node [1].

2.1.2 Physical Layer

The Physical Layer provides the direct physical connection to the communication medium for transfer of data. It provides the characteristics to activate, maintain and deactivate the physical links passing the stream of communication symbols. The Physical Layer exchanges symbols with the Data Link Layer, encoding and decoding the

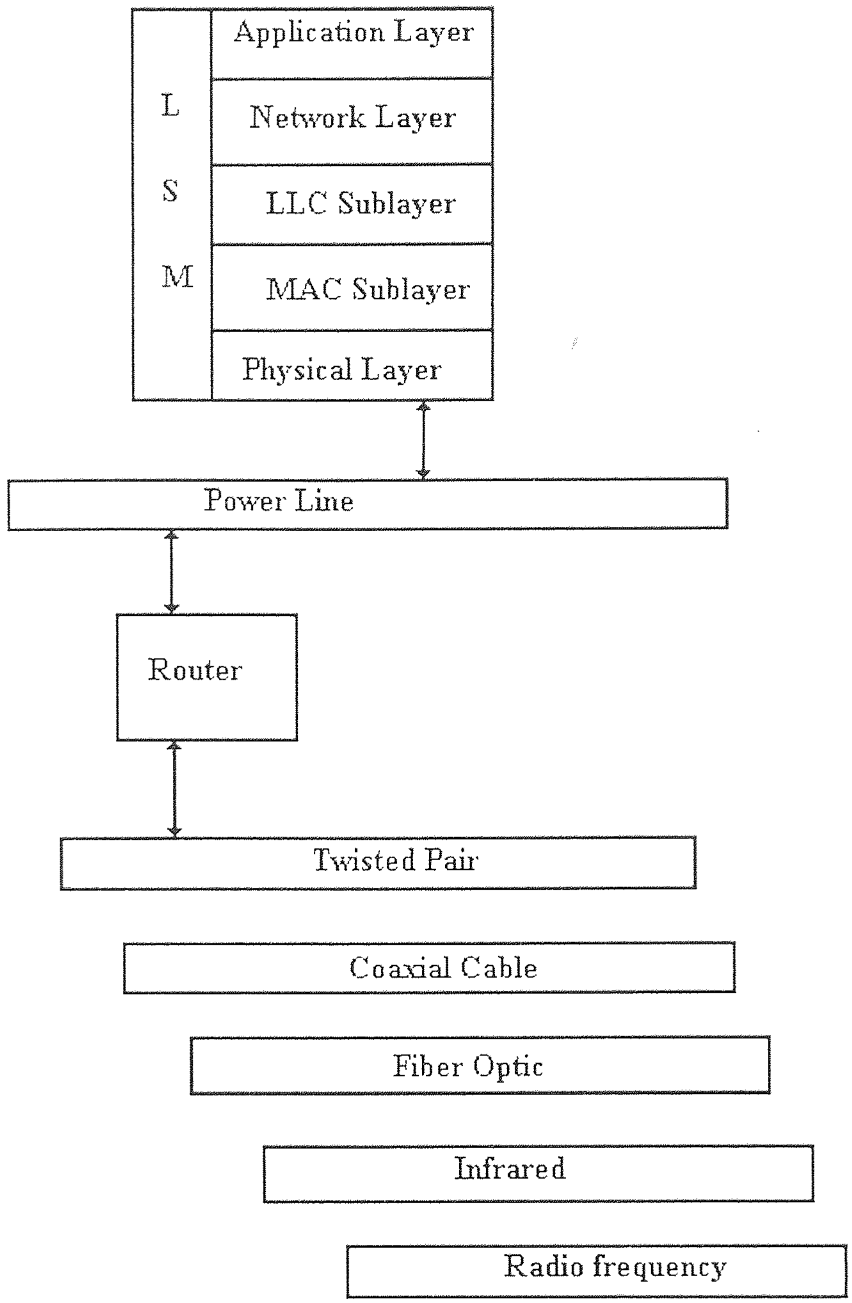


Fig. 2.1 CEBus Architecture

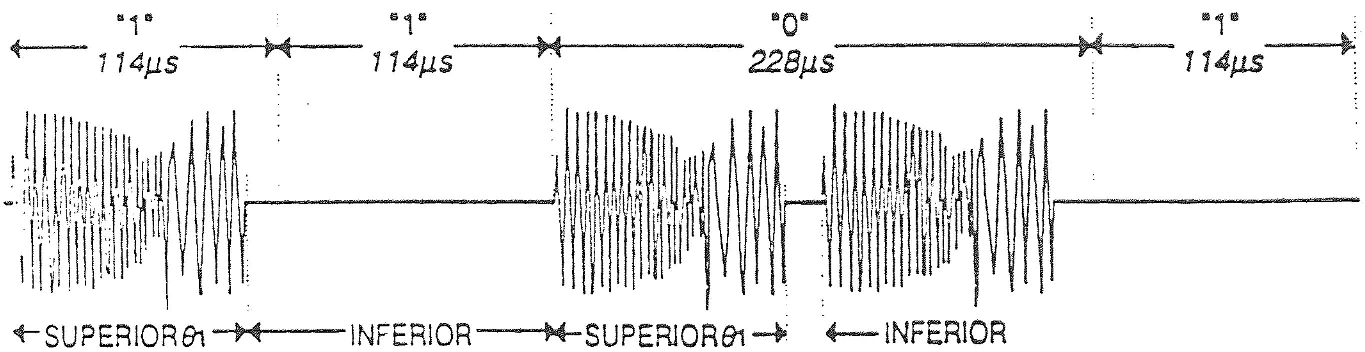
symbols to and from the medium states. The states required to represent the symbols are generated on the medium by the Physical Layer.

The signal encoding for PL control channel will be Non Return to Zero (NRZ), Pulse Width Encoding using the symbols "1", "0", "EOF", "EOP". EOF(End Of Field) denotes the end of a packet field while EOP (End Of Packet) serves to terminate the checksum field and delimit message packets. These symbols are encoded using a swept frequency carrier coupled to the power line.

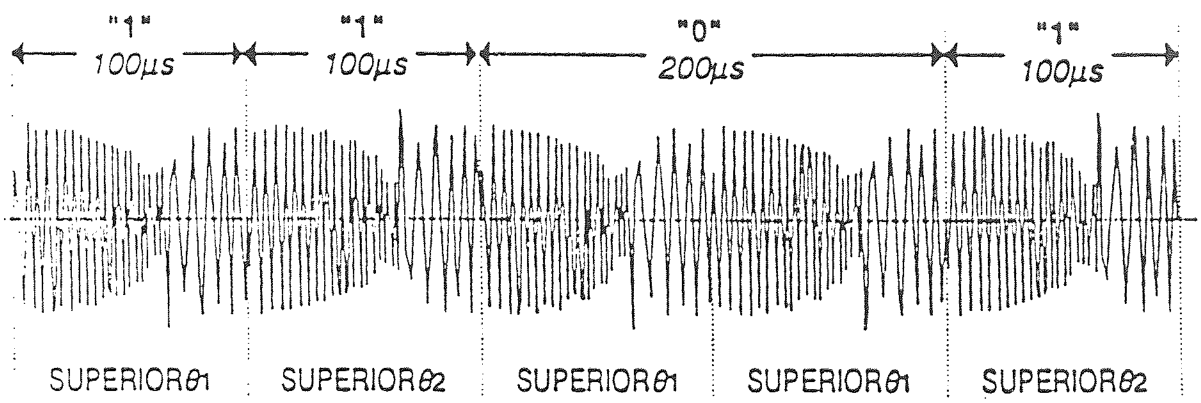
The carrier will consist of a sinusoidal waveform that is swept linearly from 203 KHz to 400 KHz for 19 cycles, back to 100 KHz in one cycle, then back to 203 KHz in 5 cycles during a 100μsec interval. This carrier sweep period represents the shortest symbol time, called the Unit Symbol Time. During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

On the PL medium, the encoding of the symbols will be performed using the SUPERIOR and INFERIOR states. During the preamble of the CEBus packet, the presence of the carrier on the PL will represent the SUPERIOR state, and the absence of the carrier will represent an INFERIOR state. During the non-preamble part of the message, the frequency swept carrier is continually transmitted and encodes the different symbols by reversing the phase of the carrier sweep at the beginning of each new sweep. This can be seen clearly in Fig. 2.2(b). If SUPERIORθ1 and SUPERIORθ2 are used to denote the different phase versions of the SUPERIOR state, then they are opposite in phase, regardless of the value of the phase. In the Figure SUPERIORθ1 will be used to denote the phase of the carrier transmitted during the preamble.

The time to transmit the shortest data symbol, "1" or ONE, on the PL network is defined as the Unit Symbol Time (UST). Since 1 UST is equivalent to 100μsec, the data rate of the Power Line is 10,000 ONE bits per second ± 0.1% over the operating



(a)



(b)

Fig. 2.2 (a) PL control channel preamble encoding example, and (b) non-preamble encoding example temperature and humidity range of the PL devices. The following table displays the four CEBUS encoded symbols and their transmission times.

To make detection of the preamble easier, the unit symbol time is longer during the preamble than the message portion of the packet.(Fig. 2.2(a)) While the unit symbol time is longer(114μs vs. 100μs), the SUPERIORθ1 carrier sweep remains constant throughout the packet. Hence, during the preamble, the time the medium is in the INFERIOR state varies, occupying the time between SUPERIORθ1 carrier sweeps.

Table 2.1 Symbol Duration for PL

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

A Twisted Pair(TP) network consists of one or more twisted pair cables attached at a TP distribution device and ending at a network tap. The cable consists of four twisted pairs referred to as TP0 through TP3. TP0 provides control channel, DC power, and data channels to attached devices. TP1-3 provide additional data channel resources to the devices in the network. Coupling between TP networks and/or other CEBus media can be accomplished by coupling between TP0 control channel and other CEBus media control channel across a router. An optional data bridge could be used for coupling the data channels between TP and other CEBus media[10].

The control channel for Twisted Pair occupies the bandwidth from 2 to 64 KHz. This channel is used to exchange CEBus protocol information and to transport device control information. No other use of this channel is permitted.

The TP control channel uses a differential bipolar signal employing three signal levels to encode the CEBus symbols "1", "0", "EOF", and "EOP". The three signal levels are used to represent the two media states of SUPERIOR and INFERIOR. A SUPERIOR state is represented by the presence of either a positive or negative differential voltage swing about the average DC supply voltage present on the TP medium. The absence of any voltage swing, or in other words zero voltage swing with respect to the average DC supply voltage, will represent an INFERIOR state.

The encoding of the symbols is strictly related to the time the INFERIOR or SUPERIOR state remains on the media, not whether the INFERIOR or SUPERIOR state is used[9]. Any symbol can be defined by either a SUPERIOR or INFERIOR state. The "1" symbol is represented by the shortest interval of the SUPERIOR or INFERIOR state, the "0" is twice the interval of "1", the "EOF" is three intervals, and the "EOP" is four intervals. (Fig. 2.3)

The signaling rate for TP control channel will be 10 K ONE bits per second $\pm$ 5% over the operating temperature and humidity range of the attached devices. This rate gives the following symbol times for the four CEBus encoded symbols.

Table 2.2 Symbol times for TP

ONE	100 μs ± 5 μs
ZERO	200 μs ± 5 μs
EOF	300 μs ± 5 μs
EOP	400 μs ± 5 μs

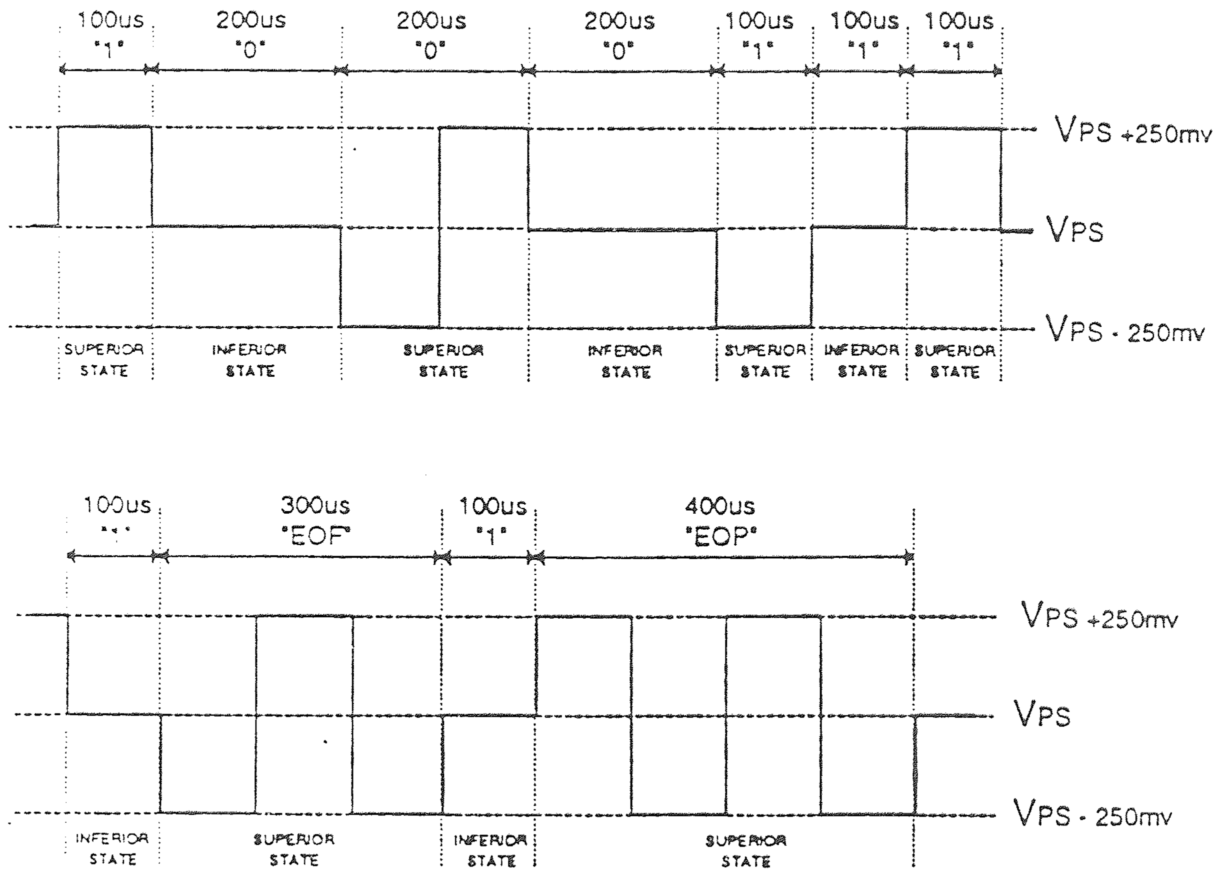


Fig.2.3 Bipolar Encoding example for TP control channel

2.1.3 Medium Access Control Sublayer

The Medium Access Control (MAC) Sublayer performs the function of transmitting and receiving Protocol Data Units from the Logical Link Control Sublayer (LPDU's). Only unacknowledged connectionless service is offered. The final form of the data for transmission is assembled in the MAC Sublayer. The MAC Sublayer incorporates an LPDU into a Medium Access Control PDU, or MPDU, before transmission. Then the MPDU is transmitted through the Physical Layer after obeying the channel access protocol. The channel access protocol used in CEBus is Carrier Sense Multiple Access with Contention Detection and Contention Resolution (CSMA/CDCR).

When the MAC Sublayer receives an MPDU from the Physical Layer, the MPDU Header is stripped away by the MAC Sublayer, and the remaining portion(LPDU) is passed up to the Logical Link Control Sublayer. Validation of the received frames is also performed through the use of the frame check sequence.

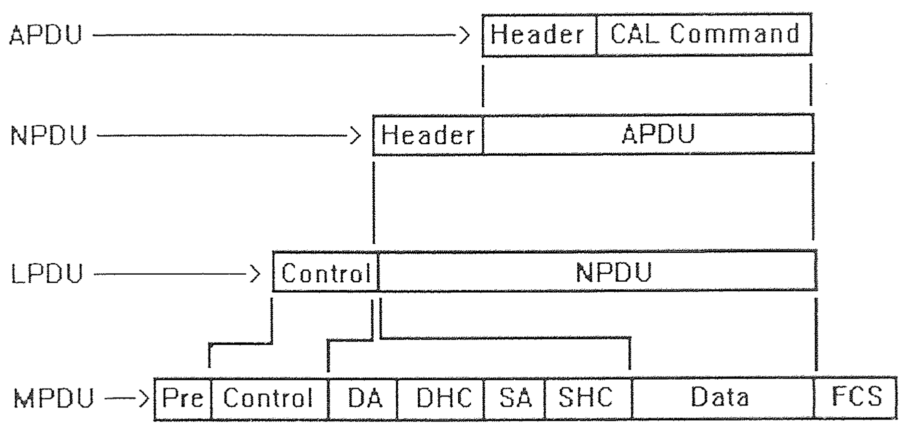


Fig. 2.4 CEBus frame generation

The MAC frame is formulated as it passes through each of the layers of the CEBus model. The user interface defines the CAL commands and header that make up the Application Layer PDU(APDU). This APDU is passed down to the CEBus Network Layer where routing and flow control information is appended. Then the new NPDU passes through the Logical Link Control Sublayer and Medium Access Sublayer, gaining control and addressing information. These processes will be explained in more detail as each CEBus Layer is discussed in detail in the following sections.

The normal MAC frame consists of the Preamble field (PRE), Control field (Control), Destination Address field (DA), Destination House Code field (DHC), Source Address field (SA), Source House Code field (SHC), information field and the Frame

Check Sequence (FCS) field[13]. The contents of each field are a sequence of 0(ZERO) and 1(ONE) symbols. All fields except the FCS field are terminated with an EOF symbol. The FCS field is terminated with the EOP symbol.

PRE	CONTROL	DA	DHC	SA	SHC	INFO	FCS	
1	1	2	2	2	2	32	1	bytes

Fig. 2.5 Normal MAC Frame Format

The frame format for the IACK consists of fewer fields. The "Acknowledge" frame has only a Preamble field, Control field, Information field and a Frame Check Sequence field. The information field can be up to 2 bytes long. This field may only contain data relevant to the Data Link Layer(MAC and LLC Sublayers), such as remaining Data Link Layer buffer space. Any information about the higher layers is not allowed. Normally, this field will be empty (Null).

PRE	CONTROL	INFO	FCS	
1	1	2	1	bytes

Fig. 2.6 IACK Frame Format

2.1.4 Logical Link Control (LLC) Sublayer

The LLC Sublayer provides the Network Layer with the facility to transmit its packets onto the network and to receive incoming packets from the network. CEBus Logical Link Control Sublayer service may be one of two types. They are "unacknowledged connectionless service" or "acknowledged connectionless service".

(a) Unacknowledged Connectionless Service

Unacknowledged connectionless service accommodates an exchange of data between peer LLC Sublayers without the use of an acknowledgment mechanism. Thus, the success or failure of a transmission cannot be verified. The term "connectionless" implies that no connection, or virtual circuit, is set up to handle the transfer between the LLC Sublayers. The peer LLC will be either the destination node, Brouter, or Router on the local medium. A transmission can be sent to a specific address, multicast to a group of addresses, or broadcast to all addresses in a particular home system.

(b) Acknowledged Connectionless Service

For Acknowledged connectionless service, the LLC Sublayer's Immediate Acknowledge(IACK) facility is used to improve the chances of successful message delivery between peer LLC Sublayers. Acknowledged connectionless service provides IACKs on a hop-by-hop basis and not end-to-end. That is, a transmission to a node in the same medium(Local Transmission) is acknowledged by the destination node. But a Non-Local transmission across a router is acknowledged by the router, and not the destination node. Multicast and broadcast transmissions are prohibited in order to prevent collisions between simultaneous, multiple acknowledgments.

By dividing the CEBus Data Link Layer into two sublayers, a certain degree of modularity is achieved. Since different media types require different channel access methods, different MAC Sublayers could be added without changing the LLC Sublayer. Thus, the medium access technique is transparent to a universal Logical Link Control Sublayer.

2.1.5 Network Layer

The job of the CEBus Network Layer is to dynamically maintain a tree structure in the network topology, correctly route packets between dissimilar media, prevent duplicate packets originating from IR/RF, and provide flow control functions for the Application Layer's segmented packet service. The Network Layer is capable of providing either unacknowledged connectionless service or acknowledged connectionless service.

Design criteria for topology and routing are derived from the nature of the CEBus network, which is the operation of consumer devices. Rules for interconnecting various media must ensure flexibility in installation. Routing must be carried out to minimize the delay between user command and device response.

The Network Layer Protocol Data Unit (NPDU) is the unit of information which is generated in the Network Layer in a transmitting node and expected by the Network Layer in a receiving node. The NPDU is exchanged between peer Network Layers in the network nodes or between nodes and routers.

The Network Layer creates the NPDU from an APDU and some additional control parameters passed down from the Application Layer in an N_DATA_REQUEST service primitive. Once the NPDU is formed it is passed down to the Data Link Layer along with additional control parameters in an LL_DATA_REQUEST or an LL_ACK_DATA _REQUEST. Once in the Data Link Layer, these pieces of information are incorporated into a frame containing control information, addresses and error detection data. The final product is the MAC Layer PDU, or MPDU, which is passed down to the Physical Layer for transmission. PDUs created by a higher layer have to be handled as an indivisible entity by the lower layers.

A received MAC frame is stripped of the MPDU Header and passed up to the LLC Layer where the control field is taken out. The remaining portion, or NPDU, is passed up to the Network Layer where its contents are recognized. If the receiving node is a Router or Brouter, the NPDU is used to make routing decisions and to generate a frame onto the next medium. If the receiving Network Layer belongs to a network node, then the NPDU is disassembled and passed up to the Application Layer.

2.1.6 Application Layer

The CEBus Application Layer is the highest in the CEBus node. It provides the user interface to the CEBus network and supports a Common Application Language (CAL) through which manufacturers may communicate with other devices in the network[8]. The Application Layer is functionally divided into four elements: the user element, the CAL element, the message element, and the association control element.

The user element is the interface to the process which controls the CEBus devices. This process, named the application process, performs actions requests by remote devices, such as TURN ON or TURN OFF, and generates requests to other devices on the network. The user element invokes the services of the CAL to formulate CAL commands and relay requests from the application process to remote devices on the network. Incoming CAL commands are also processed and the required task is relayed to the application process by the CAL element. The CAL element is also responsible for resource allocation and segmentation. Long messages are divided into shorter segments to fit into one CEBus frame.

The CAL element subscribes to the services of the message transfer element to relay the CAL commands to their destinations. The message transfer element calls on the services of the Network Layer to accomplish this task.

The association control element allows the association of two application processes. This part of the service has not yet been specified[21]. The information exchange between peer Application Layers is accomplished using Application Layer Protocol Data Units(APDUs). An APDU consists of the CAL command and a header appended by the message transfer element.

2.1.7 CEBus Router

The architecture of the CEBus routers is layered in the same manner as CEBus nodes. However, a router has two Medium Access Control (MAC) Sublayers and two Logical Link Control (LLC) Sublayers - a set for each medium connected to the router. A single Network Layer connects the two "halves" of the router. Layer System Management is adjacent to each of the layers. It initializes and maintains each layer's peer-to-peer protocol, provides an interface between non-adjacent layers, and manages issues pertaining to the system, or network as a whole, such as maintaining a correct network topology.

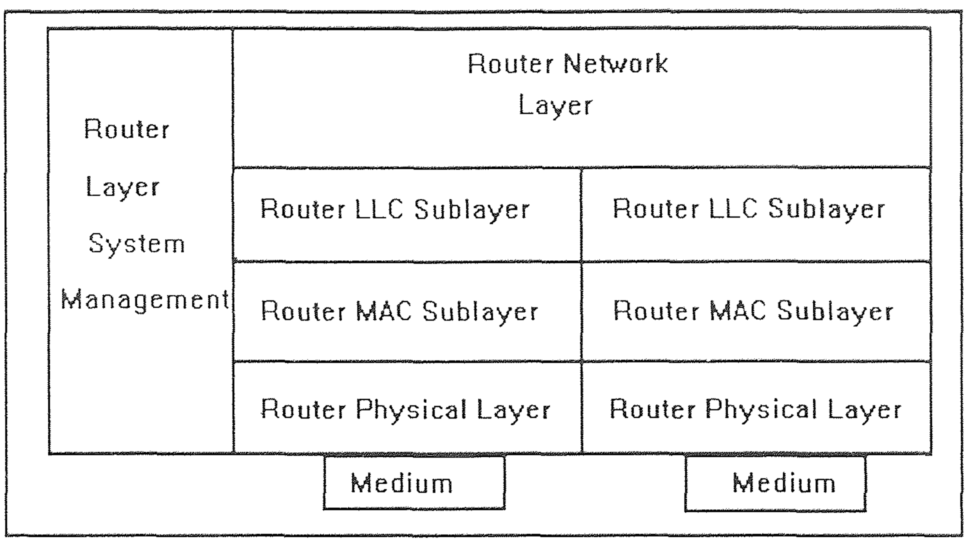


Fig. 2.7 Layered Architecture for CEBus Routers

CEBus routers form the connection between different wired media in the network. In the OSI model, a router is considered a Network Layer device. This implies that a router executes peer to peer communications with other devices at all layers upto the Network Layer. A router operates at a higher protocol layer than a repeater, which is a Physical Layer device, or a bridge, which is a Data Link Layer device. A router connects network segments which may communicate using different Data Link Layer protocols but the same Network layer protocol. Routers forward packets from one medium to another if doing so moves the packet closer to its destination.

A router must receive packets from one medium, buffer the packets, and decide whether or not to forward each packet onto the next medium, based on a routing algorithm and several other criteria. The routing algorithms used in a CEBus network are Flood Routing and Directory Routing[5]. The effect of Flood Routing is to get the packet onto all allowed media. If all media are permitted, the packet will reach all parts of the network. Loops in the network topology and the resulting duplicate packets are prevented by the network topology protocol. Directory Routing uses the Directory Routing Table(in the Router Network Layer) to determine if the Destination Address can be reached by forwarding the packet onto an adjacent medium.

Each router should also communicate with the other routers to maintain the network topology in a tree structure. The tree structure is necessary to prevent loops, which would generate redundant traffic. To accomplish this task, the topology protocol disables the forwarding function of certain routers.

The danger of having physical loops in the network is that there could be packets circling endlessly inside the network, causing duplicate packets to be received by a node. Duplicate packets may not be a problem in some cases like turning on a light, but could be a major problem in the case of turning up the volume on a stereo. One solution to this problem is to have intelligent nodes which distinguish every packet from every other packet and only processes the first instance of a packet. But this feature adds greatly to the complexity of the nodes, which being the most common element of the network, should remain as inexpensive as possible[16].

The Physical Layers which may be part of a router are Power Line (PL), Twisted Pair (TP), Coaxial Cable (CX), and Fiber Optic (FO). These Physical Layers are identical to the corresponding Layers for nodes. Infrared (IR) and Radio Frequency (RF) media are not allowed for routers. These media are restricted to be the first and/or last media in a path which spans several media[1]. IR and RF may not be used to route data traffic between wired media. To connect IR and RF to the wired media, special devices called CEBus "Brouters" are used[15]. A Brouter is a combination of a forwarding device operating at the Data Link Layer (Bridge) and a Network Layer forwarding function (Router). Brouters operate in a manner which accommodates the broadcast nature of IR and RF.

2.2 CHANNEL ACCESS PROTOCOL

Since multiple nodes are connected to an individual channel, it's probable that several nodes might want to transmit at the same time. When such conflicting transmissions occur, the conflicting nodes are said to be in a state of "contention". To ensure optimum channel conditions and increase the probability of successful transmission, the following steps are taken:

Avoid contention,

If contention occurs, resolve in favor of only one node.

Therefore, before a node may transmit a frame it must follow a channel access method designed to minimize the probability of simultaneous transmissions. The following four steps form the channel access method for CEBus.

1. Deference to other channel traffic (SUPERIOR State Deference)
2. Prioritization of channel access
3. "Round-robin" queueing to ensure equal access within a priority level
4. Randomization of start time delay interval within each priority and queueing state

2.2.1 SUPERIOR State Deference

The Physical Layer of each node constantly monitors the channel for "activity"(either noise or packet transmissions from other nodes). If the Physical Layer detects a SUPERIOR state on the medium, it sends a PH_CC_STATUS.indication (CHANNEL_ACTIVE) service primitive, causing the Data Link Layer to enter its receive mode. If the Data Link Layer has a frame to transmit, it will "defer" its transmission until the Physical Layer passes up an EOP symbol, allowing the Data Link Layer to exit its receive mode[1].

Following the EOP symbol of a passing frame, all nodes must remain quiet for a minimum of 10 USTs (Unit Symbol Times). This mandatory channel quiet time allows an immediate acknowledgment (IACK) or a retransmission to be sent without conflict for the channel. The IACK and retransmission mechanism will be explained in detail in the following sections.

If the channel remains quiet throughout the 10 USTs, nodes may begin competing for channel access. However, if the node detects channel activity before it begins transmission, the Data Link Layer will again defer its transmission until the channel is quiet. Any node that hears another node will not attempt to transmit.

2.2.2 Prioritization

Each CEBus message is associated with a priority level which is passed down from the Network Layer and denotes its relative level of importance. The purpose of priority levels is to delay the transmission of a message for an additional period of time, such that lower priority messages do not have the opportunity to interfere with higher priority messages, for control of the channel.

The three priority levels are named HIGH, STANDARD and DEFERRED. A HIGH priority message will be eligible for transmission immediately after the minimum channel access delay. A STANDARD priority will impose 4 Unit Symbol Times of additional delay to a message transmission, and a DEFERRED message will be delayed for an additional 8 Unit Symbol Times. This scheme allows nodes with higher priority frames to seize the channel before nodes with lower priority frames. Since the lower priority nodes will always hear the higher priority nodes and defer to them, contention is minimized by prioritization.

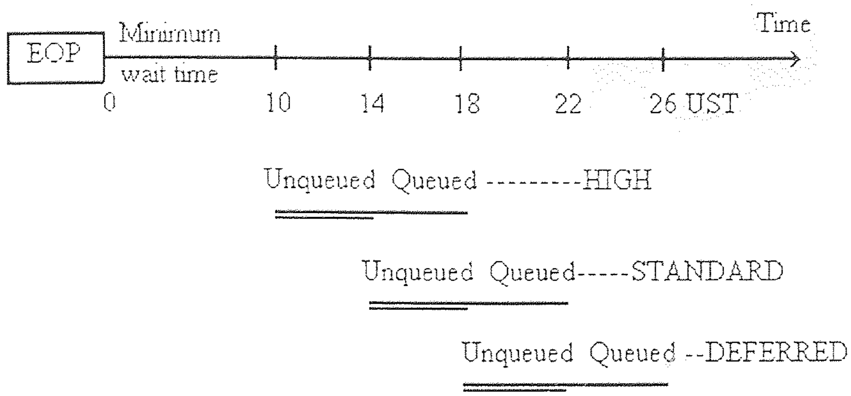
2.2.3 "Round-robin" queueing

Although the above two methods reduce the probability for conflict over use of the channel, contention may still arise between nodes at the same priority level. To ensure that contending nodes within each priority level have an equal opportunity for channel access, a "round-robin queueing" method is used. A transmitting node is considered to be in either a QUEUED or an UNQUEUED state. A node which has already completed a successful transmission is placed in the QUEUED state.(Transmission of an IACK does not count.) This state introduces an additional delay of 4 Unit Symbol Times into the node's channel access delay. A node which has not yet successfully transmitted a packet is in an UNQUEUED state. For an UNQUEUED node, no additional delay is added[4]. The effect of this queueing process is to remove the successful nodes from contention with those which have not yet been able to get a message through.

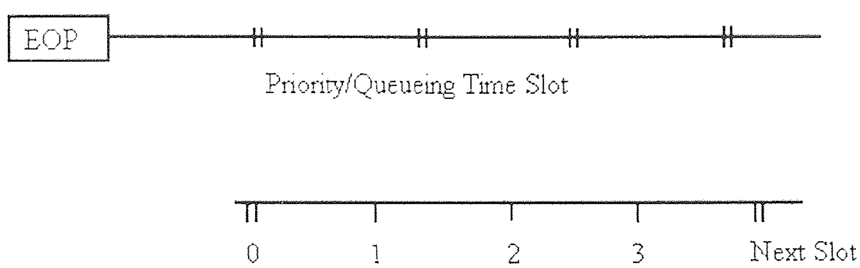
A node will become UNQUEUED if it has made an unsuccessful transmission attempt during its priority/queueing time slot. A node will also become UNQUEUED if it has no frame to send and counts quiet time on the channel for the maximum channel access time (26 UST).

2.2.4 Randomization

Because more than one node may be in the same priority level and queueing state, the probability of contention still exists. An additional measure to reduce this probability is to have each node randomize its transmission start time into four distinct periods within



(a)



(b)

Fig. 2.8 (a) Priority queuing, (b) Random access time its priority and queue.(Fig. 2.8b) A random delay of either 0, 1, 2, or 3 Unit Symbol Times is added to each transmitting node's channel access delay. This ensures that nodes in the same priority and queueing state will have different start times for transmission. Therefore, the probability of contention is further reduced.

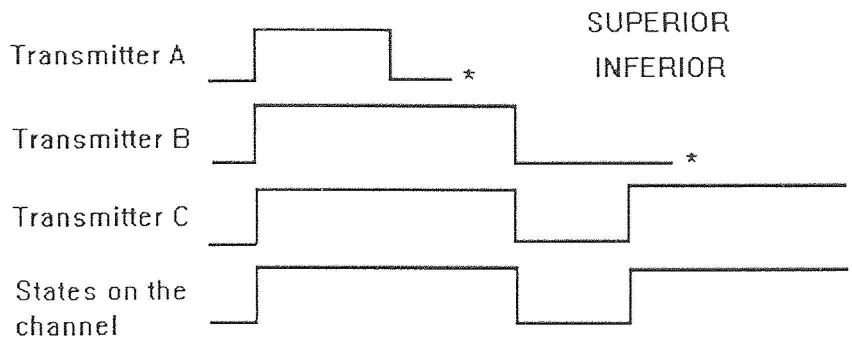
2.3 Contention Detection and Resolution

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. By definition, a SUPERIOR state on the medium will dominate any attempt to transmit an INFERIOR state. As a result of this property, 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. The Physical Layer is responsible for actually switching the state of the medium to encode symbols from the Data Link Layer, and also for sensing the current state of the medium. Therefore, contention detection is achieved by the Physical Layer.

Contention will normally occur at the beginning of the transmission. Therefore, the Preamble, positioned at the beginning of the frame, serves to provide a contending 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].

In CEBus terminology, 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 winning node is able to transmit free of contention. Contention should never result in lost information. 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(contained in the FCS field), delivery of the frame will be successful.



* Transmitter detects contention and stops

Fig. 2.9 Resolving Contention with SUPERIOR and INFERIOR states

A collision refers to overlapping transmissions after the Preamble. Although conflict over the channel during any part of the frame after the end of 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.

2.4 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.

2.4.1 Immediate Acknowledgment (IACK)

The Immediate Acknowledgment mechanism enables the transmitting node to determine the success or failure of its message 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. This method also associates the IACK with its originating frame without the use of extra information, such as sequence numbers.

An originating node, which is waiting for an acknowledgment, expects to hear the beginning of the IACK Preamble within 6 USTs of the end of the EOP symbol of its frame. As the originating node receives the IACK frame, the incoming fields are parsed to ensure that a fragment is not received. The checksum is used to determine the validity of the contents of the received frame. When the IACK is correctly received, its Preamble and FCS field are discarded, and its Control field is processed within the Data Link Layer. In CEBus, three features distinguish an IACK from an originating frame. They are its time of arrival, the way in which the frame parses(the number of EOF fields), and the Control field(Packet Type) [1].

Contention during IACK transmission constitutes a failure of the Data Link Layer protocol and will cause the receiving node to abort the IACK. Also, received noise during the time between the originating frame and the IACK will prevent the IACK from ever beginning.

If a receiving node cannot accommodate an acknowledged service frame, a Failure Packet is transmitted, rather than an IACK. The Failure Packet is an IACK frame with a Packet Type of Failure in the Control field. Normally, Failure packets will be sent by a router whose forwarding buffer is full. Reception of a Failure Packet constitutes a "negative acknowledgment".

2.4.2 Retransmission

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

If an IACK is not correctly received at the originating node, (i.e., fragmented, or checksum indicates errors in transmission, or if it is rejected during reception due to bit errors), the originating node will begin a retransmission within 7 USTs after the end of the faulty IACK. Noise received after the end of the originating frame is treated in the same manner. An EOP symbol is decoded at the end of the noise, and the retransmission will begin within 7 USTs.

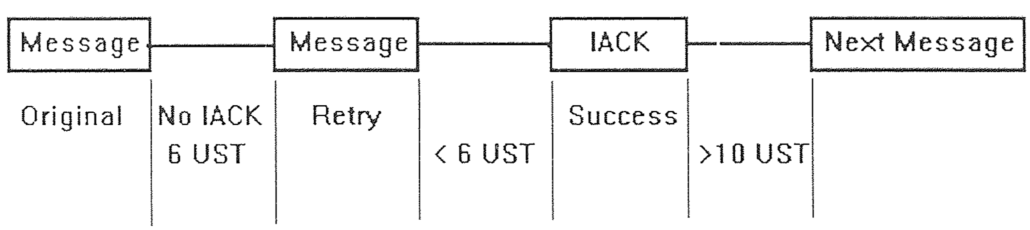


Fig. 2.10 Immediate Retry Timing

CEBus allows only one retransmission by the Data Link Layer. Its purpose is to increase the probability of successful transmission. It is assumed that the initial non-delivery was caused by noise on the channel. Therefore, an immediate retry should not be in contention with anyone and should be successful.

A received retransmission can be due to one of two things. It could be that the initial transmission was received correctly, but the IACK sent was faulty. Then the retransmission is a duplicate of the previous packet. Then it has to be discarded at the receiving node. A duplicate packet can be identified by its arrival time. Retries will begin during the seventh unit symbol time, and new frames may not begin until after the tenth unit symbol time. The tenth unit symbol time of the minimum wait time helps the receiving node handle retries by separating the time window for retries from the time for new frames. Although a duplicate is rejected, it must be acknowledged with a second IACK.

The second case of handling a retransmission occurs when the first transmission was not received correctly and an IACK was never sent. When the retry, which is not a duplicate arrives, it is simply accepted and acknowledged.

CHAPTER 3

SIMULATION MODEL

3.1 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 the C-Library functions provided by LANSF[19]. 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]. 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. The CEBus system and protocol model requires a C program using LANSF's C-Library functions while the network configuration does not require a C program. It is specified in a data file which is interpreted by the system and protocol created by the user. 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 processes executed by stations(nodes). It also contains two other subroutines that must be included with the protocol module. The first, *in_protocol*, initializes the simulator and reads the values of the global protocol-specific parameters. The second, *out_protocol*, 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.

Table 3.1 Service Primitives

Transmitter	Receiver
N_DATA.request	N_DATA.indication
L_DATA.request	L_DATA.indication
M_DATA.request	M_DATA.indication
L_ACK_DATA.request	L_ACK_DATA.indication

A station transmitter's function can be explained by the service primitives (Table 3.1) which provide the interlayer communications as described in the EIA Standards[1]. Lets consider a message fetched into the station buffer with its length defined in the input data file. The Application Layer sends a signal (N_DATA.request) to the Network Layer which in turn adds an NPDU to the packet and passes it to the LLC Sublayer with a L_DATA.request (Unacknowledged service) or a L_ACK_DATA.request (Acknowledged service). After processing, an LPDU is passed down to the MAC Sublayer with a M_DATA.request. While passing the packet between the different layers, only pointers to data are passed through the layer rather than copying the data several times. The MAC frame is transmitted after obeying the channel access protocol.

After a successful transmission, all the nodes (stations) wait for an additional delay of 10 UST before accessing the channel. After a packet is transmitted, the MAC Sublayer sends an M_DATA.confirm to the LLC Sublayer, to report a successful transmission. However, this is not an indication of successful delivery. This is the case for unacknowledged service.

For acknowledged service, a M_DATA.confirm is not sent until an acknowledgment is received. An IACK packet is sent from the receiving to the originating station within 2 USTs of the end of the EOP symbol of the originating frame. Since the originating station still owns the channel, there is no contention during IACK transmission.

At the receiver, the MAC Sublayer sends a M_DATA.indication and passes the packet to the LLC Sublayer. The LLC strips the header information and passes the packet to the layer above by sending a L_DATA.indication or L_ACK_DATA.indication depending on the type of service.

3.2 Network Model and Traffic Patterns

The Power Line (PL) and Twisted Pair (TP) physical media for CEBus both operate at a data rate of 10 Kb/s. In the simulation experiments, this data rate of 10 Kb/s has been utilized for both media. In general, local area networks using wire pairs may operate up to a couple of Mb/s. The standard operating rate for coaxial cable is in the region of 10 Mb/s. For optical fiber, the data rate is several hundred Mb/s and rising. If lasers and single mode fibers are used, the range of bandwidth is much higher and is in the Gb/s range. The low bandwidth in the home environment could lead to larger delays and high normalized throughputs, when compared to high data rate channels. However, the channel throughput turns out to be substantial. This high throughput is due to relatively larger packet sizes with respect to the network capacity[17].

The assumptions used to develop the model are as follows:

- Independent Poisson arrival process at each node with rate λ packets/sec;
- The packet lengths are exponentially distributed with mean L bits;
- The end-to-end propagation delay around the CEBus network is ignored, since it is much smaller than the packet transmission time[3];
- The bit rate on the channel is c b/s;
- There are M nodes on the network.

The total number of nodes, M, utilized in the simulation is 18 plus 2 for the router. There are 9 nodes on each medium. Three nodes each for HIGH, STANDARD, and DEFERRED priority classes. All the generated messages are symmetric for each priority class, thus each of the 18 nodes employ the same rates(e.g. same arrival time) to get access to the medium. The normalized offered load, G, is calculated using the following relationships.

$$G_{PL} = \frac{\lambda_{PL \to PL} L_p + \lambda_{PL \to TP} L_p + \lambda_{PL \leftarrow TP} L_p}{c} \tag{3.1}$$

$$G_{TP} = \frac{\lambda_{TP \to TP} L_p + \lambda_{TP \to PL} L_p + \lambda_{TP \leftarrow PL} L_p}{c} \tag{3.2}$$

$$G_{PL} = G_{TP} \tag{3.3}$$

The value c is the channel capacity or data rate in bits/sec. $Lp = L_h = L_s = L_d$ is the same packet length in bits, while $\lambda_{PL \to PL}$ denotes the arrival rate from PL to itself.

Also $\lambda_{PL \to TP}$ indicates the arrival rate from PL to TP, and $\lambda_{PL \leftarrow TP}$ indicates the same in the opposite direction. These groups have the same arrival rate when the traffic generated is symmetric. Then $\lambda_{PL \to PL} = \lambda_{PL \to TP} = \lambda_{PL \leftarrow TP} = \lambda_{xy}$. Furthermore, each direction group is composed of the three priority classes such that $\lambda_{xy} = \lambda_h + \lambda_s + \lambda_d$, where λ_h, λ_s, λ_d represent the arrival rates for the HIGH, STANDARD and DEFERRED priorities, respectively.

In this simulation study packet lengths of 100 bits, 300 bits, and 600 bits have been considered. The 600 bit packet is around the maximum allowed packet size and the 100 bit packet is around the minimum packet size as specified in the CEBus standard. Therefore, no segmentation is performed before transmission. However, for larger messages some kind of segmentation will be required to break the message into several packets prior to transmission.

A 24 bit IACK frame will be used for acknowledgment, consistent with the study by Pan and Manikopoulos [18], who investigated the acknowledgment process for PL CEBus. Furthermore, the following studies involve equal message and packet length to reveal the queueing time effect which was the approach used in the literature[12,20]. All the simulations were run for a total of 5,000 messages.

3.3 Performance Measures and Definitions

The data and framing bits that can be sent in a single block constitute a packet. A message may consist of one or more packets. The traffic generator in LANSF generates the packets and places them in station's queues. Once a packet is in a queue it waits until it reaches the top of the queue[14]. When the packet is on top of its queue it is ready to be transmitted. The time spent in the queue awaiting transmission is called the queueing 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: it is measured as the time elapsed from the moment a message is queued at the originating node(station) to the moment the entire message(all the packets in the message) is successfully received by a node[11]. Message delay includes the message queueing time.

- Packet Delay: it is defined as the time elapsed from the moment a packet becomes ready for transmission in the originating node to the moment the packet is successfully received by a node. It does not include queueing time[11].

- Channel Throughput: it is calculated as the ratio of the total number of information bits successfully transmitted through the channel to the simulation time. Packet headers and trailers do not count. This is also referred to as the effective throughput of a link, since it includes not only the bits that were successfully received on the link, but also the bits that were successfully relayed to another link, e.g. to the router.

- Message Throughput: it is measured as the ratio of the total number of bits received at the destination address to the number of bits generated at the source.

CHAPTER 4

ANALYSIS AND DISCUSSION OF SIMULATION RESULTS

4.1 CEBus Performance With and Without IACK: Case of 600 bits

(a) Message delay vs. Load

For the 600 bit message shown in Fig. A.1, the message delay for HIGH priority unacknowledged Local packets start to increase rapidly when the normalized load exceeds 2. For the STANDARD priority a similar trend is observed when the normalized load is greater than 0.85, and for DEFERRED priority it is around 0.6. In the acknowledged case the delay is higher than the unacknowledged case, for each of the corresponding priorities. Also drastic increases in delay are noticed at smaller values of normalized load for the acknowledged case. For example, the acknowledged Local packets in the HIGH, STANDARD and DEFERRED priorities begin their upward trend for loads of 1.8, 0.7, and 0.5 respectively.

Non-Local packets, or packets transmitted via the router to the other medium, also display similar tendencies, but at higher values of Message delay(Fig. A.2). For relatively small loads, the delay for Local transmissions is approximately 80 ms. However, for Non-Local traffic it is around 110 ms.

(b) Packet delay vs. Load

Packet delay for Local transmission only includes the channel access plus transmitting time, unlike Message delay which also includes the queueing time. Therefore, for HIGH priority packets, Packet delay remains small and bounded (Fig. A.3 & Fig. A.4), while Message delay becomes excessively large, for heavy traffic load.

For Non-Local packet transmissions the Packet delay is approximately equal to the Message delay (Fig. A.5 & Fig. A.6). This is due to the fact that after a message succeeds in reaching the router, it usually fails to access the channel on the other side immediately. So it has to wait in the router buffer and then try to access the channel again. Thus, most of the delay is due to the time spent in the router buffer.

(c) Message throughput vs. Load

In Fig. A.7, the relationship between Message throughput and normalized load is shown for a Local 600 bit packet, with and without acknowledgment. In Fig. A.8 the same is shown for a Non-Local packet. In heavy traffic conditions, a noticeable difference in Message throughputs is found between the Local and Non-Local traffic for all three priorities. Local traffic seems to have a better chance for successful delivery, than Non-Local traffic. For example, when the load is 1.5, the Message throughput for unacknowledged STANDARD priority is approximately 0.8 for Local traffic, while it is 0.5 for Non-Local (Fig. A.7).

Furthermore, when acknowledged and unacknowledged cases are compared, the Message throughput for acknowledged traffic is consistently on the lower side for all three priorities. This fact confirms the notion that the introduction of an IACK frame causes a reduction in effective throughput of the channel.

4.2 CEBus Performance With and Without IACK: Case of 300 bits

(a) Message delay vs. Load

In Fig. 4.1, the effect of traffic load on Message delay is illustrated for a 300 bit Local packet. As in the event of 600 bits, the delay for acknowledged case is greater than the unacknowledged case. The point at which the delay starts to increase rapidly is dependent on the priority class. For Local traffic, HIGH priority, the delay becomes excessively large

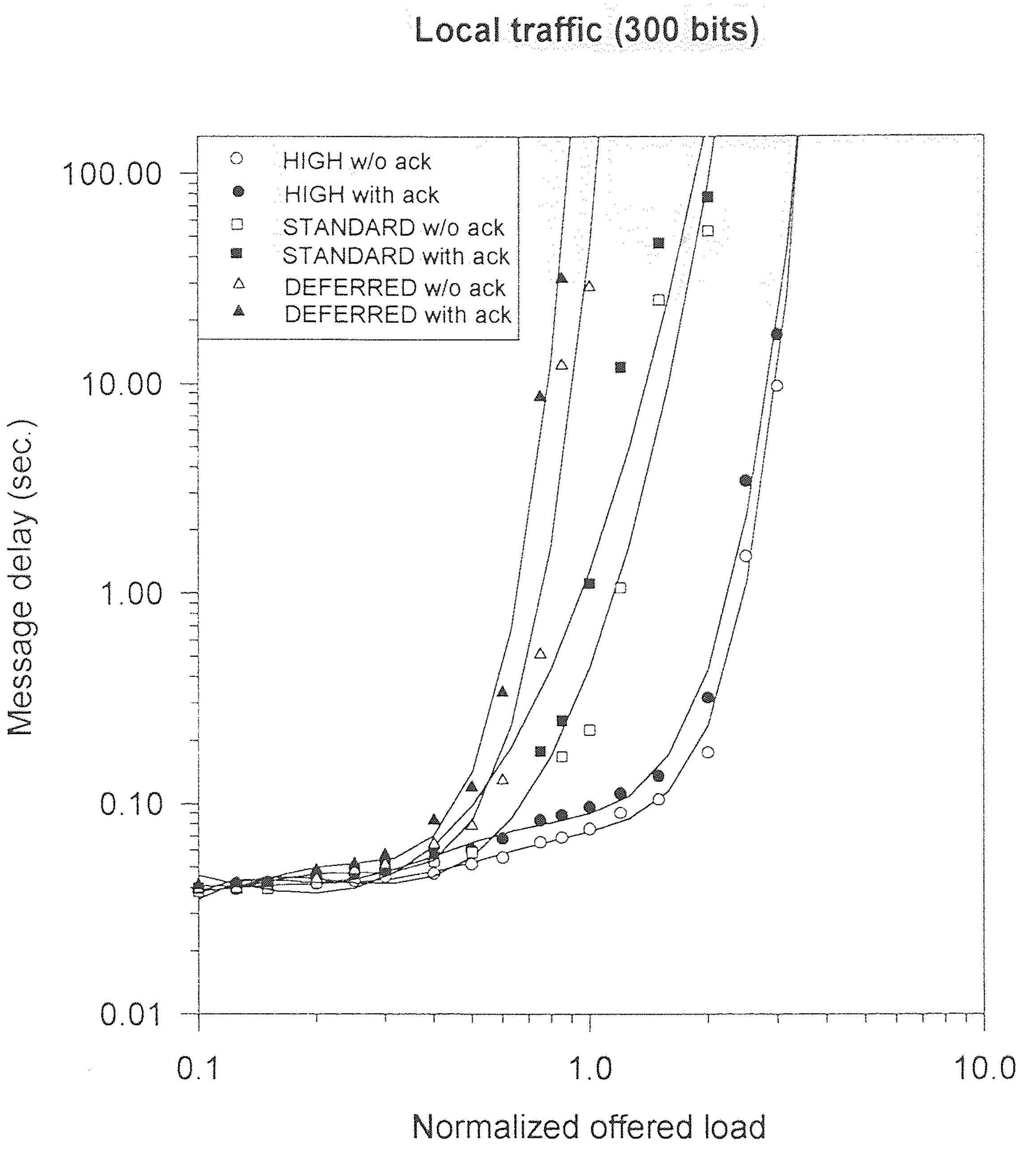


Fig. 4.1 Message delay vs. Normalized offered load for 300 bit Local packets, with and w/o IACK

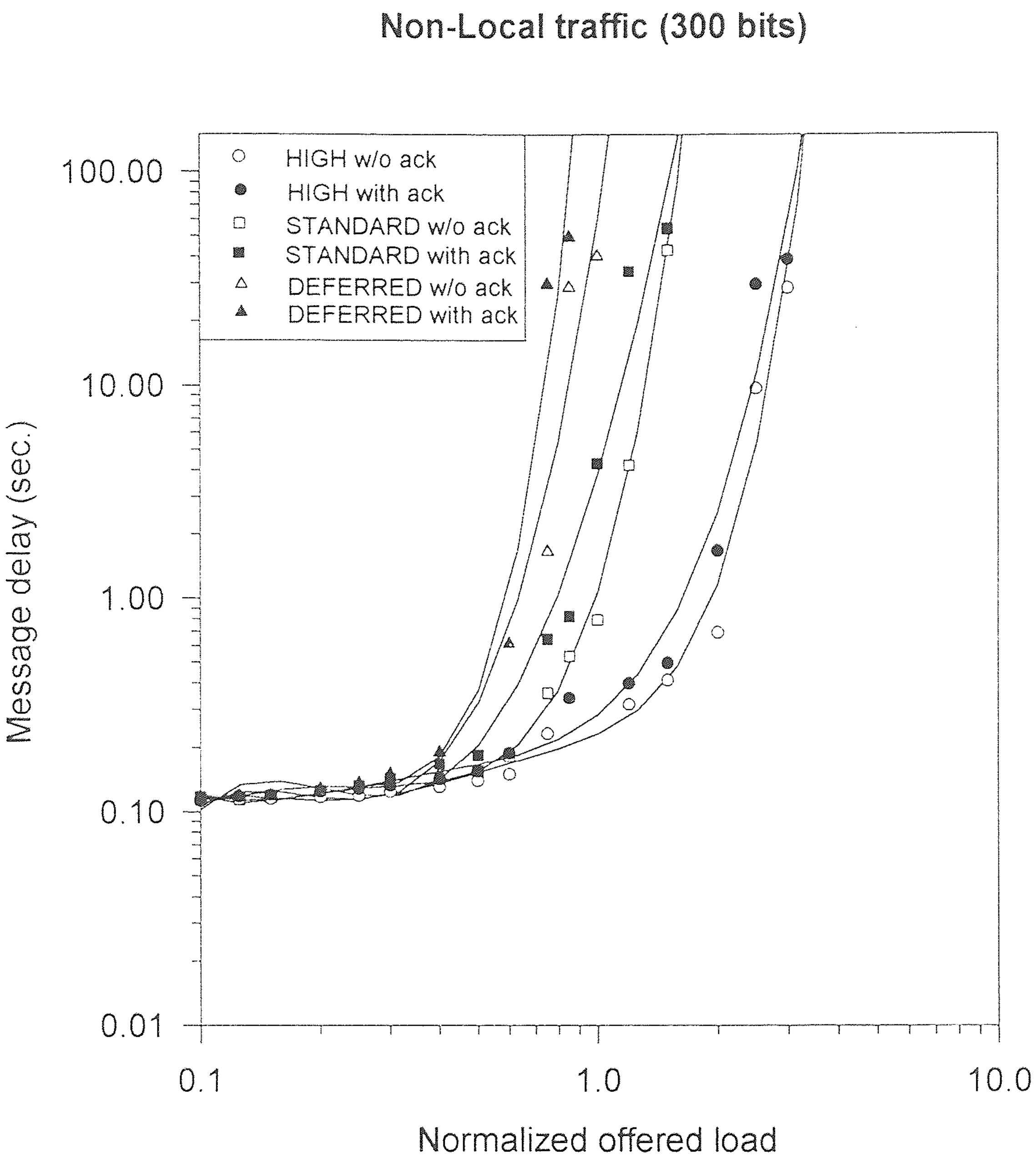


Fig. 4.2 Message delay vs. Normalized offered load for 300 bit Non-Local packets, with and w/o IACK

after the normalized load exceeds 2. Although the total normalized offered load is 2, only one third of the total traffic is due to HIGH priority packets.

At higher loads, it becomes increasingly difficult for lower priorities to get access to the channel. After the normalized load exceeds 2, only HIGH priority packets have any chance of getting through. Since contention is always among packets of the same priority, the possibility of collisions increases, thus increasing the Message delay.

For Non-Local traffic(Fig. 4.2), the Message delay is greater than the Local traffic. This is due to the extra time in the router buffer waiting to access the destination medium. The Message delay is bounded and small for light loads, while it becomes excessively large for heavy loads.

(b) Packet delay vs. Load

As in the case of 600 bits, the packet delay in bounded for HIGH priority packets. As observed in previous studies [12, 20], a special feature of Packet delay for HIGH priorities appears when the load is high, for both acknowledged and unacknowledged cases. The Packet delay seems to reach a point of saturation. The saturation occurs when the message throughputs for STANDARD and DEFERRED priorities have already reached zero, and only the 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 increased load.

For Non-Local transmissions, the differences between Packet delay for unacknowledged and acknowledged cases mirrors the same features as Message delay for the two cases. This is due to the fact that a close relationship exists between Message and Packet delay, for Non-Local transmissions, due to the time spent in the router buffer.

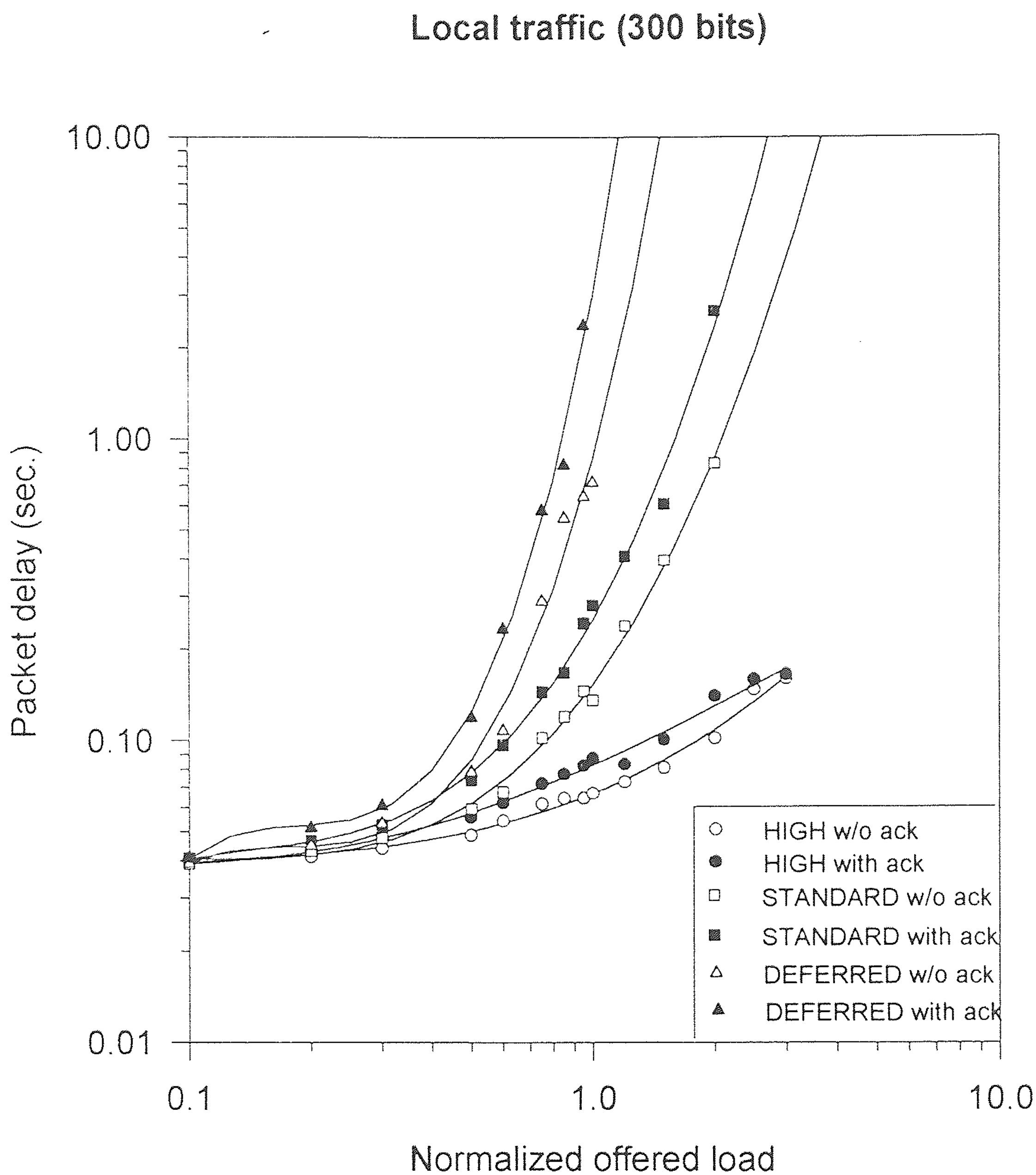


Fig. 4.3 Packet delay vs. Normalized offered load for 300 bit Local packets, with and w/o IACK

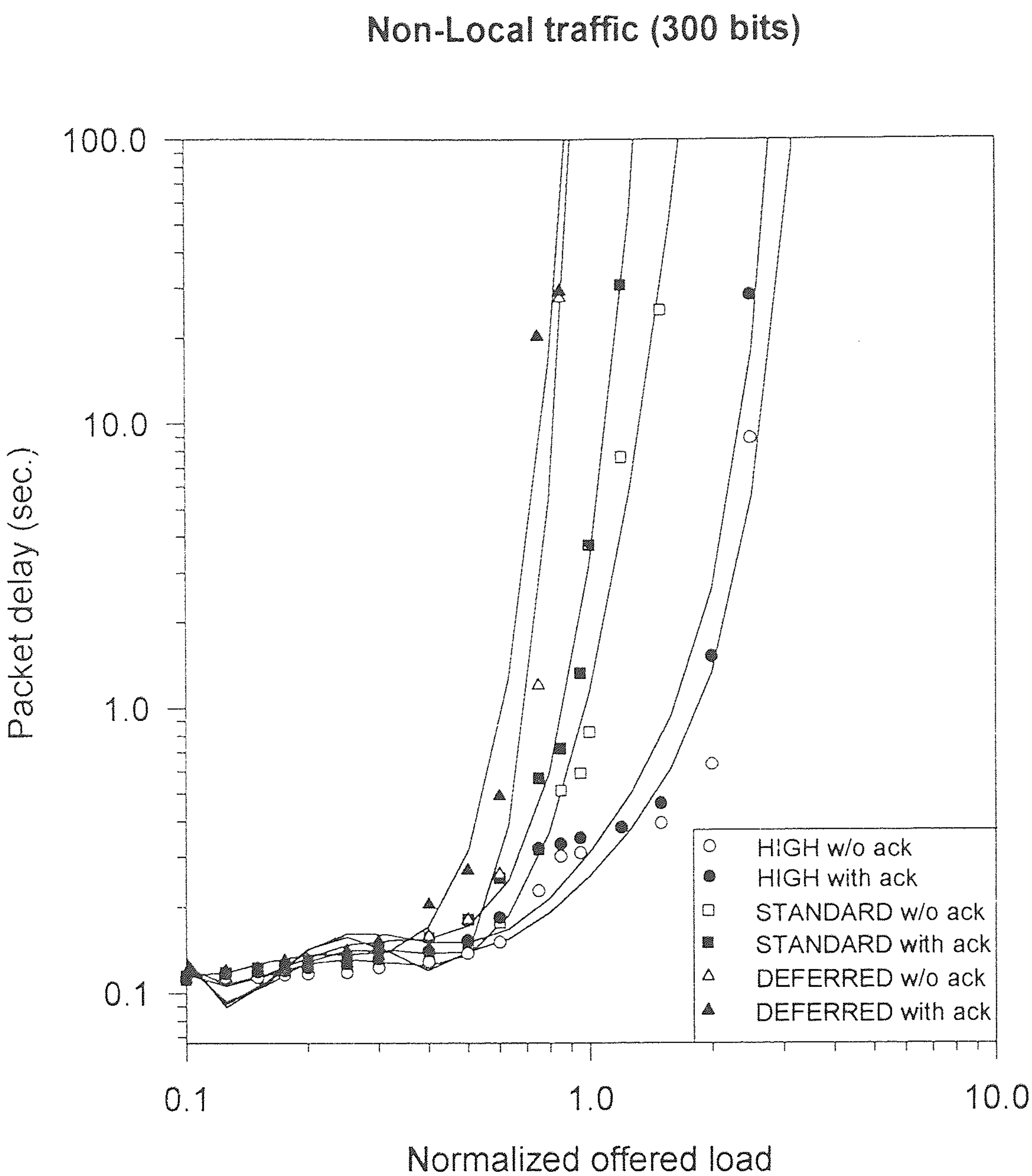


Fig. 4.4 Packet delay vs. Normalized offered load for 300 bit Non-Local packets, with and w/o IACK

(c) Message throughput vs. Load

The Message throughput vs. Normalized load for Local 300 bit packets is illustrated in Fig. 4.5. For HIGH priority, the throughput starts to fall below the ideal value of 1 when the normalized load approaches and exceeds twice the channel capacity. This is true for both acknowledged and unacknowledged traffic. For STANDARD priority, the corresponding values are 1.2 for unacknowledged traffic, and 1.0 for acknowledged traffic. Similarly, for DEFERRED priority the Message throughput begins to decrease at normalized load values of 0.7 and 0.6, for the unacknowledged and acknowledged case.

For traffic across the router (Non-Local), the pattern is similar with a steeper rate of descent(Fig. 4.6). However, the lower priorities are observed to fall off at a slightly lower value of the normalized load, when compared to Local traffic.

4.3 CEBus Performance With and Without IACK: Case of 100 bits

(a) Message delay vs. Load

In Fig. A.9, Message delay vs. Normalized load is shown for traffic on the same side of a router (Local traffic) for a 100 bit packet. Among the cases discussed, the Message delay for a 100 bit packet is the smallest for lighter loads. This is due to the shortest packet taking the least amount of time in the queue and subsequently in the channel. But the delay starts to increase at a load much smaller than the 300 and 600 bit cases. For HIGH priority it is around 1.5 for the unacknowledged case, and 1.4 for the acknowledged case. For STANDARD priority, the corresponding load values are 0.6 and 0.5, for unacknowledged and acknowledged cases, respectively.

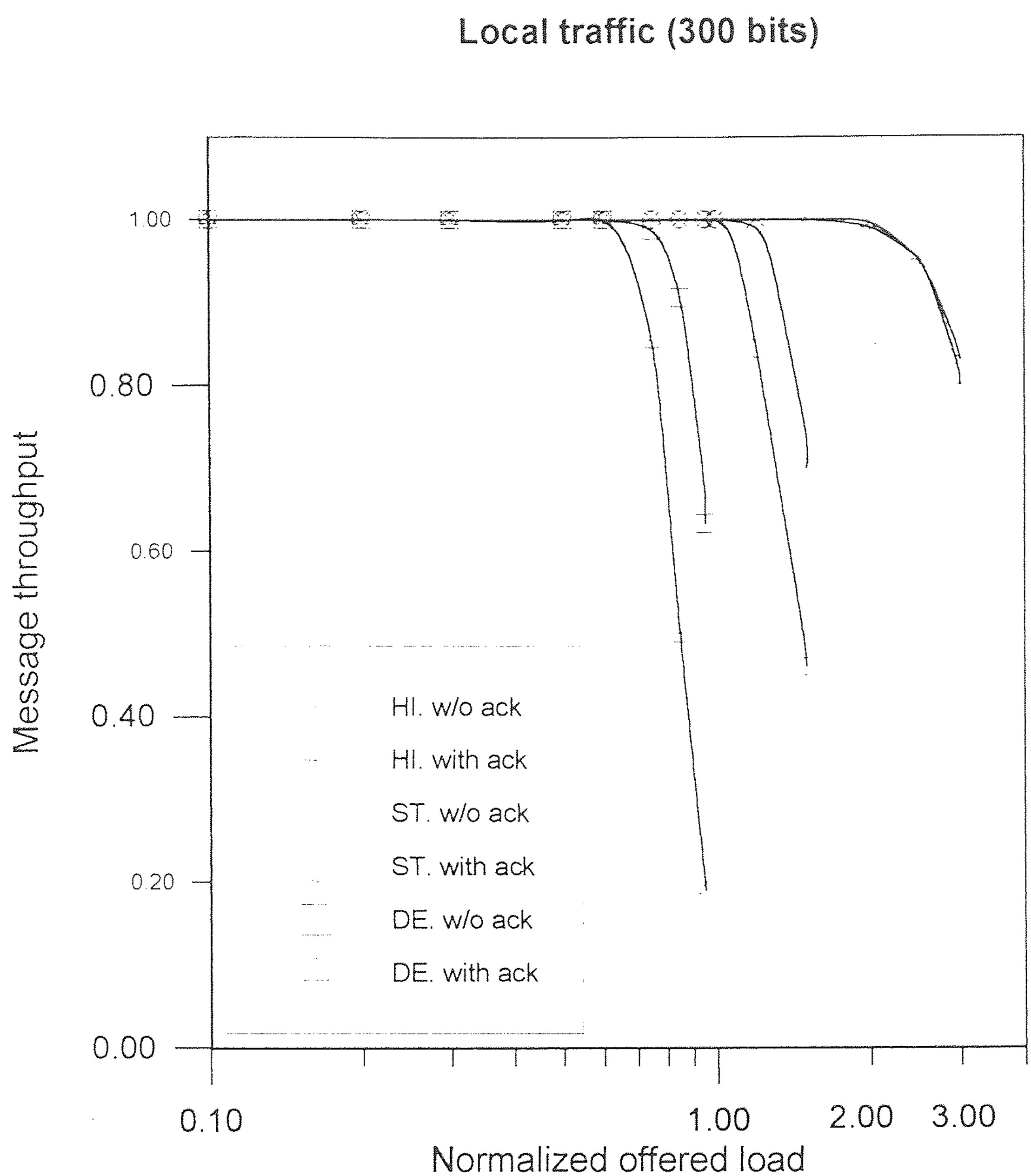


Fig. 4.5 Message throughput vs. Normalized offered load for 300 bit Local packets, with and w/o IACK

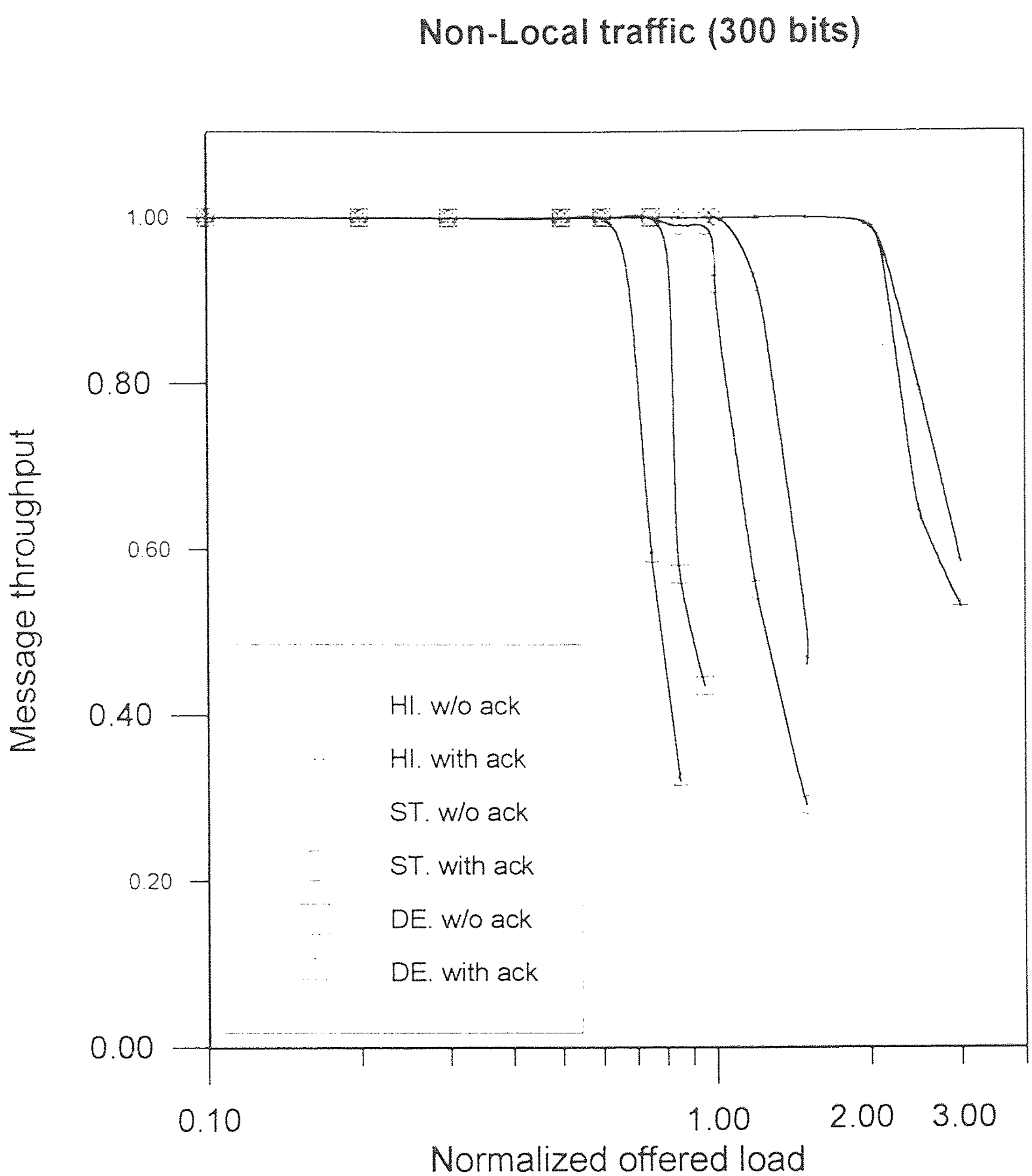


Fig. 4.6 Message throughput vs. Normalized offered load for 300 bit Non-Local packets, with and w/o IACK

(b) Packet delay vs. Load

The same observations made for the previous two cases are valid here. For smaller loads, the Packet delay is small and bounded. And for higher loads drastic increases are noticeable.

(c) Message throughput vs. Load

For Local and Non-Local traffic, the message throughput for HIGH priority unacknowledged transmissions starts to reduce at a normalized load of 1.5 (Fig. A.15 & Fig. A.16). The corresponding value for acknowledged transmissions is slightly less than 1.5. This is in agreement with the rapid increase in Message delay observed in section (a).

4.4 Comparison of Channel throughput With and Without IACK

In Fig.4.7, Channel throughputs for the three packet lengths, with and without acknowledgment, are presented. In all three cases, the unacknowledged channel throughput is greater than the acknowledged channel throughput. Since the channel throughput is a function of the channel occupation time, the extra time taken for IACK transmission reduces the throughput. Also the IACK frames do not count as information packets.

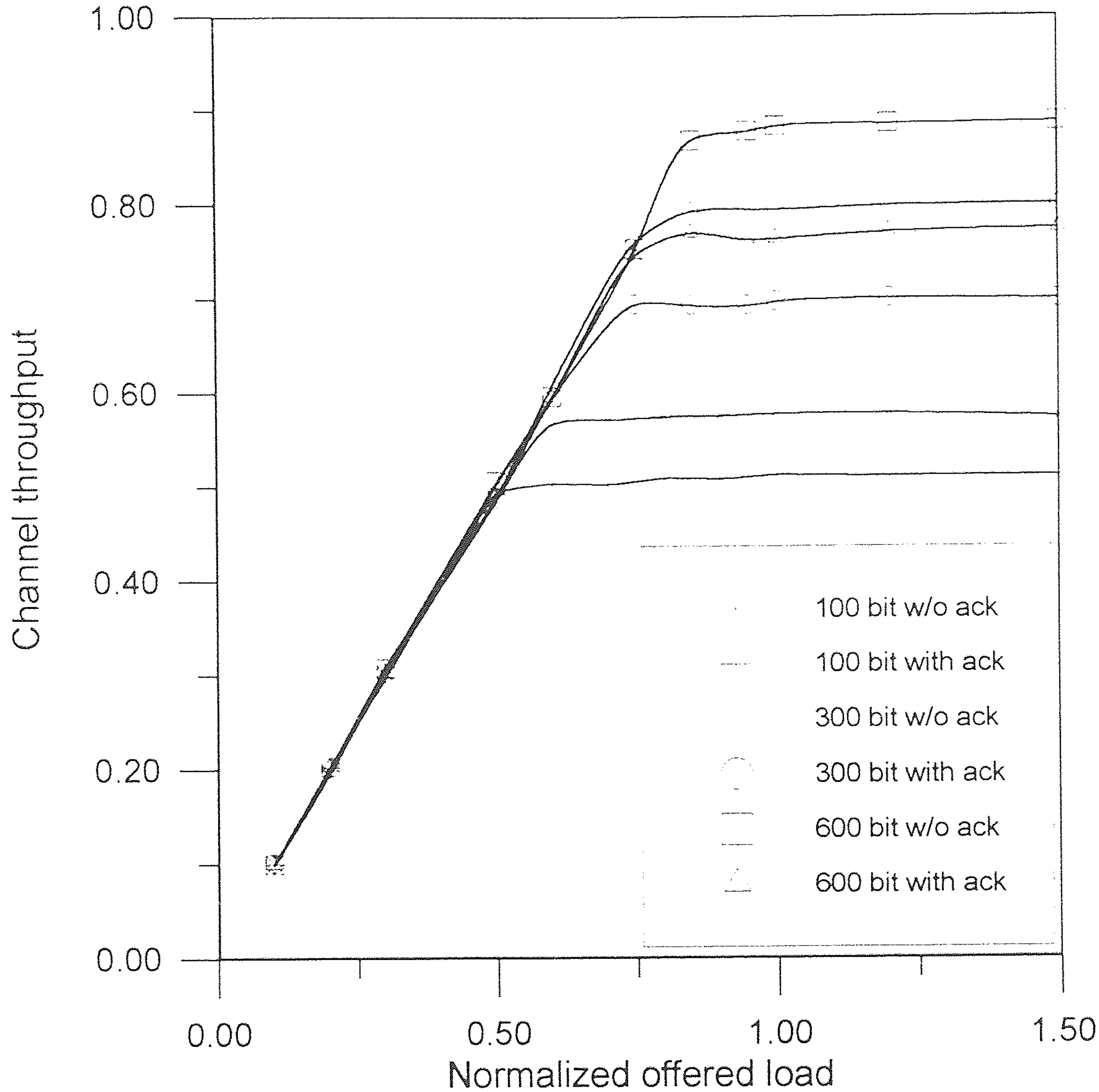


Fig. 4.7 Comparison of Channel throughput vs. Normalized offered load for packet lengths of 100,300, and 600 bits

CHAPTER 5

CONCLUSIONS

In this study, a CEBus model comprising of two different media interconnected via a router is simulated. Since both the PL and TP media operate at the same data rate, with symmetric traffic across the router, and symmetric traffic on the same channel, only one side is considered, arbitrarily, for the purpose of data evaluation. It could be either the PL or TP medium. If asymmetric traffic patterns were used on PL and TP, then the results of the simulation would not be similar on either side of the router, and two separate studies would have to be conducted for TP and PL.

Performance measures for the network, with and without acknowledgment, have been considered for different packet lengths. It was found that the IACK creates the biggest difference for smaller packets, as far as delay and throughput are concerned.

For loads below 50% of channel capacity, Message delays and Packet delays were bounded to an acceptable value. This trend was observed for both acknowledged and unacknowledged transmissions for all three priority classes, and also all three packet lengths. Furthermore, message throughput is 1 in this region. Therefore, packets can be transmitted and received with a high degree of success . Specially, the use of an acknowledgment mechanism does not effect the overall performance to a great extent. Thus, a more reliable service is guaranteed when an IACK is used.

As load increases, the ability of lower priority packets to access the channel is reduced. Under heavy load conditions, only the HIGH priority packets may have a chance, but still after an extensive delay in the queue.

The channel throughput was observed to be highest for 600 bit packets while it was lowest for 100 bit packets. The maximum channel throughput for 600 bit packet is 0.888 for unacknowledged, and 0.775 for acknowledged transmissions. Similarly, the maximum channel throughput for 300 bit packet is 0.8 for unacknowledged, and 0.7 for acknowledged traffic. The corresponding values for the 100 bit packet is 0.575 and 0.51, for the unacknowledged and acknowledged cases, respectively. The throughput increase for increased message size, was already known for unacknowledged transmissions[12,20]. According to the results, it is also valid for acknowledged transmissions.

The fact that the introduction of an IACK decreases the throughput slightly, but increases the reliability, promises to be a valuable fact to consider in the design of CEBus for home automation. Since CEBus provides distributed control, a command may be given in one room, but not obeyed in another room. Let's assume that you want to turn off a light in the bedroom, from the living room, and the destination node is beyond the field of vision of the controller. Then he has no guarantee that his command was received at the destination. But with the use of an IACK, successful arrival at the destination is guaranteed. If no IACK is received, then a retransmission could be attempted.

Since a home may be wired using several different media, for example PL, TP and Coax, the behavior of an acknowledgment mechanism across a router becomes an issue to be investigated. These simulations prove that for nominal loads, up to 50% of channel capacity, the acknowledged network functions well in terms of delays and message throughputs. For higher loads, the acknowledged network provides a more reliable service but at the expense of increased delays and reduced throughputs.

APPENDIX A

SIMULATION RESULTS FOR 100 AND 600 BIT PACKETS

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 600 bit and 100 bit packets have been included.

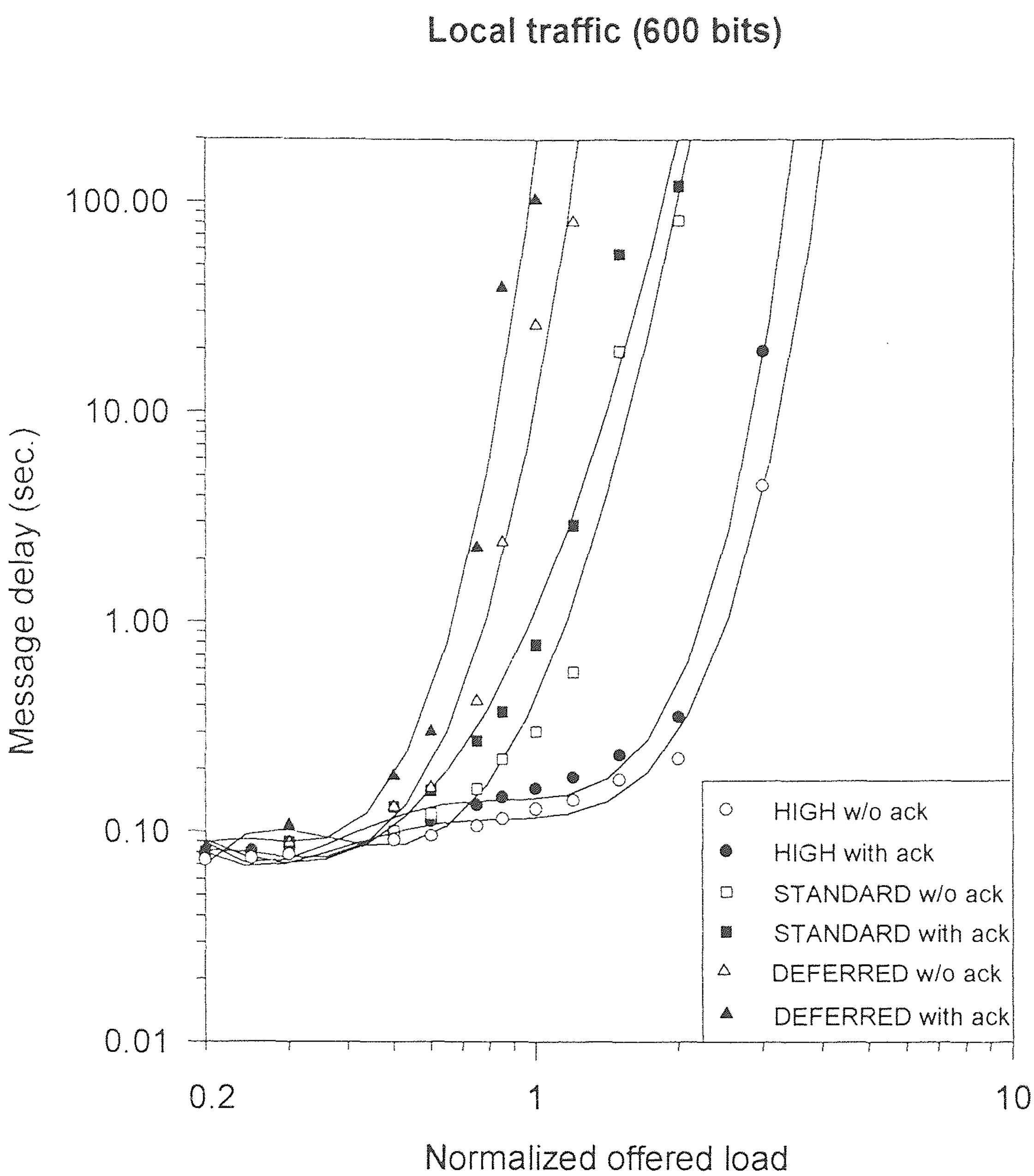


Fig. A.1 Message delay vs. Normalized offered load for 600 bit Local packets, with and w/o IACK

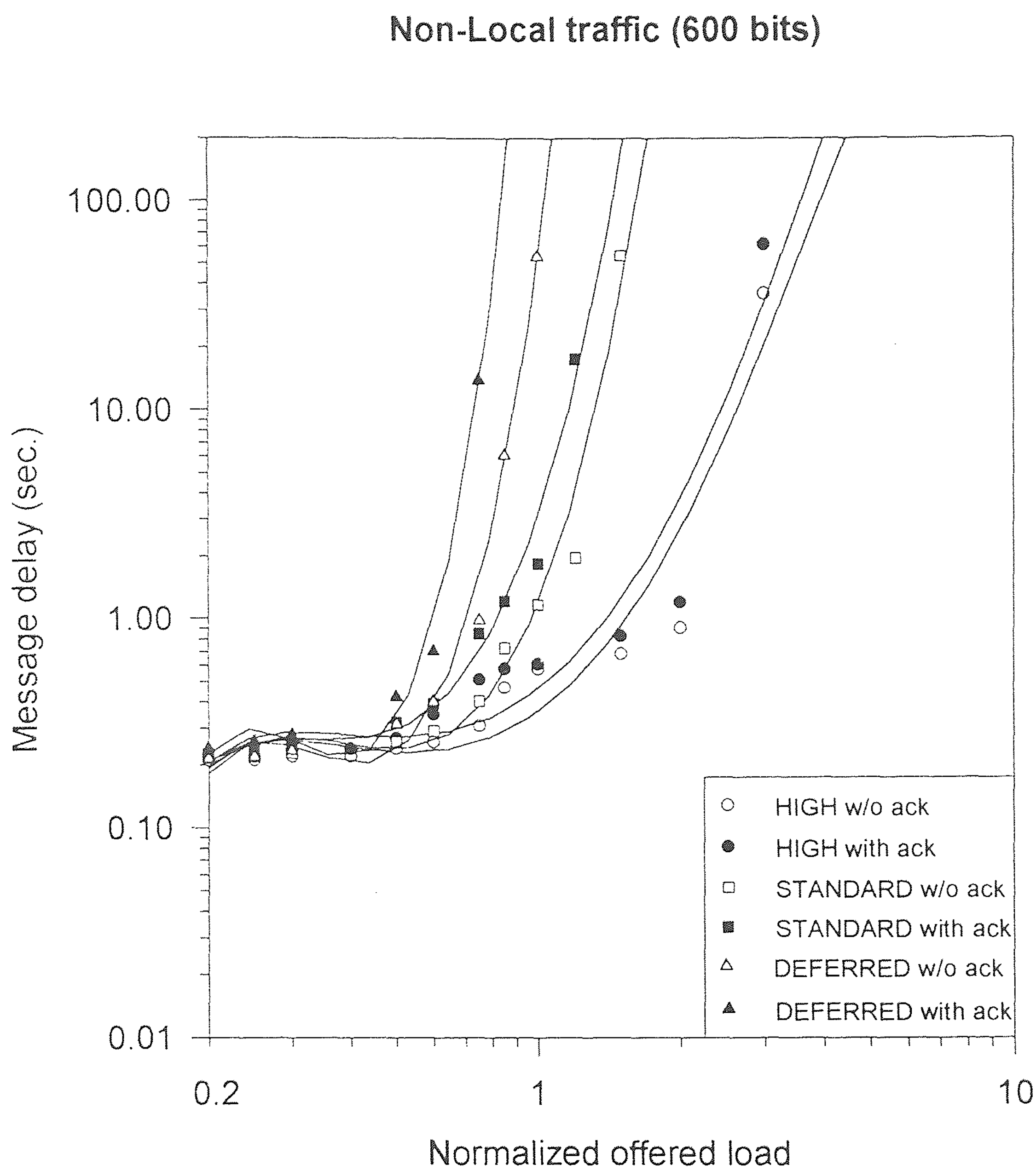


Fig. A.2 Message delay vs. Normalized offered load for 600 bit Non-Local packets, with and w/o IACK

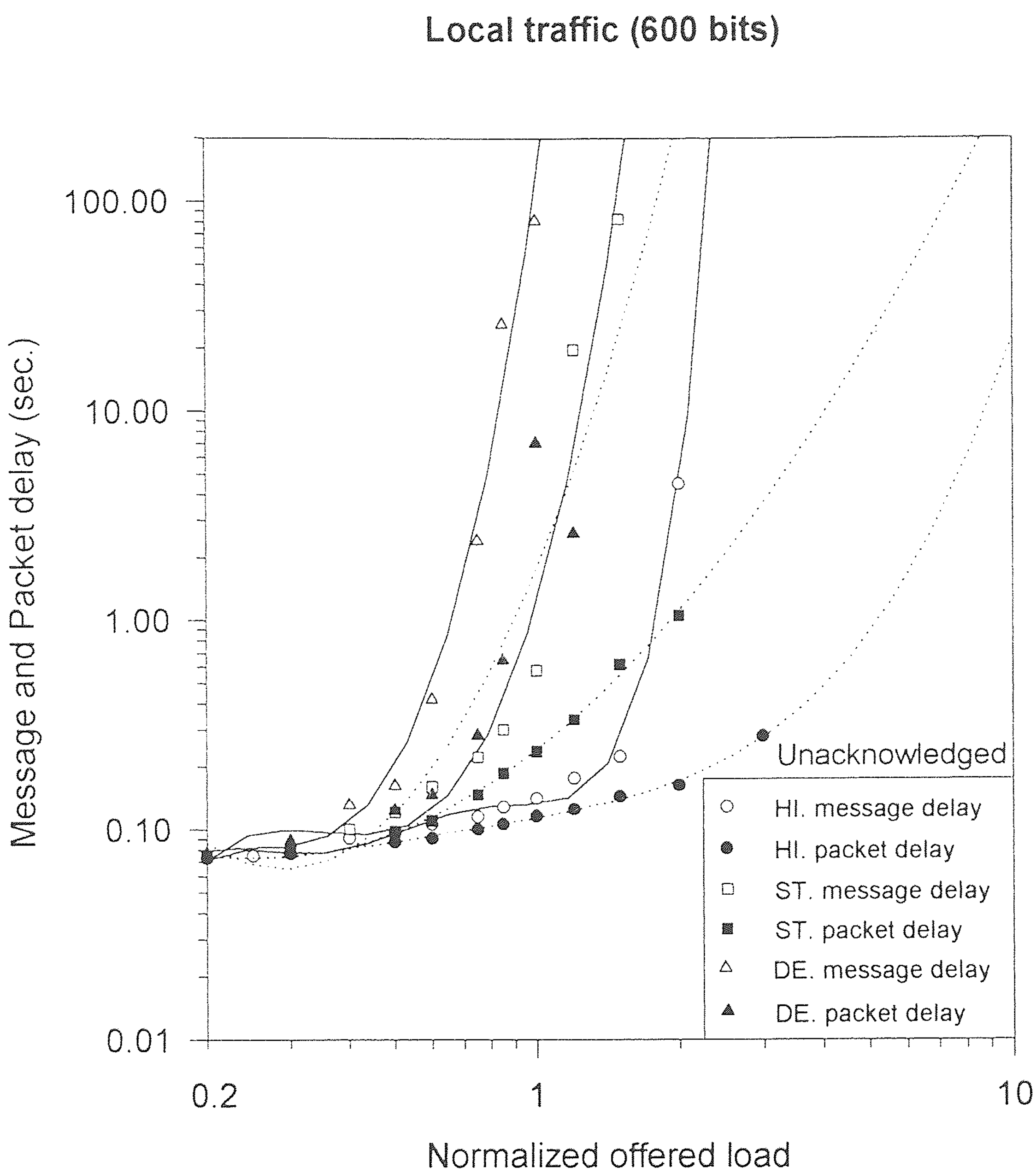


Fig. A.3 Message and Packet delay vs. Normalized offered load for 600 bit Local packets, without IACK

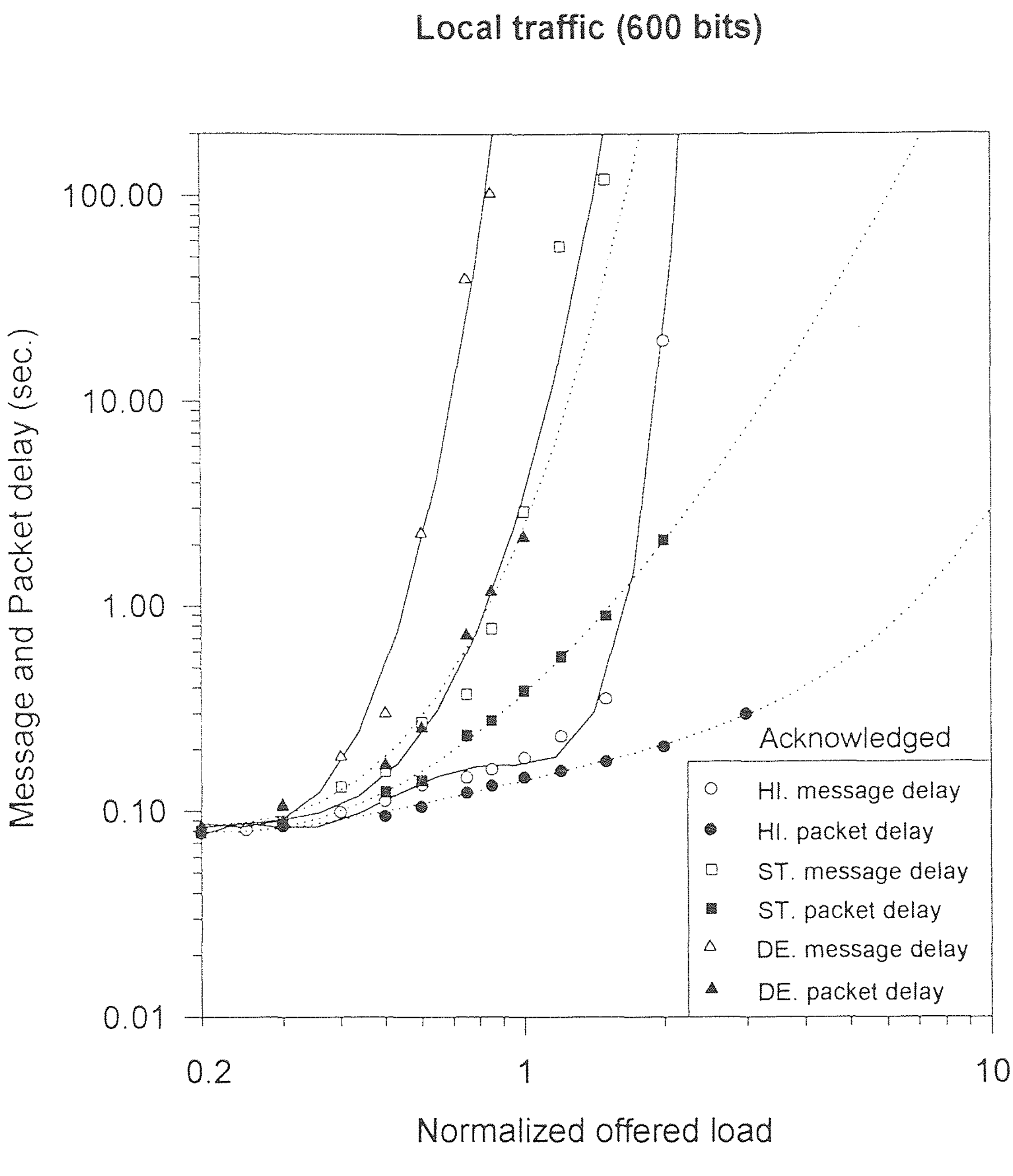


Fig. A.4 Message and Packet delay vs. Normalized offered load for 600 bit Local packets, with IACK

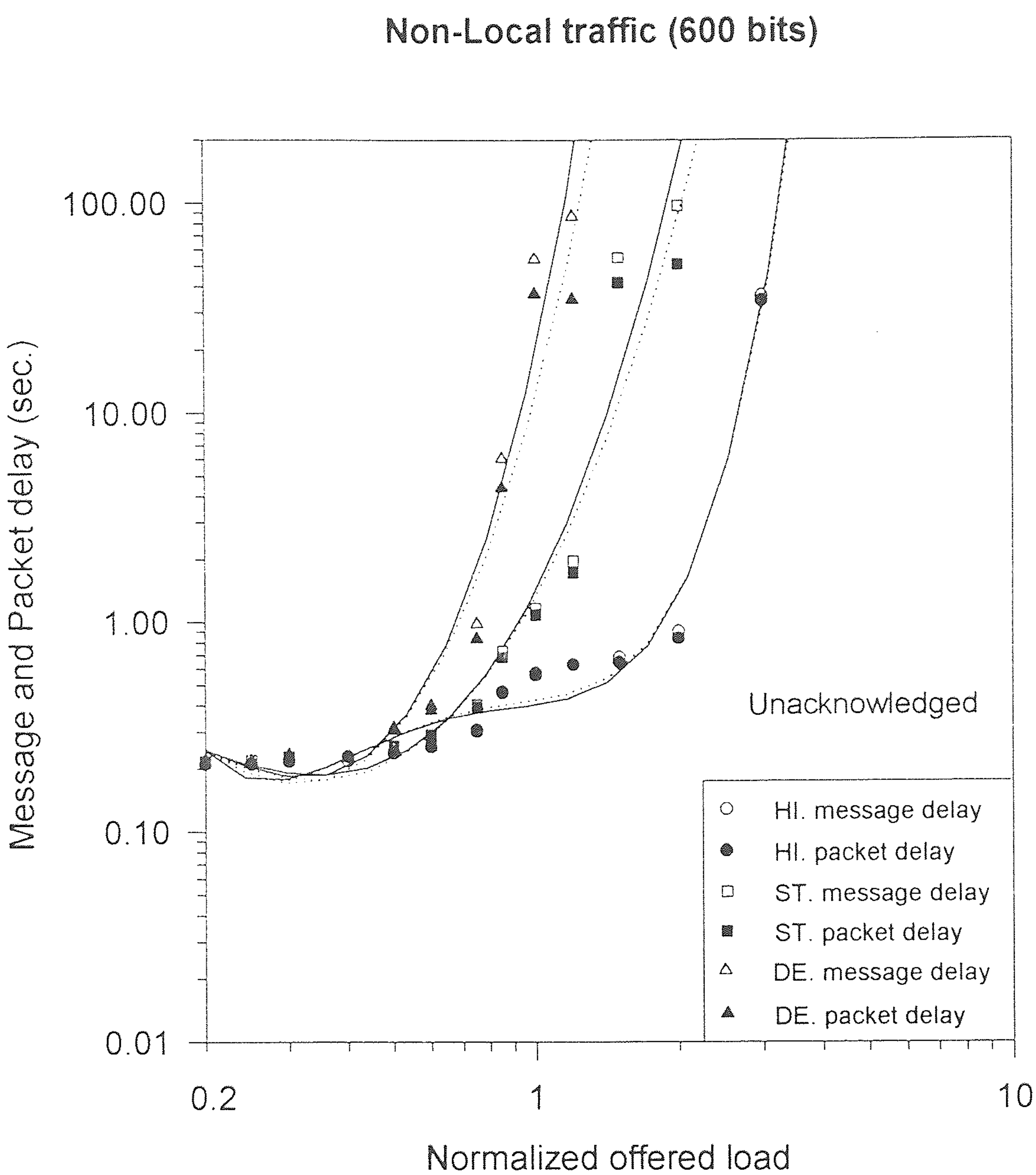


Fig. A.5 Message and Packet delay vs. Normalized offered load for 600 bit Non-Local packets, without IACK

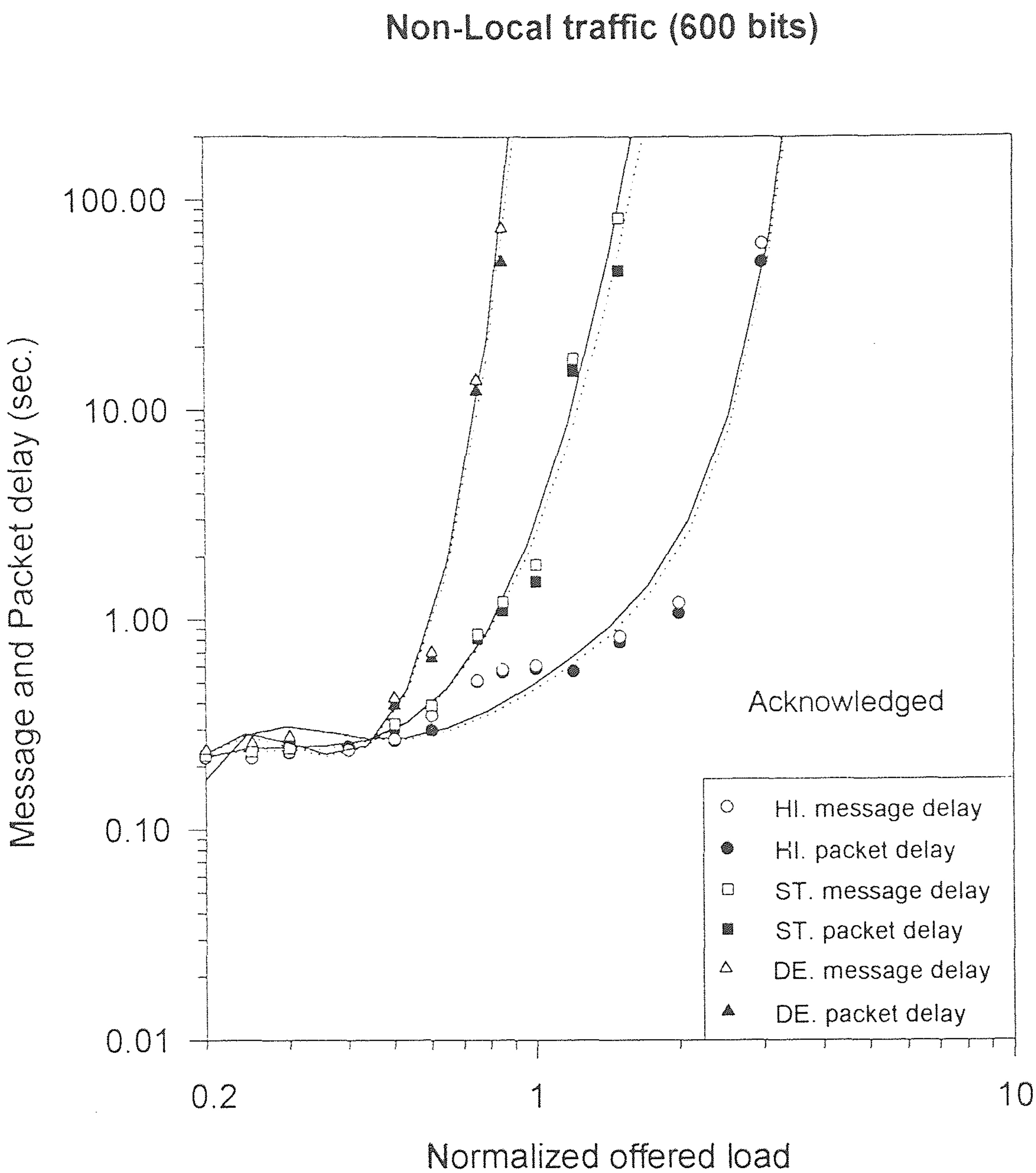


Fig. A.6 Message and Packet delay vs. Normalized offered load for 600 bit Non-Local packets, with IACK

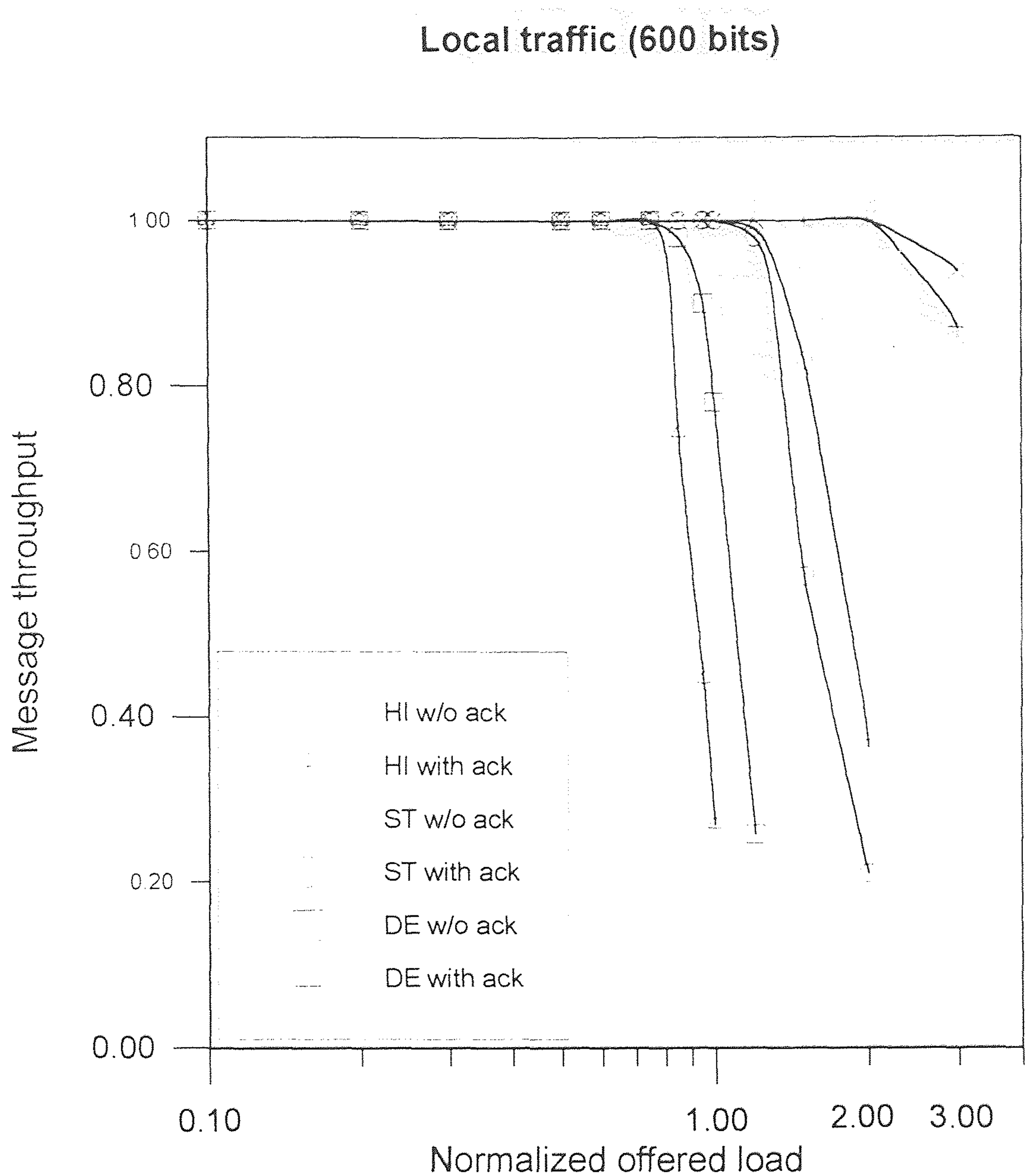


Fig. A.7 Message throughput vs. Normalized offered load for 600 bit Local packets, with and w/o IACK

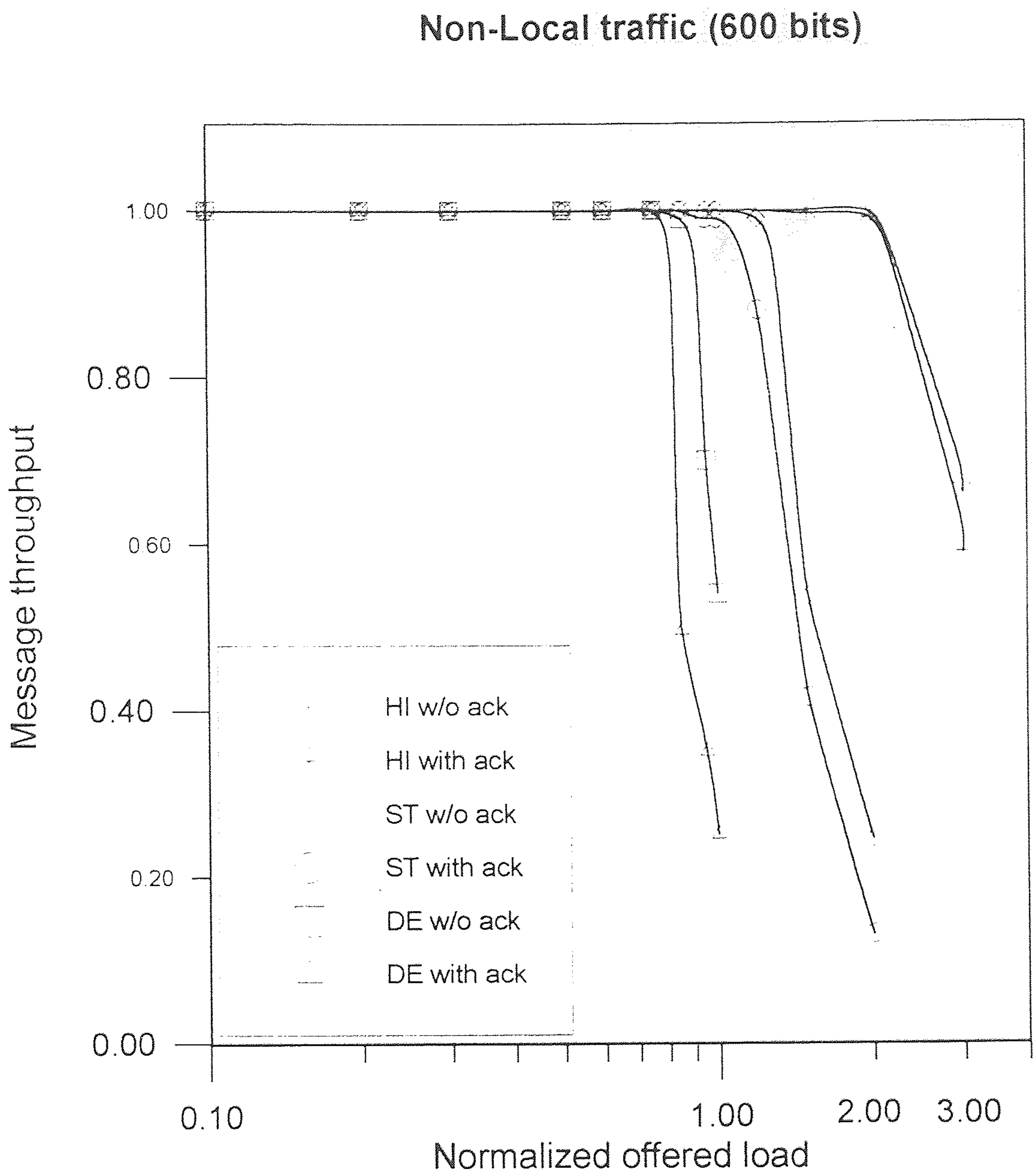


Fig. A.8 Message throughput vs. Normalized offered load for 600 bit Non-Local packets, with and w/o IACK

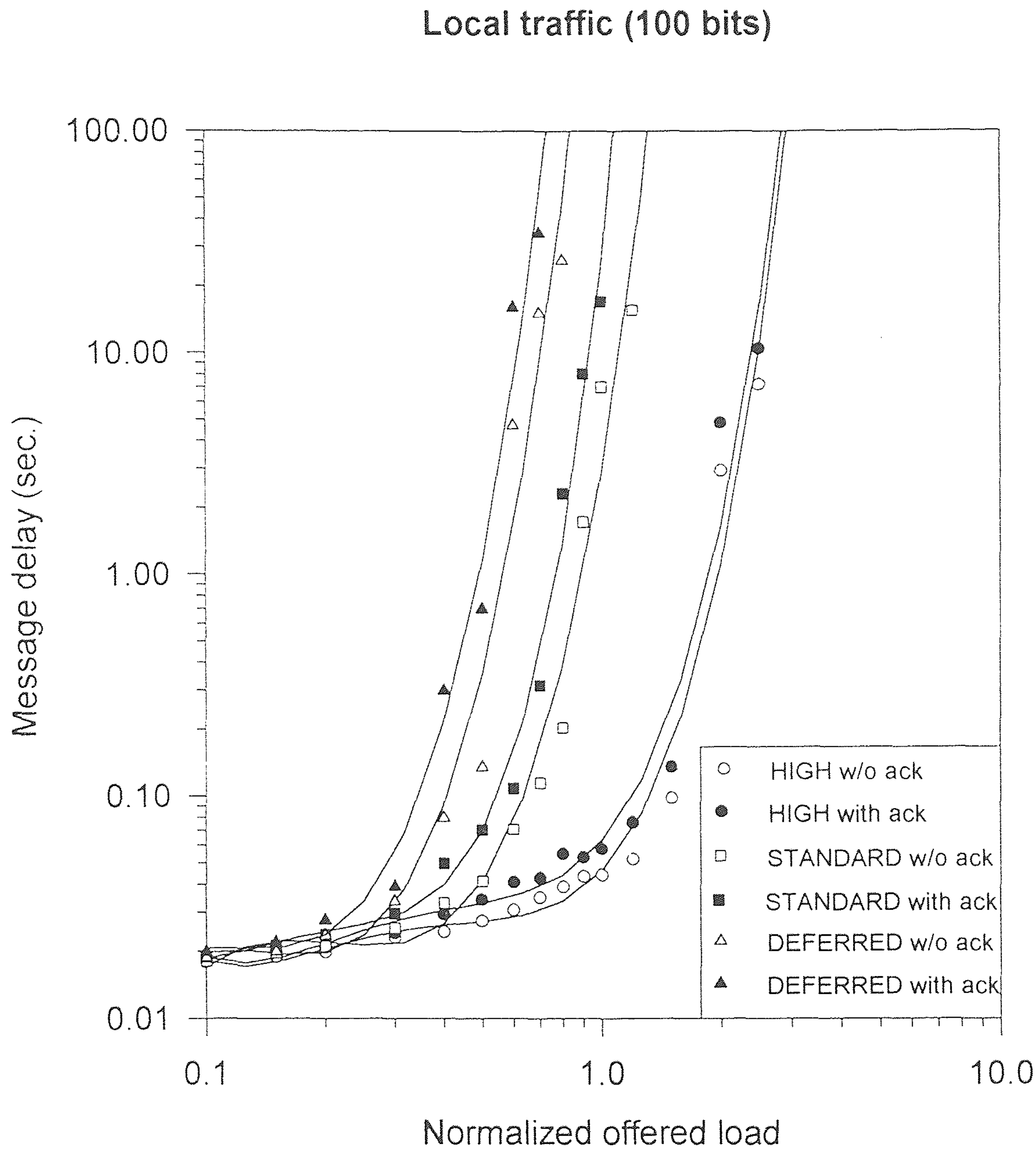


Fig. A.9 Message delay vs. Normalized offered load for 100 bit Local packets, with and w/o IACK

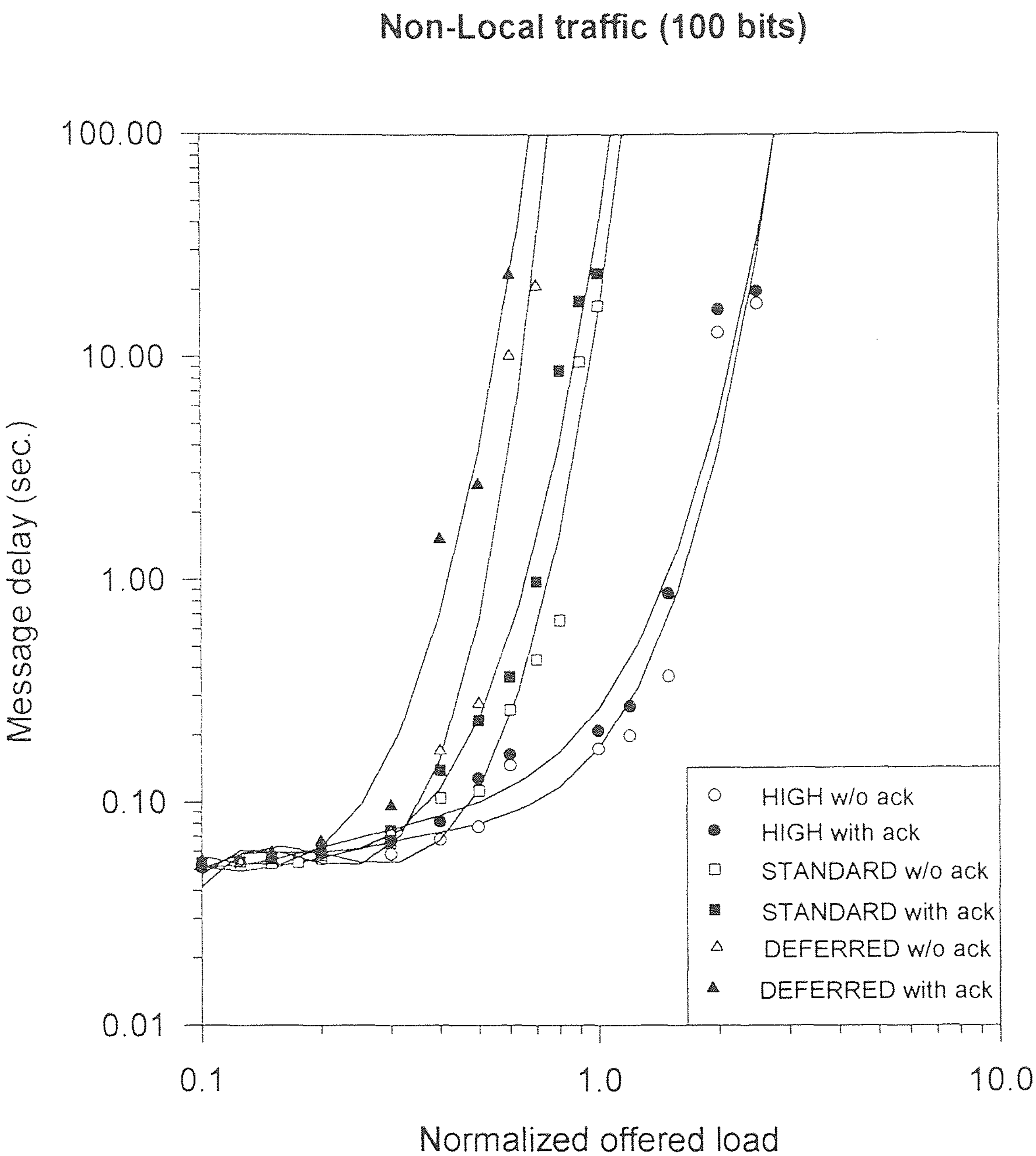


Fig. A.10 Message delay vs. Normalized offered load for 100 bit Non-Local packets, with and w/o IACK

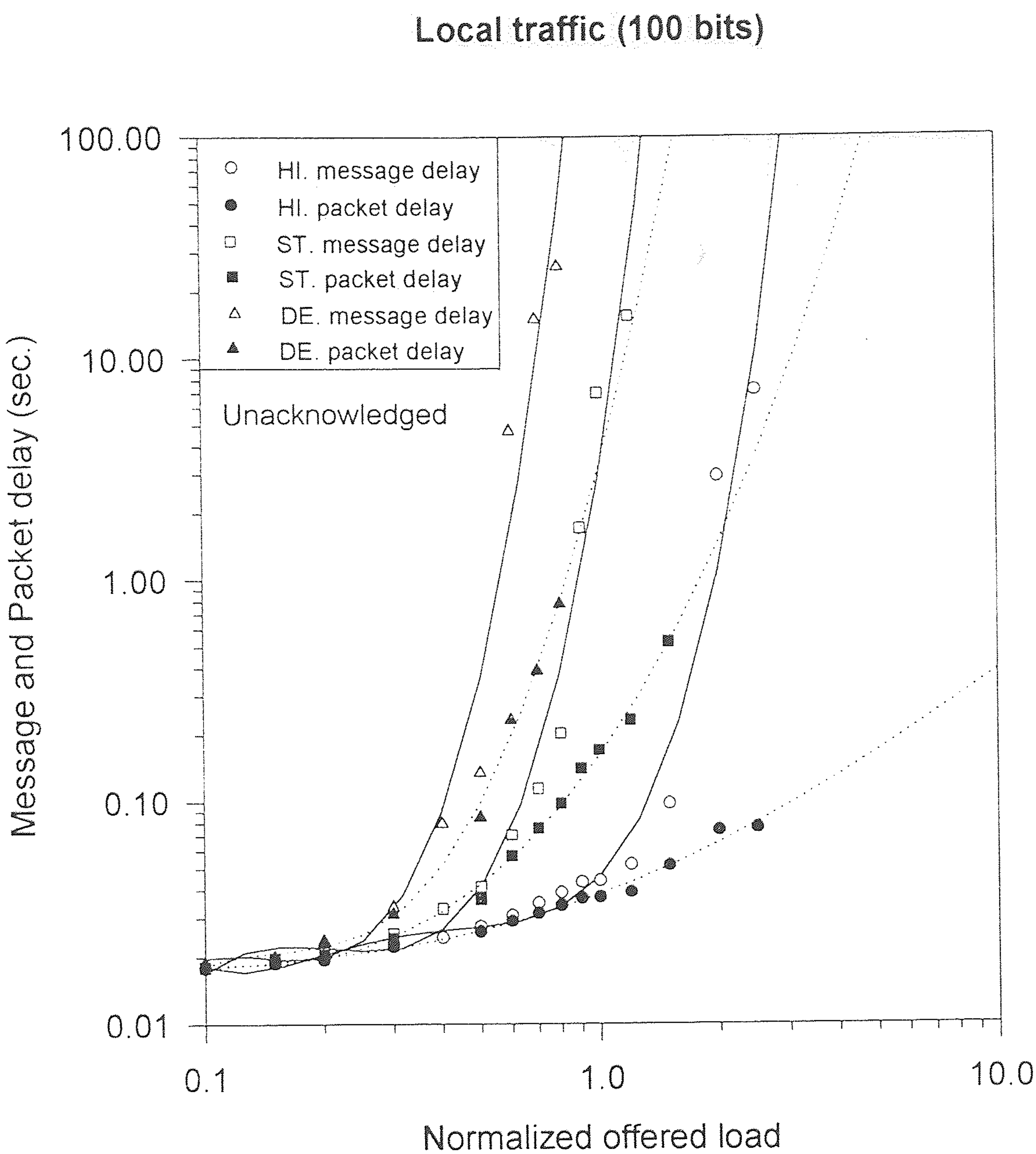


Fig. A.11 Message and Packet delay vs. Normalized offered load for 100 bit Local packets, without IACK

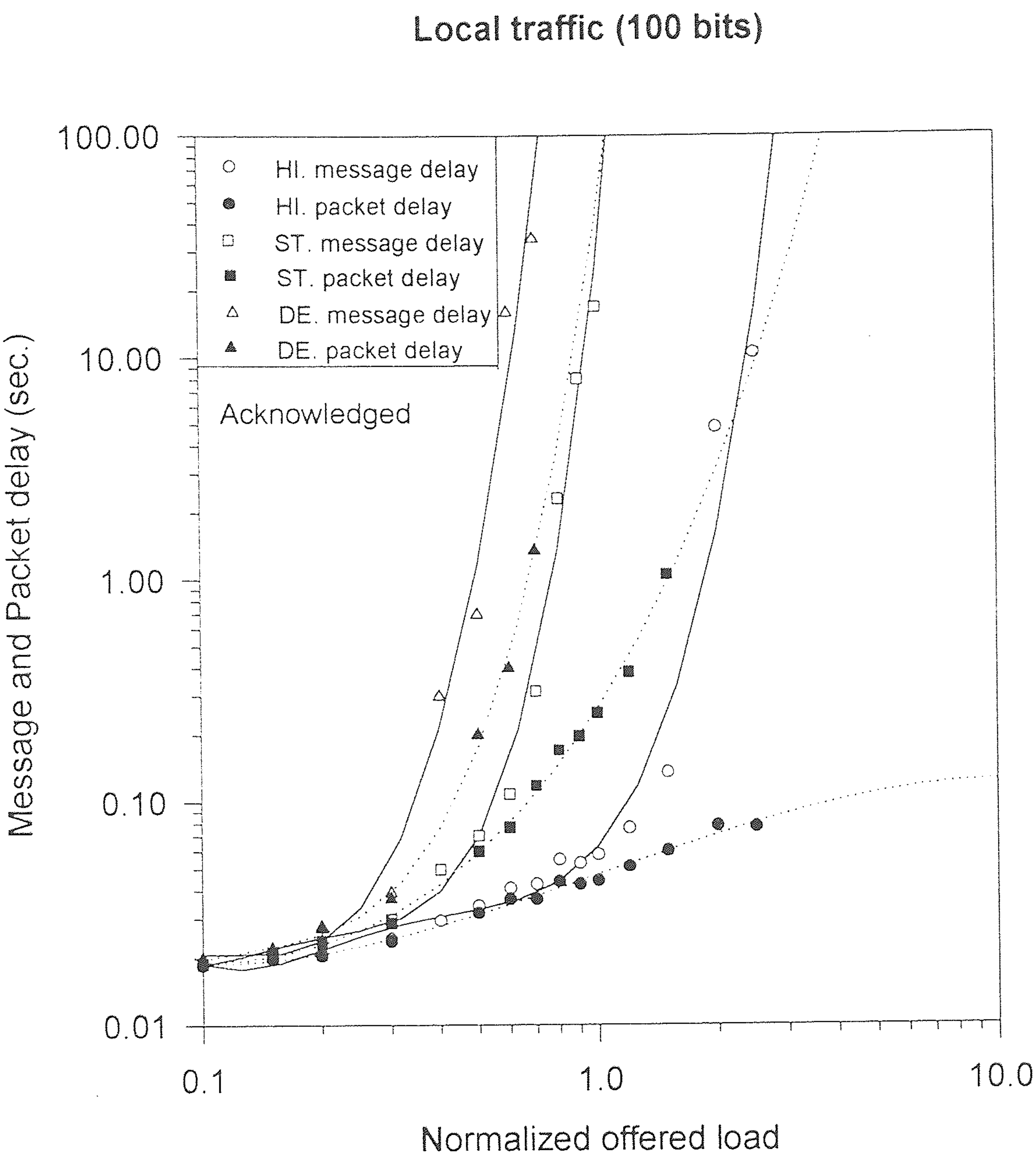


Fig. A.12 Message and Packet delay vs. Normalized offered load for 100 bit Local packets, with IACK

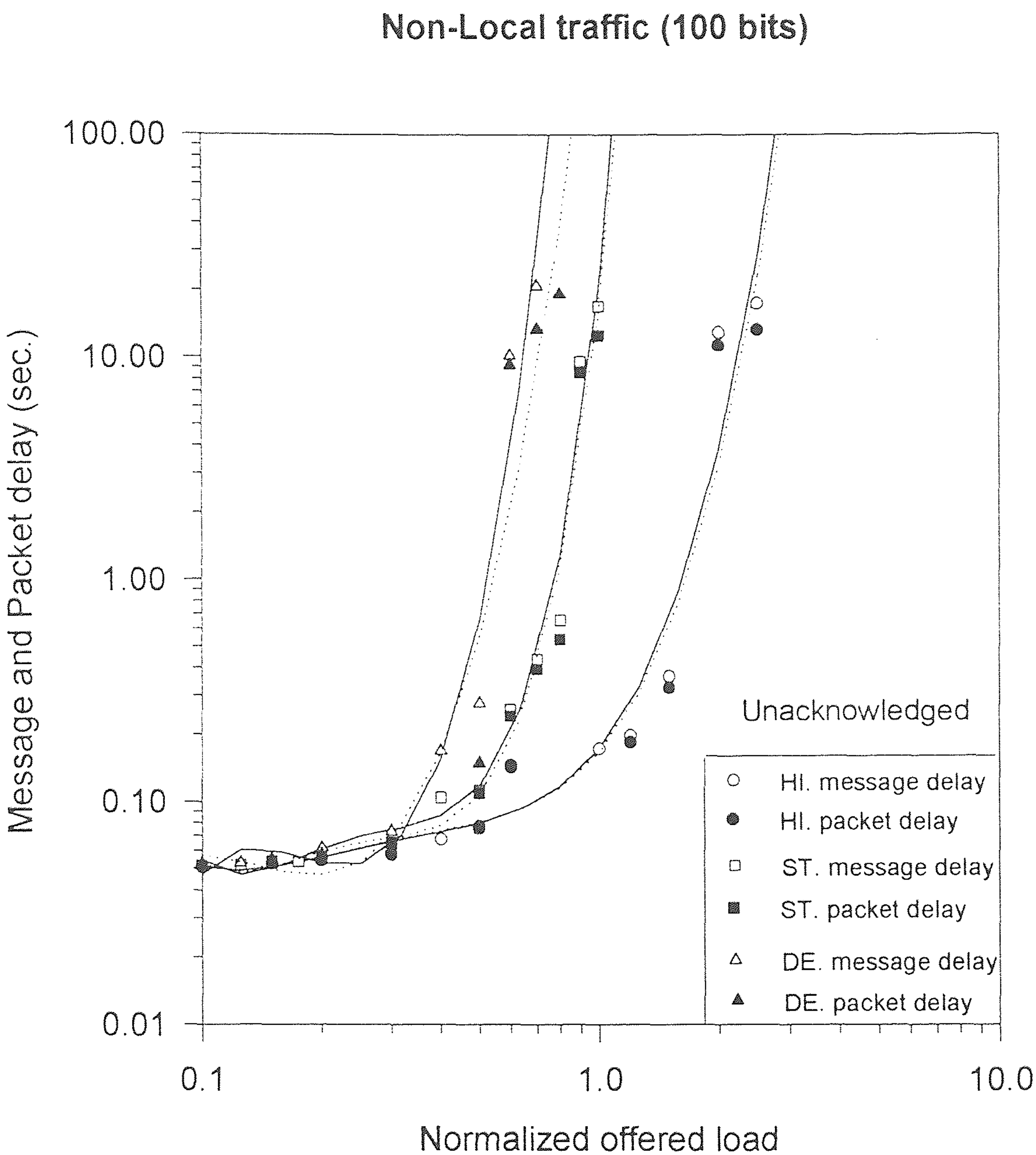


Fig. A.13 Message and Packet delay vs. Normalized offered load for 100 bit Non-Local packets, without IACK

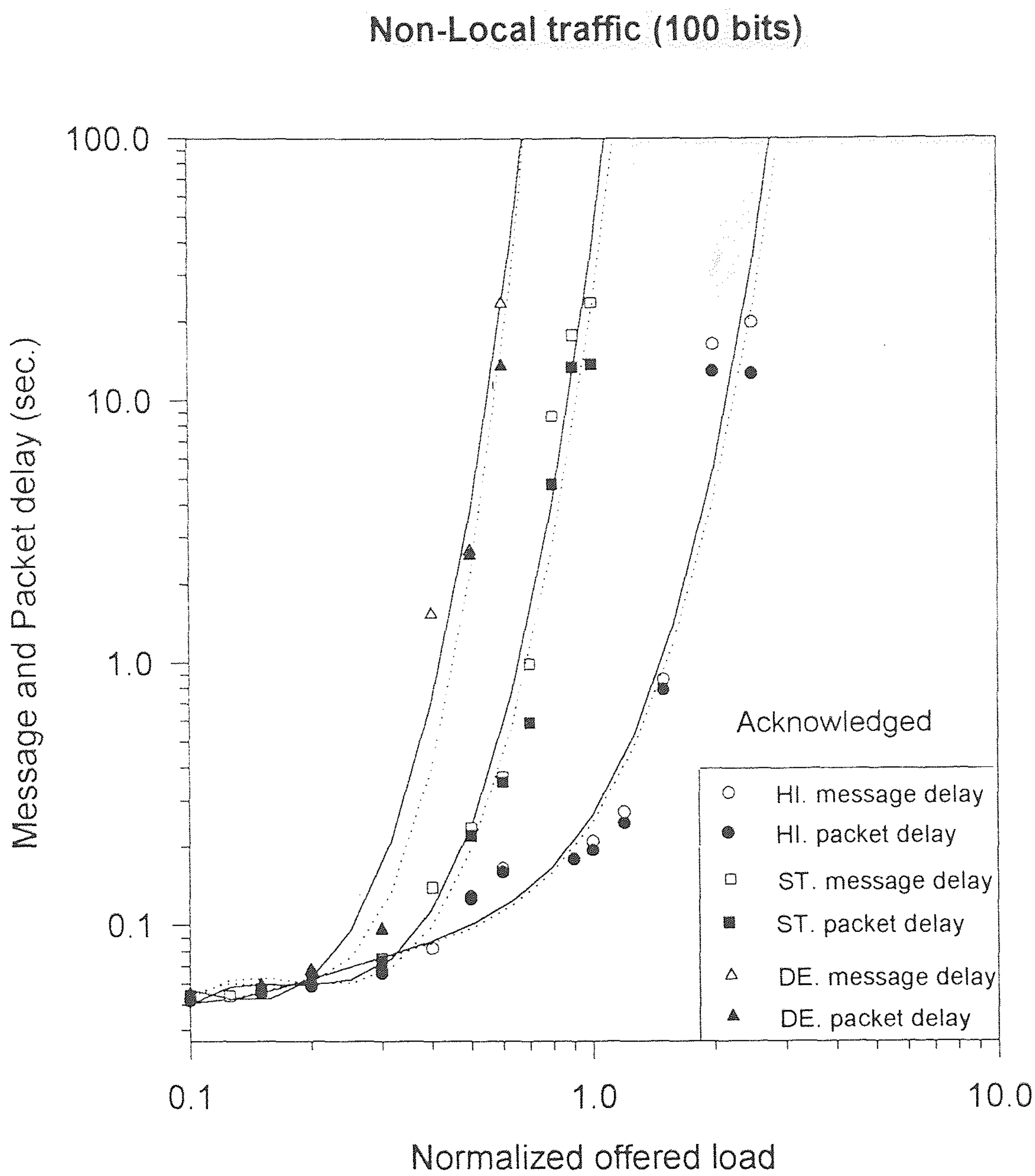


Fig. A.14 Message and Packet delay vs. Normalized offered load for 100 bit Non-Local packets, with IACK

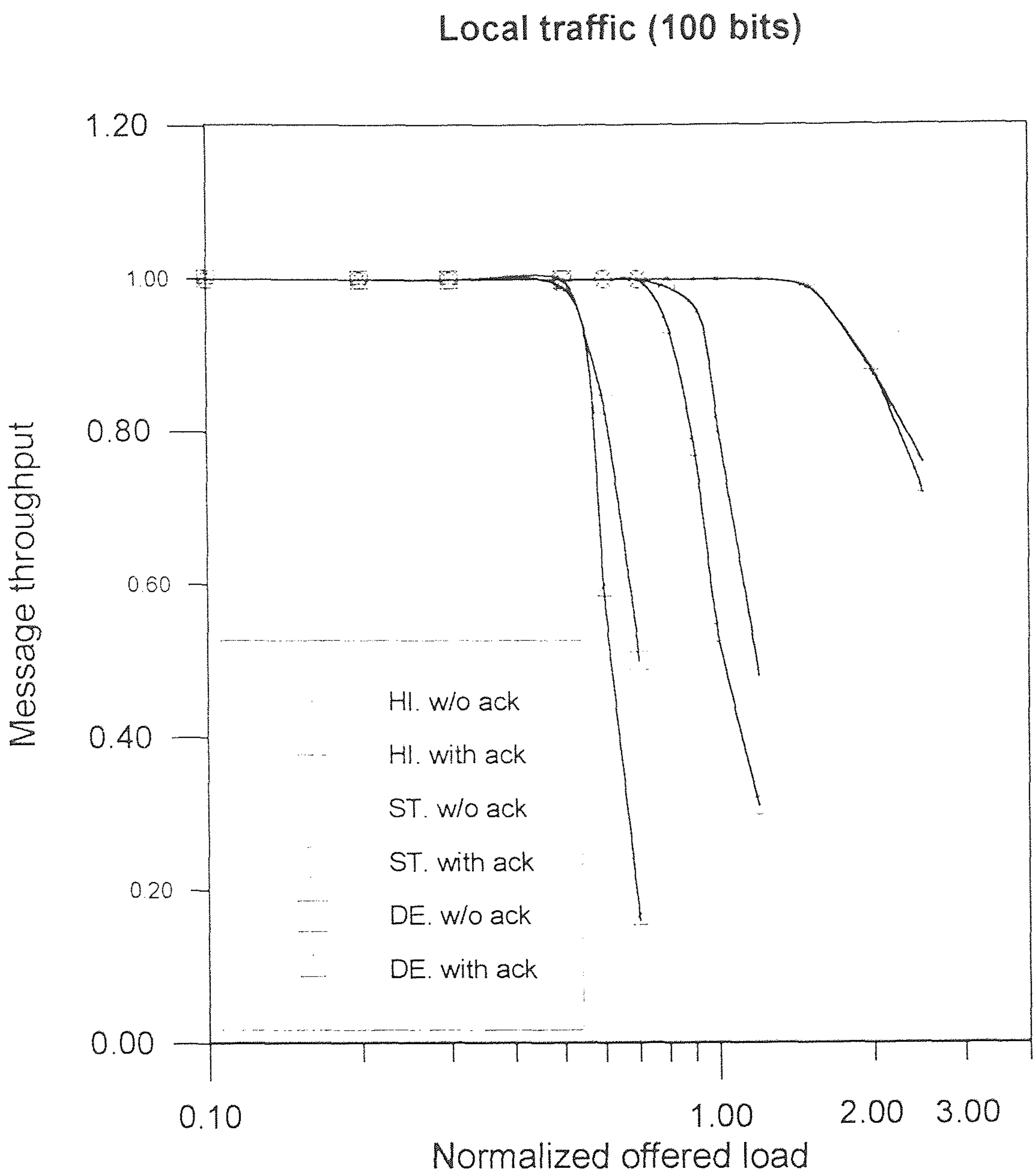


Fig. A.15 Message throughput vs. Normalized offered load for 100 bit Local packets, with and w/o IACK

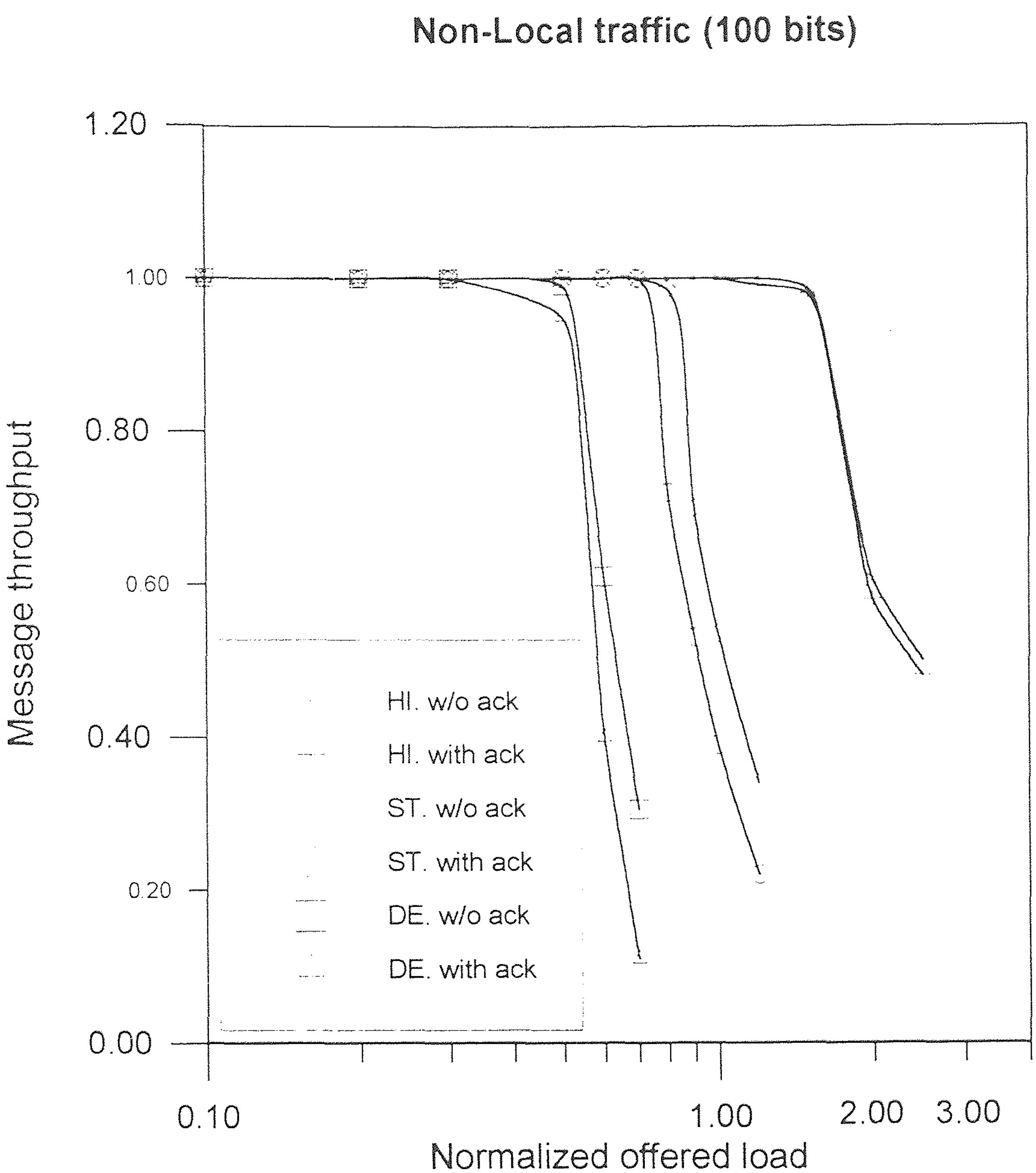


Fig. A.16 Message throughput vs. Normalized offered load for 100 bit Non-Local packets, with and w/o IACK

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