A Survey of Optical Fibers in Communication

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Abstract

In recent years there has been a major effort to integrate fiber optic media into existing communication systems. In this survey, we outline the physics behind fiber optic media and optical interfaces. Different types of optical interfaces and optical media are considered and the advantages and disadvantages of each are listed. We then discuss topologies and protocols suitable for optical fibers in communication. We also take a detailed look into the new Fiber Distributed Data Interface (FDDI) Standard for fiber-optic token rings. Finally, we list off-the-shelf optical fiber networks available as of September 1988.

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1. Introduction

As computer speeds increase, along with a corresponding increase in inter-computer communication, there is a need for high-bandwidth carriers. Optical fibers have been found to be reliable, high bandwidth communication media that are immune to several problems of conventional media. As a result, there has been a major effort to integrate fiber optic media into existing communication systems. In this paper we survey the use of these media in communication systems, with an emphasis on computer communication.

The next subsection describes the pros and cons of using fiber optics for communications. Since optical fibers are a new medium, we think it useful to provide a background in the physics of optical fiber communication in Section 2. Section 3 discusses the physical components of a fiber optic system. Section 4 is an overview of the role of optical fibers in communication. Optical fibers seem particularly suited is as a medium for Local Area Networks (LANs). Since we are particularly interested in this area, Section 5 is a detailed discussion of topologies and protocols for fiber-optic LANs. To round off our survey, Section 6 is a description of optical fiber LANs that were available off the shelf as of September 1988. Section 7 summarizes our survey and also presents some conclusions.

1.1. Pros and Cons

The primary advantage of optical fibers is their large bandwidth. Whereas the physical limit of the technology is in the range of hundreds of GHz, current technology allows transmission at the rate of 20 Ghz, corresponding to a nominal rate of 20Gbps. The other advantages of optical fibers over metallic media are:

1) Very low losses

2) Immunity from electromagnetic interference

3) No harmful radiation from the cable

4) No problems due to ground-current loops

5) More secure medium, since tapping is difficult and easily detected

6) Small diameter and light weight (important considerations for submarine cables).

On the other hand, there are some drawbacks to using optical fibers. The interface between an electronic system and an optic system is complex and quite expensive. The installation and physical handling of the cables, such as splicing together cables, is problematic. Finally, there are few standards, so inter-operability is difficult, if not impossible.

2. Physics of Optical Fibers

This section discusses the physics of optical fiber communications.

2.1. Principles

An optical fiber is a thin (~0.0125 mm) fiber of glass or other vitreous material through which light can travel with very little attenuation. A fiber is a wave guide, so light waves introduced at one end of the fiber are received at the other end even if the fiber is looped or bent.

The key principle to optical fiber communication is total internal reflection (Figure 2.1). Let us consider a particular type of optical fiber called the Step Index (SI) fiber (Figure 2.1). It has two layers, called the core and the cladding, where the core has a higher refractive index. If a light ray in the core tries to exit it, due to the lower refractive index of the cladding, it is reflected back into the core and so all the light rays that enter the core stay there.

Fig 2.1 Total Internal Reflection

Fig 2.2 Stepped Index Fiber
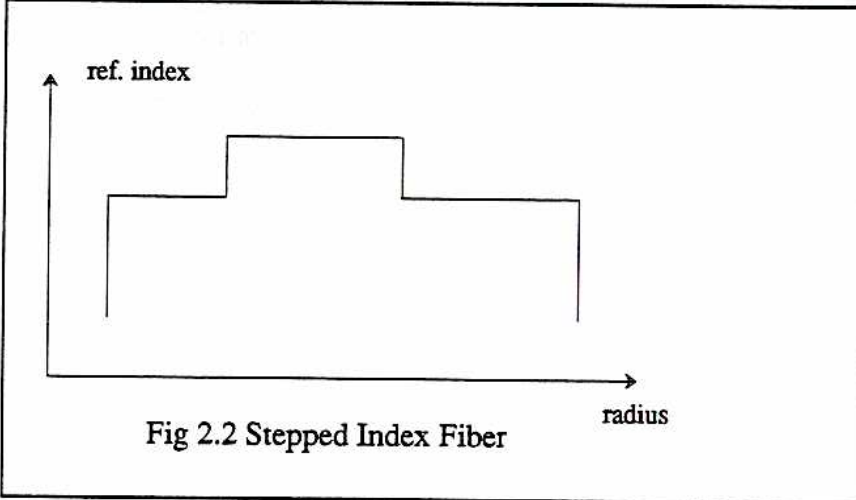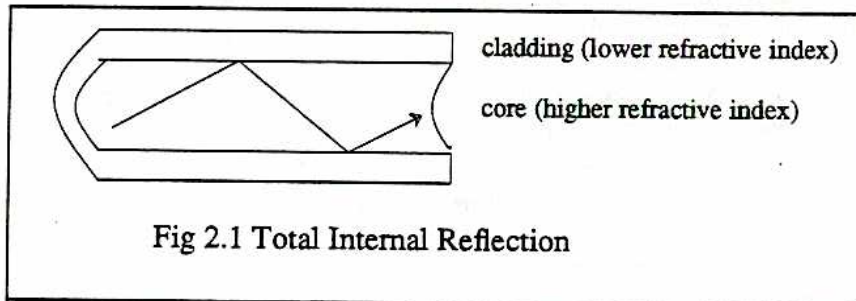
2.2. Problems

The two fundamental problems in optical fiber communications are signal attenuation and signal dispersion. **Signal attenuation** (measured in dB/km) is due to absorption or scattering of the signal by the medium. Lower attenuations allow greater fiber lengths between communicating nodes. It is found that for typical high purity SiO_2 glass minimum attenuation occurs at 1300 nm and 1550 nm. Typical values for attenuation are given in Table I. [Hal87]

Table I	
Material	Attenuation (dB/km)
Window glass	10 000
Optical Glass	300
Pure Water	90
Silica glass(1970)	20
(1972)	4
(1973)	1
(1985)	0.25
(2000)(projected)	0.001

Dispersion refers to the 'smearing' of a signal when signal waveforms that start in phase from the source arrive out of phase at the destination. Dispersion can be avoided by using graded index or single mode fibers, or by operating fibers at the Zero Dispersion Point (ZDP) which is at 1300nm [Shu84] [Li78] . Fortuitously, the minimum loss region for silica is also at 1300 nm, and

so it is critical to be able to manufacture lasers and receptors that operate at this wavelength.

Dispersion causes a time spread in the received signal and increases with the length of the cable. Thus, it is measured in the units of picoseconds (of dispersion) per nanosecond (of wavelength spread in the signaling source) per kilometer (of cable) i.e. ps/ns.km .

2.2.1. Comparison between three cable types

There are three types of fibers, single mode (SM), graded index (GI) and step index (SI). Single mode fibers have the best performance - they have the least attenuation and dispersion and the highest bandwidth. However, they are about 10 times as expensive step index fibers and are difficult to splice, since their microscopic cores have to be perfectly aligned. SI fibers are cheap and have relatively poorer performance. Graded index fibers lie somewhere in between SM and SI fibers.

Table II describes some relevant parameters [Shu84].

Table II			
	SI	GI	SM
Bandwidth	< 200Mhz/km	< 3GHz/km	> 3GHz/km
Splicing	difficult	difficult	very difficult
Application	computer data links	telephone lines	telecom long lines
Cost	least	more	most
Core dia (microns)	50-125	50-125	2-8
Cladding dia (microns)	125-440	125-140	15-60
Attenuation	10-50	7-15	0.2-2

3. Components of a Fiber Optic communication system

A optical fiber system has three essential components - the cable, the signal generator and the signal receiver. This section discusses each component in some detail, describes the state of the art for the component and also predicts the future performance of these components.

3.1. Cable

3.1.1. Physical Structure

An optical fiber is quite fragile so it is protected from the environment by a nylon sheath. Optical fiber cables are internally supported by steel members and in some instances, the fiber is wrapped in helical grooves of the support member. Most cables carry more than one fiber - typical cables carry 2-20 fibers, and as an extreme [Nak87] describes a cable that can carry 600 fibers.

3.1.2. State of the art performance

The least attenuation achieved (1987) in a pure silica core SM fiber is 0.0154 dB/km at 1550 nm [Nak87] (it is 0.29 dB/km at 1300 nm). Corning glass has manufactured a SM cable with loss of 0.2 dB/km at 1500 nm [All83]. Typical figures for dispersion are 3.5 ps/nm.km [ZaG86]

3.1.3. Future

With developments in material science, [Hal87] anticipates that attenuations as low as 0.001 dB/km should be possible by 2000 AD. These advances can be achieved by moving to higher wavelengths, by using fluoride glasses (CaF_3, BaF_3) or by using other esoteric vitreous materials, such as TlBr. The major obstacle in achieving these ultra low attenuations is overcoming dispersion, that increases sharply beyond 1300 nm.

3.2. Light Sources

3.2.1. Physical structure

Most multimoded fibers use an LED as a signal source. LEDs are preferred since signal modulation can be done simply by modulating their drive current. Further, they are cheap and reliable. The problem with LEDs is that their signal has a large wavelength spread leading to a larger dispersion and reducing the useful bandwidth. Moreover, they operate at 850nm, which is a suboptimal operating wavelength.

Thus, there is a preference for lasers as a signalling agent, particularly lasers that operate at 1300nm. At present AlGaAs lasers are popular because of their long life and operability at room temperature. However, AlGaAs lasers too signal at 850nm. We expect that in the future Fabry-Perrot tunable cavity lasers (FP lasers) which operate at 1300nm will become more popular.

3.2.2. State of the art and the future

Lasers of the future will need to operate at the ZDP of the core material. This is currently 1300nm, a wavelength at which FP lasers can be operated. However, FP lasers do not have sufficient spectral purity. Distributed feedback methods have been studied to overcome this problem [Li78]. Other promising techniques are to use distributed Bragg reflection waveguides or solid-state neodymium lasers which have emission lines at 1060 nm and 1300 nm [Li78] [Hal87].

3.3. Detectors

Detectors are of two kinds - PIN and avalanche photodiodes (APDs). PIN (P-Type Intrinsic N-Type) diodes are more reliable and need a lower biasing voltage. However, they are less sensitive than APDs. Avalanche photodiodes are very sensitive, but need a biasing voltage of the order of 400V and are subject to considerable noise. Most PIN photodiodes operate at 1300nm, but because of their poor sensitivity, they are used mainly for short haul applications. Germanium APDs that operate at 1300nm are now available. [Li78] [Hal87]

Future trends are : increasing PIN diode sensitivity, and availability of 1300nm PINs at reduced prices.

4. A Survey of Optical Fibers in Communication

Optical fibers have been found to be reliable, high bandwidth, efficient communication media. Thus, they have been used in many communication applications. This section briefly describes several such applications. Succeeding sections will examine optical fibers in computer communications in greater detail, with special emphasis on protocols and network topologies suited for optical fibers.

To a first approximation, optical fibers are used in three broad areas of communications - telecommunications, industrial applications, and computer communications. We discuss each in turn.

4.1. Telecommunications

Telecommunication services have traditionally meant telephony, teletext and television. With the use of optical fibers it has become possible to provide CATV and videophony services as well. It is convenient to discuss two aspects of the telecommunication hierarchy separately - the long haul network and the local loop.

4.1.1. Long Haul Network

The long haul component of a telecommunication service connects together major nodes of the telecom network and carries many multiplexed channels. An example of a long haul network line is the transcontinental line from say, San Francisco to New York, that provides a telephone link. Such a line is expected to provide a reliable, high bandwidth service. It is convenient to use optical fibers for this purpose because they provide an order of magnitude bandwidth more than

metallic media. Their light weight makes them easier to lay, particularly for submarine applications.

For this reason, long distance trunks using optical fibers have been in operation for some time now. The Mainland Traversing Network [Nak87] in Japan, the Tregor network in France [Zag87], and the BIGFON system in Germany [KnG86] are examples. In the US, telephone companies like AT&T, US Sprint and MCI have also laid long distance optical fiber lines.

4.1.2. Local Loop

The local loop of a telecom network is the line between an end user and a telecom node. For example, there is a local loop from the San Francisco node to all consumers in San Francisco. The loop can be considered to be the lower level of the two level hierarchy in typical telecom networks.

To provide high bandwidth communication between any two subscribers to a network, it is necessary to have a high bandwidth path in the local loop also. The Biarritz experiment [Hal87] [TMP85] showed that optical fibers can provide this functionality. In this experiment, hundreds of subscribers in the French resort town of Biarritz were provided access to a optical fiber based telecom system. This system provided telephony, teletext, CATV and stereo sound.

It is expected that using optical fibers in the local loop will become more common as the demand for high bandwidth (broadband) services increases. [Sha86] discusses several problems that will need to be overcome if optical fibers are to be widely used at the local loop level.

4.2. Industrial Applications

Industrial applications of optical fibers are mainly as media for control networks in harsh environments. We can subdivide industrial applications into two categories : control systems in manufacturing plants and applications in consumer devices.

4.2.1. Control Systems in Manufacturing Plants

The shop floor of a manufacturing plant generates a lot of electromagnetic interference. This is an incentive to use optical fibers for communication. Optical fibers used in industrial applications are either short links or loops.

Short links have become standard in implementing factory automation, particularly for sequencers and machine tools. In 1985, more than one million sets of short links were produced and installed. Short links can be as inexpensive as 7 dollars per link (1987 prices).

Local loop technology is also used in industrial applications. For example, optical fibers are used to implement communications in coal mines [Zie87] and steel plants [Nak87]. These loops link sensors to data processing units and controllers.

4.2.2. Consumer devices

The main consumer items that use short links are cars. For example, the 1982 Toyota Century used an optical link between the door locks and the dashboard. Future uses are to link a CD ROM to a dashboard display unit to allow display of route information.

Another consumer item that uses optical fibers internally is the compact disk player, where a high data rate (6Mbps) is necessary. Ordinary links cannot be used for this purpose, since they emit harmful radiations at these data rates.

4.3. Computer Communications

Computer communications span some 16 orders of magnitude of bandwidth and speed, from the communication between the CPU and CPU cache inside a chip to the use of satellites in long haul networks. A broad categorization of these is

- Within chip communication

- Chip to chip communication (busses)
- Computer to I/O device communication (channels)
- Short range computer to computer communication (LANS)
- Long distance computer to computer communication (WANs)

Optical fibers are unsuitable for within chip and chip to chip communication because the overhead in electrical-optical conversion introduces an unacceptable delay. Further, it is difficult to integrate optics with electronics within a chip. However, it is feasible to use optical fibers in the other areas of computer communication. We now discuss the use of optical fibers in channels, WANs and LANs. (The subsequent portion of the survey covers LANs in much greater detail, with emphasis on their topologies and protocols)

4.3.1. Channels

Channels are the links that allow communication between a computer and an I/O device such as a terminal, disk drive or tape drive. Optical fibers promise to be a high bandwidth medium for implementing channels [CrS80]. Currently channels are implemented as busses to allow a very high bandwidth of the order of 50-100Mbps. However, buses are strictly limited in the distance they can span. Optical fibers provide even higher bandwidth over much longer distances.

Using optical fibers for channels radically increases their functionality. The higher bandwidth allows us to do load balancing of processors connected to the same channel. Another interesting application is that storage media can be stored at a single physically secure site, and can be accessed by computers that are physically remote with no loss in functionality. Many of these ideas are discussed in [CrS80].

4.3.2. Local Area Networks (LANs)

LANs connect computers over distances of the order of a kilometer or less. Current LANs typically use a twisted pair or coaxial cable as the physical medium. Optical fibers hold out great promise as an alternate medium for LANs. Since they provide two orders of magnitude increase in bandwidth. The basic problem is that the connection cost to add a computer to the network is currently very high. However, the cost is expected to drop rapidly.

Prototype LANs using optical fibers were built in the late 1970s, the main example being Fibernet at Xerox PARC [RaM78]. Subsequently a number of topologies and protocols have been proposed and implemented. The protocol that has aroused the most interest is the proposed standard : FDDI (Fiber Distributed Data Interface). FDDI as well as many other topologies and protocols are investigated in some detail in the next section.

4.3.3. Wide Area Networks (WANs)

WANs span distances of the order of thousands of kilometers. They can be thought of as a collection of nodes and long haul lines that interconnect them. Existing WANs such as the Internet are bandwidth limited (typical links operate at 1Mbps). As discussed in the section on long haul networks, it is possible to build long haul links with a bandwidth of 20Gbps, an increase in capacity by a factor of nearly 20,000 ! It is not clear whether existing internetwork protocols are suited for optical fiber links. This is an area for active research. Such radical increases in communication bandwidth of WANs will result in somewhat different perspectives on distributed computing. An overview of such changes is provided in [AFR87].

5. Fiber Optics in Local Area Networks

Fiber optic components may be used in two different ways in LANs. They can augment already existing LANs or can provide optical fiber LANs which are plug compatible with existing systems.

5.1. Augmenting existing LANs

We present two examples of how optical fibers can be used to augment an existing LAN.

Repeaters are used to transmit data between two segments of a local area network. Links between repeaters thus increase the geographical extent of the network. [Row85] discusses the use of fiber optic inter-repeater links. Coaxial cable inter-repeater links are limited to a range of ~100m, but by using optical fibers this can be extended by a factor of 20.

Another use of optical fibers to augment existing networks is in "overlay networks". [KMR] discusses the use of a high-speed optical fiber ring, which augments and existing token passing ring. Access to the high-speed ring is controlled by token passing on a slower ring.

We will not deal with augmentations to existing LANs further. In the next subsection, we present various topologies and associated protocols for fiber optic LANs. The Fiber Distributed Data Interface (FDDI) is described in section 5.2.

5.2. Topologies and Protocols for Fiber Optic LANs

In this section we outline the various LAN topologies that have been proposed using fiber optic transmission. The tradeoffs involved in the design of each of these protocols and topologies are discussed. A good summary of existing protocols and topologies may be found in [MHT86] and in [RBJ84].

5.2.1. The Bus Topology using CSMA/CD Protocol

The most popular LAN of this type is Ethernet [MeB76]. Ethernet uses coaxial cables as a transmission medium. Access to the medium is governed by a protocol called CSMA/CD (Carrier Sense with Multiple Access and Collision Detection). Before transmitting, each station listens on the medium to check if any other station is transmitting. If the medium is free, the station goes ahead and transmits. While transmitting, a station also listens on the medium. If some other station has also commenced transmission, a collision is detected and the stations retry after a random interval [Sta88].

The fiber optic medium is not well suited for this protocol. In an Ethernet, each participating station needs to tap on to the bus to sense its state. Low-cost and low-loss optical tapping devices have not been developed [MHT86]. Moreover, the unidirectional nature of light in a fiber optic cable does not allow bidirectional data transfer that is required in a bus structure [RoH86].

Various approaches to implementing Ethernet using fiber optics have been studied. All these implement a fully-fiber Ethernet on a star configured bus with duplex data transmission. The following are some of the variations in star topology and associated protocols that have been considered [RoH86], [RoH86].
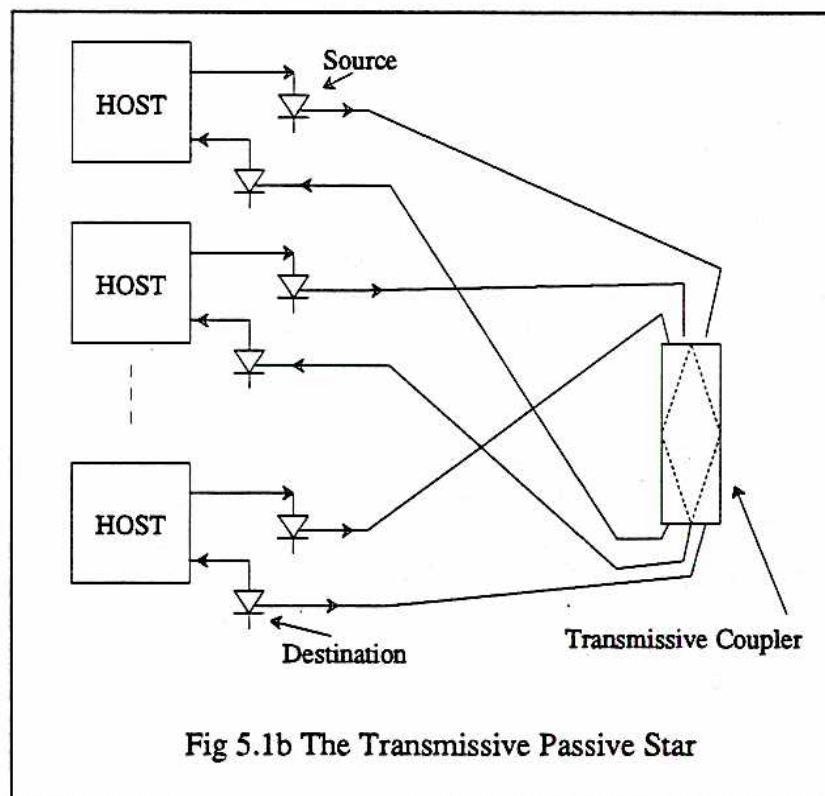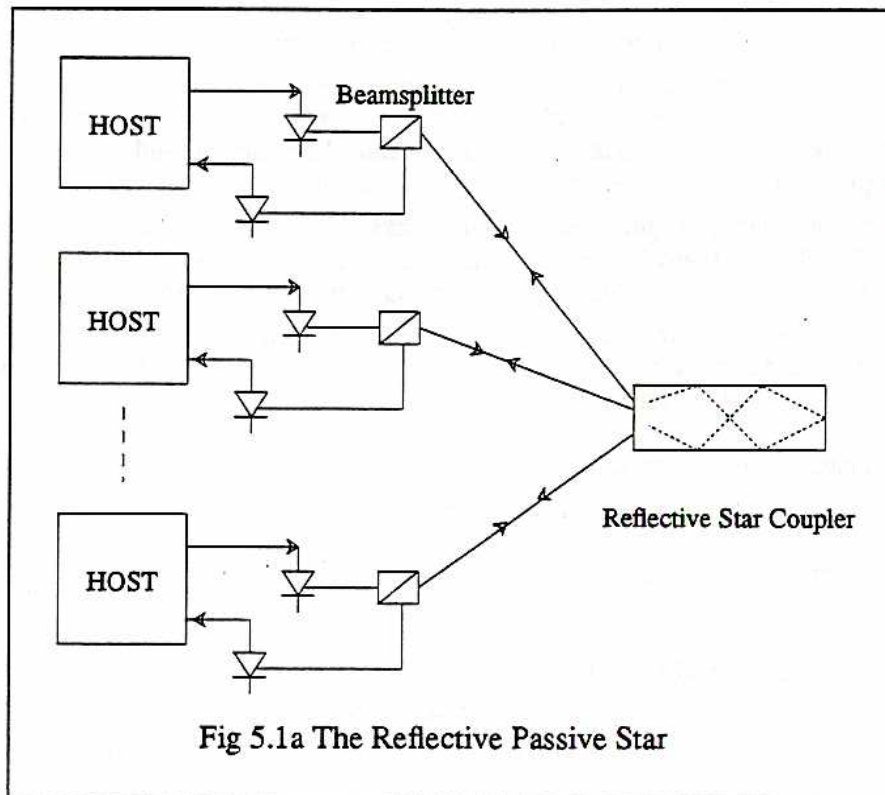
Passive Star

This approach relies upon a central passive hub which distributes the incoming packets to all the nodes. There are two types of passive stars - reflective stars and transmissive stars.

The **reflective** passive star uses a single cable between a host and the hub. The hub reflects the signal from one host into all the other cables (Figure 5.1a).

In the **transmissive** passive star, each host has a receiver cable and a transmitter cable, both of which connect to the central hub (Figure 5.1b). One of the earliest fiber-optic LANs, Fibernet (developed at Xerox PARC) used a transmissive passive star [RaM78].

Collision detection may be done by signal analysis or by time-domain analysis. When using signal analysis, a transmitting station determines collisions by detecting average power levels or by bitwise comparison of received and transmitted data. Alternately, when using time domain analysis, if the node knows the round trip-time for a message transfer, it can detect that a collision has occurred if it receives a transmission in less than the round-trip time. This approach has the obvious drawback that reconfiguration of the network changes the round-trip times for transmission.

Fig 5.1a The Reflective Passive Star

Fig 5.1b The Transmissive Passive Star

The problem with the passive star, in general, is that addition of new nodes to the network is difficult.

Active Star

In an Active Star LAN (Figure 5.2) , a central active hub detects collisions using a logical AND of the detected incoming signals. A collision is indicated to the hosts by broadcasting a jamming signal.

The disadvantage with the active star topology is that it presents a central point of failure. However, most LANs implemented with a bus topology use this approach. These include ISO-LAN which is outlined in [RoH86].
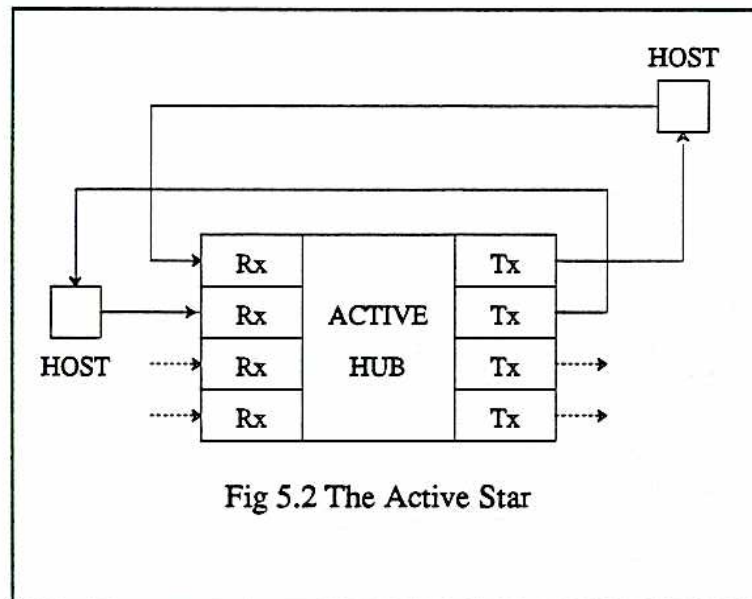
Fig 5.2 The Active Star

Hybrid Star

In this configuration (Figure 5.3), collision detection is performed by an active agent. At each of the incoming data links, a portion of the signal is tapped off. If a collision is detected, then the agent jams the network using a special jamming signal which indicates that a collision has occurred. This has the drawback that the addition of nodes is difficult.

5.2.2. Ring Topologies Using Token Passing

The most natural topology for fiber optic networks is the token ring [Sta88] since an optical fiber is an inherently point to point medium. This topology consists of point-to-point fiber optic links between nodes, the links forming a complete ring. Access to the medium is governed by a token. A node which "captures" a token can transmit data over the ring. A variety of prioritization techniques ensure fairness.

A slight variation of the token passing strategy is used in the DUAL LAN [EGC86]. The last sender node keeps the ring open (i.e. doesn't forward what it receives on its input) and keeps sending "your turn" frames. If a node wants to transmit data, it "spoils" the "your turn" packets flowing past. The original sender, on receiving the "spoiled" packet, closes the ring and the new sender opens it and begins transmission. If there are no packets on the medium, stations that detect this condition elect to start transmitting "your turn" packets. Only one of them ultimately becomes the "master" and starts transmitting "your turn" packets. The advantage of this scheme is that there is no token and so the scheme is not affected by token loss.

An interesting analytical evaluation of CSMA/CD and token passing protocols and their performances at high data rates (suitable for fiber-optic networks) can be found in [RBJ84]. This

Fig 5.3 The Hybrid Star
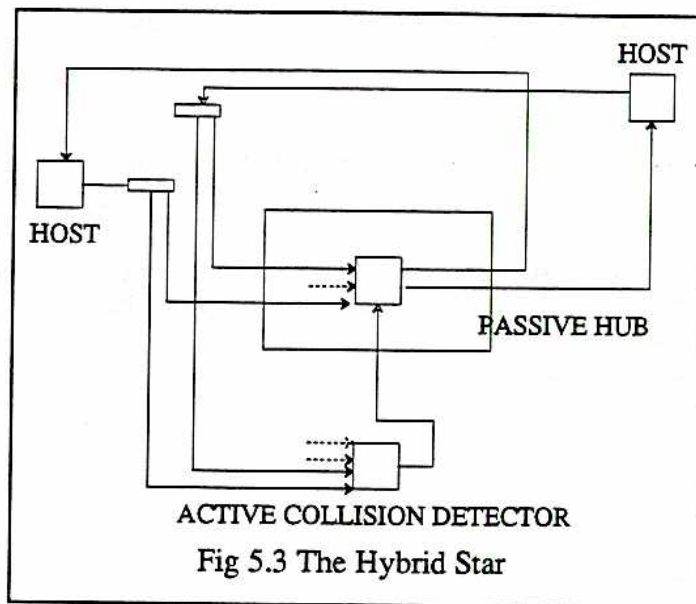
evaluation shows that with increasing bit rates, the token ring throughput increases linearly while the CSMA/CD throughput falls off. Nevertheless, token passing per se has not been used in many fiber optic networks, due to the low bandwidth utilization. Only the early experimental fiber-optic networks used a token passing strategy. The ILLINET [WSK80] is a prime example.

5.2.3. Alternative topologies and protocols

To utilize the high bandwidth provided by fiber, time division multiplexing (TDM) is widely used [FHH85], [Har85], [Wil86], [BeE84] and [HSS84]. Transmission time is divided into slots which are dedicated to stations. In each slot, one station is allowed to transmit its information.

The best example of this protocol is obtained in [AdF84]. This protocol is called ORWELL. It defines two types of services - synchronous and asynchronous. A station using the synchronous service is guaranteed an upper limit on the bandwidth, typically of the form D slots in time T. Thus a station can utilize any unused time slot for upto D times within time T. Once it has transmitted D frames, it pauses in a temporarily idle state. When all stations using this service have exhausted their guaranteed bandwidth, a RESET frame sets the count at each station to 0 at which these may restart their transmission.

Time division multiplexing is useful in Integrated Services applications where real-time voice and video have to be transmitted. Typically, real-time data uses the synchronous service while bursty traffic uses the asynchronous service.

Another alternative topology that has been studied is a ring of stars. Each node in the ring is the hub of a star. The protocol proposed for this topology uses "adaptive hybrid token passing". In this topology, time division multiplexing is used in the following fashion. In each channel, one of token passing or CSMA/CD is used depending on which group of nodes (star) is allowed to use the slot. This allows lightly loaded devices to use CSMA/CD and heavily loaded ones to use token passing. This concept can also be extended to subslots which can be either CSMA/CD-ed or token-ed [SWR87].

In an attempt to standardize fiber-optic networks, the American National Standards Institute (ANSI) has proposed the Fiber Distributed Data Interface (FDDI) Standard, that utilizes some of the concepts mentioned in this section. The standard is discussed in detail below.

5.3. The Fiber Distributed Data Interface (FDDI) Standard

We now describe the FDDI Standard for a fiber-optic ring network. The FDDI Standard is described in four documents [X3T85d], [X3T85c], [X3T85b] and [X3T85a].

5.3.1. Overview of the Standard

The FDDI standard incorporates some of the features of the existing systems covered in Sections 3.1 and 4. It specifies a fiber-optic token ring with 100 Mbps data transmission rate. Light Emitting Diodes with a nominal wavelength of 1300 nm will be used.

Physical transmission of the data uses a 4B/5B encoding which requires 125 Mbaud transmission rate. This encoding is more effective than the Manchester encoding which would require 200 Mbaud transmission rate. Clocking in each node is independent and is derived from the transmitted signal.

Upto 1000 physical connections and a total fiber path of 200 km can be accommodated. Stations can be separated by at most 2 km, owing to cable attenuation. A maximum allowable bit-error rate (BER - the average ratio of the number of bits in error to the number transmitted) of 10^{-9} between any two nodes in the network is defined.

The FDDI standards consist of the following layers (Figure 5.4):

The Physical Layer

This corresponds to the ISO Physical Layer and is subdivided into two sub-layers :

- The Physical Medium Dependent (PMD) Layer : This provides point-to-point links between FDDI stations and defines the fiber characteristics, sources and detectors, power budgets (the "balance sheet" between the cable losses and the repeater gains) and hardware related characteristics. We will not describe this layer any further [X3T85b].

- The Physical Layer Protocol (PHY) : This provides the interface between the PMD and the MAC layer described below [X3T85c].

The Medium Access Control (MAC) Layer

This controls access to the medium and generates frame checks to ensure data integrity. This layer is equivalent to the lower layer of the Data Link Layer (DLL) in the ISO model [X3T85d].

Station Management (SMT)

This ensures cooperation of the station with the others in the ring. It provides for fault-recovery and isolation. [X3T85a]

The FDDI Standard is actually a packet-switched standard. There is another standard called FDDI-II which defines circuit-switched operation using the FDDI Standard. Below, we discuss both FDDI packet switching and FDDI-II circuit switching.

5.3.2. FDDI Packet Switching

The original FDDI standard specifies a token passing protocol. Information is transmitted on the ring in the form of frames. Each frame begins with a preamble and a starting delimiter which provide synchronization. The token is a frame with a specific format and signifies the right to transmit data, much as in traditional token-rings specified by the IEEE 802.5 Standard. Once a station captures the token it sends out data frames. The receiving station acknowledges the frames by flipping bits in the frame as it passes by. The transmitting station then "strips" the frame from the medium. Due to the nature of the clocking the maximum size of each frame is limited to 4500 bytes.

Prioritizing access to the medium is done by establishing classes of service. There are two classes of service - synchronous service and asynchronous service. Synchronous service specifies that a station may capture a token whenever it has data to transmit. Asynchronous service

Fig 5.4 The FDDI Reference Model
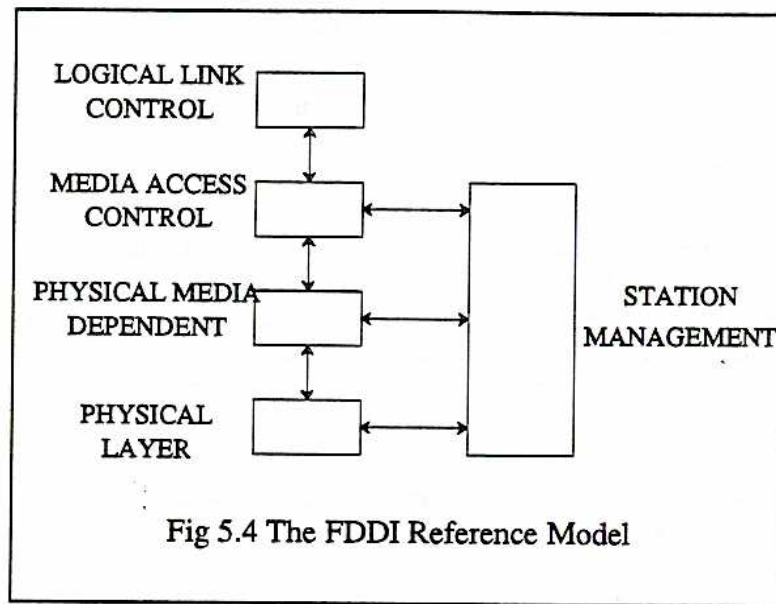
specifies that a token may be captured if the time since the token was last received is less than some parameter specified at initialization, called the Target Token Rotation Time (TTRT). Additionally, the standard also specifies two types of token (restricted and non-restricted). These are also used to establish priorities amongst stations.

5.3.3. FDDI-II Circuit Switching

To support integrated services including real-time voice and video applications, a circuit switching protocol is also defined in the FDDI-II Standard.

The objective of circuit switching is to support 64kbit/sec throughput between any pair of nodes on the LAN. In normal operation, one of the stations is elected to be the "Cycle master". The Cycle Master generates a regular "cycle structure" (CS) frame. (Figure 5.7) All stations circulate this CS frame.

A station must receive a CS frame every 125 microseconds exactly. The Cycle Master employs a latency buffer to maintain an integral number of 125 microsecond CS frames within the ring.

Each CS frame is delimited similar to a frame. Additionally, it has a dedicated "token data group" and 96 "programmable data groups". Each group is 16 bytes in length and every byte in the data groups is assigned a channel number. Since a CS frame is guaranteed to arrive every 125 microseconds, the byte assigned to a channel is also guaranteed to arrive once every 125 microseconds. Thus these channels are called "isochronous" channels. Any such channel can transmit 96 bytes of data in one CS frame or 6.144 Mb/s. There are 16 "isochronous" channels which occupy 98.304 Mb/s of the total 100 Mbps bandwidth. Therefore, even when the channels are fully occupied there exists a 1 Mbps token ring operating.

Additionally, each of the isochronous channels can be reallocated to 3 or 4 "sub-channels" to be compatible with the European and the American phone systems respectively.

On power-up, the normal packet-switching mode is brought up. This mechanism is used to set up a Cycle Master by a bidding process who also controls the regeneration of the cycle structure.

The Cycle Master captures the token and then begins transmitting the CS frame. The first CS frame contains the token which is sent in the "token data group". Then the packet and circuit switched modes begin to operate in parallel.

Fig 5.5 An FDDI Ring
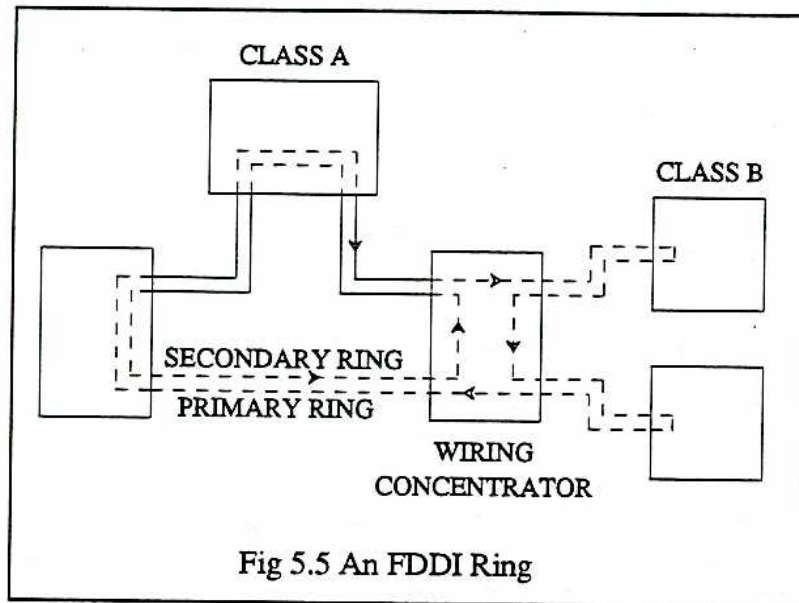
5.3.4. Station Management and Reconfigurability

The FDDI Standard specifies that the ring actually be configured with two counter-rotating rings, for reliable operation. Each of the rings are capable of operating at 100 Mbps. Two types of stations are defined. Stations of type A form part of both rings and can be connected only to another station of type A (Figure 5.5). Stations of type B form part of one ring only and can only be connected to another station of type B. Wiring concentrators are used to connect stations together.

Fig 5.6 Reconfigurability
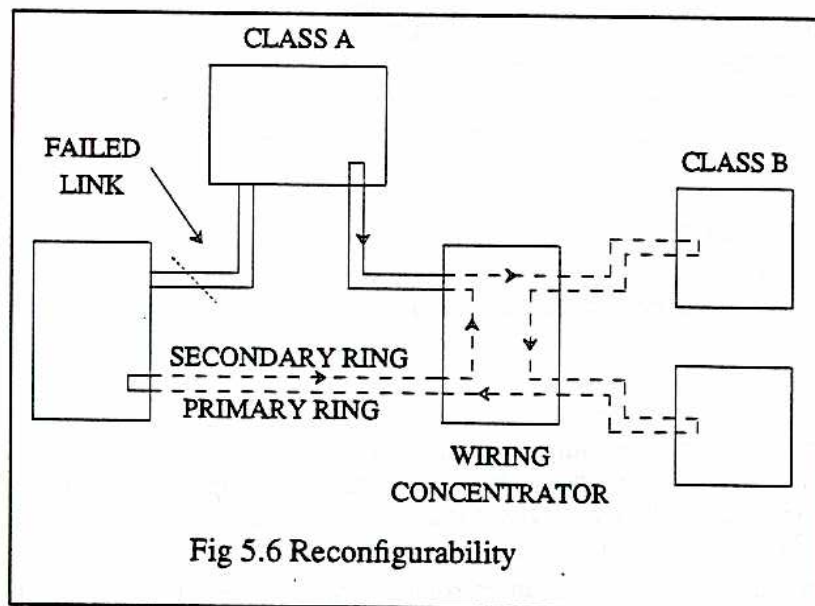
The optical fiber is reconfigurable (Figure 5.6) in the event of a single link failure. In this case, the stations at the end of the failed link detect the failure and interconnect the two rings at their interface. This causes the formation of a single link. A double link failure gives rise to a partition of the network. Reconfiguration is handled by the Station Management Layer (SMT).

Reliability is ensured in case of a station failure by an optical bypass. The incoming data is transmitted through a fiber-optic bypass. Moreover, each station obtains its own receiving and sending clock from the data. Differences in receiving and transmitting clocks are overcome by a

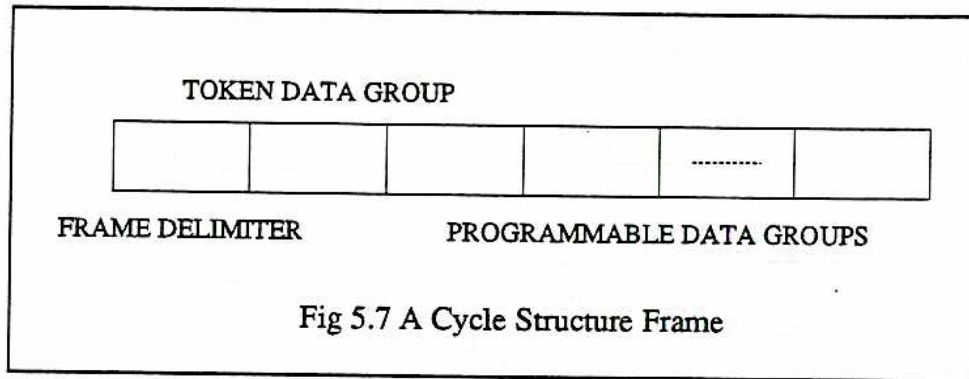latency buffer. This avoids cable jitter and maintains the required BER.

Fig 5.7 A Cycle Structure Frame

5.3.5. More on the FDDI Standards

- Some interesting descriptions of the FDDI Standards can be found in [Ros86] and [FlC86]. The PMD and the PHY layers are discussed in [KiR87] and [Bur86]. [Bea85] compares the FDDI Standard and the IEEE 802.5 reconfigurable Token Ring standards.

- The FDDI Standards have been influenced by the ESPRIT (European Strategic Programme for Research and Development in Information Technology) project [RLM].

- AMD has developed a FDDI compatible chip set that will be available in the market by mid-1988.

6. Survey of Some Off-the-Shelf Local Area Networks

The following is a survey of some of the commercially available fiber optics based local area networks. The information was gathered from various sources : by contacting manufacturers, from their catalogues, and from magazine articles [All83, Bak86, Mok87, Pro87, Shu85, THK87]. Most of the products use IEEE 802.5 for medium access control although at least one manufacturer (AMD) has announced a chip set based on FDDI to be available later this year. The products considered are listed by the standards and protocols they implement. The FDDI product is listed first, followed by Ethernet and token ring LANs.

6.1. Fiber Distributed Data Interface

FDDI is a recently proposed standard. Details have been given earlier in the paper (section 5.2). We are aware of only one manufacturer that is offering a set of chips conforming to this standard.

6.1.1. Supernet (Advanced Micro Devices)

The Five Chip Supernet is the first implementation of the FDDI standard [Mok87]. The basic components are the encoder-decoder receiver and transmitter chips, made using bipolar technology and the CMOS chips FORMAC (Fiber Optics Media Access Controller), DPC (Data Path Controller) and RBC (Ram Buffer Controller).

The physical layer consists of two counter rotating rings as specified in FDDI. The transmitter receives data from the Media Access Control (in the Data Link layer) and encodes it using 4B/5B encoding (i.e. 4 bits of data are encoded to 5 bits on the medium). The transmission rate is 125 Mbits/s . The receiver converts it back to 4 bit code. It also monitors the line states.

The media access controller (FORMAC) uses the timed token protocol described earlier. Its responsibilities include packet transmission, reception, repetition and removal from the ring. Two internal timers supply the token rotation time (TTRT) and a token holding time. This timer is loaded every time FORMAC passes the token downstream . A third timer monitors the ring either for the 'no packets received' condition or for packets that are too long. FORMAC also performs all arbitration requirements between synchronous and asynchronous transmissions.

DPC's primary function is to transfer data between the buffer memory and the FORMAC. An internal register performs the translation of incoming data to the word format of the buffer memory. Network data integrity is maintained by cyclic redundancy check.

RBC generates address and control signals for the buffer memory. It supports 256 Kbytes of address space and also includes 5 DMA channels. It arbitrates the DPC host's and node processor's requests for buffer memory.

6.2. Ethernet

It is generally difficult to use CSMA/CD on optical fibers. Thus, most manufacturers opt for star topologies. Siecor Fiberlan (Calif.), Codenell Technology (N.Y.) and Ungermann-Bass(N.C.) are the leading U.S. manufacturers offering fiber optic networks. They jointly developed Fiber Optic Net/One in 1983, based on Ungermann-Bass's Net/One. Their current product lines are discussed below.

6.2.1. Siecor Fiberlan

The company offers a large number of products implementing Ethernet. Various types of optical fibers with speed varying from 4 to 16 Mbps are offered. The following is a brief summary of the products of Siecor. Ungermann-Bass and Codenell offer similar products.

6.2.1.1. Point to Point links

At the lowest scale of cost, Siecor offers a point to point link configuration for the ethernet. A duplex optical cable connects two Ethernet/IEEE 802.3 compatible devices (DTE), e.g. transceivers, repeaters etc with an optical transceiver (IRL). This IRL contains the circuitry for collision detection. No software changes are required. However the size of a link can not exceed 4.5 km.

6.2.1.2. Passive Star System

In the passive star system offered by Siecor, the DTEs are connected to electro-optical transceivers which are connected to a passive star coupler. The optical transceiver detects collisions by analyzing the incoming signals. Thus such a star segment is logically equivalent to a coaxial segment of the ethernet. Cable lengths are typically less than 250m. It performs well under light loading conditions. (Figure 5.1)

6.2.1.3. Hybrid Star System

In this Siecor product, an additional collision detection at the star coupler is included. This system is advised for backbone networks. System components are optical transceivers, star coupler monitors (which are monitor taps added to passive couplers) and a collision detection electronics unit which can connect up to seven nodes. (Figure 5.3)

6.2.1.4. Active Star

This is the most complicated Ethernet offered by Siecor. This permits up to 32 nodes. The system components are a concentrator, a collision detection module, which alerts the DTE only if it was involved in the collision, a power supply module and optical transceivers which connect to ethernet stations. Modules may be added to the concentrator without powering down. (Figure 5.2)

6.2.2. American Photonics Corp.

64NET, offered by American Photonics Corp., allows the interconnection of up to 32 personal computers. It is also based on the active star node that allows a computer or peripheral to hook onto it through a remote terminal unit on a full duplex fiber-optic cable. This cable may be up to 1000 ft. long and can communicate at 19.2 Mbaud. The remote terminal unit plugs into and is powered by the computer or the peripheral it is serving. The cable comes terminated with

connectors and has a 50 microns core diameter. The star node contains proprietary network software. One active star may be connected to another to serve more personal computers and peripherals.

6.2.3. Codenell Technology

Codenet, offered by Codenell Technology is very similar to the Seicor networks. They claim to be able to connect upto 260,000 personal computers by using a series of powered optical repeaters. Their interface boards are equipped with jumpers that make it possible to loopback and test the electronic and optical circuitry and run tests. This helps in installation and testing.

6.2.4. Fox Research Inc.

Fox Research initially offered a twisted pair Ethernet to their customers. They have now offered fiber optic alternatives to the traditional LANs. A fiber optic system is desirable in environment with high interference or to meet high reliability requirements. Since fiber cables are expensive, they also offer mixed networks with twisted pairs and cables. The structure of the networks looks like a pyramid of hubs where each hub can connect up to eight computers. A pyramid of height 3 is allowed, allowing 512 sites to be connected together. The distance between a site and a hub has to be less that a kilometer but can be extended to a mile by changing resistors in the hub.

6.3. Token Rings

Token rings are the most commonly available fiber optics LANs, and are offered by many European and Japanese companies. Some of the more prominent manufacturers are:

6.3.1. Siecor

Siecor's token ring consists of a universal concentrator which connects up to 34 token ring transceivers in a star or tree branching topology. A logical ring is built upon this. The concentrator to token-ring-terminator separation is at most 2.5 km. Siecor allows the interconnection of the various configurations by use of repeaters and interconnections between concentrators.

6.3.2. Hitachi

Sigmanet, a product of Hitachi can transmit voice, data, facsimile and freeze frame video signals at 32 Mbits/sec. This connects up to 64 link controllers, each of which is microprocessor based. Each link controller can accommodate up to 64 terminals and can be up to 2 km away from the closest neighbor. Thus the network can span 128 km.

The system is fully redundant, employing full duplex optical fibers. The link controllers use a token ring protocol. However, although the main ring is fiber optic, the terminal to link controller is allowed to use coaxial pairs or twisted pairs.

6.3.3. NEC

NEC offers a token passing ring with special fault tolerance features like alternative path selection, loop-back, bypassing and battery backup. The fiber bandwidth is 32 Mbits/s . The net has two loops, each of which carries signals in opposite direction. One of the paths is normally active. When a failure occurs, the passive one takes over. If the control logic in a loop interface unit fails, signals bypass the module and are repeated only at the next interface unit. Battery backup takes over in case of a power failure.

6.3.4. Sumitomo Electric Industries

SUMINET-4100 series offers various kinds of token rings. SUMINET-4150 is a loop using time division multiplexing for access control. The loop is managed by a loop monitor unit, under the supervision of a network supervisory processor. The loop forms a backbone network for various other local area networks like IBM's token ring, Ethernet or a LAN offered by Sumitomo.

The transmission speed is 128 Mbps and up to 64 stations, each < 3 km apart can be connected together.

6.3.5. Leeds

FOCOM 1800 series operates over 8.6 Mbps fibers and allows a separation of 2 km between the nodes, extensible up to 5 with receivers. Twin fibers for duplex communication connect the nodes. The protocol used is a slotted ring. Access is monitored by a master node along with monitor programs in other nodes. The master node provides the system clock and synchronization information. Monitor programs are protected procedures implementing the protocol. The system provides battery backup and auto reconfiguration if any node goes down. A bandwidth utilization of 17% has been reported.

6.3.6. Proteon Inc.

Proteon offers its ProNET-10 p320x which consists of counter rotating rings. It also is an upgrade from the original copper wire network. Unlike 10-NET, where one has to change the interface on the host to upgrade, proNET allows copper cable to connect to four fiber cables via the ps3200 interface. The system allows one to control the intensity of the light in the cables. One can make it low enough so as to make attempts to tap the system to cause failures. The interface is intelligent enough to detect a break in the ring and make a short circuit as well as to remake the ring when a connection comes up. They describe the system as self-sealing and self-healing. Their system is compatible with the IBM token ring.

6.3.7. Pure Data Corp.

Pure Data Corporation have upgraded their ARCNET to allow for optical fibers. ARCNET was one of the first local area networks to reach the market. The system comes in two flavors, with a single cable or with two cables. The single cable uses two different wavelengths to transmit in two directions. This complicates the optoelectonics of the interfaces. They recommend using two fibers for short distances (< 1 km) and to use a single fiber for long distances (upto 3.5 km).

Perhaps the plus point of ARCNET is not technology but user-friendliness. A well designed set of LED indicators allows the system manager to know the status of the interface boards during installation and operation. Reconfiguring the system is easy since the network addresses of the interfaces can be obtained without disconnecting them. Since simple but useful modifications make ARCNET one of the easiest commercial systems to operate.

6.4. Summary

The above survey is not exhaustive and serves only to give a flavor of the currently available products. Some other names worth mentioning are proNET from Proteon Associates(Mass.), Hubnet from Canstar Communications (Ontario) and Optonet from Phoenix Digital.

A brief comparison of the products may be found in Table III.

7. Summary

In this paper, we have discussed the physics of fiber optic communications and fiber optic components. A survey of optical fibers in many different areas of communication is presented. Subsequent sections describe topologies and protocols for fiber optic LANs. Finally, we have reviewed some off-the-shelf fiber optic LANs.

Our survey has identified the following trends:

- Cable attenuation and dispersion are steadily decreasing and should reach very low levels by the turn of the century. This should provide high bandwidths and allow large inter-repeater distances.

Fiber Optic Networks (Table III)				
Protocol	Company	topology	Max Node Separation(km)	Max Nodes
FDDI	AMD	double ring	200*	500
Ethernet	Siecor	pt to pt.	4.5	-
Ethernet	Siecor	Active Star	0.5	32
Ethernet	Codenell	Passive Star	2	28
Ethernet	Fox Research	pyramid of hubs	1.6	512
Token Ring	Siecor	ring	-	34
Token Ring	Hitachi	ring	2	64
Token Ring	Proteon	double ring	2.5	63**
Token Ring	Pure Data	Central hub	3.5	255
Slotted Ring	Leeds	loop	3.	12
TDM	Sumitomo	loop	3	64

* 200 km. is maximum length of fiber.
** Number of ps3200 interfaces

- Future cables would be operated at 1300 nm to take advantage of ZDP and low dissipation at that wavelength.

- For integrated services, it is necessary to provide guaranteed bandwidths. Thus Fiber Optic LANs are moving towards circuit switching (e.g. FDDI-II) as opposed to Ethernet like packet switching.

- Ethernet is not a suitable paradigm for optical fiber networks.

- FDDI standards are slowly gaining accepted, but they are not yet supported by most manufacturers.

- At the moment, Japanese and European manufacturers have an edge over American manufacturers.

- The full potential of the fiber optic bandwidth is not fully exploited by current products. Most of them operate at the low end of the bandwidth spectrum.

We conclude with a quote from [CrS80]:

"It is no longer a question of *if* for fiber optics, but rather *when*"

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