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Access Protocols and Network Architectures for Very High-Speed Optical Fiber Local Area Networks

Sudhakar N. M. Ganti

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Dedicated to my beloved parents and to my teachers

Abstract

The single mode optical fiber possesses an enormous bandwidth of more than 30 THz in the low-loss optical region of 1.3 μm and 1.5 μm. Through *Wavelength Division Multiplexing (WDM)*, the optical fiber bandwidth can be divided into a set of high-speed channels, where each channel is assigned it's own unique wavelength. An $M \times M$ passive optical star coupler is a simple broadcast medium, in which light energy incident at any input is uniformly coupled (or distributed) to all the outputs. Thus, a passive star along with the WDM channels can be used to configure a Local Area Network (LAN). In this LAN, users require tunable devices to access a complete or a partial set of the WDM channels. Due to these multiple channels, many concurrent packet transmissions corresponding to different user pairs are possible and thus the total system throughput can be much higher than the data rates of each individual channel. To fairly arbitrate the data channels among the users, media access protocols are needed. Depending upon the number of data channels and the number of users, two possible situations arise. In the first case, the number of users is much larger than the number of data channels and in the second, the number of users equals to the the number of channels. In both cases, data channel contention may arise if multiple users access the same given channel and must be resolved. This thesis proposes media access protocols for passive optical star networks. All the proposed protocols are slotted in nature, i.e., the time axis on each channel is divided into slots. The well known Slotted-ALOHA and Reservation ALOHA protocols are extended to the multi channel network environment. The thesis also proposes switching protocols (equal number of channels and users), contention-based reservation protocols for this network architecture. To interconnect these star networks, a multi-control channel protocol is also proposed along with two interconnecting techniques. Since there are multiple data channels, the data packets on different channels may be destined to the same user. However, if the user is equipped with only one receiver, the user can receive only one packet and ignores others. This is called a 'receiver collision' and the thesis also studies the effect of these receiver collisions on the data channels. Two network architectures, one for a packet circulating ring network and the other for a circuit switched application are described. Finally, the thesis studies some implementation considerations for these protocols.

Acknowledgments

First, I would like to thank both my supervisors Dr.M.Kavehrad and Dr.N.D.Georganas for introducing me to the exciting field of Lightwave Networks and for their support, encouragement during my thesis work. I enjoyed the benefits of being a member of both Photonics Research Group and Multimedia Research Group at University of Ottawa.

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Chapter 1

Lightwave Networks: Introduction

1.1 Background

Although computer communication is a well developed field by now (see [1, 2]), the human aspiration to build faster and more efficient devices is bringing powerful table top computers, which is further leading to the development of very high-speed computer communication networks. A computer network is an interconnection of various computing equipment and associated peripherals. These networks are classified into Local Area Networks (LANs), Metropolitan Area Networks (MANs) and Wide Area Networks (WANs), depending upon the geographical area they serve. In a network, the users (machines or nodes) are connected by a communication subnet which transports messages among them. Each message is generally broken into a number of packets. The subnet could use point-to-point channels or broadcast channels. Most of the wide area networks employ point-to-point links and the messages are segmented and sent from source to destination through intermediate nodes, one hop at a time (called packet switching). Most local area networks employ broadcast channels in which a single communication medium is shared by all the users in the network. Circuit switching is also employed in some networks where a dedicated end-to-end path is set-up a priori between the nodes in the network before any data transmission begins and the connection is broken after the data transfer is over. The most popular technique is packet switching with virtual circuits (logical channel) establishment.

The primary purpose of a Local Area Network is to provide connectivity and switching functions between various premises equipment. Generally, LANs consist of one shared medium for the communication purpose which is accessed by the various equipment (users) according to some media access protocol. Hence, LANs can be classified according to the transmission medium, media access protocols they use and the LAN topology. The twisted pair wire, coaxial cable and optical fiber are most popular transmission media currently used. There are numerous media access protocols (see [1, 2]) out of which the most popular are Carrier Sense Multiple Access with Collision Detection (CSMA/CD) for broadcast buses and token passing for rings or buses. In CSMA/CD protocol, a user wishing to transmit a data packet first senses the medium and transmits the packet only if the medium is idle. The user continues to sense the medium during the transmission and stops if a collision is detected. For token ring networks, a token circulates around the ring. A user wishing to transmit a data packet grabs the token when it is passing by, inserts the data packet onto the ring and retransmits the token. In a token bus network, users form a logical ring and a token is passed around this logical ring. A user who receives a token can transmit the data and pass the token to the next station in a logical order. The media access protocols are necessary for the users to access the shared transmission medium as they provide means for resolving contention when multiple users simultaneously access the channel. Local Area Network topologies take several forms and the most common are star, bus, ring and the tree.

When many kinds of networks co-exist, standards become necessary to enable different vendors equipment communicate with one another. The Institute of Electrical and Electronics Engineers (IEEE) developed IEEE 802 standards [1] for the local area networks. For example, IEEE 802.3 is a CSMA/CD LAN running at 10 Mb/s and uses a coaxial cable as a transmission medium. IEEE 802.4 is a token bus standard with speeds of 1, 5 and 10 Mb/s and uses a 75 ohm coaxial cable and IEEE 802.5 is a token ring LAN with speeds of 1 or 4 Mb/s and uses a shielded twisted pair. New standards for high-speed local and metropolitan area networks are either being proposed or established. Examples include the Fiber Distributed Data Interface (FDDI) which is a 100 Mb/s dual, counter-rotating token passing ring [3]. The IEEE 802.6 standard which is a Distributed Queueing Dual Bus (DQDB) consisting of two 45 Mb/s or 150 Mb/s unidirectional buses, where the nodes access these buses through a global distributed queueing algorithm [4]. Both these networks use optical fibers as transmission medium.

As the technology is advancing, the transmission speed of the networks is also increasing, as indicated by the above mentioned standards. The commercially available fiber has two low loss regions at 1.3 μm and 1.5 μm having a total bandwidth of about 50 THz at these two wavelengths [5]. The networks described above do not make use of the full potential (bandwidth) of the optical fiber. They use the fiber optic technology due to superior transmission characteristics and higher speeds. In copper and radio channels, concurrency can be achieved through Time Division Multiplexing (TDM) or Frequency Division Multiplexing (FDM). Similarly in optical fibers, Wavelength Division Multiplexing (WDM) can be used to divide the huge optical bandwidth into a number of channels, each at a different (unique) wavelength. Thus, a system employing optical fibers with WDM channels can be viewed as a network with multiple channels. Depending upon the system design, the users can have access to either full or part of these wavelengths. A multi-channel local area network can be configured using these multiple channels and the networks which use this kind of a configuration are referred to as *Lightwave Networks*. This chapter presents an overview of lightwave network architectures and Chapter 2 reviews many media access protocols that appeared in the literature for some of these networks.

1.2 Lightwave Technology

At present, lightwave technology is widely used in long distance communications and considerable research is underway to use it in short hop communications such as local area networks [6, 7, 8, 9]. The optical fiber possess a very large bandwidth in the low-loss optical window of 1.3 μm and 1.5 μm region. However, most optical LANs operate at relatively modest bit rates, since fiber-based systems are characterized by limited signal power. Reference [10] considers such fundamental limitations. Fig. 1.1 shows a simple point-to-point optical link [10]. If P is the transmitted power and E is the minimum optical energy needed to detect a bit at the receiver, the maximum power limited transmission rate is P/E. The same energy considerations also apply for a local area network. An $M \times M$ passive optical star coupler is a device [14] which uniformly distributes the incoming light from each of the M input fibers to the M output fibers. As shown in Fig. 1.2, a simple star network can be configured using a passive star coupler [10]. The signal transmitted at any input is coupled to all the receivers and thus the star coupler acts as a simple broadcast medium. If P is the transmitted power at one of the inputs, a power of P/M is delivered to each receiver and each transmitter-receiver pair can exchange data at a

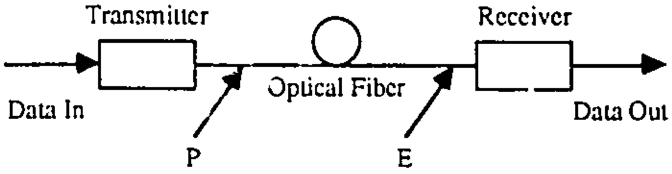


Figure 1.1: Point-to-point optical link

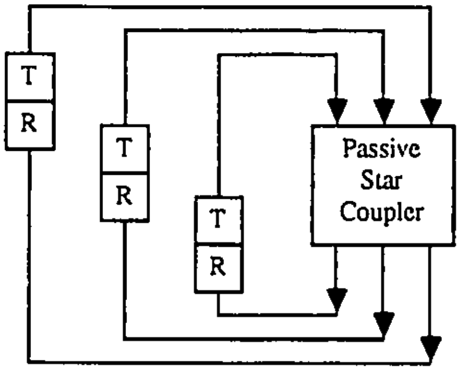


Figure 1.2: Optical Star Network

power-limited data rate of P/ME, where E is the minimum optical energy required to detect a bit. The total aggregate throughput of the network is P/E, the same as in a single optical link. The two most popular approaches for single-channel networks are based on bus and ring topologies. In Fig. 1.3, a unidirectional bus is shown. Each user is connected twice to the medium, once in the transmit direction and once in the receive direction. In this case, only P/M^2 power is coupled to each receiver in a M user bus and thus in a bus, the network throughput is proportional to $1/M$. Due to this, the power-limited throughput of ideal bus networks falls off much more rapidly than that for the star networks. Optical amplifiers [10] can be used to overcome this poor energy efficiency of the bus topology. Since the bus is shared by many users, media access protocols should be used by the users for a fair access to the bus. The CSMA/CD (Carrier Sense Multiple Access with Collision Detection) [1, 2] protocol is not well suited at very high-data rates and long propagation distances [11]. The efficiency of a CSMA/CD protocol depends on a, the ratio of propagation delay to packet length, and the protocol is more inefficient when this ratio becomes large. At very high-speeds, either the packet length should be increased or

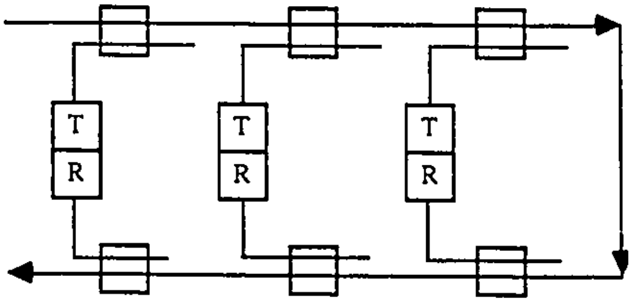


Figure 1.3: Unidirectional Bus Network

the network size should be decreased to increase the value of a. Since optical networks are bound to work at high-speeds, the CSMA/CD protocol is not suitable. To overcome the propagation time limitation, the IEEE 802.6 standard for Metropolitan Area Networks [4] uses a dual bus architecture called the Distributed Queueing Dual Bus (DQDB), as shown in Fig. 1.4. In this network, the head-end generates time slots that propagate along the buses. A user, having a data packet to transmit, waits until an idle slot appears at the transmitting side. The access to this idle slot is determined by a distributed queueing algorithm. This topology has some limitations to the total number of taps on the bus due to the insertion loss offered by each tap and in-line amplifiers may be used to regenerate the signal. Fig. 1.5 shows a ring architecture using the fiber as a transmission medium [12]. In this case, since nodes have to process all the network traffic, the system throughput will be limited due to the electronic bottleneck of the nodes. A very common medium access scheme for the ring topology is the token passing

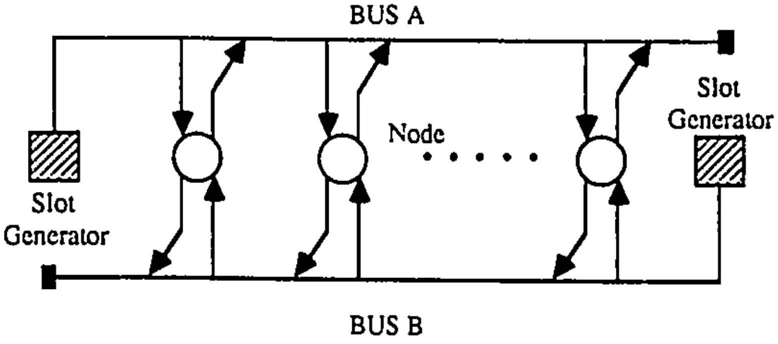


Figure 1.4: Dual Bus Network

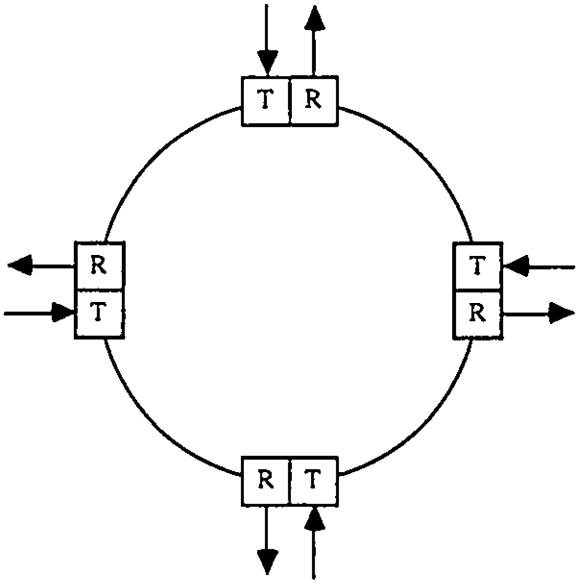


Figure 1.5: Ring Network

scheme [1]. The Fiber Distributed Data Interface (FDDI) is an example of token ring [3] using optical fibers and running at a network speed of about 100 Mb/s. In both FDDI and DQDB, the optical fiber is used for its superior transmission characteristics. The full potential (in terms of bandwidth) of the optical fiber is not used however.

1.3 Lightwave Networks

Lightwave Networks are distributed networks which tap the huge bandwidth of an optical fiber. The conventional networks (as described above), which use optical fibers for their high speeds and superior transmission characteristics are not to be considered as lightwave networks. In the following, a general introduction to lightwave networks along with some proposed architectures is presented. A schematic of a fully distributed lightwave network [13] is shown in Fig. 1.6. In this network, users interface with an optical medium which is entirely passive. The electronics appear at the distributed access ports. Each user in the network has a small set of transmitter and receiver pairs, each operating at a maximum data rate, say of 1 Gb/s. That is, the user speed is limited by the electronics. Then, to tap the huge bandwidth of the optical medium by the users who can use only a small fraction of bandwidth, not a single packet but multiple

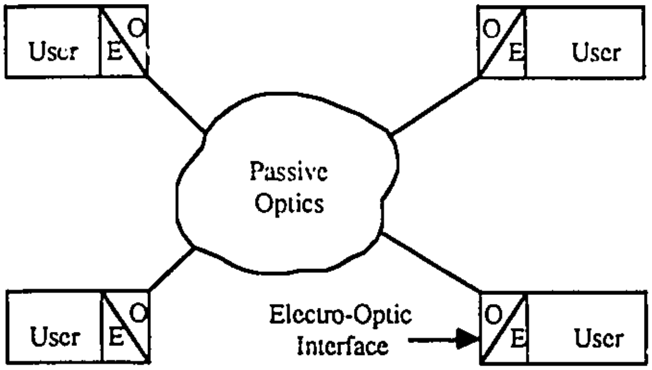


Figure 1.6: A distributed Lightwave network

packets corresponding to different user pairs must reside concurrently in the network. Out of the various concurrency techniques available such as Wavelength Division Multiplexing (WDM), Space Division Multiplexing (SDM), Code Division Multiplexing (CDM) etc., Wavelength Division Multiplexing (WDM) is gaining importance in optical fiber applications.

1.3.1 Wavelength Division Multiplexing (WDM)

The idea of wavelength division multiplexing [13, 14] is explained in Fig. 1.7. Each user is assigned an unique receiving wavelength. All the users are assumed to possess wavelength

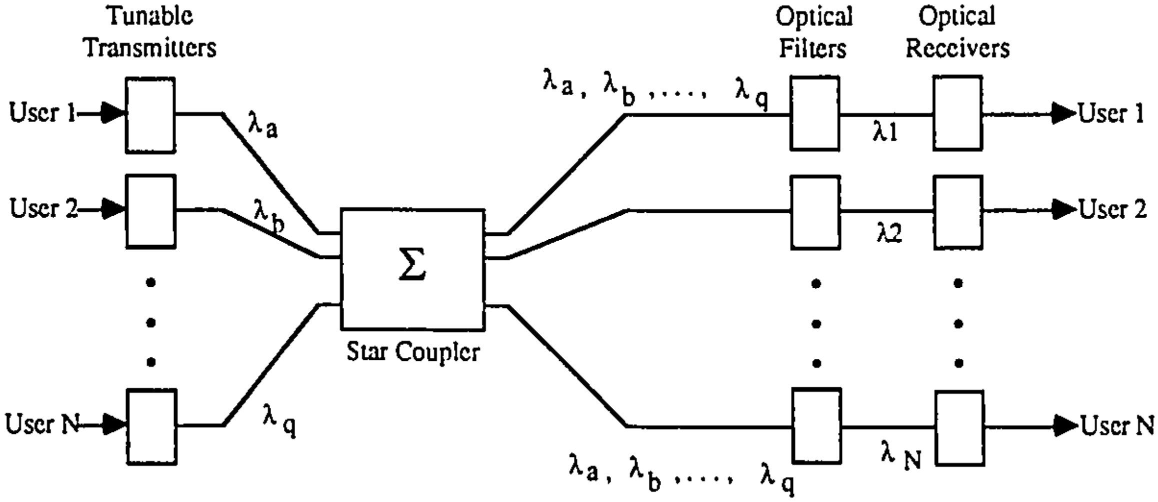


Figure 1.7: Concurrency through Wavelength Division Multiplexing

tunable transmitters. A user wishing to transmit a data packet to another user, will tune its transmitter to the receiver's wavelength and transmits the data packet. The packets transmitted by different users are linearly combined at the star coupler and the combined signal is received by all the receivers. At the receiver, proper optical filters can be used in order to receive the data packets coming on the assigned wavelength of the receiver. However, packets destined to the same user at the same time will collide and a proper medium access scheme should be adopted. This is also called Wavelength Division Multiple Access (WDMA). The main drawback of this approach is the requirement of wavelength tunable transmitters and/or receivers (or alternately a bank or an array of transmitters and receivers) which have to be tuned very fast.

1.3.2 Multihop Approach

Another approach to achieve a high capacity in the lightwave networks is the multihop approach [13]. A simple eight-node multihop network is shown in Fig. 1.8. Each node (or Network Interface Unit, NIU) has two optical transmitters and two optical receivers and a port for input and output data. The nodes are connected in a perfect shuffle. The transmitters on the right hand column are wrapped around to the receivers on the left. The interconnecting links can be separate fibers or they can be the same fiber with multiple wavelengths on each link. The network then becomes a multichannel multihop network. The advantage of a multichannel multihop network is that it could be logically imposed on many physical topologies (e.g. star, bus or tree). For example, Fig. 1.9 shows the multihop network using a bus topology. The connectivity diagram of this multihop network follows that of Fig. 1.8 and in fact the various wavelengths shown in Fig. 1.8 correspond to the wavelengths used in this bus topology. Since the connectivity graph follows a perfect shuffle pattern, this class of networks are also referred to as Shuffle Net. In this multihop network, packets are transported using a store-and-forward exchange. Each node decides whether the packet that has arrived at its destination is addressed to self or requires a retransmission. Since each packet may traverse more than one link (hop) to reach the destination, the number of hops required from a given source to various destinations is not a constant and depends upon how it is routed (for example random routing or shortest path routing).

In general, the (p, k) shufflenet [13] consists of $N = kp^k, (k = 1, 2, 3, \cdots; p = 1, 2, 3, \cdots)$ NIUs

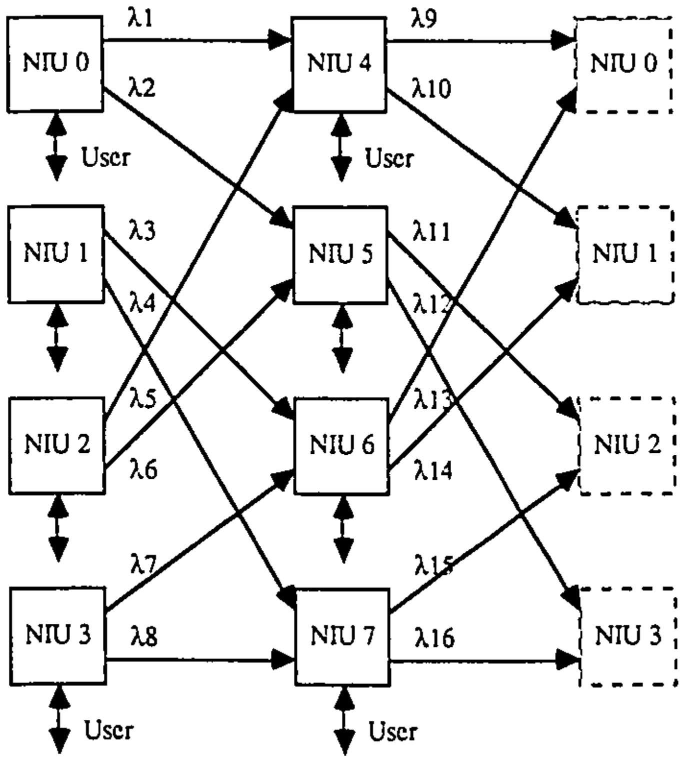


Figure 1.8: A multihop network

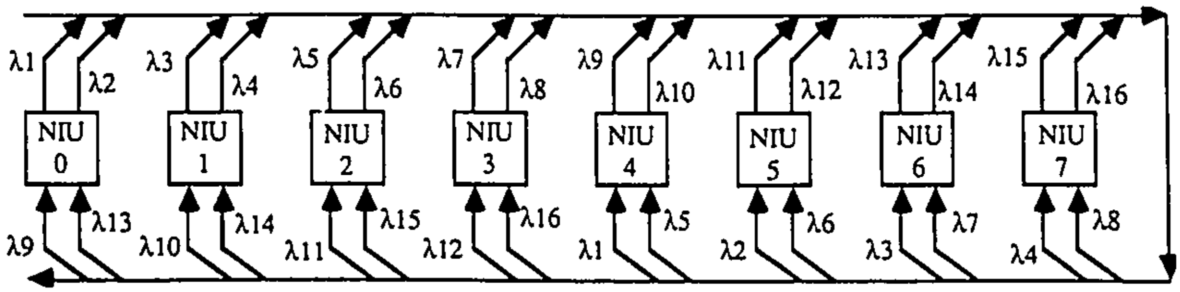


Figure 1.9: A multihop network for a bus topology

arranged in k columns of p^k NIUs each. The k^{th} column is connected to the first so that the connectivity graph is wrapped around a cylinder. From any source node in a (p,k) shuffle net, it takes utmost $2k-1$ hops to reach any other node. The total number of channels required in a (p,k) shuffle net is (kp^{k+1}). The expected number of hops (E) between two randomly selected NIUs is:

$$E = \frac{kp^k(p-1)(3k-1) - 2k(p^k-1)}{2(p-1)(kp^k-1)} \tag{1.1}$$

Under uniform traffic conditions, the maximum achievable throughput C is given by the ratio of the number of WDM channels to the expected number of hops:

$$C = \frac{2kp^{k+1}(p-1)(kp^k-1)}{kp^k(p-1)(3k-1) - 2k(p^k-1)} \tag{1.2}$$

The maximum achievable throughput per NIU is given by the ratio C/N. The shufflenet has many advantages: the connectivity graph is a symmetric structure and it also provides multiple minimum distance paths between some nodes. This would be very useful for reliability and fault tolerance. However this network also needs buffering at intermediate nodes which causes queueing delays and packet losses at very heavy loads. Similarly, other symmetrical mesh topologies [15, 16] such as the Manhattan Street Network can also be used in such multichannel environments to provide connectivity among the users.

Using this multiple channel approach through wavelength division multiplexing, the FDDI and DQDB standards can be enhanced to achieve higher throughput. Reference [17] considers such networks through multiple channel ring networks. The single channel Expressnet and Fastnet are extended to multichannel optical fiber networks in [18] with round robin protocols. Recently, a great deal of research is going on towards the development of a Broadband Integrated Services Digital Network (BISDN) and Asynchronous Transfer Mode (ATM) [19] is being considered for the same as a multiplexing and switching technique. In ATM, all the information to be transferred between users is packed into fixed size slots called the 'ATM cells'. The cells are switched at intermediate nodes for proper routing of the cells and a great body of research is underway [20] to build fast electronic/optical switches for ATM switching. In [21], some of the proposed multiwavelength networks are presented along with switching architectures for fast packet switching such as ATM. Many of these architectures, e.g., LAMBDANET, HYPASS (High Performance Packet Switching System), BHYPASS, Star-Track Switch etc. [7], use $M \times M$

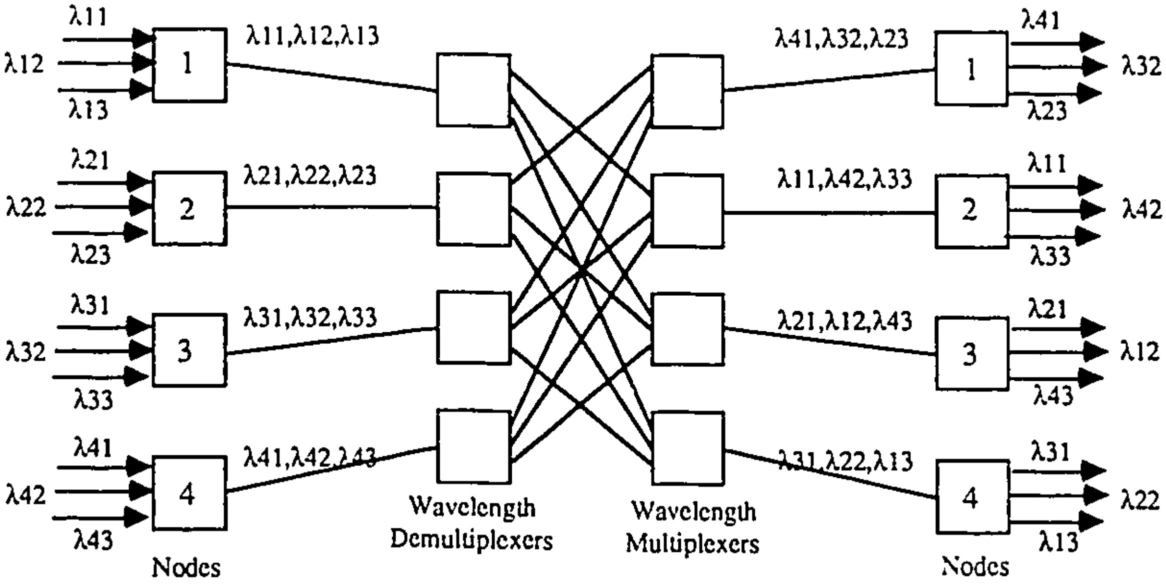


Figure 1.10: Wavelength Routing Star Network

optical star coupler as the main central hub.

In [22], a class of wavelength routing optical networks is described. These are based on the interconnection of wavelength multiplexed channels and allow re-use of the wavelengths in different transmission sections. Various structures presented in [22] provide a set of point-to-point interconnections and a full interconnection between the nodes is possible at the optical level. These structures (such as star, chain, tree and ring) use wavelength multiplexers and de-multiplexers. Fig. 1.10 shows a simple wavelength routed star interconnection network. Alternate routing is possible by re-routing at intermediate nodes. For a M node network, a total of $M(M-1)$ optical channels are needed for full interconnection. To extend the range of the network, in-line optical amplifiers can be used.

1.3.3 Broadcast and Select Networks

In Section 1.3.1, the concept of wavelength division multiplexing is introduced using an optical star network. This network belongs to the class of broadcast-and-select networks, since the information from all the inputs is broadcast to all the outputs and it is the duty of a receiver to select the appropriate channel. Many possibilities exist when using the passive optical star as a broadcast medium. In the first case, users can be assigned fixed transmitting wavelengths but are equipped with tunable receivers. So the receiver is to be tuned to the correct wavelength to receive information from any other user. In the second case, the users have tunable transmitters with fixed receivers. It is the duty of a transmitter to tune to the proper wavelength of the receiver and transmit the data packet. In the third approach, both the transmitter and receiver of the users are tunable and are both tuned to the correct wavelength in order to exchange information. A control channel becomes necessary in this case for a proper co-ordination among the users and reference [23] describes such a network.

In these select-and-broadcast networks, since the number of users is generally more than the number of available channels, contention will arise when more than one user is trying to compete for the same channel (and or the same receiver) at the same time. This causes collisions and reduces the system throughput. Hence some media access protocols become necessary in these networks to properly arbitrate the data channels among the users and Chapter 2 discusses some protocols for these networks. It should be noted that the tunability range of the transmitters and the receivers should cover the complete set of wavelengths present in the system in order to establish a direct (single hop) communication path between the transmitter and the receiver. If not, the multihop approach of Section 1.3.2 can be logically implemented on these optical star networks.

1.4 Linear Lightwave Networks

Most of the networks described so far use either passive power combiners in broadcast mode or use point-to-point links with electronic switching and multiplexing. The Linear Lightwave Network (LLN) is a network in which the nodes perform only linear operations on optical signals. This includes controllable power combining, dividing and if possible linear amplification and all operations on the signals are done at the optical level [24]. Thus there are no electronic bottlenecks in the network and the network can be of any arbitrary mesh topology. Reference [24] considers such a network in a circuit switched mode at the optical level and routing algorithms are proposed for setting up the calls. This routing involves choosing an end-to-end path for a requested call, checking for violations of the LLN constraints and finally assigning an appropriate channel to the call.

1.5 Outline of the Thesis

This chapter described various optical network technologies. Since optical star networks can support a larger number of users than a bus network for a given transmitter power, we mostly concentrate on this type of networks in this thesis. These optical star networks require coordination protocols for the users to fairly access the data channels available in the system. Many media-access protocols are proposed in the literature. Hence, Chapter 2 reviews some of the media access protocols proposed in the literature for optical networks. This thesis develops some more protocols for the multi-channel optical star network architecture. The well known Slotted-ALOHA and the Reservation ALOHA protocols are first extended in Chapter 3 for this multi-channel network. A simple contention-based reservation protocol which is based on ALOHA for contention and offers a better performance, a multi-control channel protocol which can be used for interconnection of LANs are presented in Chapter 4. Chapter 5 considers switching protocols which can be used in a network environment with equal number of users and channels. When multiple data channels exist in a network, there could be more than one packet which are destined to the same user. If the user is equipped with only one receiver, the user can receive only one packet on one of the channels and ignores all other packets. This is called 'receiver collision' and the effect of these receiver collisions is considered in Chapter 6. This thesis also proposes two network architectures, one a packet circulating ring network for packet switching and the other for circuit switched applications which uses directional coupler and wavelength converters. These are presented in Chapter 7. Chapter 8 discusses some implementation considerations which take into account important parameters such as latencies due to packet propagation, switching etc., and the final chapter concludes this thesis.

1.6 Thesis Contributions and List of Publications

The contributions of this thesis are in the areas of media access protocols and network architectures for optical networks. In the area of media access protocols, this thesis proposed and studied the following for passive optical star networks:

- Extended Slotted ALOHA Protocols
- Extended Reservation ALOHA Protocols
- Multi-Control channel Protocols

- Contention-based Reservation Protocols
- Switching Protocols
- Effect of Receiver Collisions in Multi-Channel Optical Networks

In the area of network architectures, the following are proposed:

- TDM Ring Network Architecture
- A node architecture for a circuit switched optical network

The following publications have resulted from this research:

1. G.N.M.Sudhakar, N.D.Georganas and M.Kavehrad, "Slotted - ALOHA & Reservation ALOHA Protocols for Very High-Speed Optical Fiber Local Area Networks Using Passive Star Topology," *IEEE Journal of Lightwave Technology,* Vol.9, No.10, pp.1411-1422, October 1991.
2. G.N.M.Sudhakar, M.Kavehrad and N.D.Georganas, " Multi-Control Channel Very High-Speed Optical Fiber Local Area Networks and Their Interconnections Using a Passive Star Topology," *Proc. IEEE Globecom'91,* Phoenix, AZ, pp.624-628, Dec.1991.
3. G.N.M.Sudhakar, M.Kavehrad and N.D. Georganas, " A Simple Contention-based Reservation Scheme for LAN Using a Passive Star Topology," *Proc. IEEE Photonics'92,* Montebello, March 1992.
4. G.N.M.Sudhakar, N.D.Georganas and M.Kavehrad, " A Multi Channel Optical Star LAN and Its Application as a Broadband Switch," *Proc. IEEE ICC'92,* pp.843-847, Chicago, June 1992.
5. G.N.M.Sudhakar, N.D.Georganas and M.Kavehrad, "Throughput Reductions due to Receiver Collisions in Multi-channel Optical Networks," *Proc. IEEE ICC'93,* Geneva, Switzerland.
6. G.N.M.Sudhakar, N.D. Georganas and M.Kavehrad, "Some Architectures for High-Speed Optical Networks," *Proc. IEEE Photonics'92,* Montebello, March 1992.
7. G.N.M.Sudhakar, M.Kavehrad and N.D.Georganas, "Access Protocols for Passive Optical Star Networks," to appear in Journal of Computer Networks and ISDN Systems.

Chapter 2

Lightwave Networks: Media Access Protocols

As explained before, through Wavelength Division Multiplexing (WDM), the huge bandwidth of optical fiber can be divided into a set of high-speed logical channels. A multichannel network can be configured using these WDM channels and a passive star coupler. The star coupler is a simple passive medium and for the same given signal energy consideration, the star coupler can support a larger number of users than a bus configuration. Hence, this thesis mainly considers the passive optical star networks. One of the major issues in these networks is the channel access protocols users have to follow in order to transmit their packets to other users. The purpose of these media access protocols is to let the users follow a predetermined set of rules in order to fairly access the network resources. When there is more than one user competing for a given resource at the same time, collisions will arise and the system throughput falls off. Hence media access protocols become necessary in multiple access environments. This chapter reviews many of the proposed protocols that appeared in the literature. These protocols are divided into three different categories: fixed assignment (or pre-allocation) protocols, random access protocols and hybrid protocols. The random access protocols are further divided into reservation, switching and collision avoidance protocols.

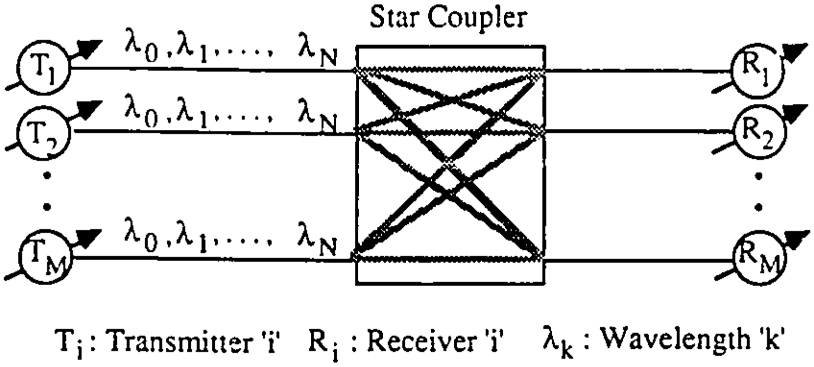


Figure 2.1: A General Passive Optical Star Network

2.1 A LAN using an Optical Star

A general network architecture using an optical passive star coupler is shown in Fig. 2.1. There are M users in the network. Each user is connected to the star coupler with input and output fibers. It is assumed that each fiber bandwidth is divided into a set of N WDM channels. Each channel is assigned a unique wavelength $\lambda_1, \lambda_2, \cdots, \lambda_N$. It is also assumed that another channel (control) at a wavelength λ_0 is available to the users for control purposes. This control channel is needed in certain protocols. It is assumed that each channel data rate is R bits per second and each user is situated at a distance D_i, where, i is the user number. Each user is equipped with a set of transmitters and receivers, with a minimum of one transmitter and one receiver per user. The set of transmitters and receivers could be tunable over the entire or a partial set of wavelengths present in the system $\{\lambda_1, \lambda_2, \cdots, \lambda_N\}$ or a bank of transmitters and receivers could be used for each wavelength, instead. The channels are assumed to be assigned in such a way that a single hop (direct) communication is possible between any two users through one or more channels. That is, if $T(i)$ and $R(i)$ are the sets of wavelengths over which user i can transmit and receive, then $T(i) \cap R(j)$ should not be a null (empty) set for users i and j to communicate. Since users have access to multiple data channels in the network, it becomes necessary to use access protocols in order to arbitrate the channels. For a small number of users and channels, a simple approach is to use Time Division Multiplexing (TDM). In this, the time axis on each channel is divided into frames and each frame is subdivided into slots. These slots are assigned to users in a non-conflicting way. But this TDM scheme is not very efficient at low loads. For a more dynamic bandwidth assignment, the channels are accessed using random access protocols. That is, users try to obtain a channel using a given access mechanism and if they are not successful, they will repeat the process after a random time (called back-off). Since multiple users may try to gain access to the same channel at the same time, these protocols may introduce collisions which must be resolved. Thus, the random access protocols generally introduce extra overhead with a corresponding delay. In the following section, some of the proposed protocols are reviewed in detail. In a multi-channel system, the bandwidth should be dynamically allocated to the users depending upon their requirements. If tunable receivers are employed in the network, the receivers must be told which channel they must be tuned to, in order to receive the data packets. Hence, depending upon the network configuration and the type of devices used, a pre-transmission co-ordination may be required in some of these networks. That is, a receiver must be informed a priori on which channel a data packet is transmitted to the user. This pre-transmission co-ordination can be done on a dynamic or a permanent basis. Most of the fixed assignment and some of the random access protocols use a permanent co-ordination. To do this co-ordination dynamically, many of the random access protocols use a separate control channel for transferring the control information. The users always monitor this control channel. When tunable devices are used in the network, another degree of complexity is introduced by the device tuning time. For a very fast dynamic allocation of the data channels, the devices should be tunable to the required wavelengths at sub-nanosecond speeds to achieve high-speed communication. Some protocols assume the device tuning speeds and the propagation delays are negligible.

2.2 Protocols for Passive Optical Star Coupler Networks

In this section, the access protocols, as applied to multi-channel networks are described. We start with fixed and semi-fixed assignment protocols, then look at some of the random access and hybrid protocols.

2.2.1 Fixed and Semi-fixed Assignment Protocols

The simplest way to assign bandwidth in single channel packet networks is time division multiplexing, where each node is assigned a slot to transmit its data packet. The same can be

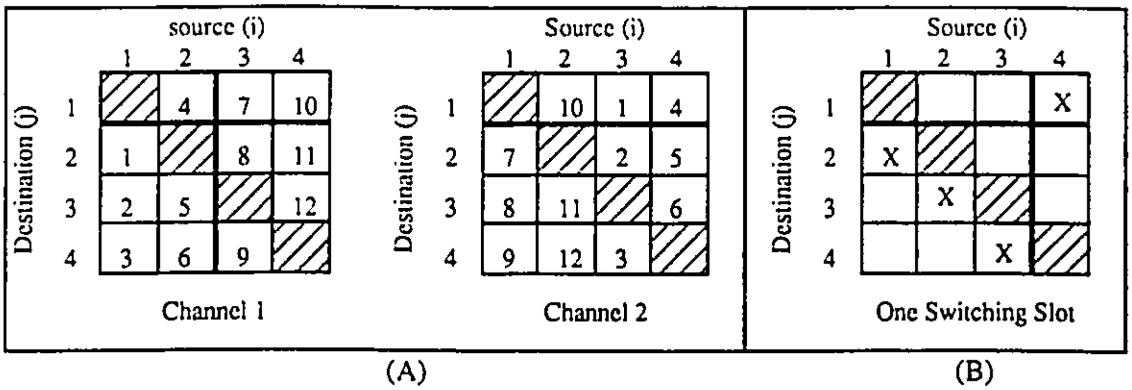


Figure 2.2: Allocation Matrix $U(x)$. Each entry in the table shows the slot assigned to the user pair (i,j). An X indicates any channel can be used.

extended to a multi-channel environment. In [25], a class of Frequency-Time Division Multichannel Allocation (FTDMA) protocols was introduced. These protocols can be used in a multi-channel environment, where M nodes are connecting through N ($N \leq M$) channels. The time axis is divided into cycles. In each cycle, source/destination oriented permissions are specified to identify the channel and the slot in which a user can transmit the data. Four different protocols are described in this reference.

The Source/Destination Allocation Protocol (Protocol I) is a fixed assignment protocol. The allocation cycle is defined to be T slots in length. In each slot, the channels are assigned to the various source destination pairs preventing any destination conflicts and collisions on the channel. The allocation matrix $U(x)$ is an $M \times M$ matrix, each entry $u_{ij}(x)$ of the matrix represents whether a permission is granted to user (i,j) in slot x where $x = 1, 2, \cdots, T; 1 \leq i, j \leq M$. For the Source/Destination Allocation Protocol, $U(x)$ is assigned such that in each slot: (1) there are destination conflict free transmissions, (2) the total number of transmissions is limited to the number of data channels N and (3) there is only a single allocation per channel per slot. This fixed assignment is definitely not very efficient at light loads and also the cycle size could be significant for large M. An example of the matrix U is shown in Fig. 2.2(A) for a four node ($M = 4$), two channel network.

To reduce the cycle size, three more protocols are proposed in [25]. These belong to the class of semi-fixed assignment protocols. In these protocols, the permission to transmit is still fixed for a given source/destination pair. However, the number of transmissions in a slot can be more than N, the number of channels and this may cause channel collisions.

In the Destination Allocation Protocol (Protocol II), up to M transmission permissions are issued to users without specifying any channel. The user who has a permission and has a packet to transmit, randomly selects one of the channels and transmits the data. Permission to transmit (allocation matrix) is chosen such that no destination conflicts occur, but channel collisions may occur in this case. The allocation matrix $U(x)$ is assigned such that there are no destination conflicts, the total number of transmissions in a slot is restricted to the number of destinations and there is a single transmission for every source. Fig. 2.2(B) shows an example of $U(x)$ for $M = 4$ and one switching slot. Similar assignment is done for other slots and channels.

In the Source Allocation Protocol (Protocol III), the allocation matrix is chosen such that there are no channel collisions. That is, $U(x)$ is chosen, such that in each slot, the total number of transmissions is limited by the number of channels N and a given channel is not allocated to more than one source node.

Note that the number of permissions to transmit is increased from protocol I to III, but so is the complexity. A lot of implementation difficulties are to be overcome. In protocol I, each node knows the allocation matrix a priori and thus it can tune its receiver to the corresponding wavelength to receive the data packets from other sources. But, in protocol II, a transmitter can randomly choose a data channel to transmit and the receiver does not have the channel information. Similarly, in protocol III, there can be destination conflicts, if the user is not equipped with multiple receivers. In the next section, we see some of the random access protocols which provide this channel information to the receiver through a separate control channel.

2.2.2 Random Access Protocols

In order to assign the bandwidth more dynamically, random access protocols should be used in the passive star network environment, when the number of users M is greater than the number of channels N. As described before, a wide variety of network configurations are possible in these multi-channel networks, depending upon the number of channels and the tunability of the receivers and transmitters. If the receivers are of fixed wavelength type (i.e., not tunable), the transmitters should know the wavelengths of all the receivers with which they wish to communicate and should be tunable over this set of wavelengths. In this case, no pre-transmission co-ordination is required but destination conflicts must be resolved. On the other hand, if fixed wavelength transmitters are used, the receivers should be tunable. But in this case, the receivers should have some additional information, e.g., identity of a transmitter wishing to communicate with a particular receiver. Whether the transmitters or the receivers are tunable, the wavelength assignment is another problem which has to be addressed. If both the transmitters and the receivers are tunable, no wavelength assignment is necessary and channels can be accessed uniformly by all users. However, this also necessitates additional control information, such as the wavelength the receiver has to tune to, in order to receive the data packets from other users. This can be done for instance through a separate control channel. Thus, a pre-transmission coordination is required in these protocols. Most of these configurations can make use of random access protocols such as ALOHA, CSMA, N-Server, etc. [1]. In this section, we discuss some of the proposed protocols for various configurations as applied to the passive optical star networks.

Random Access Protocols with no Pre-transmission Coordination

In [26], two protocols (random access and fixed transmission scheduling) were proposed for WDM passive star networks. In these protocols, each user is equipped with a tunable transmitter with limited tunability and multiple fixed wavelength receivers. Let $T(i)$ and $R(i)$ be the sets of wavelengths over which user i can transmit and receive. As before, the system consists of M users and $N(1 \leq N \leq M)$ channels. The protocols that were proposed were: a multi-channel Slotted-ALOHA protocol and a random TDMA protocol. In the Slotted-ALOHA protocol, a busy user i randomly chooses one of the channels from the set $(T(i) \cap R(j))$ and transmits the data packet to user j. The same channel can also be assigned to another user and thus channel collisions can happen. The receiving user should monitor all the channels assigned to it where by the cost of a node can be high if many channels are assigned to that user. In the random TDMA protocol, all the users follow a distributed algorithm using the same random number seed. The algorithm has the properties that, each channel is assigned to only one transmitting user per slot, each user transmits at most one packet per slot on one of the channels in its transmission range. Analytical models were developed for both protocols. The Allocation Free

Protocol (Protocol IV) in [25], is also a multichannel slotted ALOHA protocol. At the beginning of a slot, any user having a packet is allowed to transmit on a randomly chosen channel. There can be both channel and destination conflicts and the receiving user does not know the complete information about the channels. The receiver should be equipped with multiple detectors, one for each channel, in order to receive the packets from other users.

In the earlier protocols, it is the duty of the network designer to assign the data channels to the various users. This could be a difficult task considering the traffic dynamics of today's computer networks. With dense WDM, a large number of channels can easily be generated and the cost of each node could be very high, if multiple receivers are to be provided. The most natural choice is to use tunable transmitters and receivers in this case. Many protocols are proposed for this kind of architecture. Because of the tunability of both the transmitter and the receiver, a separate co-ordination channel may be required to pass the control information. In the following we discuss some protocols for this architecture.

Random Access Protocols with Pre-transmission Coordination

In [23], five random access protocols were proposed for passive optical star networks which use tunable devices and a separate control channel. It was assumed that the devices are agile and tunable over the entire set of wavelengths present in the system. There are N data channels and one control channel. Each data channel is assigned a separate wavelength from the set $\{\lambda_1, \lambda_2, \cdots, \lambda_N\}$ and the control channel is assigned a wavelength λ_0. All the idle receivers always monitor the control channel λ_0. The users in the network can transmit and receive on any of the data channels and on the control channel. Due to this, the receiver should be informed about the selected data channel. Since both the control and data channels are accessed randomly, many combinations of access protocols are possible depending upon which protocol is exercised on these channels. These are referred to as X/Y protocols in [23], where X is the control channel protocol and Y is the data channel protocol. ALOHA, Slotted-ALOHA and Carrier Sense Multiple Access (CSMA) protocols were studied for the control channel along with ALOHA, CSMA, N-Server protocols for the data channels.

The operation of the network in [23] is as follows: a busy node i, wishing to transmit a data packet to node j, first randomly selects a data channel number. Then node i transmits a small

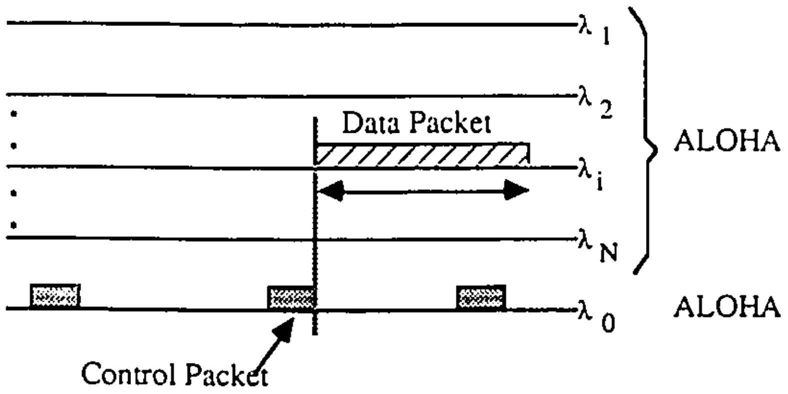


Figure 2.3: ALOHA/ALOHA Protocol

control packet on the control channel according to the protocol that is being used. This control packet includes information such as transmitter (source) address (i), receiver (destination) address (j) and the selected data channel (wavelength) number (λ_k). It is assumed that all idle receivers always monitor the control channel. Thus, if node j is idle, it will receive the control packet from node i, will decode the information and tune its receiver immediately to the data channel λ_k. Time is normalized to the control packet transmission time (one unit) and the data packet is assumed to be L units in length. Five protocols, ALOHA/ALOHA, Slotted-ALOHA/ALOHA, ALOHA/CSMA, CSMA/ALOHA and CSMA/N-Server Switch were considered. The first protocol in [23] is the ALOHA/ALOHA protocol and Fig. 2.3 shows the operation of this protocol. According to this protocol, a busy node first selects randomly a wavelength on which it will transmit the data. Then the node transmits a control packet on the control channel at random and transmits immediately the data packet on the selected data channel. If there are no collisions on both the control and data channels and if the receiver is idle, the data packet can be received correctly. The second protocol is the Slotted-ALOHA/ALOHA protocol, which is similar to the ALOHA/ALOHA protocol except that, the control channel is now slotted and its access is through the Slotted-ALOHA protocol.

Under the ALOHA/CSMA protocol, which is the third protocol, a user senses the data channels one at a time to find an idle one. After finding one, the user jams the data channel during the time it transmits the control packet on the control channel and transmits the data packet on the selected channel immediately after that. Since the jammimg signal and the control packet are transmitted at the same time, this protocol needs two transmitters, where one can be at a fixed wavelength of λ_0, the control channel wavelength. In this access combination, the ALOHA protocol can be either slotted or unslotted. The fourth protocol is the CSMA/ALOHA protocol, in which, a user first selects a data channel randomly, senses the control channel and when it is found idle, the user transmits the control packet. The data packet is transmitted immediately after on the selected data channel. The last protocol in [23] is a CSMA/N-Server protocol, in which by monitoring the control channel for a duration of L time units, a node can know exactly which channels and which receivers are idle. No packet is transmitted by a node, if all the N channels are found busy. Thus, no data channel collisions will occur in this protocol. At very high-speeds, the normalized packet propagation delay (relative to packet transmission time) is quite large thus rendering the CSMA protocols unsuitable. For example, in order to get a better system performance using the CSMA/N-Server protocol, either the number of channels N has to be small or L, the packet length has to be quite large. For larger size LANs, the ALOHA/CSMA protocol is a better choice, whose throughput also increases with L. But the main problem is that, at high-speeds, the packet lengths tend to be much shorter. Thus ALOHA based protocols may offer a better performance for small L.

Mehravari [27] proposed some improvements to two of the protocols in [23]. In particular, in the Slotted-ALOHA/ALOHA protocol above, the data packet is sent whether the control packet is successful or not. Performance improvement is possible, if the transmission of the data packet is deferred when the corresponding control packet is not successful. This leads to improvements for this protocol combination. A Slotted-ALOHA/N-server switch protocol was also proposed which is a variation of the CSMA/N-Server described above. By replacing the control channel protocol by Slotted-ALOHA, a further performance improvement has been achieved, besides avoiding the problems associated with carrier sensing, such as the propagation delay.

In the improved Slotted-ALOHA/ALOHA protocol, a data channel collision may occur, if there are two or more successful control packets using the same data channel. This is further improved in [28] using the Slotted-ALOHA/Polite Access protocol. In this case, the data packet is transmitted by the user only if the corresponding control packet is successful and if there are no other successful control packets having the same data channel number in the previous $(L-1)$ control slots. The Slotted-ALOHA/N-server switch protocol is also improved using the

Slotted-ALOHA/Synchronous N-Server switch protocol [28]. According to this protocol, users do not select the data channels. The control channel is divided into frames and each frame is further divided into control slots. The users transmit their control packets in one of the slots of the frame. The control packet contains the receiver address but no data channel number. At the end of the frame, each user knows about the success of the control packets in a frame. Then all users with successful control packets transmit on the data channels according to a predefined assignment algorithm. For example, the data channels can be assigned to the successful control packets on a First Come First Serve (FCFS) basis starting from channel 1 to N. Thus both these protocols exhibit a better performance than the ones in [27] and are independent of network propagation time. In [29], an ALOHA/Slotted-CSMA protocol was proposed for the same network architecture. According to this protocol, a user senses each data channel at the beginning of each CSMA slot. Once an idle channel is found, the user immediately transmits a control packet and only if this packet is successful, a data packet is transmitted. This protocol has a superior performance than the ALOHA/CSMA protocol.

Multi-Control Channel Protocols

In the random access protocols based on a separate control channel, all the traffic on the control channel is processed by each node for possible control packets destined to that node. To reduce the processing requirements of a node, the protocol in [30] uses multiple control channels. According to this protocol, each node requires one transmitter (FT) and one receiver (FR) which are fixed tuned, and one more transmitter (TT) and a receiver (TR), which are rapidly tunable. Each of the FT and FR is assigned a unique wavelength. Thus, $2N$ wavelengths are needed for a N station network. The TTs, FRs are used for control purposes and are designated as *control transmitters* and *control receivers*, respectively. The FTs and TRs are used for data packets which are designated as *data transmitters* and *data receivers*. Time is divided into frames of size T on each channel. Each control frame is divided into m slots. Since each user has a separate control channel, the control frame of m slots provides each user with up to m simultaneous connections. Each connection is assigned one of these m control slots. The data channel frame is divided into $n + 1$ slots, where n slots are used to transmit the data packets and one slot is used as *status slot*. This status slot is used to transmit the assignment of the control slots. These status and control slots are used to set up connections among the users. Three traffic classes were identified and connection setup and data transfer procedures were described using these channels. For example, Class1 traffic is connection oriented with bandwidth guaranteed, Class2 traffic is connection oriented but not bandwidth guaranteed and finally, Class3 traffic is datagram traffic. Some extensions, such as reducing the number of channels, transmitters and receivers were also described in this reference.

Reservation Protocols

A contention based reservation protocol is proposed in [31]. It is assumed that each node has one tunable transmitter, a tunable receiver and a fixed wavelength (λ_0) transceiver for the control channel. Both the control and data channels are slotted and the control slots are further divided into minislots. The users in the system try to reserve a data channel by sending their reservation packets on the control channel using the Slotted-ALOHA protocol. The control packet contains only the destination address. The data channel is successfully reserved, if, (1) the control packet has not collided with any other control packet, (2) no other successful control packet has the same destination address and (3) the total number of successful control packets is less than the number of data channels. At the end of a control slot, each user knows the status of the system since users always monitor the control channel. A user whose reservation is successful uses wavelength λ_i in the next slot to transmit the data packet, if the number of successful reservations before the considered user is $i - 1$. A multichannel demand assignment protocol based on the slot reservation scheme is studied in [32]. It operates such that each node has access to one slot per cycle per channel. The cycles are separated by a delay to circulate the control information for contention-free slot allocation. The control information is contained in a reservation subframe at the end of a cycle. Each node requires access to all N channels, thus the protocol requires N transmitters and receivers, wavelength division multiplexers and demultiplexers.

Switching Protocols

When the number of users and the number of channels in the system are equal ($M = N$), the multi-access problem can be viewed as a switching problem. In this case, each node can possess either a fixed wavelength transmitter and a tunable receiver or a tunable transmitter and a fixed wavelength receiver. Here, we discuss some protocols for systems of this kind. Either a separate or an embedded signalling channel can be used for signalling purposes.

A Dynamic Allocation Scheme (DAS), which reserves the slots on a packet-by-packet basis is given in [33]. Each node in the network consists of a fixed wavelength transmitter and a tunable receiver capable of tuning over the entire wavelength range. Each node has a fixed wavelength transceiver for the control channel λ_0. All nodes in the network maintain a queue status of all other nodes in the network. This can be done through passing signalling information on the control channel. The control channel is time slotted using TDM and each minislot in the frame is preassigned to a node. All the nodes execute an identical algorithm which selects packets from each node. This algorithm is executed at the beginning of each slot and each transmitter and receiver know from which queue a packet will be transmitted/received in the next slot. For the interprocessor communications applications, Slotted-ALOHA protocols were analyzed in [34]. The network uses tunable transmitters and fixed wavelength receivers.

A similar network architecture is discussed in [35]. The channels are slotted with data slots on data channels and status slots on the control channel. Each status slot is divided into M minislots, where M is the number of users. In a minislot, each node can transmit a status packet which contains a destination address, a delay D and the transmission mode of the transmitter. This transmission mode is used to indicate whether the operation is packet switched or circuit switched. The delay (D) parameter is the delay experienced by a packet since its arrival at the source. This delay for each packet is calculated as the sum of delay until the transmission instant and the time taken by the packet to reach the hub from that station. Each node transmits a status packet, if there is a packet scheduled for transmission in its queue. Since each receiver monitors the control channel, it knows if there are any data packets intended for it in the next slot. If there is more than one packet, the receiver invokes an arbitration algorithm, which may select only a packet from a transmitter in a circuit switched mode, or a packet experiencing the longest delay. Thus the algorithm supports hybrid switching. Since each node has one tunable receiver, only one packet can be received and the other packets are discarded. This problem is solved through delay lines in [36], in which QUADRO (Queuing of Arrivals for Delayed Reception Operation) was introduced. In this protocol, the receiver uses optical delay lines to buffer packets when more than one packet arrives in a slot on a different channel. If no packets are received in the next slot, the nodes can read packets from the delay lines. Also in [36], the reception strategies Last In First Out (LIFO), First In First Out (FIFO) and OPR (Oldest Packet in the Receiver) as well as the transmission strategies Random and FIFO were examined. These operations provide better results than the unbuffered case of [35].

A fast scheduling algorithm based switching protocol is given in [37]. In this protocol, users need two fixed wavelength transmitters, one at a control channel wavelength and the other at the data channel wavelength assigned to that user. Users also need two receivers, one fixed tuned filter to the control channel and the other a tunable filter. The time is slotted on both data and control channels. The control slot is further divided into N minislots, where the i^{th} minislot is assigned to user i. This control channel is used to announce (broadcast) the arrival of new packets and their destinations to all the users in the network. All users maintain a set of variables for a distributed conflict free algorithm. Since the users always monitor the control channel, th y maintain a backlog status matrix B in which the element b_{ij} indicates how many packets are destined to user j from user i. After each control slot, users update the matrix B and compute a transmission matrix T, in which $t_{ij} = 1$ means that user i can transmit to user j, else $t_{ij} = 0$. The matrix T is generated from matrix B using a sub-optimal Maximum Remaining Sum (MRS) algorithm.

Collision Avoidance Protocols

In the random access protocols considered upto now, the transmitting nodes ignored receiver collisions. There are two types of receiver collisions possible in multichannel networks. The first type occurs when multiple users send packets to the same user. The user may receive complete control information from transmitting users, and may be aware of the receiver collision. If the user is equipped with only one receiver, it can be tuned to only one channel thus ignoring the others. The second type occurs when users want to transmit data packets to a busy user tuned to some other channel. In this type, the receiver cannot receive the control and data packets from other users. This can happen in access protocols (such as ALOHA), in which, the receiver of a node may be tuned to the same transmitting wavelength to monitor any possible packet collisions. Normally, in slotted access protocols, the control and data slots are defined separately and thus the second type of receiver collision cannot occur. In a network environment with a large population of users and a small set of channels, receiver collisions are considered to be rare.

But with dense WDM, many logical channels can easily be created and the receiver collisions cannot be neglected. In [38], the receiver collisions are considered for the improved Slotted-ALOHA/ALOHA protocol of [27] in which throughput reductions were observed. If possible, these receiver collisions should be avoided and some proposals were made in the literature for passive star networks.

A passive star network with a Protection Against Collision (PAC) circuit is described in [39]. This network uses two star couplers, one the network star and the other a control star coupler. Each user has a tunable transmitter and a fixed tuned receiver. Each fixed tuned receiver is assigned its own unique wavelength. A user (i) sends a packet to another user (j) by tuning the transmitter to other user's (j) receiving wavelength. The network allows the users to access an addressed channel (receiver), only if that channel is available thus avoiding the packet collisions. Users are also denied access to the star, if there is more than one packet addressing the same available channel. To do this, each user has a PAC circuit located at the central hub and this circuit probes the state of the addressed channel by transmitting a n bit carrier burst that precedes the packet. This carrier burst is switched through the control star coupler, where it is combined with a fraction of all packets coming out of the network star and the carrier bursts from other users. The resulting signal is used to control an optical switch provided in the PAC circuit. This control signal opens the switch, if there is some energy on the addressed channel from the control star, else the switch is closed. Since this switch is connected to the input fiber to the network star, it disallows the users to simultaneously address the same channel.

A receiver collision avoidance (RCA) protocol is proposed in [40] which is capable of detecting and avoiding receiver collisions before packets are transmitted. The network consists of one control channel and several data channels. All the nodes are assumed to be synchronized. The control packets are assumed to fit in one slot and data packets have a duration of L slots. Each cycle is defined to be L slots in length. Nonzero tuning (T slots) and propagation times ($d_p = D$ slots) are considered. A deterministic algorithm is performed for data channel selection by the nodes. For example when $N = L$, each control slot is numbered cyclically from 1 to N. That is, if a control packet is successful, the node uses the data channel whose number is assigned to that control slot. Each node maintains a Node Activity List (NAL), which contains the control channel history for the past $2T + L$ slots whereby each entry contains the slot number and a

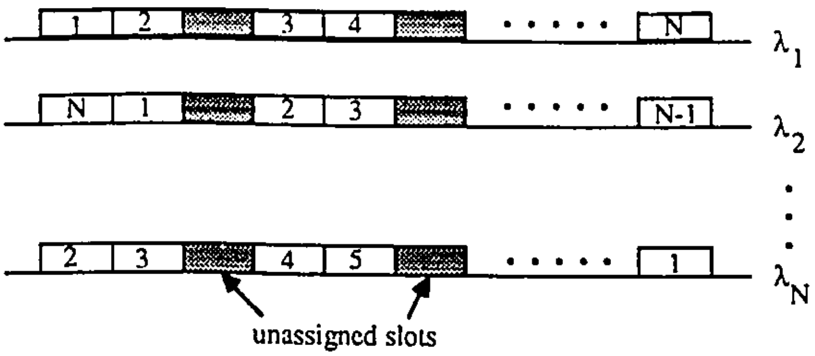


Figure 2.4: A hybrid TDM Protocol

status information. If a control packet is successful, the corresponding status is active or else it is quiet. If the status is active, the NAL entry contains the source, destination and the channel number. If node i wants to send a packet to node j, node i will send a control packet only if no control packet to node j was observed in the past $2T + L$ slots and if there is no packet scheduled to be received at node i. A receiver collision is detected if a successful control packet to node i is received during the $2T + L$ slots before the control packet returns and the packet transmission is aborted. Otherwise, if the control packet returns without a collision, the data packet is transmitted at the scheduled time. To receive a data packet, if the receiver receives a successful control packet and if no packet is scheduled for reception, the node receives the data packet at a scheduled time. Else, it ignores the control packet. Approximate analytical models were developed in [40] for this protocol.

Hybrid Protocols

A hybrid TDM scheme was also described in [33] which is a combination of the TDM and DAS (described above) schemes. In the general TDM scheme, all the data channels are divided in frames of N slots each. In the Hybrid TDM, a frame consists of $N + K$ slots, where K is an integer. The N slots are pre-assigned as in TDM, but after every n slots (where n is the next larger integer of N/K) one slot is left open, in which any node can transmit a packet to any other node (Fig. 2.4). Since collisions can occur in these open slots, users can follow the same random scheduling algorithm which was used in the DAS scheme. In the DAS scheme, N decisions on which packet to transmit have to be taken for every N slots, whereas in Hybrid

TDM only K such decisions for every $N + K$ slots are needed. Both simulation and analytical studies were done for these schemes in [33]. The hybrid scheme has a lower signalling overhead and is better than TDM under low loads and uniform traffic conditions. One main advantage is that the protocol can handle bursty traffic.

2.3 A LAN Using Point-to-Point Links

The network in [41] uses simple point-to-point links. Single-hop Space Division Multiplexing (SDM) is not feasible in a LAN environment due to the large population of users. If multihop approach is used, then SDM can offer an attractive solution and flooding is a simple way to avoid the look-up table based routing in such SDM network. Another advantage of this network is that it only needs simple light sources and receivers. The protocol proposed in [41] uses a small address packet to setup a call between the source and the destination. This packet is transmitted through the network using flooding [1] and a simple protocol is used to establish an end-to-end path. Once this path is setup, the actual call starts and the established path is not interrupted by other call setup flooding attempts or other calls in the network. A simple tree network yields about 66% capacity for average blocking delays.

In reference [42], twelve random access strategies were described for fiber optic networks that do not constrain the distance or transmission rate of the network. These twelve strategies use the three standard protocols ALOHA, CSMA, CSMA/CD in conjunction with two timing arrangements (slotted or unslotted) and two types of network devices (active or passive) and provide a mechanism for trading time synchronization, signal processing and tap structure for throughput. The slotted systems adjust the transmission times of the various sources such that all packets (fixed-size) arrive at a common point in the network at the same instant and signal processing is used to avoid collisions.

2.4 Summary

In Chapter 1, some optical fiber based network architectures were reviewed and this chapter described media access protocols. These protocols are generally classified into fixed-assignment, random access and hybrid protocols. The random access protocols are further classified into reservation, switching and collision avoidance. Some more reviews for the media access protocols can be found in [43, 44]. Still a lot of work can be done in both areas of high-speed fiber based network architectures and protocols. Here, our main interest is in multi-channel networking. For example, the simple ALOHA/ALOHA protocol can be improved by considering both the control and data channels as time slotted channels. Similarly, when users have more than one packet to transmit to the same destination reservation protocols yield better throughput than the random access techniques. Many reservation protocols were proposed for broadcast networks [1] and the same can be extended to optical fiber LANs. As mentioned before, CSMA protocols are not well suited for very high-speed networks and ALOHA type protocols do not yield a larger throughput. However, the ALOHA protocols can be used in a simple way to reserve the data channels where the reservation is based on simple contention. In the next chapter, we present Slotted-ALOHA and Reservation ALOHA protoocols for the multi-channel optical star networks.

Chapter 3

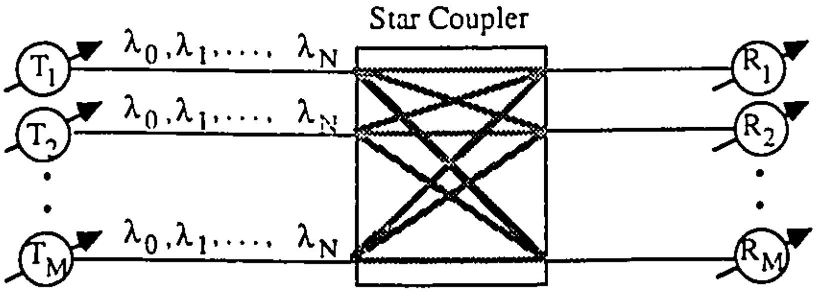
Extended Slotted & Reservation ALOHA Protocols for Passive Optical Star Networks

In the previous chapters, a Multichannel Local Area Network (M-LAN) using a passive star topology is described. One important issue of M-LANs is the channel access methed users have to follow if they choose to randomly access the network. A number of random access protocols were introduced in [23] for very high-speed Optical fiber local area networks using a passive star topology. These random access schemes are based upon the well known contention protocols such as ALOHA, CSMA etc., which are widely used in many networks. In [27], some improved protocols using ALOHA techniques are presented for the same architecture given in [23]. ALOHA is the well-known protocol mechanism [45] in which users of the network access the channel without any co-ordination among themselves. For CSMA protocols to achieve high maximum throughput in high-speed networks, the packet length should be much larger than the propagation delay [23]. Otherwise, the efficiency of CSMA protocols becomes very low. However, ALOHA protocols can be used in such environments as the protocol performance does not depend upon the packet lengths. It is well known that Slotted-ALOHA protocols achieve better throughput than corresponding unslotted ALOHA protocols. Thus, in this chapter, various cases of Slotted-ALOHA and Reservation ALOHA protocols are presented and analyzed for the same architecture given in [23]. This chapter is organized as follows: Section 3.1 describes the network architecture. In Section 3.2, Slotted-ALOHA protocols are presented and analyzed and in Section 3.3, Improved Slotted-ALOHA protocols are presented. Section 3.4 describes Reservation ALOHA protocols for the same architecture and Section 3.5 concludes this chapter with results.

3.1 Network Architecture of the High Speed Optical LAN

The hardware architecture of the network given in [23] is shown in Fig. 3.1. The fiber bandwidth is divided into $N+1$ channels, each using a different wavelength. There are $M (M > N)$ users in the network. Users are connected to the central passive star coupler. It is assumed that each user has a tunable optical transmitter and a tunable optical receiver, which can be tuned over the set of wavelengths utilized in the network. The bandwidth of the optical fiber is divided among a set of wavelengths $\{\lambda_0, \lambda_1, \ldots, \lambda_N\}$ and each user can transmit on λ_i and receive on λ_j, where λ_i and λ_j are members of the above set. Since this is a multichannel system, the wavelength λ_0 is used as a control channel for co-ordination of access among the users. We assume that all idle users are tuned to λ_0, i.e, they monitor the control channel. The control channel is used to transmit the control information and actual data is transmitted on λ_i, $\lambda_i \in \{\lambda_1, \ldots, \lambda_N\}$. The general access mechanism of the network is as follows: If user i has a data packet for user j, then user i must first randomly choose a data channel (on which the data packet will be transmitted). Then user i will inform user j about the selected data channel by transmitting a control packet (which contains the source address, destination address and the chosen data channel number) on the control channel λ_0 and then transmit a data packet on the chosen data channel λ_i. If user j is idle, it will receive the control packet (since all idle users always monitor the control channel) and immediately tune its receiver to the data channel λ_i for the data packet from user i.

Since it is assumed that the number of users is higher than the number of available data channels, both data and control channels should be accessed by users on a contention basis. Reference [23] describes a number of protocols of the form X/Y where X and Y denote the random access methods used on control and data channels, respectively. The protocols studied in [23] are ALOHA/ALOHA, Slotted-ALOHA/ALOHA, ALOHA/CSMA, CSMA/ALOHA and CSMA/N-server switch. These are described briefly in Section 2.2.2. When the ALOHA protocol is used on the control channel, the data packet is sent irrespective of whether the control packet is



T_i : Transmitter 'i' R_i : Receiver 'i' λ_k : Wavelength 'k'

Figure 3.1: A General Optical Star Network Architecture

successful or not. This causes a reduction in throughput and [27] proposes an Improved Slotted-ALOHA/ALOHA protocol where a data packet is sent only if the corresponding control packet is successful.

In section 3.2 and 3.3, various cases of Slotted-ALOHA techniques are considered, which can be used for the same architecture given in [23]. In section 3.2, six cases of Slotted-ALOHA protocols are given. Some of these protocols can be improved further by transmitting the data packet only if their control packet is successful [27] and section 3.3 presents the improved versions of these six cases. In section 3.4, two cases of Reservation ALOHA protocol are presented. In all these protocols, both data and control channels are slotted using major and minor timing references. The slots using the major timing reference are called 'cycles'. The control channel cycles are further divided into 'minislots' (which are also called as control slots) using minor timing reference. The cycle is also divided into data slots on each data channel. The protocols described below are classified according to the assignment of the control slots and when a data packet is transmitted. In Cases 1, 2 and 6 of Slotted-ALOHA and Improved Slotted-ALOHA, the control slots are pre-assigned to a data slot. However, there is no such assignment in Cases 3, 4 and 5. Since all idle users monitor the control channel in this architecture, slot synchronization can easily be achieved by transmitting timing pulses on the control channel by a master timing station. However, a station does not listen to the control channel if it is transmitting or receiving a packet. Hence, to achieve full synchronization, a dedicated channel and fixed wavelength receiver can be used instead. The analysis of these protocols is done assuming an infinite population model and Poisson arrivals on the control channel. Since there is no co-ordination among users, there is no way for a user to know the status of other users. Hence a user may transmit a packet to a busy receiver who is either transmitting or receiving from some other user. This is called receiver collision and is ignored in the present analysis.Immediate feedback about the success of the transmitted packet, negligible propagation delay and infinite retransmission scheduling for transmitting an unsuccessful packet are assumed; that is, a packet is retransmitted till it is successful. The random retransmission time associated with each retransmission depends upon the particular back-off strategy being used. In all the following protocols, no particular back-off strategy is assumed. The chapter on implementation issues considers the effect of non-zero propagation delay and switching latency in a unified way for all the protocols presented in this thesis. The following notations are used in this chapter:

$N =$ number of data channels in the system

$L =$ length of a data packet (control packet is assumed to be of unit length)

$G =$ average number of control packets transmitted per slot on a control channel

$G_d =$ average number of data packets transmitted per slot on a data channel

$P_c =$ Probability of success of a control packet on a control channel in a control slot

$P_d =$ Probability of success of a data packet on a data channel in a data slot, given that its corresponding control packet is successful in a corresponding minislot

$P_s =$ Total probability of success of a data packet in a 'cycle' (This may depend upon P_c and/or P_d)

$P_r =$ Retransmission probability of a given packet in a 'cycle'

$S_d =$ Throughput per data channel $= G_d.P_s$

$R =$ Average number of retransmissions $= \frac{1}{1-P_r}$, (In this $R-1$ are unsuccessful attempts and one final successful transmission)

$T =$ length of a 'cycle'

$t_r =$ average length of a retransmission (back-off) period

$d_w =$ average time a packet has to wait from the time it is generated till the beginning of the next cycle

$d_r =$ average total retransmission delay$=$ $(R-1)\times$ mean retransmission delay per unsuccessful attempt

$d_t =$ average time to transmit a message

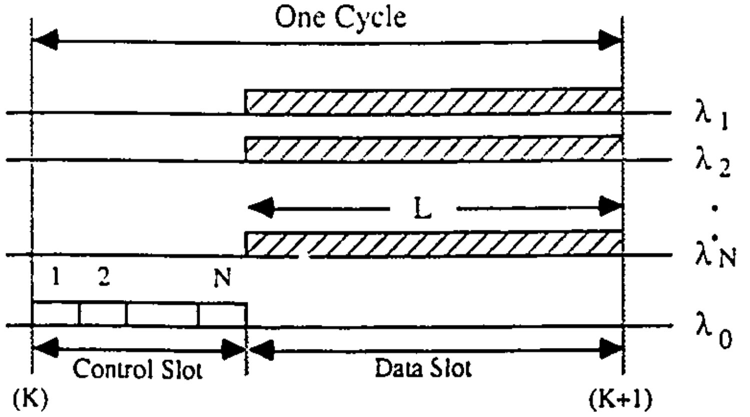


Figure 3.2: Slotted-ALOHA for Case 1

3.2 Slotted-ALOHA Protocols

Since Slotted-ALOHA protocols offer better throughput than corresponding unslotted ALOHA protocols, let us see how the multichannel LAN with both control and data channels can be slotted.

Case 1: As shown in Fig. 3.2, both control and data channels are slotted using the same time reference. This we call as one 'cycle'. The control channel is further divided into N minislots, where N is the number of channels. There are no minislots on the control channel after the N^{th} minislot and the data slots on all data channels start exactly after the N^{th} minislot. Since a user wishing to transmit a packet has to choose a data channel prior to transmission, we fix the assignment of minislots. That is, a user wishing to transmit in $[K, K+1)$ cycle on i^{th} channel will transmit a control packet on i^{th} minislot of the control channel and transmit the data packet after the N^{th} minislot. Although, some bandwidth is wasted this way on both control and data channels, this scheme presents a simple way to slot the channels. Due to the fixed assignment of a control slot for each channel, if a control packet is successful in a control slot then the corresponding data packet will be successful. Hence, the retransmissions of a given packet will only depend upon the success of a control packet. This implies P_r will only be dependent upon P_c. In this and in all the following protocols, the total delay to transmit a packet from source to destination has three components. The first one is the average time d_w a packet has to wait from the time it is generated at a station till the beginning of the next cycle. The second component is the total retransmission delay d_r. This is the total delay involved in $(R-1)$ unsuccessful attempts. The delay for each unsuccessful attempt includes the time to transmit the packet and the corresponding back off delay. The third part is the delay d_t in transmitting the successful packet. The total delay is the sum of the above three components. No particular back-off strategy is assumed.

Analysis: Let G be the average aggregate number of packets offered per control slot (mini slot). Hence, in this case, there is one data packet for each offered control packet. Therefore,

$$G_d = G \tag{3.1}$$

$$P_c = e^{-G} = (1 - P_r) \text{ and}$$

$$P_d = 1; \text{ (since a successful control packet means successful data packet)}$$

$$P_s = P_c.P_d = e^{-G} \tag{3.2}$$

$$S_d = G_d.P_s = Ge^{-G} \tag{3.3}$$

$$\begin{aligned} S1 &= \text{average number of successful packets transmitted per cycle} \\ &= \frac{L}{L+N}S_d = \frac{L}{L+N}Ge^{-G} \end{aligned} \tag{3.4}$$

$$R = \text{average number of retransmissions} = \frac{1}{1-P_r} = e^G \tag{3.5}$$

$$T = \text{duration of a cycle} = L + N$$

$$d_w = T/2\,;\; d_r = (R-1).(T+t_r)\,;\; d_t = T$$

$$\begin{aligned} D1 &= \text{average delay} = d_w + d_r + d_t \\ &= \frac{T}{2} + (R-1).(T+t_r) + T \\ &= (L+N).e^G + \frac{L+N}{2} + (R-1).t_r \end{aligned} \tag{3.6}$$

Case 2: This is an extension to Case 1. Here, both the control and data channels are divided into slots of length L each as shown in Fig. 3.3. The control slot is further divided into N minislots and we follow the same preassignment of these slots as in Case 1. That is, a user ready in $[K-2, K-1)$ cycle and wishing to transmit on i^{th} data channel will transmit a control packet on i minislot in $[K-1, K)$ cycle and corresponding data packet on i data channel in $[K, K+1)$ cycle. The analysis is similar to Case 1. The throughput and delay are given by:

$$S2 = S_d = Ge^{-G} \tag{3.7}$$

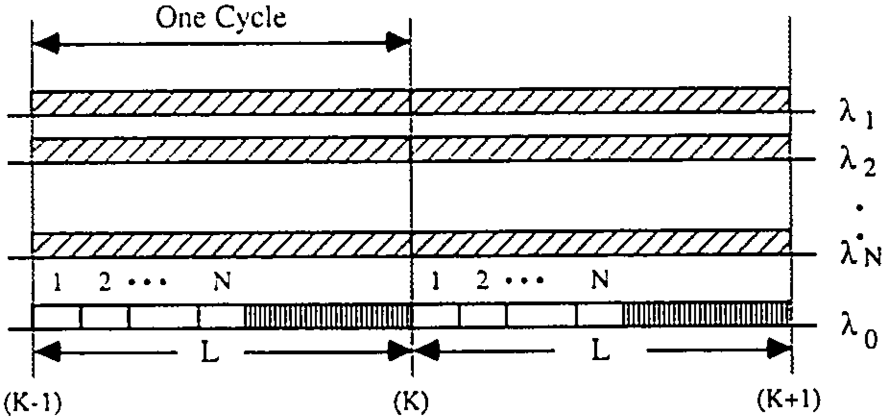


Figure 3.3: Slotted-ALOHA for Case 2

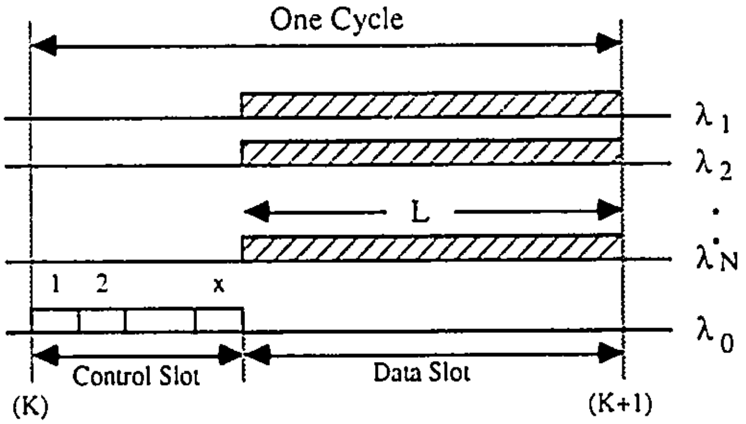


Figure 3.4: Slotted-ALOHA for Case 3

$$
\begin{aligned}
R &= e^{G} \,;\; T = L \\
d_w &= T/2 \,;\; d_r = (R-1).(2T + t_r) \,;\; d_t = 2T \\
D2 &= \text{average delay} = d_w + d_r + d_t \\
&= 2L.e^{G} + \frac{L}{2} + (R-1).t_r \qquad (3.8)
\end{aligned}
$$

Case 3: This case is similar to Case 1, except that, the control channel is divided into x minislots (Fig. 3.4) and there is no preassignment of these minislots. That is, a user wishing to transmit data in $[K, K+1)$ slot on i channel, will transmit the control packet in any one of the minislots and a data packet on i channel after the x^{th} minislot. In this case, the retransmission probability and total probability of success of a given data packet will depend upon both P_c and P_d since a successful control packet does not necessarily imply a successful data packet.

<u>Analysis:</u> Since a packet is equally probable to any of the N channels and there are x minislots on the control channel per cycle, we have,

$$\begin{aligned} G_d &= \frac{Gx}{N} \\ P_c &= e^{-G} \end{aligned} \tag{3.9}$$

To calculate P_d, let us consider one data channel, say channel 1 for example. Suppose our test control packet is transmitted on the i minislot whose data is to be transmitted on channel 1. For this data packet to be successful, there should not be any transmission on data channel 1 whose control packet is transmitted in any of the remaining $x - 1$ minislots (here a data packet is transmitted whether a control packet is successful or not).

$P_d = P$(no transmissions of control packets in remaining $(x - 1)$ slots

whose data packets are to be transmitted on data channel 1)

$= [P$(no control packet to channel 1 in one minislot)$]^{(x-1)}$

P(no control packet to channel 1 in one minislot)

$= \sum_{i=0}^{\infty} P$ (no packets to channel 1 | i arrivals in one minislot).P(i arrivals)

where $P(i \text{ arrivals}) = \frac{G^i e^{-G}}{i!}$ and

P(no packets to channel 1 | i arrivals in one minislot) $= (1 - \frac{1}{N})^i$

P (no control packet to channel 1 in one minislot) $= \sum_{i=0}^{\infty}(1 - \frac{1}{N})^i \frac{G^i e^{-G}}{i!} = e^{\frac{-G}{N}}$

$$P_d = [e^{\frac{-G}{N}}]^{(x-1)} = e^{[-G(x-1)/N]}$$

$$P_s = P_c.P_d = [e^{-G}].[e^{(-G(x-1)/N)}] = e^{[-G-G(x-1)/N]} = (1 - P_r) \tag{3.10}$$

$$S_d = P_s.G_d = \frac{Gx}{N}.e^{-[1+(x-1)/N]G} \text{ and} \tag{3.11}$$

$$\begin{aligned} S3 &= \text{average number of packets successfully transmitted per cycle} \\ &= \frac{L}{L+x} S_d = \frac{L}{L+x} \frac{Gx}{N} e^{-[1+(x-1)/N]G} \end{aligned} \tag{3.12}$$

$$\begin{aligned} R &= \text{average number of retransmissions} \\ &= \frac{1}{1-P_r} = e^{[G+G(x-1)/N]} \end{aligned} \tag{3.13}$$

$$T = (L + x) \,;\, d_w = T/2 \,;\, d_r = (R-1).(T + t_r) \,;\, d_t = T$$

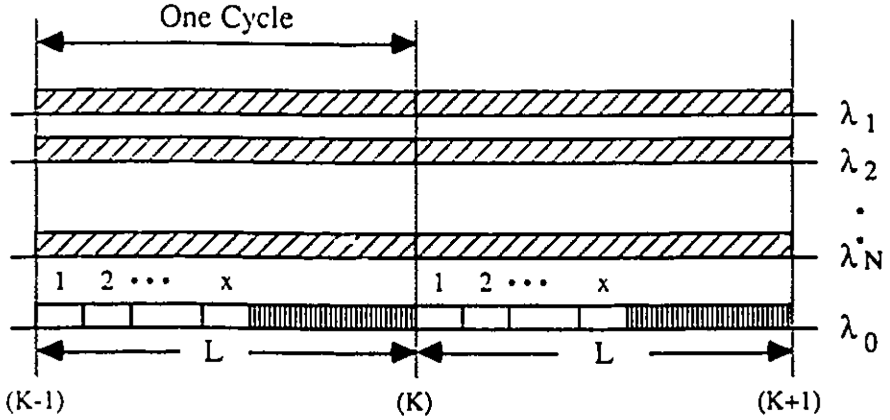


Figure 3.5: Slotted-ALOHA for Case 4

$$\begin{aligned} D3 &= \text{average delay} = d_w + d_r + d_t \\ &= (L+x).e^{[G+G(x-1)/N]} + \frac{L+x}{2} + (R-1).t_r \qquad (3.14) \end{aligned}$$

Case 4: This is an extension to Case 3. Here, both the control and data channels are divided into slots of length L each as shown in Fig 3.5. The control slot is further divided into x minislots and there is no preassignment of these slots as in Case 3. That is, a user ready in $[K-2, K-1)$ cycle and wishing to transmit on i data channel will transmit a control packet in any one of the x minislots in $[K-1, K)$ cycle and corresponding data packet on i data channel in $[K, K+1)$ cycle. The analysis is similar to Case 3. Its throughput is given by Eq. 3.12. A similar kind of slotting technique is used recently in [31] for the same network architecture, but with a different access protocol.

$$S4 = S_d = \frac{Gx}{N}.e^{-[1+(x-1)/N]G} \qquad (3.15)$$

$$R = e^{[G+G(x-1)/N]} \; ; \; T = L$$

$$d_w = T/2 \; ; \; d_r = (R-1).(2T+t_r) \; ; \; d_t = 2T$$

$$D4 = \text{average delay} = 2L.e^{[G+G(x-1)/N]} + \frac{L}{2} + (R-1).t_r \qquad (3.16)$$

Case 5: This is a special case of Case 4, with $x = L$, i.e., there are L minislots per control slot and a user wishing to transmit data can send the control packet in any one of the L minislots

$$S5 = S_d = \frac{GL}{N}.e^{-[1+(L-1)/N]G} \qquad (3.17)$$

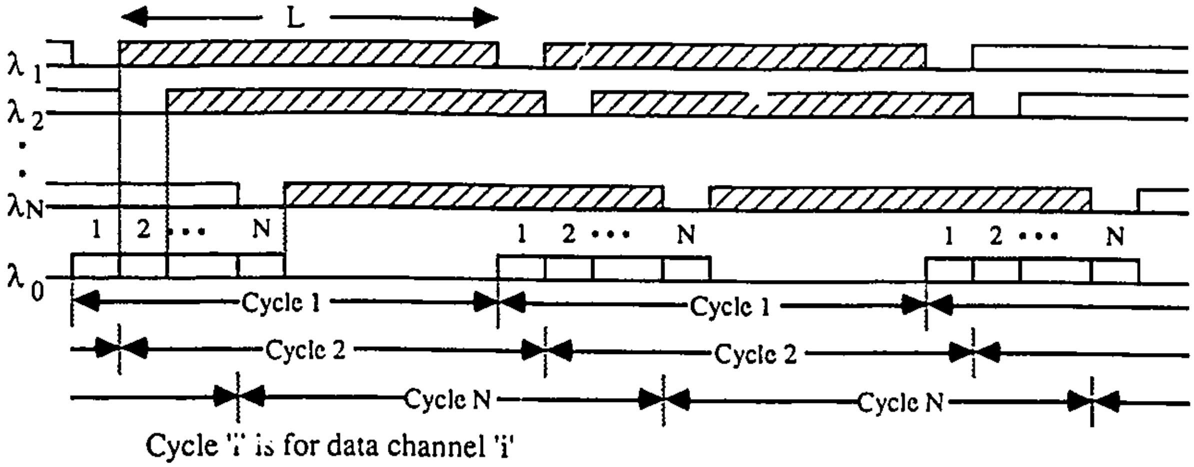


Figure 3.6: Slotted-ALOHA for Case 6

$$
\begin{aligned}
R &= e^{[G+G(L-1)/N]}\,;\ T = L\,; \\
d_w &= T/2\,;\ d_r = (R-1).(2T+t_r)\,;\ d_t = 2T \\
D5 &= \text{average delay} = 2L.e^{[1+(L-1)/N]G} + \frac{L}{2} + (R-1).t_r \qquad (3.18)
\end{aligned}
$$

Case 6: In this case, each channel has it's own cycle, each of duration $(L+1)$ minislots (Fig 3.6). In Fig. 3.6, cycle i represents the cycle of data channel i. If a user has data to transmit, first the user has to choose a data channel, wait for the beginning of the cycle on the selected channel, transmit the control packet and then transmit the corresponding data packet *immediately* on the selected channel. In all the earlier cases, the retransmission strategy is not fixed. That is, if a user's transmission is unsuccessful during the current cycle, the user could select any other channel (not necessarily the same channel chosen in earlier cycle) with equal probability and try the retransmissions in the next cycle. But, due to the slotting technique used in this protocol, we assume that the retransmission will be done on the same selected channel till the packet is successfully transmitted.

Analysis: In this case, for each data channel, we have,

$$
\begin{aligned}
G_d &= G \qquad (3.19) \\
P_c &= e^{-G} \text{ and } P_d = 1 \\
P_s &= e^{-G} = (1-P_r) \qquad (3.20)
\end{aligned}
$$

$$
\begin{aligned}
S_d &= Ge^{-G} \\
S6 &= \frac{L}{L+1} S_d = \frac{L}{L+1} Ge^{-G} \qquad (3.21) \\
R &= e^{G}\,;\ T = L+1 \\
d_w &= T/2\,;\ d_r = (R-1).(T+t_r)\,;\ d_t = (L+1) \\
D6 &= \text{average delay} \\
&= e^{G}.(L+1) + \frac{L+1}{2} + (R-1).t_r \qquad (3.22)
\end{aligned}
$$

3.3 Improved Slotted-ALOHA Protocols

In [27], a variation to the protocols given in [23] is presented. Here, a data packet is transmitted only if the corresponding control packet is successful on the control channel. We apply the same technique for various cases mentioned in section 3.2 above. In all the following cases, it is assumed that a data packet will be transmitted only if corresponding control packet is successful. This causes a reduction in delay for certain cases. Since G is the average number of control packets transmitted per control slot, then Ge^{-G} packets will be offered to the data channel per every control slot.

Case 1: This case can also be used for the Reservation ALOHA scheme, which is described in Section 3.4. In this case, a successful control packet implies successful transmission of a data packet. Since any channel can be uniformly selected between 1 and N, the average control packet transmission time is $(N+1)/2$. Therefore,

$$
\begin{aligned}
G_d &= Ge^{-G} \\
P_s &= P_d = 1 \text{ and} \\
P_c &= e^{-G} = (1-P_r) \\
S_d &= G_d.P_s = Ge^{-G} \text{ and} \\
S1 &= \frac{L}{L+N} Ge^{-G} \text{ which is the same as Eq. 3.5} \qquad (3.23) \\
R &= \text{average retransmissions} = \frac{1}{1-P_r} = e^{G} \\
T &= (L+N)\,;\ d_w = T/2\,;\ d_r = (R-1).\left(\frac{N+1}{2} + t_r\right)\,;\ d_t = T \\
D1 &= (L+N) + \frac{L+N}{2} + (R-1).\left(\frac{N+1}{2} + t_r\right) \qquad (3.24)
\end{aligned}
$$

Case 2: For this case,

$$\begin{aligned} P_s &= P_d = 1 \text{ and } P_c = e^{-G} = (1 - P_r) \\ S2 &= Ge^{-G} \qquad (3.25) \\ R &= e^G \,;\, T = L \,;\, d_w = T/2 \,;\, d_r = (R-1).\left(\frac{N+1}{2} + t_r\right) \,;\, d_t = 2T \\ D2 &= 2L + \frac{L}{2} + (R-1).\left(\frac{N+1}{2} + t_r\right) \qquad (3.26) \end{aligned}$$

Case 3: Here,

$G_d = \frac{Gx}{N}.e^{-G}$

P_d = P[successful transmission of data packet on given channel]

= P[successful transmission of one control packet whose data is to be transmitted on given channel in one of the x minislots]

= P[no successful transmission of control packet whose data is to be transmitted on given channel in remaining $(x-1)$ slots]

={P[no successful transmission of control packet whose data is to be transmitted on given channel in one minislot]}$^{(x-1)}$

But,

P[no successful transmission of control packet whose data is to be transmitted on given channel in one minislot] =

= 1 - P[successful transmission of control packet whose data is to be transmitted on given channel in one minislot]

= 1 - P[successful transmission of control packet whose data is to be transmitted on given channel | one arrival] . P[one arrival]

$= 1 - \frac{1}{N}.Ge^{-G} = 1 - \frac{G}{N}e^{-G}$

Therefore,

$P_d = P_s = [1 - \frac{G}{N}e^{-G}]^{x-1}$ and $P_c = e^{-G}$. But retransmission will take place if both data and control packet are not successful. Hence,

$$\begin{aligned} P_r &= (1 - P_c.P_d) \\ R &= \frac{1}{1-P_r} = \frac{e^G}{[1 - \frac{G}{N}e^{-G}]^{x-1}} \end{aligned}$$

$$S_d = G_d.P_s = \frac{Gx}{N}e^{-G}.[1 - \frac{G}{N}e^{-G}]^{(x-1)} \tag{3.27}$$

$$S3 = \frac{L}{L+x}S_d = \frac{L}{L+x}.\frac{Gx}{N}e^{-G}.[1 - \frac{G}{N}e^{-G}]^{(x-1)} \tag{3.28}$$

$$T = (L+x)\ ;\ d_w = T/2\ ;\ d_r = (R-1).\left(\frac{x+1}{2} + t_r\right)\ ;\ d_t = T$$

$$D3 = (L+x) + \frac{L+x}{2} + (R-1).\left(\frac{x+1}{2} + t_r\right) \tag{3.29}$$

Case 4: The throughput equation for this case is the same as S_d of Case 3 but the delay is higher.

$$S4 = \frac{Gx}{N}e^{-G}.[1 - \frac{G}{N}e^{-G}]^{(x-1)} \tag{3.30}$$

$$R = \frac{e^G}{[1 - \frac{G}{N}e^{-G}]^{x-1}}$$

$$T = L\ ;\ d_w = T/2\ ;\ d_r = (R-1).\left(\frac{x+1}{2} + t_r\right)\ ;\ d_t = 2T$$

$$D4 = 2L + \frac{L}{2} + (R-1).\left(\frac{x+1}{2} + t_r\right) \tag{3.31}$$

Case 5: This is Case 3 with $x = L$. Therefore,

$$S5 = \frac{GL}{N}e^{-G}.[1 - \frac{G}{N}e^{-G}]^{(L-1)} \tag{3.32}$$

$$R = \frac{e^G}{[1 - \frac{G}{N}e^{-G}]^{L-1}}$$

$$D5 = 2L + \frac{L}{2} + (R-1).\left(\frac{L+1}{2} + t_r\right) \tag{3.33}$$

Case 6: This case can also be used for Reservation ALOHA, which is described in Section 3.4. As in Case 6 of the last section, we assume that, if a user has data to send, the user first selects one of the N channels uniformly and then, uses the same channel till the packet transmission is successful. In this case, a data packet is transmitted only if the corresponding control packet is successful. In this case, we have, $G_d = Ge^{-G}$ and $P_s = P_d = 1$, $P_c = e^{-G} = (1 - P_r)$. Therefore for each channel,

$$S_d = Ge^{-G}$$

$$T = L+1\ ;\ R = e^G$$

$$S6 = \frac{L}{L+1}.S_d = \frac{L}{L+1}.Ge^{-G} \tag{3.34}$$

$$\begin{aligned} d_w &= T/2\,;\, d_r = (R-1).(1+t_r)\,;\, d_t = (L+1) \\ D6 &= (L+1) + \frac{L+1}{2} + (R-1).(1+t_r) \end{aligned} \tag{3.35}$$

It can be seen that the performance of Cases 1, 2 and 6 of the Improved Slotted-ALOHA is the same as the corresponding Cases 1, 2 and 6 of Slotted-ALOHA protocols. However, there is an improvement in Cases 3, 4 and 5. The delay for Case 2 is also reduced.

3.4 Reservation ALOHA (R-ALOHA)

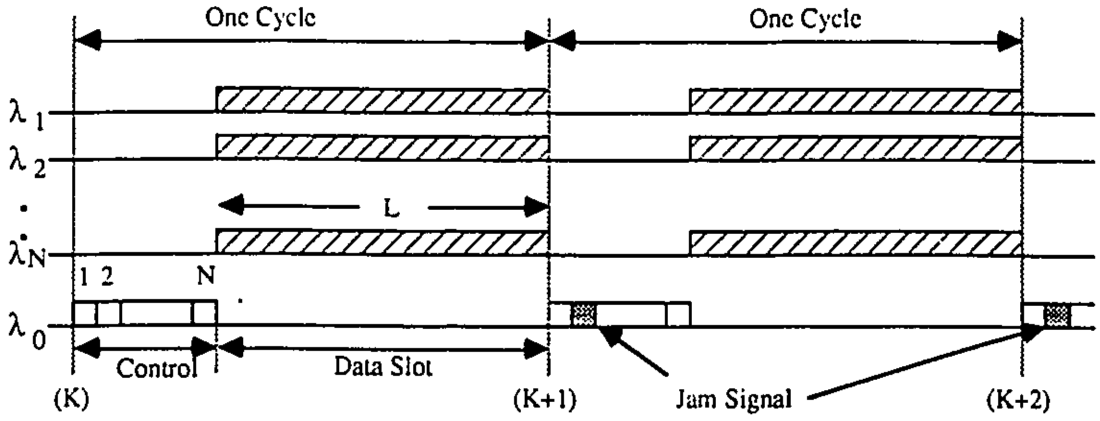
For packet broadcast networks, when a user has to transmit longer messages (which can be broken into multiple data packets), it is better to use reservation techniques for accessing the channel for increased throughput. The R-ALOHA [46] is a protocol proposed for packet broadcast networks which makes use of both the contention and reservation schemes. This protocol is described and analyzed in [46]. The single broadcast channel is divided into slots in time and each slot is further divided into N minislots. But, each user of this network has to obey certain rules in accessing the network:

- If in a slot 'm' of the previous frame, user X had a successful transmission, then slot 'm' is off limits to everyone except user X and slot 'm' is said to be reserved for user X
- All the unused slots (including the slots in which there is unsuccessful transmission) are available for all users and are to be accessed on a contention basis.

Two protocols are proposed in [46], depending upon whether the user announces an end-of-use flag in the last packet or not. In [46], this protocol is analyzed for a population of M users and for two cases of single message users (where each user handles only one message at a time) and queued users (where each user has infinite buffer and a queue is maintained for the arrivals). The throughput is given in terms of the Slotted-ALOHA throughput and delay analysis is done for both cases of users. Here, we are interested in the case of single message users and where the users include an end-of-use flag in the last packet. For this case, the throughput and delay are given by [46]:

$$U = \frac{S}{S + [(1-S)/\overline{v}]} \tag{3.36}$$

$$D = d_A + d_R = d_A + (\overline{v} - 1).T \tag{3.37}$$



Channel 2 is reserved in [K, K+1) cycle

Figure 3.7: Reservation ALOHA for Case 1

where U is the throughput of the R-ALOHA, S is the steady state Slotted ALOHA throughput, T is the duration of the frame, $\overline{v}$ is the average number of packets a user transmits before the user gives up, d_A is the mean delay incurred by a user to successfully transmit a packet into a non reserved time slot. The throughput U is maximum, when S is maximum.This implies that, maximum U occurs when $S = \frac{1}{e}$ which is the maximum possible throughput for Slotted-ALOHA. If each minislot is of duration L, then $T = N.L$. The second term d_R in the delay equation is the mean time required to transmit the remaining message. From Eq. 3.37, it can be seen that, even if d_A is small, the delay can still be very high due to T and h. If we use parallel channels instead of a single channel, the frame time can be reduced to an order of L and the data packets of N channels can be transmitted in parallel within this frame time, thus reducing the transmission delay. Since the optical LAN described here consists of N parallel channels, R-ALOHA can be effectively used and two simple schemes of R-ALOHA are described which make use of Cases 1 and 6 of the Improved Slotted-ALOHA protocols of section 3.3.

R-ALOHA (Case 1): Here, we make use of Case 1 of the Improved Slotted-ALOHA protocol. The data and control channels are slotted as described earlier in Case 1 and a user will transmit a data packet only if the corresponding control packet is successful (Fig. 3.7). If a user X has a successful transmission of both control and data packets in $[K, K+1)$ slot on λ_i channel, then X will use the same data channel for subsequent slots and transmit a 'jam' signal on i minislot till the session is finished. Since other users will transmit on λ_i only if their control packets are successful, the user who has a successful transmission of a control packet reserves the channel. The advantage with this scheme is that, users need not keep track of the channels which being used.

Analysis: We assume, a traffic of G packets/slot is offered for each channel (hence on each minislot) in every cycle. As usual, the traffic is assumed to be Poisson with parameter G. If the channel is already reserved, then a definite collision occurs on the control slot of that slot due to the jam signal and the traffic is said to be lost. Otherwise, users contend for the channel for a possible reservation. The user who grabs the channel, will transmit a message of mean length $\overline{v}$ (in slots) and we assume that the message length distribution is geometric. We follow the same approach given in [46] to find the throughput of the system. If any particular data channel is observed in the system, idle periods are embedded between the busy periods on this channel. The busy period corresponds to a reservation by a user and the corresponding message transmission. Idle period is the one in which users either did not contend (no arrivals to the channel) or collisions occurred. If G is the traffic offered per slot, then the probability that a data slot is idle $= 1 - S = 1 - Ge^{-G}$, where S is the Slotted-ALOHA throughput. Therefore, the Idle period distribution is given by,

$$P[t_{idle} = k \ slots] = (1 - S)^k S; \ k = 0, 1, 2, \ldots \text{ and}$$

$$E[t_{idle}] = \frac{1}{S} - 1$$

If the mean message length is $\overline{v}$, then

$$E[t_{busy}] = \overline{v}.$$

Therefore, the throughput U is given by,

$$\begin{aligned} U &= \frac{E[t_{busy}]}{E[t_{idle}] + E[t_{busy}]} \\ &= \frac{\overline{v}}{\left(\frac{1}{S} - 1\right) + \overline{v}} \\ &= \frac{S\overline{v}}{1 - S + S\overline{v}} = \frac{S\overline{v}}{1 + S(\overline{v} - 1)} \end{aligned}$$

The same equation is derived in [46] assuming a 'constant throughput assumption'; that is, a successful packet transmission occurs in every non reserved slot with a constant probability.

This assumption is necessary when users cannot offer traffic to the reserved channel. Under the condition that, similar traffic is offered in every cycle, our case becomes similar to the above assumption. The average delay can be found easily as follows:

Let P_s be the probability of success of acquiring a channel for each packet offered on the control slot. This probability will be the same for each slot (whether the channel is reserved or not), due to the assumption of geometric message length distribution. Since $\overline{v}$ is the average load each packet brings in to the channel and G is the traffic offered to the channel per slot, we have $G\overline{v}.P_s = U$. From this we get P_s as,

$$P_s = \frac{e^{-G}}{1 + S(\overline{v} - 1)}$$

and R, the average number of retransmissions as

$$R = \frac{1}{P_s} = \frac{1 + S(\overline{v} - 1)}{e^{-G}}$$

Since this is the Case 1 of Improved Slotted-ALOHA protocol, the delay components are given by:

$$T = (L + N)\ ;\ d_w = T/2\ ;\ d_r = (R - 1).\left(\frac{N+1}{2} + t_r\right)\ ;\ d_t = \overline{v}.T$$

Hence , the average throughput and delay per 'cycle' are given by:

$$U1 = \frac{L}{L+N}.U = \frac{L}{L+N}.\frac{S\overline{v}}{1 + S(\overline{v} - 1)} \tag{3.38}$$

$$D1 = \frac{L+N}{2} + (R - 1).\left(\frac{N+1}{2} + t_r\right) + \overline{v}.(L + N) \tag{3.39}$$

R-ALOHA (Case 2): Here, Case 6 of the Improved Slotted-ALOHA protocol is used (Fig 3.8). If user X has a successful transmission of a control packet in cycle i then the corresponding data channel i is reserved for that user and for subsequent cycles of that channel this user sends a 'jam' signal in the control slot of that cycle. Since the contending users will transmit a data packet only if their control packet is successful, this scheme reserves the channel for user X till the complete message is transmitted. The analysis is similar to Case 1 and the average throughput and delay are given by

$$U2 = \frac{L}{L+1}U = \frac{L}{L+1}\frac{S\overline{v}}{1 + S(\overline{v} - 1)} \tag{3.40}$$

$$D2 = \frac{L+1}{2} + (R - 1).(1 + t_r) + \overline{v}.(L + 1) \tag{3.41}$$

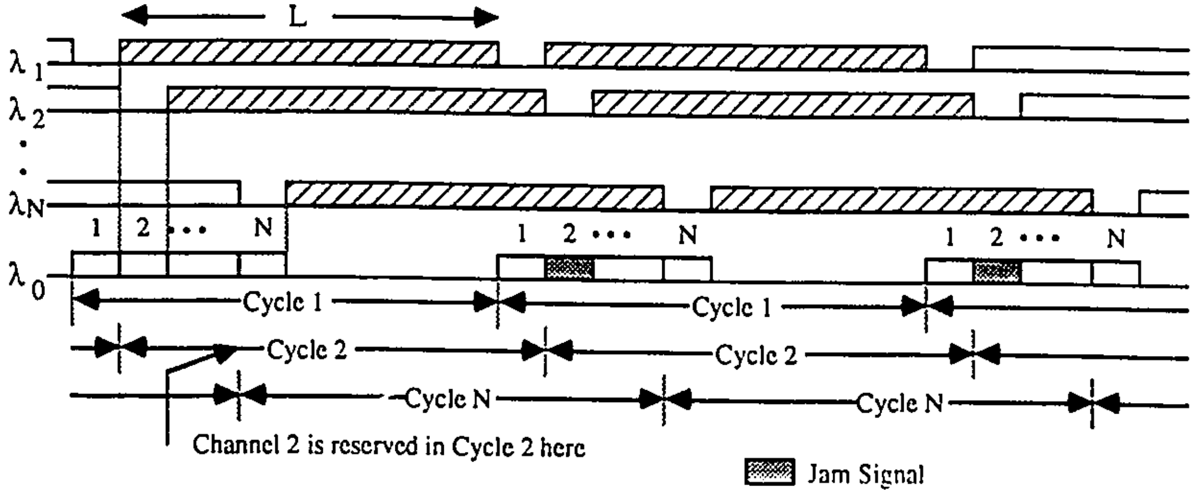


Figure 3.8: Reservation ALOHA for Case 2

where $T = L + 1$ is the cycle length. This case yields a slightly lower value of delay and better throughput than Case 1 of R-ALOHA.

3.5 Numerical Results

In this section, we plot various results (Fig. 3.9 to 3.21) from the above equations. All the plots are for a system of 10 data channels (N=10) and data slots of 100(=L) time units. In all these plots, the Slotted-ALOHA/ALOHA scheme of [23] is referred to as 'Original' and the Improved Slotted-ALOHA/ALOHA of [27] is referred to as 'Improved Original'. The throughput and delay equations for these cases are given below for reference:

$$SO = \frac{GL}{N}e^{-G}.[e^{\frac{-G}{N}}]^{2(L-1)} \tag{3.42}$$

$$DO = (L+1).e^{[1+\frac{2(L-1)}{N}]G} \tag{3.43}$$

and for the improved original case

$$SO_i = \frac{GL}{N}e^{-G}.[1-\frac{G}{N}e^{-G}]^{2(L-1)} \tag{3.44}$$

$$DO_i = \frac{(L+1)e^{-G}}{[1-\frac{G}{N}e^{-G}]^{2(L-1)}} \tag{3.45}$$

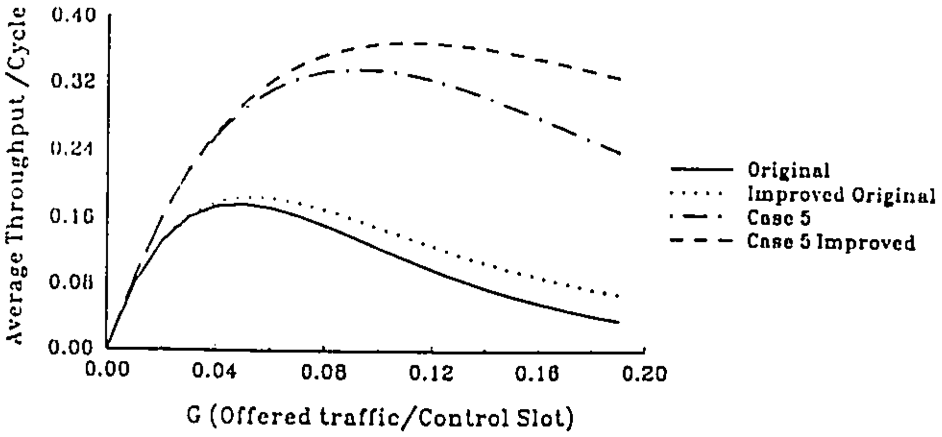


Figure 3.9: Throughput vs. $G(L = 100, N = 10)$

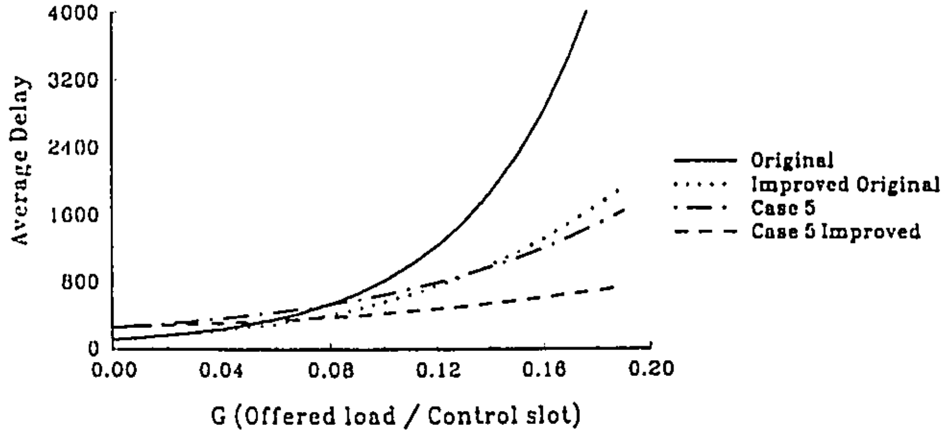


Figure 3.10: Delay vs. $G(L = 100, N = 10)$

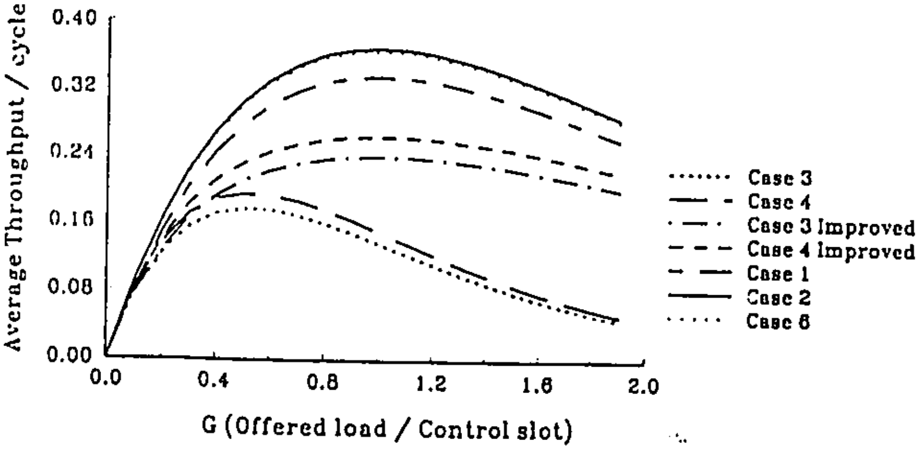


Figure 3.11: Throughput vs. $G(L = 100, N = 10, X = 10)$

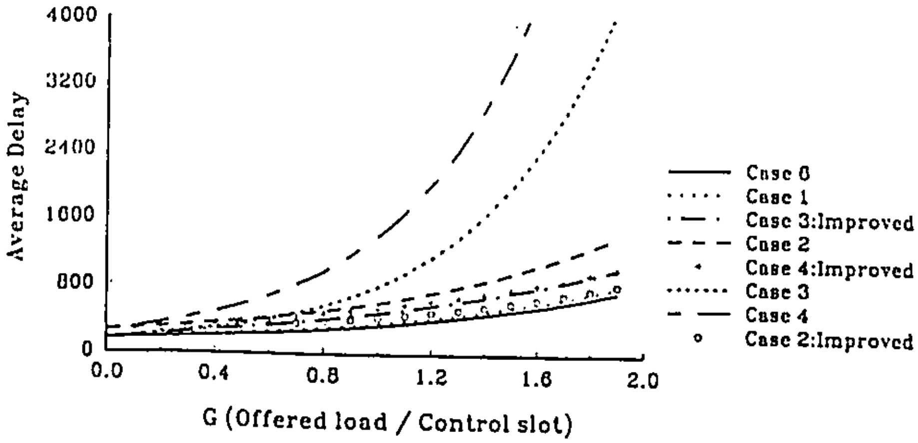


Figure 3.12: Delay vs. $G(L = 100, N = 10, X = 10)$

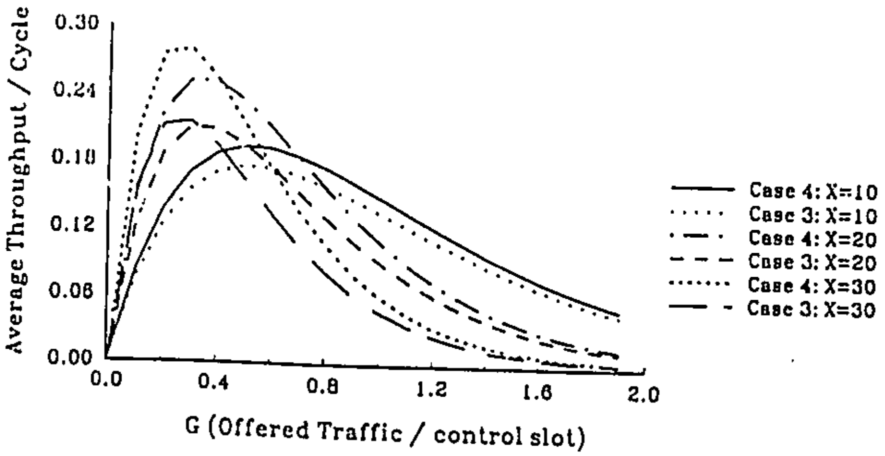


Figure 3.13: Throughput vs. $G(L = 100, N = 10)$

Similarly, the R-ALOHA of [46] is referred as 'R-ALOHA Original'. In all the cases, the retransmission delay t_r is chosen such that the retransmissions take place in the next immediate cycle. For R-ALOHA cases, t_r is chosen such that the total retransmission delay is $\overline{v}$ cycles, where $\overline{v}$ is the average message length. In Fig. 3.9 and 3.10, the average throughput/cycle and delay of the Original, the Improved Original and Case 5 of Section 3.2 and Case 5 of Section 3.3 (Case 5 improved) are plotted. It can be very clearly seen that both the schemes of Case 5 offer better throughput than the corresponding original cases. Also, it can be observed that these protocols work well under very light load conditions, that is for small values of G. If G is larger, then Cases 1,2,3,4 and 6 of sections 3.2 and 3.3 offer better performance as reflected by the Figures 3.11 and 3.12. The throughput of Case 2 is the largest, reaching 0.368 for G=1 and

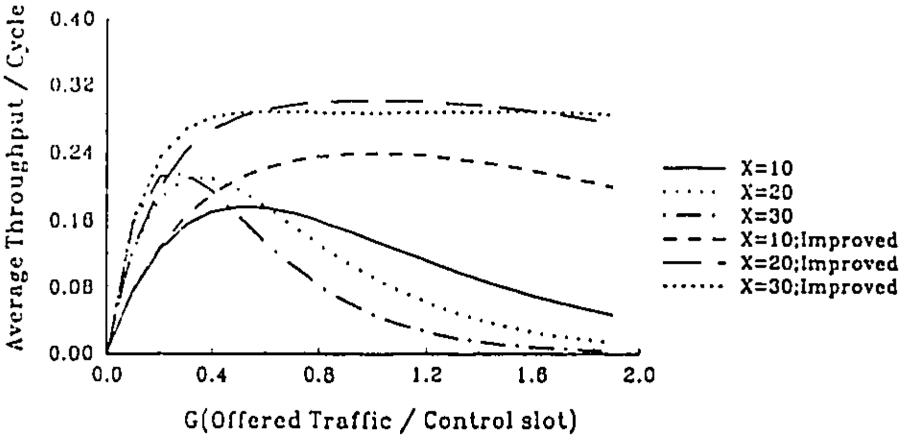


Figure 3.14: Throughput vs. G for Case 3

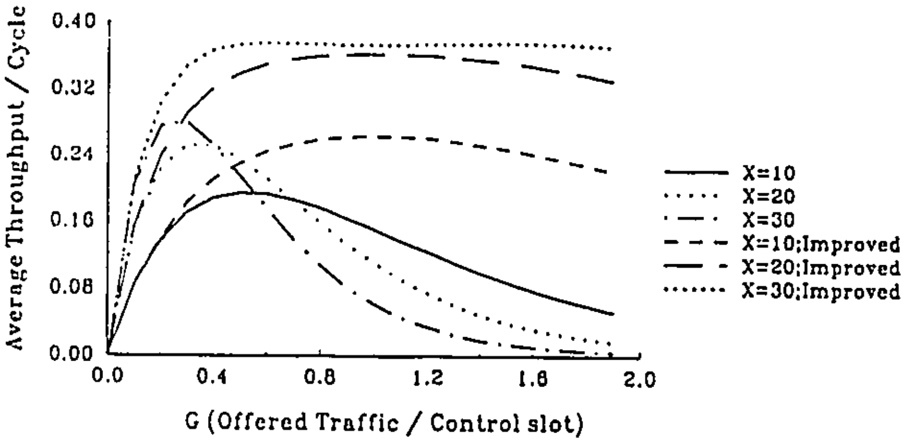


Figure 3.15: Throughput vs. G for Case 4

the delay is the lowest for Case 6 when compared to other cases (fig. 3.12). Plots for Case 3 and Case 4 for various values of x (number of minislots in a control slot) for L=100 and N=10 are presented in figures 3.14 and 3.15 along with the improved protocol and the delay for Case 4 is plotted in Fig 3.16. Also, in Fig. 3.13, both Case 3 and Case 4 are plotted together. From these plots, it can be seen that Case 4 offers better throughput than Case 3 and as the value of x is increased, the corresponding throughput increases, but the maximum occurs for smaller values of G (fig 3.13).

If Eq. 3.31 (the throughput equation for Case 4 Improved protocol) is differentiated with respect to G, it can be found that $dS4/dG$=0 whenever (a). G=1, (b). $Ge^{-G} = N$ or (c). $Ge^{-G} = \frac{N}{x}$. Since the maximum value of Ge^{-G} is 0.368 and N is an integer ($\geq$ 1), condition (b) is never

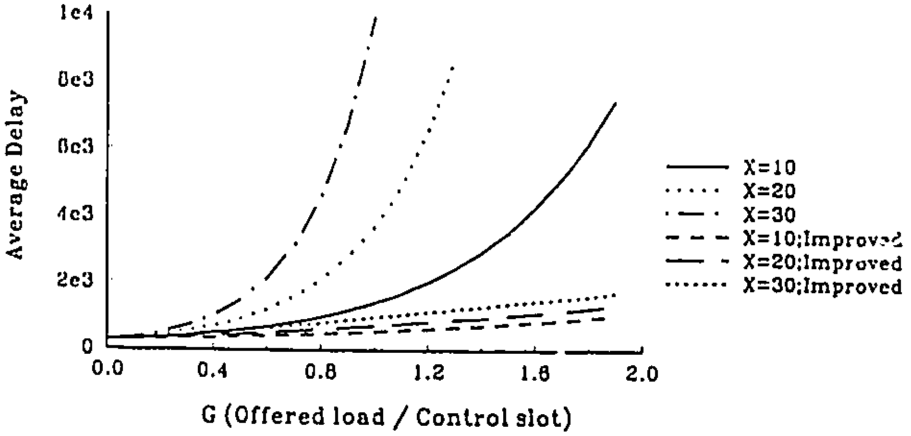


Figure 3.16: Delay vs. *G* for Case 4

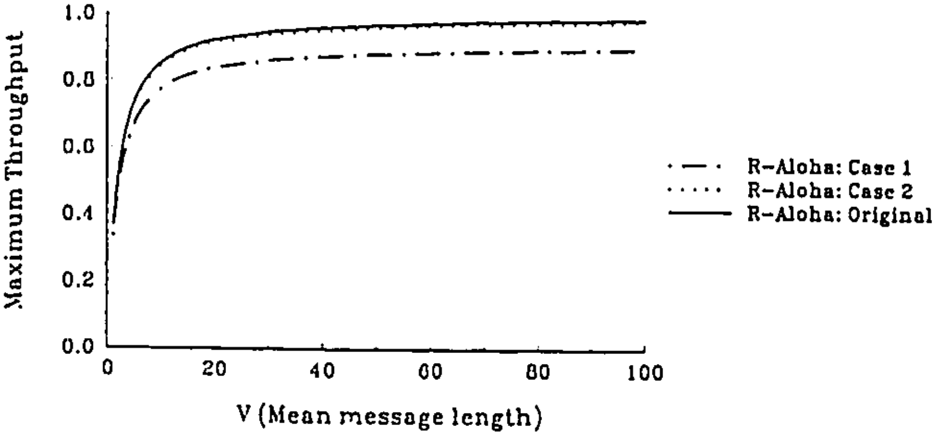


Figure 3.17: Maximum Throughput vs. *V* (R-ALOHA)

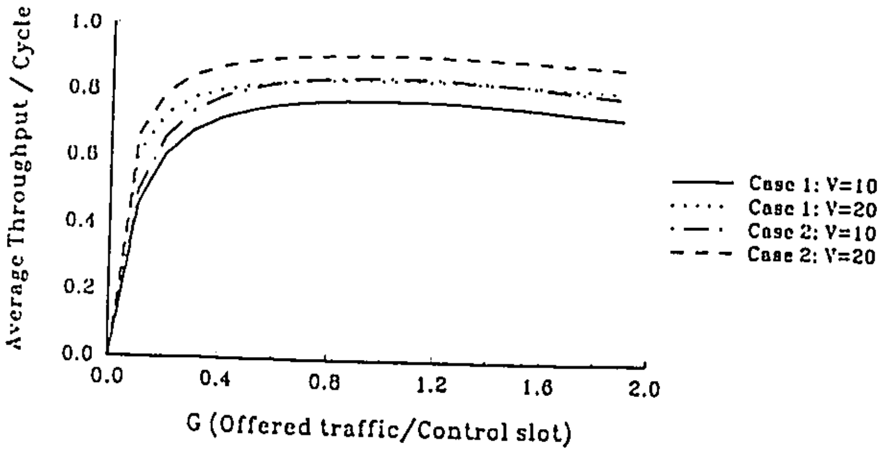


Figure 3.18: Throughput vs. G (R-ALOHA)

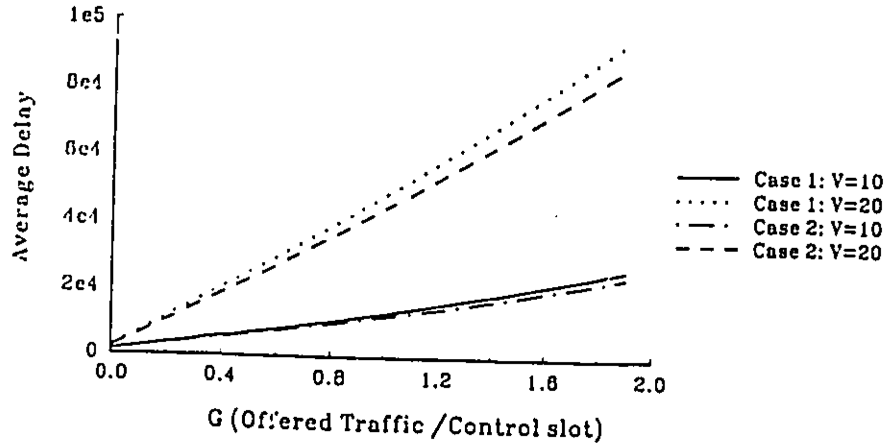


Figure 3.19: Delay vs. G (R-ALOHA)

satisfied. However condition (c) is met for two values of G, when the ratio of $\frac{N}{x}$ is less than 0.368. When N and x are such that $\frac{N}{x} > 0.368$, then $dS4/dG=0$ only at $G = 1$ and this corresponds to a maximum in the throughput curve (see curves $x = 10$, $x = 20$ of improved cases in Fig. 3.14 and 3.15). When $\frac{N}{x} < 0.368$, then there is a minimum in the throughput curve at $G=1$ and two maxima corresponding to the values of G such that $Ge^{-G} = \frac{N}{x}$ (curves $x = 30$ of improved cases in Fig. 3.14 and 3.15). The maximum value of throughput at these points is 0.3741 when $N = 10$ and $x = 30$. From Fig 3.16, it can be seen that the delay of the improved protocols is smaller than the corresponding unimproved cases. This is due to the reduced retransmissions due to the collisions. This bi-modal behavior was also observed in [38] for the Improved ALOHA protocol of [27].

L	N	Per channel Throughput							
		Case 1	Case 2	Case 6	Case 3 $x = N$ Imprv.	Case 4 $x = N$ Imprv.	SA/A Orig. Imprv.	CSMA/ N-Server	ALOHA N-Server
2	2	.184	.367	.245	.150	.300	.245	.130	.318
	5	.105	.367	.245	.077	.271	.126	.058	.147
	10	.061	.367	.245	.044	.262	.068	.029	.074
10	2	.306	.367	.334	.250	.300	.199	.506	.752
	5	.245	.367	.334	.181	.271	.199	.285	.611
	10	.184	.367	.334	.131	.262	.187	.144	.367
100	2	.360	.367	.363	.294	.300	.185	.931	.972
	5	.350	.367	.363	.258	.271	.185	.917	.971
	10	.334	.367	.363	.239	.262	.185	.877	.966

Table 3.1: Maximum Throughput per channel for various protocols

Table 3.1 shows throughput comparisons of some of the Slotted-ALOHA cases described above with ALOHA/ N-server [27], CSMA/ N-server [23] and Improved Slotted-ALOHA/ ALOHA (SA/A) presented in [27]. As can be seen from this table, some of our protocols offer better throughput than ALOHA/ N-server or CSMA/ N-server when L is comparable to N. Thus our protocols offer better performance when data packets are very small in length.

In Fig 3.17, we plot the maximum possible throughput for R-ALOHA as a function of mean message length. This is plotted using Eq. (3.37), (3.39) and (3.41) with $S = \frac{1}{e}$, the maximum steady state throughput of Slotted-ALOHA. Fig. 3.18 and 3.19 show the average throughput and delay for R-ALOHA Cases 1 and 2. To check our analytical results, R-ALOHA Case 1 is simulated using the Queueing Networks Analysis Package (QNAP2) [47]. Fig 3.20 and 3.21 show the analytical and simulation results of throughput and delay for R-ALOHA Case 1 as a function of offered load. The simulations are done with 95% confidence interval estimations. In the simulations, 128 user stations access four channels ($N = 4$) with $L = 20$. The exponential back-off strategy is used in the simulations. That is, if there is a collision of a control packet on the control channel, it is retransmitted after a random retransmission time which is chosen from

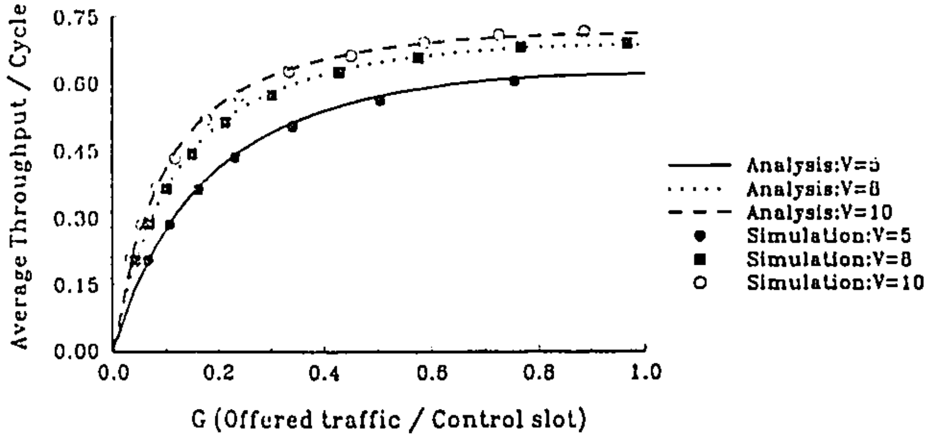


Figure 3.20: Throughput vs. G :R-ALOHA for Case 1 ($L = 20, N = 4$)

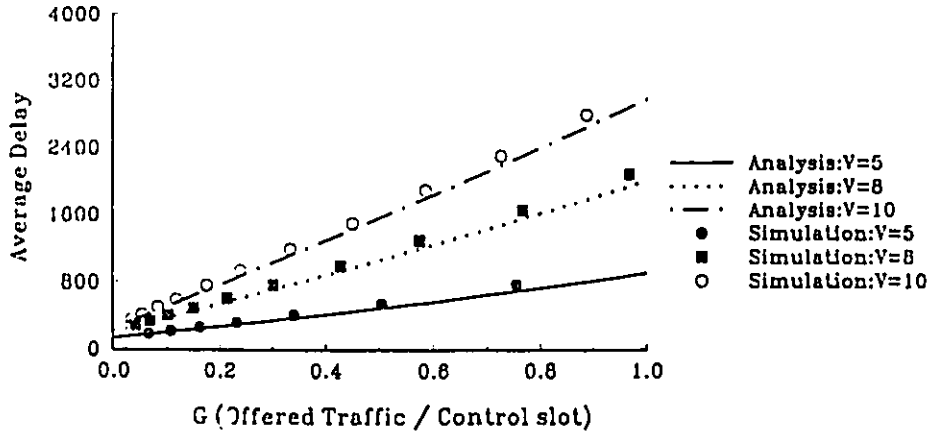


Figure 3.21: Delay vs. G :R-ALOHA for Case 1 ($L = 20, N = 4$)

an exponential distribution with mean t_r. An additional delay of $\frac{T}{2}$ will be incurred in every retransmission due to the waiting till the beginning of the next cycle. Here, T is the length of a cycle. The total delay is given by:

$$D1 = \frac{T}{2} + (R-1).\left(\frac{N+1}{2} + t_r + \frac{T}{2}\right) + \bar{v}.T \tag{3.46}$$

Fig. 3.21 shows the delay Eq. 3.46 along with the simulation results. The simulations are done for $N = 4$, $L = 20$ and for various message lengths ($\bar{v}$) of 5, 8 and 10 data slots. The value of t_r is chosen to be $\bar{v}T$. The results agree quite closely (within 5%) with the analytical solutions.

3.6 Summary

In this chapter, a number of cases of Slotted-ALOHA protocols for high speed optical fiber LANs have been presented and analyzed. The results were compared to the cases of Slotted-ALOHA/ALOHA schemes presented in [23, 27] and the proposed schemes were found to offer better throughput and delay characteristics. These cases are also compared with ALOHA/ N-server and CSMA/ N-server protocols presented in [23] and [27] and some of our protocols offer better throughput compared to these when the data packet lengths are small. Two cases of Reservation ALOHA protocols have been presented and analyzed. The Slotted-ALOHA Cases 1, 3 and 6 can be used when very fast frequency agile transmitters and receivers are available, since in these protocols the data packet has to be transmitted immediately after the control packet. Cases 2, 4 are to be used with slow devices since a control packet is transmitted in one cycle and it's data packet in the next cycle. Hence, some switching time is available to the devices. The two R-ALOHA protocols are useful for high-speed bulk data transfers. It should be observed that, if channels are pre-assigned to the receivers, no control channel will be necessary due to implicit addressing. In this case, receivers are tuned to their assigned wavelengths and users who wish to send the data to a particular receiver should send the data on the wavelength assigned to that receiver. Data channels can be slotted without any idle durations and maximum throughput of Slotted-ALOHA channel (36.8%) can be achieved. But, the problem now lies in distributing the channels between the receivers present in the system according to the traffic distribution and there is a possibility that all the channels may not be loaded equally. With the protocols presented here no such distribution is necessary and all the channels are identically loaded due to uniform selection policy of the channels by the transmitters. **Our above contributions were published in [48].**

The chapter on implementation issues considers some of the realistic parameters such as the effect of propagation delay, channel switching latency etc. Since all the proposed protocols are slotted, a slot synchronization technique is considered later. Due to this, the propagation delay reflects as increased packet transmission delay and does not effect the throughput. According to the classification of Chapter 2, all the Slotted-ALOHA protocols proposed in this chapter belong to the class of random access protocols with pretransmission co-ordination and the R-ALOHA protocols belong to the reservation protocols.

Chapter 4

Distributed Control Protocols for Passive Optical Star Networks and Their Interconnections

4.1 Introduction

In previous chapters, a high-speed multi channel LAN (M-LAN) using a passive star topology is described. The information is divided into control packets and data packets. Control packets are transmitted on a separate control channel and data packets on data channels. Chapter 3 introduced many cases of Slotted-ALOHA and Reservation ALOHA protocols for this M-LAN. But, in these protocols, each node processes all the control channel traffic. This can result in a processing bottleneck. However, this can be reduced, if distributed control protocols are developed, where each node processes a part of the traffic. This chapter proposes two kinds of such protocols. In the contention-based reservation protocol, users contend separately on each data channel and use Slotted-ALOHA protocol for contention. Some of the protocols in the last chapter can also be further improved by grouping the number of users into various groups and allocating a separate control channel for each group. Thus, the high-speed LAN can be viewed as a multiple control channel LAN. The multi-control channel protocol is such a protocol, in which users are divided into groups and are allocated a separate control channel for each group. Thus, each group now processes their own control channel traffic. Another protocol, which uses a separate control channel for each channel is recently proposed in [30]. When several optical star LANs exist, a natural question of how to interconnect them also arises. By using the concept of groups and associated Slotted-ALOHA protocol in accessing the channels in the M-LAN, the interconnection of these M-LANs can be easily achieved by extending the same concept. Hence, in this chapter, we introduce the multi-control channel LAN using Slotted-ALOHA protocols and a few methods of interconnection of the optical star LANs. The chapter is organized as follows: Section 4.2 describes the network architecture. In Section 4.3, a simple contention based reservation protocol is presented and analyzed. In Section 4.4, modification to this protocol is proposed which offers better performance with slightly different channel access mechanism. Sections 4.5 and 4.6 describe the multi-control channel LAN protocol and in Section 4.7 the interconnection of optical star LANs using the multi-control channel LAN is presented. Section 4.8 concludes with numerical results and simulations.

4.2 Network Architecture for the High-Speed Optical LAN

The hardware architecture of the network is the same as in Chapter 3 (see Fig. 3.1). The fiber bandwidth is divided into N channels, each using a different wavelength. There are $M(M > N)$ users in the network. Users are connected to the central passive star coupler. It is assumed that each user has a tunable optical transmitter and a tunable optical receiver, which can be tuned over the set of wavelengths utilized in the network. The bandwidth of the optical fiber is divided among a set of wavelengths $\{\lambda_1, \lambda_2, \ldots, \lambda_N\}$ and each user can transmit on λ_i and receive on λ_j, where λ_i and λ_j are members of the above set. A control channel is used for co-ordination of access among the users. However, there is no separate control channel as used in the previous chapter. Instead, a control slot is embedded into the cycle and we assume that control slot on wavelength λ_1 is used by the users. Also, we assume that all idle users in the system always monitor this control slot. The control channel is used to transmit the control information and the actual data is transmitted on λ_i, $\lambda_i \in \{\lambda_1, \lambda_2, \ldots, \lambda_N\}$. The general access mechanism of the network is as follows: If user i has a data packet to send to user j, then user i must select one of the data channels (say λ_k) and contend for it for a possible reservation. The contention mechanism depends upon the particular protocol being used. If user i succeeds in the contention, then that channel is reserved for user i. Then user i will inform user j about the selected data channel by transmitting a control packet (which contains the source address, destination address and the chosen data channel number) on the control channel and then transmits the data packet on the selected data channel λ_k. If user j is idle, it will receive the control packet (since all the idle users monitor the control channel) and immediately will tune its receiver to the data channel λ_k for the data packet from user i.

Since it is assumed that the number of users is higher than the number of available data channels, both data and control channels should be accessed by users on a contention basis. Here, a simple reservation protocol which offers better throughput than the Slotted-ALOHA scheme presented in Chapter 3, and a multi-control channel protocol, which is very useful in interconnections of optical stars, are presented. In these protocols, both data and control channels are slotted using major and minor timing references as before. The analysis of these protocols is done assuming an infinite population model and Poisson arrivals on the contention or control channels. Receiver collisions are ignored in the present analysis. Immediate feedback about the success of the transmitted packet and infinite retransmission scheduling for transmitting an unsuccessful packet are assumed. No particular back-off strategy is assumed. We also assume that the average propagation delay is negligible. The following notations are used in this chapter:

N = number of data channels in the system

L = length of a data packet (control packet is assumed to be of unit length)

G = average number of contention (control) packets transmitted per slot on a contention (control) minislot

P_c = Probability of success of control packet on a control channel in a control slot

P_d = Probability of success of data packet on a data channel in a data slot, given that its corresponding control packet is successful in a corresponding minislot

P_s = Total probability of success of a data packet in a 'cycle', (This may depend upon P_c and/or P_d)

S_d = Throughput per data slot of each data channel

S_c = Throughput per cycle of each data channel

P_r = Retransmission probability of each packet

R = Average number of retransmissions = $\frac{1}{1-P_r}$, (In this $R-1$ are unsuccessful attempts and one final successful transmission)

T = length of a 'cycle'

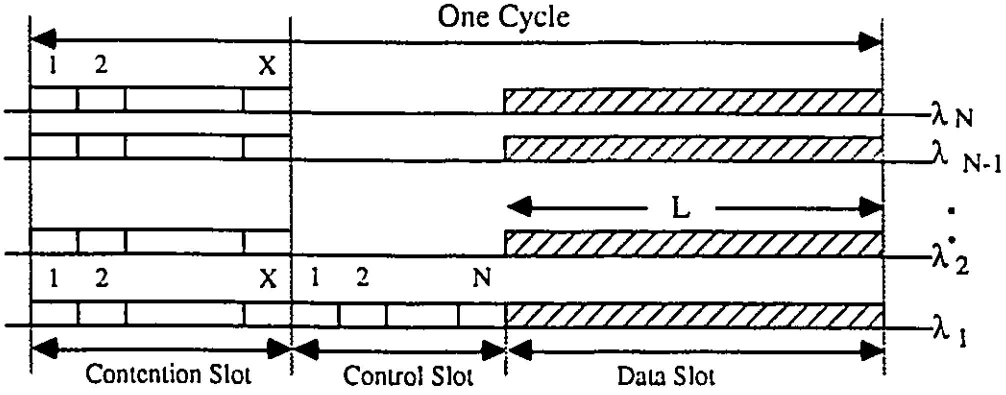


Figure 4.1: Contention-based Reservation Protocol

t_r = average length of a retransmission (back-off) period

d_w = average time a packet has to wait from the time it is generated till the beginning of the next cycle

d_r = average total retransmission delay = $(R-1)\times$ mean retransmission delay per unsuccessful attempt

d_t = average time to transmit a message

4.3 A Simple Contention based Reservation Protocol

As shown in Fig. 4.1, all the channels are slotted using the same time reference. Each cycle on all channels is further divided into three slots: contention slot, control slot and data slot. Each contention slot is further divided into x minislots. The control slot is further divided into N minislots on the channel λ_1. Each minislot on both the contention and the control slots is assumed to be of unit length and the data slot is of L units in length. The minislots on the control slot are pre-assigned to a corresponding data slot. That is, the control minislot i is to be used when the corresponding data packet is to be transmitted on λ_i. The protocol mechanism is as follows:

A user (say user i), who has got a data packet to send has to first wait till the beginning of a cycle. Then, user i has to randomly select one of the N data channels (say λ_k) on which the data packet will be transmitted. Since many users may want to transmit a data packet in this cycle, there is a possibility that some of them may choose the same data channel as user i. Hence user i has to contend for the channel λ_k first. The contention slot on λ_k is used for this purpose. All the users contending for λ_k have to tune their transmitters and receivers to wavelength λ_k during the contention slot. Thus, all the users contending for λ_k monitor the contention slot of λ_k. User i has to randomly choose one of the x minislots to transmit a contention packet. The contention packet is a small dummy packet, which contains only the source address. The first user, who has a successful transmission of the contention packet, grabs the channel. Since all the users contending for λ_k monitor this channel during the control slot, they know who is successful (since the contention packet includes source address). Thus, all the users whose contention packet is not successful or the users who could not transmit the contention packet (since the channel is grabbed in the earlier contention minislots than the one selected by these users) will try for a possible contention on the same or some other channel in the next succeeding channels depending upon the particular back-off strategy used. The user, who successfully transmitted a contention packet on λ_k, will transmit a control packet destined to user j on the k minislot of the control slot and will transmit the corresponding data packet on λ_k in the corresponding data slot. Note that, all the users who are not successful tune their receivers back to λ_1 during the control slot to receive a possible control packet from other users.

Analysis: Since all the channels in the system are statistically identical, we look at one channel in the system and analyze it. Each cycle of a channel consists of a contention slot of duration x, a control slot of duration N and a data slot of duration L. We assume that the contention traffic offered on each minislot of the contention slot is Poisson with parameter G. Since each contention minislot is independent and each minislot is accessed using the Slotted-ALOHA protocol, a successful contention packet is generated with probability $S = G.e^{-G}$ in each minislot and no successful contention packet is generated with probability $1 - S$ due to no arrivals to that minislot or due to collisions. Since the data slot is grabbed by only one user, the throughput of each data slot can be defined as the probability of grabbing that data slot. A data slot cannot be grabbed if there are collisions of the contention packets on all the minislots. This happens with a probability of $(1 - S)^x$. Therefore, the throughput of each data slot is:

$$\begin{aligned}\text{Throughput} = S_d &= \mathrm{P}\{\text{a data slot is grabbed successfully}\}\\ &= 1 - \mathrm{P}\{\text{a data slot is not grabbed by any user}\}\end{aligned}$$

$$= 1 - (1 - S)^x$$

Therefore,

$$S_d = \text{Throughput / data slot} = \{1 - (1 - S)^x\} \tag{4.1}$$

$$\begin{aligned} S_c &= \text{Throughput / cycle} \\ &= \frac{L}{L+N+x}.S_d = \frac{L}{L+N+x}.\{1 - (1 - S)^x\} \end{aligned} \tag{4.2}$$

The average delay in transmitting a packet to the destination can be easily found, as follows. The users, who selected a given channel in a given cycle can randomly select one of the x contention slots and transmit their contention packet. Let P_s be the probability of acquiring a data slot by a contention packet in a cycle. Then, $1 - P_s$ is the probability that the data slot is not grabbed by a contention packet either due to collisions or due to the blocking (if channel is grabbed by some other user in one of the earlier contention slots, then remaining users will not transmit their contention packets and can be viewed as lost due to blocking). The total contention traffic that would be offered is $G.x$. Some of it is lost due to collisions and some due to blocking. Therefore, the traffic that goes through is $G.x.P_s$ which should be equal to the data slot throughput S_d. Therefore,

$$\begin{aligned} G.x.P_s &= S_d = \{1 - (1 - S)^x\} \text{ or} \\ P_s &= \frac{\{1 - (1 - S)^x\}}{G.x} \\ P_r &= 1 - P_s \end{aligned} \tag{4.3}$$

The average number of retransmissions R is,

$$R = \frac{1}{P_s} = \frac{G.x}{\{1 - (1 - S)^x\}} \tag{4.4}$$

The total delay in transmitting a packet successfully has three components. The first one is the average time d_w a packet has to wait from the time it is generated at a station till the beginning of the next cycle. The second is the total retransmission delay d_r, which is the total delay involved in $(R - 1)$ unsuccessful attempts. The third is the delay d_t in transmitting the successful packet. Since a contention packet could be successful or it could fail in any one of the x minislots, the average contention packet transmission time is $\frac{x+1}{2}$. If t_r is the average retransmission (back-off) delay, then,

$$T = \text{cycle duration} = (L + N + x)$$

$$
\begin{aligned}
d_w &= \frac{T}{2} \; ; \; d_r = (R-1).(\frac{x+1}{2} + t_r) \; ; \; d_t = T \\
D &= \text{average delay} = d_w + d_r + d_t \\
&= \frac{T}{2} + (R-1).(\frac{x+1}{2} + t_r) + T \\
&= \frac{3}{2}.(L + N + x) + (R-1).(\frac{x+1}{2} + t_r) \qquad (4.5)
\end{aligned}
$$

4.4 Modified Contention based Reservation Protocol

In the protocol presented above, the throughput per cycle depends on N, the number of data channels present in the system. Although the total aggregate system throughput increases with N, the throughput of each data channel per cycle is actually reduced. This is because of the slotting technique used in this protocol due to which the data channel bandwidth is wasted during the control slot. The protocols proposed in [23, 27] and [48] make the entire system symmetrical. That is, all the channels and all the users in the system are identical. In these protocols, the users have to know only the addresses of other users in the system. Hence, a control channel becomes necessary as a common communication channel through which information is passed about the selected data channels. However, this relieves the network designer of the burden of assigning the channels among the users so that the total load is distributed fairly among the channels at the expense of one extra control channel. In reality, not all the users in a network are identical and there may not be any (or little) traffic flow between some pairs of users. Hence, given the traffic flow matrix among the users and the number of channels, the users could be divided into N groups, in an optimized way such that there would be equal traffic flow among all the given channels. Then each group of users will be sharing the same receiving channel. If the address of the user includes the receiving channel information, then no extra control channel will be necessary in the system. The contention protocol described in Section 4.3 can still be used and the modification is now shown in Fig. 4.2. For a moment ignore the information slot shown in this figure.

The protocol mechanism now works as follows: if user i has a data packet to user j, user i tunes its transmitter and receiver to the receiving wavelength of user j. Since this receiving wavelength is shared by other users of the group, data slot contention may arise. Hence, users have to contend for the data slot in the contention period by transmitting a contention packet which contains

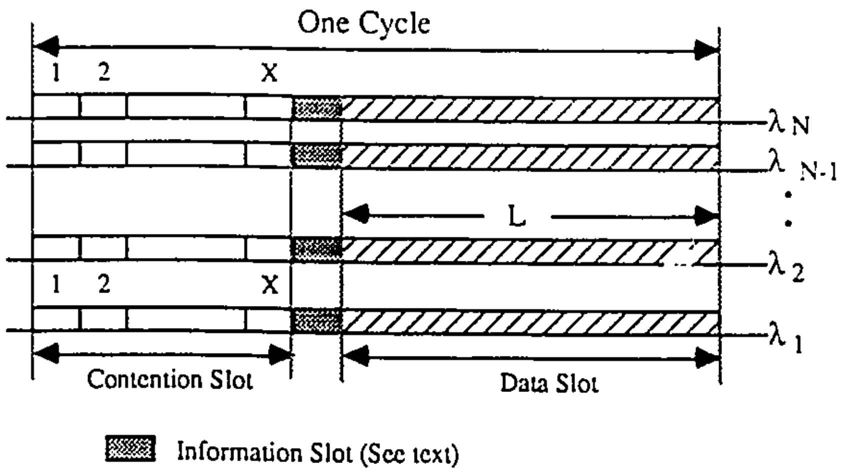


Figure 4.2: Modified Contention based Reservation Protocol

source and destination addresses. The user who first transmits a contention packet successfully reserves the channel. The idle group members always monitor their receiving channel. Hence, if a user is idle, it will monitor the contention slot, will know about the success of contention packet if any and, if the packet is meant to self, then it will receive the data packet during the data slot. After the data transfer is over, the user who successfully transmitted a data packet would tune its receiver back to its receiving wavelength.

There is a major difference between the two access mechanisms: in the protocol of Section 4.3, a user who is not successful in reserving the required data channel could still receive a data packet meant for itself since the user monitors the control slot. In the modified access mechanism, since the user is not monitoring its own receiving wavelength while transmitting a data packet, the user cannot receive any data packet meant for itself even if the user is not successful in reserving a data channel. In our present analysis we ignore the receiver collisions. Under Poisson arrival assumption to the contention minislot, the analysis of this protocol is the same as that of Section 4.3. The throughput and delay are given by:

$$\begin{aligned} S_d &= \text{Throughput / data slot} = \{1-(1-S)^x\} \\ S_{cm} &= \text{Throughput / cycle} \\ &= \frac{L}{L+x}.S_d = \frac{L}{L+x}.\{1-(1-S)^x\} \qquad (4.6) \\ T &= \text{cycle duration} = (L+x) \end{aligned}$$

$$\begin{aligned}
d_w &= \frac{T}{2} \; ; \; d_r \; = \; (R-1).(\frac{x+1}{2} + t_r) \; ; \; d_t \; = \; T \\
D_m &= \text{average delay} \; = \; d_w + d_r + d_t \\
&= \frac{T}{2} + (R-1).(\frac{x+1}{2} + t_r) + T \\
&= \frac{3}{2}.(L+x) + (R-1).(\frac{x+1}{2} + t_r) \qquad (4.7)
\end{aligned}$$

The receiver collisions mentioned above could be avoided, if one information minislot (shown in Fig. 4.2) is included. Since the receivers are assigned a particular wavelength, all the users who could not reserve the data slot in this cycle will tune their receivers back to their receiving wavelength in the information slot. The user who grabbed the data slot in the current cycle on λ_k will transmit a small information packet, which includes source and destination addresses in the information slot. All the idle users who are assigned λ_k as their receiving wavelength monitor the information slot and the particular user whose destination address is in the information packet receives the data packet in the data slot. The receiver collisions due to a busy user still cannot be avoided. In this case, idle users do not have to monitor the contention slot and the contention packet contains only the source address to indicate whose contention is successful. But this protocol allows multi-cast reception. If the information minislot is assumed to be of unit length, then the throughput (Eq. 4.6), and delay (Eq. 4.7) are modified by changing the value of x to $x+1$.

4.5 Slotted-ALOHA Protocols for Multi Control channel LAN

The network architecture for this protocol is the same as before. The bandwidth of the optical fiber is divided among a set of wavelengths $\{\lambda_1, \lambda_2, \ldots, \lambda_N\}$ and each user can transmit on λ_i and receive on λ_j, where λ_i and λ_j are members of the above set. We assume that the users are divided into K groups and group i users use λ_i as their control channel. We assume that all the users in a group monitor their control channel, i.e., group i users monitor λ_i. The control channel is used to transmit the control information and actual data is transmitted on λ_d, $\lambda_d \in \{\lambda_1, \lambda_2, \ldots, \lambda_N\}$. The general access mechanism of the network is as follows: Normally group k users communicate among themselves. If user i of group k has a data packet for user j of group k, then user i must first randomly choose a data channel λ_d (on which the data packet will be transmitted). Then user i will inform user j about the selected data channel by transmitting

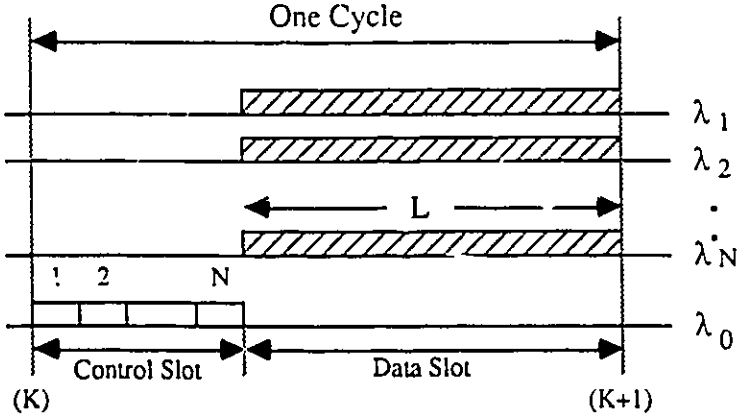


Figure 4.3: Slotted-ALOHA for Case 3 of Chapter 4

a control packet (which contains the source address, destination address and the chosen data channel number) on the control channel λ_k and then immediately transmit a data packet on the chosen data channel λ_d. If the user j is idle, it will receive the control packet (since all idle users of a group always monitor their control channel) and immediately tune its receiver to the data channel λ_d for the data packet from user i. To communicate between various groups, users of each group follow the following mechanism: if a user from group k wants to communicate to another user from group l, the group k user temporarily becomes a group l user by monitoring the control channel of group l and transmitting the control packet on λ_l and the corresponding data packet on the selected channel. After the required data transfer is over, the group k user returns back to its permanent group. We assume that all the channels in the system are identical, and every user knows the control channel wavelengths of other groups and addresses of all users in the system and to which group each user belongs to.

In Chapter 3, many Slotted-ALOHA cases were proposed for the Optical star LAN in which users have frequency agile transmitters and receivers. The network architecture uses one control channel for transmitting the control information and N data channels for transmitting the data packets. Here we are interested in slotted ALOHA Case 3 of Chapter 3, which is shown in Fig. 4.3 for reference. This case is modified for the multi-control channel ALOHA protocol as shown in Fig. 4.4. The channels are divided into cycles in the same way, but now the control slots are provided on K data channels, corresponding to K groups. Each control slot is further divided

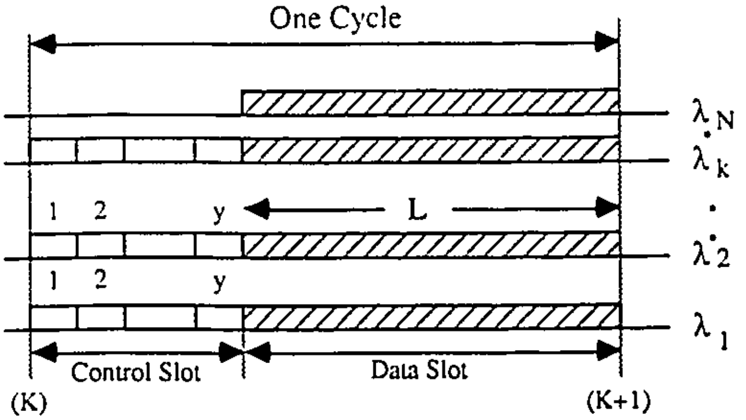


Figure 4.4: Slotted-ALOHA for Multi-Control Channel Network

into y minislots. It should be observed that, in Chapter 3, the total number of channels available are $N+1$ which are divided into one separate control channel and N data channels. However in the present case there is no separate control channel and the total number of channels in the system are N. A group i user (both temporary and permanent members of the group) wishing to transmit data in $[K, K+1)$ slot on channel d, will transmit the control packet in any one of the minislots of the control slot on λ_i and a data packet on channel d after the y^{th} minislot. The retransmission probability and total probability of success of a given data packet will depend upon both probability of success of the control packet (P_c) and probability of success of the data packet (P_d), since a successful control packet does not necessarily imply a successful data packet. The total delay to transmit a packet from source to destination has three components: d_w, d_r and d_t as explained in Section 4.3. The total delay is the sum of the above three components. No particular back-off strategy is assumed. We follow the same analysis as before.

Analysis: There are K groups hence there are K control channels. Each control slot is divided into y minislots. We assume that G is the aggregate number of packets offered per minislot on each control channel and we assume the traffic offered is Poisson with parameter G. The offered traffic includes all the packets transmitted in this control minislot by all possible users (both temporary and permanent members of the group). Since a packet is equally probable to be transmitted to any of the N channels and there are y minislots on the control channel per cycle, we have,

$$\begin{aligned} G_d &= \frac{G}{N}.y.K \\ P_c &= e^{-G} \end{aligned}$$

To calculate P_d, let us consider one data channel, say channel 1, and one control slot of any channel, say channel 2 for example. Suppose our test control packet is transmitted on the i minislot on channel 2 whose data is to be transmitted on channel 1. For this data packet to be successful, there should not be any transmission on data channel 1 whose control packet is transmitted in any of the remaining $y-1$ minislots (here a data packet is transmitted whether a control packet is successful or not) on channel 2 and on remaining $[(K-1).y]$ minislots of all other control channels.

$P_d = P$(no transmissions of control packets in remaining $(y-1)+(K-1).y = Ky-1$ minislots whose data packet is to be transmitted on data channel 1)

$= [P(\text{no control packet for data channel 1 in one minislot})]^{(Ky-1)}$

P(no control packet for data channel 1 in one minislot)

$=\sum_{i=0}^{\infty} P$ (no packets to channel 1| i arrivals in one minislot).P(i arrivals)

where $P(i \text{ arrivals}) = \frac{G^i e^{-G}}{i!}$ and

P(no packets to channel 1 | i arrivals in one minislot) $= (1-\frac{1}{N})^i$

P (no control packet to channel 1 in one minislot) $= \sum_{i=0}^{\infty}(1-\frac{1}{N})^i \frac{G^i e^{-G}}{i!} = e^{\frac{-G}{N}}$

$$\begin{aligned} P_d &= [e^{\frac{-G}{N}}]^{(Ky-1)} = e^{[-G(Ky-1)/N]} \\ P_s &= P_c.P_d = [e^{-G}].[e^{(-G(Ky-1)/N)}] = e^{[-G-G(Ky-1)/N]} = (1-P_r) && (4.8) \\ S_d &= P_s.G_d = \frac{G.Ky}{N}.e^{-[1+(x-1)/N]G} \text{ and} && (4.9) \\ Sm &= \text{average number of packets successfully transmitted per cycle} \\ &= \frac{L}{L+y}S_d = \frac{L}{L+y}\frac{G.Ky}{N}e^{-[1+(Ky-1)/N]G} && (4.10) \\ R &= \text{average number of retransmissions} \\ &= \frac{1}{1-P_r} = e^{[G+G(Ky-1)/N]} && (4.11) \\ T &= (L+y)\,;\ d_w = T/2\,;\ d_r = (R-1).(T+t_r)\,;\ d_t = T \\ Dm &= \text{average delay } = d_w + d_r + d_t \\ &= (L+y).e^{[G+G(Ky-1)/N]} + \frac{L+y}{2} + (R-1).t_r && (4.12) \end{aligned}$$

When $Ky = x$, the equations of P_d and S_d are exactly the same as the equations of P_d and S_d of Slotted-ALOHA Case 3 of [48]. However, the delay per cycle is reduced due to a reduction in the number of minislots per control slot and the throughput is increased.

4.6 Improved Slotted - ALOHA Protocols for Multi Control channel LAN

This is an improvement to the one presented above and is analogous to Case 3 of the improved Slotted-ALOHA protocol of the previous chapter. Here a data packet is transmitted, only if the control packet is successful on the control slot. Since G is the average number of control packets transmitted per control minislot, then $\frac{G.e^{-G}}{N}$ packets will be offered to the data slot on every channel. Here,

$$G_d = \frac{G.Ky}{N}.e^{-G}$$

P_d = P[successful transmission of a data packet on the given channel]

= P[successful transmission of one control packet whose data is to be transmitted on given channel in one of the Ky minislots]

= P[no successful transmission of control packet whose data is to be transmitted on a given channel in the remaining $(Ky - 1)$ slots]

={P[no successful transmission of a control packet whose data is to be transmitted on a given channel in one minislot]}$^{(Ky-1)}$

But,

P[no successful transmission of control packet to the given data channel] =

= 1 - P[successful transmission of a control packet to the given channel]

= 1 - P[succ. transmission of a control packet to a given channel | one arrival] . P[one arrival]

$= 1 - \frac{1}{N}.Ge^{-G} = 1 - \frac{G}{N}e^{-G}$

Therefore,

$P_d = P_s = [1 - \frac{G}{N}e^{-G}]^{Ky-1}$ and $P_c = e^{-G}$. But, retransmission will take place if both data and control packet are not successful. Hence,

$$P_r = (1 - P_c.P_d)$$

$$
\begin{aligned}
R &= \frac{1}{1-P_r} = \frac{e^G}{[1-\frac{G}{N}e^{-G}]^{Ky-1}} \\
S_d &= G_d.P_s = \frac{G.Ky}{N}e^{-G}.[1-\frac{G}{N}e^{-G}]^{(Ky-1)} && (4.13) \\
Smi &= \frac{L}{L+y}S_d = \frac{L}{L+y}.\frac{G.Ky}{N}e^{-G}.[1-\frac{G}{N}e^{-G}]^{(Ky-1)} && (4.14) \\
T &= (L+y)\,;\; d_w = T/2\,;\; d_r = (R-1).\left(\frac{y+1}{2}+t_r\right)\,;\; d_t = T \\
Dmi &= (L+y)+\frac{L+y}{2}+(R-1).\left(\frac{y+1}{2}+t_r\right) && (4.15)
\end{aligned}
$$

4.7 Interconnection of WDM Optical Star LANs using Slotted ALOHA protocols

In this section, two methods are presented for interconnecting WDM optical star LANs. When multiple optical star LANs are present in a geographical area, the natural question of interconnecting them arises. There is no problem, if the fiber bandwidth can be divided into many channels such that one optical star is sufficient for the entire geographical area. But, at present there is a device limitation for achieving many WDM channels on the fiber and many stars may be needed to serve an area. Wavelengths may have to be reused at various stars. Hence, the means for interconnecting these optical stars has also to be developed. In general, there are two possible approaches for interconnection: in the first approach, we only use optical amplifiers and filters or optical bandpass amplifiers. This method is useful when there is a limitation on the optical star size. The data that passes between the stars (inter-star traffic) is not buffered in this case. In the second approach, we use active repeaters which store the data and retransmit them. This is useful when there is a limitation on the number of wavelengths. We explain these concepts with some examples below.

4.7.1 Method 1: Using Optical filters and Amplifiers

In Fig. 4.5, a two star interconnection using filters and amplifiers is shown. Alternately one can use bandpass amplifiers. The amplifiers are used to amplify signals between the stars. Since the two stars are directly connected, the same set of wavelengths cannot be used between them. We assume that there is a system wide synchronization mechanism. We also assume that the receivers and transmitters are agile and are capable of tuning over the whole set of wavelengths

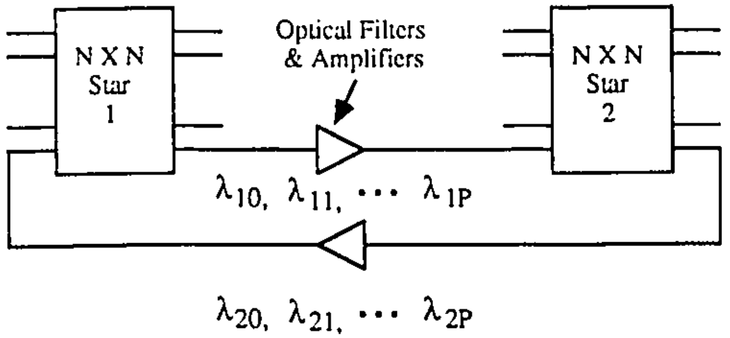
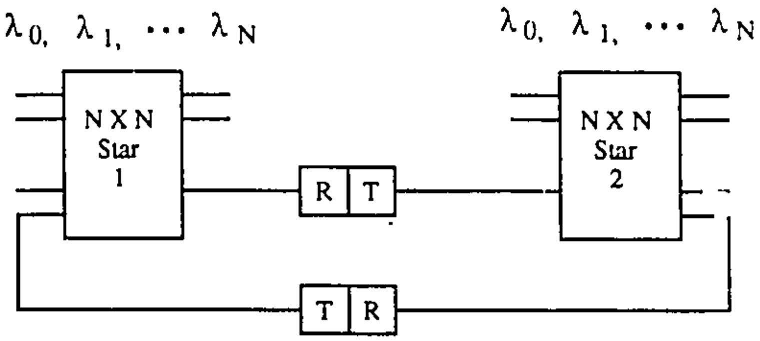


Figure 4.5: Two Star Interconnection Using Optical Filters and Amplifiers

present in the system.

As shown in Fig. 4.5, a set of wavelengths is dedicated to interconnect the stars and the two stars use different wavelengths as control channels. The group protocols described before can be used in this case. Users connected to star 1 communicate using the wavelengths $\{\lambda_{10}, \lambda_{11}, \ldots, \lambda_{1P}, \lambda_{1Q}, \ldots, \lambda_{1N}\}$ where λ_{10} is also used as control channel. The set of wavelengths $\{\lambda_{10}, \lambda_{11}, \ldots, \lambda_{1P}\}$ are also to be shared by users of star 2. Similarly, the users of star 2 have access to wavelengths $\{\lambda_{20}, \lambda_{21}, \ldots, \lambda_{2P}, \lambda_{2Q}, \ldots, \lambda_{2N}\}$ where λ_{20} is also used as control channel and the set $\{\lambda_{20}, \lambda_{21}, \ldots, \lambda_{2P}\}$ is shared by users of star 1. It should be noted that the full set of wavelengths can also be shared. Normally, the users of a star communicate among themselves. When they want to communicate to any user of the other star, they temporarily become part of the other star by transmitting on the shared set of wavelengths. Since the feedback mechanism is not there, the process of listening to one's own transmission for communication between the stars is lost. Hence, carrier-sense protocols cannot be used and neither the improved ALOHA protocols. We can however use the protocol of Section 4.5 (multi-control channel Slotted-ALOHA) in this case, in conjunction with positive acknowledgements. That is, the receiver has to send a positive acknowledgment, if the packet is received correctly.

The same philosophy can be applied to multiple stars. The filters basically have to eliminate the wavelengths of the optical star to which their input is connected to and amplify (or pass) all other wavelengths. This way, all the stars can be connected in series and still maintain a direct connection with other stars. The main problems associated with this approach for multiple



T: transmiter R: receiver

Figure 4.6: Two Star Interconnection Using Active Repeater Nodes

stars is that the number of wavelengths present in the system grows linearly with the number of stars. This means that the tunability of agile receivers and transmitters should be very large. Wavelength reuse is not possible in this case. This is a direct interconnection approach when the number of stars is small in the system and when each optical star has a limited number of inputs.

4.7.2 Method 2: Using Active Nodes

Fig. 4.6 shows an example of two star interconnection using active nodes. In this case, both stars use only one set of wavelength $\{\lambda_0, \lambda_1, \ldots, \lambda_{N-1}\}$. If a user of one star wants to communicate with another user of the other star, the data packet has to be sent to the active repeater node. The data packet is buffered by this node and in turn transmitted on to the other star. The active repeater's receiver is part of one star and transmitter is part of another star. One can use multiple nodes to reduce delays due to queueing. If only one node per star is used, all the inter-star traffic has to go through this one, thus increasing the queueing delay if the traffic is large. On the other hand, if multiple nodes are used, users can randomly select one of the nodes and transmit their data. In this way the traffic load can be distributed among the nodes, thus reducing queueing delays.

The same connection pattern can also be extended to a large number of stars. A lot of interconnection patterns are possible among the stars depending upon the number of active repeater nodes used. A simple connection is to arrange all the stars in series. This causes the queueing

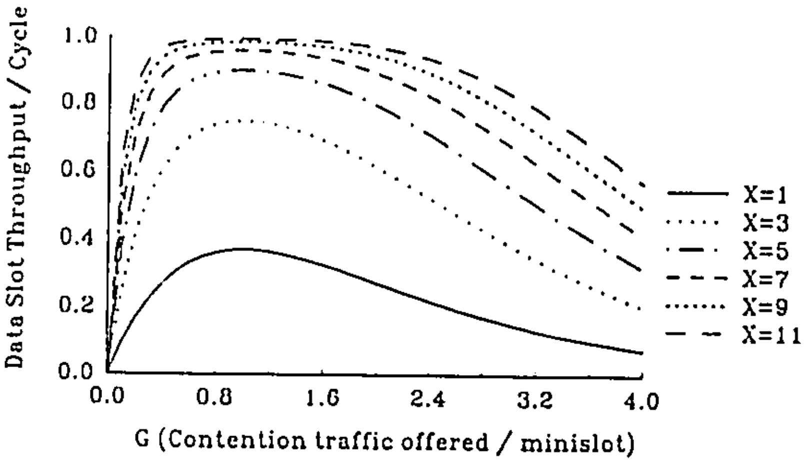


Figure 4.7: Data Slot Throughput vs. G

delays to be added up at every node. Alternately, one could impose a logical Shufflenet [13] pattern among the repeaters. Whatever be the interconnection pattern, the main problems associated with this approach are: repeaters have to switch the packets at very high speeds and they may become bottlenecks for the system operation. At high speeds, a node could collect a lot of packets within a short time thus requiring a large buffer. This introduces packet losses into the system and also causes large queueing delays. But the main advantage is the wavelength reusability at every star in the network and the method can be used when there is a limitation on the number of WDM channels the fiber can be divided into.

4.8 Numerical Results

In this section, the performance of the proposed protocols is presented. First, we study the performance of the reservation protocol. In Fig. 4.7, the data slot throughput per cycle (S_d;Eq. 4.1) is plotted against the offered contention traffic (G) per minislot. By providing two contention minislots ($x = 2$), the data slot throughput (S_d) can be increased to 0.6 as against 0.367 of Slotted-ALOHA throughput ($x = 1$). S_d is increased to 0.9898 by providing 10 contention minislots ($x = 10$). The maximum throughput is attained when $G = 1$. It can be seen from Fig. 4.7 that as x increases, the throughput curves attain almost a flat region (small change in the value of S_d) for a large range of offered traffic and the throughput curves start to fall down after this. However, the actual throughput per cycle (S_c) will be less than S_d due to wastage of bandwidth due to slotting and due to the contention period. The proposed protocol is simulated using

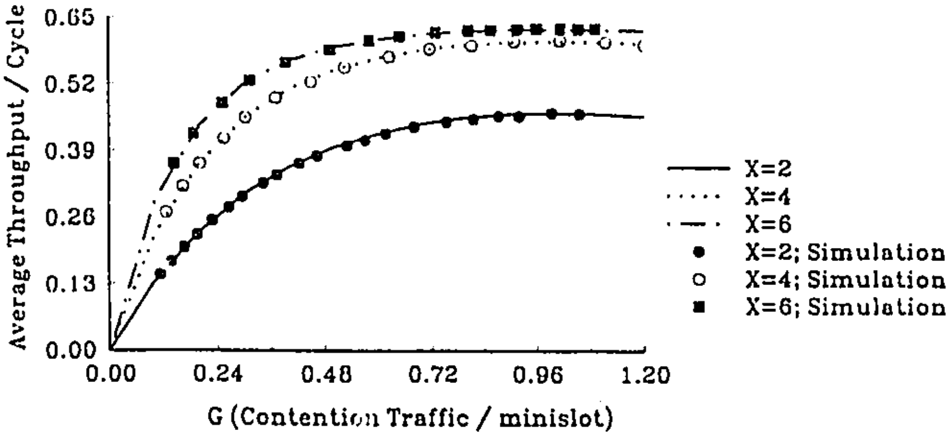


Figure 4.8: Average Throughput vs. $G(L = 20, N = 4)$

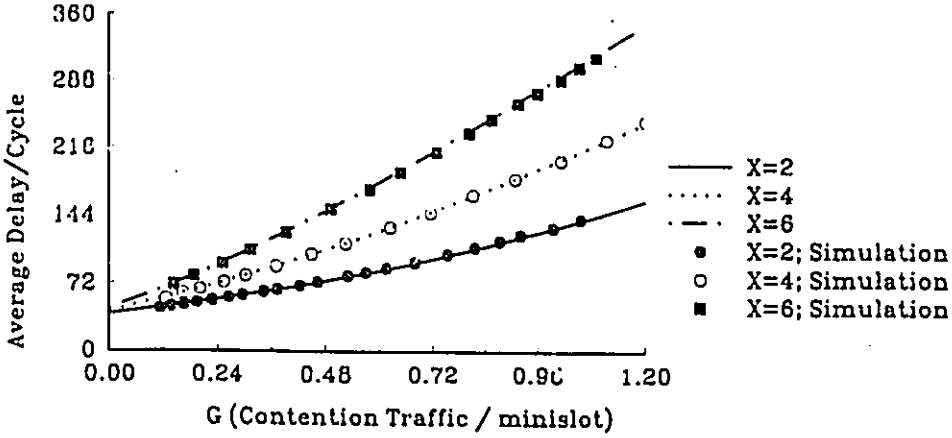


Figure 4.9: Average Delay vs. $G(L = 20, N = 4)$

Queueing Networks Analysis Package 2 (QNAP2) [47] with 95% confidence interval estimations for a data packet length of $L = 20$ and the number of channels $N = 4$ and for $x = 2, 4, 6$. The value of t_r, the random retransmission time is chosen such that the retransmissions occur in the next immediate cycle. Thus the delay plotted is a lower bound on the delay. The average throughput per cycle (Eq. 4.2) and the delay (Eq. 4.5) are plotted as a function of contention traffic (G) in Figures 4.8 and 4.9 respectively. The simulated results are also plotted on the same figures. It can be seen that the simulation results agree very closely with the analysis presented earlier.

In Fig. 4.10 and 4.11, the throughput per cycle (S_c) and the Average delay D are plotted for two cases of $L = 20, N = 4$ and $L = 100, N = 10$ for various values of x. Also the throughput

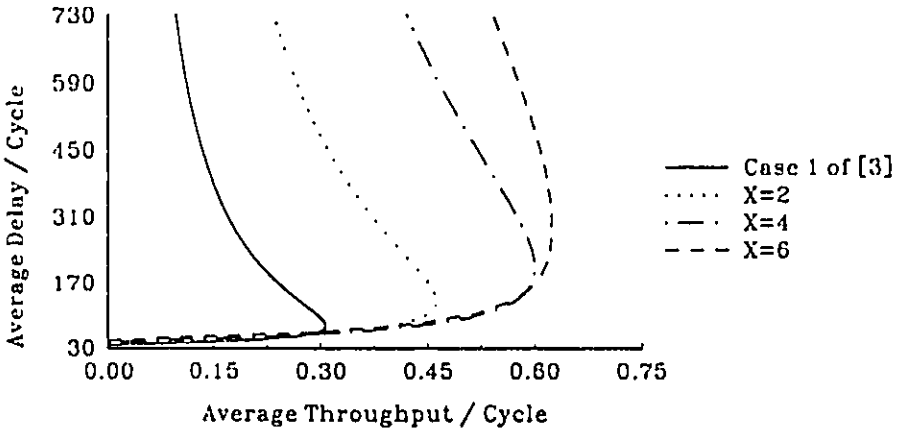


Figure 4.10: Throughput vs. Delay ($L = 20, N = 4$)

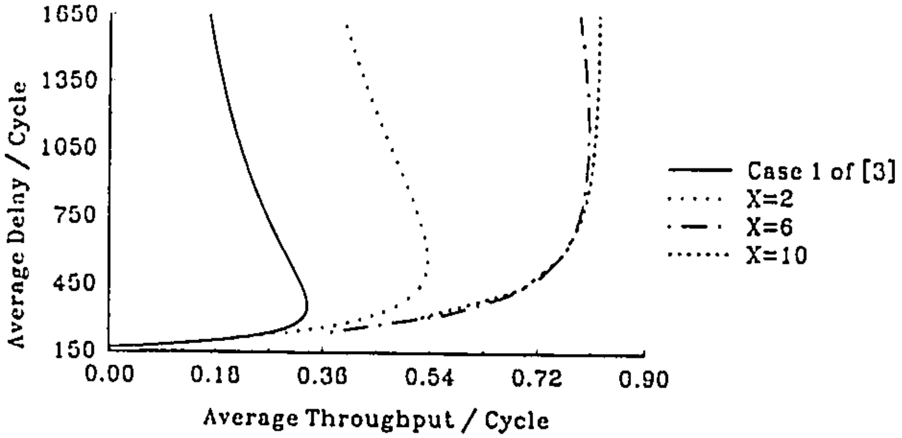


Figure 4.11: Throughput vs. Delay ($L = 100, N = 10$)

and delay of the simple Slotted-ALOHA scheme for this multiple channel LAN presented in [48] (Case 1) is also plotted in these figures. The slotting technique used in the simple Slotted-ALOHA (Case 1 of [48]) is similar to Fig. 4.3 with $x = N$ and each minislot on the control slot is preassigned to a data channel. That is slot i is to be used when the corresponding data packet is to be transmitted on λ_i. Although the initial delay is a little higher than the simple Slotted-ALOHA (due to increase in cycle length due to inclusion of contention period) the overall performance of the proposed protocol is much better In Fig. 4.12, 4.13 and 4.14 the proposed reservation and modified reservation protocols are compared with CSMA/N-Server of [23] and Slotted-ALOHA/N-server of [27]. In these figures, the average throughput per data channel is plotted against the average delay. The protocols CSMA/N-server of [23] and Slotted-

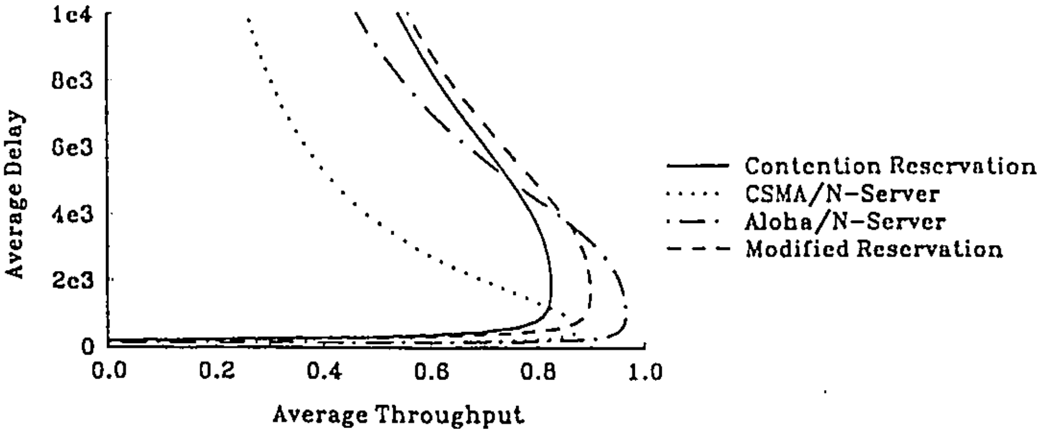


Figure 4.12: Throughput vs. Delay ($L = 100, N = 10, X = 10$)

ALOHA/N-server of [27] are described briefly here for reference:

CSMA/N-server: In this protocol, a user, after generating a data packet, monitors the control channel over one data packet length time (L). The user is then capable of identifying the idle channels and idle users in the system. If there are any idle channels, the user then transmits a control packet using the CSMA protocol on the control channel and the corresponding data packet on the chosen idle channel after the transmission of control packet. If all the N channels are busy, the user is said to be blocked and will repeat the process after a back-off time.

Slotted-ALOHA/N-server: This is similar to the CSMA/N-server except that the control channel is now a Slotted-ALOHA channel. If there is a collision on the control channel or if all the channels are busy, the user with a packet to transmit repeats the process after a back-off time.

Fig. 4.12 shows the throughput versus delay curve for $L = 100$ and Fig. 4.13 and 4.14 show the same for $L = 50$ and $L = 10$. In all the figures, the number of data channels N is chosen to be 10 and for the reservation protocol, the number of contention minislots x is chosen to be 10. The contention reservation scheme achieves higher throughput than the CSMA/N-server protocol when L is small. The delay is higher than that for both of N-server protocols. However, the proposed protocol offers better throughput when the offered traffic increases, of course at the expense of increased delay. That is, under large loads, when the throughput of other two protocols drops down very steeply, the proposed protocol still offers a modest throughput. This is predominantly true in Fig. 4.13 and 4.14. The modified reservation protocol of Section 4.4

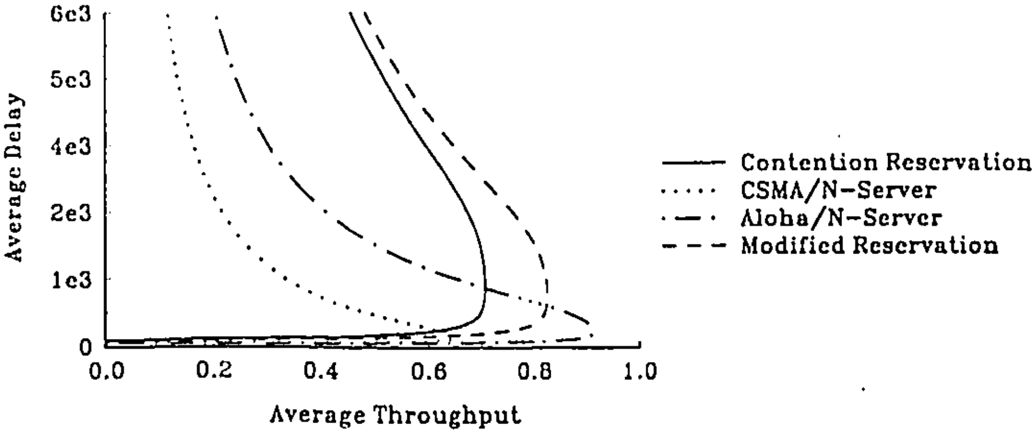


Figure 4.13: Throughput vs. Delay ($L = 50, N = 10, X = 10$)

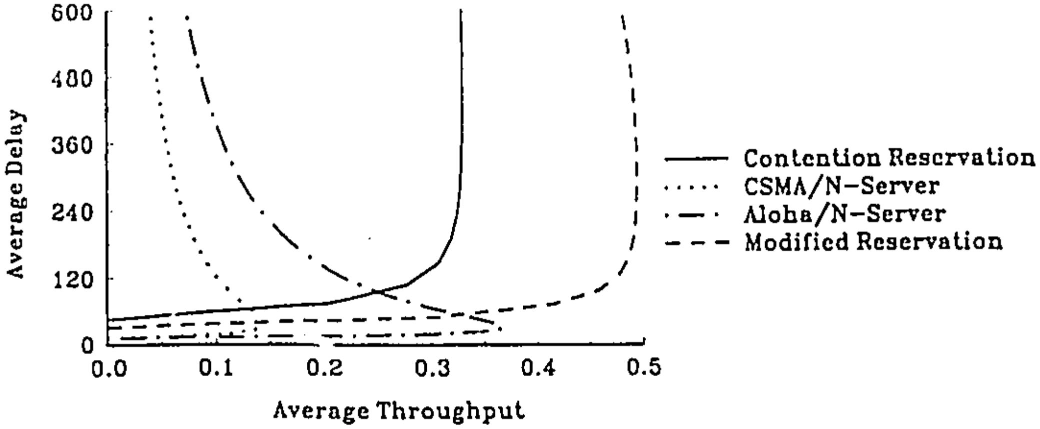


Figure 4.14: Throughput vs. Delay ($L = 10, N = 10, X = 10$)

offers a better performance as indicated by these plots. For a given x, the throughput per data channel of the reservation protocol reduces as N increases due to wastage of bandwidth. Remember that N control minislots are provided on the control slot and the data channel is not utilized during the period of the control slot.

As the number of channels in the system increases, the cycle length T also increases due to the N control minislots provided on the control slot. Hence, the maximum throughput decreases with N due to the denominator term $(L + N + x)$ in S_c of Eq. 4.2. However, the throughput increases with L and x. The modified reservation protocol is not dependent on N and the maximum possible throughput increases with L for a given x and also increases with x for a given L. It should be noted that the data packet length L is given relative to the control packet length which

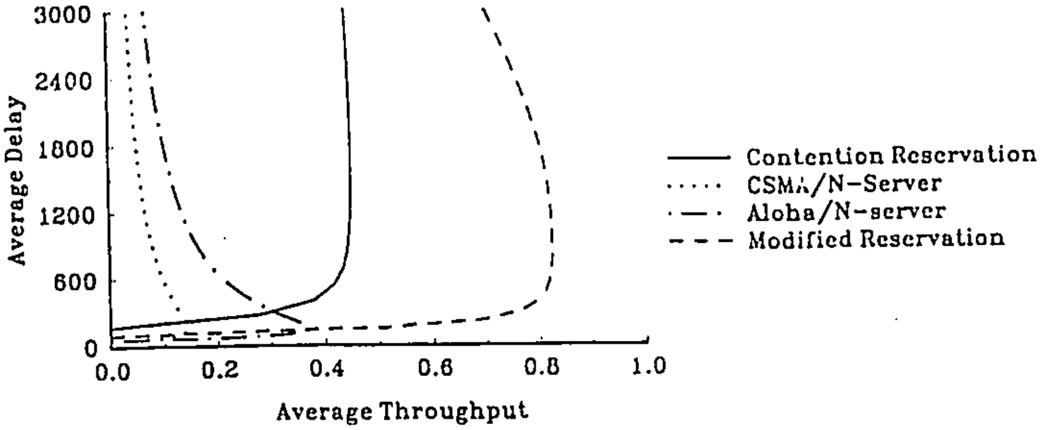


Figure 4.15: Throughput vs. Delay ($L = 50, N = 50, X = 10$)

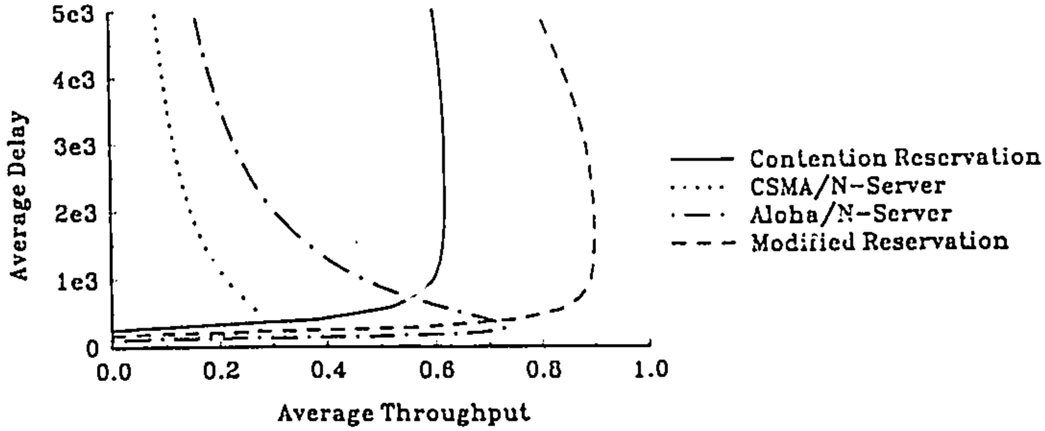


Figure 4.16: Throughput vs. Delay ($L = 100, N = 50, X = 10$)

is assumed to be unity. As mentioned in [23], at high data rates of 1 Gb/s, the CSMA-N server protocol can be used only with a network size of a few meters. To achieve better performance, the value of L should be increased. In both CSMA/N-server and ALOHA/N-server, if the value of N is increased for a given L, the system performance deteriorates. But, at higher data rates the packet lengths tend to be much shorter. In Fig. 4.15 and 4.16 the throughput and delay for various cases are plotted for large N and small L. It clearly shows that the proposed protocols offer better performance, especially the modified reservation scheme.

It should be observed that the duration of each control minislot and contention minislot is assumed to be of unit length. However, the contention packet only contains the source address and is of much shorter duration than the control packet which contains source, destination

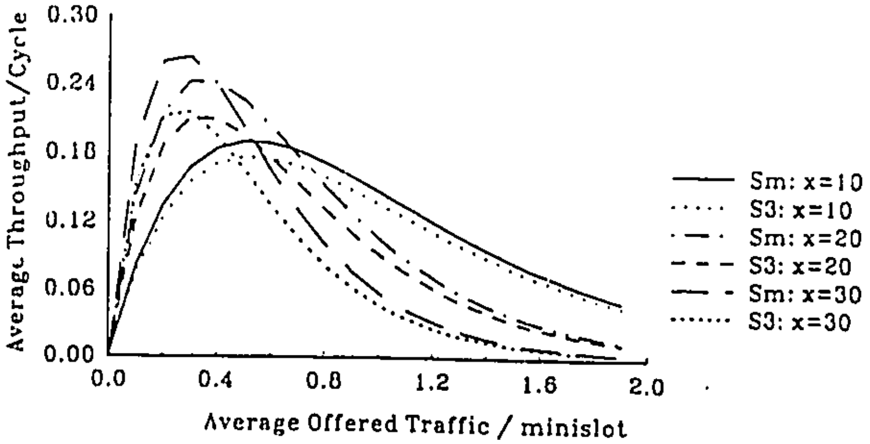


Figure 4.17: Throughput vs. $G(L = 100, N = 10, K = 5)$

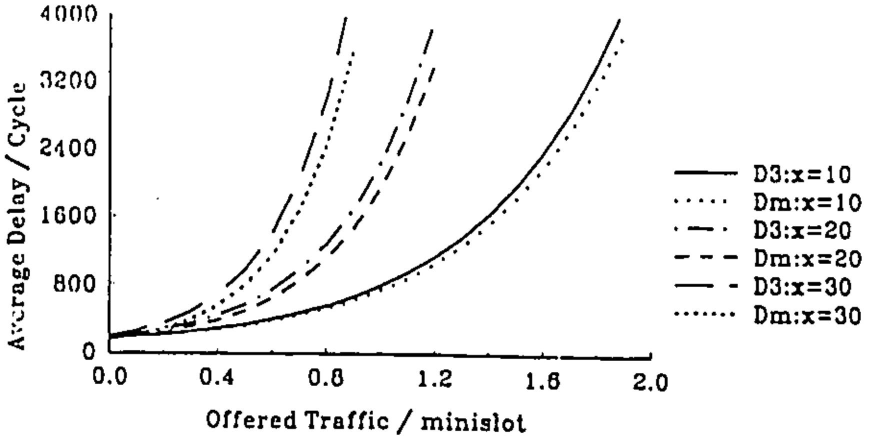


Figure 4.18: Delay vs. $G(L = 100, N = 10, K = 5)$

addresses and the data channel number. Hence, the actual contention slot will be much smaller than the duration x. If this is taken into account, the throughput will be a little higher and delay will be a little lower due to reduction in cycle length.

For the multi-control channel protocol, the throughput equations (Eq. 4.10), (Eq. 4.14) and the delay equations (Eq. 4.12), (Eq. 4.15) are plotted in Fig. 4.17 through 4.20 for the case of $L = 100$, $N = 5$ and $K = 5$ where K is the number of groups the users are divided into. The results are also compared with Case 3 of Slotted-ALOHA protocols and Improved Slotted-ALOHA protocols of previous chapter. For reference, the throughput and delay equations for these cases are included below:

$$S3 = \frac{L}{L+x}\frac{Gx}{N}e^{-[1+(x-1)/N]G} \tag{4.16}$$

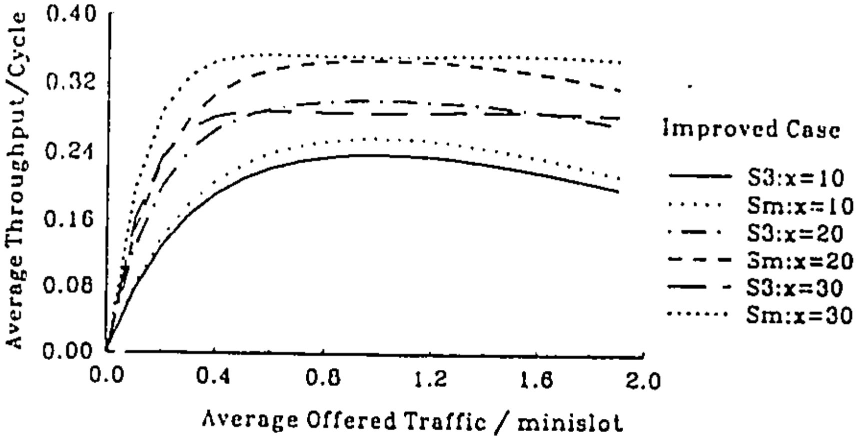


Figure 4.19: Throughput vs. $G(L = 100, N = 10, K = 5)$ for Improved Case

$$
\begin{aligned}
R &= e^{[G+G(x-1)/N]} \\
D3 &= (L+x).e^{[G+G(x-1)/N]} + \frac{L+x}{2} + (R-1).t_r && (4.17) \\
S3_i &= \frac{L}{L+x}.\frac{Gx}{N}e^{-G}.[1-\frac{G}{N}e^{-G}]^{(x-1)} && (4.18) \\
R_i &= \frac{e^G}{[1-\frac{G}{N}e^{-G}]^{x-1}} \\
D3_i &= (L+x) + \frac{L+x}{2} + (R_i-1).\left(\frac{x+1}{2}+t_r\right) && (4.19)
\end{aligned}
$$

where $S3$ and $S3i$ correspond to the throughput of Slotted-ALOHA Case 3 and improved Slotted-ALOHA and the corresponding delays are given by $D3$ and $D3i$. When $Ky = x$, the numbers of control minislots in both the systems are identical and the results are plotted for this value. This causes significant improvement in throughput and delay due to the reduction of the number of minislots on the control channel, as reflected by all the figures. The cycle duration is also reduced. The value of t_r is chosen such that the retransmission occurs in the next cycle, thus representing the minimum delay for all the delay plots. It can be observed that the multi-control channel LAN offers better throughput and delay characteristics.

4.9 Summary

In this chapter, a simple contention-based reservation protocol is proposed for optical star local area networks. This works on the principle of reserving a data channel by contention. For this purpose, a contention period is provided on each data channel and users contending for

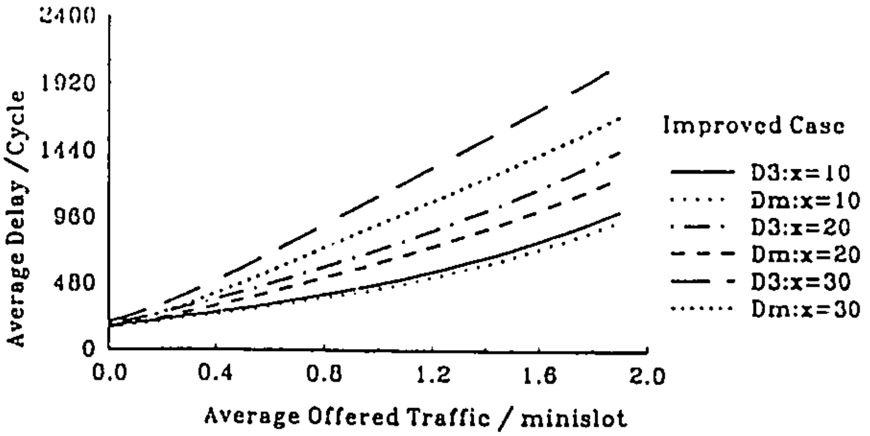


Figure 4.20: Delay vs. $G(L = 100, N = 10, K = 5)$ for Improved Case

a data channel first transmit a contention packet on randomly selected contention minislot on that data channel. The user who is first successful in transmitting the contention packet reserves the channel. The data slot throughput increases very rapidly with the number of contention minislots. By providing 10 minislots, data slot throughput of about 0.9898 can easily be achieved. However, the actual throughput is a function of offered load, the data packet length, the number of channels in the system and the number of minislots in the contention period. The protocol is found to offer better throughput even at large offered loads at the expense of higher delay. A modified protocol is also proposed which offers better performance than the above reservation protocol. But, in this case, it is the network designer's duty to assign various channels among the users according to the traffic flow between the users. A multi-control channel LAN configuration was also introduced for optical star networks using ALOHA protocols. This works on the principle of grouping the users of the system into various groups and providing a separate control channel for each group. The users in a group usually monitor their control channel for a possible control packet from other users. The users in a group can temporarily become members of other groups thus achieving inter-group communication very easily. This offers better throughput and delay performance than the optical star network which uses only one control channel and Slotted-ALOHA protocols. This principle can also be used to interconnect optical star LANs using the WDM technology and ALOHA protocols. Two methods for star interconnections were presented in this chapter, their choice depending upon whether there is a limitation on the optical star size or on the number of WDM channels. The protocols proposed in this chapter belong to the reservation and multi-control channel type protocols, as per the classification introduced in Chapter 2. We have published results of this chapter in [49] and [50].

Chapter 5

Switching Protocols for an Optical Star LAN and Applications

5.1 Introduction

The previous chapters presented some random access protocols for optical star networks when the number of channels in the system is more than the number of users. When the number of users is equal to the number of channels in the system, then slot contention arises if two or more users want to transmit data to the same user in the given time slot. However, these conflicts can be avoided, if the slots are assigned such that in one data slot only one pair of users communicate. This is considered to be a switching problem and such an optical star network is considered in this chapter along with some access protocols. This chapter is organized as follows: Section 5.2 describes the network architecture. In Section 5.3 we present protocols for this optical star network and Section 5.4 discusses how this network can be used as an integrated broadband switch. Sections 5.5 and 5.6 present some numerical results and conclusions.

5.2 Network Architecture of the Multi-Channel Optical LAN

We follow the same network architecture as before. The optical fiber bandwidth is divided into N channels using wavelength division multiplexing and each channel uses a distinct wavelength. Here, we are considering a system in which there are equal numbers of users and channels. Hence, the number of users in the system is also equal to N. It is assumed that each user has a tunable transmitter and each user is assigned a fixed receiving wavelength. Hence, in this network users do not require a tunable receiver and instead they use fixed wavelength receivers. It is assumed that the bandwidth of the optical fiber is divided into the following set of wavelengths $\{\lambda_1, \lambda_2, \ldots, \lambda_N\}$ and each transmitter is capable of tuning over the above set of wavelengths. It is also assumed that the user i is assigned the receiving wavelength of λ_i and the receiver is capable of receiving this wavelength. The protocols proposed in [23, 27, 48, 49, 50] require a separate control channel due to the wavelength agility of the receivers. No such mechanism is necessary in this case. The general access mechanism is as follows: if user i wants to communicate with user j, user i will transmit a small control packet (which contains the source address only) on the receiving wavelength according to the protocol presented in the next section. User j receives all the requests from the users and selects one (or more) contending users according to the protocol and informs them about the success. The actual transmission of data then follows in the data slot. We assume that all the channels are slotted using the same timing reference and all users are synchronized to this reference clock. All the channels are divided into slots using major and minor timing references. The slot with major timing reference is called a 'cycle'. The cycles are further divided into data, control and information slots using minor timing references. It is also assumed that each user knows the addresses (hence the receiving wavelength) of all other users in the system. The following notations are used in this chapter:

N = number of data channels in the system
M = number of minislots in the information slot
L = length of a data packet (control and information packets are assumed to be of unit length)

S_d = Throughput per data slot of each data channel
S_c = Throughput per cycle of each data channel
P_r = Retransmission probability of each data packet
P_b = Blocking probability of each data packet
R = Average number of retransmissions= $\frac{1}{1-P_r}$, (In this $R-1$ are unsuccessful attempts and one final successful transmission)
T = length of a 'cycle'

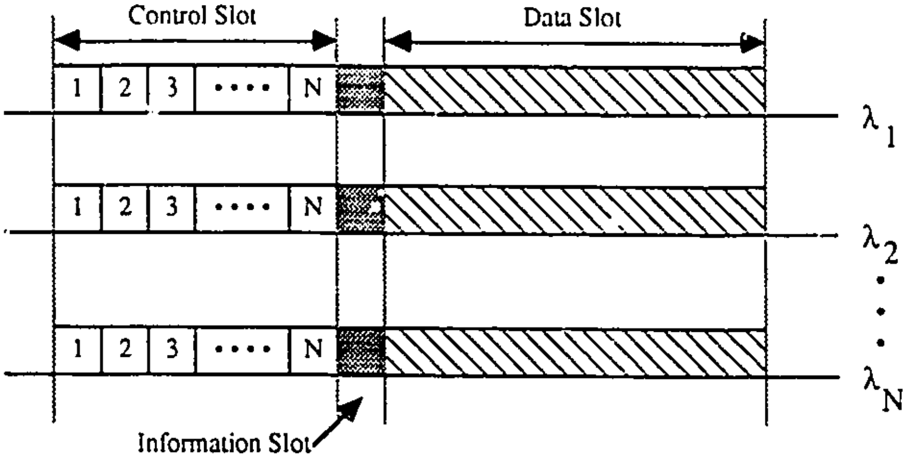


Figure 5.1: Switching Protocol 1 (SP1)

5.3 Switching Protocols for the Multi-Channel LAN

In this section, some switching protocols are presented for the LAN architecture described earlier, in which there are N users in the system and each user has a separate receiving wavelength.

Switching protocol 1 (SP1): As shown in Fig. 5.1, all the N channels are slotted in 'cycles' and each cycle is further divided into a control slot, information slot and a data slot. The control slot is further divided into N minislots and each minislot is *preassigned* to a particular user, that is, minislot i is to be used by user i only. The protocol mechanism is as follows: if user i has a packet for user j, then user i will transmit a small request packet (containing the address of user i) in the minislot i of the receiving wavelength λ_j of user j during the control slot. Since each user has a separate control minislot on each channel to send the request packets, no collisions will occur in this protocol. Since every user monitors the receiving wavelength at all the times, at the end of the control slot, user j will receive all the request packets from various contending users. At this point, user j will make a decision. Here, various decision policies are possible. One simple policy is to select uniformly one among all the contending users and allow that user to transmit the data packet. Priority selection is also possible when some kind of priority information is included in the request packets. However, in the following analysis we assume uniform selection policy among the contending users. User j informs the winner (say user k) of the decision process by transmitting a small information packet (a dummy packet) in the information slot of user k's receiving wavelength λ_k. Then, user k knows about the success and transmits the data packet to user j on wavelength λ_j in the data slot. Note that there are no collisions anywhere in this protocol.

The analysis of this protocol and the following protocol is done assuming that each user has a packet (either new or retransmitting) with a probability p at the beginning of the cycle, equally destined to any one of the N users. It is also assumed that every user and each channel in the system are identical.

Analysis: Since all the channels are identical, we look at any particular channel (say λ_1) to find the throughput of the channel. Since every user has a packet to send with a probability p at the beginning of the cycle, this packet is destined to the channel being observed (λ_1) with a probability p/N. There are N minislots on the control slot and under uniform selection policy one among the contending users is selected for data packet transfer. The data slot goes wasted if there is not even a single request packet destined to this channel (λ_1). Therefore, the probability P_0 that no request packet is destined to this channel is given by:

$$P_0 = \binom{N}{0} \cdot \left(\frac{p}{N}\right)^0 \cdot \left(1 - \frac{p}{N}\right)^N = \left(1 - \frac{p}{N}\right)^N$$

Therefore, the throughput of the data slot S_d is given by:

$$S_d = 1 - P_0 = 1 - \left(1 - \frac{p}{N}\right)^N \tag{5.1}$$

Considering the overheads due to control and information slots, the throughput per cycle S_c of the data channel is given by:

$$S_c = \frac{L}{L+1+N} . S_d = \frac{L}{L+1+N} \cdot \left[1 - \left(1 - \frac{p}{N}\right)^N\right] \tag{5.2}$$

In order to find the delay, we first calculate the blocking probability P_b of the request packet, that is, the probability that the request packet is not selected in the contention process and hence the packet will be retransmitted later. The request packet is not selected in the contention if there are more than two contending packets and one of them is selected. Let there be x contending request packets on the given data channel (λ_1) and let p_x be the probability that the request packet is blocked when there are x contending packets and P_x be the probability that there are x contending packets. Then, p_x and P_x are expressed as:

$$p_x = \text{P(request packet blocked} \mid x \text{ contending packets)}$$

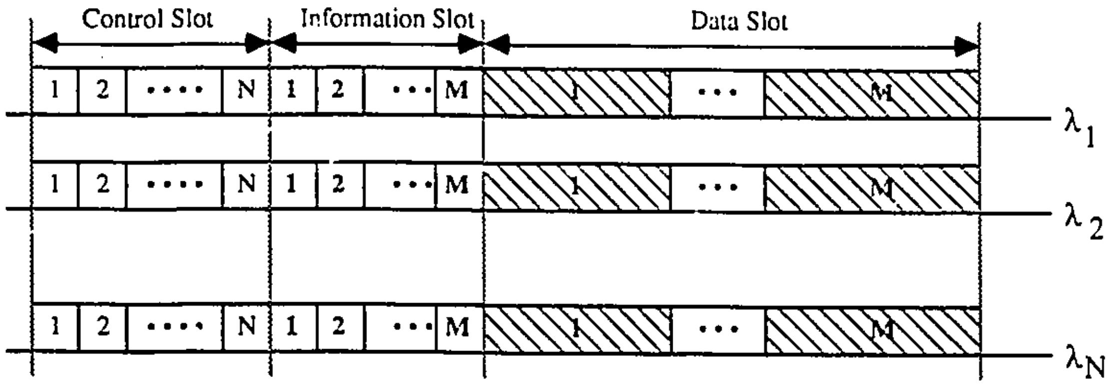


Figure 5.2: Switching Protocol 2 (SP2)

$$= (1 - \frac{1}{x})$$

and

$$\begin{aligned} P_x &= \text{P(there are } x \text{ contending packets)} \\ &= \binom{N}{x}.\left(\frac{p}{N}\right)^x.\left(1-\frac{p}{N}\right)^{N-x} \end{aligned}$$

Hence, the blocking probability P_b is given by:

$$\begin{aligned} P_b &= \sum_{x=2}^{N} p_x.P_x \\ &= \sum_{x=2}^{N}(1-\frac{1}{x}).\binom{N}{x}.\left(\frac{p}{N}\right)^x.\left(1-\frac{p}{N}\right)^{N-x} \qquad (5.3) \end{aligned}$$

If the packet is blocked (not selected), it has to be retransmitted in the next or succeeding cycles according to the retransmission strategy that is followed. The probability of retransmission P_r will be the same as the blocking probability P_b and from this the average number of retransmissions can be calculated by using $R = 1/(1 - P_r)$ under infinite retransmission scheduling. Then, the total delay experienced by a packet is $D_1 = R.T$, where $T = N + 1 + L$ is the total cycle duration

Switching protocol 2 (SP2): In the earlier protocol, only one request is selected among the various contending packets. It is possible to select more than one packet and the switching cycle has to be modified as shown in Fig. 5.2. All the N channels are slotted into 'cycles' and each cycle is further divided into a control slot, information slot and a data slot as earlier. Here, we are considering the case where up to M contending users can be selected in one switching cycle. Hence, M minislots are also provided on every information slot now. The control slot is further divided into N minislots and each minislot is *preassigned* to a particular user, that is, minislot i is to be used by user i. The protocol mechanism is as follows: if user i has a packet for user j, user i will transmit a small request packet (containing the address of user i) in the minislot i of the receiving wavelength λ_j of user j during the control slot. Since every user monitors the receiving wavelength all the time, at the end of the control slot, user j will receive all the request packets from various contending users. At this point, user j will make a decision and select upto M request packets among the contending user's. User j informs the winners of the decision process by transmitting a small information packet. Since there can be up to M winners, M mini slots will be required on each information slot so that user j can transmit the information packets to all the winners 'cyclically'. (Note that only one information slot will be needed if each user is equipped with M tunable transmitters so that these packets can be transmitted in parallel). These packets will be transmitted on the respective receiving wavelengths of the winners and the information packet now should also include which data slot should be used by the winner. The winners know about the success and transmit the data packet to user j on wavelength λ_j in the assigned data slot. Note that, again there is no chance for collisions anywhere in this protocol.

Analysis: We follow a similar analysis as we did earlier. The probability P_x that there are x request packets in a control slot of a given channel (say λ_1) is given by:

$$\begin{aligned} P_x &= \text{P(there are } x \text{ contending packets)} \\ &= \binom{N}{x} \cdot \left(\frac{p}{N}\right)^x \cdot \left(1 - \frac{p}{N}\right)^{N-x} \end{aligned}$$

Since there are M data slots in a cycle, it is not always necessary that all M of them will be used. It is assumed that the data slots on a given channel are assigned in a serial order. That is, if there is only one request packet, data slot 1 is assigned. If there are two, then data slots 1 and 2 are assigned, etc. Then, one data slot is used with probability P_1, two are used with probability P_2, etc., and all the M data slots will be used with a total probability of $\sum_{x=M}^{N} P_x$. Here, it is assumed that $M \leq N$ since it does not make sense to provide more data slots than the number of users for each channel. Therefore, the total data slot throughput (of all the data slots) S_d is given by:

$$\begin{aligned} S_d &= P_1 + 2P_2 + 3P_3 + \cdots + M(P_M + P_{M+1} + \cdots + P_N) \\ &= M - MP_0 - (M-1)P_1 - (M-2)P_2 - \cdots - P_{M-1} \qquad (5.4) \end{aligned}$$

and the throughput in the total cycle S_c is given by:

$$S_c = \frac{ML}{ML+M+N}.S_d \qquad (5.5)$$

The delay experienced by a packet in successfully getting through to the destination can be calculated as earlier, by first calculating the blocking probabilities. It should be noted that out of N minislots provided on the control slot, there could be x packets contending for that channel. The user (node) selects up to M users for data transfer since there are M data slots available in every cycle. If $x \leq M$, then all the packets contending will be selected and there is no blocking. Hence, blocking arises only if $x > M$. Under the condition that $x > M$, the probability that a given data packet is selected for transmission is $\binom{x-1}{M-1}/\binom{x}{M} = M/x$. Therefore, the probability p_x that a given request packet is blocked is expressed as:

$$\begin{aligned} p_x &= \text{P(a given request packet is blocked} \mid x \text{ contending packets)} \\ &= \left(1 - \frac{M}{x}\right) \end{aligned}$$

Hence, the blocking probability P_b is given by:

$$\begin{aligned} P_b &= \sum_{x=M+1}^{N} p_x.P_x \\ &= \sum_{x=M+1}^{N} \left(1-\frac{M}{x}\right)\binom{N}{x}.\left(\frac{p}{N}\right)^x.\left(1-\frac{p}{N}\right)^{N-x} \qquad (5.6) \end{aligned}$$

Under infinite retransmission scheduling, the average number of retransmissions is $R = 1/(1-P_b)$ and the total delay experienced by a packet is $D_2 = R.T$ where $T = ML + L + N$ is the cycle duration.

It should be observed that, in both switching protocols, the control slot (the number of minislots) is a function of N, the number of nodes in the network. Hence, as N increases, the throughput per cycle will reduce for a given L. In protocol 1 (SP1), the network throughput is limited due to head of line contention, that is, the packets could not go to the requested outputs due to contention. In protocol 2 (SP2), since there is a speed-up (up to M data packets can be switched per channel in a cycle), both the transmitter and receiver should operate at higher speeds.

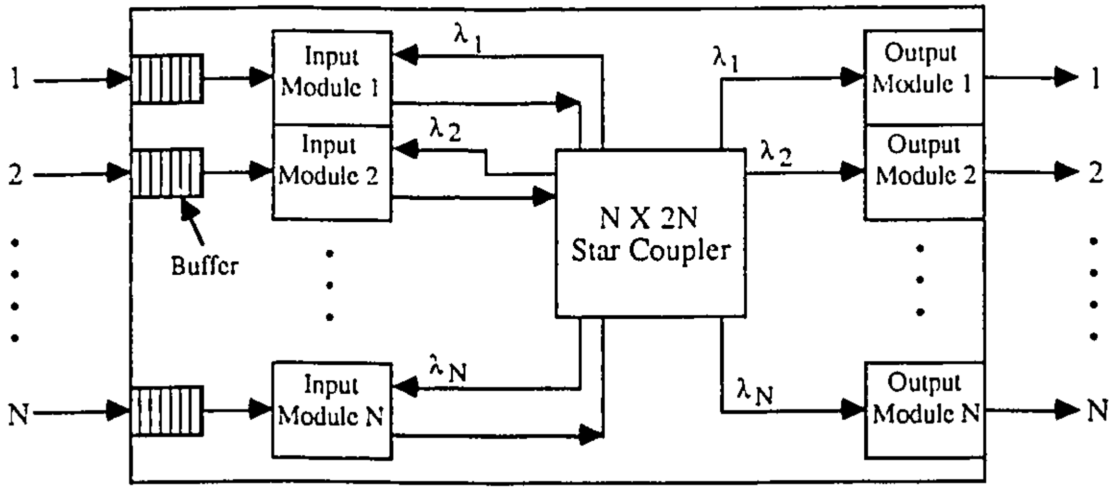


Figure 5.3: A Broadband Switch Architecture

5.4 Applications

Application 1: The network described above, along with the switching protocols can be used as a high-speed integrated broadband switch with slight modifications. At present, great deal of research is going on to build high-speed switches [51] for Broadband ISDN [19] in which Asynchronous Transfer Mode (ATM) will be used as switching and multiplexing technique. Some switch architectures with an optical star coupler as switch fabric were also proposed [52, 53]. A very simple switch architecture can be developed by using a $N \times 2N$ star coupler as the switch fabric and using the switching protocols proposed in Section 5.3. Fig. 5.3 shows the architecture of the switch in which all the nodes of the multi-channel optical network are collapsed into the input modules. As in the network architecture, it is assumed that there are N WDM channels in the switch and each input module is equipped with a tunable transmitter and fixed- wavelength receiver. Each receiver (input module) is assigned a particular receiving wavelength which is also assigned to one of the output modules. That is, the input module i basically controls the switching functions to the output port i in this $N \times N$ switch. We can also use an $N \times N$ optical star coupler. In this case, the output module controls the switching function and there should be a separate control path between the input and output modules, for control purposes. If a $N \times 2N$ star coupler is used, this control is done optically. If a multi-stage interconnection network is used to form larger switches, then the output module can be a part of the next stage input module.

Since an optical star is a non-blocking switch fabric (there are no collisions if all N inputs transmit on different wavelengths to the N outputs), input queueing can be used to store the packets when they cannot go to the requested output due to output port contention. If switching protocol SP1 is used, no output queues are necessary, as only one packet is being switched to a given output port in one switching cycle. As mentioned earlier, the control slot duration increases with N, due to the N minislots required on each channel. The total switching cycle can be kept constant for any N, if the control minislot duration is decreased (alternately, the request packets are transmitted at much higher data rates) with N. The analysis of the non-blocking switches with various kinds of queueing is done in [54] and the results of input queueing from [54] directly apply here. When First-In-First Out (FIFO) buffers are used, the maximum possible throughput is about 0.5858 for $N = \infty$. This throughput can be increased to 0.632 when packets are dropped at the input queues instead of storing them [55]. In this case, the throughput equation is exactly the same as the data channel throughput (Eq. 5.1) of our network under protocol SP1.

When Switching Protocol 2 (SP2) is used with this switch architecture, then the switch should have output buffers, since in a single switching cycle up to M packets can be switched to a given output. This is called 'speed-up' and the performance of the non-blocking switch with speed up when there are only output buffers and when there are both input and output buffers is analyzed in [56]. When $M = 1$, the switch throughput is 0.5858 for a large N and is more than 99% when $M \geq 4$. The throughput equation (Eq. 5.4) of the switching protocol 2 becomes the throughput of the switch when packets are dropped, if the contending packets did not go through in this switching cycle.

Application 2: Both cellular telephone systems and optical networks are characterized by power limited signals. Since an $N \times N$ optical star uniformly distributes the incoming signal among the N outputs, the size of the star would be limited by the minimum detectable signal at the receiver. Also, there are practical limitations on the number of wavelengths that can be employed through WDM networks. Hence, multiple star centers may have to be used

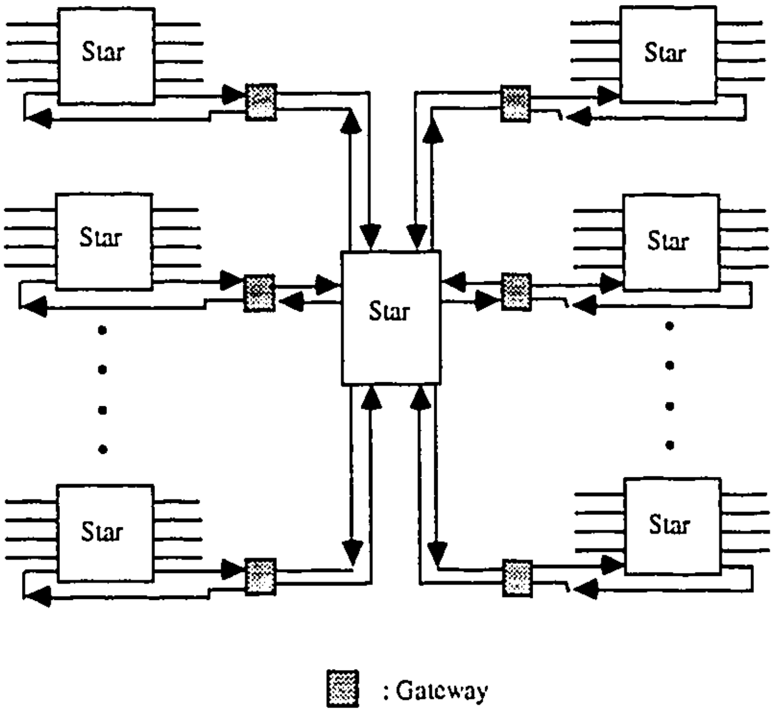


Figure 5.4: An Optical Star Network Architecture

to form a large network of users. In [49], a multi-control channel protocol is proposed for high-speed optical networks. This can be used to directly interconnect various optical star networks using a Slotted-ALOHA technique and assumes system wide synchronization. Two simple interconnection techniques were presented in [49] depending upon whether there is a limitation on the size of the optical star or on the number of WDM channels present in the system. For improved throughput of the system, the switching protocols described in this chapter and the reservation protocols described in [50] can be used to form a larger optical network (Fig. 5.4). Within a star center, users have a direct optical connection using either the switching protocols (if the number of users equals to the number of channels) or the reservation protocols. However, no direct optical connection is possible between users of various stars. Instead, users send their packets to the gateways which send the data packets to the gateways of other stars. Alternately, the broadband switch described above can also be used. Multiple gateways per star can also be used to improve the packet delays and hierarchical switching system can also be implemented by extending this network architecture. Each gateway requires two transmitters and two receivers.

5.5 Numerical Results

In this section, we present some numerical results of the throughput and delay equations for our switching protocols. Fig. 5.5 shows the throughput S_c versus the packet transmission probability (p) in a switching cycle. The cycle throughput reduces with N, the number of users in the system due to the control slot. There are N minislots on each control slot of every data channel. Hence the data channel utilization drops off with N. The same is the cause of increasing the delay in Fig. 5.6.

Although the delay curves follow the same pattern, there is a step increase with N due to the increase in the cycle time. Similarly, Fig. 5.7 and Fig. 5.8 show the throughput and delay plots for switching protocol 2 when up to $M = 4$ contending users are switched in a cycle. Figures 5.9 and 5.10 show the throughput and delay plots for various M when $L = 100$ and $N = 64$. As can be seen, the throughput and also the packet delay are higher in this case. The delay is higher due to the cycle duration which increases with N and M. This increase is substantial due to the M data sub-slots provided on each data slot. The delay curves are constant for $M > 1$ suggesting that the packet blocking probability P_b is very small and the delay is just the cycle

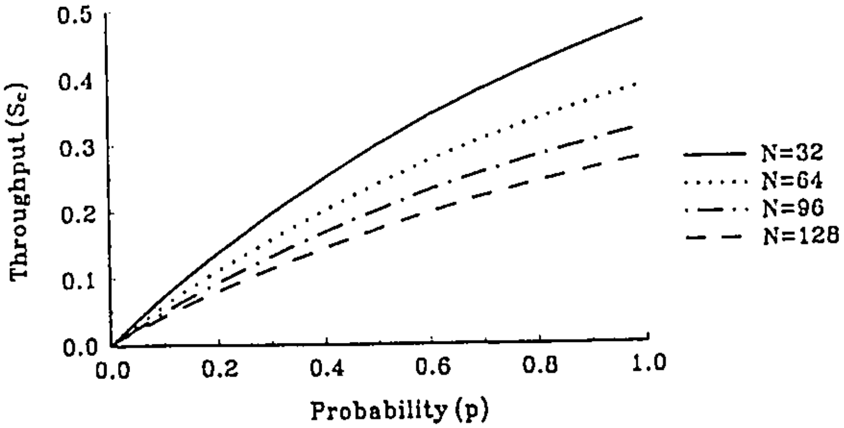


Figure 5.5: Throughput vs. p (L=100)

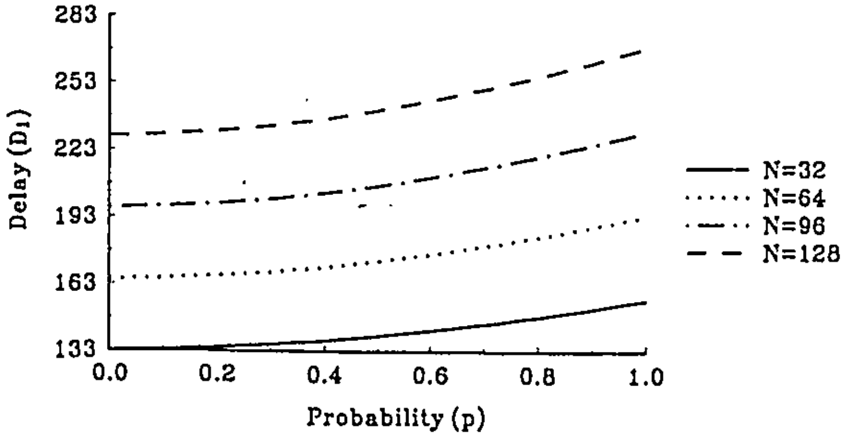


Figure 5.6: Delay vs. p (L=100)

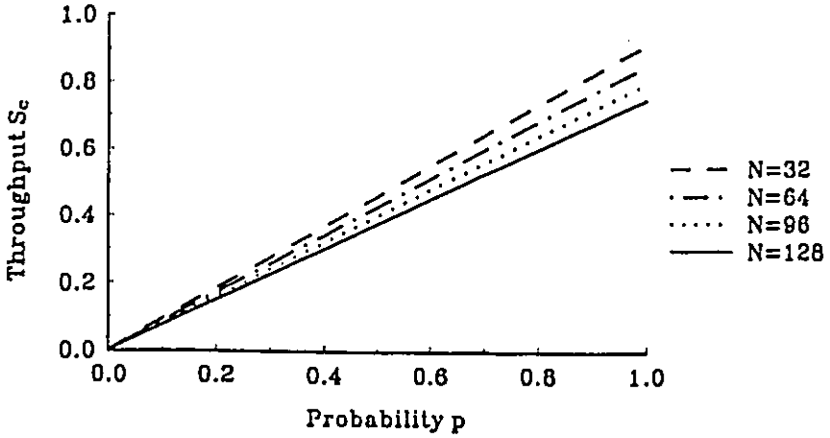


Figure 5.7: Throughput vs. p (L=100;M=4)

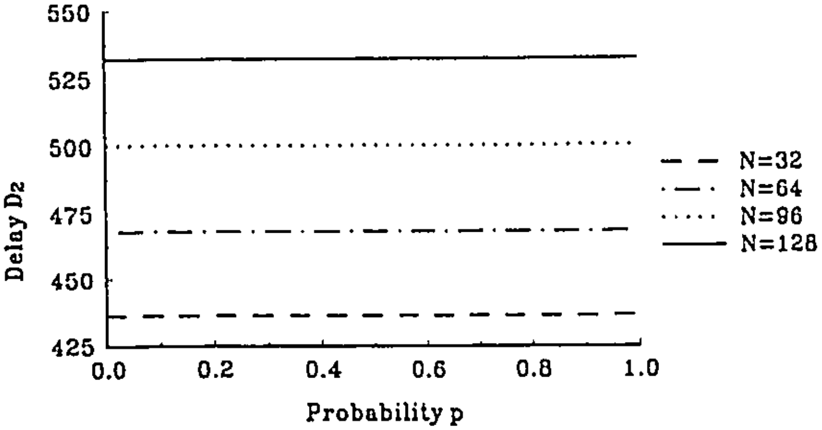


Figure 5.8: Delay vs. p (L=100;M=4)

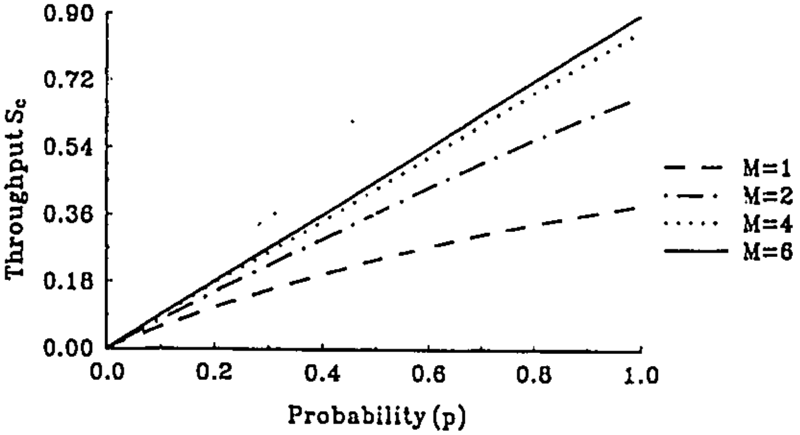


Figure 5.9: Throughput vs. p (L=100;N=64)

time involved in transmitting the packet. The blocking probability P_b increases with N for a given M and decreases with M for a given N. For example, when $N = 64$, P_b is 1.47×10^{-1} for $M = 1$ and reduces to 9.21×10^{-5} when $M = 5$. However, for $N = 128$, the value of P_b is 1.47×10^{-1} when $M = 1$ and it is 1.08×10^{-4} when $M = 5$.

In Fig. 5.11, the maximum possible throughput (when $p = 1$) is plotted as a function of the number of data sub-slots (M) for SP2 and $N = 32$. The maximum throughput increases with M due to the switching of more packets which otherwise would have been blocked. When $M = 2$, the throughput reaches 77.1% and is about 87.7% when $M = 3$ and more than 90% when $M \geq 4$. The maximum throughput as a function of the number of users in the network is plotted in Fig. 5.12 for various M. It can be seen that a good amount of throughput is

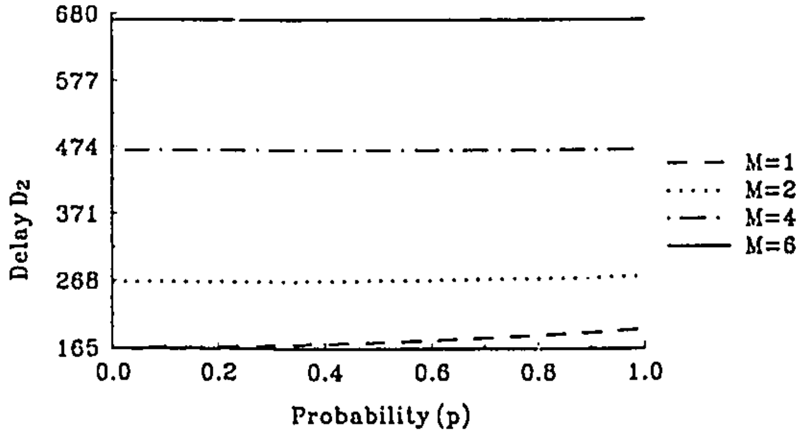


Figure 5.10: Delay vs. p (L=100;N=64)

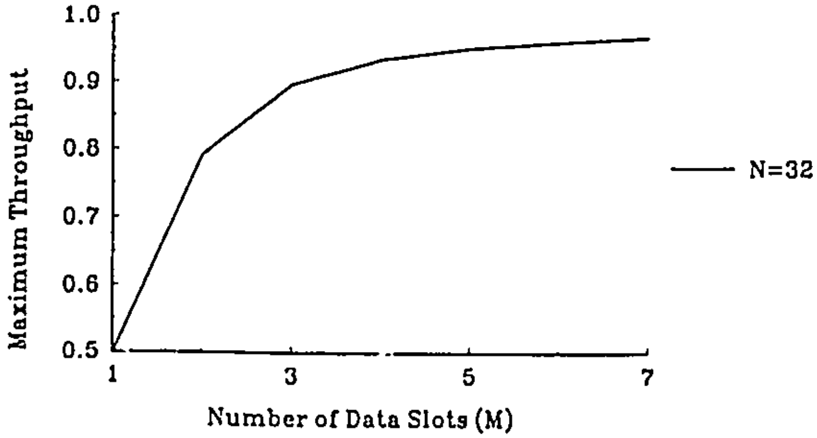


Figure 5.11: Maximum Throughput vs. M (L=100)

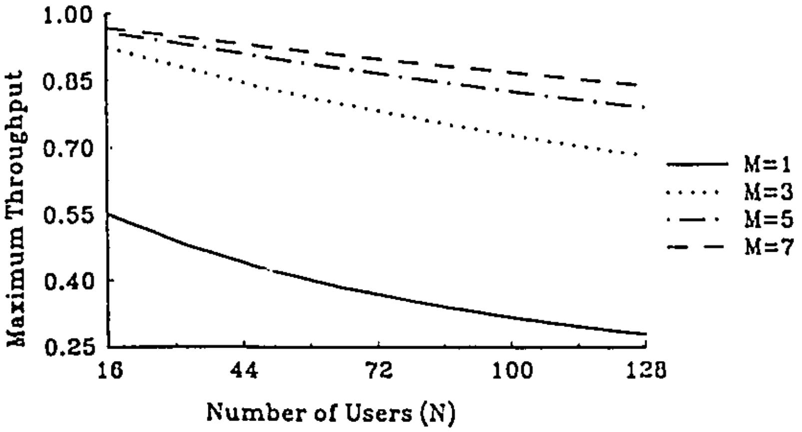


Figure 5.12: Maximum Throughput vs. N (L=100)

maintained up to 128 users when $M = 3$. and the maximum throughput is more than 85% when $M > 5$ and up to $N = 128$.

Note that, the throughput mentioned above include the channel inefficiency due to the embedded control cycle in the total switching cycle. The data slot throughput will be much higher if this is not considered.

5.6 Summary

In this chapter, a simple optical star local area network is considered with equal number of users and channels in the system and four switching protocols were developed for the same. A simple analysis is done with finite number of users and channels in the system for protocols SP1 and SP2. The same concepts can be used in a broadband switch by using a $N \times 2N$ star coupler as the switch fabric and the same switching protocols can be used for controlling the switch. Since there are practical limitations on the number of wavelengths that can be employed through WDM, this chapter proposes an Optical Star Network architecture using gateways and the proposed switching protocols. The results in this chapter were published in [57].

Chapter 6

Throughput Reductions Due to Receiver Collisions in Multi-Channel Optical Networks

6.1 Introduction

Many data link protocols appeared in [23, 27, 48, 43, 44] for passive optical star networks. But, all these references ignored the "receiver collisions". Receiver collisions occur when users transmit their data packets to the busy receivers. Since the receiver is busy, it cannot receive the data packets sent by other users. Thus, these data packets are essentially lost. Here, we want to distinguish between two types of receiver collisions that occur in multi-channel networks. In the first type, a receiver collision occurs when two or more users are successful in obtaining data channels and wish to communicate to the same given user at the same time (also, called contention to the destination or output contention). Since there is only one tunable receiver, the receiver can receive only one data packet at a time ignoring the other data packets. Although the users are successful in obtaining a data channel, the data packet may not be delivered to the busy receiver and thus the actual throughput will be much less than the data channel throughput. Here, it is assumed that the receiver knows the status of successful transmitters and selects one among them using a prescribed selection policy, such as uniform or random. This is more common to slotted protocols with separate control and data slots such as the ones proposed in this thesis. In certain data link protocols (such as ALOHA), a user has to tune its transmitter and receiver to the same channel to monitor possible packet collisions on the data channel while transmitting its own data packets. In this case, if the node is equipped with only one receiver, the receiver may not be able to monitor whether there will be any packet transmissions meant to self from other users since the node does not receive the control packets. This is the second type of receiver collision and is specific to the data link protocol that is being used and may appear in protocols with overlapping time intervals. However, all the slotted protocols proposed in this thesis contain separate control and data slots in disjoint time intervals. Hence, the second type of receiver collision will not be present in our case, since the control packets are not transmitted while data packets are being transmitted. In a multi-channel network environment with a large population of users and with a small number of channels, these events are considered to be rare and are generally ignored.

A passive star network with a Protection Against Collision (PAC) circuit is described in [39] and was reviewed in Chapter 2. In this network, a control star along with a PAC circuit is used to allow the access to an addressed channel, only if the channel is available thus avoiding the receiver collisions. In [38], the receiver collisions are considered for the improved Slotted-ALOHA/ALOHA protocol of [27] in which throughput reductions were observed. These receiver collisions are of second type. A receiver collision avoidance (RCA) protocol is proposed in [40] by the same authors, which is capable of detecting and avoiding receiver collisions before packets are transmitted.

With dense wavelength division multiplexing, it is possible to obtain many channels whose number can be comparable to the number of users. In this case, the reduction in data channel throughput due to first type of receiver collisions cannot be ignored. In this chapter, we consider such a passive optical star multi-channel network with two data link protocols proposed in [48, 50] and present both analytical and simulation results. When using random access protocols, it is found through simulations that, the slot-to-slot dependency (correlation) can be ignored in these multi-channel networks for these protocols.

In this chapter, the same network architecture is considered as before (c.f.,Fig. 3.1). The network consists of M users and the users are connected to the passive star through optical fibers. It is assumed that the bandwidth of the fiber is divided into $N+1$ Wavelength Division Multiplexed (WDM) channels, each on a different wavelength $\{\lambda_0, \lambda_1, \cdots, \lambda_N\}$. For a single communication hop between the users, the users should have access to all the channels to transmit and receive their data packets. The users in the system are equipped with rapidly tunable transmitters and receivers that are tunable to all the wavelengths present in the system. A separate control channel (λ_0) is used to pass the control information which is monitored by all the idle users. When there are multiple channels in the system, different users will be transmitting their data packets on the channels. In such a situation, more than one packet can be destined to the same receiver. In the network architecture described above, each node has only one receiver. This implies that each node can receive only one packet at a given time, ignoring all others, even though it has the complete knowledge through monitoring the control channel. Thus, even if a transmitter is successful in obtaining a data channel, the packet may not be actually received by the destination and a "receiver collision" of the first type occurs. This has to be considered when calculating the throughput of the data channel. Since the receiver collisions of the first type are common to almost all protocols, we consider this as a more general problem associated with the multi-channel networks.

6.2 Effect of Receiver Collisions in Slotted Multi Channel Networks

Consider a slotted multi-channel data network as described above. Let us assume that there are M users and N channels in the system. Each user can access all the channels in the system and a user randomly selects a data channel when transmitting a data packet. All the users follow a predetermined random access protocol when transmitting the packets on these channels. Let us further assume that, each user transmits a data packet with probability p (transmission or retransmission) at the beginning of each slot and P_S is the throughput/slot of each data channel. P_S is actually the probability that any packet is successfully transmitted in a data slot on any channel and is dependent upon the particular data link protocol. It is also assumed that the selection of channels from slot-to-slot is independent. That is, each user selects a data channel randomly (not necessarily the same as previous one) in every slot the user is transmitting. Because of the random access protocol that is followed, each user's transmission may not be successful and the user tries to transmit the same packet (with the same destination) in the succeeding slots with a probability p. Even if the user is successful in transmitting the packet, the packet may not be delivered to the destination due to the receiver collisions of the first type described before. It is assumed that an immediate positive feedback is available from the destination when a user's packet goes through. If the packet is not delivered to the destination, the user tries again to transmit the packet in the succeeding slots with a probability p. Thus each user faces two problems when transmitting a data packet: (1) contention to data channels, and (2) contention to the destination if the user is successful in obtaining a data channel. In a non-blocking switch environment, there is no contention for the channels and hence the slot-to-slot dependency cannot be ignored [54] when considering the contention to the destination. But the slotted multi-channel network can be considered as a blocking switch network and this slot-to-slot dependency could be small due to the contention on the channels. In the following, we assume such an independency and show through simulations that this indeed is the case. We follow the following notations in this chapter:

N = number of data channels in the system
M = Total number of users in the system
R = Total number of transmissions per successful packet
P_S = Probability that any data packet is successful on a given channel
P_{SN} = Probability that a node successfully transmits a packet without receiver collisions
P_{SNR} = Probability that a node successfully transmits a packet with receiver collisions
P_{SR} = Throughput of a data channel with receiver collisions
D = Total delay in transmitting a packet without receiver collisions
D_{RC} = Total delay in transmitting a packet with receiver collisions

Throughput due to Receiver Collisions:

Here, we consider the actual throughput of the data channels when these receiver collisions are considered, ignoring the slot-to- slot dependency. The system consists of M users and N channels. Consider a particular (tagged) destination node. The probability that any data packet is successful on a given channel is P_S. Let P_{SNR} be the probability that each node 'successfully' transmits a data packet in a data slot with receiver collisions and P_{SN} the probability without receiver collisions. Here, the word 'successful' means that the data packet from this node is actually delivered to the destination. Since there are M nodes, the probability that a packet goes to the given destination is P_S/M. Since there are N channels, the probability that no packet is to the tagged destination in a given slot is $(1-\frac{P_S}{M})^N$. Therefore, the probability that at least there is one packet to the tagged destination is, $(1-(1-\frac{P_S}{M})^N)$. This is the throughput of each node and, under equilibrium conditions, this probability must be equal to P_{SNR}. Similarly, under equilibrium conditions, the total throughput of the nodes and the channels in every slot should be the same which is the total system throughput. Let P_{SR} be the actual probability (or throughput) of the data channel that any packet is successful in a slot with receiver collisions. Then, we have,

$$\begin{aligned} P_{SR}.N &= M.(1-(1-\frac{P_S}{M})^N) \quad \text{or} \\ P_{SR} &= \frac{M}{N}.(1-(1-\frac{P_S}{M})^N) \end{aligned} \tag{6.1}$$

The probability P_S is dependent upon the particular protocol. To calculate the delay (D_{RC}), in transmitting a packet from a node, we observe that the total number of transmissions (R) in transmitting a packet successfully by a node equals to $1/P_{SNR}$ under infinite retransmission scheduling. Thus, the total delay D_{RC} in transmitting a packet under receiver collisions is given by,

$$D_{RC} = T/P_{SNR} = T/(1-(1-\frac{P_S}{M})^N) \tag{6.2}$$

where T is the cycle time. If the receiver collisions are not considered, the throughput per node is $P_{SN} = N.P_S/M$ and the delay in transmitting a packet will be $D = T/P_{SN}$. Now, we consider two slotted protocols for the multi-channel optical networks, proposed earlier by us. One is a simple Slotted-ALOHA protocol of [48], the other is a contention-based reservation protocol of [50] and we apply the results described above.

Slotted-ALOHA Protocol:

A Slotted-ALOHA protocol was proposed in Chapter 3 (also in [48]) and is shown in Fig. 6.1. The channels are divided into 'cycles' and each cycle is further divided into control and data slots. Each control slot is divided into N minislots, where minislot i is assigned to the data channel λ_i. If a user wants to transmit a data packet, the user selects a data channel (k) randomly, transmits a control packet in the k^{th} minislot and then transmits the data packet on λ_k. The

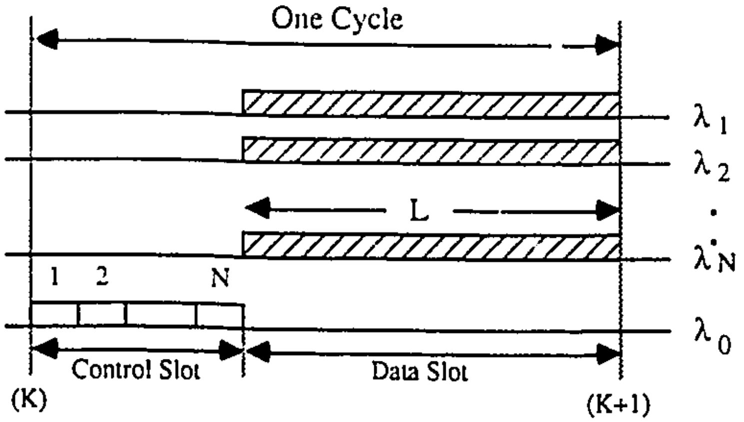


Figure 6.1: Slotted-Aloha Protocol

calculation of P_S is straight forward in this case. It is assumed that there are M users and each user transmits with a probability p in every cycle. Given a data channel, the probability that a given node transmits on this channel is p/N. Since we are using a Slotted-ALOHA protocol, P_S is the probability that only one packet is transmitted on a given channel, which in this case becomes

$$P_S = M.\frac{p}{N}.(1-\frac{p}{N})^{M-1} \tag{6.3}$$

As in [48], including the channel inefficiency due to slotting and considering the receiver collisions using equation (Eq. 6.1), the data channel throughput per cycle without and with receiver collisions can be written as,

$$P_{SC} = \frac{L}{L+N}.P_S \tag{6.4}$$

$$P_{SRC} = \frac{L}{L+N}.\frac{M}{N}.(1-(1-\frac{P_S}{M})^N) \tag{6.5}$$

and the delay without (D) and with (D_{RC}) receiver collisions is given by,

$$D = T/P_{SN} = (L+N).N.P_S/M \tag{6.6}$$

$$D_{RC} = T/P_{SNR} = (L+N)/(1-(1-\frac{P_S}{M})^N) \tag{6.7}$$

where $T = L + N$ is the cycle time.

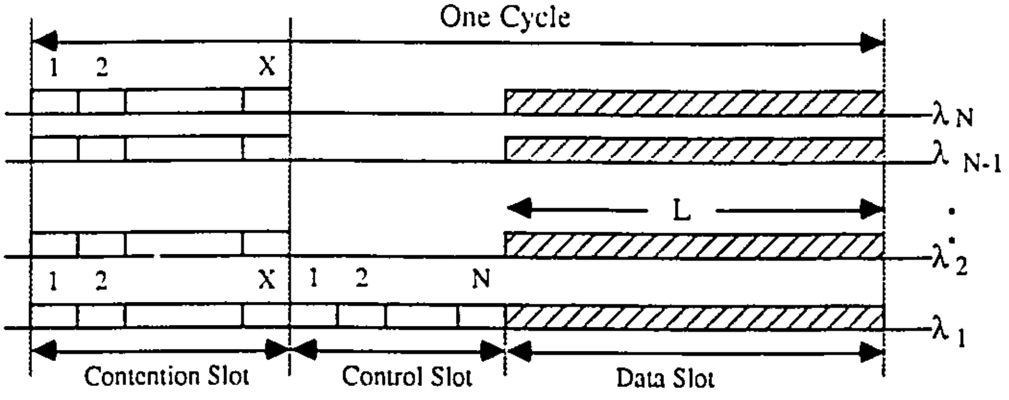


Figure 6.2: Contention-based Reservation Protocol

Contention-based Reservation Protocol:

A simple contention-based reservation protocol is proposed in Chapter 4 (also in [50]) which is shown in Fig. 6.2 for reference. A user, who wants to transmit a packet in a cycle, has to first randomly select a data channel and contend for it. The contention slot is used for this purpose. Both the contention and control slots are further divided into minislots. There are X minislots provided on each contention slot and N minislots on the control slot. The control minislots are pre-assigned to a given data channel as earlier. That is, control minislot i is assigned to data channel λ_i. The reservation to a channel is done slot-by-slot and is done as follows: if a user wants to transmit on channel k, the user has to contend for it first. This is done by transmitting a contention packet in one of the minislots on the contention slot of λ_k. All the users contending for a channel monitor the contention slot of that channel. The user who successfully transmits a contention packet first gets the channel and all other users do not contend for that channel any more and refrain from using it. The data channel throughput for the finite population can easily be found as follows: a user transmits with a probability p in every slot and the user transmits with a probability p/N on a given channel and selects a given contention slot on that channel with a probability $p/(NX)$. The probability that any user is successful in obtaining a given data channel is the probability that there is only one successful transmission on one of the X contention minislots on that channel. The probability P_C, that any user is successful on any minislot is,

$$P_C = M.\frac{p}{NX}.(1-\frac{p}{NX})^{M-1}$$

Therefore, the probability that at least one user is successful on a given data channel is the data channel throughput per data slot and is given by,

$$P_S = 1-(1-P_C)^X \tag{6.8}$$

As before, the data channel throughput/cycle without and with receiver collisions is given by,

$$P_{SC} = \frac{L}{L+N}.P_S \tag{6.9}$$

$$P_{SRC} = \frac{L}{L+N}.\frac{M}{N}.(1-(1-\frac{P_S}{M})^N) \tag{6.10}$$

and as before, the delays D and D_{RC} are given by,

$$D = T/P_{SN} = (L+N).N.P_S/M \tag{6.11}$$

$$D_{RC} = T/P_{SNR} = (L+N+X)/(1-(1-\frac{P_S}{M})^N) \tag{6.12}$$

where $T = L+N+X$ is the cycle time.

6.3 Analytical and Simulation Results

In this section, we present some analytical and simulation results for the protocols described above. All the simulations are done using the Queueing Networks Analysis Package 2 (QNAP2) [47], with 95% confidence interval estimation. For the simulations, we consider an optical star center with M nodes and N channels. Each switching node generates a packet for transmission with probability p, at the beginning of every cycle. The packet is retransmitted with the same probability p in every slot, if the packet transmission were not successful. No other packet is generated at this node till this packet is successfully transmitted. Separate simulations are done for the Slotted-ALOHA protocol and for the contention-based reservation protocol. We consider the receiver collisions of the first type, where the data packets are lost due to head-of-line blocking. In the simulations, the receiver collisions are taken care of as follows: a monitor station monitors the total control slot and at the end of the control slot, if there is more than one successful control packet to the same destination, the station selects one among them (randomly) for packet transmission and disables other transmitters. These disabled nodes again contend

Users (M)	Channels (N)	Simulation P_{SC}	Simulation P_{SRC}	%Chg	Analysis P_{SC}	Analysis P_{SRC}	%Chg
16 (L=50)	16	0.2882	0.2401	16.69	0.2877	0.2418	15.95
	8	0.3291	0.2998	8.9	0.3274	0.3015	7.91
	4	0.3466	0.3407	1.7	0.3517	0.3394	3.49
32 (L=50)	32	0.2283	0.1905	16.56	0.2279	0.1911	16.15
	16	0.2833	0.2608	7.94	0.2831	0.2596	8.30
	8	0.3211	0.3110	3.15	0.3222	0.3093	4.00

Table 6.1: Maximum Throughput for Slotted-ALOHA Protocol

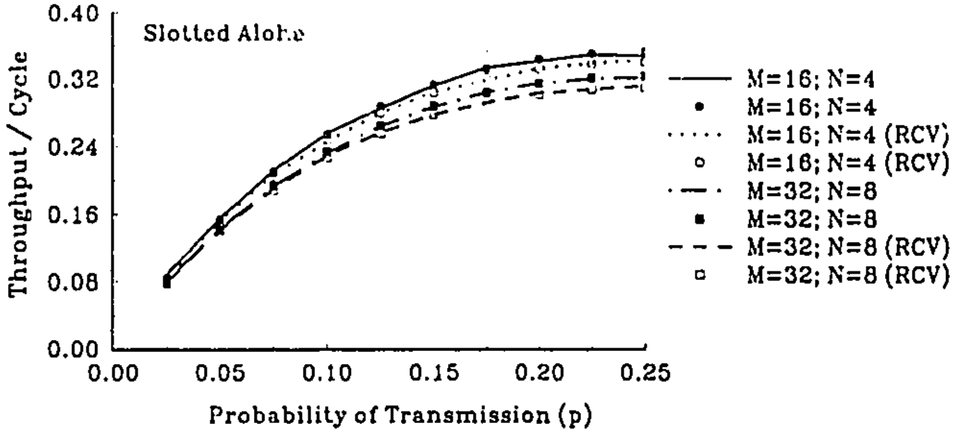


Figure 6.3: Throughput vs. p $(L = 50)$

for the channel in the next succeeding slots with a probability p. Thus now the data channel throughput represents the exact throughput of the channel with receiver collisions. Table 6.1 summarizes the maximum throughput achievable for the Slotted-ALOHA protocol with and without receiver collisions and the percentage change in the throughput and Table 6.2 shows the same for the reservation protocol. Both simulation and analytical results are shown in these tables. The variable P_{SC} is the average throughput per cycle without receiver collisions and the variable P_{SRC} is the throughput per cycle with receiver collisions.

The simulations are done for 16 and 32 users with various numbers of data channels. The reduction in the throughput is more prominent when M is comparable to N and for a larger data channel throughput, as in the case of the reservation scheme. Fig. 6.3 shows the throughput

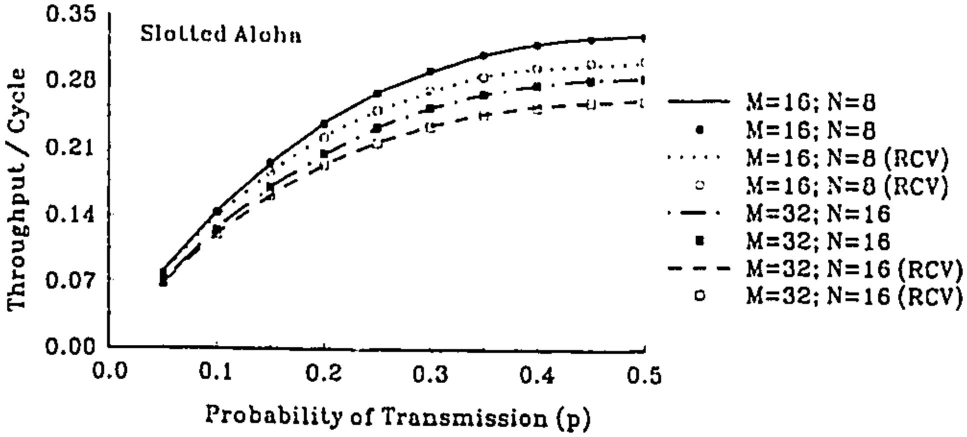


Figure 6.4: Throughput vs. p ($L = 50$)

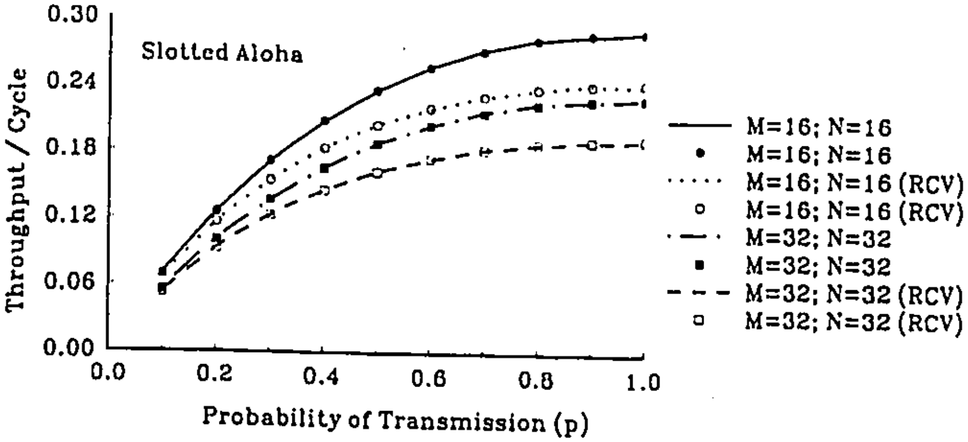


Figure 6.5: Throughput vs. p ($L = 50$)

curves for the Slotted-ALOHA protocol with and without receiver collisions for $M = 16, N = 4$ and for $M = 32, N = 8$. In all the plots, simulation results are shown as solid curves, whereas scatter plots indicate the analytical results and the label RCV in the legend implies that the results on the curve incorporate receiver collisions. Similarly Fig. 6.4 shows results for the Slotted-ALOHA protocol for $M = 16, N = 8$ and $M = 32, N = 16$ and Fig. 6.5 shows results for $M = 16, N = 16$ and $M = 32, N = 32$.

Figs. 6.6-6.8 show the results for the contention-based protocol. Due to the slotting technique employed in these protocols, there is some wastage of data channel bandwidth due to the embedded control slot in a cycle. When the data slot length (L) relative to the control packet is larger, these protocols offer a better throughput. This is shown in Fig. 6.9 for the reservation

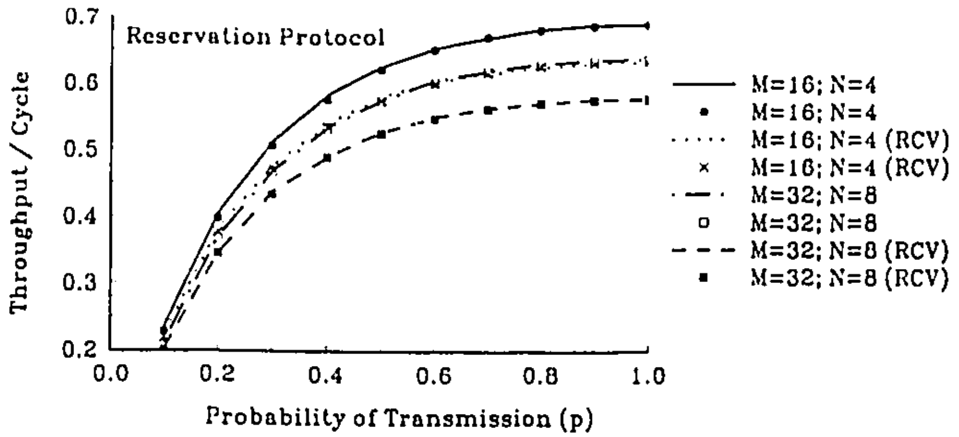


Figure 6.6: Throughput vs. p $(L = 50)$

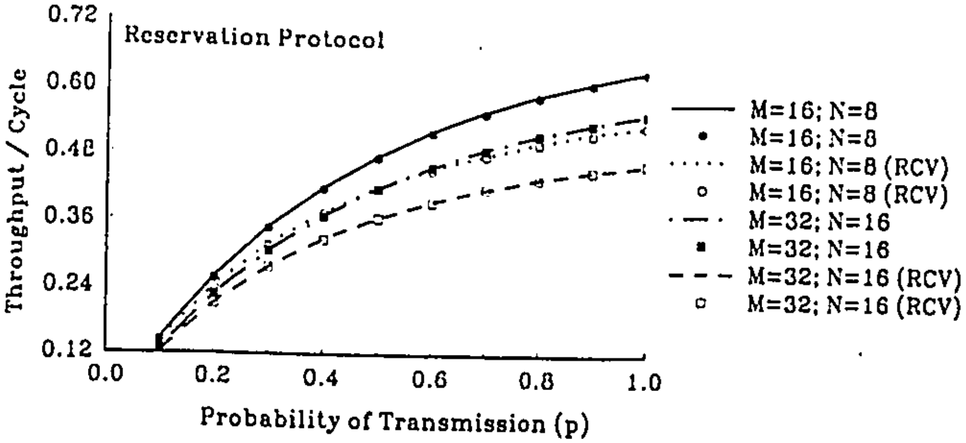


Figure 6.7: Throughput vs. p $(L = 30)$

protocol for $M = 32$ and $N = 32$. Two values of L, the data packet length, are taken for the plots. As can be seen from these figures, the actual throughput of the data channel is lower than the data channel throughput without considering the receiver collisions.

This is more prominent when M is comparable to N. In [38], the improved Slotted-ALOHA protocol of [27] is further analyzed with and without receiver collisions. It can also be observed from this reference, that the actual throughput drops a lot with receiver collisions when the number of users is comparable to the number of channels.

Although, we did not take care of slot-to-slot dependency, both simulation and analytical results agree quite closely with an error less than 5% in both cases. In the simulations, a node uses the

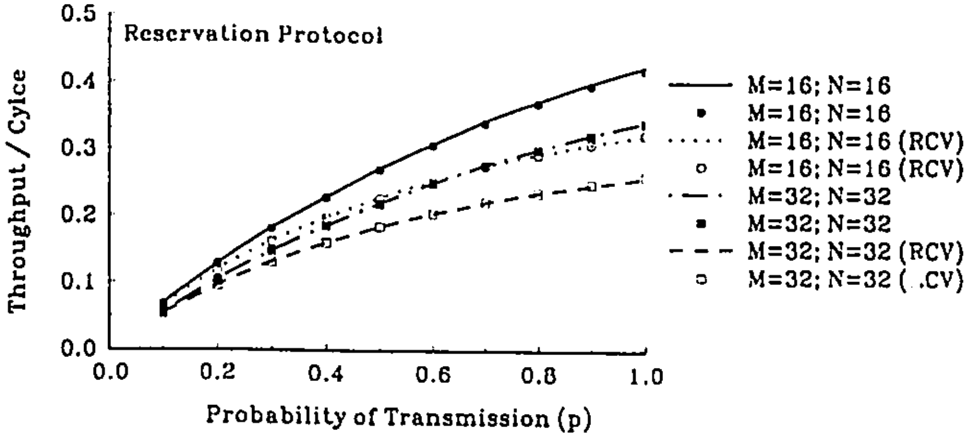


Figure 6.8: Throughput vs. p $(L = 50)$

Users (M)	Channels (N)	Simulation P_{SC}	Simulation P_{SRC}	%Chg	Analysis P_{SC}	Analysis P_{SRC}	%Chg
16 (L=50)	16	0.4221	0.3198	24.26	0.4179	0.3207	23.26
	8	0.6264	0.5285	15.63	0.6242	0.5282	15.38
	4	0.7341	0.6784	7.59	0.7345	0.6779	7.70
32 (L=50)	32	0.3401	0.2564	24.61	0.3385	0.2583	23.69
	16	0.5500	0.4599	16.38	0.5494	0.4607	16.14
	8	0.6824	0.6225	8.78	0.6824	0.6225	8.78
32 (L=150)	32	0.4724	0.3554	24.77	0.4695	0.3583	23.68

Table 6.2: Maximum Throughput for Reservation Protocol

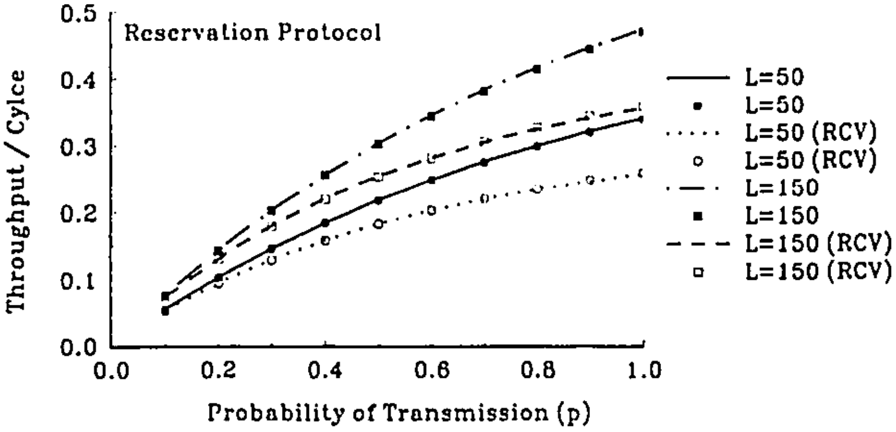


Figure 6.9: Throughput vs. p $(M = 32; N = 32)$

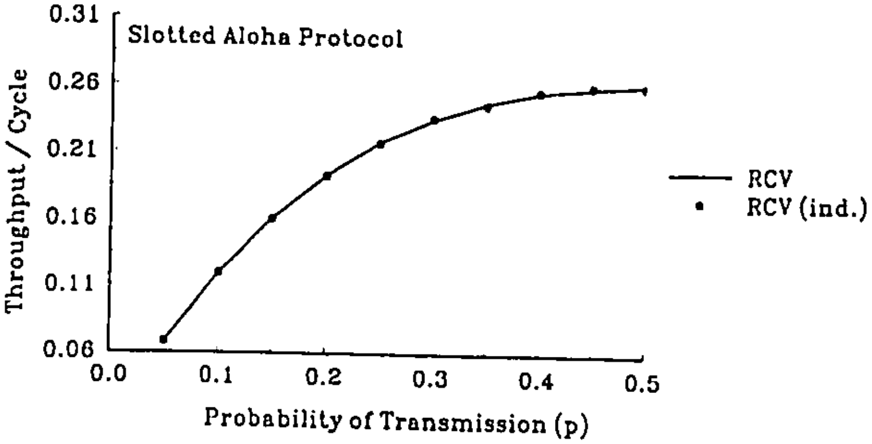


Figure 6.10: Throughput vs. p $(L = 50; M = 32; N = 16)$

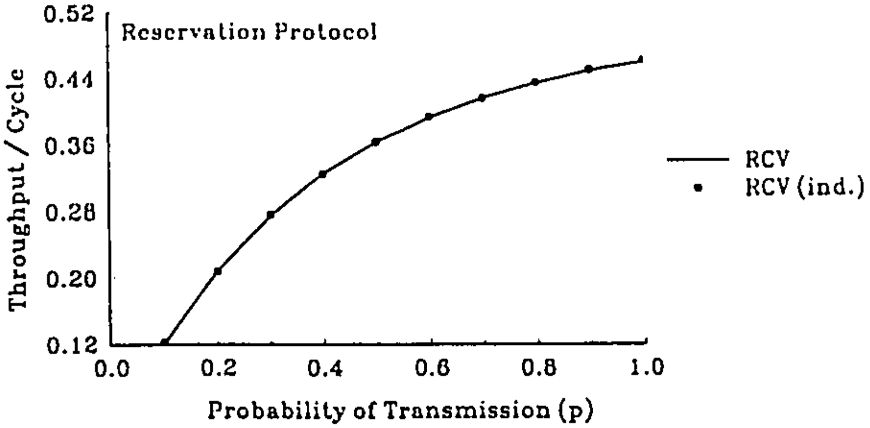


Figure 6.11: Throughput vs. p $(L = 50; M = 32; N = 16)$

same destination address till the packet is successful. If the node uses a different destination address in every slot, a slot-to-slot independency is created. We simulated both these cases for $M = 32, N = 16$ using the Slotted-ALOHA protocol as shown in Fig. 6.10 and for the reservation protocol in Fig. 6.11. In these two plots, only the simulation results are plotted and RCV(ind.) means that the plot is with receiver collisions, but with slot-to-slot independency. From these figures it is very much evident that, when there is a contention on the channels as well as on the destination, the slot-to-slot correlation is reduced very much. In [54], a $N \times N$ non-blocking switch was considered and it was shown that the maximum possible output line saturation throughput is 0.586 under input queueing. This implies that, in our network, if the number of users equals the number of channels $(M = N)$ and if the channels are assigned to the users in a non- conflicting way (i.e. the data channel throughput is 100%), the maximum possible channel throughput under receiver collisions is about 0.586. This represents a change of about 41.4% from the maximum possible data channel throughput. If slot-to-slot correlation is not considered, then the maximum possible throughput is 0.6321. The percentage change in throughput between these two cases is about 7.29%. But this change is very small in our simulations and analysis. Table 6.3 shows the various delays in transmitting the packet for both the protocol for $M = 16$ and $N = 8$ and maximum possible p. As can be seen, both simulations and analysis agree very well for the delays too.

Users (M)	Channels (N)	p	Simulation D	Analysis D	Simulation D_{RC}	Analysis D_{RC}	Protocol
16	8	0.5	303.8	305.44	333.5	331.68	S-ALOHA
16	8	1.0	159.6	160.21	189.2	189.32	Reservation

Table 6.3: Various delays for $M = 16$, $N = 8$, $L = 50$ and $X = 4$

6.4 Summary

In this chapter, we consider receiver collisions of the first type in multi-channel networks. When there are multiple data channels in the slotted system, more than one packet may be destined to the same receiver in the same slot. When the destination is equipped with only one receiver, it can receive only one packet ignoring all others. This causes a receiver collision of the first type and reduces the corresponding throughput on the data channels. When there is contention on both the channels and the destinations, it is found through simulations that the slot-to-slot correlation is reduced very much and, for all practical purposes, an independence assumption can be a very good approximation in these slotted multichannel networks. The results of this chapter were published in [58].

Chapter 7

Some Architectures for High-Speed Optical LANs

Till now, we concentrated on protocols for passive optical star networks. Chapter 1 also reviewed some other network architectures. This chapter presents two architectures for optical fiber local area networks using directional couplers and wavelength switches. The first architecture is a ring based TDM (Time Division Multiplexing) network, in which optical fibers are used as delay lines and the network is used as a packet switched network. In the second architecture, wavelength switches are used with optical directional couplers to form a circuit switched network, analogous to the existing telephone network.

7.1 Introduction

Recent advances in optical components [7, 8], along with Wavelength Division Multiplexing (WDM) are making the very high-speed high-capacity optical networks a reality. Till now, most of the proposed network architectures extended the current LAN solutions to optical networks. At very high-speeds, the main cause of concern is the packet propagation delay and the packet processing time (for header and routing), which become comparable to the packet transmission times. These should be kept very small in order to make efficient use of the bandwidth. The packet processing times could be kept small by high-speed hardware decoding and routing. Propagation delay however cannot be avoided in optical networks. A network based on Shuffle exchange topology [13], has queuing and packet processing delays at each intermediate node. A network based on passive optical stars requires coordination protocols [23] and the corresponding collision resolution overheads for data transfers. Reference [59] describes purely optical networks based on setting up an optical path (or light path) between nodes by allocating the same wavelength through the route. Reference [60] describes linear lightwave networks which use directional couplers and set up an optical path among users. Some routing algorithms were developed for these networks in [61].

7.2 Network Architectures for High-Speed Optical LANs

In this section, we present two network architectures. The first one is based on a ring topology [1] and uses the TDM (Time Division Multiplexing) approach rather than the standard token passing approach. The second architecture is suitable for circuit switched applications. Both networks exploit the multichannel capability of the optical networks through Wavelength Division Multiplexing (WDM).

Architecture 1: Ring based TDM Network

As mentioned earlier, packet propagation delay is a major contributing factor in reducing the network throughput at very high-speeds. For example [23], at a bit rate of 1 Gbps and for a packet size of 1000 bits, the propagation delay for a network size of 200 meters is one packet transmission time. If the packet size is only 100 bits, then the propagation delay for a network size of only 20 meters is one packet transmission time. Hence, for small packet sizes, the optical fiber can be used as a delay line at these high-speeds and the network architecture described below makes use of this fact.

Here, we consider a network in which the nodes are connected as a ring (Fig. 7.1) using optical fibers. It is assumed that the number of nodes in the network equals N, the packet size is a constant (L) and all the nodes in the network are well synchronized. Let us first assume that there is only one optical channel in the network and the channel is divided into slots, with each slot time equal to the packet transmission time. The packet includes source, destination addresses and data. It is also assumed that the fiber length (not necessarily the physical distance) between two nodes is such that the propagation delay is exactly one slot duration. We define one 'cycle' as N data slots.

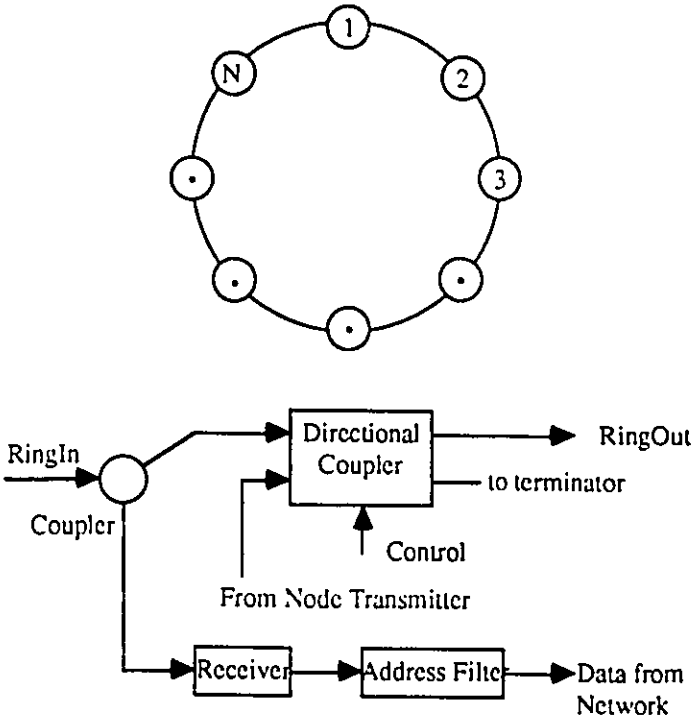
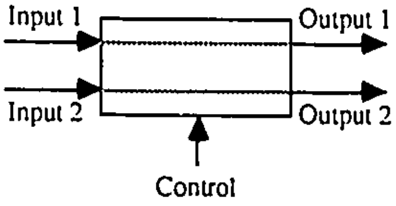
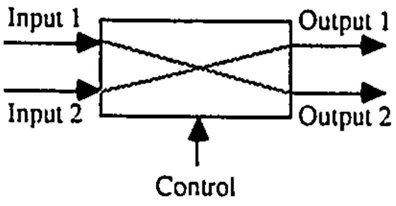


Figure 7.1: TDM ring network and its node architecture



"BAR" State



"CROSS" State

Figure 7.2: A directional coupler

For a single channel system, each node simply consists of a directional coupler [62]. As shown in Fig. 7.2, the directional coupler is an electro-optic device that can be switched to either of two states by applying an appropriate control voltage at the electrodes. When the coupler is set to 'bar' state, the signal at Input 1 (Input 2) is coupled to Output 1 (Output 2) and in 'cross state' the signal at Input 1 (Input 2) is coupled to Output 2 (Output 1). Fig. 7.1 shows the node architecture of this network. The input from the network 'RingIn' is connected through a coupler to both the directional coupler and an optical receiver. The receiver output is passed through an address filter so that only the packets destined to this node are taken in. One of the directional coupler inputs (Input 1) comes from the 'RingIn' and the other (Input 2) comes from the local optical transmitter. Only one output channel (say Output 1) is used to connect to the next station in the ring. The other output is not necessary.

The operation of the network is as follows: It is assumed that the nodes are well synchronized and each node knows exactly when a 'cycle' starts. The node synchronization can be achieved through techniques similar to those presented in [63]. At the beginning of every cycle, all the nodes switch their directional couplers to 'cross' state thus letting the signal from the optical transmitter on to the 'RingOut'. At the end of the first data slot (note that each cycle is divided into N data slots), all the nodes switch their directional couplers to 'bar' state by applying a proper control voltage. These couplers remain in the 'bar' state for the remaining $N-1$ data slots and the above operation repeats itself. Since the logical distance between two adjacent nodes is equal to one packet transmission time, all the nodes can simultaneously launch their signals on to the optical channel without any conflict and the data slots are circulated around for the remaining $N-1$ slots. This is like placing N trains on a circular track and circulate them around the track N times. The length of each train is equivalent to one packet propagation time between two adjacent nodes and the tail of one train faces the head of next train with no gaps. Since at the beginning of each cycle the coupler is switched to 'cross' state, the signal from 'RingIn' is transferred to Output 2 which is properly terminated. Thus, the packet that was transmitted in the earlier cycle by a node will be automatically removed by that node. Note that once the packet is launched on to the fiber, the packet goes around the ring on a complete optical path with no intermediate electro-optic conversion or buffering. Fig. 7.3 shows the timing diagram, showing the various packet transmissions at the nodes. Since each packet

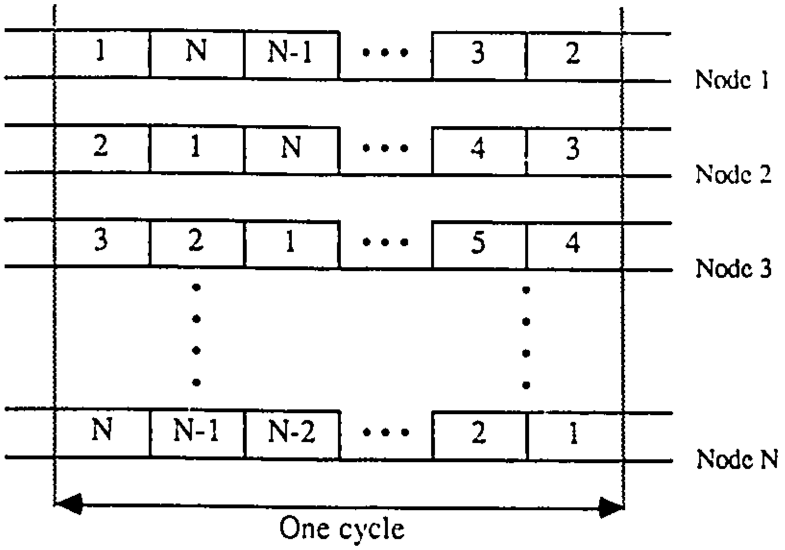


Figure 7.3: Timing Diagram for the Packet Transmission

traverses through $N - 1$ optical couplers, the transmitted power should be enough to detect the signal at the last hop. Otherwise, optical amplifiers may have to be used to boost the light intensity at intermediate points.

Since this network is operating as a simple TDM network, if R is the channel data rate, each node can transmit a maximum of R/N bits per second in a cycle and the average delay per packet to reach the destination is $N/2$ slots. For a large N this delay may be quite large and it can be reduced by using multiple channels in the system. If we use two counter rotating rings (in two directions), the cycle time can be reduced to a half. The packets destined to one half are transmitted on one ring and the other half are transmitted on the other ring. In this case, the maximum bit rate per each node is still limited to $2R/N$. Using Wavelength Division Multiplexing (WDM) [7], each optical fiber can be divided into many logical channels. If this technique is used, then a separate cycle can be defined on each channel and transmission capacity of each node can be increased. But, the hardware complexity of each node increases since each node now requires a separate directional coupler on each channel and the 'RingIn' at each node should be coupled to many receivers (as per the number of available logical channels) and the outputs of the directional couplers should be coupled back to form a 'RingOut' signal at each node, as shown in Fig. 7.4. This may cause excessive coupling losses and optical amplifiers may

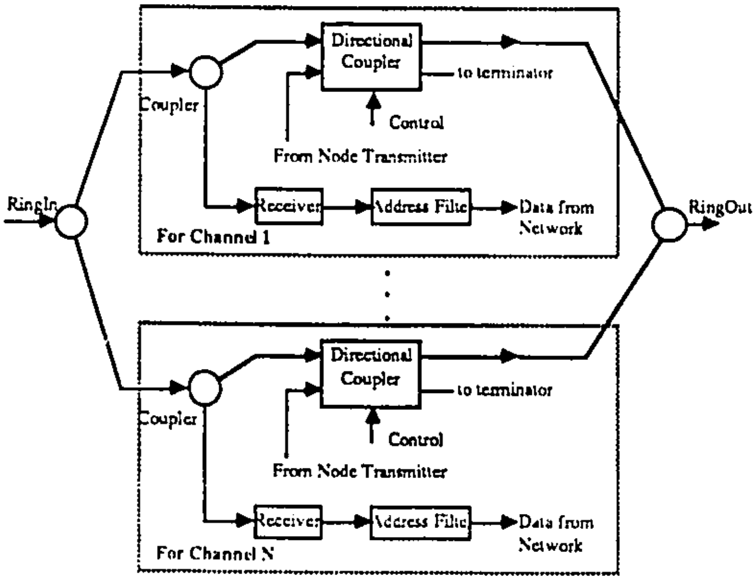


Figure 7.4: Node architecture for multichannel ring

have to be used in the network.

Architecture 2: A Circuit Switched Optical Network

In all-optical networks based on optical paths [60, 59], the main principle is to set a light path between the source and the destination. Routing algorithms are used to set up a connection between the source destination pairs using a particular wavelength (color). To keep the hardware cost low, the same color (wavelength) is to be used through the entire path. But, this increases the blocking probability for some circuits. For example, consider a two segment network AB, BC where A,B,C are the main nodes and the segments AB, BC are the optical fibers. Suppose a user at site A wants to reach another user at site C. Let us say the only wavelengths available are λ_1 on AB and λ_2 on BC. Then a circuit cannot be set up between the users at sites A and C. If color conversion is provided at site B, then λ_1 on AB can be converted to λ_2 on BC and thus a circuit can be setup between the users. This color conversion can be easily done by a wavelength switch (λ-switch) [21]. In this switch, the signal from each input wavelength is detected and re-modulated using a tunable transmitter which is capable of tuning to any one of the output channel wavelengths. Thus any input channel of a given wavelength can be retransmitted on any output channel at a different wavelength. All the re-modulated signals are combined optically

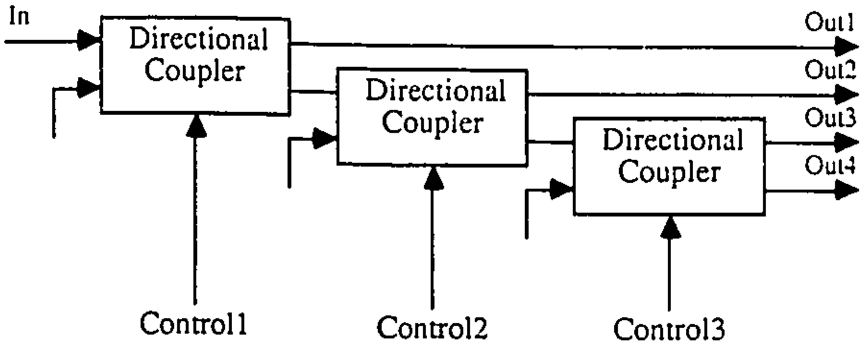


Figure 7.5: A one to four way router

and can be launched on to a fiber. The only condition is that, there should not be any conflicts among the re-modulated signals, i.e., no two signals should be re-modulated using the same wavelength.

The network architecture described below needs a routing function (a router) for the optical signals. That is, one optical signal should be routed to only one of the Y (say) available output routes. This router function can be easily implemented using the directional couplers described above. As an example, Fig. 7.5 shows a one-to-four routing function where one signal can be routed to any of the four outputs by applying the proper control voltages. Let us assume that a '0' applied as control would put the directional coupler in 'bar' state and a '1' applied as control will place the coupler in the 'cross' state. Then the sequence of signals applied at (Control1, Control2, Control3) will route the input signal in the following way: a '0XX' will route the 'In' to 'Out1', a '10X' will route the 'In' to 'Out2', a '110' will route the 'In' to 'Out3' and a '111' will route the 'In' to 'Out4'. Note that 'X' is a don't care condition in these sequences. Basically a Y-way router needs $Y-1$ couplers and a $Y-1$ bit control sequence.

Fig. 7.6 shows an arbitrary network, in which, the sites are connected by optical fibers. It is assumed that the optical fiber bandwidth can be divided into multiple channels through wavelength division multiplexing. The sites represent major switching centers and many users are connected to each site. To setup a circuit between two users, the calling user will send a small request packet to its local site, which in turn will try to find an optical channel (not necessarily on the same wavelength) to the destination site. We can use schemes similar to

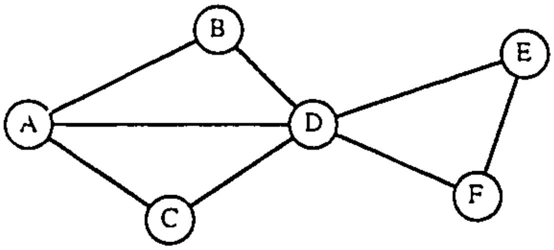


Figure 7.6: An arbitrary network

Common Channel Signalling [1] between the sites. Since this circuit switched network is similar to the well developed telephone network, most of the principles can be borrowed from this field. Our main interest is in the design of a node, and as an example, we consider one such node in the network which has two input fibers and two output fibers for circuits in one direction (Fig. 7.7). We assume a similar arrangement for circuits in the opposite direction and also assume that there are N WDM channels on each fiber. Since there are two input (output) fibers, there is a total of $2N$ input (output) channels for this node. Each of the $2N$ input channels can be routed to any one of the $2N$ output channels. Hence, each input channel should first go through a λ−switch which performs a color conversion on this channel. The signal should then go through a router and coupler combination to the destined output fiber. Since in this example, the node contains only two output fibers, the router for each input channel is a simple directional coupler. Fig. 7.7 shows the node architecture for this example.

The same concepts can be further extended to multiple input and output fibers at a node. Note that, it is the duty of a controller at the site to properly program the routers and the λ−switches such that there is no conflict among the assigned wavelengths to the output circuits. When ultra-fast λ−switches and routers become available, then each channel can be further divided into logical channels through TDM. Now, the controller has to program the routers and the switches in every TDM slot.

7.3 Summary

In this chapter, we presented the architectures for packet and circuit switched applications. The packet switched network uses a simple TDM scheme for ring based networks. The packets are

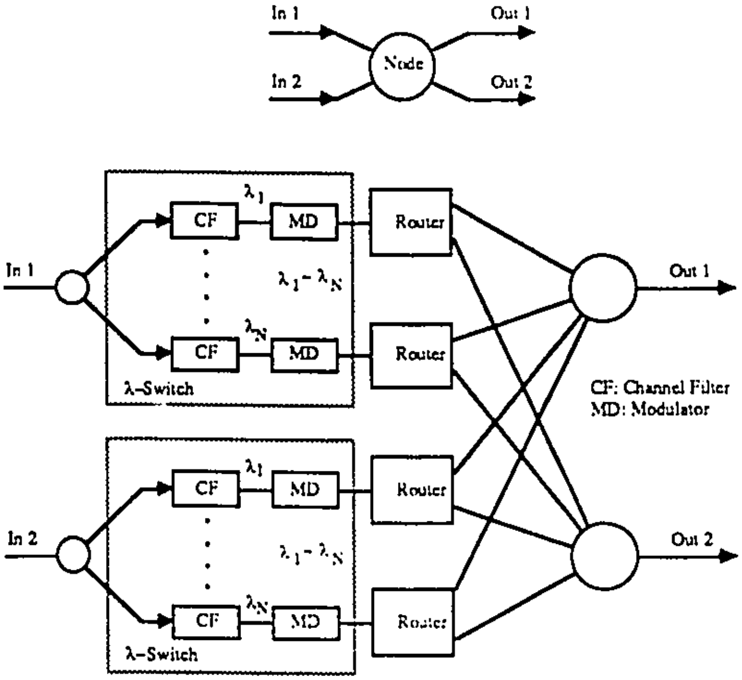


Figure 7.7: Architecture for the example node

circulated around the ring on a all-optical path with no intermediate electro-optic conversion or buffering. The circuit switched network is based on routers and wavelength switches. We also presented the design of a one input to Y output router using directional couplers where a signal can be routed to any one of the Y output routes. A simple example of the node design is presented for the circuit switched network. The results of this chapter were presented in [64].

Chapter 8

Implementation Considerations

In the earlier chapters, this thesis proposed many access protocols for the passive optical star networks. In this final chapter, we look at some of the implementation considerations for these protocols. These take into account some of the realistic parameters such as non-zero propagation delay, tuning time of the devices, protocol processing times, etc. These are very important parameters, on which, the performance of the protocol depends upon. In Section 8.1, we identify these parameters and discuss how to take care of them. Since all the proposed protocols are slotted in nature, slot synchronization is a very important issue. Therefore, in Section 8.2, we discuss synchronization issues related to these networks.

8.1 Parameters that effect Protocol Performance

This thesis mainly considered a passive optical star network and proposed many random access protocols to arbitrate data channels among the users. The network architecture consists of a simple passive optical star coupler (refer to Fig. 3.1) where individual users are connected through optical fibers. It is assumed that, users are equipped with tunable devices (transmitters, receivers). Currently, a lot of research is going on to develop fast tunable optical devices [6, 7, 8, 9, 65]. Generally, the optical transmitters require lasers or Light Emitting Diodes (LEDs) and the optical receivers require optical filters or photodiodes. With single mode optical fibers, lasers are normally used to launch optical power because of the distribution of their field pattern. There are many physical parameters associated with these devices [65, 66] which we discuss a few of them below.

8.1.1 Device Tunability

All the protocols proposed in this thesis require tunable transmitters and tunable or fixed wavelength receivers depending upon the protocol being considered. Since the channels are assigned unique wavelengths, the transmitters and receivers should be tuned to appropriate wavelengths to receive and transmit data. Thus, these protocols need tunable optical sources and filters. The main important parameters associated with these tunable devices are: (1) *tuning range* and (2) *tuning speed.* The *tuning range* can be defined as the band of wavelengths, over which, the devices can either transmit or receive optical signals. The *tuning speed* can be defined as the response time of the device to switch from one wavelength to another. Reference [67] gives an overview of the characteristics of some of the existing tunable lasers and filters. If the device tuning range is not broad enough to cover the set of wavelengths used in the system, then single-hop communication between users will not be possible. In this case, a multihop approach (see Chapter 1) can be used. Alternately, one could use an array of tunable devices, in which, each device covers a partial set of wavelengths.

However, the device tuning speed (say t_{dev}) affects the performance of the protocol very much. Here, we assume that the users in the network are perfectly synchronized. Some synchronization issues are discussed in the next section. At very high-speeds, the bit times and hence the packet times could be very small. For example, at 1 Gb/s, each bit is 1 nSec and a 1 Kbyte packet is 8 μSec long. Hence, if t_{dev} is not comparable to the bit time, the penalty due to device tuning speed could be very high. Since the protocols proposed in this thesis are slotted in nature, generally, each slot definition should also include this t_{dev} at the beginning of the slot, to account for the tuning latency. Thus, in all the protocols described in this thesis, each data, control and contention slots should include an extra overhead of t_{dev}. Hence, in the Slotted-ALOHA protocols of Chapter 3, the cycle time will be $T + 2.t_{dev}$ and, for contention and switching protocols, the cycle time becomes $T + 3.t_{dev}$. This causes further reduction in average throughput (due to wastage of bandwidth) and increases the average packet delay. For example, consider the Slotted-ALOHA protocol (Case 1) of Chapter 3. For this protocol, the data slot was defined to be L and the control slot N (or N minislots) time units. If the device tuning time is included, then the data slot will be $L + t_{dev}$, the control slot will be $N + t_{dev}$ and the total cycle will be $T + 2.t_{dev}$. Therefore, the throughput equation (Eq. 3.5) becomes,

$$S1 = \frac{L}{L + N + 2.t_{dev}} S_d = \frac{L}{L + N + 2.t_{dev}} G.e^{-G} \quad (8.1)$$

Thus, a large t_{dev} can reduce the effective throughput very much because of the denominator term. Hence, to implement the proposed protocols, we need very fast tunable lasers and filters, of the order of nano-sec switching speed, if users are equipped with only one set of transmitter and receiver pair.

The effect of tuning latency can be reduced somewhat by two methods: (1) provide each user with an array of transmitters and receivers, (2) use protocols such as R-ALOHA. This is explained in detail below.

For control channel based (pre-transmission) protocols, it is better to use a separate transmitter/receiver pair for the control wavelength, since the switching latency on the control channel is removed completely. Then, with method 1, we need at least two transmitters and two receivers for all the protocols in Chapter 3, if the switching latency is less than a 'Cycle' (T). In this case, start tuning the devices one cycle ahead, to transmit/receive data in the current cycle. If the device tuning time is larger than one cycle time, a larger number of devices is needed. In fact, $\lceil \frac{t_{dev}}{T} \rceil$ transmitting devices and similar number of receiving devices are needed for each user, where the $\lceil . \rceil$ is a ceiling function and indicates the next larger integer. Now, the average throughput does not depend upon t_{dev}, but the average packet delay increases. This is due to the fact, that a packet generated in the current cycle is transmitted much later. Similar techniques can be adopted for other protocols.

But the method above, of providing an array of devices for each user, could be very expensive. Hence, an alternate method (method 2) is to use protocols such as R-ALOHA. As we recall from Section 3.4 of Chapter 3, in R-ALOHA, a user relinquishes an obtained channel after transmitting multiple packets. Thus, a user tunes only once to transmit these packets. Since the tuning overhead is not there for every packet, the effect of tuning latency is reduced very much. For example, consider a successful slot in Slotted-ALOHA and R-ALOHA. Let us assume that in R-ALOHA, $\overline{v}$ packets are transmitted for every transmission. Then, the effective successful slot throughput for Slotted-ALOHA is $\frac{1}{1+t_{dev}}$ while for R-ALOHA, it is $\frac{\overline{v}}{\overline{v}+t_{dev}}$. If $\overline{v}$ is much larger when compared to t_{dev}, then the effective throughput per successful slot of R-ALOHA approaches unity. Similar methods can also be employed for other protocols.

But, the method of R-ALOHA proposed in this thesis is used for long message transmissions (aimed for the same destination), which are generally broken into smaller packets and then transmitted. If the R-ALOHA method is to be employed for single-packet transmission case, but for reducing the tuning latency, then the channels should be pre-assigned to users. Then, the control slot is still to be used as an access mechanism to obtain the data channel. In this case, a user, after obtaining a data channel (say channel 1), will transmit data packets to all the users who are assigned channel 1 for reception, in the succeeding slots and then relinquishes. Users still need tunable transmitters, but fixed wavelength receivers can be used for packet reception along with a separate transceiver for the control channel.

8.1.2 Propagation and Processing Delays

Till now, we ignored the propagation delay in all the proposed protocols. But at high-speeds, the propagation delay is a very important factor [68], since it can be comparable to the packet transmission time. Let us assume that the velocity of light in optical fiber is 2×10^8m/sec. Then, it takes about $5D$ *nsec* for the optical energy to travel D meters. As before, if we consider 1 Gbps transmission rate, it takes about 8 μsec for the packet transmission time of a 1 Kbyte packet. If we consider a distance of 1 Km, then the propagation delay is $5D = 5000\ nsec = 5\ \mu$sec, which is very much comparable to 8 μsec packet transmission time. Since most of the proposed protocols in this thesis are based on contention, *slot reference* becomes a very important issue, if users are located at different distances. One could assume that all the users are at a constant distance from the central hub (passive star coupler). This can be done by using the same length of fiber for each user, irrespective of the distance the user is located at. However, for a more realistic situation, we assume that users are situated at different distances. Then, users have to compensate for their distances by appropriately scheduling their transmissions and receptions. This is explained in detail below:

Consider, two users A and B located at different distances from the central hub. For this discussion, we assume that the device tunability is negligible. Let us further assume that, user A is farthest to the star coupler and B is closest among all the users. Also, we assume that 2τ is the end-to-end propagation delay of farthest user (user A) and 2ω is the end-to-end delay

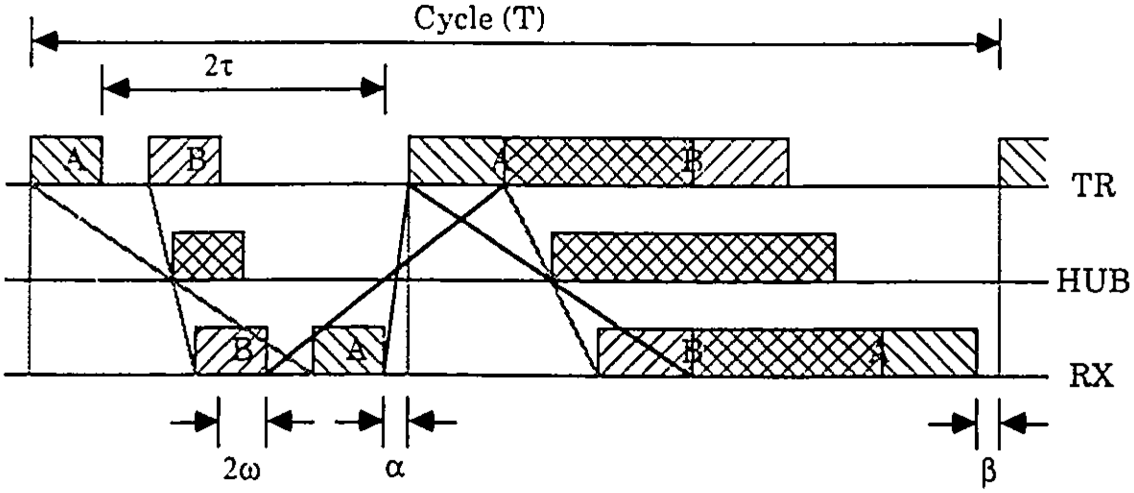


Figure 8.1: Time Referencing in Optical Star Networks

of closest user (user B) in the network. Then, to take the propagation delay into account, the slot definition has to be changed as shown in Fig. 8.1. Here, we do not consider any particular protocol but the figure is included for illustration purposes. In this figure, the cycle time T is extended to include both processing and propagation delays. This figure shows the timing reference on one channel and the same is followed on all WDM channels. The figure shows the timing reference at three points: TR is at the transmitter, HUB is at the central star coupler and RX is at the receiver. Since we consider contention based protocols, all the users in the network should consider the same slot reference to find any possible collisions and resolve them. If, users are situated at different distances from the central hub, then, to reference the same slot at the central hub, users have to schedule their transmissions and receptions appropriately. In the figure, it is assumed that users transmit a small control packet and then a data packet. Thus, for a slot reference at the central hub, user A transmits its control and data packets τ time units before the slot reference at the central star, while user B transmits the same ω time units before. Then, when the control and data packets arrive at the hub, they will map to the same time reference.

Since user A receives its control packet after 2τ, A can transmit its corresponding data packet α time units after reception of the control packet. Here, we assume that α is the control packet processing delay and β is the data packet processing delay. Although user B receives its control

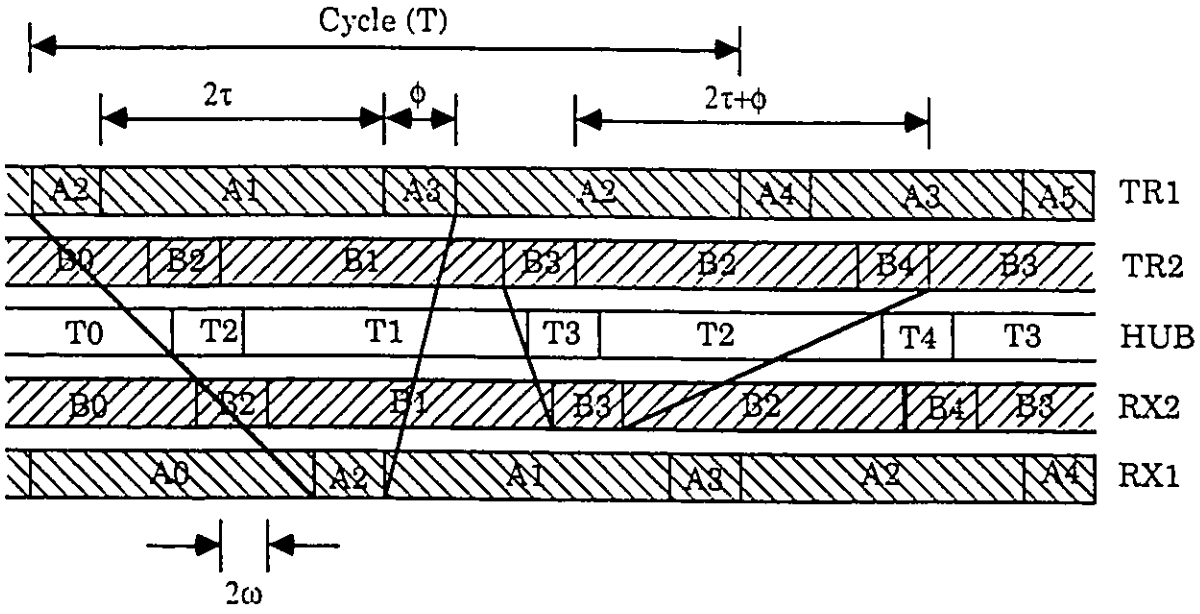


Figure 8.2: Pipeline in Optical Star Networks

packet after 2β time units (which is much small compared to 2τ), user B cannot transmit the corresponding data packet until $2\tau - 2\beta$. Hence, each user transmits a data packet 2τ units after the corresponding control packet is transmitted. This method gives a very simple slot referencing. However, this method wastes a lot of bandwidth, since nothing is transmitted while the packets are in propagation. The cycle time in this case increases by about $4\tau + \alpha + \beta$. If τ is comparable or larger than the cycle time, the slot efficiency reduces very much, with a corresponding penalty as increased packet delay.

Hence, for larger values of τ, the pipeline due to propagation delay can be effectively used by transmitting more packets. This is shown in Fig. 8.2. This figure shows the timing reference at transmitter, receiver and at the star coupler. In the figure, $TR1$ indicates the transmission time reference of user A and $TR2$ is for user B. Similarly, $RX1$ is the receiver time reference for user A and $RX2$ is for user B. As before, it is assumed that 2τ is the end-to-end propagation delay for user A and 2ω is for user B. Users schedule their transmissions according to the distances they are located. If, ϕ is the maximum processing and scheduling delay, then a data packet can be transmitted $2\tau + \phi$ time units after the transmission of the corresponding control packet. In this interval, packets corresponding to other cycles can be transmitted. The figure shows one more such transmission. The cycle time T increases by an amount $2\tau + \phi$ for the calculation of delay.

Note that we ignored device tunability in the above discussion. We can adopt similar techniques of Section 8.1.1 to consider non-zero device tuning time. If a single set of devices is used, then the tuning latency further increases the slot time by $2.t_{dev}$, with a corresponding penalty in wasting the bandwidth. Note that, similar techniques have to be adopted for star interconnections presented in Section 4.7.

8.2 Synchronization Issues

For all the protocols presented in this thesis, the time axis is divided into slots. Thus, all the protocols assume a perfect synchronization among the users. Two kinds of synchronization are necessary in these networks: slot (or frame) synchronization and bit synchronization [69].

For optical star networks, reference [70] presents a method of slot synchronization on different wavelengths. It is assumed that a station always sends synchronization (SYNC) slots on one of the wavelengths (λ_s). By knowing the propagation delay from the transmitter to a reference point (RP) and from the RP to the receiver for all wavelengths, each node can compute the time instant of the N^{th} slot after the SYNC. In our case, the reference point is the star coupler itself, since our protocols are contention based. This reference takes care of the 'chromatic dispersion' by a padding technique, so that slots sent on different wavelengths arrive in the same slot at the reference point. Since the refractive index of fiber material is a function of wavelength, different signals transmitted on different wavelengths travel at different velocities. This is called the 'chromatic dispersion'. This could be a very important factor when the network spans long distances and uses a wide band of wavelengths. But, for small size networks, this may not be the case. If M is the material dispersion (in ps/nm.Km), Δ_λ is the difference between the two wavelengths and L is the distance traveled in Kms, then the difference in time interval (at destination) for two slots transmitted at the same time is given by [70]:

$$D = M\Delta_\lambda L \tag{8.2}$$

For example, when $L = 100Km$, $M = 20$ and $\Delta_\lambda = 200nm$, then $D = 400nS$. But, when $L = 10Km$ and $\Delta_\lambda = 50nm$, then $D = 10nS$. This is still about 10 bits at 1 Gbps transmission rate. If the network uses band of wavelengths around a particular wavelength (say 1500 nm), then one could use dispersion shifted fibers [65] for 1500 nm wavelength to reduce the value of

M, which further reduces the value of D.

The slot synchronization is also an important issue for star interconnection. This is prominent when a direct method of interconnection is possible such as Method 1 of Section 4.7. In this method, a user of one star can directly access a user of another star. Each star will have its own reference clock generator, which transmits the SYNC slots for synchronization purposes. If these clock generators adjust their clock phases according to the distance they are situated from a possible main reference slot generator, then a network wide synchronization can be achieved. The users in the network should also know the relative physical distance (or else the propagation delay) of the star with which they want to communicate for inter-star communication. Then, users will correspondingly adjust their transmission schedule (advance or retard), so that packets transmitted at one star center arrive properly at other star center.

Another important problem in these slotted networks is the bit synchronization within a slot. In these networks, there is a dynamic switching of wavelengths by both transmitter and receivers, i.e., each receiver may listen to different transmitters on different wavelengths in each time slot. Hence, receiver synchronization becomes very necessary to properly receive the bits in a time slot, assuming that the time slots on all wavelengths are well synchronized. Phase locked Loop (PLL) based circuits may not work well at high-speeds due to the finite response time. This may require lots of overhead bits in form of preamble which has to be transmitted on each slot. For example, if the response time of a PLL is about 1 μsec at 1 Gbps, then we need about 1000 bits as preamble for each slot. This could be a very large value, considering all the protocols in this thesis are based on small control slots. Other possible techniques are [71]: (1) Pseudo-Bipolar transmission, (2) Manchester Coding and (3) Separate Clock strobe. This reference considers the last technique, in which a separate clock is transmitted on a different wavelength. At the transmitter, two lasers are used to transmit the clock strobe and the data. These are wavelength multiplexed onto the fiber. At the receiver, these signals are demultiplexed and the demultiplexed clock is used as a strobe to bit synchronize the data stream. Since the experiment in [71] considered two widely separated wavelengths for clock and data, the chromatic dispersion had to be compensated by using a stub length differential. However, if the wavelengths are closely apart, this may not be a severe problem. Probably, tunable laser arrays can be used in transmitters for the optical star network. Alternately, one could employ techniques similar to sub-carrier multiplexing [65], to send the clock strobe on the same wavelength using one laser.

5.3 Summary

In this chapter, we considered the effect of some physical parameters on the protocol performance. All the protocols proposed in this thesis were analyzed assuming negligible propagation, device tuning time and processing delays. However, at high-speeds these are very much comparable to packet transmission times, and hence should be properly accounted for. Therefore, this chapter discusses some techniques for taking care of these parameters. Since all the proposed protocols are slotted in nature, bit and frame synchronization issues are also very important for proper time reference.

Chapter 9

Conclusions

In this thesis, media access protocols were proposed for the passive optical star networks. This thesis also proposes two network architectures. We first reviewed architectures for lightwave networks in Chapter 1. Due to the superior performance of a star coupler in supporting a larger number of users, this thesis mainly considered the optical star network architecture. Using Wavelength Division Multiplexing (WDM), many logical channels can be created and media access protocols become necessary to arbitrate these data channels among the users. In Chapter 2, we reviewed some of the proposed media-access protocols for these multi-channel optical star networks. At the time, when this research was started, there were not many proposals for the protocols. For the protocols based on the control channel, only the control channel was slotted. Hence, we started with an extension of Slotted-ALOHA to both control and data channels and this is presented in Chapter 3. In this chapter, six cases of Slotted-ALOHA protocols and another six cases of improved Slotted-ALOHA protocols were presented. For longer message transmissions, the R-ALOHA protocol was extended to multi-channel environment. These protocols are found to offer better performance for small packet lengths.

In the control channel based slotted protocols of Chapter 3, the traffic on the control channel can be very high since only one control channel is used for many data channels. This contention can be reduced by using multiple control channels. This is done in protocols of Chapter 4. In the contention-based reservation protocols, users contend on each of the data channel separately and in the multi-control channel protocols, users are grouped and each group is assigned its own control slot. This grouping technique is easily used to interconnect optical star LANs. This distributed control improves the performance. Specifically, the contention based protocols offer very good throughput performance. Chapter 5 proposes two switching protocols for the case when there are equal number of users and channels. In this case, data channel contention may arise if more than one user wants to send data to the same destination and must be resolved. In Chapter 6, we considered the effect of receiver collisions in the multi-channel environment for two protocols. Some issues in implementing these protocols were presented in Chapter 7. The parameters considered were the latencies due to propagation, switching and processing.

Table. 9.1 is a snap shot of some the protocols that appeared in the literature. This table also includes the protocols proposed in this thesis which are in boldface. This table is divided into 12 columns. The first column indicates the class of the protocol, followed by the reference, the subtype to which the protocol belongs to, and the number of protocols proposed in that reference. In the subtype column, the following abbreviations are used: MC - multi control channel protocol, SW - switching protocol, RP - reservation protocol, CA - collision avoidance. The fifth and sixth columns indicate how many transmitters and receivers each user requires to implement the protocol. Here, TT means a tunable transmitter, TR - a tunable receiver, FT - a fixed tuned transmitter and FR - a fixed tuned receiver. The next columns indicate how many control and data channels are needed. Some protocols use embedded control slots on the data channels, which is indicated as 'emb' in the table. For the throughput column, the abbreviations are: L - low (≤ 0.4), M - medium (between 0.4 and 0.7), H - high (above 0.7). This column indicates the average throughput of each data channel in the protocol. The protocols vary a lot in terms of the processing requirement. Some protocols need to monitor only their control channel (low processing) where as a few monitor complete network traffic (medium processing). This is indicated as: L - low processing, M - medium and H - high, in which distributed algorithms have to be executed to generate a switching matrix. The column 'Sync' indicates whether the protocols need any slot synchronization. A few protocols need extra hardware such as Mux (multiplexers), DeMux (demultiplexers), delay lines, control stars and Protection Against Collision (PAC) circuits. This is shown in the last column. The variable parameters are shown as x. This thesis also proposed two interconnecting techniques for optical star networks using the Multi-Control channel protocol. The switching protocols can be used in a integrated B-IDSN switch and one such switch architecture was also proposed. The thesis also developed one packet circulating ring network and a circuit switched network. Some implementation considerations to implement these high-speed networks were also discussed.

Lots of difficulties are yet to be overcome to implement these networks at high-speeds. Users in the network will be at different distances from the central star coupler (hub). At high-speeds, the latency due to the propagation is a dominant factor [68]. Hence, protocols which assume immediate feedback can work for very short distances (few meters). To extend the range of the network, propagation delay of the packets should be taken care by appropriately scheduling the transmission and reception of packets as discussed in Chapter 8. For protocols such as ALOHA, this scheduling should be done such that users have a common reference point (star coupler in this case) to check for possible packet collisions. This can be done a little easy with slotted protocols due to the slot reference. Users located at different distances can schedule their packet transmissions such that the slots arrive at the same time to the hub. The protocols can make use of the pipeline effect due to propagation delay by transmitting the control packets for data packets that will be transmitted later. For slotted protocols, the main issues are slot and bit synchronization. Some more issues and some experimental networks are described in [67].

9.1 Suggestions for Future Research

This thesis considered medium access protocols for the optical star networks. Other protocols also appeared in literature [43]. The selection and usage of these protocols depend upon the application and the type of devices used in the system. Future services will use B-ISDN (Broadband Integrated Digital Services Network) with Asynchronous Transfer Mode (ATM) [19] as a standard transport and multiplexing technique. Many of these services require guaranteed bandwidth and delay. These networks use packet switches to transport data between users. We considered one such application along with two switching protocols in this thesis. Some work in this direction towards the implementation of an optical ATM is a good area of future research.

Most of the future services will be heterogeneous in nature. That is, each user has requirement of sending data from various sources which have varied data transfer requirements. For example, voice packets should suffer minimum delay while important data packets should have a low packet loss rate. Each of these services may also require different priorities. Hence, proposals and performance study of media access protocols with built in priorities is also an important area for future research. The media access protocol proposed in [35] caters for two kinds of traffic, i.e., both circuit and packet switched applications while the protocol proposed in [30] uses three different traffic classes. The three classes dealt with here are connection oriented traffic with or without a guarantee of bandwidth and datagram traffic.

The multi-control channel protocol proposed in this thesis achieves direct interconnection of optical star LANs. However, the protocol is based on Slotted-ALOHA which limits the data channel throughput to less than 36%. Hence, further research can also be done in the areas of protocols and architectures for the interconnection of these networks.

Protocol Class	Ref.	Sub Type	#	Xmitters /User	Receivers /User	Control Channels	Data Channels	Throughput	Processing	Sync.	Extra Hardware
Fixed	[25]	-	1	1 TT	1 TR	0	≥ 1	H	M	yes	-
Semi-Fixed	[25]	-	2	1 TT	1 TR	0	≥ 1	M to H	M	yes	-
Random	[26]	-	2	1 TT	x FR	0	≥ 1	L, H	M	yes	-
	[23]	-	5	1 TT	1 TR	1	≥ 1	L to M	M	some	-
	[27]	-	2	1 TT	1 TR	1	≥ 1	L to M	M	some	-
	[28]	-	2	1 TT	1 TR	1	≥ 1	M to H	M	some	-
	[29]	-	1	1 TT	1 TR	1	≥ 1	M to H	M	some	-
	[48]	-	**12**	**1 TT**	**1 TR**	**1**	≥ 1	**L**	**M**	**yes**	-
	[34]	-	1	1 TT	1 FR	0	≥ 1	L	M	yes	-
	[49]	**MC**	**1**	**1 TT**	**1 TR**	x **(cmb)**	≥ 1	**L**	**M**	**yes**	-
	[30]	MC,SW	1	1 TT,1 FT	TR, 1 FR	N	N	H	L	yes	-
	[48]	**RP**	**2**	**1 TT**	**1 TR**	**1**	≥ 1	**M to H**	**M**	**yes**	-
	[31]	RP	1	1 TT,1 FT	1 TR, 1 FR	1	≥ 1	M to H	M	yes	-
	[32]	RP	1	N FT	N FR	1	≥ 1	M to H	M	yes	Mux/DeMux
	[50]	**RP**	**1**	**1 TT**	**1 TR**	**1 (cmb)**	≥ 1	**M to H**	**M**	**yes**	-
	[33]	SW	1	2 FT	1 TR, 1 FR	1	N	H	H	yes	-
	[35]	SW	1	2 FT	1 TR, 1 FR	1	N	M	M	yes	-
	[36]	SW	1	2 FT	1 TR, 1 FR	1	N	H	M	yes	Delay Lines
	[57]	**SW**	**2**	**1 TT**	**1 FR**	**1 (cmb)**	N	**M to H**	**M**	**yes**	-
	[39]	CA	1	1 TT	1 FR	0	N	M to H	M	no	PAC, Star
	[40]	CA	1	1 TT	1 TR	1	≥ 1	L	M	yes	-
Hybrid	[33]	SW	1	2 FT	1 TR, 1 FR	1	N	H	H	yes	-

Table 9.1: A Summary of the Access Protocols for Passive Star Networks

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