Double Linked Backbone Ring Interconnected Network

by

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(ABSTRACT)

The token ring has several advantages over other networks, especially under a heavy load. However, Bux and Grillo showed that all desirable characteristics of IEEE 802.2 and 802.5 protocols for a single token ring are severely degraded in an interconnected token ring network. In order to address the problem, Bux and Grillo suggested a method of dynamically adjusting the size of windows depending on the traffic of a network. In this thesis, a different method of addressing the problem was proposed. The proposed method is to add a secondary transmission link to the backbone ring of a network to form a double linked backbone ring network.

Simulation results show that the most influential element contributing to the degradation of performance is congestion at the bridges in a network. The processing speed of bridges for the proposed double linked backbone ring network is essentially double that of the original network. The increased processing speed of the bridges enhances the performance of the network. Experimental results for the utilization, throughput and response time of the original network and the proposed double linked backbone ring are presented.

Acknowledgements

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1.0 Introduction

1.1 Local Area Networks

A local area network (LAN) is a computer communication network limited by its geographical size as its name implies [9]. A LAN is usually located in a building, such as a campus, a factory, or a community ranging from several stations to hundreds of stations. Hence, a LAN, in terms of geographic scope, is smaller than a telecommunication network which usually spreads out nationwide or worldwide, and results in simpler hardware structures and software protocols. For hardware structures, LANs share with other communication networks two basic elements: 1. *physical transmission links* such as twisted pairs, coaxial cable, fiber optics, or microwave, and 2. *interfaces* between stations and transmission links, which usually consist of microprocessors and their associated logical circuits such as encoders, decoders, and amplifiers. Like all other communications networks, a LAN also has a software element which controls the entire network to enable conversations between stations. Software is one way to implement a *protocol.* Currently, the most popular LAN protocols adopted by the industry are a se-

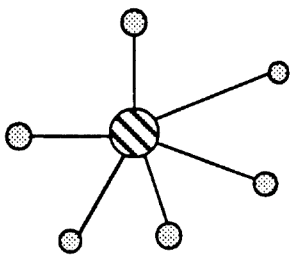
ries of IEEE 802 standards which were first defined by the IEEE 802 committee in 1980 and later revised in 1984 [1,2,3]. They are as follows.

1. IEEE 802.1 describes the relationship between IEEE 802 standards and their common elements with the OSI (Open System Interconnections) Model and their interface to higher layers. A brief description of the OSI Model is stated in Chapter 2. IEEE 802.1 also addresses the issues of network management and network interworking.
2. IEEE 802.2 deals with parts of the data link layer of the OSI Model such as flow control, error recovery, packet sequencing, frame synchronization, etc. IEEE 802.2 is given the name *Logical Link Control* (LLC) by the committee.
3. IEEE 802.3, 802.4, 802.5, and 802.6 are *Medium Access Control* (MAC) schemes for Carrier Sense Multiple Access and Collision Detection (CSMA/CD) bus, token passing bus, token passing ring, and metropolitan area network, respectively. Medium Access Control layers control access to transmission links and handle the frame-delimiting and address-recognition functions.

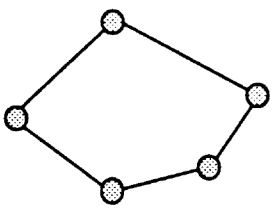
LANs can be classified into three types, *star, ring* and *bus*, according to their topologies. A star network [26], shown in Fig.1 (a), consists of a central station and other subordinate stations. All routing decisions are made at the central station which makes both the software and the hardware implementation of each subordinate station simple. A disadvantage of star networks is that the central station takes the responsibility for the entire network and must have sufficient capacity to handle all simultaneous conversations [20,35]. This requirement makes its implementation complex and expensive. The ring and bus networks attempt to eliminate the central station on the network. A ring network, shown in Fig. 1(b), does not have a central station and subordinate stations.

Instead, it has a closed-loop physical link to which all stations are attached. There is no need of routing functions or a central station for the network [32]. Hence the hardware and software implementation of each station of a ring network is simple and inexpensive. A message sent by a station passes from station to station along the unidirectional link and reaches its destination station. A disadvantage of a ring network is that any broken section of the link will bring down the entire network which is intolerable for some applications. Another disadvantage is that it is difficult to add or remove stations on the ring. The addition of a new station requires a cut and reconnection of the link. During this time the network would be inactive. A bus network, shown in Fig. 1(c), does not require a central station to perform routing functions either. All stations on a bus network are treated with the same priority and are responsible for setting up communication paths for themselves. A station may start a conversation with one or more destination stations by transmitting a message along the physical link. Any station whose local address matches with the destination address field of the message copies the message, other stations stand by if the message is not addressed to them. One advantage of such a hardware configuration is that a broken section of the physical link will not bring down the entire network. One disadvantage of the bus network is related to software protocols [33]. Because all stations on a bus network are treated with the same priority for accessing the network, a bus network becomes unsuitable in a real time computing environment in which some stations' priorities must be higher than others in order to perform real time jobs such as speech delivery and real time control.

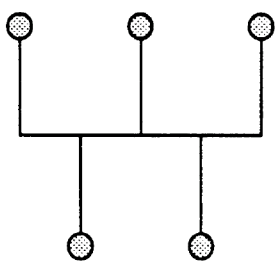
Due to the disadvantages described above, star networks are not as popular as ring and bus networks. Ethernet, developed at XEROX [28], and IBM's Token Ring [11] are two successful examples of LANs for bus networks and ring networks, respectively. The history of development work of Ethernet dates back to the early 1970s and was



(a) Star network



(b) Ring network



(c) Linear Bus network

Figure 1. Network topologies.

commercialized in 1980. Ethernet is a bus network based on CSMA/CD access method [2,4]. In CSMA/CD, a station on the bus wanting to send out a message must stand by and sense the link. If there is no other message traffic flowing on the link, the station transmits its message to the destination station through the link. At the moment that the transmission begins, other stations may also send their messages on the link. In this case, several messages are flowing on the link at the same time and hence, collision occurs. When a sending station senses the collision, it stops the transmission and broadcasts a short jamming signal to notify all other stations of the collision. After a random delay time, the station may retransmit the message.

Another type of popular LAN is IBM's Token Ring which is a ring network associated with a token passing access method [3,11]. The token passing access method is probably the oldest control scheme for ring networks, initially proposed in 1969 [12]. The IBM Token Ring, initially put on market as a product in 1985, was based on research results of IBM Zurich Research Center [5] and later became the prototype of IEEE 802.5 [3]. Unlike CSMA/CD, a token passing method is a contention-free method. It employs a short frame called a *token* with a unique frame format circulating around the physical link of the ring network. Initially, when a network is brought into service, only one token circulates around the ring link. The token in this state is called a *free token*. Any station intending to transmit its messages must wait for the free token to arrive. After catching the free token, the station changes the token from *free* to *busy* by changing one special bit in the token, and appends its message to the token, then sends it out. The message led by the token starts to travel around the link and passes through each station. Each station will examine the destination address field of the message to determine if the message is addressed to it or not. A station copies the message if it is addressed to it, otherwise the station stands by. The circulating message finally reaches the origi-

nating station, where the status of token is restored to *free*, so that other stations on the link may have opportunity to catch the token and use it. This scheme guarantees that only one station at a time may transmit. Hence, no contention is involved in the transmission between stations. This achieves a fairness of sharing channel bandwidth for each station on the link.

Both networks, bus with CSMA/CD and ring with token passing, have their own advantages and disadvantages. One factor contributing to the wide use of Ethernet based on CSMA/CD is that its hardware and software implementation is simple and hence inexpensive. Another factor is that any new station can be easily added to or removed from the network without shutting down the entire network.

Although the hardware configuration and software protocols of a CSMA/CD bus network have the advantages of low-cost and easy-implementation, the performance of the network may degrade under heavy load. The stochastic characteristics of collisions with CSMA/CD make the access time and response time of Ethernet statistical rather than deterministic. Therefore, the minimum response time of the network cannot be guaranteed, which makes Ethernet unsuitable for real time applications. Experimental results reveal that the efficiency of a heavily loaded Ethernet varies between 97 percent with a packet size of 512 bytes to 54 percent with a packet size of 64 bytes [33]. The results also show that the network achieves high performance under a lightly offered load, but low performance when the ratio of load to link capacity is over 50 percent.

Due to the closed loop configuration, a token ring network is sensitive to the failure of the physical link. This problem is alleviated by employing a concentrated wiring scheme as shown in Fig. 2 [5]. The wiring connector automatically bypasses the failed section of the link, if it is present. As mentioned earlier, it is difficult to add or remove a station

from a token ring network. However, token ring networks have some advantages over Ethernet such as fairness in sharing channel bandwidth, deterministic characteristics and good performance under heavy load. Experimental results [13] show that a token ring LAN achieves its maximum throughput under heavy load, which is a sharp contrast to CSMA/CD. Token rings also have a flatter performance curve than that of the CSMA/CD. With the advent of fiber optics, token rings gained further advantage over Ethernets because point-to-point fiber optics connections used in rings cause less energy loss of the signal travelling on a fiber optic link than splicing or tapping as required on a bus network [22].

1.2 Interconnected Local Area Networks

With the advent of LANs, distributed processing becomes more economical [29,37]. Since a single LAN can support only a limited number of users due to the distance limitations of its high rate transmission media, a large user community such as a campus may need more than one LAN to operate. This necessitates the interconnection of LANs. However, the interconnection of LANs gives rise to several problems such as protocol conversion, the distance of transmission media, and bottlenecks caused in bridges, etc. Various solutions have been suggested to solve these problems [23, 26, 27, 36, 38].

A major design goal of an interconnected LAN is the achievement of high performance by preserving desirable characteristics of a single LAN, such as high capacity, low queuing delay, packets in sequence, low error rate, etc. A traffic bottleneck could occur

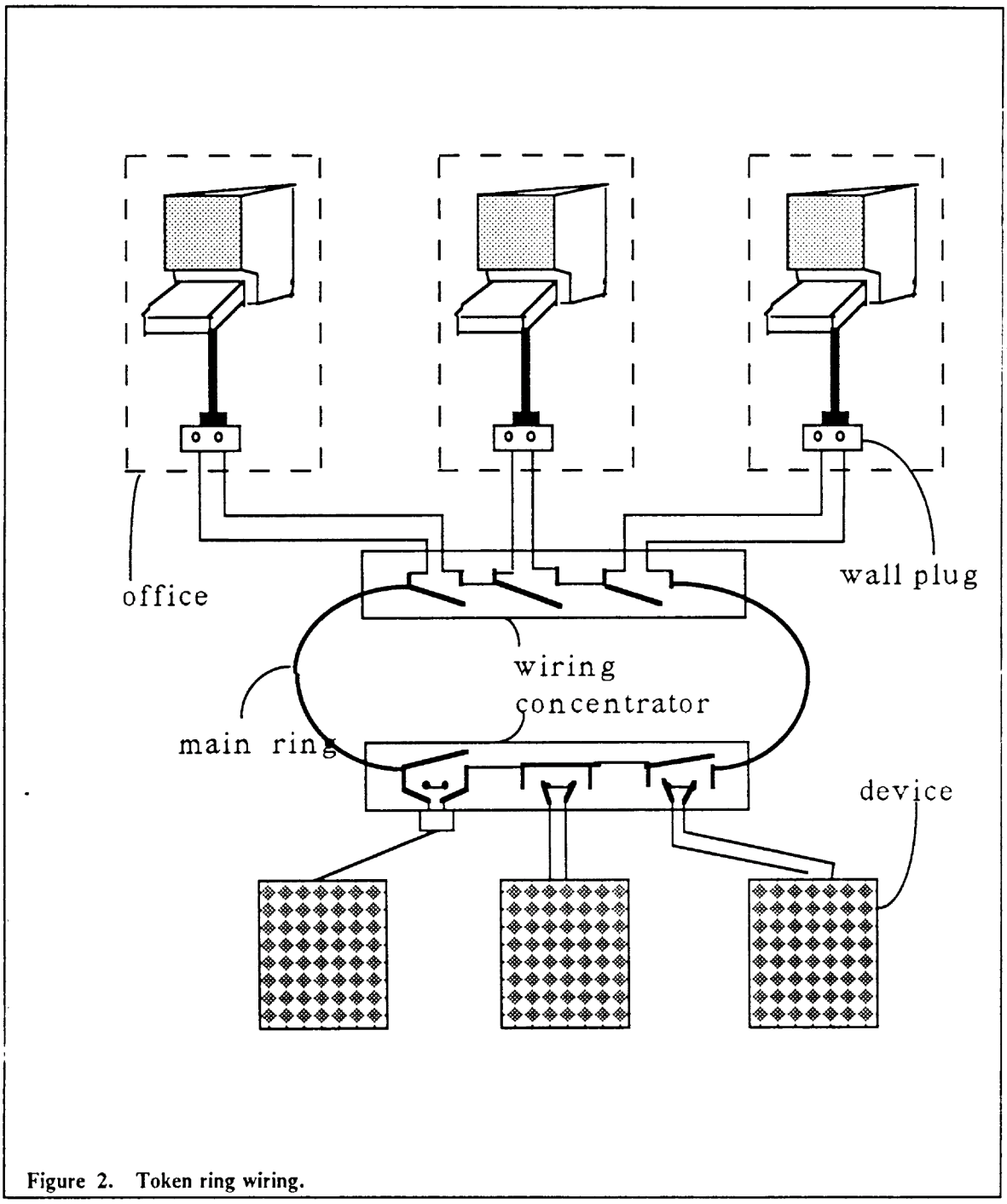


Figure 2. Token ring wiring.

when several LANs are linked together through bridges and backbones. A bridge is a specific station which is designated to connect two LANs and a backbone is a ring used for the purpose of supporting the interconnections. An intuitive explanation of the bottleneck is that all traffic in a local LAN which intends to go to other LANs will flock to a bridge first and, due to the limited buffer space in the bridge and the transmission rate of backbones, only a certain amount of traffic flow in a local LAN can pass through the bridge and be handled by the backbone. The rest of the traffic waits either on the channel link of the LAN or in its own stations. This defers other traffic and inflicts the whole network with a traffic jam. Increasing the processing capability of bridges and backbones is one possible solution to this problem. Three methods may be considered to increase the processing capability of bridges and stations. One method is to expand the buffer space in bridges. However, according to the experimental results reported by W. Bux [6], this method is not as effective as might be expected. The other two methods are to increase the transmission rate of backbones and to add one more transmission link medium to the backbone as proposed in this thesis.

To investigate the performance of the two methods, we considered two network models in this thesis. Both network models are composed of three local rings and one backbone ring. Each local ring is connected to the backbone ring through a bridge. The operation of the local rings and the backbone ring is confined to the IEEE 802.5 standard. In the first network model, the backbone ring consists of one transmission link, called single linked backbone ring. For the second model, the backbone ring consists of two links, creating double-linked backbone ring. By increasing backbone ring transmission speed alone, network performance is expected to be improved. By adding one more link to the backbone ring, the network performance is also expected to be improved. Simulation results, as reported in Chapter 4, show that the latter achieves a greater performance

improvement than the former in terms of throughput, utilization and response time. The double linked backbone ring especially improves the throughput by 40 percent for short messages. Therefore, we suggest that the double linked backbone ring be a solution to the bottleneck problem incurred in an interconnected network. Furthermore, double-linked ring structures can be used with the Fiber Distributed Data Interface (FDDI) [22], a proposed standard which is very close to the IEEE 802.5 standard.

Recently, some of new schemes have been proposed to improve the performance of LANs, such as the improvement of MAC protocol [21] or of the transmission protocol [30]. But these are based on the software protocols. The double linked ring structure which is based on the hardware structure may also be one of candidates for meeting LAN requirements for high capacity and high transmission rates applications such as voice/data integrated networks, facsimile, and video transmission, especially when fiber optics [34] are used.

The organization of this thesis is as follows. The protocols of the IEEE 802.2 Logical Link Control (LLC) and the 802.5 Media Access Control (MAC) standards are briefly described in Chapter 2. The two network models studied in this thesis are presented in Chapter 3. Simulation results on the two network models are reported in Chapter 4. Several suggestions for further study of the performance of double linked backbone ring network are also presented in this chapter. Chapter 5 concludes this thesis.

2.0 Protocols

With the ever increasing complexity of modern computer facilities, computer communications and networking become very complicated. A common set of well-organized and well-recognized design rules are therefore needed in order to promote product compatibility and reduce product development cost. In 1978, the International Standardization Organization (ISO) proposed a set of rules as a framework for development of networks, and in 1983, defined the set of rules as a reference model called the ISO OSI Reference Model [8,10,15,16]. The model is organized as a series of seven *layers*. Each layer has its own rules for performing a certain function. The rules for each layer are called the *protocol*. The services offered by a layer can be generally categorized into three types [18]:

1. the service to its immediate upper layer,
2. the service to its immediate lower layer, and
3. the service for conversations between peer layers.

2.1 *ISO OSI Reference Model*

The following is a brief list of the seven layers of the OSI model and their services.

1. *Physical layer* - concerns the definition of the electrical characteristics of bit streams flowing on the physical link such as voltages for logical *1* and *0*, the period of a bit, and mechanical interface, such as connectors.
2. *Data Link layer* - groups a bit stream into frames, and provides reliable data transfer across the physical link, such as frame-checking/recovery, and flow control.
3. *Network layer* - performs routing from source to destination, establishes communication paths for upper layers, and regulates traffic congestion.
4. *Transport layer* - provides network-independent and reliable transfer for its upper layers.
5. *Session layer* - provides services to establish sessions between users on different computer facilities. Issues related to the Session layer are session management and synchronization for the users' file exchange.
6. *Presentation layer* - unlike the five lower layers which deal with moving bit streams reliably from source to destination, this layer concerns itself with the syntax and semantics of the data transfer, such as data encryption, text compression and reformatting.
7. *Application layer* - provides general services such as virtual terminal and file transfer to users.

2.2 *IEEE 802.5 Medium Access Control (MAC)*

For LANs, the IEEE 802 standard defines two sublayers together to carry out the functions required in OSI Data link layer and Physical layer. The two layers are the IEEE 802.5 Medium Access Control (MAC) [3] sublayer and the IEEE 802.2 Logical Link Control (LLC) [1] sublayer. The MAC sublayer covers all physical layer requirements and a part of the Data link layer. The LLC layer covers most of the Data Link layer and a small portion of the Network layer as shown in Fig. 3.

The IEEE 802.5 MAC standard specifies bit-stream frame formats and control schemes for the token passing method. Fig. 4(a) and Fig. 4(b) sketch the token format and the data frame format which are the two basic formats of the IEEE 802.5 MAC sublayer, Fig. 4(c) is the LLC format which is formed at the LLC layer.

A token is a 3-byte unit consisting of a 1-byte Starting Delimiter (SD), a 1-byte Access Control (AC), and a 1-byte Ending Delimiter (ED). The Starting Delimiter and Ending Delimiter serve to identify the beginning and the end of the token format. The Access Control is used to indicate the token priority level and token status, which is either *free* or *busy*. The token passes through each station unidirectionally when all stations have no messages to transmit. A station having a message to transmit may wait to seize the token, change the token status bit in Access Control byte from *free* to *busy*, insert its data frame in between Access Control byte and Ending Delimiter byte, and then append a Frame Status byte to the Ending Delimiter. By this scheme, a free token can be converted to a busy token carrying a transmitted data frame, traveling around the physical link toward its destination station(s), and then returning to the originating station. The

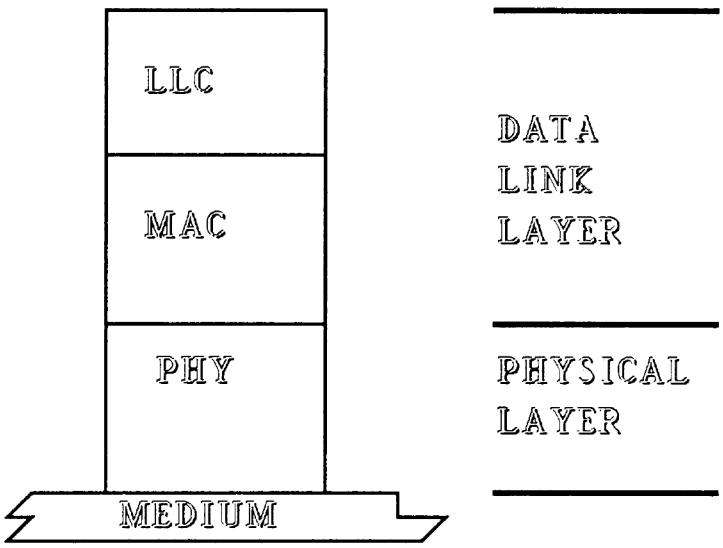
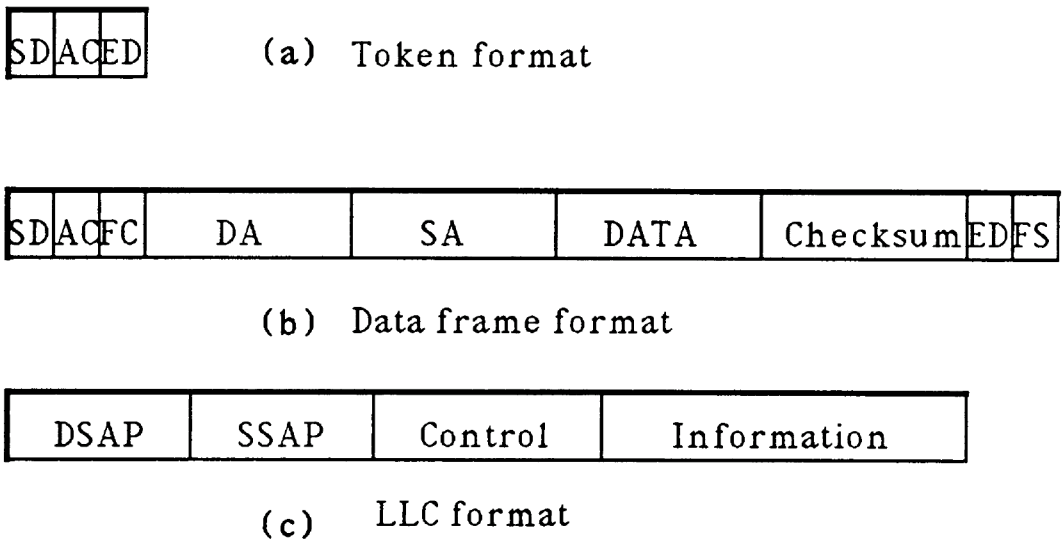


Figure 3. MAC sublayer and LLC sublayer.



SD: Starting Delimiter
AC Access Control
FC Frame Control
DA Destination Address
SA Source Address
FS Frame Status
DSAP Destination Service Access Point
SSAP Source Service Access Point
ED Ending Delimiter

Figure 4. IEEE 802.5 MAC and IEEE 802.2 LLC frame formats.

originating station is responsible for restoring the busy token back to a free token by removing the data from the returned data frame and changing the Token Status bit from busy to free.

As indicated in Fig. 4(b), a data frame uses the converted token as its start-of-frame sequence. The Frame Status byte is used by the originating station to differentiate among the following three conditions which may happen at the destination station.

- The destination station is either non-existent or non-active on the link.
- The destination station exists and does not copy the frame. This may happen when a congestion hinders the destination station from copying the frame.
- The destination station copies the frame.

The Data byte may contain either MAC data for the purpose of physical link maintenance or data coming from the LLC sublayer. Although there is no limit specified for data length, it is understood that the time required to transmit a data frame should not be greater than the token holding time specified at each station.

2.3 *IEEE 802.2 Logical Link Control (LLC)*

The IEEE 802.2 LLC sublayer provides two types of services, *connectionless* which is called Type 1, and *connection-oriented* called Type 2 which is adopted for this thesis, for communicating with peer destination sublayer(s). In Type 1, no logical connection needs to be set up prior to transmitting data. Therefore, there is no guarantee for data delivery by the LLC sublayer. In contrast to Type 1 service, Type 2 service requires setting up a

logical connection between two LLC sublayers before transmitting data. Therefore, more service primitives are required and more steps are needed to set up a connection and to transmit data, but data delivery can be guaranteed.

In Type 2 service, a station staying in Asynchronous Disconnected Mode (ADM) having messages in its higher layer, such as the Network layer, to transmit must send a Link_Connect_Requirement command primitive to the LLC sublayer before data transmission. Once the command is received, the LLC sublayer gives its MAC sublayer a Connect_Setup command, and changes itself from ADM to another mode, SETUP Mode, to wait. The MAC sublayer then puts LLC data in the data bytes of MAC data frame and sends it out over the physical link to the destination station. The LLC sublayer of the destination station will then receive the command from its immediate MAC sublayer if no transmission error occurs. Once the command is received, the destination LLC sublayer then replies with a Link_Connect_Indication to its higher layer to indicate a connection-setup request has been issued by a remote station. If the higher layer accepts the indication, then it gives its LLC sublayer a Link_Connect_Response command primitive. The primitive will then go through a procedure similar to the one at the source station. Once the LLC sublayer in the source station receives the response, it then replies with a Link_Connect_Confirm to its higher layer. Thus, a logical connection is set up by the peer LLC layers using four service primitives between the LLC sublayers and higher layers, and messages may start to transmit over the logical connection.

3.0 Network Modeling

3.1 Models of Networks

In this thesis, we study two token ring interconnected networks through simulations and the simulation work is based on the graphical methodology [17]. The methodology is based on a graphical representation of the network model. The network model is constructed interactively on a computer from the graphical representation without writing code. The two networks as shown in Fig. 5 and Fig. 6 are identical except in the number of links for the backbone ring. The network of Fig. 5 is called a *Single Linked Backbone Ring* (SLBR) interconnected token ring network. The network of Fig. 6 is called a *Double Linked Backbone Ring* (DLBR) interconnected token ring network. Each network consists of three local rings, labeled as *ring 1, ring 2,* and *ring 3* in Fig. 5 and Fig. 6, and one backbone ring, labeled as *ring 0.* Each local ring has four stations attached. The three local rings are connected together through the backbone ring and three bridges (labeled as *bridge 11, 21,* and *31*). In Fig. 5, all stations on a ring are connected through a single physical point-to-point transmission link, which may be either a twisted-pair or

a coaxial cable. The operation of each ring is modeled as described in the IEEE 802.5 Standard. A bridge is considered to be a station with limited functions. For example, a bridge performs only message storing and message forwarding. In Fig. 6, the operation of the backbone ring of the DLBR is confined to IEEE 802.5, but consists of two physical transmission links instead of one.

3.1.1 Models of Stations

Stations on ring 1 of Fig. 5 and Fig. 6 are labeled as *station 12, 13, 14,* and *15*, on ring 2 as *station 22, 23, 24,* and *25*, on ring 3 as *station 32, 33, 34,* and *35*. The model of a station is shown in Fig. 7 which can be found in Bux and Grillo [6]. Each station is modeled as four layers: *higher* layer, *LLC* layer, *MAC* layer, and *physical* layer. Corresponding to the higher layers in the ISO OSI seven-layer model, the higher layer receives messages from the station's traffic source and processes them while incurring processing delay and frame overheads (the process unit is denoted in Fig. 7 by the box "MSG XMT"). The frame overheads include source and destination addresses, frame-checking bytes, control bytes, frame-synchronization bytes, etc. A traffic source is a user or a host computer which generates messages at a random rate with a pre-assumed mean value and an upper and lower bound value. The lengths and interarrival times of generated messages are exponentially distributed [24,25]. The interarrival time is the length of time between two successively generated messages.

A message generated in the traffic source is sent to the LLC layer after being processed in the higher layer. The LLC layer processes the message received from the higher layer by the processing unit. The processing time and the LLC overhead are taken into ac-

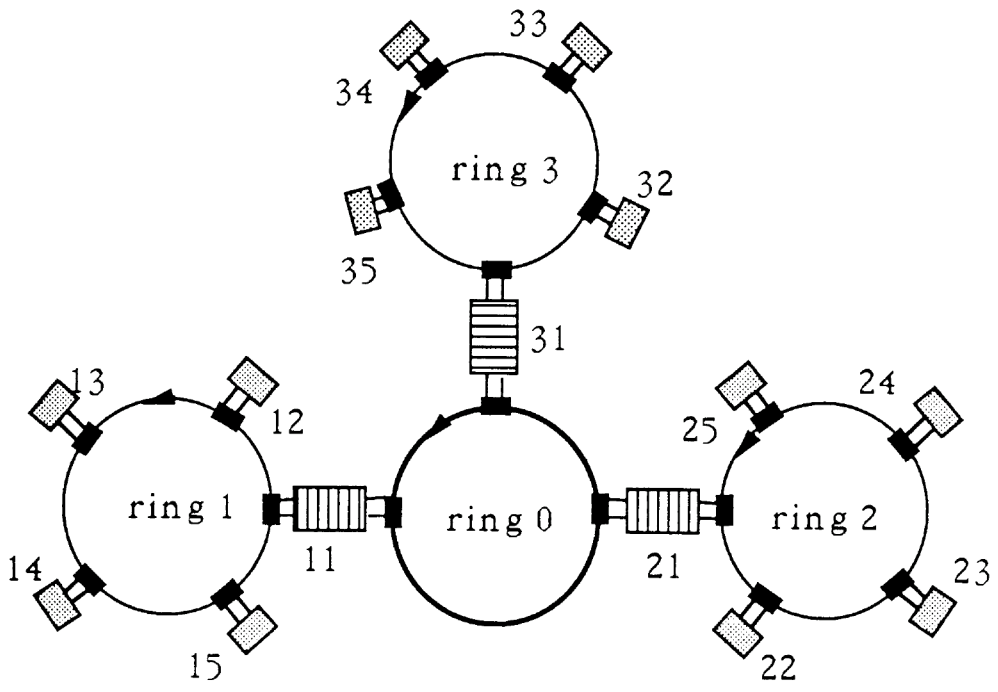


Figure 5. Single linked backbone ring interconnected token ring.

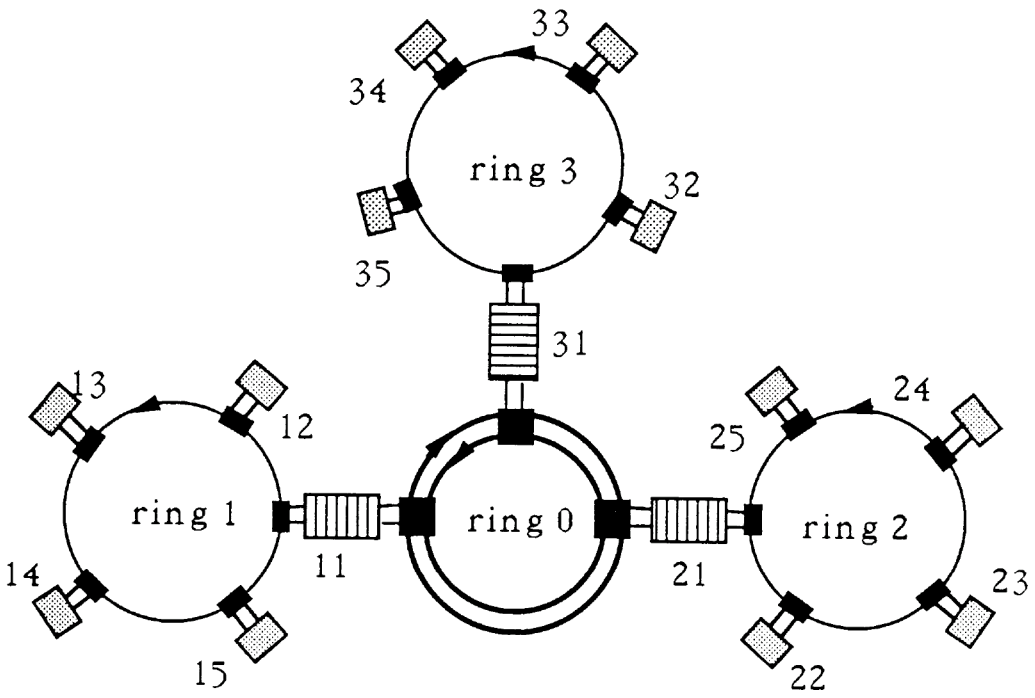


Figure 6. Double linked backbone ring interconnected token ring.

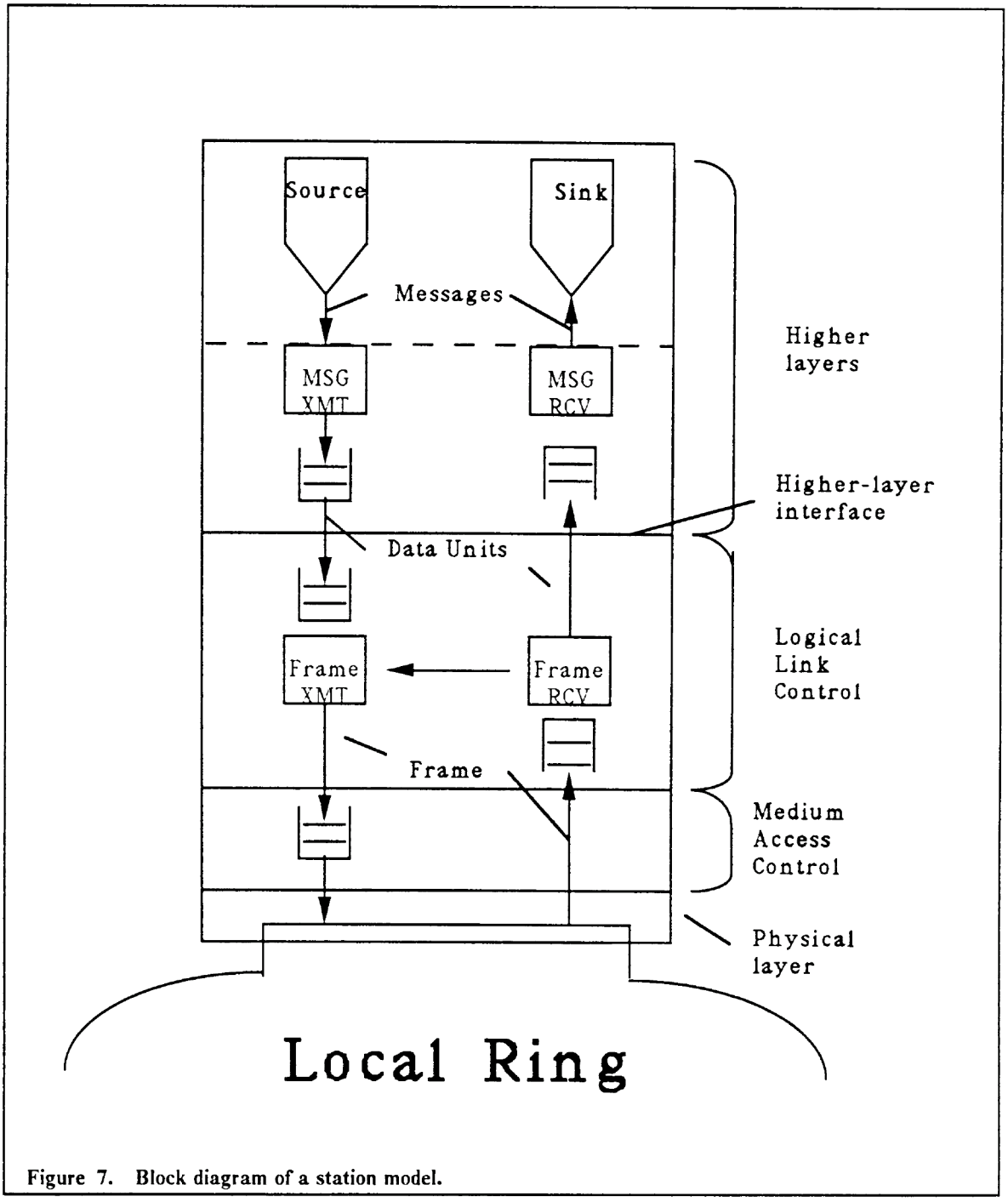


Figure 7. Block diagram of a station model.

count for the performance evaluation. The processing unit in the LLC layer is denoted by the box "Frame XMT." After the LLC layer finishes processing the message, it passes the message down to the MAC layer which is responsible for catching a free token and transmitting the message to the destination station. When the station is so busy that it can not handle other messages, the traffic source in the station will be notified to suspend the generation of messages until the station can handle more messages. When the station gains the access right to the link by grasping a token, an I/O setup time is required for input and output connection setup between the station and the ring. The I/O set up time is the time required by the MAC layer and physical layer to process frames and convert them into electronic signals using a predefined signalling protocol.

The two processing units described above are for message transmission. For the receiving elements within a station, there are also two processing units, "Frame RCV" in the LLC layer and "MSG RCV" in the higher layer, and a traffic sink. When a message frame arrives, the station copies it into the LLC layer where the LLC overhead of the frame is removed and processed within a processing time period (the processing unit for this process is denoted by a box "Frame RCV"). After the LLC finishes processing the message, the message is sent to the process unit in the higher unit. The processing unit in the higher layer is denoted by a box "MSG RCV." The message will be finally sent to the traffic sink after it is processed by the process unit "MSG RCV". Every successfully received message passing through the traffic sink is used to measure performance, because the user's data are sent and received at the traffic source and sink level.

3.1.2 Models of Bridges

As shown in Fig. 5 and Fig. 6, the three bridges are labeled *bridge 11*, *bridge 21*, and *bridge 31*. Each bridge consists of two buffer pools and two processors. The model of a bridge used in a single linked backbone ring network is shown in Fig. 8, and the model of a bridge used in a double linked backbone ring network is shown in Fig. 9. The difference between these two bridges is that the latter has two I/O setup units while the former has only one for the reason that the latter is connected to two physical transmission links. To achieve high efficiency, the bridges are modeled to perform a simple routing and store-and-forward function only [6]. Frames coming from a local ring or a backbone ring are put into a buffer pool at the bridge until they can be sent again on the backbone ring or another local ring. The two buffer pools are each responsible for one direction of data-flow, i.e., for backbone-to-local ring and for local ring-to-backbone. Each direction of data flow is controlled by two processors. These processors are modeled by two independent servers and denoted by two boxes in Fig. 8 or in Fig. 9 labeled "Frame processing" which process all incoming messages on a first-come first-serve basis.

3.1.3 Models of Local Rings

Local rings in the network are labeled as *ring 1*, *ring 2*, and *ring 3* in Fig. 5 and Fig. 6. Local rings are connected to the backbone ring, ring 0, through bridge 11, bridge 21, and bridge 31. Each local ring is modeled identically, and the operation of a local ring is modeled according to the IEEE 802.5 Standard. Each local ring has four stations and one bridge.

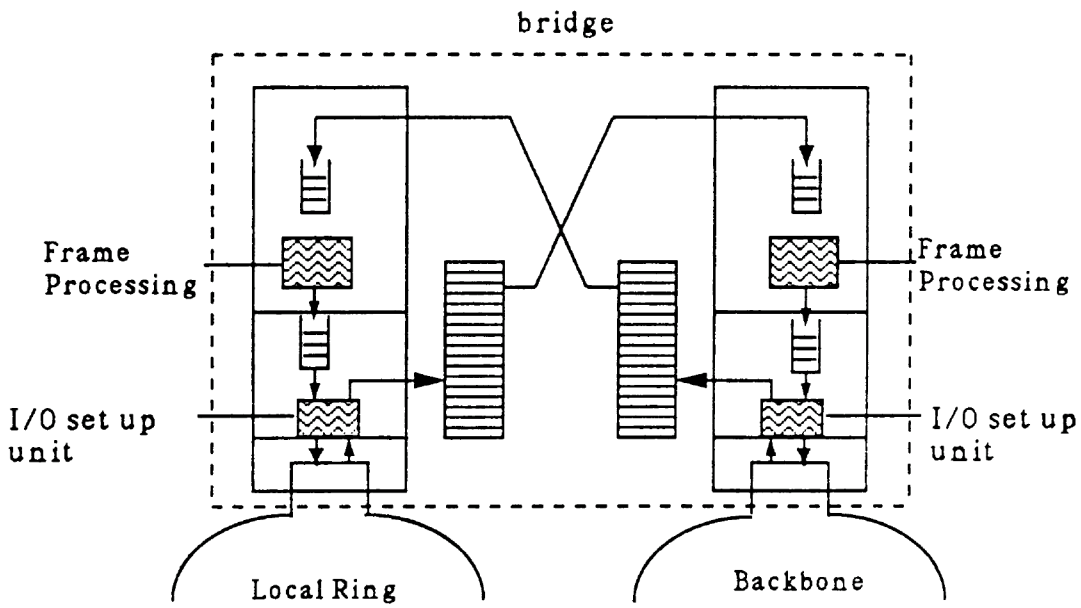


Figure 8. Block diagram of a bridge model in a single linked backbone ring network.

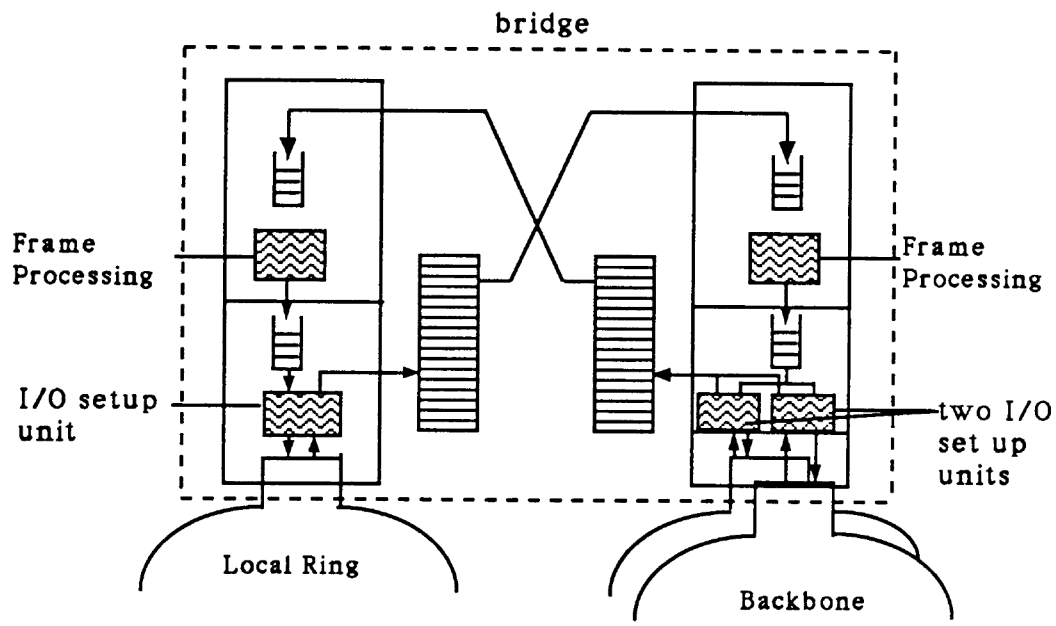


Figure 9. Block diagram of a bridge model in a double linked backbone ring network.

3.1.4 Models of Backbone Rings

The backbone ring of Fig. 5 and Fig. 6 is labeled as *ring 0*. The backbone ring in Fig. 5 consists of one physical transmission link. The backbone ring in Fig. 6 consists of two physical transmission links. The usage of this structure is different from the one of FDDI in which a ring consists two physical links, one is active, while the other stands by for the purpose of redundancy. The operation of each link is as defined in IEEE 802.5. Each of the links is assumed to share the responsibility for delivering messages. For example, when a message occupies one link while the other link is idle, the idle link will be available immediately to a bridge which has messages to transmit to the backbone ring. Therefore, two streams of data may flow on the backbone ring at the same time.

3.2 Implementation of the Network Models

The implementation of the network model is modularized by using a simulation tool, NETWORK II.5 which is a product of CACI, Inc. [7]. The implementations of network models for both the single linked backbone ring network and the double linked backbone ring network are quite similar except that in the latter case the modules residing at the bridges to handle message forwarding through the backbone ring contain an additional decision function to choose one of two backbone ring links. The source-destination station pairs in both networks are fixed, i.e., each station has only one fixed destination station. For example, station 12 always sends and receives messages from station 35. The other station pairs are station 13 and station 34, station 14 and station 23, station 15 and station 22, station 32 and station 25, station 33 and station 24. We first describe

modules in a station and a bridge, and since all message flows are implemented in the same way except with different source-destination station pairs, we then show one data flow between station 12 and station 35 in two phases, i.e. logical connection setup phase and data transfer phase, starting from station 12, traveling through ring 1 to bridge 11 to ring 0 to bridge 31 to station 35 for discussion of network model implementations.

The modules for implementing a station model are depicted in Fig. 10 and Fig. 11. The modules for implementing a bridge are depicted in Fig. 12. The symbols in the figures and terms used for the following description are from the *NETWORK II.5 Users' Manual* [7]. The name of each bridge appears in a module labels "St xx" instead of "Br xx" for the convenience of programming, where xx stands for the bridge number, 11, 21, or 31. The following sections describe each software module in station 12 and bridge 11.

3.2.1 The Implementation of Station 12

Send Hello from St 12 resides in station 12 and is driven by incoming messages from a traffic source. The interarrival period between two successive messages is not fixed but exponentially distributed. This module starts running when a message is received from a traffic source, and then generates a 22-byte acknowledgement message frame named "HELLO" which corresponds to the command frame "SABME" specified in the IEEE 802.2 Standard. In most cases, the command frame "SABME" is used by a station to set up a logical connection. "HELLO" is used for the same purpose to set up a logical connection between station 12 and station 35. The logical connection setup may be started either from station 12 or station 35. If it starts from station 35, then the

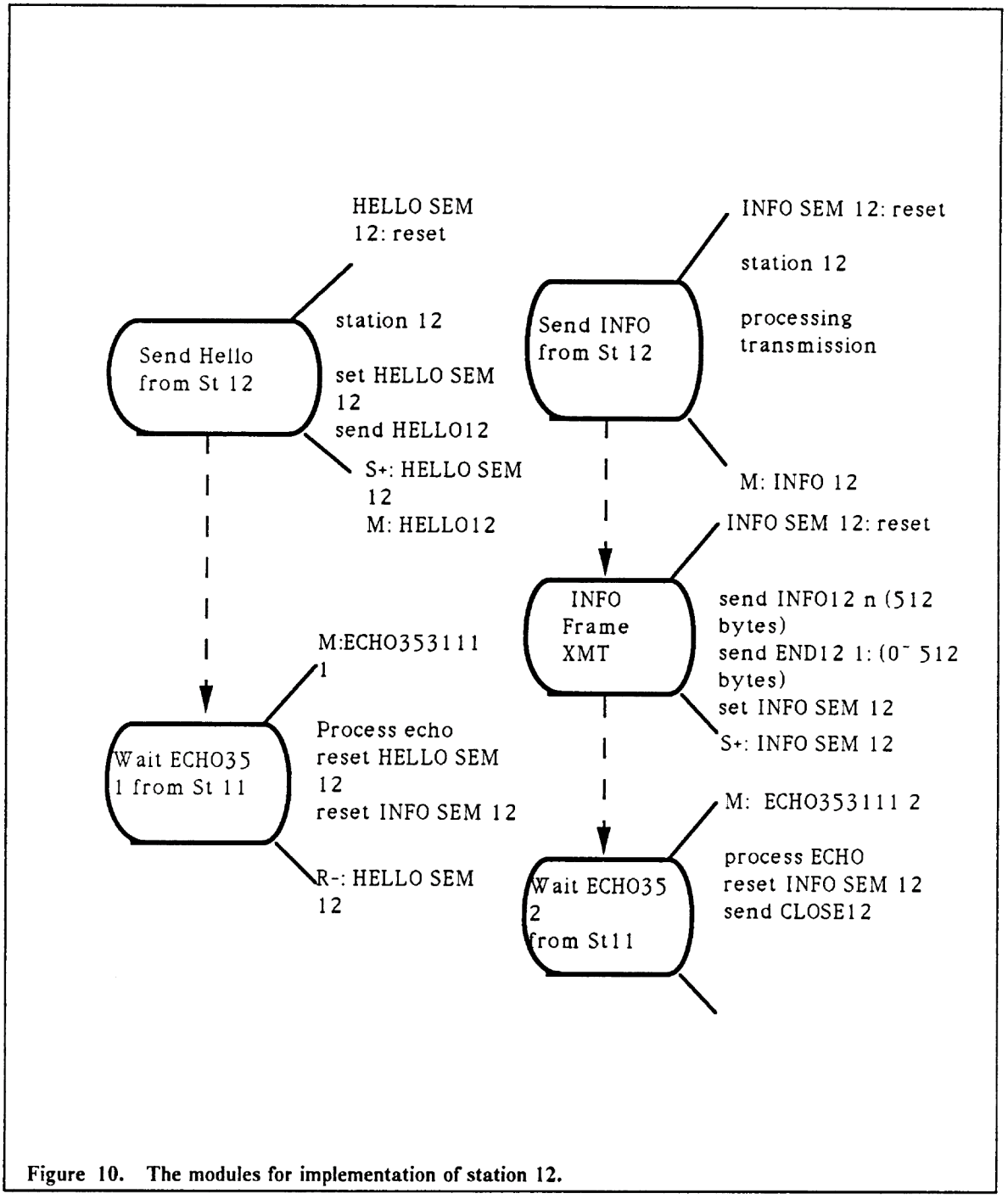


Figure 10. The modules for implementation of station 12.

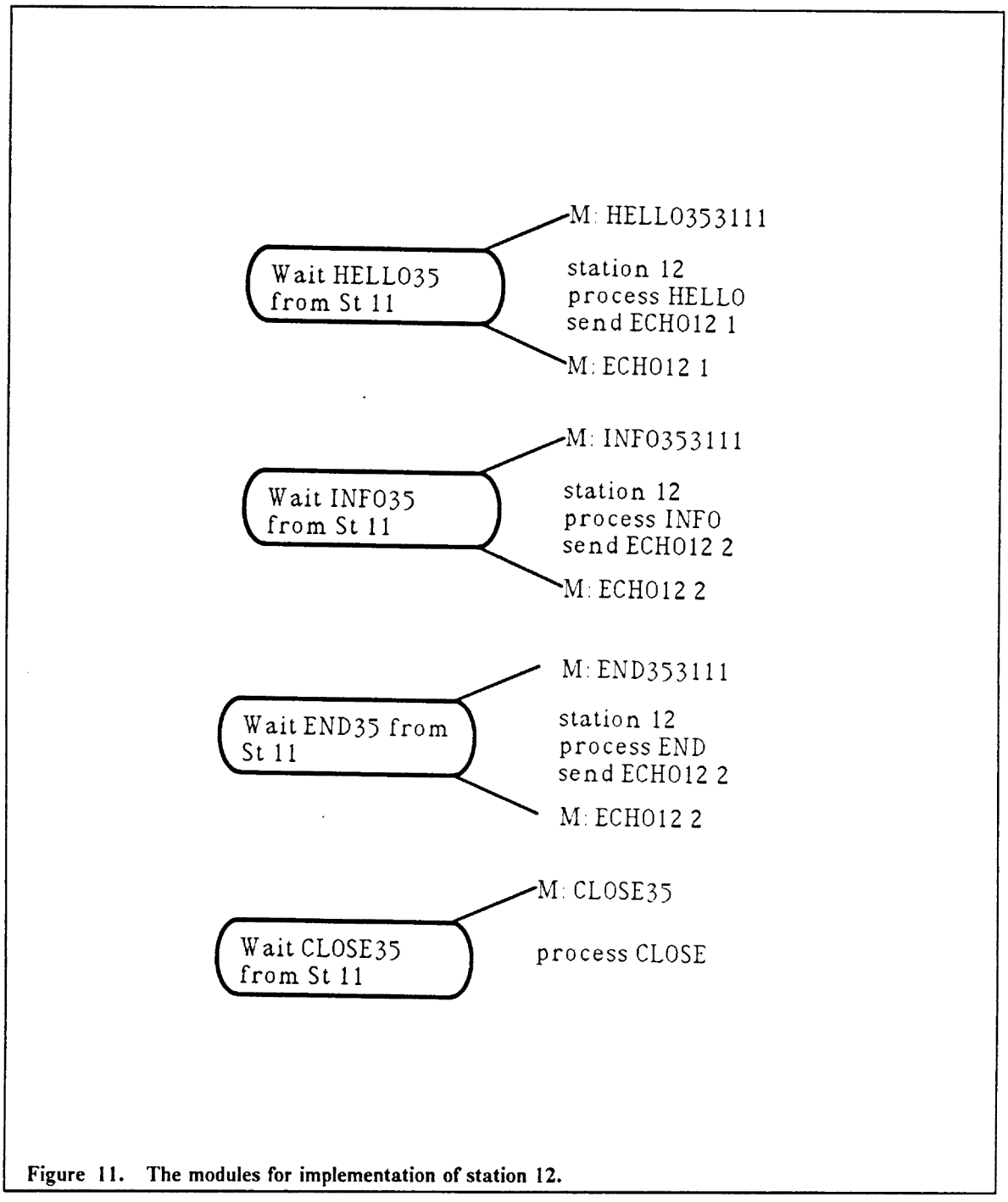


Figure 11. The modules for implementation of station 12.

"HELLO" is originated from station 35 instead of station 12 by one module "Send Hello from St 35" residing in station 35.

One semaphore "HELLO SEM 12" is used as a flag for the purpose of concurrent execution of several modules within one station. The semaphore "HELLO SEM 12" is set to 1 after the station has received a message from the traffic source. Once the semaphore "HELLO SEM 12" is set, the station is put in a queue waiting to catch a free token running on ring 1. The rules for waiting for and catching a free token strictly follow the IEEE 802.5 Standard. Once a free token is caught, the "HELLO" acknowledgement message in station 12 is sent to bridge 11 through ring 1 and the module "Send Hello from St 12" halts until the semaphore "HELLO SEM 12" is reset to 0 by the module "Wait ECHO35 1 from St 11".

Wait ECHO35 1 from St 11. This module is activated after the previous module, "Send Hello from St 12" stops. When this module starts, a timer with a predefined timeout value in the module is activated to monitor the process of setting up the connection with the destination station. The timer counts the simulation clock and processes a response message, "ECHO35 1", from the destination station if the response message is received before the timeout is reached. The messages "ECHO35 1" is a connection-setup-agreed response message from the destination station, which corresponds to the UA command defined in the IEEE 802.2 Standard. The semaphore "HELLO SEM 12" will be reset to 0 by the module after either a response message is received or time out is reached. If the response message is received in time, the following module, "Send INFO from St 12", will be activated, and the user-generated messages will then be sent. Otherwise, the "Send Hello from St 12" will be started again because the previous try of setting up the logical connection fails. Attempts will be then repeated until it succeeds.

Send INFO from St 12 together with the module "INFO Frame XMT" executes messages transmission from station 12. The module "Send INFO from St 12" processes the message generated in the traffic source and then passes it down to the LLC sublayer in which the module "INFO Frame XMT" is started. In the simulation, processing is modeled as a fixed delay.

INFO Frame XMT performs the LLC function in a station, which receives a message from the module "Send INFO from St 12" and splits it into several packets and then puts the station in a queue to wait for a free token. After a packet is sent out, the semaphore "INFO SEM 12" is set to 1 and the module "INFO Frame XMT" stops to trigger the execution of module "Wait ECHO35 2 from St 11".

Wait ECHO35 2 from St 11 is started after the module "INFO Frame XMT" suspends execution. This module has similarity with another module "Wait ECHO35 1 from St 11". The module monitors the process of message transmission across the network by a timer in station 12. The timer counts the simulation clock and the module processes the response message, "ECHO35 2", coming from the destination station if the response message is received before the timeout is reached. The message "ECHO35 2" is used as a message-received acknowledgement from the destination station. The semaphore "INFO SEM 12" is reset after either an acknowledgement is received or time out is reached. In the former case, the module "INFO Frame XMT" is re-activated and another packet is sent out again. The process "INFO Frame XMT" → "Wait ECHO35 2 from St 11" → "INFO Frame XMT" is continued until all packets in the LLC layer are sent out. In the latter case, the "INFO Frame XMT" will re-send the previous packet because the previous attempt failed.

Wait HELLO35 from St 11 is responsible for processing the incoming acknowledgement message frame "HELLO" from station 35 if the attempt to set up a connection between station 35 and station 12 is made in station 35 first. The module copies the message into the LLC layer and processes it, and responds by sending a response message "ECHO12 1" across the network to station 35 to complete the connection setup procedure.

Wait INFO35 from St 11 handles an incoming packet from station 35. The module processes the packet in a period of processing time and returns a response message, "ECHO35 2", which represents the successful arrival of the last packet to the station 35.

Wait END35 from St 11 is responsible for processing an incoming acknowledgement message "END35" from station 35 which requires the end of the transmission of a message.

Wait CLOSE35 from St 11 is responsible for processing a coming acknowledgement message "CLOSE35" from station 35 which requires the termination of the connection between station 35 and station 12.

3.2.2 The Implementation of Bridge 11

Store and Forward 12 and **Store and Forward 31_35** reside in bridge 11 and execute the store-and-forward function for data flow between station 12 and station 35. "Store and Forward 12" buffers any message from station 12 by putting it into bridge 11's buffer pool and pops another message onto the top of the buffer pool and forwards it to bridge 31. If the bridge does not find enough space in the buffer pool for the incoming messages, it then discards the message. The decision of choosing a backbone ring link is

made in this module. This module is responsible for unidirectional data flow from station 12 to station 35. Another module "Store and Forward 31" handles another data flow between the same station pair from station 35 to station 12. Thus, two modules in a bridge handles two different directional data flows traveling on a logical connection between a station pair. The other modules residing in the bridge 11 handle other data flows between other station pairs. They are "Store and Forward 13" and "Store and Forward 31_34" for data flows between station 13 and station 34, "Store and Forward 14" and "Store and Forward 21_23" responsible for data flows between station 14 and station 23, "Store and Forward 15" and "Store and Forward 21_22" responsible for data flows between station 15 and station 22.

3.2.3 Phase 1: Connection Set Up

As described in Chapter 2, for Type 2 service, a logical connection must be set up before a message transfer starts. The connection setup procedure and software modules involved are modeled as follows. The module "Send Hello from St 12" is driven by an incoming message from the traffic source, and hence starts when a message is generated. The module processes the message and generates an acknowledgement message "HELLO", and then puts station 12 in a queue waiting to catch the free token on the local ring. The purpose of "HELLO" is to set up a connection between two stations. After sending the acknowledgement message "HELLO", the module "Send Hello from St 12" suspends the execution and another module "Wait ECHO35 1 from St 11" begins. The module "Wait ECHO35 1 from St 11" triggers a timer in station 12 and waits for a response message "ECHO35 1" from station 35 to come. When the message "HELLO" from station 12 reaches bridge 11, a module called "Store and Forward 12" in the bridge

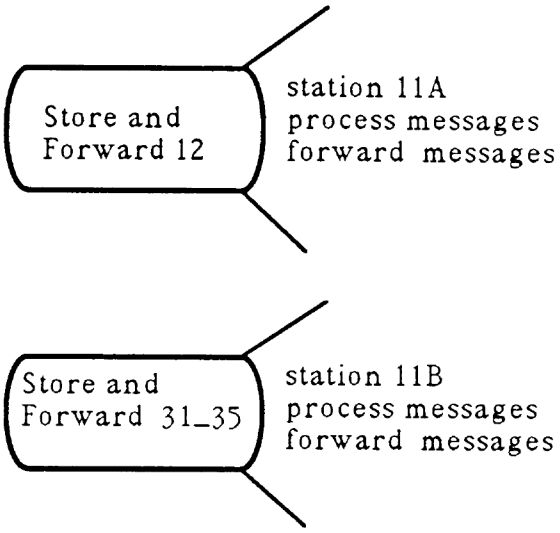


Figure 12. The modules for implementation of bridge 11.

starts and copies the message into the bridge's buffer pool if the buffer space is available for the message. Whenever the buffer pool is filled with one message and the backbone ring's token is caught by the bridge, the module at the bridge pops one message from the top of the buffer pool at the bridge and sends it over the backbone ring, ring 0, to another bridge, bridge 31. If the buffer pool becomes empty, the module "Store and Forward 12" stops running until the next messages from station 12 arrives. When the message "HELLO" coming out from bridge 11 arrives at bridge 31, a module "Store and Forward 11_12" starts. The module "Store and Forward 11_12" performs the same functions as "Store and Forward 12" does, except it targets station 35. If there is no other message in bridge 31, the message "HELLO" should be sent out to station 35 after a short stay in bridge 31. The time of the short stay for "HELLO" represents the bridge's processing time. The message "HELLO" from bridge 31 travels over the local ring, ring 3, until it reaches station 35. A module, "Wait HELLO12 from St 31" in station 35, starts when the message "HELLO" arrives and processes the "HELLO". Station 35 generates a response message "ECHO35 1" to respond to station 12 for the agreement of setting up the connection. The message "ECHO35 1" coming out from station 35 will rush to bridge 31 to start the module "Store and Forward 35". The module "Store and Forward 35" performs the function similarly for the message "ECHO35 1" as the other module "Store and Forward 11_12" does for the message "HELLO". The message "ECHO35 1" goes through bridge 31 and bridge 11 to reach station 12. After station 12 receives the message "ECHO35 1" within the timeout period, the module, "Wait ECHO35 1 from St 11", stops the timer and sets it to 0, and another module, "Send INFO from St 12" in station 12, is activated to start delivering the message generated from the traffic source over the logical connection to station 35. At this point, the first phase, connection set up, is finished, and the second phase, data transfer begins.

3.2.4 Phase 2: Data Transfer

The second phase, data transfer, starts with module "Send INFO from St 12". When the semaphore "INFO SEM 12" is reset by the module "Wait ECHO35 1 from St 11", the module "Send INFO from St 12" starts and processes the message. When the message processing is finished, another module called "INFO Frame XMT", which executes the LLC functions, starts. The message is divided into packets of 512 bytes and then delivered packet by packet. When a packet is sent, a timer in the station is immediately activated, and the module "INFO Frame XMT" stops to trigger another module "Wait ECHO35 2 from St 11". A response message is required to be returned to the source station from the destination station as soon as each packet sent by the source station is received by the destination station. The module "INFO Frame XMT" stops after each packet sent and the semaphore "INFO SEM 12" is set to 1 until a response message, ECHO35 2", from station 35 comes or the timer in the station times out. The timer is triggered by the module "Wait ECHO35 2 from St 11". If a response message from station 35 is received in time, the semaphore "INFO SEM 12" will be reset and the module "INFO Frame XMT" proceeds to send another packet. After a packet is released from station 12, it travels over the local ring, ring 1, to bridge 11. When bridge 11 receives the packet, the module "Store and Forward 12" starts. The packet goes through the same procedure as the setup acknowledgement message "HELLO" from bridge 11 to bridge 31. When the packet comes from bridge 31 and reaches station 35, the module "Wait INFO12 from St 31" in station 35 starts to process the incoming message and returns a response message, "ECHO35 2", to station 12 by going through the same route to acknowledge the success of the arrival of the previous packet. The modules in bridge 31 and bridge 11 responsible for handling the message are "Store and Forward 35" and

"Store and Forward 31_35". The module in station 12 to handle the message, "ECHO35 2", is "Wait ECHO35 2 from St 11" which times the sending process. The process of sending a packet is complete when the response message "ECHO35 2" arrives. The same process is repeated until all packets in the LLC sublayer are sent.

3.3 Simulation Parameters

The first eleven simulation parameters are from W. Bux [6].

1. The transmission rate of each local ring is 4 megabits per second (Mbps).
2. The transmission rate of a backbone ring is 4 Mbps or 16 Mbps.
3. The processing time for message transmission for the higher layer of each station is 2 ms.
4. The processing time for message reception from the higher layer of each station is 2 ms.
5. The processing time for data frame transmission for the LLC sublayer of each station is 1.5 ms.
6. The processing time at the LLC sublayer for correct data frame received from the MAC layer and forwarded to the higher layer is 1.5 ms.
7. The processing time for receiving an acknowledgement frame is 1 ms.
8. The processing time for transmitting an acknowledgement frame is 0.5 ms.
9. The bridge processing time for storing and forwarding data is 1 ms.
10. The default size of the buffer pools at a bridge is 4 Kbytes.
11. The maximum I-field length of a LLC frame is 0.5 Kbytes.

12. The framing overhead of a LLC frame plus MAC frame and the length of an acknowledgement frame are 22 bytes, which are obtained from Fig. 4.
13. The I/O setup time is 1 ms. for both stations and bridges. This setup time is generally required for most of the network interface circuits in industry.
14. The statistical distribution of the interarrival times between successive messages and the length of message frames are exponential. This assumption is adopted in Hammond and O'Reilly [14] for the analytical study of network performance.
15. The timeout value of the timer in a station is set to 500 ms. to make sure that all sending stations will receive responses within the timeout.
16. The traffic patterns are: Station 12-bridge 11-bridge 31-station 35, station 13-bridge 11-bridge 31-station 34, station 14-bridge 11-bridge 21-station 23, station 15-bridge 11-bridge 21-station 22, station 25-bridge 21-bridge 31-station 32 and station 24-bridge 21-bridge 31-station 33.

3.4 Network Performance

The performance of a network can be represented in terms of throughput, utilization, and response time. The three measures of network performance are measured at the level of the source and sink of each station, where correct messages are generated and returned.

In the following, definitions of the three terms and total offered data rate are given.

- *Utilization* is defined as the average fraction of time in which a device is occupied. It is expressed as a percentage. A device may be a station, a ring link, or a bridge. In this thesis, utilization is considered for bridges and backbone rings. The occupancy time of a bridge, as modeled in Fig. 8 and Fig. 9, includes message-receiving time, message-waiting time in a buffer pool, message-processing time in a processing unit, the token-waiting time, I/O setup time, and message-transmitting time. Among them, only message-receiving time and message-transmitting time are exponentially distributed since they are determined by message length which is assumed to be exponentially distributed. I/O setup time and message-processing time are fixed, as defined in Sec. 3.3. Because we are only interested in high utilizations, we assume that the I/O setup time of a bridge in the double linked backbone ring network in Fig. 9 is half that of a bridge in single linked backbone ring network as shown in Fig. 8 since there are two I/O setup units operating in parallel as shown in Fig. 9.
- *Throughput* is defined as the average number of bits passing through sinks of all stations each second. Thus it is measured in bits per second (bps). For example, each sink of any station may receive 10 Kbps on average, then for the whole network, the total throughput should be 100 Kbps × 12 (stations) = 1.2 Mbps.
- *Response time* is the average time measured starting from a message being generated at a station until a confirming response message from the destination station is received. The response time is measured in milliseconds (ms.).
- *Total offered data rate* is the average message generation rate in bps for the entire network. This is an input parameter exerting control over the entire simulation. Each station may generate messages at a random rate, which differs from station to station. The sum of the data generation rate of all stations in the network is then the total offered data rate for the entire network. In this thesis, the offered data rate for each station is assumed to be equal. Therefore, if the offered data rate for individual

station is equal to 100 Kbps, then the total offered data rate is equal to 100 Kbps × 12 (stations) = 1.2 Mbps.

3.5 *Abbreviations*

The following abbreviations are used.

SLBR: Single Linked Backbone Ring.

DLBR: Double Linked Backbone Ring.

4M-SLBR: A SLBR with transmission rate of 4 Mbps.

16M-SLBR: A SLBR with transmission rate of 16 Mbps.

4M-DLBR: A DLBR with transmission rate of 4 Mbps for each link.

16M-DLBR: A DLBR with transmission rate of 16 Mbps for each link.

3.6 *Research Area*

We may expect a problem, specially a bottleneck problem, to occur in the bridges or in the backbone ring for the network of Fig. 5. The three local rings in the network are connected through a backbone ring by three bridges. Therefore, all messages traveling between different local rings must go through the bridges and the backbone ring, and thus the traffic flows in the bridges and the backbone ring are heavier than those in the local rings. It is very likely that traffic jams may start from the bridges or the backbone

rings when the amount of data coming to the bridges increases beyond the bridges' capabilities. When a bridge's processing capability reaches saturation, all deliveries of later incoming data will be deferred and hence the total data throughput of the network will be decreased and the response times increased. Such problems, causing the network performance to deteriorate due to the limited processing capabilities of bridges and the backbone ring are called bottleneck problems.

To overcome the problem, we studied two alternatives. The two alternatives focus on the backbone ring and bridges, since they may be the place where traffic jams occur due to their limited processing capabilities. Intuitively, we expect that the bottleneck problem may be alleviated by increasing the processing capabilities of the bridges and the backbone ring. For the following two alternatives, both the bridge processing speed and the backbone ring transmission speed are the same. One alternative we examine is the network performance effects due to different transmission rates of the backbone ring. In this thesis, we studied two different transmission rates of the backbone rings: 4 Mbps and 16 Mbps. The other alternative we studied is to add one more physical link to the backbone ring and one more I/O setup unit to each bridge. Therefore, the backbone ring becomes double linked and the operation of the backbone ring is changed from half duplex to full duplex and the number of I/O setup units near the backbone ring in each bridge is doubled to two so that the I/O setup time for the backbone ring can be considered to be half that of a bridge in a single linked backbone ring. By this change, we expect the entire network's performance to be improved.

To obtain performance measures, we simulated the network models using a network simulator, NETWORK II.5. NETWORK II.5 takes a user-specified computer system description and provides measures of hardware utilization, software execution time, and

system performance, such as response time, and throughput. The simulator runs on SUN 386i workstations.

4.0 Performance Measures

In this chapter, experimental results on the performance of the two modeled networks described in Chapter 3 are presented. The utilization, throughput and response time of the networks was measured in terms of the total offered data rate. Three different mean message frame lengths, 2, 4, and 8 Kbits, were considered in the experiments. The knee rate, to be explained later, of a utilization or throughput curve is obtained as the total offered data rate corresponding to the ninety five percent of the saturated value of the curve in the experiments. The critical rate of a response time curve is obtained as the total offered data rate corresponding to the ninety five percent of the saturated value of the curve. The last value of each response time curve is taken as the saturated value in the experiments.

4.1 Utilization

As defined in the previous chapter, utilization curves are used to depict the traffic condition of a specific device, such as a bridge or a backbone ring. Low utilization of a bridge or a backbone ring is desirable for the efficient operation of the network. The utilization of bridges and the backbone rings of the SLBR and DLBR networks was measured for the two backbone ring transmission rates, 4 Mbps and 16 Mbps.

Fig. 13 shows two sets of utilization curves for a bridge and the backbone ring of the SLBR network of Fig. 5 with the transmission rate equal to 4 Mbps, i.e., 4M-SLBR. Each set consists of three curves and each curve represents the simulation result for a mean message frame length. The curves of Fig. 13 show that the utilization of a bridge or the backbone ring increases as the total offered data rate increases. When the total offered data rate reaches a certain rate called the knee rate, the bridge on ring saturates and the utilization starts to reach a constant level. The utilization curve remains at that level for a total offered data rate higher than the knee rate. A higher knee rate is more desirable, since it implies that a device, a bridge or a backbone ring, can handle more messages without saturating.

In Fig. 13, the knee rate for both the bridge and backbone ring utilization with 2-Kbit mean message frame length is about 0.9 Mbps. The saturated value for the bridge utilization is 100 percent, while that for the backbone ring is only 20 percent. This means that the bottleneck occurs at the bridges, not at the backbone ring. Since the bridges are saturated at a total offered data rate of about 0.9 Mbps, the amount of traffic supplied to the backbone ring is limited to a certain level. This is the reason for the low

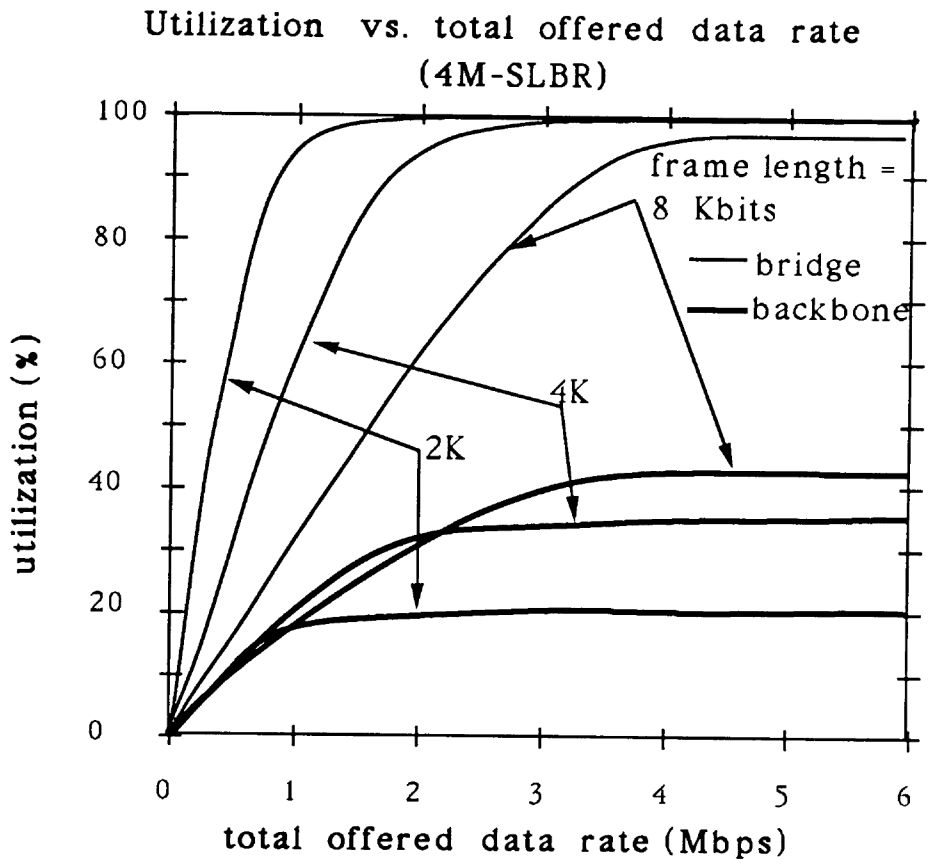


Figure 13. Utilization versus the total offered data rate for 4M-SLBR.

saturated value of the backbone ring and the same knee rate for both the bridge and backbone ring utilization. When the mean message frame length is increased to 4 Kbits, the knee rate for both the bridge and the backbone ring is increased to about 1.9 Mbps. The saturated value of the backbone ring is also increased to 35 percent from 20 percent for a 2-Kbit mean message frame length. It should be noted that the bridge is saturated at 96 percent instead of 100 percent for the mean message frame length of 8 Kbits. This is due to the amount of traffic in the network not increasing when the total offered data rate reaches beyond 4 Mbps, which is the transmission rate of the backbone ring and the local rings.

We also studied the same type of the network, SLBR, but with a higher backbone ring transmission rate of 16 Mbps. It is expected that the utilization performance of bridges and the backbone ring would be improved. Fig. 14 shows the experimental results. The knee rate of both the bridge and the backbone ring utilization for 2-Kbit mean message frame length is about 1.2 Mbps. The saturated value for the bridge utilization is 100 percent, while that for the backbone ring is only 12 percent. When the mean message frame lengths are increased to 4 Kbits and 8 Kbits, the knee rates for both the bridge and the backbone ring are increased to about 2.5 Mbps and 3.8 Mbps, respectively. The saturated values of the backbone ring are also increased to 18 percent and 21 percent, respectively.

When compared with the results of the transmission rate 4 Mbps in Fig. 13, both the knee rates and the saturated values of the bridge and the backbone ring are improved for the transmission rate 16 Mbps. For example, as the transmission rate is increased from 4 Mbps to 16 Mbps, the knee rate of the bridge and the backbone ring utilization

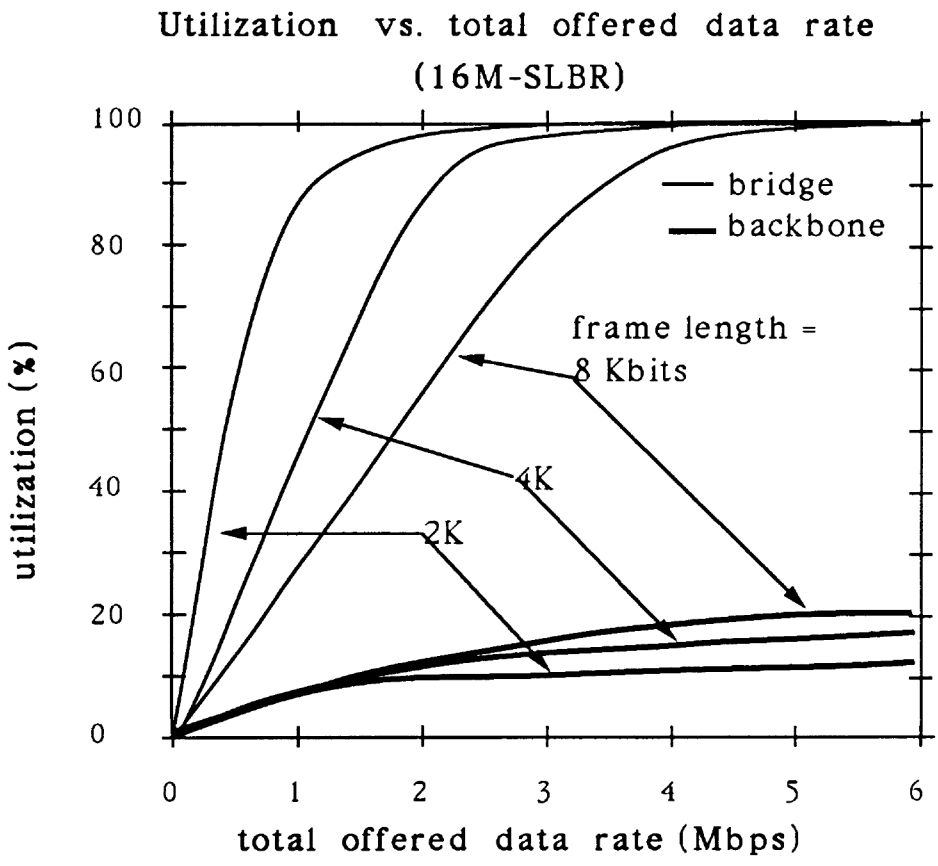


Figure 14. Utilization versus the total offered data rate for 16M-SLBR.

for mean message frame length 2 Kbits is increased by 33 percent and the saturated value of the backbone ring is decreased by 40 percent.

In contrast to the method of increasing the transmission rate of a backbone ring, the addition of the second link to the backbone ring also improves the utilization as discussed in Chapter 3. Fig. 15 shows the experimental results for the DLBR network of Fig. 6 with the transmission rate 4 Mbps, i.e., the 4M-DLBR network. Knee rates and saturated utilization values for the DLBR network are increased compared to that for the SLBR network (cf. Fig. 13). From Fig. 15, the saturated values of the backbone ring utilization with 2-Kbit, 4-Kbit and 8-Kbit mean message frame lengths are 45 percent, 70 percent, and 81 percent, respectively. These saturated values are higher than that of the SLBR network counterparts of 20 percent, 35 percent and 42 percent, respectively in Fig. 13. This is mainly caused by the increased processing speed of bridges for the DLBR network. Since the two I/O setup units near the backbone ring of a bridge for the DLBR network process messages in parallel, the effective I/O setup processing speed in a bridge is double that for the SLBR network. The increased processing speed supplies more messages to the backbone ring to achieve higher saturated values for the backbone ring. It is also observed that the bridge utilization for the mean message frame length of 8 Kbits goes flat at 78 percent instead of 100 percent. As explained on page 47 for Fig. 13, the amount of traffic supplied to the bridges are limited by the the transmission rate of the backbone ring and the local rings which is 4 Mbps in Fig. 15.

Fig. 16 shows the utilization of a bridge and the backbone ring of the 16M-DLBR network. The knee rate for the bridge utilization for a 2-Kbit mean message frame length is about 1.9 Mbps, about 3.7 Mbps for a 4-Kbit mean message frame length, and about 5.5 Mbps for an 8-Kbit mean message frame length. The knee rates for the 16M-DLBR

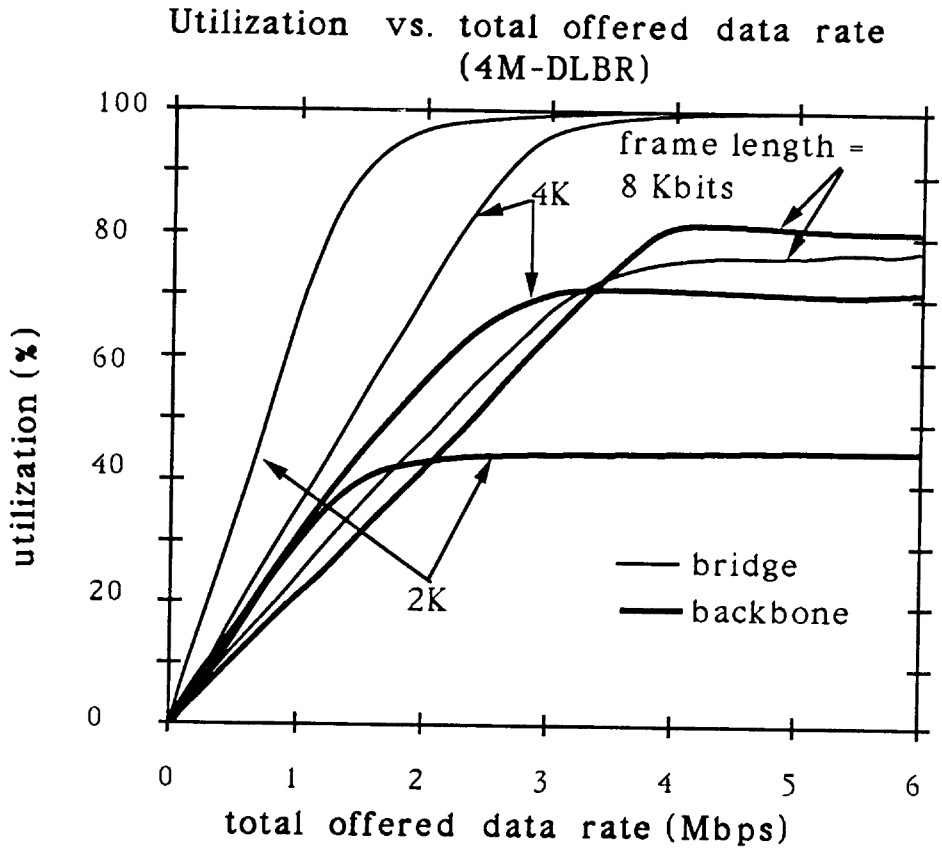


Figure 15. Utilization versus the total offered data rate for 4M-DLBR.

network are increased compared with the utilization of the 4M-DLBR network shown in Fig. 15. But the improvement is not as great as in the case of the SLBR networks. For example, the improvement of the knee rate from the 4M-DLBR network to the 16M-DLBR network with a mean message frame length of 2 Kbits is only 12 percent as shown in Fig. 15 and Fig. 16. However, the improvement from the 4M-SLBR network to the 16M-SLBR network is 33 percent as shown in Fig. 13 and Fig. 14. In other words, the impact of increasing backbone ring transmission rate for the DLBR networks is less than that for the SLBR networks. This is because the message-receiving and the message-transmitting time near the backbone ring, which is determined by message frame lengths, of a bridge for DLBR networks is reduced effectively by half, because there are two I/O setup units operating in parallel, compared to that for SLBR networks. Therefore, the influence of the message-receiving and message-transmitting time of a bridge for a DLBR network is less significant than that for a SLBR network.

Fig. 17 compares the bridge utilization of the 4M-SLBR and 4M-DLBR networks. As can be seen from Fig. 15, the 4M-DLBR network has higher utilization knee rates than the 4M-SLBR network. However, as the mean message frame length increases, the difference in the knee rates between two networks becomes smaller. For example, the improvement of the knee rates from the 4M-SLBR network to the 4M-DLBR network for a 2-Kbit mean message frame length is 89 percent; for a 4-Kbit mean message frame length, the improvement is reduced to 60 percent. This is because when the length of messages becomes longer the message-receiving and message-transmitting time becomes more significant in determining the overall bridge occupancy time both for the SLBR and DLBR networks. For a long mean message frame length, the overall bridge occupancy time for both the SLBR and DLBR networks is almost determined by the message-receiving and message-transmitting time, which makes other processing times,

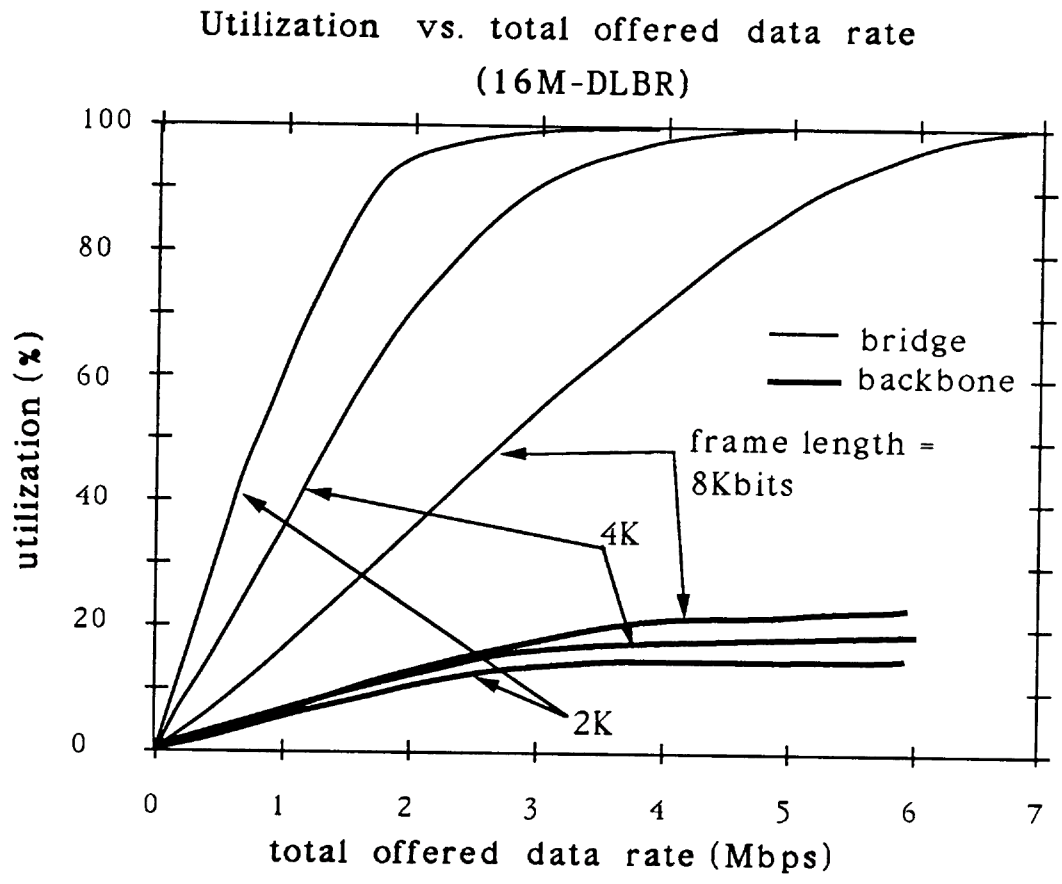


Figure 16. Utilization versus the total offered data rate for 16M-DLBR.

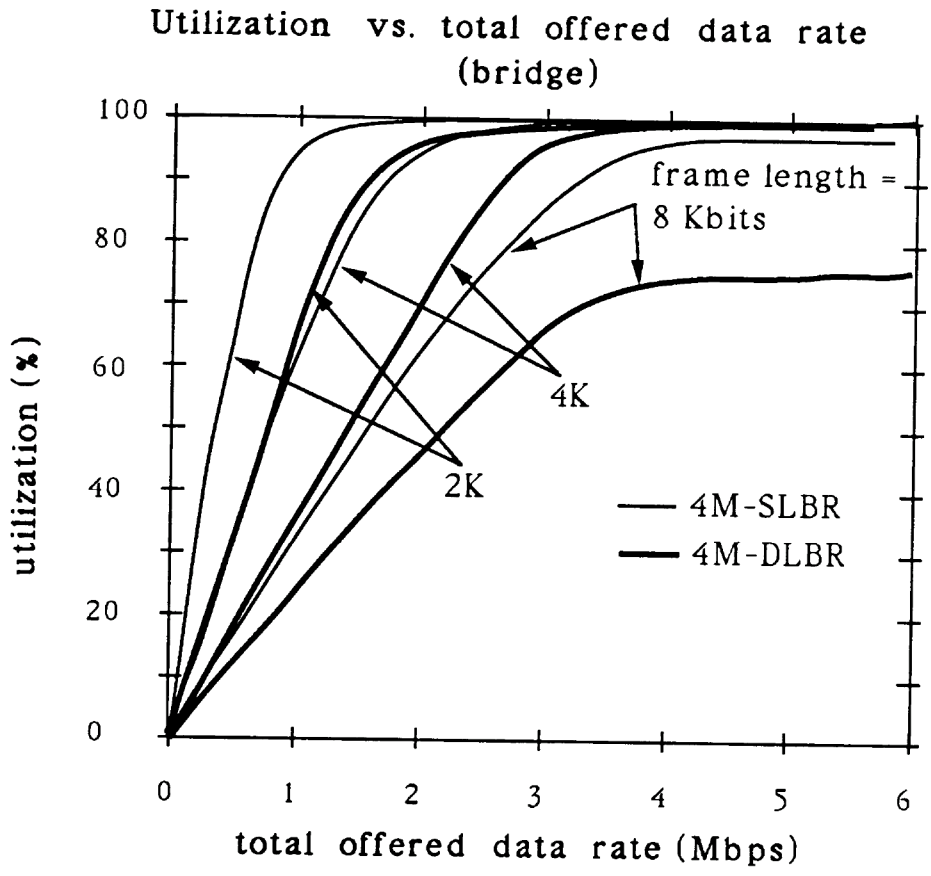


Figure 17. Utilization versus the total offered data rate for a bridge at 4 Mbps.

such as the I/O setup time of bridges, which makes the major difference between an SLBR network and a DLBR network, less significant. This reduces the bridge utilization gap between the SLBR and DLBR networks when the mean message frame length becomes large.

Fig. 18 compares the bridge utilization of the 16M-SLBR and 16M-DLBR networks. For a mean message frame length of 2 Kbits, the knee rate from 16M-SLBR to 16M-DLBR is improved by 58 percent and for a 4-Kbit length, the knee rate improvement is 48 percent. Compared with the knee rate improvement discussed in Fig. 17, the knee rate improvement in Fig. 18 is less sensitive to the mean message frame length. This is because with the high transmission rate, the message-receiving and message-transmitting time becomes relatively small. Hence the message-receiving and message-transmitting time rarely becomes a dominant factor in the overall bridge processing time unless the mean message frame length is very large.

For the direct comparison of the two schemes, the increase of the transmission rate and the addition of a secondary link, the bridge utilization of the 4M-DLBR and 16M-SLBR networks is presented in Fig. 19. Fig. 19 shows that the 4M-DLBR network performs better than the 16M-SLBR network with respect to bridge utilization. The knee rates of the bridge utilization for the 4M-DLBR network with a 2-Kbit and a 4-Kbit mean message frame lengths are 41 percent and 20 percent, respectively, higher than those of the 16M-SLBR network. Hence, the addition of the second link is more effective than the increase of transmission rate of a backbone ring, especially for short messages. This is essentially owing to the increased processing speed of bridges in which the bottleneck congestion starts.

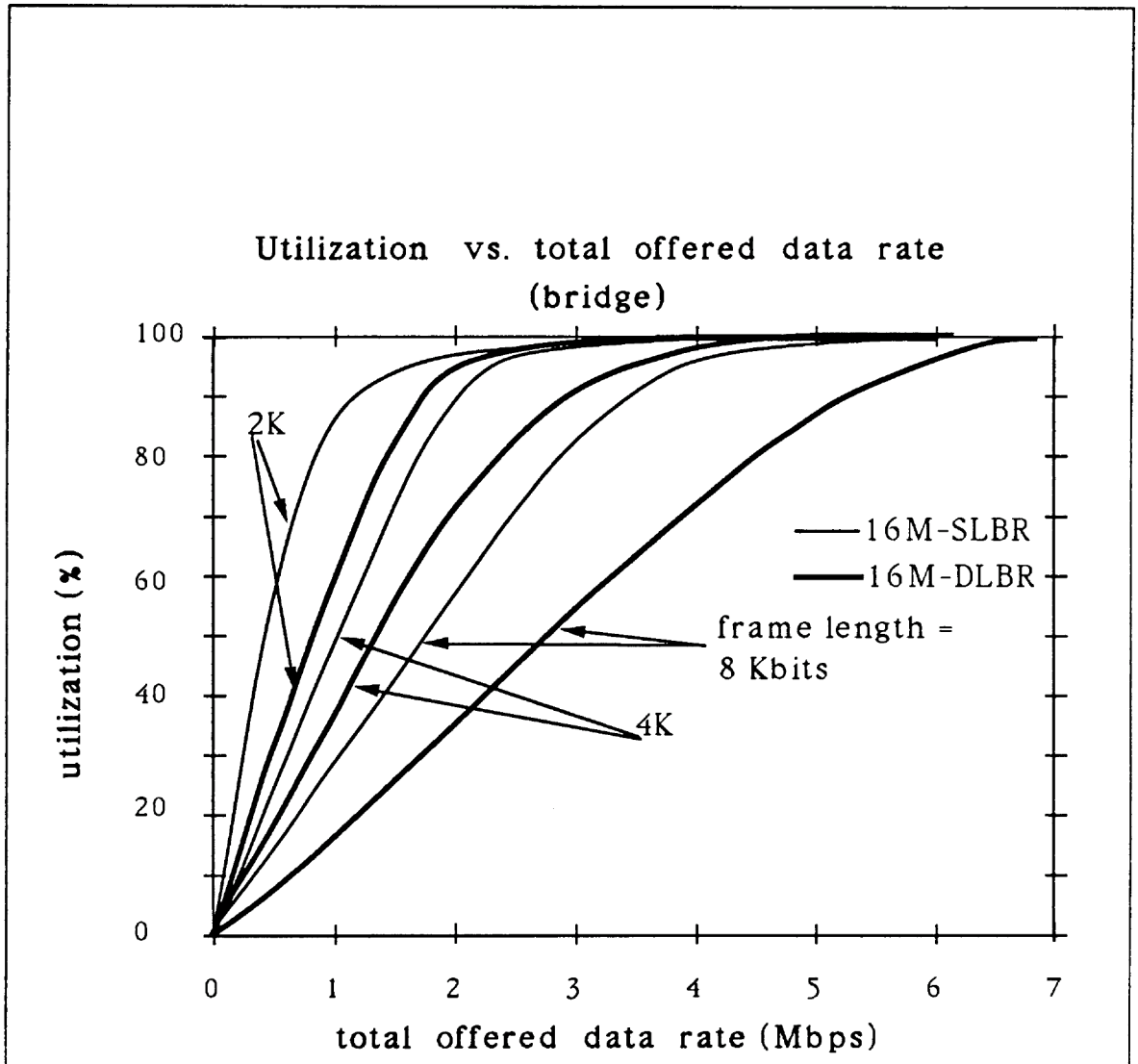


Figure 18. Utilization versus the total offered data rate for a bridge at 16 Mbps.

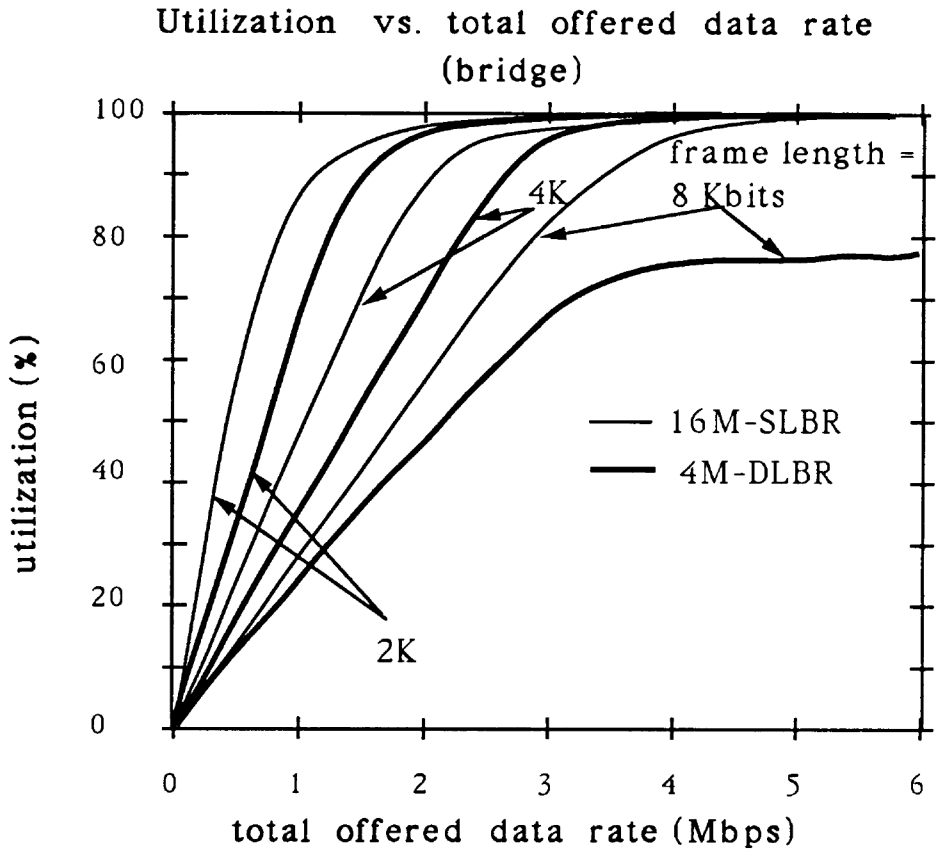


Figure 19. Utilization versus the total offered data rate for 16M-SLBR and 4M-DLBR.

From experiments described above for bridge and backbone ring utilization, the following can be made.

1. As the mean message frame length increases, knee rates and saturated values of utilization increase.
2. For a given total offered data rate, bridges and the backbone ring of a network are better utilized for shorter messages.
3. The bridge utilization of a network is always higher than the backbone ring utilization. This implies that bottleneck congestion starts at bridges first.
4. The utilization of bridges and the backbone ring of a DLBR network is less sensitive to the backbone ring transmission rate than that of an SLBR network.
5. The addition of a second link to the backbone ring of a network is more efficient than the increase of the transmission rate of the backbone ring in terms of bridge and backbone ring utilization.

4.2 Throughput

In this section, the network performance of the SLBR and DLBR networks were measured in terms of throughput and the experimental results are presented. The throughputs were measured at the level of sink and source of each station where messages were generated and received. Since messages traveling through the network can be corrupted, only error-free bits were counted in measuring the throughput. For a given total offered data rate, it is desirable for a network to have higher throughput.

Fig. 20 shows the throughputs of the 4M-SLBR and 4M-DLBR networks. As the total offered data rate increases, the throughput of a network also increases until the knee rate is met. The knee rate of the throughput of a network is higher for a longer mean message frame length. The knee rates of the 4M-SLBR network for 2-Kbit, 4-Kbit and 8-Kbit mean message frame lengths are about 1.0 Mbps, 2.0 Mbps and 3.5 Mbps, respectively. The knee rates of the 4M-DLBR network for the three different mean message frame lengths are about 2.0 Mbps, 3.2 Mbps and 4.0 Mbps, respectively. For the same mean message frame length, the knee rate of the 4M-DLBR network is higher than that of the 4M-SLBR network. However, the relative difference becomes smaller as the mean message frame length increases. For example, the knee rate of the 4M-DLBR network with a 2-Kbit mean message frame length is 100 percent higher than that for the 4M-SLBR network. When the message length is doubled to 4 Kbits, the knee rate of the 4M-DLBR network is only 60 percent higher.

The knee rate of the throughput of a network is essentially the point where the utilization of a device, a bridge or a backbone ring in general and a bridge for the SLBR and DLBR networks, approaches to 100 percent. The amount of traffic through the network is limited to a certain level and the throughput remains at the same level. This fact suggests that the knee rate of the throughput of the 4M-SLBR or 4M-DLBR networks might be close to that of the bridge utilization of the network. This is verified by observing the bridge utilization of the 4M-SLBR and 4M-DLBR networks in Fig. 17 and the throughput of the networks in Fig. 20. For example, the utilization knee rate of 4M-SLBR for a 2-Kbit mean message frame length is about 0.9 Mbps while the corresponding throughput knee rate is about 1.0 Mbps.

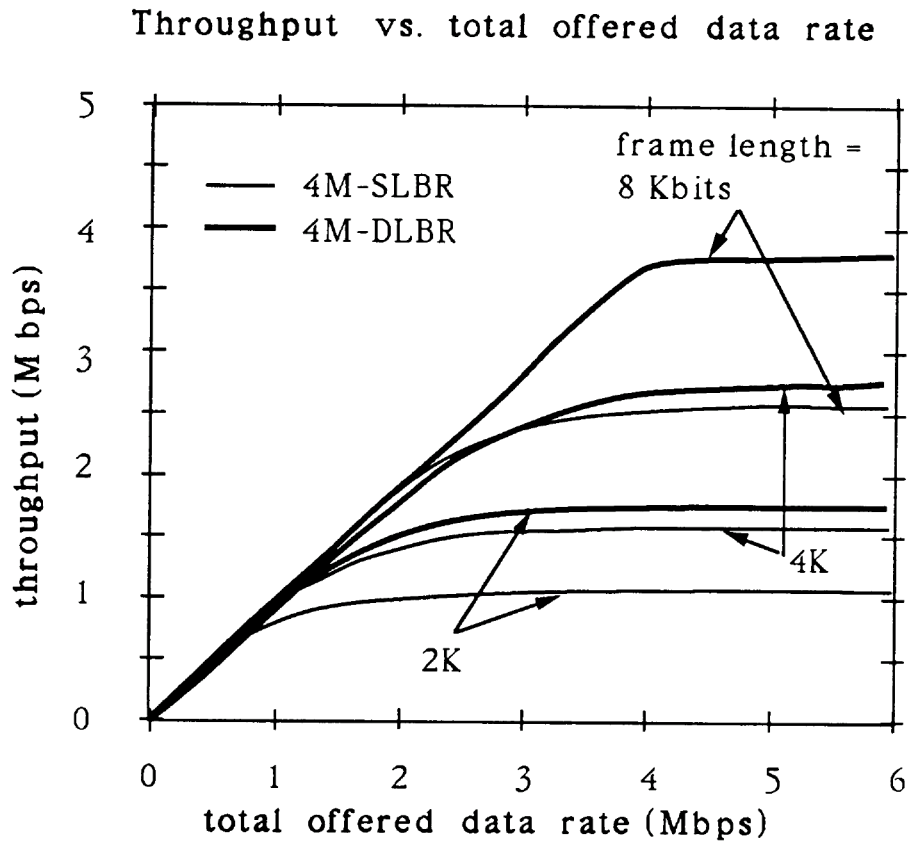


Figure 20. Throughput versus the total offered data rate for a transmission rate of 4 Mbps.

The saturated values of the throughputs of the 4M-SLBR network for 2-Kbit, 4-Kbit and 8-Kbit mean message frame lengths are about 1.0 Mbps, 1.6 Mbps and 2.6 Mbps, respectively. The saturated values of the 4M-DLBR network for the three different mean message frame lengths are 1.8 Mbps, 2.7 Mbps and 3.8 Mbps, respectively. For the same mean message frame length, the saturated value of the 4M-DLBR network is higher than that of the 4M-SLBR network. For 2-Kbit and 4-Kbit mean message frame lengths, the saturated values of the 4M-DLBR network are increased by 80 percent and 68 percent from that of the 4M-SLBR network, respectively.

Fig. 21 shows the throughputs of the 16M-SLBR and 16M-DLBR networks. The knee rate of the 16M-DLBR network for a 8-Kbit mean message frame length is beyond the scope of Fig. 21 and is not measured in the experiment. However, we predict the knee rate to be somewhere around 7 Mbps from Fig. 16. The knee rates of the throughputs of a network are very close to the knee rates of the utilization of bridges. As expected, the throughputs and knee rates are increased as the transmission rate of a backbone ring increases. The saturated values of throughputs of the 16M-DLBR network are increased by 57 percent for a 2-Kbit mean message frame length and 38 percent for a 4-Kbit mean message frame length, when compared to the 16M-SLBR network. The 16M-DLBR network still gains over the 16M-SLBR network, but the gain is not as significant as that of the 4M-SLBR and 4M-DLBR networks.

Fig. 22 compares the throughputs of the 16M-SLBR and 4M-DLBR. From Fig. 22, the 4M-DLBR network performs better in terms of throughput than the 16M-SLBR network. The saturated values of throughputs of the 4M-DLBR network for 2-Kbit and 4-Kbit mean message frame lengths are 25 percent and 28 percent, respectively, higher than those of the 16M-SLBR network.

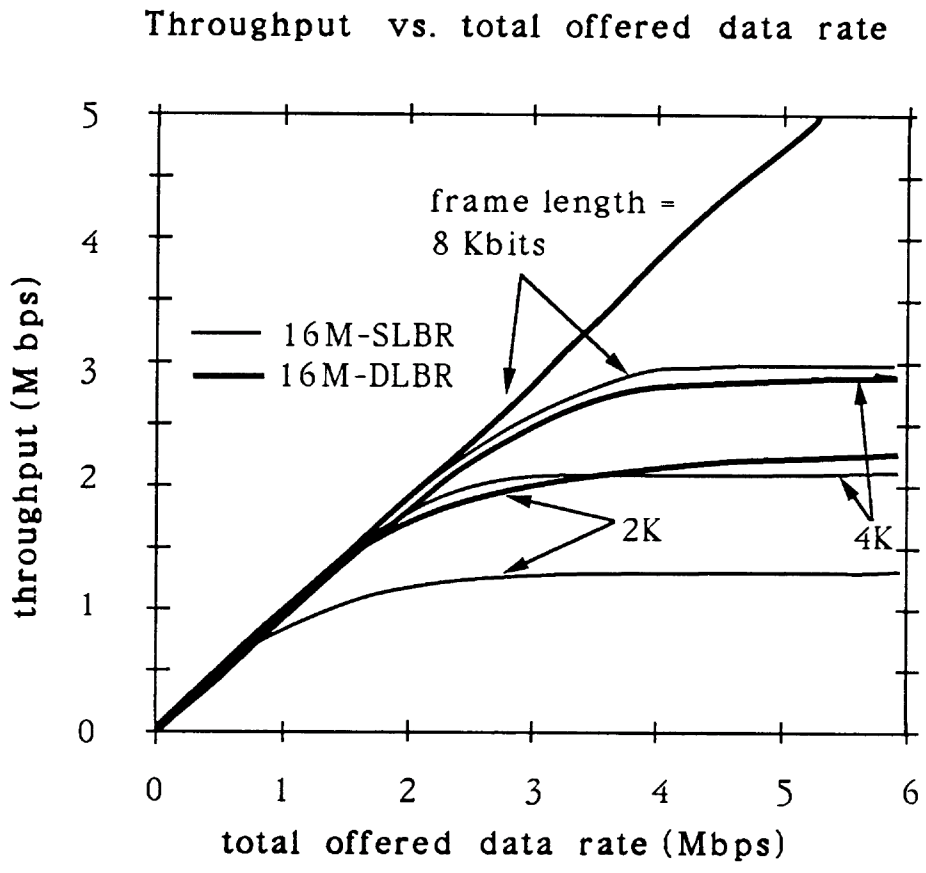


Figure 21. Throughput versus the total offered data rate for a transmission rate of 16 Mbps.

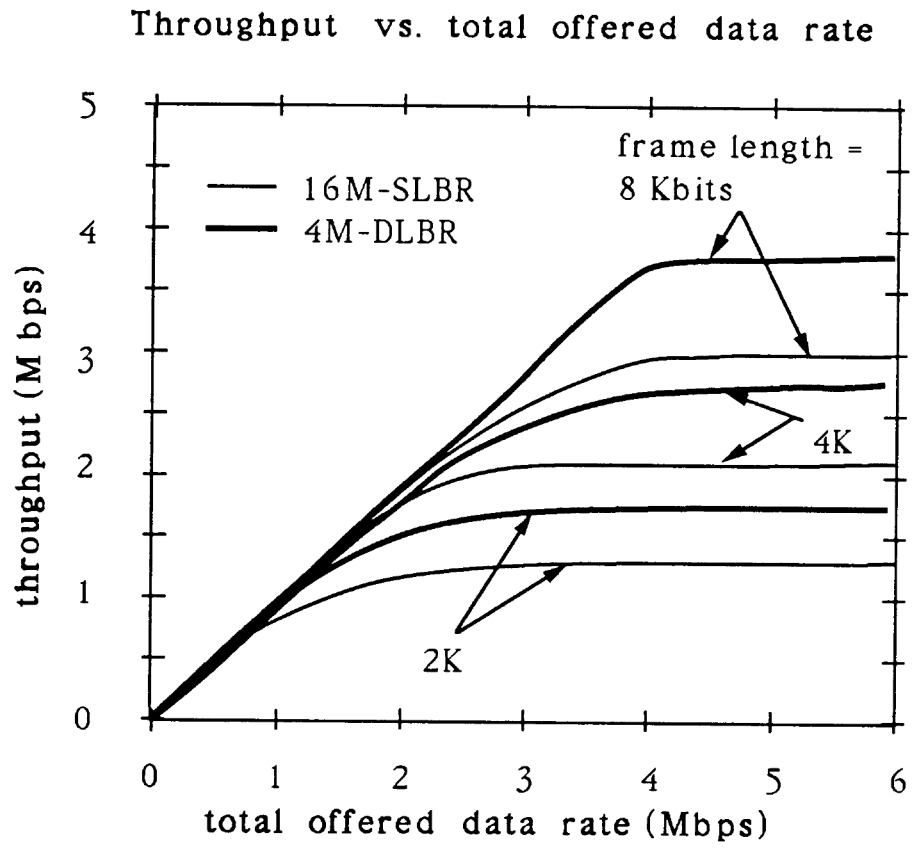


Figure 22. Throughput versus the total offered data rate for 16M-SLBR and 4M-DLBR.

From the experimental results cited above, the following observations are made.

1. As the mean message frame length increases, the knee rates and saturated values of throughputs increase.
2. The knee rates of throughputs are close to the knee rates of either the bridge or the backbone ring utilization. This implies that either the bridges or the backbone ring dominate the overall performance of the network.
3. The saturated values of the DLBR networks are higher than those of the SLBR networks for the same mean message frame length and the same backbone ring transmission rate.
4. For a given total offered data rate, the network obtains higher throughput for longer mean message frame length. In other words, the network operates more efficiently for shorter mean message frame lengths than longer mean message frame lengths.

4.3 Response Time

Experimental results for the response time of the SLBR and DLBR networks are presented in this section. As for the case of throughput, the response times were measured at the level of sink and source of each station where messages of error-free bits are generated and received.

Fig. 23 shows the response times of the 4M-SLBR and 4M-DLBR networks. As the total offered data rate increases, the response time of the networks increases until a critical rate is met. When the total offered data rate goes beyond the critical rate, the response

time becomes virtually infinite. This is due to the bottleneck congestion which causes the traffic flows in the network stagnant. It can be observed that the critical rates of the response times of a network in Fig. 23 are close to the knee rates of the throughputs of the network in Fig. 20 and close to the knee rates of bridge utilization in Fig. 13 and Fig. 15. The increasing rate of the response time of a network with respect to the total offered data rate becomes lower as the mean message frame length increases. This is explained as the network operates more efficiently for longer mean message frame length, as explained in the previous section. For a given total offered data rate, the response time decreases as the mean message frame length increases. For example, at the total offered data rate 0.5 Mbps, the response time for the 2-Kbit mean message frame length of a 4M-SLBR network is 20 ms., that for the 4-Kbit message length is 10 ms., and that for the 8-Kbit message length is 8 ms. The response time of the 4M-DLBR network is less than half that of a 4M-SLBR network for a given total offered data rate below the critical rate. Therefore, the 4M-DLBR network performs better than the 4M-SLBR network in response time.

Fig. 24 shows response times of the 16M-SLBR and 16M-DLBR networks. The response times in Fig. 24 shares the same characteristics of those of the 4M-SLBR and 4M-DLBR networks. It is observed that the critical rates of the response times of a network in Fig. 24 are close to the knee rates of the throughputs of the network in Fig. 21 and close to the knee rates of bridge utilization in Fig. 14 and Fig. 16. For longer mean message frame length, the network obtains the lower increasing rate of the response time with respect to the total offered data rate. From Fig. 24, the 16M-DLBR network outperforms the 16M-SLBR network for the critical rates of the 16M-DLBR network are higher and the increasing rates are lower than that of the 16M-SLBR net-

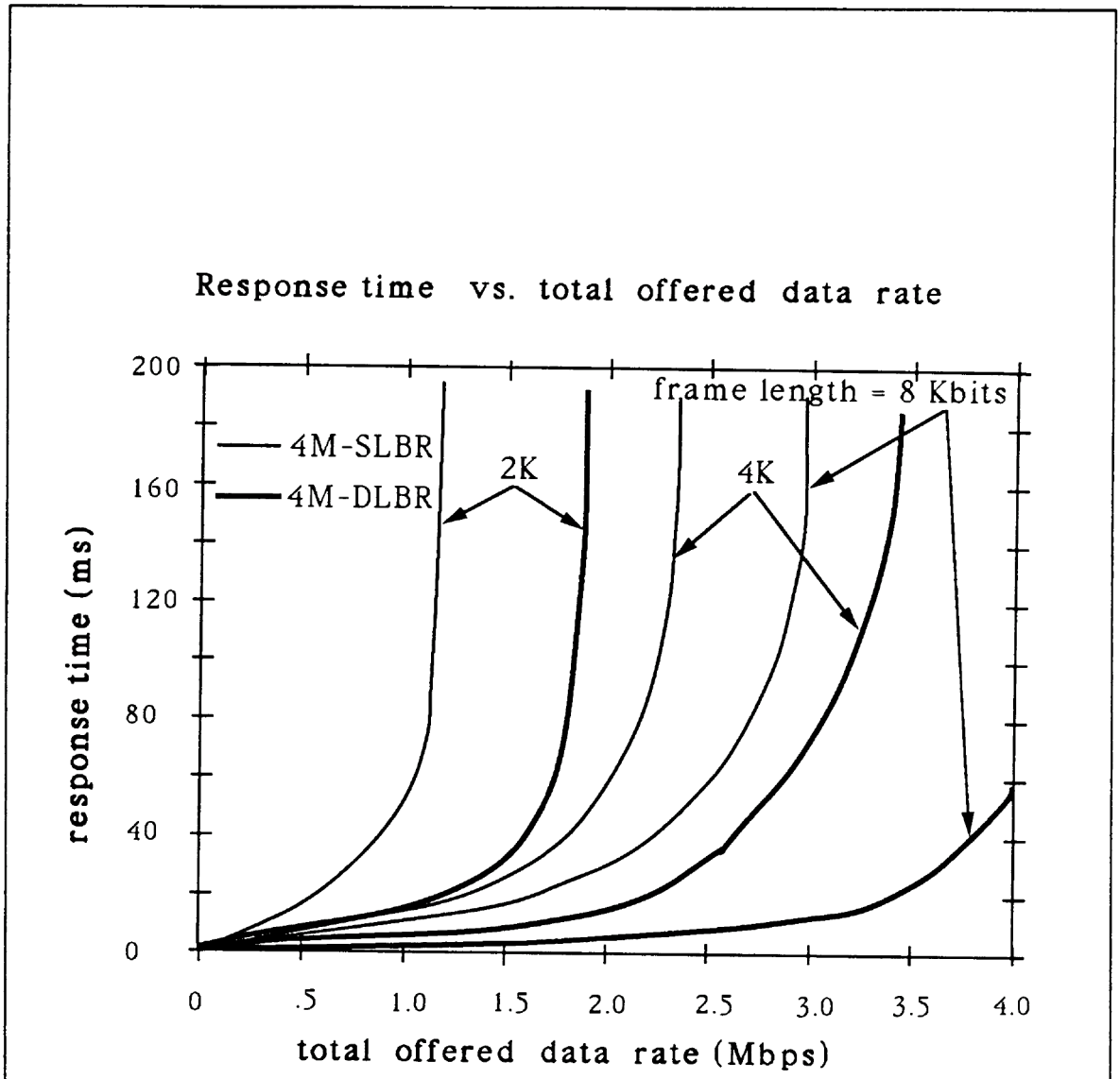


Figure 23. Response time versus the total offered data rate for a transmission rate of 4 Mbps.

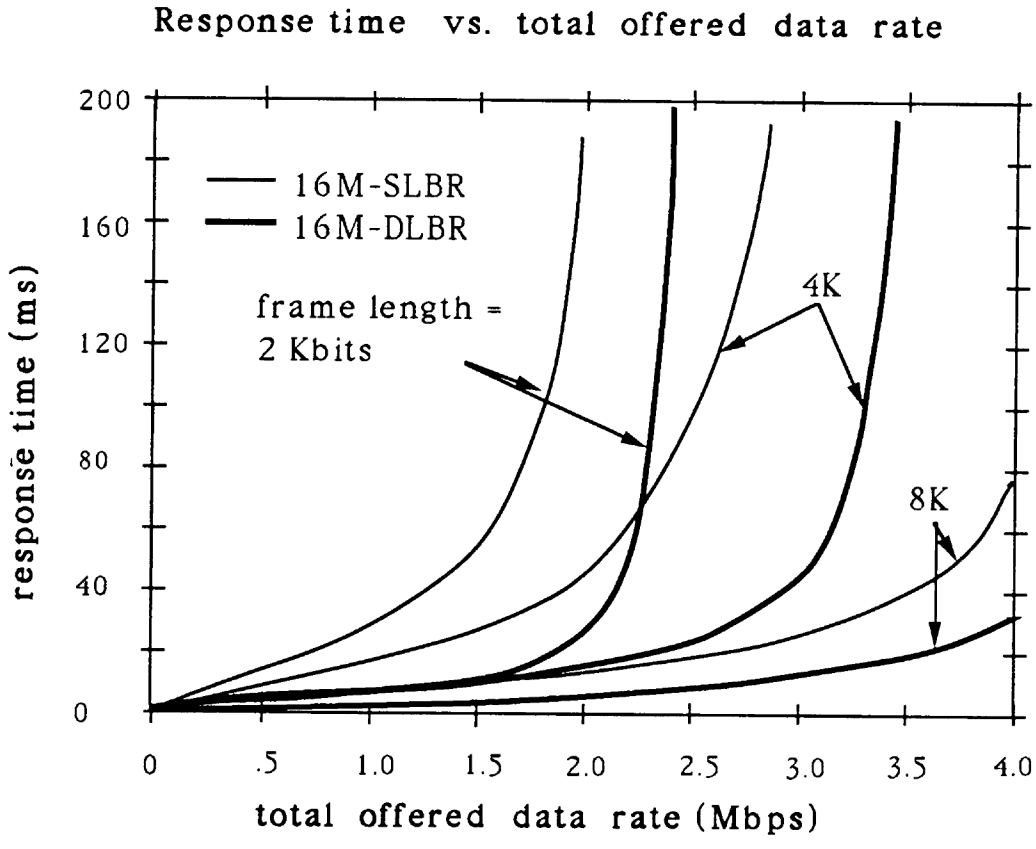


Figure 24. Response time versus the total offered data rate for a transmission rate of 16 Mbps.

work, and for a given total offered data rate, the 16M-DLBR network has shorter response time than 16M-SLBR network.

Fig. 25 compares the response times of the 16M-SLBR network and 4M-DLBR network. The 4M-DLBR network has higher critical rates than the 16M-SLBR network for each mean message frame length. For a given total offered data rate, the 4M-DLBR network has shorter response time than the 16M-SLBR network. In other words, the 4M-DLBR network performs better than the 16M-SLBR network in response time.

From the above experiments, the following observations are made.

1. As the mean message frame length increases, critical rates increase but the increasing rate of response time decreases.
2. The critical rates of the response times of a network are close to those of the bridge and backbone ring utilization and throughputs.
3. The critical rates of a DLBR network are higher than that of a SLBR network. This implies that the DLBR network can handle more messages than the SLBR network without creating a bottleneck congestion.
4. The 4M-DLBR network performs better than the 16M-SLBR network.

4.4 Remarks

The experimental results given in this chapter show that the 4M-DLBR network performs better than the 16M-SLBR network in terms of utilization, throughput and response times. However, the addition of the secondary link to the backbone ring requires

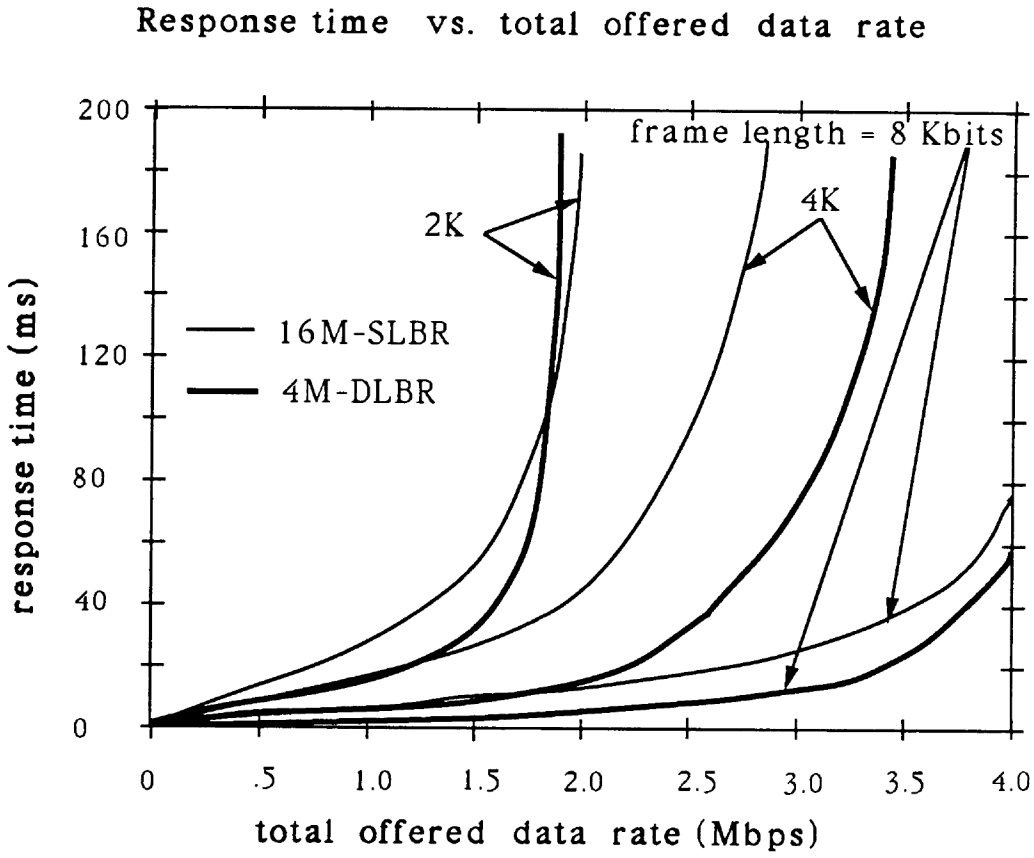


Figure 25. Response time versus the total offered data rate for 4M-DLBR and 16M-SLBR.

both hardware and software modifications of the bridges attached to the backbone ring. For the hardware part, a minor modification of transmitting/receiving circuits is expected; for the software part, a function for selecting links needs to be included.

All the knee rates, critical rates and saturated values are tabulated in Appendix A.

5.0 Conclusion

IEEE 802.2 and 802.5 are currently the most popular token ring protocols in the industry. The token ring has several advantages over other networks, especially under a heavy load [13]. However, Bux and Grillo showed that all desirable characteristics of a single token ring are severely degraded when multiple rings are connected to form an interconnected network [6]. To address the problem, Bux and Grillo suggested a method called dynamic flow control. The method is to adjust dynamically the size of windows depending on the traffic of the network.

In this thesis, a different method of addressing the problem was presented. The method is to add a secondary link to the backbone ring of the network to form a double linked backbone ring network. The performance of the double linked backbone ring network was compared with that of a single linked backbone ring network for two different backbone ring transmission rates, and the experimental results are summarized as follows.

1. As the mean message frame length increases, the knee rates and saturated values of utilization and throughputs, and critical rates of response times increase, but the increasing rates of response times decrease.
2. The knee rates of throughputs and the critical rates of response times are close to the knee rates of the bridges or backbone ring utilization. This implies that the bridges or the backbone ring dominate the performance of the entire network.
3. Bridges and the backbone ring of a network are better utilized for shorter messages.
4. The bridge utilization is always higher than the backbone ring utilization. This implies that the bottleneck congestion begins at bridges.
5. The bridge and backbone ring utilization of the DLBR network is less sensitive to the backbone ring transmission rate than that of the SLBR network.
6. The DLBR network has higher knee rates of utilization and of throughputs, higher critical rates of response times and higher saturated values of throughputs than the SLBR network.

From the experimental results, the DLBR network performs better than the SLBR network in terms of utilization, throughput and response time. Therefore, we suggests that a double linked backbone ring may be one of alternatives to improve the performance of an interconnected token ring network as depicted in Fig. 6.

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Appendix A. List of Critical Results

1. Utilization

Knee Rates (Mbps)

type / length	4M-SLBR	16M-SLBR	4M-DLBR	16M-DLBR
2 K	0.9	1.2	1.7	1.9
4 K	1.9	2.5	3.0	3.7
8 K	3.5	3.8	4.0	5.5

Saturated Values (bridges, %)

type / length	4M-SLBR	16M-SLBR	4M-DLBR	16M-DLBR
2 K	100	100	100	100
4 K	100	100	100	100
8 K	96	100	78	100

Saturated Values (backbone, %)

type / length	4M-SLBR	16M-SLBR	4M-DLBR	16M-DLBR
2 K	20	12	45	15
4 K	35	18	70	19
8 K	42	21	81	23

2. Throughput

Knee Rates (Mbps)

type / length	4M-SLBR	16M-SLBR	4M-DLBR	16M-DLBR
2 K	1.0	1.5	2.0	2.3
4 K	2.0	2.6	3.2	3.7
8 K	3.5	3.8	4.0	x

Saturated Values (Mbps)

type / length	4M-SLBR	16M-SLBR	4M-DLBR	16M-DLBR
2 K	1.0	1.4	1.8	2.2
4 K	1.6	2.1	2.7	2.9
8 K	2.6	3.0	3.8	x

3. Response Time

Knee Rates (Mbps)

type / length	4M-SLBR	16M-SLBR	4M-DLBR	16M-DLBR
2 K	1.0	1.5	1.8	2.3
4 K	2.0	2.6	3.2	3.3
8 K	3.1	4.0	4.0	x

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