Performance Studies of A Very High-Speed LAN Interconnected by a Passive Star Coupler

by

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Abstract

Optical local area network (LAN) design has become one of the most important issues in computer communications. In this thesis, we propose an ALOHA/Slotted-CSMA protocol for a very high-speed optical LAN interconnected by a passive star coupler. The network performance based on channel throughput and delay characteristics are analyzed and the numerical results are given. Comparisons are made with the other protocols based on the same network architecture.

Detailed network modeling and modifications are given by using the software package BONeS (Block Oriented Network Simulator). A computer simulation program was developed to simulate the performance of the ALOHA/Slotted-CSMA protocol.

Finally, results of the simulation and analytical studies are given and the comparisons and suggestions for future studies are made.

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Acronyms

BONeS	Block Oriented Network Simulator
BER	Bit Error Rate
CAD	Computer Aid Design
CAM	Computer Aid Manufacture
CATV	Cable Television
CCITT	the International Telegraph and Telephone Consultative Committee
CDM	Code Division Multiplexing
CSMA	Carrier Sense Multiple Access
CSMA/CD	Carrier Sense Multiple Access with Collision
DQDB	Distributed Queue Dual Buses
FDDI	Fiber Distributed Data Interface
Gbps	Gigabits per second
HSLAN	High Speed Local Area Network
IEEE	Institute of Electrical and Electronics Engineers
ISDN	Integrated Services Digital Network
ISO	International Organisation for Standardization
Kbps	Kilobits per second
LAN	Local Area Network
LLC	Logical Link Control
MAC	Media Access Control
MAN	Metropolitan Area Network
Mbps	Megabits per second
OSI	Open System Interconnection
TDM	Time Division Multiplexing
WAN	Wide Area Network
WDM	Wavelength Division Multiplexing

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Chapter 1

Introduction

One of the great influences on industry and society during the second half of the 20th Century is the computer. Originally it was thought to be used only for "number-crunching" jobs in scientific research establishments, but very soon it was applied with outstanding success to the manipulation of information.

The second great development has been the application of telecommunications techniques to the transport of data between different users. The falling cost of electronic components has led to the development of many pieces of equipment with build-in microprocessors. Such computer-controlled devices are now found in offices, factories, schools, homes, etc. Computer-based equipment is much more flexible than hard-wired devices designed to serve the same computer-based device and can be used for a variety of applications and modified to meet changing needs.

In the 1970's and early 1980's, there was a merge of the fields of computer science and data communications that profoundly changed the technology, products, and companies which are the computer communication industry now. The introduction of communication networks makes it possible for all systems including computers, printers and other electronic devices in the network to communicate over a common transmission medium. Such networks are classified as local area networks (LANs), wide area networks (WANs) and metropolitan area networks (MANs) according to the geographical area they cover, and have been developed and standardized. The transmission rates range from several Kbps (kilobits per second) to hundred Mbps (megabits per second). The latest networks can even operate in the Gbps (gigabits per second) range with optical techniques. These networks enable the attached systems to share resources and to exchange data. Some networks can support integrated services including voice, data and video transmissions.

The computer communications revolution has produced several remarkable facts:

- There is no fundamental difference between data processing (computers) and data communications (transmission and switching equipments);
- There are no fundamental transmission differences among data, voice, and video communications, since today they are transformed into digital before transmission;
- The lines between single-processor computer, multi-processor computer local area network, metropolitan area network, and long-haul network have blurred.

The result has been a growing overlap of the computer and communications industry, from component fabrication to system integration. The forthcoming result is the development of integrated systems that transmit and process all types of data and information. Both the technology and the technical standards organizations are driving toward a single public system that integrates all communications and makes virtually all data and information sources around the world easily and uniformly accessible.

In its simplest form, data communication takes place between two devices that are directly connected by some form of point-to-point transmission medium. However, it is impractical for two devices to be directly, point-to-point connected. This is so for one (or both) of the following contingencies:

- The devices are very far apart. It would be inordinately expensive, for example, to string a dedicated link between two devices thousands of miles apart;
- There is a set of devices, each of which may require a link to many of the others at various times. Examples are all of the telephones in the world and all of the terminals and computers owned by a single organization. Except for the case of a very few devices, it is impractical to provide a dedicated wire between each pairs of devices.

The solution of this problem is to attach each device to a communication network. Fig.1.1 illustrates this concept in a general way. We have a collection of devices that wish to communicate, we will refer to them generally as stations. The stations may be computers, terminals, telephones, or other communicating devices. Each station is attached to a network node. The set of nodes to which stations attach is the boundary of a communication network that is capable of transferring data between pair of stations. Communication networks may be categorized based on the

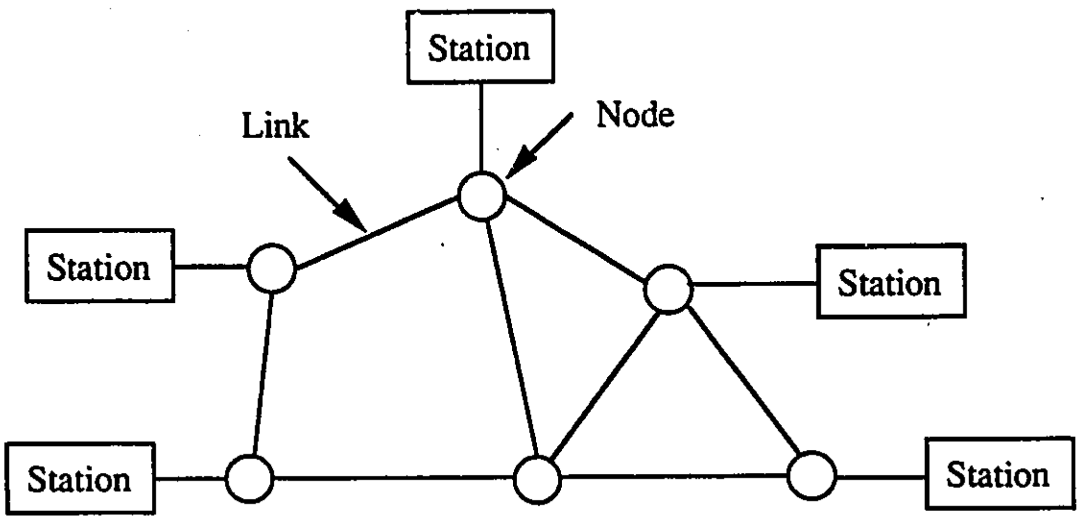


Figure 1.1: Interconnection via a communication network

architecture and techniques used to transfer data, such as circuit-switched networks, packet-switched networks, satellite network, local and metropolitan area networks, etc.

1.1 Objective of the Thesis

A lot of work has been done based on a very high-speed local area network interconnected by a passive star coupler [47] [49] [50]. There were some problems in the previous work:

- The major impairment on network performance was data channel bandwidth waste. Since pretransmission coordination is needed in the network under studies and it is done by sending a control packet before sending the data packet to the intended recipient. If the control packet is lost due to control channel collision and data packet is still transmitted, the intended recipient can not obtain the switching information to tune to the correct data channel to receive the data packet. This will cause waste of data channel bandwidth;

- The procedure of control channel collision detection was not clearly mentioned [50];
- No simulation studies under more realistic considerations were performed;
- Unnecessary control channel traffic was generated by the users which did not sense the idle data channels;
- Hardware complexity existed in ALOHA/CSMA protocol [47]. It required each user use two tunable lasers for transmission.

The objective of this thesis is to solve those problems and increase the channel efficiency.

1.2 Outline of the Thesis

In the following sections of this chapter, we will overview the aspects of computer networks such as local area networks, wide area networks, OSI standards and other standards, and multiple access protocols. Since these are the foundations of the network, therefore, it is necessary to mention the techniques.

In Chapter 2, a review of optical local area network is presented. Different configurations for the optical local area networks are considered, which include bus, ring, star, mesh and a hybrid. We also review the access methods such as time division multiplexing, code division multiplexing, wavelength division multiplexing and multihop techniques. Also, some protocols for optical LANs are discussed.

In Chapter 3, we will first discuss and evaluate a very high-speed optical local area network interconnected by a passive star coupler. Several random access protocols will be reviewed and the proposed ALOHA/Slotted-CSMA protocol will be presented.

The network performance based on channel throughput and delay characteristics will be analyzed and the numerical results will be given. The comparisons with the other protocols in the previous work based on the same network architecture will be made.

In Chapter 4, the detailed network modeling and modifications are given. A computer simulation program was developed to simulate the performance of ALOHA/Slotted-CSMA protocol and comparison was made between the simulation and analytical results.

In Chapter 5, concluding remarks are given to evaluate the proposed ALOHA/Slotted-CSMA protocol for a very high-speed optical local area network interconnected by a passive star coupler. Also suggestions for further works are given.

Finally, appendices including the BONeS modules and the data base designs are included for reference.

1.3 Local area networks

A local area network (LAN) is a resource-sharing data communication network, which provides connectivity and switching functions between various premise equipment within a limited geographic range of 0.1-10 km, with high bandwidth (above 1 Mbits/sec) over inexpensive transmission media at a low bit error rate, and is usually privately owned. LANs differ from conventional long-haul communication networks in transmission bandwidth, network protocols, and topologies. Usually, in long-haul communication networks, the transmission bandwidth is expensive and network design is focused on the link utilization efficiency. Designers of LANs, unlike designers of long-haul networks, do not consider optimizing bandwidth as a critical issue, since bandwidth in a LAN environment is not a precious resource [1] [2]. The economic and technical characteristics of LANs offer simple solutions for network problems. Complicated routing and control algorithms for long-haul networks are not needed for LANs with their wide bandwidth and short-delay attributes. With their small geographic size, any one of several different LAN topologies and resource sharing mechanisms can be selected to provide economic communications for their users.

The main attributes of local area networks can be summarized as [3]:

- Inexpensive transmission media;
- Inexpensive devices (modems, repeaters and transceivers) to interface the media;
- Sharing expensive computer resources such as large disk drives and high-quality printers;
- Easy physical connection of devices to the media;
- High data transmission rate;
- Low bit error rate;
- Network data transmission rate independent of the rates used by the attached devices, making it easier for devices of one speed to send information to devices of another speed;
- A high degree of interconnection and exchanging information among members of a group;
- Every attached device having the potential to communicate with every other device on the network;
- There is seldom a central controlling processor which polls the attached device on the network;
- In the majority of cases, each attached device hears (but does not process) messages intended for other devices as well as for itself.

It is obvious that a networked computer is much more powerful than a stand-alone computer. With the expansion of the information exchange, both the connection of stand-alone computers and the connection of networks become increasingly necessary and important.

Typical environments where LANs are applicable today include [4]:

- Offices where integrated voice and data communications support office automation functions such as electronic mail, text processing, document distribution, and voice storage;
- Universities that need to provide a communication network for accessing central or distributed processing facilities and special-purpose application software such as word processing;
- Factories that are increasingly moving toward automation , including automated manufacturing techniques such as CAD/CAM, robotics, and numerically controlled manufacturing processes;
- Laboratories that need networks to support distributed computing and distributed process control for experiments;
- Hospitals where communications are crucial for patient file retrieval, status monitoring, and diagnostics;
- Distribution and sales where communications links are needed for order entry and inventory control systems.

The most relevant applications of local area networks are:

- File transfer and access;
- Word and text processing;
- Electronic message handing;
- Personal filing and information handling;
- Graphical information;
- Remote database access;
- Personal computing;
- Digital voice transmission and storage.

The primary purpose of LANs is to provide connectivity and switching functions for premise equipment (such as terminals, workstations, personal computers, and shared resources like disk storage and high-speed printers), thus allowing users to efficiently accomplish required tasks. Such tasks include accessing databases or application software residing in a mainframe, distributing files, mailing messages, and most importantly, communicating with other devices either intrapremises or interpremises. Other user needs are uniform, easily installed and maintained building wiring distribution systems and extensive network management services for system administration and maintenance. LANs provide an economic means to satisfy these user's needs, owing to technological advances that have resulted in cost decreases in hardware components.

The nature of a local area network is determined primarily by three factors: *transmission medium, topology, and medium access protocol*. It is also determined by the type of transmitted data, the speed and efficiency of communications, and even the kinds of applications that a network may support.

The common topologies used for local area networks are star, ring, and bus/tree, shown in Fig.1.2, each of which manifests its advantages and disadvantages [5]. In a star topology, a central element is used to connect all the nodes in the network. The central element uses circuit switching to establish a dedicated path between two stations wishing to communicate. This configuration was referred to as a one-node circuit-switched network. Twisted pair is used to link the central switch, this is adequate to support the transmission needs of individual stations. In optical local area networks, both active and passive star couplers could be used as broadcast channels and nodes are connected to the star coupler by optical fibers.

The ring topology consists of a closed loop, with each node attached to a repeating element. Data circulate around the ring on a series of point-to-point data links between repeaters. A station wishing to transmit waits for its turn and sends data out onto the ring in the form of a data packet. The packet contains source and destination address fields as well as data. As the packet circulates, the destination station copies the data into a local buffer. The packet continues to circulates until it returns to source station, providing a form of acknowledgement. A distributed control

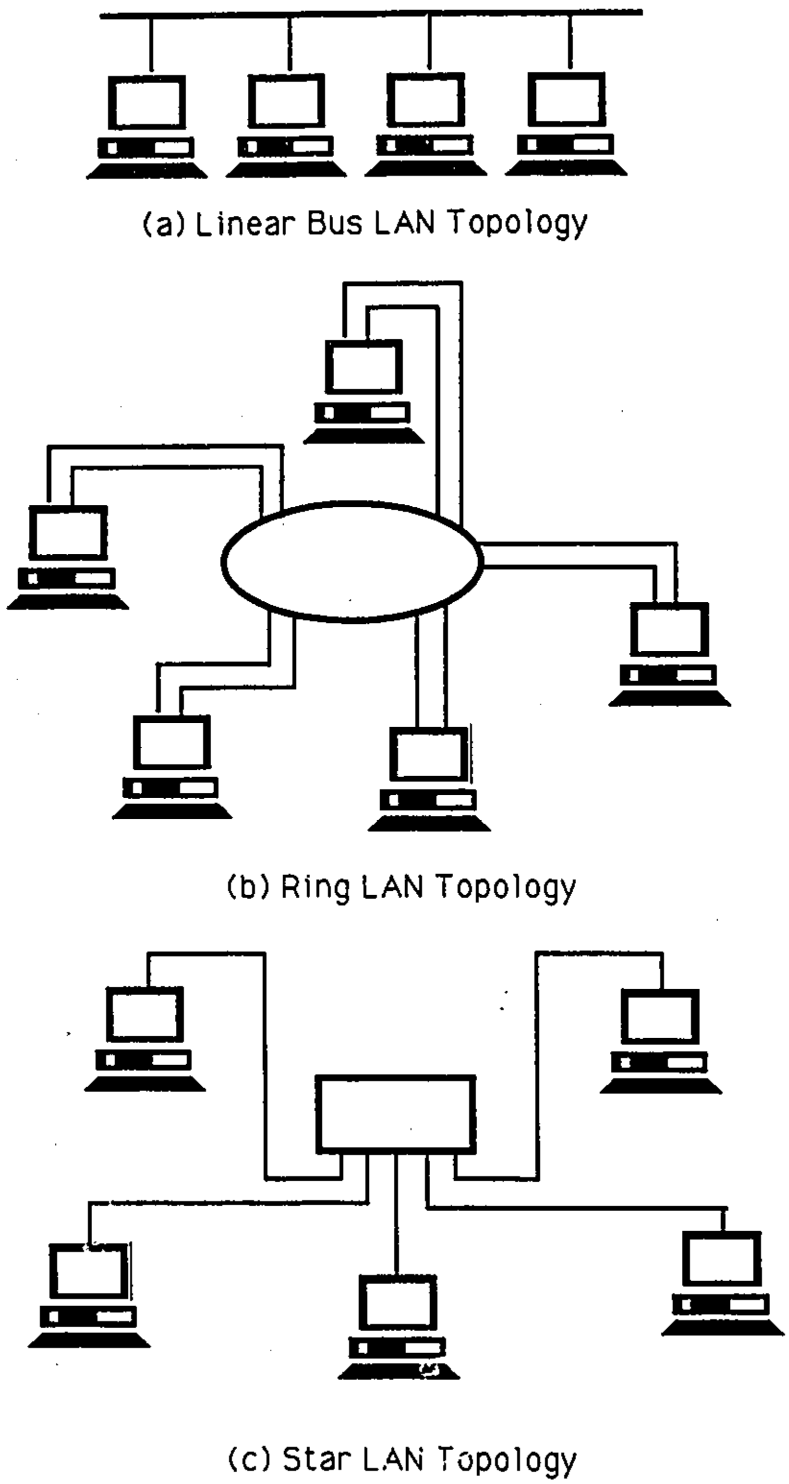


Figure 1.2: Local area network topologies

protocol is used to determine the sequence in which nodes transmit. Because the ring is constructed as a series of point-to-point links, almost any transmission medium can be used.

Bus or tree topology is characterized by the use of a multipoint medium. A bus is simply a special case of a tree, in which there is only one trunk, with no branches. Because all devices share a common communication medium, a distributed medium access protocol is used to determine which station may transmit. As with the ring, transmission employs a packet containing source and destination address fields. Each station monitors the medium and copies packets addressed to itself.

The common media have been used in local area networks: twisted pair wire, coaxial cable and fiber optics. The most common communications medium is twisted pair wire which is certainly applicable to bus/tree local area networks. Although it is typically used for low-speed transmission, data rates of up to a few Mbps (megabits per second) can be achieved. Twisted pair is relatively low-cost and is typically preinstalled in office buildings. It is the most cost-effective choice for single-building, low-traffic requirements.

Higher performance requirements can best be met by coaxial cable, which provides higher throughput, can support a larger number of devices, and span greater distances than twisted pair wires. Two transmission methods, baseband and broadband can be employed on a coaxial cable. Baseband systems are typically from 1 to 10 Mbps and generally limited to a single building. However, by limiting the distance covered and the number of devices attached, data rates in order of 50 Mbps can be achieved. Broadband systems are also typically in the range of 1 to 10 Mbps for a single data path, with 20 Mbps representing a practical upper limit. However, broadband can support multiple data paths in contrast to the single data path of baseband. Broadband systems use CATV (Community Antenna Television) cable, which is suitable for outdoor as well as indoor environments. Hence interbuilding and even intracity networks can be supported.

Optical fiber has even a greater capacity than coaxial cable and is a promising candidate for future local area network installations. As the interest in multimedia applications increases, ever higher speeds and greater bandwidths must be made available. A LAN operates over 50 Mbps is called a high-speed LAN (HSLAN) and optical fiber is a desired transmission medium for HSLAN. Optical fiber has already enjoyed considerable use in long-distance telecommunications and its use in military application is growing. However, it has been little used so far due to the cost and technical limitations. The continuing improvements in performance and decline in prices, together with the inherent advantages of optical fibers will result in new areas of applications, especially for the local area networks with a high data rate requirement. Optical fiber technology for LAN applications is maturing rapidly and there are now a number of commercial fiber-optic LANs available.

Applications for LANs are continually evolving and hence LAN architectures should be designed to adapt to system growth and new applications. Some requirements imposed by certain application segments and a budget must be considered by LAN designers. Other considerations involved in LAN design or selection may be interpremises networking capability, interface to other networks such as public data networks or other types of LANs, wiring distribution, and appropriate network protocols including such factors as flow control, congestion control and error control. The LAN is a technology that will serve an important role in data communications. With knowledge of the architecture strengths of different approaches and through some practical experience, both designers and users of LANs can make informed decisions on the appropriate LAN approaches to satisfy their needs.

1.4 Metropolitan Area Networks

Metropolitan area network (MAN) is a relatively new concept in networking [6]. A MAN is a network capable of providing connectivity between users spread across typical distance of a metropolitan area and supporting for different types of traffic to be carried simultaneously. Metropolitan area networks are being developed to interconnect individual users and heterogeneous LANs across increased distances at high speeds. Correspondingly, there is a need to distribute information among potential large number of users, providing a large bandwidth connection, supporting various types of services each with a different traffic demand and performance constraint.

The design of a MAN can be considered as a network interconnection problem at a new and higher level of complexity. The challenging problems includes the following:

- Support a large number of stations (several hundreds to several thousands);
- Cover a large geographical area;
- Support real-time traffic (voice, video);
- Meet very high bandwidth requirements (in the Gbps range).

Metropolitan area networks need to address other problems that local area networks do not face [7]. LANs are typically owned and operated by the same organization that uses them. Thus security and privacy are not serious issues. MANs however, will likely be owned and operated by common carriers. Security is a much more serious issue. Network reliability will be of much greater importance.

Additional requirements in a MAN design (which are also common to more traditional LAN designs) are: high availability, fault tolerance, and growth flexibility. Considerations must be given to available technologies and to the design of protocols, interconnection methods and so on. Many of the MAN design issues, such as the topology, the addressing schemes, routing strategies, flow and congestion control methods, etc., are inter-related and must be considered together to give a good network performance.

Until recently, the focus on metropolitan area network services has been data communications. This has been primarily true because the trust for MANs has come via local area networks and the computing community. The communication world, however, has become interested and is now taking an active role in providing integrated services on MANs [8].

The demand for high capacity channels will increase as the impact of fiber reduces the cost of bandwidth and customers seek to transmit a high array of services [9]. As the demand for high-speed data and visual services increase, Gbps capacities will be required. Examples of applications using such high-transmission rates include medical imaging, advanced CAD/CAM, videophone and videomail, computer center consolation, etc.

There is a growing interest nowadays in MANs as providers of high-speed integrated services in limited geographical areas. It is anticipated that MANs will become widespread both in public and private environments.

1.5 Standards of Communication Networks

In the mid-1970's, the development and use of computer networks began to attract considerable attention. The early successes of the ARPANET, the immediate commercial potential of packet switching, satellite and local network technology, and the declining cost of hardware made it apparent that computer networking was quickly becoming an important field. When communication is desired among the computers from different vendors or even the computers with different models of the same vendor, the software development effort could be a nightmare without a standard. Different vendors use different data formats and data exchange conventions. Therefore, a special-purpose approach to communications software development is too costly to be acceptable. The only solution is that computer vendors adopt and implement a common set of conventions. For this to happen, a set of international, or at least national standards must be announced by appropriate organizations. Such standards are of benefit to both vendors and customers. The formal protocol specification becomes a rapid growing area of research in computer communications.

Among standards-making organizations, the International Organization for Standardizations (ISO) has been proposing the *Open Systems Interconnection* (OSI) standards for communication networks. The model logically groups the functions and sets of rules called protocols necessary to establish and conduct communication between two or more parties. It is concerned not only with the basic data transport but also with the applications using networks and the services which are needed to support them. The term *open* was chosen to emphasize that by conforming to OSI standards, a system would be open to communication with any other system obeying the same standards anywhere in the world. The purpose of the standards is to ensure easy and effective communication among many communication entities. Ideally, each user of the communication network should not need to know the technical characteristics of any other one for the reason of privacy. All it really needs to know is that the others observe the same conversions. In OSI, three levels of abstractions are explicitly recognized: architecture, service specifications, and protocol specifications. The attractiveness of the OSI approach is that it promises to solve the communication problems between different computers.

The basis of OSI is a *reference model* [10] for the coordination of standards development. It is intended that the model should provide a common reference for maintaining consistency of all related standards. The model does not define precisely the services and protocols of the interconnection architecture but it does identify the areas where such standards should exist.

The idea of layering was introduced in the discussion of high- and low-level protocols to divide up the interworking model into processing- and communications-oriented functions. The ISO Reference Model for OSI, as shown in Fig.1.3, uses seven layers to simplify the work of defining all the protocols and services required for internetworking. This allows separate teams of experts to work independently on developing standards for each layer. Each layer has a specific job. It performs

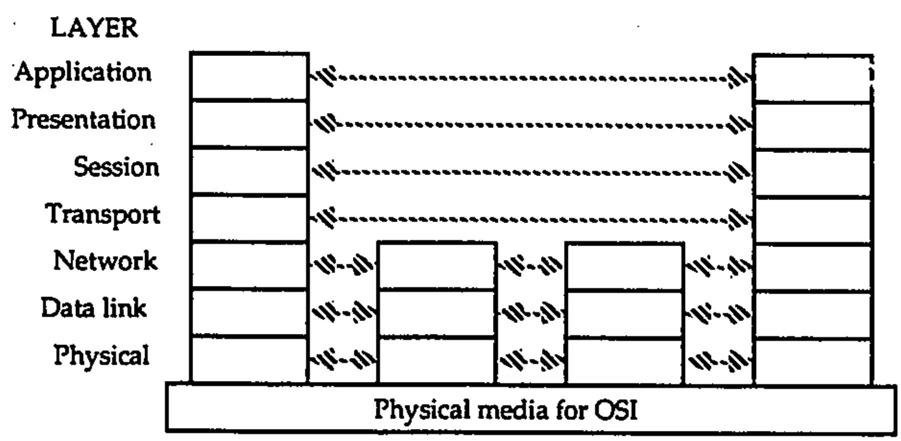


Figure 1.3: ISO Seven-Layer Reference Model

a particular set of functions to provide a service to the layer above. In its turn, it makes use of the services from the layer below. The OSI seven-layer model defines two basic things: the services which each layer must provide, and the protocols, by which it provides the services.

The OSI service definition specifies what each layer must be able to do, and what options there are in how the services are provided. It defines the commands and responses that the layer must be able to understand and decide when communicating with the layers above and below.

There is a protocol definition for each layer, which defines the way the layers communicate with their peers. When two systems communicate, each layer communicate with the equivalent layer (its peer layer) in the opposite system using a defined protocol.

The following is a brief description of the layers from the reference [11] that identifies some of the services provided by each layer:

- The *Application Layer* provides identification of intended communication partners (e.g., by name, by address, by definite description) and identification of the subjects to be communicated (e.g., banking, text processing, airline reservations, determination of adequacy of resources, agreement on resources, and agreement on privacy mechanisms).

- The *Presentation Layer* provides data transfer and selection of the user data syntax.

- The *Session Layer* provides session connection establishment and release, turn management, session synchronization, and exception reporting.

- The *Transport Layer* provides end-to-end sequence control, flow control, error recovery, multiplexing, and blocking.

- The *Network Layer* provides quality of service, routing, sequencing, network flow control, and segmenting. It is the highest layer assigned to intermediate nodes in OSI Model (see Fig.1.3).

- The *Data Link Layer* provides error detection and correction, establishment and release of data link connections, link flow control, identification, and parameter exchange.

- The *Physical Layer* provides mechanical, electrical, functional, and procedural means to activate, maintain, and deactivate physical connections, and transparent transmission of bit streams.

The bottom three layers, Physical, Data Link, and Network cover the components of the network used to transmit the message are refered to as lower-level layers. The top four layers,Transport, Session, Presentation, and Application which generally reflect the characteristics of the communicating end systems are refered to as high-level layers.

1.6 Multiple Access Communications Networks

Multiple Access Communications Networks are those in which the multiple users share the same transmission channel in their attempt to communicate [12]. This sharing may be necessary because of efficiency considerations, or due to the nature of the application. Due to the sharing, if more than one user transmit simultaneously, the reception will be garbled; and if no user transmits, the channel will be idle. It is desirable to have multiple access schemes which resolve the conflict among the users such that the channel could be used most of the time. Multiple access networks may include satellite networks, local area networks, and packet radio networks.

1.6.1 Multiple Access

Multiple access protocols may be categorized into two classes: random (or contention) access protocols and scheduled (or controlled) access protocols [13]. Random access protocol is an optimistic protocol in which transmission rights are simultaneously offered to the users in the network, a user with a message will transmit immediately, hoping no other users will transmit at the same time. Since there is no coordination among users, if more than one user transmit simultaneously on the channel, a collision may occur. Algorithms must be developed such that collided messages are retransmitted efficiently until they are successfully received by their destinations. Scheduled access protocols are pessimistic protocols in which no one is allowed to transmit until a reservation has been made successfully on its behalf. Therefore, there is no collision. However, scheduling process consumes some of the channel capacity regardless of whether or not the users require to access. While such protocols are efficient when traffic is heavy, under light traffic conditions, they are unnecessary message delays as the users that want to transmit wait their turns.

In contrast, random access protocols exhibit small message delays under light traffic conditions. The users transmit as soon as they want access to the channel, and the probability of a collision is low when the traffic is light. This kind of protocols perform well when the network is subject to bursty traffic conditions. Another attractive aspect of random access protocols is their simplicity, making them easy to implement.

Most random access protocols handle the resolution of collisions by using part of the channel capacity to allow contending users to establish a schedule for transmissions among themselves. There is therefore an unavoidable loss of channel capacity when collisions occur. As the traffic intensity increases in such a network, so do the chances for collisions, and channel utilization and message delays increase accordingly. It would be nice to have hybrid protocols which have the benefits of random access (in particular low delay in light traffic), but at the same time do not suffer from lost channel capacity when traffic is heavy [14].

The best known random access protocol is the ALOHA protocol. It was developed in 1970 to allow communications between remote terminals and the central computer at the University of Hawaii. The geographic problems of the Hawaiian Island, and the lack of very reliable telephone circuits, forced the University to find a new way for the computer terminals on the outlying islands to communicate with the computer center. The significance of ALOHA is in its use of a shared-medium in which there was no direct control over who transmitted packets. ALOHA introduced the concept of contention networks.

Since then, many multiple access protocols have been developed. A summary is given in Fig.1.4 [15].

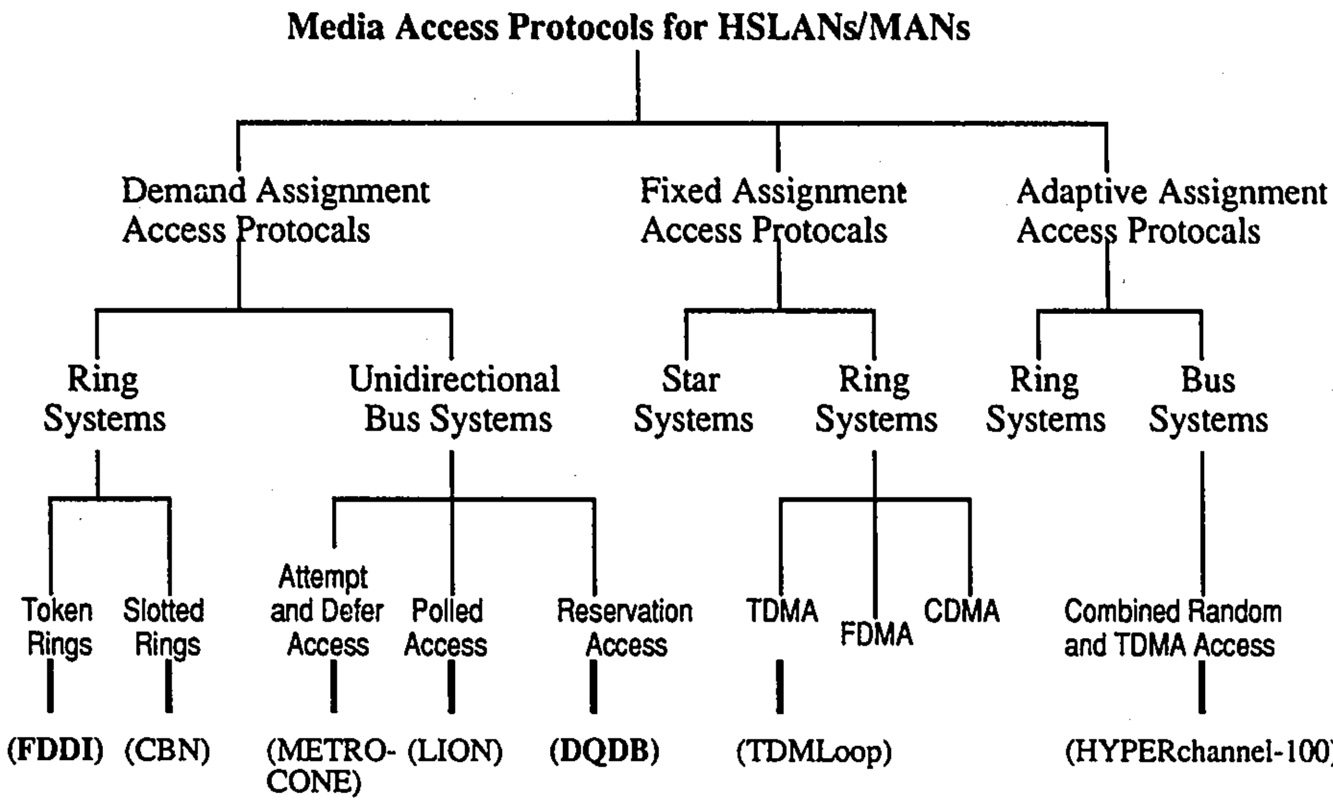


Figure 1.4: Media Access Protocols

1.6.2 IEEE Standards for Multiple Access Protocols

A set of standards have been developed by the IEEE and also adopted by ISO as international standards for LANs and MANs. For LANs, they are the IEEE standard 802.3 for CSMA/CD bus, the IEEE standard 802.4 for token-passing bus, and the IEEE standard 802.5 for token-passing ring. These standards cover the Physical layer and a part of the Data Link layer, referred to as MAC (Medium Access Control) sublayer. The IEEE 802.2 standard describes the upper part of the Data Link layer which uses the LLC (Logical Link Control) protocol and is common to the various MAC methods that are defined and supported by the 802 standards activities.

IEEE 802.3: CSMA/CD The IEEE CSMA/CD (Carrier Sense Multiple Access with Collision Detection) protocol operates on a bus configuration. The algorithm of this protocol is quite simple. All stations listen for transmission on the line. A station that wishes to transmit does so only if it detects the channel is idle. Once a collision is detected during the transmission, the transmission is immediately aborted, and a jamming signal is transmitted to assure that all stations know there has been a collision. After waiting a random amount of time, the station attempts to transmit again using CSMA.

On a bus, use of CSMA/CD has some advantages such as simple implementation, fair access, good performance at low and medium load, easy installation of stations, no modem required, and a wide usage. Some disadvantages are collision detection using the analog circuits, minimum packet size required, poor performance under very heavy load, cable length limitation, nondeterministic behavior and no priorities.

IEEE 802.4: Token Bus The token-passing bus is designed for manufacturing automation activities. The bus used in this fashion still acts as a broadcast simultaneous channel. All stations receive the same traffic at the same time if transmission delays are ignored. Therefore, a token must be addressed to the successor station. Only a station whose address is in the token can respond and utilize it. The physical location of the successor is not important; only its address is needed. The token-passing bus must be utilized by a logical ring structure. Each station must remember the address of the station that passed the token and the station to which it passes the token. The details of the protocol are complicated involving issues such as adding stations, deleting stations, fault management by token holder, ring initialization and classes of service [16].

The token bus can overcome some disadvantages of CSMA/CD. It supports the priorities, provides a guarantied fraction of the bandwidth to high-priority traffic, and at high loads has an excellent throughput and efficiency. However, the disadvantage is that the protocol is extremely complex and has a substantial delay at low loads. Its broadband physical medium needs modems and wide bandwidth amplifiers.

IEEE 802.5: Token Ring In a ring structure, there are several medium access techniques, such as register insertion, slotted ring and token ring. The token ring has become the most popular ring access technique and has been selected for standardization by the IEEE 802 committee. IBM's token ring network is compatible with the IEEE 802.5 standard [17] [18]. It should be noted that a ring is not really a broadcast medium, but a collection of individual point-to-point links that happen to form a circle. A ring consists of ring stations and a transmission medium to which they are attached. The token ring operates with a token-passing procedure taylored to the characteristics of a ring. The data are transmitted in only one direction. A station that wishes to transmit must wait until it detects a free token passing by and changes that token into a busy one. The station then transfers data to the medium, where the data travel sequentially from station to station. Each station repeats the data, checking it for errors and possibly modifying some of its bits before sending it on. When the data returns to the originating station, the station removes it from the ring and inserts a new free token on the ring.

A token ring has some advantages over a token bus. Furthermore, it is a full digital connection in the physical medium. A ring can be used with virtually any transmission medium, from twisted pair to fiber optics. The use of wire centers makes the token ring the only LAN that can detect and eliminate cable failures automatically. A major disadvantage is the presence of a centralized monitor function which introduces a critical component. Another disadvantage is that there is some delay at low loads.

For the high speed networks, there are two well known standards: FDDI (Fiber Distributed Data Interface) and DQDB (Distributed Queue Dual Buses) .

FDDI FDDI is a high performance fiber optic token ring network running at 100 Mbps over distances up to 200 km. FDDI-II is a modified FDDI to handle synchronous circuit switched PCM data for voice or ISDN traffic in addition to ordinary data [19], [10]. FDDI consists of two counterrotating fiber rings. The stations attached can be divided into two classes depending on the importance of station fault tolerance. Class A stations connect to both rings and the cheaper class B stations connect to one of the rings only. The FDDI standard employs the token ring protocol based on the IEEE 802.5 standard. However, many differences between them may be identified, such as in physical link, transmission rate, line code, clocking, token generation, reliability specification, etc [21]. The FDDI standards have accepted 802.2 (LLC) standards as the way to reach higher-layer protocols. Therefore, the FDDI MAC layer must also support the services required for communication at the interface between MAC and LLC sublayers.

Several levels of fault tolerance are possible in FDDI. For example, since wire centers can be used, if there is a cable fault in the cable going to a class B station, this station is cut off from the network, and the wire center provides a bypass for the node. If a cable fault happens in the cable going to a class A station, the two rings can be joined into a single ring. In FDDI, this reconfiguration happens automatically within a few milliseconds.

IEEE 802.6: DQDB IEEE 802.6 standard is a medium access control procedure for a MAN covering a large area such as a city or a campus. The physical configuration is a dual-bus architecture [22] [23]. Unlike FDDI, the structure of DQDB consists of a dual loop of the medium arranged physically as a ring but logically as a bus. The dual bus architecture carries unidirectional traffic in opposite directions. Each node is connected to both buses with read and unidirectional write capability. Thus, every node can communicate with every other node by sending information on one bus and receiving it on the other. One node, serving as master, generates the empty frames to two buses in different directions for the use of data transmission by the other nodes and does not repeat the data coming in from either direction. The distributed queuing MAC protocol is fundamentally different from existing LAN packet access protocols.

When failures occur in a node, no reconfiguration of the bus is necessary, because faulty nodes are easily bypassed. If the cable has to be cut or a node failure can not be bypassed with relays, the logical opening can be closed. The original ends of the bus are instructed to pass the data rather than to terminate it. The detailed description of the DQDB protocol can be found in the IEEE 802.6 standard and [23].

Chapter 2

Optical Local Area Networks

One of the most exciting developments in communications today is the application of lightwave technology to telecommunication systems [24] [25]. All over the world, optical fibers are superseding metallic wires in a wide variety of applications including metropolitan telephone exchanges, long-haul commercial communication systems, and undersea transmission links and local area networks. Optical fibers enjoy a number of charming properties that make them natural candidates for high-capacity transmission systems. The most important of these properties are:

- Large bandwidth $\times$ distance products supporting data attaining transmission at rates up to, say, 100 Gbps over 100 km;
- Since it is a dielectric medium, immune to electromagnetic interference and free from sparking, optical fibers are useful in electrically hostile environments;
- Extremely small physical dimensions–the diameter of an uncabled optical fiber may vary from 5-10 μm for high-performance single-mode fibers to between 50 to several hundreds μm for multimode fibers;
- The information carried by optical fibers can not be detected merely by placing a pick-up alongside, so making fiber more secure from unauthorized eavesdroppers;
- Low attenuation, typically below several decibels per kilometer.

The basic components of an optical-fiber communications system are [26] optical transmitters, optical receivers, optical fibers connecting transmitter-receiver pairs, connectors and splitters, and couplers. A simple optical link consisting of a transmitter-receiver pair interconnected by single-mode fiber is shown in Fig 2.1. The transmitter converts incoming binary data into on-off light pulses, which are launched into the optical fiber. At the receiver end, the optical stream is detected and converted back into electrical signals. Several crucial system parameters that determine whether this optical link works or not are:

- the optical power of the signal received at the detector;
- the distortion of the signal transmitted through the fiber;
- the system rise time.

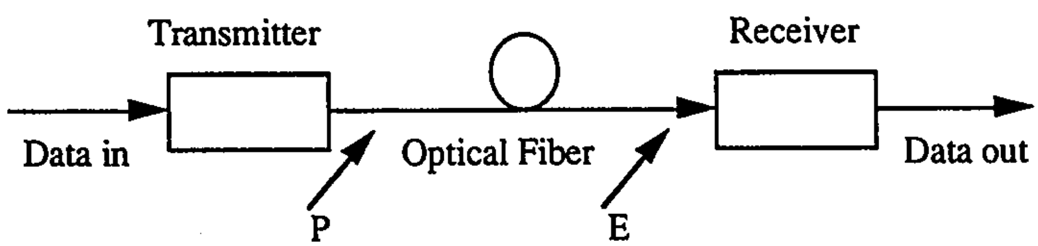


Figure 2.1: A simple optical communication link

As a transmission medium, optical fibers have proven to be extremely effective in long-haul communication systems. However, when one restricts attention to LANs, optical technique has yet to be exploited to the limits of its enormous bandwidth. Such things as expensive optical components, optical tap loss, optical transmitter-receiver pair behavior, and complexity of the medium access mechanisms limit their applications in LANs at the present stage of technology. Tremendous effort has been made on the research of optical LANs in order to find a suitable technique for the future networks.

2.1 General Overview of Optical Fiber LANs

When applying lightwave technology in LANs, one of the most exciting possibilities is to push LANs beyond basic data transport into the realm of integrated total communications services for a local entity such as building or campus. The most likely area of application for the optical medium is the high-speed LANs, say above 100 Mbps, or for metropolitan area networks, which cover distances greater than 5-10 km [27]. In both of the above cases, optical fibers have a much lower attenuation (in the range of 0.5-0.6 dB/km, depending on the type of fibers and the wavelength of operation) than other transmission media. In the near future, networks with throughputs in excess of several Gbps are likely to be needed to keep pace with developments in computer and communication technology [28].

The potentially usable bandwidth of the optical transmission medium (single-mode fiber) is enormous, with about 15 THz bandwidth for the low-loss windows at 1.3 μm or 1.5 μm, alone. We could construct multiple access networks carrying a total traffic of perhaps 5×10^4 Gbps (50 Tbps), roughly four orders of magnitude greater than the traffic flow through a high-capacity electronic telephone switch (e.g., the AT&T 5ESS) [27]. Sharing the enormous bandwidth among all the users of a network with a variety of different applications is the major attraction of lightwave technology for multiuser communication networks. Today, of course, we are far from realizing this potential. The fundamental processes that limit network performance have not yet been fully elucidated, and the devices likely to be required do not exist. Yet we still have reasons to believe that these networks will ultimately be built.

So far there have been numerous demonstrations of optical LANs, most of them have operated at relatively modest bit rates ($\leq$ 100 Mbps), thus failing to take advantage of the multigigabit transmission capacity of optical fiber already in long-distance systems. The basic problem is that a LAN is much more complicated than the point-to-point links used in long-distance transmission systems, and gigabit data rates are much more difficult to achieve. The most important point to emphasize is that fiber can not simply be a substitute for copper to upgrade the capacity of a wire-based LAN: the differences between photonic and electronic communications techniques are too great [29]. Compared with copper networks, fiber-based systems are characterized by:

- severely limited signal power;
- abundant transmission bandwidth.

Most of the research activities in lightwave LANs is directed toward solving the two basic problems arising from these characteristics: the *power division* problem and the *electronic bottleneck*.

Power division problem is among the most troublesome problems which limits the applications of optical fiber LANs [30]. The relatively small amount of signal power available from optical sources and the cumulative loss of many concatenated waveguide components combine to limit the number of users in the LAN among which the signal power can be divided. This is true especially in the passive networks.

The traffic capacity of a fiber LAN, though extremely large, can be limited to far less than the bandwidth of the fiber itself by fundamental energy considerations [26]. Consider the simple point-to-point optical link shown in Fig.2.1, which consists of a transmitter coupled to a receiver via a lossless fiber. To detect a transmitted bit, the receiver requires a minimum amount of optical energy E. In the ideal (shot-noise-limited) case, E is independent of bit rate. At a link rate B, a power level of EB is required at the receiver. We conclude that for a transmitter with output power P, the maximum (power-limitted) transmission rate is $\frac{P}{E}$. A similar limitation appears when these same energy considerations are applied to a LAN, such as the star network shown in Fig.2.2.

If a passive star coupler is considered to accept signals from all the transmitters simultaneously and to broadcast them to all the receivers. Thus, each receiver has access to all the traffic in the network and selects out those massages intended for itself. Assume again that signal power P is available from each of the N users' transmitters and that the fibers are lossless. The star coupler uniformly distributes these signals across its N output fibers, so each one delivers to its receiver a contribution $\frac{P}{NE}$. The total throughput (aggregate traffic) of the network, defined as the product of the user

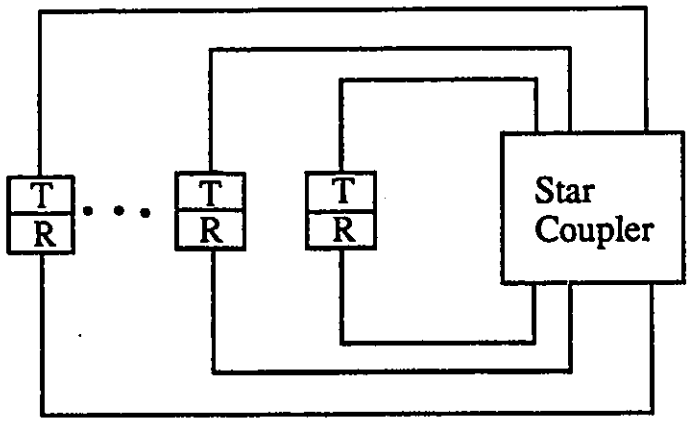


Figure 2.2: Star Network

bit rate times the number of users, is therefore $\frac{P}{E}$ -the same limitation as for the simple point-to-point link, independent of the number of users N. Although power-limited throughput is not an all-purpose figure of merit, it is a very useful quantity, because it provides a bound, or an upper limit, against which the performance of networks can be judged.

The power division problem makes it difficult to translate many high-capacity networking concepts into practical photonic implementations. For example, the unidirectional bus is especially desirable for high-speed networks because the sequential ordering of the nodes permits efficient, collision-free access [26]. Although attractive for use with coaxial cable, this architecture is impractical with fiber because it wastes signal power. A tapped unidirectional bus network is shown in Fig.2.3. Each user's traffic is first injected into the "talk side" of the bus, via directional couplers, then broadcast to the receivers on the "listen side", via a second set of couplers. In an N-user network with ideal frequency-independent couplers to inject and broadcast the optical signals, only $\frac{P}{N^2}$ useful power is delivered to each receiver (compared to $\frac{P}{N}$ for the star network), so the power-limited network throughput is proportional to $\frac{1}{N}$ [27].

In practice, the power-limited throughput of a network can be substantially poorer than the ideal performance mentioned above, because of the excess loss (in effect, dissipation) associated with the fiber couplers or taps used to collect and distribute

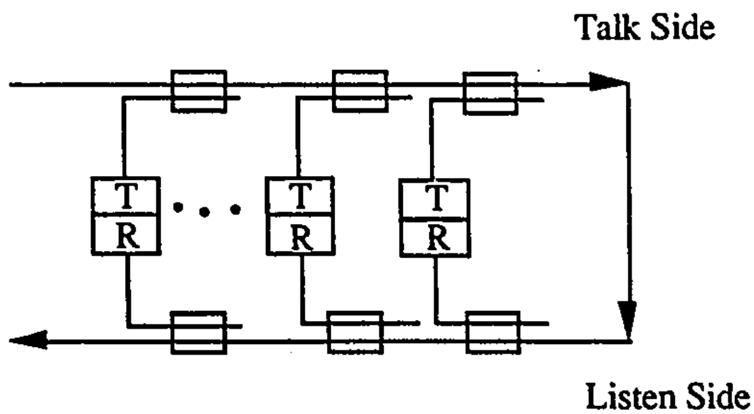


Figure 2.3: Unidirectional Bus Network

the optical signals. For the star topology, the problem is minor, because the network can be constructed so that each signal passes through only about $\log_2 N$ couplers, or an efficient integrated-optical structure can be used. In either case, total excess loss is relatively modest and power-limited throughput remains high [31].

Extensive research efforts have been made in solving the power division problem in optical applications, because the energy efficiency becomes an extremely important, and usually dominant factor in optical LANs. Throughout this thesis, we always assume that the opto-electronic components (lasers and detectors) used in the network have adequate optical bandwidth to support the power-limited throughput. Our assumption is justified since in multiple medium access networks, we can always invoke multiple devices to cover the required network throughput.

Although photonic technology is capable of supporting many Tbps of throughput, the digital electronic components at the nodes of the lightwave network, which typically operate at rates of 1 Gbps or less, can dramatically limit the transmission rate of each user. In the rest of this thesis, we will exploit the methods which can be used to solve this *electronic bottleneck*.

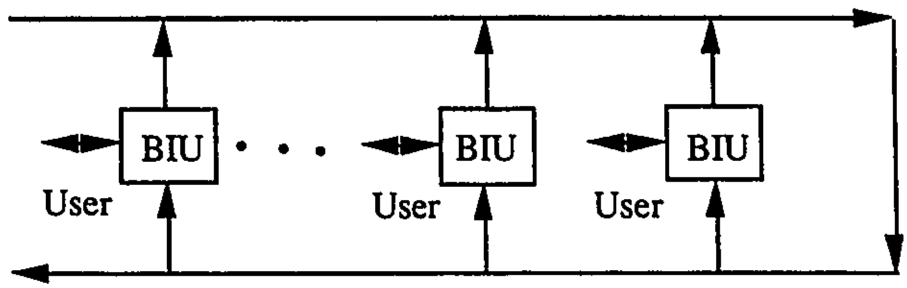
2.2 Configurations of Optical Fiber LANs

Optical fiber is essentially a unidirection transmission medium. This property makes the all-optic switching very difficult. So the topologies and medium access methods are extremely important for optical LANs. The topology of a network describes the geometrical routing required to interconnect the terminals and distribution elements in the network. The common topologies proposed for implementation of fiber optic LANs are bus, ring, star and mesh topologies or hybrids of these [32]. The star and ring are the most commonly utilized as opposed to the bus, since these topologies have been easier to implement with existing electro-optic devices. The star and bus topologies have limitations in achieving a large number of nodes with adequate optical power margin, while the ring and bus topologies have difficulty to provide adequate fault tolerance especially in severe environments.

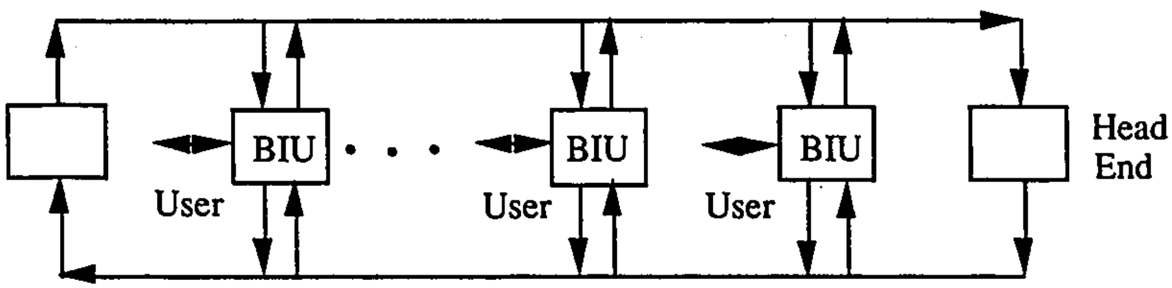
2.2.1 Bus Topology Lightwave Networks

The topologies of optical bus networks are shown in Fig.2.4 a and b. These topologies utilize couplers or taps to couple optical energy from a linear succession of nodes. The insertion optical power loss is caused by the fiber size and total attenuation, which includes connector, splice, and coupler losses. There is a limitation to the number of such devices to make sure that the level of received photons per bit do not fall below the threshold required to maintain an acceptable communication link. The number of terminals in the bus network is limited accordingly. Wide dynamic range receivers must be utilized to accommodate the linear power drop down the fiber. Couplers can be tailored to couple variably decreasing amounts of light in relation to the position along the length of the bus.

Although high reliability is achieved by the use of passive couplers, this may be offset by the high output power required from the source to accommodate a relatively large number of terminals, since high drive current may affect the source lifetime. Linear systems typically utilize large core diameter fibers, but even with these fibers, expansion in the number of terminals as well as repair can be proven difficult without exceeding the system power margin.



(a) Unidirectional Bus



(b) Dual Bus

BIU-- Bus Interface Unit

Figure 2.4: Optical Bus Networks Topologies

2.2.2 Ring Topology Lightwave Networks

The ring network (shown in Fig.2.5) topology utilizes an optical source and detector at each terminal in the ring. These devices act as a repeater by detecting and regenerating the optical signal for data passing through the terminal. They also serve as the means to extract optical data for use by the terminal or for sending information generated by a given terminal to the next adjacent terminal. If one examines this topology, it quickly becomes evident that the entire network consists of a series of point-to-point links. Thus, a major element in the power budget equation, coupler loss, is eliminated. This arrangement permits the use of low-sensitivity and low-dynamic range receivers, since only the next adjacent terminal must be accessed where the optical signal is regenerated with an optical source. This permits the use of reliable low-power sources as well as low sensitivity and dynamic range receivers. This topology is ideal for networks with a large number of terminals, and it can be easily expanded. The margin built into this design can be utilized to advantage in adverse environments such as military, automotive, or factory applications [33]. The ring topology is useful in private networks where privacy and security are not considerations and where the total bandwidth requirements are not too high.

While providing the advantages listed above, the point-to-point nature of the ring topology presents reliability concern since a single point failure in either the optical, electronic, or power supply elements can cause a failure in the entire ring. The use of *counter-rotating rings* is typically utilized to prevent a total failure of the ring in the case of a single point failure. Redundant hardware (transmitters, receivers, fibers, power supplies, and/or bypass devices) is required to obtain fault tolerance. Spring loaded electromechanical bypass switches are costly, and slow (on the order of milliseconds) causing significant loss of data during loopback. Repeaters at each node add to the total time delay of a network, especially a network with extremely large number of terminals. Because of the high-speed operation of the ring, the repeater delays are usually insignificant in relation to the time delays caused by the circuits while the data is being transferred at the terminal. The counter-rotating ring topology has received wide adoption as the commercial *Fiber Distributed Data Interface* (FDDI) standard, and has also been selected for use in the US Navy shipboard standard and the proposed NASA space station *Freedom* [33].

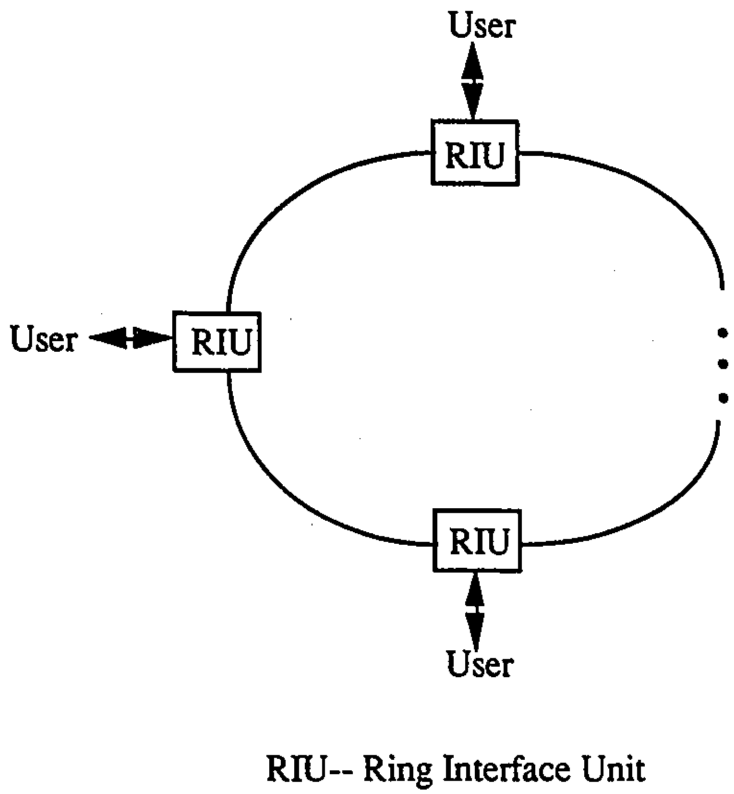


Figure 2.5: Optical Ring Networks Topology

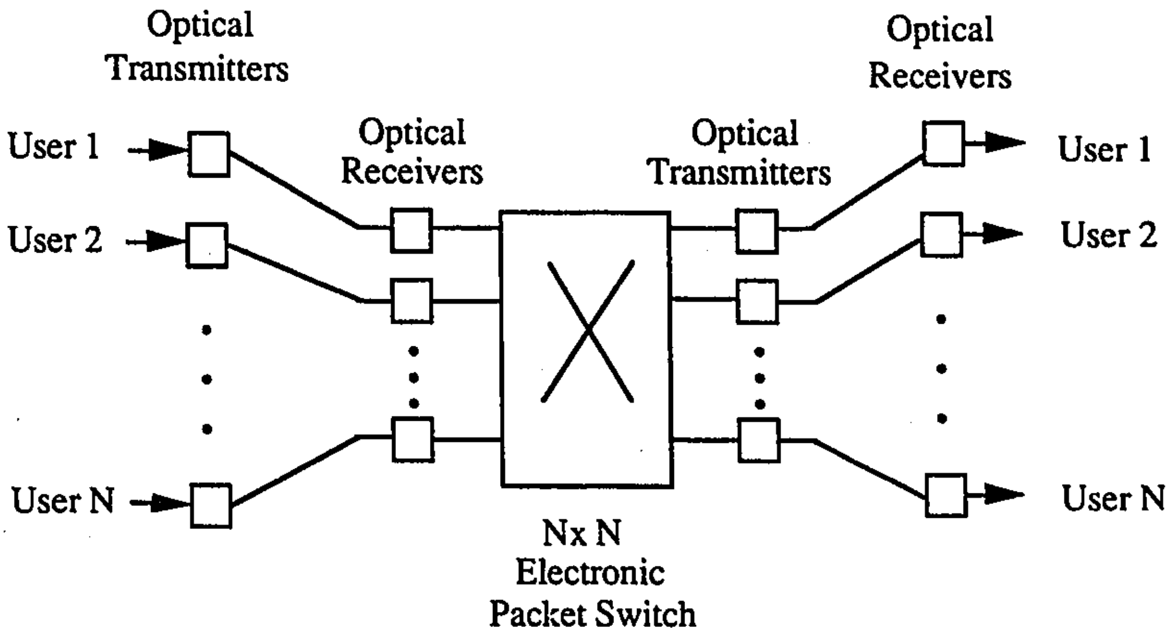
2.2.3 Star Topology Lightwave Networks

An alternative to bus- and ring-based topologies is star topology shown in Fig.2.6. Users inject packets on the dedicated inbound fibers toward the receivers at the other end of the network. Both active and passive star couplers can be used. Active star coupler is an electronic, self-routing, real-time packet switch with N inputs and N outputs. The packet switch read the header of each inbound packet and accordingly routes the packet to the appropriate output. The network consists of a series of point-to-point links between the transmitter and the active star coupler, and between the active star coupler and the receiver. Thus, there is no power divisional problem in this topology. Low-sensitivity and low-dynamic range receivers can be used. Since the active star coupler acts as a repeater, the electronic bottleneck between the electronic and optic transforms limits the network bandwidth. Passive star coupler acts as a broadcast channel in star topology lightwave networks, broadcasting the incoming optical signals onto all the outgoing fibers. Since there are no active components in transmission, the network bandwidth is higher than in the active case. The drawbacks of passive star networks are: either tunable transmitters or tunable receivers, or both must be used and the power division problem will limit the number of users in the networks.

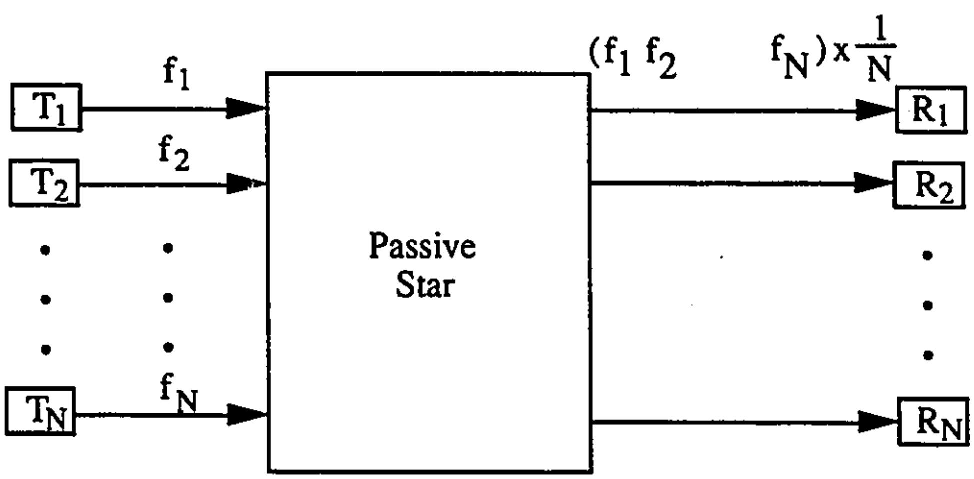
Contention arises within the active star coupler if two or more same wavelength light packets addressed to a common output should arrive, simultaneously. In such an event, the switch ships one packet to that output and buffers the rest; all such stored packets are sequentially discharged onto the output. For passive star networks, when two or more packets transmitted onto the same data channel (WDM) or addressed to a common terminal arrive during the vulnerable period (if two or more packets arrive during this time period), collision happens and all involved packets must be retransmitted by their sources according to certain medium access protocol.

In the passive star topology, optical power is divided equally among a number of terminals through the utilization of a transmissive or reflective passive star coupler. If the fiber lengths or the number of connecters in each fiber are not equal for all terminals, which is most likely the case in LANs because of large distance difference between the terminals, receiver dynamic range and sensitivity become the design issues. Since light from any terminal must reach all other terminals, the source must be driven at a high output power, posing potential reliability problems especially with operation at a high temperature. By a loss budget calculation, one can soon determine that this system is limited in its number of terminals for operation in harsh environments with provision for connectors, splices and very little margin.

Star topology lightwave networks should be considered when the potential exists for a demand on a full range of services, when high-reliability/security is required, or when the distances are short enough that the initial cost is not a critical parameter [34].



(a) Active Star Optical Network



(b) Passive Star Optical Network

Figure 2.6: Optical Star Networks Topologies

2.2.4 Hybrid and Mesh Topology Lightwave Networks

Hybrid topology lightwave networks combine the above three basic topologies to meet the different implementation requirements. When considering special applications, careful evaluation must be made of such factors as the long-term service requirements, initial and recurring costs, and reliability and security objects. Several hybrid topology lightwave network architectures are give in Fig.2.7 [34].

The mesh topology can be utilized for specialized applications where very high reliability is required. This topology uses totally redundant links to interconnect all nodes of the network, which adds considerably to wiring and hardware complexity and cost. The total redundancy of components, including uninterruptable power supplies is often warranted where extremely high reliability is necessary, since no other cost-effective solution has been forthcoming to date.

2.3 Access Methods for Lightwave Technology

The use of single-mode fibers for transporting information in telecommunications networks makes possible many new services that are difficult to support in metallic cable networks. This is because single-mode fibers have a much larger bandwidth than metallic cables. However, in today's fiber-optic networks, only a small fraction of the potential transmission capacity can be utilized. The reason for this is two-fold: First, opto-electronic components at the input and output of the fiber are not capable of operating at speeds comparable to the fiber's bandwidth. Second, a multiple access or multiplexing protocol must be used to allocate portion of the channel bandwidth among the users. In this way, many low-bandwidth users can share the extraordinarily large bandwidth of the fiber. However, the required electronic components for multiple access processing are not capable of operating at speeds that commensurate with the fiber's bandwidth.

A schematic diagram for a generic, fully-distributed lightwave network is shown in Fig.2.8 [32]. The users are portrayed as connecting to the optical medium at the periphery of the network. The optical medium is entirely passive, and the only electronics appear in the distributed user access ports. It also contains the enormous

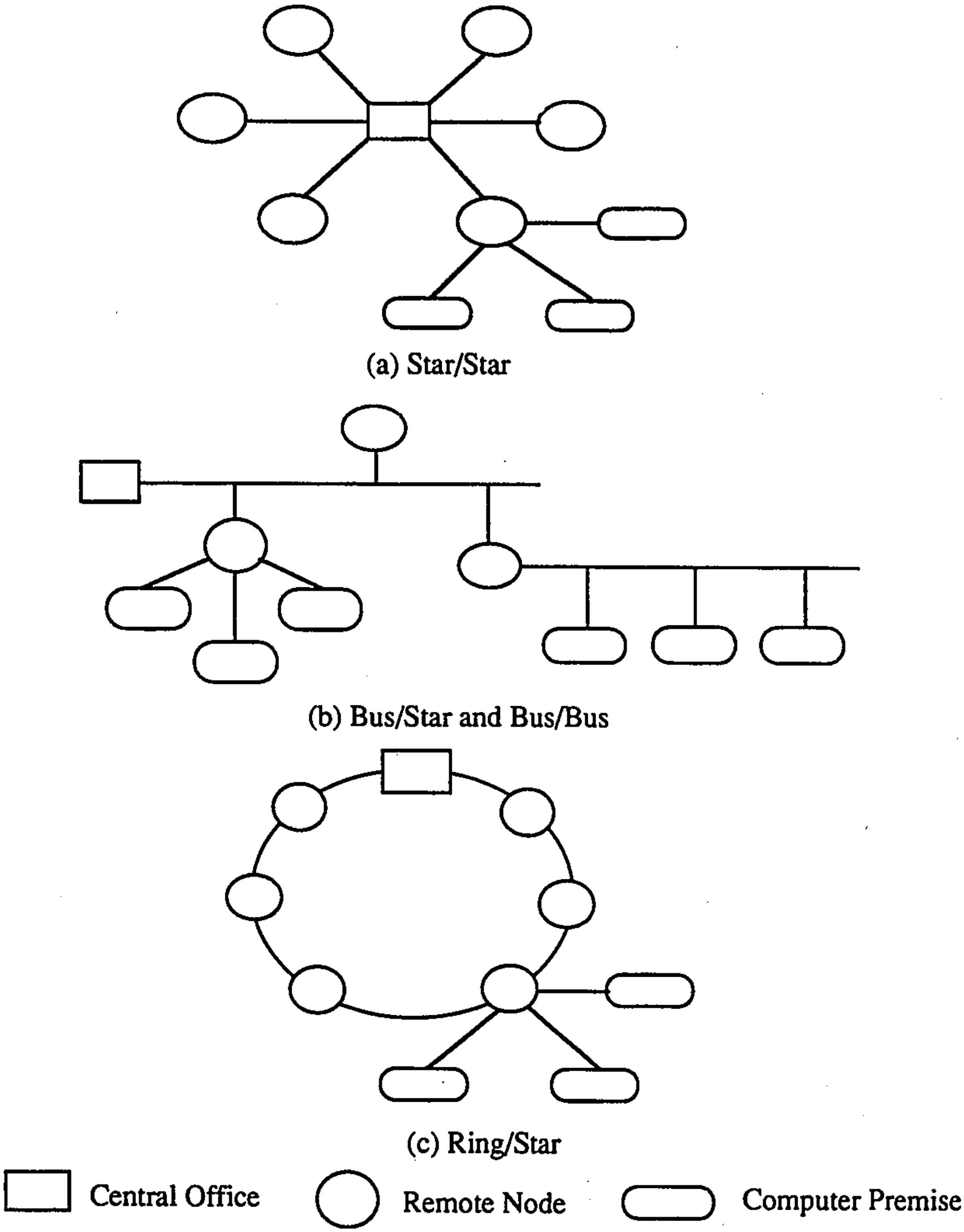


Figure 2.7: Optical Networks Hybrid Topologies

bandwidth to be accessed, and each user is restricted to some number of electro-optic transmitters and receivers, each of which operates at a maximum data rate set by electronic/electro-optic technology.

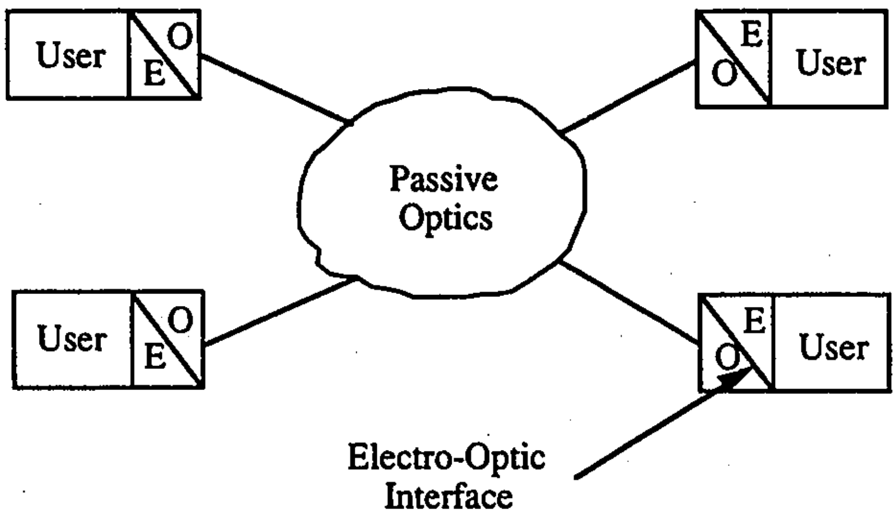


Figure 2.8: A Fully-Distributed Lightwave Network

To circumvent these electronic bottlenecks, optics can be used to replace electronics in the processing for multiple access. For example, all of the high-speed (aggregate-rate) signal processing or multiplexing in the network might be performed optically. The electronics need only to operate at the bit rate of the individual user.

A new generation of fiber-optic networks called *Optical Multiaccess Networks* attracts much research interest [35]. These networks use optical signal processing and/or multiplexing techniques for multiple access and other low-level functions at physical and network layers. Optical multiaccess networks are made possible by continuing advances in devices and novel network architectures which exploit these devices. Among the concurrency techniques being considered to implement multiaccess optical networks are *time, code and wavelength division multiplexing* (TDM, CDM, and WDM, respectively).

The WDM technology is recognized as one of the most promising solution for the next generation of very high-speed LANs. Another type of networks is a multihop lightwave network which employs an architecture that can achieve a high capacity.

2.3.1 Time Division Multiplexing

Time division multiplexing technique is shown in Fig.2.9. The optical source is a mode-locked laser, which is capable of generating very narrow optical pulses (say, 1 to 10ps), corresponding to a bandwidth of 100-1000 GHz, but the pulse repetition rate is limited to much slower electro-optic speeds. The narrow pulses are split N ways, with one path for each user. The narrow pulse is modulated by the user's data, which either allows the pulse to pass or blocks the path. Thus, once per user bit interval (say, once per nanosecond for a 1 Gbps data rate), a narrow pulse will either be passed or not, corresponding to whether the user bit is a logical one or a logical zero. Prior to superimposing the signals for all such paths, a finite delay is inserted into each path such that successive paths, offset in time by one narrow bit associated with each user, are time multiplexed into a TDM frame. The number of positions in the frame is equal to the ratio of the user bit duration to the narrow pulse width produced by the mode-locked laser, with one bit position uniquely associated with each transmitter.

After superposition, the composite signal is split prior to reaching the receivers, which have access to all the concurrent data. Then, using a suitably delayed replica of the original mode-locked pulse stream, each receiver picks the desired bit out of each frame by means of an optical AND gate with one input fed by the composite signal and the second input fed by the suitably delayed replica of the original pulse stream. The output of the AND gate is then processed by an optical receiver (with the usual electro-optic bandwidth restriction) to electronically regenerate the desired packet.

There are two principle difficulties with this approach. First, the required wide-band optical AND gate is beyond the current state of the art. Second, the amount of delay equalization needed to keep all the pulses aligned in their proper time slots is a formidable challenge.

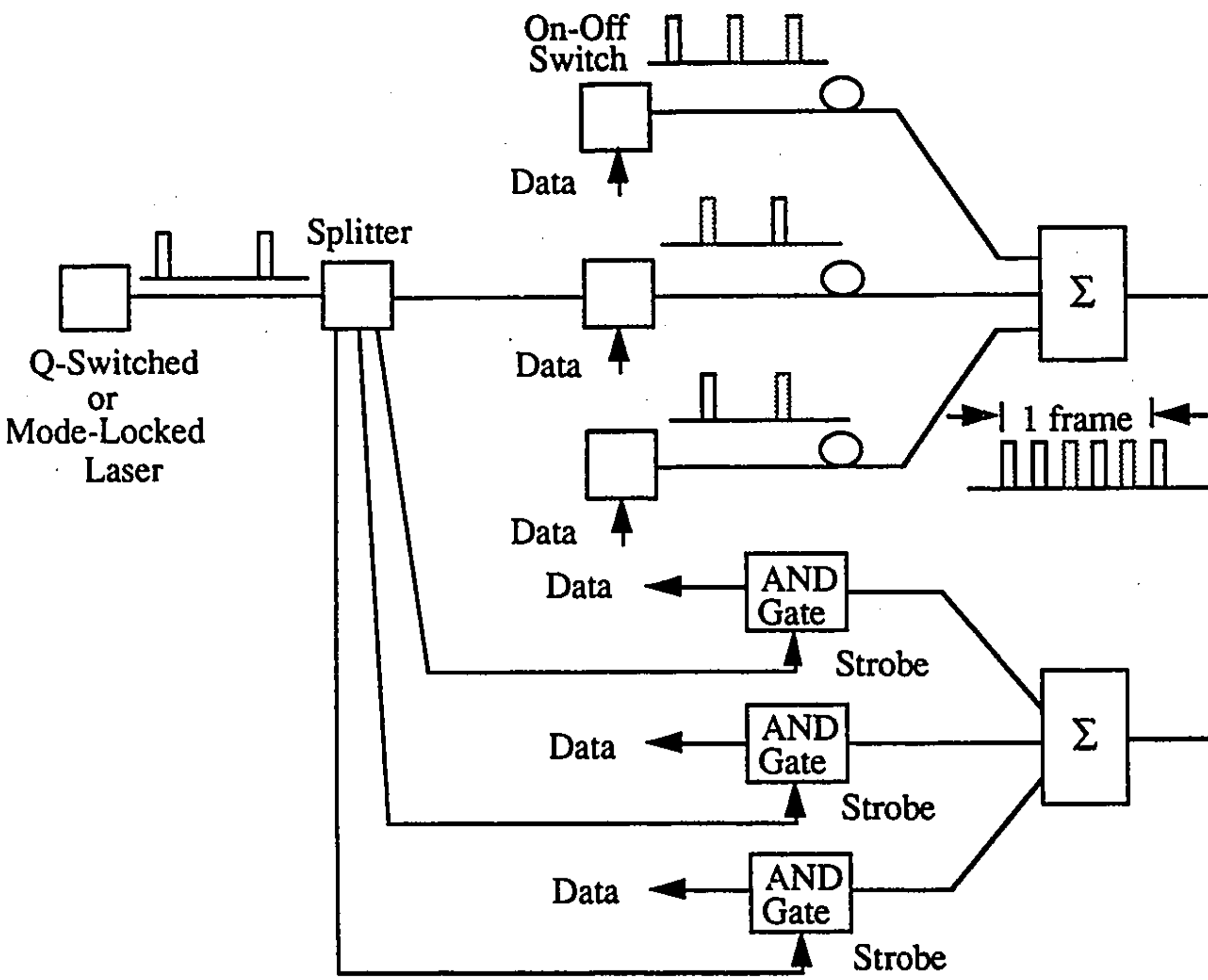


Figure 2.9: Time Division Multiplexing

2.3.2 Code Division Multiplexing

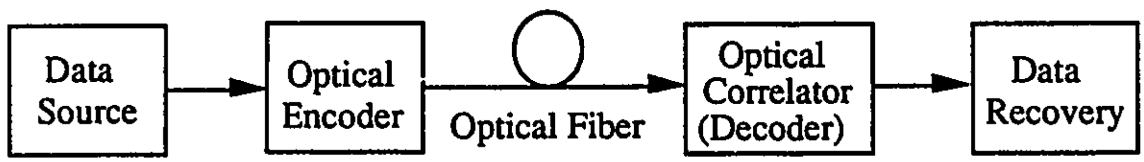
Code division multiplexing (CDM) takes advantage of excess bandwidth in single-mode fibers to map a low information rate electronic or optical signal into high-rate optical sequences to achieve random, asynchronous communication access, free of network control, among many users. A typical optical CDM communication system is best represented by an information data source, followed by a laser when the information is in electronic form and an optical encoder maps each bit of the output information into a very high rate optical sequence, which is then coupled into the single-mode fiber channel. At the receiver end of the optical CDM systems, the optical sequence would be compared to a stored replica of itself (correlation process) and to a threshold level at the comparator for data recovery (shown in Fig.2.10 a).

In optical CDM, there are N such transmitter and receiver pairs (users). Fig.2.10 b shows one such network in a star configuration [36]. The set of optical sequences essentially becomes a set of address code or signature sequences for the network. To send information from user j to user k, the address code for the receiver k is impressed upon the data by the encoder at the jth node. One of the primary goals of optical CDM is to extract data with the desired optical sequence in the presence of all other users' optical sequences. This approach to asynchronous multiplexing allows transmission without delay, and handles multiple access interference as an inherent part of the multiplexing scheme.

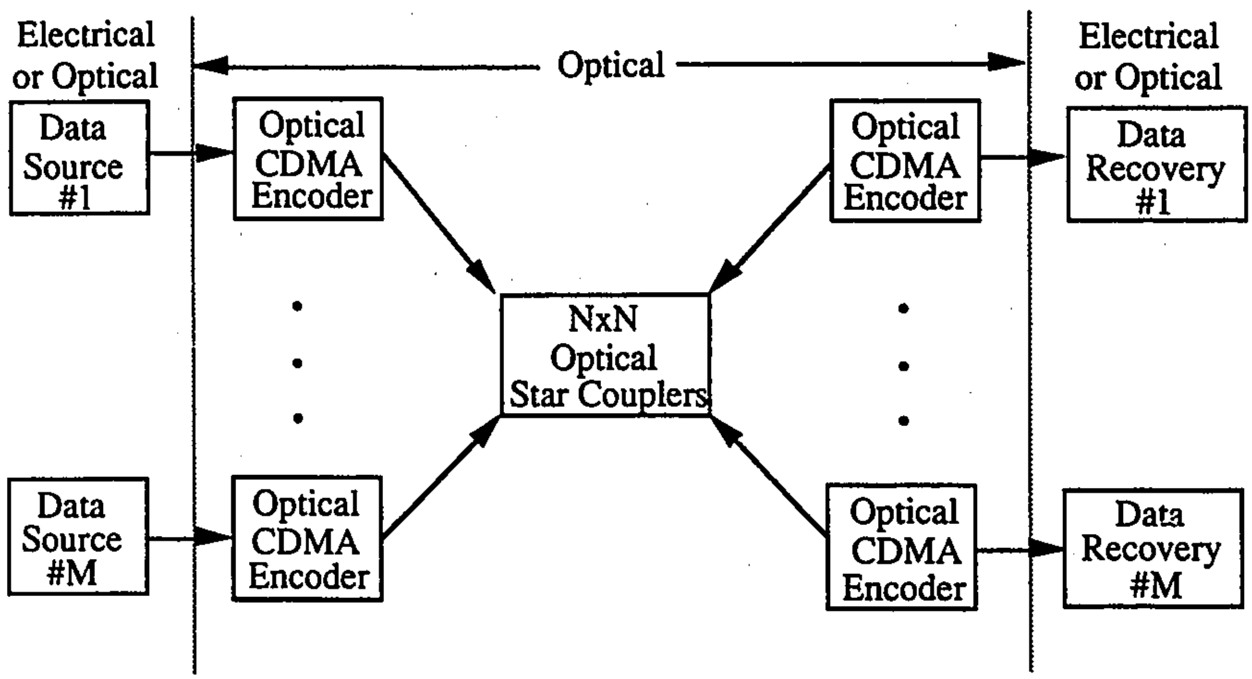
2.3.3 Wavelength Division Multiplexing

Wavelength division multiplexing (WDM) is now an established technology within optical fiber communication [37] and a powerful means of providing a multichannel facility over an optical fiber network.

For long-haul communications, such multiplexing enables parallel transmission of several optical signals at different nominal peak (center) optical wavelengths on a single fiber link. Moreover, these signals may be independently modulated by different information sources. To date, the implementation of WDM has generally required multiple optical sources (i.e. semiconductor lasers or LEDs) each launching an optical



(a.) Optical CDM Channel



(b) Optical CDM Star Network

Figure 2.10: Code Division Multiplexing

signal at a different nominal peak wavelength into a single optical fiber using a wavelength division multiplexing device. At the receive terminal, the different wavelength optical signals may be separated using a passive wavelength division demultiplexer and the signals can then be detected using wideband photodiodes. The long-haul configuration of a WDM network is shown in Fig.2.11 [38]. The WDM technology is now recognized as the most promising solution for the next generation of very high-speed LANs. By assembling a large number of closely spaced wavelength-multiplexed channels, WDM carries the potential of providing the high transmission speeds required by future applications. The potential of sharing the enormous bandwidth provided by the WDM among all the users of a network is the major attraction of lightwave technology for multiuser applications. As a result, there have been many recent proposals for various architectures for optical multiuser communications.

Although a ring topology is the subject of a standardization proposal (FDDI) for the optical fiber LANs, the passive star is emerging as one of the dominant LAN configurations for tapping the high bandwidth provided by the WDM technology [39] [40]. The star coupler represents an efficient topology for a purely passive optical fiber network based on optical power budget considerations [41]. Hence, multichannel optical networks have often adopted a broadcast topology based on passive star couplers. In this configuration, the hub is a passive transmissive element which wavelength-selectively distributes information to the periphery (nodes) of the network. The operation of this network is primarily determined by the following factors:

- Number of available wavelengths;
- Transmitter/receiver design and particularly, number of transmitters and receivers per node and their tunability.
- Number of high-speed buffers for transmission and reception.

These factors will be critical in determining the extent to which multiple wavelengths can be utilized and in determining the character of the media access control needed.

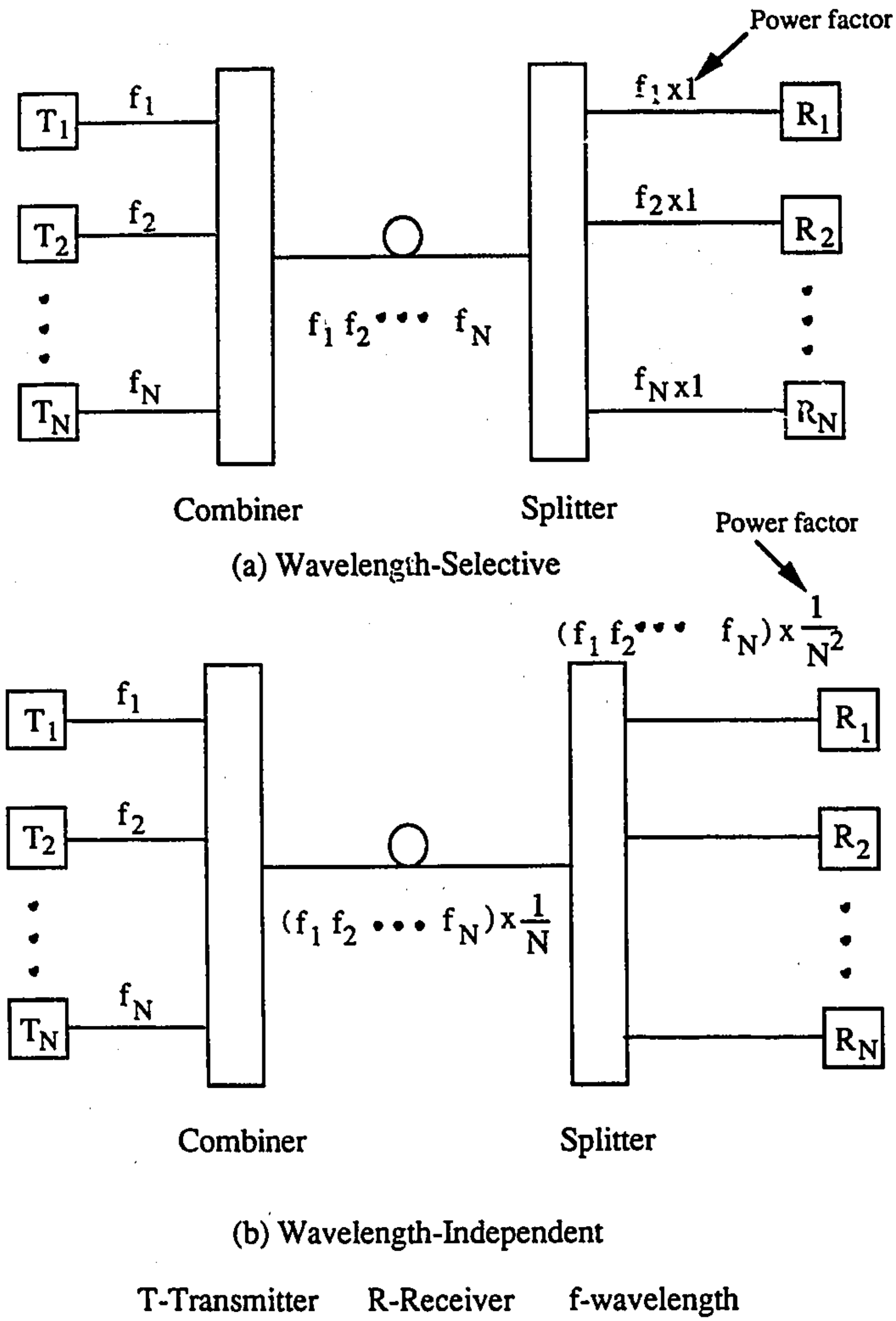


Figure 2.11: Wavelength Division Multiplexing Long-Haul Networks

The wide range of parameters in the design of a WDM star is primarily associated with the existence of multiple "parallel" channels (wavelengths). As the number of users in a LAN can be large, the channels (wavelengths) may have to be shared among the users dynamically. Secondly, in a multiple channel network the replication of receivers and transmitters has the most significant effect on the ability of the network to utilize the combined bandwidth of multichannel. In a WDM multichannel network, the situation is further complicated by the transceiver tunability issue. To fully utilize all the channels, a node dose not need a number of transmitters/receivers equal to the number of wavelengths as long as these can be tuned to transmit/receive on the "*correct*" wavelength at the "*right*" time. Such coordination among the transmitters/receivers and wavelengths is necessary.

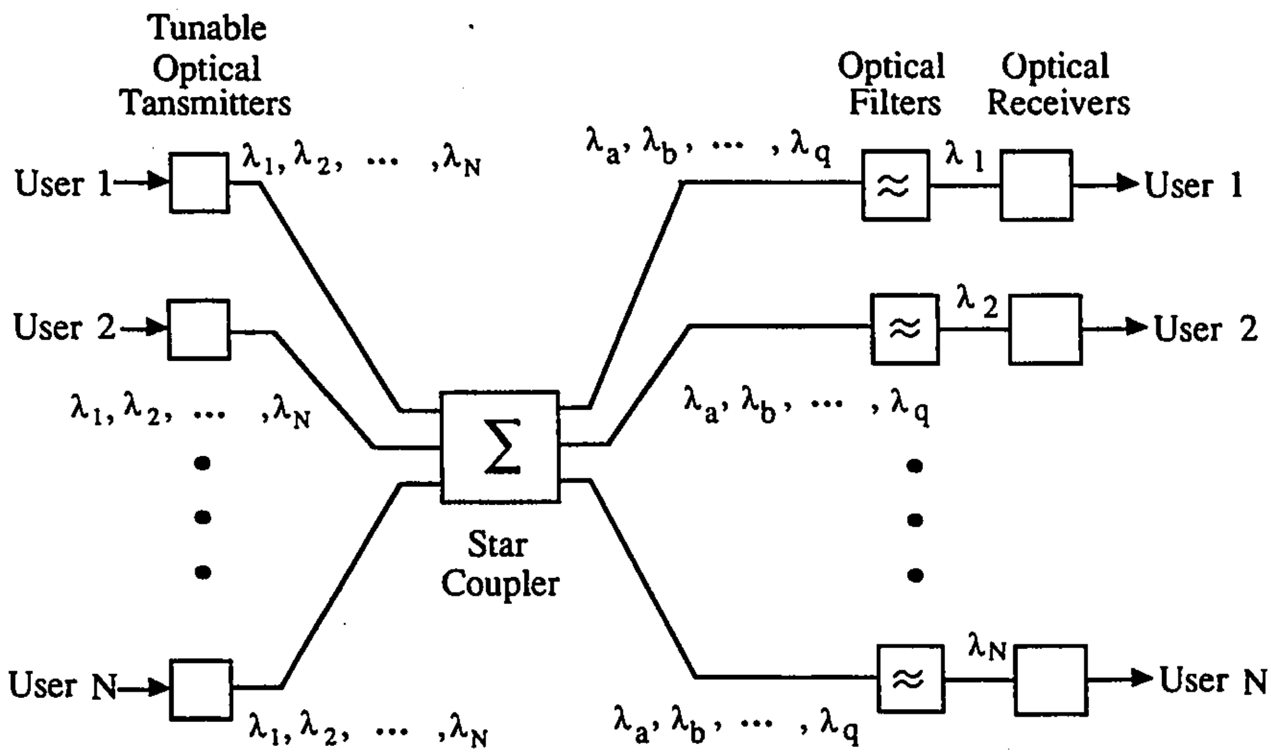


Figure 2.12: Concurrency via Wavelength Division Multiplexing

The basic approach to WDM is shown in Fig.2.12 [32]. Here, each receiver is assigned a unique wavelength, and a transmitter wishing to access a receiver tunes its transmitting wavelength to that of receiver's wavelength and sends its packet. It is noticed that the above example admits the possibility of a multitude for non-interfering packets to be simultaneously resident in the network, thereby achieving concurrency by spreading signals over a vast portion of the optical band.

The primary drawback of a packet switched WDM approach is the need for wavelength agility at each transmitter and/or receiver. Either a bank of transmitters and/or receivers, or a single tunable transmitter and/or receiver must be provided. The former is too expensive and will bring some installation problems. The latter requires wavelength tunable transmitters and/or receivers which are rapidly tunable on a time scale consistent with packet switching over a sizable portion of the optical band. Thus, we see that the WDM offers promise for high capacity networks, but the implementation must wait for some difficult technological breakthroughs.

2.3.4 Multihop lightwave networks

Multihop lightwave networks are optical communication systems that use wavelength division multiplexing to exploit the enormous fiber bandwidth without requiring tunable lasers [43]. With the basic multihop concept, all communication channels are operated at opto-electronic data rates, and all channels (or links between nodes) are wavelength multiplexed onto a common optical medium. To increase the system aggregate capacity still further, some network architecture variations are introduced in which each link consists of a dedicated fiber link. Multihop is a wavelength multiplexing scheme to produce terabit networks out of gigabit piece-parts. In a multihop lightwave network, packets destined from one user to another may be routed via intermediate users in a sequence of "*hops*" on the fiber, each hop using a different fiber channel. A user (node) in such a network has a small fixed number of incoming and outgoing links, independent of the total number of users. Users interface to the optical medium through network interface units (NIU).

The multihop networks are appropriate for bus and star topologies (Fig. 2.13) [32]. Except for the fixed laser sources located near the user in the users' NIUs, all other optical components are completely passive (i.e., fiber and couplers only). No agile lightwave technology is needed and neither centralized nor decentralized network control is required. For all the above topologies, the active repeater circuitry is decentralized, appearing physically in close proximity to the end-user locations. The packets received by each node will first be stored and their addresses will be checked. The node will receive the packets destined for itself and will retransmit the others to the next intermediate nodes [27]. In multihop networks, a packet may go through more than one hop to get to its destination. The number of hops for a node to any other node in the network varies and depends on the network architecture and the routing algorithm. The performance analysis of a store and forward multihop shuffle network connecting $N = kp^k$ ($k = 2, 3, ... p = 2, 3, ...$) users in k columns of p^k users in each column was given in [32]. For the shuffle network in Fig.2.13 b, $k = 2$ and $p = 2$. According to the analysis, the expected number of hops (E) between two randomly selected nodes is given by,

$$E = \frac{kp^k(p-1)(3k-1) - 2k(p^k-1)}{2(p-1)(kp^k-1)} \tag{2.1}$$

If the traffic generated by each user is uniformly distributed, the maximum achievable throughput C is given by the ratio of the number of WDM channels (kp^{k+1}) to the expected number of hops,

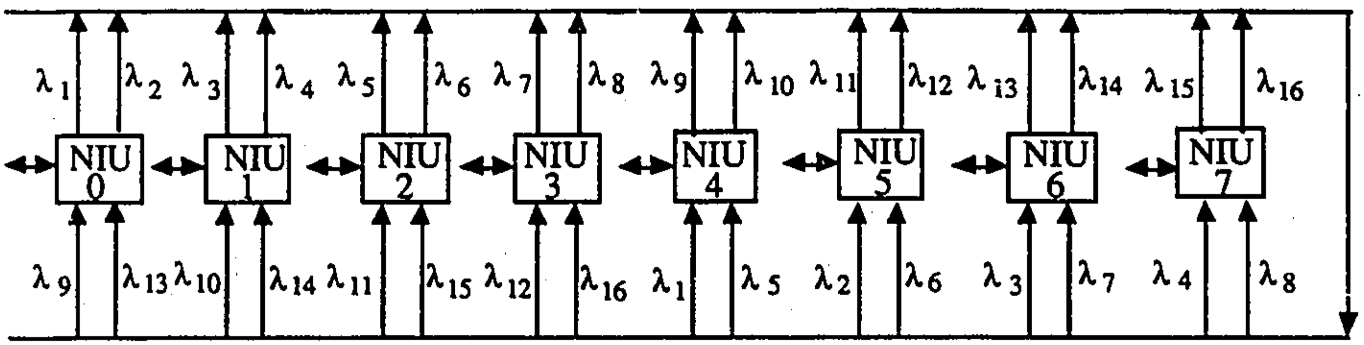
$$C = \frac{2kp^{k+1}(p-1)(kp^k-1)}{kp^k(p-1)(3k-1) - 2k(p^k-1)} \tag{2.2}$$

The maximum achievable throughput per node is,

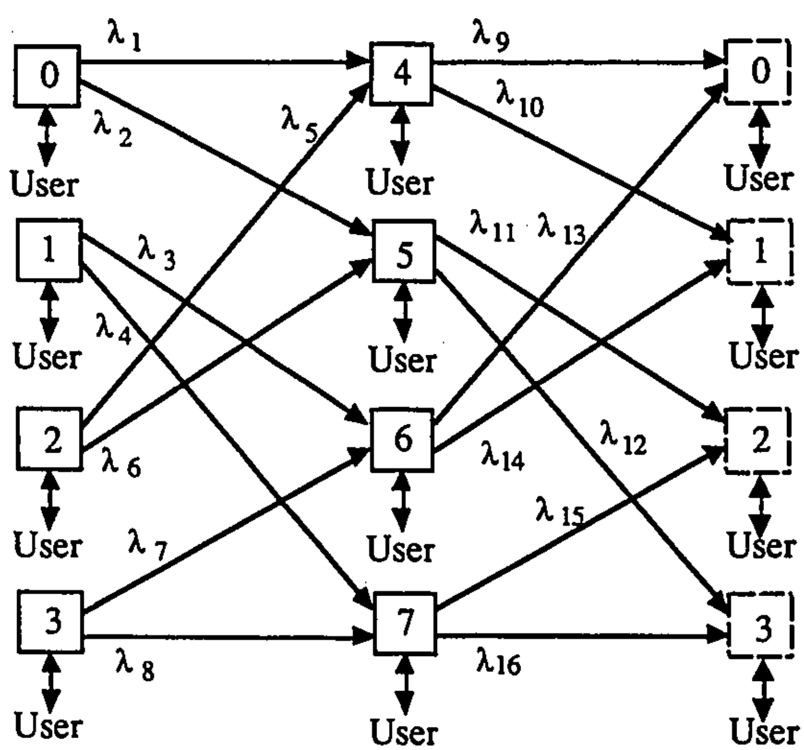
$$\frac{C}{N} = \frac{2p(p-1)(kp^k-1)}{kp^k(p-1)(3k-1) - 2k(p^k-1)} \tag{2.3}$$

A shufflenet lightwave network has a number of important properties and desirable features. First, its connectivity graph is a symmetric, homogeneous structure that closely approximates an ideal spanning tree rooted at each NIU. This helps minimizing the number of hops from a source to a destination. The second property is its modular growth in small increments. This means it is not necessary to fully deploy all the nodes at first implementation, always reserve some nodes for future development.

One of the attractions of the multihop approach is that it can be applied to the existing networks, such as FDDI ring, to provide enhanced throughput. Another



(a) A Multihop Lightwave network for a bus topology



(b) 8-NIU (p=2, k=2) ShuffleNet

Figure 2.13: Multihop Lightwave Networks

advantage is the traffic in the network is spread out over many nodes, thereby easing the processing burden at each node [27]. However, a packet transmitted in multihop lightwave network may have to hop through several intermediate users, each repeating the packet on a new wavelength, until it gets to its destination. Buffer space is needed at each node. The processing time and queuing delay at each node will make the total delay very large for a packet passing through the network, especially for heavy traffic.

2.4 Protocols for Optical Fiber LANs

In the past two decades, various multiple-access protocols have been developed and applied to different types of multiple-access networks. The existing multiple-access protocols may be categorized according to how much coordination is required between the potentially conflicting terminals. At one extreme is random access and at the other end is scheduled access. Random access is an optimistic protocol in which a terminal with a message will transmit it immediately, hoping that no other terminals will transmit at the same time and thus collide with it. Since there is no coordination among the terminals, collisions may occur. The retransmission mechanism must be developed for the collided messages. Scheduled access is a pessimistic protocol in which no one is allowed to transmit until a reservation has been made successfully on its behalf. Therefore, there is no collision. However, a price is paid in the additional overhead due to the scheduling process. There are many protocols which have been developed [44].

In high-speed networks, round trip delays will primarily be contributed by propagation delays, since emission delays and processing delays will be relatively small. With propagation delays and hence round trip delays in high-speed networks remaining constant, the higher the transmission speed, the more bits there are in the delay time period. Although round trip delays are relatively small in the optical LANs because of the small network diameter, this phenomenon has a major impact on the design of network control [45].

In high throughput applications, a small amount of loss can result in a large amount of retransmission and can lead to a significant reduction of overall network throughput. Therefore, a major issue in high-speed optical LANs is to develop suitable protocols so that the achievable network throughput is commensurate with the high transmission bandwidth available. The traditional protocols used in communication networks must be examined and new protocols be explored. The new protocols which provide data transfer must minimize proceeding overheads and be amenable to hardware implementation. The approaches to increased protocol speeds are improved implementation of protocols, optimized design of packet formats, and etc. [45].

In this thesis, several proposed protocols are compared based on their performance characteristics for an optical LAN connected by a passive star coupler.

Chapter 3

Performance Analysis of an Optical LAN Interconnected by a Passive Star Coupler

3.1 Motivation

Computer communications networks have evolved very rapidly during the last decade. Recently, as a part of continuing advancement in networking technology, several impressive developments have been witnessed in the form of broadcast networks, local area networks, and integrated voice and data networks. Performance evaluation of these networks has remained, and will remain important mainly because it helps in:

- Assessing the performance of a network against the introduced overhead;
- Tuning the parameters of a network in order to optimize its performance;
- Comparing the performance of two or more networks in quantitative terms.

Performance evaluation criteria for a computer communications network may vary from one individual to another, depending on how one is associated with the network under consideration. Also, performance criterion of one individual may contradict that of another. For instance, take the case of a network user and the manager. The user always wishes to have a turn-around time which is as small as possible, while at the same time, the manager would like to see the network's utilization as high as possible. These two demands are obviously contradictory to each other.

The common criteria used to evaluate the network performance are [46]:

- User-oriented criteria;
- Manager-oriented criteria;
- Designer-oriented criteria.

One thing that should be mentioned here, is that no matter which performance criterion an individual may start with, eventually it takes the shape of *"cost-performance tradeoff"*. In this thesis, the designer-oriented criterion is used in the network performance evaluation.

A designer measures the performance of a network in order to see how closely the actual performance is to the predicted one, or how closely the design objectives are being met. If these are not met to the designer's satisfaction, then the measured performance can be used for tuning the network parameters so as to achieve the desired objectives. A designer, therefore, is mainly concerned with the following performance criteria: buffer efficiency, protocol efficiency, and flow control effectiveness and adaptability. In this thesis, the protocol efficiency requires a knowledge of the statistics, such as throughput and delay characteristics, in order to improve the design.

The performance evaluation techniques used in computer communications networks are:

- Analytical techniques;
- Measurement (experimental) techniques;
- Simulation.

Measurements can only be made after a network has already been implemented. However, analytical and simulation techniques can be used even in the planning stages of a network. It is an established fact that it is better to know about performance characteristics of a network (or any system) before putting it into practice or even expanding it. This is because a designer has more freedom, and it is less costly to adjust various parameters in the planning stages rather than in the operational stage. The following two chapters are devoted to performance evaluation of an optical LAN interconnected by a passive star coupler using analytical and simulation techniques.

3.2 Network Architecture

When we design optical LANs, we must provide the networks with excellent extensibility in terms of performance/complexity and fault tolerance so a wide range of network sizes are supported, and achieve satisfactory performance. Some passive star-coupled network architectures were introduced to achieve low complexity and high-performance [47] [48] [49]. Through agile laser diode sources and wavelength tunable optical filters, multiple high-bandwidth communications channels can be formed on a single physical link. This provides the low network complexity: a single physical link with multiple high data-rate channels through wavelength division multiplexing (WDM) technique. The available optical bandwidth is partitioned into a comb of narrow subchannels, and the optical self-routing characteristic is achieved through WDM technique by tunable receivers and/or transmitters. The number of users in the network is mainly bound by the optical power that must be delivered to each receiver to maintain a specified bit error rate. The number of subchannels is directly proportional to the total bandwidth of the network, but is limited by the agility of the transmitters and receivers. Two multichannel network architectures are introduced.

Fig. 3.1 illustrates the first configuration. This architecture is based on tunable transmitters and fixed wavelength receivers. This network, as with the following one, are assumed to interconnect M users and have a total of $N+1$ channels, denoted by $\{\lambda_0, \lambda_1, ..., \lambda_N\}$. Each user has an agile transmitter which is capable of tuning to any one of the $N+1$ channels. The subchannels support concurrent transmissions: a station can simultaneously transmit on channel λ_i and receive on channel λ_j, $i \neq j$. Node n_i has an agreed upon *home channel destination address* s_i, where $0 \leq i \leq M$, and $s_i \in \{\lambda_0, \lambda_1, ..., \lambda_N\}$.

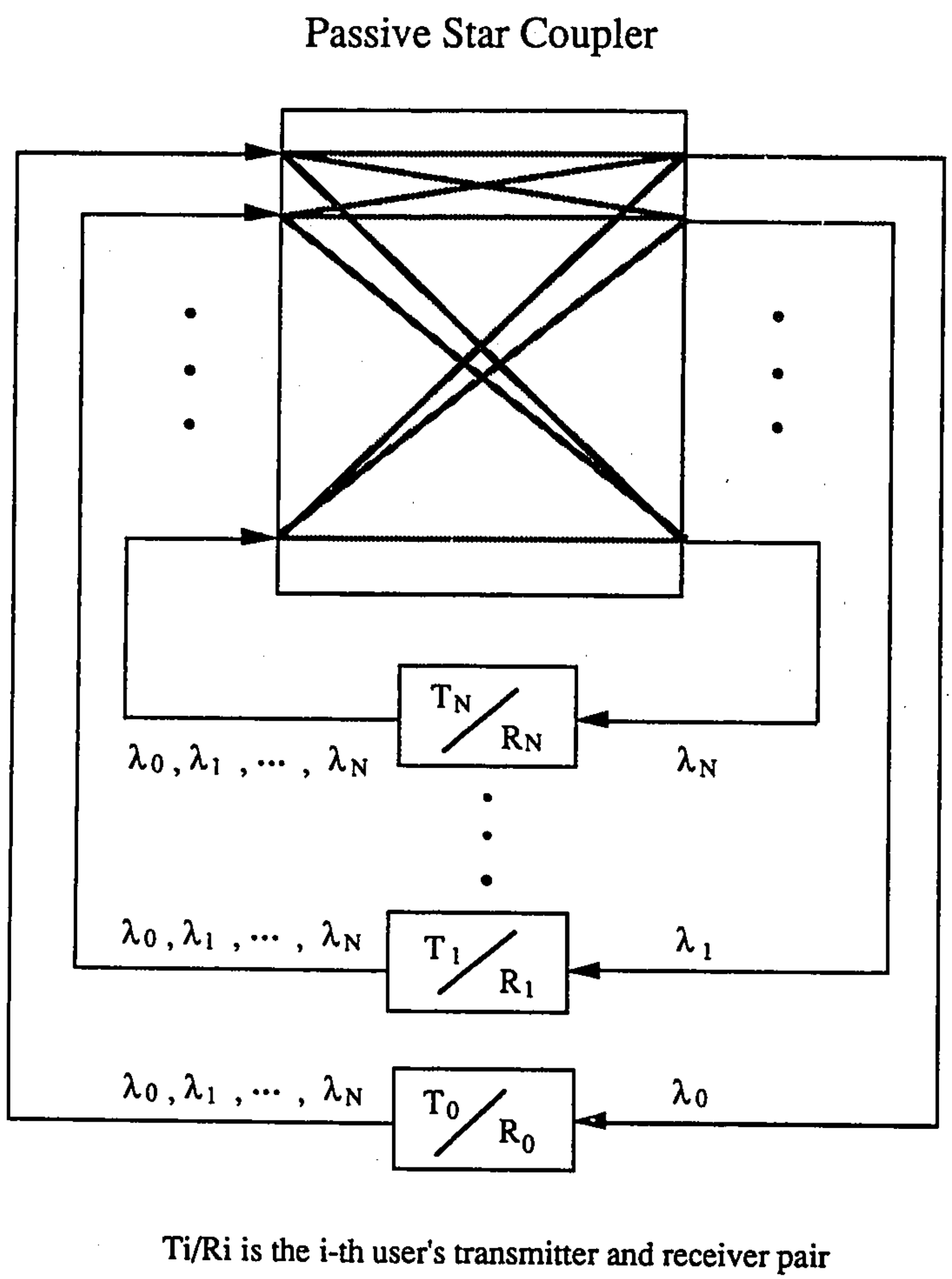


Figure 3.1: Passive Star Optical LAN with Agile Transmitters

When $M = N + 1$, this network architecture offers a total *self-routing*, since each user has a unique channel. All the traffic transmitted along the channel is destined to the user which owns that channel. When $M > N + 1$, partial self-routing is achieved. A channel is shared by approximately $\frac{N+1}{M}$ users. A user must decode all traffic along the home channel to identify the packets destined for itself. This will reduce the percentage of total number of packets to be received. However, in both of the above cases, no pretransmission coordination is needed.

The architecture introduced to achieve greater flexibility is shown in Fig.3.2 [47] [49]. The key component in the network is a multiport passive star coupler which acts as a multiaccess passive broadcast channel. The users are connected to the star coupler by single-mode fibers. The enormous optical bandwidth is divided into $N + 1$ channels by WDM technique, each centered at a different wavelength. The channel operating at wavelength λ_i ($i = 0, 1, ..., N$) is referred to as channel i. There are M users in the network. Each user has one tunable optical transceiver which is capable of operating at any one of the $N + 1$ wavelengths $\lambda_0, \lambda_1, ..., \lambda_N$. The number of users in the network is limited by the power budget, but it is desirable to have the number of users greater than the number of available wavelengths.

We assume that one of the channels is used as a control channel for establishing an end-to-end link between users in a very short time interval before the actual data transmission starts. This can be done by sending a control packet over the control channel to the recipient before sending the data packet to it. There is one channel operating at wavelength λ_0 for the control traffic and the other N channels operating at wavelengths λ_1, λ_2,..., λ_N are assigned to actual data transmission. The M users in the network can transmit or receive on any one of the data channels as well as on the control channel by using tunable transceivers. Since each user can only receive on one wavelength at a time, a transmitting user must inform the intended recipient which channel (wavelength) it is planning to use for the transmission of its data packet. The control channel which is shared by all the users is only used during the call setup on a packet-by-packet basis and the actual data transmission takes place over one of the N data channels. As shown in Fig.3.3, the length of a control packet is typically much smaller than that of the actual data packet. In this

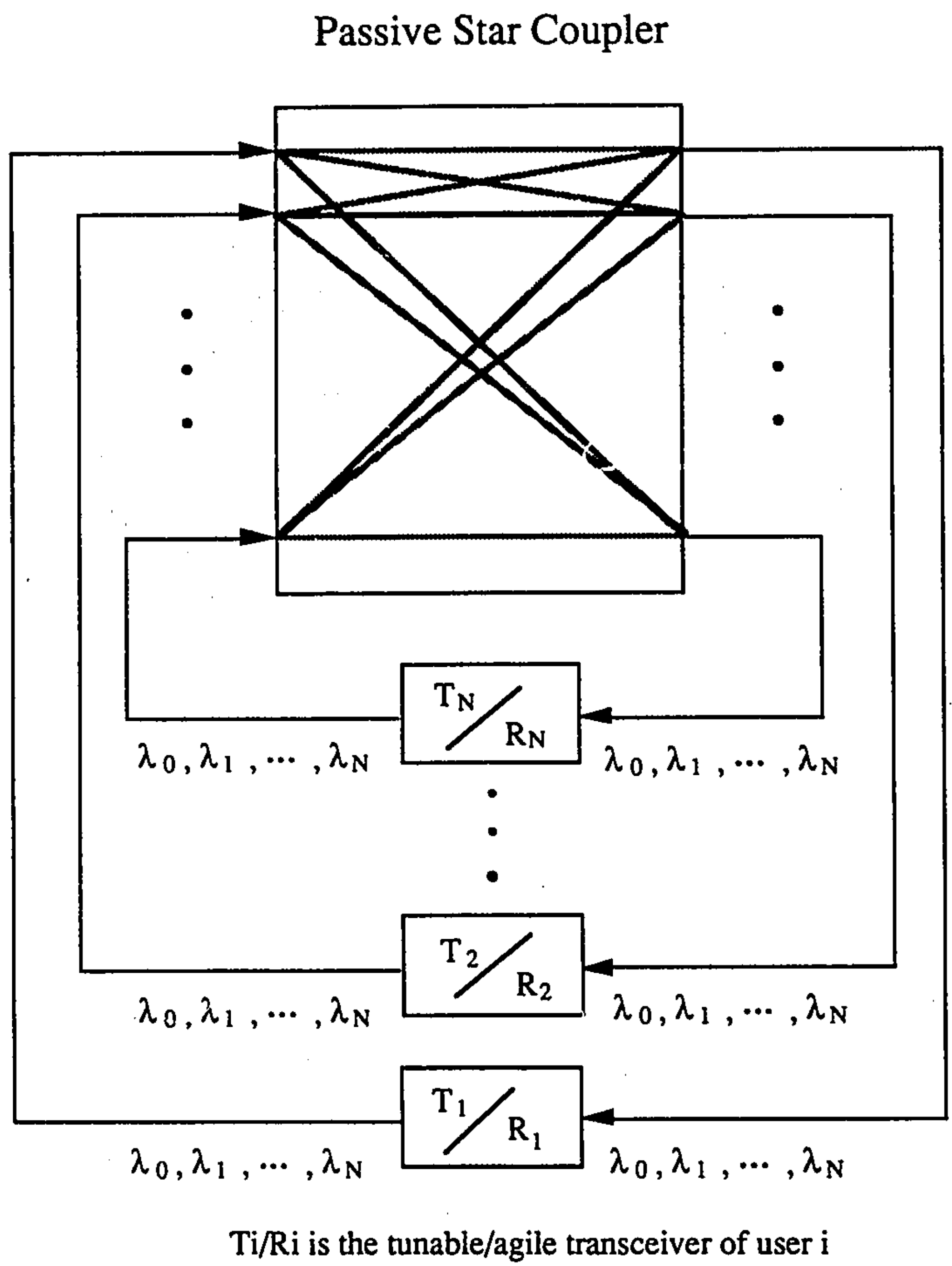


Figure 3.2: Passive Star Optical LAN with Tunable/Agile Transceivers

work, we always assume a data packet length is L (an integer) times the length of a control packet. Because the coordination is provided by the control channel, an idle receiver constantly monitors the control channel for the switching information. This information, if correctly delivered, allows the intended recipient to tune his receiver to the correct data channel to receive the data packet destined for it. The receiving user will tune its receive wavelength back to λ_0 after the data transmission is over. The control packet consists of the transmitter address bits, the destination address bits, and the channel number (wavelength) to be used for data transmission.

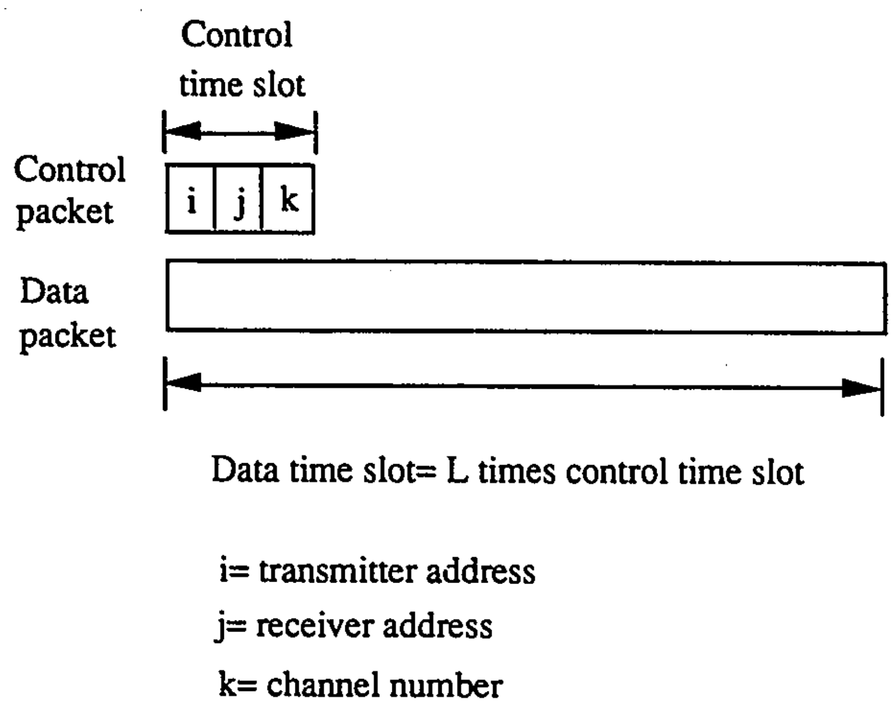


Figure 3.3: Formats of control packet and data packet

Since two or more users may transmit over the control or any one of the data channels, the users of this network, in general, are to employ two contention access methods over the network. One is needed to transmit the control packet over the control channel and the other is needed to send the data packets over the data channel. Throughout this thesis x/y denotes the use of random access method x over control channel and y over data channels. Acknowledgements of success or failure of the combined control and data packets can be obtained by each user by comparing the received one with the original one it sent, because the star coupler is a broadcast medium. However, this may require additional hardware.

3.3 Random Access Protocols and Performance Analysis

In a LAN intended for computer communications, traditionally and logically, uncoordinated user interconnection (switching means) has been used instead of employing costly time division multiplexing and inflexible fixed preassigned wavelength division multiplexing techniques. Because the bandwidth of single-mode fibers is very large for a local area network, a simple random access method is introduced to reduce the overall cost [48]. Many random access protocols are proposed to maintain good performance with high capacity optical channels [47] [48] [50] [51]. Those protocols are based on the network architecture where the channels for the data transmission have not been preassigned.

3.3.1 Assumptions and Notations

In order to analyze the network performance in terms of throughput and delay characteristics, some assumptions and definitions must be made. We assume that our traffic source consists of an infinite number of users which collectively form a Poisson source with an aggregate mean packet generation rate on the control channel. This is an approximation to a large but finite M users network. Whenever a portion of one user's transmission overlaps with another user's transmission on either control channel or data channel, the two collide and destroy each other. The packets involved in a collision must be retransmitted at some later time. The transmission time of a control packet is normalized to one. If a data packet destines for a busy receiver, receiver collision happens. We ignore the receiver collision phenomenon in the analysis because it is rare under assumption of infinite number of users. No retransmission mechanism is specified, we simply let the average data packets generated per control slot be those of new plus the retransmitted.

The following are the notations used for analysis purpose in the rest of the thesis. Let

- N– be the number of channels in the network excluding the control channel,
- L– be the ratio of the length of a data packet to a control packet,
- a– be the ratio of the propagation delay to the control packet transmission time, and let $\frac{1}{a}$ be an integer,
- b– be the ratio of the propagation delay to the data packet transmission time, $b = \frac{a}{(L+1)}$,
- G– be the average number of control packets (new plus retransmission) per control slot on control channel, then the average number of control packets transmitted per CSMA slot on the control channel is aG,
- P_c– be the probability of successful transmission of a control packet over control channel,
- P_d– be the probability of successful transmission of a given data packet on a given data channel,
- P_s– be the probability of successful transmission of a data packet.
- G_d– be the average number of data packets transmitted per data slot on data channel, $G_d = G\frac{L}{N}$,
- S_d– be the throughput per data channel, which is the average number of data packets successfully transmitted per data slot on a given data channel.

3.3.2 Several Protocols and Their Performance Analysis

Several random access protocols were proposed and analyzed in [48] [50]. Those protocols are discribed briefly and analyzed under above assumptions for the purpose of comparisons.

ALOHA/ALOHA Random Access Protocol Fig.3.4 shows the ALOHA/ ALOHA access scheme. In this protocol, a user wishing to transmit a data packet first transmits a control packet over the control channel and immediately transmits the corresponding data packet over the randomly selected data channel, both using ALOHA access protocol. Since random access protocols are employed, collisions may happen over both control and data channels. The vulnerable time period for the packet offered to the control channel on an unslotted ALOHA basis is simply 2 units of time (2 control packets length). Under the Poisson arrival assumption, the probability of successful transmission of a control packet over control channel is

$$P_c = e^{-2G}. \tag{3.1}$$

Since a data packet is placed on a data channel immediately after transmitting the control packet, the vulnerable time period for each data packet is the length of (L-1) control packets on each side of the control packet vulnerable time period. The probability of successful transmission of a given data packet on a given data channel is

$$P_d = exp\{-2\frac{G}{N}(L-1)\}. \tag{3.2}$$

The probability of successful transmission of a data packet is

$$P_s = P_c P_d = e^{-2G} exp\{-2\frac{G}{N}(L-1)\}. \tag{3.3}$$

The data channel throughput is given by

$$S_d = G_d P_s = G_d e^{-2G} exp\{-2\frac{G}{N}(L-1)\} = G_d exp\{-2G_d(1+\frac{N-1}{L})\}. \tag{3.4}$$

The average delay experienced by a data packet in the network is given by the ratio of the average offered channel traffic to the channel throughput

$$D = \frac{G_d}{S_d}. \tag{3.5}$$

The average delay for the ALOHA/ALOHA protocol is

$$D = \frac{G_d}{S_d} = e^{2G} exp\{2\frac{G}{N}(L-1)\} = exp\{2G_d(1+\frac{N-1}{L})\}. \tag{3.6}$$

The ALOHA/ALOHA protocol is the simplest among the various random access protocols for this special network architecture and can easily be implemented. It achieves maximum throughput of 18.4% at $G = 0.5$ [47].

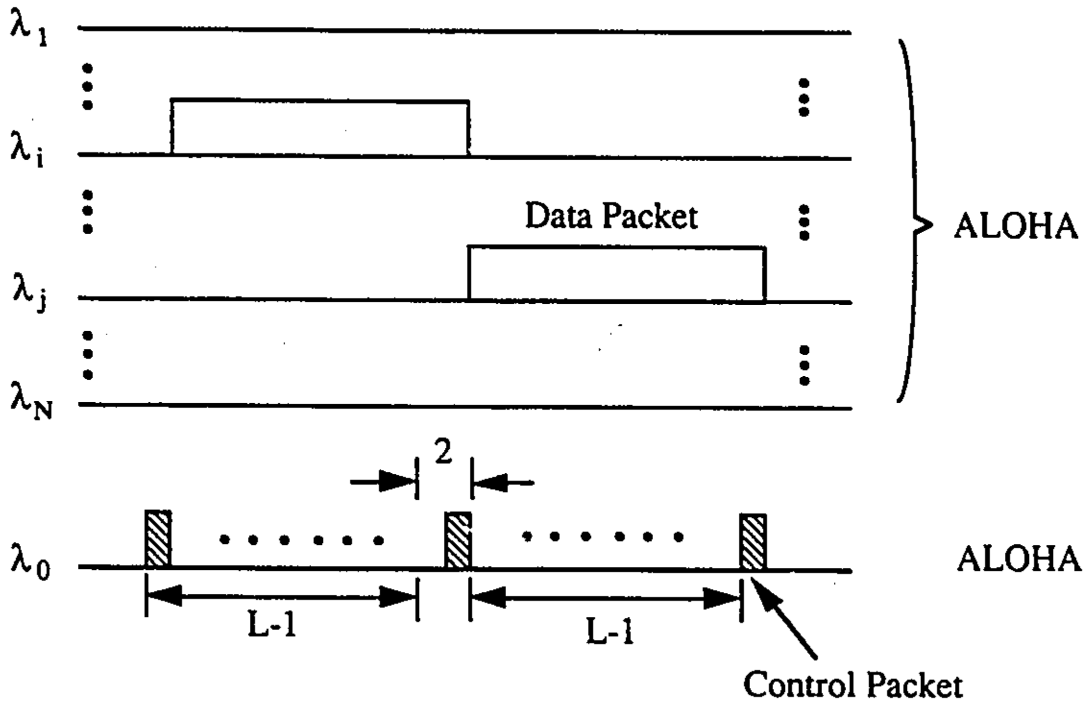


Figure 3.4: ALOHA/ALOHA Access Protocol

Slotted ALOHA/ALOHA Random Access Protocol In this protocol, the control channel is accessed by using slotted ALOHA protocol and the data channels are still accessed by using ALOHA protocol. Each time slot is equal to the control packet frame time. In this protocol, a user wishing to transmit a data packet first transmits a control packet over the control channel at the beginning of each preassigned time slot and starts transmitting the corresponding data packet over one of the data channels λ_i in the next time slot, as shown in Fig.3.5. Notice that, according to this protocol, the control packet lasts for one slot time while each data packet lasts for L successive slots following the control packet slot.

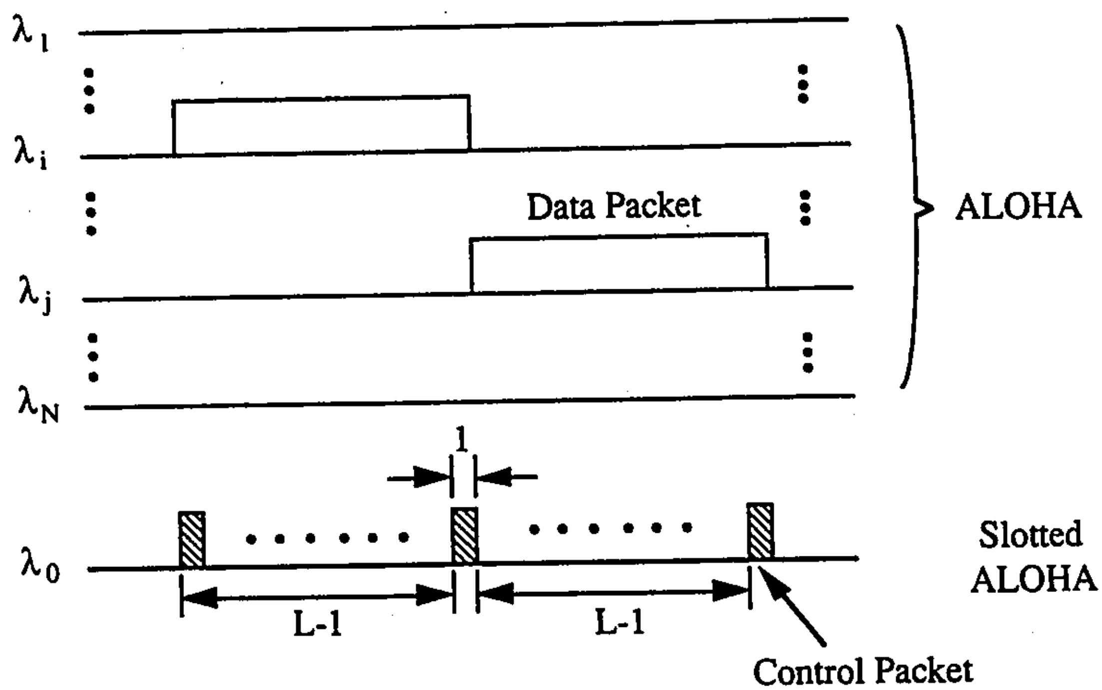


Figure 3.5: Slotted ALOHA/ALOHA Access Protocol

In this case, the traffic offered to the control channel is slotted and the vulnerable time period for the control packet is reduced to one time unit. But the vulnerable time period for the data packet is still $2(L-1)$ time units. This is due to the fact that the successful transmission in the slots prior to the control packet slot could still cause collisions on a data channel. Therefore,

$$P_c = e^{-G}, \tag{3.7}$$

$$P_d = exp\{-2\frac{G}{N}(L-1)\}, \tag{3.8}$$

$$P_s = P_c P_d = e^{-G} exp\{-2\frac{G}{N}(L-1)\}, \tag{3.9}$$

$$S_d = G_d P_s = G_d e^{-G} exp\{-2\frac{G}{N}(L-1)\} = G_d exp\{-2G_d(1+\frac{N-2}{2L})\}, \tag{3.10}$$

$$D = \frac{G_d}{S_d} = e^{G} exp\{2\frac{G}{N}(L-1)\} = exp\{2G_d(1+\frac{N-2}{2L})\}. \tag{3.11}$$

The transmitting time coordination between the users results in increasing the channel throughput and decreasing the average delay. The maximum throughput of 36.8% is achieved at an offered traffic $G = 1.0$ [47].

ALOHA/CSMA Random Access Protocol In this protocol, a user senses the data channels randomly to find an idle one. After finding one, the user jams the data channel for one control packet time and simultaneously sends a control packet on the control channel using ALOHA technique, as shown in Fig.3.6. Immediately after the transmission of the control packet, the user transmit the data packet on the selected data channel. Since the jamming and the control packet are transmitted at the same time, this protocol requires two lasers at every user terminal unit. For this protocol, there are,

$$P_c = e^{-G}, \tag{3.12}$$

$$P_d = \frac{exp\{-b\frac{G}{N}(L+1)\}}{\frac{G}{N}(L+1)(1+2b) + exp\{-b\frac{G}{N}(L+1)\}}, \tag{3.13}$$

$$P_s = P_c P_d = \frac{e^{-G} exp\{-b\frac{G}{N}(L+1)\}}{\frac{G}{N}(L+1)(1+2b) + exp\{-b\frac{G}{N}(L+1)\}}, \tag{3.14}$$

where b is the normalized (relative to a data packet plus a control packet length) propagation time [52]. Since the jam period has been included as a part of the data packets as it occupies the data channel time, the effect of the jam period should be taken out of the actual channel throughput. Therefore,

$$S_d = \frac{L}{L+1} G_d P_s = G_d \frac{L}{L+1} exp\{-2G_d \frac{N}{L+1}\} P_d, \tag{3.15}$$

$$D = \frac{G_d}{S_d}. \tag{3.16}$$

Since the users listen before they transmit, the maximum channel throughput is quite high.

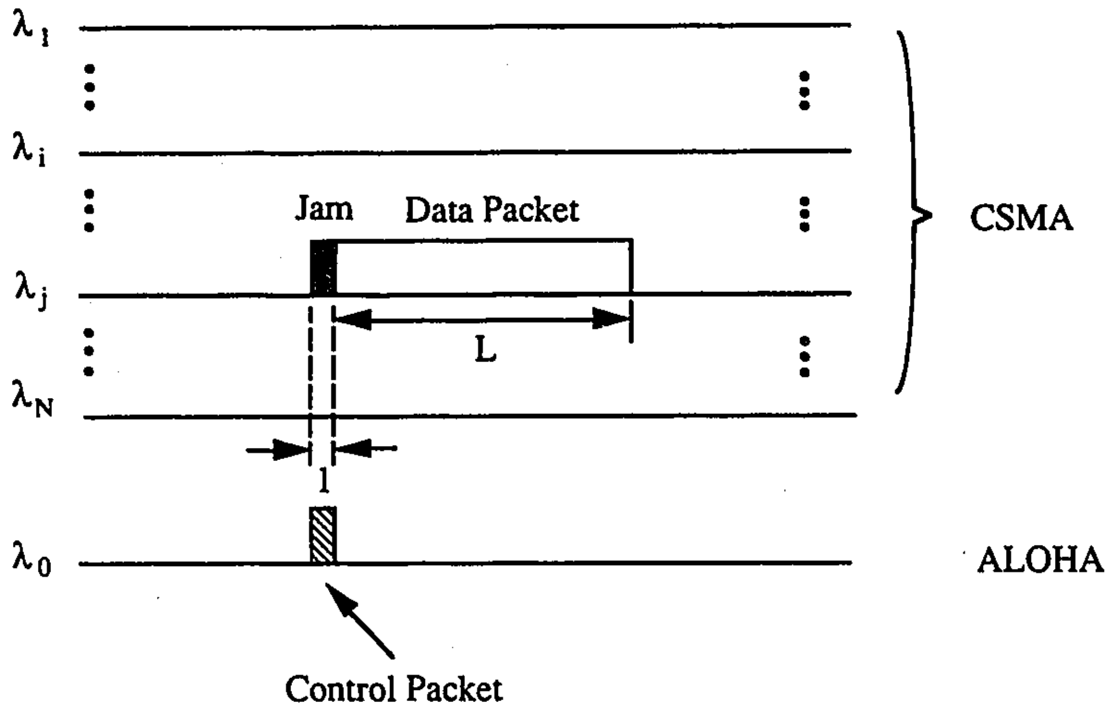


Figure 3.6: ALOHA/CSMA Access Protocol

Improved Slotted ALOHA/ALOHA Random Access Protocol In this protocol, each user transmits a newly generated control packet in the first control slot after the packet generation time. If the control packet is transmitted successfully, then immediately after it, the user transmits the corresponding data packet over one of the N data channels chosen at random. When a collision occurs on either the control channel or the data channel, the user waits some random number of control slots before retransmitting the original control packet and the corresponding data packet as described above for newly generated packets [50].

In the original Slotted ALOHA/ALOHA protocol, a data packet is transmitted even if its accompanying control packet has experienced a collision and therefore has not been received by the intended recipient. Since the data packets require L times a control packet duration for transmission, the channel throughput is severely decreased. The main improvement of this protocol is the decision to transmit a data packet based on successful transmission of its corresponding control packet. If the control packet has experienced collision on the control channel, the user will not transmit the corresponding data packet. The performance analysis was done in [50],

$$P_c = e^{-G}, \tag{3.17}$$

$$P_d = \{1 - \frac{G}{N}e^{-G}\}^{2(L-1)}, \tag{3.18}$$

$$P_s = P_c P_d = e^{-G}\{1 - \frac{G}{N}e^{-G}\}^{2(L-1)}, \tag{3.19}$$

$$S_d = G_d e^{-G}\{1 - \frac{G}{N}e^{-G}\}^{2(L-1)}, \tag{3.20}$$

$$D = \frac{G_d}{S_d}. \tag{3.21}$$

This protocol outperforms the Slotted ALOHA/ALOHA protocol in the reasonable range of network parameters due to the data packet transmission decision.

Some other protocols were also introduced in [47] and [50].

3.4 Proposed ALOHA/Slotted CSMA Access Protocol and Performance Analysis

3.4.1 ALOHA/Slotted CSMA Access Protocol

According to this protocol, a user senses the data channels one at a time at the beginning of each CSMA slot with a slot size equal to the propagation delay. Upon finding an idle data channel, the user sends a control packet over the control channel using ALOHA protocol. Assuming the user is not in receiving state before data transmission starts, the user tunes its receiver to λ_0 in order to receive the information on the control channel. If the control packet is received free of errors, it implies no collision on the control channel. After the control packet gets through this channel successfully, the user will send the data packet on the selected data channel immediately. If the collision happens over either the control channel or no idle data channel is located, the user will stop transmitting the data packet and will begin to sense the data channels at some later time.

In [50], the author introduced an acknowledgement for the successful transmission of the control packet, but did not mention the details of realization. Here, we propose our method to realize the acknowledgement of the control packet. Since the passive star coupler acts as a broadcast channel, the user that transmits the control packet is also listening to the control channel and will receive the control packet sent by itself. It will know whether or not this control packet experienced collisions over the control channel by comparing the received packet to the original one.

3.4.2 Performance Analysis

We now analyze the throughput of the network under this protocol. As defined in 3.3.1, the normalized throughput of a given data channel is given by

$$S_d = \frac{L}{L+1} G_d P_s \tag{3.22}$$

where G_d is the offered traffic per data channel in data packets per data packet slot, and P_s is defined as the probability of successful transmission of a given data packet on a given data channel. We will also evaluate the average delay experienced by a data packet in the network. For the average delay calculations we use the ratio of the average offered traffic to the average channel throughput. That is, the average delay is defined as in (3.5).

Successful transmission of a data packet over a given data channel depends on successful transmission over the control channel as well as over the data channel. The probability of a successful transmission over a data channel by using slotted-CSMA technique is [52],

$$P_d = \frac{b e^{-b\frac{G}{N}(L+1)}}{(1 - e^{-b\frac{G}{N}(L+1)}) + b} \quad . \tag{3.23}$$

As shown in Fig.3.7, the vulnerable time period for the control packet is $(\frac{2}{a} - 1)$ CSMA slots. If a user senses an idle data channel and sends a control packet over the control channel immediately, whether or not its control packet gets through the control channel successfully depends on whether other users transmit their control packets during the vulnerable period. The probability of successful transmission of a control packet is defined as,

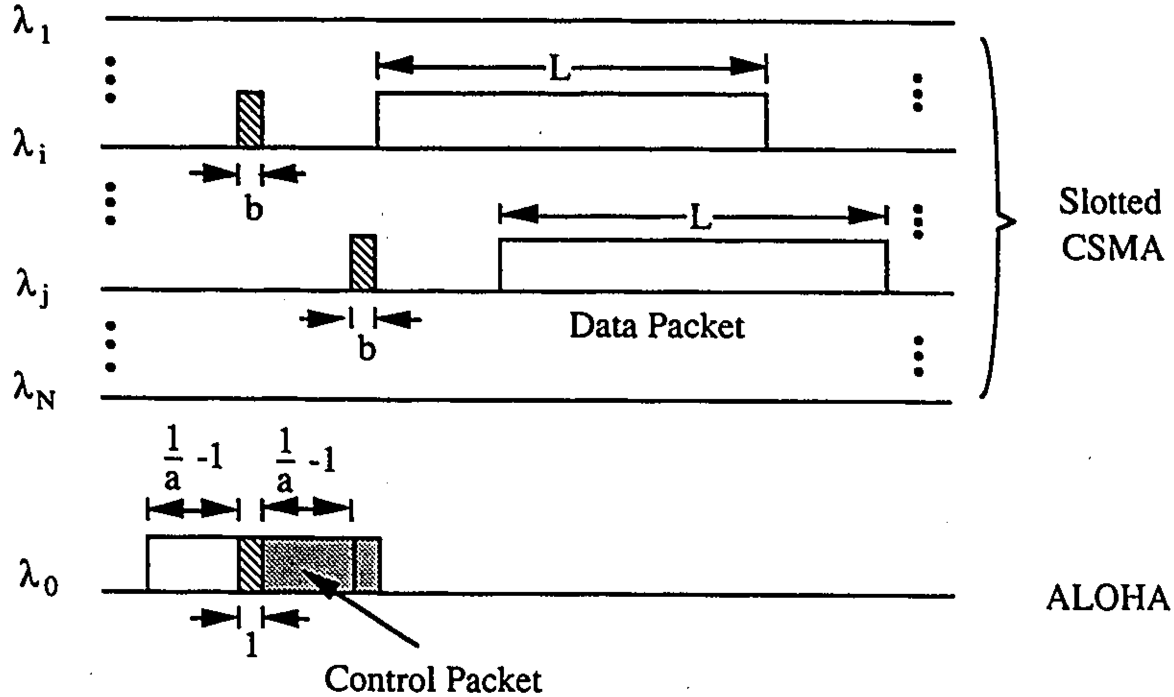


Figure 3.7: ALOHA/Slotted CSMA Access Protocol

$$
\begin{aligned}
P_c &= Pr\{ \text{ the control packet of a user which has already sensed an idle data channel is successfully transmitted on the control channel} \} \\
&= Pr\{ \text{ no other control packets will be transmitted on the control channel during the vulnerable period} \} \\
&= Pr\{ \text{ no other users will sense any one of the data channels idle during the vulnerable period} \} \quad .
\end{aligned}
\tag{3.24}
$$

The probability that no user senses other $N-1$ channels during the same CSMA slot in which a user senses an idle channel is $e^{-aG\frac{N-1}{N}}$, and the probability that no user senses all the N channels during other $2(\frac{1}{a}-1)$ CSMA slots in the vulnerable period is $e^{-aG2(\frac{1}{a}-1)}$. The probability that no user senses the data channels during the vulnerable period is

$$P_1 = e^{-aG(\frac{N-1}{N}+2(\frac{1}{a}-1))} \quad . \tag{3.25}$$

Since the successful transmissions can only make the data channels busy, the data channels are idle with a probability $1 - P_d P_c$. Then (3.24) can be expressed as,

$$P_c = 1 - (1 - P_1)(1 - P_d P_c) \quad . \tag{3.26}$$

Solving equation (3.26), we get

$$P_c = \frac{P_1}{1 - (1 - P_1)P_d} \tag{3.27}$$

and,

$$P_s = P_d P_c \quad . \tag{3.28}$$

Substituting (3.28) into (3.21), we get an expression for the throughput of a given data channel as,

$$S_d = \frac{L}{L+1} G_d P_d P_c \quad . \tag{3.29}$$

The average delay can be derived by using (3.22).

3.4.3 Numerical Results

In this section, the numerical results will be presented for the ALOHA/Slotted-CSMA access protocol. The results are presented in a sequence of plots that depict throughput versus offered traffic, delay versus offered traffic and delay versus throughput. The unit on the delay axis is measured in terms of the length of a control packet frame time, thus making it independent of the signaling rate.

The delay values obtained from the previous equations are in unit of combined length of control and data packets. These values are multiplied by $(L + 1)$ in order to obtain the normalized values on the plots. The plotted delay D_c is related to the

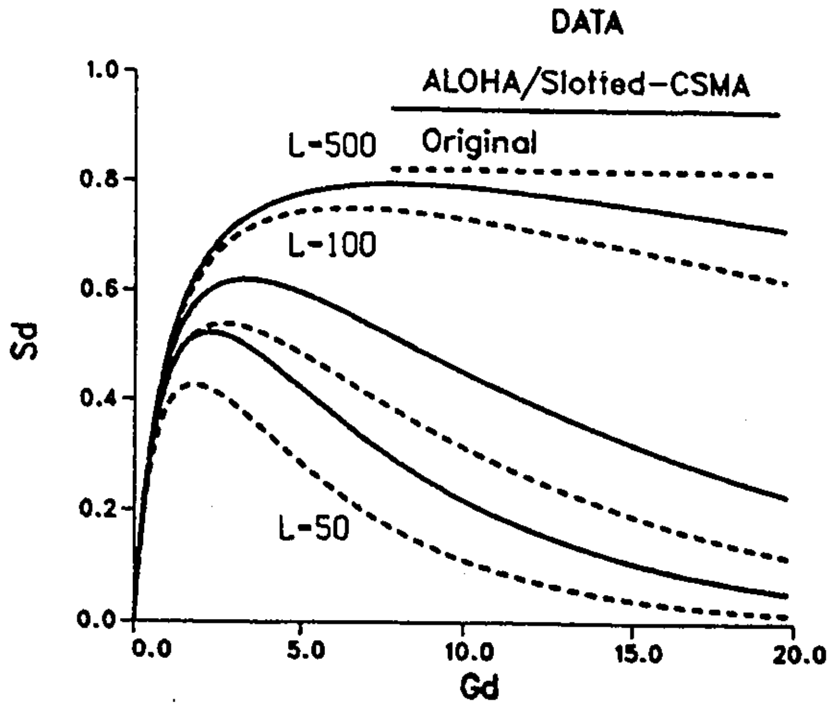


Figure 3.8: Throughput S_d versus offered traffic G_d with $N = 5$ and $a = 0.5$

delay D obtained from the previous expressions by

$$D_c = (L+1)D \quad . \tag{3.30}$$

Fig.3.8 through Fig.3.10 show the results obtained for the ALOHA/Slotted-CSMA protocol and the original ALOHA/CSMA protocol [47] for the values of $N = 5$, $a = 0.5$, and $L = 50, 100$ and 500. It is shown that for small G_d, there is almost no difference between the two protocols. This is due to the fact that for light traffic, almost every user which wishes to send a message can access an idle channel, and both the control and the data packets will get through without collision with a high probability. However, for heavy traffic, the ALOHA/Slotted-CSMA protocol achieves a much better performance than the original one because of introduction of the acknowledgements. As L gets large, the throughput increases. The delay of the ALOHA/Slotted-CSMA protocol is much less than that of the original one for similar throughput values.

Fig.3.11 through Fig.3.13 show the results for $N = 5$, $a = 1.0$, and $L = 50$, 100 and 500. It is shown that the original protocol is insensitive to the propagation delay a. The proposed protocol even achieves a higher throughput because of the shorter vulnerable time period. The protocol is attractive for relatively large LANs when a

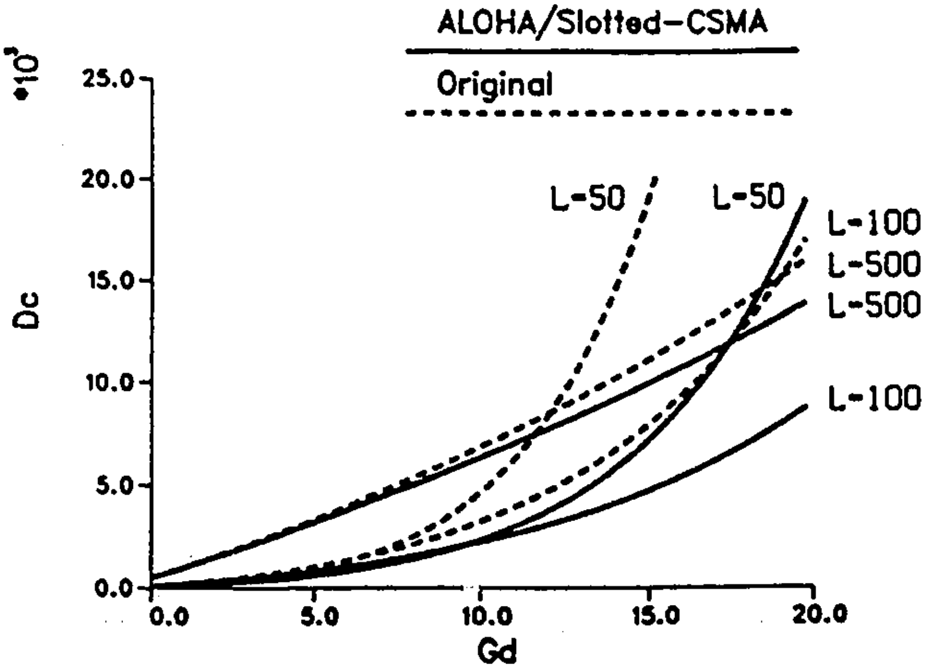


Figure 3.9: Delay D_c versus offered traffic G_d with $N = 5$ and $a = 0.5$

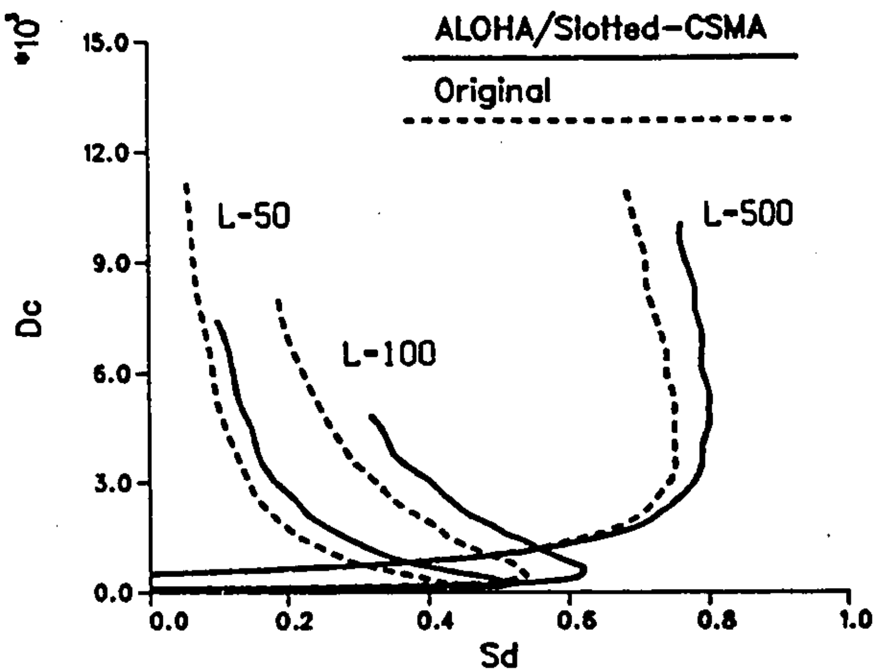


Figure 3.10: Delay D_c versus throughput $\hat{S}_d$ with $N = 5$ and $a = 0.5$

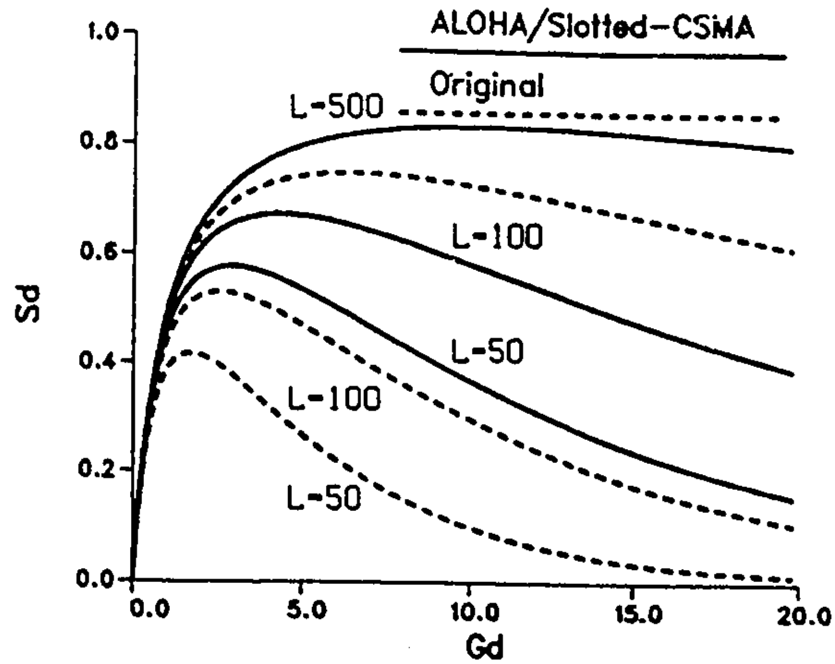


Figure 3.11: Throughput S_d versus offered traffic G_d with $N = 5$ and $a = 1.0$

rather high throughput is expected.

Fig.3.14 through Fig.3.16 show the results for $N = 10$, $a = 0.5$, and $L = 50$, 100 and 500. By comparing Fig.3.8 and Fig.3.14, one can see the throughput shown in the latter is lower because of the increased number of channels. Since more data channels are using one control channel, according to the notations in section 3, the value of G increases for larger N under the same value of G_d. The increased G causes the control packets to go through the control channel with a lower probability. That is why the throughput in the latter case is lower. The delay in the latter case is larger for the same reason.

The total network throughput is given by

$$S = NS_d. \tag{3.31}$$

3.5 Concluding Remarks

In this chapter, we have presented and analyzed protocols for a multiuser very high-speed optical local area network based on a passive star topology. In this network architecture, the users' traffic is assumed bursty as in the case of computer communications. Tunable transmitters and receivers which are capable of tuning to $N + 1$

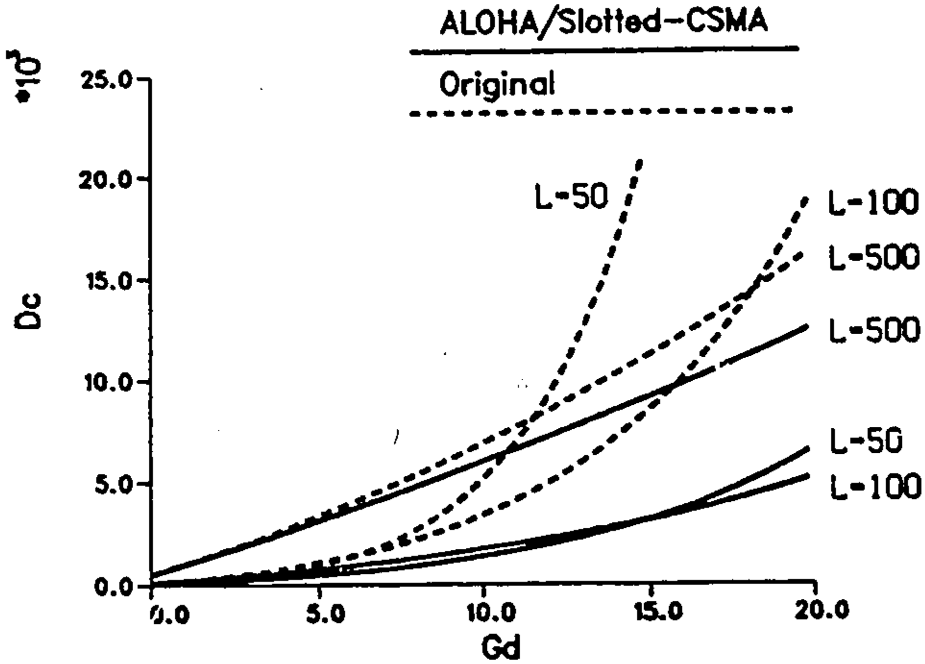


Figure 3.12: Delay D_c versus offered traffic G_d with $N = 5$ and $a = 1.0$

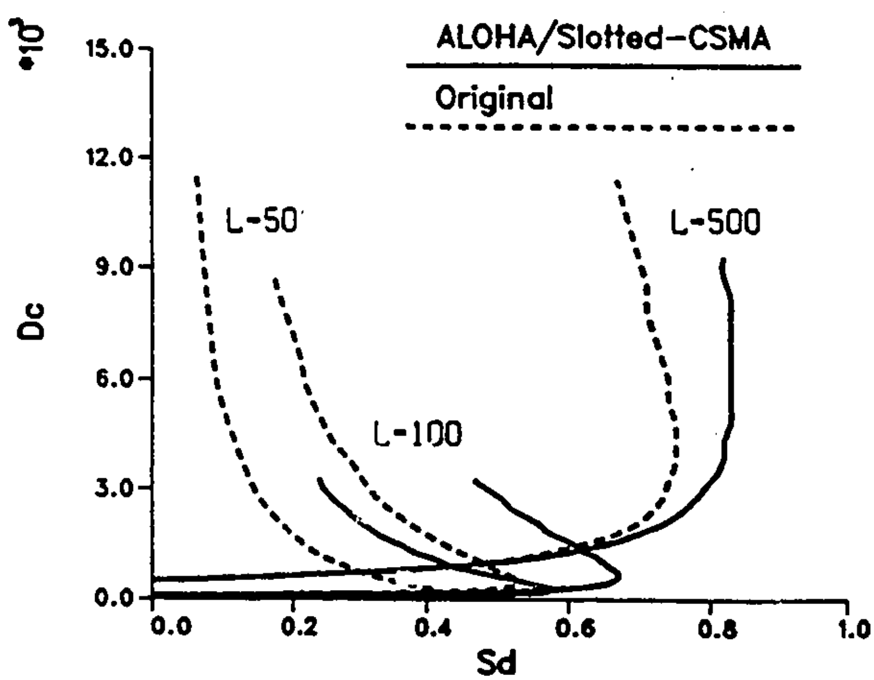


Figure 3.13: Delay D_c versus throughput S_d with $N = 5$ and $a = 1.0$

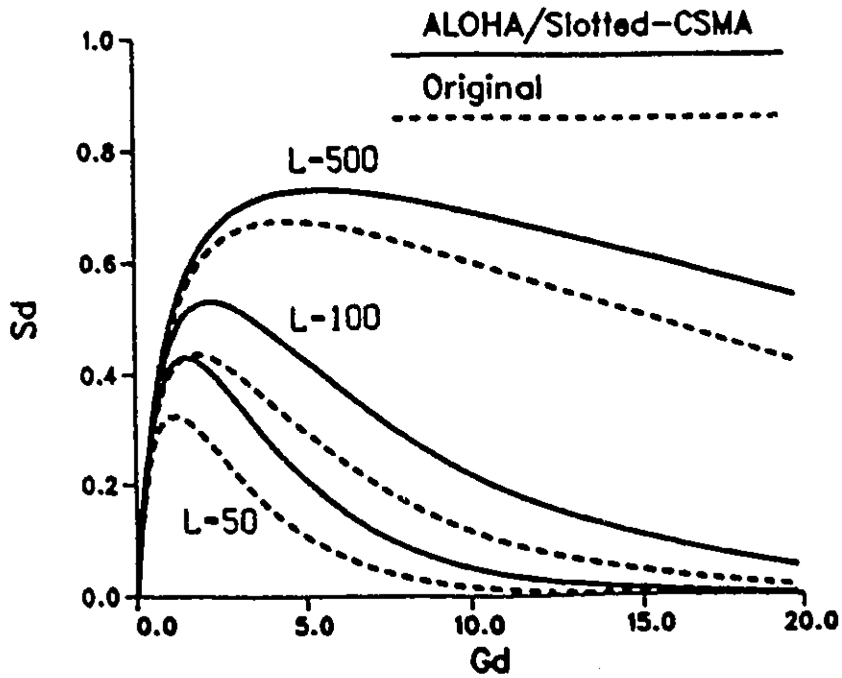


Figure 3.14: Throughput S_d versus offered traffic G_d with $N = 10$ and $a = 0.5$

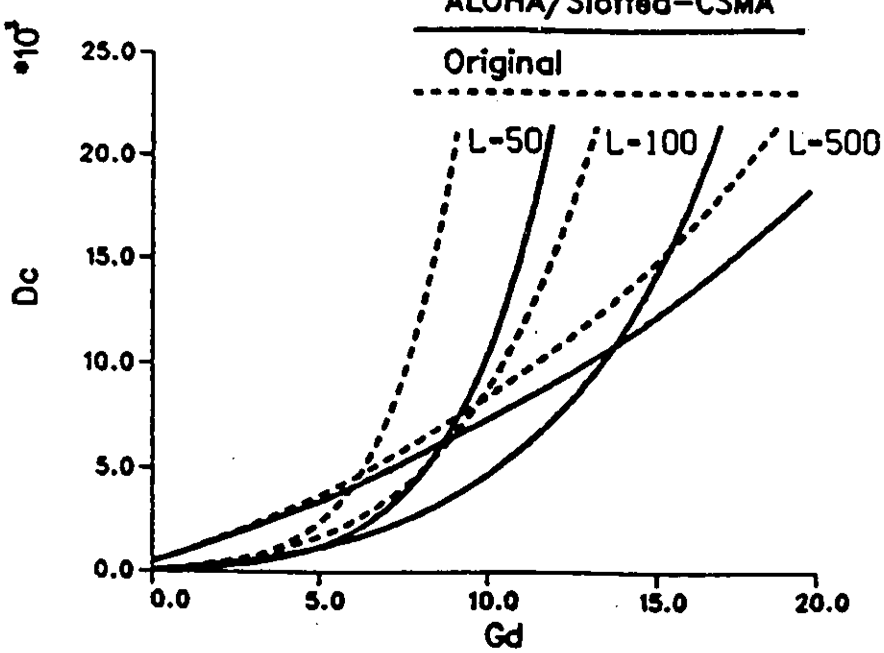


Figure 3.15: Delay D_c versus offered traffic G_d with $N = 10$ and $a = 0.5$

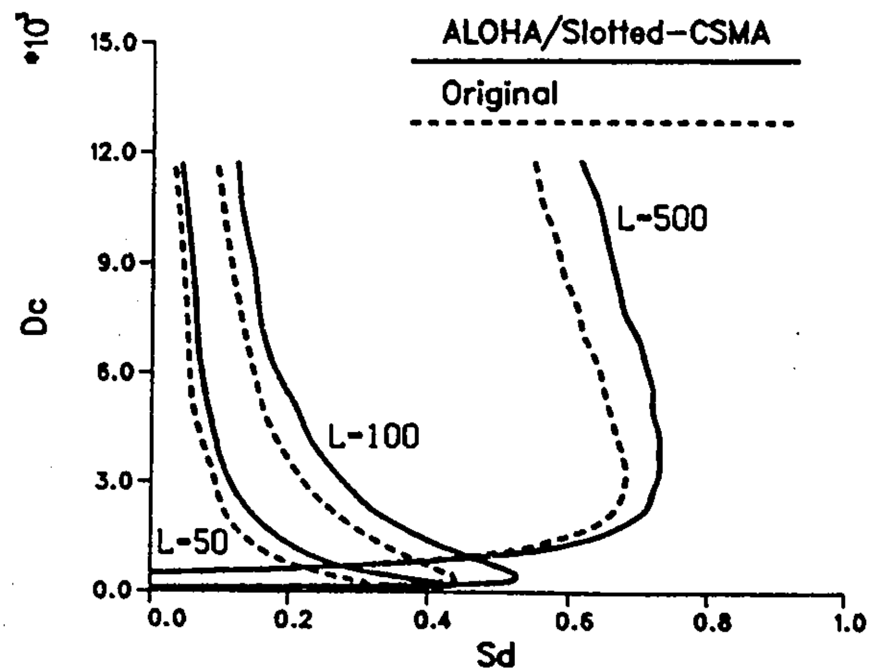


Figure 3.16: Delay D_c versus throughput S_d with $N = 10$ and $a = 0.5$

relatively stable wavelengths are required to get cross-connected via a passive optical star coupler to the other users of the network. One of the $N+1$ wavelengths is used to provide the switching information to the receivers. The other N wavelengths are used for actual data transmission. A source node uses the control channel to inform the destination node of its intention to transmit a packet and the specific data channel to receive this packet. The destination node tunes to the specified data channel to receive the data packet.

In this network architecture, certain amount of time must be spent in establishing an end-to-end link between the sender and the reference receiver if the sender wants to transmit a data packet. This time period would be considered as overhead no mater what random access protocol is used. The ALOHA type protocols do not require any type of carrier sensing and their performances is independent of the network diameter. The proposed ALOHA/Slotted CSMA protocol aims at fully using the pretransmission time period to achieve a better performance without requiring extra node hardware.

Our protocol employs the pure ALOHA random-access scheme on the control channel and the slotted-CSMA scheme on the data channels. In [47], the users transmit the data packets immediately after the transmission of the corresponding control packets. Bandwidth is wasted when a data packet is transmitted on the data channel while its accompanying control packet is lost on the control channel due to the control packet collision. The main improvement in our protocol is due to introducing acknowledgement between the sender and the receiver. Therefore, the decision to transmit a data packet is based on the condition of the successful transmission of the corresponding control packet. The channel utilization will be increased. To implement the protocol presented here in a star network, each user needs only one tunable/agile transceiver and does not need to jam the data channel for one control packet frame time after sensing it idle, as proposed in [47]. It has an economic advantage over the corresponding protocol [47] which requires each user to use two lasers.

The numerical results for different values of wavelength number, propagation delay time and data packet length were presented. It is shown that for the heavy traffic conditions, our protocol achieves a higher throughput and it causes much less delay for a reasonable range of system parameters.

In all the above analysis, we do not consider receiver collisions. Since under infinite number of users assumption, the receiver collisions are very rare. Also the protocols discussed here are at the low levels of data network protocol hierarchy, it is reasonable to assume that the higher level protocols will take care of receiver collisions.

Chapter 4

The Simulation Studies of a Very High-Speed Optical LAN Interconnected by a Passive Star Coupler

4.1 Simulation Technique in Network Designs

Digital communications and computers are having a tremendous impact on the world today. In order to meet the increasing demand for digital communications services, engineers must design systems in a timely cost-effective manner. The design, analysis, and optimization of performance can be very demanding and difficult. Performance evaluations and tradeoff analysis are central issues in the design of communication links and networks. Unfortunately, except for some idealized and often oversimplified cases, it is extremely difficult to evaluate the performance of a complex communication network in closed form using analytical techniques alone. Digital simulation provides a useful and effective compliment to direct analytical evaluation of communications system performance.

There are two main advantages in computer simulation. First, simulation frees the analyst from a great deal of repetitive work involved in substituting numbers into formulas and enables the analyst to concentrate on the results. Second, simulation is the insight into system performance provided by both the modeling process itself and the experience gained from simulation experiments.

Computer simulations can be performed at any point in the life cycle of a communication product: before significant development effort, as an ongoing part of development, in manufacturing, through installation, and out into field operations, service, and support. The results of these simulations should be checked with data or measurements on actual systems whenever possible because inevitably any model ignores some phenomena (confidence is needed in both modeling assumptions as well as the numerical parameters in the model).

A communications network is made up of a set of interconnected transmission facilities and is designed to serve the needs of a variety of users. For simulation purposes, it is convenient to model the network using two levels: transmission system level and a network level [53]. The transmission system level includes the transmission channel, transmitters, receivers, modulators, demodulators, encoders, decoders, filters, and amplifiers. The network level deals with issues such as message formatting, multiplexing, concentration, protocols, routing, switching, flow control, and other network control functions. Modeling and simulation based on computer-aided design and analysis can reduce the complexity of network design and performance evaluation to a manageable level, allowing systematic and quantitative exploration of design alternatives.

4.2 Modifications Based on Implementation Considerations

In previous chapter, we proposed the ALOHA/Slotted-CSMA protocol for a very high-speed optical LAN interconnected by a passive star coupler and presented the performance evaluations based on theoretical studies. Here, we present some simulations results bv using BONeS (Block Oriented Network Simulator) and our own modifications are made based on implementation considerations.

The CSMA protocol is commonly used for local area networks. Implementations of this protocol are available at different transmission speeds and for different technologies. This protocol provides channel arbitration for a large number of independent users sharing the transmission medium and treats all of the individual users equally.

No node is given a higher priority than others. The lack of any central control greatly contributes to the reliability of this protocol, the failure of one node will not disable the entire network.

The main disadvantage of CSMA protocol is that its performance is greatly affected by network diameter, which is defined as the longest distance between the users. The longer the distance, the worse the network performance. In our protocol, we choose slotted CSMA protocol for data packet transmission. The reason for this choice is that the link set-up time which includes control packet transmission time, the control packet frame time and the laser wavelength switching and tuning time can not be ignored in this high-speed network architecture. A protocol must be properly chosen based on the above factors to use the channel capacity, effectively. The ALOHA/Slotted-CSMA protocol has been chosen for the simulation studies.

The algorithm for ALOHA/Slotted-CSMA protocol is shown in Fig.4.1. An essential part of our protocol is that when a user has a data packet to send, it first has to sense the data channel randomly at the beginning of the next CSMA slot, if an idle channel is located, it sends the control packet over the control channel using ALOHA protocol. Since each user in the idle condition tunes its receiver to the control channel wavelength, the control packet will be received by the reference receiver as well as its sender. After the whole control packet is received, the sender will know whether or not its control packet is through the control channel without collision by comparing the received one to the original one. If no collision is detected, the user sends the data packet over the selected data channel and the reference receiver will tune its receive wavelength to the selected data channel according to the switching information.

In the following analysis, we always assume that the retransmissions caused by transmission error can be ignored compared to those caused by control packet collisions or when randomly selected data channel happens to be busy. This assumption is especially applicable to the optical communication network, because the BER for the single-mode fiber is about 10^{-12}.

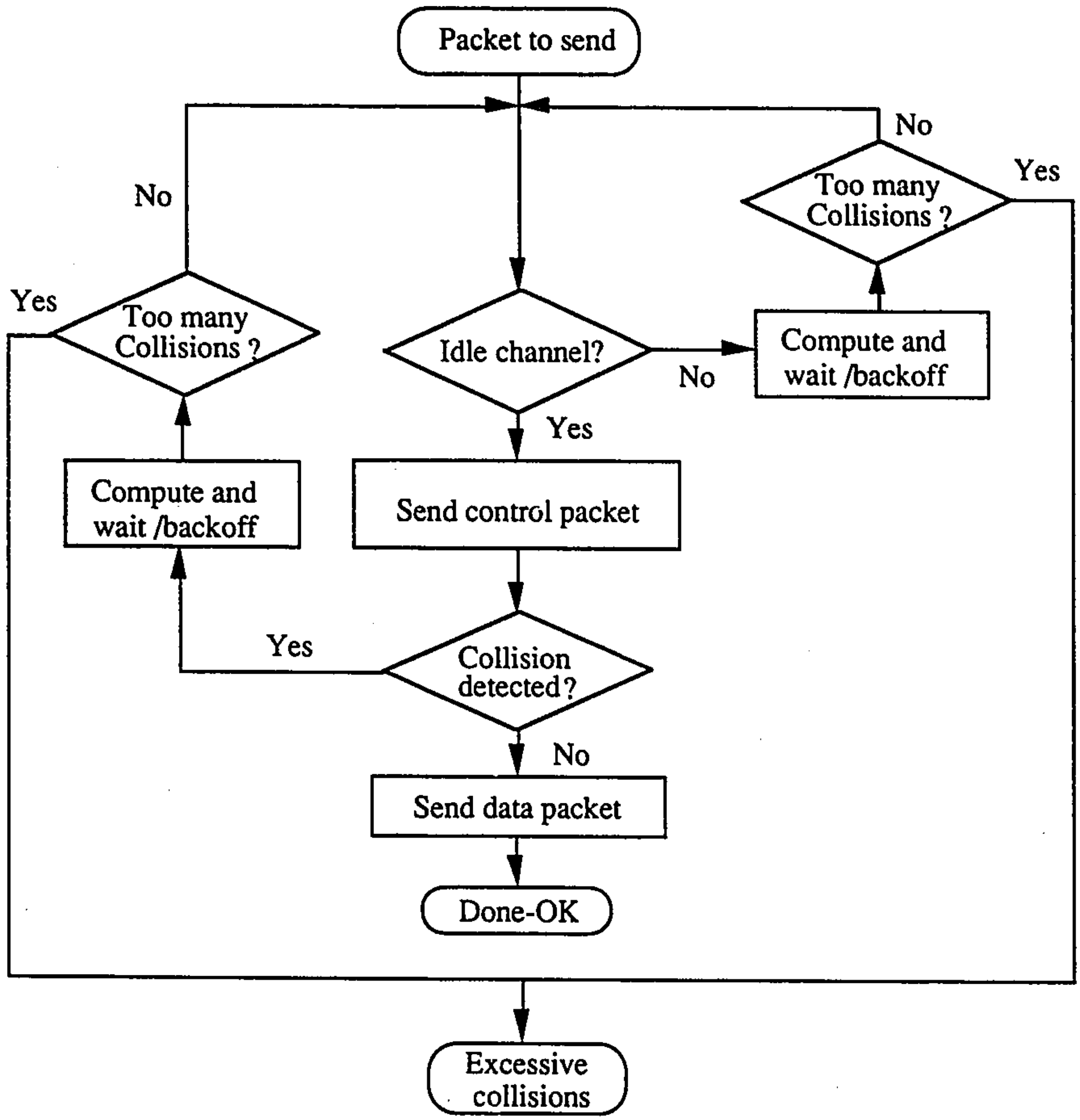


Figure 4.1: ALOHA/Slotted-CSMA Transmission Procedure

4.2.1 Implementation Considerations

The network architecture being studied here was introduced in the previous chapter. In this network architecture, certain amount of time must be spent in establishing an end-to-end link between the users before the actual data transmission starts, and this pretransmission coordination is required in WDM networks. This time period consists of:

- Propagation delay time for the first bit of the control packet to be received by the reference receiver and the sender itself.
- Control packet frame time, since only after the whole control packet is received, the reference receiver will know the switching information and the sender will know whether or not collisions happened over the control channel.
- Time for the reference receiver to tune to the selected wavelength.

As shown in Fig.4.2, the slot time must be larger than or at least equal to the sum of the above three factors to achieve higher channel throughput. The choice of the slot time is a classical engineering compromise. Making the slot time very small would restrict the size of the network, while a large slot time would increase the overhead significantly.

We assume that data packet is transmitted over the optical fiber at a bit rate of 1 *Gbits/sec* in simulation. The round trip delay time and the laser tuning time become the dominant factors and can not be ignored because of the fast channel transmission speed. So, we choose one CSMA slot time equal to the sum of round trip propagation time, control packet frame time and laser tuning time. The round trip propagation delay is

$$t_p = \frac{maximum\ round\ trip\ distance}{light\ speed}. \tag{4.1}$$

If we choose the maximum round trip distance to be equal to 0.6 km, then $t_p = 2\ \mu s$. If the transmission speed is 1 *Gbits/sec*, then 2000 bits can be transmitted within this time period, so the propagation delay time can not be ignored.

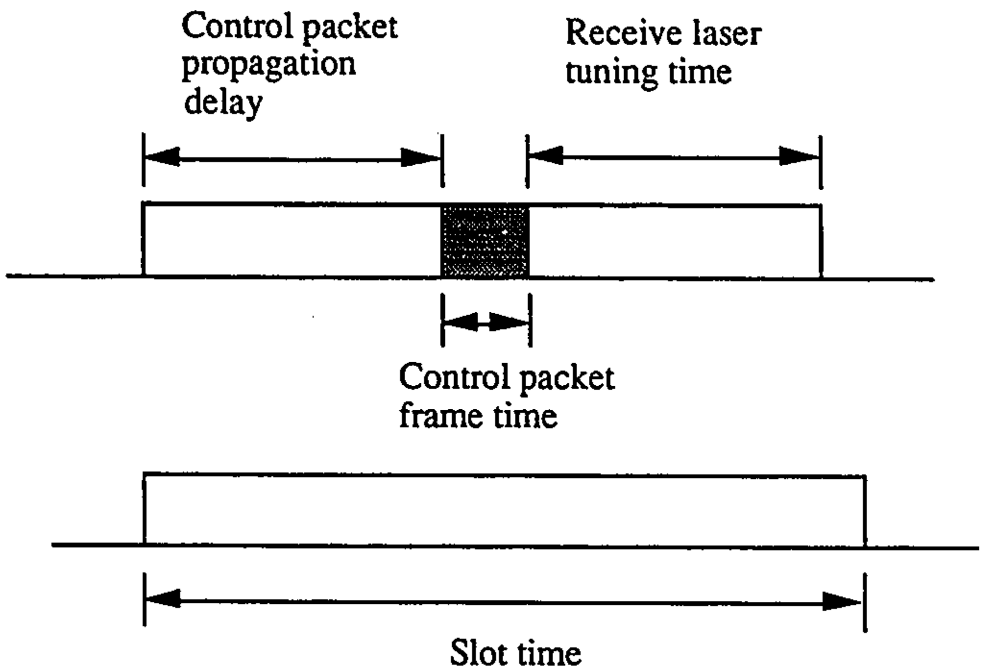


Figure 4.2: Slot Time Selection

In a local area network, the round trip propagation time varies dramatically according to the locations of the users in the network. Some users may be located at the farthest positions in the LAN and may have the longest round trip distance d_{max}. Some may be located just near the star coupler and have the shortest round trip distance, d_{min}. In our protocol, if more than two users try to transmit their control packet over the control channel during the same CSMA slot, a collision occurs over the control channel. If the control packet is too short, as shown in Fig.4.3, user A and user B which have a propagation delay time difference larger than the control packet frame time will get their control packet through in sequence, even though they transmit in the same CSMA slot. The assumption that if more than two users try to transmit their control packet over the control channel during the same CSMA slot a collision occurs over the control channel could not be met in this case. In real operation, the control packet length must satisfy

$$Control\ packet\ length \geq \frac{(d_{max} - d_{min}) \times\ Transmission\ Speed}{2 \times\ Light\ Speed}\ (bits). \qquad (4.2)$$

The control packet length is 1000 bits in our simulation. Usually, the control packet contains the source address, the destination address, and the selected wavelength used to transmit a data packet. The information added by the upper layers may occupy the remaining bits of the control packet.

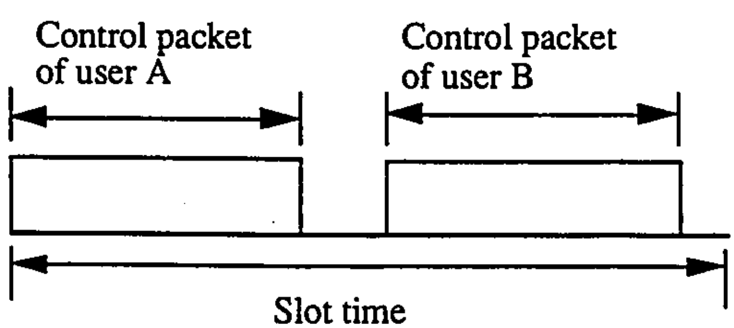


Figure 4.3: Control Packet Length Selection

The laser tuning time is roughly in the order of 1-10 μs according to recent developments on tunable lasers. We choose a tuning time equal to 2 μs which is equal to the propagation delay time in the simulation, since the sender transmits its data packet immediately after it receives the whole control packet and detects no collision. It will take the first bit of the data packet another round trip delay time to get to the receiver, so the reference receiver can tune its receive wavelength to the selected data channel during this time. When the beginning of the next CSMA slot arrives, other users with data packets to send will sense the data channel selected by the previous user busy. If we choose the tuning time as above, there is no need to jam the channel after sensing it idle and a tunable laser is needed for transmission.

4.2.2 Backoff Slot Time

In ALOHA/Slotted-CSMA protocol, successful transmission of a data packet depends on sensing an idle data channel successfully and detecting no collision in control packet transmission. If no idle data channel is found or a collision happens over the control channel, the sender must retransmit the data packet according to a certain backoff procedure. The retransmission procedure is an important factor in the network design.

In the previous chapter, no retransmission mechanism was specified for the theoretical analysis, we simply let the average data packets generated per control slot to be those of new plus the retransmitted one. Here, we use a binary exponential backoff mechanism in the simulation. In this mechanism, the backoff time is the result of an integer chosen from $[0, 2^k)$ multiplied by the backoff slot time (called B/slot time in the following analysis). Parameter k is the minimum number of attempts made to transmit the data and the protocol backoff limit. Here, we choose a backoff limit (k value) equal to 10. For the collision resolution to be efficient, the B/slot time must be large enough to avoid unnecessary repeated collisions. Excessively long B/slot time will cause backoff time to be longer than necessary leading to additional delay and unused transmission capacity. It must be chosen properly.

4.3 The Network Modeling

4.3.1 Network Layered Structure

According to the OSI Reference model, the network functions are grouped into layers at each node. Each layer communicates with its peer layer in other nodes using a protocol with precisely defined frame formats. Each layer must also communicate with the layer above it to provide transmission services. The communication is accomplished by using service primitives which are conceptually subroutines. Each service has parameters to supply data and control information. The relationship between the OSI protocol layers and LAN layers is shown in Fig.4.4. In the LAN protocol, the network layer is needed only in the case of interconnecting LANs.

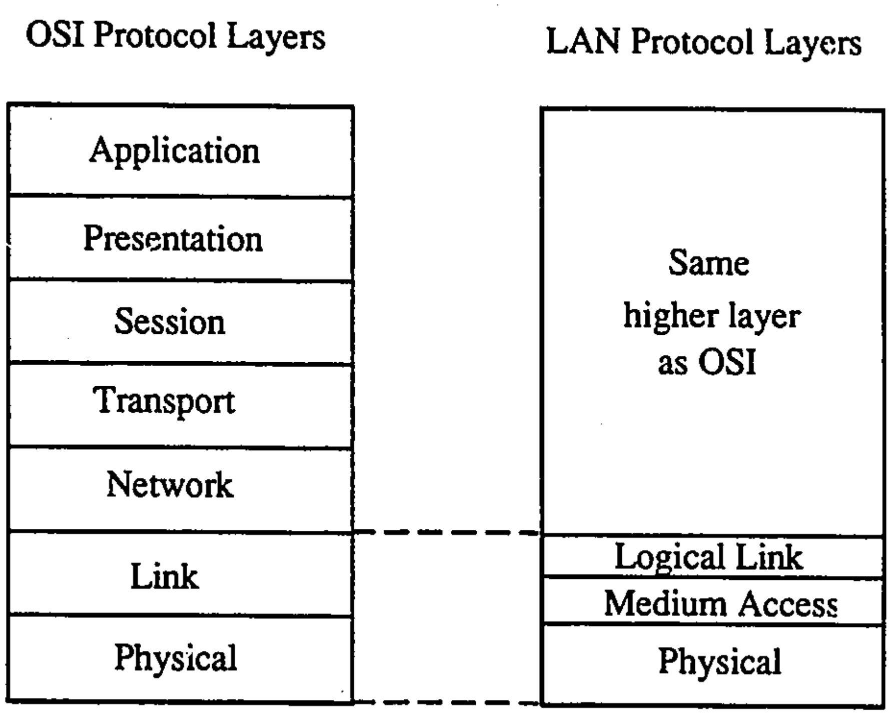


Figure 4.4: Relationship between the OSI protocol layers and LAN layers

Our network model is concerned with the interface between layers. In the simulation, we consider MAC (Medium Access Control) layer and its upper layer LLC

(Link Level Control) layer referring to the IEEE 802.2 standard. Two distinct types of primitives are used in the interface between the MAC and the LLC layers:

- A request primitive is used by the LLC to request the transmission of a frame.
- An indication primitive is used by the MAC layer to inform the LLC of the arrival of data or the completion of a request.

Fig.4.5 shows the communication interface between the LLC and the MAC layers.

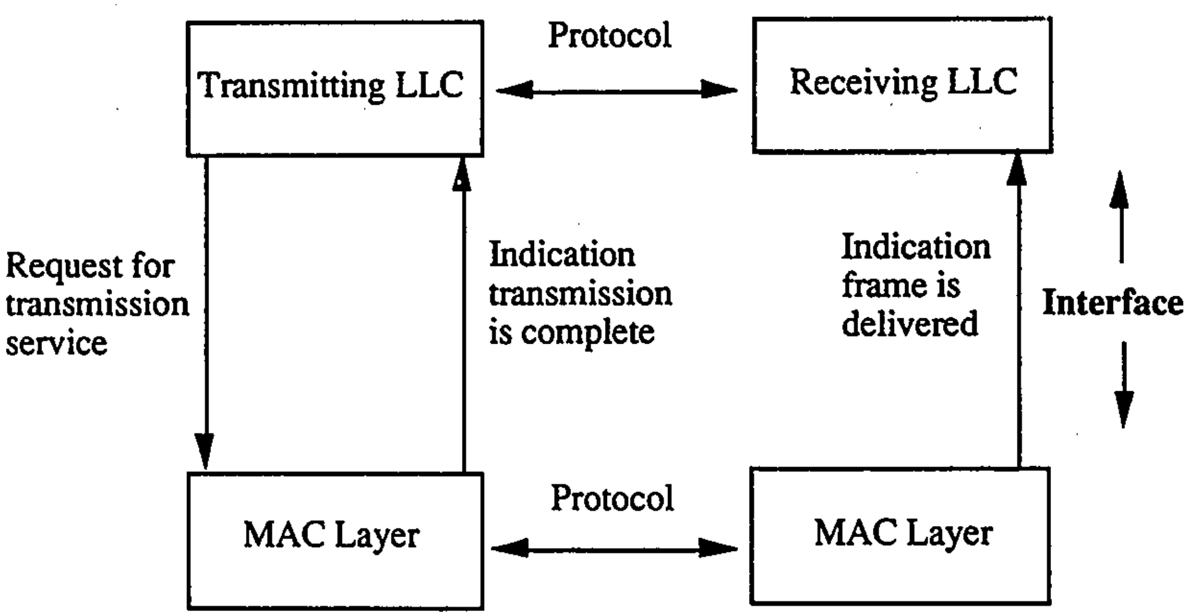


Figure 4.5: Interface between the LLC and MAC

4.3.2 Network Modeling Approach

This is a detailed modeling procedure of the ALOHA/Slotted-CSMA protocol. Control channel collisions and absence of available data channel are the main network performance impairments. An accurate timing model including propagation delay resulting from network geometry is necessary to model the protocol in detail. To simulate network performance with a event-driven simulator BONeS, we break the frame transmission process into important events that are worth studying at every node. These events are "the start of a data packet", "the end of a data packet", "the start of a control packet", "the end of a control packet" and so on.

These events are modeled by propagating a data structure along the channels connecting the nodes. A delay is placed between the nodes to model the time to propagate the frame over the channels. The function of timing mechanism is discussed in more detail in this section illustrating the construction of models, such as "Carrier Sense", "Collision Detection" and so on.

4.4 Data Base Structures for the Simulation Modeling

In the ALOHA/Slotted-CSMA model, two distinct sets of data structures are used. The first set consists of structures that define the interface between the MAC layer (service provider) and the LLC layer (service user). The other set of data structures is used for communication between peer layers. These structures are private to the MAC layer model and do not need to be understood by the models outside this layer. The structures and their derivatives are shown in Fig.4.6.

4.4.1 Interface Structures

The data structure Service Primitives, shown in Fig.4.7, is a place holder that is used to organize all the service primitives. The derivatives of this structure are the service primitives for communication between the MAC and the LLC [54].

Request

The request data structure, shown in Fig.4.8, implements the MA-UNITDATA request primitive. That service primitive is issued by the LLC to the MAC to request a frame to be sent. The fields of the structure correspond to the parameters of that primitive are:

- source address is the address of the user that sends the frame.

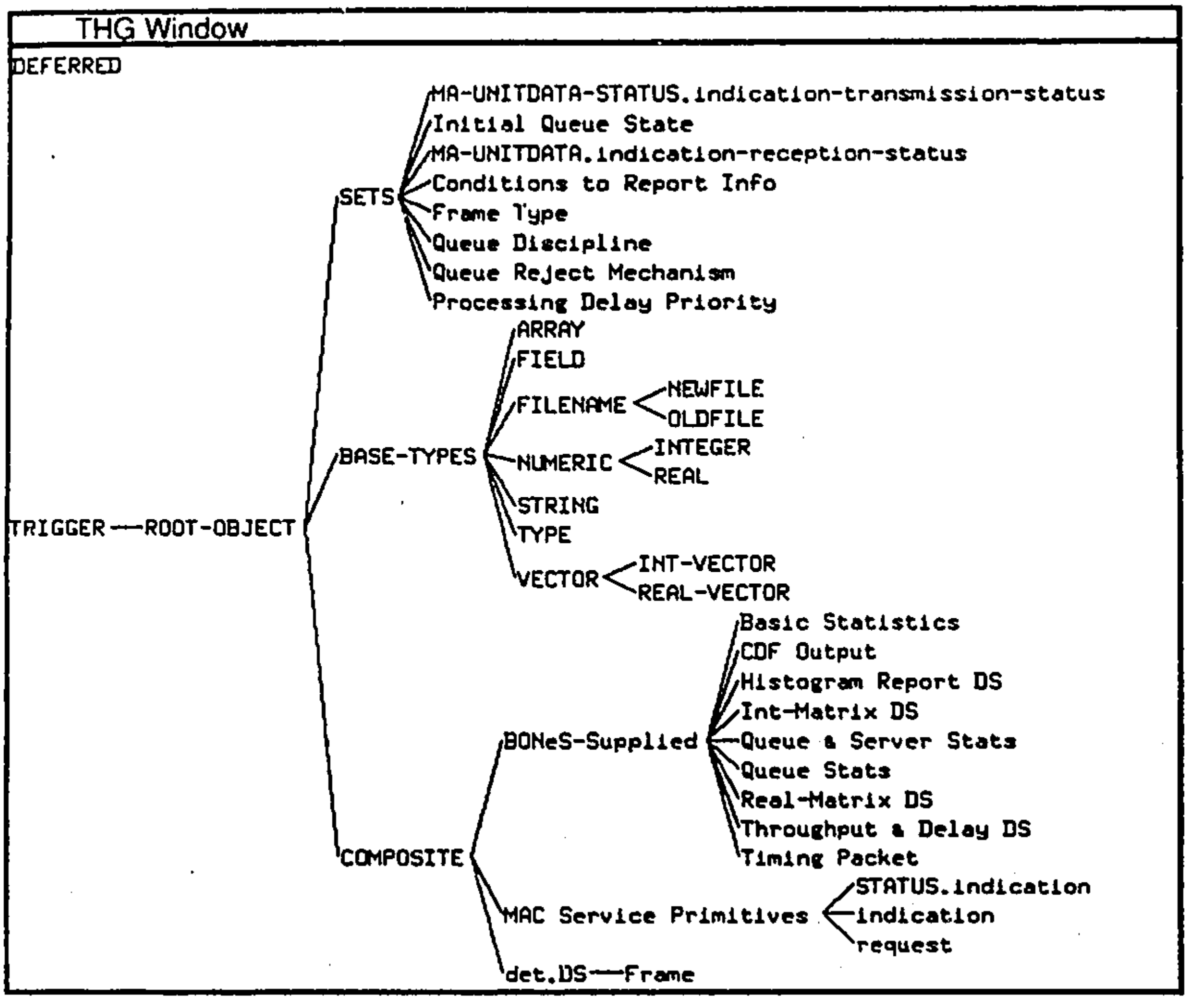


Figure 4.6: Type Hierarchy Graph of ALOHA/Slotted-CSMA Structures

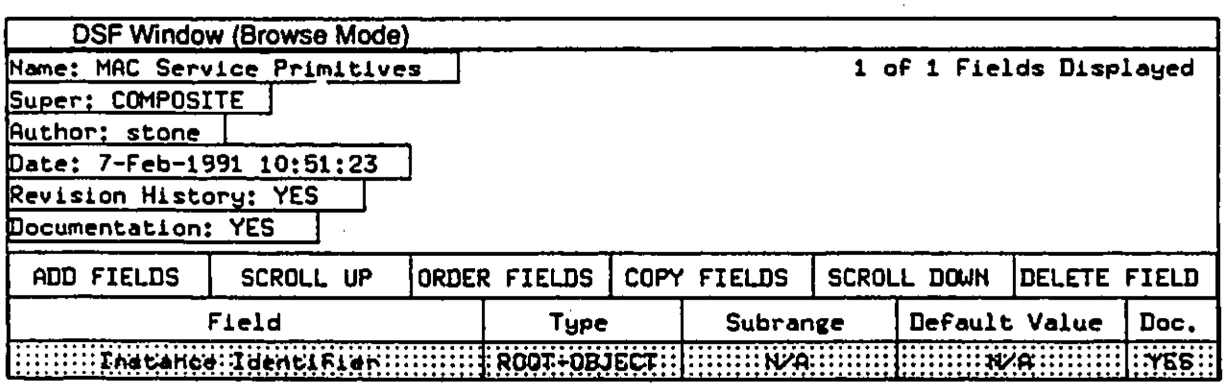


Figure 4.7: Service Primitives

- destination address is the address of the user to which the frame is to be sent.
- data is the data packet to be sent. The contents of this field are encapsulated by the ALOHA/Slotted-CSMA model and transported to the destination. This field is typed ROOT-OBJECT so that any type of data can be sent by the proposed protocol.
- Length of data is the length packet in bits of the data to be transmitted. The value of this field is used to compute transmission delays, and probability of transmission error.
- priority is an integer chosen from 0 to 1 indicating the priority of the transmission. The ALOHA/Slotted-CSMA protocol offers only fair access and does not support priorities, but this field is retained for compatibility with other MAC protocols.
- service-class is used to request a certain grade of service (that is requesting an acknowledgement of successful transmission). It is not used here, but the field remains for compatibility with other MAC protocols.
- Lower Destination Address and Upper Destination Address are used to define the minimum and maximum user address numbers.

Status.indication

The Status.indication data structure, shown in Fig.4.9, implements the MA-UNITDATA-STATUS.indication primitive which informs the sending LLC of the status of its last transmission. After the LLC makes a request, the MAC layer issues a status primitive indicating that the transmission has taken place or that the MAC layer has given up. The fields of this structure correspond to the parameters of the service primitive are:

- source address is the address of the user that sends the frame.
- destination address is the address of the user to which the frame is to be sent.

DSF Window (Browse Mode)

Name: request — 9 of 9 Fields Displayed

Super: MAC Service Primitives

Author: stone

Date: 12-Feb-1991 11:29:04

Revision History: YES

Documentation: YES

ADD FIELDS | SCROLL UP | ORDER FIELDS | COPY FIELDS | SCROLL DOWN | DELETE FIELD

Field	Type	Subrange	Default Value	Doc.
Instance Identifier	ROOT-OBJECT	N/A	N/A	YES
source-address	INTEGER	+- Infinity	N/A	YES
destination-address	INTEGER	+- Infinity	N/A	YES
data	ROOT-OBJECT	N/A	N/A	YES
length of data	INTEGER	>= 0	0	YES
priority	INTEGER	0 to 1	0	YES
service-class	ROOT-OBJECT	N/A	N/A	YES
Lower Destination Address	REAL	>= 0	N/A	YES
Upper Destination Address	REAL	>= 0	N/A	YES

Figure 4.8: Request

- transmission-status field indicates the success or failure of the transmission. The values of this field are defined by the SET MA-UNITDATA-STATUS indication-transmission-status (Fig.4.13). Currently this field can have either the value transmit OK (indicating that the frame has been sent), or excessive Collision Error (indicating that the MAC layer has given up on that frame). Additional values can be added to the set to support other MAC protocols.

- Length of data is the length of the data packet in bits to be transmitted. The value of this field is used to compute transmission delays, and probability of transmission error.

- provided-priority is an integer from 0 to 1 indicating the priority of the transmission. The ALOHA/Slotted-CSMA protocol offers only fair access and does not use the field.

- provided-service-class was actually provided. The type and contents of service-class are MAC layer dependent and our protocol does not use this field.

DSF Window (Browse Mode)

Name: STATUS.indication

6 of 6 Fields Displayed

Super: MAC Service Primitives

Author: stone

Date: 7-Feb-1991 12:46:25

Revision History: YES

Documentation: YES

ADD FIELDS | SCROLL UP | ORDER FIELDS | COPY FIELDS | SCROLL DOWN | DELETE FIELD

Field	Type	Subrange	Default Value	Doc.
Instance Identifier	ROOT-OBJECT	N/A	N/A	YES
destination-address	INTEGER	+- Infinity	N/A	YES
source-address	INTEGER	+- Infinity	N/A	YES
transmission-status	MA-UNITDATA-STATUS.indication	All Values	transmitOK	YES
provided-priority	INTEGER	0 to 1	0	YES
provided-service-class	ROOT-OBJECT	N/A	N/A	YES

Figure 4.9: Status indication

Indication

The indication data structure, shown in Fig.4.10, models the MA-UNITDATA.indication service primitive used by the MAC to signal the receipt of a frame to the LLC. After the MAC layer receives a frame, it issues a MA-UNIDATA indication service primitive to the LLC to indicate the reception, reports any errors, and delivers the data. The field of this structure corresponds to the parameters of the service primitive are:

- source address is the address of the user that sends the frame.
- destination address is the address of the user to which the frame is to be sent.
- data is the data to be sent. The contents of this field are encapsulated by the ALOHA/Slotted-CSMA model and transported to the destination. This field is typed ROOT-OBJECT so that any type of data can be sent by the proposed protocol.
- Reception Status field indicates that the condition of the received frame. The values of this field are defined by the SET MA-UNITDATA-STATUS indication-reception-status (Fig.4.14). Currently this field may have the following values:

DSF Window (Browse Mode)

Name: indication — 8 of 8 Fields Displayed
Super: MAC Service Primitives
Author: stone
Date: 7-Feb-1991 13:00:48
Revision History: YES
Documentation: YES

ADD FIELDS	SCROLL UP	ORDER FIELDS	COPY FIELDS	SCROLL DOWN	DELETE FIELD

Field	Type	Subrange	Default Value	Doc.
Instance Identifier	ROOT-OBJECT	N/A	N/A	YES
destination-address	INTEGER	+- Infinity	N/A	YES
source-address	INTEGER	+- Infinity	N/A	YES
data	ROOT-OBJECT	N/A	N/A	YES
Length of data	INTEGER	>= 0	0	YES
Reception Status	MA-UNITDATA.indication-recept	All Values	receiveOK	YES
priority	INTEGER	0 to 1	0	YES
service-class	ROOT-OBJECT	N/A	N/A	YES

Figure 4.10: Indication

receive OK (indicating that the frame is received without error), length Error (indicating that the frame does not have the the expected length), frame Check Error (indicating that one or more bit errors are presented in the received frame), and aligment Error (indicating that number of bits in the frame is not a multiple of certain integer).

- provided-priority is the priority (an integer chosen from 0 to 1) that is actually given to the transmission. The ALOHA/Slotted-CSMA protocol offers only fair access and does not support priorities, but this field is retained for compatibility with the other MAC protocols.

- The type and contents of service-class are MAC layer dependent and our protocol does not use the field.

4.4.2 Protocol Model Structures

These structures are the communication mechanism between the nodes implementing the ALOHA/Slotted-CSMA protocol model. In contrast to the interface structures, these structures are private to the protocol model. To model the timing

DSF Window (Browse Mode)

Name: det.DS
Super: COMPOSITE
Author: stone
Date: 28-Feb-1991 11:09:09
Revision History: YES
Documentation: YES

4 of 4 Fields Displayed

ADD FIELDS | SCROLL UP | ORDER FIELDS | COPY FIELDS | SCROLL DOWN | DELETE FIELD

Field	Type	Subrange	Default Value	Doc.
Instance Identifier	ROOT-OBJECT	N/A	N/A	YES
Source Address	INTEGER	+- Infinity	N/A	YES
Time Placed on Channel	REAL	>= 0	N/A	YES
Frame Type	Frame Type	User Defined	N/A	YES

Figure 4.11: det.DS Data Structure

of the ALOHA/Slotted-CSMA, the data structures are propagating over the channels to represent "the start of data packet", "the end of data packet", "the start of control packet" and "the end of control packet".

"The start of data packet", "the end of data packet", "the start of control packet" and "the end of control packet" are modeled with det.DS (detailed Data Structure). The end of a packet (end frame) is modeled by the Frame data structure which is a derivative of det.DS. The reason why two data structures are used is to increase the efficiency of the simulation. "The end of a data packet" has extra fields for statistical purposes as well as for accomplishing the transmission of the data. "The end of control packet" contains the switching information such as source address, destination address and the selected wavelength. The inclusion of all of the fields of "the end packet in the start" of data packet and "start of control packet" would produce unnecessary overhead by copying the unused fields. The connections to the channel are typed as det.DS and can accommodate either det.DS structure or the more detailed Frame data structure. Upon receiving a data structure, the node checks the type of the frame and declares all frames to be of different frame types.

det.DS Data Structures

The det.DS data structure (Fig.4.11) is used to model the events of starting transmission, starting a control and ending a control. It has three fields:

- Source Address is the address of the node generating this packet.
- Time Placed on Channel is the simulation time when this frame is placed on the channel. This is used to make time plots of channel activity with the Post Processor.
- Frame Type indicates whether the frame is a "start of data packet", "end of data packet", "start of control packet" or "end of control packet". This field can assume the values of the SET det.DS Frame Type (Fig.4.15). The values are start of data packet, end of data packet, start of control packet and end of control packet.

Frame

The Frame data structure (Fig.4.12) is used to model the end of a control packet or a data packet. In addition to its superior det.DS, it has fields to contain statistical information as well as the actual data to be sent. Frame has the following fields:

- Destination Address is the address of the user to which the frame is to be sent.
- Channel Number is the number of data channel to be used to transmit data packet.
- Packet Length is the length of frame in bits.
- Packet Generation Time is the simulation time when the request to generate this frame was made to the MAC. This field is used for statistical purposes only.
- Packet Initial Transmission Time is the simulation time when the first attempt was made to send this frame. If the number of attempts does not exceed the backoff limit, this field is not updated when subsequent attempts to transmit are made. This field is used for statistical purpose only.

DSF Window (Browse Mode)

Name: Frame
Super: det,DS
Author: stone
Date: 28-Feb-1991 11:19:30
Revision History: YES
Documentation: YES

12 of 12 Fields Displayed

ADD FIELDS | SCROLL UP | ORDER FIELDS | COPY FIELDS | SCROLL DOWN | DELETE FIELD

Field	Type	Subrange	Default Value	Doc.
Instance Identifier	ROOT-OBJECT	N/A	N/A	YES
Source Address	INTEGER	+- Infinity	N/A	YES
Time Placed on Channel	REAL	>= 0	N/A	YES
Frame Type	Frame Type	User Defined	N/A	YES
Destination Address	INTEGER	+- Infinity	N/A	YES
Channel Number	INTEGER	>= 0	N/A	YES
# Transmission Errors	INTEGER	>= 0	0	YES
Other Errors	MA-UNITDATA.indication-recept	User Defined	FrameCheckError	YES
Packet Length	INTEGER	>= 0	N/A	YES
Packet Generation Time	REAL	>= 0	N/A	YES
Number of Collisions	INTEGER	>= 0	0	YES
Packet Initial Transmission T	REAL	>= 0	N/A	YES

Figure 4.12: Frame Data Structure

- Number of Collisions is the number of times that the frame retransmitted before being successfully transmitted.

- # Transmission Errors is the number of transmission errors in the frame. This field is provided so that the model could be easily extended to study the effects of error correcting codes.

- Other Errors is the field provided so that the model can be extended to model other transmission impairments

The detailed module descriptions and programs will be provoded in Appendix.

4.5 Simulation Studies

We are going to explore the results of several simulations of the ALOHA/Slotted-CSMA protocol. These simulations are related to the testing, throughput and delay studies, and the network performances under influence of different network parameters.

```
DSF Window (Browse Mode)
Name: MA-UNITDATA-STATUS.indication-transmission-status
Super: SETS
Author: stone
Date: 7-Feb-1991 12:19:56
Revision History: YES
Documentation: YES
SET TYPE VALUES:
  transmitOK
  excessiveCollisionError
```

Figure 4.13: MA-UNITDATA-STATUS indication-transmission-status

```
DSF Window (Browse Mode)
Name: MA-UNITDATA.indication-reception-status
Super: SETS
Author: stone
Date: 7-Feb-1991 12:32:02
Revision History: YES
Documentation: YES
SET TYPE VALUES:
  receiveOK
  lengthError
  frameCheckError
  alignmentError
```

Figure 4.14: MA-UNITDATA indication-reception-status

```
DSF Window (Browse Mode)
Name: Frame Type
Super: SETS
Author: stone
Date: 14-Feb-1991 15:21:45
Revision History: YES
Documentation: YES
SET TYPE VALUES:
  Start of Packet
  End of Packet
  Start of Control
  End of Control
```

Figure 4.15: Frame Type

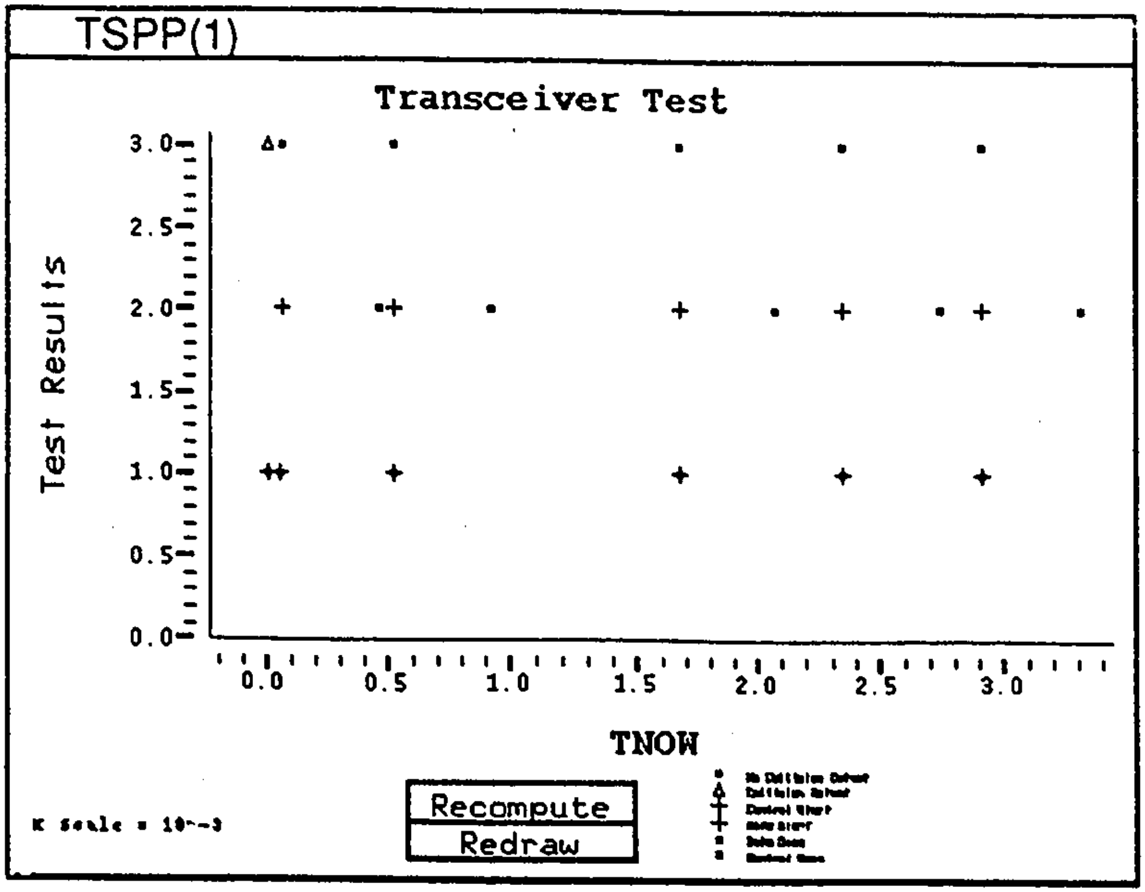


Figure 4.16: Transceiver Test

4.5.1 2-Node Testing System

This is a simple simulation of a two-node network. The main purpose of this simulation is to verify the simulation modeling and getting some "real time" feeling of the packet transmissions. The "Generic Probes" are placed in many important points to record the data packet and control packet transmissions of both users over certain data channel and control channel, and the modules of "carrier sense", "collision detect", "retransmission" and so on.

Fig.4.16 shows the test results of the transceiver module of one user in the simulated network. The results at 3.0 (vertical axis) shows the detection of the control channel collisions, the results at 2.0 shows the start and end of data packets, and the remaining shows the start and end of the control packets. At the starting time ($TNOW = 0.0\ sec$), the two users generate requests to send their data packets. Their control packets will collide over control channel. The collision will be detected

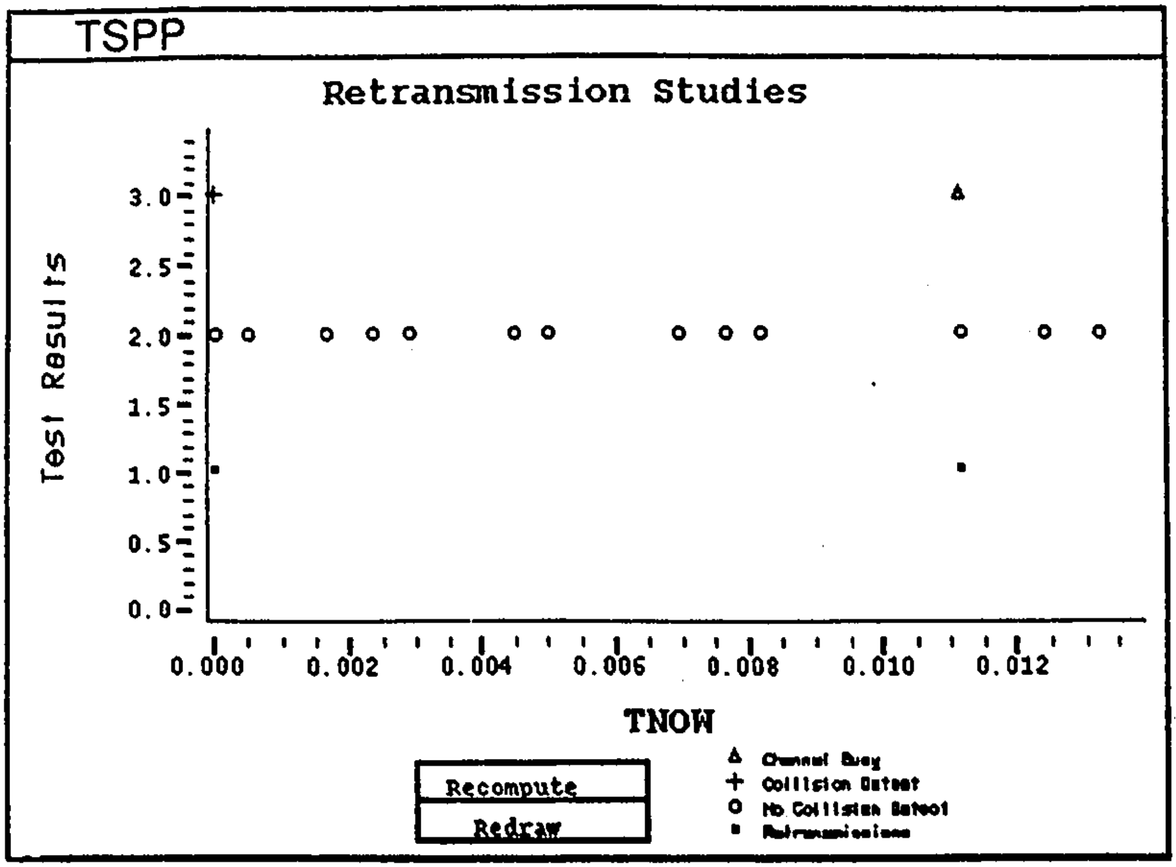


Figure 4.17: Retransmission Studies

by the transceiver model and the involved packets will be retransmitted, as shown in Fig.4.17. The following packets generated by both users will have no difficulty to get their control as well as data packets through successfully, so no collision is ever detected. Since the control and data packet frame times can be measured between the "start" and "end" of the packets, it is also possible to verify the modeling of the control and data packet frame times, and the time delay introduced by the channel propagation delay.

Fig.4.18 shows the test results of data channel selection and retransmissions caused by selecting a busy data channel. First, the user with a data packet to transmit senses the data channels randomly at the beginning of each CSMA slot. The randomly selected data channel numbers for data transmission requests of user one is shown in the figure. Once an idle data channel is located, the user will send its control packet over the control channel. If the selected data channel is found busy, as shown at $TNOW = 0.0112$ *sec*, the transceiver of the user will know the data channel is being

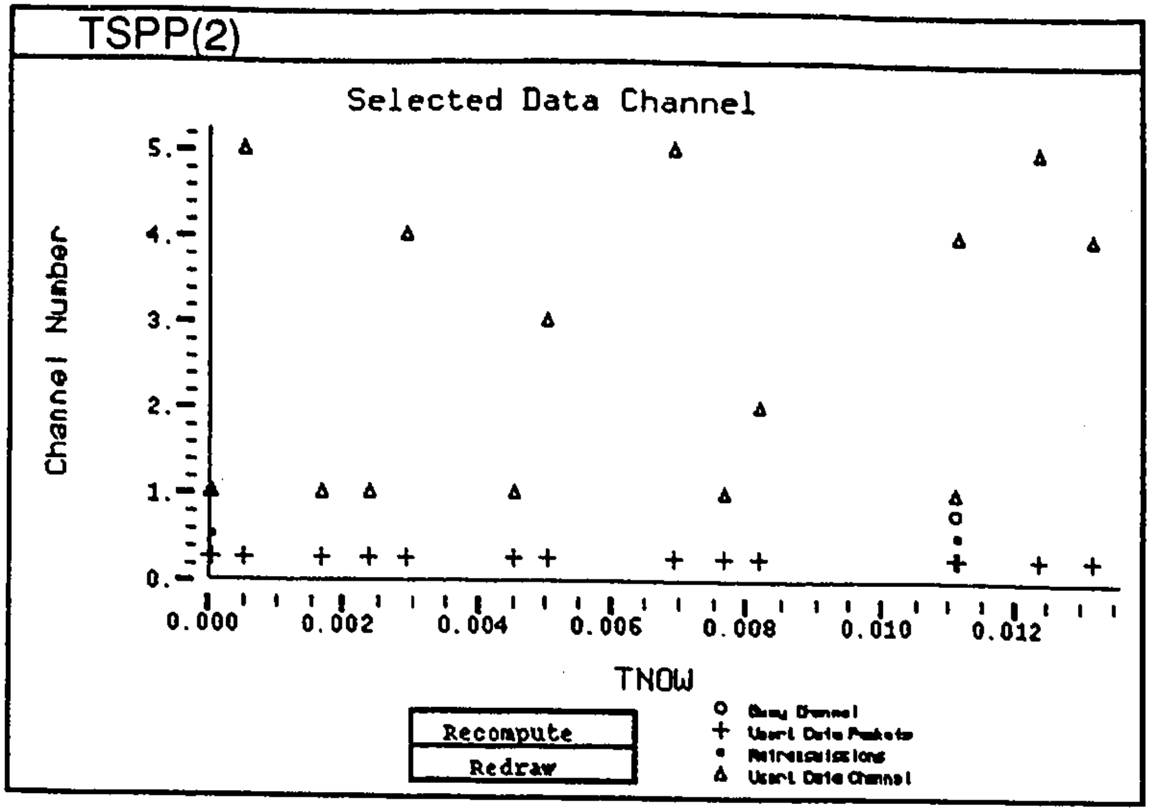


Figure 4.18: Selected data channel

used and will restart to sense the data channels. The retransmission mechanism is also tested by intentionally introducing seccussive retransmissions.

Many other tests are also performed to verify the important modules in the network modeling. It shows that the simulation modeling and programming are correct.

4.5.2 32-Node Simulation System

We are going to explore the results of several simulations of the ALOHA/Slotted-CSMA model. These simulations are related to the throughput and delay studies for different data packet lengths, network performance under different network parameters and data packet collision history.

The simulations are run to get the performance of the network using the ALOHA/Slotted-CSMA protocol under the conditions roughly comparable to those of the analytic results of our previous work. Some external parameters will affect the simulation results.

The first factor is the finite network size. A combination of the binary exponential backoff algorithm and a finite number (32) of nodes increases the stability of the network, because under very heavy load situations most nodes will be in long backoffs (because of exponential backoff algorithm) and will not be able to interfere with other traffic on the network. That is why most simulations have a much better performance than those of theoretical analysis for the heavy load. As noted in our previous work, the throughput of the ALOHA/Slotted-CSMA protocol with infinite population tends to zero as the load increases. It becomes unstable in this sense.

The second factor relates to the modifications we made in the previous section.

Thirdly, we always assume in our analytic studies that the load offered to the data channel is the sum of the newly generated and the retransmitted packets. This has a certain value under certain load and is Poisson distributed. However, the statistical results can not be obtained before the simulation is over in block oriented simulator and the load contributed by retransmission is unknown during the simulations. In the simulations, the load to the network which is Poisson distributed represents only the newly generated traffic. The actual load to the network will include the retransmitted part, which will make the total channel traffic load higher than that we used in our analytic studies.

4.5.3 Simulation Results

Several simulation studies have been done. The results and the analyses are given.

Throughput and Delay Studies

Several simulation studies have been done and the results are presented. In the figure of Throughput vs Load, the vertical axis is in *bits/sec*. In the figure of Delay vs Load, the vertical axis is in seconds. The statistical results presented here are obtained from any one of the data channels [55].

The results presented in Fig.4.19 and Fig.4.21 are obtained for data lengths equal to 5000, 10000, and 50000 bits. They are comparable to the results in cases with

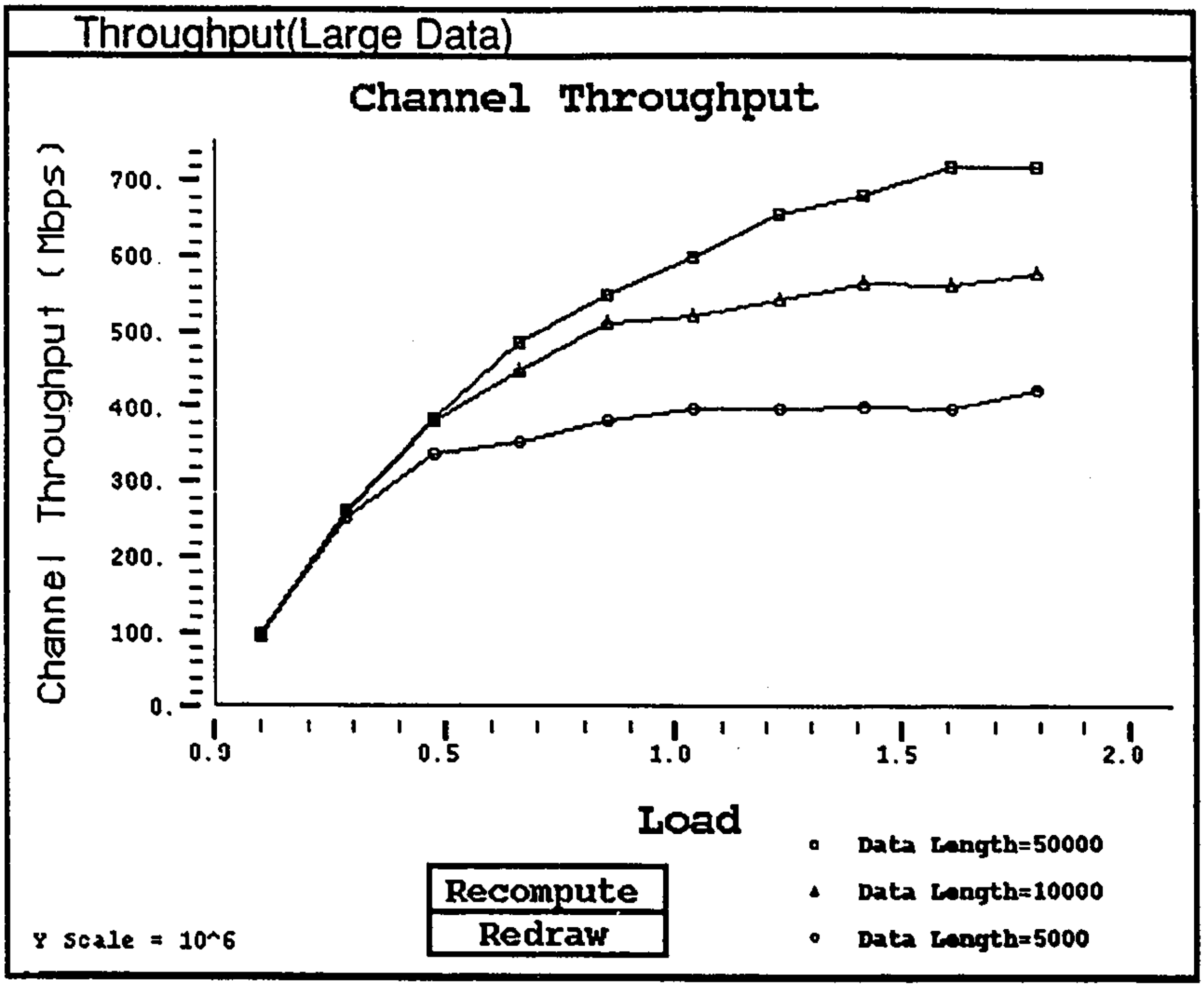


Figure 4.19: Channel throughput vs. channel traffic load

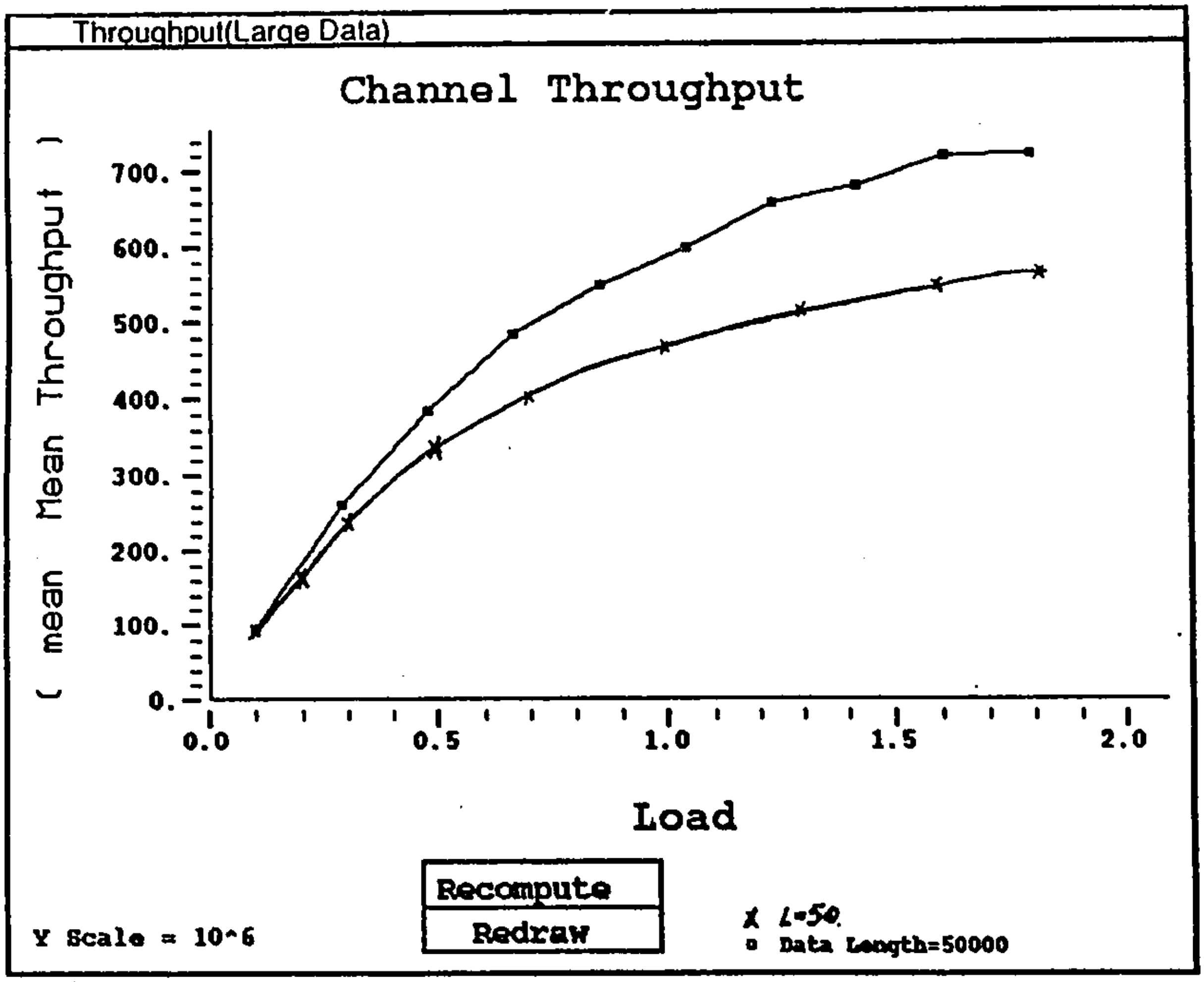


Figure 4.20: Channel throughput comparison

N = 5 and L =5, 10, and 50 in our previous work. From Fig.4.21, we find that the simulation results roughly match the theoretical analysis and we get even better performance than those by theoretial studies. The difference in results is due to three points discussed above and the fact that in theoretical analysis we always consider the worst case. Because of the introduction of the backoff mechanism, the packets which have retransmission numbers exceed the backoff limit will be discarded and their statistics will not be recorded, the Throughput vs Load and the Delay vs Load characteristics are not quite smooth under heavy channel traffic loads. But in any case, the maximum channel throughput is limited by

$$Maximum\ channel\ throughput \leq \frac{Data\ packet\ frame\ time \times Transmission\ speed}{Slot\ time + Data\ packet\ frame\ time}. \quad (4.3)$$

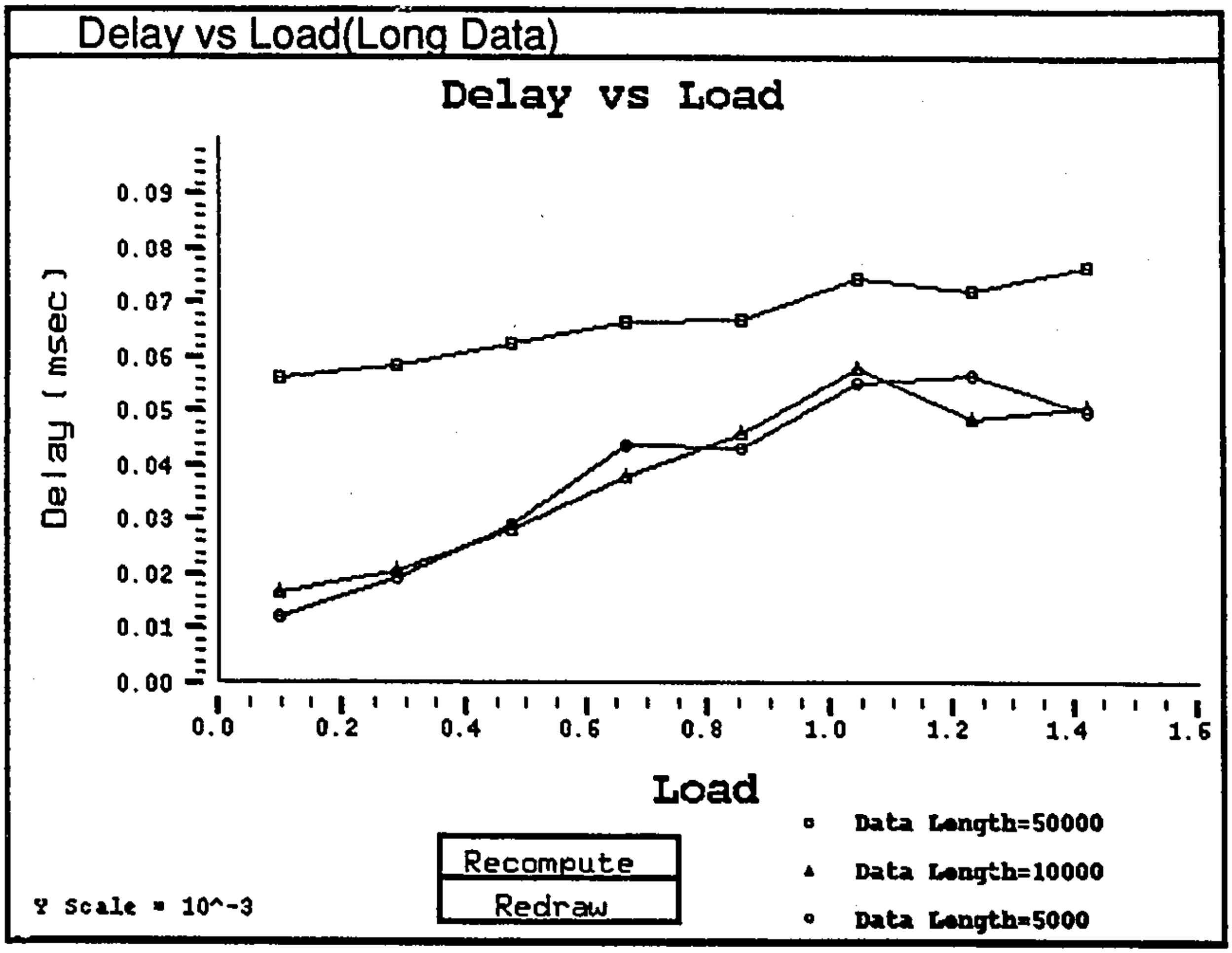


Figure 4.21: Delay vs. channel traffic load

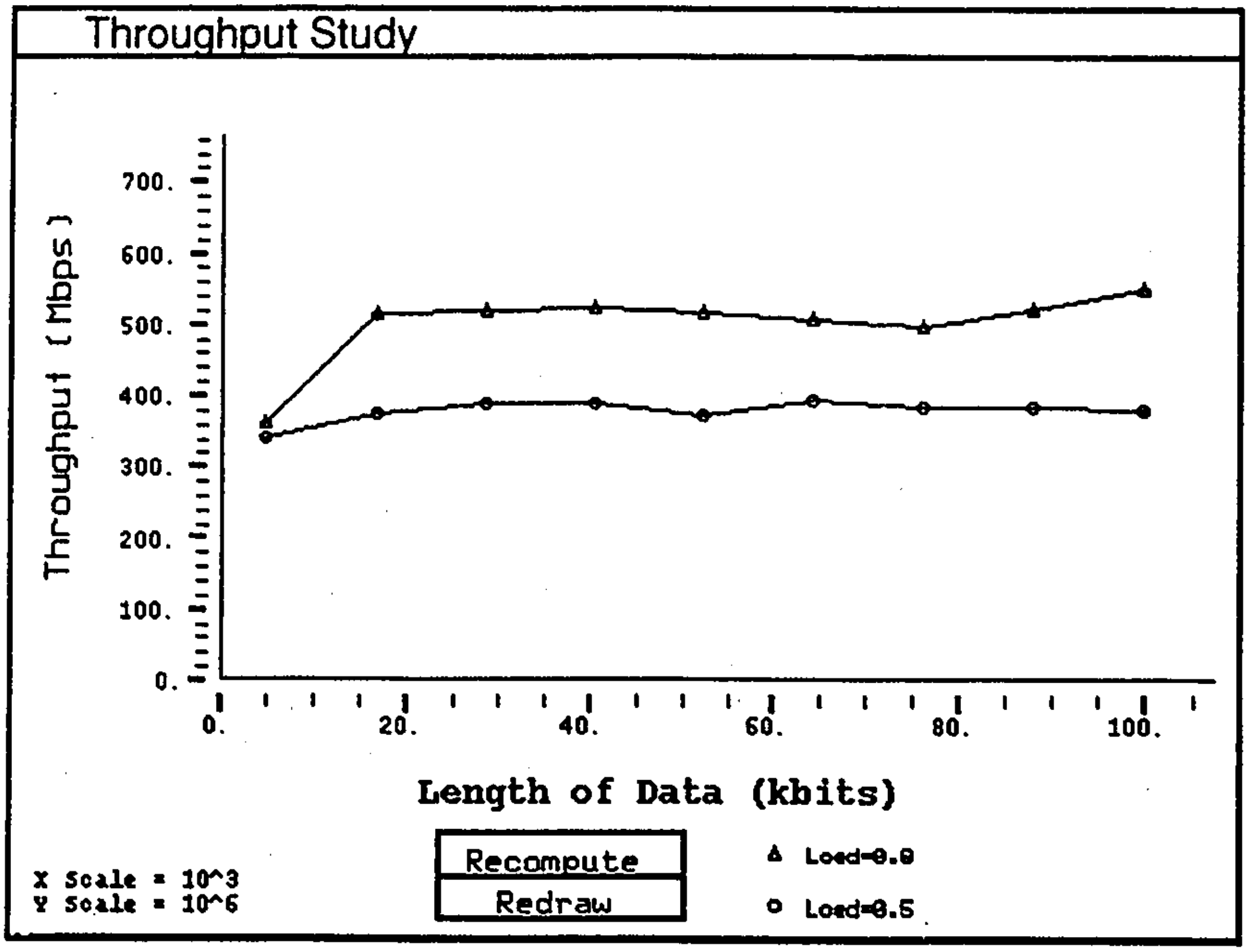


Figure 4.22: Channel throughput vs. data packet length

Channel throughput vs. data packet length

The simulation results of the Throughput vs Data packet length at different channel load values are presented in Fig.4.22. It shows that for the data packet length ≥ 20000 bits, the channel utilizations are almost the same. We should choose the data packet length as short as possible to meet certain throughput requirements in order to save the buffer space at the receiver end.

Collision Study

Fig.4.23 shows a histogram of the data packet collision percentage at different channel loads. Data packets under channel loads 0.2, 0.5, and 0.8 are studied. It can be seen that the less the channel traffic load, the larger the percentage of data

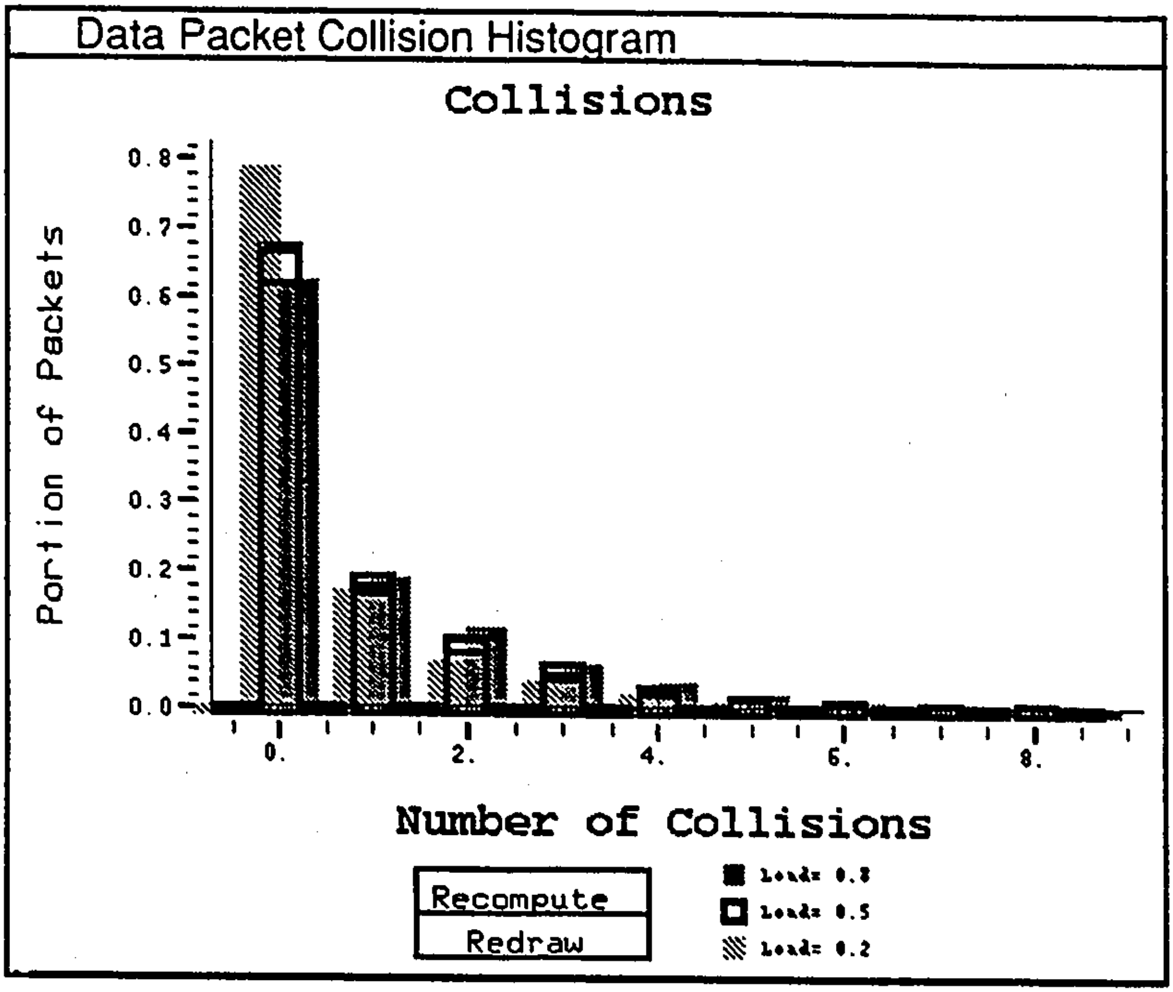


Figure 4.23: Data Packet Collision Histogram

packets that get through the data channel at the first attempt. Note that, 60-80% of the data packets are successful on the first attempt for the studied load range. Most of the data packets under study pass the data channels sucessfully before the fifth attempt. This result is quite satisfactory.

4.6 Concluding Remarks

The simulations of the ALOHA/Slotted-CSMA model is limited by the detailed procedural model of the protocol which is being used. This model is appropriate for modeling of medium size networks in details, and for evaluating variations to the protocol parameters and procedures and to give the readers a good understanding. However, for the simulations of large LANs, it is not an appropriate model because it is too detailed (reflects every procedure in network transmission), would require much simulation time and would only need to model the lower layers of the protocol. For large networks or an internetworking study, a simpler model which only uses the necessary modules will save much time.

In this chapter, computer simulation results are presented for an ALOHA/Slotted-CSMA protocol for a very high-speed optical LAN interconnected by a passive star coupler. Tunable transmitters and receivers which are capable of tuning to $N+1$ wavelengths are required to get cross-connected via a passive optical star coupler to the other users of the network. Pretransmission coordination is always needed in this WDM local area network and can be done easily by sending a control packet over the control channel to the reference receiver before the actual data transmission starts. The control packet usually contains the sender address, destination address and the selected data channel number. The headers added by the upper layers may occupy the remaining bits of the control packet to make efficient use of channel capacity. Since the random access protocols are used on both control and data channels, the collided packets must be retransmitted according to the binary exponential backoff mechanism.

The main improvement in our protocol is the transmission of a data packet based on a successful transmission of its own control packet. Bandwidth is saved by eliminating the case that a data packet is still transmitted over a data channel while its control packet has already been lost due to a control packet collision. Also because the users which do not sense the idle channels will not generate the control packets and cause unnecessary control channel collisions. Another advantage is that the tunable receiver can tune its receive wavelength to the selected data channel during the transmission time of the data packet destined for it and asks for less overhead. The simulation results show that a better channel utilization is achieved. It is also more cost effective because of simplifying the node structure. If the transmission speed is in the range of 100 $Mbits/sec$ to 1 $Gbits/sec$, the optical LAN may have a diameter of 0.6–6 km.

Chapter 5

Concluding Remarks and Suggestions for Further Study

5.1 Concluding Remarks

The demand for highly-efficient high-speed communication networks in local and metropolitan environments is opening new research horizons. High bandwidth, as well as a suitable topology and protocols are needed to support different types of traffic (data, voice, video, etc.). In addition, real time traffic, i.e. voice, and video require low average and variance of packet delay. The requested high bandwidth can be met by either increasing the data rate, or alternatively using parallel channels. The last case is a practical approach to high bandwidth networking based on wavelength division multiplexing, in which multiple simultaneous channels operate independently at different preassigned optical wavelengths. Wavelength division multiplexing (WDM) provides a powerful means to solve the electro-optic bottleneck and offer significant opportunities for ultra high-speed networks. This has led to the development of a new generation of LANs and MANs, based on passive and tunable optical components and WDM techniques. The key components of a WDM network are:

- Passive optical elements, including couplers, splitters, and combiners;
- Wavelength division multiplexing means, namely tunable lasers, detectors, filters, and wavelength switches;

- Network management, multiaccess protocols are needed to match the data transmission speed of optical communication technology.

In this thesis, we first reviewed existing optical network topologies, access methods, and protocols. Power divisional and electronics bottleneck are two basic problems in optical LANs. We reviewed the multihop and WDM techniques which were proposed to solve those two problems and analyzed the advantages and disadvantages of them. We then proposed the ALOHA/Slotted-CSMA protocol for a very high-speed optical LAN interconnected by a passive star coupler. The network performance based on channel throughput and delay characteristics are analyzed and the numerical results are given. Comparisons are made with the other protocols based on the same network architecture.

Finally, a detailed network modeling and modifications are given. A computer simulation program was developed to simulate the performance of the ALOHA/Slotted-CSMA protocol and the comparison was made between the simulation and analytical results.

The main improvement in our protocol is the transmission of a data packet based on a successful transmission of its own control packet. Bandwidth is saved by eliminating the case that a data packet is still transmitted over a data channel while its control packet has already been lost due to a control packet collisions. In proposed protocol, only the users which find idle data channels will transmit their control packets on the control channel, this will not cause unnecessary increase of control channel traffic. The other advantage is that the tunable receiver can tune its receive wavelength to the selected data channel during the transmission time of the data packet destined for it and asks for less overhead. The numerical results for different values of wavelength number, propagation delay time and data packet length were presented. It is shown that for the heavy traffic conditions, our protocol achieves a higher throughput and it causes much less delay for a reasonable range of system parameters.

To implement the protocol presented here in a star network, each user needs only one tunable/agile transceiver and does not need to jam the data channel for one control packet frame time after sensing it idle, as proposed in [47].

The simulation results show a better channel utilization is achieved. A total of 60–80% of the data packets are successful on the first attempt for the load range of 0.2-0.8. Most of the data packets under study pass the data channels successfully before the fifth attempt. The results are quite satisfactory.

5.2 Further Research Suggestions

In our work, we do not consider the receiver collisions, since the protocols discussed here are at the low levels of data network protocol hierarchy. In future research, higher level protocols will be developed and will take care of receiver collision problem. Other network architectures, protocols and even interconnections for the optical networks may be other interesting topics.

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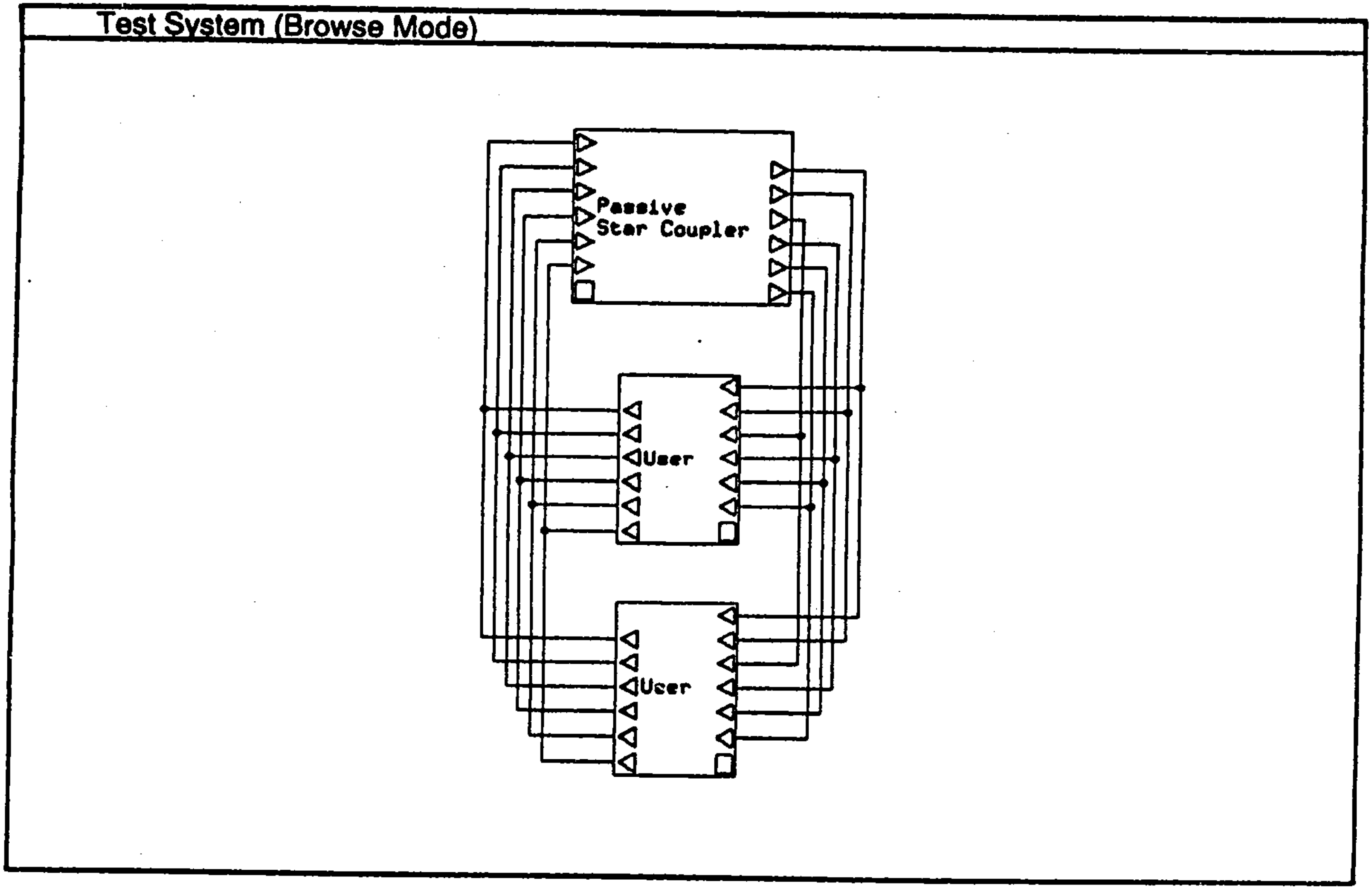
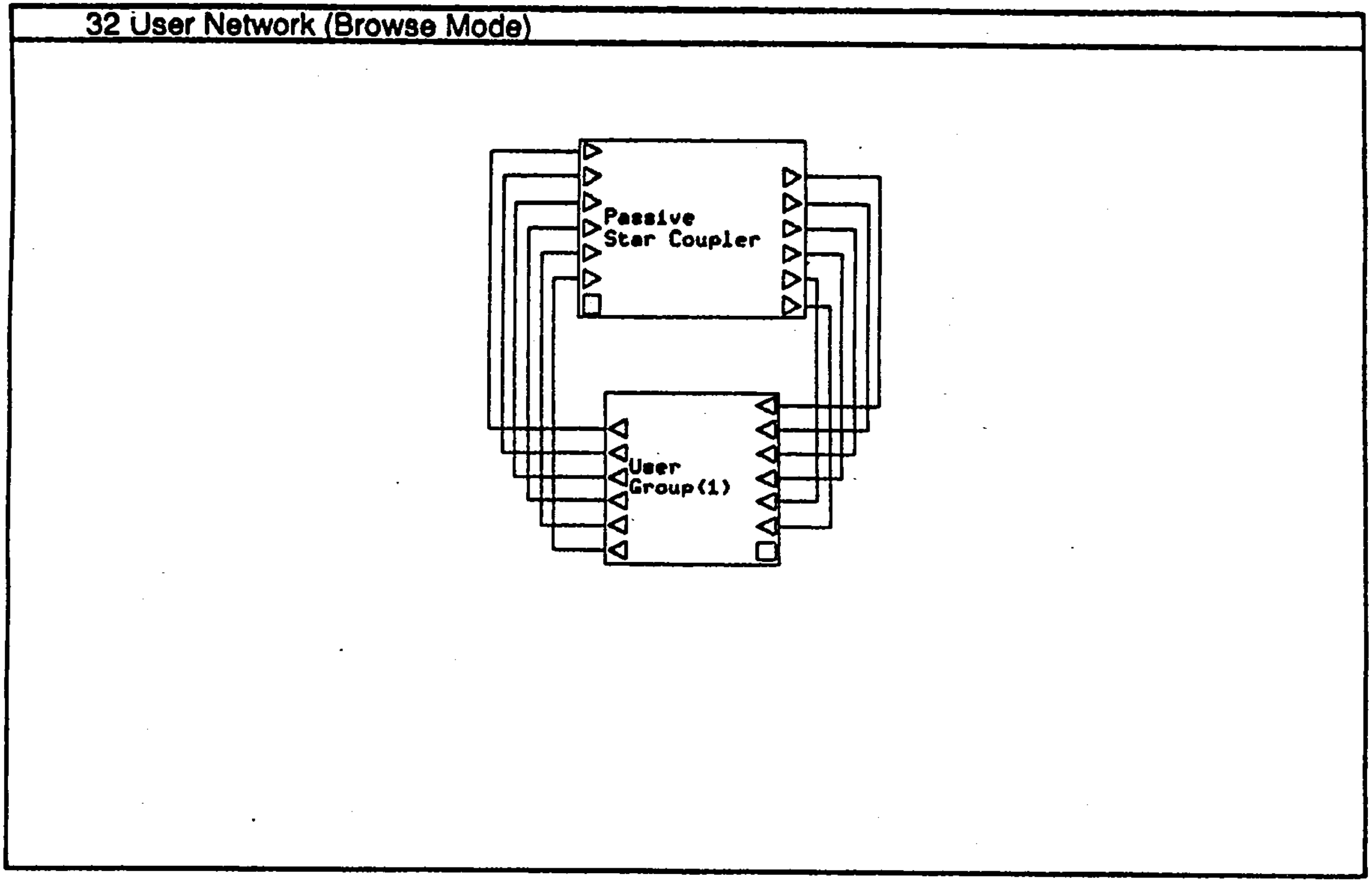
dian Conference on Electrical and Computer Engineering, pp 60.3.1-60.3.4, Quebec, Canada, September 1991.

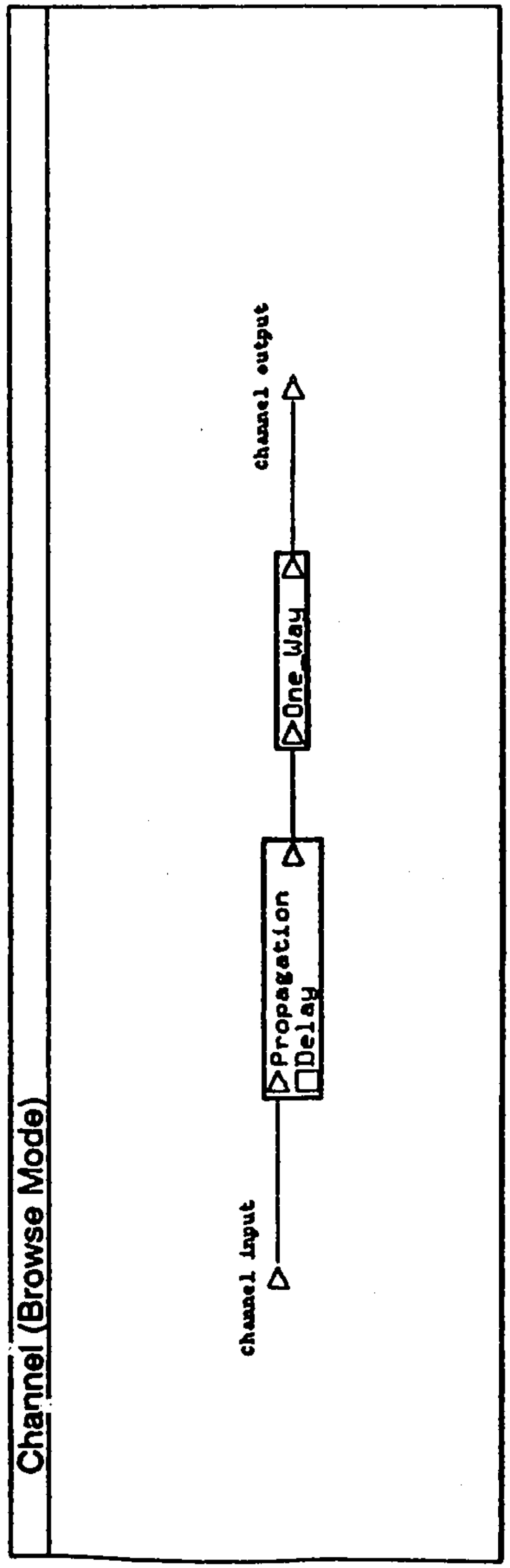
Appendices

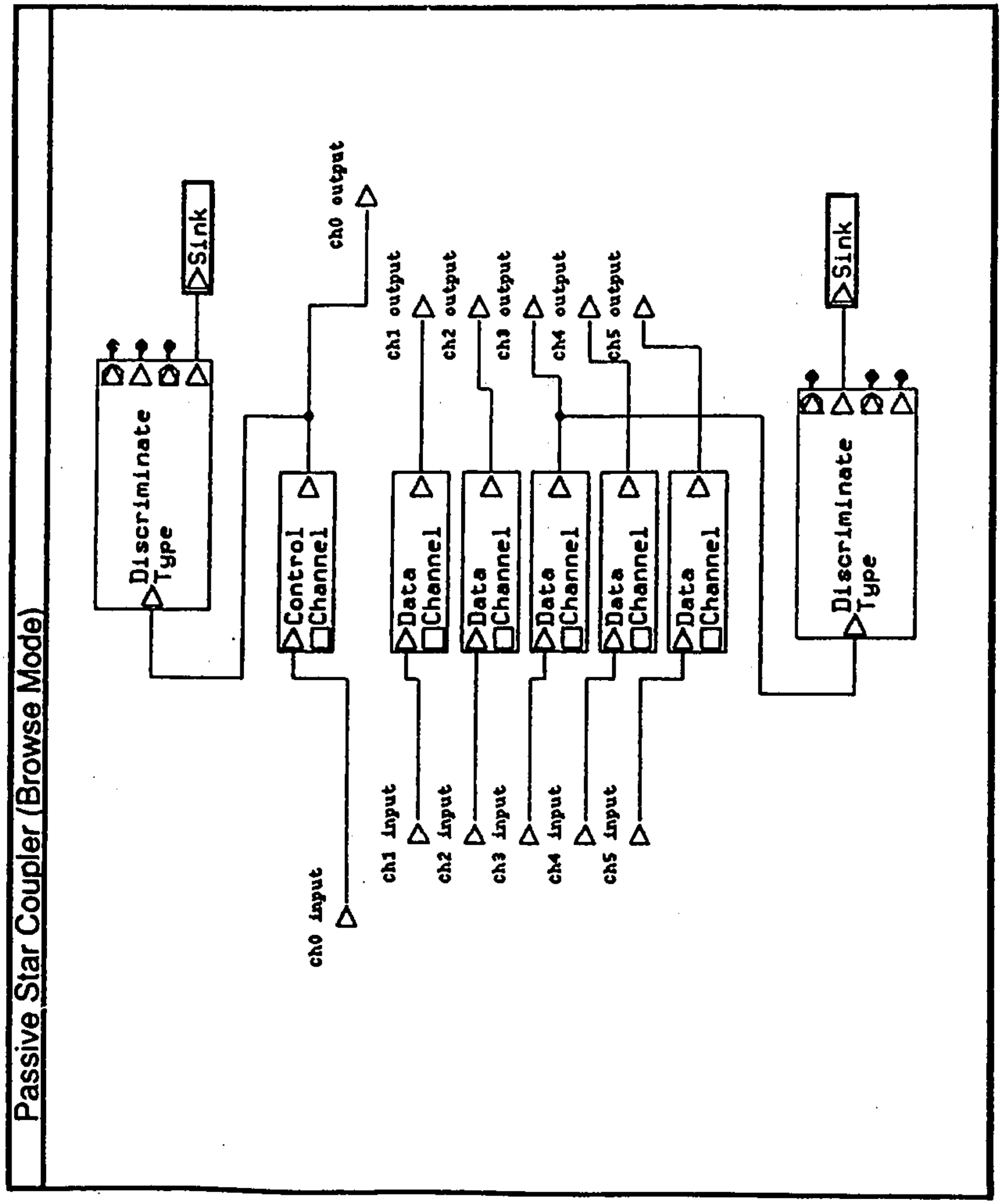
Appendix A

BONeS Modules

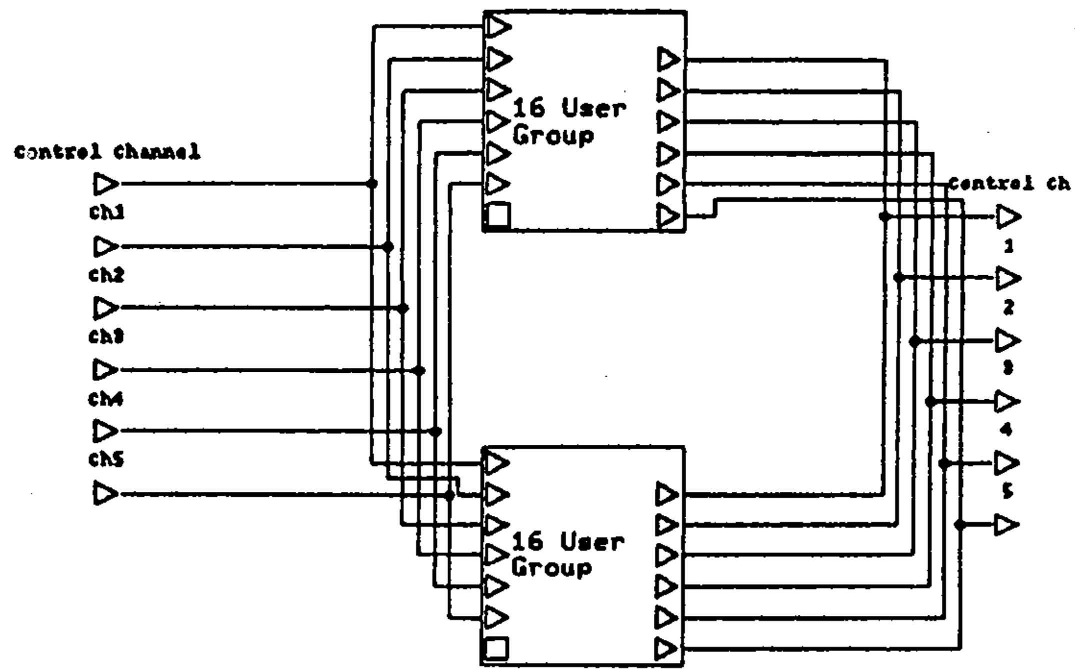

Test System (Browse Mode)
Passive
Star Coupler
User
User


32 User Network (Browse Mode)
Passive
Star Coupler
User
Group(1)

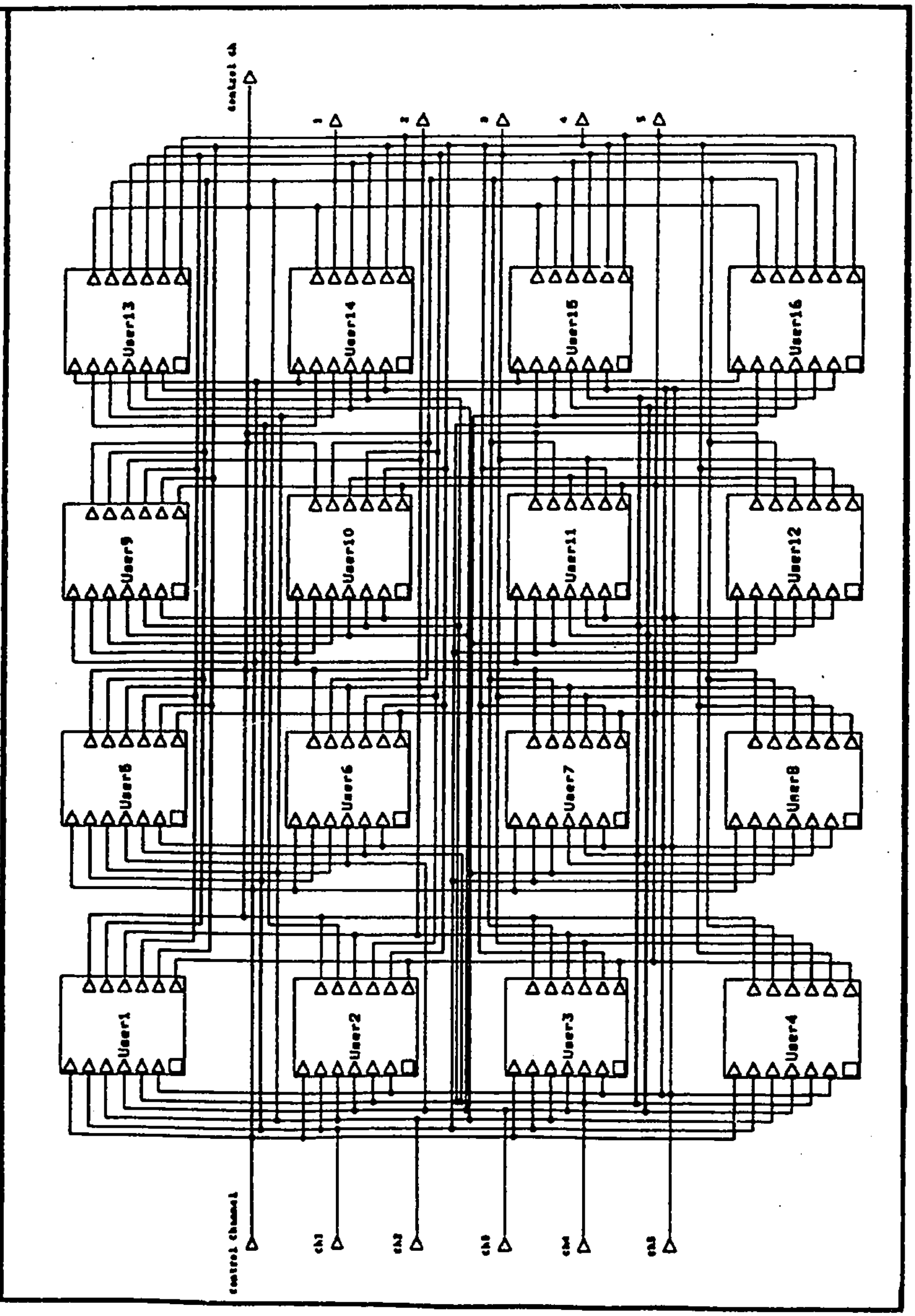

Channel (Browse Mode)
channel input
Propagation
Delay
One_Way
channel output

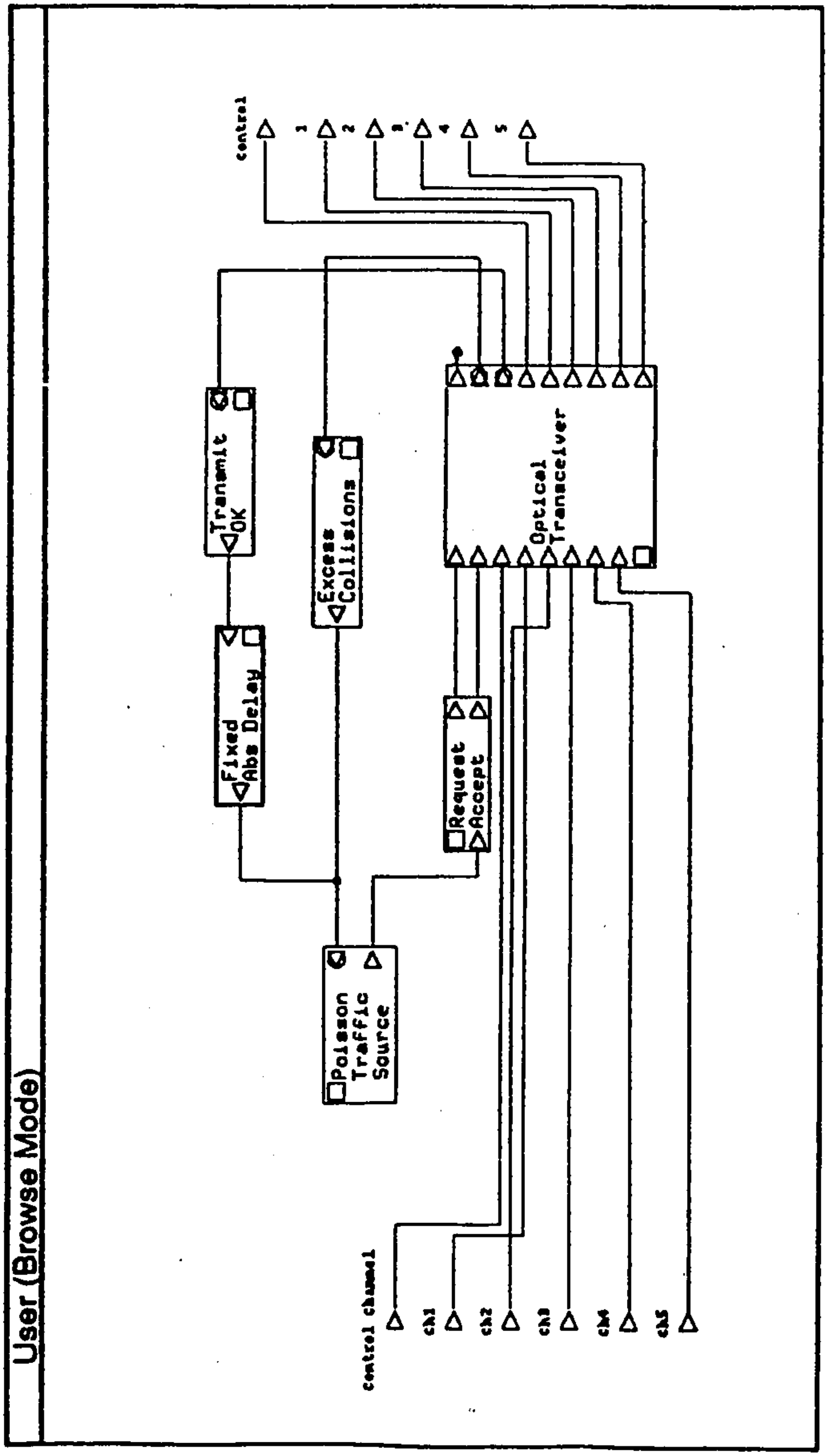

Passive Star Coupler (Browse Mode)
Discriminate Type
Sink
Control Channel
Data Channel
Data Channel
Data Channel
Data Channel
Data Channel
Discriminate Type
Sink
ch0 output
ch1 output
ch2 output
ch3 output
ch4 output
ch5 output
ch0 input
ch1 input
ch2 input
ch3 input
ch4 input
ch5 input

32 User Group(1) (Browse Mode)

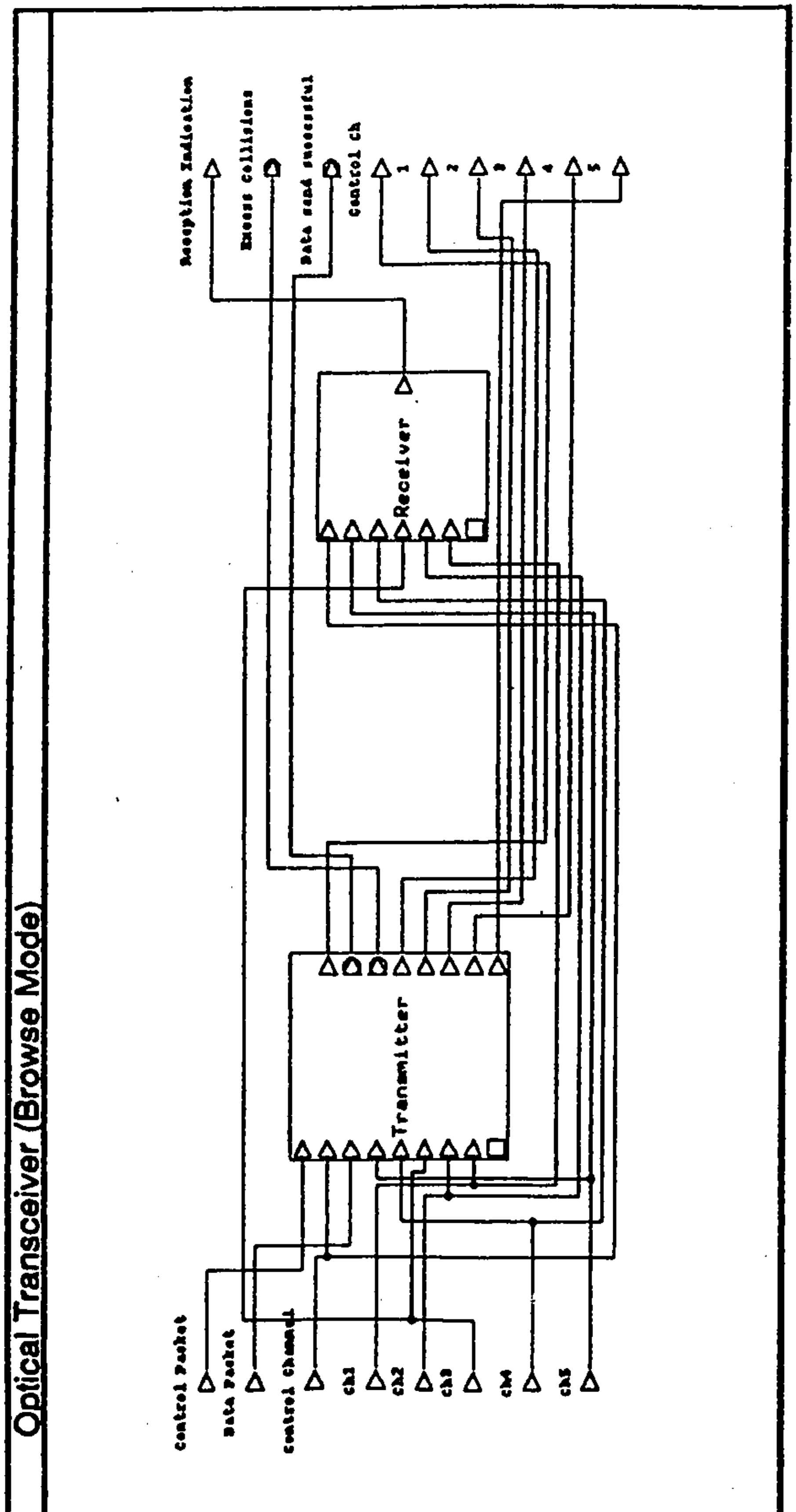


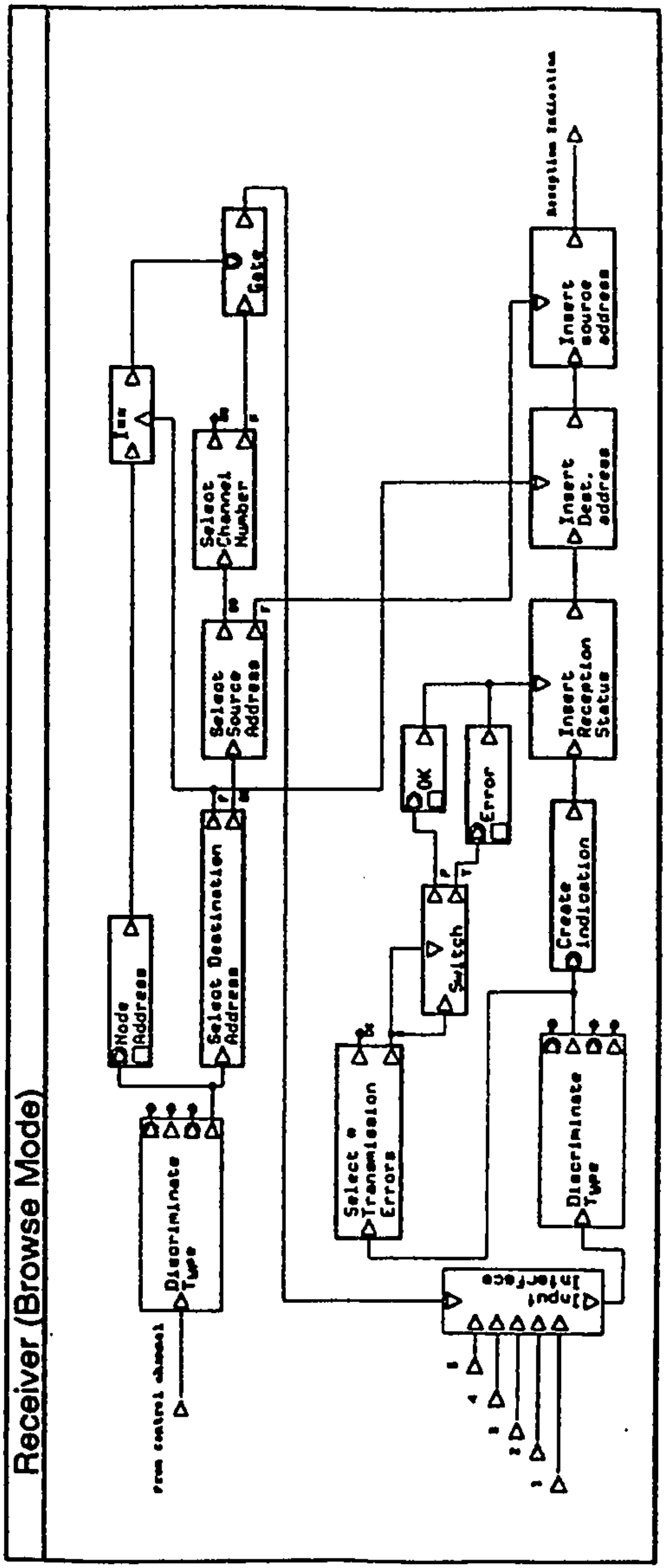
16 User Group (Browse Mode)



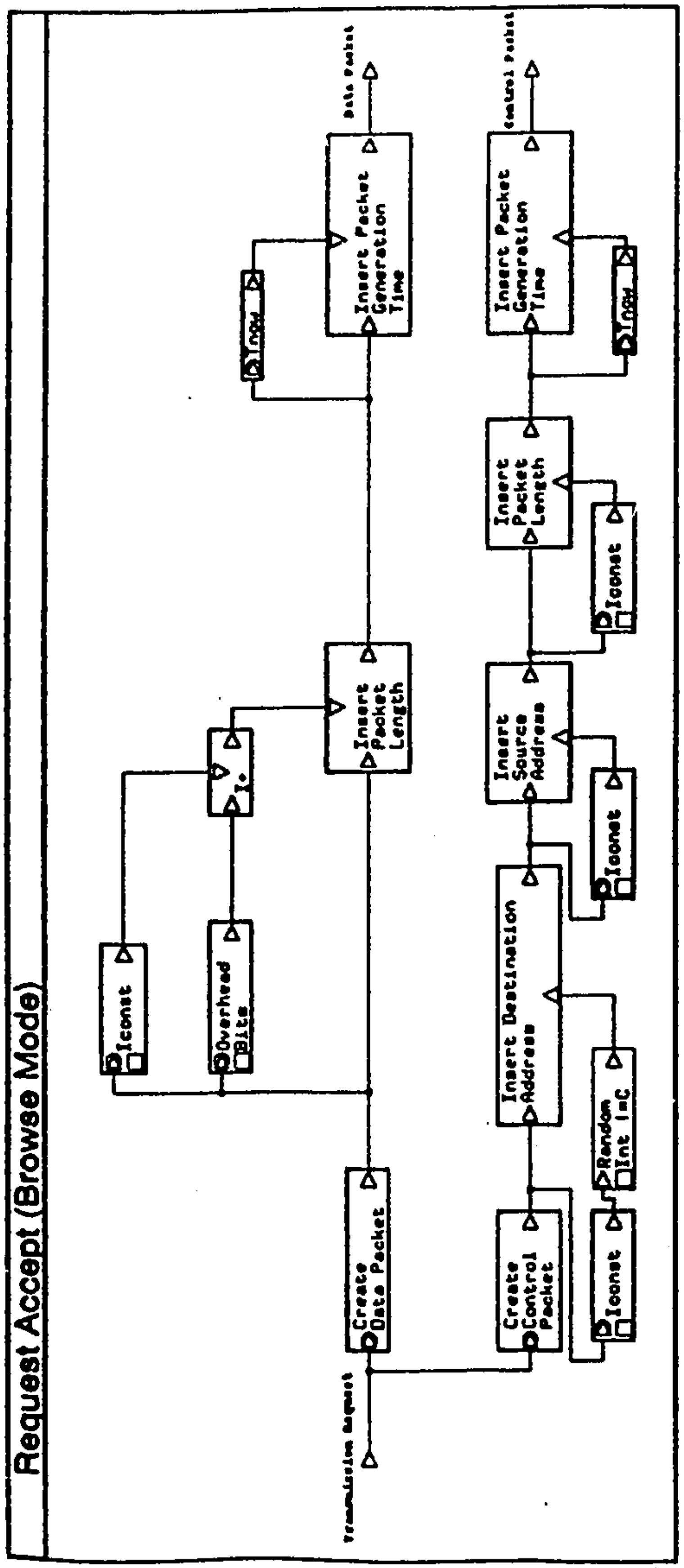


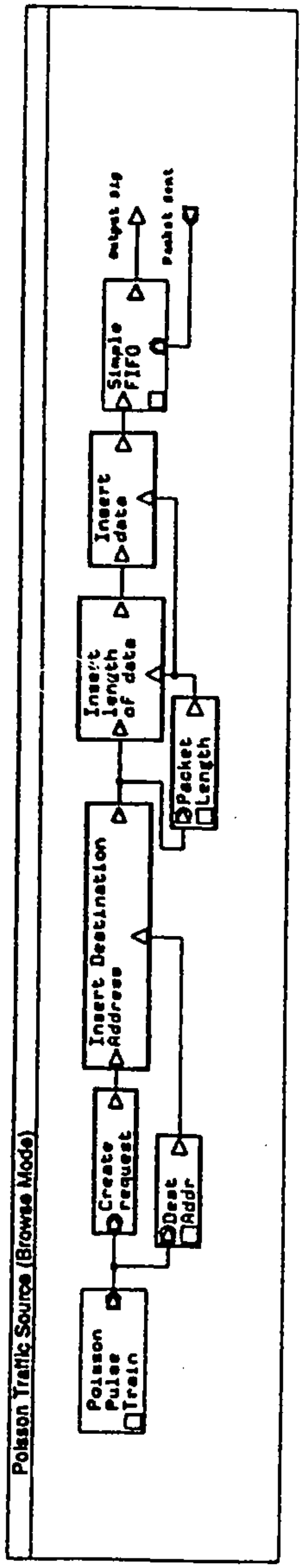
User (Browse Mode)
control
1
2
3
4
5
Transmit OK
Excess Collisions
Optical Transceiver
Fixed Abs Delay
Request Accept
Poisson Traffic Source
control channel
ch1
ch2
ch3
ch4
ch5

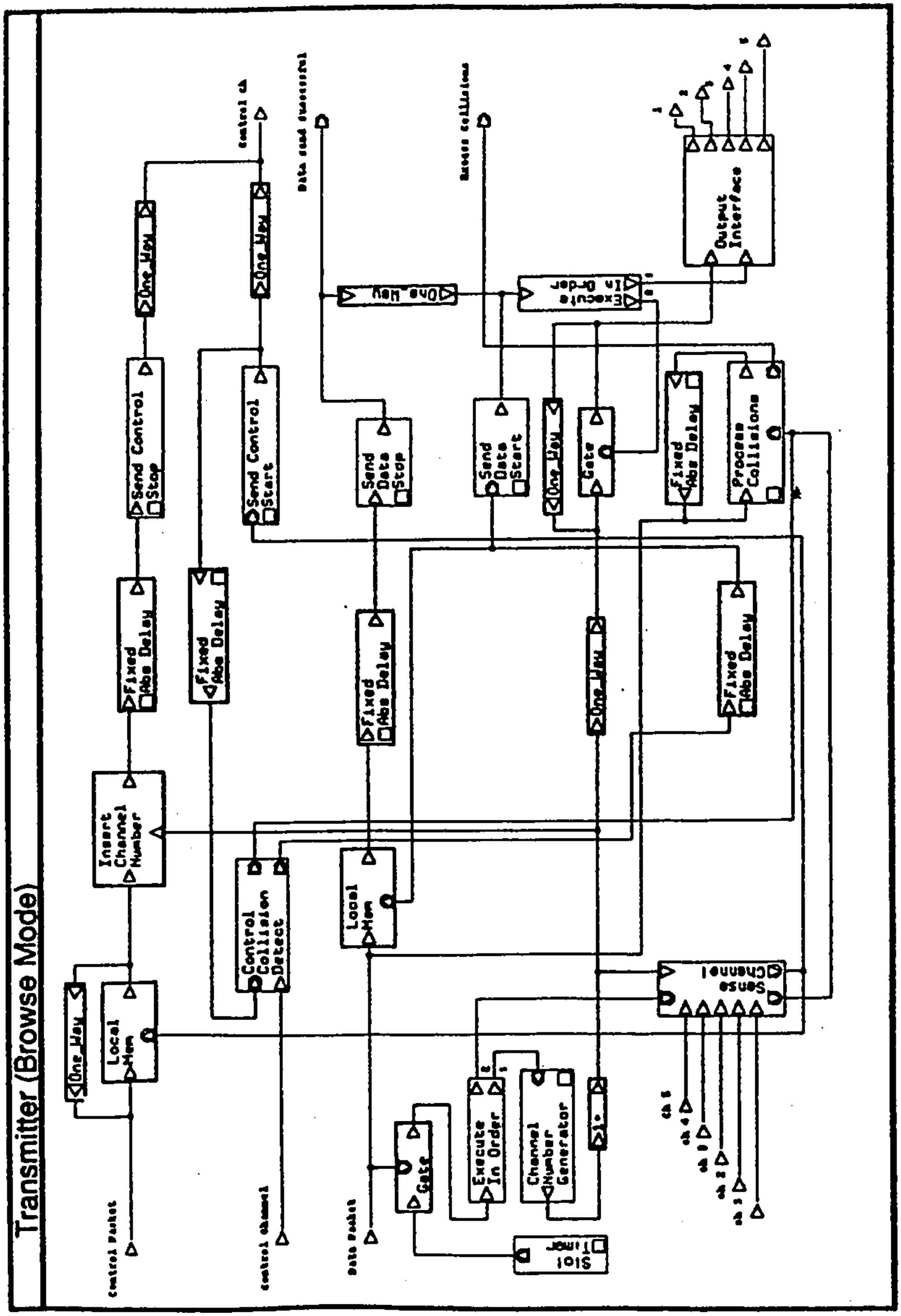

Optical Transceiver (Browse Mode)
Control Packet
Data Packet
Control Channel
ch1
ch2
ch3
ch4
ch5
Transmitter
Receiver
Reception Indication
Excess collisions
Data send successful
Control ch
1
2
3
4
5

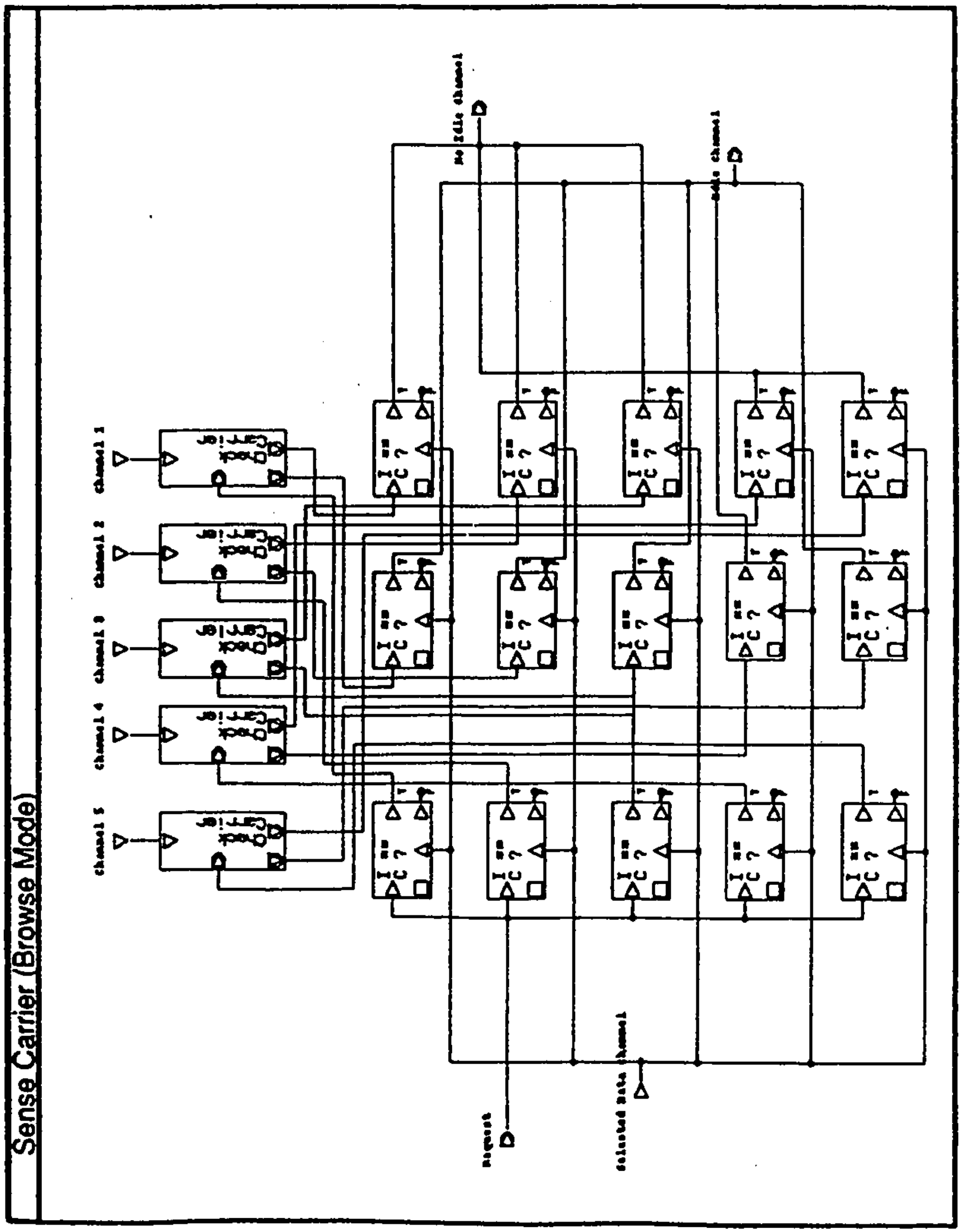


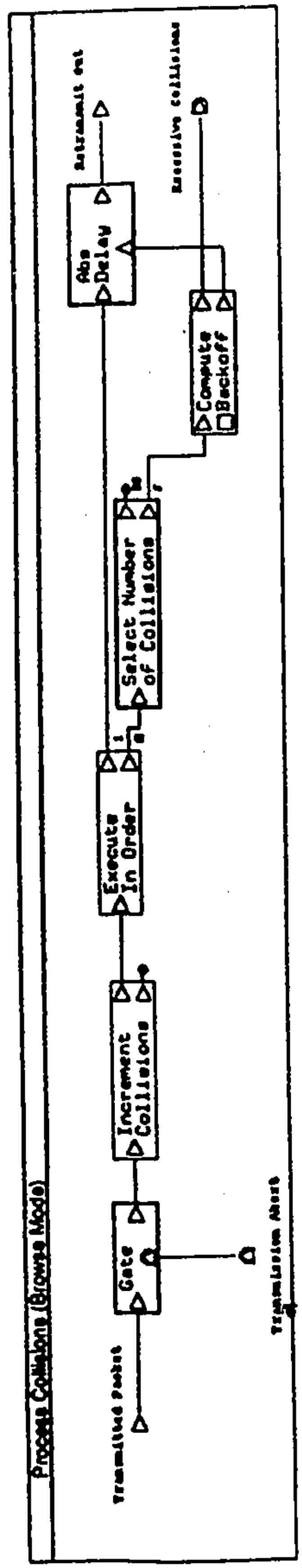
Receiver (Browse Mode)
from control channel
Discriminate Type
Node Address
Select Destination Address
Select Source Address
Select Channel Number
Gate
Select
Transmission
Errors
Switch
OK
Error
Create Indication
Discriminate Type
Input Interface
Insert Reception Status
Insert Dest. address
Insert source address
Reception Indication
1
2
3
4
5

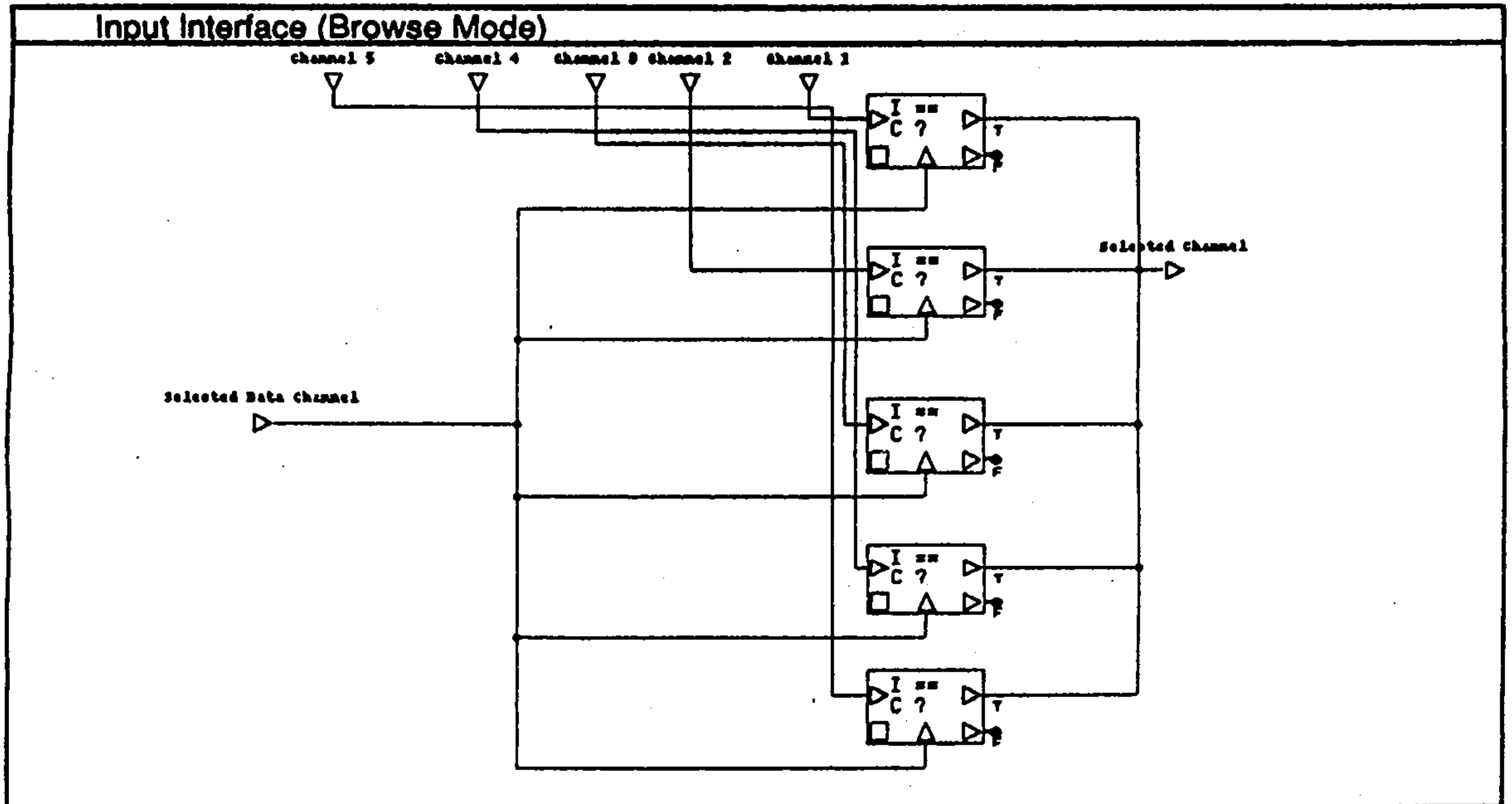

Request Accept (Browse Mode)
Create Data Packet
Iconst
Overhead Bits
Insert Packet Length
Insert Packet Generation Time
Tnow
Data Packet
Create Control Packet
Iconst
Random Int InC
Insert Destination Address
Iconst
Insert Source Address
Iconst
Insert Packet Length
Insert Packet Generation Time
Tnow
Control Packet


Poisson Traffic Source (Browse Mode)
Poisson Pulse Train
Create request
Dest Addr
Insert Destination Address
Packet Length
Insert length of data
Insert data
Simple FIFO

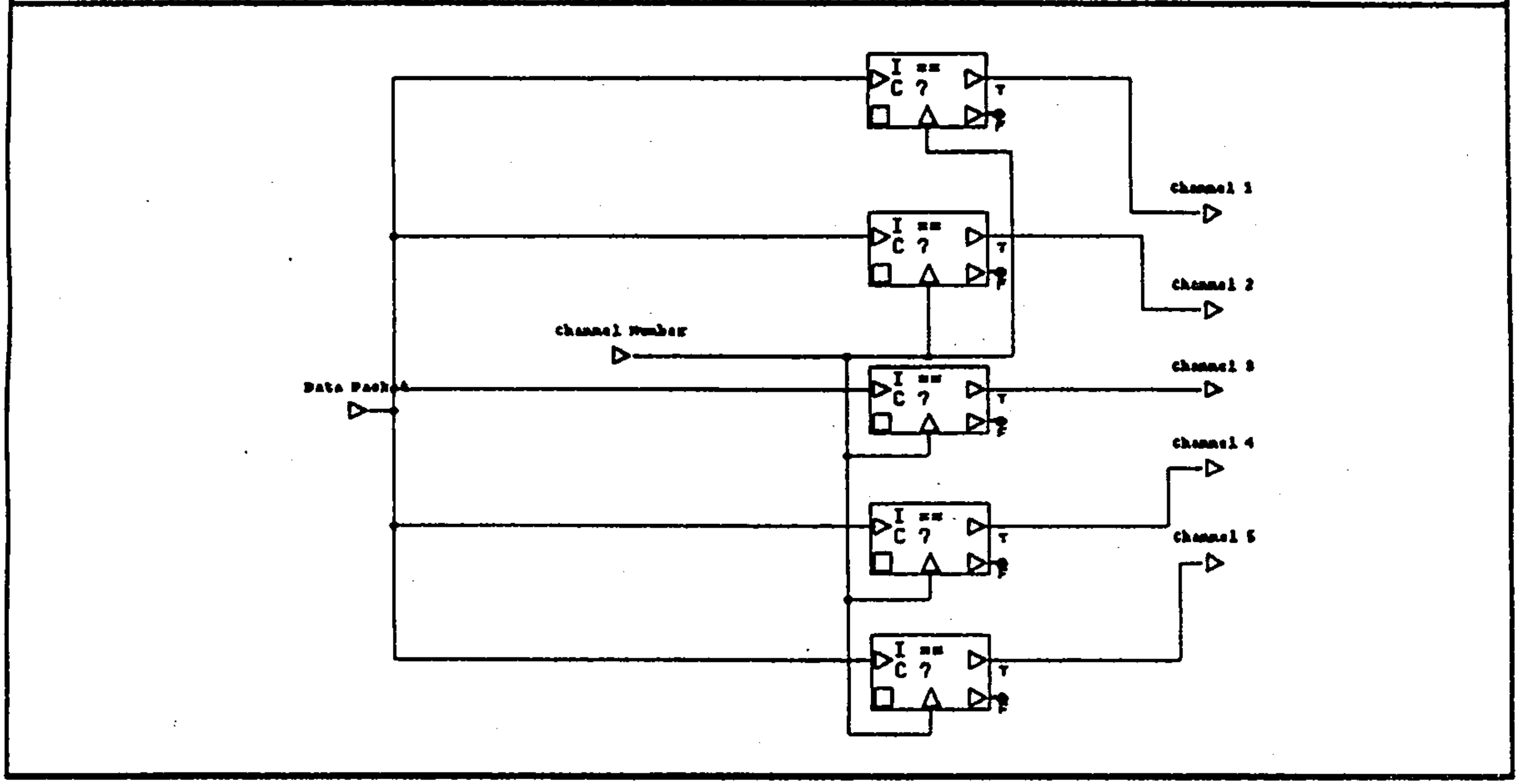

Transmitter (Browse Mode)
Control Packet
Control channel
Data Packet
Local Mem
One Way
Insert Channel Number
Control Collision Detect
Fixed Abs Delay
Send Control Stop
Send Control Start
Send Data Stop
Send Data Start
Gate
Execute In Order
Channel Number Generator
Slot Timer
Sense Channel
Process Collisions
Output Interface
Control ch
ch 1
ch 2
ch 3
ch 4
ch 5

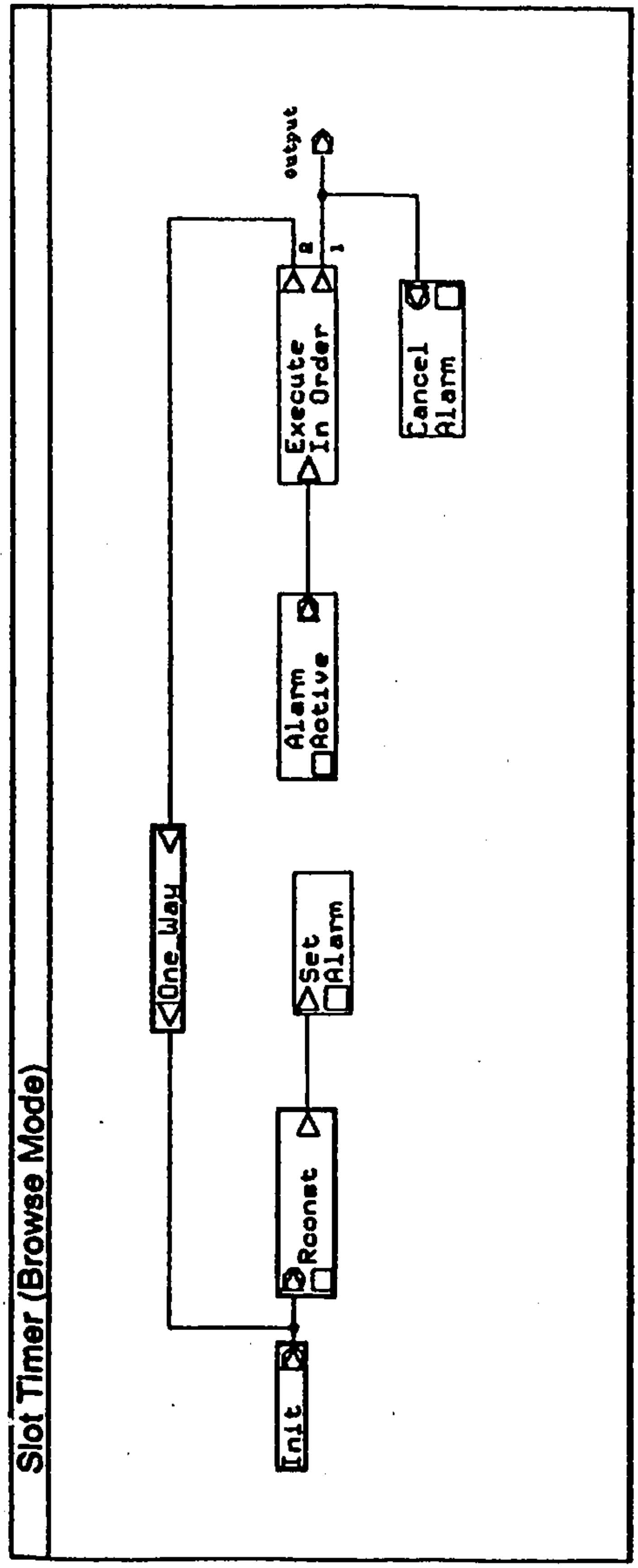

Sense Carrier (Browse Mode)
channel 1
channel 2
channel 3
channel 4
channel 5
Request

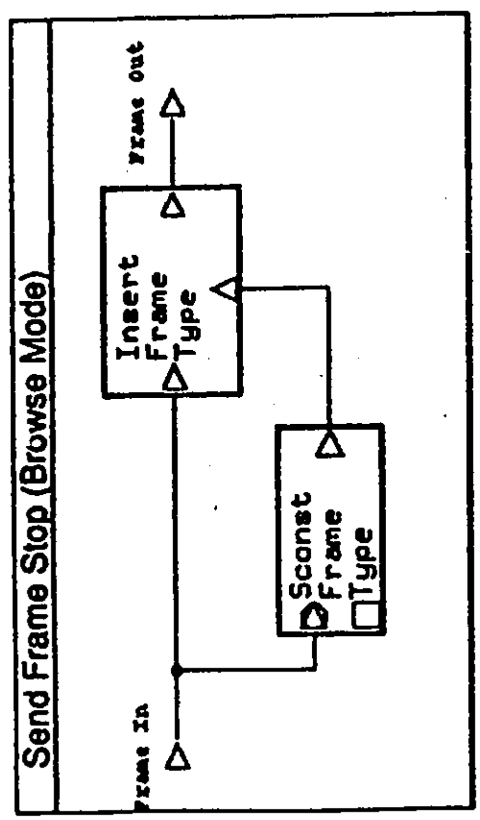

Process Collisions (Browse Mode)
Transmitted Packet
Gate
Transmission Abort
Increment Collisions
Execute In Order
Select Number of Collisions
Compute Backoff
Abs Delay
Retransmit out
Excessive collisions

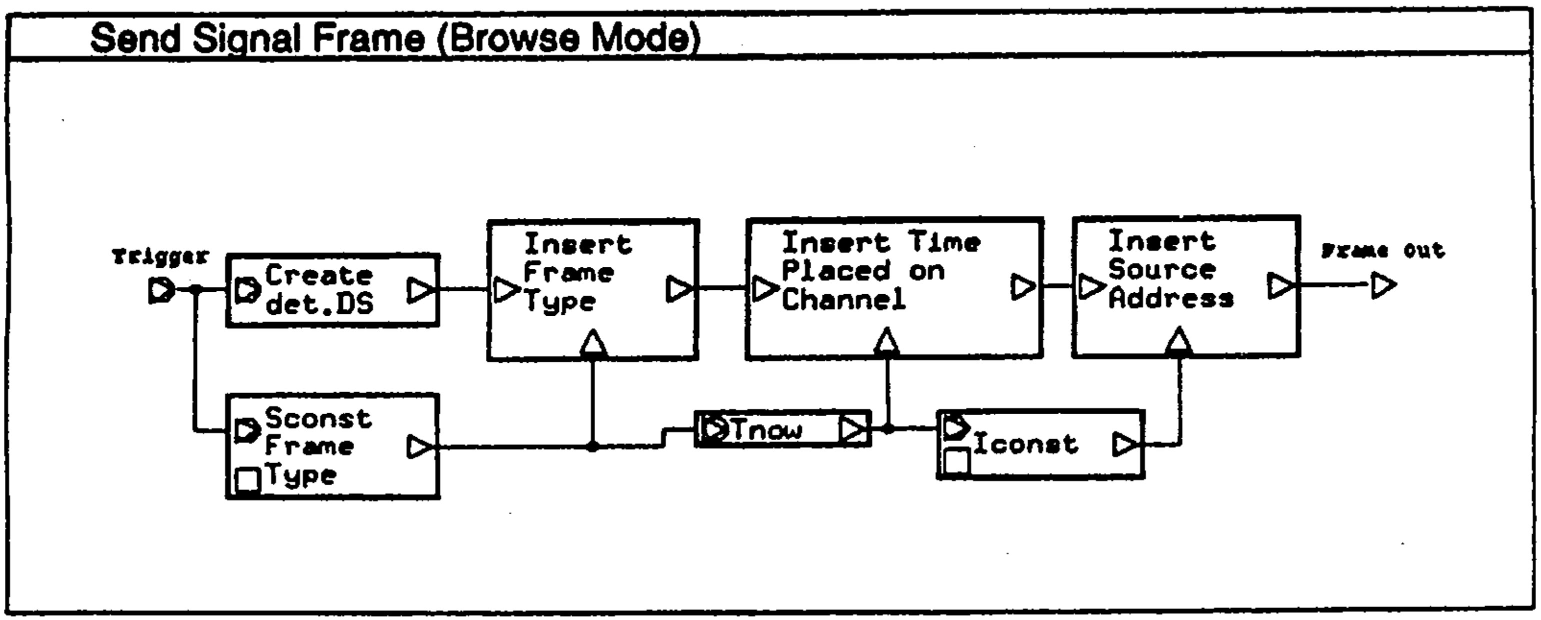

Input Interface (Browse Mode)
Channel 5
Channel 4
Channel 3
Channel 2
Channel 1
Selected Channel
Selected Data Channel

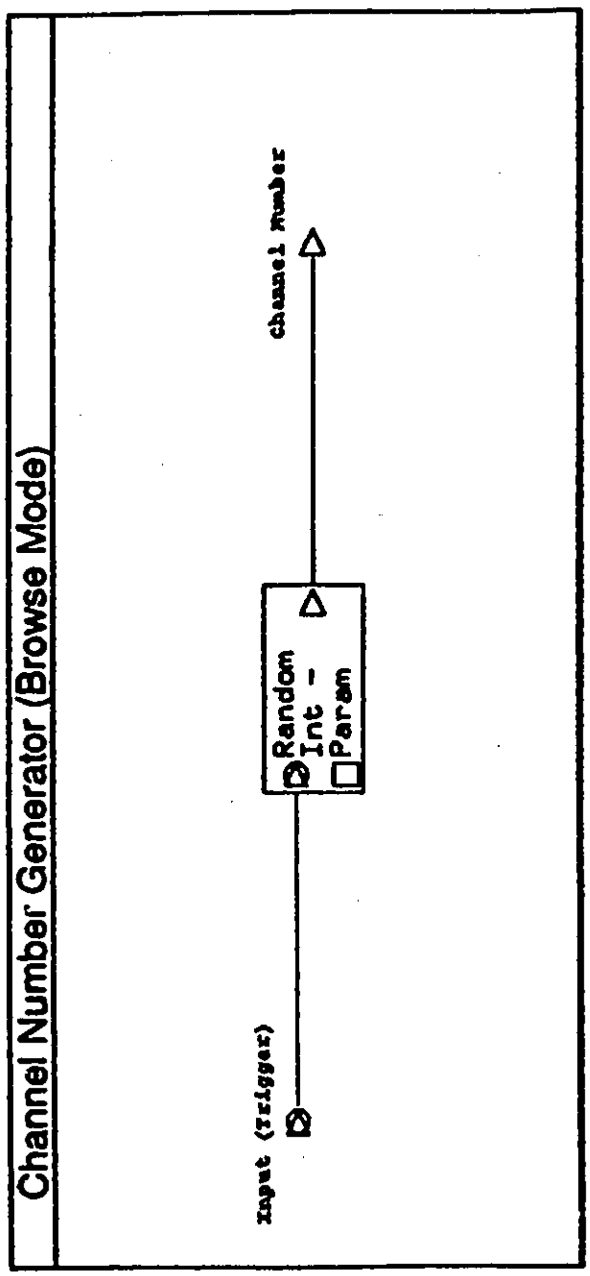
Output Interface (Browse Mode)

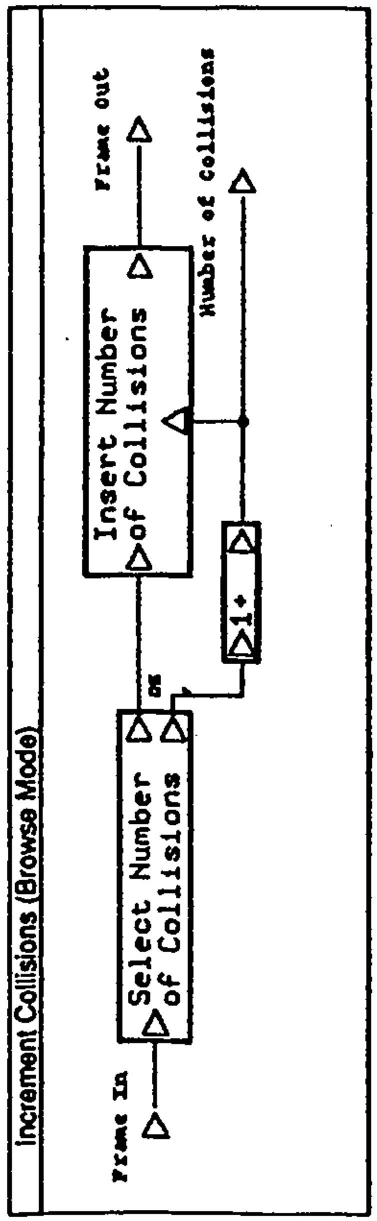


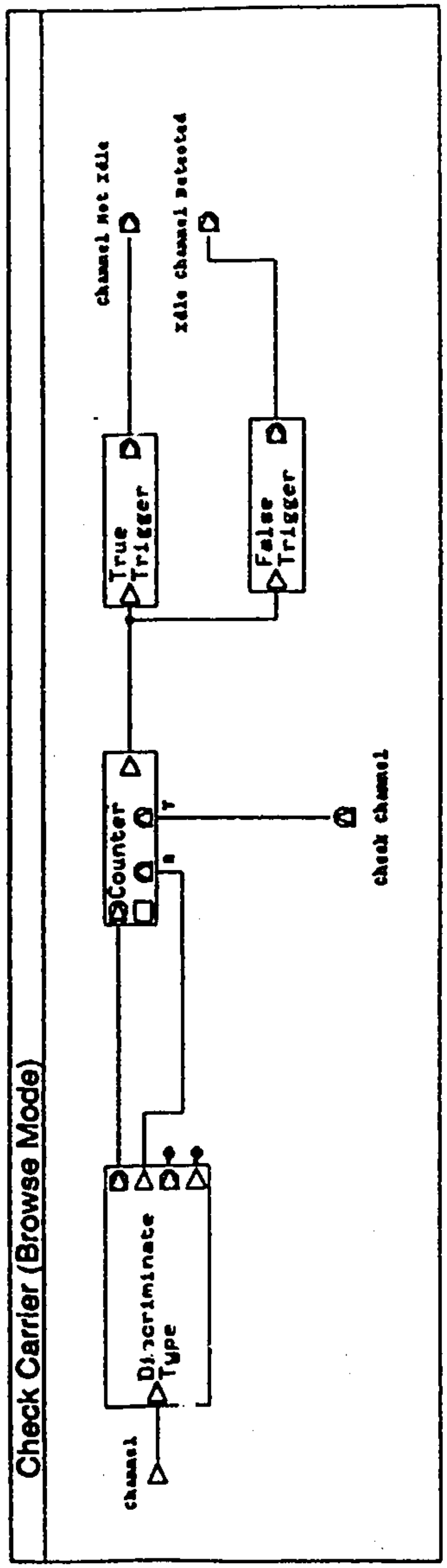

Slot Timer (Browse Mode)
Init
Rconst
Set Alarm
One Way
Alarm Active
Execute In Order
Cancel Alarm
output
2
1

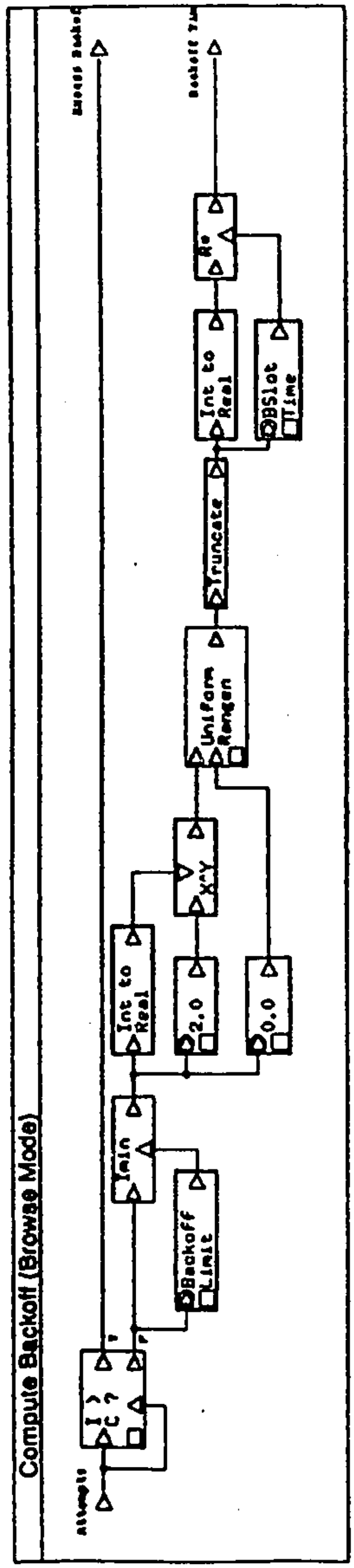

Send Frame Stop (Browse Mode)
Frame In
Frame Out
Insert Frame Type
Sconst Frame Type

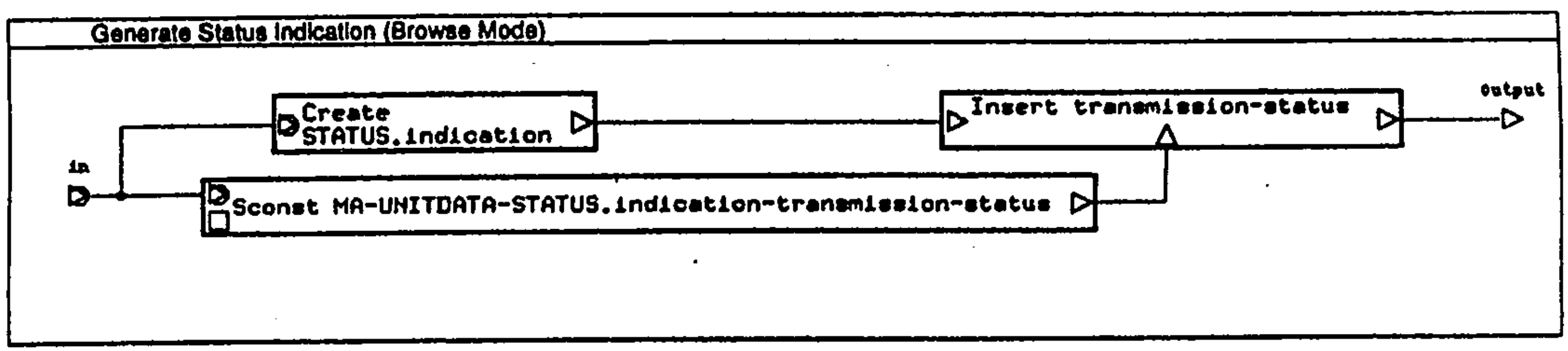

Send Signal Frame (Browse Mode)
Trigger
Create det.DS
Sconst Frame Type
Insert Frame Type
Tnow
Insert Time Placed on Channel
Iconst
Insert Source Address
Frame out

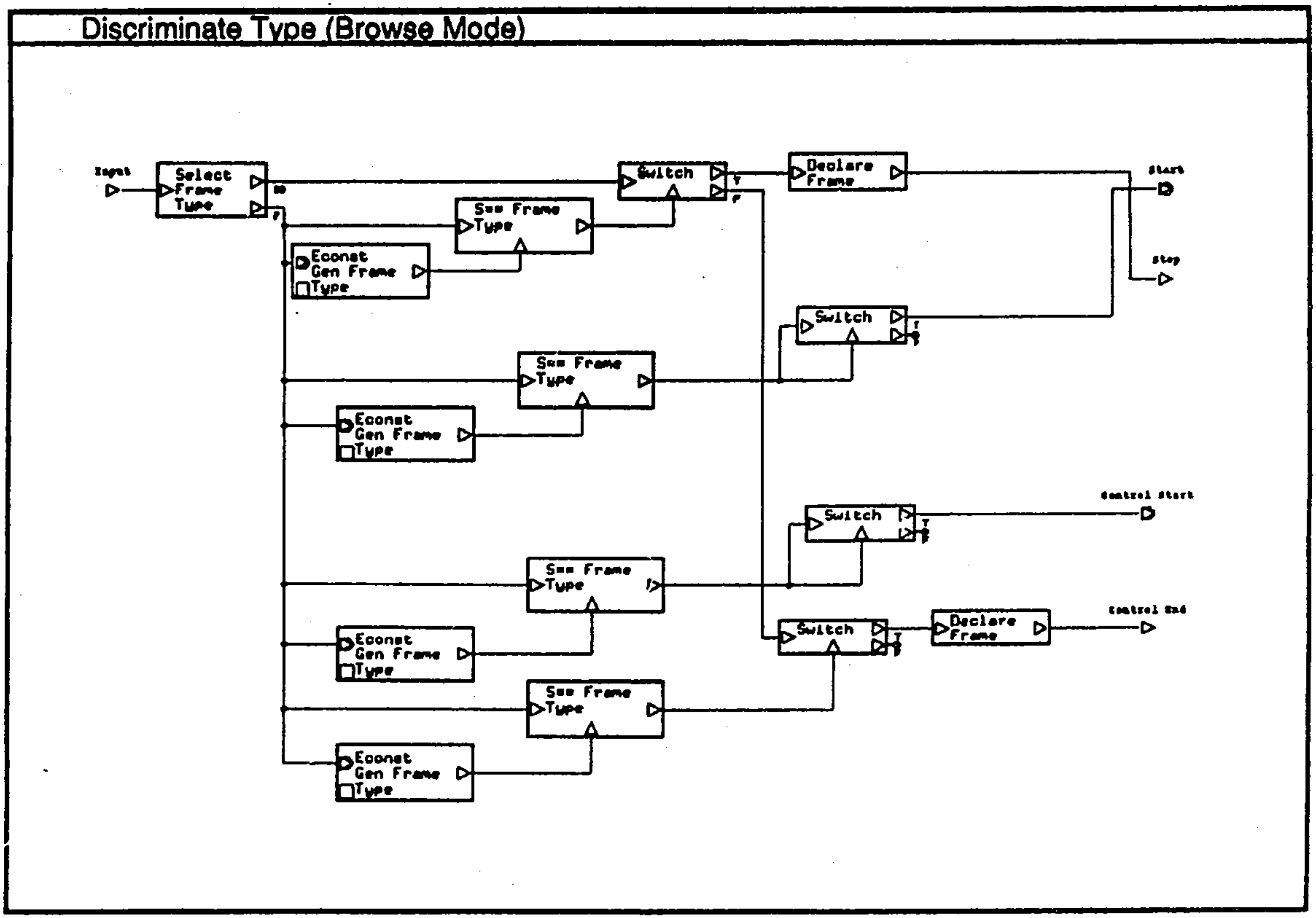

Channel Number Generator (Browse Mode)
Input (Trigger)
Random
Int -
Param
Channel Number


Increment Collisions (Browse Mode)
Frame In
Select Number of Collisions
1+
Insert Number of Collisions
Frame out
Number of Collisions


Check Carrier (Browse Mode)
channel
Discriminate Type
Counter
check channel
True Trigger
False Trigger
channel Not Idle
Idle Channel Detected


Compute Backoff (Browse Mode)
Backoff
Limit
Imin
Int to
Real
2.0
0.0
X^Y
Uniform
Rangen
Truncate
Int to
Real
BSlot
Time
Re


Generate Status Indication (Browse Mode)
in
Create
STATUS.indication
Insert transmission-status
output
Sconst MA-UNITDATA-STATUS.indication-transmission-status


Discriminate Type (Browse Mode)
Input
Select Frame Type
Switch
Declare Frame
S== Frame Type
Econst Gen Frame Type
S== Frame Type
Switch
Econst Gen Frame Type
Start
Stop
S== Frame Type
Switch
Control Start
Econst Gen Frame Type
S== Frame Type
Switch
Declare Frame
Control End
Econst Gen Frame Type

Appendix B

Simulation Parameters

The following parameters are exported to the system module level and will be set for the simulation.

- Load is the parameter which represents the ratio of the traffic offered to the data channel to the channel capacity (1 *Gbits/sec*). This parameter is not directly used by any module, but it is used in the equations for other parameters and statistical purpose.
- Application Queue Size is set to 0 because application queuing would seriously compromise the Poisson distributed assumption.
- Length of Data is set to a fixed length in our simulations. Different data lengths may be used to study the network performance.
- Backoff limit is set to 10.
- Attempt Limits is set to 16.
- Control Packet Length is set to 1000 bits.
- User Number is 32.
- Data Channel Number is 5.
- Slot Time (CSMA) is set to 5 μs based on previous discussion. It is a very important parameter in the network design.

- B/slot time is set to slot time for the following simulations.
- Transmission Speed is set to 10^9 bits/sec.
- Propagation Delay is $2\mu s$.
- Interarrival Mean is set to $\frac{Data\ Length \times\ User\ Number}{Load \times\ Transmission\ Speed \times\ Data\ Channel\ Number}$.
- TSTOP is set to $Interarrival\ Mean \times\ Load \times\ 500$ for the following simulations.

Probe Placement

A Throughput and Delay Probe and a Histogram Probe are placed in the receiver end of data channel 3. The probes start to record the network performance characteristics at $0.1 \times TSTOP$ to avoid the initial transient period of the simulations.