NEAR EAST UNIVERSITY

Faculty of Engineering

Department of Electrical and Electronic Engineering

FIBER OPTICAL NETWORKING

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Student: Umair Waheed (980673)

Supervisor: Prof. Dr. Fakhreddin Mamedov

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ABSTRACT

Fiber optics cables are those cables that contain thin strands of glass that carry light instead of electricity. Fiber optics are lighter, immune to electrical interference, and carry information faster than standard network cables. Fiber optics are used in high-speed computer networks. Some general types of fiber optics are Step index multimode, Graded index multimode, Step index multimode and plastic optical fibers.

Networking may be broadly defined as the transfer of information from one point to another. When the information is to be conveyed over any distance a Network is usually required. Within the network the information transfer is frequently achieved by superimposing or modulating the information on to an electromagnetic wave which acts as a carrier for the information signal. This modulated carrier is then transmitted to the required destination where it is received and the original information signal is obtained by demodulation.

The transfer of information in the form of light propagating within an optical fiber requires the successful implementation of an optical fiber networking. This network, in common like all networks, is composed of a number of discrete component which are connected together in a manner that enables them to perform a desired task. Hence, to achieve reliable and secure network using optical fibers it is essential that all the components within the transmission system are compatible so that their individual performances, as far as possible, enhance rather than degrade the overall system performance.

Wavelength Division Multiplexing is a new technology that begins to help resolve this disparity. WDM takes advantage of the fact that multiple frequencies of infrared light can be transmitted simultaneously down a single optical fiber, and each of those frequency channels can carry independent information, just as each FM radio channel carries its own station. With the use of WDM, the capacity of a single strand of fiber, 250 microns in diameter, can carry between 10 and 80 Gbps. A typical cable of 18 millimeters in diameter contains up to 200 fibers.

INTRODUCTION

Nearly exponential increase in usage of voice, video and data communications, nationally and internationally, places new requirements on the transmission media. The need for low loss, low dispersion, ultra-wide bandwidth, and high dynamic range, durability, upgradability, and low cost communications networks, have shifted the focus from traditional copper coax to optical fiber links. The project presents a comprehensive overview of the evolution and the present state-of-the-art of Optical Fiber Networking. This project consists of the four chapters.

Chapter-1 is the introduction to the fiber optics networking. In this chapter there is brief touch of History and safety of the Fiber Optics. This chapter also shows the basic Network for the transmission and receiving of data through fiber optics with its advantages.

Chapter-2 presents the optical fiber network. Some general types of fiber optics are explained with the transmission characteristics of them. After that it has been explained that how data travels through the network. For that, at source there must be a transmitter and at the destination a receiver, this is all shown with their diagrams. Also packet switching is discussed, as for high speed data transfer, packet switching is more efficient than circuit switching. At the end designing of the fiber optical network is explained.

In chapter-3 Multiple-Domain Access Methods are described. Generally there are two methods, Time-Domain Multiple Access and Wavelength Domain Multiple Access.

Chapter 4 consists of some applications of fiber optical networks, These application can be Trunk Network, Junction Network, Synchronous Networks, Communication Links, Local Area Network, Industrial Networks

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CHAPTER 1
INTRODUCTION TO FIBER OPTICAL NETWOKRING

1.1 Historical development of Fiber Optics:

Optical communication systems date back two centuries, to the "optical telegraph" that French engineer Claude Chappe invented in the 1790s. His system was a series of semaphores mounted on towers, where human operators relayed messages from one tower to the next. It beat hand-carried messages hands down, but by the mid-19th century was replaced by the electric telegraph, leaving a scattering of "Telegraph Hills" as its most visible legacy.

Alexander Graham Bell patented an optical telephone system, which he called the Photophone, in 1880, but his earlier invention, the telephone, proved far more practical. He dreamed of sending signals through the air, but the atmosphere didn't transmit light as reliably as wires carried electricity. In the decades that followed, light was used for a few special applications, such as signaling between ships, but otherwise optical communications, like the experimental Photophone Bell donated to the Smithsonian Institution, languished on the shelf.

In the intervening years, a new technology slowly took root that would ultimately solve the problem of optical transmission, although it was a long time before it was adapted for communications. It depended on the phenomenon of total internal reflection, which can confine light in a material surrounded by other materials with lower refractive index, such as glass in air. In the 1840s, Swiss physicist Daniel Collodon and French physicist Jacques Babinet showed that light could be guided along jets of water for fountain displays. British physicist John Tyndall popularized light guiding in a demonstration he first used in 1854, guiding light in a jet of water flowing from a tank. By the turn of the century, inventors realized that bent quartz rods could carry light, and patented them as dental illuminators. By the 1940s, many doctors used illuminated plexiglass tongue depressors.

Optical fibers went a step further. They are essentially transparent rods of glass or plastic stretched so they are long and flexible. During the 1920s, John Logie Baird in England and Clarence W. Hansell in the United States patented the idea of using arrays of hollow pipes or transparent rods to transmit images for television or facsimile systems. However, the first person known to have demonstrated image transmission through a bundle of optical fibers was Heinrich Lamm, than a medical student in Munich. His goal was to look inside inaccessible parts of the body, and in a 1930 paper he reported transmitting the image of a light bulb filament through a short bundle. However, the unclad fibers transmitted images poorly, and the rise of the Nazis forced Lamm, a Jew, to move to America and abandon his dreams of becoming a professor of medicine.

In 1951, Holger Moller [or Moeller, the o has a slash through it] Hansen applied for a Danish patent on fiber-optic imaging. However, the Danish patent office denied his application, citing the Baird and Hansell patents, and Møller Hansen was unable to interest companies in his invention. Nothing more was reported on fiber bundles until 1954, when Abraham van Heel of the Technical University of Delft in Holland and Harold. H. Hopkins and Narinder Kapany of Imperial College in London separately announced imaging bundles in the prestigious British journal Nature.

Neither van Heel nor Hopkins and Kapany made bundles that could carry light far, but their reports the fiber optics revolution. The crucial innovation was made by van Heel, stimulated by a conversation with the American optical physicist Brian O'Brien. All earlier fibers were "bare," with total internal reflection at a glass-air interface. van Heel covered a bare fiber or glass or plastic with a transparent cladding of lower refractive index. This protected the total-reflection surface from contamination, and greatly reduced crosstalk between fibers. The next key step was development of glass-clad fibers, by Lawrence Curtiss, then an undergraduate at the University of Michigan working part-time on a project to develop an endoscope to examine the inside of the stomach with physician Basil Hirschowitz, physicist C. Wilbur Peters. (Will Hicks, then working at the American Optical Co., made glass-clad fibers at about the same time, but his group lost a bitterly contested patent battle.) By 1960, glass-clad fibers had attenuation of about one decibel per meter, fine for medical imaging, but much too high for communications.

Meanwhile, telecommunications engineers were seeking more transmission bandwidth. Radio and microwave frequencies were in heavy use, so they looked to higher frequencies to carry loads they expected to continue increasing with the growth of television and telephone traffic. Telephone companies thought video telephones lurked just around the corner, and would escalate bandwidth demands even further. The cutting edge of communications research were millimeter-wave systems, in which hollow pipes served as waveguides to circumvent poor atmospheric transmission at tens of gigahertz, where wavelengths were in the millimeter range.

Even higher optical frequencies seemed a logical next step in 1958 to Alec Reeves, the forward-looking engineer at Britain's Standard Telecommunications Laboratories who invented digital pulse-code modulation before World War II. Other people climbed on the optical communications bandwagon when the laser was invented in 1960. The July 22, 1960 issue of Electronics magazine introduced its report on Theodore Maiman's demonstration of the first laser by saying "Usable communications channels in the electromagnetic spectrum may be extended by development of an experimental optical-frequency amplifier."

Serious work on optical communications had to wait for the continuous wave helium-neon laser. While air is far more transparent at optical wavelengths than to millimeter waves, researchers soon found that rain, haze, clouds, and atmospheric turbulence limited the reliability of long-distance atmospheric laser links. By 1965, it was clear that major technical barriers remained for both millimeter-wave and laser telecommunications. Millimeter waveguides had low loss, although only if they were kept precisely straight; developers thought the biggest problem was the lack of adequate repeaters. Optical waveguides were proving to be a problem. Stewart Miller's group at Bell Telephone Laboratories was working on a system of gas lenses to focus laser beams along hollow waveguides for long-distance telecommunications. However, most of the telecommunications industry thought the future belonged to millimeter waveguides.

Optical fibers had attracted some attention because they were analogous in theory to plastic dielectric waveguides used in certain microwave applications. In 1961, Elias Snitzer at American Optical, working with Hicks at Mosaic Fabrications (now Galileo Electro-Optics), demonstrated the similarity by drawing fibers with cores so small they carried light in only one waveguide mode. However virtually everyone considered fibers too lossy for communications; attenuation of a decibel per meter was fine for looking inside the body, but communications operated over much longer distances, and required loss no more than 10 or 20 decibels per kilometer.

One small group did not dismiss fibers so easily a team at Standard Telecommunications Laboratories initially headed by Antoni E. Karbowiak, which worked under Reeves to study optical waveguides for communications. Karbowiak soon was joined by a young engineer born in Shanghai, Charles K. Kao.

Kao took a long, hard look at fiber attenuation. He collected samples from fiber makers, and carefully investigated the properties of bulk glasses. His research convinced him that the high losses of early fibers were due to impurities, not to silica glass itself. In the midst of this research, in December 1964, Karbowiak left STL to become chair of electrical engineering at the University of New South Wales in Australia, and Kao succeeded him as manager of optical communications research. With George Hockham, another young STL engineer who specialized in antenna theory, Kao worked out a proposal for long-distance communications over single-mode fibers. Convinced that fiber loss should be reducible below 20 decibels per kilometer.

"According to Dr. Kao, the fiber is relatively strong and can be easily supported. Also, the guidance surface is protected from external influences. ... the waveguide has a mechanical bending radius low enough to make the fiber almost completely flexible. Despite the fact that the best readily available low-loss material has a loss of about 1000 dB/km, STL believes that materials having losses of only tens of decibels per kilometer will eventually be developed."

Kao and Hockham's detailed analysis was published in the July 1966 Proceedings of the Institution of Electrical Engineers. Their daring forecast that fiber loss could be reduced below 20 dB/km attracted the interest of the British Post Office, which then operated the British telephone network. F. F. Roberts, an engineering manager at the Post Office Research Laboratory (then at Dollis Hill in London), saw the possibilities, and persuaded others at the Post Office. His boss, Jack Tillman, tapped a new research fund of 12 million pounds to study ways to decrease fiber loss.

With Kao almost evangelically promoting the prospects of fiber communications, and the Post Office interested in applications, laboratories around the world began trying to reduce fiber loss. It took four years to reach Kao's goal of 20 dB/km, and the route to success proved different than many had expected. Most groups tried to purify the compound glasses used for standard optics, which are easy to melt and draw into fibers. At the Corning Glass Works (now Corning Inc.), Robert Maurer, Donald Keck and Peter Schultz started with fused silica, a material that can be made extremely pure, but has a high melting point and a low refractive index. They made cylindrical performs by depositing purified materials from the vapor phase, adding carefully controlled levels of dopants to make the refractive index of the core slightly higher than that of the cladding, without raising attenuation dramatically. In September 1970, they announced they had made single-mode fibers with attenuation at the 633-

nanometer helium-neon line below 20 dB/km. The fibers were fragile, but tests at the new British Post Office Research Laboratories facility in Martlesham Heath confirmed the low loss.

The Corning breakthrough was among the most dramatic of many developments that opened the door to fiber-optic communications. In the same year, Bell Labs and a team at the Ioffe Physical Institute in Leningrad (now St. Petersburg) made the first semiconductor diode lasers able to emit continuous-wave at room temperature. Over the next several years, fiber losses dropped dramatically, aided both by improved fabrication methods and by the shift to longer wavelengths where fibers have inherently lower attenuation.

Early single-mode fibers had cores several micrometers in diameter, and in the early 1970s that bothered developers. They doubted it would be possible to achieve the micrometer-scale tolerances needed to couple light efficiently into the tiny cores from light sources, or in splices or connectors. Not satisfied with the low bandwidth of step-index multimode fiber, they concentrated on multi-mode fibers with a refractive-index gradient between core and cladding, and core diameters of 50 or 62.5 micrometers. The first generation of telephone field trials in 1977 used such fibers to transmit light at 850 nanometers from gallium-aluminum-arsenide laser diodes.

Those first-generation systems could transmit light several kilometers without repeaters, but were limited by loss of about 2 dB/km in the fiber. A second generation soon appeared, using new In GaAsP lasers which emitted at 1.3 micrometer, where fiber attenuation was as low as 0.5 dB/km, and pulse dispersion was somewhat lower than at 850 nm. Development of hardware for the first transatlantic fiber cable showed that single-mode systems were feasible, so when deregulation opened the long-distance phone market in the early 1980s, the carriers built national backbone systems of single-mode fiber with 1300-nm sources. That technology has spread into other telecommunication applications, and remains the standard for most fiber systems.

However, a new generation of single-mode systems is now beginning to find applications in submarine cables and systems serving large numbers of subscribers. They operate at 1.55 micrometers, where fiber loss is 0.2 to 0.3 dB/km, allowing even longer repeater spacings. More important, erbium-doped optical fibers can serve as optical amplifiers at that wavelength, avoiding the need for electro-optic regenerators. Submarine cables with optical amplifiers can operate at speeds to 5 gigabits per second, and can be upgraded from lower speeds simply to changing terminal electronics. Optical amplifiers also are attractive for fiber systems delivering the same signals to many terminals, because the fiber amplifiers can compensate for losses in dividing the signals among many terminals.

The biggest challenge remaining for fiber optics is economic. Today telephone and cable television companies can cost-justify installing fiber links to remote sites serving tens to a few hundreds of customers. However, terminal equipment remains too expensive to justify installing fibers all the way to homes, at least for present services. Instead, cable and phone companies run twisted wire pairs or coaxial cables from optical network units to individual homes. Time will see how long that lasts.

1.2 The Basic Network:

Our current "age of technology" is the result of many brilliant inventions and discoveries, but it is our ability to transmit information, and the media we use to do it, that is perhaps most responsible for its evolution. Progressing from the copper wire of a century ago to today's fiber optic cable, our increasing ability to transmit more information, more quickly and over longer distances has expanded the boundaries of our technological development in all areas.

Today's low-loss glass fiber optic cable offers almost unlimited bandwidth and unique advantages over all previously developed transmission media. The basic point-to-point fiber optic transmission system consists of three basic elements: the optical transmitter, the fiber optic cable and the optical receiver.

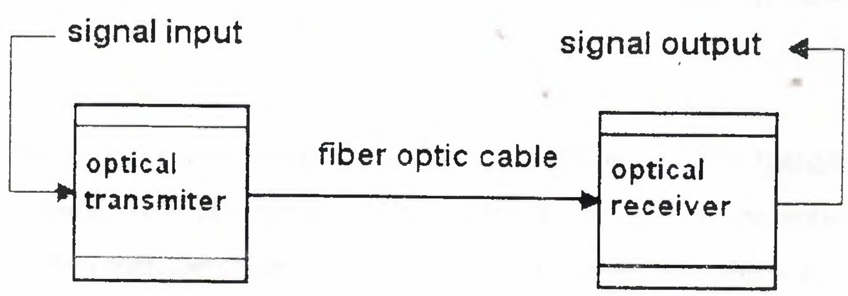

Figure 1.1 The Basic Network

(a) The Optical Transmitter:

The transmitter converts an electrical analog or digital signal into a corresponding optical signal. The source of the optical signal can be either a light emitting diode, or a solid state laser diode. The most popular wavelengths of operation for optical transmitters are 850, 1300, or 1550 nanometers.

(b) The Fiber Optic Cable:

The cable consists of one or more glass fibers, which act as waveguides for the optical signal. Fiber optic cable is similar to electrical cable in its construction, but provides special protection for the optical fiber within. For systems requiring transmission over distances of many kilometers, or where two or more fiber optic cables must be joined together, an optical splice is commonly used.

(c) The Optical Receiver:

The receiver converts the optical signal back into a replica of the original electrical signal. The detector of the optical signal is either a PIN-type photodiode or avalanche-type photodiode.

1.3 Advantages of Optical Fiber Networking:

Networking using an optical carrier wave guided along a glass fiber has a number of extremely attractive feature, several of which were apparent when the technique was originally conceived. Furthermore, the advances in the technology to date have surpassed even the most optimistic predictions, creating additional advantages. The following are the advantages which can be described for fiber optical networking.

(a) Enormous potential bandwidth:

The optical carrier frequency in the range 10^{13} to 10^{16} Hz (generally in the near infrared around 10^{14} Hz or 10^{5} GHz) yields a far greater potential transmission bandwidth than metallic cable systems (i.e. coaxial cable bandwidth up to around 500 MHz) or even millimeter wave radio systems (i.e. systems currently operating with modulation bandwidths of 700 MHz). At present, the bandwidth available to fiber systems is not fully utilized but modulation at several gigahertz over a hundred kilometers and hundreds of megahertz over three hundred kilometers without intervening electronics (repeaters) is possible. Therefore, the information-carrying capacity of optical fiber systems has proved far superior to the best copper cable systems. By comparison the losses in wideband coaxial cable systems restrict the transmission distance to only a few kilometers at bandwidths over one hundred megahertz.

Although the usable fiber bandwidth will be extended further towards the optical carrier frequency, it is clear that this parameter is limited by the use of a single optical carrier signal. Hence a much enhanced bandwidth utilization for an optical fiber can be achieved by transmitting several optical signals, each at different center wavelengths, in parallel on the same fiber. This wavelength division multiplexed operation, particularly with dense packing of the optical wavelengths (or, essentially, fine frequency spacing), offers the potential for a fiber information-carrying capacity which is many orders of magnitude in excess of that obtained using copper cables or a wideband radio system.

(b) *Small size and weight:*

Optical fibers have very small diameters which are often no greater than the diameter of a human hair. Hence, even when such fibers are covered with protective coatings they are far smaller and much lighter than corresponding copper cables. This is a tremendous boon towards the alleviation of duct congestion in cities, as well as allowing for an expansion of signal transmission within mobiles such as aircraft, satellites and even ships.

(c) *Electrical isolation:*

Optical fibers which are fabricated from glass, or sometimes a plastic polymer, are electrical insulators and therefore, unlike their metallic counterparts, they do not exhibit earth loop and interface problems. Furthermore, this property makes optical fiber transmission ideally suited for communication in electrically hazardous environments as the fibers create no arcing or spark hazard at abrasions or short circuits.

(d) *Immunity to interference and cross-talk:*

Optical fibers form, a dielectric waveguide and are therefore free from electromagnetic interference (EMI), radiofrequency interference (RFI), or switching transients giving electromagnetic Pulses(EMP). Hence operation of an optical fiber communication system is unaffected by transmission through an electrically noisy environment and the fiber cable requires no_shielding from EMI. The fiber cable is also not susceptible to lightning strikes if used overhead rather than underground. Moreover, it is fairly easy to ensure that there is no optical interference between fibers and hence, unlike communication using electrical conductors, crosstalk is negligible, even when many fibers are cabled together.

(e) Signal security:

The light from optical fibers does not radiate significantly and therefore they provide a high degree of signal security. Unlike the situation with copper cables, a transmitted optical signal cannot be obtained from a fiber in a noninvasive manner (i.e. without drawing optical power from the fiber). Therefore, in theory, any attempt to acquire a message signal transmitted optically may be detected. This feature is obviously attractive for military, banking and general data transmission (i.e. computer network) applications.

(f) Low transmission loss:

The development of optical fibers over the last twenty years has resulted in the production of optical fiber cables which exhibit very low attenuation or transmission loss in comparison with the best copper conductors. Fibers have been fabricated with losses as low as 0.2 $dBkm^{-1}$ and this feature_has become a major advantage of optical fiber communications. It facilitates the implementation of communication links with extremely wide repeater spacing (long transmission distances without intermediate electronics), thus reducing both system cost and complexity. Together with the already proven modulation bandwidth capability of fiber cable this property provides a totally compelling case for the adoption-of optical fiber communication in the majority of long-haul telecommunication applications.

(g) Ruggedness and flexibility:

Although protective coatings are essential, optical fibers may be manufactured with very high tensile strengths. Perhaps surprisingly for a glassy substance, the fibers may also be bent to quite small radii or twisted without damage. Furthermore, cable structures have been developed which have proved flexible, compact and extremely rugged. Taking the size and weight advantage into account, these optical fiber cables are generally superior in terms of storage, transportation, handling and installation to corresponding copper cables, whilst exhibiting at least comparable strength and durability.

(h) System reliability and ease of maintenance:

These features primarily stem from the low loss property of optical fiber cables which reduces the requirement for intermediate repeaters or line amplifiers to boost the transmitted signal strength. Hence with fewer repeaters, system reliability is generally enhanced in comparison with conventional electrical-conductor systems. Furthermore, the reliability of the optical components is no longer a problem with predicted lifetimes of 20 to 30 years now quite common. Both these factors also tend to reduce maintenance time and costs.

(i) Potential low cost:

The glass, which generally provides the optical fiber transmission medium, is made from sand not a scarce resource. So, in comparison with copper conductors, optical fibers offer the potential for low cost line communication. Although over recent years this potential has largely been realized in the costs of the optical fiber transmission medium which for bulk purchases is now becoming competitive with copper wires (i.e. twisted pairs), it has not yet been achieved in all the other component areas associated with optical fiber communication~. For example, the costs of high performance semiconductor lasers and detector photodiodes are still relatively high, as well as some of those concerned with the connection technology (demountable connectors, couplers, etc.).

Overall system costs when utilizing optical fiber communication on long-haul links, however, are substantially less than those for equivalent electrical line systems because of the low loss and wideband properties of the optical transmission medium. As described before the requirement for intermediate repeaters and the associated electronics is reduced, giving a substantial cost advantage. Although this cost benefit gives a net gain for long-haul links it is not always the case in short-haul applications where the additional cost incurred, due to the electrical optical conversion (and vice versa), may be a deciding factor. Nevertheless, there are other possible cost advantages in relation to shipping, handling, installation and maintenance.

The reducing cost of optical fiber communications has not only provided strong competition with electrical line transmission systems, but also for microwave and.

millimeter wave radio transmission systems. Although these systems are reasonably wideband the relatively short span 'line of sight' transmission necessitates expensive aerial towers at intervals no greater than a few tens of kilometers. Hence optical fiber is fast becoming the dominant transmission medium within the major industrialized societies.

Many advantages are therefore provided by the use of a lightwave carrier within a transmission medium consisting of an optical fiber. The fundamental principles giving rise to these enhanced performance characteristics, together with their practical realization, are described in the following chapters. However, a general understanding of the basic nature and properties of light is assumed

1.4 Fiber Optic Safety:

The safety issues for fiber optics are not what everyone thinks of first: getting your eyeball burned out by laser light in a fiber. Most fiber optic systems have power levels too low to do any damage. In addition, the light is coming out of the fiber in an expanding cone, meaning the further away the end of the fiber is, the less the danger. Most systems also operate with light over 1000 nm wavelength, where the liquid in your eye absorbs the light heavily, preventing retinal damage. First of all, most of the light is invisible to the human eye, so you can't see anything anyway. Secondly, if it is high enough power to be a problem, the damage is likely irreversible. So don't look into fibers! Use a power meter to see if power is present, especially if looking at the end of a connector with a microscope.

The two major safety issues are proper disposal of the glass shards created by cleaving the fiber or accidentally breaking it and the cleaning chemicals and adhesives used. While working with fiber optics always wear safety glasses with side shields. Treat fiber optic splinters the same as you would glass splinters. So do not touch your eyes while working with fiber optic systems until your hands have been thoroughly cleaned.

CHAPTER 2

OPTICAL FIBER NETWORK

The transfer of information in the form of light propagating within an optical fiber requires the successful implementation of an optical fiber networking. This network, in common with all networks, is composed of a number of discrete component which are connected together in a manner that enables them to perform a desired task. Hence, to achieve reliable and secure network using optical fibers it is essential that all the components within the transmission system are compatible so that their individual performances, as far as possible, enhance rather than degrade the overall system performance.

The principal components of a general optical fiber communication system for either digital or analog transmission are shown in the system block schematic of figure 2.1. The transmit terminal equipment consists of an information encoder or signal shaping circuit preceding a modulation or electronic driver stage which operates the optical source. Light emitted from the source is launched into an optical fiber incorporated within a cable which constitutes the transmission medium. The light emerging from the far end of the transmission medium is converted back into an electrical signal by an optical detector positioned at the input of the receive terminal equipment. This electrical signal is then amplified prior to decoding or demodulation in order to obtain the information originally transmitted.

The operation and characteristics of the optical components of this general system have been discussed in some detail within the preceding chapters. However, to enable the successful incorporation of these components into an optical fiber communication system it is necessary to consider the interaction of one component with another, and then to evaluate the overall performance of the system. Furthermore, to optimize the system performance for a given application it is often helpful to offset a particular component characteristic by trading it off against the performance of another component, in order to provide a net gain within the overall system. The electronic components play an important role in this context, allowing the system designer further choices which, depending on the optical components utilized, can improve the system performance.

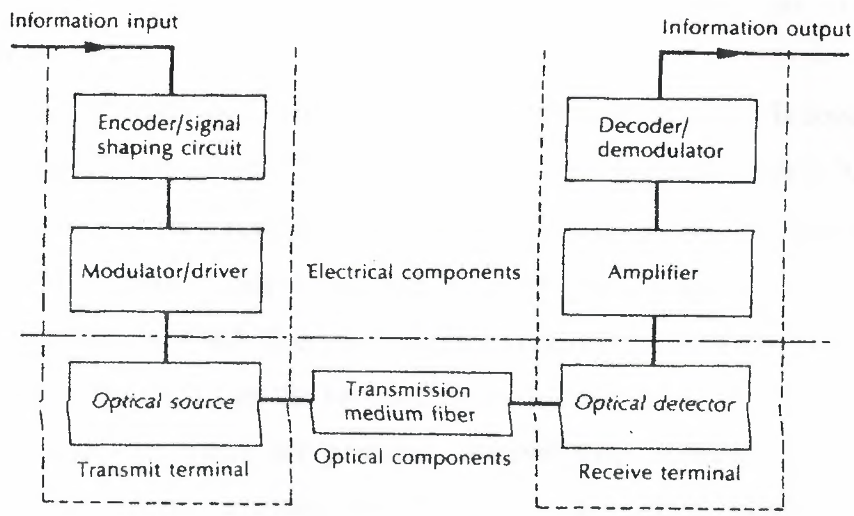

Figure 2.1 The principal component of an optical fiber network

2.1 Optical fibers cables:

In order to plan the use of optical fibers in a variety of line communication applications it is necessary to consider the various optical fibers currently available.

The following is a summary of the dominant optical fiber types with an indication of their general characteristics. The performance characteristics of the various fiber types discussed vary considerably depending upon the materials used in the fabrication process and the preparation technique involved. The values quoted are based upon both manufacturers' and suppliers' data, and practical descriptions for commercially available fibers, presented in a general form rather than for specific fibers. Hence in some cases the fibers may appear to have somewhat poorer performance characteristics than those stated for the equivalent fiber types produced by the best possible techniques and in the best possible conditions.

This section therefore reflects the relative maturity of the technology associated with the production of both multi-component and silica glass fibers. In particular, high performance silica-based fibers for operation in three major wavelength regions (0.8 to 0 9, 1.3 and 1.55 μm) are now widely commercially available. Moreover, complex refractive index profile single-mode fibers, including dispersion modified fibers and polarization maintaining fibers, are also commercially available and in the former case are starting to find system application within communications. Nevertheless, in this section we concentrate on the conventional circularly symmetric step index design which remains at present the major single-mode fiber provision within telecommunications.

Another relatively new area of commercial fiber development is concerned with mid-infrared wavelength range (2 to 5 μm), often employing heavy metal fluoride glass technology. However, the fiber products that exist for this wavelength region tend to be multimode with relatively high losses and hence at present are only appropriate for specialized applications. Such fibers are therefore considered no further in this section. Finally, it should be noted that the bandwidths quoted are specified over a 1 km length of fiber (i.e. $B_{opt} * L$). These are generally obtained from manufacturers' data which does not always indicate whether the electrical or the optical bandwidth has been measured. It is likely that these are in fact optical bandwidths which are significantly greater than their electrical equivalents.

2.1.1 Types of fiber optical cables:

Generally there are two main optical fiber categories with distinctive operational attributes are multimode and single-mode fibers. Within the multimode category, another important characteristic is between step index and graded index. Further definition of fibers relates to physical size, optical performance, coatings and strength.

All fibers consist of a number of substructures including:

A core, which carries most of the light, surrounded by a cladding, which bends the light and confines it to the core, surrounded by a substrate layer (in some fibers) of glass which does not carry light, but adds to the diameter and strength of the fiber, covered by a primary buffer coating, which provides the first layer of mechanical protection, covered by a secondary buffer coating, which protects the relatively fragile primary coating and the underlying fiber.

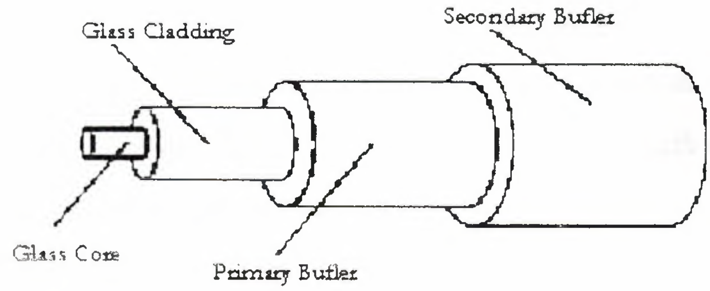

Figure 2.2 Configuration of Fiber Optical cable

Multimode step index fibers:

Multimode step index fibers may be fabricated from either multi-component glass compounds or doped silica. These fibers can have reasonably large core diameters and large numerical apertures to facilitate efficient coupling to incoherent light sources such as light emitting diodes (LEDs). The performance characteristics of this fiber type may vary considerably depending on the materials used and the method of preparation; the doped silica fibers exhibit the best performance. Multi-component glass and doped silica fibers are often referred to as multi-component glass/glass (glass-clad glass) and silica/silica (silica-clad silica), respectively, although the glass-clad glass terminology is sometimes used somewhat vaguely to denote both types. A typical structure for a glass multimode step index fiber is shown in Figure 2.3

Structure:

Core diameter:	50 to 400 μm
Cladding diameter:	125 to 500 μm
Buffer jacket diameter:	250 to 1000 μm
Numerical aperture:	0.16 to 0.5.

Performance characteristics:

Attenuation:

2.6 to 50 $dBkm^{-1}$ at a wavelength of 0.85 μm, limited by absorption or scattering. The wide variation in attenuation is due to the large differences both within and between the two overall preparation methods (melting and deposition). To illustrate this point Figure 2.4 shows the attenuation spectra from suppliers' data for a multi-component glass fiber (glass-clad glass) and a doped silica fiber (silica-clad silica). It may be observed that the multi-component glass fiber has an attenuation of around 40 $dBkm^{-1}$ at a wavelength of 0.85 μm, whereas the doped silica fiber has an attenuation of less than 5 dB km at a similar wavelength. Furthermore, at a wavelength of 1.3 μm losses reduced to around 0.4 $dBkm^{-1}$ can be obtained.

Bandwidth:

6 to 50 MHz km.

Applications:

These fibers are best suited for short-haul, limited bandwidth and relatively low cost applications.

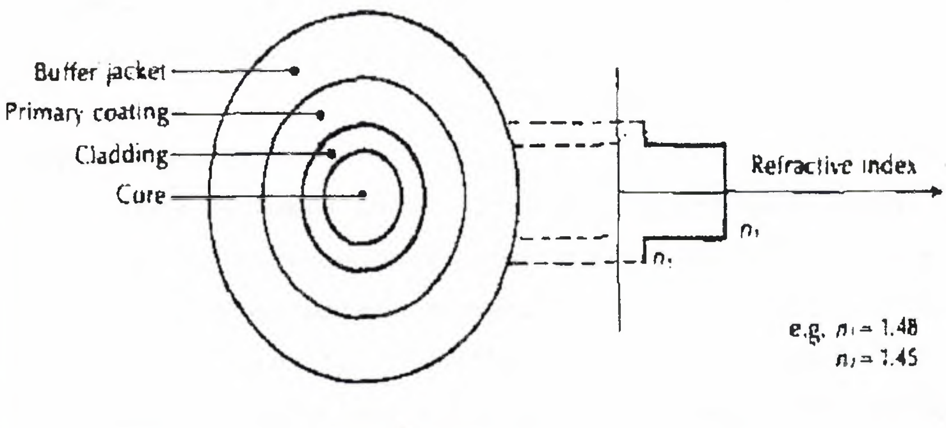

Figure 2.3 Typical structure for a glass multimode step index fiber.

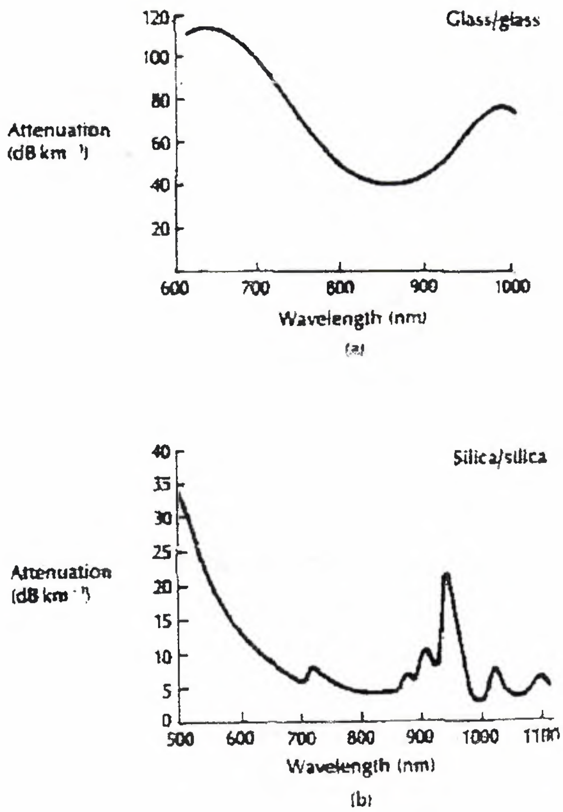

Figure 2.4 Attenuation spectra for multimode step index fibers: (a) multi-component glass fiber; (b) doped silica fiber. Reproduced with the permission of Ray Proof.

Multimode graded index fibers:

These multimode fibers which have a graded index profile may also be fabricated using multi-component glasses or doped silica. However, they tend to be manufactured from materials with higher purity than the majority of multimode step index fibers in order to reduce fiber losses. The performance characteristics of multimode graded index fibers are therefore generally better than those for multimode step index fibers due to the index grading and lower attenuation. Multimode graded index fibers tend to have smaller core diameters than multimode step index fibers, although the overall diameter including the buffer jacket is usually about the same. This gives the fiber greater rigidity to resist bending. A typical structure is illustrated in Figure 2.5.

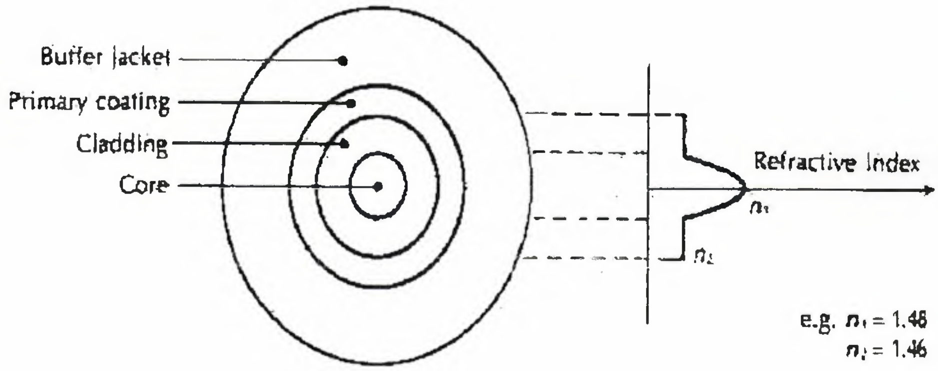

Figure 2.5 Typical structure for a glass multimode graded index fiber.

Structure:

Core diameter:	30 to 100 μ m
Cladding diameter:	100 to 150 μ m,
Buffer jacket diameter:	250 to 1000 μ m.
Numerical aperture:	0.2 to 0.3 μ m.

Although the above general parameters encompass most of currently available multimode graded index fibers, in particular the following major groups have now emerged:

(a) 50 μ m/125 μ m (core-cladding) diameter fibers with typical numerical apertures between 0.20 and 0.24. These fibers were originally developed and standardized by the CCITT for telecommunication applications at wavelengths of 0.85 and 1.3 μ m but now they are mainly utilized within data links and local area networks (LANs).

(b) 62.5 μ m/125 μ m (core-cladding) diameter fibers with typical numerical apertures between 0.26 and 0.29. Although these fibers were developed for longer distance subscriber loop applications at operating wavelengths of 0.85 and 1.3 μ m, they are now mainly used within LANs.

(c) 85 μ m/125 μ m (core-cladding) diameter fibers with typical numerical apertures 0.26 and 0.30. These fibers were developed for operation at wavelengths of 0.85 and 1.3 μ m in short-haul systems and LANs.

(d) $100\,\mu$ m /$125\,\mu$ m (core-cladding) diameter fibers with a numerical aperture of 0.29. These fibers were developed to provide high coupling efficiency to LEDs at a wavelength of $0.85\,\mu$ m in low cost, short distance applications. They can, however, be utilized at the $1.3\,\mu$ m operating wavelength and have therefore also found application within LANs.

Performance characteristics:

Attenuation:

2 to 10 $dBkm^{-1}$ at a wavelength of $0.85\,\mu$ m with generally a scattering limit. Average losses of around 0.4 and 0.25 $dBkm^{-1}$ can be obtained at wavelengths of 1.3 and $1.55\,\mu$ m respectively.

Bandwidth:

300 MHz km to 3GHz km.

Applications:

These fibers are best suited for medium-haul, medium to high bandwidth applications using incoherent and coherent multimode sources (i.e. LEDs and injection lasers respectively).

It is useful to note that there are a number of partially graded index fibers commercially available. These fibers generally exhibit slightly better performance characteristics than corresponding multimode step index fibers but are somewhat inferior to the fully graded index fibers described above.

Single-mode fibers:

Single-mode fibers can have either a step index or graded index profile. The benefits of using a graded index profile are to provide dispersion modified single-mode fibers. The more sophisticated single-mode fiber structures used to produce polarization maintaining fibers make these fibers quite expensive at present and thus they are not generally utilized within optical fiber communication systems. Therefore at present, commercially available single-mode fibers are still usually step index. They are high quality fibers for wideband, long-haul transmission and are generally fabricated from doped silica (silica-clad silica) in order to reduce attenuation.

Although single-mode fibers have small core diameters to allow single-mode propagation, the cladding diameter must be at least ten times the core diameter to avoid losses from the evanescent field. Hence with a buffer jacket to provide protection and strength, single-mode fibers have similar overall diameters to multimode fibers. A typical example of a single-mode step index fiber is shown in Figure 2.6

Structure:

Core diameter:	5 to 10 μ m, typically around 8.5 μ m
Cladding diameter:	generally 125 μ m
Buffer jacket diameter:	250 to 1000 μ m
Numerical aperture:	0.08 to 0.15, usually around 0.10.

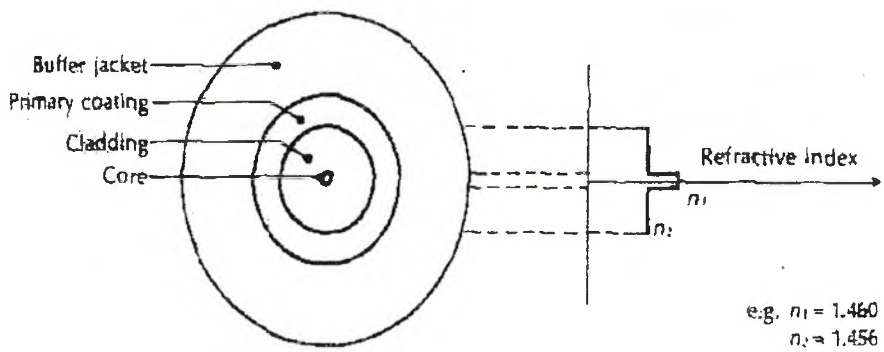

Figure 2.6 Typical structure for a silica single-mode step index fiber.

Performance characteristics:

Attenuation:

2 to 5 dBkm^{-1} with a scattering limit of around 1 dBkm^{-1} at a wavelength of 0.85 μ m. In addition, average losses of 0.35 and 0.21 dBkm^{-1} at wavelengths of 1.3 and 1.55 μ m can be obtained in a manufacturing environment.

Bandwidth:

Greater than 500 MHz km. In theory the bandwidth is limited by waveguide and material dispersion to approximately 40 GHz km at a wavelength of 0.85 μ m. However, practical bandwidths in excess of 10 GHz km are obtained at a wavelength of 1.3 μ m.

Applications:

These fibers are ideally suited for high bandwidth very long-haul applications using single-mode injection laser sources.

Plastic-clad fibers:

Plastic-clad fibers are multimode and have either a step index or a graded index profile. They have a plastic cladding (often a silicone rubber) and a glass core which is frequently silica (i.e. plastic clad silica—PCS fibers). The PCS fibers exhibit lower radiation-induced losses than silica-clad silica fibers and, therefore, have an improved performance in certain environments. Plastic-clad fibers are generally slightly cheaper than the corresponding glass fibers, but usually have more limited performance characteristics. A typical structure for a step index plastic-clad fiber (which is more common) is shown in Figure 2.7

Structure:

Core diameter:	Step index	100 to 500 μ m
	Graded index	50 to 100 μ m
Cladding diameter:	Step index	300 to 800 μ m
	Graded index	125 to 150 μ m
Buffer Jacket diameter:	Step index	500 to1000 μ m
	Graded index	250 to 1000 μ m
Numerical aperture:	Step index	0.2 to 0.5
	Graded index	0.2 to 0.3.

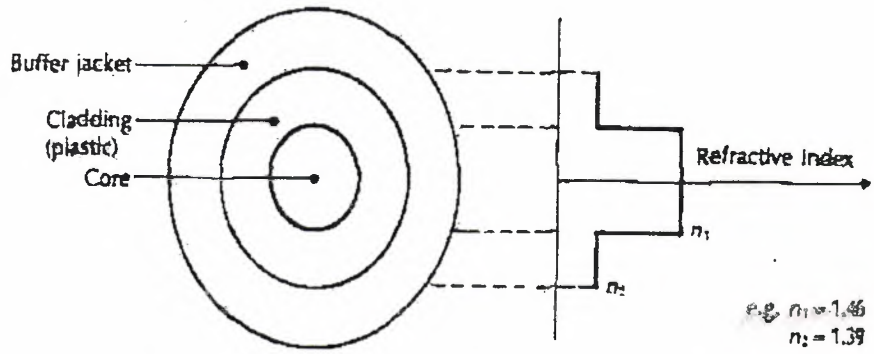

Figure 2.7 Typical structure for a plastic-clad silica multimode step index fiber.

Performance characteristics:

Attenuation:

Step index	5 to 50 $dBkm^{-1}$
Graded index	4 to 15 $dBkm^{-1}$

Plastic Optical Fiber (POF):

Plastic optical fiber (POF) has always been "lurking in the background" in fiber optics; a specialty fiber useful for illumination and low speed short data links. There is now a greatly increased interest in POF, as R&D has given it higher performance to go along with its ease of installation and low cost.

POF is large core step-index fiber with a typical diameter of 1 mm. This large size makes it easy to couple lots of light from sources and connectors do not need to be high precision. As a result, typical connector costs are 10-20% as much as for glass fibers and termination may be as easy as cutting with a razor blade! Being plastic, its also rugged and easy to install without fear of damage.

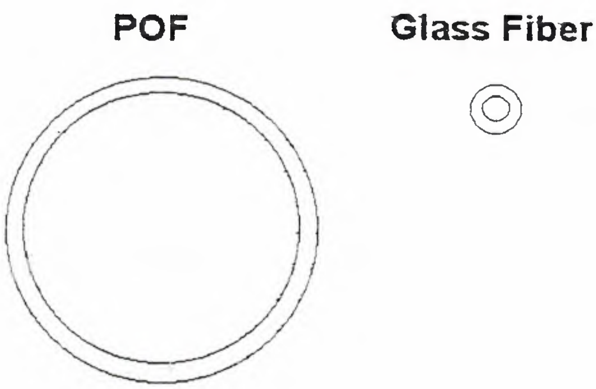

Figure 2.8 Structure of Plastic Optical Fiber

From an optical standpoint, conventional POF is much lower in performance than glass fiber. It has a loss of 0.15-0.2 dB per meter at 650 nm and its bandwidth is limited by its large NA and step-index profile. However, it is adequate for running short links, such as inside of instruments or within a room for desktop connections up to 50 meters. And of course in automobiles, where it has gained a foothold.

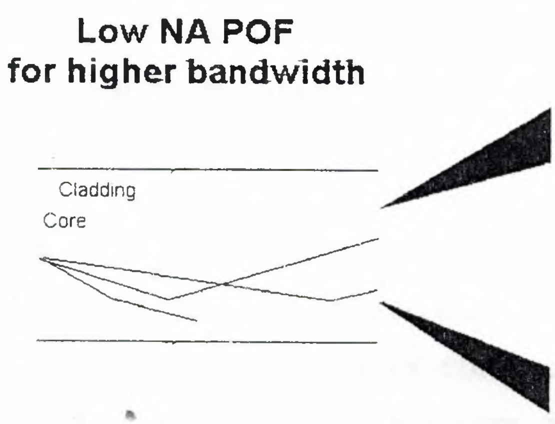

Figure 2.9 illustrating POF

But recent developments in POF technology have led to low NA POF that offers higher bandwidth and graded-index POF (GI-POF) that combines the higher bandwidth of graded-index fiber with the low cost of POF. Current designs of GI-POF offer up to 2 Ghz bandwidth at distances of 100 meters, but manufacturing problems have hampered its adoption. Recent developments in a new laser (VCSEL of vertical cavity surface emitting laser) promise extremely low cost, high power, high speed transmitters.

POF offers promise for desktop LAN connections. It can be installed in minutes with minimal tools and training. Bandwidth exceeds anyones estimates for the next decade. Prices are competitive with copper. Standards groups are now looking at options for POF.

2.2 Transmission Characteristics of Optical Fibers:

There are number of factors which effect the performance of optical fibers as a transmission medium. These transmission characteristics are of utmost importance when the suitability of optical fibers for communication purposes is investigates. The transmission characteristics of most interest are-those of attenuation (or loss) and bandwidth; The huge potential bandwidth of optical communications helped stimulate the birth of the idea that a dielectric waveguide made of glass could be used to carry wideband telecommunication signals. However, at the time the idea may have seemed somewhat ludicrous as a typical block of glass could support optical transmission for at best a few tens of meters before it was attenuated to an unacceptable level. Nevertheless, careful investigation of the attenuation showed that it was largely due to absorption in the glass, caused by impurities such as iron, copper, manganese and other transition metals which occur in the third row of the periodic table. Hence, research was stimulated towards a new generation of 'pure' glasses for use in optical fiber communications.

A major breakthrough came in 1970 when the first fiber with an attenuation below 20 $dBkm^{-1}$ was reported. This level of attenuation was seen as the absolute minimum that had to be achieved before an optical fiber system could in any way compete economically with existing communication systems. Since 1970 tremendous improvements have been made, leading to silica-based glass fibers with losses of less than 0.2 dB km^{-1} in the laboratory. Hence, comparatively low loss fibers have been incorporated into optical communication systems throughout the world. Moreover, as the fundamental lower limits for attenuation silicate glass fibers have virtually been achieved, activities are increasing in relation to the investigation of other material systems which may exhibit substantially lower losses when operated at longer wavelengths. Such mid-infrared (and possibly far-infrared) transmitting fibers could eventually provide for extremely long-haul repeater-less communication assuming that, in addition to the material considerations, the optical source and detector requirements can be satisfactorily met.

The other characteristic of primary importance is the bandwidth of the fiber. This is limited by the signal dispersion within the fiber, which determines the number of bits of information transmitted in a given time period. Therefore, once the .attenuation was reduced to acceptable levels attention was directed towards the dispersive properties of fibers. Again this is has led to substantial improvements, giving wideband fiber bandwidths of many tens of gigahertz over a number of .kilometers,

2.2.1 Attenuation:

The attenuation or transmission loss of optical fibers has proved to be one of the most important factors in bringing about their wide acceptance in telecommunications. As channel attenuation largely determined the maximum transmission distance prior to signal restoration, optical fiber communications became especially attractive when the transmission losses of fibers were reduced below those of the competing metallic conductors (less than 5 $dBkm^{-1}$).

Signal attenuation within optical fibers, as with metallic conductors, is usually expressed in the logarithmic unit of the decibel. The decibel, which is used for comparing two power levels, may be defined for a particular optical wavelength as the ratio of the input (transmitted) optical power P_I into a fiber to the output (received) optical power P_o from the fiber as:

$$\text{Number of decibels (dB)} = 10 \log_{10} \frac{P_i}{P_o}$$

This logarithmic unit has the advantage that the operations of multiplication and division reduce to addition and subtraction, whilst powers and roots reduce to multiplication and division. However, addition and subtraction require a conversion to numerical values which may be obtained using the relationship:

$$\frac{P_i}{P_o} = 10^{(dB/10)}$$

In optical fiber communications the attenuation is usually expressed in decibels per unit length (i.e, dB k/m) following:

$$\alpha_{dB} L = 10 \log P_i/P_o$$

where the α_{db} is the signal attenuation per unit length in decibels and L is the fiber length.

2.2.2 Dispersion:

Dispersion of the transmitted optical signal causes distortion for both digital and analog transmission along optical fibers. When considering the major implementation of optical fiber transmission which involves some form of digital modulation, then dispersion mechanisms within the fiber cause broadening of the transmitted light pulses as they travel along the channel. The phenomenon is illustrated in Figure 2.6, where it may be observed that each pulse broadens and overlaps with its neighbors, eventually becoming indistinguishable at the receiver input. The effect is known as intersymbol interference (ISI). Thus an increasing number of errors may be encountered on the digital optical channel as the ISI becomes more pronounced. The error rate is also a function of the signal attenuation on the link and the subsequent signal to noise ratio (SNR) at the receiver. Signal dispersion alone limits the maximum possible bandwidth attainable with a particular optical fiber to the point where individual symbols can no longer be distinguished.

For no overlapping of light pulses down on an optical fiber link the digital bit rate B_T must be less than the reciprocal of the broadened (through dispersion) pulse duration (2τ). Hence:

$$B_T \leq \frac{1}{2\tau} \qquad (2.1)$$

This assumes that the pulse broadening due to dispersion on the channel is r which dictates the input pulse duration which is also r. Hence Eq. (2.1) gives a conservative estimate of the maximum bit rate that may be obtained on an optical fiber link as $1/2_T$.

Another more accurate estimate of the maximum bit rate for an optical channel with dispersion may be obtained by considering the light pulses at the output to have a Gaussian shape with an rms width of σ . Unlike the relationship given in Eq. (2.1), this analysis allows for the existence of a certain amount of signal overlap on the channel, whilst avoiding any SNR penalty which occurs when intersymbol interference becomes pronounced. The maximum bit rate is given approximately by

$$B_T(\max) = \frac{0.2}{\sigma} bits/s \tag{2.2}$$

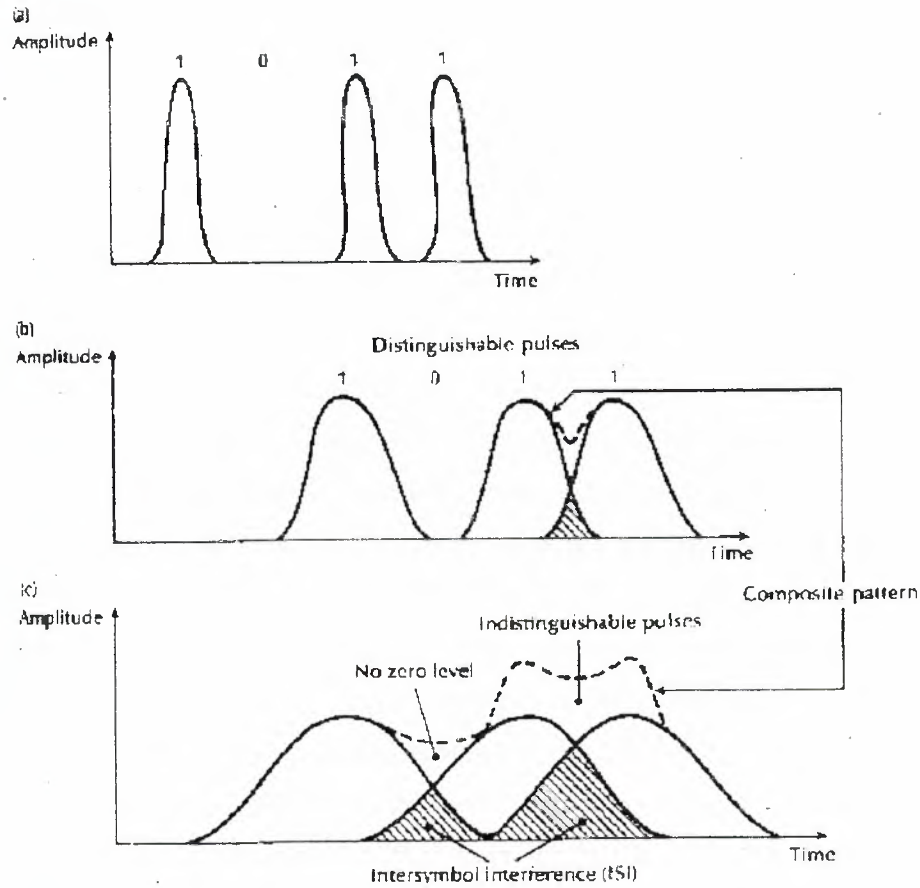

Figure 2.10 An illustration of using the digital bit pattern 1011 of the broadening of light pulses as they are transmitted along a fiber: (a) fiber input; (b) fiber output at a distance L_1; (c) fiber output at a distance $L_2 > L_1$

It must be noted that certain sources give the constant term in the numerator of Eq. (2.2) as 0.25. However, we take the slightly more conservative estimate given, following Olshansky and Gambling *et al.* Equation (2.2) gives a reasonably good approximation for other pulse shapes which may occur on the channel resulting from the various depressive mechanisms

within the fiber. Also, (σ may be assumed to represent the rms impulse response for the channel.

The conversion of bit rate to bandwidth in hertz depends on the digital coding format used. For metallic conductors when a nonreturn to zero code is employed, the binary one level is held for the whole bit period T. In this case there are two bit periods in one wavelength (i.e. two bits per second per hertz), as illustrated in Figure 2.11 (a). Hence the maximum bandwidth B is one half the maximum data rate Or

$$B_T(\max) = 2B \tag{2.3}$$

However, when a return code is considered, as shown in Figure 2.11 (b), the binary one level is held for only part (usually half) the bit period. For this signaling scheme the data rate is equal to the bandwidth in hertz (i.e. one bit per second per hertz) and thus $B_T=B$. The bandwidth B for metallic conductors is also usually denned by the electrical 3 dB points (i.e. the frequencies at which the electrical power has dropped to one half of its constant maximum value). However, when the 3 dB optical bandwidth of a fiber is considered it is significantly larger than the corresponding 3 dB electrical bandwidth. Hence, when the limitations in the bandwidth of a fiber due to dispersion are stated (i.e. optical bandwidth B_{opt}), it is usually with regard to a return to zero code where the bandwidth in hertz is considered equal to the digital bit rate.

However, when electro-optical devices and optical fiber systems are considered it is more usual to state the electrical 3 dB bandwidth, this being the more useful measurement when interfacing an optical fiber link to electrical terminal equipment. Unfortunately, the terms of bandwidth measurement are not always made clear and the reader must be warned that this omission may lead to some confusion when specifying components and materials for optical fiber communication systems.

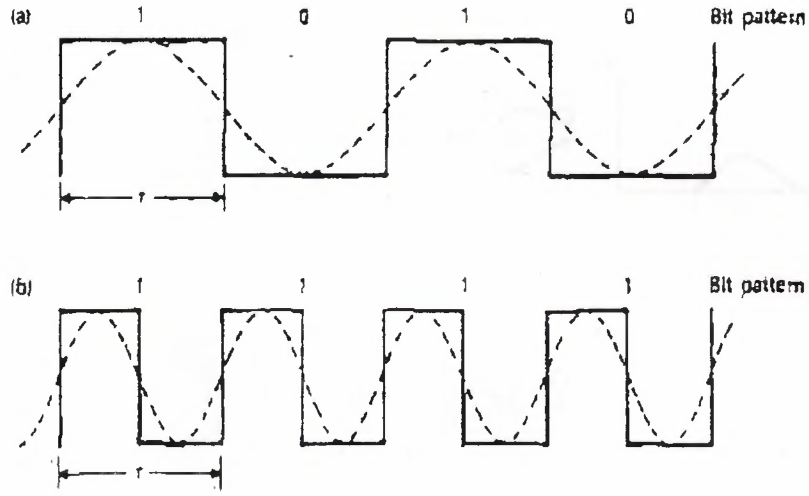

Figure 2.11 Schematic illustration of the relationships of the bit rate to wavelength for digital codes: (a) nonreturn to zero (NRZ); (b) return to zero (RZ).

Figure 2.12 shows the three common optical fiber, structures, multimode step index, multimode graded index and single-mode step index, whilst diagram illustrating the respective pulse broadening associated with each fiber type. It may be observed that the multimode step index fiber exhibits the greatest dispersion of a transmitted light pulse and the multimode graded index fiber gives a considerably improved performance. Finally, the single-mode fiber gives the minimum pulse broadening and thus is capable of the greatest transmission bandwidths which are currently in the gigahertz range, whereas transmission via multimode step index fiber is usually limited to bandwidths of a few tens of megahertz. However, the amount of pulse broadening is dependent upon the distance the pulse travels within the fiber, and hence for a given optical fiber link

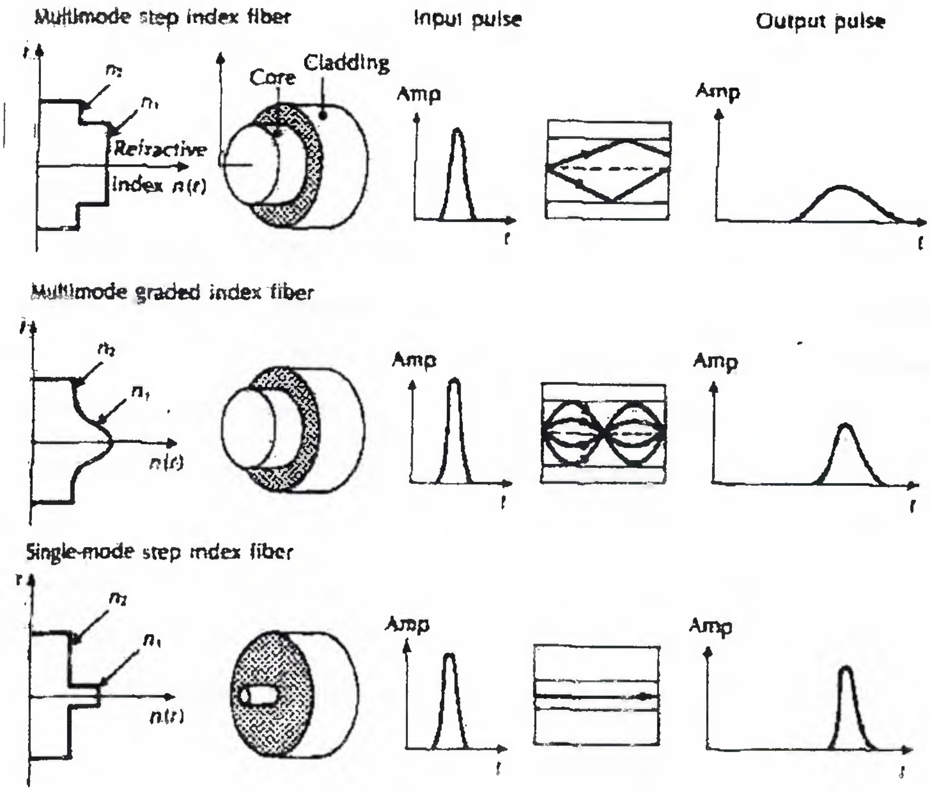

Figure 2.12 Schematic diagram showing a multimode step index' fiber, multimode graded index fiber and single-mode step index fiber, and illustrating the pulse broadening due to intermodal dispersion in each fiber type.

the restriction on usable bandwidth is dictated by the distance between regenerative repeaters (i.e. the distance the light pulse travels before it is reconstituted). Thus the measurement of the dispersive properties of a particular fiber is usually stated as the pulse broadening in time over a unit length of the fiber (i.e. ns km 1).

Hence, the number of optical signal pulses which may be transmitted in a given period, and therefore the information-carrying capacity of the fiber, is restricted by the amount of pulse dispersion per unit length. In the absence of mode coupling or filtering, the pulse broadening increases linearly with fiber length and thus the bandwidth is inversely proportional to distance. This leads to the adoption of a more useful parameter for the information-carrying capacity of an optical fiber which is known as the bandwidth—length product (i.e. B_{0-1} x L). The typical best bandwidth—length products for the three fibers shown in Figure 2.12, are 20 MHz km, 1 GHz km and 100 GHz km for multimode step index, multimode graded index and single-mode step index fibers respectively.

2.2.3 Linear scattering Losses:

Linear scattering mechanisms cause the transfer of some or all of the optical power contained within one propagating mode to be transferred linearly (proportionally to the mode power) into a different mode. This process tends to result in attenuation of the transmitted light as the transfer may be to a leaky or radiation mode which does not continue to propagate within the fiber core, but is radiated from the fiber. It must be noted that as with all linear processes there is no change of frequency on scattering.
Linear scattering may be categorized into two major types: Rayleigh and Mie scattering. Both result from the nonideal physical properties of the manufactured fiber which are difficult and, in certain cases, impossible to eradicate at. present.

(a) Rayleigh scattering:

Rayleigh scattering is the dominant intrinsic loss mechanism in the low absorption window between the ultraviolet and infrared absorption tails. It results from inhomogeneities of a random nature occurring on a small scale compared with the wavelength of the light. These inhomogeneities manifest themselves as refractive index fluctuations and arise from density and compositional variations which are frozen into the glass lattice on cooling. The compositional variations may be reduced by improved fabrication, but the index fluctuations caused by the freezing-in of density inhomogeneities are fundamental and cannot be avoided. The subsequent scattering due to the density fluctuations, which is in almost all directions, produces an attenuation proportional to $1/\lambda^4$ following the Rayleigh scattering formula. For a single component glass this is given by:

$$\gamma_R = \frac{8\Pi^3}{3\lambda^4} n^8 p^2 \beta_c K T_F \tag{2.4}$$

where γ_R is the Rayleigh scattering coefficient, λ is the optical wavelength, n is the refractive index of the medium, p is the average photoelastic coefficient, β_c is the isothermal compressibility at a fictive temperature T_F, and K is Boltzmann's constant. The fictive temperature is defined as the temperature at which the glass can reach a state of thermal equilibrium and is closely related to the anneal temperature.

Furthermore, the Rayleigh scattering coefficient is related to the transmission loss factor (transmissivity) of the fiber ℓ following the relation:

$$\ell = \exp(-\gamma_R L) \tag{2.5}$$

where L is the length of the fiber. It is apparent from Eq. (2.4) that the fundamental component of Rayleigh scattering is strongly reduced by operating at the longest possible wavelength.

(b) Mie scattering:

Linear scattering may also occur at inhomogeneities which are comparable in size to the guided wavelength. These result from the nonperfect cylindrical structure of the waveguide and may be caused by fiber imperfections such as irregularities in the core-cladding interface, core-cladding refractive index differences along the fiber length, diameter fluctuations, strains and bubbles. When the scattering inhomogeneity size is greater than $\lambda/10$, the scattered intensity which has an angular dependence can be very large.

The scattering created by such inhomogeneities is mainly in the forward direction and is called Mie scattering. Depending upon the fiber material, design and manufacture, Mie scattering can cause significant losses. The inhomogeneities may be reduced by:

(a) removing imperfections due to the glass manufacturing process;
(b) carefully controlled extrusion and coating of the fiber;
(c) increasing the fiber guidance by increasing the relative refractive index difference.

By these means it is possible to reduce Mie scattering to insignificant levels.

2.2.4 Nonlinear scattering losses:

Optical waveguides do not always behave as completely linear channels whose increase in output optical power is directly proportional to the input optical power, Several nonlinear effects occur, which in the case of scattering cause disproportionate attenuation, usually at high causes the optical power from one mode to be transferred in either the forward or backward direction to the same, or other modes, at a different frequency. It depends critically upon the optical power density within the fiber and hence only becomes significant above threshold power levels.

frequency. It depends critically upon the optical power density within the fiber and hence only becomes significant above threshold power levels.

The most important types of nonlinear scattering within optical fibers are stimulated Brillouin and Raman scattering, both of which are usually only observed at high optical power densities in long single-mode fibers. These scattering mechanisms in fact give optical gain but with a shift in frequency, thus contributing to attenuation for light transmission at a specific wavelength. However, it may be noted that such nonlinear phenomena can also be used to give optical amplification in the context of integrated optical techniques.

(a) Stimulated Brillouin scattering:

Stimulated Brillouin scattering (SBS) may be regarded as the modulation of light through thermal molecular vibrations within the fiber. The scattered light appears as upper and lower sidebands which are separated from the incident light by the modulation frequency. The incident photon in this scattering process produces a phonon of acoustic frequency as well as a scattered photon. This produces an optical frequency shift which varies with the scattering angle because the frequency of the sound wave varies with acoustic wavelength. The frequency shift is a maximum in the backward direction reducing to zero in the forward direction making SBS a mainly backward process.

As indicated previously, Brillouin scattering is only significant above a threshold power density. Assuming that the polarization state of the transmitted light is not maintained, it may be shown that the threshold power P_B is given by:

$$P_B = 4.4*10^{-3} d^2 \lambda^2 \alpha_{dB} \nu \qquad (2.6)$$

where d and λ are the fiber core diameter and the operating wavelength, respectively, both measured in micrometers, α_{dB} is the fiber attenuation in decibels per kilometer and ν is the source bandwidth (i.e. injection laser) in gigahertz. The expression given in Eq. (2.6) allows the determination of the threshold optical power which must be launched into a single-mode optical fiber before SBS occurs.

(b) Stimulated Raman scattering:

Stimulated Raman scattering (SRS) is similar to stimulated Brillouin scattering except that a high frequency optical phonon rather than an acoustic phonon is generated in the scattering process. Also, SRS can occur in both the forward and backward directions in an optical fiber, and may have an optical power threshold of up to three orders of magnitude higher than the Brillouin threshold in a particular fiber.

Using the same criteria as those specified for the Brillouin scattering threshold given in Eq. (2.6), it may be shown that the threshold optical power for SRS P_R in a long single-mode fiber is given by:

$$P_R = 5.9\text{-}10^{-2} d^2 \lambda \alpha_{dB} \text{ watts} \tag{2.7}$$

where d, λ and α_{dB} are as specified for Eq. (2.6).

2.2.5 Fiber bend loss:

Optical fibers suffer radiation losses at bends or curves on their paths. This is due to the energy in the evanescent field at the bend exceeding the velocity of light in the cladding and hence the guidance mechanism is inhibited, which causes light energy to be radiated from the fiber. An illustration of this situation is shown in Figure 2.9. The part of the mode which is on the outside of the bend is required to travel faster than that on the inside so that a wavefront perpendicular to the direction of propagation is maintained. Hence, part of the mode in the cladding needs to travel faster than the velocity of light in that medium. As this is not possible, the energy associated with this part of the mode is lost through radiation. The loss can generally be represented by a radiation attenuation coefficient which has the form:

$$\alpha_r = c_1 \exp(-c_2 R)$$

where R is the radius of curvature of the fiber bend and c_1, c_2 are constants which are independent of R. Furthermore, large bending losses tend to occur in multimode fibers at a critical radius of curvature Re which may be estimated from:

$$R_c = \frac{3n_1^2\lambda}{4\Pi(n_1^2 - n_2^2)^{3/2}} \tag{2.8}$$

It may be observed from the expression given in Eq. (2.8) that potential macrobending losses may be reduced by:

(a) designing fibers with large relative refractive index differences;

(b) operating at the shortest wavelength possible.

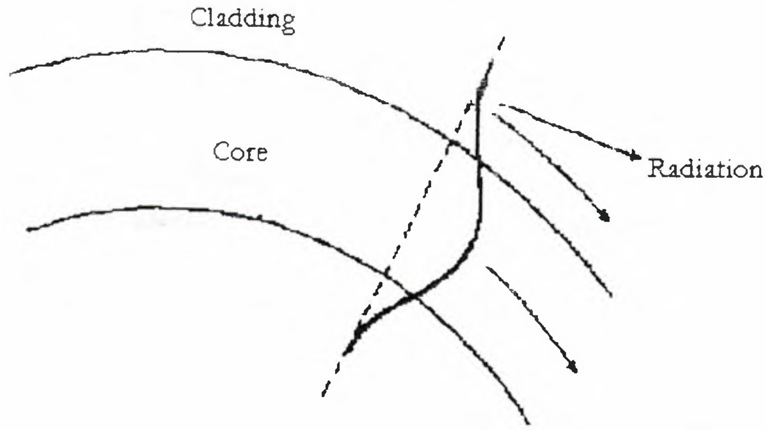

Figure 2.13 An illustration of the radiation loss at a fiber bend. The part of the mode in the cladding outside the dashed arrowed line may be required to travel faster than the velocity of light in order to maintain a plane wavefront. Since it cannot do this, the energy contained in this part of the mode is radiated away.

The above criteria for the reduction of bend losses also apply to single-mode fibers, based on the concept of a single quasi-guided mode, provides an expression from which the critical radius of curvature for a single-mode fiber R_{CS} can be estimated as:

$$R_{CS} = \frac{20\lambda}{(n_1 - n_2)^{3/2}}(2.748 - 0.996\frac{\lambda}{\lambda_c})^{-3} \qquad (2.9)$$

where λ_c is the cutoff wavelength for the single-mode fiber. Hence again, for a specific single-mode fiber (that is, a fixed relative index difference and cutoff wavelength), the critical wavelength of the radiated light becomes progressively shorter as the bend radius is decreased.

2.3 Optical transmitter:

The basic optical transmitter converts electrical input signals into modulated light for transmission over an optical fiber. Depending on the nature of this signal, the resulting modulated light may be turned on and off or may be linearly varied in intensity between two predetermined levels. Figure 2.14 shows a graphic representation of these two basic schemes.

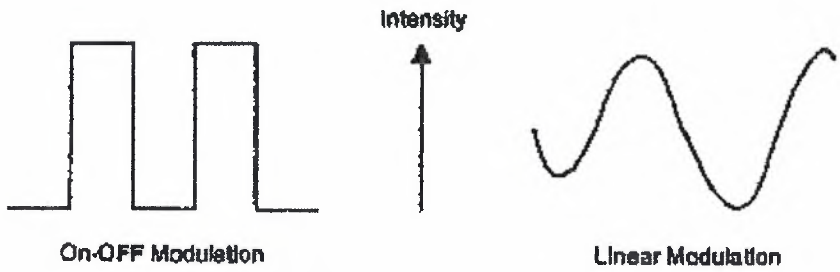

Figure 2.14 Basic Optic Modulation Method

The most common devices used as the light source in optical transmitters are the *light emitting diode* (LED) and the *laser diode* (LD). In a fiber optic system, these devices are mounted in a package that enables an optical fiber to be placed in very close proximity to the light emitting region in order to couple as much light as possible into the fiber. In some cases, the emitter is even fitted with a tiny spherical lens to collect and focus "every last drop" of light onto the fiber and in other cases, a fiber is "pigtailed" directly onto the actual surface of the emitter.

LEDs have relatively large emitting areas and as a result are not as good light sources as LDs. However, they are widely used for short to moderate transmission distances because they are much more economical, quite linear in terms of light output versus electrical current input and stable in terms of light output versus ambient operating temperature. LDs, on the other hand, have very small light emitting surfaces and can couple many times more power to the fiber than LEDs. LDs are also linear in terms of light output versus electrical current input, but unlike LEDs, they are not stable over wide operating temperature ranges and require more elaborate circuitry to achieve acceptable stability. In addition, their added cost makes them primarily useful for applications that require the transmission of signals over long distances.

LEDs and LDs operate in the infrared portion of the electromagnetic spectrum so that their light output is usually invisible to the human eye. Their operating wavelengths are chosen to be compatible with the lowest transmission loss wavelengths of glass fibers and highest sensitivity ranges of photodiodes. The most common wavelengths in use today are 850 nanometers, 1300 nanometers, and 1550 nanometers. Both LEDs and LDs are available in all three wavelengths.

LEDs and LDs, as previously stated, are modulated in one of two ways; on and off, or linearly. Figure 2.15 shows simplified circuitry to achieve either method with an LED or LD. As can be seen from

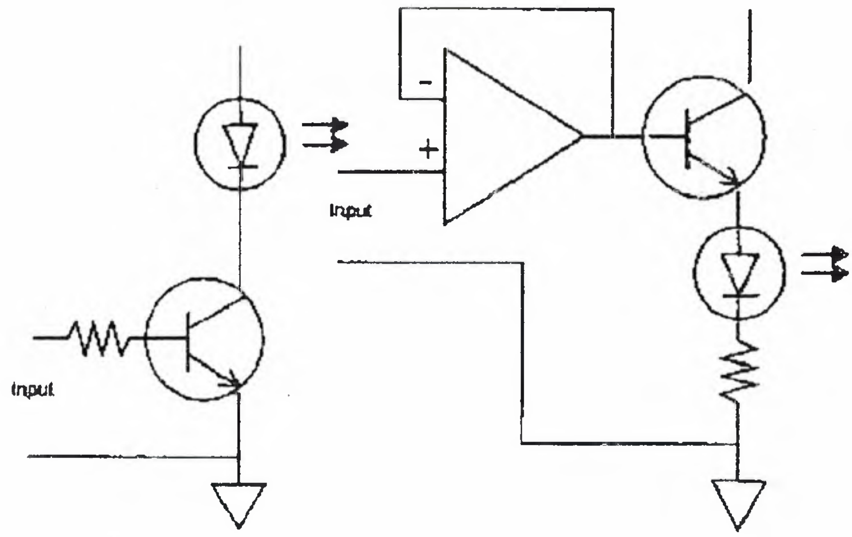

Figure 2.15 Methods of modeling LED's of Laser Diodes

In the figure 2.15, a transistor is used to switch the LED or LD on and off in step with an input digital signal. This signal can be converted from almost any digital format by the appropriate circuitry, into the correct base drive for the transistor overall speed is then determined by the circuitry and the inherent speed of the LED or LD. Used in this manner, speeds of several hundred megahertz are readily achieved for LEDs and thousands of megahertz for LDs. Temperature stabilization circuitry for the LD has been omitted from this example for simplicity. LEDs do not normally require any temperature stabilization.

Linear modulation of an LED or LD is accomplished by the operational amplifier circuit of figure 2.15. The inverting input is used to supply the modulating drive to the LED or LD while the non-inverting input supplies a DC bias reference. Once again temperature stabilization circuitry for the LD has been omitted from this example for simplicity.

Digital on/off modulation of an LED or LD can take a number of forms. The simplest, as we have already seen, is light-on for a logic "1", and light-off for a logic "0". Two other common forms are *pulse width modulation* and *pulse rate modulation*. In the former, a constant stream of pulses is produced with one width signifying a logic "1" and another width, a logic "0". In the latter, the pulses are all of the same width but the pulse rate changes to differentiate between logic "1" and logic "0".

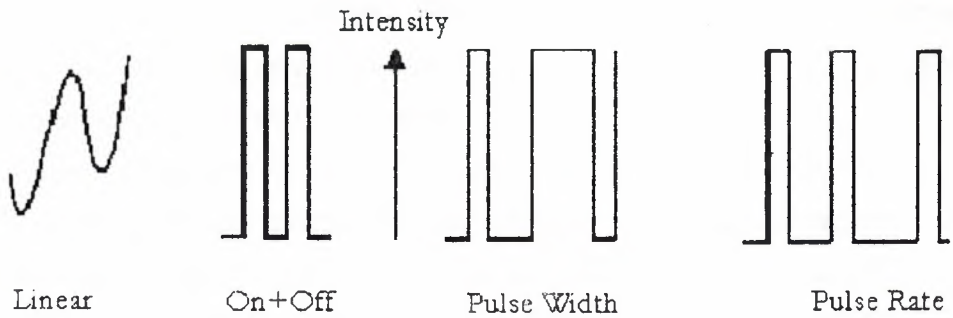

Figure 2.16 Various methods of optically transmit analog information

Analog modulation can also take a number of forms. The simplest is intensity modulation where the brightness of an LED is varied in direct step with the variations of the transmitted signal. In other methods, an RF carrier is first frequency modulated with another signal or, in some cases, several RF carriers are separately modulated with separate signals, then all are combined and transmitted as one complex waveform. Figure 2.16 shows all of the above modulation methods as a function of light output.

The equivalent operating frequency of light, which is, after all, electromagnetic radiation, is extremely high – on the order of 1,000,000 GHz. The output bandwidth of the light produced by LEDs and Laser diodes is quite wide. Unfortunately today's technology does not allow this bandwidth to be selectively used in the way that conventional radio frequency transmissions are utilized. Rather, the entire optical bandwidth is turned on and off in the same way that early "spark transmitters" (in the infancy of radio), turned wide portions of the RF spectrum on and off. However, with time, researchers will overcome this obstacle and "coherent transmissions", as they are called, will become the direction in which the fiber optic field progresses.

2.4 Optical Receiver:

The basic optical receiver converts the modulated light coming from the optical fiber back into a replica of the original signal applied to the transmitter.

The detector of this modulated light is usually a photodiode of either the PIN or the Avalanche type. This detector is mounted in a connector similar to the one used for the LED or LD. Photodiodes usually have a large sensitive detecting area that can be several hundred microns in diameter. This relaxes the need for special precautions in centering the fiber in the receiving connector and makes the "alignment" concern much less critical than it is in optical transmitters.

Since the amount of light that exits a fiber is quite small, optical receivers usually employ high gain internal amplifiers. Because of this, optical receivers can be easily overloaded. For this reason, it is important only to the size fiber specified for use with a given system. If, for example, a transmitter/receiver pair designed for use with single-mode fiber were used with multimode fiber, the large amount of light present at the output of the fiber (due to over-coupling at the light source) would overload the receiver and cause a severely distorted output signal. Similarly, if a transmitter/receiver pair designed for use with multimode fiber were used with single-mode fiber, not enough light would reach the receiver, resulting in either an excessively noisy output signal or no signal at all. The only time any sort of receiver "mismatching" might be considered is when there is so much excessive loss in the fiber that the extra 5 to 15 dB of light coupled into a multimode fiber by a single-mode light source is the only chance to achieve proper operation. However, this is an extreme case and is not normally recommended.

As in the case of transmitters, optical receivers are available in both analog and digital versions. Both types usually employ an analog preamplifier stage, followed by either an analog or digital output stage (depending on the type of receiver). Figure 2.17 is a functional diagram of a simple analog optical receiver.

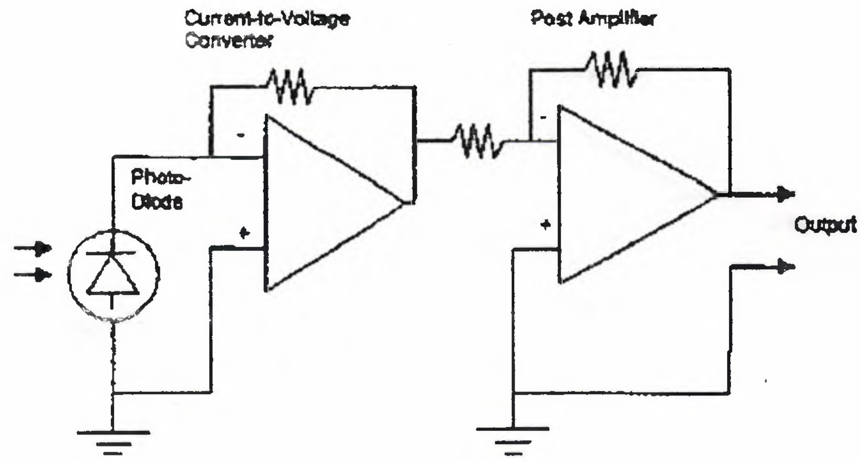

Figure 2.17 Basic Analogue Fiber Optic Receiver

The first stage is an operational amplifier connected as a current-to-voltage converter. This stage takes the tiny current from the photodiode and converts it into a voltage, usually in the millivolt range. The next stage is a simple operational voltage amplifier. Here the signal is raised to the desired output level.

Figure 2.18 is a functional diagram of a simple digital optical receiver. As in the case of the analog receiver, the first stage is a current-to-voltage converter. The output of this stage, however, is fed to a voltage comparator, which produces a clean, fast rise-time digital output signal. The trigger level adjustment, when it is present, is used to "touch up" the point on the analog signal where the comparator switches. This allows the symmetry of the recovered digital signal to be trimmed as accurately as desired.

Additional stages are often added to both analog and digital receivers to provide drivers for coaxial cables, protocol converters or a host of other functions in efforts to reproduce the original signal as accurately as possible.

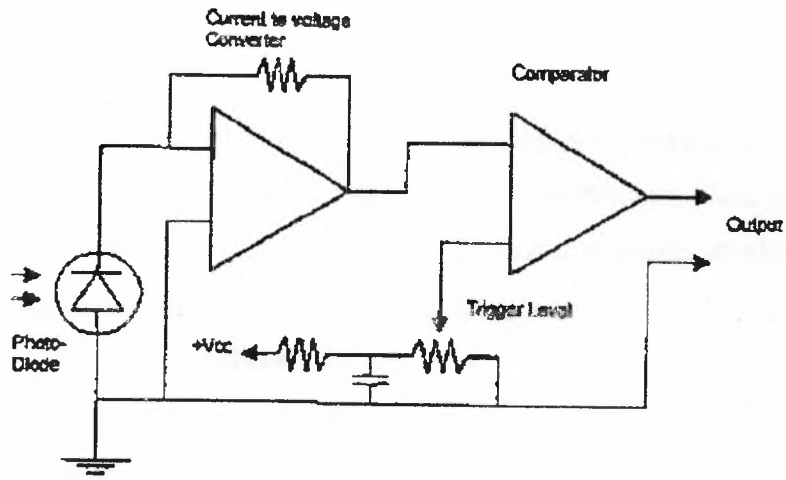

Figure 2.18 Basic Digital Fiber Optical Fiber Receiver

It is important to note that while fiber optic cable is immune to all forms of interference, the electronic receiver is not. Because of this, normal precautions, such as shielding and grounding, should be taken when using fiber optic electronic components.

2.5 Switching in fiber optical network:

We know that networks establish communication links based on either circuit or packet switching. For high-speed optical transmission, packet switching holds the promise for more efficient data transfer.

Network packet switching can be accomplished in a straightforward manner by requiring a node to optoelectronically detect and transmit each and every incoming optical data packet. As for the routing, all the switching functions can occur in the electrical domain prior to optical retransmission of the signal. Unfortunately, this approach suffers from an optoelectronic speed bottleneck. Alternatively, much research is focused toward maintaining an all-optical data path and performing the switching functions all optically with only some electronic control of the optical components. However, there are many difficulties with optical switching, for instance:

1) A redirection of an optical path is not easy since photons do not have as strong interaction with their environment as electrons do.
2) Switching has to be extremely fast due to the high speed of the incoming signal.
3) Switching nodes cannot easily tap a signal and acquire information about the channel.

Contention Resolution:

Consider a situation in which two or more input ports request a communications path with the same output port, known as output-port contention. Since we are dealing with a high-speed system, a rapid contention resolution is required, in which one signal is allowed to reach its destination while the other signal is delayed or rerouted in some fashion. In our multiplexing scheme, the issue of contention exists when signals from two different input ports would request routing to the same output port and contain identical wavelengths.

Several approaches exist for resolving contention. One of them is buffering: The packet is retained locally at the switching node and then it is switched to the appropriate output port when that port is available. The local buffering can be implemented either in electrical or optical form. Electronic buffering is straightforward but requires undesirable optoelectronic conversions and may require very large buffers. On the other hand, optical buffering is difficult because many buffering schemes require updating a priority bit (it is difficult to change a priority bit of an optical data stream), and optical memory is not an advanced art, consisting mostly of using an optical delay line.

Synchronization:

A high-speed network transmitting digital signals must have adequate time synchronization to recover the data stream. Time synchronization is especially required with packet switching, asynchronous packet arrival times, and long-distance transmission.

In a WDM network, it is also possible that wavelength synchronization will be required in addition to time synchronization. In such a scenario, a wavelength standard could be broadcast through the network. However, the hope is that the network wavelength stability and accuracy will be robust and will not require its own system overhead and complexity.

Data-Format Conversion:

In a large network, it is quite possible that a combination of data formats will be used. This may occur, for instance, if some links may more efficiently use TDM signaling, whereas other links may more effectively use WDM. This explains the need for data-format conversion at network gateways, as illustrated in figure 2.19.

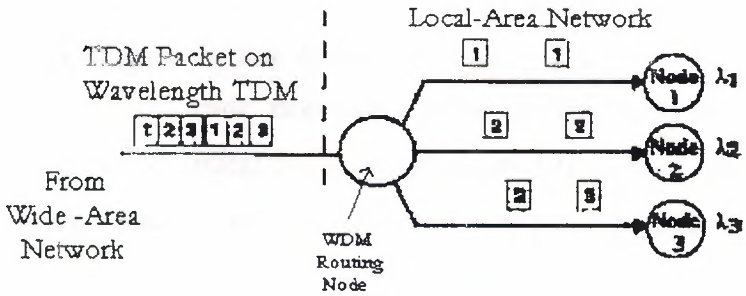

Figure 2.19 Data-Format Conversion from one TDM signal to several lower speed WDM at the network gateway.

2.6 Multiplexing:

In order to maximize the information transfer over an optical fiber communication link it is usually to multiplex several signals onto a fiber. It is possible to convey these multi-channel signals by multiplexing in the electrical time or frequency domain, as with conventional electrical line or radio communication., prior to intensity modulation of the optical source. Hence digital pulse modulation schemes may be extended to multi-channel operation by Time-Division-Multiplexing (TDM) narrow pulses from multiple modulators under the control of a common clock. Pulses from the individual channels are interleaved and transmitted sequentially, thus enhancing the bandwidth utilization of a single fiber link.

Alternatively, a number of baseboard channels may be combined by Frequency-Division-Multiplexing (FDM). In FDM the optical channel bandwidth is divided into a number of non-overlapping frequency bands and each signal can be extracted from the combined FDM signal by appropriate electrical filtering at the receiver terminal. Hence frequency division multiplexing is generally performed electrically at the transmit terminal prior to intensity modulation of a single optical source.

However, it is possible to utilized a number of optical sources each operating at a different wavelength on the single fiber link. In this technique, often referred to as Wavelength-Division-Multiplexing (WDM), the separation and extraction of the multiplexed signals (i.e, wavelength separation) is performed with optical filters (e.g, interface filters, diffraction grating filters, or prism filters).

Finally, a multiplexing technique which does not involve the application of several message onto a single fiber is know as Space-Division-Multiplexing (SDM). In SDM each signal channel is carried on a separate fiber within a fiber bundle or multi-fiber cable form. The good optical isolation offered by fiber means that cross coupling between channels can be made negligible. However, this technique necessitates an increase in the number of optical components required (e.g, fiber connectors, sources, detectors) within a particular system and therefore is not widely used.

2.7 Designing a Fiber Optical Network:

The optical network design plays an important role in error-free system reliability. Choice of the proper type of network depends on the type of process controlled, possible need for expansion, and degree of failure immunity desired - all of which must be balanced with cost considerations.

2.7.1 Three Basic Designs:

As is the case with electrical control system networks, three basic optical networks prevail: bus, star, and ring. For each type, the purpose of the network is to provide communication between the devices, or nodes in the system. The term node is a general term that refers to a programmable logic controller (PLC), remote input/output (I/O) drop, distributed control system (DCS) controller, or any communication device.

Each of the three network types has advantages and disadvantages, depending on the application. Historically, bus layouts have been preferred by PLC suppliers - and star layouts by DCS suppliers - on equipment OEM-configured for fiber optic signal transmission. Recently, both PLC and DCS suppliers have begun to offer more ring layouts than in the past.

(a) Bus Network:

In a bus network, all the nodes are attached in a line. This layout lends itself especially well to automobile assembly lines, lumber and paper mills, and other operations that begin with raw materials at one end, and finish at the other end of a production line with a finished good. The control devices are laid out in a linear array alongside the process machinery. Because the process machinery requires adequate clearances and right-of-way, it is usually easy to set up the cableways along the same right-of-way.

In an electrical bus signal transmission system, devices are connected to the nodes in parallel by direct attachment or attenuating taps. Attenuating taps allow higher speeds and greater bandwidth, but do not provide for easy network expansion.

In a fiber optic system, fibers cannot simply be "paralleled" as can copper conductors. Present fiber optic technology does not provide for effecting the equivalent of an electrical tap. In a fiber optic system, "taps" are effected through modems. All intermediate modems in the string (with the exception of the two at the extreme ends of the bus) are repeaters that interface with their respective nodes, and send the optical signal on to all other modems on the bus.

(b) *Star Network:*

The star network consists of a star (central) node device with arms extending out to other nodes. The star is used predominantly in facilities where different processes are physically separated, but must be centrally controlled, such as in petroleum refineries, chemical and pharmaceutical plants, and power generating stations.

Outlying nodes handle individual complex tasks, or have many alternative paths, and must therefore function somewhat independently. For example, one node might be connected to thermocouples with slow temperature changes in a 4 to 20-ma control loop, a second node might be a high-speed remote computer on a 10-Mbps RS-485 link, and a third node might be a controller operating a motorized process control valve.

Because the controlled functions might have no well-defined path of their own, or the path might not readily lead back to the central deviçes, locating the cable ways and securing right-of-way can be more complex than with linear layouts.

In a star network, the central device is always a repeater, capable of transferring communications from one separate node to another. Sometimes the central node has overall control over the separated nodes. Each separated node is connected to the central device by a point-to-point link. Because each node receives and sends messages solely with the central device, only these two devices must understand the message. Thus, the different nodes can communicate at different speeds and use different protocols or languages. If the star node has enough power and intelligence, it handles many different speeds and protocols. This feature makes it easier to use devices utilizing various technologies from different manufacturers.

In a star network, however, each separated node requires two modems - one attaching to the star and other to the node for a point-to-point link. As a result, a star requires twice as many modems as a bus layout, and thus costs more.

(c) Ring Network:

Devices in a ring layout are connected in a circular fashion. Each node is a repeater, and all nodes operate at the same speed under the same protocol. In theory, a simple ring handles complex processes, but in practice, relatively few processes lend themselves to a ring layout.

A ring network can, however, be advantageous in high-reliability applications, because it can be installed in a modified "self healing" configuration.

2.7.2 Expansion Considerations:

To expand a bus network, one adds to either end. Expansion is easy if growth is linear, but difficult if links must be added between the ends or on a branch.

The star is expanded by adding more arms with separated nodes, and their connecting cables. As long as cableways are available and the central device has enough capacity, expansion is straightforward. Moreover, it is possible for units to be added while the network is up and running.

In a ring layout, expansion is difficult. Because any addition requires disrupting the ring, it cannot be done quickly or while the network is running.

(a) Achieving High Reliability:

Studies show that in fiber-optic telephone systems, 80% of interrupted service is due to cable damage. Much the same might be true in industrial environments, where cable is exposed to potential damage from sources such as fork lift trucks, dropped tools and equipment, and cutting and welding torches.

In a bus or ring, the entire network usually goes down if a cable is damaged, because the network devices usually have neither the power nor the intelligence to operate as isolated entities. And in the rare event that a modem or repeater fails, communication is also disrupted throughout the network.

(b) Self-healing ring network :

It has the capability for being installed in a modified, ultrahigh-reliability configuration. The ring is made to send signals clockwise and counter-clockwise by duplicating the cable and installing two optical transmitters/ receivers at each node. Importantly, the two cables can be strung alongside each other in the same cableway, because operations are not disrupted if either or both cables are damaged.

If one or both cables between any two devices is damaged, communication is disrupted at that point. However, the nodes adjacent to the break continue to receive communications from either the clockwise or the counter-clockwise signal stream. Likewise, if one node fails, communication continues among the other nodes.

A modular fiber-optic design can bring down the cost of a self-healing ring layout. That is, rather than duplicating the entire modem, one need add only a transmitter/receiver module and a self-healing ring module to each modem. If regular modems are already in place in a bus layout, the network can become self-healing by connecting the two ends and inserting the additional modules. The ability to insert additional modules, rather than replace modems, also reduces installation time.

In practice, different parts of a network require varying levels of reliability. The most critical processes can be arranged in a self-healing ring, and less critical processes in a bus, star, or other hybrid configuration.

Many hybrid variations on the basic network types are possible, incorporating the star in one form or another. If a cable is damaged in a star, communication stops only with the node served by the damaged cable; the other nodes continue to operate. It must be borne in mind, however, that if the star (center) node itself fails, all control is lost.

(c) Bus-star layout:

This topology is commonly used in PLC networks with distributed I/O modules. In a paper mill, for example, PLCs and I/O modules controlling various processes are typically laid out in a linear bus. However, the I/O drops that control chemical kitchens in the pulp preparation area have control points that radiate out in star configurations. If the bus cable is damaged, the star nodes can continue to control local pulp operations. And if a bus node fails, the other star-connected nodes can continue to communicate among themselves.

(d) Star-bus hybrid:

This configuration is often used in spread-out operations such as oil production fields or far-spread petrochemical processing operations. For example, each device, such as an individual oil well, local storage tank, or pump and valve controller, is regulated by nodes on a local bus. The many buses are linked back to a central control room in a star layout. If a local bus cable fails, other local buses in the layout continue to control their respective processes.

(e) Ring-bus and ring-star:

These configurations show how a ring network can be combined with either a bus or a star network. One node on the ring can be one of several nodes on a local bus, or it can be the central node for a local star. The ring is connected in a self-healing configuration for the most critical elements of the network, with less critical nodes connected in bus or star.

(f) Triple-hybrid combinations:

It combine all three basic networks into a ring-bus-star configuration. The most critical items are connected in a self-healing ring; other items are connected in either bus or star as best satisfies their location and application.

2.7.3 Redundant Systems:

While a hybrid layout can improve performance and enhance reliability, ultimate failure resistance often requires a redundant system - that is, a second or duplicate system that takes over in the event the first stops functioning.

Depending on the layout and hazards involved, many system designers opt to duplicate the cable only. The redundant systems, however, need not be identical. The primary system might be fiber optic, with the backup system electrical, and wired with copper conductors. For maximum reliability in bus and star layouts, cables of the redundant systems should be placed in separate cableways some distance from the primary systems. Setting up a second cableway can be enormously expensive.

Duplicating only the cable poses a significant disadvantage in systems with long distances between modems. In order to send the signal down the duplicate cables, each modem needs an optical splitter and combiner. Each splitter introduces a signal loss of 3 to 6 dB, which can create distortion unless the distance between modems is limited.

In a star layout, if the central node is especially in risk of destruction, one option is to duplicate only the star node. It is usually not necessary to duplicate the outlying nodes, because other portions of the system can continue to operate if one node fails. Even duplicating only the star node can be expensive, though, when this central device is very powerful or complex. As with duplicate cables, the duplicate central node should be located some distance from the first, which also increases costs.

CHAPTER 3
NETWORKING

High-speed networks, broadband applications and better quality of service are the demands of today. The increase of IC capacity is not fast enough. The challenge is to replace the speed limiting electronics by faster components.

One very promising answer to the problem is optical networking due to several advantages of optical fibers. The transfer capacity of an optical fiber exceeds the transfer capacity of a legacy copper wire by a large margin. By utilizing novel optical transmission technologies such as WDM (Wavelength Division Multiplexing) or OTDM (Optical Time Division Multiplexing), the transfer capacity of the optical network can be in Tbits range. Also the losses during transfer are remarkably small, so the need of amplifiers decreases. The fibers are immune to electromagnetic radiation and they generate no electromagnetic radiation to their surroundings.

Although the properties of optical fibers seems to be perfect, there still are some linear and unlinear phenomena, which restrict the possibilities of optical networks. On the other hand such phenomena can be utilized to implement all optical devices for packet switching, signal regeneration, etc.

VTT Information Technology (Espoo, Finland) has been doing research on optical fiber networks since 1998. Our main research interest is on optical packet switching as we have long experience in implementing and modeling broadband networks. Thus we are upgrading our existing switching systems with optical components and designing and modeling new schemes for all optical packet switching at the same time.

3.1 Optical fiber bandwidth:

All of the above attenuation factors result in simple attenuation that is independent of bandwidth. In other words, a 3 dB loss means that 50% of the light will be lost whether it is being modulated at 10 Hz or 100 MHz.

There is an actual bandwidth limitation of optical fiber however, and this is measured in MHz per km. The easiest way to understand why this loss occurs is to refer to next Figure:

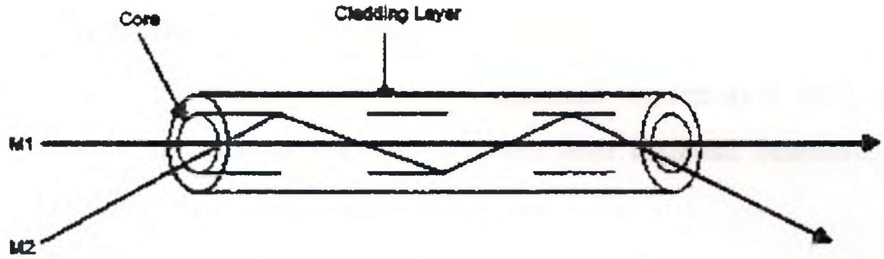

Figure 3.1 Different light paths lengths determine the bandwidth of Fiber

As Figure above illustrates, a ray of light that enters a fiber at a small angle (M1) has a shorter path through the fiber than light which enters at an angle close to the maximum acceptance angle (M2). As a result, different "rays" (or modes) of light reach the end of the fiber at different times, even though the original source is the same LED or LD. This produces a "smearing" effect or uncertainty as to where the start and end of a pulse occurs at the output end of the fiber – which in turn limits the maximum frequency that can be transmitted. In short, the less modes, the higher the bandwidth of the fiber. The way that the number of modes is reduced is by making the core of the fiber as small as possible. Single-mode fiber, with a core measuring only 8 to 10 microns in diameter, has a much higher bandwidth because it allows only a few modes of light to propagate along its core. Fibers with a wider core diameter, such as 50 and 62.5 microns, allow many more modes to propagate and are therefore referred to as "multimode" fibers.

Typical bandwidths for common fibers range from a few MHz per km for very large core fibers, to hundreds of MHz per km for standard multimode fiber, to thousands of MHz per km for single-mode fibers. And as the length of fiber increases, its bandwidth will decrease proportionally. For example, a fiber cable that can support 500 MHz bandwidth at a distance of one kilometer will only be able to support 250 MHz at 2 kilometers and 100 MHz at 5 kilometers.

Because single-mode fiber has such a high inherent bandwidth, the "bandwidth reduction as a function of length" factor is not a real issue of concern when using this type of fiber. However, it is a consideration when using multimode fiber, as its maximum bandwidth often falls within the range of the signals most often used in point-to-point transmission systems.

3.2 Fiber Distributed Data Interface (FDDI):

FDDI (fiber optical data interface) is a standard written as a specification for local area networks and optical fibers by the American National Standards Institute Commitee X3T9.5.

(a) Using optical fibers in LANs

Several reasons exist for placing computers on optical channels:

1. Computers operate at very high speeds. When computer are linked together, the slow path between them can be a bottleneck. So the high speed optical fiber can be a complementary path to the high speed computer.
2. The improving technology of disk units will provide r/w speeds approaching 40
3. to 50 Mbit/s, a capability that can be hampered by the slow channel between the disk unit and the computer, and optical fibers can relieve this bottleneck.
4. Digitized voice conversations require a greater bandwidth than the typical telephone channel provides, especially if the converstions are in an interactive, real-time mode. Optical fibers provide the bandwidth capability to accomodate real-time voice transmissions.

(b) Specifications for the FDDI:

1. The standard operates with a 100 Mbit/s rate.
2. Dual rings are provided for the LAN so the full speed is 200 Mbit/s.
3. The protocol is a timed token procedure operating on the dual ring (the ANSI standard defines both multimode and single-mode optical fiber). Packets maximum length is 4500 bytes.
4. FDDI provides for failure recovery by bypassing problem nodes.
5. It has station management capabilities.
6. FDDI permits the LAN topology to extend up to 200 km (ring circumference).
7. Up to 1000 nodes can be placed on the optical-fiber ring.
8. Two independent, counter rotating optical-fiber rings provide for an overall bit rate

   of 200 Mbit/s, with each channel operating at 100 Mbit/s.
9. The components (such as terminals, computers, or work stations) are tied together through a wiring concentrator.
10. The concentrator is a reconfiguration and concentration point for all optical

wring and data traffic. It also serves to isolate troubleshooting.

11. The inner channel connects only certain devices (called 'A' devices, connected by both rings).
12. The B devices are connected by only one ring.
13. Specifications 11) and 12) allow a user facility to designate those critical stations which need additional backup and higher channel speeds as Class A stations. The other, less important units, such as isolated work stations, can be hooked up as Class B stations, at a lesser cost. (See following figure).
14. FDDI does not specifically require that all the channels be optical fibers.

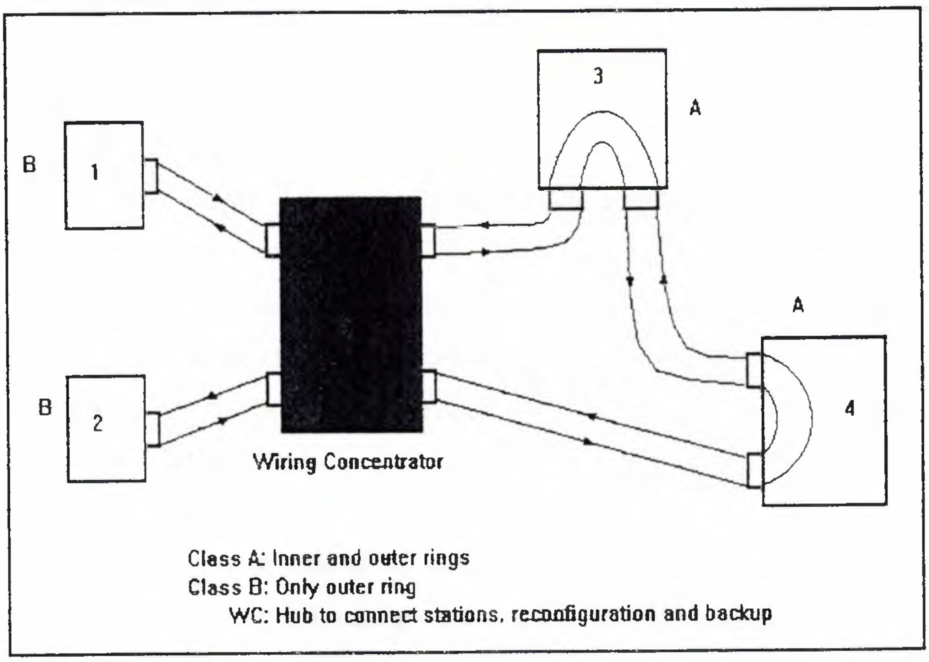

Figure 3.2 Schematic diagram for the specification of FDDI

(c) How a FDDI is fault tolerant:

1. In the event of a lost channel or channels the network remains intact.
2. FDDI provides a reconfiguration by changing the loops through devices between which the channel is lost.
3. All devices have access to the net through the reconfiguration of the inner and outer loops from the wiring concentrator to the couple of devices between which the channel was lost.
4. If a station malfunctions and goes down, FDDI also stipulates that the node can be bypassed: a mirror directs the lightwaves through an alternative path.

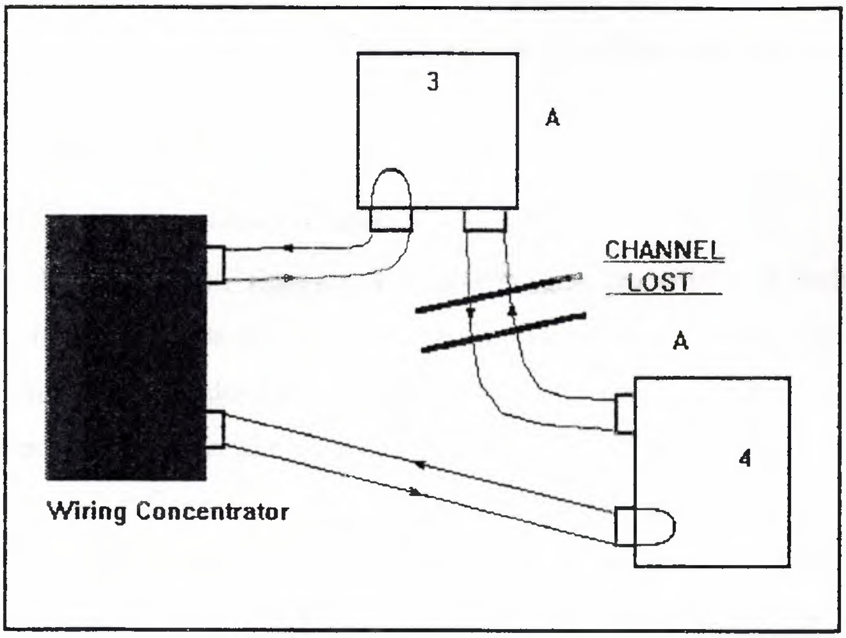

Figure 3.3 illustration of FDDI as a fault tolerant

The above figure depicts a possible reconfiguration in the event of a lost channel or channels. In the figure, the channel between devices 3 and 4 is lost. As can be seen, the network remains intact. All devices have access to the net through the reconfiguration of the inner and outer loops from the wiring concentrator to devices 3 and 4.

It can also be seen that if device 4 malfunctions and becomes inoperable, the signal can be diverted away from the device by using the same channels and the mirrors.

(d) Timing and clocking:

The best code to be used in a network is one which provides frequent signal state changes: the changes allow the receiver to continue to adjust to the incoming signal thereby assuring that the transmitter and the receiver are synchronized with each other. The Manchester code used in IEEE 802.3 standard is only 50% efficient, because every bit requires a two state transition on the line (two baud); using Manchester code, a 100 Mbit transmission rate requires 200 Mbit of bandwidth (a 200 MHz rate). This means that Manchester code requires twice the band for its transmission. Since the 200 MHz rate would create more expense in manufacturing the interfaces and clocking devices, ANSI devised a code called 4B/5B where a four-bit code is used to create a five-bit code: for every four bits transmitted, FDDI creates five bits. These provide clocking for the signal itself. Therefore, the 100Mbit/s rate on FDDI requires only 125 MHz of band.

3.3 Time-Domain Medium Access:

When the form of the shared resource is in time, frequency, or code, we have time-domain, frequency-domain, and code-domain access, respectively. To access the shared medium in the time-domain, a transmission node needs to know when and how long it can send its data. One sample approach is to divide time into frames and partition each frame into a certain number of time slots. In this way, communication nodes can share the same medium by sending data in different slots. Once a slot is allocated during the call setup, a node can repeat the transmission in the same slot of each frame throughout the call duration. This is called deterministic access and there is no traffic contention after the call setup.

Data transmission in two adjacent slots can be continuous in bit timing or separated by guard time. To transmit data in different slots continuously, bit timings from different sources first need to be synchronized. This medium access scheme is called Time Division Multiplexing (TDM). When a network is used for multiple access, it is impossible to synchronize the timings of all nodes distributed over the network. As a result, guard time that separates consecutive slot transmissions is necessary, and the medium access scheme is called Time Division Multiple access (TDMA).

Because TDM requires bit timing synchronization, its implementation is more involved. To synchronize input bit rates, electronic implementation has to be used and direct optical domain multiplexing is not practically feasible. A TDM standard called Synchronous Optic Network (SONET) has been designed for optical transmission. To avoid the electronic bottleneck in high speed multiplexing, SONET introduces an innovative floating payload concept that can synchronize input signals at low speeds.

Because of no need for bit timing synchronization, TDMA can be done directly in the optical domain. An optical transmitter in this case gets access to the medium by transmitting an optical burst consisting of binary bits over a time slot. When all optical networking is concerned, TDMA is an attractive choice compared to TDM. However, TDMA has a worse access efficiency than TDM because of the guard time.

3.3.1 Time Domain Multiple Access:

As illustrated in Figure 3.4, a TDMA frame consists of a reference burst and a certain number of time slots. The reference burst is used for frame synchronization, signaling, and the time slots are used to carry data.

The reference burst consists of three parts: a preamble, a start code, and control data. The preamble is a periodic bit sequence for bit timing synchronization. Depending on how rapid synchronization can be achieved, the preamble length can range from 10 to several hundred symbols.

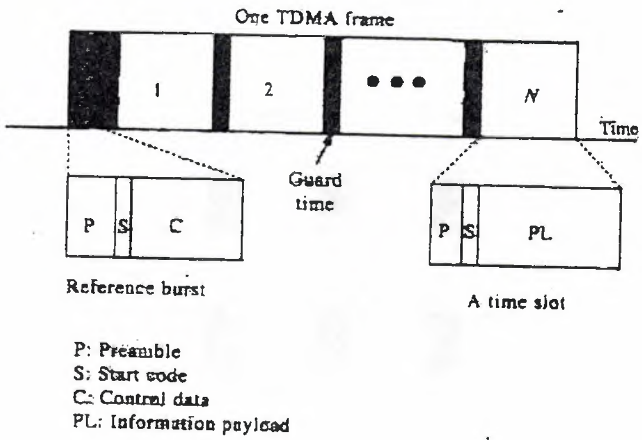

Figure 3.4 A TDMA frame consisting of N slots

Once the bit timing is established, the content in the rest of the reference burst can be read. Following the preamble is a unique start code indicating the end of the preamble and the start of the information portion of the reference burst. By recognizing the word, control data can be interpreted correctly; In general, control data carries information such as station timing, call setup status, and signaling information.

The reference burst in a TDMA frame is the overhead and occupies only a small portion of the frame. The rest of the frame is divided into time slots separated by guard time. Similar to the reference burst, each time slot consists of a preamble, a unique start code, and the information payload. Because of different propagation delays between stations, the guard time between time slots is necessary to avoid overlap between two consecutive time slots.

(a) *Shared Medium:*

Consider a TDMA network made of a shared medium where a node can immediately receive what it just transmits. A single Ethernet coaxial cable and an ALOHA radio network are examples of such a shared medium.

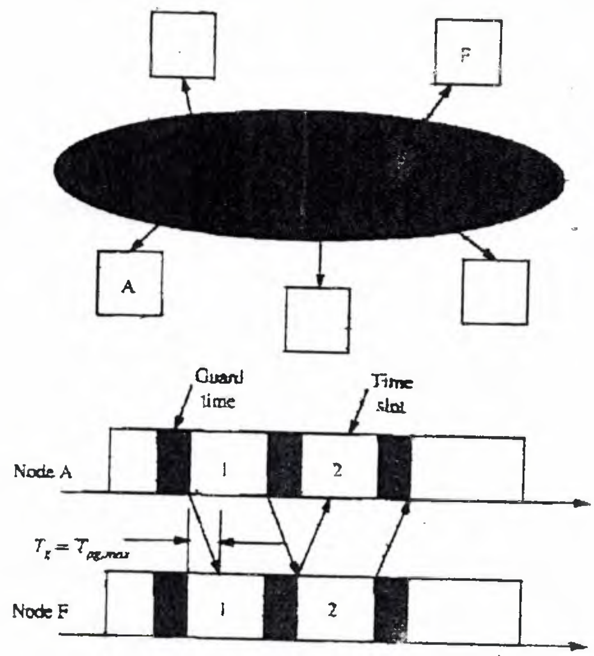

Figure 3.5 Required guard time of a shared TDMA network.

(b) *Medium Access and Time Compression:*

When nodes attached to a TDMA network have data to transmit, they need to wait for available time slots. In TDMA, a slot is obtained through a call setup process. Once a node is granted with an available slot, it can use the same slot in every frame throughout the call. As mentioned earlier, this medium access is called deterministic.

Because of the deterministic access, TDMA is primarily used for constant bit transmission. To support such transmission, input bits of a constant bit-rate signal are tip; Stored in a transmitter buffer. When the assigned time slot arrives, all the bits stored will be transmitted at a much higher speed. This process is illustrated in Figure 3.5. Clearly, data bits are compressed in time during the high-speed transmission. For this reason, TDMA also called Time Compression Multiplexing.

From the compression mechanism described, the payload size of a time slot can be determined for a constant bit-rate input. For an input signal of a bit rate B_S b/s, the total number of input bits during a time frame is $T_f B_S$, where T_f is the TDMA frame size. To transmit these bits over the payload of a time slot, the payload size $T_{S,pload}$ should be at least

$$T_{f,pload} = T_f \frac{B_S}{R} \tag{3.1}$$

Where R is the instantaneous transmission rate.

Slot, Size, Compression Delay and Access Efficiency:

In addition to its payload, a time slot has an overhead for synchronization and signaling. Therefore, the time slot size T_S is

$$T_S = T_{S,oh} + T_{S,pload} \tag{3.2}$$

Where $T_{S,oh}$ is the overhead size for preamble, signaling and control.

From equation (3.2) and (3.1) the time slot size is

$$T_S = T_{S,oh} + T_f \frac{B_S}{R} \tag{3.3}$$

At a given reference burst size T_{ref} and guard time T_g, the total number of time slots that can be accommodated within a frame is

$$N = \left\lfloor \frac{T_f - T_{ref}}{T_S + T_g} \right\rfloor = \frac{R}{B_S} \frac{1 - T_{ref} / T_f}{1 + (R / B_S)(T_{S,oh} + T_g) / T_f} \tag{3.4}$$

From equation (3.4), note that N has an upper bound of R / B_S and can be improved by increasing T_f. At a given $T_g, T_{ref}, T_{S,oh}, R / B_S$, the upper bound can be approached when $T_f >> T_{ref}$ and $T_f >> (R / B_S)(T_{S,oh} + T_g)$.

At a given N, the access efficiency is defined as the ratio of the total data transmission time to the frame size. From equation (3.4)

$$\eta_{TDMA} = \frac{NT_{S,pload}}{T_f} = \frac{NB_S}{R} = \frac{B_S}{R} \left[\frac{R}{B_S} \frac{1 - T_{ref} / T_f}{1 + (R / B_S)(T_{S,oh} + T_g) / T_f} \right] \tag{3.5}$$

When T_f is large enough, the upper limit of the access efficiency is $(B_S / R)\lfloor R / B_S \rfloor$.

3.3.2 Optical Domain Time-Division Multiple Access:

In spite of the difficult trade-off mentioned above, optical domain TDMA is still attractive because of no need to synchronize bit timings among transmission nodes. As a result, as long as the receiver knows the transmission bit rate, each transmission node can have its independent bit clock. Because the bit rate is usually high in optical domain TDMA, this clock independence that avoids the need of bit clock synchronization among transmission nodes is an important characteristic.

The star topology is preferred to minimize the effect of guard time. A block diagram of such an optical domain TDMA network is shown in figure 3.5. To synchronize the access, master frame timing is needs to be distributed to all nodes. To achieve this one of the nodes in the network is called master node, which generates a reference burst every T_f.

To receive data over a certain time slot, a gating signal that is high during the slot interval is generated from the derived slot timing. As illustrated in figure 3.5, data in this slot interval can pass through the gate, be detected, and then be stored in the decompression buffer. The received slot timing derived is also sent to the local transmitter to determine its slot timing for transmission.

Therefore, to have same frame timing at the star coupler, the additional delay D_A is added so that

$$\lfloor T_{M,pg} + T_{A,pg} + D_A \rfloor + T_{A.pg} = T_{M,pg} \bmod T_f \tag{3.6}$$

Where $T_{M,pg} + T_{A,pg} + D_A$ is the relative delay of the transmitter frame timing at the user node with respect to the master frame timing. From equation (3.6)

$$D_A = mT_f - 2T_{A,pg} \tag{3.7}$$

Where m is the smallest integer such that $mT_f - 2T_{A,pg} > 0$. Equation (3.7) shows that a large delay line is needed when T_f is large to have a high access efficiency.

3.3.3 Time-Division Multiplexing:

TDM was first used in digital telephony, where multiple lower rate digital streams called tributary signals are interleaved in the time domain to form a higher rate digital signal. Similar to TDMA, TDM is time domain medium access scheme and each of its frames consists of a certain number of time slots. However, different from TDMA, data carried by different time slots are first synchronized in bit timing, and then interleaved by a higher bit clock. The process of bit timing synchronization is called frequency justification, which is necessary when upstream signals have different bit clock frequencies.

Because all tributary signals are synchronized in bit timing, no guard time is required between adjacent time slots as in TDMA, and there is no need to include a preamble at the beginning of each time slot, When bit synchronization can be achieved, TDM is consequently a better choice then TDMA.

(a) Frame Structure:

A TDM frame structure is illustrated in figure 3.6. It consists of time slots to carry information bits of tributary signals. Because there is no need to include the guard time and preamble for each time slot, the time slot size in TDM is much smaller than that in TDMA for small compression delay. A typical slot size in TDM is only one byte.

In addition to time slots, a TDM frame consists of overhead bits for synchronization, signaling and transmission maintenance. Synchronization bits are necessary to recognize frame boundaries and perform frequency justification; signaling is used to setup and maintain each circuit connection; and maintenance bits such as error check sequence are used to monitor the bit error rate of transmission.

(b) Frequency Justification:

Lower bit rate signals need to have the same bit clock when they are interleaved into a higher bit rate signal. If the frequencies of the lower rate input signals are exactly the same, the TDM system is called synchronous TDM. Otherwise, it is called asynchronous TDM. For asynchronous TDM, lower rate signals of different frequencies cannot be multiplexed directly. They need an intermediate step called frequency justification, which aligns all input tributary signals to a common local clock.

3.4 Wavelength Domain Medium Access:

Wavelength-domain medium access allows multiple transmissions and multiple access through sharing multiple wavelength carriers. Because the wavelength of an optical carrier is inversely proportional to its frequency, WDoMA is essentially the same as frequency-domain medium access that has long been used in radio communications, such as frequency division multiplexing (FDM).

Because of parallel transmission in wavelength domain, WDoMA avoids the speed bottleneck. Therefore it has the potential to utilize a large transmission bandwidth of optical fibers. Because current electronics technology and modulation bandwidths of laser diodes can operate only up to tens of GHz, parallel transmission from WDoMA is a key to high utilization of fiber bandwidths.

3.4.1 Wavelength Domain Multiple Access:

In WDMA, wavelength channels are the shared resources. To access the network, each source node needs to first acquire a wavelength channel. To ensure proper transmission to the final destination, either the destination receiver must be tuned to the wavelength channel or there must exist an efficient routing algorithm that can forward data to the destination. Over the last few years, many access protocols and routing algorithms have been proposed. In general, a good WDMA access protocol should both perform satisfactorily and be easy to implement. That is, from the system prospective, the protocol should achieve a high access efficiency, high throughput, and low transmission delay. From the implementation prospective, the required tuning speeds of tunable devices should be feasible, the number of total wavelength channels needed should be attainable, and the channel allocation algorithm should be simple and fast.

(a) Logical configurations and routing in fixed tuning WDMA:

When the traffic pattern in a WDMA network is stationary, fixed tuning is a good choice to simplify the design and relax the fast tuning requirement. By choosing the tuning wavelengths of individual transceivers properly, a WDMA network can have a logical configuration independent of its physical connections. Once the logical configuration is determined, simple and efficient routing algorithms can be derived.

(b) Dynamic tuning WDMA:

When the traffic pattern changes rapidly and high speed-tuning technology is available, a more efficient medium access control is to allow transceivers to tune dynamically. As a result, single-hop can be achieved by setting up a common wavelength channel between the source transmitter and destination receiver.

From the logical configurations, note that a wavelength channel can be mapped logically to spatial channel. Therefore, dynamic tuning in WDMA is in principle logically equivalent to dynamic spatial switching. Consequently, borrowing switching techniques used in packet switching networks can perform dynamic tuning.

(c) Frequency Reuse:

In a WDMA network where all wavelength channels are coupled in the same-shared medium, the number of wavelengths required is

$$N_{\lambda} = pN \qquad (3.8)$$

Where N is the total number of nodes and p is the number of transceiver pairs per node. Therefore, when N and p are large, the number of channels can be too large to be implemental.

To reduce the number of wavelengths required, the concept of frequency reuse has been proposed. There are several approaches to achieving this. First, multiple shared media can be used for wavelength isolation, As illustrated in figure 3.7, a logical hypercube configuration can be implemented by partitioning wavelength channels into three physical networks. As shown for a network size of 8, the number of wavelength channels can be reduced from 24 to 8. As a result, frequency resolution is reduced by a factor of 3. However, three separate sets of fibers, couplers, and splitters are needed.

3.4.2 Wavelength Division Multiplexing:

Until the late 1980s, optical fiber communications was mainly confined to transmitting a single optical channel. Because fiber attenuation was involved, this channel required periodic regeneration, which included detection, electronic processing, and optical retransmission. Such regeneration causes a high-speed optoelectronic bottleneck and can handle only a single wavelength. After the new generation amplifiers were developed, it enabled us to accomplish high-speed repeaterless single-channel transmission. We can think of single ~Gbps channel as a single high-speed lane in a highway in which the cars are packets of optical data and the highway is the optical fiber. However, the ~25 THz optical fiber can accommodate much more bandwidth than the traffic from a single lane. To increase the system capacity we can transmit several different independent wavelengths simultaneously down a fiber to fully utilize this enormous fiber bandwidth. Therefore, the intent was to develop a multiple-lane highway, with each lane representing data traveling on a different wavelength. Thus, a WDM system enables the fiber to carry more throughputs. By using wavelength-selective devices, independent signal routing also can be accomplished. The highway principle is illustrated in the figure below.

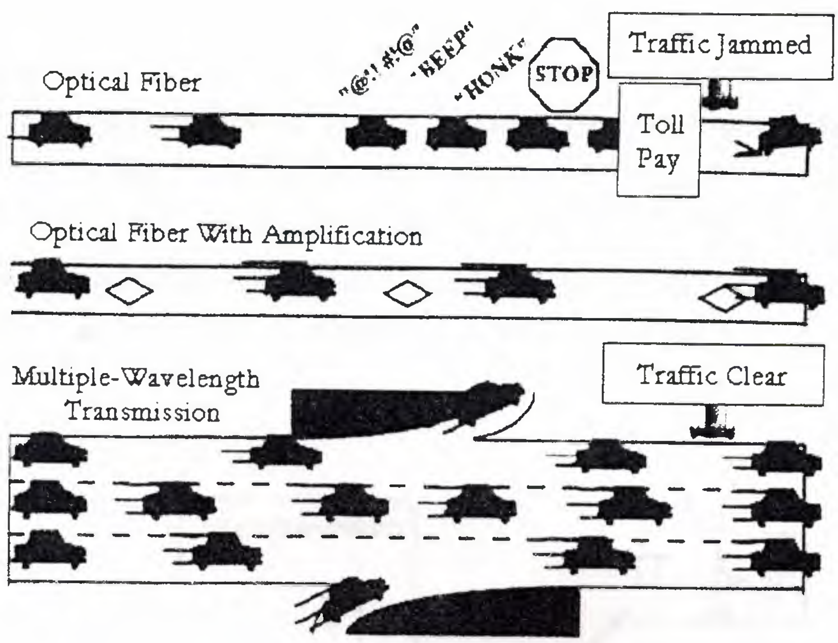

Figure 3.6 illustration of WDM

It is expected that WDM will be one of the methods of choice for future ultra-high bandwidth multi-channel systems. Of course, this could be changed as the technology evolves.

(a) Basic Operation:

As explained before, WDM enables the utilization of a significant portion of the available fiber bandwidth by allowing many independent signals to be transmitted simultaneously on one fiber, with each signal located at a different wavelength. Routing and detection of these signals can be accomplished independently, with the wavelength determining the communication path by acting as the signature address of the origin, destination or routing. Components are therefore required that are wavelength selective, allowing for the transmission, recovery, or routing of specific wavelengths.

In a simple WDM system figure 3.7, each laser must emit light at a different wavelength, with all the lasers, light multiplexed together onto a single optical fiber. After being transmitted through a high-bandwidth optical fiber, the combined optical signals must be demultiplexed at the receiving end by distributing the total optical power to each output port and then requiring that each receiver selectively recover only one wavelength by using a tunable optical filter. Each laser is modulated at a given speed, and the total aggregate capacity being transmitted along the high-bandwidth fiber is the sum total of the bit rates of the individual lasers. An example of the system capacity enhancement is the situation in which ten 2.5-Gbps signals can be transmitted on one fiber, producing a system capacity of 25 Gbps. This wavelength-parallelism circumvents the problem of typical optoelectronic devices, which do not have bandwidths exceeding a few gigahertz unless they are exotic and expensive. The speed requirements for the individual optoelectronic components are, therefore, relaxed, even though a significant amount of total fiber bandwidth is still being utilized.

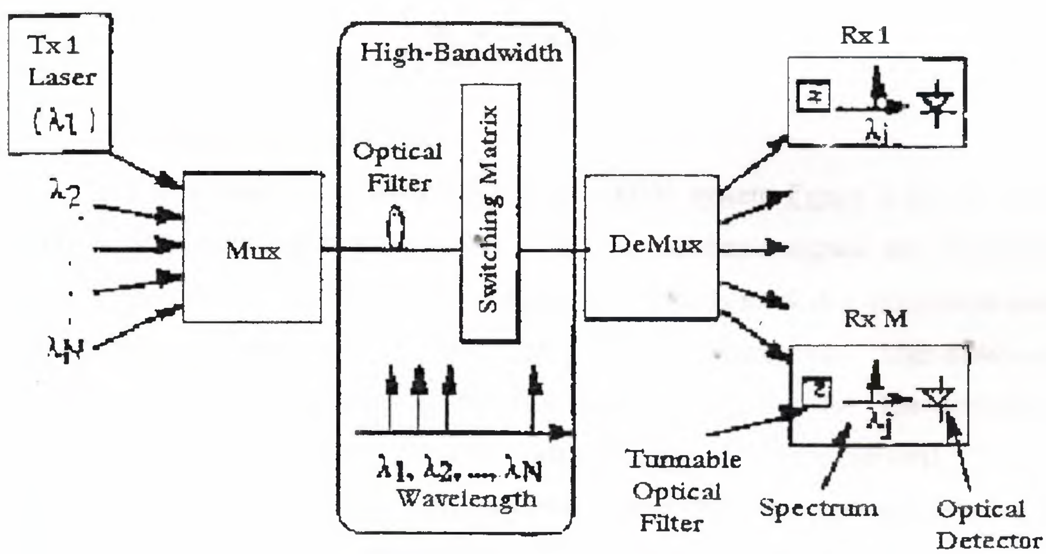

Figure 3.7 Diagram of a simple WDM system

The concept of wavelength demultiplexing using an optical filter is illustrated in Figure 3.8. In the figure, four channels are input to an optical filter that has a nonideal transmission filtering function. The filter transmission peak is centered over the desired channel, in this case, l3, thereby transmitting that channel and blocking all other channels. Because of the nonideal filter transmission function, some optical energy of the neighboring channels leaks through the filter, causing interchannel, interwavelength cross-talk. This cross-talk has the effect of reducing the selected signal's contrast ratio and can be minimized by increasing the spectral separation between channels. Although there is no set definition, a nonstandardized convention exists for defining optical WDM as encompassing a system for which the channel spacing is approximately 10 nm.

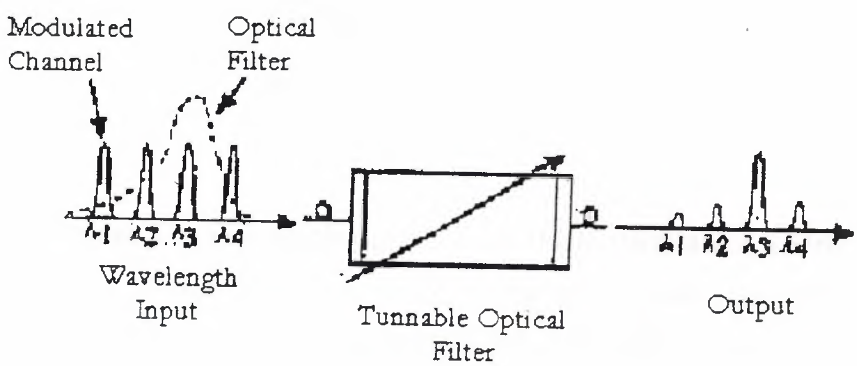

Figure 3.8 Optical WDM channels being demultiplexed
By an optical filter

(b) Topologies and Architectures:

Let us consider a simple point-to-point WDM system Figure 3.9(a) in which several channels are multiplexed at one node, the combined signals are transmitted across some distance of fiber, and the channels are demultiplexed at a destination node. This facilitates high-bandwidth fiber transmission. Additionally, high-bandwidth routing can be facilitated through a multiuser network Figure 3.9(b). The wavelength becomes the signature address for either path through an optical network. Because nodes will want to communicate with each other, either the transmitters or the receivers must be wavelength tunable to facilitate the proper link set-up (in this example, the transmitters were chosen to be tunable).

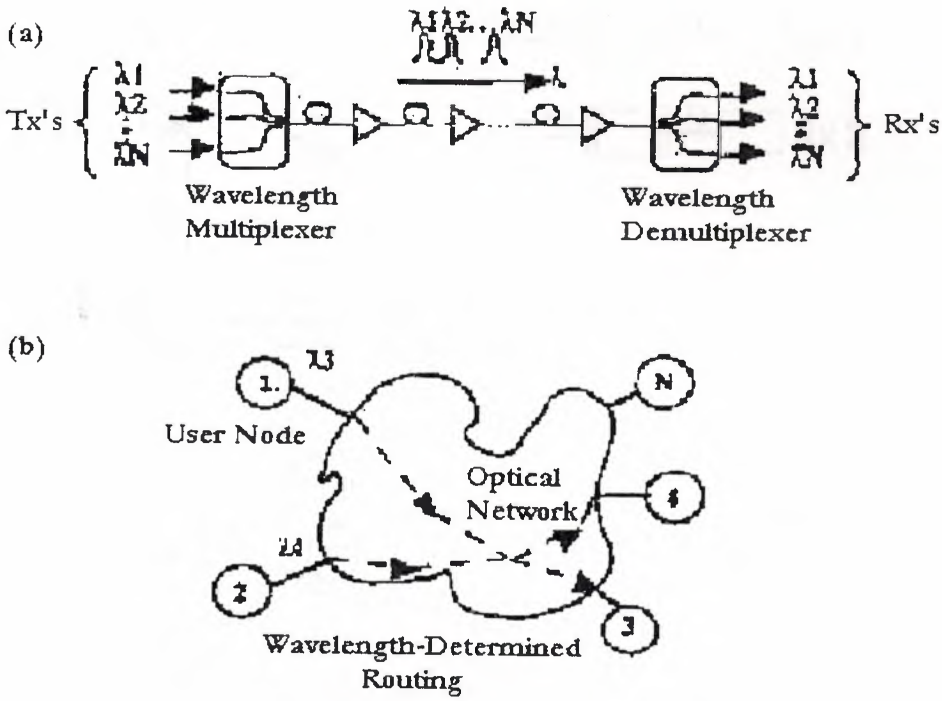

Figure 3.9 **(a)** A simple point-to-point WDM transmission system, **(b)** A generic mutiluser network in which the communication links and routing paths are determined by the wavelength used within the optical switching fabric.

Two common network topologies can use WDM, namely, the star and the ring networks Figure 3.10. Each node in the star has a transmitter and a receiver, with the transmitter connected to one of the central passive star's inputs and the receiver connected to one of the star's outputs. WDM networks can also be of the ring variety. Rings are popular because so many electrical networks use this topology and because rings are easy to implement for any network geographical configuration. In this example, each node in the unidirectional ring can transmit on a specific signature wavelength, and each node can recover any other node's wavelength signal by means of a wavelength-tunable receiver.

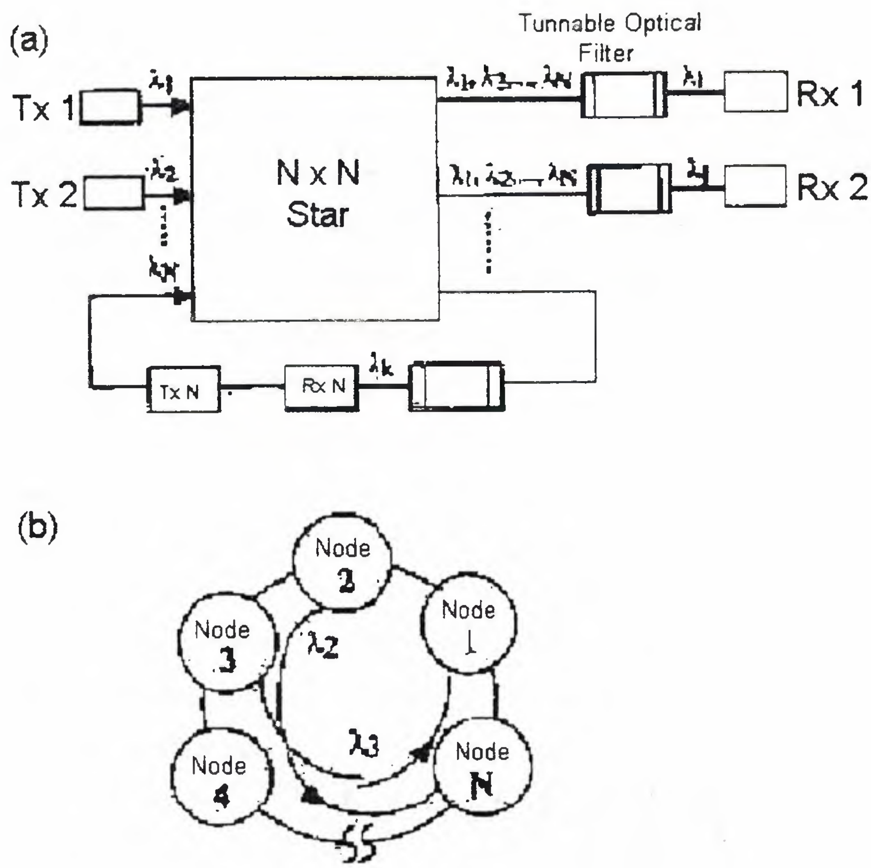

Figure 3.10 (a) Diagram of a simple star network in Which WDM is used for routing and multiplexing purposes **(b)** An example of WDM unidirectional ring network

In both the star and the ring scenarios, each node has a signature wavelength, and any two nodes can communicate with each other by transmitting on that wavelength. This implies that we require N wavelengths to connect N nodes. The obvious advantage is that data transfer occurs with an uninterrupted optical path between the origin and the destination, known as a single-hop network. The optical data start at the originating node and reach the destination node without stopping at any other intermediate node. A disadvantage of a single-hop WDM network is that the network and all its components must accommodate N wavelengths, which may be difficult (or impossible) to achieve in a large network. Current fabrication technology cannot provide and transmission capability cannot accommodate 1,000 distinct wavelengths for a 1,000-user network.

An alternative to requiring N wavelengths to accommodate N nodes is to have a multihop network, in which two nodes can communicate with each other by sending through a third node, with many such intermediate hops possible. A dual-bus multihop eight-node WDM network is shown in Figure 3.11 for which each node can transmit on two wavelengths and receive on two other wavelengths. The logical connectivity is also shown. As an example, if node 1 wants to communicate with node 5, it transmits on wavelength l_1 and only a single hop is required. However, if node 1 wants to communicate with node 2, it first must transmit to node 5, which then transmits to node 2, incurring two hops. Any extra hops are deleterious in that they:

(a) Increase the transmit time between two communicating nodes, since a hop typically requires some form of detection and retransmission

(b) Decrease the throughput, since a relaying node can transmit its own data while it in the process of relaying another node's data

However, a multihop networks do reduce the required number of wavelengths and the wavelength tunability range of the components.

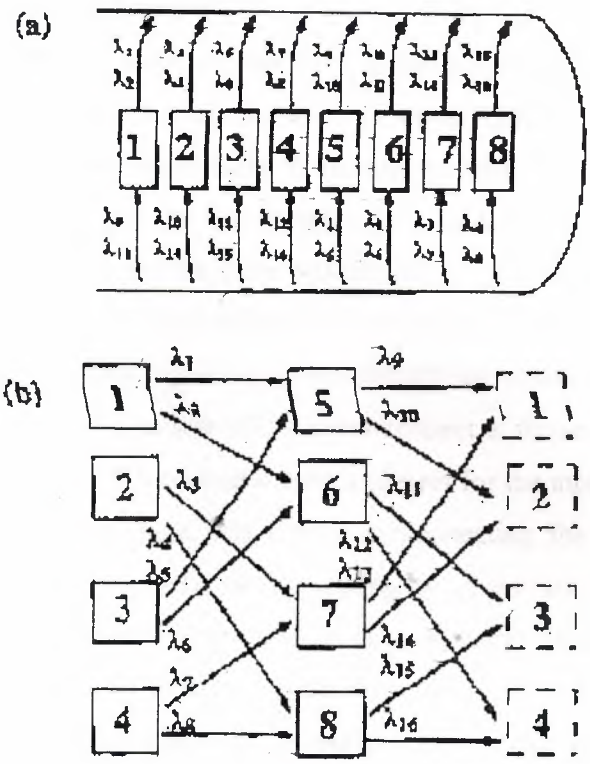

Figure 3.11 (a) A dual-rail WDM bus multihop 8 Node network and (b) the logical network connectivity.

(c) Wavelength Shifting and Wavelength Reuse:

In an ideal WDM network, each user would have its own unique signature wavelength. Routing in such a network would be straightforward. This situation may be possible in a small network, but it is unlikely in a large network whose number of users is larger than the number of provided wavelengths. In fact, technologies that can provide and cope with 20 distinct wavelengths are the state of the art. There are some technological limitations in providing a large number of wavelengths, for instance: due to channel-broadening effects and non-ideal optical filtering, channels must have minimum wavelength spacing. Wavelength range, accuracy, and stability are extremely difficult to control.

Therefore, it is quite possible that a given network may have more users than available wavelengths, which will necessitate the reuse of a given set of wavelengths at different points in the network.

(d) Passive Wavelength Routing:

In case we have a limited number of available wavelengths, a network can use passive routing of a signal through the network based only on its wavelength. The routing is designed to reuse wavelengths in non-shared links. For example, we can see in Figure 3.12 that user I can use wavelength l_1 to establish a link with user II, while simultaneously user V can reuse the same wavelength, l_1, to establish a connection with user III. This functionality is accomplished by the proper arrangement of the cross-connects that route an input signal to a wavelength-determined output. A simple example of the operation of a passive WDM cross-connect is shown in Figure 3.13. The cross-connect is composed of wavelength demultiplexers for the input stage, wavelength multiplexers for the output stage, and fibers interconnecting the two stages. In the example, although there are only two wavelengths, there are four possible non-interfering routing paths based on both wavelength and origin. In general, instead of N wavelengths and N possible connection paths, now there are N wavelengths and N^2 connections. The same wavelength could be reused by any of the input ports to access a completely different output port and establish an additional connection. This technique increases the capacity of a WDM network.

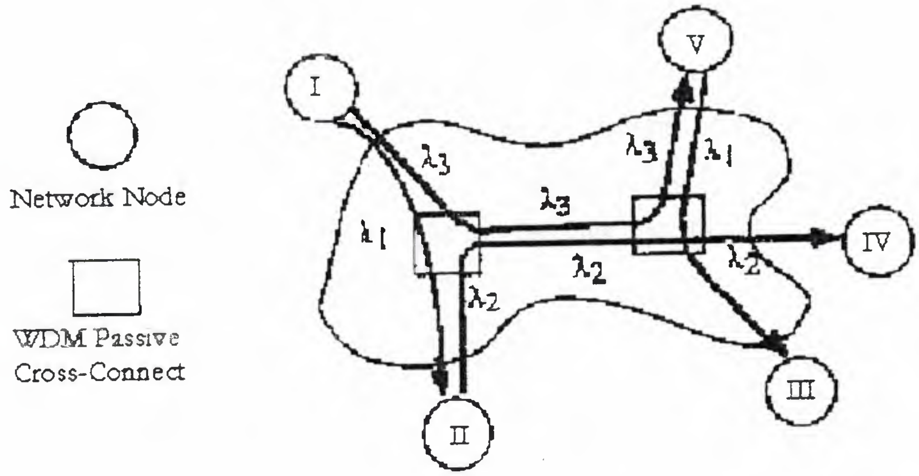

Figure 3.12 Passive wavelength routing in a network utilizing wavelength reuse

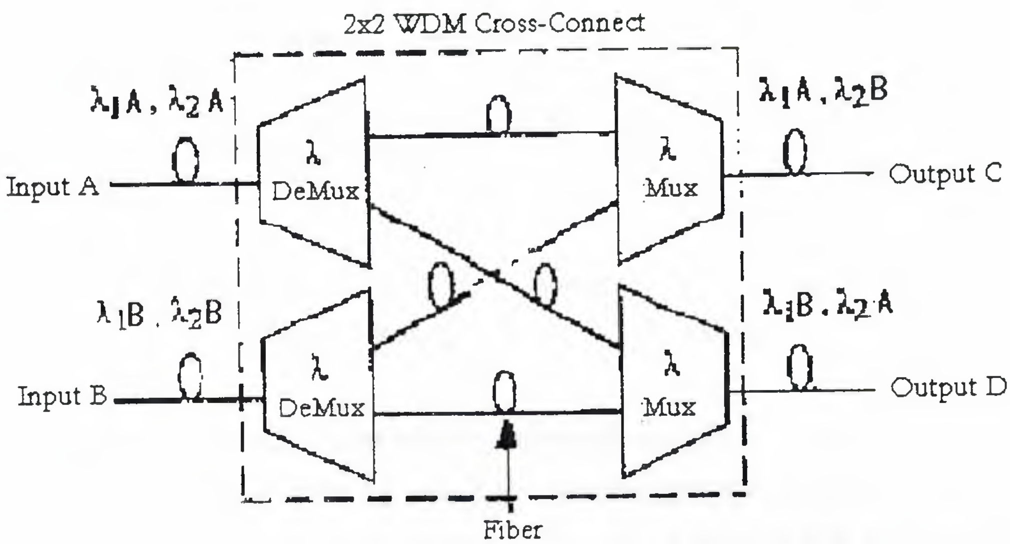

Figure 3.13 A 2-by-2 wavelength cross-connect in which output port routing determined both by the specific input wavelength and by the specific input port

(e) Active Wavelength Shifting:

In contrast to passive routing, which is limited to a static network conditions, active wavelength shifting is dynamically deals with changes of the network condition. It does that by changing the routing depending on the available links and wavelengths. This concept of a network requiring active wavelength shifting is illustrated in Figure

3.14. In the figure there are two small LANs connected to a larger WAN, and each LAN can transmit on only two available wavelengths (l_a and l_b). Node I wishes to communicate with node II. When node I wishes to transmit, the only wavelength available is l_a. However, when the signal reaches the right LAN, it is revealed that l_a is already being used by the right LAN. Therefore, the only way for the signal to reach node II is to be actively switched onto the available l_b.

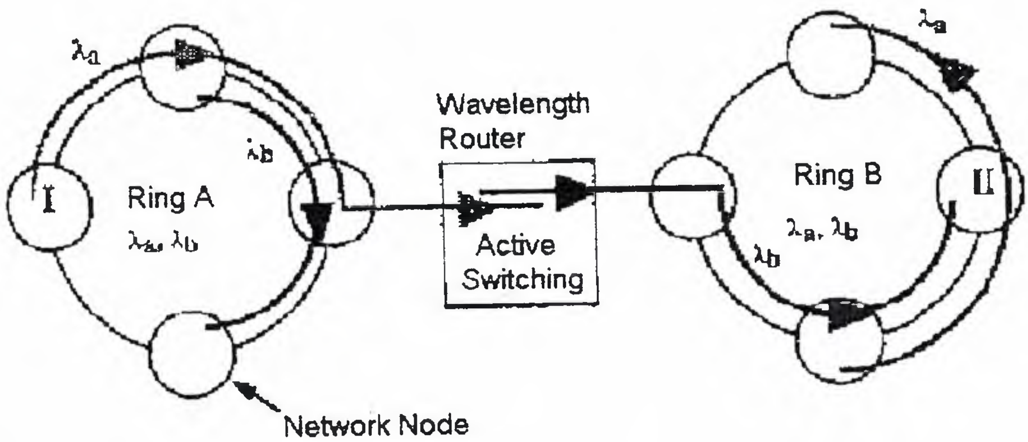

Figure 3.14 Active wavelength switching in a dynamic WAN in which two smaller LAN can transmit on only a limited set of wavelengths.

Another scenario that would require active wavelength switching is where one set of wavelengths are used exclusively by each LAN, whereas another set of wavelength is used exclusively for communication between LANs. The wavelengths that are used in a LAN that can be reused by each LAN since it will not interfere with another LAN.

Shifting one wavelength to another wavelength complexes the network functionality. One method to perform the active wavelength switching is to employ optoelectronic wavelength shifters. This method necessitates optoelectronic conversions and will cause an eventual optoelectronic speed bottleneck. In order to overcome this problem the final goal is to achieve all-optical active wavelength shifting to retain a high speed data path. All-optical means that all the shifters are purely optical, i.e. not using optoelectronic conversion of the optical data.

CHAPER 4

APPLICATION OF FIBER OPTICAL NETWORKING

In order to appreciate the many areas in which the application of lightwave transmission via optical fibers may be beneficial, it is useful to review the advantages and special features provided by this method of networking. The primary advantages obtained using optical fibers for line transmission were discussed in Section 1.3 and may be summarized as follows:

(a) Enormous potential bandwidth;

(b) Small size and weight;

(c) Electrical isolation;

(d) Immunity to interference and crosswalk;

(e) Signal security;

(f) Low transmission loss;

(g) Raggedness and flexibility;

(h) System reliability and ease of maintenance;

(I) Potential low cost.

The use of fibers for optical communication does have some drawbacks in practice. Hence to provide a balanced picture these disadvantages must be considered. They are:

(a) The fragility of the bare fibers;

(b) The small size of the fibers and cables which creates some difficulties with splicing and forming connectors;

(c) Some problems involved with forming low loss T-couplers;

(d) Some doubt in relation to the long-term reliability of optical fibers in the presence of moisture

(e) An independent electrical power feed is required for any repeaters;

(f) New equipment and field practices are required;

(g) Testing procedures tend to be more complex.

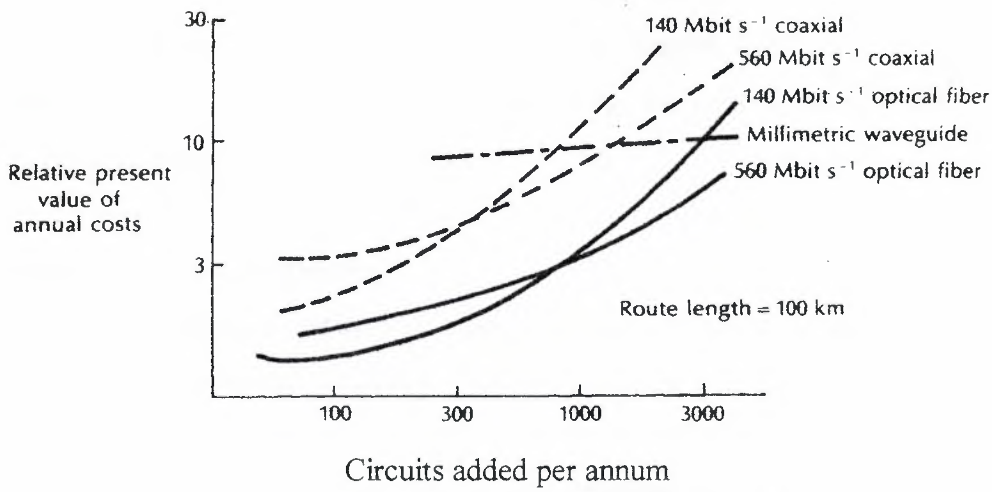

Figure 4.1 Relative present value cost comparison of different high capacity line transmission media.

4.1.2 Junction Network:

The junction or interoffice network usually consist of routes within major conurbation's over distance of typically 5-20 Km. However, the distribution of distance between switching centers (telephone exchange) or offices in the junction network of large urban areas varies considerably for various countries as indicated in Figure 4.2.

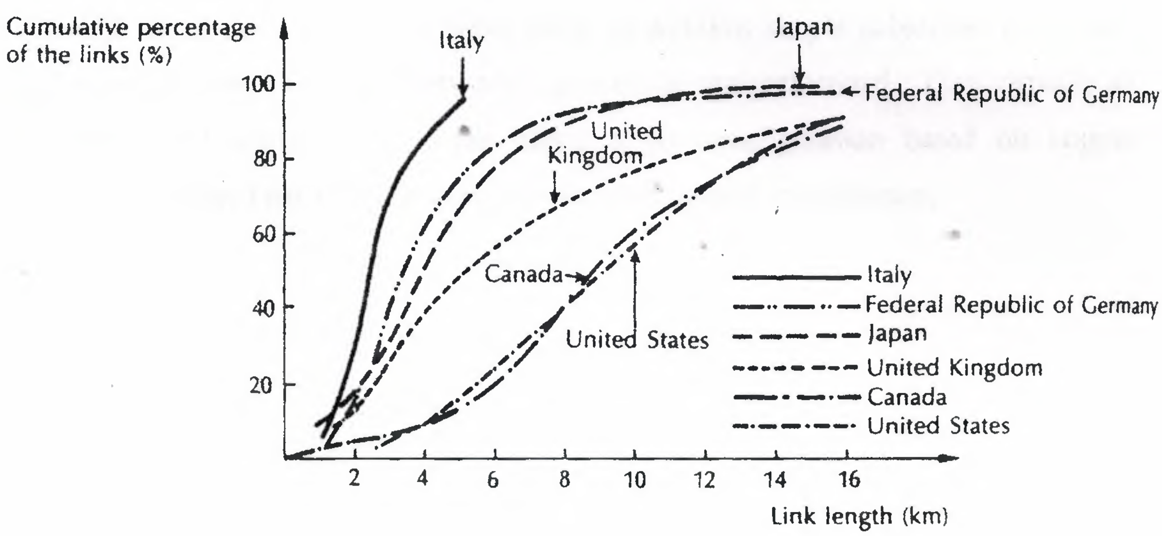

Figure 4.2 Distribution of distances between switching centers in metropolitan area.

It may be observed from Figure 4.2 that the benefits of long unreported transmission distances offered by optical fiber systems are not as apparent in the junction network due to be generally shorter link lengths. Nevertheless optical fiber junction systems are often able to operate using no intermediate repeaters whilst alleviating duct congestion in urban areas.

4.1.3 Local and Rural Networks:

The local and rural network or subscriber loop connects telephone subscribers to the local switching center or office. Possible network configurations are shown in Figure 4.3 and include a ring, tree and star topology from the local switching center.

In a ring network Figure 4.3 (a) any information fed into the network by a subscriber passes through all the network nodes and hence a number of transmission channels must be provided between all nodes.

The tree networks, which consists of several branches as indicated in Figure 4.3 (b), must also provide a number if transmission channels on its common links. However in comparison with the ring network it has the advantage of greater flexibility in relation to topological enlargement, Nevertheless in common with the ring network, the number of subscriber is limited by the transmission capacity of the links used.

In contrast, the star network Figure 4.3 (c) provides a separate link for every subscriber to the local switching center. Hence the amount of cable required is considerably increased over the ring or tree network, but is offset by enhanced reliability and availability for the subscribers. In addition simple subscriber equipment is adequate (i.e, no TDM) and network expansion is straightforward. Thus virtually all local and rural telephone networks utilize a star configuration based on copper conductors (twisted pair) for full duplex (both ways) speech transmission.

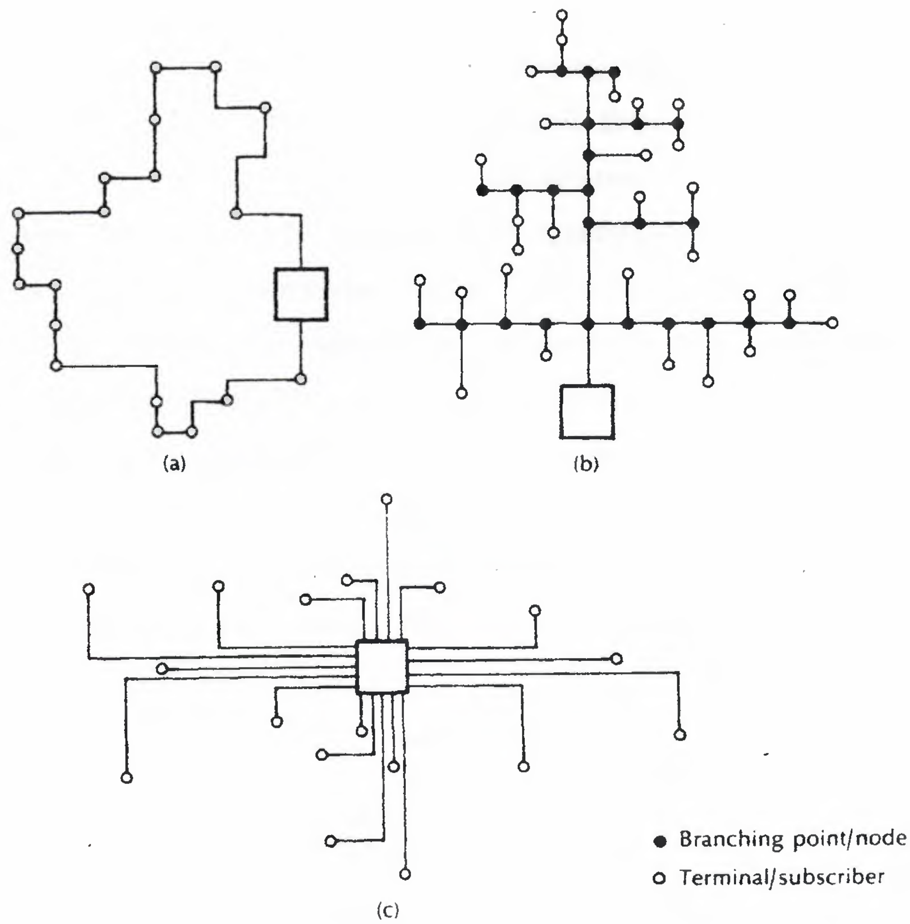

Figure 4.3 Local access network configurations: (a) Ring network, (b) Tree network, (c) Star network

These field trials utilize star configuration providing a full range of wideband services to each subscriber through the use of both analog and digital signals on optical fibers.

4.2 Military Applications:

In these applications, although economics are important, there are usually other, possibly overriding, considerations such as size, weight, deployment, survivability (in both conventional and nuclear attack) and security. The special attributes of optical fiber networking therefore often lend themselves to military use.

4.2.1 Mobiles:

One of the most promising areas of military application for optical fiber networking is within military mobiles such as aircraft, ships and tanks. The small size and weight of optical fibers provide an attractive solution to space problems in these mobiles which are increasingly equipped with sophisticated electronics. Also the wideband nature of optical fiber transmission will allow the multiplexing of a number of signals on to a common bus. Furthermore, the immunity of optical transmission to electromagnetic interference (EMI) in the often noisy environment of military mobiles is a tremendous advantage. This also applies to the immunity of optical fibers to lightning and electromagnetic pulses (EMP) especial within avionics. The electrical isolation, and therefore safety, aspect of optical fiber networking also proves invaluable in these applications, allowing routing through both fuel tanks and magazines.

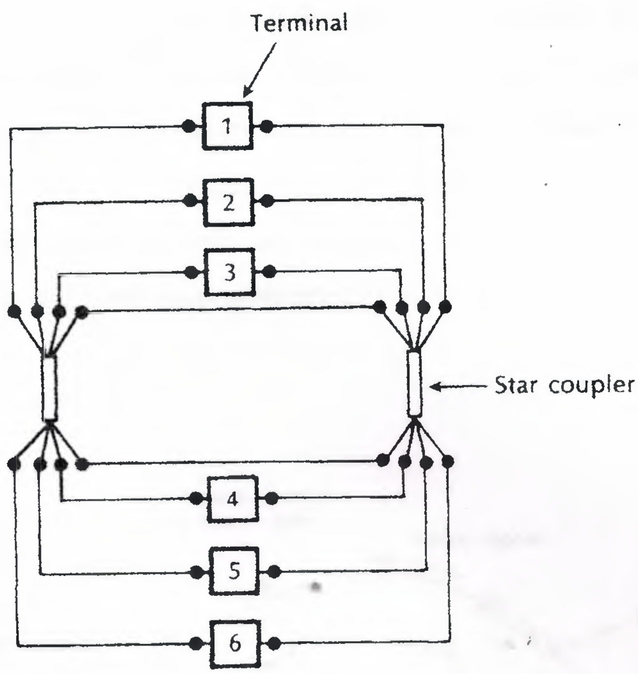

Figure 4.4 Multiple access bus showing the interconnection of six terminals using two four-way tranmissive star couplers

The above advantage were demonstrated with preliminary investigation involving fiber bundles and design approaches now include multi terminal data systems using single fibers, and use of an optical data bus. In the former case, the time division multiplex system allows ring or star configuration to be realized, or mixtures of both to create bus networks. The multiple access data highway allows an optical signal injected at nay access point-to-appear at all other access points. An example is shown in Figure 4.4 which will illustrate the interconnection of six terminals using two four-way transitive star coupler. These devices give typically 10 dB attenuation between any pair of port.

4.2.2 Communication Links

The other major area for the application of optical fiber networking in the military sphere includes both short and long distance networks links. Short distance optical fiber systems may be utilized to connect closely spaced items of electronic equipment in such areas as operations rooms and computer installations. A large number of these systems have already been installed in military installations in the UK. These operate distances from several centimeters to a few hundred meters at transmission rates between 50 bauds and 4.8 k bit/s. In addition a small number of 7 MHz video links operating over distances of up to 100 m are in operation. There is also a requirement for long distance communication between military installations which could benefit from the use of optical fibers. In both these cases advantages may be gained in terms of bandwidth, security and immunity to electrical interference and earth electrical interference and earth loop problems over conventional copper systems.

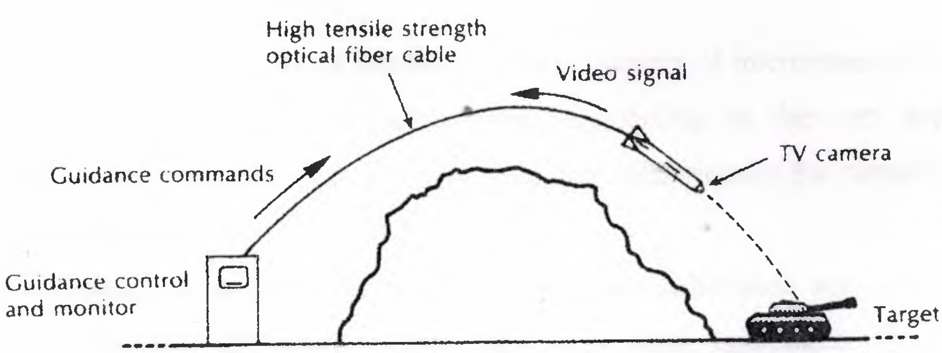

Figure 4.5 A fiber guided weapon system

Other long distance applications include torpedo and missile guidance, informatioon links between military vessels and maritime, towed sensor arrays. In these areas the available bandwidth and long unrepeatered transmission distances of optical fiber systems provide a solution which not generally available with conventional technology. A fiber guided weapons system is illustrated in Figure 4.5, whereby a low loss, high tensile strength fiber is used to relay a video-signal back to a control station to facilitate targeting by an operator.

Optical fiber cables have been installed and rested within the Ptarmigan tactical communication system developed for the British Army. They may be utilized as a direct replacement for the HF quad cable system previously employed for the intranodal multichannel cable links within the system. The optical fiber element of the system comprises an LED source emitting at a wavelength of 0.9 μ m, graded index fiber and an APD detector. It is designed to operate over a range of up to 2 km at data rates of 256,512 and 2048 kbit/s without the use of intermediate repeaters. The optical fiber cable assemblies are about half the weight of the HF quad cable, and are quick and easy to deploy in the field Furthermore, special ruggedized expanded beam optical connectors have been shown to be eminently suitable for use in conditions involving dust, dirt, rough handling and extreme climates. Successful integration of an optical fiber system into a more complex tactical communication system for use in the military environment has demonstrated its substantial operational and technical advantages over HF metallic cable systems.

In summary, it appears that confidence is being established in this new technology such that its widescale use in military applications in the future is ensured.

4.3 Computer Applications:

Modern computer systems consist of a large number of interconnections. These range from lengths of a few micrometers (when considering on chip very large scale integration (VLSI) connections) to perhaps thousands of kilometers for terrestrial lonks in computer networks.

Nevertheless it is likely that optical transmission techniques and optical fibers themselves will find application within data processing equipment. In addition, investigations have already taken place into the use of optical fibers for mains isolators and digital data buses within both digital Telephones exchanges and computers. Their small size, low loss, low radiation properties and freedom from ground loops provide obvious advantages in these applications.

At present, however, a primary potential application for optical fiber networking occurs in interequipment connections, These provide noise immunity, security and removal of earthy loops problems, together with increased bandwidth and reduced cable size in comparison with conventional coaxial cable computer system interconnection. The interequipment connection topology for a typical mainframe computer system (host computer) is illustrated in Figure 4.6.

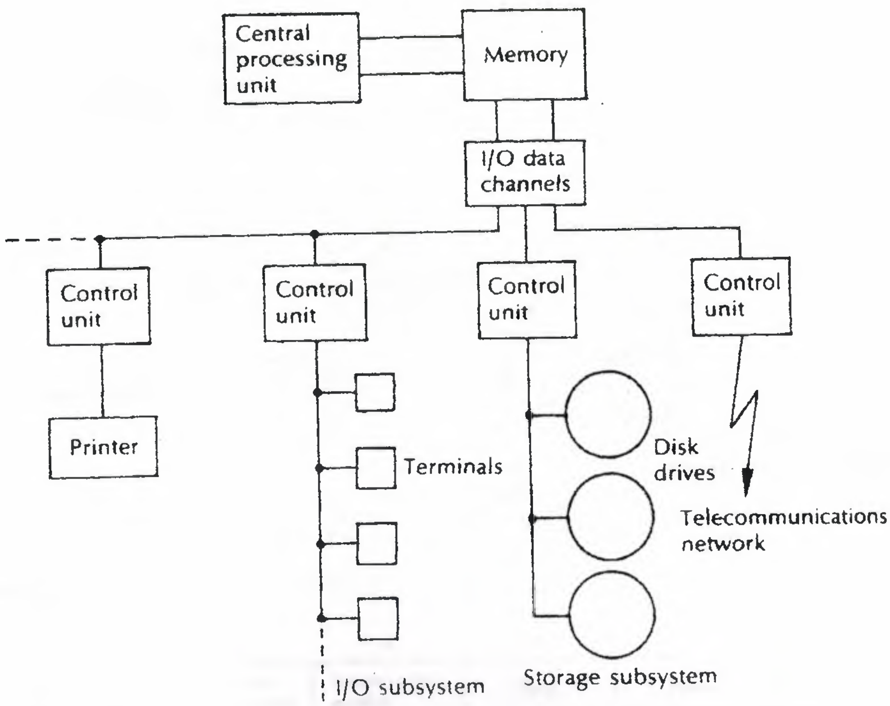

Figure 4.6 Block schematic of a typical mainframe computer system

4.3.1 Local Area Network:

A local area network (LAN) is generally defined as an interconnection topology entirely confined within a geographical area of a few square kilometers. It is therefore usually confined to either a single building or a group of buildings contained within a site or establishment (industry, military, educational, etc.). Hence, the data processing and peripheral equipment together with any networks are usually under the control of the owning body rather that a common carrier….

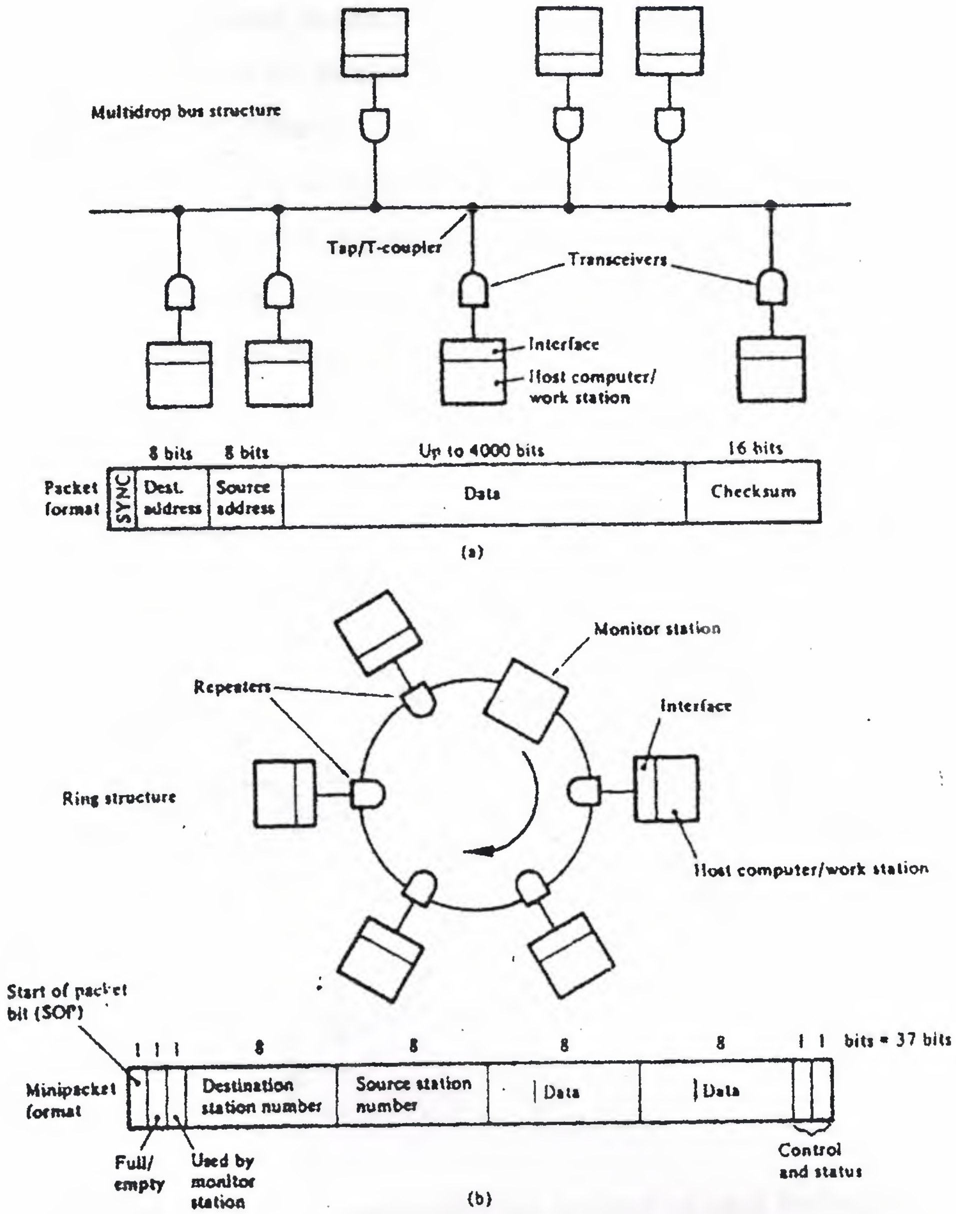

Figure 4.7 Local Area Networks, (a) the Ethernet network topology and packet format; (b) the Cambridge ring topology and packet format.

In common with local and rural networks LANs may be designed in three major configurations: the star, ring and bus. Work has been in progress for a number of years on various network architectures and protocols, in the main utilizing metallic communication links. To date a standard configuration has not been universally adopted. However, two basic techniques for the implementation of local area computer networks have obtained partial acceptance. These two network topologies are illustrated in Figure 4.7 and are known as the Ethernet and the Cambridge ring. The Ethernet network, developed by Xerox, consists of a multidrop bus configuration whereby host computers or work stations are attached to a coaxial cable which forms a transmission line operating at a rate of 3 Mbit/s.

The Cambridge ring network developed at the University of Cambridge, UK and illustrated in Figure 4.3(b) also utilizes data packets. The ring consists of a monitor station as well as a number of work stations (or host computers) with associated repeaters which together form ring nodes.

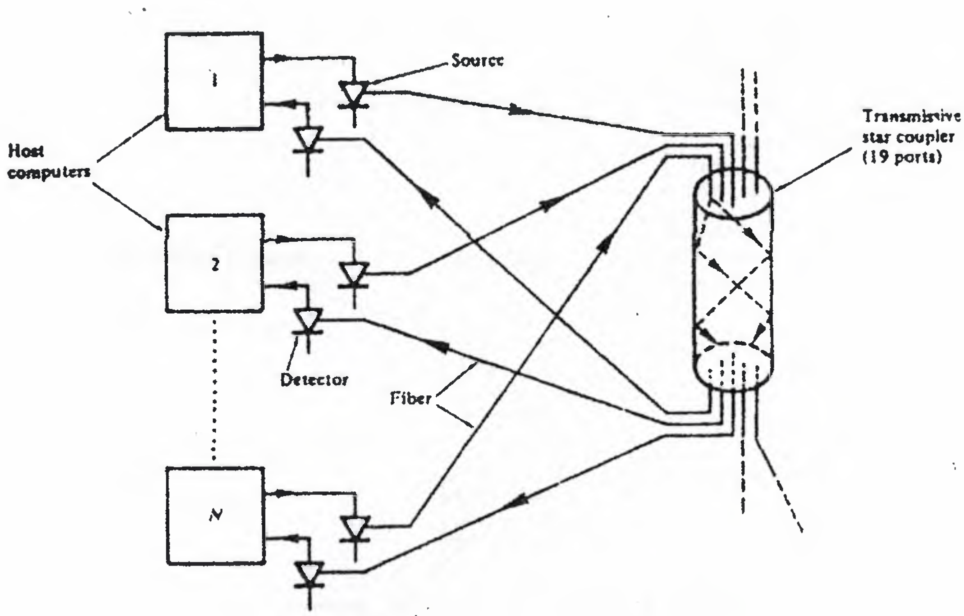

Figure 4.8 The passive transmissive star network adopted for Ethernet

Optical fibers, however, displayed drawbacks when used in the multidrop bus network. These resulted from the high insertion losses encountered at optical beam splitters (or T-couplers) which only allowed a small number of work stations to be connected (generally less than ten). Consequently a passive transitive star network Figure 4.8 was adopted for Fibernet. A 19 port transitive star coupler was utilized which gave an insertion loss of 10 dB between any 2 ports. Using the Ethernet packet switching and protocol, data were successfully transmitted at 150 Mbit/s and 100 Mbit/s over distances of 0.5 and 1.1 km respectively, with zero errors.

Perhaps the largest scale applications at present for optical fiber systems within local area networks are with regard to single channel and multiplexed star networks. These network configurations tend to match the communication system design of large mainframes and minicomputers. A typical network is shown in Figure 4.9. The high bandwidth provided by optical fibers often allows both asynchronous and synchronous terminals to be drive at full rate without the need for the statistical multiplexing required in the case of Fibernet.

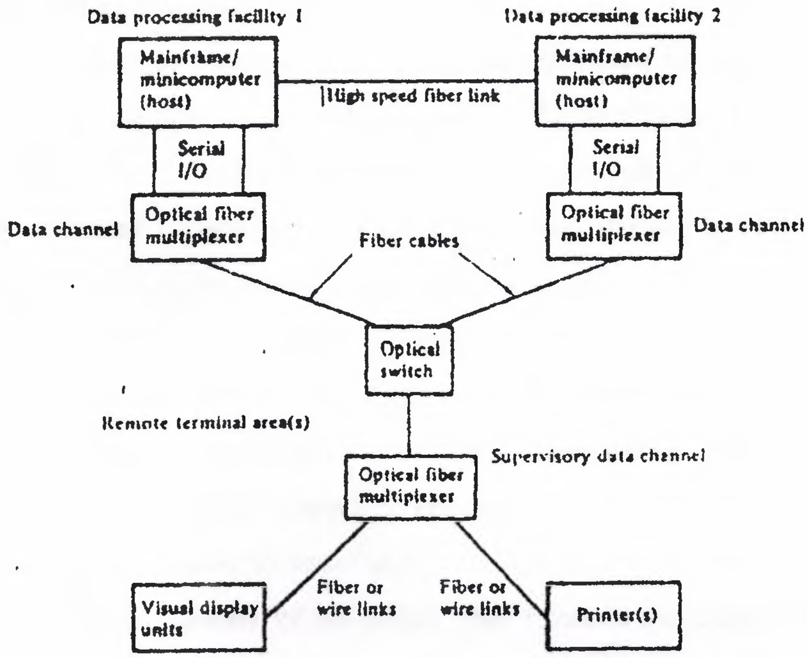

Figure 4.9 An example of an optical fiber local area network

Optical system are also being utilized in the Cambridge ring configuration. They have fueled the development of a higher performance ring operating at 40 Mbit/s which promises to find significant application. Furthermore, improvements in optical fiber connector technology and in the optical output power provided by light sources may lead to the extensive use of bus networks in the future.

CONCLUSION

Nearly exponential increase in usage of voice, video and data communication, places new requirements on the transmission media. The need for low loss, low dispersion, ultra-wide bandwidth, and high dynamic range, durability, upgradability, and low cost communications networks, have shifted the focus from traditional copper coaxial wire to optical fiber links. The optical network design plays an important role in error-free system reliability. Optical fibers utilize light as a signal source, instead of electrical signals. A laser or a light-emitting diode generates the light which is transmitted through an extremely thin reflective glasslike cable. The light is switched on and off by a transmitter to obtain a binary code that represents the user data. The light waves travel through the *core* of the cable, bouncing off a layer called *cladding*

The project covers the bandwidth and data rate capabilities of optical fibers and the essentially unlimited capabilities for capacity increase of existing fiber links. It also covers the properties of single-mode, multi-mode and plastic optical fibers and their use in short-haul and long-haul networking. Optical transmitters, optical receivers, packet switching, Time division multiplexing, wavelength division multiplexing (WDM) have been studied with intensive care. Optical transmission has several significant advantages over electrical systems: greater capacity, immunity to electrical interference, small dimensions, more secure, easier to install and operate at high or low temperatures, lower error rate. The transfer capacity of an optical fiber exceeds the transfer capacity of a legacy copper wire by a large margin. By utilizing novel optical transmission technologies such as WDM (Wavelength Division Multiplexing), the transfer capacity of the optical network can be in Terabits range. Also the losses during transfer are remarkably small, so the need of amplifiers decreases. The fibers are immune to electromagnetic radiation and they generate no electromagnetic radiation to their surroundings.

Although the property of optical fibers seems to be perfect, there still are some linear and non-linear phenomena, which restrict the possibilities of optical networks. On the other hand such phenomena can be utilized to implement all optical devices for packet switching.

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