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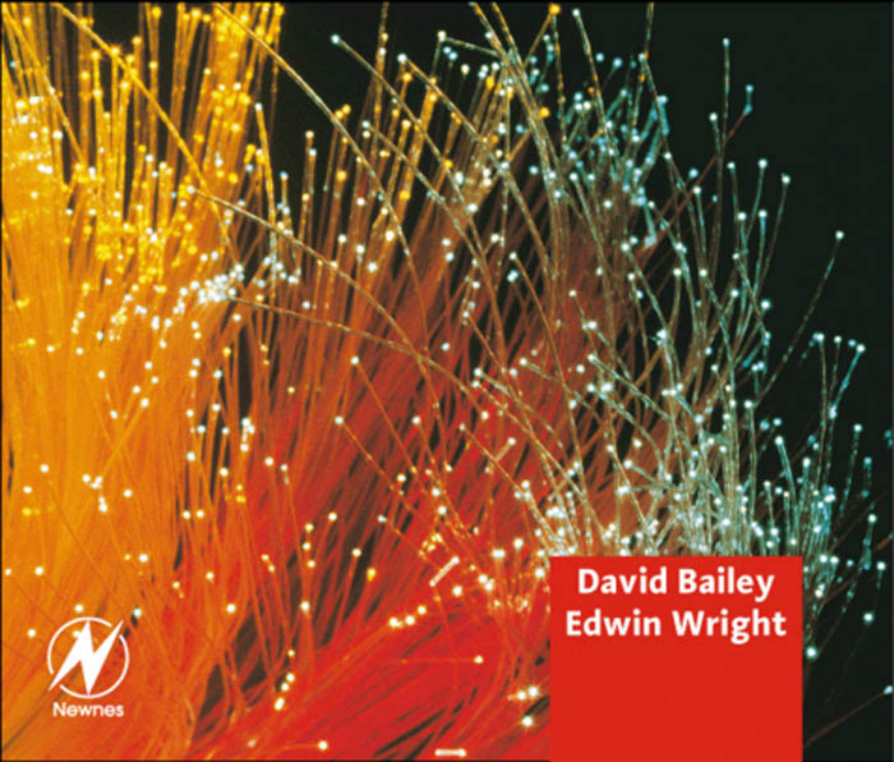

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Contents

Preface

Light in a glass medium can carry more information over longer distances than electrical signals over a copper medium. It is also immune to electrostatic or electromagnetic interference. This book provides an extensive overview of the construction, operation, and applications of optical fiber, with more emphasis on installation and troubleshooting.

The first step in the development of fiber for data communications applications was to develop a glass so pure that one per cent of the light would be retained at the end of a one kilometer length, the existing distance (without repeaters) for copper-based telephone systems. This represents an attenuation of 20 decibels per kilometer (20 dB/km). During the 1960s, researchers all over the world worked on the challenge and the breakthrough came in 1970 when Corning scientists Dr. Maurer, Dr. Keck and Dr. Schultz created a fiber with the required attenuation characteristics.

Since then, glass fiber technology has advanced tremendously in terms of performance and applications.

Current fiber performance is approaching the theoretical limits of silica-based glass materials and this enables fiber to transmit digitized light signals well beyond 100 km without amplification, when used in conjunction with appropriate electronics. When compared with the early attenuation levels of 20 dB per km, present achievable levels of less than 0.35 dB/km at 1310 nanometers (nm) and 0.25 dB/km at 1550 nm are quite remarkable.

Optic fiber is used extensively in the following applications, to name but a few:

- Automotive
- Healthcare
- Imaging
- Lighting
- Machine vision
- Microscopy
- Night vision
- Traffic control
- Data communications
- Local area networking

This book gives both the novice and the experienced user a solid grasp of the principles and practical implementation of fiber optic cabling for industrial applications. After reading this book, we believe you will have:

- A solid knowledge of fiber optic communications systems
- An understanding of state of the art fiber optics technology and installation practices
- The knowledge to attempt jointing, splicing and testing fiber optic systems
- Knowledge of the correct procedures for cable installation and termination
- The know-how to install your own fully operational fiber optics system
- Insight into new approaches on troubleshooting fiber optics

This book is intended for engineers and technicians who are:

- Instrumentation and control engineers
- Electrical engineers
- Project engineers and managers
- Design engineers
- Telecommunications engineers and technicians
- Process control engineers
- Maintenance engineers, technicians and supervisors
- Consulting engineers
- Systems engineers
- Electricians
- Electrical and instrumentation technicians

A basic knowledge of electrical and electronic principles is useful in understanding the outlined concepts, but the book also focuses on the fundamentals, hence understanding the key concepts should be easier.

The book is laid out in a sequential manner to provide a logical study of the subject of fiber optics. It is also laid out in the order that would be used to design a fiber optic transmission system. The structure of the book is as follows.

Chapter 1: Introduction to fiber optic systems. This chapter provides a background to the contents of the book, an historical overview of the development of fiber optic communications and a comparison of copper and optical fiber technologies.

Chapter 2: Definitions and fundamental principles. This chapter provides an introduction to the important fundamentals and concepts of electronic communications. This chapter also provides a brief review of the different types of copper cables and their operating parameters.

Chapter 3: Theory of fiber optic transmission. This chapter discusses the theory associated with transmission of information down optical fibers. It covers the different types of fibers available, transmission parameters, the different modes of transmission and the losses associated with optical fibers.

Chapter 4: Fiber optic cable construction. This chapter details the different type of cables that are available with optical fibers and how they are constructed. It provides details of the application and environment for using each type of cable construction.

Chapter 5: Jointing and connectors. This chapter provides a detailed description of the different types of connections and joints that are used in fiber optic cables and the advantages and disadvantages of each. It also provides a thorough practical description of how to splice, joint and connect fiber optic cables.

Chapter 6: Optical devices. This chapter discusses the theory and operation of optical devices, including drivers, detectors, couplers, grates and amplifiers. It provides details of the different types of optical devices that are available and their working parameters and limitations.

Chapter 7: Installing fiber optic cables. This chapter describes the various methods used to install fiber optic cables. It provides a practical approach to installing cables in different environments and highlights all the potential problems that may be encountered.

Chapter 8: Fiber optic system design. This chapter provides a methodical and practical approach to designing a fiber optic communications system. It discusses in detail both loss budget and bandwidth budget analysis, and provides useful information on effective cost control when implementing fiber optic systems.

Chapter 9: Testing of fiber optic systems. This chapter describes the tests that can be carried out on optical fibers and explains how to carry out standard pre-installation and post-installation testing on fiber optic systems. It also provides a brief description of how the parameters of a fiber are measured.

Chapter 10: Technologies that use fiber optics. This chapter briefly discusses the main technologies and standards that use optical fibers as their transmission medium.

1

Introduction

The rapidly changing face of data communications and telecommunications has seen a continued growth in the need to transfer enormous amounts of information across large distances. The technologies that were used extensively in the past say 20 years, such as coaxial cable, satellite and microwave radio for transferring information were, very quickly running out of capacity. The demand for transmission capacity was far outstripping its availability.

There was a growing requirement to provide a communications medium that was more suitable to the noisy industrial environment where the need for data communications and networking of control systems was rapidly expanding. With the introduction of fiber optic communications systems, the solution to the problems of transmission capacity shortage and to noisy industrial environments has been successfully found.

An optical fiber is simply a very thin piece of glass which acts as a pipe, through which light can pass. The light that is passed down the glass fiber can be turned on and off to represent digital information or it can be gradually changed in amplitude, frequency, or phase to represent analog information.

Fiber optic transmission has become one of the most exciting and rapidly changing fields in telecommunications engineering. To most of us, who have not previously encountered this technology, it can look like a form of black magic and one that is best left to experts. However, in reality it is a relatively simple communications technology. Compared to copper cable transmission and particularly radio and microwave transmission (which really are black magic!), fiber optic transmission systems are far easier to design and understand.

Fiber optic transmission systems have many advantages over more conventional transmission systems. They are less affected by noise, do not conduct electricity and therefore provide electrical isolation, carry extremely high data transmission rates and carry data over very long distances. These and other advantages are discussed in detail throughout this book.

Fiber optic transmission systems are not perfect and there are difficulties involved in designing, implementing, and operating fiber optic communications systems. This book is designed to provide a thorough background to fiber optic communications systems and to illustrate the design and installation of these systems. The many pitfalls associated with the implementation of fiber optic systems are discussed and workable solutions to these problems are provided.

The objective of this book is to provide a thorough, detailed, and practical reference to the reader. It contains information that is of practical use and avoids the trap many texts on the subject fall into of getting involved in the maze of technical and mathematical irrelevance.

A brief overview of the basic concepts involved in fiber optic communications, historical background to fiber optics and a comparison of copper and optical fiber transmission mediums is provided in this chapter.

1.1 Historical background to fiber optics

Fiber optic technology did not advance enough to be a commercially viable proposition for communication purposes until the 1980s. However, there were evolving international telecommunications standards that were predicting very high data rate requirements. Although transmission capacity could be obtained from conventional cable, microwave and satellite technologies, there was a definite shortage of transmission capacity for the term data transfer requirements. Fiber optic transmission systems have provided the enormous capacity required overcoming the potentially disastrous short falls.

A brief chronological description of the main events in the technological history that have shaped the development of fiber optic communications is given here:

Prehistoric	Early societies used signal fires to send digital messages to distant locations. Polybious, a Greek mathematician, developed a method of sending characters using fires by setting up a matrix of characters where one set of fires represented rows of the matrix and the other set represented the columns of the matrix.
1700	Isaac Newton discovered the diffraction of light and that light is constructed of a spectrum of many different colors.
1790	French engineer Claude Chappe developed the first optical telegraph system using semaphores. Messages were relayed from one hill to the next using moving semaphore arms.
1800	William Herschel discovered that a certain part of the spectrum of light contained infrared energy. French mathematician Augustine Fresnel developed the first mathematical model to explain the properties of light. His proposal was based on the premise that light is constructed of sinusoidal waves. Physicist James Maxwell laid the foundations for the development of the study of light transmission in the form of electromagnetic waves. Maxwell’s equations are still used to explain the behavior of radio and light waves in transmission systems.
1854	British physicist John Tyndall set up an experiment whereby he passed light down a beam of water, demonstrating the transmission of a signal by total internal reflection.

1880	The famous inventor Alexander Bell invented a device called Photophone, which contained a membrane made of reflective material. When sound caused photophone to vibrate, it would modulate a light beam that was shining on it and reflect this light to a distant location. The reflected light could then be demodulated using another photophone. Applying this method, Bell was able to communicate to a maximum distance of 213 meters. American engineer William Wheeler designed a lighting system for a building that was based on a series of pipes and ducting. Light was injected into one end and the internal reflection through pipes carried the light rays to a number of pipe ends that emanated in rooms where the light was to be diffused. Although the system would probably have never worked efficiently, the idea was sound and eventually led to the advent of fiber optic communications.
1907	A chemist named Round discovered that by forward biasing different types of silicon carbide crystals, they emitted yellow, green, orange, or blue light.
1910	Two physicists, Hondros and Deybe, published an important paper on the transmission of electromagnetic waves in dielectric solids.
1923	Lossew, a physicist, developed the light emitting diode (LED)
1927	Baird, an engineer, proposed the use of uncoated fibers to transmit images for television purposes.
1934	AT & T engineer Norman French first patented the idea of transmitting communications signals down a thin piece of glass. At that time, there were no transparent materials available with sufficiently low attenuation to make the technology feasible.
1955	An RCA engineer Braunstein developed a device made of gallium arsenate that emitted an infrared signal.
1956	NS Kapany, an American company, first used the term ‘fiber optics’. It has the credit of having invented the glass rod for the first time.
1960	Theodore Maiman, an engineer from Hughes Aircraft, developed the first operating gas laser. IBM, General Electric, and Massachusetts Institute of Technology all virtually simultaneously developed injection laser diodes.
1966	Two researchers at STL in Harlow developed a glass fiber that had an attenuation of approximately 1000 dB/km.
1970	The Corning Glass Works company developed a technique for manufacturing glass fibers that exhibited an attenuation of 20 dB/km. Bell laboratories, RCA, and scientists in the then Soviet Union developed continuous operation semiconductor injection lasers.

1972	Signal attenuation in optical fibers was reduced to 4 dB/km.
1976	Rediffusion installed the first commercial fiber optic system for transmission of analog television signals.
1980	Fiber optic communication systems became commercially available.

1.2 Comparison of fiber optic and copper cabling systems

Fiber optic technology will definitely be used in the future as the main medium for information transmission. It is one of the reasons for the massive increase in international telecommunications and arguably the perception of the apparent ‘shrinking planet’. This technology has been the backbone that has enabled the Internet to become the incredible information medium it is today. However, contrary to popular belief, it is not everything to all people. There are still many limitations to fiber optic systems and many challenges yet to overcome.

Before discussing the theory of fiber optic transmission, this section will compare copper cables to fiber cables and weigh the advantages and disadvantages of using each.

1.2.1 Bandwidth

Fiber

Fiber optic cables have enormous bandwidth with transmission speeds up to 40 Gbps operating today and over 100 Gbps is expected in the near future. The factors presently limiting an increase in data speeds are: firstly, the time responses of the source and detectors are slow compared to the pulse periods for high data rates; secondly, the wavelength of light is close enough to the pulse period to cause differentiation problems at the detectors. Methods of multiplexing several wavelengths onto one fiber (referred to as wave division multiplexing (WDM)) increase combined transmission speeds over a single fiber to over several Tbps.

To provide a feel for what this represents in terms of information transfer, a fiber optic link operating at approximately 1 Gbps per second can carry over 30 000 compressed audio telephone calls simultaneously. A link operating at 30 Gbps can carry up to 1 million telephone calls simultaneously on a single glass fiber!

Copper

Coaxial cables with diameters of up to 8 cm can carry speeds reaching 1 Gbps over distances of 10 km. The limiting factor is the very high cost of copper.

Significant research is presently going on into increasing transmission speeds on twisted pair cables. Speeds of 100 Mbps are now quite common in many local area networks. Commercial systems are also available that operate up to 1 Gbps. Laboratory tests have successfully been carried out at 10 Gbps and products are nearing commercial release. The reason for such active development in this area is to make use of the over abundance of twisted pair cable infrastructure already installed and hence provide significant cost savings associated with trenching, ducting and laying of new fiber optic cables. For this reason, twisted pair cable technology is presently very competitive compared to fiber optic technology as both have many common applications.

1.2.2 Interference

Fiber

Fiber optic cables are completely unaffected by electromagnetic interference (EMI), radio frequency interference (RFI), lightning and high voltage switching. They do not suffer from capacitive or inductive coupling problems. If designed correctly, fiber optic cables should be unaffected by nuclear magnetic pulses from nuclear explosions, and they should be unaffected by background nuclear radiation. (The greater majority of the population will be comforted by this knowledge after a nuclear war!)

As an adjunct to this fact, fiber optic cables do not emit any electromagnetic interference or radio frequency interference. This characteristic is very important in the areas of computing, video, and audio, where low noise environments are increasingly more vital for increased performance and production quality.

Copper

Copper cables are affected by external interference. Depending on the type of cable and the amount of shielding around the cable, they are affected to varying degrees by EMI and RFI through inductive, capacitive, and resistive coupling. Copper cable-based communications systems are permanently destroyed by nuclear magnetic pulses.

Copper cables also emit electromagnetic radiation, which can cause interference to other copper cable-based communications systems. The amount of radiation they emit depends on the magnitude of the signal they are carrying and the quality of the shielding.

1.2.3 Electrical isolation

Fiber

Fiber optic cables provide complete galvanic isolation between both ends of the cable. The characteristic of non-conductivity of fibers makes the cables immune to voltage surges. This eliminates interference that may be caused from ground loops, common mode voltages, as well as shifts and shorts in ground potential. The fiber optic cable acts like a long opto-isolator. A further advantage is that because optical fibers do not emit radiation and are not affected by interference, there is no cross talk between cables (that is, emission of radiation from one communications cable interfering with another cable, which is running next to it).

Copper

Copper cables, simply working in their designed purpose, provide an electrical connection between both their ends. Therefore, they are susceptible to ground loops, common mode voltages, and ground potential variations. They will also suffer from potential cross talk problems.

1.2.4 Transmission distances

Fiber

As for cheap simple fiber optic systems, distances up to 5 km between repeaters are possible. For high-grade commercial systems, distances up to 300 km between repeaters are now readily available. Systems have been installed between two end points (where repeaters were not required) for distances upto 400 km. Distances close to 1000 km have been achieved in the laboratory but have not made it into the commercial world as yet. A European company has claimed that it is presently developing a fiber cable that could be laid completely around the larger diameter of the earth, and without any repeaters, and can carry a signal from one end to the other! How is this possible? Using a slightly radioactive cladding, the incoming low energy light photons excite electrons in the cladding, which in turn release higher energy light photons. Thus, a form of self-amplification occurs. The chapters that follow will help the reader to understand these terms.

Copper

Distances upto 2.4 km between repeaters at data speeds of 4 Mbps are commercially available as for twisted cables. Distances upto 25 km between repeaters at speeds of less than 1 Mbps are possible in case of coaxial cables.

1.2.5 Size and weight

Fiber

Compared to all other data transmission cables, fiber optic cables are extremely lightweight and very small in diameter. A four-core fiber optic cable will weigh approximately 240 kg/km and a 36-core fiber optic cable will weigh only about 3 kg more. Because of their small size compared to copper cables of the same transmission capacity, they are generally easier to install in existing conduits, and installation time and cost are generally reduced since they are light in weight and easier to handle.

Copper

Copper cable might weigh from 800 k/km for a 36 twisted pair sheathed cable to 5 tons for a kilometer of high quality large diameter coaxial cable.

1.2.6 Use in hazardous gas areas

Fiber

Multimode fibers operating with LED light sources are suitable for use in hazardous gas areas. Until recently, it was thought that all fibers were suitable for use in hazardous areas; research has however, shown that certain fiber links with powerful light sources (lasers) can raise the temperature of a metal surface they are shining on to the point of gas ignition or, they may cause sparks under certain conditions.

Copper

Unless copper cable transmission systems are very stringently designed and adhere to strict intrinsic safety standards, they are not suitable for use in hazardous gas areas. Copper cables that are carrying even small currents can form sparks or arc between cables, unless current limiting controls are applied to the transmission circuits.

1.2.7 Security

Fiber

It is almost impossible to hook across a fiber optic cable and ‘bug’ the data transmission. The fibers have to be physically tapped to extract the data, which will decrease signal levels and increase error rates, both of which are easily detected. With presently available technology, fiber optic systems are considered highly secure systems. It is anticipated that this will change in the near future, as methods of multidropping of fibers improve.

Copper

Tapping into a copper cable transmission system is simply a matter of hooking across the cable with an equivalent high impedance cable. Copper cables are not considered highly secure systems.

1.2.8 Multidropping for LANs

Fiber

At present, there are a few methods of multidropping from a fiber optic transmission system, but they are not very effective. They are difficult to implement, and are very costly. Significant research is presently being undertaken into this area but cost effective systems are probably still some years away.

Optical fiber cables are also difficult to install, delicate and must be kept clear of possible physical stress that may damage them.

Copper

Multidrop copper-based systems are commonplace, simple to install and are very cost effective. Twisted pair cables, in particular, are cheap, easy to install and terminate, reliable and robust.

1.2.9 Jointing and connectors

Fiber

Jointing of optical fibers is relatively difficult and requires specialized training and tools. These days, most short distance cables are bought pre-terminated, where machines in factories apply the terminations. The costs of connectors and tools are relatively high.

Copper

Jointing of twisted pair cables is comparatively easy and relatively cheap. Coaxial cables can be difficult to terminate and components are relatively expensive but not to the extent of fiber optic systems.

1.2.10 Terminal equipment

Fiber

The biggest single factor limiting the mass distribution of fiber optic systems is the very high costs of the terminal transmission and receiving equipment. For high-speed systems, the costs can be between four and ten times those of equivalent copper-based systems. Slower speed systems are gradually reducing in cost but are still generally slightly more expensive than their equivalent copper-based systems.

Copper

The electronics of the terminal equipment for copper-based systems is significantly easier to design and manufacture than fiber optic terminal equipment and is therefore, significantly cheaper.

1.2.11 Test equipment and testing (fiber and copper)

Both fiber optic and copper system test equipment is complicated and generally very cumbersome and expensive. The only exception is in copper systems that have low speed transmission links.

2

Definitions and fundamental principles

Data communications

Communications systems exist to transfer information from one location to another. The components of the information or message are usually known as **data** (derived from the Latin word '*datum*' for *item of information).* All data are made up of unique code symbols or other entities on which the sender and receiver of the messages have agreed. For example: binary digital data is represented by two states '0' and '1'. These are referred to as **BI**nary digi**TS** or 'bits'. These bits are represented inside our computers by the voltage level of the electrical signals within storage elements; a high level could represent a '1', and a low level represent a '0'. Alternatively, the data may be represented by the presence or absence of light in an optical fiber cable.

2.1 Transmitters, receivers and communication channels

A communications process requires the following components:

- A **source** of the information
- A transmitter to convert the information into data signals compatible with the communications channel
- A communications channel
- A receiver to convert the data signals back into a form the destination can understand
- The destination of the information

Figure 2.1 shows the communications process.

Figure 2.1
Communications process

Encoding is the process of converting data to code, and decoding is the process of converting code back to data. The codes that represent the data can exist in many different forms.

The transmitter encodes the information into a suitable form to be transmitted over the communications channel. The communications channel moves this signal as electromagnetic energy from the source to one or more destination receivers. The channel may convert this energy from one form to another, such as electrical to optical signals, while maintaining the integrity of the information so that the recipient can understand the message sent by the transmitter.

For the communications to be successful, the source and destination must use a mutually agreed method of conveying the data. The main factors that must be considered are:

- The form of signaling and the magnitude(s) of the signals to be used
- The type of communications link (twisted pair, coaxial, optic fiber, radio etc.)
- The arrangement of signals to form character codes from which the message can be constructed
- The methods of controlling the flow of data
- The procedures for detecting and correcting errors in the transmission

The form of physical connections is defined by interface standards**.** Some agreed coding is applied to the message and the rules controlling the data flow and detection and correction of errors are known as protocol.

2.1.1 Interface standards

An interface standard defines electrical and mechanical aspects of the interface to allow the communications equipment from different manufacturers to operate together. A typical example is the EIA/TIA 232 C interface standard commonly known as RS-232-C. This specifies the following three components:

- **Electrical signal characteristics**
  This component defines the allowable voltage levels, grounding characteristics etc.
- **Mechanical characteristics**
  This component defines the connector arrangements and pin assignments.
- **Functional description of the interchange circuits**
  This component defines the function of the various data, timing and control signals used at the interface.

It should be emphasized that the interface standard only defines the electrical and the mechanical aspects of the interface between devices and does not cover how data is transferred between them.

Other examples of physical interfaces include EIA/TIA-485 (RS-485), X.21, G703, ISO 11801 etc.

2.1.2 Coding

This describes the way data is converted into symbols before transmission. The number and format of symbols used to represent each piece of data makes up the code.

Wide varieties of codes have been used for communications purposes. Early telegraph communications used Morse code with human operators as transmitter and receiver. The

Baudot code introduced a constant 5-bit code length for use with mechanical telegraph transmitters and receivers. The commonly used codes for data communications today are the Extended Binary Coded Decimal Interchange Code (EBCIDIC) and the American Standard Code for Information Interchange (ASCII). The ASCII code is shown in Table 2.1.

Most significant bits
MSB

	HEX	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**
HEX	BIN	000	001	010	011	100	101	110	111
0	**0000**	(NUL)	(DLE)	Space	0	@	P	‘	p
1	**0001**	(SOH)	(DC1)	!	1	A	Q	a	q
2	**0010**	(STX)	(DC2)	“	2	B	R	b	r
3	**0011**	(ETX)	(DC3)	#	3	C	S	c	s
4	**0100**	(EOT)	(DC4)	$	4	D	T	d	t
5	**0101**	(ENQ)	(NAK)	%	5	E	U	e	u
6	**0110**	(ACK)	(SYN)	&	6	F	V	f	v
7	**0111**	(BEL)	(ETB)	‘	7	G	W	g	w
8	**1000**	(BS)	(CAN)	(	8	H	X	h	x
9	**1001**	(HT)	(EM)	)	9	I	Y	i	y
A	**1010**	(LF)	(SUB)	*	:	J	Z	j	z
B	**1011**	(VT)	(ESC)	+	;	K	[	k	{
C	**1100**	(FF)	(FS)	‘	<	L	\	l	|
D	**1101**	(CR)	(GS)	-	=	M	]	m	}
E	**1110**	(S0)	(RS)	.	>	N	^	n	~
F	**1111**	(SI)	(US)	/	?	O	_	o	DEL

Least significant bits
LSB

Table 2.1
ASCII code table

2.1.3 Protocols

A protocol is essential for defining the common message format and procedures for transferring data between all devices on the network. It includes the following important features:

- **Initialization**
  Initializes the protocol parameters and commences the data transmission.
- **Framing and synchronization**
  Defines the start and end of the frame and how the receiver can synchronize to the data stream.
- **Flow control**
  Ensures that the receiver is able to advise the transmitter to regulate the data flow and ensure no data is lost.

- **Line control**
  Used with half-duplex links to reverse the roles of transmitter and receiver and begin transmission in the other direction.
- **Error control**
  Provides techniques to check the accuracy of the received data to identify transmission errors. These include block redundancy checks and cyclic redundancy checks.
- **Time out control**
  Procedures for transmitters to retry or abort transmission when acknowledgments are not received within agreed time limits.

Examples of some of the commonly used communications protocols are:

- Xmodem or Kermit for asynchronous file transmission
- Binary synchronous control protocol (BSC), synchronous data link control (SDLC), high level data link control (HDLC), fiber distributed data interface (FDDI), transport control protocol/Internet protocol (TCP/IP), multi-protocol label switching (MPLS) and asynchronous transfer mode (ATM) for synchronous transmissions.

Industrial protocols include manufacturing automation protocol (MAP), technical office protocol (TOP), Modbus, Data Highway Plus, HART, Fieldbus etc. Detailed discussion of protocol operation is beyond the scope of this book.

2.2 Types of communication channels

2.2.1 Analog communications channels

An analog communications channel conveys analog signals, which are changing continuously in either one or a combination of frequency, phase and amplitude. These signals are commonly used for audio and video communication as illustrated in Figure 2.2. It is worth noting that some fiber optic systems operate as an analog channel.

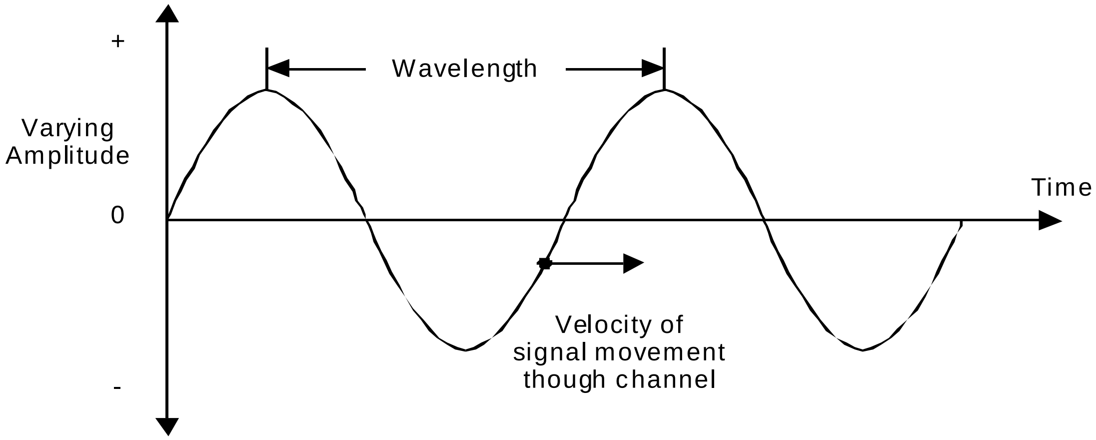


Figure 2.2
Analog signals

2.2.2 Digital communications channels

A digital communications channel conveys digital signals, which are characterized by the use of discrete signal amplitudes. A binary digital signal, for example, has only two allowed values representing the binary digits 'ON' and 'OFF'. In fiber optic communications channels, these states are normally represented by the presence or absence of light.

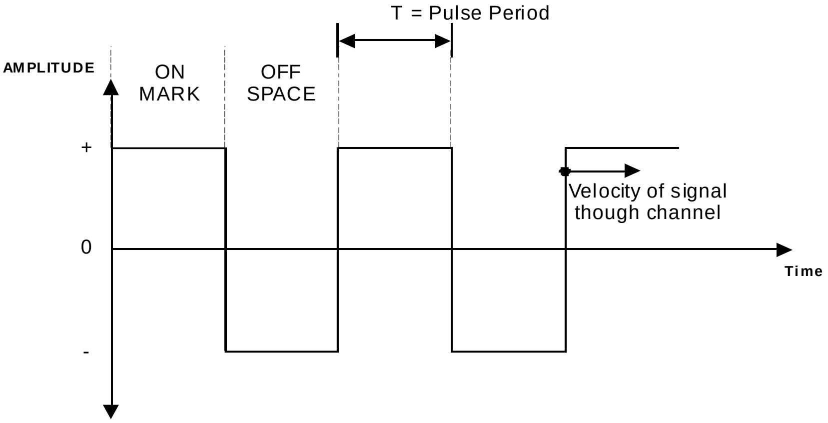


Figure 2.3
Digital signals

2.3 Communications channel properties

The physical properties of the communications channels limit their ability to carry information in either analog or digital form. The principal effects are signal attenuation, channel bandwidth and noise.

2.3.1 Signal measurement on a communications channel

The majority of engineering measurements performed on voice and date systems are carried out as a measurement of power levels. The equations for power are:

$$P = VI$$

$$P = \frac{V^2}{R}$$

$$P = I^2R$$

Where:

P = Power (in watts)
V = Voltage (in volts)
I = Current (in amperes)
R = Load resistance

The measurement of level with respect to power originated when Alexander Graham Bell invented a unit of measure for sound levels. This unit became known as the **'bel'.** One tenth of a bel is called a **decibel (dB).**

The human ear hears sound in a logarithmic manner. So a level of 100 watts to the human ear would sound twice as loud as a level of 10 watts (not 10 times).

One decibel increase in sound is approximately the smallest increase in sound level detectable by the human ear.

This unit of measure is now used as the basis for measuring relative power levels in radio, voice and data networks. For the network in Figure 2.4 below, the gain of the system becomes:

$$\text{Gain} = Log_{10}\left(\frac{P_B}{P_A}\right) \text{ Bels}$$

$$= 10Log_{10}\left(\frac{P_B}{P_A}\right) \text{ Decibels}$$

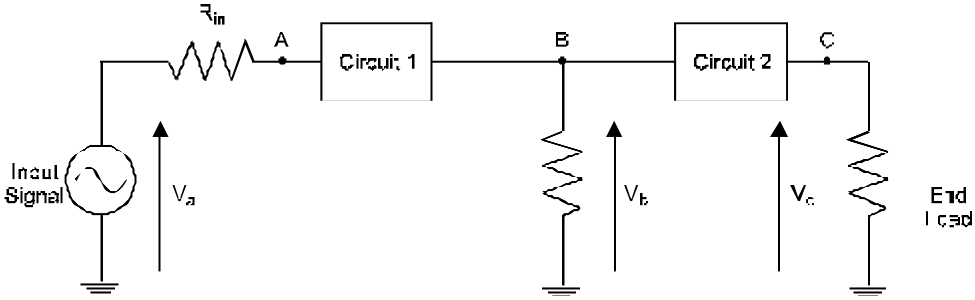


Figure 2.4
Circuit gain and loss

Note that this is a relative measurement. The resulting value is a measure of the power level at point B with reference to the power level at point A (power at B relative to power at A). The resultant is NOT an absolute value.

For example, if for the system shown in Figure 2.4 there is an input signal at point A of 1 watt and an output signal at point B of 10 watts, the system gain is:

$$\text{Gain} = 10Log_{10}\left(\frac{10}{1}\right)$$

$$= 10 \times (1)$$

$$= 10 \text{ decibels}$$

10 Decibels is written as 10 dB.

When working with voice, data, and radio equipment, measurements can be made at single points in a system with reference to 1 watt or 1 milliwatt (instead of with reference to a level at another point). The equation then becomes:

$$Level = 10Log_{10}\left(\frac{P}{1}\right) : \text{dBW}$$

(*With reference to 1 watt)*

$$\text{Level} \quad = \quad 10Log_{10}\left(\frac{P}{10^{-3}}\right) : \text{dBm}$$

(*With reference to 1 milliwatt)*

If measurements are required to be carried out in volts or amperes, then replacing power with:

$$\frac{V^2}{R} \text{ or } I^2R$$

gives:

$$\text{Gain} \quad = \quad 10Log_{10}\left(\frac{V_{\text{B}}^2 R_{\text{A}}}{V_{\text{A}}^2 R_{\text{B}}}\right)\text{dB}$$

when $R_{\text{A}} = R_{\text{B}}$:

$$\text{Gain} \quad = \quad 20Log_{10}\left(\frac{V_{\text{B}}}{V_{\text{A}}}\right)\text{dB}$$

or:

$$\text{Gain} \quad = \quad 10Log_{10}\left(\frac{I_{\text{B}}^2 R_{\text{B}}}{I_{\text{A}}^2 R_{\text{A}}}\right)\text{dB}$$

if $R_{\text{A}} = R_{\text{B}}$:

$$\text{Gain} \quad = \quad 20Log_{10}\left(\frac{I_{\text{B}}}{I_{\text{A}}}\right)\text{dB}$$

Generally, R_{A} will equal R_{B} and the second formula can normally be used.

Voltages are also sometimes given in decibel forms, where they are measured with respect to 1 volt or 1 microvolt i.e., dBV or dBμV respectively.

2.3.2 Signal attenuation

As the signal travels along a communications channel, its amplitude decreases as the physical medium resists the flow of the electrical or electromagnetic energy. This effect is known as signal attenuation. In electrical signaling, some materials such as copper are more efficient conductors of electrical energy than others. However, all conductors contain impurities that resist the movement of electrons that constitute the electric current. The resistance of the conductors causes some of the electrical energy of the signal to be converted to heat energy as the signal progresses along the cable resulting in a continuous decrease in the electrical signal. The signal attenuation is measured in terms of signal loss per unit length of the cable, typically decibels per kilometer (dB/km).

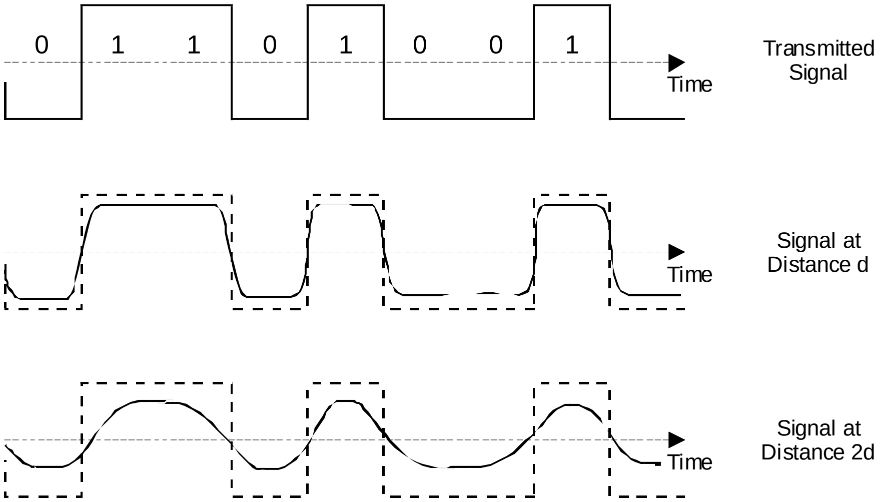


Figure 2.5
Signal attenuation

To allow attenuation, a limit is set for the maximum length of the communications channel. This is to ensure that the attenuated signal arriving at the receiver is of sufficient amplitude to be reliably detected and correctly interpreted. If the channel is longer than this maximum length, amplifiers or repeaters must be used at intervals along the channel to restore the signal to acceptable levels.

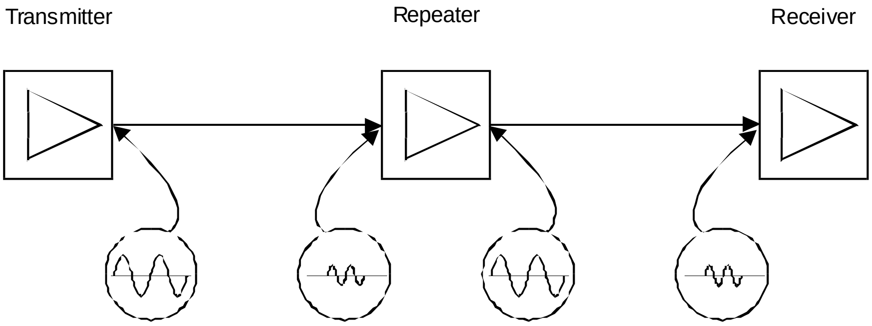


Figure 2.6
Signal repeaters

Signal attenuation increases as the frequency increases. This causes distortion to practical signals containing a range of frequencies. For example, a digital signal has a very sharp, fast rising edge to the pulse, which contributes a very high frequency component. The sharper (faster) the rise, the higher will be the frequency component. This is illustrated in Figure 2.5 where the rise-times of the attenuated signals progressively decrease as the signal travels through the channel, caused by the greater attenuation of the high frequency components. This problem can be overcome by the use of special amplifiers referred to as equalizers, which amplify the higher frequencies caused by greater attenuation.

Light also attenuates through glass for much the same reasons as mentioned above. Electromagnetic energy (light) is absorbed by natural resistance properties of glass.

2.3.3 Channel bandwidth

The quantity of information a channel can convey over a given period is determined by its ability to handle the rate of change of the signal, that is, its frequency. An analog signal varies between a minimum and maximum frequency and the difference between those frequencies is the bandwidth of that signal. The bandwidth of an analog channel is the difference between the highest and lowest frequencies that can be reliably received over the channel. These frequencies are often those at which the signal has fallen to half the power relative to the mid band frequencies, or the frequency levels at the input to the channel, referred to as 3 dB points**.** In which case, the bandwidth is known as the 3 dB bandwidth.

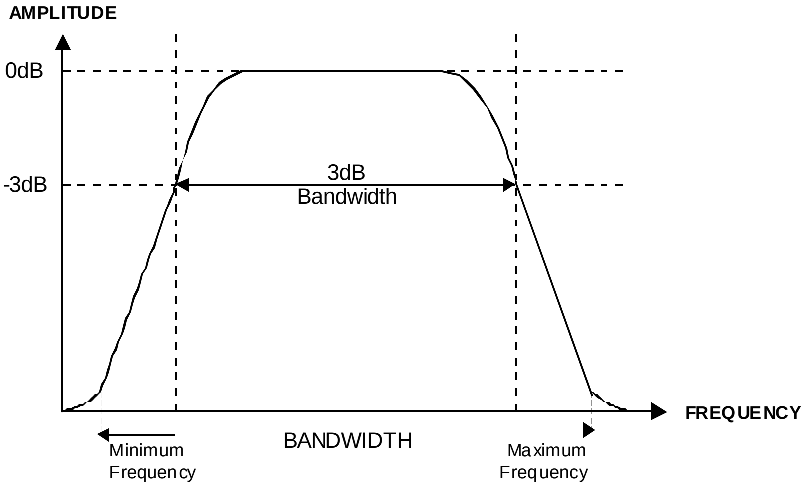


Figure 2.7
Channel bandwidth

Digital signals are made up of a large number of frequency components, but only those within the bandwidth of the channel will be able to be received. The larger the bandwidth of the channel, the higher the data transfer rate can be and more high frequency components of the digital signal can be transported, and so a more accurate reproduction of the transmitted signal can be received and decoded.

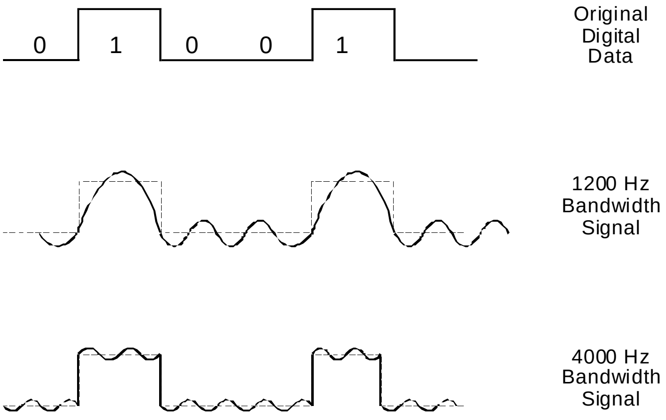


Figure 2.8
Effect of channel bandwidth on digital signals

The maximum data transfer rate (C) of the transmission channel can be determined from its bandwidth, by use of the following formula derived by the mathematician, **Nyquist**.

$$C = 2 B \log 2 M \text{ bps}$$

where:
B is the bandwidth in hertz
M levels are used for each signaling element.
In the special case where only two levels, 'ON' and 'OFF' are used (binary) then:

$$M = 2 \text{ and } C = 2B.$$

As an example, the maximum Nyquist data transfer rate for a PSTN channel of bandwidth 3100 hertz carrying a binary signal would be 2 × 3100 = 6200 bps. The achievable data transfer rate is reduced in practical situations because of the presence of noise on the channel.

2.3.4 Noise

As the signals pass through a communications channel the atomic particles and molecules in the transmission medium vibrate and emit random electromagnetic signals as noise. The strength of the transmitted signal is normally large relative to the noise signal. However, as the signal travels through the channel and is attenuated, its level can approach that of the noise. When the wanted signal is not significantly higher than the background noise, the receiver cannot separate the data from the noise and communication errors occur.

An important parameter of the channel is the ratio of the power of the received signal (S) to the power of the noise signal (N). The ratio S/N is called the signal to noise ratio, which is normally expressed in decibels, abbreviated to dB;

$$S/N = 10 \log 10(S/N) \text{ dB}$$

where:
S = signal power in watts
N = noise power in watts

A high signal to noise ratio means the wanted signal power is high compared to the noise level, resulting in good quality signal reception. The theoretical maximum data transfer rate for a practical channel can be calculated using the **Shannon-Hartley Law**, which states:

$$C = B \log 2 (1 + S/N) \text{ bps}$$

where:
C is the data rate in bps
B is the bandwidth of the channel in hertz
S is the signal power in watts
N is the noise power in watts

It can be seen from this formula that increasing the bandwidth or increasing the signal to noise ratio will allow increases to the data rate, and that a relatively small increase in bandwidth is equivalent to a much greater increase in signal to noise ratio.

Digital transmission channels make use of higher bandwidths and digital repeaters or regenerators to regenerate the signals at regular intervals and maintain acceptable signal to noise ratios. The degraded signals received at the regenerator are detected, then retimed and retransmitted as nearly perfect replicas of the original digital signals, as shown in Figure 2.9. There is no accumulated noise on the signal, even when transmitted thousands of kilometers, provided reasonably good signal to noise ratios are maintained.

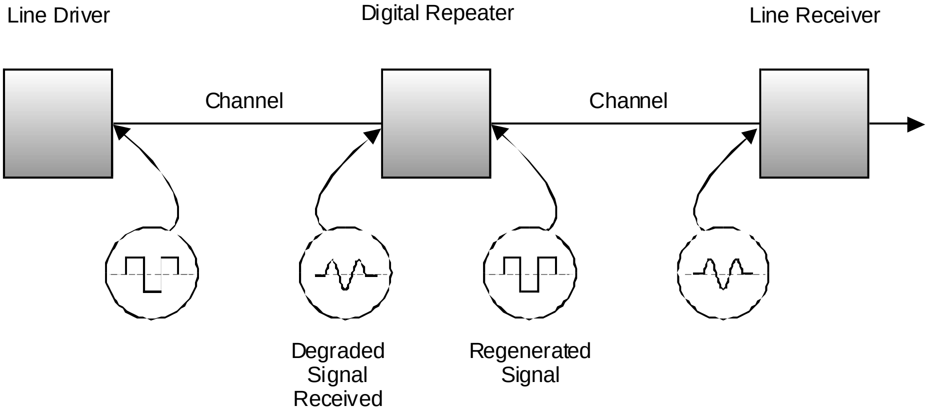


Figure 2.9
Digital link

2.4 Data transmission modes

2.4.1 Direction of signal flow

Simplex

A simplex channel is unidirectional that allows data to flow in one direction only, as shown in Figure 2.10. Public radio broadcasting is an example of a simplex transmission. The radio station transmits the broadcast program, but does not receive any signals back from your radio receiver.

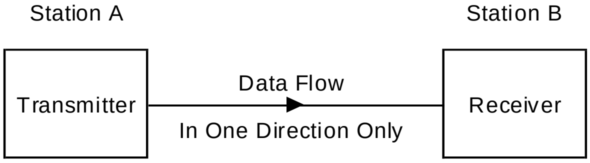


Figure 2.10
Simplex transmission

This has limited use for data transfer purposes, as we invariably require the flow of data in both directions to control the transfer process, acknowledge data etc.

Half-duplex

Half-duplex transmission allows us to provide simplex communication in both directions over a single channel, as shown in Figure 2.11. Here the transmitter at station ‘A’ sends data to a receiver at station ‘B’. A line turnaround procedure takes place whenever transmission is required in the opposite direction. The station ‘B’ transmitter is then enabled and communicates with the receiver at station ‘A’. The delay in the line turnaround procedures reduces the available data throughout the communications channel.

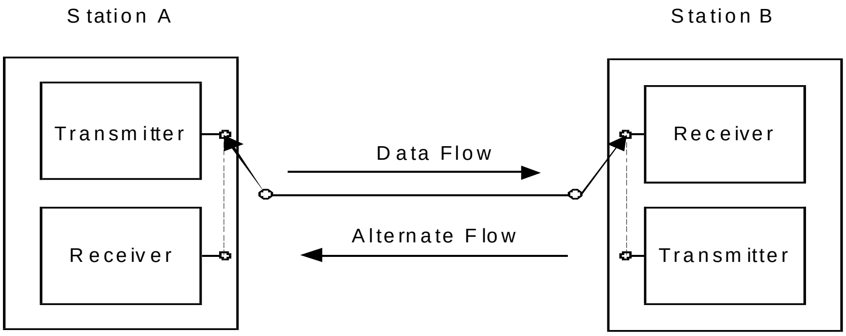


Figure 2.11
Half-duplex transmission

Full-duplex

A full-duplex channel gives simultaneous communications in both directions, as shown in Figure 2.12.

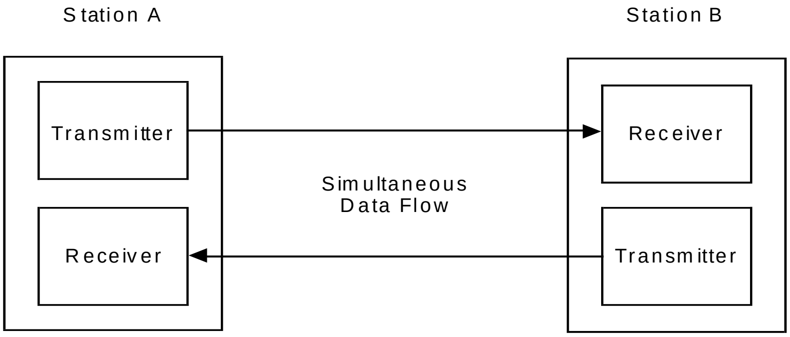


Figure 2.12
Full-duplex transmission

2.4.2 Synchronization of digital data signals

Data communications depends on the timing of the signal generation and reception being kept correct throughout the message transmission. The receiver needs to look at the incoming data at the correct instants before determining whether a ‘1’ or ‘0’ was transmitted. The process of selecting and maintaining these sampling times is called synchronization.

In order to synchronize their transmissions, the transmitting and receiving devices need to agree on the length of the code elements to be used, known as the bit time. The receiver needs to extract the transmitted clock signal encoded into the received data stream. By synchronizing the bit time of the receiver’s clock with that encoded into the data by the sender, the receiver is able to determine the right times to detect (sample) the data transitions in the message and correctly receive the message. The devices at both ends of a digital channel can synchronize themselves using either asynchronous or synchronous transmission as outlined below.

2.4.3 Asynchronous transmission

Here, the transmitter and receiver operate independently and exchange a synchronizing bit pattern at the start of each message code element (frame). There is no fixed relationship between one message frame and the next. This is experienced with communication devices such as a computer keyboard input with potentially long random pauses between keystrokes.

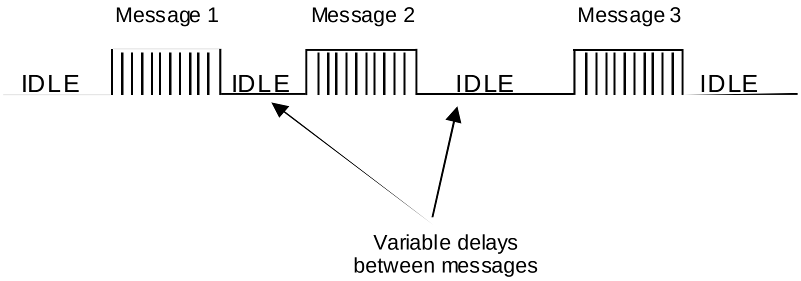


Figure 2.13
Asynchronous data transmission

The speed setting initially sets the sampling rate before transmission starts (except 'Autobaud' systems). At the receiver the channel is sampled at a high rate, typically in excess of 16 times the bit rate of the data channel, to accurately determine the center of the synchronizing pattern (start bit) and its duration (bit time).

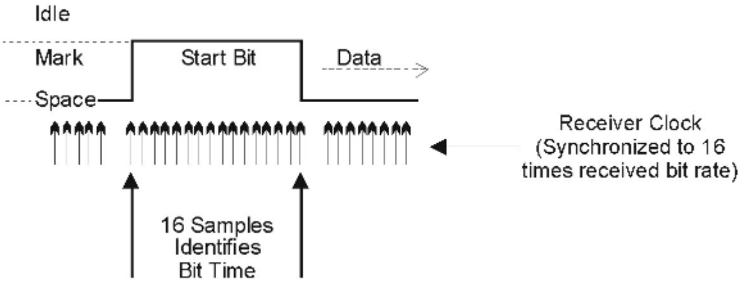
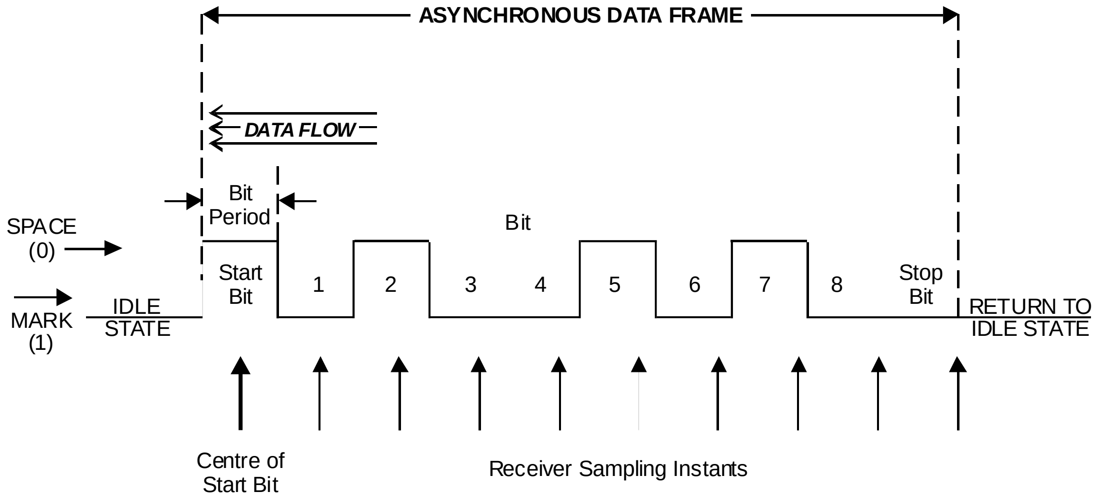


Figure 2.14
Clock extraction

The data bits are then determined by the receiver sampling the channel at intervals corresponding to the center of each transmitted bit. These are calculated by counting multiples of the bit time from the center of the start bit. For an eight-bit serial transmission, this sampling is repeated for each of the eight data bits then a final sample is made during the ninth time interval. This sample is to identify the **stop bit** and confirm that the synchronization has been maintained to the end of the message frame. Figure 2.15 illustrates the asynchronous data reception process.



Data Bit	1 2 3 4 5 6 7 8
Received Data	1 0 1 1 0 1 0 1

Figure 2.15
Asynchronous data reception

2.4.4 Synchronous transmission

The transmitter and receiver here establish an initial synchronization then continuously transmit data maintaining their synchronization throughout the transmission. This is achieved by special data coding schemes, such as Manchester Encoding, which ensure continuous encoding of the transmitted clock into the transmitted data stream. This enables the synchronization to be maintained at the receiver right to the last bit of the message, which could be as large as 4500 bytes (36 000 bits) long. This allows larger frames of data to be efficiently transferred at higher data rates. The synchronous system packs many characters together and sends them as a continuous stream, called a block. For each transmission block there is a preamble, containing the start delimiter for initial synchronization purposes and information about the block, and a postamble, to give error checking etc. An example of a synchronous transmission block is shown in Figure 2.16.

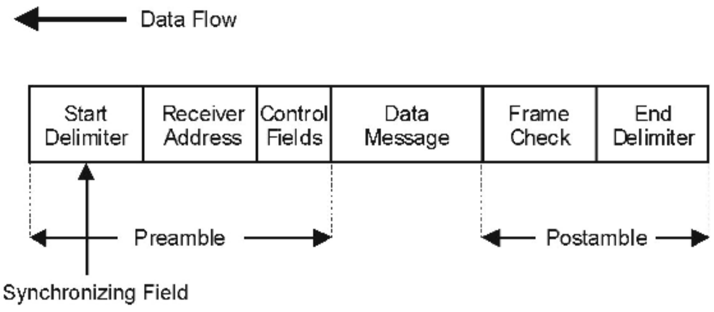


Figure 2.16
Synchronous transmission block

2.5 Light

In modern physics, light is represented by either electomagnetic waves or photons.

2.5.1 Electromagnetic waves

Electromagnetic waves involve a combination of electric and magnetic effects. Consider a static charge. It produces an electric field around it. If the charge is moving, it also produces a magnetic field. It has been shown theoretically and experimentally verified that these electric and magnetic fields combine to cause a disturbance that is propagated through space, called a radiated electromagnetic wave. This wave is self propagating since the changing electric field induces a changing magnetic field which then induces a new changing electric field, and so on. Energy is thus being constantly exchanged between the electric and magnetic fields.

When an electromagnetic wave strikes some matter, its electric and magnetic fields cause the charges in the matter to oscillate in the same manner as those in the originating wave. This enables the energy to be transferred through the material with no net transfer of matter. All electromagnetic waves have the following common properties:

- They are produced by moving charges
- They are transverse waves in which the electric and magnetic fields are mutually perpendicular to one another and perpendicular to the direction of propagation of the waves
- They do not require a medium for propagation but can propagate through material with no net transfer of matter
- They all travel at the same relative speed in free space, which is called the speed of light

The behavior of electromagnetic waves is elegantly quantified in Maxwell's equations, but this is beyond the scope of this book where we will concentrate on practical applications rather than abstract theory.

2.5.2 Photons

Photons are considered discrete quantities of electromagnetic energy. Planck proposed that energy is radiated in bursts called 'quanta' where the amount of energy is proportional to the frequency. This is expressed by the formula:

$$Q = h\,f$$

Where:
h = Planck's constant (6.63×10^{-34} joule-seconds).

A quantum of light is called a photon. Photons have some characteristics of a particle being both discrete and finite. Light, however, is also a wave as can be shown by diffraction and interference effects. It thus appears that light is both a particle and a wave. This is contradictory as a particle is finite and discrete while a wave is infinite and continuous. Physicists consider both theories complementary but do not apply them together! This is known as the wave-particle duality of light and both physical models are equally valid and are useful in describing different optical effects. It is interesting to note that there are parts of both models which do not agree.

Light, as photons or waves, travels in free space at approximately 300 000 km/s (3×10^8 m/s). Many effects can be best envisaged by representing the light as rays that travel in straight lines between or through optical components. These rays are modified (reflected, diffracted, refracted etc.) at the optical surfaces of these devices. This optical behavior is explained in Chapter 3.

2.6 The electromagnetic spectrum

All electromagnetic radiation is fundamentally the same, with photons or waves traveling at the speed of light. The properties of this radiation can be measured in different ways: by the frequency of the electromagnetic waves, their wavelength, or the photon energy present. An arrangement of the order of frequencies, wavelengths, or energy of various types of electromagnetic waves is known as electromagnetic spectrum.

The frequencies and wavelengths are related by the formula:

$$\text{Frequency} = \text{Velocity}/\text{Wavelength}$$

Photon energy can be measured in electron volts (eV), which is the energy gained by an electron moving through a 1 volt electric field. This can be related to the wavelength, in micrometers, by the formula:

$$\text{Energy (eV)} \quad = \quad 1.2406/\text{Wavelength } (\mu\text{m})$$

The electromagnetic spectrum represents a continuum of frequencies with no distinct lines of separation between the variously named forms of electromagnetic phenomena. The spectrum is shown in Figure 2.17 below.

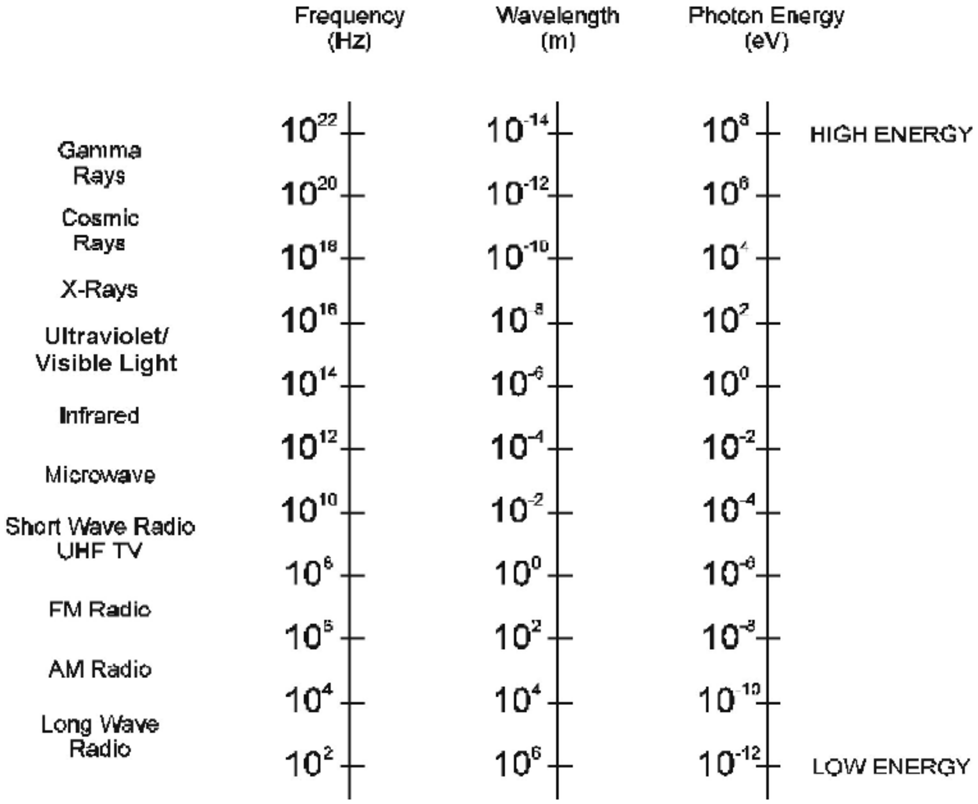


Figure 2.17
Electromagnetic spectrum

2.6.1 Optical region of the spectrum

This is the small part of the spectrum where our fiber optic devices operate, from about 200 nanometers up to 20-micrometer wavelengths. It includes the visible spectrum at wavelengths of around 400 to 700 nanometers and the adjacent infrared and ultraviolet regions.

The wavelength used in fiber optic systems is matched to the particular fiber's transmission characteristics. Most optical fibers use silica glass, which is most transparent in the near infrared region, 700 to 1600 nanometers. Plastic fibers operate best at visible wavelengths, non-silica glass fibers are designed to operate at infrared wavelengths, and special grades of silica can be used in the near-ultraviolet region. The properties of these optic fibers are detailed in Chapter 3.

2.7 Revisiting copper cables

Contrary to popular belief copper cables are not dead. In fact, today, a far greater length of copper cable is installed throughout the world for communication purposes than of fiber optic cable.

The advantages and disadvantages of copper cables compared to fiber optic cables were discussed in Chapter 1. This chapter also provides a brief review of copper cables used for communication purposes. The author has included this section for the reasons of revision, reference, and completeness of this book.

2.7.1 Cable types

Two main types of copper cable used are:

- Coaxial cable, also called coax
- Twisted pair cable, which can be shielded (STP) or unshielded (UTP)

Each of the cable types is subdivided into more specialized categories and it has its own design and specifications, standards, advantages and disadvantages. Cable types differ in price, transmission speed, and recommended transmission distance. For example, twisted pair wiring is currently the cheapest but has the most limited performance. Coaxial cable lies between twisted pair and fiber optic cables on most of the performance and price features.

2.7.2 Cable structure

All cable types have the following components in common:

- One or more conductors to provide a medium for the signal
- Insulation of some sort around the conductors to help keep the signal in and interference out
- An outer sheath, or jacket, to ensure the cable-elements. The sheath keeps the cable components together, and may also help protect the cable components from water, pressure, vibration or other external environmental factors.

Conductor

For copper cable, the conductor is known as the signal, or carrier wire, and it may consist of either solid or stranded wire. Solid wire is a single thick strand of conductive material, usually copper. Stranded wire consists of many thin strands of conductive material wound tightly together.

The signal wire is described in the following terms:

- The wire's conductive material (for example, copper)
- Whether the wire is stranded or solid
- The carrier wire's diameter, expressed directly (for example, in inches, centimeters or millimeters), or in terms of the wire's gauge, as specified in the AWG (American Wire Gauge).
- The total diameter of the strand determines some of the wire's electrical properties, such as resistance and impedance. These properties, in turn, help to determine the performance of the wire.

Insulation: The insulating layer keeps the transmission medium's signal from escaping and also helps to protect the signal from outside interference. For copper wires, the insulation is usually made of a dielectric such as polyethylene. Some types of coaxial cable have multiple protective layers around the signal wire. The size of the insulating layer determines the spacing between the conductors in a cable and therefore its capacitance and inductance.

Cable sheath

The outer casing, or sheath of the cable, provides a shell that keeps the cable's elements together. The sheath differs for indoor and outdoor exposure. Outdoor cable sheaths tend to be black or blue, with appropriate resistance to UV light, and have enhanced water resistance. Two main indoor classes of sheath are plenum and non-plenum.

Plenum cable sheath

In some countries, plenum cable is required to be used in certain environments by law. It would be required to be used where the cable is being run 'naked' (without being put in a conduit) inside walls. Plenum sheaths are made of less-flammable fluoropolymers such as Teflon or Jynar. They are highly fire-resistant and give out less toxic fumes when burning. They are also considerably more expensive (by a factor of 1.5 to 3) than cables with non-plenum sheaths. Studies have shown that copper cables with plenum sheaths have less signal loss than non-plenum cables.

Non-plenum cable sheath

Non-plenum cable uses less expensive material for sheaths, so it is consequently less expensive than cables with plenum sheaths. Non-plenum cable sheaths are made of polyethylene (PE) or polyvinyl chloride (PVC), which has a greater tendency to burn and give off toxic fumes than Plenum cables.

Cable packaging

Cables can be packaged in different ways, depending on its application and the location where they are laid. For example, the older IBM token ring cable topology specifies a flat cable for use under carpets. The following types of cable packaging are available:

- Simplex cable – one cable within one sheath, which is the default configuration
- Duplex cable – two cables, or fibers, within a single sheath
- Multifiber core – multiple cables within a single sheath

2.8 Factors affecting copper cable performance

Copper cables are good media for signal transfer, but they are not perfect. Ideally, the signal at the end of a length of cable should be the same as at the beginning. Unfortunately, this will not be true in practical cables. All signals degrade when transmitted over a distance through any medium. This is due to a decrease in signal amplitude, as the medium resists the flow of energy. The signals become distorted, as the shape of the electrical signal changes over distance. Any transmission also consists of signal and noise components. Signal quality degrades for several reasons, including attenuation, crosstalk, and impedance mismatches.

2.8.1 Attenuation

Discussed in Section 2.3.2.

2.8.2 Crosstalk

Crosstalk is interference in the form of a signal from a neighboring cable or circuit; for example, signals on different pairs of twisted wire in a twisted pair cable may interfere with each other. A commonly used measure of this interference in twisted pair cable is **near-end crosstalk** (NEXT), which is represented in decibels. The higher the decibel value, the less crosstalk and the better the cable. Additional shielding between the carrier wire and the outside world is the most common way to decrease the effects of crosstalk.

2.8.3 Characteristic impedance

The *impedance* of a cable is defined as the opposition to the flow of electrical energy at a particular frequency. The *characteristic impedance* of a cable is the value of impedance, which is characteristic of that particular cable. The characteristic impedance is the input impedance of the cable seen when it is terminated to a load impedance equal to the characteristic impedance, as shown in Figure 2.18. Such a cable then appears electrically to be infinitely long and has no signals reflected from the termination. If one cable is connected to another of differing characteristic impedance, then signals are reflected back from their interface. These reflections cause interference with the data signals and must be avoided by using cables of the same characteristic impedance.

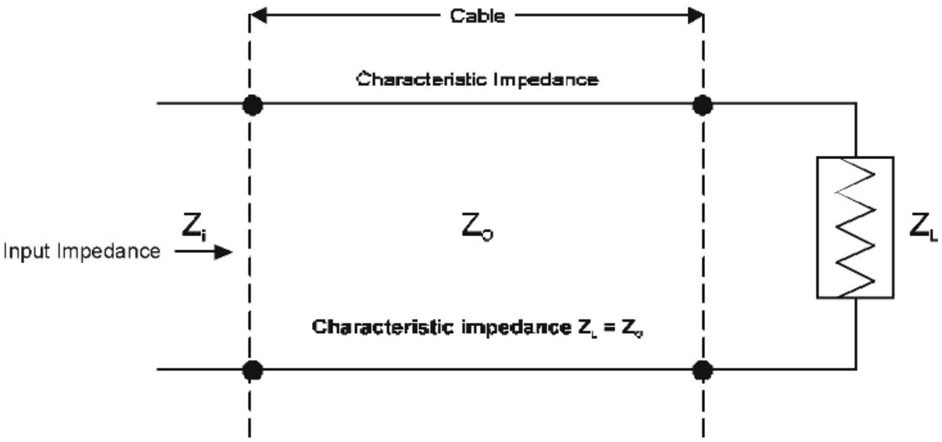


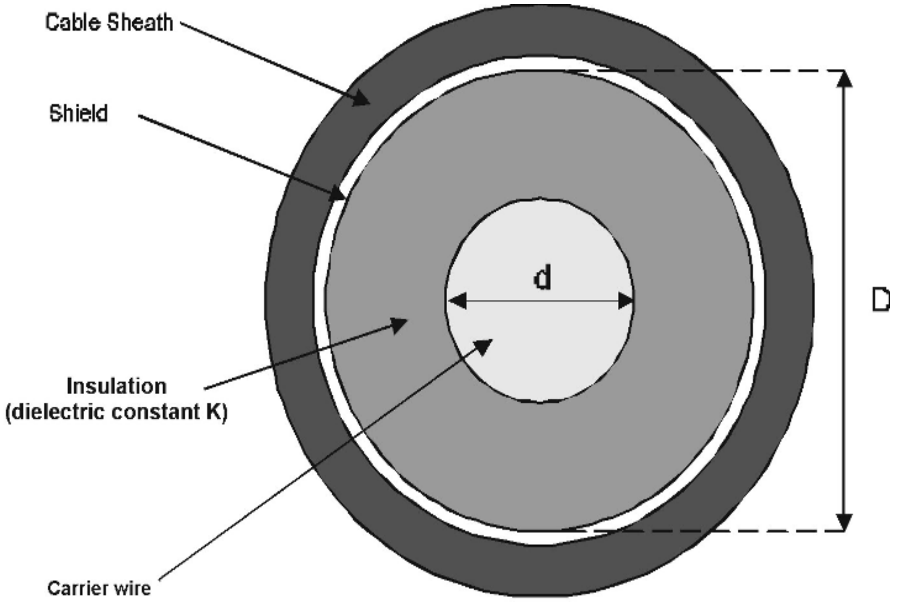
Figure 2.18
Characteristic Impedance

2.9 Coaxial cable

Coaxial cable, often called coax, is used for radio applications and data transmission. The cable is remarkably stable in terms of its electrical properties at frequencies below 4 GHz (Gigahertz). This makes the cable popular for radio and microwave systems, cable television (CATV) distribution, as well as for creating local area networks (LANs). The telephone companies also make use of coaxial cable to route long distance calls.

2.9.1 Coaxial cable components

A coaxial cable consists of the following layers (moving outward from the center) as shown in Figure 2.19.



Characteristic impedance $Z_0 = (138/\sqrt{K})(\log D/d)$

Figure 2.19
Coaxial cable

Carrier wire

A conductor wire or signal wire is in the center. This wire is usually made of copper and may be solid or stranded. There are restrictions regarding the material composition for certain applications. The diameter of the signal wire and the number of strands in a multistrand conductor affect the signal attenuation.

Insulation

An insulation layer consists of a dielectric around the carrier wire. This dielectric is usually made of some form of polyethylene or Teflon.

Foil shield

A thin foil forms a shield around the dielectric. This foil shield usually consists of aluminum bonded to both sides of a tape. Not all coaxial cables have foil shielding. Some have two foil shield layers, interspersed with braid shield layers.

Braid shield

A braid, or mesh, conductor, made of copper or aluminum, that surrounds the insulation and foil shield. This conductor can serve as the ground for the carrier wire. Together with the insulation and any foil shield, the braid shield protects the carrier wire from electromagnetic interference (EMI) and radio frequency interference (RFI). Note that the braid and foil shields provide good protection against electrostatic interference, but little protection against magnetic interference.

Sheath

The outer protection cover that can either be plenum or non-plenum. The layers surrounding the carrier wire also help prevent signal loss due to radiation from the carrier wire. The signal and shield wires are concentric, or coaxial. Common coaxial cable impedances are 50, 75, 93 and 120 ohms.

2.9.2 Coaxial cable connectors

A segment of coaxial cable has an end connector at each end. Connectors differ in their attachment mechanism and components. Different size coaxial cables require different sized connectors, matched to the characteristic impedance of the cable, so that the introduction of connectors cause minimal reflection of the transmitted signals.

For coaxial cable, the following types of connectors are available:

- **BNC (bayonet nut connector)**
  This connector is used for radio and data.
- **N-series connector**
  This connector is used for radio and data.
- **UHF series**
  This connector is used for radio.
- **TNC (threaded nut connector)**
  This connector may be used in the same situations as a BNC, provided the other connector is also using TNC.
- **J-type**
  This connector is used for radio.

It is recommended that connectors for coaxial cable should be silver plated rather than tinned. This improves the contact and the durability of the connector.

2.9.3 Baseband versus broadband over coaxial cable

Functionally, coaxial cable is grouped into baseband and broadband varieties. To understand these terms, you need to understand the difference between baseband and broadband signaling. A baseband system is one in which the whole bandwidth of the transmission medium (the cable in this situation), is taken up by a single signal. The information may be digital or analog but the signals are impressed directly on to the cable and transmitted using the natural frequency components. The alternative is broadband signaling. In this system, each signal is modulated with a separate carrier frequency (fc). By using a series of carrier frequencies that are separated by a sufficiently wide guard band, simultaneous transmission of multiple data streams can be supported on one cable.

2.9.4 Advantages of a coaxial cable

Coaxial cable has the following general advantages over other types of cable. These advantages may change or disappear over time, as technology advances or products improve.

- Broadband coaxial can be used to transmit voice, data, radio, TV, and video
- The cable is relatively easy to install
- Coaxial cable is reasonably priced compared to other cable types
- High frequency applications (up to 4 GHz for distances up to several hundred metres)
- Wide bandwidth of operation
- Stable characteristics over wide operating range of frequencies
- Relatively low attenuation.

2.9.5 Disadvantages of coaxial cable

Coaxial cable has the following disadvantages when used for a network:

- It is easily damaged and sometimes difficult to work with, especially in the case of thicker coaxial cable.
- Coaxial cable is more difficult to work with than twisted pair cable.
- Some thicker coaxial cable can be expensive to install, especially if it needs to be pulled through existing cable conduits.
- Connectors can be expensive.
- Connectors are difficult to install.
- Coaxial cable provides limited bandwidth compared to fiber.

2.10 Twisted pair cable

Twisted pair cable is widely used, inexpensive, and easy to install. Twisted pair cable comes in two main varieties:

- Shielded (STP)
- Unshielded (UTP)

This cable can transmit data at an acceptable rate – up to 1 Gbps in some local area network architectures. Several companies are in the process of developing 10 Gbps STP systems. The most common twisted pair wiring is telephone cable, which is unshielded and is usually voice-grade, rather than the higher-quality data-grade cable used for local area networks.

In a twisted pair cable, two conductor wires are wrapped around each other. A signal is transmitted as a differential between the two conductor wires. The current flows in opposite directions in each wire of the active circuit, as shown in Figure 2.20.

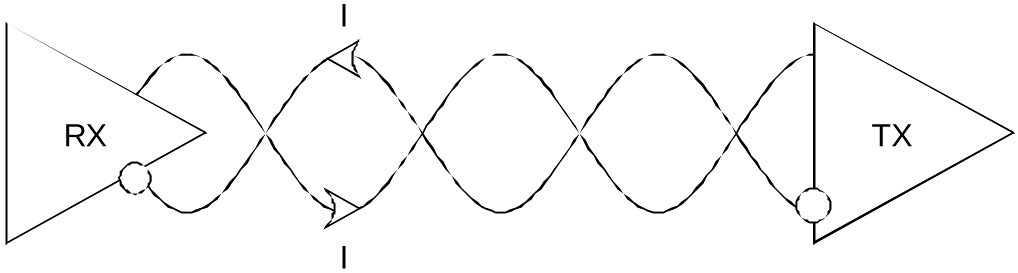


Figure 2.20
Current flow in a twisted pair cable

Since these currents are equal and opposite, their magnetic fields cancel each other, and cancel any magnetic interference caused by outside noise sources. This type of cable is therefore self-shielding and is less prone to interference.

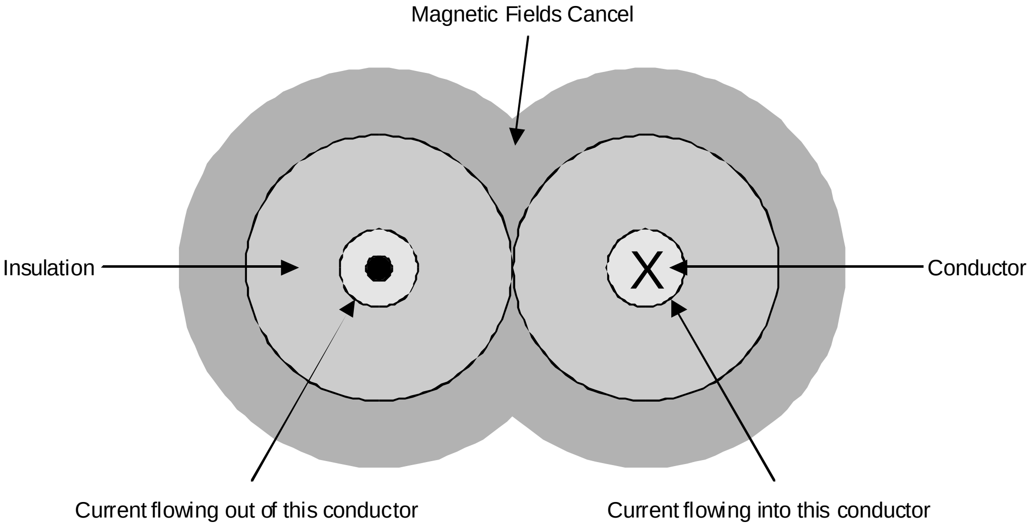


Figure 2.21
Magnetic shielding of twisted pair cables

Twisting within a pair minimizes crosstalk between pairs. The twists also help deal with electromagnetic interference (EMI) and radio frequency interference (RFI), as well as balancing the mutual capacitance of the cable pair. The performance of a twisted pair cable can be improved by increasing the number of twists per meter in a wire pair. Each of the pairs in a 2-pair cable will have a different twist rate to reduce the crosstalk between them.

2.10.1 Components of twisted pair cable

A twisted pair cable has the following components:

Conductor wires

The signal wires for this cable come in pairs that are wrapped around each other. The conductor wires are usually made of copper. They may be solid (consisting of a single wire) or stranded (consisting of many thin wires wrapped tightly together). A twisted pair cable usually contains multiple twisted pairs: 2, 4, 6, 8, 25, 50, or 100 twisted pair bundles are common. For local area network applications, 2- and 4-pair cables are most commonly used.

Shield

Shielded twisted pair (STP) cable includes a foil shield around each pair of conductors.

Sheath

The wire bundles are encased in a sheath made of polyvinyl chloride (PVC) or, in plenum cables, of a fire-resistant material, such as Teflon or Knar.

Twisted pair cable comes in two main varieties: shielded (STP) and unshielded (UTP). STP contains an extra shield or protective screen around each of the wire pairs to cut down on external interference signals. This added protection also makes STP more expensive than UTP. (The price of thin coaxial cable generally lies between UTP and STP prices.)

2.10.2 Shielded twisted pair (STP) cable

STP cable has pairs of conductors twisted around each other. Each pair is covered with a foil shield to reduce interference and minimize crosstalk between wire pairs. It can handle high-speed transmissions, but the cable itself is relatively expensive. It can be quite bulky and heavy, and is rather difficult to work with.

2.10.3 Unshielded twisted pair (UTP) cable

UTP cable does not include any extra shielding around the wire pairs. This type of cable is used in some slower speed data networks (in particular, 10Base-T, 10 Mbps) and for voice applications.

2.10.4 Cable categories

To distinguish varieties of UTP, the United States Electronic Industries Association/Telecommunications Industries Association (EIA/TIA) has formulated five categories. The electrical specifications for these cables are detailed in the following: EIA/TIA 568A, TSB-36, TSB-40 documents and their successor document SP2840. These categories are:

- **Category 1: voice-grade UTP telephone cable**
  Voice-grade, UTP telephone cable describes the cable that has been used for years in North America for telephone communications. Officially, such cable is not considered suitable for data-grade transmissions. In practice, however, it works fine over short distances and under ordinary working conditions. You should be aware that other national telecommunications providers have often used cable that does not even come up to this minimum standard, and is totally unacceptable for data transmission.
- **Category 2: voice-grade UTP cable**
  This cable is capable of supporting transmission rates of up to 4 Mbps. IBM type 3 cable falls in to this category.

- **Category 3: data-grade UTP cable**
  This cable is used extensively for supporting data transmission rates of up to 10 Mbps. An Ethernet network cabled with twisted pair requires at least this category of cable.
- **Category 4: data-grade UTP cable**
  This cable is capable of supporting transmission rates of up to 16 Mbps. An IBM token ring network transmitting at 16 Mbps requires this type of cable.
- **Category 5: data-grade UTP cable**
  This cable is capable of supporting transmission rates of up to 155 Mbps (but officially only up to 100 Mbps). The proposed CDDI (copper distributed data interface) networks and 100Base/TX network architecture require such cable.
- **Category 6: data-grade UTP cable**
  This cable is specified to operate at frequencies up to 250 MHz but manufacturers are obtaining operating frequencies of 550 MHz. It is specified to support IEEE 802.3 specifications for 1000base-T (gigabit Ethernet).
- **Category 7: data grade STP**
  This cable has just been commercially released. Each pair is shielded and the whole cable is shielded too. Manufacturers are quoting operating frequencies of up to 1.2 GHz.

2.10.5 Performance requirements

Twisted pair cable is categorized in terms of its electrical performance properties. The features that characterize the data grades of UTP cable are defined in EIA/TIA 568 as follows:

Attenuation

This value indicates how much power the signal loses and is dependent on the frequency of the transmission. The maximum attenuation per 1000 feet of UTP cable at 20 degrees Celcius at various frequencies is specified as follows:

Frequency (Mhz)	Category 3	Category 4	Category 5
0.772	6.8	5.7	5.5
1.0	7.8	6.5	6.3
4.0	17	13	13
8.0	26	19	18
10.0	30	22	20
16.0	40	27	25
20.0	-	31	28
25.0	-	-	32
31.25	-	-	36
62.5	-	-	52
100.0	-	-	67

Table 2.2
Maximum attenuation in dBs per 1000 ft @ 20°C

Mutual capacitance

Cable capacitance is measured in capacitance per unit length, for example, pF/ft, and lower values indicate better performance. The standards equate to mutual capacitance (measured at 1 kHz and 20°C) for category 3 cable not exceeding 20 pF/ft and for categories 4 and 5 cables 17 pF/ft.

Characteristic impedance

All UTP cable should have a characteristic impedance of 100 ohms over the frequency range from 1 MHz to the cables highest frequency rating. Note these measurements need to be made on a cable of length, at least one-eighth of a wavelength.

NEXT

The near end crosstalk (NEXT) indicates the degree of interference from neighboring wire pairs. This is measured by applying a balanced signal to one pair of wires and measuring its disturbing effect on another pair, both of which are terminated in their nominal characteristic impedance of 100 ohms. This is shown in Figure 2.22.

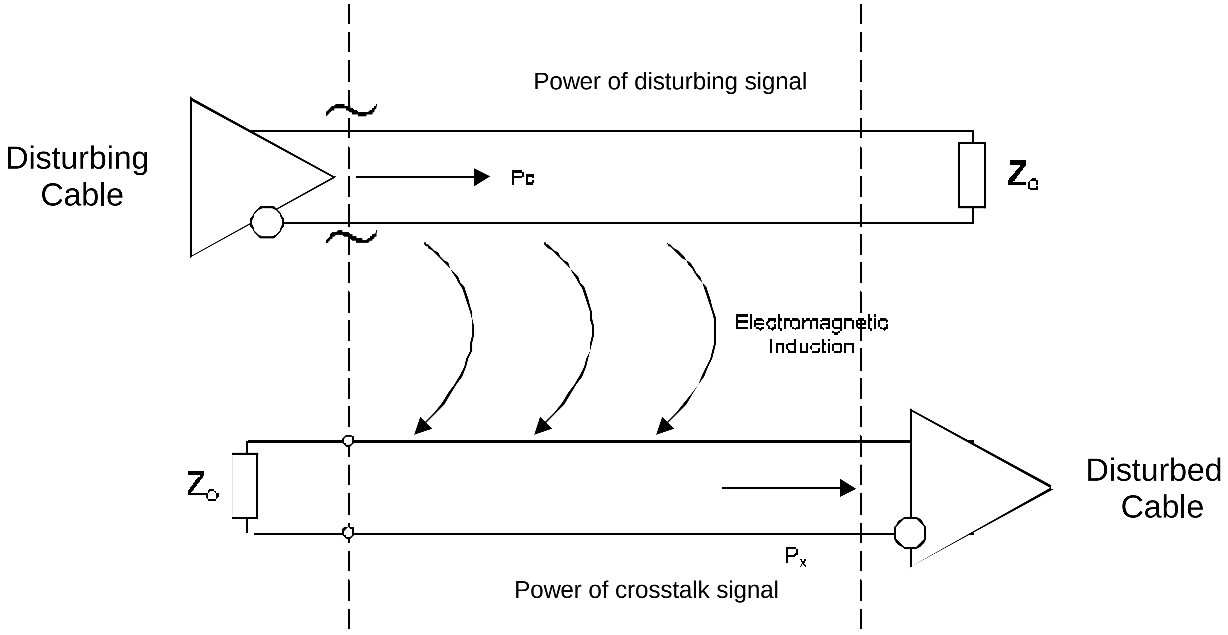


Figure 2.22
Near end crosstalk

NEXT is expressed in decibels, in accordance with the following formula:

$$\text{NEXT} = 10\,log\left({}^{P_x}\!/\!{}_{P_d} \right)\text{dB}$$

where:
P_d is the power of the disturbing signal
P_x is the power of the crosstalk signal

NEXT depends on the signal frequency and cable category. Performance is better at lower frequencies and for cables in the higher categories. Higher NEXT values indicate small crosstalk interference.

The standard specifies minimum values for NEXT for the fixed 10Base-T cables, known as horizontal UTP cable and also for the connecting hardware. The following tables show these values for the differing categories of cable at various frequencies.

Frequency (MHz)	Category 3 (dB)	Category 4 (dB)	Category 5 (dB)
0.150	54	68	74
0.772	43	58	64
1.0	41	56	62
4.0	32	47	53
8.0	28	42	48
10.0	26	41	47
16.0	23	38	44
20.0	-	36	42
25.0	-	-	41
31.25	-	-	40
62.5	-	-	35
100.0	-	-	32

Table 2.3
Minimum NEXT for horizontal UTP @ 20°C

It should be noted that the twists in the UTP cable, which enhance its crosstalk performance, need to be removed to align the conductors in the connector. To maintain adequate NEXT performance the amount of untwisted wire and the separation between the conductor pairs should be minimized. The amount of untwisting should not exceed 13 mm (0.5 inch) for category 5 cables and 25 mm (1 inch) for category 4 cables.

Structural return loss

The structural return loss (SRL) is a measure of the degree of mismatch between the characteristic impedance of the cable and the connector. This is measured as the ratio of the input power to the reflected power.

$$\text{SRL} = 10 \log (\text{Input Power}/\text{Reflected Power}) \text{ dB}$$

Higher values are better implying less reflection. For example 23 dB SRL corresponds to a reflected signal of seven per cent of the input signal.

Frequency Range (MHz)	Category 4	Category 5	Percentage Reflected
1 to 20	23 dB	23 dB	7%
20 to 100	-	14 dB	20%

Table 2.4
Minimum structural return loss (SRL) @ 20°C

Direct current resistance

The DC resistance is an indicator of the ability of the connectors to transmit DC and low frequency currents. The maximum resistance between the input and output connectors, excluding the cable, is specified as 0.3 ohm for category 3, 4 and 5 UTP cables.

Ground plane effects

It should be noted that if cables are installed on a conductive ground plane, such as a metal cable tray or in a metal conduit, the transmission line properties of mutual capacitance, characteristic impedance, return loss and attenuation can become two or three per cent worse. This is not normally a problem in practice.

2.10.6 Advantages of twisted pair cable

Twisted pair cable has the following advantages over other types of cables for networks:

- It is easy to connect devices to twisted pair cable.
- If an already installed cable system, such as telephone cable, has extra unused wires, you may be able to use a pair of wires from that system – BUT see the warnings on this above.
- STP significantly reduces external interference.
- UTP is quite inexpensive.
- UTP is very easy to install.
- UTP may already be installed (but make sure it all works properly and that it meets the performance specifications your network requires).

2.10.7 Disadvantages of twisted pair cable

Twisted pair cable has the following disadvantages:

- STP is bulky and difficult to work with.
- UTP is more susceptible to noise and interference than coaxial or fiber optic cable.
- UTP has higher signal attenuation than other cables.
- Skin effect can increase attenuation. This occurs when transmitting data at a fast rate over twisted pair wire. Under these conditions, the current tends to flow mostly on the outside surface of the wire. This greatly decreases the cross-section of the wire being used, and thereby increases resistance. This, in turn, increases signal attenuation.
- Narrower bandwidth of operation than coaxial cables.

2.11 Sources of interference and noise on cables

Noise is normally introduced into cable circuits through electrostatic (capacitive) coupling, magnetic (inductive) coupling, and resistive coupling. The reduction of these noise signals takes the form of shielding and twisting of signal leads, proper grounding, separation and good insulation.

Shielding is the protection of the signal wires from noise or unwanted signals.

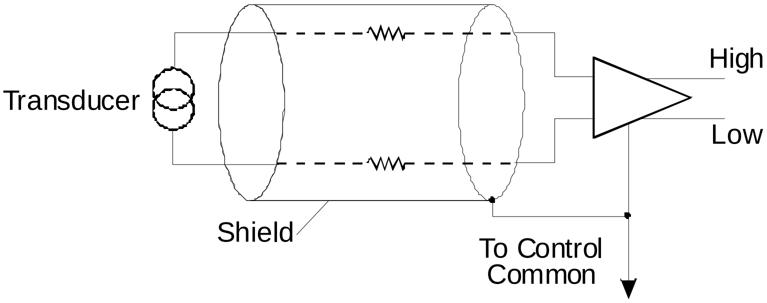


Figure 2.23
Typical shield

The purpose of the shield is to reduce the magnitude of the noise coupled into the low-level signal circuits by electrostatic or magnetic coupling. The shield may be considered an envelope that surrounds a circuit to protect the cable from the coupling.

2.11.1 Electrostatic coupling

Electrostatic or capacitive coupling of external noise is illustrated in Figure 2.24. The external noise source couples the noise into the signal wires through capacitors C1 and C2 and the resulting flow of current produces an error voltage signal across R1, R2 (the cable resistance) and RL. The error signal is proportional to the length of the cable leads, the resistance of the cable leads, the amplitude and the frequency of the noise signal and the relative distance of the cable leads from the noise source.

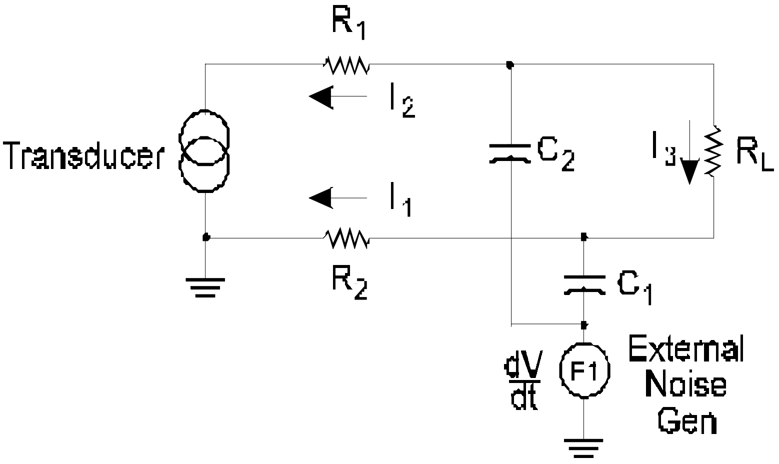


Figure 2.24
Electrostatic coupled noise

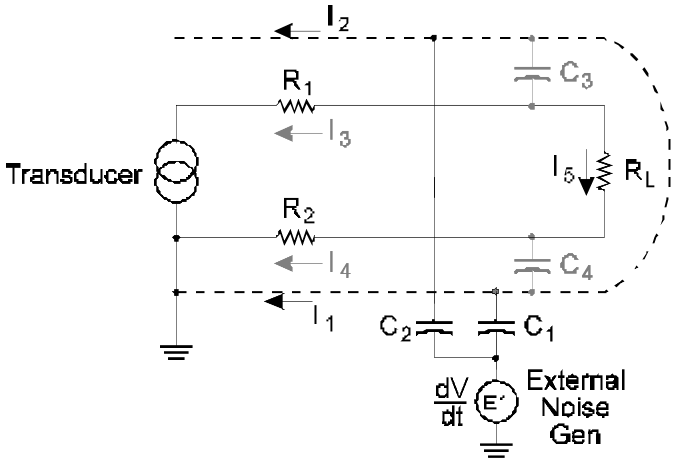


Figure 2.25
Use of shield to reduce electrostatic noise

The noise due to electrostatic coupling can be reduced by the use of shielded wire, by separation and by twisting of the leads. As the separation between the noise source and the signal wires is increased, the noise coupling is thereby reduced. Twisting of the leads provides a balanced capacitive coupling which tends to make C1 = C2. Therefore, the induced voltages at the load will be equal in magnitude.

The use of a shield to reduce electrostatic noise is illustrated in Figure 2.25. The noise-induced currents now flow through the shield and return to ground instead of flowing through the signal wires. With the shield and signal wire tied to ground at one end, a zero-potential difference would exist between the wires and the shield. Hence, no signal current flows between wire and shield.

The quality of the shield will determine how large C1 and C2 are compared to C3 and C4. The better quality shield (possibly 2 or 3 shields on one cable) will have the higher value of C1 and C2 and the lower value of C3 and C4. The lower the value of C3 and C4 the less noise value induced into the signal cables.

2.11.2 Magnetic coupling

Magnetic coupling is the electrical property that exists between two or more conductors: when there is a current change in one, there will be a resultant induced voltage in the other conductor. Figure 2.26 illustrates a disturbing wire (noise source) magnetically coupling a voltage into the signal circuit.

The alternating magnetic flux from the disturbing wire induces a voltage in the signal loop, which is proportional to the frequency of the disturbing current, the magnitude of the disturbing current and the area enclosed by the signal loop and is inversely proportional to the square of the distance from the disturbing wire to the signal circuit.

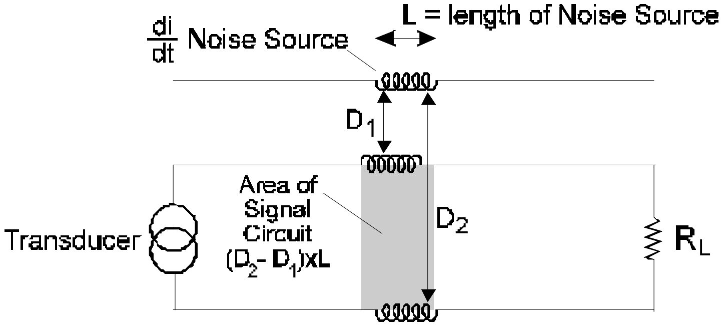


Figure 2.26
Magnetic noise coupling

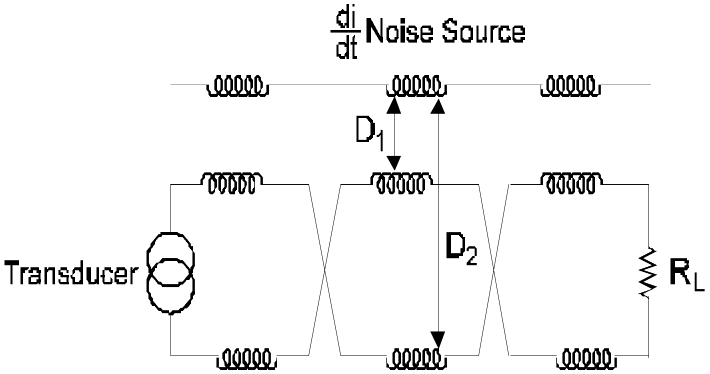


Figure 2.27
Reducing magnetic noise by twisting of wires

Figure 2.26 illustrates all of the factors necessary to introduce an error voltage: rate of change of current, a signal loop with a given area and a separation of the conductors from the disturbing signal (D1 and D2). A common method of reducing the effect of magnetic coupling is the use of twisted conductors in the signal circuits, as illustrated in Figure 2.27. The distance of these two signal wires in respect of the disturbing wire is approximately equal and the area of the circuit loop is almost zero. Reducing this area to practically zero will reduce the voltage induced by the magnetic field to almost zero due to the equal magnitude of current induced in each lead that will result in a near zero net circulating current. (The currents will induce voltages in the load that are equal and opposite in magnitude and will therefore cancel.)

Employing a shield made of a high ferrous content material around the signal wires can also reduce magnetic coupling. This shield is effective because the magnetic field produces eddy currents in the shield that will produce magnetic flux in the opposite direction to the inducing flux and will oppose the original magnetic field. A sketch of this type of noise reduction is illustrated in Figure 2.28. This type of shield is very rare and would have to be specially manufactured upon request. High ferrous content conduits are used sometimes but these are subject to corrosion problems.

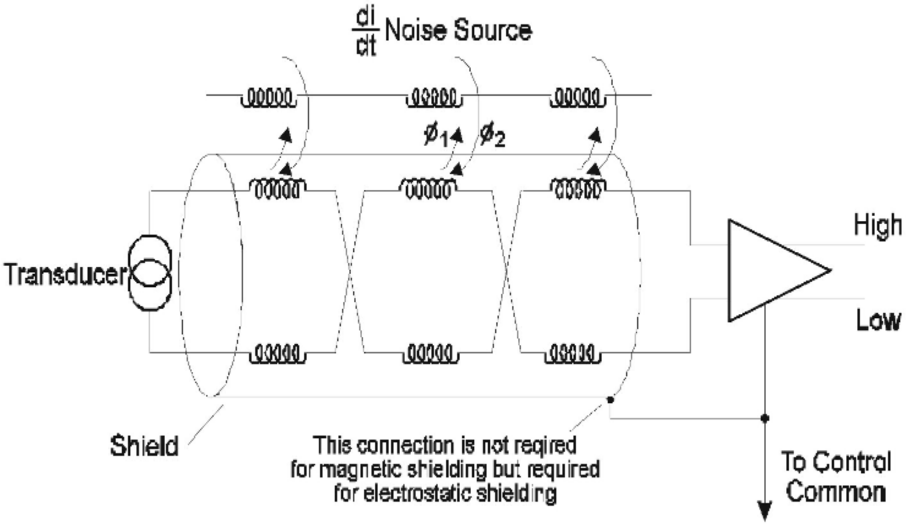


Figure 2.28
Effects of shield in reducing magnetic coupling

2.11.3 Impedance coupling

Impedance coupling (as illustrated in Figure 2.29) is the electrical property that exists when two or more signal wires share the same common return signal wire. If there is any resistance in the common return wire, then the signal current from any of the loads will cause the voltage to rise at all the loads. In addition, noise that induces current flow into the common return will cause noise voltage at all the loads.

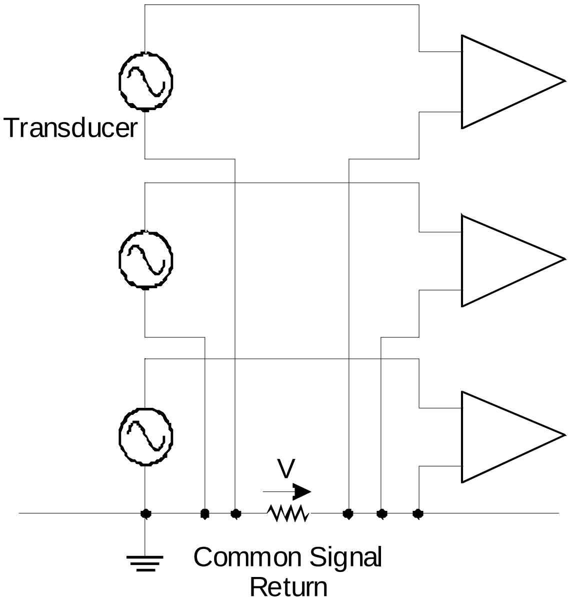


Figure 2.29
Resistance or impedance coupling

To avoid impedance coupling in signal circuits, either of the following can be carried out:

- Employ a low-resistance wire or bus for the common return when a common return cannot be avoided. (For critical applications both the resistance and the inductance of the bus should be minimized.)
- Wherever possible, employ separate signal return leads.

A few alternative solutions to the problem of impedance coupling are indicated in the following diagrams. Figure 2.30 indicates the ideal approach of separate signal returns. Here, the common return conductor is reduced to a single terminal point on one side of the links. Figure 2.31 illustrates the use of a large low impedance return bus. Note that the individual returns from each transmitter and receiver should also be as low impedance as possible.

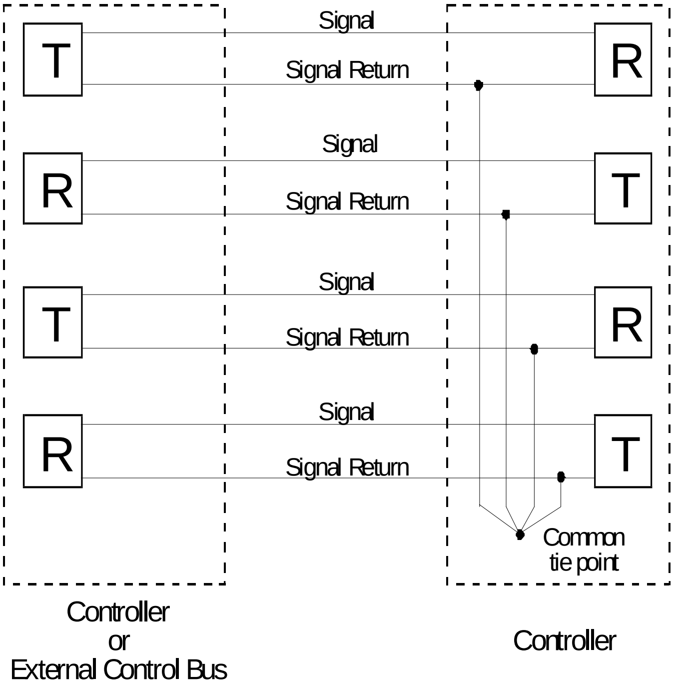


Figure 2.30
Cabling system illustrating individual signal returns

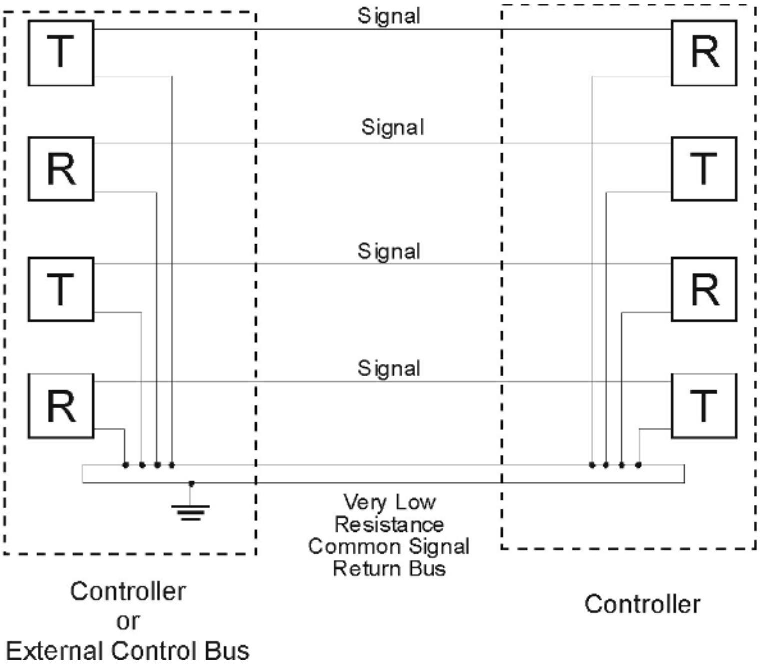


Figure 2.31
Cabling system illustrating common signal returns

3

Theory of fiber optic transmission

Introduction

This chapter will examine the theory of transmission of information over optical fibers. It covers in detail all of the relevant theory behind fiber optic transmission. The chapter begins with the fundamental concepts of the behavior of light and then moves into the more complex issues of light transmission in optical fibers.

Areas to be covered in this chapter include fundamental principles and the basic mathematical representation of light transmission down a glass fiber, modes of light transmission, construction of a fiber, transmission capacities and limitations, fabrication processes and future developments.

3.1 Fundamental principles of operation

3.1.1 Introduction

The fundamental principle behind communicating through optical fibers is that electromagnetic energy is tunneled down a tube of glass from a transmitter to a receiver. The tube of glass acts like a pipe that ducts all the electromagnetic energy from one point to another. The electromagnetic energy that is used in this transmission system is in the near visible light section of the electromagnetic spectrum. Therefore, glass is the ideal medium to duct this electromagnetic energy, as light passes through glass with low levels of attenuation.

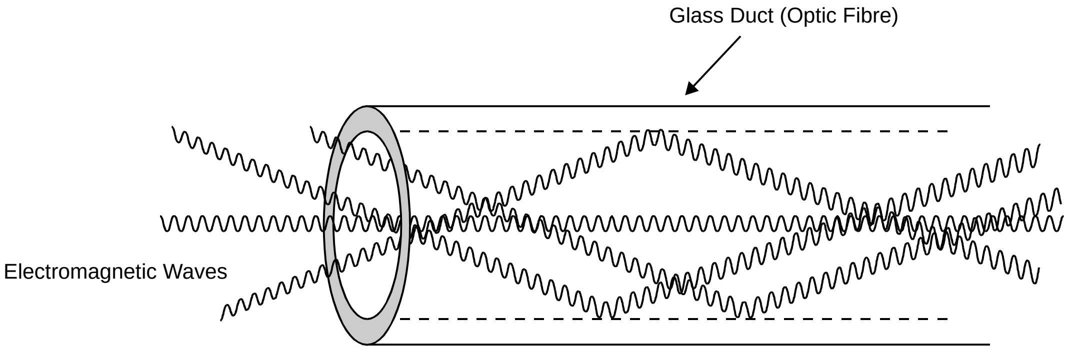


Figure 3.1
Illustration of electromagnetic energy passing through a glass duct

3.1.2 Reflection, refraction and diffraction

The following is a brief revision of some fundamental principles of physics. Reflection, refraction and diffraction are the three main effects that cause changes to the direction of an electromagnetic wave (this includes light, radio waves, x-rays, gamma rays etc). We will be concentrating on the specific behavior of light for the purpose of this.

Reflection

This is where a light ray that is traveling through a medium of a particular density strikes a medium of different density to the one in which it is traveling and partially or totally bounces off the interface of the two mediums.

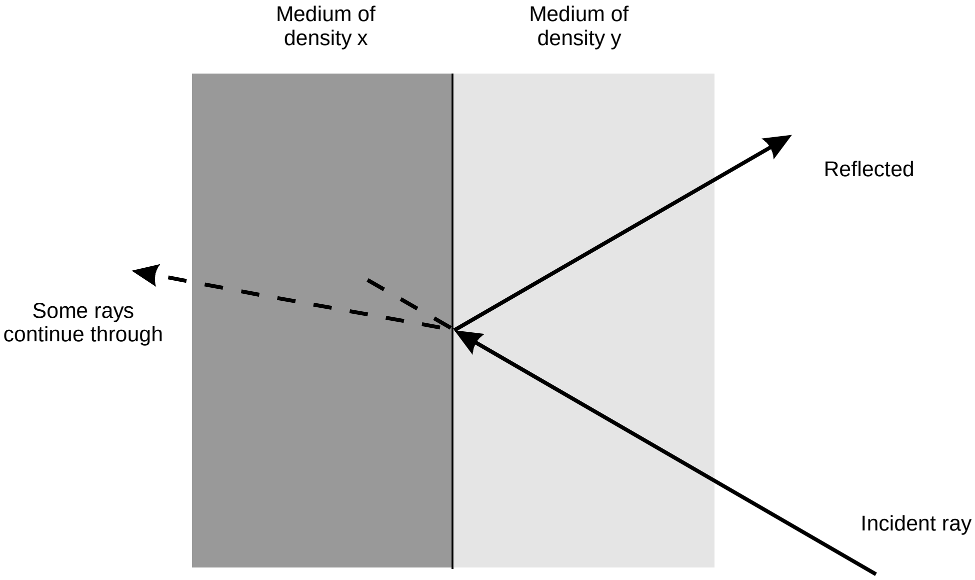


Figure 3.2
Illustrating reflection

Refraction

This is where a light ray totally or partially passes into a medium of different density from the one in which it is traveling and changes direction slightly, compared to its direction in the previous medium. A small amount of the energy is also reflected at the interface as shown in Figure 3.3.

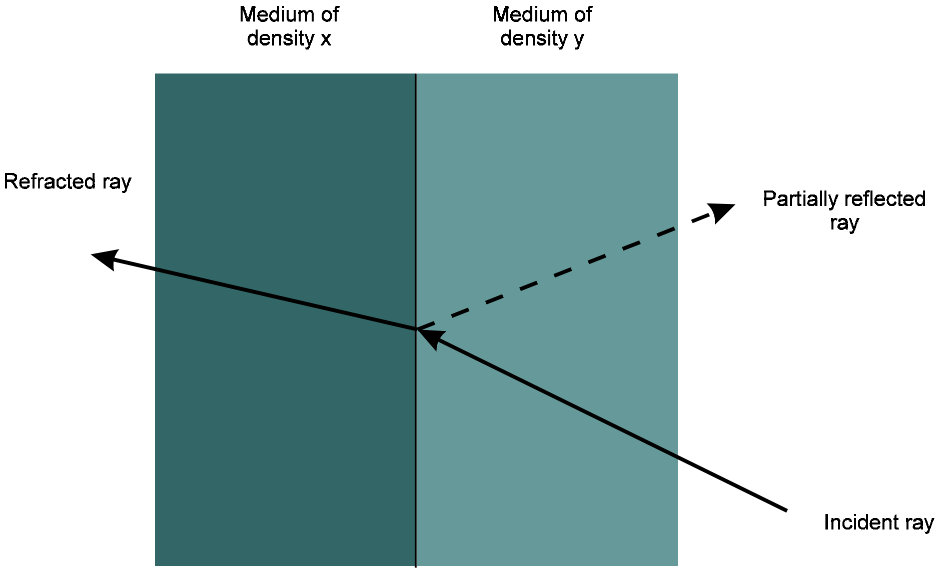


Figure 3.3
Illustration of refraction

Diffraction

This is where a light ray passes over an obstacle and changes direction slightly towards the obstacle. A similar phenomenon is noted when ripples of water strike a protruding rock or piece of land and then move around the rock or land with a slight change of direction towards it.

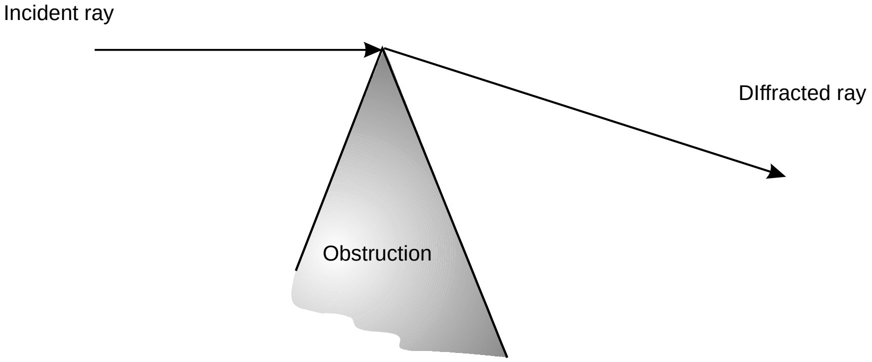


Figure 3.4
Illustration of diffraction

3.1.3 Refractive index

Light by nature, travels at different speeds in different mediums. The denser the medium the slower will be the speed at which the light travels. A measure of these factors has been established, which relates directly to both the density of the material and the speed of light through the material. This is referred to as refractive index. This measure for any material is made relative to the speed of light in a vacuum (the vacuum is often referred to as free space). The following formula describes this relationship.

$$\text{Refractive Index } N \text{ of a Medium} = \frac{\text{Speed of light in a vacuum}}{\text{Speed of light in a medium}}$$

$$N = \frac{3 \times 108 \text{ meters per second}}{\text{Actual light speed (meters per second)}}$$

$$N = \frac{C}{V}$$

The higher the refractive index of a material, the denser that material is. As a ray of light passes from one medium to another, where each medium has a different refractive index, the angle of refraction will differ from the angle of incidence. A ray of light passing into a medium of lower refractive index will leave at an angle greater than the angle of incidence. A ray of light passing into a medium of higher refractive index will leave at an angle less than the angle of incidence. This is illustrated in Figure 3.5.

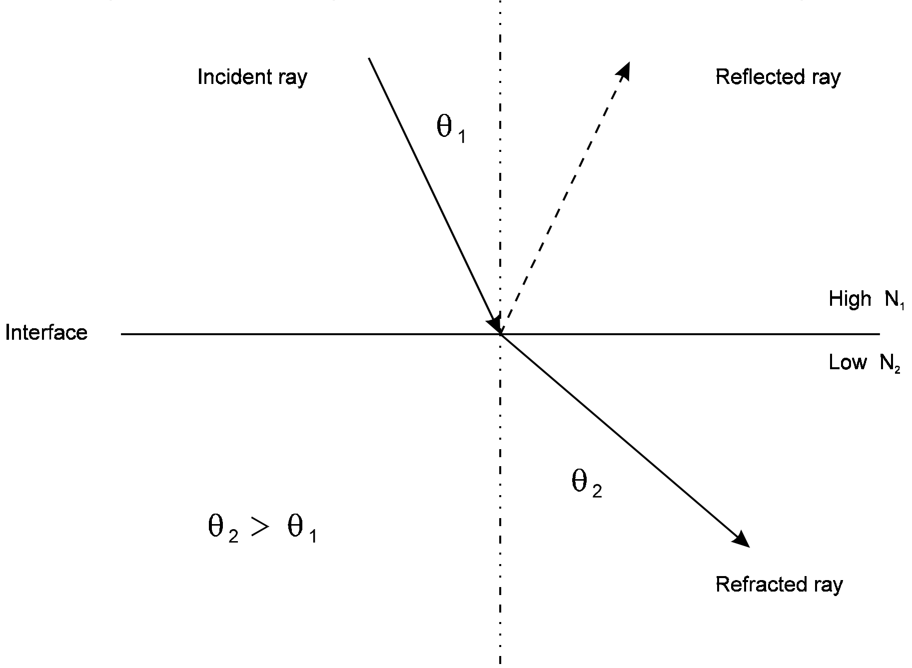


Figure 3.5a
Ray passing from high N_1 to low N_2

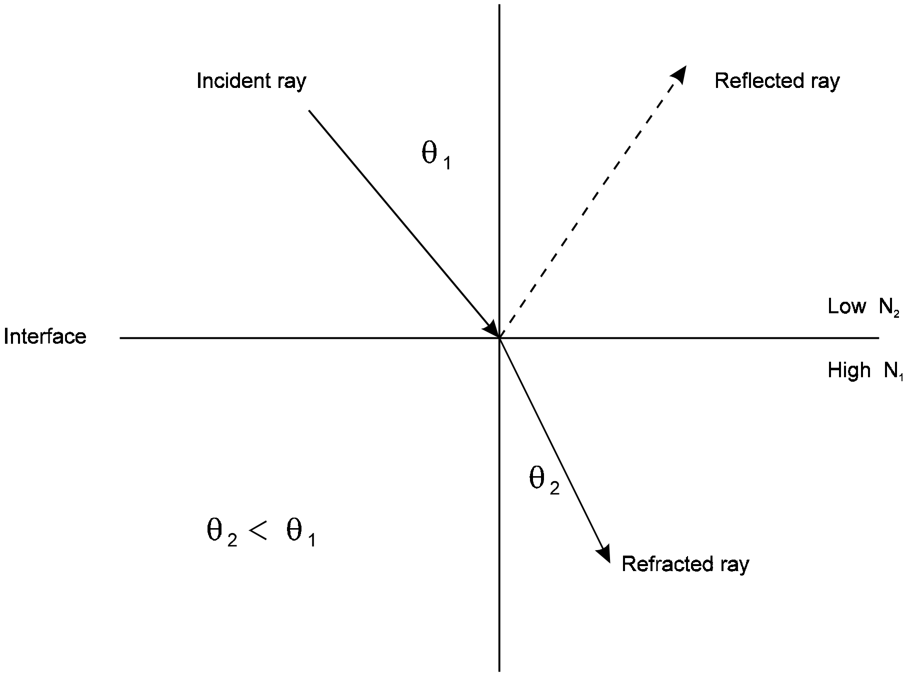


Figure 3.5b
Ray passing from low N_2 to high N_1

In that case, θ_1 is the angle of incidence and θ_2 is the angle of refraction. Some typical examples of refractive index are listed below:

Vacuum	1.0000
Air	1.0002
Water	1.333
Fused Silica	1.452
Crown Glass	1.517
Dense Flint Glass	1.655
Diamond	2.421
Ethyl Alcohol	1.360
Silicone	1.405

As a note of interest, x-rays always have a refractive index less than air in glass and therefore bend away from the normal when traveling from air into glass, rather than toward the normal as the light ray.

3.1.4 Snell's law

A Dutch astronomer and mathematician by the name of Willebrod van Roijen Snell described a relationship in 1621 that relates to the refraction of light traveling through different mediums. The relationship is expressed as follows:

$$N_1 * \sin(\theta_1) \quad = N_2 * \sin(\theta_2)$$

Where N_1 and N_2 are the refractive indices of medium 1 and medium 2 respectively; (θ_1) and (θ_2) are the corresponding angles of incidence or refraction in the respective mediums.

Therefore, from the above equation the following is arrived at:

$$\frac{N_1}{N_2}=\frac{\sin(\theta_2)}{\sin(\theta_1)}=\frac{C_2}{C_1}$$

where C_1 and C_2 are the speeds of light in medium 1 and medium 2 respectively.

3.1.5 Internal reflection

When light is traveling from one medium into a medium of different density, a certain amount of incident light is reflected. This effect is more prominent where the light is traveling from a high-density medium into a lower density medium. The exact amount of light that is reflected depends on the degree of change of refractive index and on the angle of incidence.

If the angle of incidence is increased, the angle of refraction is increased at a greater rate. At a certain incident angle (θ_C), the refracted ray will have an angle of refraction that has reached 90° (that is, the refracted ray emerges parallel to the interface). This is referred to as the 'critical angle'. For rays that have incident angles greater than the critical angle, the ray is internally reflected totally. In theory, total internal reflection is considered to reflect 100% of the light energy but in practice, it reflects about 99.9% of the incident ray. This is illustrated in Figure 3.6.

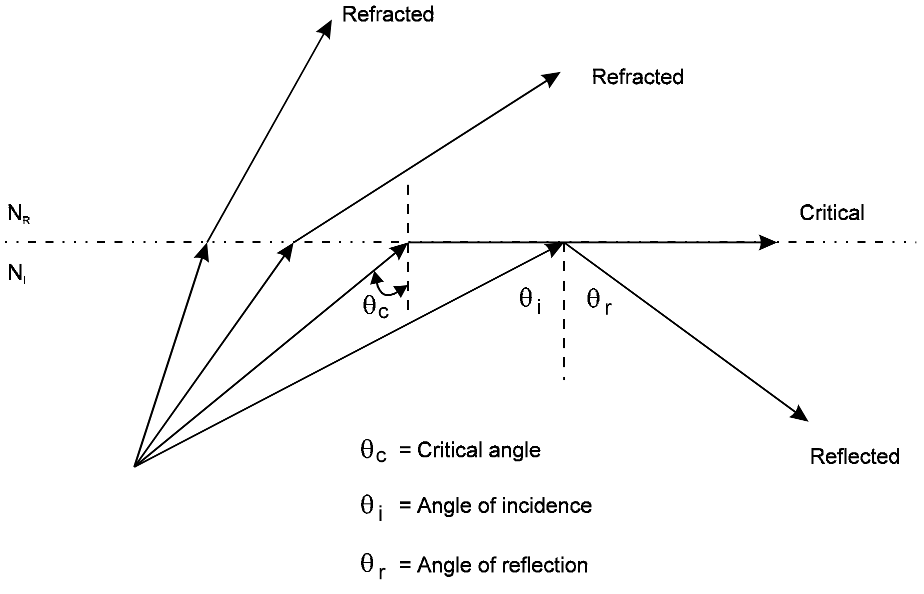


Figure 3.6
Illustration of critical angle

The critical angle (θ_C) is given by:

$$(\theta_C) = \text{arc sin}\left(\frac{N_R}{N_I}\right)$$

where total internal reflection occurs, the angle of incidence equals the angle of reflection.

3.1.6 External reflection

When a light ray is traveling in a medium and strikes an interface with a denser medium at greater than the critical angle, the same effect occurs as internal reflection but to a lesser degree. This is referred to as external reflection. Total external reflection only occurs when the angle of incidence equals 90^0.

3.1.7 Construction of an optical fiber

An optical fiber consists of a tube of glass constructed of a number of layers of glass, which when looked at in profile, appear to have a number of concentric rings. Each layer (or ring) of glass has a different refractive index. From the previous discussion, it can be seen that to send light down the center of these concentric glass tubes, it is a requirement that total internal reflection occurs. This will duct the light through the fiber. To achieve total internal reflection the outer glass rings require a lower refractive index than the inner glass tube in which the light is traveling. Figure 3.7 illustrates the construction of a typical optical fiber. The cladding diameter and sheath diameter illustrated in this figure, are accepted as standard for most fibers used world-wide, with the core diameter and refractive indices varying depending on the type of fiber (discussed in the following sections).

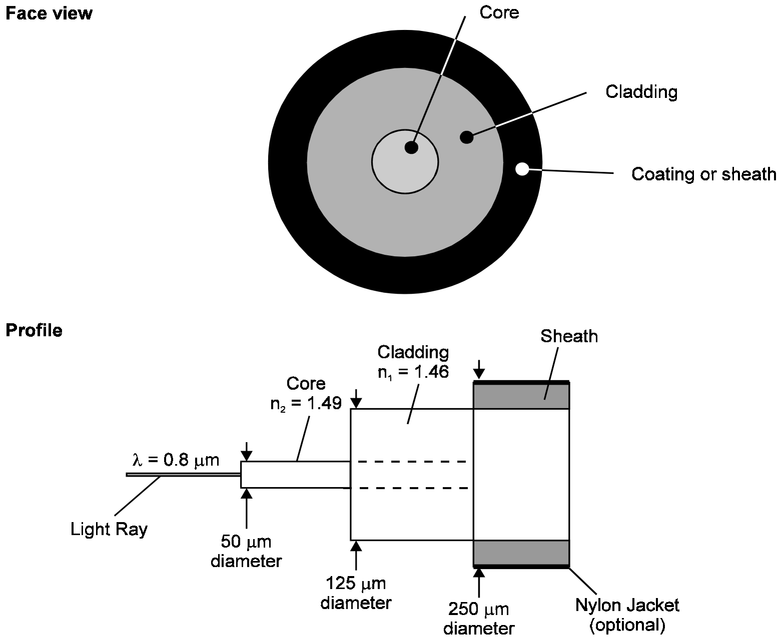


Figure 3.7
Construction of an optical fiber

The core and the cladding will trap the light ray in the core provided the light ray enters the core at an angle greater than the critical angle. The light ray will then travel down the core of the fiber, with minimal loss in power, by a series of total internal reflections. Figure 3.8 illustrates this process.

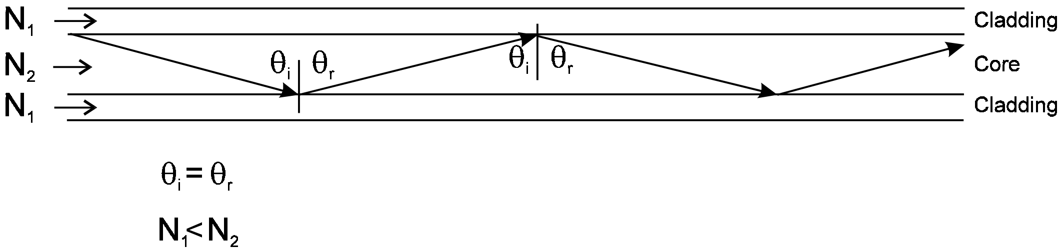


Figure 3.8
Light ray traveling through an optical fiber

It would, in theory, be possible to simply have a tube of glass of uniform refractive index acting as the core, with air acting as the outer cladding. This is possible as air has a refractive index lower than glass. This type of implementation does not generally work well because an unprotected core that is covered in scratches, dirt, and oil will appear to have an irregular cladding, with a higher refractive index at these irregular points than the core. Therefore, a lot of light will not be reflected and will be radiated out of the glass. This is illustrated in Figure 3.8a.

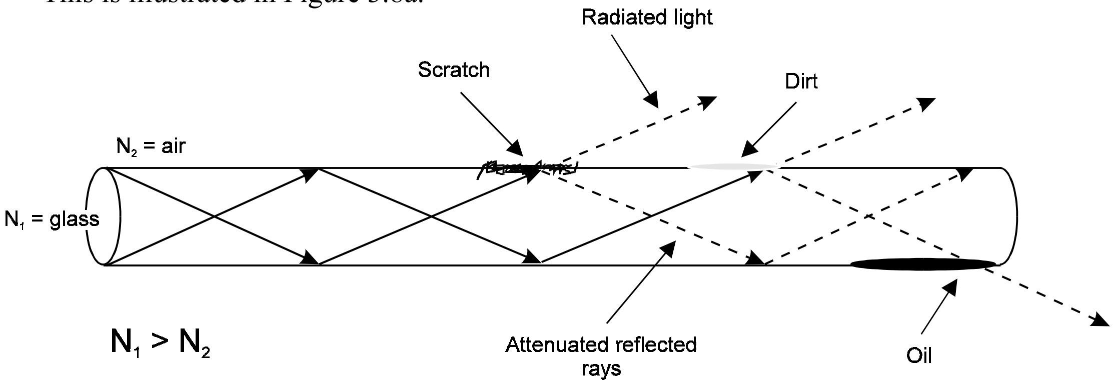


Figure 3.8a
Problems associated with a glass-air interface

In reality, the transmission of light down a fiber is far more complex than has been described because light actually travels in a three-dimensional stepped helical manner in glass. The mathematics required to precisely analyze this transmission phenomenon is extremely complex, of no real practical value, and beyond the scope of this book. This book will analyze the transmission of light in optical fibers in a two dimensional manner.

The core is generally constructed of germania-doped silica glass. The cladding is generally constructed of near pure silica glass. The cladding therefore has a lower refractive index than the core (the more impurities there are in glass, the higher the density of that glass). The sheath is generally constructed of ultraviolet cured plastic, which provides protection against abrasion and external forces. The sheath will also be color coded in a similar manner to multi-core copper cables to enable the user to distinguish between fibers.

3.1.8 Fresnel reflection

When light enters the core of a fiber and strikes the cladding at an angle less than the critical angle, then most of the light energy is refracted into the cladding and is lost (as is desired). A very small amount of light will be reflected back into the core. This reflected light is referred to as ‘Fresnel reflected’ light. It is generally less than 4% of the total incident light energy (calculated using the formula given in section 5.1.5) and therefore generally not powerful enough to carry a spurious signal to the other end of the fiber. This is illustrated in Figure 3.8b.

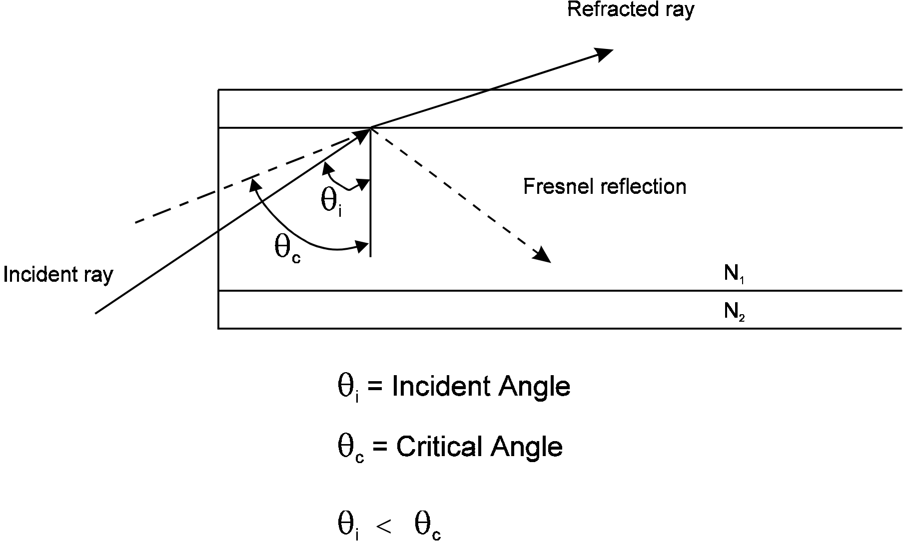


Figure 3.8b
Fresnel reflection

3.2 The light transmission nature of glass

From the discussion of frequency spectrum in Chapter 2, it is noted that visible light covers a broad range of frequencies. Transmission down optical fibers is generally in the near infrared band of frequencies. In this range of frequencies, the optical fiber exhibits the lowest signal attenuation. Figure 3.9 illustrates typical attenuation characteristics of glass that is used in fiber optics. Note that this curve does vary to some degree depending on the type of glass used for the manufacture and the type and degree of impurities infused into it.

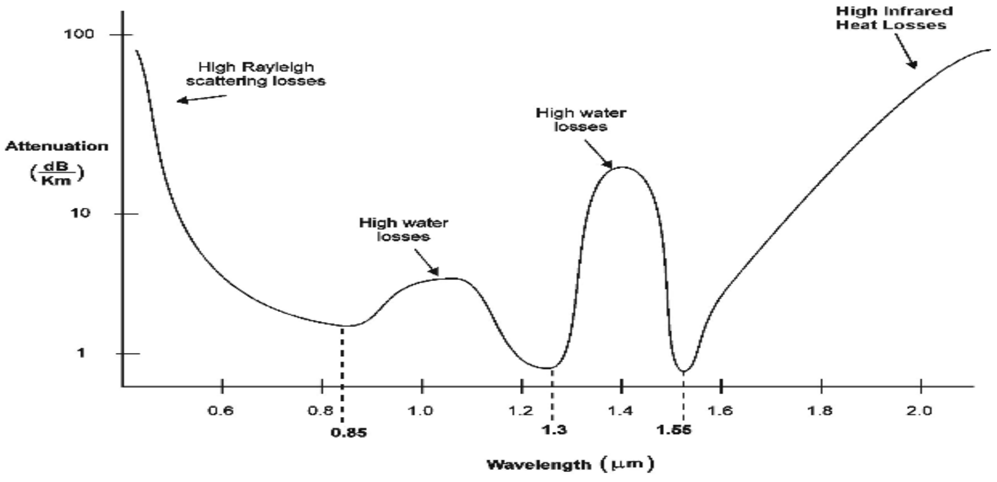


Figure 3.9
Typical attenuation responses for a fiber

From this diagram, it can be seen that there are three dips in the attenuation curve at 0.85 µm, 1.3 µm and 1.55 µm. These are referred to as ‘operating windows’. These are the gaps of bandwidth at which transmission down an optical fiber can take place and provide reliable communications over relatively long distances due to the low attenuation. The various types of losses that are noted in Figure 3.9 will be discussed in detail in section 3.7.

The 0.85 µm window was the first to be used for fiber optic communications because the transmission sources and the receiving detectors were easy to manufacture and very efficient. It is still the preferred wavelength of operation for systems operating over short distances because the transmitting and receiving equipment is relatively inexpensive. A typical range of attenuation figures for an optical fiber at this wavelength is 2 to 3.2 dB per km.

For the majority of fiber optic systems, the 1.3 µm window is the preferred window of operation because the overall losses are much lower than the 0.8 µm window. A typical range of attenuation figures for an optical fiber at this wavelength is 0.3–0.9 dB per km. Although the light sources are readily available, they are expensive and difficult to manufacture. Hence, this wavelength is generally used for high speed data and long distance telecommunications applications.

The third window, which operates at 1.55 µm, exhibits less loss than the second window. A typical range of attenuation figures for an optical fiber in this band is 0.15–0.6 dB per km. The trade off unfortunately is that the transmitting and receiving devices are not as advanced or as efficient as those operating in the 1.3 µm window. It is anticipated that recent technological developments will make this the most popular window of operation in the future.

A technology known as wave division multiplexing (WDM) is allowing multiple wavelengths to be simultaneously transmitted down the fiber at the same time. Normally there are multiple wavelengths close to either the 1.3 µm or 1.55 µm wavelengths. This technique effectively multiples the single wavelength data rate bandwidth by the number of wavelengths being transmitted.

3.3 Numerical aperture

Previous sections of this chapter have discussed the process of light traveling through an optical fiber. This section will discuss the requirements for transmitting into an optical fiber.

As was discussed in section 3.1.7, it is a requirement for light to successfully travel down an optical fiber, it must enter the fiber and reflect off the cladding at greater than the critical angle. Due to the refractive changes to the direction of the light as it enters the core of a fiber, there is a limit to the angle at which the light can enter the core to successfully propagate down the optic fiber. Any light striking the cladding at less than the critical angle will go straight through into the cladding and be lost. This is illustrated in Figure 3.10.

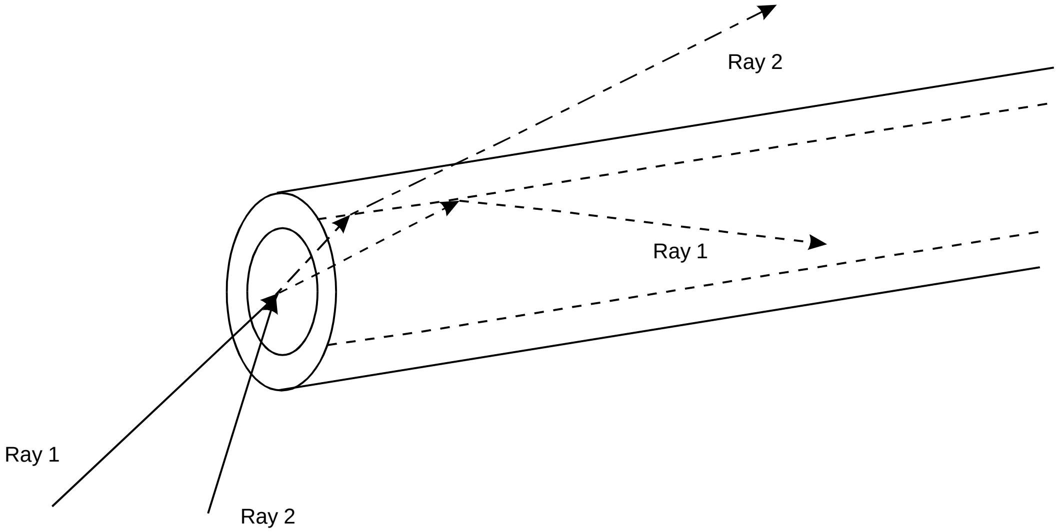


Figure 3.10
Light entering the core of a fiber

Since the fiber is cylindrical, there will be a geometrical cone at the entrance to the fiber. For light entering the core within this cone, all the light rays will strike the cladding at greater than the critical angle and will therefore allow successful transmission down the fiber. This is referred to as the ‘acceptance cone’ and is illustrated in Figure 3.11.

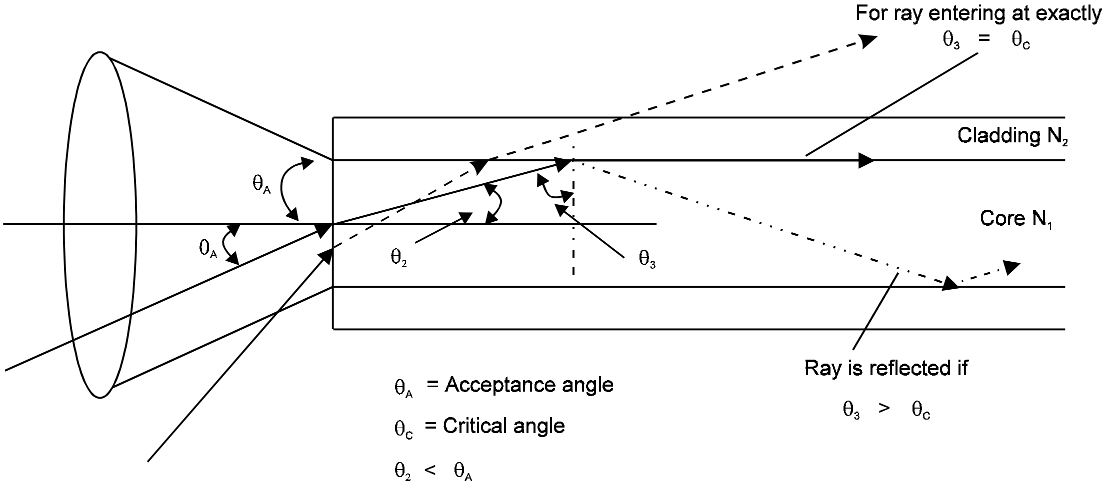


Figure 3.11
Cone of acceptance of an optic fiber

The half angle (θ_1) of this acceptance cone is referred to as the ‘acceptance angle’. The value of the acceptance angle will depend on the refractive indices of the core, cladding and air (air having a refractive index of 1) or whatever material the source of light is. A light ray entering the core at an angle greater than $\theta_1$will disperse into the cladding. A light ray coming in at an angle of exactly θ_1 will strike the core/cladding interface at angle θ_c (critical) and will leave parallel to the interface.

A measurement is used to specify the light collecting ability of a fiber. This is referred to as the ‘numerical aperture’ (*NA*). *NA* is the sin of the acceptance angle, that is:

$$NA = \sin(\theta_1)$$

It can also be expressed as a factor of the refractive indices of the fiber.

$$NA = \sqrt{(N_1^2 - N_2^2)}$$

$$= N_1 \sin(\theta_2)$$

If there are two fibers with the same core diameter but different *NA*s, then the fiber with the larger *NA* will accept more light energy radiated from a light source than the fiber with smaller *NA*. If there are two fibers with the same *NA*s but different diameters then the fiber with the larger diameter will allow more light energy into the core than the fiber with the smaller diameter. This is illustrated in Figure 3.12.

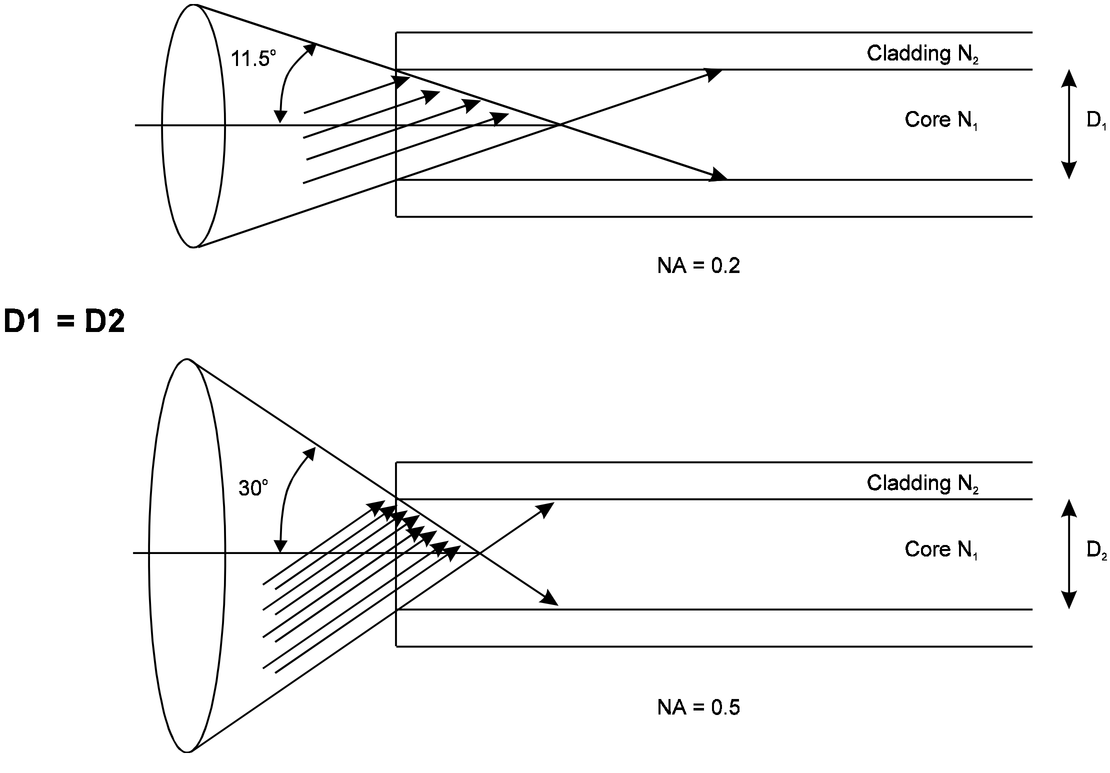


Figure 3.12a
Fibers with different NAs but same diameters

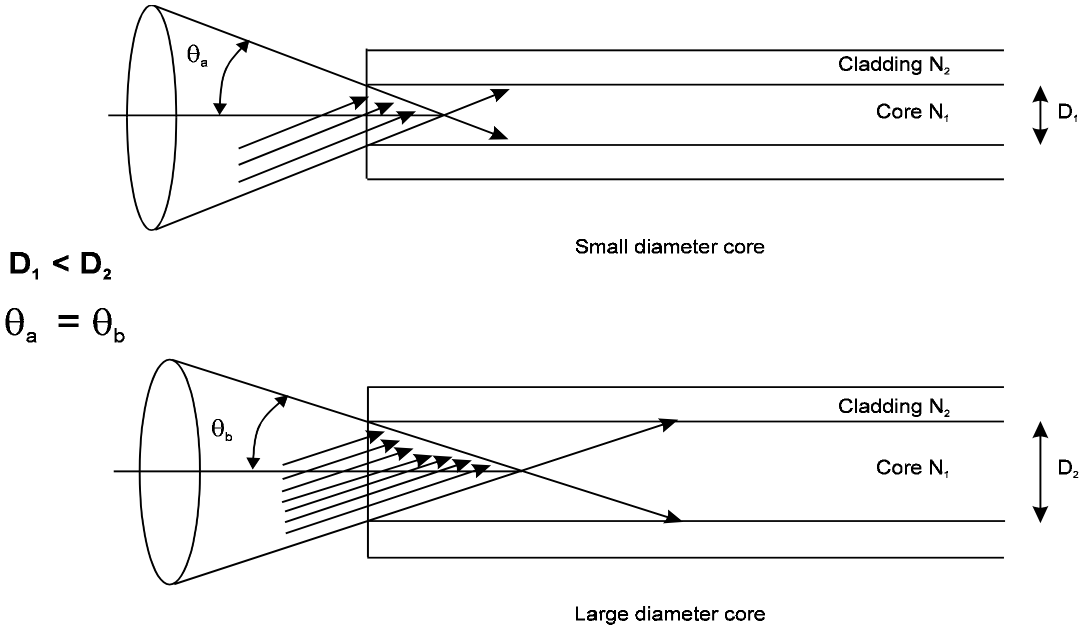


Figure 3.12b
Fibers with same NAs but different diameters

As optical fibers with large *NA*s or diameters will accept more light than fibers with smaller *NA*s or diameters, the larger *NA* or diameter fibers will be more suitable for less expensive light transmitters such as LEDs, which are unable to concentrate their output energy into a narrow coherent beam (as do lasers) and radiate over a larger angle. However, the disadvantage of a fiber that is constructed with these parameters is that there will be a greater dispersion (spreading) of the light that is injected into the core and therefore a reduction in the fiber transmission bandwidth (discussed further in sections 3.5 and 3.6). At the other end of the scale, the fiber with a small *NA* or diameter will have a greater bandwidth. This is because only relatively parallel rays of light will enter the core and there will be less dispersion of the light down the core. However, the disadvantage here is that it will require a more expensive light source that provides a narrower beam of light (such as a laser) and a more precise alignment of the transmitter and the core.

3.4 Modal propagation in fibers

3.4.1 Introduction

Optical fibers are classified according to the number of rays of light that can be carried down the fiber at one time. This is referred to as the ‘mode of operation’ of the fiber. Therefore, a mode of light is simply a ray of light. The higher the mode of operation of an optical fiber, more rays of light that can travel through the core. It is possible for a fiber to carry as many as several thousand modes or as few as only one.

The following section discusses various modes of propagation in optical fibers and the effects of modal dispersion.

3.4.2 Modal dispersion

It is important firstly to examine the nature and effects of modal transmission. A fiber that has a high *NA* and/or diameter will have a large number of modes (rays of light) operating along the length of that fiber. An omnidirectional light source (i.e. one that effectively radiates light rays equally in all directions) such as an LED will emit several thousand rays of light in a single pulse. Because the light source injects a broad angle of beam into the core, each mode of light traveling at a different angle as it propagates down the fiber will therefore travel different total distances over the whole length of the fiber. It follows therefore that it will take different lengths of time for each light ray to travel from one end of the fiber to the other. The light transmitter will launch all modes into the fiber exactly at the same time, and the signal will appear at the beginning of the fiber as a short sharp pulse. By the time the light reaches the end of the fiber, it will have spread out and will appear as an elongated pulse. This is referred to as 'modal dispersion'. This is illustrated in Figure 3.13.

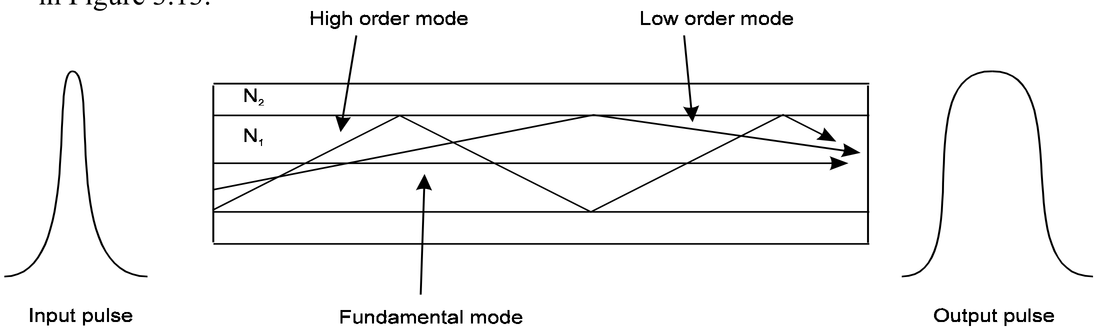


Figure 3.13
The dispersion effect on a pulse due to multiple modes of propagation

The light ray that travels down the center axis of the fiber is referred to as the fundamental mode and is the lowest order mode possible. The light rays that travel the shorter distances down the length of fiber are the lower order modes and the light rays that travel the longer distances down the length of fiber are the higher order modes.

If the input pulses are too close together, then the output pulses will overlap on each other, causing inter-symbol interference at the receiver. The effect of modal dispersion would rely on this development. This situation will make it difficult for the receiver to distinguish between pulses and will introduce errors into the data. This is the major factor in fiber optic cables (multimode types) that limits transmission speeds. This is illustrated in Figure 3.14.

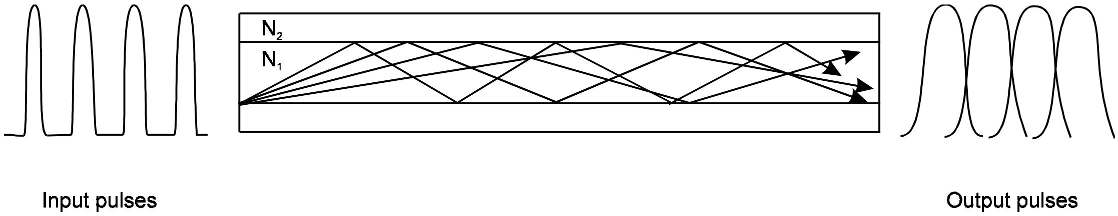


Figure 3.14
Inter-symbol interference due to modal dispersion

It can be seen from this diagram that it will be difficult for the receiver to distinguish between the output pulses as they overlap on each other as they exit the fiber core (inter-symbol interference).

Modal dispersion is measured in nanoseconds and is given by the following formula:

$$D = \sqrt{\left(D_0^{\,2} - D_i^{\,2}\right)}$$

where:

D = total dispersion of a pulse

D_o = pulse width at the output of the fiber in nanoseconds

D_i = pulse width at the input of the fiber in nanoseconds

Modal dispersion increases with increasing *NA*, and therefore, the bandwidth of the fiber decreases with an increase in *NA*. The same rule applies to the increasing diameter of a fiber core. This is illustrated in the graphs in Figure 3.15.

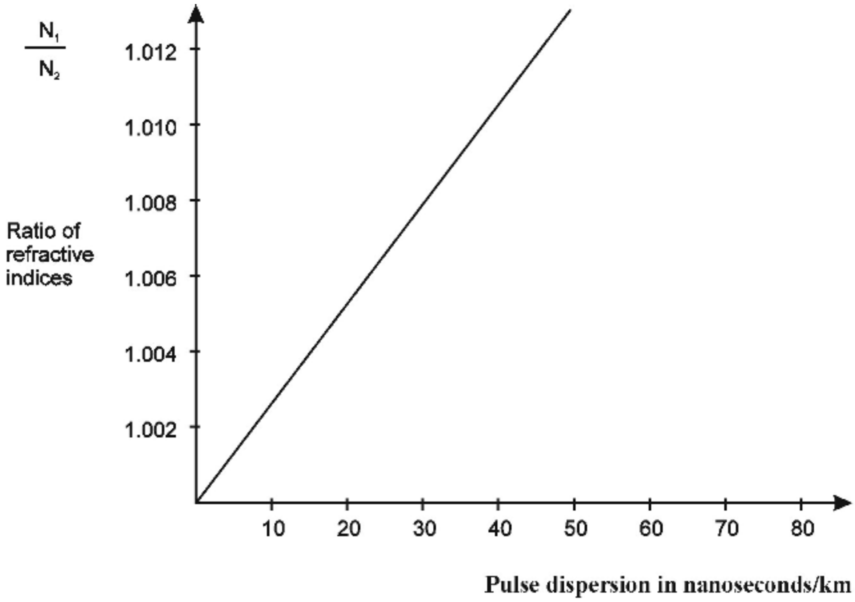


Figure 3.15a
Pulse dispersion vs the ratio of refractive indices

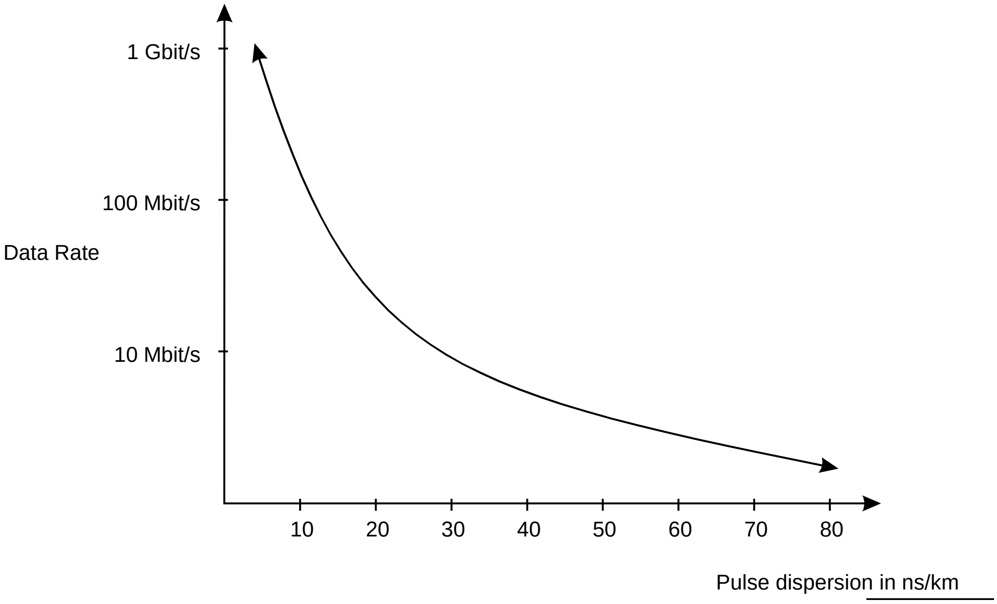


Figure 3.15b
Pulse dispersion vs data rates

Cable suppliers provide a dispersion figure in the cable specification. The unit of measure will be given as peco seconds (or nanoseconds) of pulse spreading per kilometer of fiber (ps/km). Generally, the supplier does not give this figure directly but it is easily determined from the bandwidth. For example, a 400 MHz-km bandwidth represents a maximum modal dispersion you would expect from the fiber of 1/400 MHz/km, which equals 2.5 ns/km.

Section 8.3.2 describes the techniques for calculating the effects of modal dispersion on a system.

3.4.3 Number of modes

When the core and cladding each have a constant refractive index across their cross sectional area but the core refractive index being different to the cladding refraction index, then they behave like an optical waveguide. This is referred to as 'step index' and is discussed in the next section. In this waveguide only a specific number of modes can propagate.

The number of discrete modes is determined by the following formula:

$$M = \frac{0.5\,[\theta d\,(NA)^2]}{\lambda}$$

where:

d = the diameter of the fiber core

λ = the wavelength of the light

NA = the numerical aperture

It can be seen from this formula that as the diameter and the *NA* decrease, so do the number of modes that can propagate down the fiber. The decrease in modes is more significant with a reduction in diameter than a reduction in *NA*. The *NA* tends to remain relatively constant for a wide range of diameters. Note also that as the diameter starts to approximate the wavelength of light, then only one mode will travel down the fiber. This state is referred to as 'single mode' or 'mono mode' propagation. Figure 3.16 illustrates the rate at which the number of modes increases with increasing core diameter.

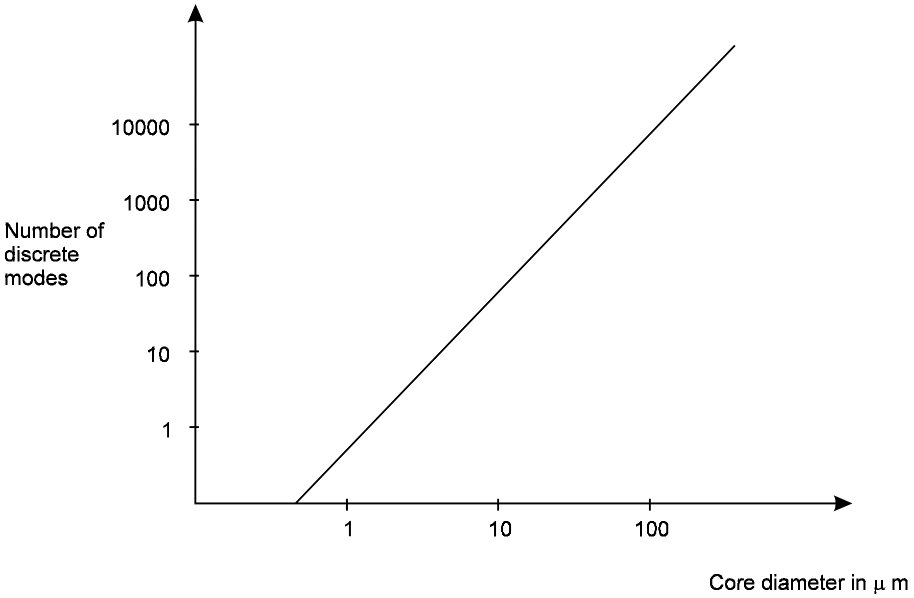


Figure 3.16
Number of propagation modes vs core diameter

3.4.4 Leaky modes

An unusual phenomenon is noted when the *NA* for very short lengths of fiber is compared to the *NA* for very long lengths of fiber. For example, the *NA* of 3 meters of multimode fiber may be measured at 0.36 but for 1 km of the same cable, it may be measured at 0.3.

The reason for this spurious result is due to the way *NA* is measured. A certain amount of light will escape into the cladding at the point of connection with the light source and will transverse down the cladding and be detected by the receiving detector several meters away. As *NA* is a measure of the light acceptance ability of the fiber, it appears to have a larger *NA* than it actually has.

The light that enters the cladding will be very small in amplitude and will readily leak out of the cladding with any slight bends in the fiber. Therefore, the light traveling in the cladding will have significantly dispersed after 10 or 20 meters only. These are referred to as leaky modes.

3.4.5 Refractive index profile

The discussion so far has assumed that the refractive index of the core and the cladding are constant across their surface areas. This is the case for a lot of fibers but not all. For example, the graded index multimode fiber to be discussed in section 3.6.5 has a gradual changing refractive index in the core and cladding. To help distinguish between optical fibers, they are generally specified with a graphed profile of their refractive indices. Figure 3.17 illustrates three examples of refractive index profiles.

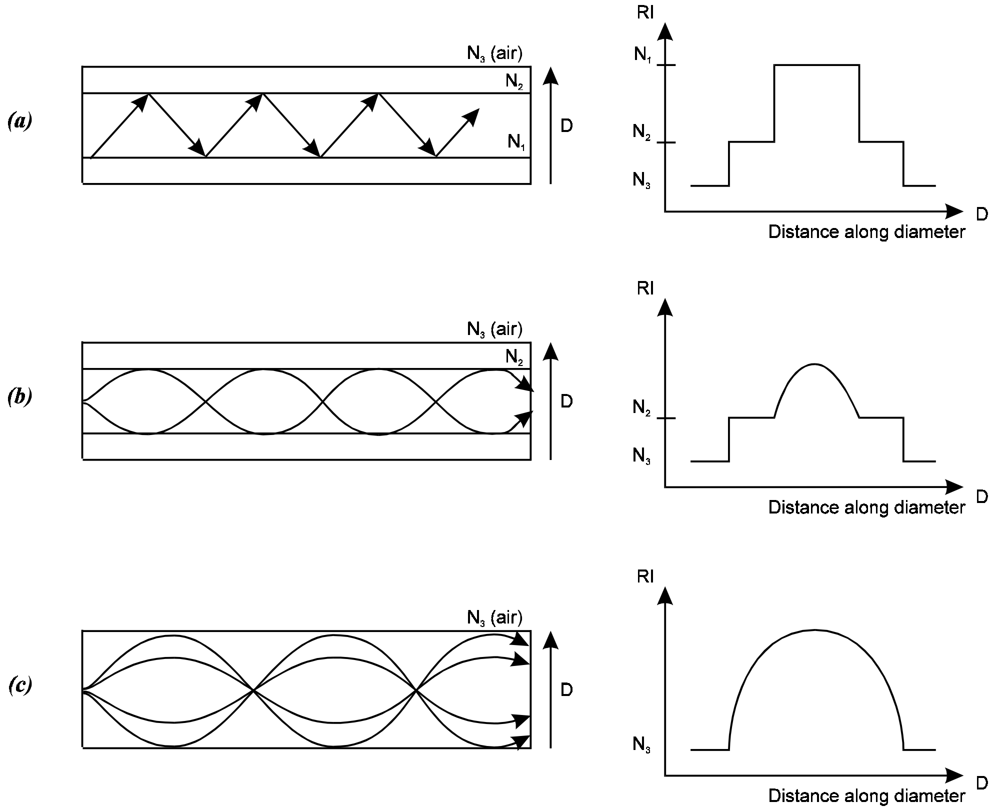


Figure 3.17
Examples of refractive index profiles

3.4.6 Multimode step and graded index fibers

The term 'multimode' generally applies to fibers with a diameter of 50 micrometers or greater. Because of the relatively wide diameter of the core, multiple modes of light are able to travel down the core. As was discussed in section 3.4.2, allowing multiple modes of light to travel down a fiber causes modal dispersion.

The modal dispersion that occurs in a multimode fiber affects or is affected by a number of operating parameters of the fiber.

Attenuation

Multimode fibers have a maximum operating distance of approximately 5 km.

Bandwidth

Multimode fibers have a maximum operating data speed of approximately 2–300 Mbps.

Wavelength

They generally operate at wavelengths of 850 nm or 1300 nm. Some fibers are available that operate at both wavelengths (different physical communications standards use different operating wavelengths).

The wide diameter of the multimode fiber makes it suitable for using with LED light sources. This, in turn, makes the complete transmission system a lot cheaper than compared to fibers that have a thinner diameter and which require the use of lasers. Recently, the introduction of VCSEL lasers (refer to Chapter 6) has significantly reduced the cost of lasers and they are now starting to be used for high-speed data links up to 10 Gbps on multimode fiber (over distances of less than 90 meters). A further advantage with using multimode fibers is that the wider diameter makes them easier to splice and to terminate, which makes the final installed system cheaper.

Multimode fibers are constructed in three main sizes. The following section discusses the advantages and disadvantages of each. The first piece of text in each of the following three sections illustrates how the fiber is specified and next to it, the meaning of each part of the specification.

50 Micron cores

50/125/250 µm	50 µm core diameter
	125 µm cladding diameter
	250 µm sheath diameter
50/125/900 µm	900 µm tight buffer sheath diameter

This particular size fiber is used extensively in Europe.

Attenuation

Compared to the other two fiber sizes discussed, this fiber experiences lower signal attenuation. But to counter this, the smaller diameter fiber does not allow as much signal energy to be coupled into the fiber from the LED.

Bandwidth

Overall, this fiber has a higher bandwidth than the other two fibers and therefore achieves higher data rates. The higher bandwidth is due to lower modal dispersion.

NA

This fiber has the lowest numerical aperture of the three fiber sizes, generally around 0.2. The relatively small core size and *NA* result in this fiber coupling the least amount of energy from the light source. For long cable runs the lower attenuation will tend to counter this.

62.5 Micron cores

62.5/125/250 µm	62.5 µm core diameter
	125 µm cladding diameter
	250 µm sheath diameter
62.5/125/900 µm	900 µm tight buffer sheath diameter

This size fiber is predominantly used throughout the USA and the Asian/Australasian regions.

Attenuation

Compared to the other two fiber sizes, there is marginally more signal attenuation than the 50 µm fiber and significantly less attenuation than the 100 µm fiber.

Bandwidth

This fiber has a bandwidth that is only slightly less than the 50 µm fiber. Therefore it is used in systems that operate at the same data rates as those using 50 µm fibers.

NA

It has a relatively high *NA* that is close to the *NA* of the 100 µm fiber, generally around 0.275. The higher *NA* of this fiber will couple approximately 5 dB more power than a 50 µm fiber when connected to a same capacity source. This will generally counter the lower attenuation characteristic of the 50 µm fiber over distances of several kilometers and provide similar distances of transmission.

100 Micron cores

100/140/250 µm	100 µm core diameter 140 µm cladding diameter 250 µm sheath diameter

This size fiber is rarely used today in commercial or industrial data communications applications. It was one of the first fibers introduced in the market and had a large core diameter because of the limitations of early fabrication techniques.

Attenuation

This fiber exhibits attenuation characteristics approximately twice that of the 50 µm and 62.5 µm multimode fibers. This has made it unsuitable for most data communications applications.

Bandwidth

It has the lowest bandwidth of the three fiber sizes. This is generally around 20 or 30% of the other fiber sizes. Therefore it will only support relatively slow data rates.

NA

Compared to other multimode fibers, this fiber has the largest *NA*, generally around 0.290. This represents an extra coupling of approximately 9 dB when compared to a 50 µm cable connected to the same capacity light source. Because of its larger diameter, it is easier to splice and to couple to the transmitters and receivers. The increase in *NA* of this fiber is only slightly more than the 62.5 µm fiber and does not compensate for the very high attenuation and low bandwidth.

Note that it is possible to use 50 µm fiber with 62.5 µm connectors and transmitting and receiving equipment, and vice versa, because both have the same cladding diameter. There will be a small loss introduced due to the misalignment of the fiber cores.

Multimode fibers are manufactured in two types:

- Step index
- Graded index

Step index

A step index fiber consists of a glass core of constant cross-sectional refractive index, surrounded by a cladding of a different constant cross-sectional refractive index. Because of this sudden change in the refractive index light will reflect off the core/cladding interface and transverse its way down through the core. It has a refractive index profile as shown in Figure 3.18.

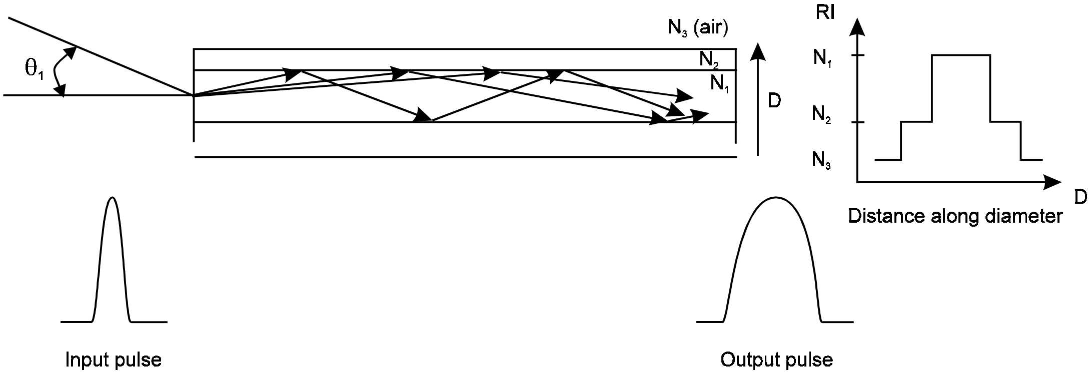


Figure 3.18
Step index fibers

The refractive index of the core (N_1) is typically 1.48 and the cladding (N_2) approximately 1.46. The acceptance angle (θ_1) is typically around 14°.

Step Index fibers exhibit significant modal dispersion. This is generally around 15 to 40 nanoseconds per kilometer and limits the transmission bandwidth to approximately 25 MHz – km. This in turn limits the digital transmission speed to not much greater than 10 Mbps/km. It is suitable for many industrial applications where only slow data rates are required but is unsatisfactory for most commercial telecommunication applications where much higher data rates are required.

Graded index

A graded index multimode has a core that has a gradual changing cross-sectional refractive index. The center of the core has the highest refractive index that gradually reduces moving away to the edges of the core. Because of this smooth changing refractive index, the light ray refracts (rather than reflects as in step index fibers) as it moves through the core, and sets up a set of sinusoidal light wave patterns in the fiber. This is illustrated in Figure 3.19.

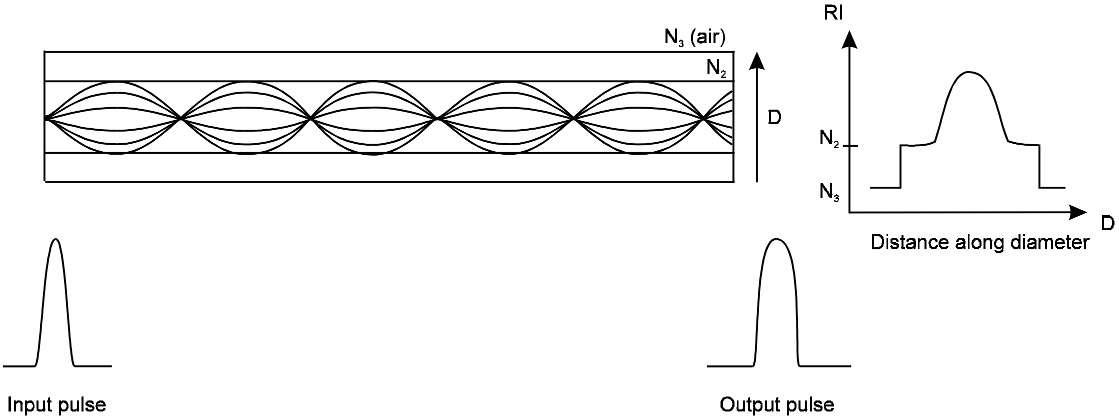


Figure 3.19
Multimode graded index fiber transmission

The practical effect of this curved refractive index profile is that the light rays that are traveling further from the center axis of the core will have the furthest distance to travel but will be traveling through the lowest refractive index glass and will therefore be traveling the fastest (as suggested by Snell's law). The light rays that are traveling closer to the center of the core will be traveling the shortest distance but will be traveling through the highest refractive index glass and will therefore be traveling the slowest. The end result of all this is that the rays will all tend to arrive at the same point on the center axis of the core at the same time, which means that the modal dispersion has been greatly reduced.

The center of the core has a refractive index of approximately 1.48, which gradually reduces to 1.46 as it approaches the cladding. The acceptance angle or θ_1 is typically around 12° (an *NA* of approximately 0.2).

In practice, graded index fibers have a modal dispersion which is well below 5 nanoseconds and transmission bandwidths on good quality cables that go as high as 2 GHz/km (standard readily available fibers have bandwidths of 600 MHz-km) for both 850 μm and 1300 μm operating wavelengths. This allows data transmission rates up to approximately 2–300 Mbps for a cable with approximately 600 MHz/km and up to 1 Gbps for fiber with better than 2 GHz/km (the latter using VCSEL laser transmission devices). This type of fiber is suitable for virtually all industrial applications and for a number of commercial telecommunication applications. Although modal dispersion is low in graded index fibers compared to step index fibers, it is still significant and does have a limiting effect on the bandwidth.

Some graded index fibers are constructed in such a way that there is no distinction between the core and cladding refractive indices, just a gradual reduction from the center axis to the outside of the cladding.

Standards

The international standard for customer premises cabling ISO/IEC11801, which contains recommendations for both copper and optical fiber cable, has classified different multimode fiber for customer premises' use. At the time of writing this book, the standard was under review and being updated.

The standard provides details on three different classes of multimode fiber (OM1 to OM3) and one class of singlemode fiber (OS1). It details the required minimum bandwidth-kilometer product that is expected from each of the cables. It also distinguishes between when the fibers are driven from LEDs and when they are driven from lasers (VCSELs are normally used – refer to Chapter 6). The following table shows the bandwidth–distance product for the three multimode fiber types.

Fibre Class	**LED 850 nm**	**LED 1300 nm**	**Laser 850 nm**
OM 1	200 MHz*km	500 MHz*km	N/A
OM 2	500 MHz*km	500 MHz*km	N/A
OM 3	1500 MHz*km	500 MHz*km	2000 MHz*km

Table 3.1
The bandwidth–distance product for the three multimode fiber types

Although LEDs may be able to reach 1 Gbps in multimode fiber, it is not in normal practice to manufacture links at this speed using LEDs. The preferred practice is to use the cheaper laser products (VCSELs), which will provide data speed up to 10 Gbps on OM-3 quality singlemode fibers. 1 Gbps Ethernet applications on multimode fiber are now running up to 500 meters at the 850 nm wavelength. 1300 nm VCSELs have just been released and 1550 nm VCSELs are still under development.

3.4.7 Singlemode fibers

With reference to the formula given in section 3.4.3, it can be seen that in order to reduce the number of modes traveling down a fiber (and therefore reduce the modal dispersion) the core diameter and/or the *NA* must be reduced, and/or the wavelength of transmission should be increased. These are the fundamental principles behind the operation of singlemode cables.

A singlemode fiber (or sometimes referred to as a single mode cable) is basically a step index fiber with a very small core diameter. In theory, because the cores are so small, only a few modes of light can travel down the fiber. To further reduce the number of modes, the fiber is constructed with very little difference between the refractive indices of the core and the cladding. From the formula given in section 3.2.4, as the difference between the refractive indices of the core and cladding decrease, the critical angle increases. Therefore, only light approaching at a very large angle of incidence will be internally reflected and all other rays will dissipate into the cladding. Because of this construction, only a single mode of light is able to transverse down the fiber (i.e. the fundamental mode). This is illustrated in Figure 3.20.

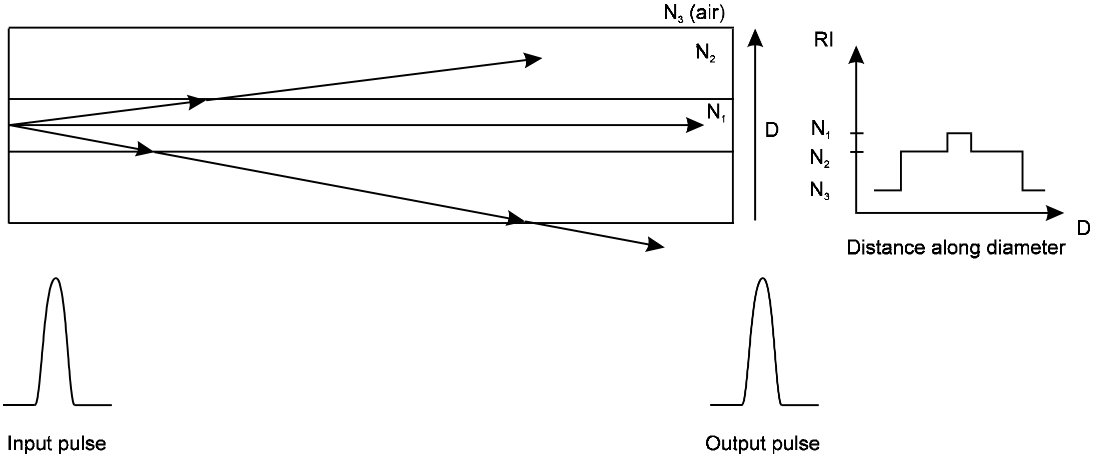


Figure 3.20
Singlemode optic fiber transmission

For the transmission of light down a singlemode fiber to operate as described above, the pulse of light that is injected into the core must be very precisely aimed down the center of the core or the majority of the light will be lost in the cladding. If the system is implemented correctly, the input signal pulse into the fiber will appear at the output of the fiber as a signal pulse with almost exactly the same shape. With only the fundamental mode traveling down the fiber, there can theoretically be no modal dispersion in singlemode fiber.

The core diameter of a singlemode fiber is generally in the region of 8 to 9 μm. A typical measurement specification for a singlemode fiber is 8.5/125/250 μm.

Attenuation

A typical singlemode fiber will exhibit between 0.35 and 1.0 dB attenuation per kilometer at an operating wavelength of 1310 nm, and between 0.25 and 1.0 dB attenuation per kilometer at an operating wavelength of 1550 nm. Recent research has achieved losses for the 1550 nm wavelength down to approximately 0.15 dB/km.

Bandwidth

A modern singlemode fiber will generally exhibit very high bandwidths, often in excess of 100 GHz/km. Presently, this represents commercial data transmission rates of between approximately 10 & 40 Gbps for systems operating with single wavelength. Laboratory work is currently being carried out on lasers that transmit upto 100 Gbps. Data speeds beyond this for one wavelength are becoming more difficult to obtain because the response time of the receiving devices are unable to detect the difference between the bit length and the wavelength of light. As has been previously mentioned, the use of wavelength division multiplexing will allow singlemode transmission speeds upto several Tera bps on a single fiber.

NA

The *NA* of singlemode fibers is extremely small (generally in the region of 0.1 to 0.15), which greatly reduces the number of modes of light that can pass down the fiber. To overcome the problem of a very small acceptance angle, lasers are used to provide a coherent and powerful beam of light that is very precisely aligned on to the end of the fiber to ensure maximum amount of energy is radiated into the fiber. Misaligned light rays will dissipate into the cladding and be lost, therefore, correct alignment is very important.

The singlemode fiber has a cladding diameter of 125 μm and it is therefore physically possible to connect this fiber to multimode source and detector equipment. Due to the small *NA* and core diameter, very little light energy will radiate down the fiber and therefore the system will not operate satisfactorily. For the reverse of this scenario where singlemode source and detector equipment are connected to multimode cables, the systems will work very successfully for speeds of up to 1 Gbps over relatively long distances.

Distance between repeaters

Modern singlemode fiber optic link systems that are of a very high quality are capable of distances between repeaters of up to 300 km for speeds up to 2.5 Gbps (using non zero – dispersion shifted fiber; discussed in section 3.6.1). Research programs currently taking place are quoting future distances between repeaters of up to two orders of magnitude greater than this.

Wavelength of operation

Most singlemode fiber systems operate with the 1300 nm and 1550 nm wavelengths, although there is a preference to operate in the 1550 nm region because of the lower fiber attenuation at this wavelength. The lasers operating at the latter wavelength are not as efficient as the 1300 nm lasers but a significant amount of research and development is currently being carried out to improve them.

One of the problems with the construction of singlemode cables that was discussed is that since there is little difference between the core and the cladding refractive indices a small amount of light tends to travel down the cladding. This will add further distortion to the output signal. This is generally referred to as ‘waveguide dispersion’. This is discussed further in section 3.6.1. The manufacturer will generally include this dispersion figure in the published chromatic dispersion figure in the optical fiber specification.

3.4.8 A comparison of data rate, distance and fiber type

The following graph shows the expected data rates and transmission distances for the various mode and indexed fibers at different wavelengths.

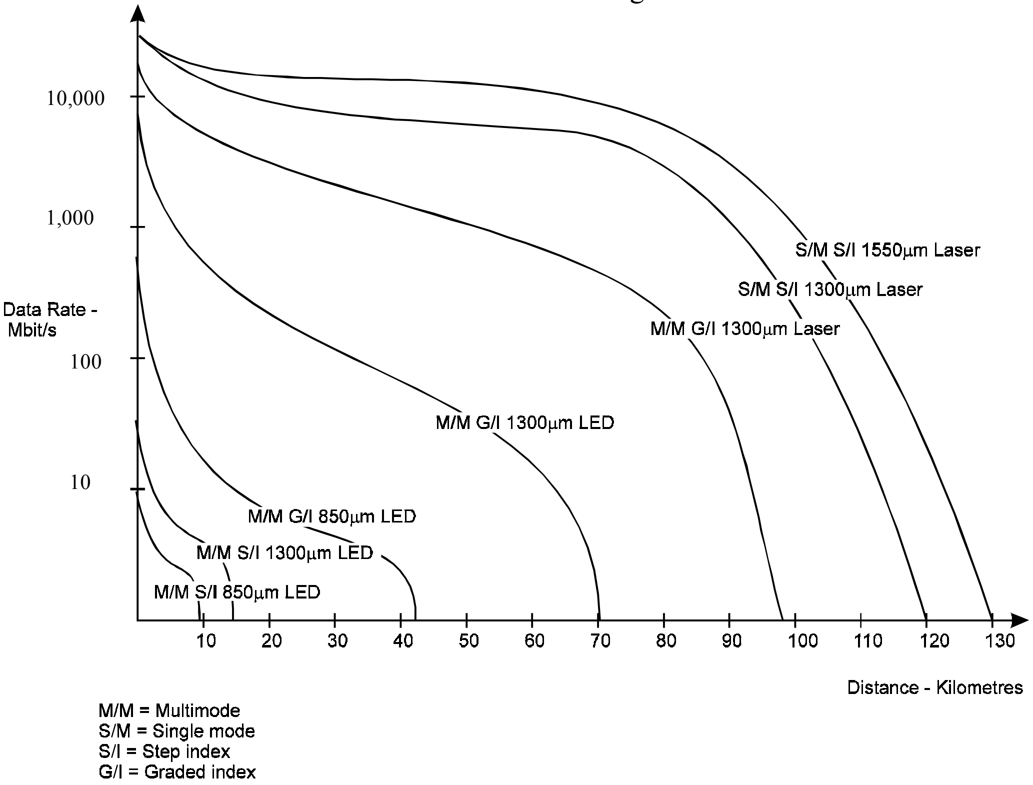


Figure 3.21
Comparison of data rate, distance and fiber type

3.4.9 Cost

Contrary to what is often expected, the price of singlemode fiber is cheaper than multimode fiber. It is the authors’ opinion that the reason for this aberration is simply that the quantity of multimode fiber produced is enormous when compared to the quantity of singlemode fiber produced. Therefore, economies of scale prevail. The cost of fabrication of both multimode and singlemode fibers are very similar.

Unfortunately, the cost of light source (lasers) and detection equipment for singlemode equipment is anything from three to ten times the cost of the equipment used with multimode fiber systems (LEDs). Therefore, the overall cost of installing singlemode systems is prohibitive unless there is a requirement for data systems that operate at greater than 1 Gbps or for distances of greater than 5 km.

The introduction of VCSEL lasers (discussed in Chapter 6) is beginning to change this scenario. VCSELs are cheaper to manufacture, easier to test and more efficient than traditional lasers. In the near future, more VCSELs will begin to replace LEDs in short distance singlemode and multimode applications.

3.5 Bandwidth

The concept of bandwidth in the frequency spectrum was discussed in Chapter 2. With respect to optical fibers, the operational bandwidth does not correspond to changes in frequency to the extent that it does with copper cable, but is more directly related to distance. All the factors that affect the bandwidth will increase as the length of the cable increases. For example, as the length of the cable increases, the modal dispersion increases (increasing the pulse widths at the end of the cable and therefore increasing the degree of inter-symbol interference), which effectively decreases the maximum data transmission rate. Other factors that affect bandwidth will be discussed in section 3.6.

The bandwidth for a fiber is given in the manufacturer's data sheets. It will be specified in the form, 'frequency bandwidth by kilometers' (i.e. MHz/km).

The bandwidth of a fiber is where the operating baseband has dropped by 3 dB in optical power (6 dB in electrical power from an optical power detector). As an example, if a fiber system is specified to operate at a mean wavelength of 1310 nm, which is equivalent to a laser or LED operating at a frequency of 2.3×10^{14} Hz, and the optical fiber has a specified bandwidth of 500 MHz, then the source will be able to modulate at a rate that produces frequency components up to 250 MHz either side of that operating frequency. This is illustrated in Figure 3.22.

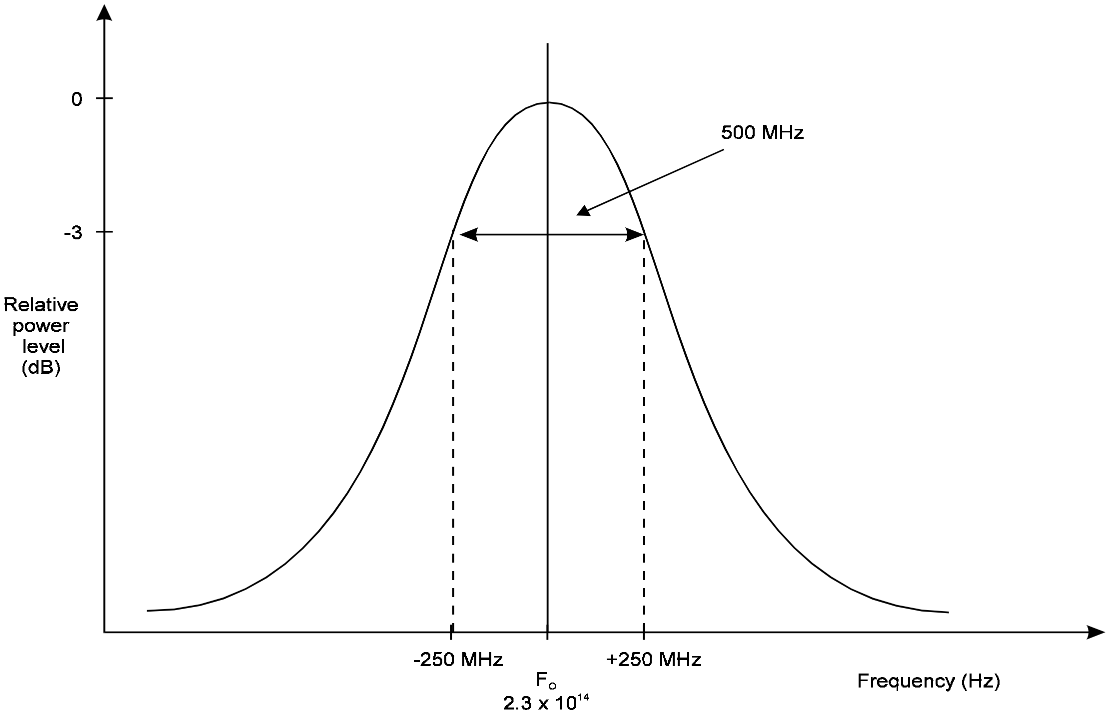


Figure 3.22
Bandwidth of operation of a fiber

Therefore a cable with an operating bandwidth of 500 MHz–km will provide a 3 dB frequency response of 500 MHz over 1 km or a 3 dB response of 250 MHz over 2 km and so on. Over 5 km, this fiber would have a net bandwidth of 100 MHz.

3.6 Wave division multiplexing

A method that is commonly used in long line bearer systems to significantly increase bandwidth is the techniques of wave division multiplexing (WDM) or sometimes referred to as dense wave division multiplexing (DWDM). This technique works by multiplexing highly precise temperature stabilized lasers operating on slightly different wavelengths onto a single fiber. Optical filters are used at the transmitting ends of the link to precisely define the wavelengths and to ensure that there is no overlap from each transmitting laser. Filters are also used at the receiving end to enable each channel (wavelength) to be captured and decoded.

For example, a system may consist of 32 lasers transmitting 32 different wavelengths into an optical multiplexing unit. The wavelengths will be centered around either the 1310 or 1550 nm wavelengths but be spaced very close together. A system of this size may have wavelengths that are 1.6 nm apart. Commercial systems are commonly available that combine 80 wavelengths at 0.4 nm apart onto a single fiber. If each laser is transmitting at a speed of 10 Gbps, then the single fiber system will have a capacity of 800 Gbps.

Systems are now appearing in the market that will support up to 160 wavelengths onto a single fiber.

There is also a range of lower capacity cheaper systems available in the market, which are sometimes referred to as course wave division multiplexing (CWDM) systems. These are fundamentally WDM systems that do not use temperature-stabilized lasers and have distances of 20 nm between wavelengths. These provide cost effective high capacity solutions. A system like this may operate with 8 wavelengths at speeds of 1.2 Gbps each, providing a total of 9.6 Gbps throughput.

3.7 Effects on optical signal transmission

There are a number of physical characteristics that are inherent in optical fibers. These characteristics affect the bandwidth, attenuation, and signal quality of the transmission. In multimode fibers, the main factor that affects signal transmission quality is modal dispersion. This was discussed in detail in section 3.6.1. The following section examines in detail the other factors that affect the transmission characteristics of an optical fiber.

The losses that are incurred in optical fibers behave in a similar manner to losses that are incurred in most other dielectric physical environments by electromagnetic energy. The phenomenon that is noted is an exponential loss of energy that is directly proportional to the linear length of the fiber. This is illustrated in Figure 3.23.

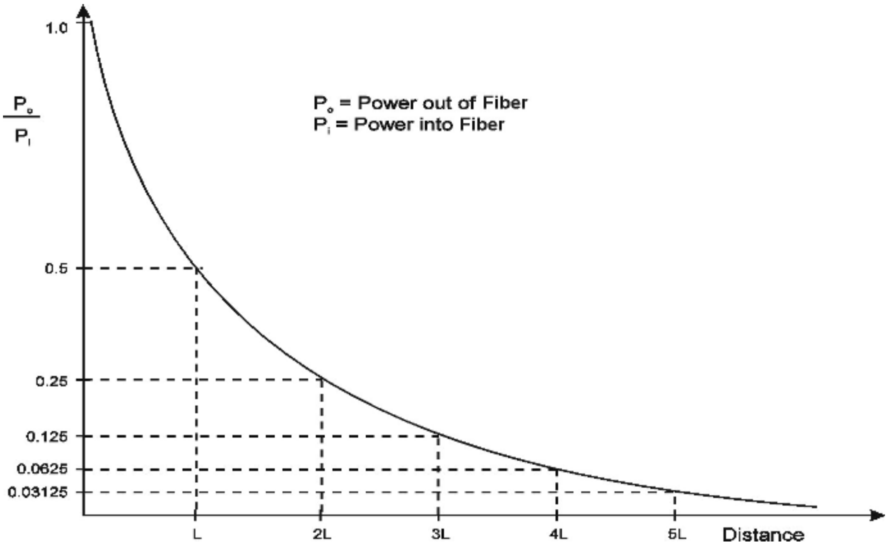


Figure 3.23
Attenuation curve for an optical fiber

This diagram shows that the output power will drop by half for every incremental length of fiber i.e. it absorbs energy at an exponential rate. It is worth noting here that radio waves experience a similar attenuation as they travel through air or free space.

3.7.1 Chromatic dispersion

The major dispersion effect in multimode fibers is modal dispersion. In singlemode fibers, there are no modal dispersion effects. More complex dispersion problems occur with singlemode fibers and also with graded index multimode fibers to a significant degree. .

There are two further types of dispersion to be discussed:

- Material dispersion
- Waveguide dispersion

These are combined together and referred to as chromatic dispersion.

The reason that other types of dispersion occur is because the refractive index of glass is a function of wavelength. Therefore, with reference to Snell's law discussed earlier in this section, the speed of light in years will also be a function of wavelength. Therefore the overall modal transmission effects of the fiber refractive index also depend upon wavelength.

Material dispersion is a phenomenon that occurs because light sources put out a signal, which contains a number of different wavelengths. No light source can produce just one frequency (wavelength). It will produce a spectral spread around a central frequency. As the different wavelengths travel through the same material, they will effectively encounter different refractive indexes. Relating this to Snell's law, this means different rays of light will be traveling at different speeds. The result of this is similar in nature (but lesser in degree) to modal dispersion in which, the light rays will arrive at the end of the fiber at different times.

This phenomenon is particularly noticeable with LED light sources because they emit a very broad spectrum of light. However, material dispersion is significantly less in magnitude than modal dispersion and generally is not a significant problem with LEDs unless the system is operating at relatively high speeds at a wavelength of 850 ɡm. The use of lasers as a source of light significantly reduces material dispersion because the laser provides a coherent beam of light with a very narrow spectral spread (i.e. range of wavelengths).

When manufacturing singlemode fibers, not only is the diameter reduced, but the difference between the core and the cladding refractive indices is also reduced. Here the effect of modal dispersion disappears, but then material dispersion becomes the significant problem. The effects of material dispersion become more noticeable in single-mode fibers because of the higher bandwidths (data rates) that are expected of them. For example, a few picoseconds of dispersion at a data rate of 10 Gbps can cause severe data corruption. It is possible to partially compensate for this problem by allowing a certain amount of modal dispersion in the singlemode fiber so that the faster rays travel the longer distances and therefore arrive at roughly the same time as the slower rays. In this case, the faster wavelengths would be traveling the higher order modes and the slower wavelengths, the lower order modes.

The second form of dispersion that makes up chromatic dispersion is waveguide dispersion. Waveguide dispersion occurs in singlemode fibers (which are of step index construction) where a certain amount of the light travels in the cladding. The dispersion occurs because the light moves faster in the low refractive index cladding than in the higher refractive index core. The degree of waveguide dispersion depends on the proportion of light that travels in the cladding.

Chromatic dispersion in real terms is a measure of the change in the refractive index with wavelength (ps/nm/km). For this reason dispersion measurement can read as going positive or negative. That is, the change in refractive index with wavelength can be an increase or a decrease. Material dispersion has a positive slope of change and the waveguide has a negative slope of change. At roughly 1300 nm, the two dispersion types tend to cancel each other out. This is referred to as the zero dispersion wavelength. This phenomenon is illustrated in Figure 3.24.

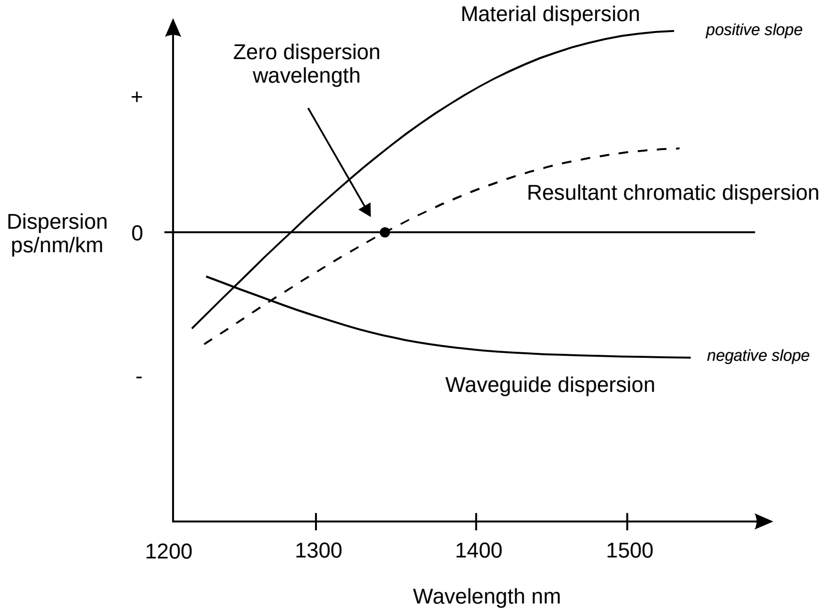


Figure 3.24
Chromatic dispersion showing the zero dispersion wavelength

In a physical sense, it can be perceived that material dispersion is causing the pulse to travel faster (relative to other wavelengths) and waveguide dispersion is causing the pulse to travel slower, and therefore the overall effect is the cancellation of some of this movement.

Therefore, at present, most moderately priced high-speed fiber optic data link systems tend to operate at the 1300 nm wavelength. If very high-speed operation over longer links is required, then the 1550 nm wavelength is used. These link systems cost more because special fiber has to be installed (discussed later).

It is important to remember that chromatic dispersion is primarily a function of wavelength and has nothing to do with whether the cable is multimode or singlemode.

Cable suppliers generally provide a chromatic dispersion figure in the cable specification. The unit of measure will be given as picoseconds of pulse spreading per kilometer of fiber per nanometer of the light source spectral spread (bandwidth of source). Refer to section 8.3.3 for details of how chromatic dispersion is calculated.

It is generally preferred to operate at a wavelength of 1550 nm because of the lower signal attenuation of this wavelength compared to the 1300 nm operation. But as indicated in Figure 3.24, operation at this wavelength introduces dispersion. This can be overcome to some degree by using a laser source that emits only a very narrow spectral spread, i.e. it has very narrow bandwidth. This type of laser is commonly used for longer distance requirements. Note that this will reduce the pulse spreading due to the number of frequencies traveling, but not that caused by the inherent chromatic dispersion of the fiber itself.

Another method is to use what is referred to as ‘dispersion shifted fibers’. This technique uses fibers that have lower chromatic dispersion at 1550 nm. It is not possible to change the overall effect of material dispersion, as this is a function of glass material itself. But as waveguide dispersion is caused by a certain amount of the light traveling in the cladding, it is possible to change the construction of the core and cladding (and also to add further layers of cladding) so that the waveguide dispersion is shifted downward and therefore makes the zero dispersion wavelength move toward 1550 nm. This technique works well with only an extremely small increase in attenuation, but the cost of producing the fibers increases significantly.

One common dispersion shifted fiber used today is the non-zero dispersion shifted fiber (NZ DSF). This is used extensively for DWDM systems operating at distances of over 70 kms in the 1440 to 1625 nm region. It also helps to compensate for other non-linearities that occur in singlemode systems such as wave mixing and phase modulation. A typical NZ DSF fiber will have a dispersion figure of better than 8 ps/nm/km. Most of the major fiber manufacturers have a version of the NZ DSF commercially available.

The NZ DSF fibers are designed for use at high data rates and are used extensively with the 40 Gbps lasers. Commonly, single non-repeated links are established up to 300 kms at 2.5 Gbps.

3.7.2 Absorption losses

During the manufacturing process of optical fiber, every effort is made to fabricate the glass as pure as possible. The requirements for cleanliness, purity and quality control in the manufacturing process are as stringent as those applied to the semiconductor industry. Unfortunately, it is impossible to produce 100% pure glass. The impurities that are left in the glass will absorb light.

These impurities are in the form of ionized molecules. Metal ions such iron, copper and nickel are the main offenders. They absorb the light particles (photons) and in the energy exchange process the fiber will heat up. The absorption losses caused by metal ion impurities are substantial in poor quality glass.

Glass will also contain significant amounts of water ion (OH^-) impurities that resonate at certain frequencies. Most signal attenuation due to water ions occurs in the 850 nm wavelength region. This was the major source of signal attenuation when fiber optic cables were first manufactured on a commercial basis. Significant advances in the manufacturing technology have greatly reduced this problem.

3.7.3 Scatter losses

There are two types of scatter losses that occur in fibers. The first type occurs because all manufactured or naturally occurring material is never perfect in its molecular structure throughout the entire volume of the material. If a piece of optical fiber is placed under an electron microscope it can be seen that there are irregularities in the molecular structure of the glass. These irregularities (or inhomogenetics as they are referred) are unavoidable because molecules and atoms are naturally random in nature and will set in a random pattern when the material is formed. The irregularities will scatter some of the light waves as they transverse through the length of fiber, which will then be dispersed in the cladding and lost.

This type of scatter loss is referred to as **Rayleigh** scattering. The degree of scattering very rapidly decreases with increasing wavelength and acceptably low scatter losses are achieved using the infrared wavelengths (1300 and 1550 nm). The Rayleigh scattering loss in fused silica glass is approximately 0.8 dB per kilometer at a wavelength of 1000 nm.

The second type of scatter loss that occurs is due to irregularities in the core/cladding interface. These appear as physical imperfections and are introduced during the fabrication process. When a light ray strikes one of these imperfections, it may change to a higher order mode and be dissipated through the cladding. This results in higher signal attenuation.

The various scattering that takes place causes light to often change modes. For example, a lower order mode may scatter and become a higher order mode. This is referred to as mode coupling or mode mixing. Modal mixing can be advantageous by averaging the traveled distances of the light rays and therefore helping to cancel some modal dispersion.

3.7.4 Bending losses

It is sometimes assumed intuitively that if a fiber is bent, then losses will be introduced into the transmission path. This is not true as the inside of a fiber is normally seen as a mirror to light rays, and slight bends in the fiber do not introduce losses. Losses occur only when the radius of the bend causes the light ray to be incident at an angle less than the critical angle. This could be from a ray that is directly incident into the bend at less than the critical angle or from a ray that reflects off a bend and then into the cladding at an angle less than the critical angle.

The manufacturer of the cable will specify the minimum installed bending radius requirement for that particular fiber optic cable. This specified figure indicates the minimum inside radius a bend in the cable is allowed to have when the cable has been finally laid to rest.

There are two types of bend that cause losses. The first is referred to as a ‘Macrobend’. This is where the cable is installed with a bend in it that has a radius less than the minimum bending radius. Light will strike the core/cladding interface at an angle less than the critical angle and will be lost into the cladding. This is illustrated in Figure 3.24.

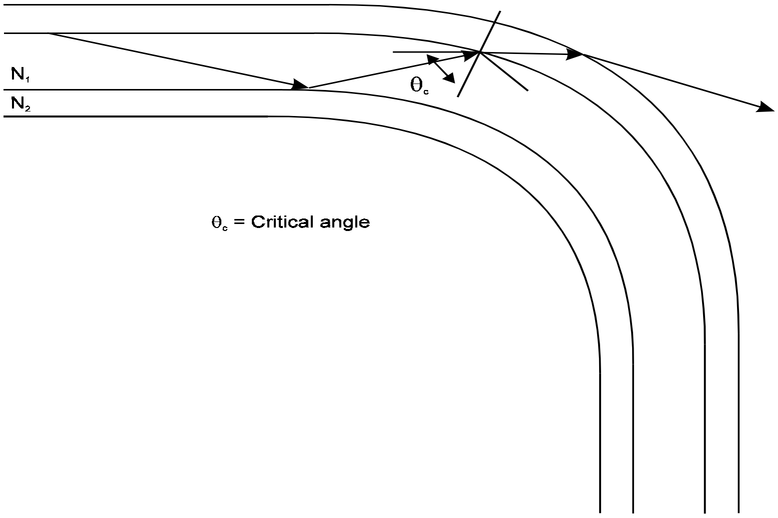


Figure 3.25
Losses due to macrobending

The second type of bending loss is referred to as 'Microbending'. The microbend takes the form of a very small sharp bend (a kink) in the cable. Microbends can be caused by imperfections in the cladding, ripples in the core/cladding interface, tiny cracks in the fiber and external forces. The external forces may be from a heavy sharp object being laid across the cable or from the cable being pinched, as it is pulled through a tight conduit. As for the occurrence of macrobends, the light ray will hit the bend at an angle less than the critical angle and will be refracted into the cladding. This is illustrated in Figure 3.26.

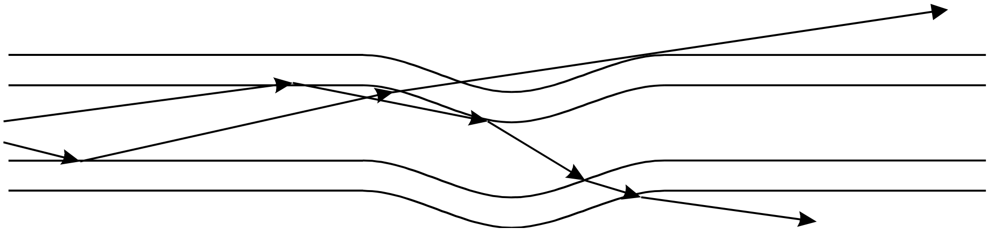


Figure 3.26
Losses due to microbending

3.7.5 Radiation losses

A close analysis of the energy field of the light pulse that is carried down the fiber shows that a certain amount of the total light energy is carried in the cladding of the fiber. This is particularly noticeable in graded index multimode and in step index singlemode fibers where the core/cladding refractive index change is minimal. The total cross-section of the moving energy field in the fiber will try to move as a constant field. There appears to be a natural cohesion between the light rays that keep the energy field constant, as it moves through the fiber. When there is a bend in the fiber, the light energy traveling through the larger outer curve will be required to travel faster than the energy traveling in the center of the core. The light will naturally resist this and will tend to radiate away.

The amount of energy that is normally lost through large radius bends in the fiber is almost negligible. But if the outside light rays are required to travel faster than the speed of light because there is a very sharp kink in the fiber (i.e. there is a very small radius bend in the fiber) then the radiation loss becomes quite significant and can be disastrous to the transmission link. The radius at which this occurs is very small, generally around 60 μm depending on the type of optical fiber that is being used. This is a further reason to avoid microbends.

3.7.6 Fresnel connection loss

It was previously discussed in section 3.1.8 that where the core and the cladding meet and light strikes this boundary at an angle less than the critical angle, about 4% of the light is reflected back into the core. The same phenomenon, referred to as Fresnel reflection, is also noted where two fibers are joined together. Even though the two fibers may have been joined with perfectly flat and smooth ends, there is still an unavoidable change in the refractive indices due to a small amount of air between the two fibers. This effectively represents a 4% loss in signal level at each interface (glass to air and air to glass). Therefore, the total amount of energy lost is 8%. When assessing power loss over a link, this represents approximately 0.17 dB loss per fiber to air interface and 0.34 dB loss per fiber-to-fiber joint. This is illustrated in Figure 3.27. Section 5.1.6 discusses this phenomenon further and describes methods of overcoming this problem.

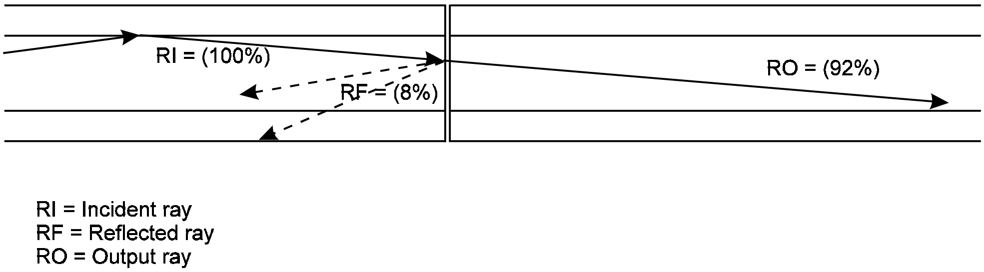


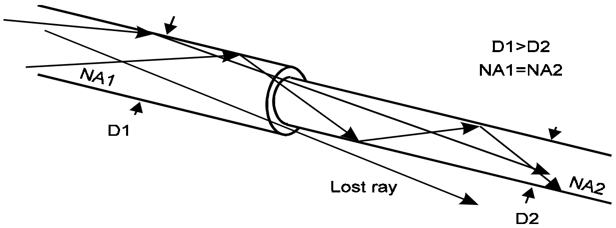
Figure 3.27
Fresnel loss due to fiber-to-fiber connections

3.7.7 Fiber size and *NA* mismatch

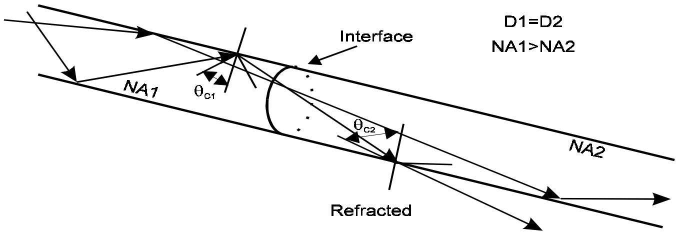
Although it is not desirable, the occasion does arise when it is required to connect fibers of different sizes and of different *NA*s. If the fiber from which the light is emanating is larger than the fiber, which is receiving the light, then light rays will escape out of the fringes of the larger fiber. If the two fibers have the same diameters but have different *NA*s and the fiber from which light is emanating has the larger *NA*, then this fiber will lose a small amount of its energy through refraction into the cladding of the second fiber. If the fiber from which the light is emanating has a smaller diameter or smaller *NA* than the receiving fiber, then there is no signal loss incurred. The mismatch is illustrated in Figure 3.28. The following formula approximates the losses incurred.

$$\text{Loss (dBs)} = -20\log(NA1/NA2) \qquad \text{for } NA1 > NA2$$

$$\text{Loss (dBs)} = -20\log(D1/D2) \qquad \text{for } D1 > D2$$



(a) Diameter Mismatch



(b) NA Mismatch (same diameter)

Figure 3.28
Losses due to diameter and NA mismatch

Note that it is implicit that there is a *NA* mismatch if there is a diameter mismatch because *NA* is dependent upon diameter.

3.8 Other losses

There are two other main types of losses in fiber systems:

- Connector to fiber losses is covered in Chapter 5.
- Source/detector to fiber mismatches are covered in Chapter 6.

3.9 Other types of fibers

Glass (fused silica) is by far the most commonly used material for manufacturing optical fibers.

It is worth noting though that there are many other types of optical fibers available. The following section provides a short description of a number of such other types of optical fibers.

3.9.1 Plastic fibers

Optical fiber transmission principles also work very successfully with optical fibers made from plastic. They are however limited to a step index multimode construction. Because of the nature of plastics, the fabrication process produces a core and cladding with significantly different refractive indices. Typical figures obtained are a core with a refractive index of approximately 1.5 and a cladding of approximately 1.4. A typical *NA* is 0.5, which represents an acceptance angle of 30 degrees (an acceptance cone of 60 degrees).

There are three main advantages associated with using plastic fibers. Firstly, they are a lot more robust than glass fibers. They can sustain significantly more shock, pressure and stress without damage than glass fibers can. For this reason, they are often used in harsh environments such as in automobiles. Secondly, they are far more flexible, easier to handle and therefore easier to terminate than glass fibers. Finally, if they are bought in bulk, they are generally cheaper than glass fibers.

On the other hand, there are a number of significant disadvantages. They have a significantly higher attenuation than glass fibers and are generally used over very short distances (100 m maximum) only. Plastic has an optimum operating wavelength of 650 nm (red LEDs are used), which has an attenuation of approximately 300 dB per kilometer. They also have very limited operating bandwidths with maximum operating data speeds up to approximately 10 Mbps over a maximum of 50 m. Therefore they are rarely used for telecommunications purposes. They are sometimes used with RS-232 to optical converters up to 20 kbps and very short distance Ethernet data links to 10 Mbps. One further problem of note is that they have much lower maximum operating temperature than glass fibers (generally around 85°C).

3.9.2 Ultraviolet fibers

Although most fiber transmission is in the near infrared region because of the correspondingly low attenuation through glass at these frequencies, some fibers are fabricated for special applications in the ultraviolet region. Typical attenuation figures are around 200 dB per kilometer at 350 nm and 2000 dB per kilometer at 200 nm. Therefore they are only used for specific applications over very short distances. The most common application is for scientific measurements.

3.9.3 Mid infrared fibers

The lower infrared frequencies provide the lowest losses in glass fibers. Also, the longer the wavelength the less scattering that occurs, which is a significant cause of signal attenuation in fiber transmission. Therefore, it would be desirable to operate with longer wavelength systems, moving into the mid-infrared region. Unfortunately, glass almost absorbs these frequencies totally.

However, there are certain materials that provide very low resistance to the flow of energy at these wavelengths. It has been suggested by scientists that attenuation as low as 0.001 dB per kilometer should be possible using these special materials. Zirconium fluoride and barium fluoride are two compounds currently being researched. The problem encountered though is the difficulty and the cost associated with fabricating these substances in a very pure form. The best attenuation figures that have been achieved to date are approximately 25 dB per kilometer at 2600 nm and approximately 700 dB per kilometer at 5500 nm. Despite this, scientists are enthusiastic about the future of this form of fiber technology, which will mean significantly greater distances between repeaters.

3.9.4 Polarized fibers

In section 2.5, it was discussed how light has an electric field and a magnetic field. The electric field is classified as traveling either vertically or horizontally to the ground. In the former case, the light ray is said to be vertically polarized and in the latter case, the light ray is said to be horizontally polarized. The light rays can also be of some degree of polarization in between these. When polarized light is passed along an optical fiber, the plane of the polarization generally changes with distance along the fiber.

Optical fibers can be constructed to maintain its polarization as the light passes down the fiber. At present, these types of fibers are only used for special sensing applications but it is planned to use them in the future with very high data speed singlemode fiber systems.

3.10 Fabrication of fibers

Optical fibers are manufactured from very pure raw materials and in spotlessly clean conditions. As an indication of the purity of glass, it is said that a kilometer thick block of optical fiber glass has about the same translucence as a normal windowpane.

There are four main methods of manufacturing optical fibers, which are briefly discussed below.

3.10.1 Inside chemical vapor deposition

This fabrication process commences with a hollow Quartz tube about 15 mm in diameter and about 4 mm thick. The tube is rotated on a burner to heat it up. Various chemical components of glass are then passed through the tube in a gaseous form. Included in this gas are various other chemicals that act as reactants, metal impurities, and catalysts to form glass of differing refractive indices. Once the quartz is heated, the gases will react with it to form a layer of glass on the inside of the tube. Depending on how long and to what temperature the quartz is heated, the impurities will impregnate the quartz to different depths and concentrations.

Different concentrations of gasses are passed through the tube to form different layers of the core and cladding refractive index. Once this is complete, the tube is passed through a furnace and collapsed into a solid tube of glass. This tube is approximately 10 mm thick and is referred to as a **preform**.

The tip of the preform is then fed into an extrusion unit, which is encased in a furnace. A fiber is drawn from the tip down from a high drawing tower. Lasers are used to monitor the fiber diameter, and then the diameter size is fed back to control the speed at which the fiber is drawn (which directly correlates to the drawn diameter). The fiber is then passed through a plastic fluid to provide the fiber sheath. This process is illustrated in Figure 3.29.

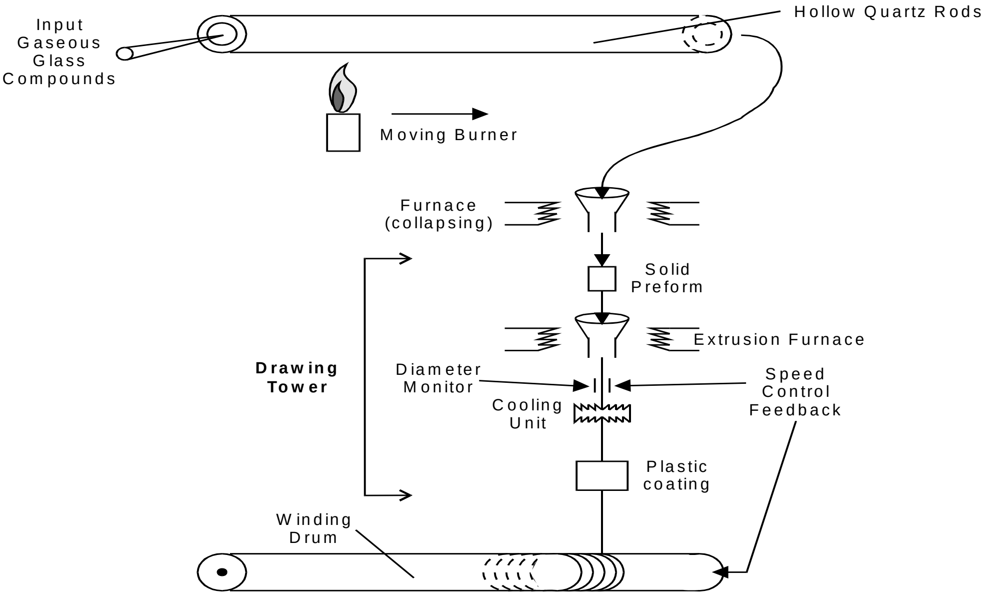


Figure 3.29
Inside chemical vapor deposition

This method of fiber fabrication is the most commonly used.

3.10.2 Outside chemical vapor deposition

This is a similar fabrication process to that described above except that the glass is layered on the outside of a rotating metal rod. The glass gaseous compounds are fed into the burner and are formed into layered glass onto the outside of the rod, as the burner moves along the rod. Once the glass formation is completed, the metal rod is removed and the glass tube is fed into a furnace and collapsed into a preform. Once the preform is complete, the fiber is drawn in the manner described above. This process is illustrated in Figure 3.30.

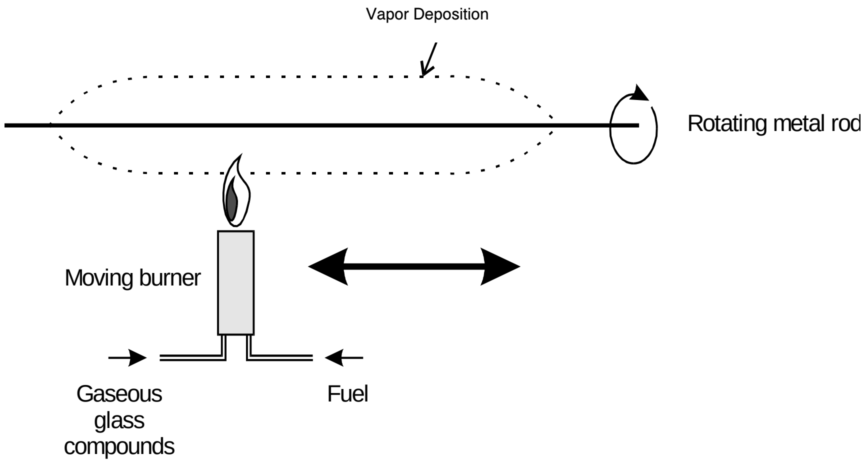


Figure 3.30
Outside chemical vapor deposition

3.10.3 Vapor axial deposition

This fabrication process uses a glass seed rod on which the glass ‘preforms’. The seed rod is held vertically and rotated while the gaseous glass chemicals are blown onto the end of the seed rod through a burner. As the preform is forming, the glass seed rod is raised at a controlled speed so that the preform is constantly at the same distance from the burners (and therefore the same diameter). Different concentrations of gases are blown through different burners to form the required different refractive indices of the core and the cladding. The preform that is formed here is very porous, so it is fed through a heater and collapsed into the required preform density. Once the preform is complete, the fiber is drawn in the conventional manner. This process is illustrated in Figure 3.30.

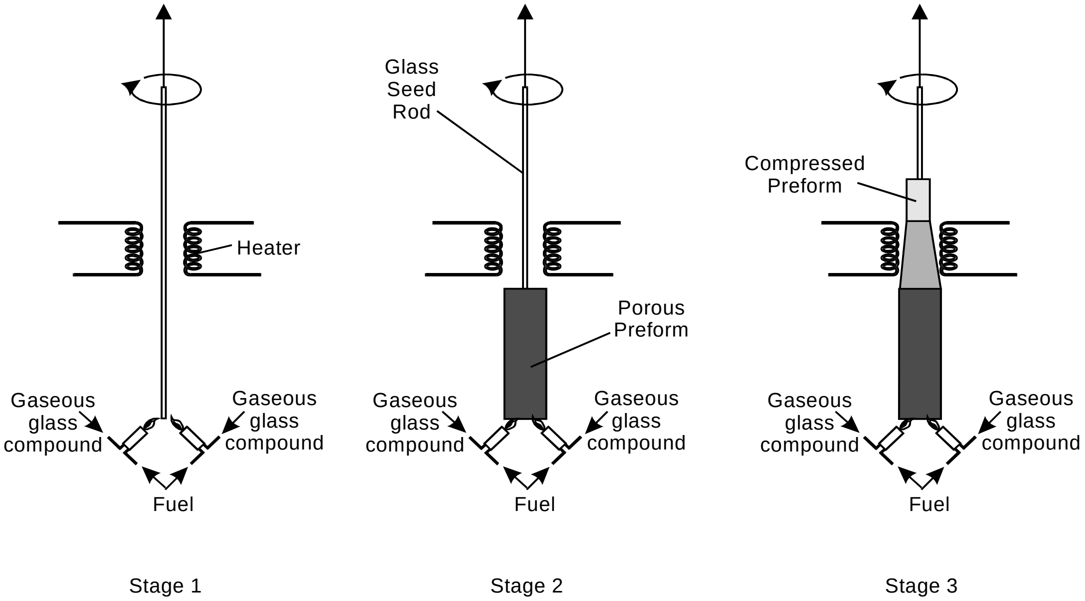


Figure 3.30
Vapor axial deposition

This technique is becoming the most popular method of fabrication. The advantage of this method is that very long preforms can be made, which in turn means that long continuous fibers can be drawn. Continuous fibers up to 100 km are regularly drawn using preforms from the process. With the first two fabrication methods discussed the preform length is limited to the length of the quartz tube or metal rod used in the lathe.

3.10.4 Double crucible drawing

This fabrication process is the cheapest and easiest to implement, but produces the poorest quality cable. It is generally used to produce large quantities of step index multimode fiber. If extreme care is taken, graded index multimode fibers can be manufactured.

Separate glass rods are produced, one with the refractive index of the core and the second with the refractive index of the cladding. These are fed into a furnace, which has two concentric crucibles. The core glass is fed into the central crucible and the cladding glass is fed into the outer crucible. As the rods are fed into the crucibles, the furnace melts them and turns them into molten glass. At the bottom of the double crucible is a small hole through which the fiber is drawn. This process is illustrated in Figure 3.31.

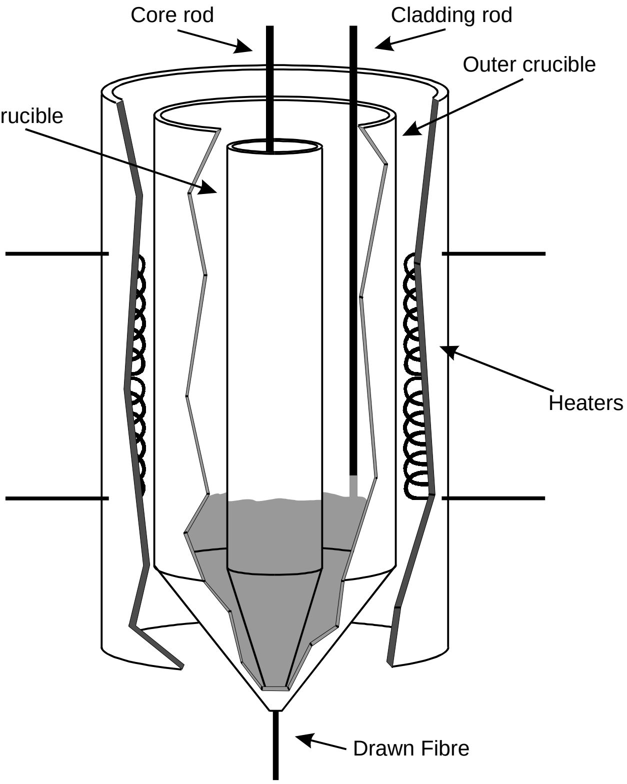


Figure 3.31
Double crucible drawing

4

Fiber optic cable construction

Introduction

This chapter discusses the important characteristics of fiber optic cable structures, the properties of some of the main types of cable construction and particular uses of each type.

4.1 Basic cable construction objectives

The cable structure is needed to protect the optical fiber from the rigors of the outside world during its installation and throughout its operational life. The cable construction needs to provide some, or all of the following features:

- Mechanical protection for the fibers
- Make them easier to handle
- Provide protection against environmental hazards
- A non-conductive cable for special environments

4.1.1 Mechanical protection

The cable structure needs to give protection to the fibers against tensile stress, abrasion, cutting, flexing, bending and crushing experienced during the installation and subsequent operational life of the fibers. Stresses imposed on the fibers can cause microbending losses, as discussed in Chapter 3, resulting in greater attenuation. Higher stress levels could lead to eventual fiber failure.

4.1.2 Easier handling

Optical fibers are much easier to handle when combined in cable structures. The plastic coated fibers are typically between a quarter- and one-millimeter in diameter (250–900 μm) making them difficult to pick up etc. Most cables contain many fibers, catering to future requirements. These fibers need to be handled together in a single, common structure. The cable structure also acts as the mounting point for the cable. For example, aerial cables are attached to support structures at the end of each span. In addition, the cable connectors are attached to the cable structure, keeping the strain off the individual fibers.

4.1.3 Environmental protection

The cable structure needs to protect fibers from the environmental hazards of moisture, chemicals, and other conditions.

Moisture

The cable structures are designed to prevent ingress of moisture into the fibers. Petroleum jelly is often utilized in various forms, to act as a water barrier. The long-term exposure to water vapor can result in hydroxyl-ion (OH^- found in water) penetration of the fibers, causing loss of strength and increased attenuation.

In cold environments, any water vapor in the cables can freeze, expanding as it does so, causing stresses on fibers.

Hydrogen diffusion

It has been found that when fibers are kept for long periods in an atmosphere with a high hydrogen content, the hydrogen molecules can diffuse into the fiber and cause increased attenuation at longer wavelengths (1300 and especially 1500 nm). Fibers containing phosphorous dopants are most susceptible to this problem. While the hydrogen concentration in air is very low, it can be produced within some cables by the decomposition of plastic materials. Similarly, electrolysis of moisture may be produced within submarine cables by electric currents used to power-feed the regenerators. Another source of hydrogen is from lead acid batteries, which can damage cables in common, equipment rooms.

4.1.4 All-dielectric cables (galvanic isolation)

All-dielectric cables do not contain any metallic components. Such non-conducting cables are inherently safe for use in hazardous situations where the presence of explosive gas makes metallic cables unsafe (because of their potential to produce sparks). These sparks are capable of causing explosions. All-dielectric cables are not affected by any form of electromagnetic fields and are therefore immune to lightning and high voltages (with respect to earth) that can be caused by power fault conditions. It is necessary to eliminate all metallic components, including aluminum laminate moisture barriers and steel wire armoring, in order to achieve all dielectric construction.

4.2 Fiber tensile ratings

Optical fibers are potentially stronger than steel, with unblemished fibers having theoretical tensile strength per unit area of over a giga newton per square meter. However, in practice, fibers break at lower tensions, with cracks that begin from small surface defects. Although the force per unit area appears impressive, remember, we are dealing with a very small cross-sectional area. A standard fiber of 125 microns diameter has a cross-sectional area of 1.2×10^{-8} square meters, so a one-kilogram force applied to the fiber produces 8 giga newtons per square meter.

When longitudinal tensile or transverse forces are applied to an optical fiber, it can cause minute surface defects. These potential weak points can develop into microcracks, which may cause breakage of the fiber when it is later subjected to an equal or greater tension.

Optical fibers have some elasticity, stretching under light loads before returning to their original length when the load is removed. Theoretically, the fiber may stretch as much as 9% before breaking under heavy loads. However, it is considered advisable to limit permanent strains to less than 0.2%. This limitation will avoid development of premature failures. Soft copper, on the other hand, is inelastic. It may permanently stretch up to 25% under light loads, and will remain stretched once the load is removed. When a conventional cable with copper conductors is subjected to extra heavy tension, the conductors are able to stretch; whereas extra heavy tension could break the fibers in a cable if stretched to more than 5%.

This has an important bearing on how the fibers are installed within the cable. The fibers need to be isolated from the tensile and bending forces to prevent breakage and prolong their life. The following section describes how the cables are constructed to provide necessary isolation.

4.3 Cable structural elements

Fiber optic cables are constructed in different ways and some of the main types will be discussed in the following chapters. The basic structural elements used in cables are a central member, strength members, a fiber housing, water barrier, and a cable sheath. Some cables also require additional protective armor. A typical structure is depicted in Figure 4.1.

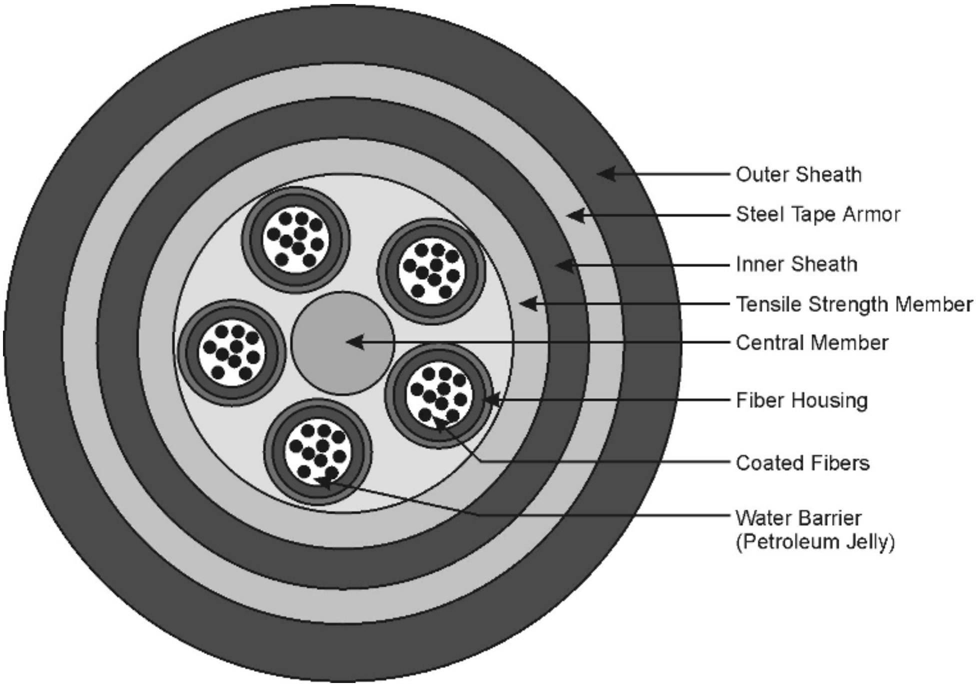


Figure 4.1
Basic cable structure

4.4 Central member

Many cables are built around a central member. As the name implies, a central member of the cable is a structure at the center of the cable. It is usually made of fiberglass, possibly incorporating steel. It provides rigidity to the cable, thus preventing the fibers from being bent too sharply, even to the extent of microbending. It contributes to the tensile strength of the cable and is the core about which the cable is built up and the fibers are supported. However, small indoor cables often do not use central members.

4.5 Strength members

The fiber cable needs to incorporate a relatively inelastic strength member, running the length of the cable, to withstand any tensile forces and prevent excessive stretch of the fibers. This can be metallic or non-metallic depending on the application. The mechanical properties of the commonly used strength member materials are shown in Table 4.1.

Material	Load to break (kg)	Diameter (mm)	Elongation at break (%)	Weight (g/m)	Tensile strength (MN/m²)
Fiber glass epoxy rod (FRP)	1050	1.14	3	2.1	3000
Steel	1050	1.6	2-25	11	500-3000
Aramid yarn	2080	2.4	3	2.7	3000
Nylon yard	400	2.5	20-50	2.0	500-700

Table 4.1
Strength member load table

4.5.1 Metallic strength members

Steel wire is the obvious choice where metallic strength members can be used. The advantages of steel wire are low cost, relatively small size, good rigidity. In addition, with its thermal mass providing good temperature stability, the steel wire can be depended on for very low temperature performance. The disadvantages are greater weight, loss of galvanic isolation, corrodibility, and the safety considerations associated with metallic components. Steel strength members are often incorporated in the center of a plastic extruded central member, as in the slotted core construction shown in Figure 4.4.

4.5.2 Non-metallic strength members

The common non-metallic strength member materials are Aramid yarn (commonly referred to under the Dupont trade name of Kevlar) and fiberglass reinforced plastic rods (FRP). Other materials include plastic monofilaments such as processed polyester, other textile fibers (nylon, Terylene and Dacron), carbon and glass fibers. Aramid yarn has a high breaking strain, and when comparing the equivalent weights, it is five times stronger than steel. Advantages of non-metallic strength members are the low weight and all-dielectric construction. The disadvantages are greater cost and higher elongation. FRP strength members have greater rigidity and contribute to the bending resistance of the cable. FRP is also better suited to extreme low temperature operation because its thermal mass provides better temperature stability.

4.6 Fiber housing

In Chapter 3, it was shown that fibers are given a primary coating during production, to protect the pristine fiber surface from mechanical and chemical attack. The fiber is then given a secondary or buffer coating for further protection. This is either of a loose buffer construction, usually for outdoor use, or of a tight buffer for indoor use. These fiber housings are shown in Figure 4.2.

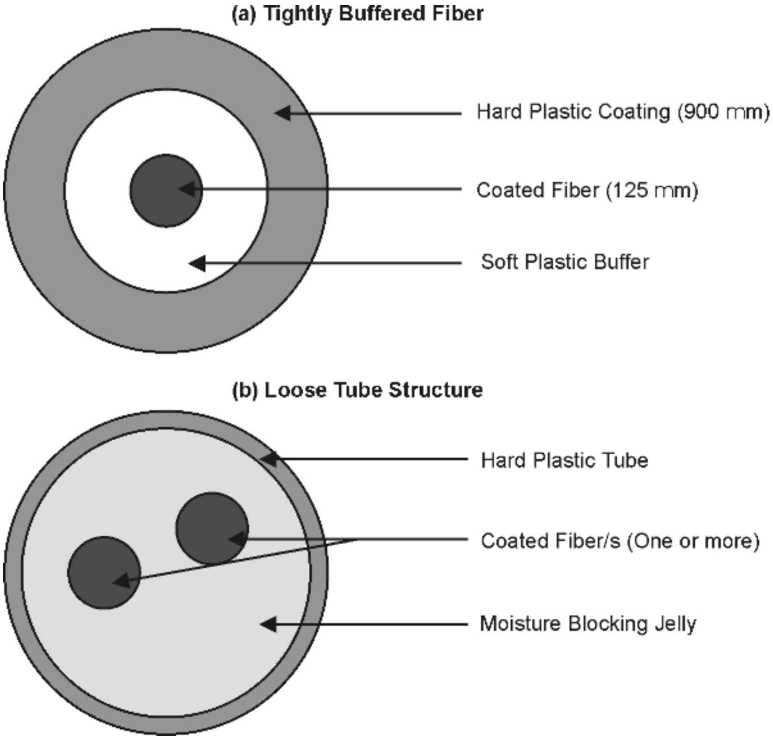


Figure 4.2
Fiber housing types

4.6.1 Loose buffer construction

Loose buffering, using either a loose tube or the slotted core construction, is used for most outdoor applications where fibers are likely to be subjected to external stresses such as tensile forces or extreme temperature change. Loose buffer construction is used in aerial cables, duct cables, and direct buried cables.

4.6.2 Loose tube construction

Loose tube construction makes use of a hard, smooth flexible tube, whose inner dimensions are much greater than the fiber diameter. One or more fibers can be installed in a loose helical fashion inside this tube so that they can move freely inside it. The tube isolates the fibers from any external stresses, such as temperature changes or bending forces, applied to the external structure. Even if the tube is stretched, the fibers remain unstressed because they have excess length and are free to move relative to the tube. The tube is usually filled with a moisture resistant compound as a water barrier for outside applications. Figure 4.3 illustrates the use of loose tube construction.

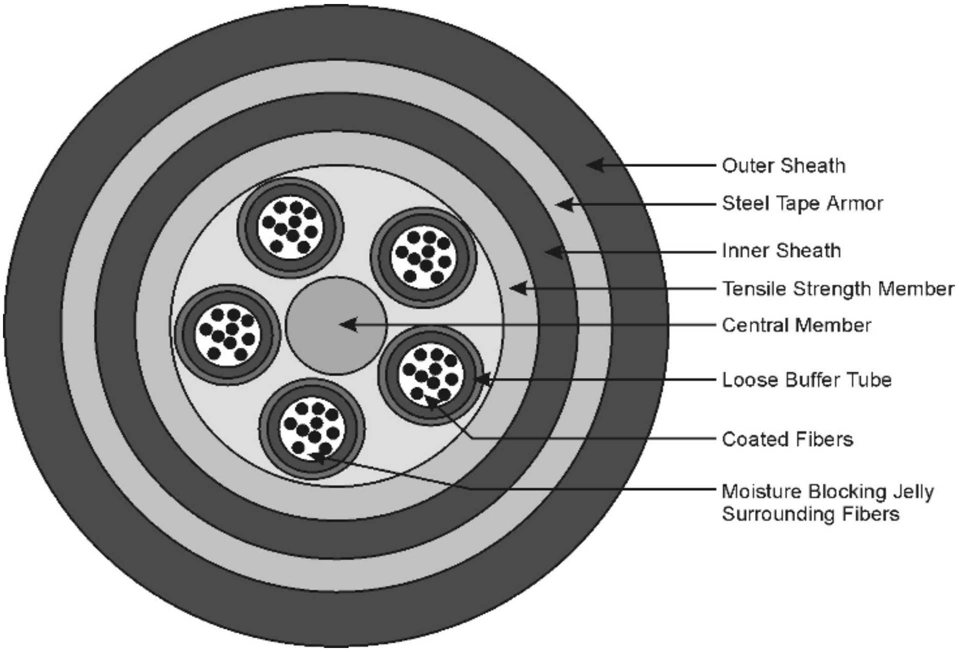


Figure 4.3
Loose tube cable construction

Loose tube construction can accommodate up to about 12 fibers per tube, using colored tubes and colored fiber coatings to facilitate identification.

4.6.3 Slotted core construction

The slotted core type of cable construction uses an extruded plastic structural member surrounding a central strength member, as shown in Figure 4.4. The slots in the core accommodate the fibers, allowing radial movement and isolating them from external forces. This minimizes residual fiber strain and its resulting microbending losses.

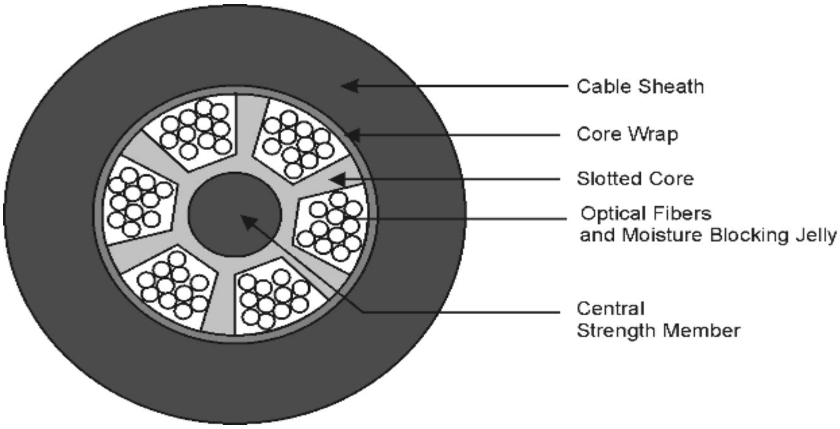


Figure 4.4
Slotted core cable construction

4.6.4 Tight buffered fibers

Tightly buffered fibers are encased in a soft plastic, which reduces the forces applied to the fiber, and then have a further external buffer of harder plastic, such as nylon, Hytrel or Tefzel providing physical protection. The total buffer coatings increase the diameter to the extent of between 250 and 1000 microns and provide stiffening to the fiber, protecting against microbending. 900-micron fibers are the most common in use today.

Advantages for indoor cables

- Single fiber tight buffered cables, such as those used in patch cords, do not need to have their buffer removed to install connectors, and predictably align the fiber in the connector.
- Individual tightly buffered fibers within a cable can be distributed to different devices without the use of patch panels (this is not necessarily good practice though).
- Greater crush and impact resistance than loose buffered cables.
- Riser cables utilize tightly buffered fibers to control the longitudinal stress on the fibers.
- Tightly buffered cables are physically smaller than loose tube cables for low fiber counts.

Disadvantages

- The tight buffer tends to introduce some microbending losses, so fibers often have higher losses than in loose tube cables. Generally, this is not a problem, as indoor distances are usually short.
- There is lower isolation of the fiber from the stresses caused by temperature variations.

4.6.5 Ribbon cable construction

A variation of the tight buffered construction is the use of ribbon cable. A group of coated fibers is arranged in parallel and then encapsulated in plastic to form a miltifiber ribbon cable. Individual ribbons may contain 5 to 12 fibers, and multiple ribbons can be stacked together to form the core of the cable.

Advantages of ribbon cables

- Very high density of fibers
- Effective splicing techniques for connecting multiple fiber ribbons in a single splice
- Multifiber connectors for joining ribbons

Disadvantages

Installation forces are generally not uniformly distributed over the ribbon width, so individual fibers can have uneven strains, resulting in excessive losses and fiber damage.

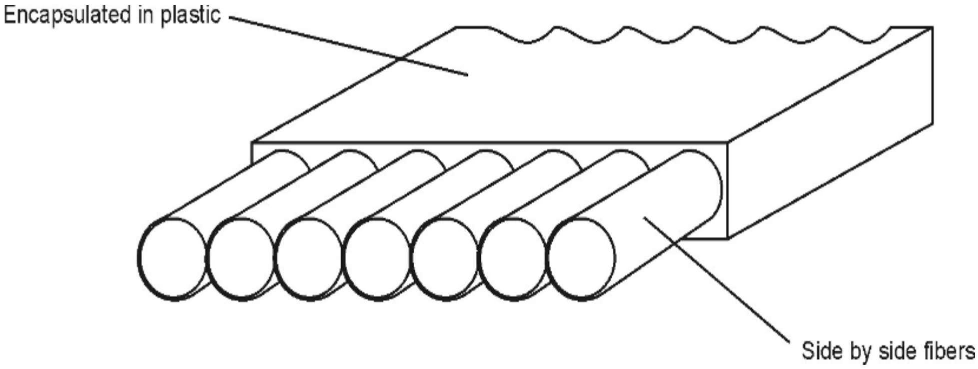


Figure 4.5
Ribbon cable construction

4.7 Moisture barrier

We have already seen that fibers are susceptible to long-term degradation caused by hydroxyl ion (OH^-) contamination. An appropriate moisture barrier is required to prevent the penetration of water into cables. This is obviously of paramount importance for submarine cables, which may be subjected to the static pressure of several kilometers of seawater! Common moisture barriers for ordinary cables include; an axially laid aluminum foil/polyethylene laminated film immediately inside the polyurethane or polyethylene plastic sheaths (which are permeable to moisture); and/or the use of moisture resistant compounds around the fibers.

Moisture resistant compounds include petroleum jelly and silicone rubber. These filling compounds need to be soft, self-healing, easily removed, provide corrosion protection for metallic cable components and do not degrade over time or harm the other components, particularly the fiber itself. These materials have another useful property in cushioning the fibers from vibration.

4.8 Cable sheaths

The cable is usually covered with a heavy plastic sheath, which provides primary protection against abrasion, cut resistance, crushing resistance and additional resistance to excessive bending. Light duty cables can utilize polyvinyl chloride (PVC), or polyurethane sheath materials. The more durable polyethylene (PE) materials are used on outdoor and heavier duty cables. It should be reiterated that plastic sheath materials provide limited protection against penetration of water into cables, and require moisture barriers as discussed in section 4.7. Thin layers of hard plastic materials such as nylon can be utilized as over-sheaths to provide greater abrasion and cut resistance. Sometimes, Teflon, because of its very slippery surface, provides protection against rodents such as termites.

Special cable sheath materials are sometimes used for cables installed in air-handling spaces or ‘plenum’ areas. These are defined as the spaces above suspended ceilings, below elevated floors and in heating and ventilation ducts. In some countries, cables that are used in plenum areas must have flame retardant properties producing little smoke. For further information on plenum cable requirements in your country, check the relevant fire codes applicable in your area.

Sheaths normally incorporate a ripcord to facilitate the sheath removal without facing the risk of damage to the fibers when cutting into the sheath material.

4.9 Cable armoring

Direct buried cables require armoring on them if they are buried in areas where physical damage to them is likely. Such cables include shallow shore ends of undersea cables where anchoring and fishing activities pose constant dangers. Direct buried cables need protection against crushing damage caused by rocks, rodent attacks and disturbance caused by road works or farming operations. Steel wire armoring is generally utilized, with the steel wound over the inner plastic sheath then surrounded by a further plastic sheath to prevent corrosion.

4.10 Classes of fiber optic cables

There are four broad application areas into which fiber optic cables can be classified: aerial cable, underground cable, subaqueous cable and indoor cable. The special properties required for each of these applications will now be considered. Note that the list is not all encompassing, and that some specialized cables need to combine the features of several of these categories.

4.10.1 Aerial cable

Aerial cables are literally exposed to the elements more than any other application, and as such, are exposed to many external forces and hazards. Aerial cables are installed between poles with the weight of the cable continuously supported by usually a steel messenger wire to which the cable can be directly lashed, or by the strength members integral to the cable construction. The effects of combined wind and ice loadings can produce greatly increased tensile forces. Other considerations are the wide variations in temperature to which the cable may be subjected, affecting the physical properties of the fibers and the attenuation of the fibers. The longitudinal cable profile is important for reducing the wind and ice loadings of such cables. Moisture barriers are essential, with jelly filled, loose buffered fiber cable configurations predominating. Any water freezing within the fiber housings would expand and could produce excessive bending of fibers.

The cable sheath material is required to withstand the extremes of temperature and the intense ultraviolet light exposure from continuous exposure to sunlight. UV stabilized polyethylene is frequently used for this purpose.

The installed span length and sag requirements are important design parameters affecting the maximum cable tension. They also dictate the type of cable construction to be used. Short span cables have less stringent tension requirements, which can be met by the use of integral Kevlar layers, whereas long span cables may need to utilize multiple stranded FRP rods to meet the required maximum tensions.

Installation aspects for aerial cables are discussed in section 7.5.1.

Cable types

Self-supporting cables

These cables have a separate messenger wire, usually steel, which can be clamped to the support structures on the poles, to carry the tensile forces on the cable. The construction of the cable is illustrated in Figure 4.6. The separate messenger wire facilitates installation.

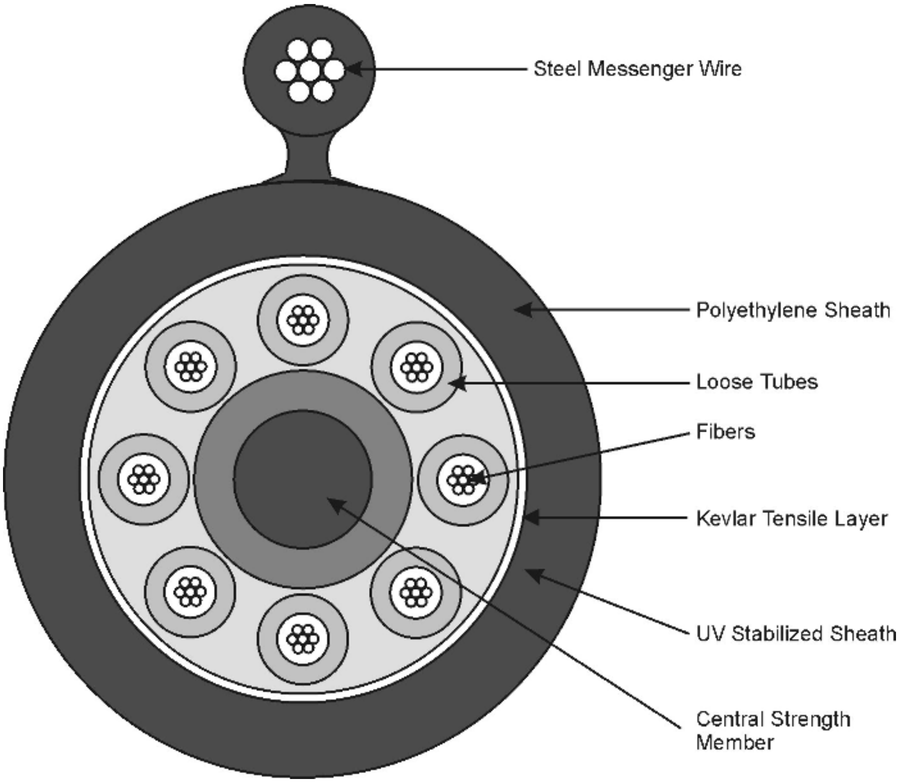


Figure 4.6
Self supporting cable (messengered)

Short span dielectric

These cables use non-metallic strength elements. They have peripheral Kevlar layers and a slotted core that use FRP strength members. Such cables allow spans up to 150 m with maximum allowable tensions of around 300 kg. The construction of this type of cable is shown in Figure 4.7.

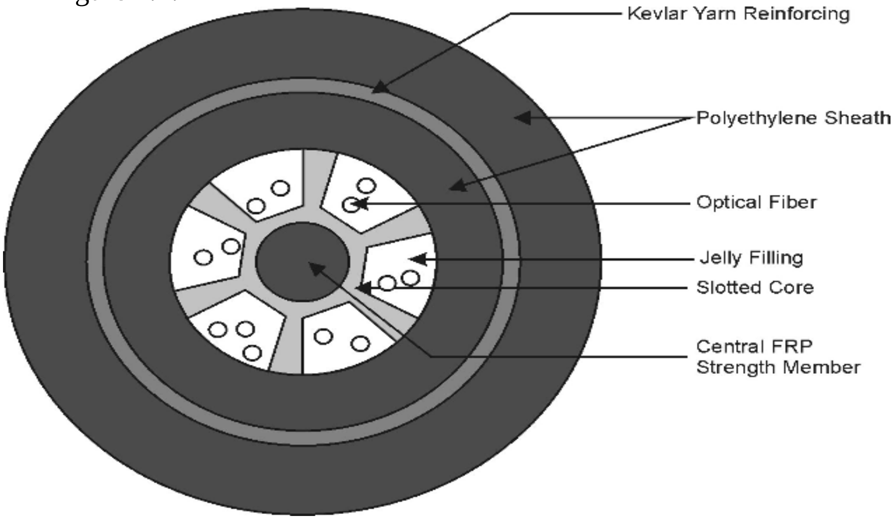


Figure 4.7
Short span dielectric cable

Long span dielectric

These cables also use non-metallic strength elements. They consist of a peripheral layer of stranded FRP rods and a slotted core with FRP strength members. Such cables allow spans up to 1000 m with maximum permissible tensions of around 1200 kg. The construction of this type of cable is shown in Figure 4.8.

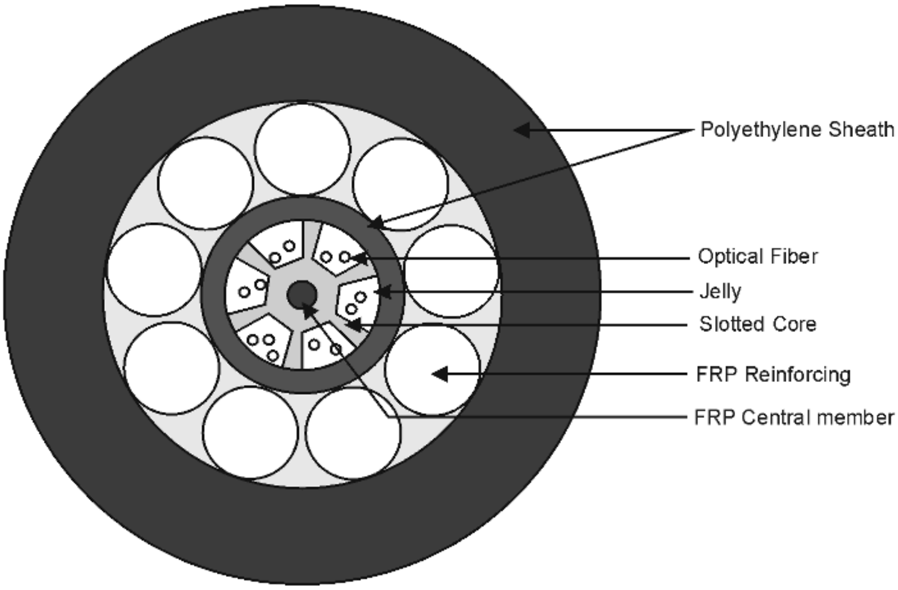


Figure 4.8
Long span dielectric cable

Advantages of aerial cable

- Useful in areas where it may be very difficult or too expensive to bury the cable or install it in ducts
- Also useful where temporary installations are required

Disadvantages

- System availability is not as high as for underground cables. Storms can disrupt these communication bearers, with cables damaged by falling trees, storm damage and blown debris. Roadside poles can be hit by vehicles and frustrated shooters seem unable to miss aerial cables!

4.10.2 Underground cable

Underground cables experience less environmental extremes than aerial cables. Underground cables are usually pulled into ducts or buried directly in the ground, with the cable being placed in a deep narrow trench, which is backfilled with dirt or else ploughed directly into the ground.

Cable type

Loose buffering, using loose tube or slotted core construction, is generally used to isolate fibers from external forces including temperature variations.

Installation aspects of these cables are discussed in detail in Chapter 7.

Metallic moisture barrier

This incorporates a longitudinally applied polymer coated aluminum laminate, which is bonded to the inside of the polyethylene sheath. The tape is closely formed around the cable core and the overlap welded by melting the polymer with hot air. This hermetically seals the core against water entry through the sheath.

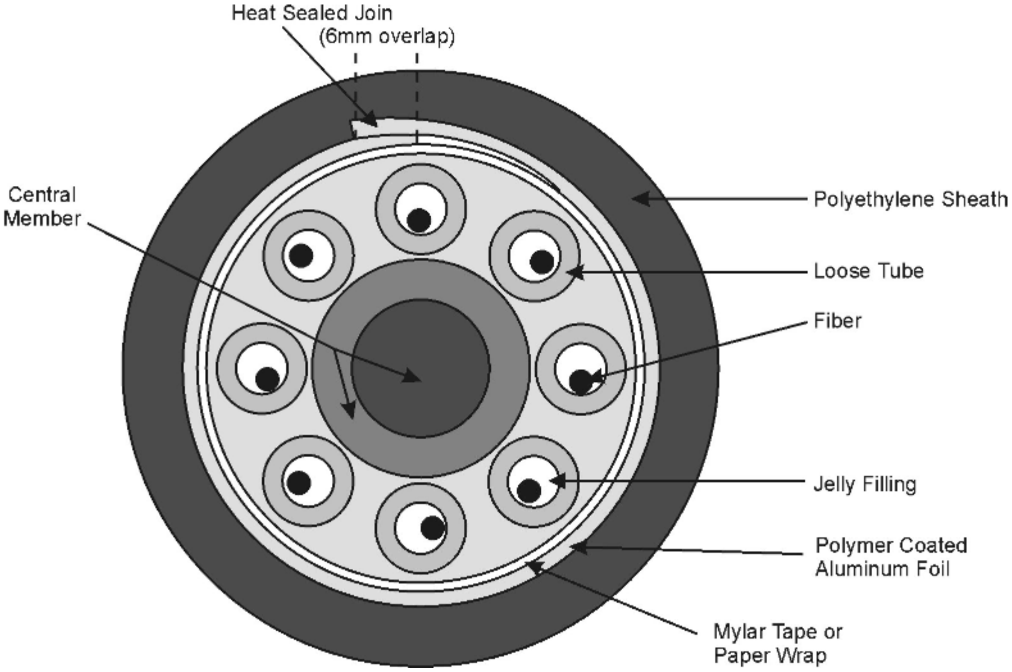


Figure 4.9
Metallic moisture barrier cable

Advantages

- Usually, the most cost-effective method of installing cables outdoors.
- Greater environmental protection compared to aerial cable.
- Usually, more secure than aerial cable.

Disadvantages

- Can be disrupted by earthworks, farming, flooding etc.
- Rodents biting cables can be a problem in some areas. This is overcome with the use of steel tape armor or steel braid, or the use of a plastic duct of more than 38 mm OD for all dielectric cable installations. In addition, the use of Teflon coatings on the sheath makes the cable too slippery for a rodent to grip it between its teeth.

4.10.3 Subaqueous cables

Subaqueous cables are outdoor cables designed for continuous immersion in water. While the most sophisticated cables are used for deep ocean communications by international telecommunications carriers, there are practical applications for subaqueous cables for smaller users. These include cabling along or across rivers, lakes, water races, or channels where alternatives are not cost effective. Subaqueous cable is a preferred option for direct buried cabling in areas subjected to flooding or with a high water table, where for example, if the cable were buried at say 1 meter depth, it would be permanently immersed in water.

The installation aspects of subaqueous cables are discussed in Chapter 7.

Cable types

The basic elements of a subaqueous cable are shown in Figure 4.10. These are essentially outdoor cable constructions incorporating a hermetically sealed unit, using a welded metallic layer encasing the fiber core.

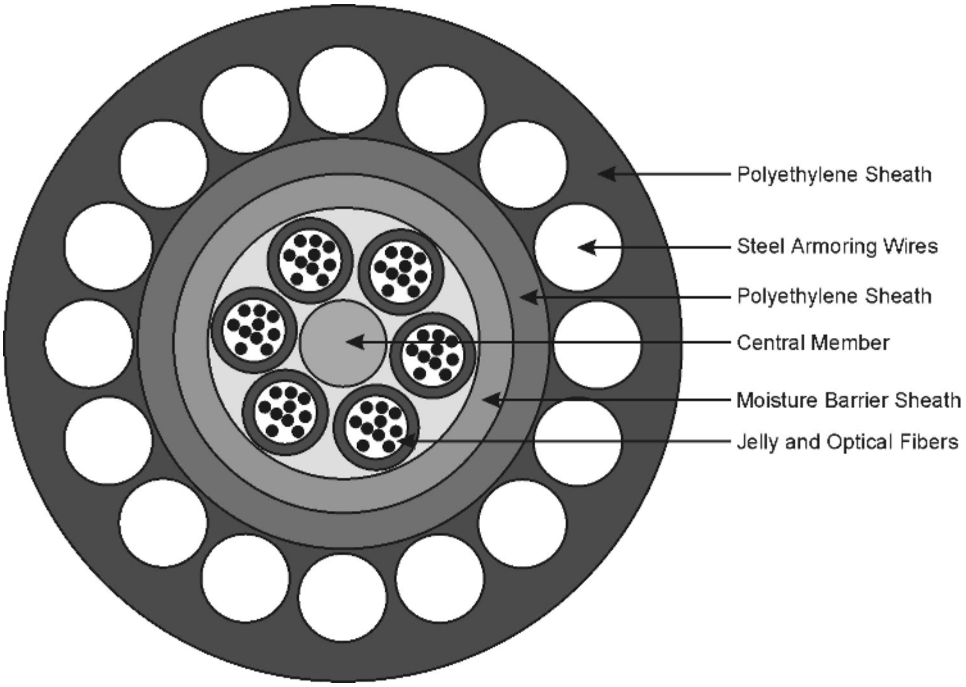


Figure 4.10
Subaqueous cable

Advantages

- Cheaper installation in some circumstances

Disadvantages

- Unit cost of cable is higher

4.10.4 Indoor cables

Indoor cables are used inside buildings and have properties dictated by fire codes. Such cables need to minimize the spread of fires, and must comply with your relevant local fire codes, such as those outlined in the National Electrical Codes (NEC) in USA. Outdoor cables generally contain oil-based moisture blocking compounds like petroleum jelly. These support combustion and so, their use inside buildings is strictly controlled in some countries. Outdoor cables are sometimes spliced to appropriate indoor cables close to the building entry points. This would avoid the expense of encasing long runs of outdoor cable inside metallic conduit as is required in some countries.

The fibers in indoor cables and the indoor cable itself are (usually) tightly buffered as was discussed in section 4.5.2. The tight buffer provides adequate water resistance for indoor applications but such cables should not be used for long outdoor cable runs. The buffered fibers can be given sufficient strength to enable them to be directly connected to equipment from the fiber structure without slicing to patch cords.

Installation of indoor cables is discussed in detail in Chapter 7.

Cable types

Patch cords

Designed for repeated handling at patch panels, these use internal Aramid fiber layers to provide tensile strength while allowing considerable flexibility. Outdoor cables and loose tube cables that contain fibers, which are not tightly buffered, need to be spliced to tightly buffered internal cables or patch cords for termination to equipment.

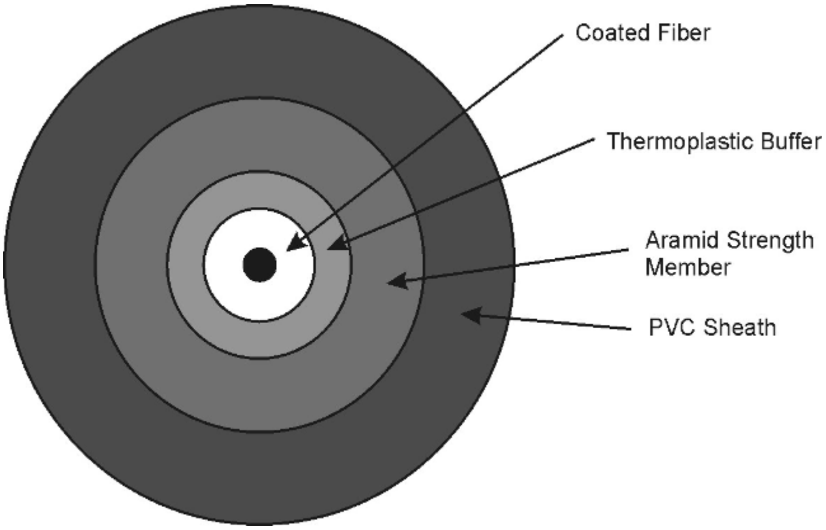


Figure 4.11
Patch cord

Distribution (breakout) cables

These have tightly buffered fibers in subunits, which have sufficient protection to enable them to be broken out of the cable structure and run direct to equipment.

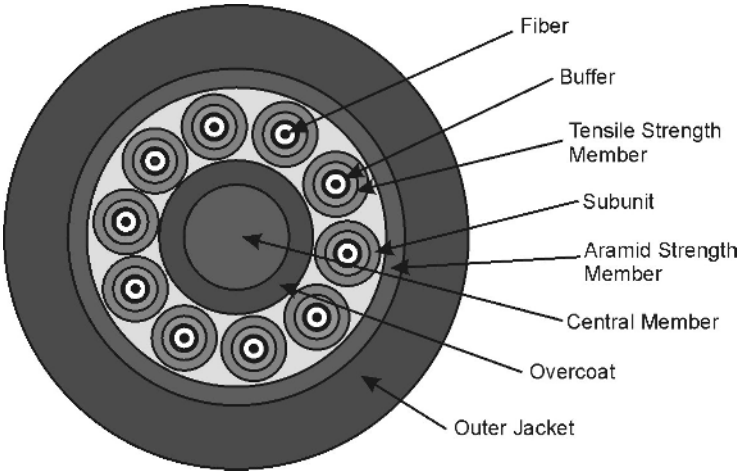


Figure 4.12
Distribution or breakout cables (tight buffered subunits)

Riser cables

These have multiple tightly buffered fibers in a structure designed to withstand long vertical runs without support.

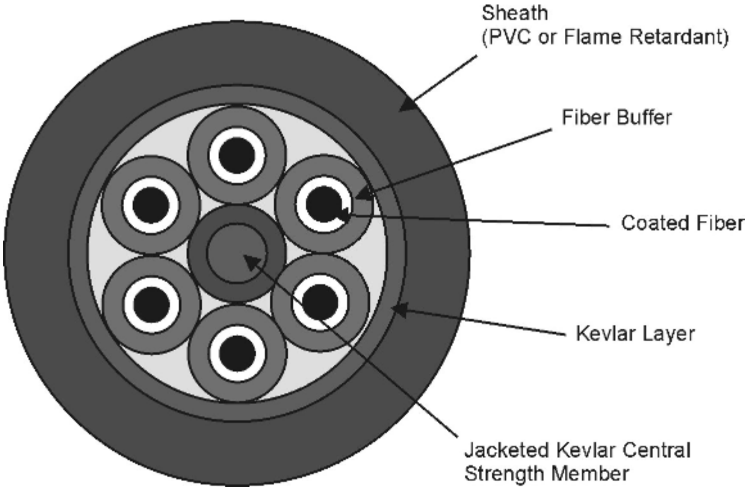


Figure 4.13
Riser cables

Plenum cables

Plenum cables are required by the fire safety codes used in some countries, in areas where the cables are installed directly in the air-return path of an air-conditioning system. This can often include cable installations above suspended ceilings. In some cases, these cables may need to be installed within conduit or have sheath materials complying with the UL 910 standard, which, unless under very intense heat, do not support the spread of fires. Unless the cables are actually burning they will not emit poisonous gases and will have low smoke emission. They do emit very poisonous gases if they eventually burn. Such materials include MEGOLON, which is a filled polyolefin, a copolymer of ethylene vinyl acetate filled with hydrated aluminum oxide. This has no significant halogen content and therefore, cannot emit any halogenated acids when burned.

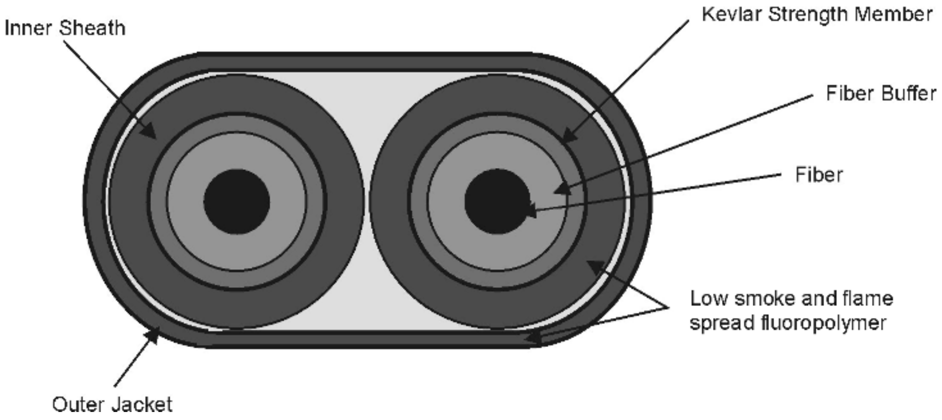


Figure 4.14
Duplex plenum cable

Zip cord cables

These are small diameter cords having internal Kevlar reinforcement, making them easy to handle with good tension, compression and bending properties. These are used with computer data links, terminal links and remote instrumentation connections. They are also used for patch cords since connectors can be attached firmly to the cord structure.

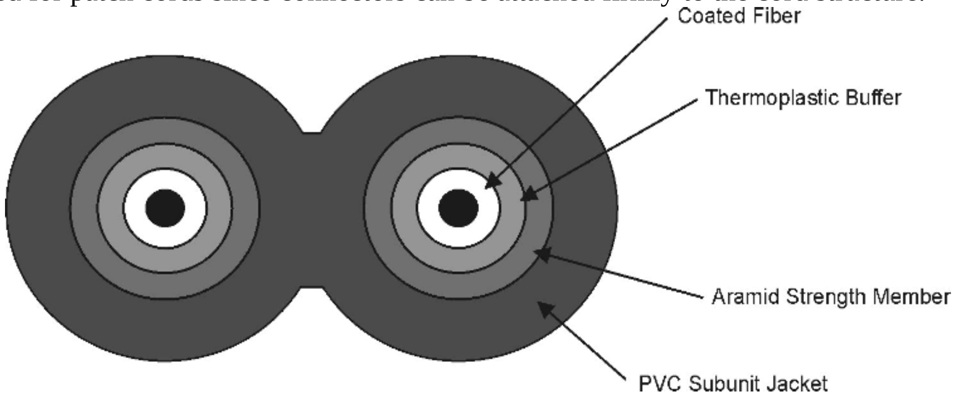


Figure 4.15
Zip cord cable

Advantages of indoor cables

- Ability to connect tight buffered fibers direct to equipment without patch panels
- Compliance with fire codes

Disadvantages of indoor cables

- Unsuitable for long external runs
- Higher attenuation than loose buffer fibers
- Unsuitable for extreme temperature variations

5

Connecting fibers

Introduction

This chapter will identify the main issues involved in connecting fibers together and to optical devices, such as sources and detectors.

This can be done using splices or connectors. A splice is a permanent connection and a connector is used where the connection needs to be connected and disconnected repeatedly. A device used to connect three or more fibers or devices is called a coupler. This chapter will examine the following areas:

- Different splicing techniques
- Step by step fiber jointing procedures
- Practical connector types
- Step by step procedures for attaching connectors to fibers
- The operation of optical couplers

5.1 Optical connection issues

The main parameter of concern when connecting two optical devices together is the attenuation; that is, the fraction of the optical power lost in the connection process. This attenuation is the sum of losses caused by a number of factors, the main ones being:

- Lateral misalignment of the fiber cores
- Differences in core diameters
- Misalignment of the fiber axes
- Numerical aperture differences of the fibers
- Reflection from the ends of fibers
- Spacing of the ends of the fibers
- End finish and cleanliness of fibers

Theoretical analysis of the losses caused by these factors is complicated by the fact that the distribution of the power across the face of the fiber is usually unknown and varies according to the type and length of fibers, method of excitation etc. The following discussion of idealized connections will illustrate the sensitivity of the attenuation to various loss mechanisms.

5.1.1 Lateral misalignment of fiber cores

Here, it is assumed that fibers of the same diameter are displaced by a distance *d*, and are otherwise perfectly aligned as shown in Figure 5.1. For simple, worst-case analysis, it is assumed that the power is uniformly distributed across the fiber cores.

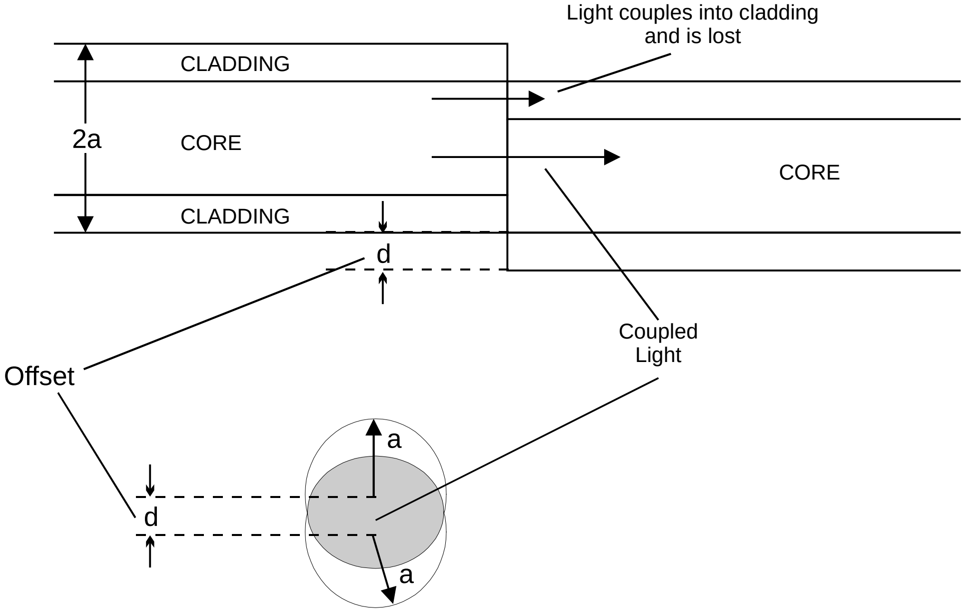


Figure 5.1
Lateral misalignment of fibers

The coupling efficiency η is calculated from the ratio of the overlapping area to the core area. For small displacements where *d* is less than 20% of the radius of the core, η can be approximated as:

$$\eta = 1-(2d/\theta a)$$

$$\text{Attenuation} = 10 \log \{1-(2d/\theta a)\}$$

This equation is plotted in Figure 5.2 for a step index multimode fiber, and shows how important the lateral alignment of fibers in the connection process is. For a step index multimode fiber, the assumption of uniform power distribution over the fiber is not unreasonable, but it overestimates the loss for graded index fibers where the distribution is less uniform and concentrated more on the axis.

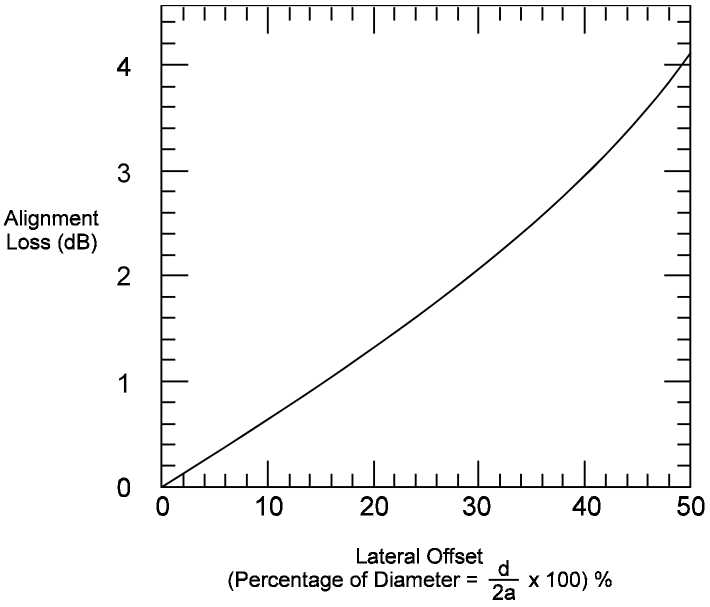


Figure 5.2
Typical lateral alignment loss

5.1.2 Differences in core diameters

Similar mismatches of the emitting and collecting areas of the interface can occur if fibers are perfectly aligned but have differing core diameters. For fibers with emitting diameter of d_1 and collecting diameter d_2, the loss is given by the formula:

$$\text{Loss} = 10 \log (d_1/d_2)^2 \text{ dB}$$

$$= 20 \log (d_1/d_2) \text{ dB}$$

Consider the example of a nominal 50 µm fiber with typical manufacturing tolerance of ± 3µm. It is possible to have a worst case mismatch of a fiber with 53 µm core jointed to one of 47 µm. Assuming uniform distribution of light over the fiber diameter, this results in a loss of 21% of the light and equates to about 1 dB loss. This is a conservative worst case estimate, as the light is generally not uniformly distributed.

This effect is severe if different types of fiber are connected, such as a 62.5 µm multimode fiber connected to a 50 µm fiber where a loss of more than 1.9 dB can be expected.

Note that there is no significant loss incurred going from a small fiber to a large one, which can collect the entire incident light.

5.1.3 Angular fiber misalignment

When the axes of fibers are not aligned, the light enters the second fiber at greater angles and depending on the numerical aperture *NA*, some of the rays are unable to be confined to the core. This is illustrated in Figure 5.3.

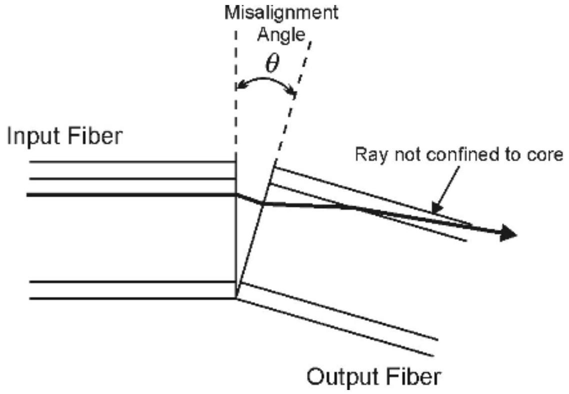


Figure 5.3
Angular misalignment

The coupling efficiency η for small angular misalignments of θ radians is given by:

$$\eta = 1 - \frac{N_o \theta}{\theta\, NA}$$

The loss calculated as:

$$10 \log \ \eta \text{ dB}$$

This loss equation is plotted in Figure 5.4 for some multimode step index fibers. The loss can be seen to decrease with the larger numerical apertures, attributable to the fact that at a large *NA*, the radiation is distributed over wide angles so small angular errors affect less of the total power. The effect of an index matching liquid of refractive index N_o = 1.5 on a glass fiber is also illustrated in Figure 5.4. This shows that the angular misalignment loss increases (although the end separation loss as discussed in section 5.1.6 is decreased) compared to no index matching (N_o = 1).

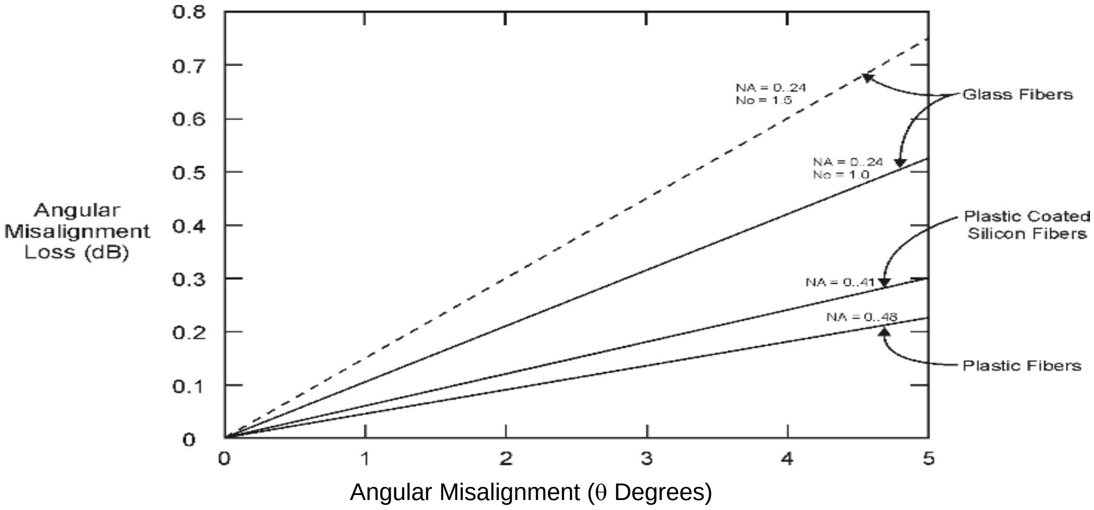


Figure 5.4
Typical angular misalignment losses

5.1.4 Numerical aperture differences

Differences in the numerical aperture (*NA*) of fibers can also contribute to the interface loss. If the receiving fiber has a smaller *NA* than the source fiber, then light will enter the fiber outside the acceptance angle as shown in Figure 5.5. Then such light will not be confined to the core, and subsequently, will leak away.

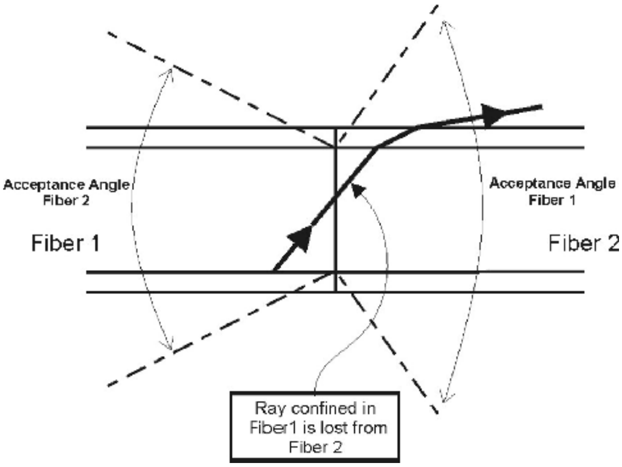


Figure 5.5
Numerical aperture differences

The loss can be quantified by the following formula:

This equation is plotted in Figure 5.6 and it assumes a uniform modal distribution. This applies with equal validity to multimode step and graded index fibers. There is no loss if the receiving fiber has a greater *NA* than the source fiber.

$$\text{Loss} = 10 \log (NA_1/NA_2)^2 \text{ for } NA_1 > NA_2$$

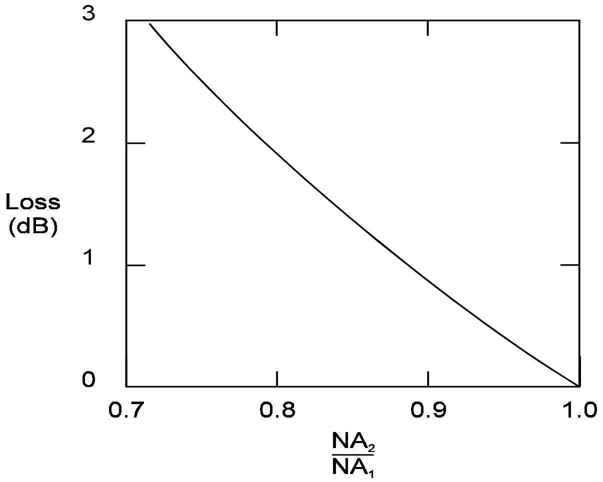


Figure 5.6
Effect of different NAs

5.1.5 Reflection at the end of fibers

When there is a gap between the fibers, Fresnel reflection, as discussed in section 3.1.8, takes place at each of the air-fiber boundaries. If it is assumed for simplicity that all the light is aligned to go straight through between media of refractive indices N_1 and N_2, then the loss is given by the formula:

$$\text{Loss} = 10 \log (1 - \text{ч})\ \text{dB}$$

where ч is the reflection coefficient and is equal to:

$$\text{ч} = [(N_1 - N_2)/(N_1 + N_2)]^2$$

For an air–glass interface, (N_1 is glass at 1.5 and N_2 is air at 1.0) this gives a 4% reflectance (0.177 dB); thus both reflecting surfaces add 0.35 dB. This can be reduced by the use of an index matching gel, with refractive index closer to that of glass, but not necessarily a precise match. For a gel of refractive index 1.4, with glass of refractive index 1.5, the above formula shows the Fresnel loss to be 0.005 dB per surface or 0.01 dB total.

As was seen in Figure 5.4, such index matching increases the sensitivity to angular misalignment. Many practical mechanical splices and connectors incorporate index-matching gels. These can be thick, viscous liquids like glycerin or silicon grease for unglued joints or transparent epoxy glues.

Reflection from the end of the fibers is also referred to as back reflection. Optical return loss (OPL) is given by the ratio of the back reflection to the input power:

$$\text{OPL (dB)} = -10 \log (\text{reflected power/input power})$$

Optical return loss measurements are discussed in Chapter 9. Reflection from the ends of the fibers can be a major contributor of errors on high bit-rate singlemode systems. This occurs when the reflected light interferes with the laser diode, causing mode hopping. This can be reduced by the use of non-perpendicular cleaves, on mechanical splices, to ensure the back reflectors are absorbed in the fiber cladding. At connectors, a similar technique is used to prevent the reflections causing interference. The end of the fibers are normally polished to a slightly convex surface by the action of a polishing puck moved in a figure 8 pattern on an abrasive sheet.

5.1.6 End separation of fibers

When the fibers are separated, losses occur due to the spreading of the light from the fibers, as illustrated in Figure 5.7. The light exits the source fiber in a conical beam with the spreading angle dependent on the *NA*. With a gap separating the fibers, some of the transmitted light is not intercepted by the receiving fiber. Fibers with large *NA* have greater separation losses because their beams diverge more quickly. Index matching liquid placed in the gap reduces the amount of spreading, and hence the loss.

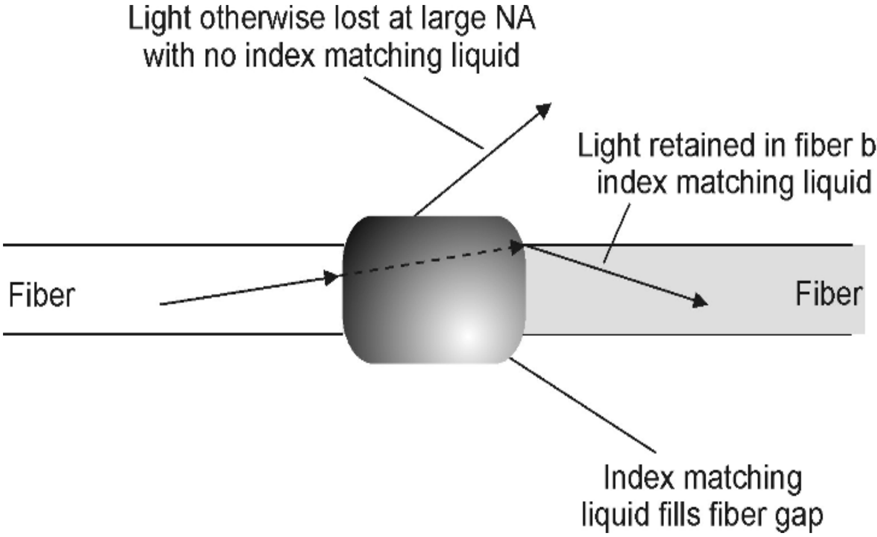


Figure 5.7
Index matching gel reduces end separation effects

The loss for small separation (*s*) is given by the formula:

$$\text{Loss} = -10 \log \{1 - (s\, NA)/4aN_0\} \text{ dB}$$

Where N_0 is the refractive index of the index matching gel and a is the core radius of the fiber. A uniform power distribution is assumed. This equation is plotted as Figure 5.8 for differing types of fiber, and the beneficial effect of the index matching gel ($N_0 = 1.5$) can be seen.

For singlemode fibers, a similar analysis shows that the fiber end gap is even less critical, with a gap of 10 times the core radius producing a loss of less than 0.4 dB.

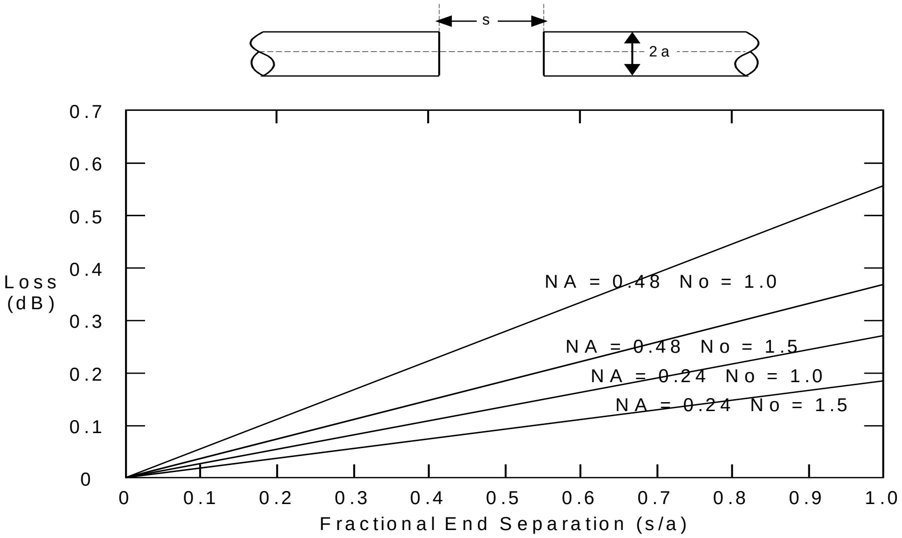


Figure 5.8
Typical end separation losses

5.1.7 End finish and cleanliness of fibers

The end of the fiber needs a smooth finish across its core to prevent light being scattered at the rough surface. This is achieved by cleaning the ends of glass fibers or polishing the fiber.

The fibers need to be clean as particles of dirt can scatter or absorb light. Joint preparation always involves cleaning the fibers, normally with a lint free cloth and isopropyl alcohol.

5.1.8 Connection loss summary

We have seen in the above discussion of the various loss mechanisms involved in connecting multimode fibers that the most important is the axial misalignment of the fibers.

With connectors, the minimum loss across the glass/air interface between them will always be about 0.35 dB unless index matching gel is used.

5.2 Fiber end preparation

A necessary preliminary for connecting optical fibers together or to a connector is to prepare the end of the fiber. There are three basic methods; the scribe and break method, the cleavering method and the lap and polish method. The scribe and break technique and the cleavering tool are usually used prior to splicing of glass fibers, while the lap and polish approach is needed for plastic fibers and attachment of connectors.

5.2.1 Preparation of glass fibers

The first step in preparing the glass fiber is to carefully bare the fiber, removing any plastic jacket material, strength members and buffering etc. This can be done using wire strippers, razor blades, or similar sharp tools. Great care needs to be exercised to avoid damaging the surface of the cladding. Chemicals, such as methylene chloride, can also be used for the stripping process. Some of these are dangerous to handle and require special precautions. After stripping, the bare fiber is chemically cleaned, using typical industrial solvents like isopropyl alcohol.

5.2.2 Scribe and break method

The cleaned glass cladding is now nicked by a hard cleaving tool, with typically a diamond, sapphire or tungsten-carbide blade. The fiber is kept under moderate tension while the cleaving blade passes across it and the tension is then increased until the fiber breaks. When performed properly, this produces a flat, mirror-finish surface approximately (within +/– 3 degrees) perpendicular to the fiber axis. This is the quickest and cheapest method of preparing the fiber ends for connection, although the result is generally least effective. The end should be carefully inspected to verify that a smooth clean break has been produced.

5.2.3 Cleavering tool

This is a very similar method to the scribe and break method, but is done with a very precise mechanical cleavering tool. The end of the fiber is placed into the tool and held fast. Then a gentle action cross-sectional pressure is applied and a clean flat break is achieved. This generally produces a far better result than the scribe and break method.

5.2.4 Lap and polish method

The lap and polish method is used where the cleaving approach is not practical; for example, in attaching connectors to the fibers. Most connectors have polishing attachments and procedures unique to that design. A generalized connector attachment procedure will now be discussed as an illustration.

The fiber is first inserted into a metal, plastic, or ceramic ferrule, whose purpose is to hold the fiber accurately in position, protect it from damage, and mechanically position the fiber into precise alignment within a matching connector. Connector construction is discussed in detail in section 5.4.

The bare fiber and its protective jacket are permanently cemented into the ferrule with epoxy around the protruding fiber. The fiber is scribed and broken to create a reasonably straight edge. The ferrule is fitted to a removable lapping tool, which is used to hold the ferrule perpendicular throughout the grinding process. The fiber is ground down with successively finer grades of abrasive to achieve a polished surface flush with the end of the ferrule. Water is used with the abrasive paper to lubricate the fiber and flush away the residues of glass and abrasive. Final lapping is done with polishing paste or lapping paper having abrasive particles of less than 1-micron diameter.

5.2.5 Preparation for plastic fibers

Plastic clad silica and all plastic fibers usually need to use the lap and polish technique because the plastic does not fracture as precisely as glass. The outer coverings of the fiber need to be removed by the same methods as for glass fibers detailed in section 5.2.1. The fiber and its jacket are secured in removable polishing clamp or in the connector ferrule and polished to the required extent, in a similar manner to that detailed above.

5.3 Splicing fibers

Two basic techniques are used for splicing of fibers; fusion splicing or mechanical splicing. With mechanical splicing, the fibers are held together in an alignment structure, using an adhesive or mechanical pressure. With the fusion splicing technique, the fibers are welded together, requiring expensive equipment but will produce consistently lower loss splices with low consumable costs. Mechanical splicers require lower capital cost equipment but have a high consumable cost per splice.

Today, fusion splicing is the main technique for joining fibers. It is far better joining with significantly lower loss. Over the long term, it is also far more reliable.

5.3.1 Fusion splicing

Fusion splices are made by melting the end faces of the prepared fibers and fusing the fibers together. Practical field fusion splicing machines use an electric arc to heat the fibers. Factory splicing machines often use a small hydrogen flame. The splicing process needs to precisely pre-align the fibers, then heat their ends to the required temperature and move the softened fiber ends together sufficiently to form the fusion joint, whilst maintaining their precise alignment.

During fusion, surface tension tends to naturally align the fiber axes minimizing any losses caused by lateral misalignment as discussed in section 5.1.1. Properly made fusion splices are as strong as the original fibers. Production fibers breaking under the proof test are simply fusion spliced for repair by the manufacturer. Such factory splices have typically less than 0.1 dB loss and have a tensile strength comparable to that of the original fiber. Commercial field splicing equipment, in skilled hands, can consistently produce splices with losses less than 0.1 dB.

Fusion splicing equipment typically provides the following features:

- **A fusion welder**
  This is normally an electric arc and its electrode spacing and arc timing need to be adjustable to suit the fibers being fused.
- **Fiber holders and positioners**
  Devices to rigidly hold the fibers, accurately move them in three-dimensions so that the fiber cores are precisely aligned with each other and with the splicer electrodes. The fiber ends need to be brought together in alignment to complete the splice once the ends have been melted in the arc.
- **Alignment devices**
  These are devices to ensure correct alignment of the fibers. Manual systems use a microscope or video camera to magnify the fiber ends by at least 50 times, to enable the operator to see the fibers while manually aligning them. Automatic systems use computer controlled positioners to align the fibers so as to optimize the light transmission.
- **Optical performance checking**
  This is a method for checking the quality of the splice by checking the optical power transmitted across the splice. With automatic fusion splicing machines, this is usually done by coupling light into one fiber by tightly bending it around a light injecting post and similarly, coupling the light out of the fiber on the other side. This is also used to allow automatic alignment as described above as well as checking the loss of the finished splice. The simplest fusion splicers do not include this feature.

These basic components of a fusion splicer are shown in Figure 5.9.

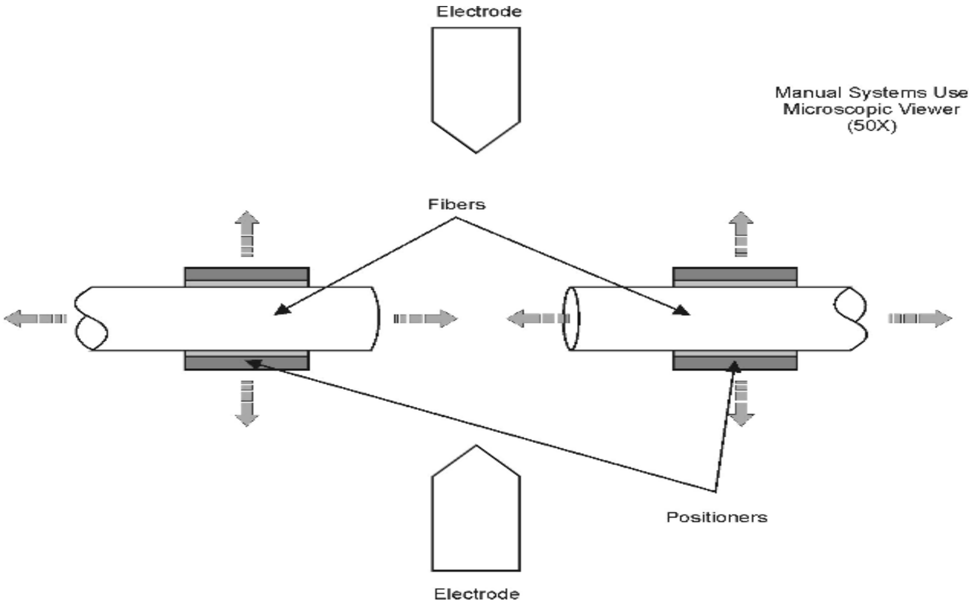


Figure 5.9
Fusion splicer components

5.3.2 Fusion splicing process

The basic steps involved in making a fusion splice are as follows:

Fiber end preparation

The protective plastic fiber jacket on both fibers must be stripped and cleaned for the appropriate distance; both fiber ends are then cleaved so the end faces are approximately perpendicular, (±3 degrees) to the fiber axis.

Fiber alignment

Each fiber end is clamped into a micro-positioner on the fusion splicer. The fiber ends are then brought into alignment: automatic splicers use computer control to optimize the light transmission as described above. Manual splicers rely on the operator to align the fibers using the micro-positioners, microscopic viewer, and mirror to inspect the alternative axis.

Arc cleaning

The ends of the fibers are separated at appropriate distance and a moderate arc is used for about one second to clean the fiber ends and round their edges.

Pre-fusion

Some splicers then bring the two molten ends of the fibers into contact to pre-fuse the fibers. The fibers are then checked again for transmission effectiveness, to confirm their alignment.

Fusion

The main fusing arc then melts the fiber ends and the molten fibers are brought closer together to complete the splice. The surface tension of the molten glass tends to align the fibers, thereby minimizing any lateral offset. The power, spacing, and timing of the arc are critical to achieve the correct temperature for the particular type of fiber.

Protection

When cool, the splice area can be coated with a plastic coating such as RTV or epoxy, for atmospheric protection. Some form of mechanical protection, such as a heat-shrink sleeve or mechanical clip is then fitted.

5.3.3 Mechanical splicing

Mechanical splicing involves many different approaches for bringing the two ends of the fibers into alignment and then clamping them within a jointing structure or gluing them together. Mechanical splices are generally used for short-term fixes only. Longer term fixes are provided by using fusion splices.

Mechanical splices generally rely on aligning the outer diameters of the fiber cladding and assume that the cores are concentric with the outside of the cladding. This is not always the case, particularly with singlemode fibers. Some systems therefore allow active alignment where the fiber loss is monitored and the fibers rotated within the jointing structure to minimize the splice loss. Various mechanical structures are used to align the fibers, including V-grooves, sleeves, 3-rods and various proprietary clamping structures. Some of these are shown in Figure 5.10.

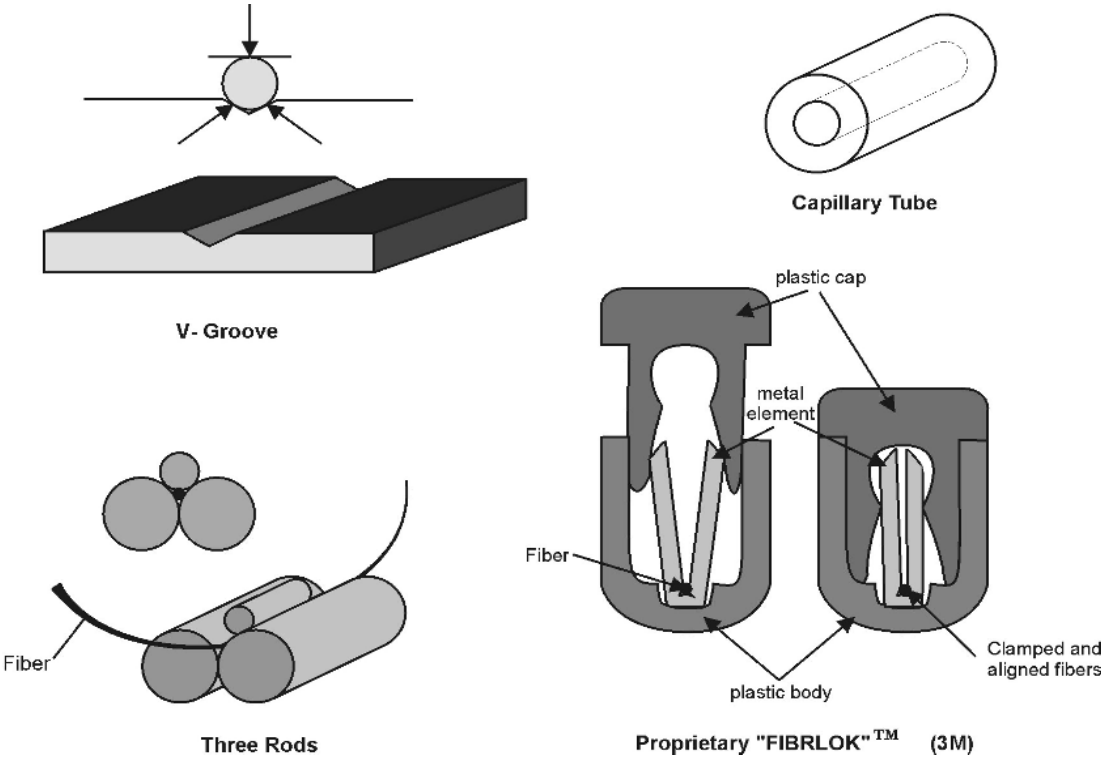


Figure 5.10
Splice alignment structures

Some of the main mechanical splice categories are as follows:

Capillary mechanical splice

Here, the prepared fiber ends are inserted into a capillary tube matched to the outer diameter of the fiber. This is illustrated in Figure 5.11. An index-matching gel or liquid may be used to reduce reflections from the butted ends of the fibers. Often, an adhesive is used to hold the fibers into the capillary tube, although compression from an external strain relief clamp or simply friction can be used. This provides a cheap, simple, easy to install splice, which is able to compensate for minor differences in the fiber diameters. This is the most common technique for mechanical splices.

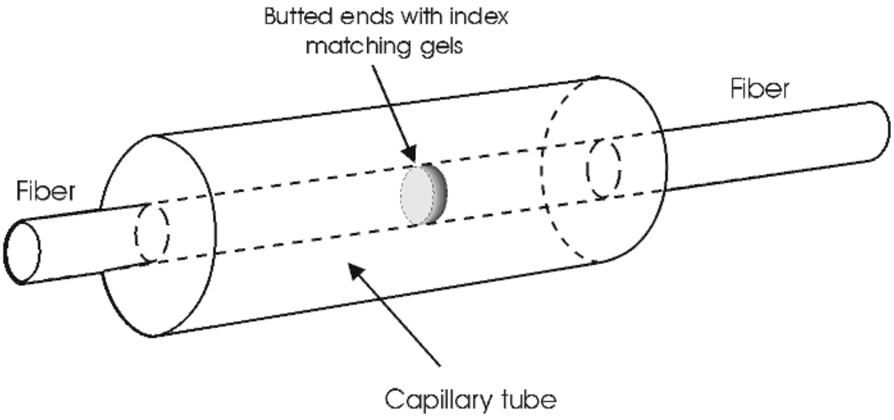


Figure 5.11
Capillary mechanical splice

Polished ferrule mechanical splice

The polished ferrule mechanical splice, or rotary splice is a more complex jointing system capable of precise alignment of the fibers. The process is shown in Figure 5.12. Here each of the cleaned fiber ends is inserted into a ferrule which mounts the fiber slightly off-center. The fibers are glued into the ferrules, then their ends cleaved and polished flush with the ferrule tip. The two ferrules are butted together, with index-matching gel, inside an alignment sleeve. The ferrules are rotated to minimize the splice loss, and then they are fixed in place. This method is more complex and time consuming but can result in lower loss splices. It is well suited for splicing polarization-sensitive fibers.

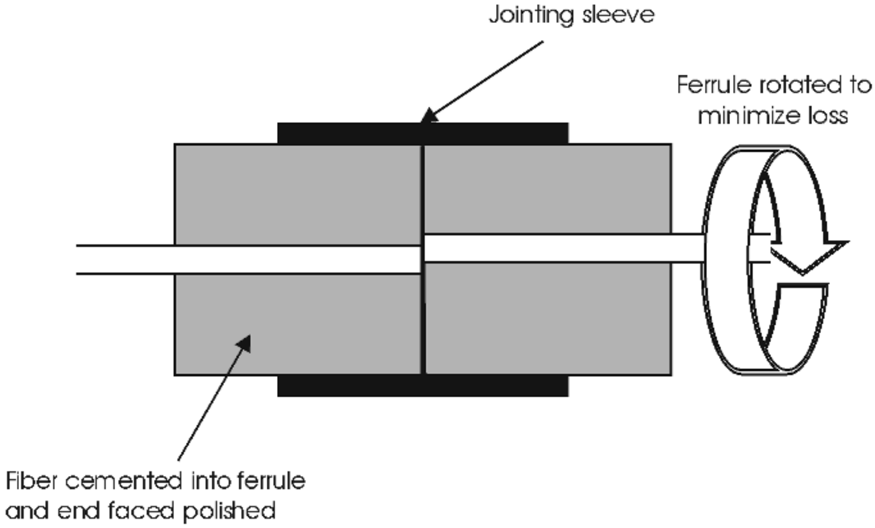


Figure 5.12
Polished ferrule mechanical splice

Elastomeric mechanical splices

The elastomeric splice uses a V-shaped groove in a flexible plastic insert for the alignment of the fibers, as shown in Figure 5.13. The top of the splice sleeve exerts pressure to clamp the fiber into the V-shaped alignment groove. An index-matching gel or epoxy glue is inserted into the splice. The prepared ends of the fibers are then inserted halfway into the splice until they meet. These splices have typical losses of about 0.25 dB, so are suitable for the less critical applications, and for emergency service restoration.

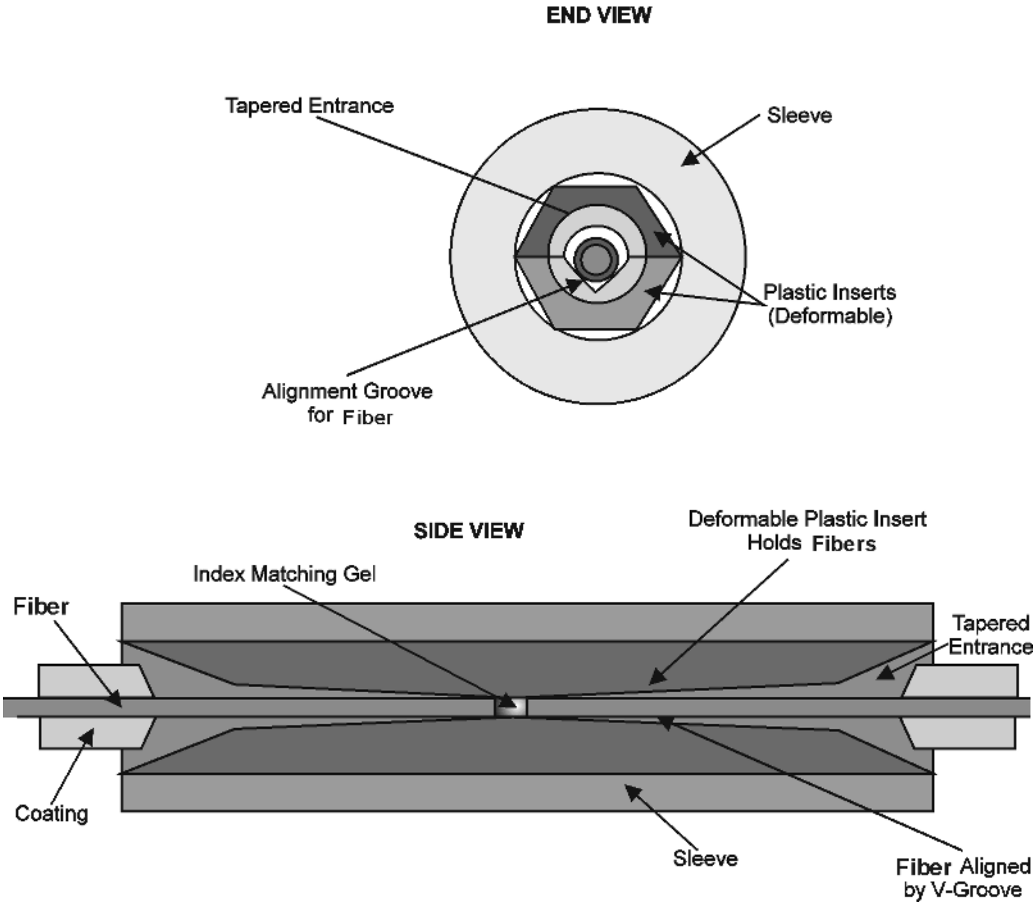


Figure 5.13
Elastomeric mechanical splices

Multiple fiber V-groove splicing

Multiple fiber ribbon cables can be simultaneously spliced by using suitably grooved plates. The ends of the ribbons are prepared by stripping the sheath, cleaning then polishing the fiber ends as a unit. The two ribbons are mated together on the grooved plates with an index-matching liquid. Each fiber fits into a separate groove in the plate and a matching plate fitted on top to hold the fibers in alignment, as shown in Figure 5.14. The technique requires tight tolerances on the grooves in the plates. Suitable precision can be attained by etching the grooves in silicon chips.

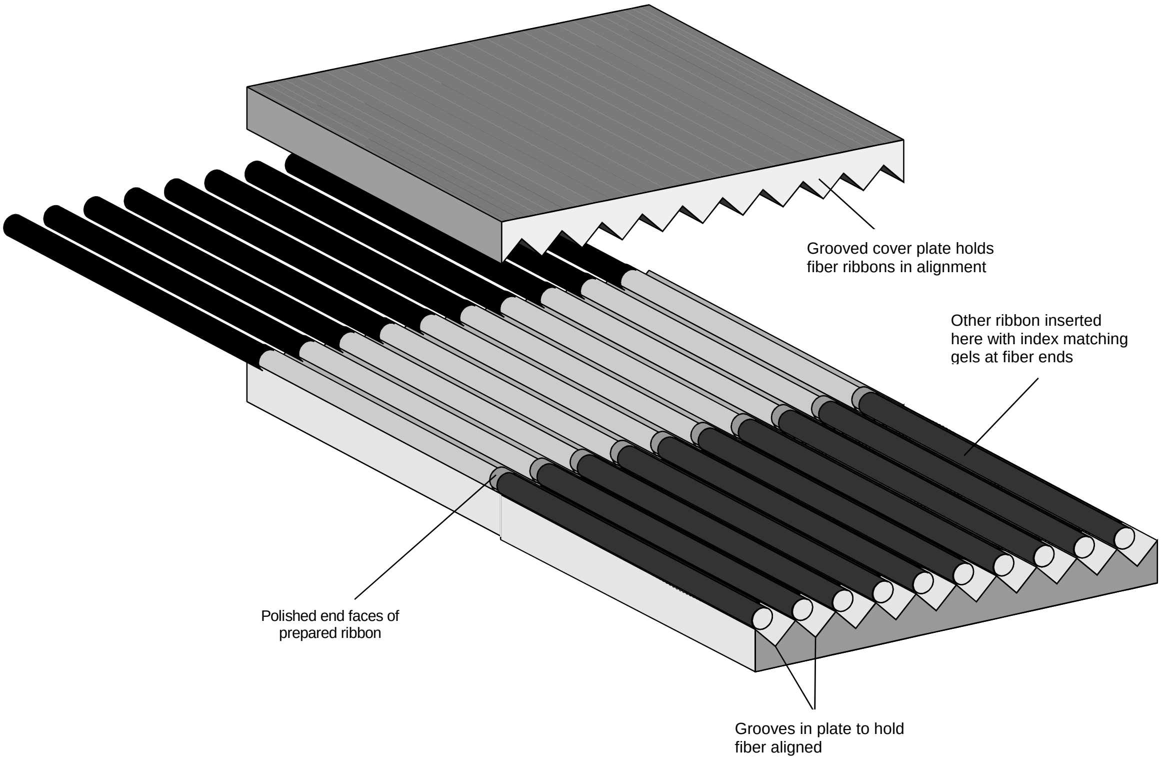


Figure 5.14
Multiple fiber splicing

5.4 Connectors

5.4.1 Connector properties

Connectors are used to make flexible interconnections between optical devices. The optical parameters discussed in section 5.2 need to be achieved in a unit, which is to be repeatedly connected and disconnected. A good connector needs the following mechanical properties to ensure consistently low loss throughout its lifetime:

- **Repeatability**
  The coupling efficiency of the connectors should not change much with repeated matings.
- **Predictability**
  The loss of the connector with a particular type of fiber should be consistent and relatively insensitive to the skill of the installer.
- **Long life**
  The connector loss should not degrade over time, nor should repeated matings of the connector cause damage or degradation.
- **High strength**
  The connector needs to be able to withstand significant stresses in use. This can arise through normal mating and unmating of the connectors, to abnormal forces on the cable and/or connector caused by bumping into connectors or tripping over cables etc.

- **Environmental protection**
  The connector needs to provide protection to the optical interface from dirt, moisture, chemicals, temperature changes, vibration etc.
- **Installation simplicity**
  The preparation of the fiber and its fitting into the connector should be relatively quick and easy.
- **Easy to use**
  Connecting and disconnecting the connection should be simple, requiring minimal force or dexterity.
- **Economical**
  Connectors should be reasonably priced. Precision components are required to achieve good performance components. As a rule, cheaper connectors, often plastic, are not precise for good performance.

Connectors have significantly greater losses than splices since it is much more difficult to repeatedly align the fibers with the required degree of precision. Active alignment, as was used to minimize some splice losses, is not possible. As was seen in section 5.2, axial misalignment of the fibers contributes most of the loss at any connection. Consequently, connector loss can be expected to be in the range from 0.2 to over 3 dB.

5.4.2 General connector construction

There are many different types of connector. The basic concepts in the connector design are illustrated in Figure 5.15 and described below.

Most connector designs produce a butt joint with the fiber ends as close together as possible. The fiber is mounted in a ferrule with a hole size to closely match the fiber cladding diameter. The ferrule is typically made of metal or ceramic and its purpose is to center and align the fiber as well as provide mechanical protection to the end of the fiber. The fiber is normally glued into the ferrule then the end cut and polished to be flush with the face of the ferrule.

The ferrules on two connectors mate with a precise, smooth fitting sleeve, also known as an adapter or coupling receptacle, which provides the necessary axial and angular alignment. The ferrules and sleeves may be tapered, as in biconical connectors, in which case plastic connectors may be used. This is because there is little abrasive wear when tapered components are repeatedly connected and disconnected.

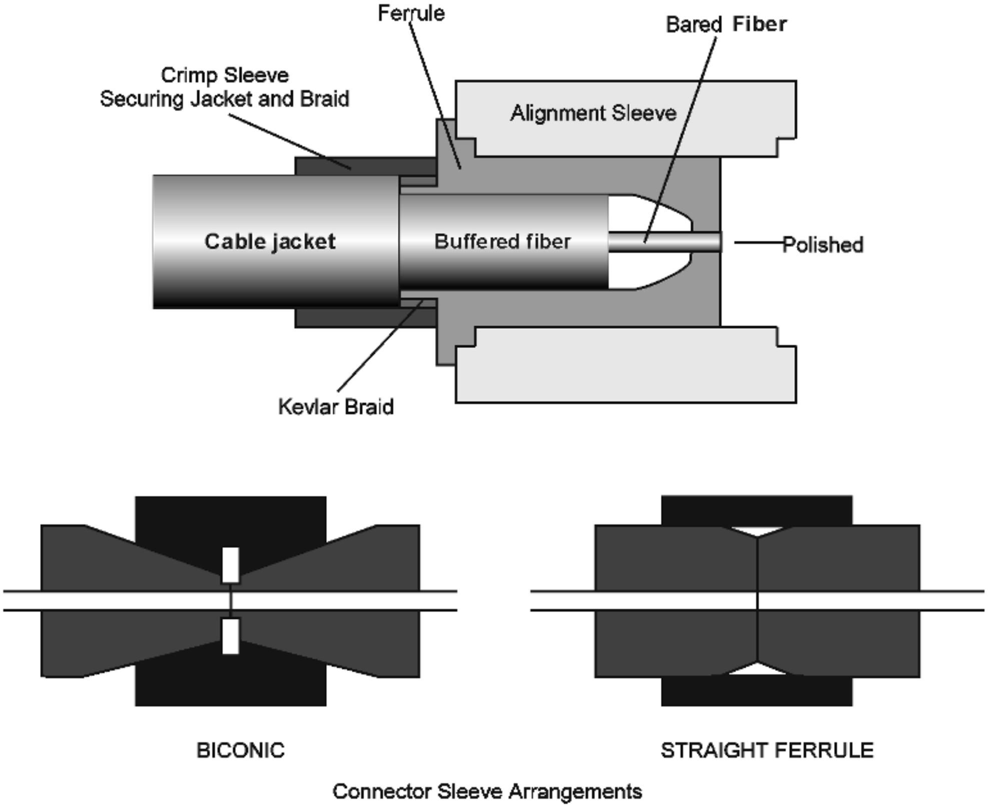


Figure 5.15
General connector construction

The ferrules are mounted in the connector body, normally metal or plastic, with provision for strain relief of the fiber. The cable strength member and jacket are usually attached to the body and a strain-relief boot can provide additional protection to the junction with the connector. The connector body also usually requires a mechanism to secure it to the coupling adapter. This can take the form of a screwed connection (SMA, FC and biconic types), a spring-loaded bayonet connection (ST and SC connector).

An alternative type of connector follows a lensed approach. This is shown diagrammatically in Figure 5.16. A lens is used to collimate the beam emerging from the end of the fiber. The fiber-lens distance is equal to the focal length of the lens. This produces a parallel beam of the lens diameter. This arrangement, when matched with a similar connector, has less sensitivity to lateral offset and gap between the connectors. In addition, it allows glass windows to be fitted over the lens to protect against dirt and scratches. Such connectors are more expensive and are used where rugged performance is critical, such as for military use.

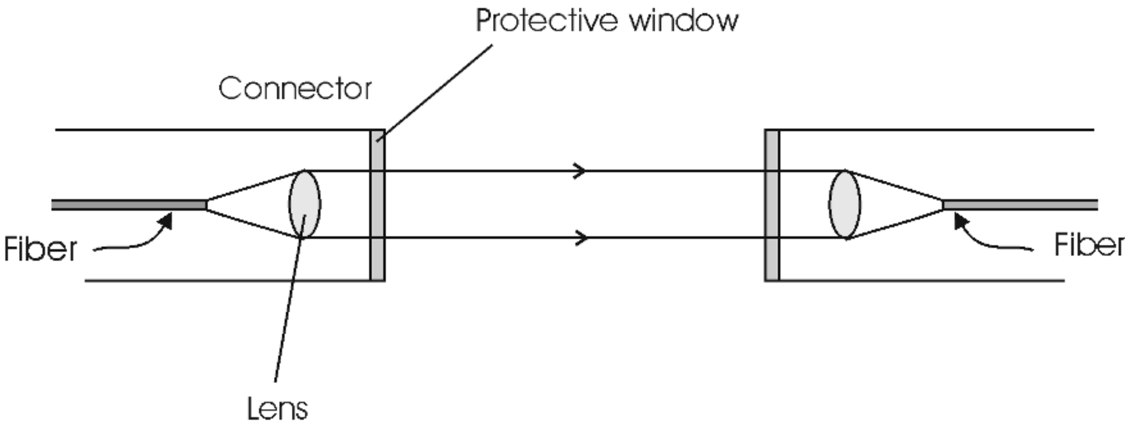


Figure 5.16
Lensed connector

5.4.3 Common connector types

There are many proprietary designs for connectors. Some standardization is now emerging and the International Standards Organization (ISO), the International Electrotechnical Commission (IEC) and the Telecommunications Industries Association (TIA) have all endorsed one connector type, the SC connector. Two other types of connector are widely used: the ST connector in the data and telecommunications industries, and the duplex FDDI connector in local area networks. These connectors are described in detail below.

SC connector

The SC connector is the most commonly used connector in industry today. The SC connector is shown in Figure 5.17. This is built with a cylindrical ceramic ferrule, which mates with a coupling receptacle. The connector has a square cross-section for high packing density on equipment, and has a push–pull latching mechanism. The ISO and TIA have adopted a polarized duplex version as standard and this is now being used as a low-cost FDDI connector. The SC connector has a specified loss of less than 0.6 dB (typically 0.3 dB) for both singlemode and multimode fibers and a typical return loss of 45 dB.

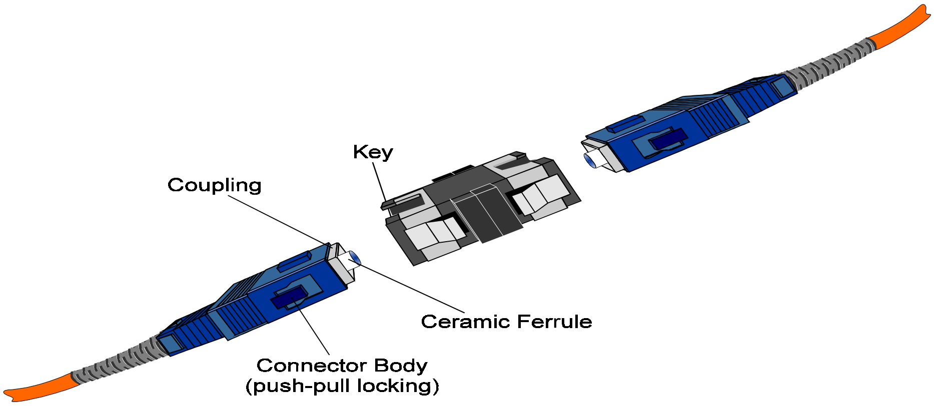


Figure 5.17
SC connector

ST connector

The ST connector is shown in Figure 5.18. This is an older standard used for data communications. This is also built with a cylindrical ceramic ferrule, which mates with a coupling receptacle. The connector has a round cross-section and is secured by twisting to engage it in the spring-loaded bayonet coupling. Since it relies on the internal spring to hold the ferrules together, optical contact can be lost if a force greater than about one kilogram is applied to the connector.

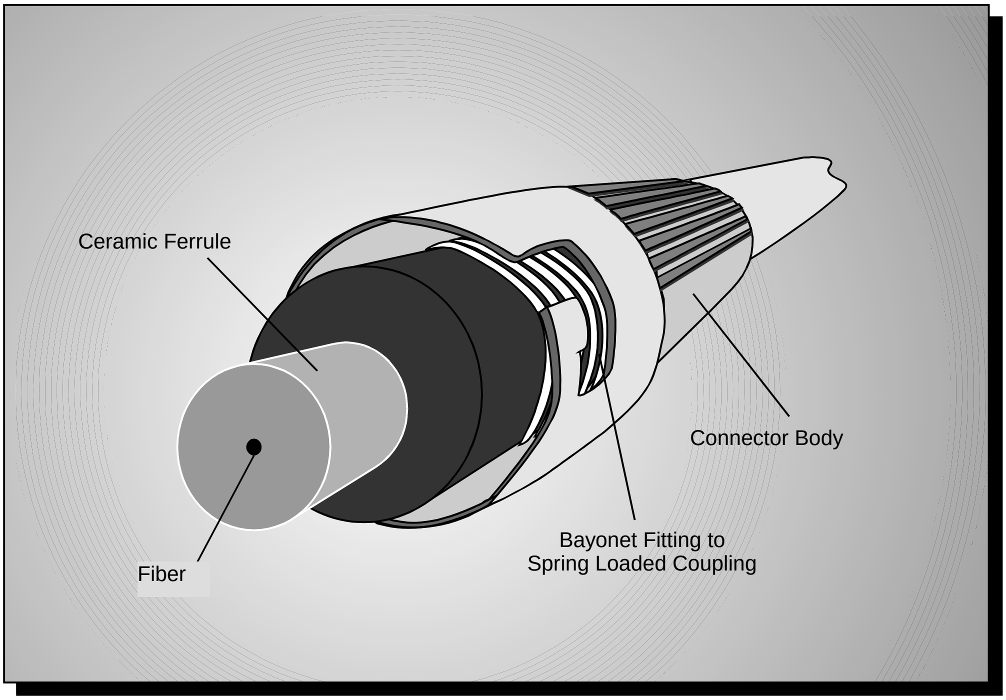


Figure 5.18
ST connector

FDDI connector

The fiber distributed data interface (FDDI) system developed its own standard duplex connector. This is shown in Figure 5.19. The FDDI connector is seen less frequently in industry simply because the FDDI standard is becoming less and less common. It is similar to the SC and ST connectors using a cylindrical ceramic ferrule design, which mates with a coupling receptacle. It is keyed so that it can only be installed with one polarity. This is essential for the FDDI system, which uses a pair of unidirectional fibers, to ensure accidental plugging of the transmit fiber into the receiver does not happen. Polarized duplex SC connectors are now being adopted for the low-cost FDDI standard.

FC connector

This is one of the earlier type of connectors that is rarely used today. It is similar to the ST connector but has a screw in bayonet.

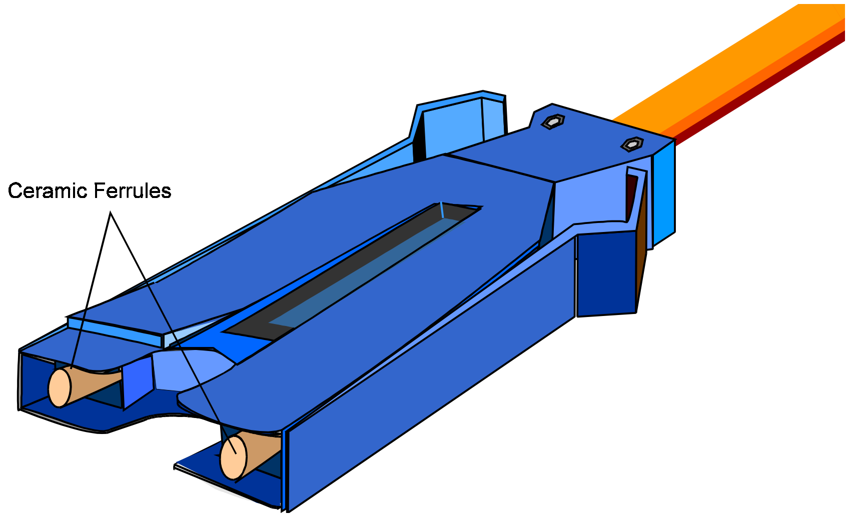


Figure 5.19
FDDI connector

5.4.4 Connector handling

Most fiber optic connectors are designed for indoor use. It is very important to protect them from contamination. The optical performance can be badly degraded by the presence of dirt or dust on the fiber ends. Even though a single dust particle would be 10 microns only in diameter, it could scatter or absorb the light and totally disrupt a singlemode system. Connectors and patch panels are normally supplied with protective caps. These should always be fitted whenever the connectors are not mated. These not only protect from dust and dirt, but also provide protection to the vulnerable, polished end of the fiber. Compressed air sprays are available for cleaning connectors and adapters, without needing to physically touch the mating surfaces.

Take care not to touch the end of the connector ferrules as the oil from your fingers can cause dirt to stick on the fiber end. Cleanse connectors with lint-free wipes and isopropyl alcohol.

Durability of the connectors is important throughout their lifetime. Typical fiber connectors for indoor use are specified for 500 to 1000 mating cycles, and the attenuation is typically specified not to change by more than 0.2 dB throughout that lifetime. Repeated connection and disconnection of the connectors can wear the mechanical components and introduce contamination to the optical path.

Connectors for outdoor use require to be hermetically sealed. The lensed connectors described in section 5.4.2 are well suited to this application, with an optical window on the end of the connector providing the environmental protection. The much greater diameter of the light beam at the interface reduces the effects of any surface contamination on the optical performance.

5.4.5 Pig-tail

The most common method of installing connectors on cables today is to buy a piece of fiber with a connector already installed. A piece of patch cord, which may be 1, 2, or 3 meters in length, and has a connector installed onto it in a factory. This is referred to as ‘pig-tail.’ The pig-tail is then simply spliced onto the incoming cable.

Doing it this way guarantees a high quality connection. The factory process is carried out by robots and ensures that the end result is of a consistently high quality. If the installer then uses the process of fusion splicing to install the patch cord to the incoming fiber, this ensures a very low loss overall.

5.5 Optical couplers

Optical couplers or splitters and combiners are used to connect three or more fibers or other optical devices. These are devices, which split the input power to a number of outputs. While the splitting of the light is done passively, active couplers include optical amplifiers, which boost the signal before or after the splitting process. Coupler configuration depends on the number of ports and whether each of these is unidirectional, (also called directional couplers), or bi-directional. This leads to three main types of couplers, the T coupler, tree coupler, and star coupler, as shown in Figure 5.20.

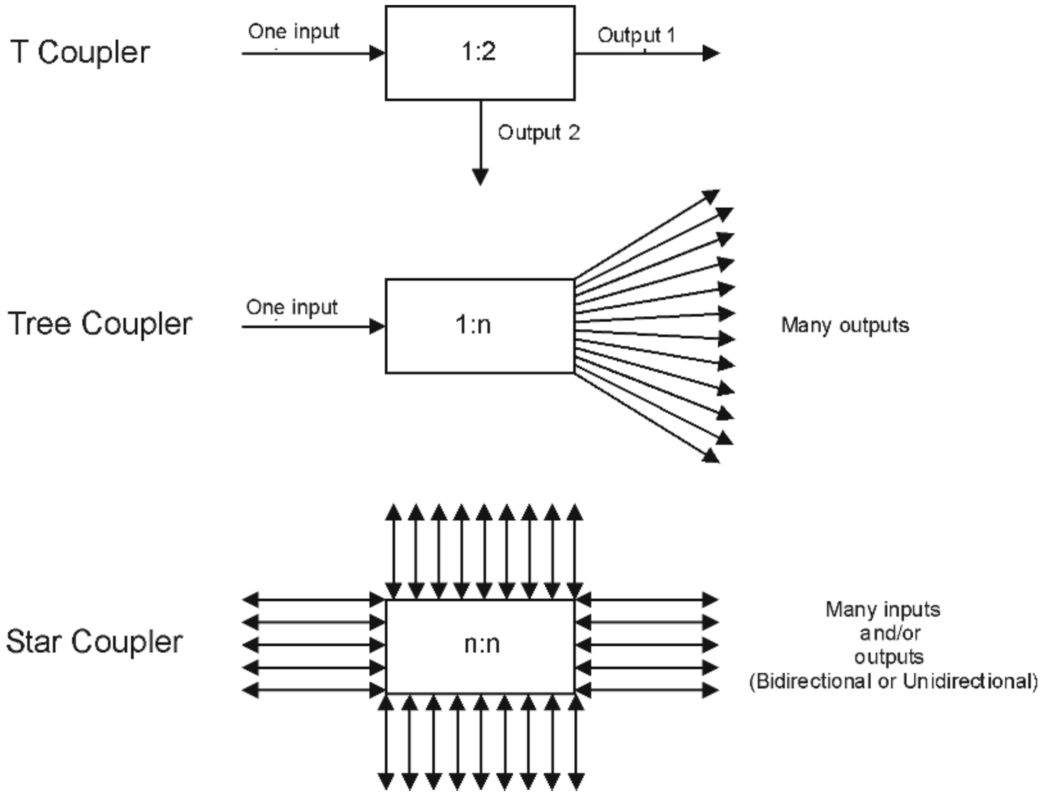


Figure 5.20
Passive coupler configurations

The T coupler normally has one input and two outputs. The output power from the coupler ports can be designed for particular applications, such as 20% at one port and 80% at the other. Tree couplers have a one-to-many configuration, with one input to many outputs or vice versa. Star couplers can have multiple inputs and multiple outputs. The type of fiber used with couplers is important: some couplers are designed for singlemode fibers only, because the light needs to be concentrated in a small area. Other types of couplers are more efficient with large core multimode fibers.

Practical couplers can take many forms:

- Fused fiber couplers use a pair of fibers with their cores placed in close proximity, so that light can be transferred between the cores. This is illustrated in Figure 5.21. This produces a directional coupler.

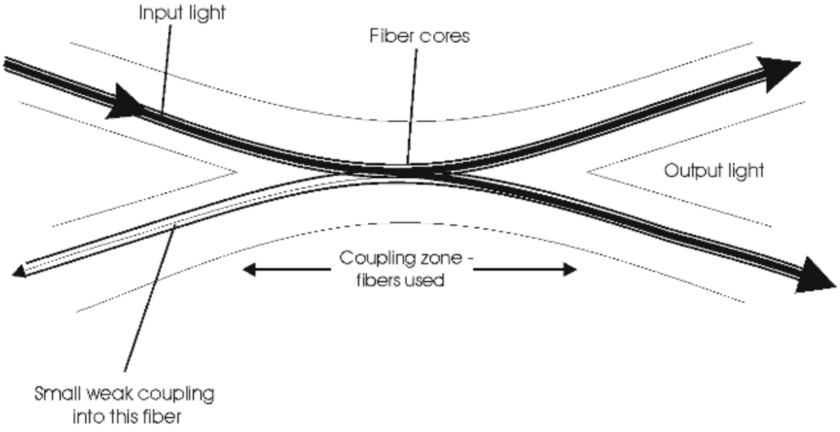


Figure 5.21
Fused fiber directional coupler

- Transmissive star couplers are made by fusing a number of fibers (as many as 64) together to form a mixing region, where the light from whichever source fiber is spread to all the output fibers. The operating principle is shown in Figure 5.22.

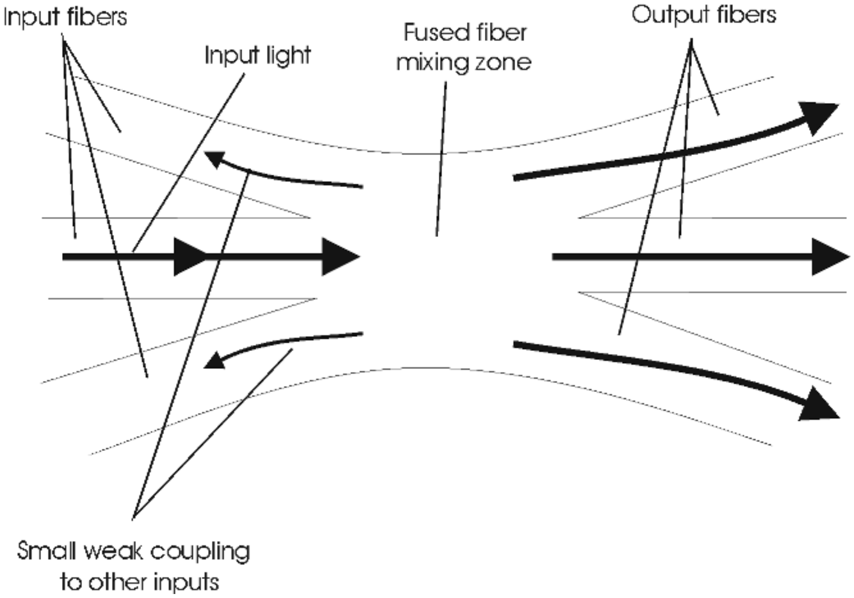


Figure 5.22
Transmissive star coupler

- Reflective star couplers are used if the signals on the fibers are bidirectional, and the light enters the mixing zone from any fiber and is reflected to emerge from all the fibers, including its input fiber. This is shown in Figure 5.23.

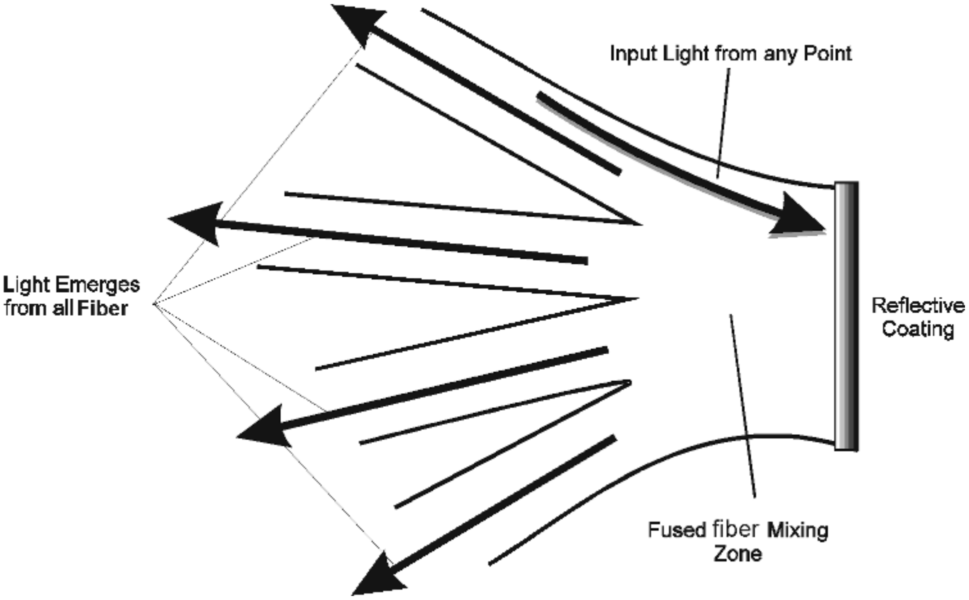


Figure 5.23
Reflective star coupler

6

Optical drivers and detectors

Introduction

This chapter will examine the operation of the optical sources and their associated detectors used with fiber optic systems. It will also cover the practical aspects required to turn these devices into fiber optic transmitters and receivers.

Performance issues for these devices will be investigated. Future developments such as the use of optical amplifier systems will also be discussed.

6.1 Optical sources

Effective optical sources for fiber optic transmission need to have several important properties:

- To be able to effectively couple the small fiber core, as small as 8.5 micrometers for singlemode fibers
- Easily modulated by electrical signals to convey data, with good linearity to prevent harmonics and intermodulation distortion
- Provide high optical output power
- Have high reliability
- Small size and weight
- Low cost

Light emitting junction diodes (LED) and laser diodes (LD) fulfill many of these requirements and we will now examine their properties in detail.

6.2 Light emitting diodes (LED)

6.2.1 Construction

A simple light emitting diode is made as a junction of two semiconductor regions, each of which is doped with impurities to give appropriate electrical characteristics. The ‘p’ type region contains impurities that have fewer electrons than atoms in the crystal lattice and so create atoms with a net positive charge. These are known as ‘holes’ as they create room for electrons to move in the crystal lattice. Similarly, the ‘n’ type regions use impurities, which provide more electrons than atoms and effectively donate electrons so that electrons are left floating in the crystal lattice. The most important optical semiconductors are made of elements from groups IIIa and Va of the periodic table as listed in Table 6.1.

Group IIIa	Group Va
Aluminum (Al) Gallium (Ga) Indium (In)	Nitrogen (N) Phosphorus (P) Arsenic (As) Antimony (Sb)

Table 6.1
Optical semiconductor materials

6.2.2 Basic LED operating principles

When a positive voltage is applied to the p-region and a negative voltage applied to the n-region, electrons and holes flow towards the junction of the two regions where they combine. When an electron combines with a hole, the atom returns to its neutral state and energy is released, having been converted into optical energy in the form of photons. In its simplest form, the radiated energy from the LED is caused by the recombination of the electrons and holes, which are injected into the junction by the forward bias voltage. Figure 6.1 illustrates this process.

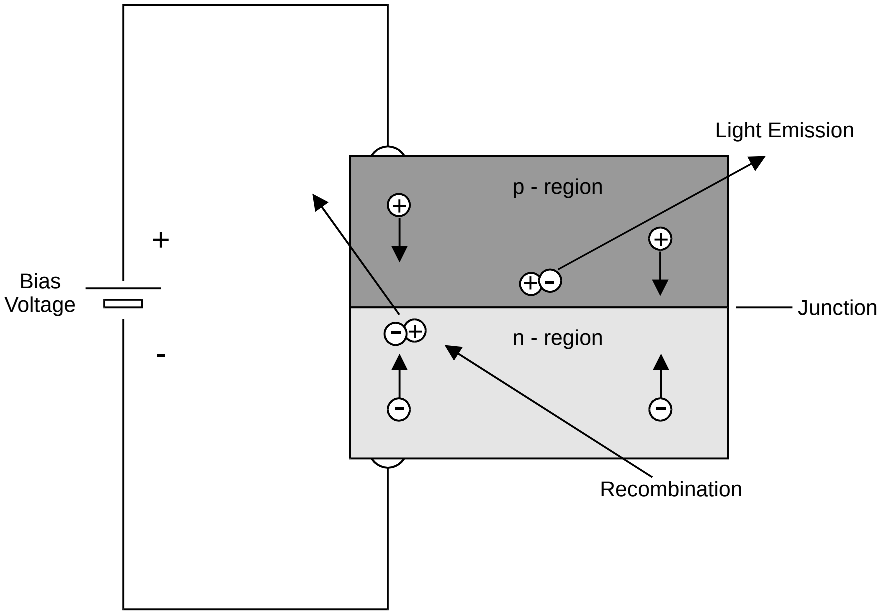


Figure 6.1
Basic LED operation

Band theory provides a simple explanation of the semiconductor emissions. Two allowed bands of energies, separated by a forbidden region called the bandgap, exist, as shown in Figure 6.2. At the upper level in the n-region, known as the conduction band, the unbound electrons are free to move, while at the lower level in the p-region, known as the valence band, the unbound holes are free to move.

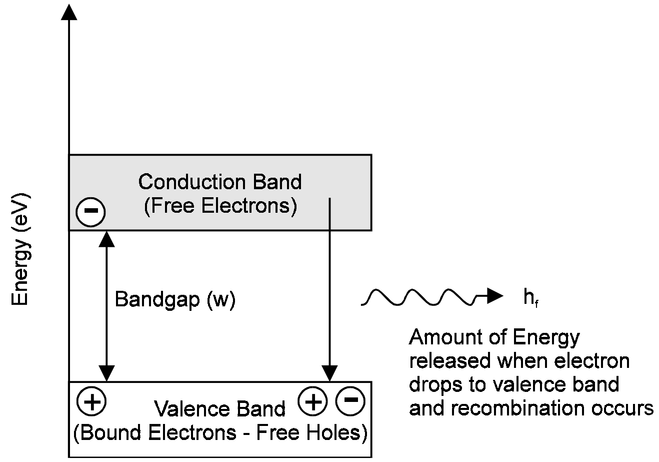


Figure 6.2
Bandgap determines energy emission.

The size of the bandgap determines the energy of the emitted photon. Different semiconductor materials have different bandgap energies and the gap energy (W) in electron volts (eV) can be related to the wavelength (λ) by the equation:

$$\lambda = 1240 / W \text{ nanometers}$$

The usual LEDs applied in fiber optic systems use gallium aluminum arsenide (GaAlAs) for 800 to 900 nm wavelengths and gallium arsenide (GaAs) for 930 nm. LEDs for use with plastic fibers need to operate at about 660 nm and are produced with gallium arsenide phosphide (GaAsP) compounds. Various indium gallium arsenide phosphide (InGaAsP) compounds are used for longer wavelengths of 1300 and 1550 nm. The semiconductor types, their respective bandgap energies and wavelengths are shown in Table 6.2.

Semiconductor	**Bandgap Energy (eV)**	**Wavelength (nm)**
GaAsP	1.88	660
GaAlAs	1.55–1.38	800–900
GaAs	1.33	930
InGaAsP	0.95–0.80	1300–1550

Table 6.2
Semiconductor bandgap energies and wavelengths

6.2.3 LED geometry

An essential ingredient of optical sources is the ability to couple the light into the small fiber core. Basic LEDs as outlined above emit light in all directions. This makes it difficult to couple the light into the fiber. Various internal structures can be used to concentrate the light into a narrow beam. Two commonly used structures are the Burrus diode and the edge emitting diodes.

The Burrus or etched well diode structure uses a hole etched in the substrate coupled with internal structures to confine the light emissions. A fiber can be directly inserted into the hole in the top of the device to collect the light output.

Edge emitting diodes (ELED) generate the light in a thin, narrow active junction layer as shown in Figure 6.3. The emitting zone can be as small as a few micrometers in thickness and ten micrometers in width. The structure incorporates features designed to confine the light output and guide it to one end of the device. These devices generally produce lower light output than surface LEDs because of the smaller cross-section of the active emitting area, but the beam is more efficiently coupled to the fiber. The brighter and more tightly collimated beams require a more complex construction, associated with higher cost structures and have greater heat generation.

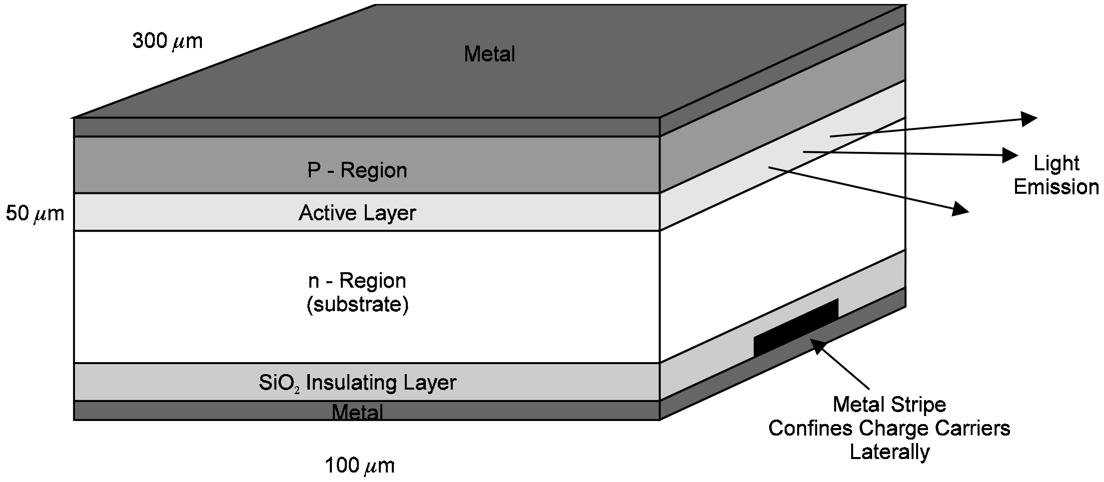


Figure 6.3
Edge emitting LED

6.2.4 Operating characteristics

Output power and power construction

The output power is generally not greater than 1 mW but can be as low as several microwatts. The output power of an LED is linearly related to the forward driving current. Fiber optic LEDs typically operate at currents of 20 to 100 mA and require forward bias voltages of 1.2 to 1.8 volts. With power dissipation of up to 180 mW from the small device, appropriate heat-sink design is needed to prevent excessive temperature rises and consequently reduced device reliability and lifetime. As LEDs age, their output power decreases.

Spectral widths

The total power emitted by the transmitter is distributed over a range of wavelengths spread about the center wavelength. This is quantified as the spectral width, ɦ$_{\lambda}$, which is the 3 dB optical power width, usually measured in nm. A typical LED operating at 850 nm will have a spectral width of approximately 40 nm and an LED operating at 1300 nm, a width of approximately 80 nm. Wide spectral widths cause increased chromatic dispersion of the light pulses, as they propagate through the fiber.

Operating lifetimes

The lifetime of an LED is the time taken for the light output to reduce to half its initial value (i.e. drop by 3 dB at its central operating wavelength). Good LEDs should have a lifetime of around 105 hours (11 years).

Modulation

Digital modulation of the LED output is simply achieved by use of a current source turning the LED on or off.

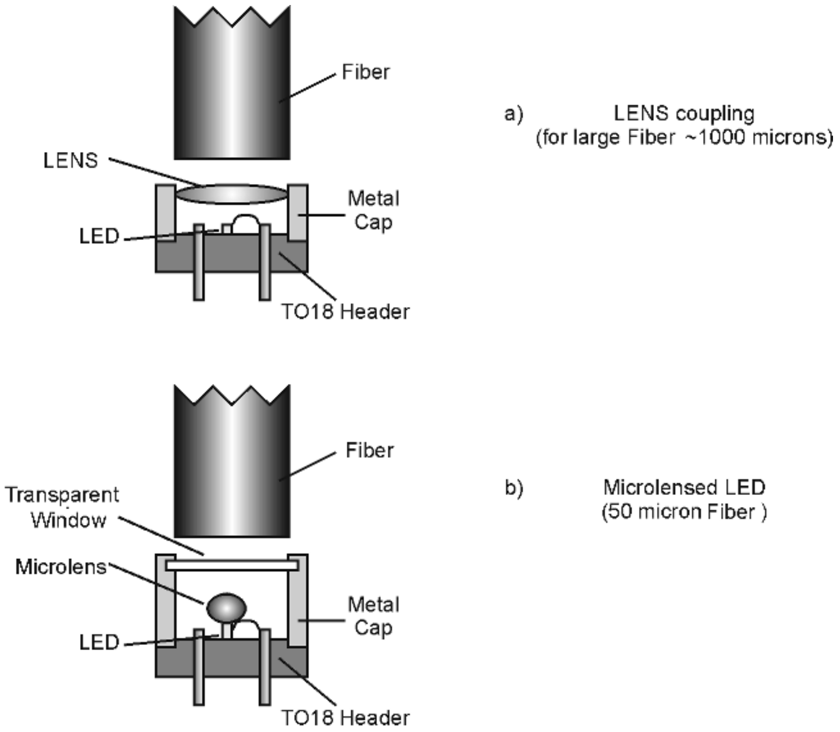
Analog modulation requires LED to have a DC bias applied to ensure the LED is forward biased at all times.

Temperature effects

Operating temperature ranges of –65° to 125°C are possible. Output power decreases as the junction temperature rises, typically at the rate of 0.012 dB/°C.

6.2.5 Practical LED devices

The LED chips need to be mounted on appropriate packages to dissipate the heat effectively and enable the fiber to be coupled to the light source. Many different approaches are used by manufacturers including transparent windows or lenses in metal caps, holes in packages for the insertion and gluing of fibers, attachment of pig-tails direct to the chip or provision of micro lenses on the chips to collimate the beam. Two of these are illustrated in Figure 6.4. The use of a large lens as the device cover is shown in Figure 6.4(a). This produces a large beam because of the distance separating the lens and LED and as such, is only suitable for large diameter fibers. Figure 6.4(b) shows the use of a micro lens fitted directly to the LED. The beam in this case does not enlarge before being collimated by the lens and so can be effectively coupled to 50 µm fiber core diameters. The losses involved in coupling fibers and sources are discussed in Chapter 5.



a) LENS coupling (for large Fiber ~1000 microns)

b) Microlensed LED (50 micron Fiber)

Figure 6.4
Practical LED packages

6.3 Laser diodes

6.3.1 Basic principles of laser operation

LASER stands for light amplification by the stimulated emission of radiation. LEDs and lasers use very similar principles of operation. In section 6.2.2, we saw that light is emitted from a LED when an electron drops from a high energy level to a lower one. When this occurs without outside influence, it is known as spontaneous emission. This occurs in some radioactive material. With the LED discussed in the previous section, a forward bias voltage was used to stimulate the emission. An electron sitting at the upper energy level can also be stimulated to drop to the lower level by a photon with the right amount of energy. In this way, the external photon can stimulate the emission of a second photon at the same wavelength.

Laser action takes place through optical resonance. The laser structure is very similar to an edge LED, having a thin, narrow active region with the addition of reflective end facets and reflective sides as shown in Figure 6.5. In this resonator, the light is confined and reflected backward and forward through the excited medium. The laser is biased to begin the emission of photons. The photons reflect backward and forward and stimulate further emission of photons from electrons waiting to recombine. The light traveling back and forth along the axis of the resonator continues this action and builds up in strength until it is strong enough to break through the reflective end and thus, a laser beam is formed.

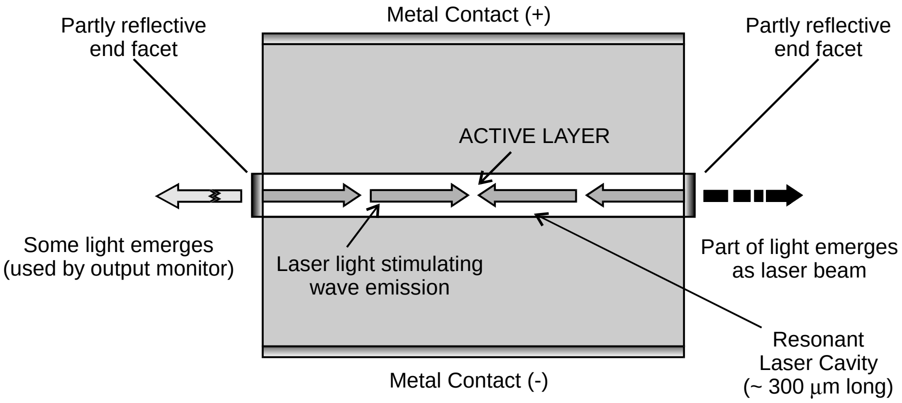


Figure 6.5
Basic laser diode operation

6.3.2 Operating characteristics

Lasers need to operate at higher drive currents than LEDs so as to generate a sufficiently high density of electrons ready to recombine at the high energy level.

Output power and power consumption

The optical output power of a laser diode shows two distinct slopes as shown in Figure 6.6. Below the threshold current, the device operates as an LED with low or no output. Laser action only occurs above the threshold. The threshold currents are usually in the range of 30 to 250 mA, with forward voltages of 1.2 to 2 volts. Practical devices are usually operated at 20 to 40 mA above the threshold current and can generate optical outputs of 1 to 10 mW continuously, even more if pulsed with low duty cycles. Some lasers operate up to several hundred milliwatts optical output.

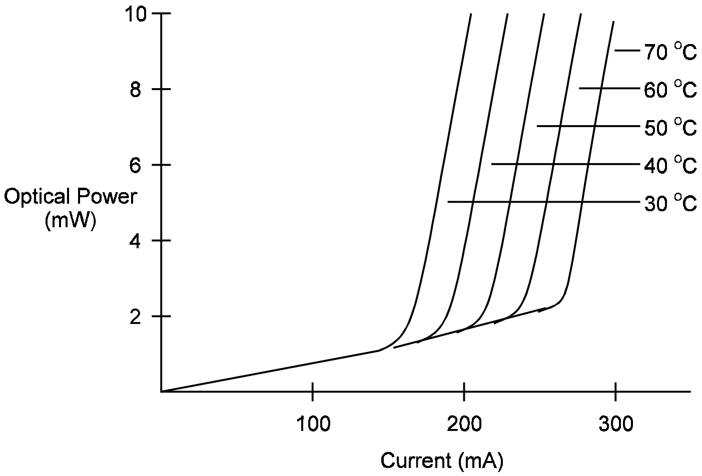


Figure 6.6
Laser diode power–current–temperature curves

Spectral width

Laser diodes have typical line widths of 1 nm at 850 nm and 3 nm at 1300 nm and 1550 nm, which is considerably less than those of LEDs. Therefore, they suffer a lot less from chromatic dispersion problems.

Operating lifetimes

Continuously operating laser diodes can have typical lifetimes of 10^5 hours at room temperature, but they degrade faster at higher temperatures. Commercial laser diodes typically exceed 10^4 hours at 70°C.

Modulation

Digital modulation of lasers makes use of the threshold current. The laser is biased to just below the threshold current to switch the beam off for logic ‘0’ and it is rapidly switched on by increasing the current above the threshold for the logic ‘1’. Analog modulation uses a bias current above the threshold so that the operation remains in the linear region of the power–current (P–I) curve, shown in Figure 6.6.

Temperature effects

Laser diodes are much more temperature sensitive than LEDs, as illustrated in Figure 6.6. The threshold current increases at about 1.5% per °C showing that more current is needed to start laser action at higher temperatures. At constant current, the output power will drop, as the temperature rises. In addition, as the threshold current changes with temperature, this affects the required bias voltage for modulation. Temperature stabilization is therefore needed for practical transmitters as discussed in section 6.4.

6.3.3 Practical laser devices

Similar packaging requirements apply, as were discussed for LEDs and these include hermetically sealing all leads, enabling precise alignment of the fiber and laser chip, providing suitable heat-sinking or mounting the chip on a thermoelectric cooler. For active feedback control of the bias current, a photodiode (optical detector) can be mounted inside the package to monitor the power emitted from the rear facet of the laser. Fiber pig-tails can be fitted by the manufacturer to maximize coupling efficiency. One package configuration is illustrated in Figure 6.7. Here a fiber pig-tail is fitted in a grooved block in precise alignment with the laser diode. The user can fit a connector to the pig-tail or splice it direct to the incoming fiber.

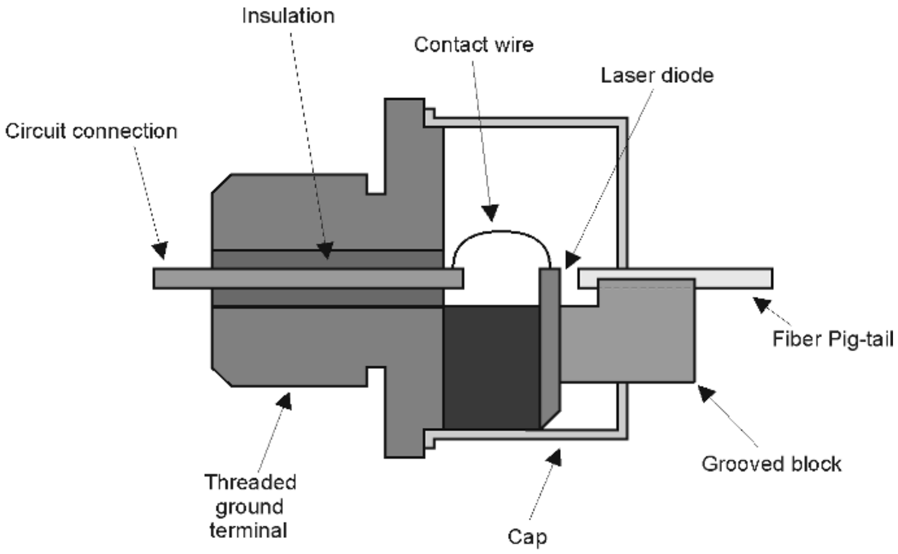


Figure 6.7
Laser diode package with integral pigtail.

6.3.4 Advances in laser technology

The more common, 'older' type lasers are called edge emitting diodes, and emit coherent infrared light parallel to the boundaries between the semiconductor layers. This is shown in section 6.3.1 above.

The latest technology is vertical cavity surface emitting diodes (VCSEL; pronounced 'vixel'). This is a specialized laser diode that promises to revolutionize fiber optic communications by improving efficiency and increasing data speed.

Research on VCSELs began in 1993, but the first commercial devices were not released until 2000. The first devices operated in the 850 nm range. In 2002, the first 10 Gbps VSCELs were released, which operated in the 850 nm and 1300 nm range.

The VCSEL emits its coherent light perpendicular to the boundaries between the layers of semiconductors. Until very recently, the VCSELs had only operated in the 850 nm range but recent releases have operated in the 1300 nm range.

The VCSEL has several advantages over edge emitting diodes. The VCSEL is cheaper to manufacture in quantity, easier to test, more efficient and it requires less electrical current to produce a given coherent energy output. The VCSEL emits a narrow, more circular beam than edge emitting diodes. This makes it easier to couple to an optical fiber.

The next challenge is to produce a cost effective and reliable VCSEL that operates in the 1550 nm range where there is the lowest fiber attenuation.

6.4 Optical transmitter modules

Practical transmitter modules can incorporate a Peltier effect device that is a type of thermoelectric cooler. The laser chip is mounted on the cooler with a temperature monitoring thermistor to control the cooling process. The other approach to stabilization uses a photodiode to monitor the output power radiated at the rear facet of the laser. This is used to control the DC bias current and stabilize the output.

The laser diode in Figure 6.8 incorporates a photodiode power monitor measuring the power emitted from the rear facet of the device. Such devices can be mounted in multiple pin industry standard packaging such as the dual inline package (DIP). Individual pins can then be provided for the laser, photodetector, thermoelectric cooler, and temperature sensor.

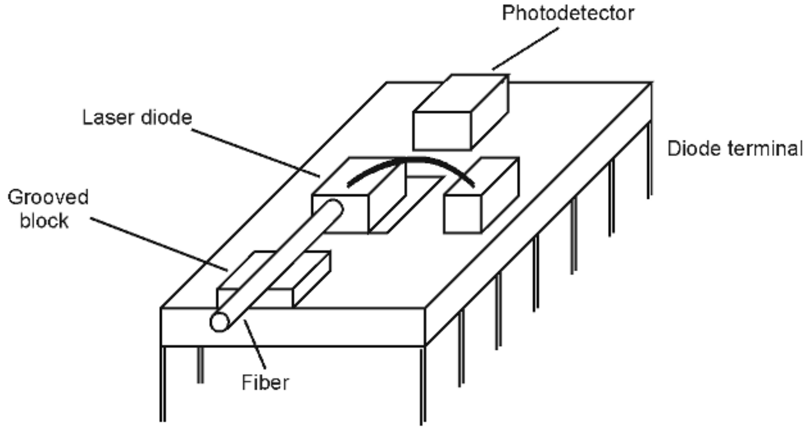


Figure 6.8
Laser diode transmitter module

6.5 Laser safety considerations

The brightness of some laser beams and their high degree of collimation make them a potential hazard to the human eye, and suitable safety precautions must be taken when working with them. Systems operating at 1300 and 1550 nm use high power lasers for long distance communications. These wavelengths are invisible to the human eye but can cause permanent damage to the retina of the eye. Strict safety codes of practice have been developed governing the use of all laser devices. No optical source or illuminated fiber should ever be viewed by a microscope or by the naked eye.

6.6 Optical detectors

The function of the optical detector is to efficiently convert the small amount of light energy received from the fiber, as photons, into electrical signals. The detector needs to be a low inherent noise device, incorporating appropriate amplification to generate useful output signals from low level inputs. Two main types of devices are used for practical detectors; PIN diodes and avalanche photodiodes.

6.7 Pin photodiodes

6.7.1 Operating principles

Photodiodes convert the optical signals directly into electrical signals, using the reverse of the physical process in the LED. The PIN photodiode has a wide intrinsic semiconductor layer separating the p- and n-regions, as shown in Figure 6.9. The diode is reverse biased (5–20 volts) and this helps draw the current carriers away from the intrinsic region.

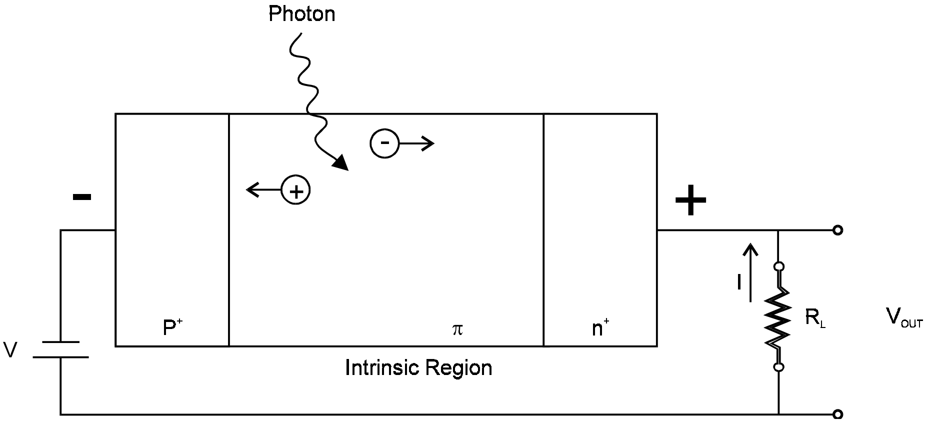


Figure 6.9
PIN photodiode

The width of the intrinsic layer ensures that there is a high probability of incoming photons being absorbed in it rather than in the p- or n-regions. The intrinsic layer has a high resistance because it has no free charges. This results in most of the diode voltage appearing across it, and the resultant electrical field raises the response speed and reduces noise. When light of suitable energy strikes the intrinsic layer, it creates electron-hole pairs by raising an electron from the valence band to the conduction band and leaving a hole behind in the process. The bias voltage causes these current carriers (electrons in the conduction band) to quickly drift away from the junction region, producing a current proportional to the incident light, as shown in Figure 6.9.

6.7.2 Operating characteristics

Cutoff wavelength

The incoming photon must have enough energy to raise an electron over the bandgap to create an electron-hole pair. Different semiconductor materials have different bandgap energies and the gap energy (W) in electron volts (eV) can be related to the wavelength (λ) by exactly the same equation as for LEDs:

$$\lambda = 1240 / W \text{ nanometers}$$

For a particular detector, the bandgap W is fixed so the above equation gives the longest wavelength that can be detected, i.e. the cutoff wavelength.

Responsivity

The responsivity ρ is the ratio of the output current (i) of the detector to its optic input power (P).

$$\rho = i / P \text{ amperes per watt}$$

At 800 nm silicon has a responsivity of about 0.5 A/W and InGaAs has peak responsivity of about 1.1 A/W at 1700 nm, reducing to 0.77 A/W at 1300 nm.

Spectral response

The spectral response is shown as the variation of responsivity with wavelength. Typical spectral response curves for silicon and InGaAs PIN diodes are shown in Figure 6.10.

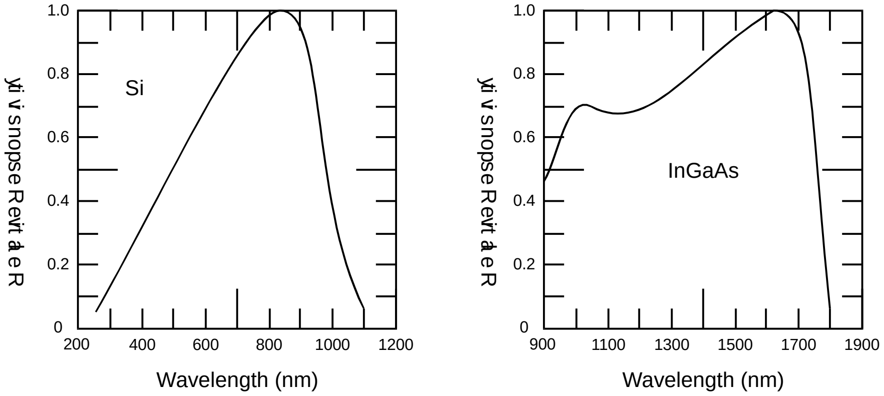


Figure 6.10
PIN diode spectral responses

Quantum efficiency

The quantum efficiency η of the emitter is defined as the ratio of the number of emitted electrons to the number of incident photons. Silicon and InGaAs have peak quantum efficiencies of about 80%.

Response speed

The speed of response of the detector is limited by the transit time, which is the time it takes for free charges to cross the width of the intrinsic layer. This is a function of the reverse voltage and the physical width. For fast PIN diodes, this ranges from 0.5 to 10 ns. Capacitance also affects the device response, with the junction capacitance formed by the insulating intrinsic layer between the electrodes formed by the p- and n-regions. High-speed photodiodes can have responses as fast as 10 picoseconds, requiring capacitances of a few picofarads, with very small surface areas.

Current–voltage characteristic

The typical current–voltage (*I*–*V*) curves for a silicon PIN photodiode are shown in Figure 6.11. It can be seen that even when there is no optic power, a small reverse current flows called the dark current. This is caused by the thermal generation of free charge carriers, typically doubling with each subsequent 10°C increase in temperature after 25°C.

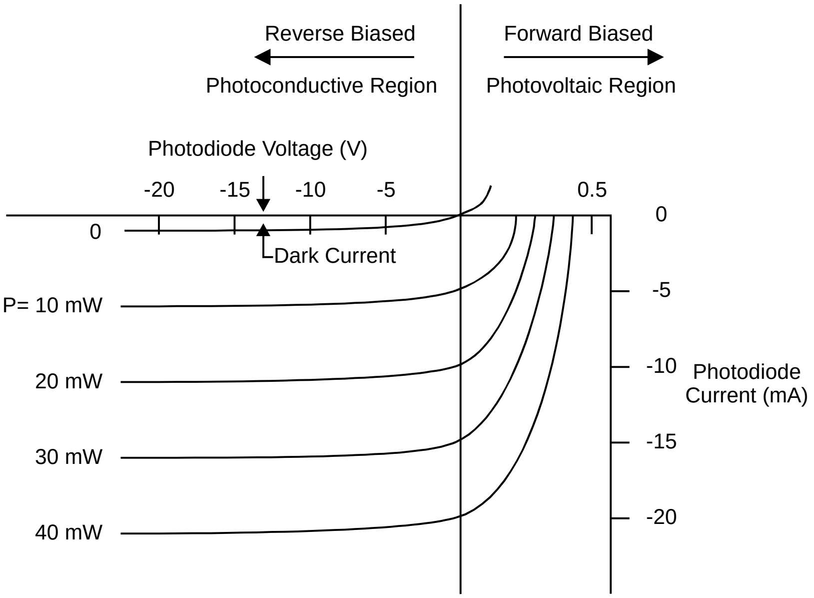


Figure 6.11
Silicon PIN photodiode I–V characteristics

Dynamic range

The linear relationship between voltage and optic power shown in Figure 6.11 is maintained typically over six decades giving a dynamic range of some 50 dB.

6.7.3 PIN photodiode packaging

PIN photodiode packaging is similar to those used for LEDs and lasers, but the optical requirements are less critical. The detectors' active area is usually much larger than the core of the fiber, so lateral misalignment is less of a problem.

6.8 Avalanche photodiodes

6.8.1 Operating principles

Avalanche photodiodes use semiconductor junction detectors with internal gain through avalanche current multiplication. A very high reverse bias voltage (50–300 volts) is applied to a p–n junction. A photon is absorbed in the depletion region, creating a free electron and a free hole. These charges accelerate in the strong electric field. When they collide with neutral atoms in the crystal lattice, their kinetic energy is sufficient to raise electrons across the bandgap and create additional electron-hole pairs. These secondary charges also accelerate creating more electron-hole pairs. In this way, the current produced by one photon is multiplied.

6.8.2 Avalanche photodiode structure

One form of avalanche diode is the reach-through diode, as illustrated in Figure 6.12. The p^+ and n^+ layers are highly doped regions with very small voltage drops. The depletion region is lightly doped, almost intrinsic. Most of the photons are absorbed in this area, forming electron-hole pairs. The electrons move to the p-region that has been depleted of free charge by the large reverse voltage. The depletion region at the p–n^+ junction effectively reaches right through the p layer. The strong electric fields across the p-layer cause avalanche multiplication of the electrons. The holes produced drift across the π layer to the p^+ electrode but do not cause further multiplication. Because this structure limits the charge carrier multiplication to electrons only, it has better noise performance.

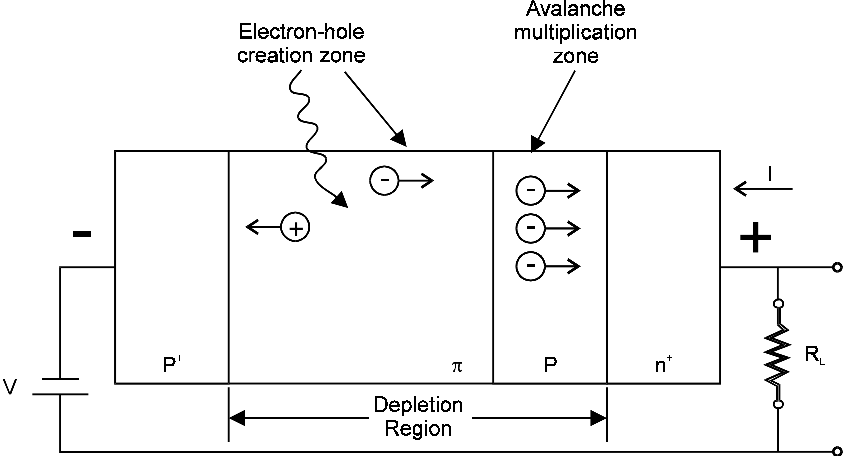


Figure 6.12
Avalanche photodiode

6.8.3 Operating characteristics

Cutoff wavelength

Avalanche photodiodes are variations of PIN diodes so the materials, spectral ranges and cutoff wavelengths are the same as for PIN diodes.

Current–voltage characteristic

The typical current–voltage (*I–V*) characteristic curves for an avalanche photodiode are shown in Figure 6.13.

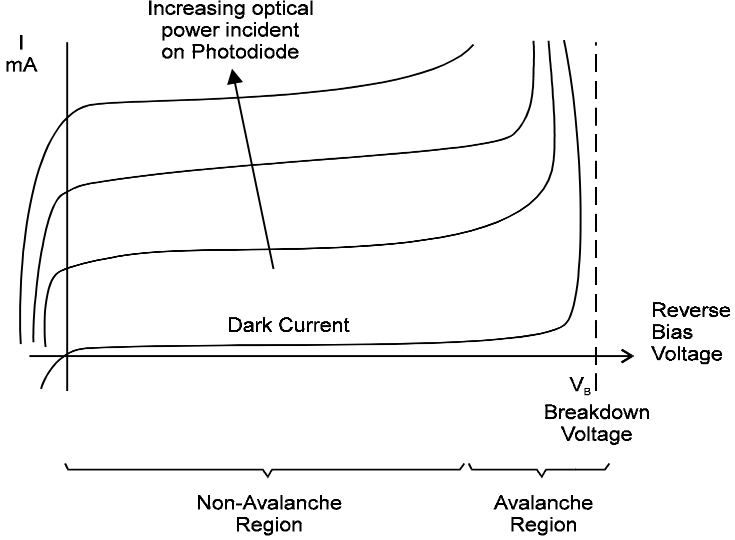


Figure 6.13
Avalanche photodiode characteristic curves

Response speed

The response speed is limited by the charge carrier transit time and the RC time constant as for PIN diodes. Transit-time-limited avalanche diodes are produced with rise times of the order of a few tenths of a nanosecond. Rise times less than 100 picosecond are achievable.

Dynamic range

Avalanche diodes are similar to PIN diodes in having excellent linearity, over a wide dynamic power range, typically from fractions of a nanowatt to several microwatts.

Gain

The gain of an avalanche photodiode is temperature dependent, generally decreasing as temperature rises. Temperature stabilization may be required for devices operating over extended temperature ranges. Gains from 20 to 150 are typical.

6.8.4 Avalanche photodiode applications

The avalanche photodiode requires a stable high voltage power supply and more complex bias circuitry. This increases costs and decreases the reliability. The avalanche diodes are generally less reliable than standard PIN diodes. It follows that PIN diodes are generally the preferred devices for normal applications. Avalanche diodes provide increased sensitivities of 5 to 10 dB and half the rise time of standard PIN diodes. Such avalanche diodes are required when the system has high losses and needs to work at low signal to noise ratios, such as on long distance communications links. On such systems, the savings in providing increased repeater spacing outweigh the disadvantages.

6.9 Optical receiver modules

6.9.1 Basic elements of a ractical receiver

The basic elements of a ractical receiver are:
(a) a detector to convert the received optical signal to an electrical signal
(b) an amplifier to increase the electrical signal to a level where it can be processed
(c) a demodulator or decision circuits to recover the original data from the input signal.

We have seen that avalanche photodiodes incorporate internal amplification, so these devices combine the functions (a) and (b).

6.9.2 Amplifiers

The typical optical signals reaching a fiber optic receiver can be as low as one microwatt. Using a PIN diode with a 0.6 A/W responsivity to detect such a signal would produce an output of around 600 nanoamps. This output needs to be amplified and converted to a voltage for subsequent processing.

Amplifiers can be divided into four types depending upon the type of input transistor (FET or bipolar) and the amplifier configuration, irrespective of high-impedance or transimpedance.

The high impedance amplifier gives high gain, but it can saturate for a relatively low input signal. The transimpedance amplifier uses negative feedback to reduce the gain as shown in Figure 6.14. This gives the amplifier an increased dynamic range, wider bandwidth, but less sensitivity.

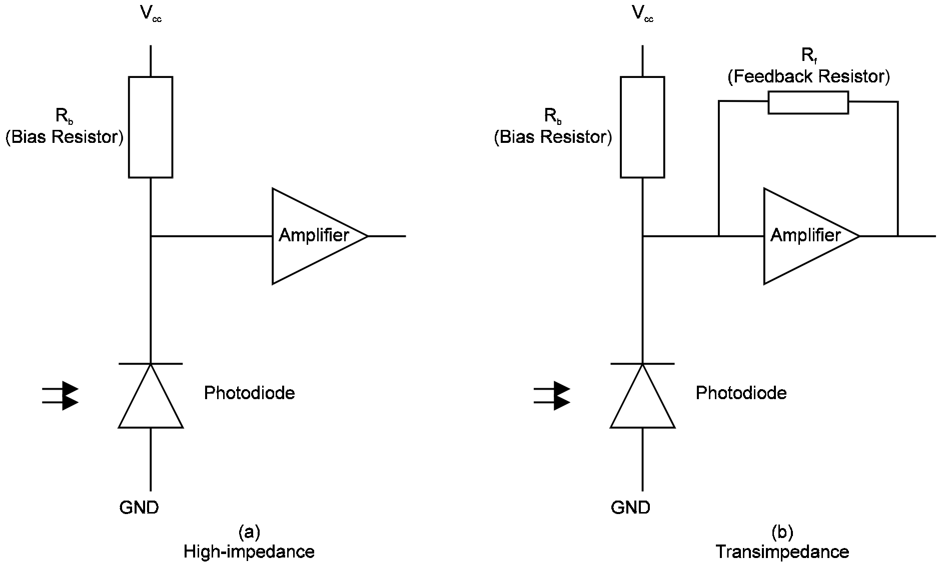


Figure 6.14
Amplifier configurations

The pre-amplifier characteristics at different data rates with PIN and avalanche photodetectors are shown in Figure 6.15. It can be seen that the avalanche diode has greater sensitivity at all data rates. A FET amplifier provides greater sensitivity at lower data rates, while the bipolar amplifiers have superior performance at higher data rates. The quantum limit shown is the minimum detectable power caused by the statistical nature of the photon detection and carrier pair generation mechanisms.

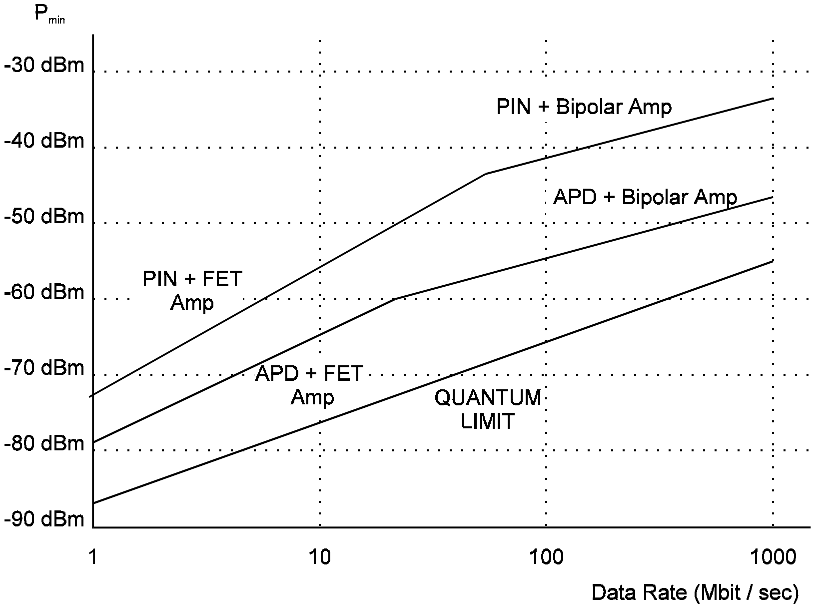


Figure 6.15
Pre-amplifier characteristics.

Some amplifier configurations make use of an amplifier mounted on the same chip as the photodetector. This increases the signal level without lowering the ratio of signal power to noise power. External amplifiers by contrast always add noise and reduce the signal to noise ratio.

6.9.3 Receiver packaging

Receiver packaging needs to address mechanical, electronic, and optical issues. The main mechanical concern is how to mount the fibers with the receiver module itself, following typical industry standard packaging such as dual inline packages (DIP). The electronic interfacing needs to address the bias voltages required by the photodetector, amplifier and the detector circuitry, as well as the gain controls and output requirements. The optical interfacing is simpler than transmitters because the detector areas are larger than the core of most fibers and butting the fiber against the detector collects sufficient light. Some modules use fiber connectors on the case to link direct to the detector, or use a large multimode fiber to collect all the light from the small core of a singlemode fiber.

6.10 Optical amplifiers

Optical amplifiers increase the signal strength without converting the signal into electrical form. They work on the stimulated emission principle as specialized forms of lasers, which amplify the light in a single pass through the amplifier. There are currently two basic types of optical amplifiers in use; doped fiber amplifiers and semiconductor laser amplifiers.

6.10.1 Doped fibers

Doped fiber amplifiers make use of fibers whose cores are doped with elements, which can amplify light at particular wavelengths. Fibers doped with the rare earth erbium are effective at wavelengths between 1520 and 1560 nm and praseodymium doped fibers operate at the 1300 nm wavelengths. The dopant atoms in the fiber are excited by a pump laser, operating at a shorter wavelength. Light at the signal wavelength can stimulate these energetic atoms to emit their excess energy, as light at the signal wavelength, in phase with the signal pulses. The operating principle of these devices is illustrated in Figure 6.16.

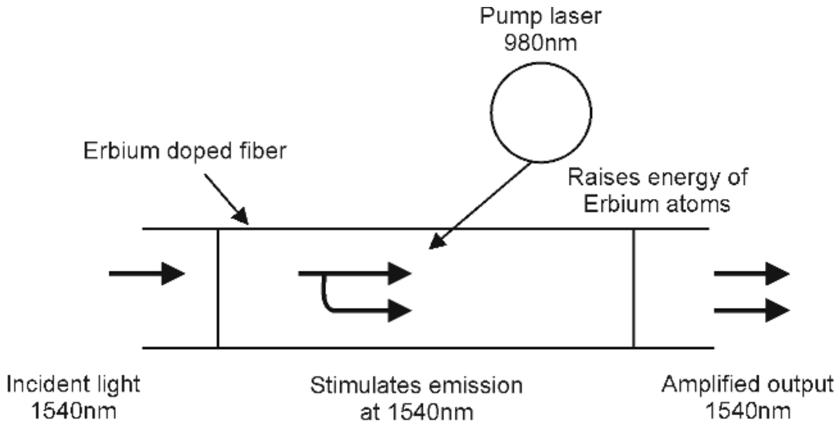


Figure 6.16
Doped fiber amplifiers

6.10.2 Semiconductor laser amplifiers

Semiconductor laser amplifiers operate like ordinary lasers without the mirrors. Light from the external source makes one pass through the active area and stimulates further photon emissions. One major difficulty with these devices involves the coupling of light into the laser, as shown in Figure 6.17. The semiconductor laser has an active area several microns wide and less than a micron thick. The light exiting a singlemode fiber will produce a beam of at least 9 microns diameter. Clearly, most of this light from the fiber will miss the active input layer of the laser and be lost. This high transfer loss from fibers offsets most of the gain produced by the laser amplifier. However, these devices can be usefully integrated onto chips with other semiconductor optical devices, such as laser sources, to avoid such transfer losses.

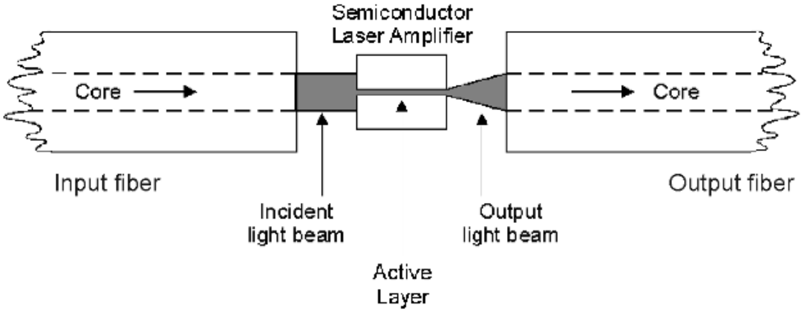


Figure 6.17
Semiconductor laser amplifiers

7

Installing fiber optic cables

Introduction

Installation of fiber optic cables is not the delicate type of operation that one might first think. As was discussed in Chapter 4, fiber optic cables are extremely strong and can be used in very harsh environments. Generally, fiber optic cables are considered easier to install in cable trays and in conduits than are copper cables because of their comparatively small size and lightweight.

The rules and procedures that apply to installing fiber optic cables are very similar to those that apply to installing coaxial cables. However, there are a number of important differences that need to be carefully considered. These are discussed in detail in this chapter.

This chapter is broken into two main sections. Firstly, it looks into the specified installation procedures that apply to fiber optic cables. It then provides a methodology for planning and carrying out an installation. It examines the requirements associated with indoor and outdoor installations, along with a detailed description of all the precautions that need to be taken into account in order to carry out a successful installation.

Secondly, the chapter examines some of the techniques and equipment that are used to organize and store cables and splices at their end points and at junctions along the cable route.

7.1 Initial preparation for a cable installation

The successful execution of a fiber optic cable installation requires careful planning of the project and contingencies to be allowed for, before the installation commences. The following details some of the preliminary requirements for the installation of fiber optic cable installations.

7.1.1 Site survey

Before the planning of a cable system begins, it will already be known what kind of services the fiber optic cable is meant for and the locations where the cables will have to be laid. With this objective in mind, the first requirement has to be carried out with a comprehensive site survey of the location where the cables are to be installed. The site survey should focus on determining the following factors:

- The most appropriate route for each cable. This could be with regard to the existing cable runs or in respect of the proposed newly installed cable housings. It will generally be more cost effective to use existing infrastructure, but the decision depends on the amount of space in the existing housing and on the condition of the housing. Also, an existing cabling route may take a longer path and the extra cabling costs associated with this may exceed the costs of installing a new route.
- The need to run the cables in cable trays, underground, in roof tops or as aerial cables.
- The condition of existing cable housings. (Whether costly maintenance is required before new cables are installed.) Is there any potential danger that could cause damage to the cable because of the poor condition of housings? For example, are the housings prone to be affected by flooding?
- Whether there are any locations that need special attention. Should tradesmen with special skills be deployed to carry out the job? Are there any locations that could subject cables to extreme temperatures? If so, provision is necessary to use fire or explosion-proof cables.
- Are there locations that could subject cables to possible physical damage? If so, provision is necessary to provide appropriate steel armored cables.
- Would the cable route run near high power cables? If so, ensure that the fiber optic cable does not contain any metal (strengthening member or sheath).
- Would the cable route run near areas of high transient voltages (for example, lightning)? If so, ensure the fiber optic cable does not contain any metal.
- Ensure that the installation adheres to all existing electrical and fire codes of the country to which the installation is planned.
- Obtain all required council and government permits before commencing any civil works on public land.
- Will there be sufficient room to use the cable pulling equipment? If not, what equipment needs to be moved to carry out the installation without hindrance.
- Will cars or trucks be driving over the cable, people walking over it or heavy objects laid across it? If so, plan to take the necessary precautions to protect the cable (for example, conduits) and/or to use the correct sheathed cables.
- Locate all the intermediate points from where the cable is to be pulled and where junction boxes are to be located.
- Identify appropriate locations for installing termination cabinets and splicing trays.
- Determine the exact locations for each data equipment hub.
- Talk to local employees to determine if there are any foreseeable problems that may arise during the installation that can be averted now by careful planning.
- All these particulars should be carefully noted during the site survey and then officially and completely documented after the survey is done. These findings would be useful while designing the cable system.

7.1.2 Designing the cabling system

The cable layout should be designed and a cable pulling plan developed, using the findings obtained during the site visit.

The proposed cable layout should be drawn on to an existing cabling diagram of the site if it is not a new site installation. The cabling diagram that is used should include all existing cabling and cable housings. For example, all cable trays, conduits and pole lines should be illustrated. For the purpose of orientation, it is essential to incorporate outlines of buildings, roads, and fixed machinery in the diagram. The new fiber optic cable routes should then be drawn over the top of this with a dark pencil. Termination cabinets and fiber node points containing splicing trays and patch panels should also be drawn on to the diagram in pencil.

A typical building cable network layout is shown in Figure 7.1. In some countries, according to their local fire prevention codes, outdoor cables that are filled with jelly should be spliced to non-flammable indoor cables close to the cable entries. Alternatively, the fibers can be cleaned and enclosed in protective sleeving e.g. 'zero cable', and taken to the patch panel or optical fiber distribution frame (OFDF) directly. The cross-connection arrangements and distribution hardware needs to be specified for each cable.

Figure 7.1 illustrates a typical cable layout diagram. Note that the diagram includes the cable fiber sizes (the number of strands in the fiber) to be installed, the locations for new and old pit boxes, the requirement for new conduit and for fiber optic termination cabinets.

If a fiber ring is being formed, the cables are normally cut in the pit, both ends are taken into the building where they are either spliced through or pig-tails are connected to the fibers before taken to a patch panel. Often, there is a combination of spliced fibers (which are more secure compared to those on a patch panel) and fibers with pig-tails taken to a patch panel. Taking them to a patch panel allows the rings to be made or broken as required, but leaves them free to accidental removal. Compare the length of each cable run with the length of fiber optic cables on the reels that are to be used. Using this information, determine the location of any additional intermediate splicing locations that are required.

Once the cable layout diagram is complete, a cable installation program should be drawn up. This document will be used by the contractor's installation team and therefore, it should contain precise but lucid detail of all the installation procedures and requirements. It should contain a thorough description of all the considerations and potential problems that were noted during the site survey.

The installation program should include a detailed description of the following information:

- The logistics of pulling the cable.
- Where the pulling equipment and cable reels should be located during the installation for each separate pull.
- The precise location where the pit boxes, termination cabinets and splicing trays are to be located.
- Which fibers are to be spliced and which fibers are to be taken through to a patch panel
- Each separate cable pull and the cable size and type to be pulled.
- Each separate conduit installation and the size and type of conduit to be installed. Specify which conduit is to be used over each section.
- Which cable trays are to be used.
- The routes to be taken for cable runs through the roof space.
- All the cable trays, conduits or other housings that will need replacing.
- An installation schedule that would minimize traffic congestion while carrying out road works during peak hours.

- The setting up of 'no parking' areas where installation equipment is to be located. This should be carried out the day before the installation begins. This requirement should cover all pit boxes and manholes.
- All observations that were made during the site visit.
- The specific responsibilities of each member of the installation team should be defined.

When the installation is complete, document all the changes made during the installation and produce final 'as installed' drawings. This will help to ensure that the cables have been installed correctly and that future fault finding and any system upgrades will be hassle free.

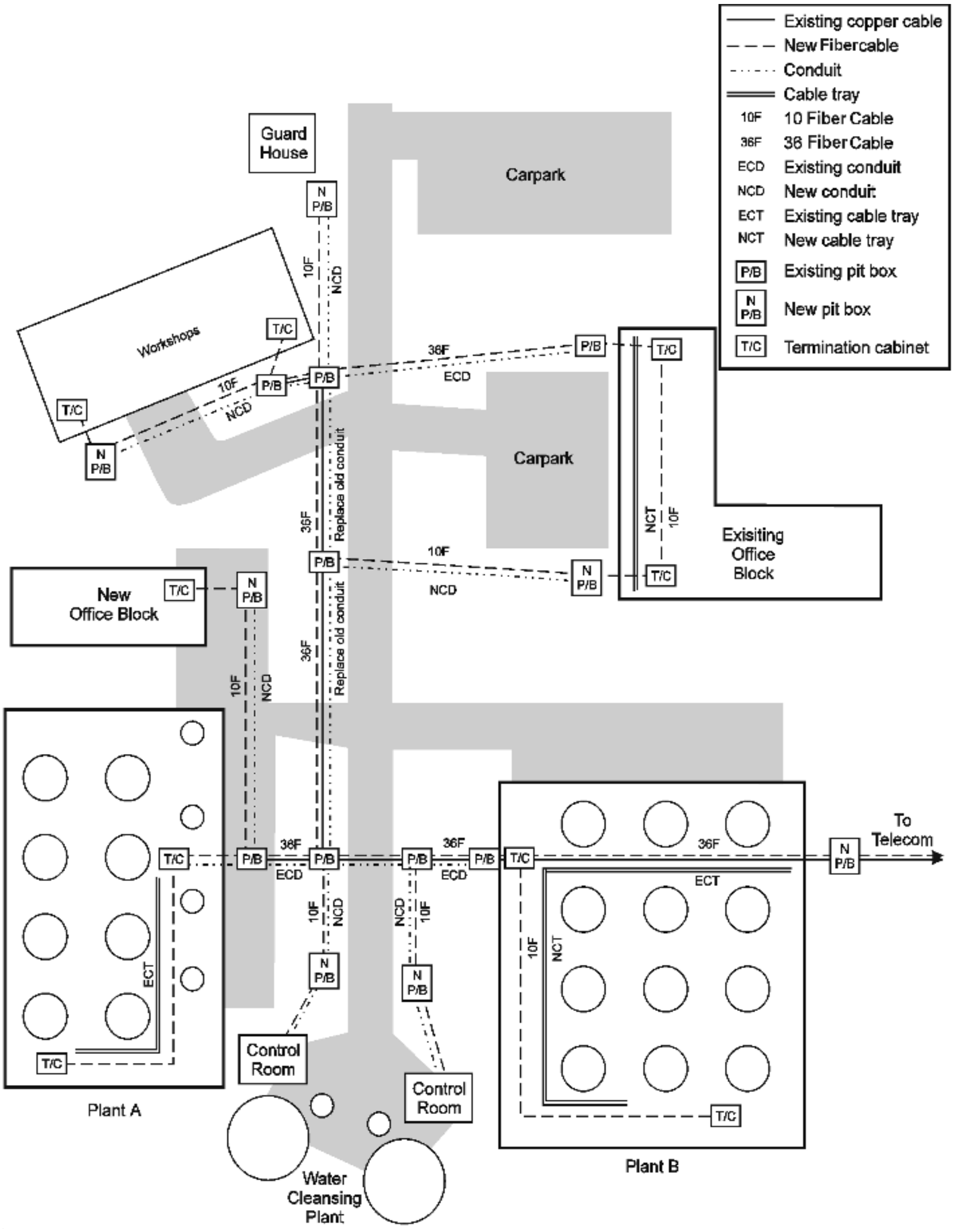


Figure 7.1
Example of cable layout schematic

7.2 General installation rules and procedures

The following section provides general installation rules and procedures that should be followed when installing fiber optic cabling systems. They are broken into related subsections for the convenience of reference.

7.2.1 Cable bend radius

- The rules and general cable specifications applied to minimum fiber bending radius that were discussed in Chapter 4 would apply here also.
- The most important consideration when installing fiber optic cables is to ensure that during an installation, the cable radius is always not less than the recommended minimum-bending radius of the installation.
- Avoidance of sharp bends along the installation route is absolutely essential. Sharp edges in cable trays or in conduits can cause macrobends or microbends in the fiber, which will significantly affect signal attenuation.
- Ensure that the conduit or the cable tray is constructed with no sharp edges. Use curved construction components and not right angle or T piece components.
- Ensure that the cables are laid on to a flat surface, and that no heavy objects will be laid on to the cables in the future.

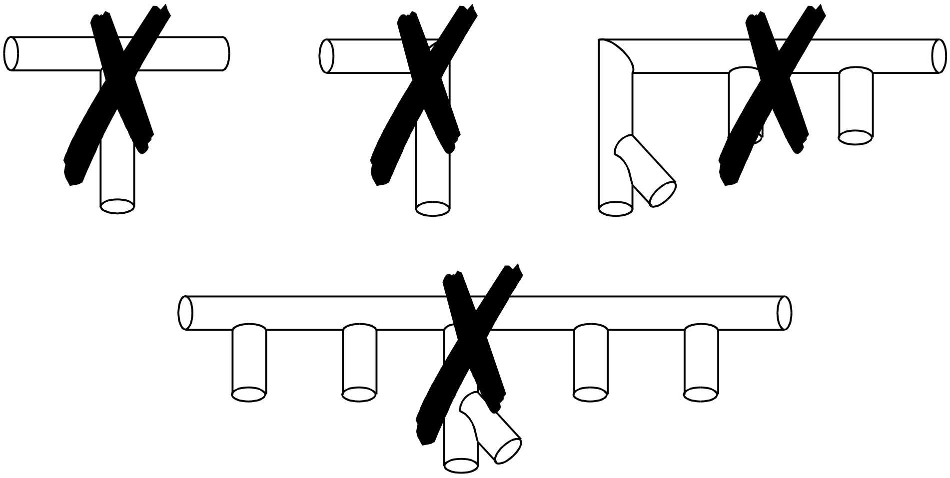


Figure 7.2
Avoid use of conduit or cable trays that have T connection of 90° angles

- Avoid putting kinks or twists into the cable. This is best achieved by pulling the cable directly off the reel and entrusting a member of the installation team with carefully watching any cable slack for possible formation of kinks.
- Cable manufacturers will specify a minimum bending radius that applies during the installation of the cable and a minimum bending radius that applies to the long term final installed cable. The long-term radius is significantly larger than the installation radius. Once the cable has been installed and the tension has been released, ensure that the cable radius is not less than the long term installed radius at any point along the cable.

- For any single cable pull, whether it be through conduit, cable tray or otherwise, there should be no more than three 90° changes of direction. If there are more than three 90° changes, then cable should be pulled through to an intermediate point, straight after the third 90° change of direction and the use of back feeding must be performed.

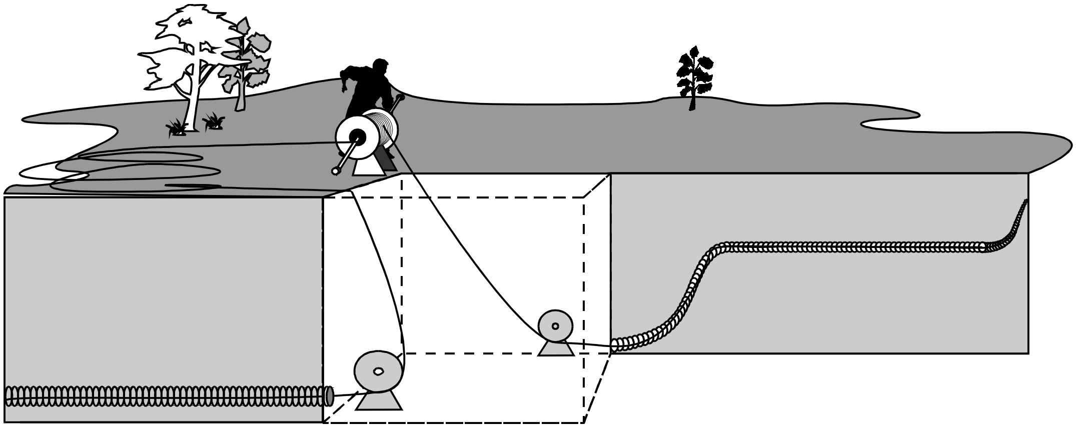


Figure 7.3
A cable with three 90° bends using an intermediate pulling point

- As a general rule of thumb, a fiber optic cable that has a diameter equal to 2 cm or less than that will not exceed its minimum installation bending radius if it is limited to a minimum bending radius of 30 cm during installation.

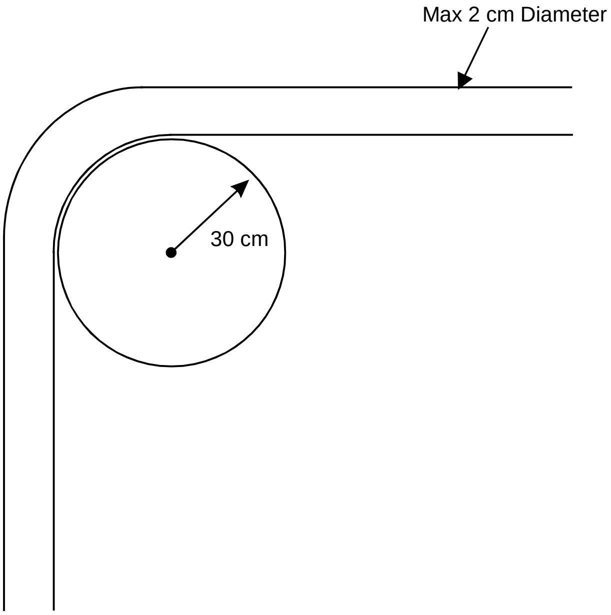


Figure 7.4
Approximate minimum bending radius

7.2.2 Cable tension

- The rules and general cable specifications applying to maximum allowable cable tension, as were discussed in Chapter 4 would apply here.
- Although modern fiber optic cables are generally stronger than copper cables, failure due to excess cable tension during installation is more catastrophic (i.e. fiber snapping rather than copper stretching).
- A general rule of thumb used sometimes is that the maximum allowable cable tension during installation is approximately the weight of 1 km of the cable itself.
- When pulling the cable during installation, avoid sudden, short and sharp jerking. These sudden forces could easily exceed the maximum cable tension. The cable should be pulled in an easy smooth process.
- When pulling the cable off a large drum, ensure that the cable is smoothly rotated by one team member to feed off the cable. If the cable is allowed to jerk the drum around, the high moment of inertia of the drum can cause excessive tension in the cable.
- It is very important to minimize cable stress after the installation is complete. A slack final resting condition will help to ensure that the fiber optic cable has a long operating life.
- When pulling the cable through bends, it is recommended that the pulling be performed on the side of the bend where the cable is longer. This reduces the tension in the cable because the majority of the weight is being pulled directly. The bend has the effect of multiplying the tension, so it is better to multiply the small tension at the source rather than the larger tension at the end of the pull.

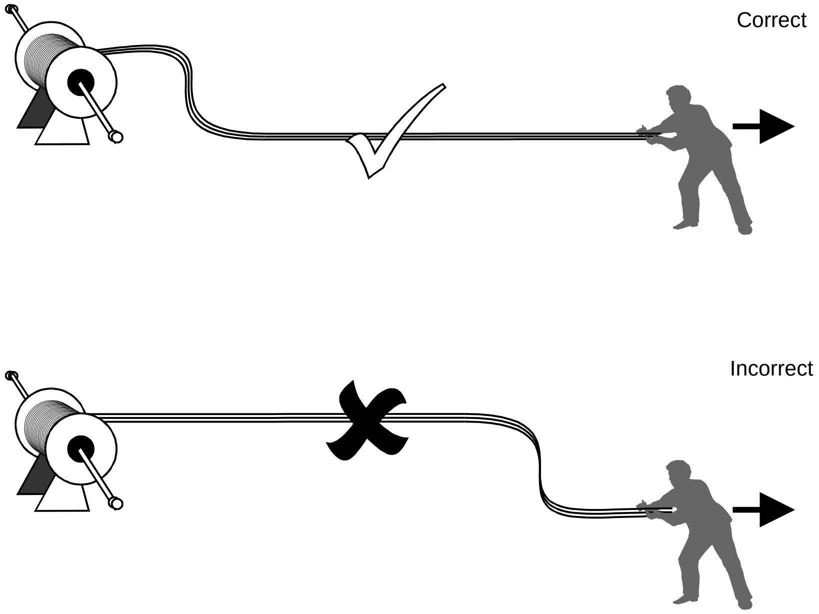
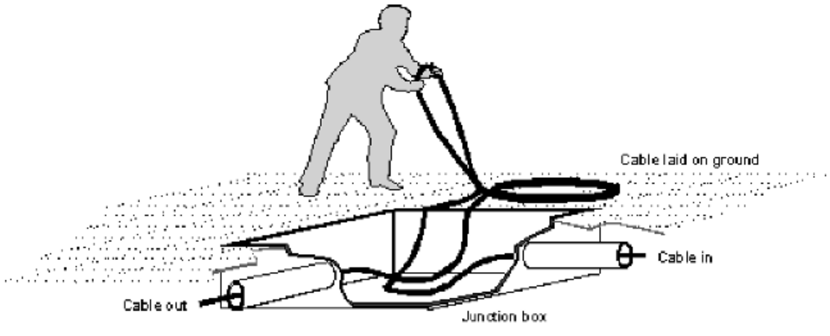
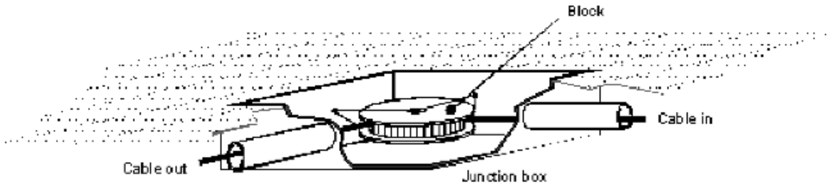


Figure 7.5
Pull the cable on the long side of a bend

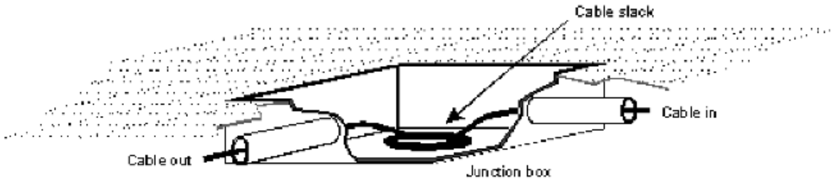
- If there are many bends in the cable route, it is recommended that as many intermediate junction boxes as possible be used to reduce cable tension. The cable is pulled through at these points, laid out in a large figure ‘8’ pattern on the ground, and then pulled into the next section. Laying the cable in a figure ‘8’ pattern naturally avoids kinking and twisting of the cable. Block systems may be used in the junction boxes. It is recommended that slack be left in the junction boxes at the completion of the installation to reduce overall stress in the cable.



(a) Use Junction box for intermediate pulling point



(b) Use blocks in Junction boxes if permissible



(c) Leave cable slack in the Junction box

Figure 7.6
Running cables through junction boxes

- Most cable manufacturers provide a maximum cable tension value for installation and a maximum cable tension value for the long-term final installed cable. This is of relevance to cables that are installed in cable risers. Regular tying of the cable along its length will help to alleviate this problem.
- Another important type of cable tension that can cause severe damage to the fibers and quite often overlooked is that of torsional twisting forces. Cable twisting can be caused by using incorrect installation techniques or from forcing cables through tight conduits. When using an ordinary layed-up rope it would twist considerably as tension is applied and it might also twist the

cable. This should be avoided by using a swivel connection to the cable. To help prevent this problem, lay all cables in a figure '8' pattern onto the ground at intermediate pulling points, and always have a member of the installation team manually guiding and watching the cable, as it is fed into the conduit or cable tray.

7.2.3 Cable reels

- Every cable installed should be given a separate number that is noted on the cabling diagram during installation. Cable suppliers usually place a serial number on the side of the reel, which can be used for this purpose.
- Each fiber on the reel should be tested for attenuation figures before commencing installation.
- Cable manufacturers normally leave the end of the cable that is on the inside of the reel protruding out so that it can be used for testing. After each reel of cable is installed, a second attenuation test should be carried out on each fiber to ensure that there has been no significant damage incurred during installation. The results of these tests should be recorded with the results of the pre-installation tests.
- The cable end that is on the inside of the reel should be taped firmly to the side of the reel so that it does not catch on the outgoing cable during payoff.

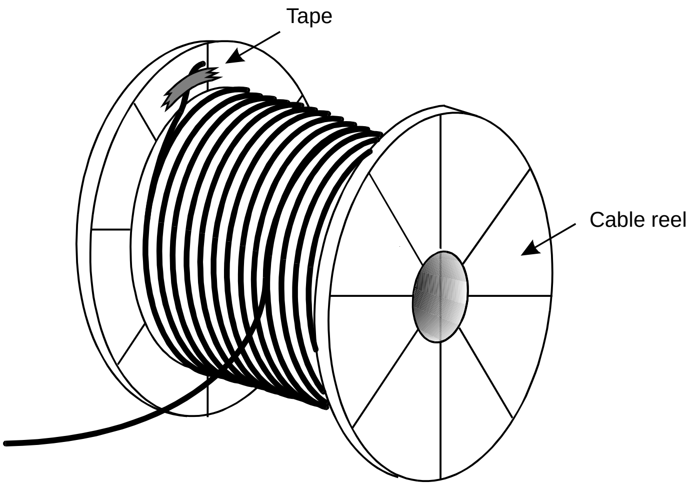


Figure 7.7
Tape the inside loose cable end to the reel

- In order to minimize damage and unnecessary handling of the cable during installation, it is advisable to payoff directly from the reel. This can be achieved by holding the reel on a rod and directly unreeling it as you walk along the cable tray or trench, or by placing the reel on a payoff stand at the beginning of the cable run and directly payoff from there. This method of payoff also helps to prevent unwanted twisting and torsional tension of the cable.

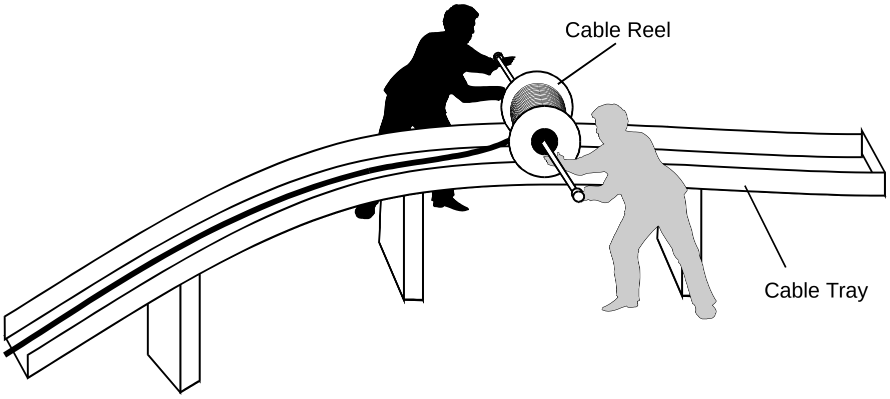


Figure 7.8a
Laying the cable by direct payoff from the reel

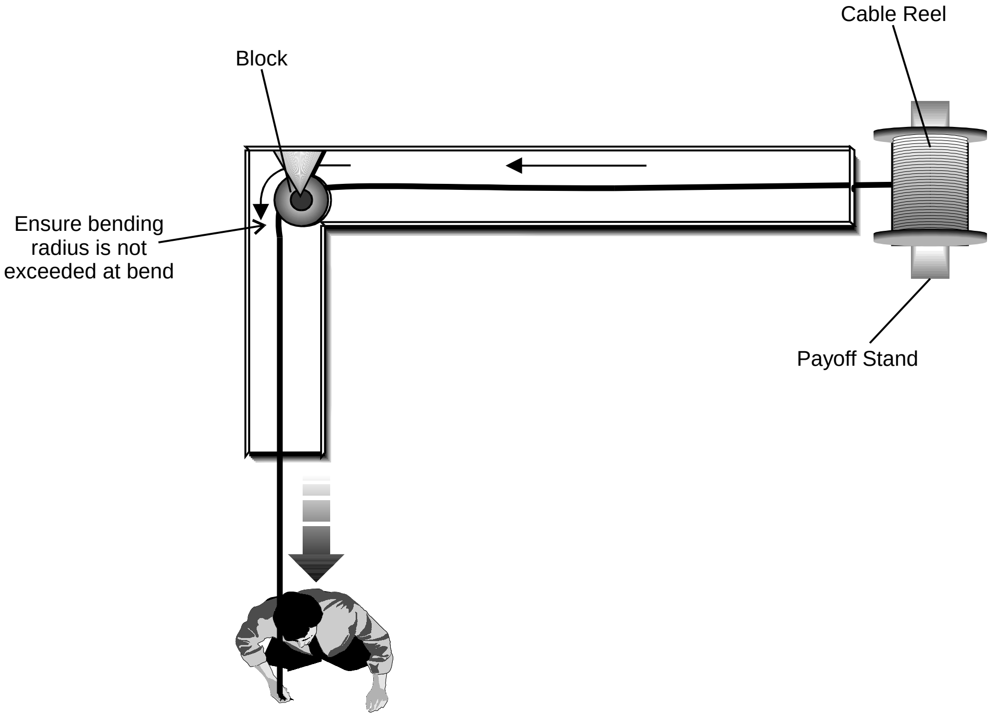


Figure 7.8b
Pull the cable directly in with the reel on a payoff stand

7.2.4 Installation in cable trays

- Laying the cable directly on to the cable tray from the reel will cause the least stress and damage to the fibers. This is often very difficult because of space restrictions around the cable trays and the tray hangers. Refer to Figure 7.8a.
- If the cable cannot be laid directly, then it should be pulled in. Ensure that it is not pulled against hard sharp bends. Have a second person to pull cable slack into the bends or set up a system of temporary blocks. Refer to Figure 7.8b.
- Ensure that the cable does not cross any cable tray hangers.

- Ensure that the cable is laid flat in the tray and not over any uneven cables.
- It is recommended to lay the cables loose in the cable tray and not tied to other cables or to the tray itself.
- It is possible to simply tie the pulling rope to the strengthening member with a knot. This is enough for very simple pulls with low resistance. But generally, it is not advisable as the knot may get entangled along the route and may break. Tape over the joint to reduce similar risk to the cable and prevent ingress of dirt or water into cable.

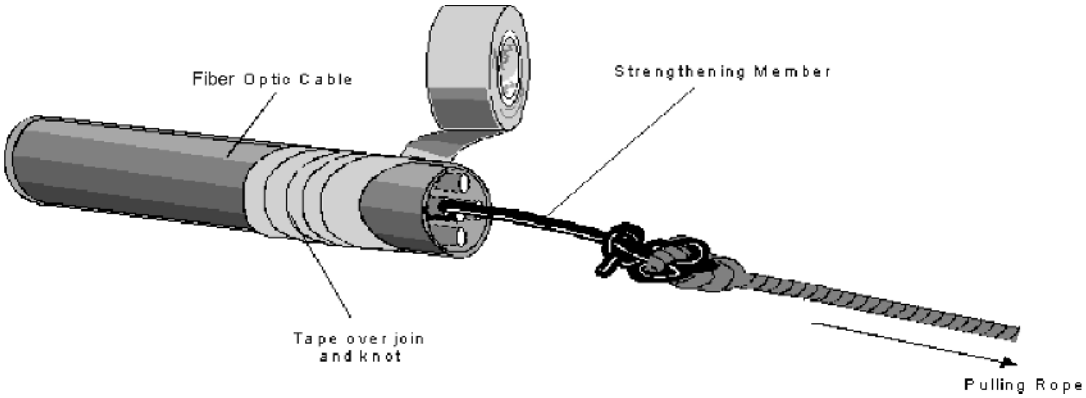


Figure 7.9
Attach pulling rope to cable strength member with knot

The following is the recommended method for attaching a pulling line to a fiber optic cable:

- Strip back the cable to expose 15 cm of the strengthening member only.
- Cover the strengthening member with epoxy glue.
- Place the pulling rope 30 cm back from the stripped end, and tightly tape the rope to the cable with insulation tape moving from the end of the rope to the end of the cable.
- Continue to tape the cable until a smooth transition is reached between the strengthening member and the cable.

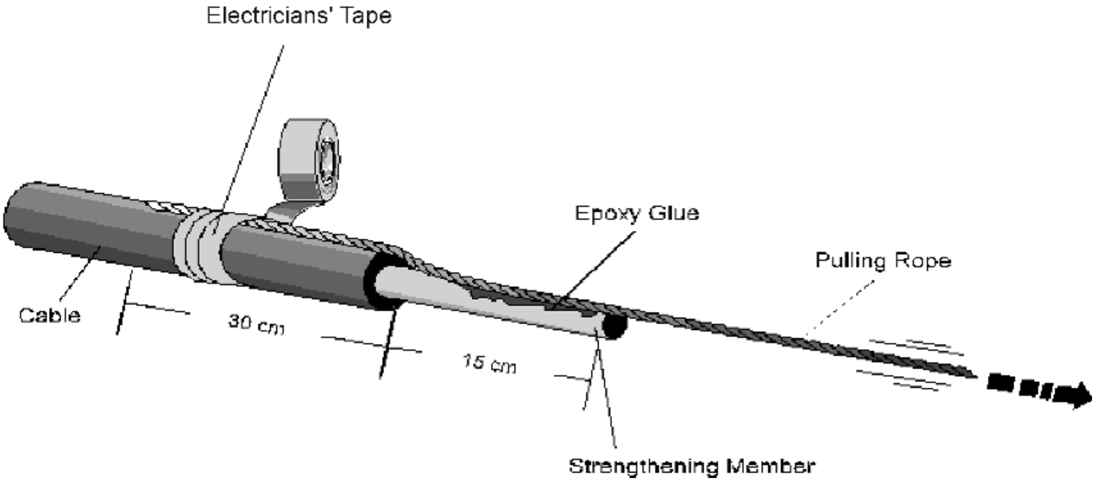


Figure 7.10
Attaching a pulling line for cable tray runs

If the fiber optic cable has pre-terminated connectors, the following is the recommended method to attach a pulling line:

- Do not use any epoxy glues.
- Place the pulling rope 1 m along the cable, and using insulation tape, tightly wrap the rope to the cable until 2 cm approximately from the connectors.
- Ensure that protective caps have been placed on the ends of the connectors.
- Carefully wrap the connectors and pulling rope with tape. Ensure it is smooth but not tight.
- Place several small pieces of wood, bamboo or basket weaves about 10 cm in length around the connector ends, and smoothly but not tightly wrap these to the cable with tape. The reason for doing this is to prevent the connector ends from being bent back and the fibers from being broken while the cable is being pulled.

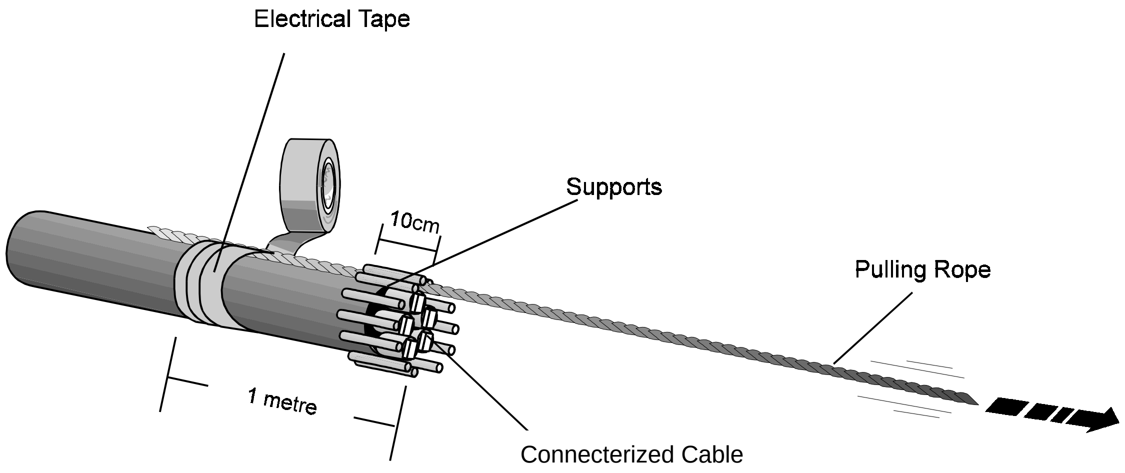


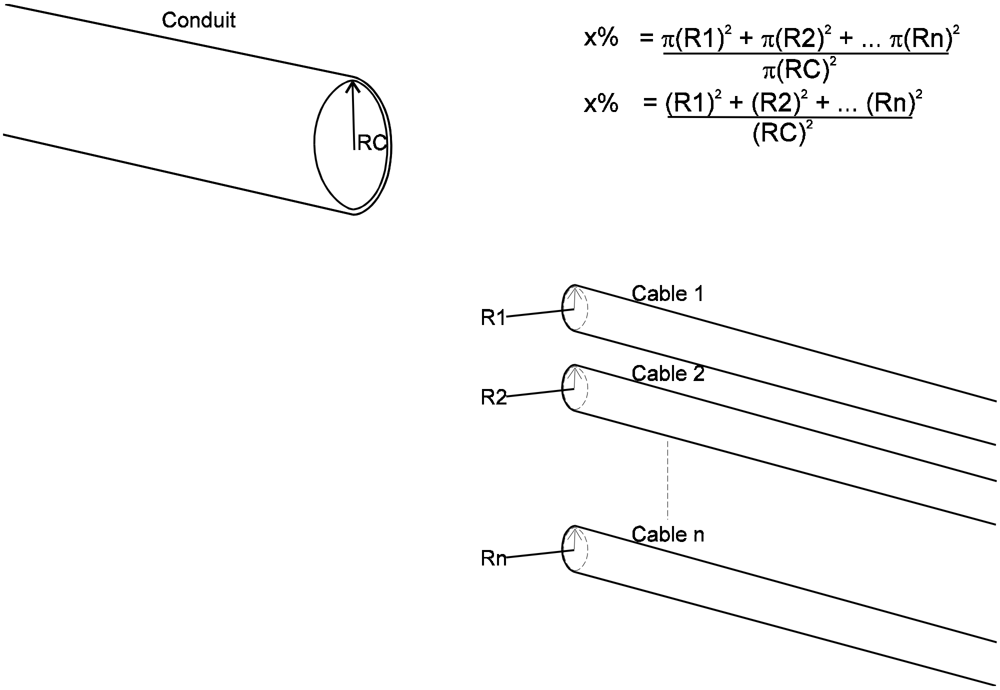
Figure 7.11
Attaching a pulling rope to a preconnectorized cable for cable tray runs

7.2.5 Installation in conduits

- Ensure that the cable is sufficiently covered in lubricant before it is pulled into the conduit.
- The cable should be pulled by hand wherever possible.
- If the cable is to be pulled by winch, it is essential that a tension gauge is attached to ensure that the maximum permissible cable tension is not exceeded.
- The ends of cables must be completely sealed and made waterproof before pulling commences. Moisture around the fibers will cause permanent long-term damage.
- The larger the surface area of the cable compared to the surface area of the conduit, the more friction that will exist as the cable is pulled through the conduit. To determine the number and size of cables that can be pulled through a given size conduit, a general rule of thumb is to divide the cross-sectional area of the cable by the cross-sectional area of the conduit and compare this calculated percentage figure with maximum permissible

percentage figures. Approximate figures used for the *X*% value illustrated in Figure 7.12 are:

- – Less than 55% for a single cable
- – Less than 30% for two cables
- – Less than 40% for three or more cables



$$x\% = \frac{\pi(R1)^2 + \pi(R2)^2 + \ldots \pi(Rn)^2}{\pi(RC)^2}$$

$$x\% = \frac{(R1)^2 + (R2)^2 + \ldots (Rn)^2}{(RC)^2}$$

Figure 7.12
Determining if cables will fit into a conduit

- It is possible to simply tie the pulling rope to the strengthening member with a knot. This is enough for very simple pulls with very low resistance. But for conduit runs, this is generally considered unacceptable as the knot may catch along the route and may suffer from breakage.

The following is the recommended method for attaching a pulling line to a fiber optic cable using a ‘pulling eye’.

- Strip back the cable to expose 15 cm of the strengthening member only.
- Cover the strengthening member with epoxy glue.
- Fill the pipe section of a pulling eye with epoxy glue and fit it to the strengthening member. Allow the epoxy to set before commencing the payoff.
- Cover the end of the cable with tape to ease the transition between strength member and cable. This protects the end of the fibers also and stops ingress of dirt or water.

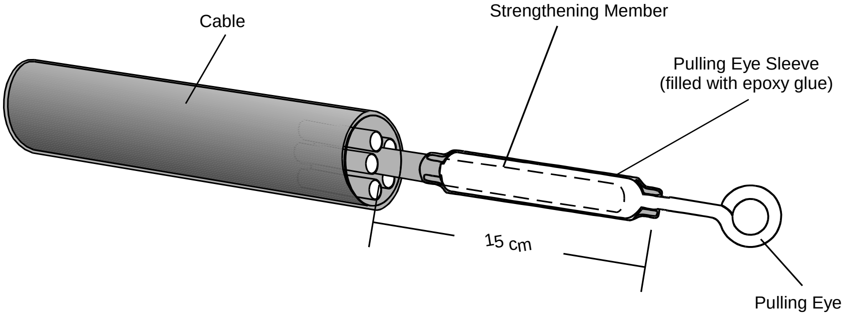


Figure 7.13
Attaching a pulling eye to the cable

- For long cable runs, use intermediate pulling points where the cable is pulled through and coiled up in a figure '8' pattern on the ground and then fed into the next conduit section.
- At intermediate pulling points, reapply lubricant to the cable before pulling through the next conduit section.
- For cable runs greater than 500 m, it is advisable that intermediate junction boxes be installed with several meters of cable slack at each entry. The junction boxes should be strategically located to account for possible future extension of the cabling system to other locations.
- Another very popular method of attaching a pulling rope to a fiber optic cable is the 'Chinese Basket' or 'Kellems Grip'. This works most effectively on larger diameter cables (generally greater than 0.75 cm diameter). It consists of a pulling eye with a long cylindrical weave (up to 1 meter) attached to it. The weave is placed over the end of the cable and is glued or taped to the cable. If it is glued, the end of the cable is cut off and thrown away after the pull is complete.

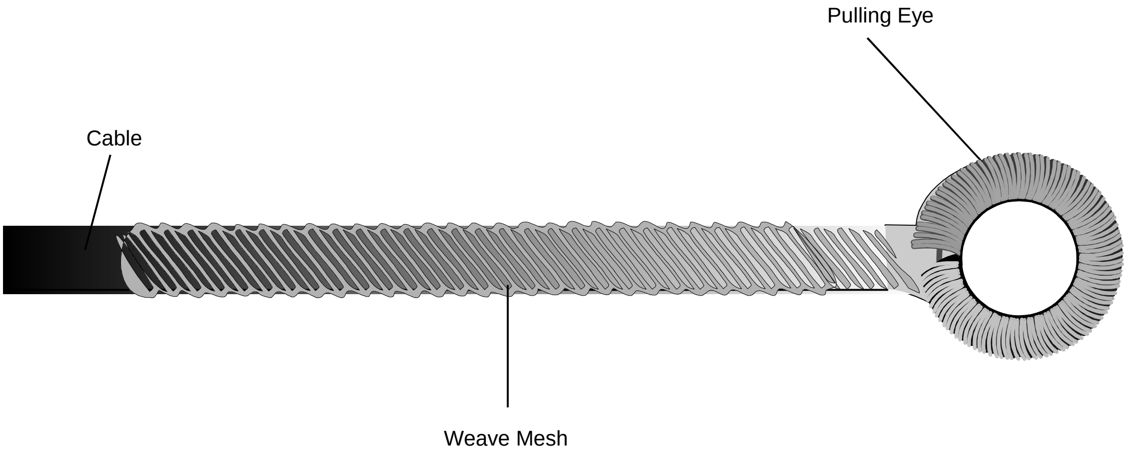


Figure 7.14
The 'Kellems' cable grip

If the fiber optic cable has pre-terminated connectors, the following is the recommended method to attach a pulling line:

- Do not use any epoxy glues.

- Place the pulling rope 3 m along the cable, and using electricians tape, tightly wrap the rope to the cable until approximately 10 cm from the connectors.
- Ensure that protective caps have been placed on the ends of the connectors.
- Place a metal pipe with a sealed end over the connectors and tightly wrap the pipe to the pulling rope with insulation tape. The main purpose of the pipe is to prevent the connector ends from being bent back and the fibers from being broken while the cable is being pulled.

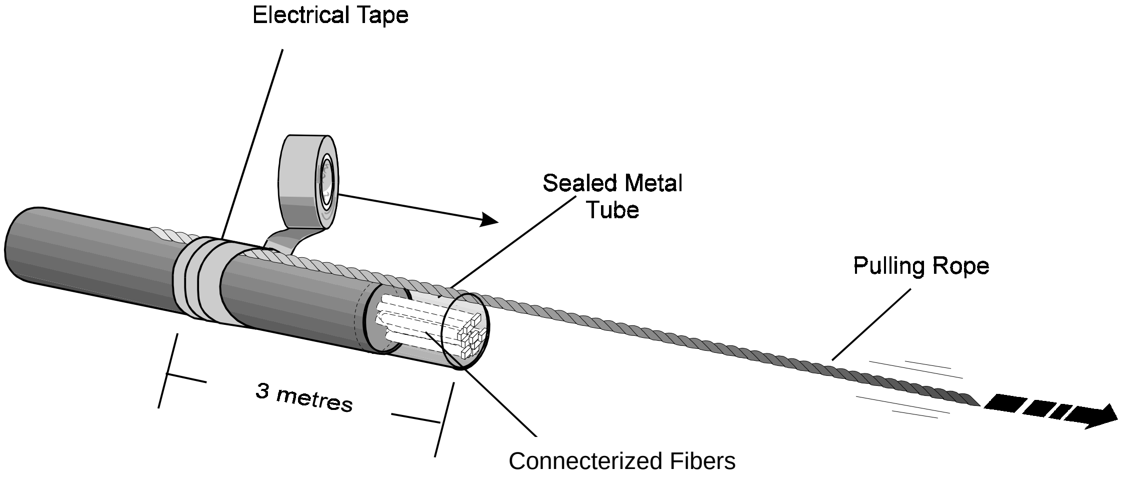


Figure 7.15
Attaching a pulling rope to a connectorized cable for conduit runs

7.2.6 Leaving extra cable

- It is considered mandatory that significant cable slack is left at the beginning and end of every cable run. Cable slack should be left at all termination cabinets, junction boxes, pit boxes, splicing centers, splicing trays, cable vaults and at the end equipment. This cable slack is useful for cable repair, entry into the cable along its length and equipment movement.
- Cable slack is important when a cable requires repairing. If the cable is accidentally cut or dug up, the cable slack can be shifted to the damaged location, necessitating only one splicing point in the permanent repair, rather than two splices that would be required if additional cable were added. This results in reducing costs and less link loss. Generally, 3 to 6 m of cable at each end of a cable run is sufficient for this contingency.
- Additional cable slack at any planned future points of cable system expansion will provide significant cost and labor savings when the new cable drop is required. For this purpose, a minimum of 10 meters of cable slack should be left at these points.
- Additional cable slack will allow relocation of equipment, terminals, hubs and the cable itself with relative ease and without requiring new splices.
- Splicing of cables is a relatively involved process and it requires significant working space to be performed correctly. Splicing cannot be performed in confined spaces or in mid air. Enough slack cable must be left to allow the cable to be taken to a table to be spliced. This may be as far away as 5 m and

should be planned for and written into the cabling installation plan before installation commences. In this case, allow approximately 10 m of cable slack.

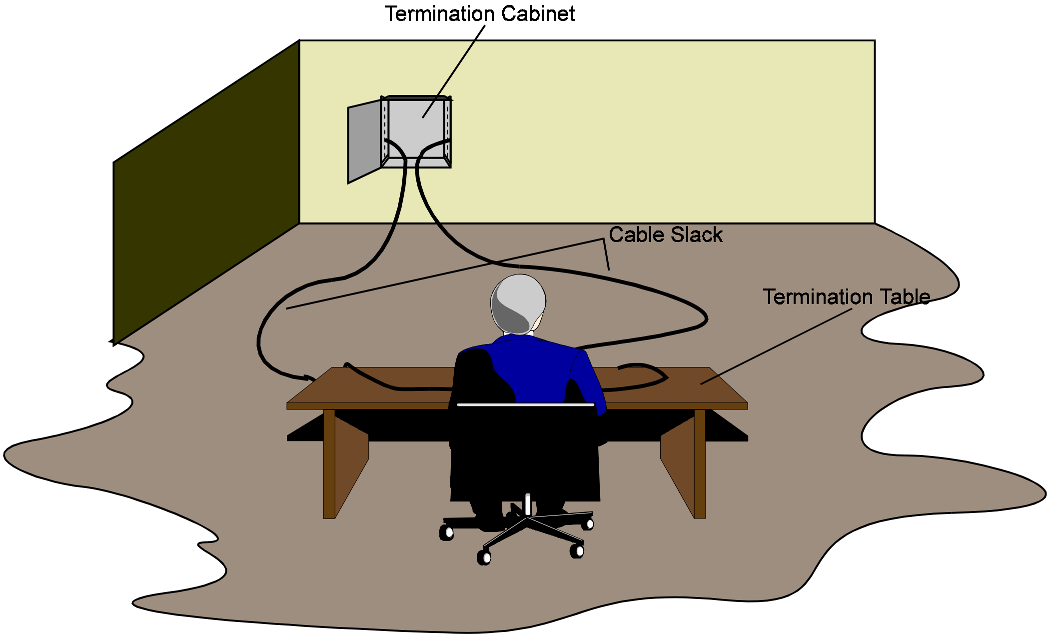


Figure 7.16
Leaving sufficient slack at termination points

- Consideration is necessary as to where the cable slack is to be stored once installation is complete. The location where it is to be stored should have sufficient space so the cable does not suffer from macrobends and should be located where it will not be disturbed and will therefore be protected from potential damage. For external cables, it is often convenient to use round (at least 1 m diameter) jointing pits, and to coil the cables back into the pit after jointing above ground.
- Spare fibers should be coiled up in the splice trays and carefully clipped out of the way.
- Remember to include all cable slack requirements in the cable length calculations.

7.2.7 Lubricants

- Use standard cable pulling lubricants for installations where excessive friction is anticipated. The coefficient of friction per dry Blyethylene cable sheath in a PVC duct has been measured as about 0.45. This is clearly a function to find out how smooth and clean the ducts are, with no excess glue at joints etc. Using a proprietary cable pulling lubricant such as ‘Polywater’ values of coefficient of friction as low as 0.1 have been measured if complete coverage of the cable is achieved. Practical field applications have tended to show results in the range 0.15–0.25 due to lesser coverage. As these products are expensive, they are normally only used when essential.
- For long pulls of external cables, water is the best lubricant. This has been shown to reduce the coefficient of friction to about 0.3. Its great advantage is

cost so we can ensure adequate covers of the ducts. Flood the ducts with water continuously throughout the pulling process and ‘float’ the cables in.

- For cables that are to be pulled through conduit, it is recommended to always use lubricants.

7.2.8 Environmental conditions

- Avoid installing cables when the ambient temperature is less than 0°C or greater than 70°C. Beyond these limits, there is a possibility of damage to the cable sheath, and in some cases, to the internal components of the cable and subsequently, the fibers themselves.
- Avoid installing cables when the humidity is greater than 95% for ambient temperatures greater than 60°C.
- Cable suppliers specify a maximum temperature and humidity at which the cable should be stored before installation.

7.3 Indoor cable installations

- This section of the chapter examines particular requirements that are associated with the installation of fiber optic cables in indoor environments.
- Rubber floor ducts should be used to protect the cable, if cables are to be installed on to floor areas that people would walk over.

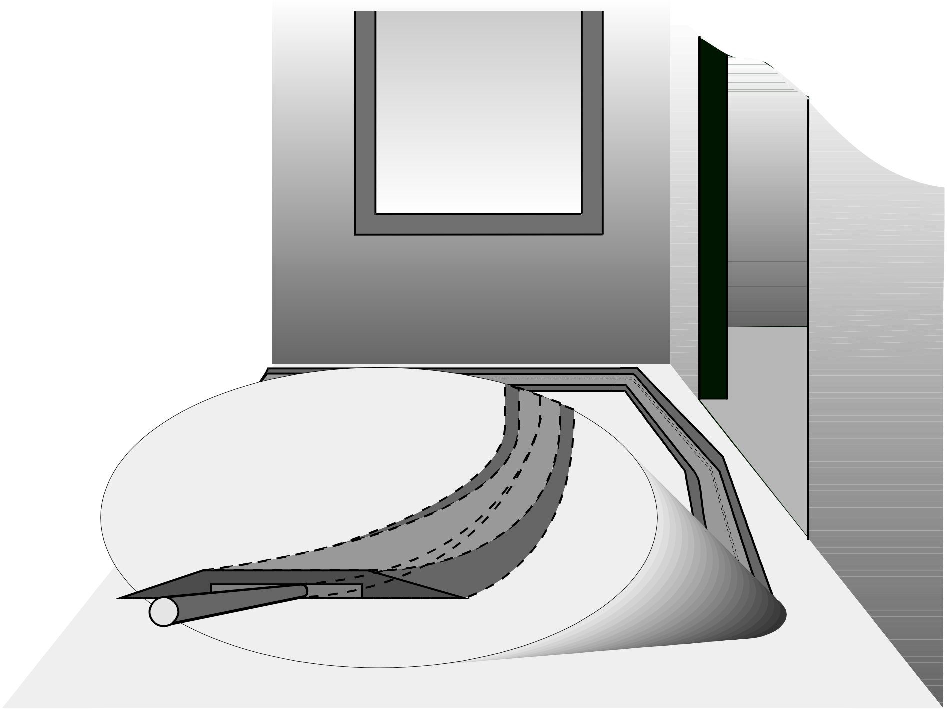


Figure 7.17
Rubber floor ducts

- If cables are to be installed under the carpet, ensure the cable type has a strong sheath and is of a loose tube construction. Special cables are available specifically for installing under the carpet.
- If cables are to be laid around the walls of a room near the skirting, ensure that they are taped to the skirting with a high quality strong tape. This will help prevent damage to the cable or its connectors when accidentally pulled up by a passing foot.
- If a cable is to be run vertically up a wall, then cable clips that are screwed to the wall should be used to hold it in place. Wrap electrical tape around the cable before inserting it into the cable clip. The tape will provide more malleable sheath, which will firstly provide a better grip for the clip and secondly, cause less damage to the cable from the clip.

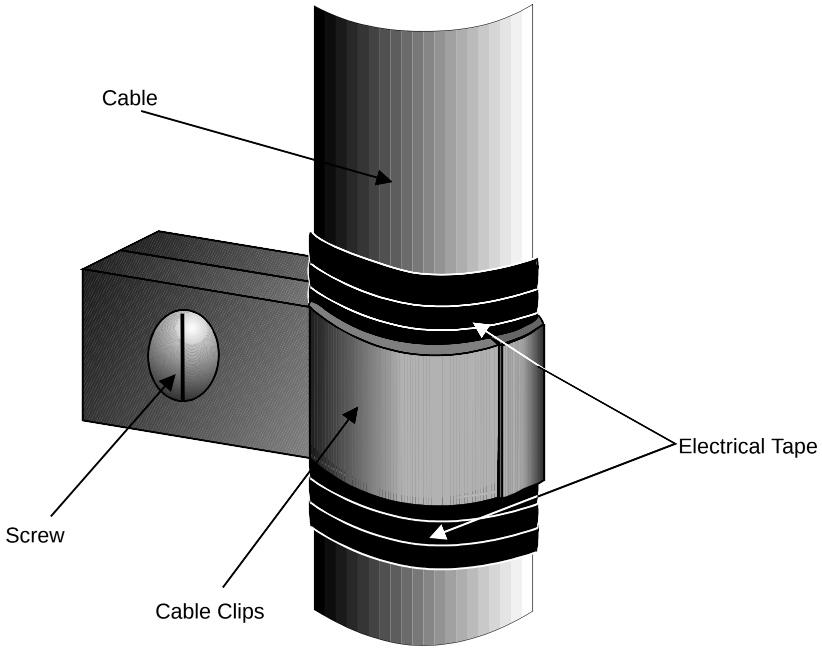


Figure 7.18
Cable wall clips

- Rubber grommets should be used where the cable enters or leaves a plastic or metal cable duct. They protect the cable from sharp edges and from bending tighter than the minimum bending radius.

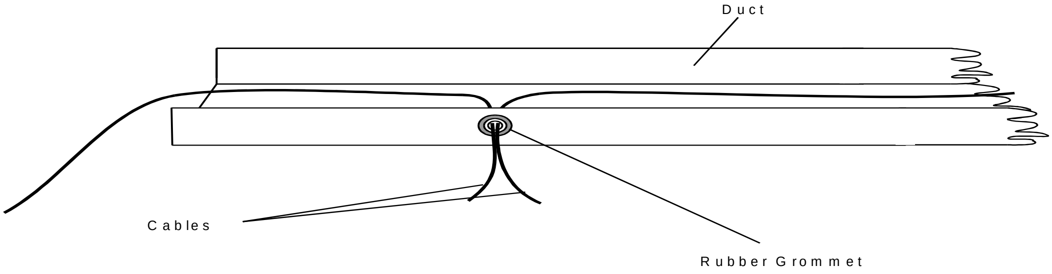


Figure 7.19
Rubber grommets used in cable ducts

- Often, installers will bolt a second smaller cable tray to the side of the main cable tray for the fiber cables only. This ensures that no other cables will crush or damage the fibers. The trays are generally made of plastic and are often colored yellow. Flexible plastic tubing then runs from the fiber cable tray down to the rack.
- As the majority of indoor installations are only short cable runs, it is often more cost effective to have the cables pre-terminated in the factory before being transported to site for installation. This procedure generally saves both time and money.
- Cables that are installed under raised floors are subject to crushing and kinking. Therefore, cables should be either of a high quality (have a strong sheath and be of loose tube construction) or installed in a conduit or a separate underfloor cable tray. The conduit will aid in the pulling of the cable and will provide valuable protection when the inevitable rearrangement of the copper cables occurs.
- If the cable is to be laid directly into the ceiling (which is often the most cost effective method of indoor installation), care should be taken to avoid cross members, ceiling hangers, sharp edges and corners, sharp screws or nails or metal studs and around areas warranting heavy potential maintenance (e.g. air conditioning ducts, water or gas piping, electrical installations). If the cable is to unavoidably run near these dangers, then install it in conduit, even if the conduit lengths are only of short sections.
- For vertical installations, most tight buffered riser fiber optic cables will self support approximately 100 m of their own weight over the life of the cable. Ensure the bending radius is not exceeded at any vertical transitions and use clamps on the sheath at regular intervals.
- For installations in cable risers or elevator shafts, it is recommended that the cable be tied at every floor of the building. Wrap the cable in electrical tape before a tie is attached and ensure that the tie is not pulled too tight. This will ensure that the cable does not exceed its maximum tensile load and would help prevent cable movement.
- Connection to any data equipment or patch panel should be with a large loop of slack cable (generally about 30 cm).

7.4 Outdoor cable installations

This section of the chapter examines particular requirements that are associated with the installation of fiber optic cables into outdoor environments.

- Obtain the relevant permission or permit that is required to run the cable through government or private property that does not belong to the cable owner.
- Carefully plan all installations and carry out thorough cost analysis, so that the final cable route is of minimum cost.
- For outdoor installations, it is vital to use the correct cable. The cable should be chosen to suit the application and the environment in which it is to be used. Do not hesitate to seek professional advice from cable suppliers if required.
- The parameters of cable type, fiber type, sheathing, diameter, moisture barrier, strengthening members, connectors and splicing type all need to be carefully considered.

- It is recommended that all underground cables be installed in conduit. The conduit would provide protection from water, excessive temperature variations, physical stress from cars or trucks that drive over the top of the cable, attacks by vermin and to some extent, from persons accidentally digging through the cable with spades and mechanical diggers. Also, of significant importance, it allows new cables to be laid without having to dig the trench again and to easily replace damaged or old cables.

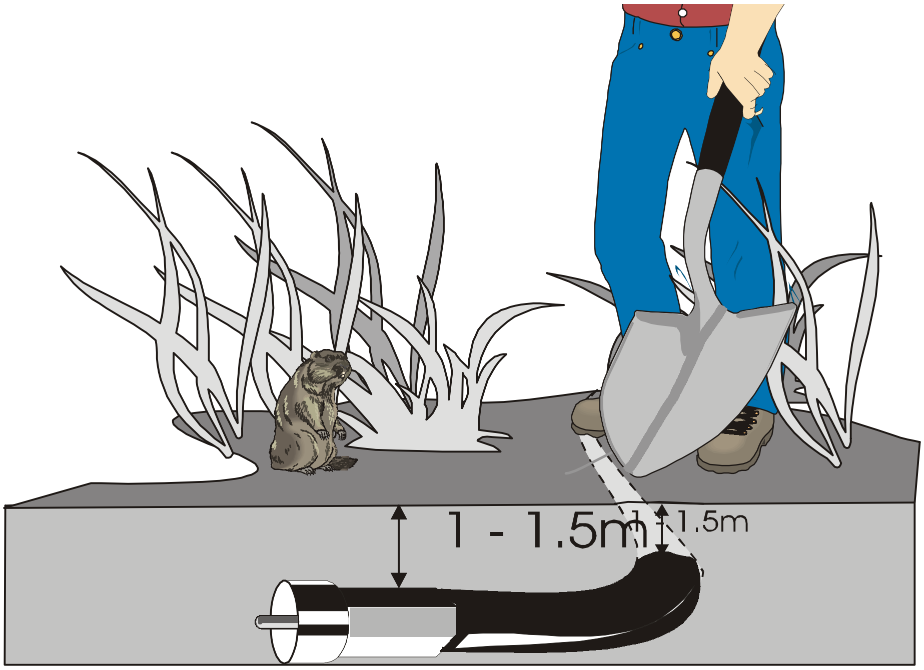


Figure 7.20
Bury underground cables in conduit where possible

- Cables can be buried directly in the ground, but they should have a suitable sheath that provides protection against vermin and serves as a good moisture barrier (preferably jelly filled). The sheaths can be double jacketed, nylon, Teflon and/or metal armored.
- The deeper a cable is buried the less likely it is to suffer from temperature variations, physical stress or attacks from vermin. A depth of 1 to 1.5 m is ideal.
- Allow a minimum of 3–6 m of cable slack at the end of each run to reduce any possibility of undue cable tension, and to allow for the possibility of repairs.
- Place a termination cabinet and patch panel at the end of each cable run between buildings so that the system can be easily reconfigured and maintenance can be carried out as is required.
- At intermediate points where cable is pulled out and stored on the ground before being pulled through the next section of conduit, the cable should be laid on the ground in a large figure '8' pattern. This helps prevention of twists

and tangles forming in the cable when it is pulled into the second stage of the route.

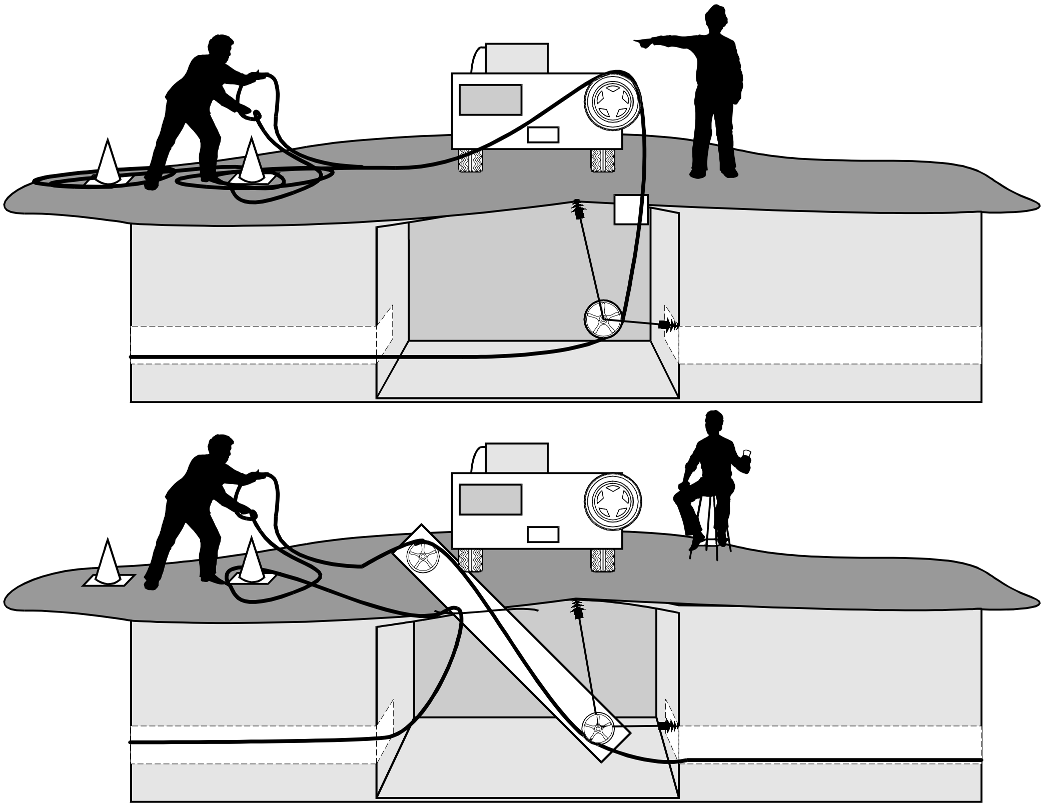


Figure 7.21
Carrying out an intermediate cable pull

- If pressurized cables are to be used, ensure that the cable pressure is checked before and after installation. With this type of cable, particular care should be taken to ensure that the pulling eye and end cap seals are not broken during installation.

7.5 Other installation methods

This section briefly looks into two other methods of installing fiber optic cables.

7.5.1 Aerial installations

Fiber optic cables are often installed as aerial cables hanging from electric power poles. Special cables that have significant internal strength are manufactured and those can be installed hanging directly between two poles. Other cables are designed to be supported along a steel support wire (also referred to as a messenger wire). It is also possible to tie the fiber optic cable to the power cable itself. The use of a support wire is generally preferred because it provides extra strength and puts less stringent strength requirements on the fiber optic cable itself.

Aerial cables are designed to withstand large forces that result from strong winds and extremes of temperatures. The sheath of the cable is made from UV stabilized plastic and is designed for an extended operating life of 10 years or more.

If the aerial fiber optic cable is to be attached to a steel support wire, the cable should be securely tied or taped to the support wire every 30 cm. The ties of tape that is used should be UV stabilized and designed for outdoor weather conditions. At the mid point of each 30 cm span, the cable should have a droop of approximately 3 cm to allow for expansion and contraction of the steel support wire. The support wire often passes through a pulley block on the pole or is attached to a ring bolt on the pole using dead end grips.

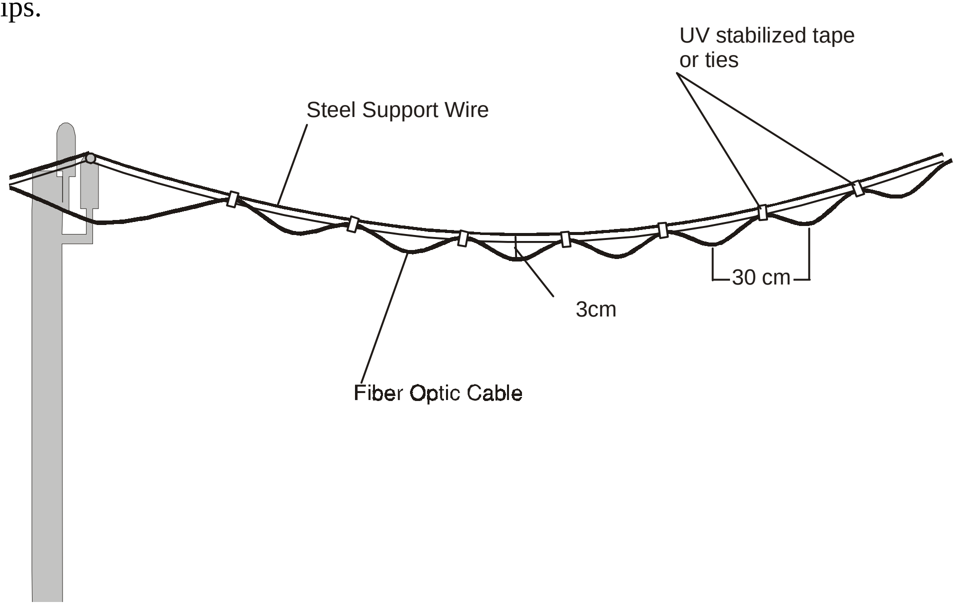


Figure 7.22
Aerial cable attached to support wire

Most slotted core or loose tube fiber optic aerial cables are compatible with the standard helical lashing or clamping techniques that are normally used with other telecommunications cables.

7.5.2 Blown fibers

This is a technique developed by British Telecom, which involves the use of fibers installed directly within a 6 mm microduct. The fibers are drawn directly along the duct by the aerodynamic drag of the viscous flow of air from a small blower producing up to 150 psi. This technique can be used over distances up to several kilometers.

Special fibers that have a rough outer coating that is designed to create significant drag in one direction and very smooth in the other is used in this technique. In this way, the fiber is picked up by the forced air through the tube but has minimal resistance, as it is dragged through the tubing.

The microduct is installed as bundles of color-coded tubes within an overall sheath of polyethylene. These tube bundles can be installed into cable ducts using conventional cable techniques. The individual microducts are joined together by push-on fittings to make a continuous leak-free path from one end to the other. Individual tubes can be brought out from the bundle at the intermediate points and diverted off to individual customers.

The advantages of the technique are that there is virtually no strain imposed on the fibers during installation. Accordingly, the fibers do not require extra strength members. Up to six fibers can be installed in each microduct and fibers can be blown into the duct over existing ones at a later date, enabling fiber provision to be deferred.

This technique is becoming more popular throughout the world, particularly in building distribution systems. It is sometimes preferred because the fibers can be installed on an as required basis, making building cabling management significantly easier. The fibers will also have good mechanical protection as they run through risers, over hung ceiling and under raised floors.

7.6 Splicing trays/organizers and termination cabinets

This section looks into different types of storage units that are used for housing optical fiber splices and end of cable terminations.

7.6.1 Splicing trays

Splices are generally located in units referred to as 'splicing centers', 'splicing trays' or 'splicing organizers'. The splicing tray is designed to provide a convenient location to store and to protect the cable and the splices. They also provide cable strain relief to the splices themselves.

Splicing trays can be located at intermediate points along a route where cables are required to be joined or at the termination and patch panel points at the end of the cable runs.

The incoming cable is brought into the splicing center where the sheath of the cable is stripped away. The fibers are then looped completely around the tray and into a splice holder. Different holders are available for different types of splices. The fibers are then spliced onto the out going cable if it is an intermediate point or on to pig-tails if it is a termination point. These are also looped completely around the tray and then fed out of the tray. A typical splicing tray is illustrated in Figure 7.23.

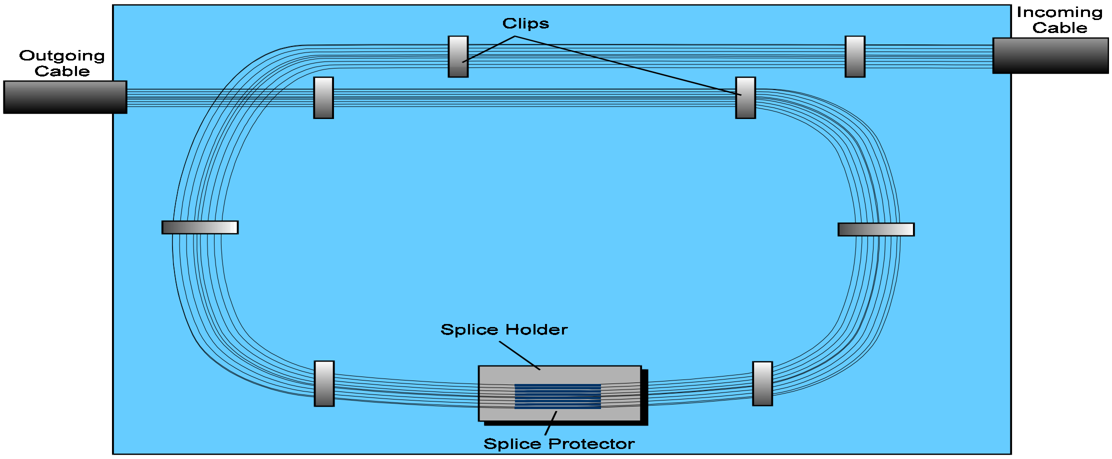


Figure 7.23
A typical splicing tray

The fibers are looped completely around the tray to provide slack, which may be required to accommodate any changes in the future, and also to provide tension relief on the splices.

Each splice joint is encased in a splice protector (plastic tube) or in heat shrink before it is clipped into the holder.

Splicing trays that have patching facilities are available. This allows different fibers to be cross connected and looped back for testing purposes.

7.6.2 Splicing enclosures

As a general rule, it is always preferred that splicing of fibers is carried out inside the building, and stored within an equipment rack in the building. External splices are difficult to change once they are installed. They are a perennial concern for network maintenance personnel. Unfortunately though, there will be times when external splicing is required.

The splicing trays are not designed to be left in the open environment and must be placed in some type of enclosure. The enclosure that is used will depend on the application. The following are examples of some enclosures used for splicing trays.

Electrical signal characteristics

- **Direct buried cylinders**
  At an intermediate point where two cables are joined to continue a cable run, the splices can be directly buried by placing the splice trays in a tightly sealed cylindrical enclosure, that is generally made of heavy duty plastic or aluminum. The container is completely sealed from moisture ingress and contains desiccant packs to remove any moisture that may get in. A typical direct buried cylinder is illustrated in Figure 7.24.

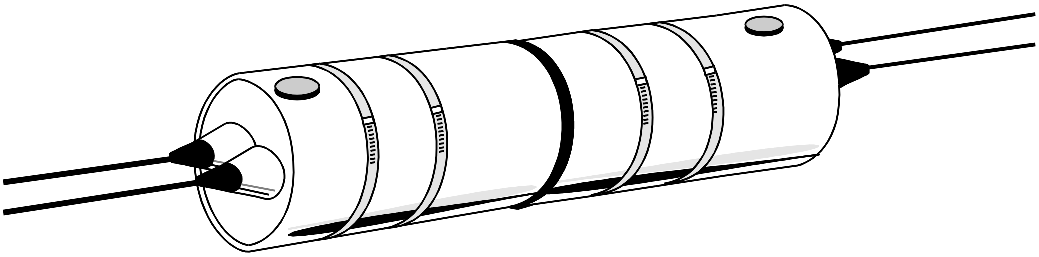


Figure 7.24
Direct buried splicing enclosure

- **Outdoor cases**
  The splicing trays are generally stored in metal sealed cases at outdoor junction points, as the splices need to be protected from environment. Such outdoor junction points are located in pit boxes or manholes. The case has a screw on lid that can be removed to carry out changes or to test the cable. Again, the case is completely sealed from moisture ingress. An outdoor case is illustrated in Figure 7.25.

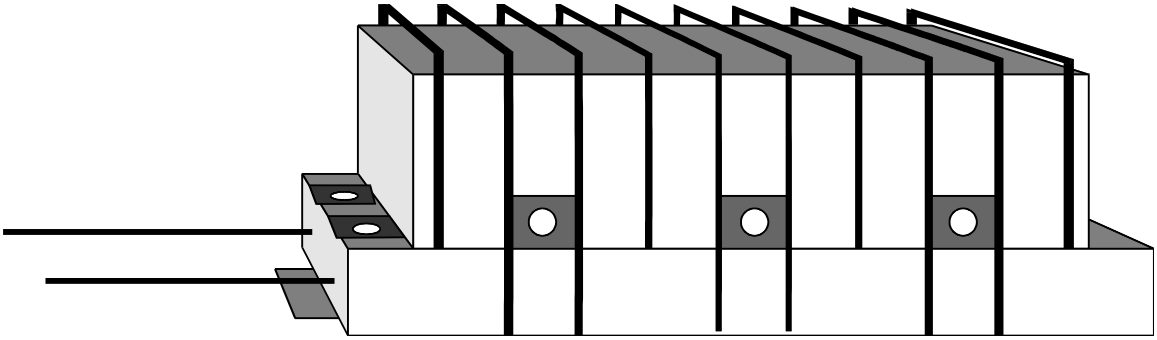


Figure 7.25
Outdoor connection boxes

- **Indoor connection boxes**
  At intermediate points or at junction points that are required indoors, the splice tray is placed in a metal or plastic box with a screw on or slide on lid. The boxes are then screwed to the wall or installed into an equipment rack. An indoor enclosure is illustrated in Figure 7.26.

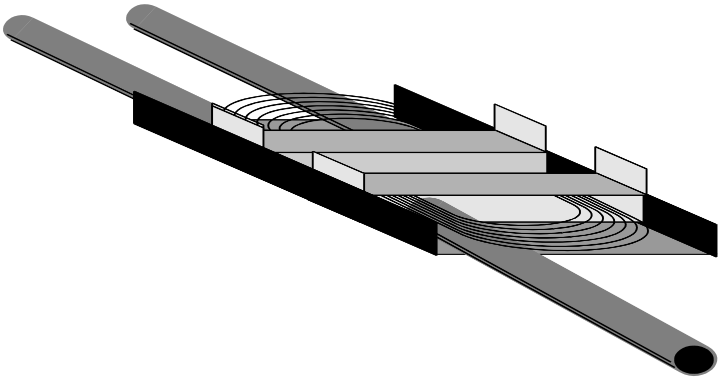


Figure 7.26
Indoor connection box for splices (cover removed)

- **Termination cabinets**
  At junction points where a lot of cables meet, the splicing trays are stored in a larger wall mounted cabinet (approximately 500 × 500 × 100 mm) with a hinged door. For outdoor use, the cabinets must be sealed against bad weather conditions. Figure 7.27 illustrates a splicing tray in a termination cabinet.

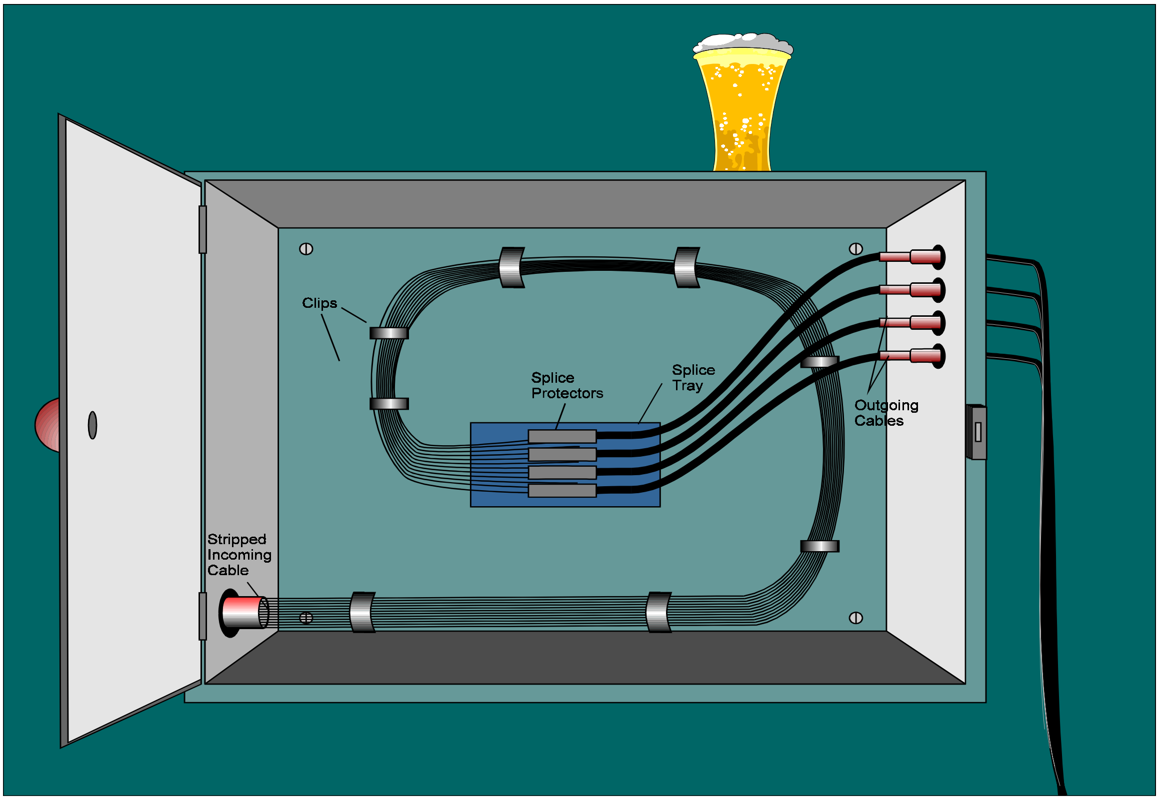


Figure 7.27
Termination cabinet for splicing trays

- **Patch panels and distribution frames**
  Splice trays can be used in the back of patch panels and distribution frames for connection of patch cords to the main incoming cable. These enclosures are commonly referred to, as fiber optic break out terminals (FOBOT). An example of a FOBOT is illustrated in Figure 7.28.

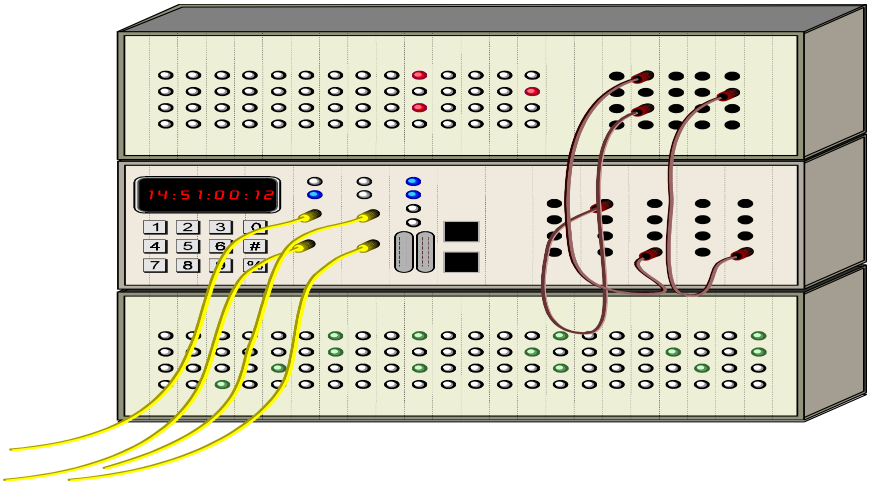


Figure 7.28
Patch panel

7.6.3 Termination in patch panels and distribution frames

There are three main methods of connecting an incoming cable into a patch panel or distribution frame. Firstly, if the incoming cable contains fibers that have a large minimum bending radius, then it is recommended to splice each fiber to a pre-connected fiber pig-tail that has a smaller bending radius. This reduces undue stress on the incoming fibers and introduces only small losses into the link. This also replaces the more fragile glass of the incoming cable with the more flexible and stronger cable of the pig-tails. This particular technique is now by far the most commonly used technique to connect incoming cables into FOBOTs. This is illustrated in Figure 7.29.

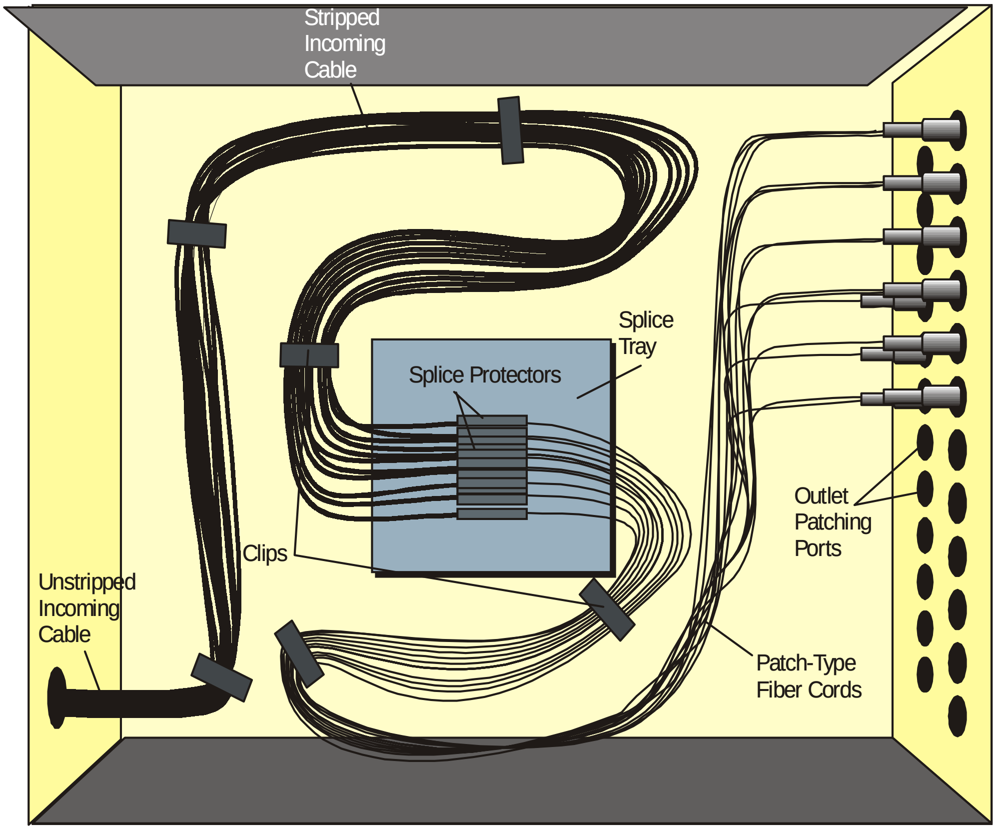


Figure 7.29
Top view of a FOBOT with splicing tray using pig-tails

The second method is to place the fibers from the incoming cable into a breakout unit. The breakout unit separates the fibers and allows a plastic tube to be fitted over the incoming fibers to provide protection and strength as they are fed to the front of the patch panel. Note here that there are no splices, which therefore keeps losses to a minimum. The downside is that the connectors have to be fitted by hand, which can introduce variations and the human element of uncertainty in connector quality and losses (which is not seen in the robot produced pig-tail connectors). This is illustrated in Figure 7.30.

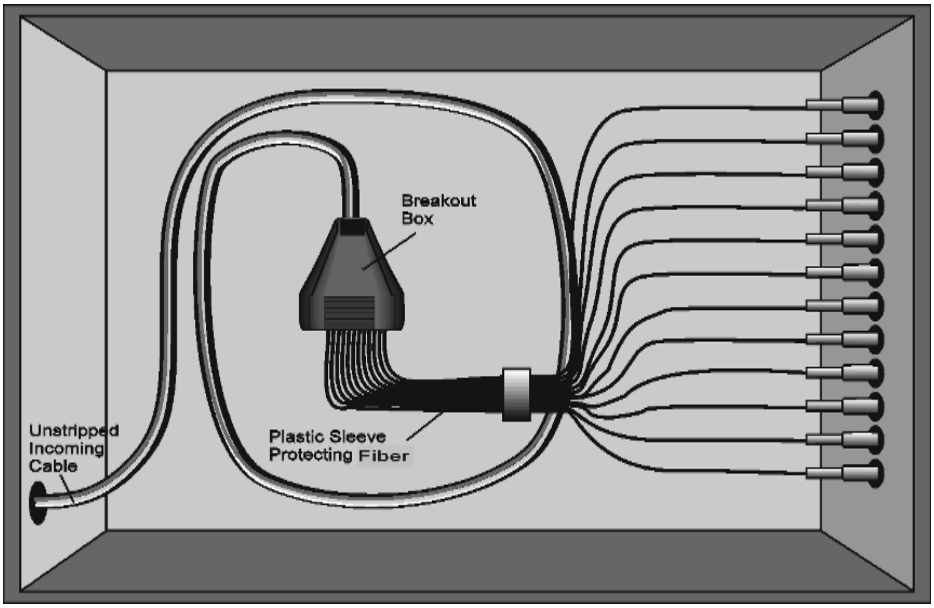


Figure 7.30
Patch panel with breakout box

If the incoming cable contains tight buffered fibers that are flexible and strong with sufficient buffering, then they can be taken directly to the front of the patch panel. Again, there is the introduced human element of uncertainty when the connectors are fitted by hand. This is referred to as direct termination, and is illustrated in Figure 7.31.

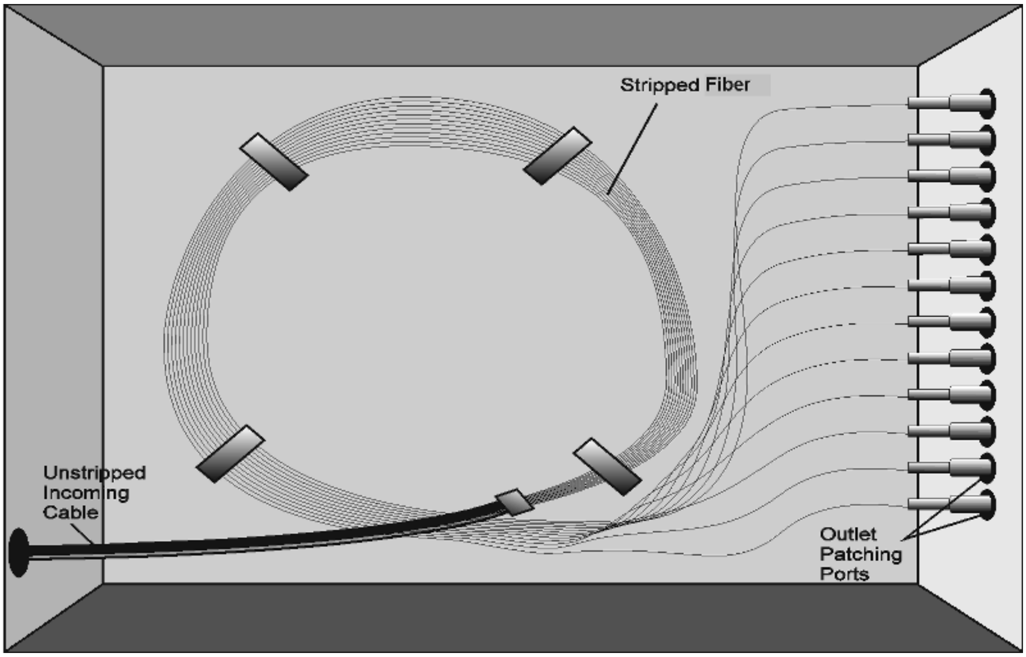


Figure 7.31
Direct termination of cables in a patch panel

8

Fiber optic system design

Introduction

This chapter discusses various aspects involved in designing a fiber optic system link. The process of designing a successful fiber optic link can be broken down into three separate sections.

The first requirement is to determine all the fundamental design parameters of the link. This would include such parameters as the services to be provided, data speed requirements, link distances, cable routes, etc. Included in this are the performance objectives of the fiber optic system. Some of these design parameters and considerations have been discussed in depth in previous chapters. The first part of this chapter will discuss other important design considerations.

The next requirement is to calculate the anticipated operational performance of the link. This is often referred to as 'link budgeting', 'power budgeting', or 'loss budgeting'. The different operating parameters of the link, including transmit powers, receiver sensitivity, fiber link losses and performance objectives are used to determine the theoretical performance expectations of the optic fiber system. It is also required to calculate the maximum operating bandwidth of the fiber optic system, that is, the maximum data rate the system will support. The second section of this chapter discusses how to calculate the loss budget and bandwidth budget for a fiber optic link. A software package is available from the author's website that can be used to automatically calculate the power budget and bandwidth budget for each link, by entering the required parameters into the spreadsheet.

The third requirement is to determine the cost of the system that has evolved from the design steps discussed above. Once a budgetary cost has been calculated, then a cost/performance analysis can be carried out. There will always be trade offs between the cost of the system and its preferred level of performance. The main issues involved in determining the most cost-effective system design and the compromises that are available are incorporated in the discussions of the first section of this chapter. A costing package is included in the software that is available from the author's website.

8.1 Initial design considerations

A number of design considerations have been discussed in previous chapters. This section will briefly review these requirements and will examine some new considerations.

8.1.1 Data transmission technology

The fiber optic system design will be developed and prepared around the initial data services proposal and planned requirements. The transmission system technology that is chosen will depend on the user's application, transmission speed, and capacity requirements. An overview of the different types of technologies that are available is provided in Chapter 10. It is vital that all the data requirements of the organization are extracted from the personnel concerned before design begins. This will ensure that the systems that are installed will cater to all the organization requirements.

8.1.2 Transmission parameters

Considerations during the design phase include the data rate requirements, the bandwidth requirements and the transmission distances. These parameters have been discussed at length in other sections of this book.

8.1.3 Future data transmission capacity growth

During the design of a fiber optic system, it is extremely important that the expected future system growth of data transmission at a site be determined. It is the author's experience that if there is availability of communications capacity, no matter how large, someone will find a reason to use it.

It is far cheaper to accommodate the future fiber optic cable requirements in the initial installation phase than to upgrade the cable installation at a later date. The cost per meter of fiber in a fiber optic cable can be lower than one hundredth of the cost of digging the trench to bury it. For example, if it cost 20 cents per meter for a single fiber within a cable, it could cost up to $20.00 per meter to dig a trench, bury a conduit and pull a cable through it (though the cable itself may contain 96 fibers and cost $25.00 per meter). Therefore, the cost of adding extra fibers in a cable run is often almost insignificant in the total cost of the project. For this reason, it is considered prudent to over design the fiber optic system transmission capacity and bandwidth and avoid enormous cost blowouts at a later date.

For cable runs of hundreds or thousands of kilometers, the cost of the cable/fiber will become a much larger percentage of the total system cost. This is usually the case for systems put in by large telecommunications companies. The typical proportional cost for a cable in a system is illustrated in Figure 8.1.

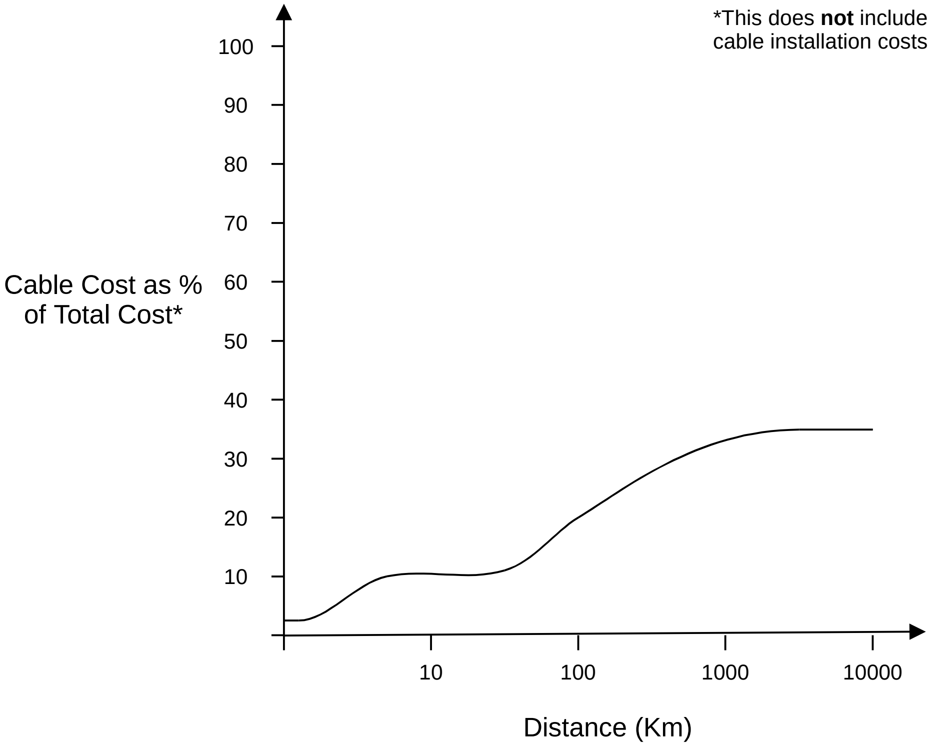


Figure 8.1
A comparison of cable costs and distance

8.1.4 Reliability

One of the most difficult design considerations to account for is the system reliability. The most fundamental consideration in system reliability is the manufactured quality of the transmitting and receiving equipment, data network/processing equipment, and the fiber optic cable. This is often a subjective problem, especially when every supplier will tend to claim that they have the best quality equipment! Seeking advice from independent consultants, talking to a number of other users and reading the appropriate trade magazines will provide a good idea of what are the relative merits of each make of equipment.

Reliability will also depend on the level of the physical design that is implemented. For example, the two extremes of cable installation would be, firstly, a very high reliability system where the cable is steel armored, buried in conduit in 0.5 m of concrete at a depth of 5 m. Secondly, a very low reliability system requirement would be where a standard plastic sheathed cable is simply just laid across the ground without any protection. Other factors to be considered here include the quality of pit boxes, splice encasings, termination cabinets and the degree of locking and environmental protection that is required of them.

Over designing a system will add significant cost to the overall project. Therefore, there has to be a trade off between an acceptable level of reliability and a cost-effective system.

The majority of system failures are caused by human error. The two all time classics are someone digging the cable up with a shovel or a backhoe and secondly, a technician cutting the wrong cable when carrying out maintenance on the system. To help avoid these problems, run the cables through areas where they are less likely to be tampered with, clearly mark the cables at all termination points and ensure that the system is thoroughly documented and that the documentation is kept up to date.

As part of this cost analysis equation, it is essential that other types of transmission technologies be considered. For example, it may be more cost effective to install a microwave link or use public telecommunications facilities for all or certain sections of the communications route. In this case, data rates and leasing costs need to be taken into account. Figure 8.2 provides an example comparison of technologies with an illustration of some of the advantages and disadvantages of using microwave radio or fiber optic cable over a 30 km route.

	Digital capacity	**Cost of equipment for a 30 km route**	**Possible advantages**	**Possible disadvantages**	**Risks to system reliability**
Radio	34 MB to 155 MB	$150 K	High capacity Simple to install relatively easy to secure sites	Interruptions due to extreme rain	Lightning sabotage access to repeater sites
Fiber cable	34 MB to 622 MB	$240 K cable $120K equipment	Very high capacity secure against storm damage	High installation cost may require land permits etc	Termites roadworks farming sabotage floods

Figure 8.2
Some comparisons between radio and fiber cable systems

8.1.5 Selecting an operating wavelength

One of the first decisions to be made before detailed system design can begin in earnest is the selection of the system operating wavelength. Generally, the fiber wavelength used is dictated by the application that it is to be used on the system. For example, the fiber distributed data interface (FDDI) standard (refer to Chapter 10) requires transmission at the 1300 nm wavelength.

Once a wavelength is chosen, it is recommended that it may be used throughout the entire network. This will avoid problems with compatibility of the transmitter and receiving equipment as well as having to double up on spares and the test and maintenance equipment.

The 850 nm wavelength is often used for slow speed short distance links. For example, data rates up to approximately 20 Mbps and distances up to approximately 3 km are possible.

The 1300 and 1550 nm wavelength will provide the high data rates and the longer transmission distances discussed in previous chapters. But as a result, the system costs increase significantly.

As a general design rule, it is always preferable to choose the shortest possible wave length of operation that will still provide satisfactory data rates and transmission distances for the application in which it is to be used simply because of the cheaper costs.

8.1.6 Cable type selection and installation route

The next step in the design process is to select the cable type to suit the application and the route that the cable will follow. These aspects of system design are discussed in detail in Chapter 7. The following provides details of a number of additional requirements.

It is worth noting that due to the economics of scale in production (there is far more singlemode fiber produced than multimode), coupled with the extra material costs, multimode fiber is generally more expensive than singlemode fiber.

Low loss, high bandwidth fiber will accept less light than higher loss, lower bandwidth fibers. This is because the latter fibers have larger NAs. Therefore, over relatively short distances, it is generally more cost effective, and will provide less signal attenuation, to use the multimode fiber, which has the higher intrinsic loss. The cost might slightly be more but multimode fiber collects the light far more efficiently from the significantly lower cost LED light sources.

The topology of a data network (the physical layout), is generally determined by the type of network that is to be installed. The topology that is chosen (star, bus or ring as illustrated in Figure 8.3) can significantly affect the overall cost of the project. Different types of networks will use different lengths of cable and different types and numbers of transmitter and receiver devices. This needs to be carefully evaluated during the design phase.

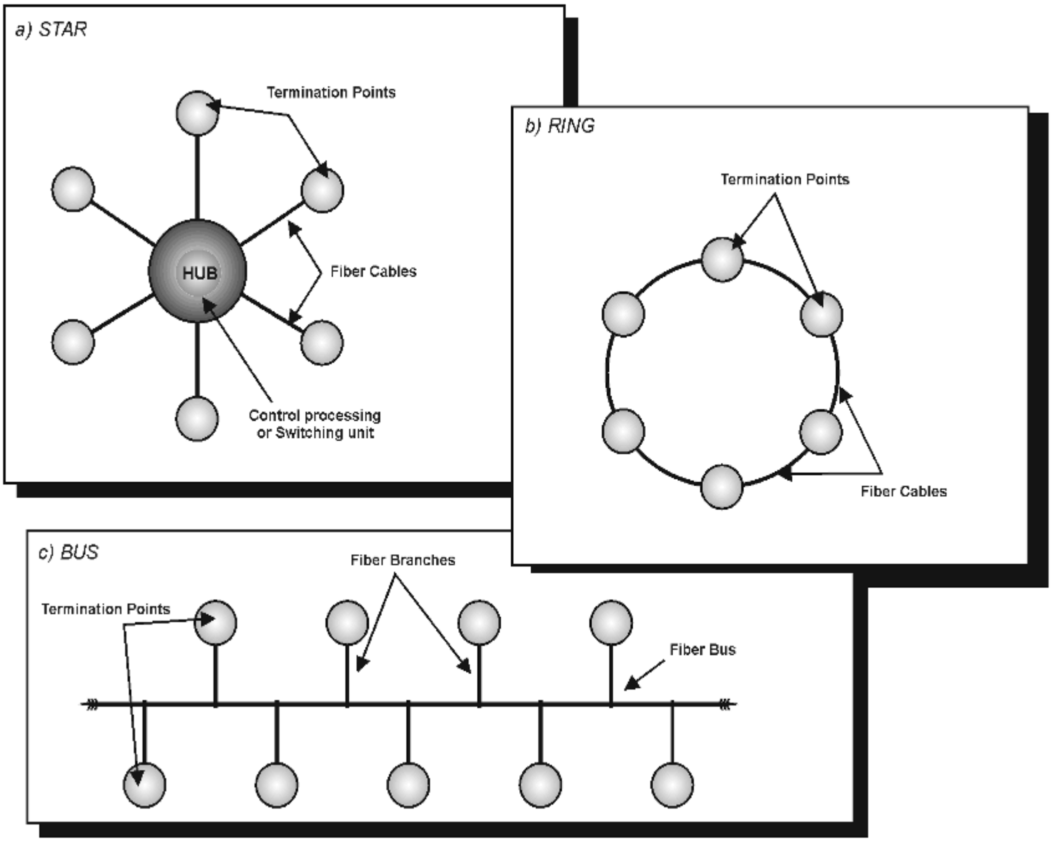


Figure 8.3
Illustration of star ring and bus topologies

It is also advisable to consider the relative merits of route duplication and/or alternative routing. This subject can become very complex and is beyond the scope of this book. It is advisable to seek professional advice for this level of design, as it will have a significant affect on the overall cost and reliability of the network.

During system design, remember to add the extra costs of cable slack requirements, splice enclosures, termination cabinets and patch panels that were discussed in Chapter 7.

8.1.7 Repeaters and amplifiers

For long cable runs where the attenuation introduced by the cable, connectors and splices drops the transmitted signal level below the minimum level required by the receiver, an insitu repeater, or an amplifier is required. The amplifier can be placed directly between the transmitter and the cable or between the receiver and the cable or can be placed at any distance along the cable. The amplifier simply increases the level of the incoming signal. Because the amplifier does nothing to the incoming signal, except amplifying it, the amplifier will inherently add noise to the outgoing signal.

The repeater, on the other hand, is installed at a distant point along the cable where the signal has dropped to the near minimum acceptable level. It takes the weak incoming light pulse, which will also have suffered from dispersion; it regenerates this pulse into a new square shaped pulse and then amplifies it and transmits it onto the next section of cable. This will inherently remove noise from the signal.

To determine whether repeaters and amplifiers are required, loss budgets must be calculated. This procedure is discussed in section 8.2.

If possible, avoid repeaters because they require maintenance and are generally expensive capital items. Optical amplifiers are not very effective and may also be very expensive.

It is important that a thorough cost analysis is carried out of various alternatives to using repeaters and amplifiers. For example, it may be cheaper to use a single long cable run of high quality singlemode fiber with laser sources than to use multiple hops of multimode fiber cable with repeaters and LED sources. On the other hand, the reverse of this scenario may be true.

8.1.8 Transmitter and receiver equipment selection

Once the design is complete for the parameters discussed in the previous sections, it is then possible to select the required transmitters and receivers to match these design parameters of the system.

If a particular standard of data transmission is being installed, for example, gigabit Ethernet, then the transmitter and receiver modules will be designed to operate to a very stringent set of standards that all manufacturers are required to adhere to. In this case, it should be possible to interface equipment from different manufacturers and they should communicate successfully.

If the system to be installed does not conform to a particular standard, then it is wise to have matched transmitter and receiver module sets from one source of manufacturer for each route. Unfortunately, although the transmit and the receive modules from different manufacturers may claim to adhere to a single physical standard, quite often, they will not communicate with each other at a physical level. It is recommended that the same type and model of transmitter and receiver modules from a single manufacturer be used throughout, until the completion of installation. This will assist in simplifying maintenance procedures and will reduce the spares holding requirements.

The parameters that must be considered before selecting a transmitter and receiver module set are:

- The maximum data transmission rate requirement
- The wave length of operation
- The maximum transmission distance requirement
- The losses introduced along each route
- The maximum dispersion expected along the link
- The maximum permissible rise time for each component and for the system as a whole
- Whether a LED or a laser source is preferred
- The NA and diameter of the fiber to be used and the required NA and diameter of the source and detectors to match
- Matching the transmitter and receiver modules to the chosen fiber
- The required data encoding to be used, if it is carried out by the transmitter and receiver modules (NRZ, Manchester etc)
- Whether it is a commercial or industrial application
- The required reliability of the equipment
- The required availability of each link (including anticipated BER)

Wherever possible, it is preferable to use LEDs rather than lasers as they are significantly cheaper; they require less protection from the environment and are more stable and less sensitive to physical stress and vibration.

At present, the 1300 nm light sources are cheaper than the 1550 light sources. If 1550 nm sources are to be used, they must have a very narrow spectral width and should be used with dispersion compensated fibers.

8.2 Design loss calculations

The next step in designing a fiber optic system is to determine whether each separate section of cable link in a system is going to operate or not, and what level of performance it is going to provide. The main objective here is to determine whether there will be enough power left in the transmitted signal for it to activate the receiver when it reaches the end of the cable, and will the signal be sufficiently free of noise and dispersion so as to be interpreted correctly. The following section provides a detailed description of the procedures and calculations required to carry out a loss budget and a bandwidth budget. Firstly, it will look at the definition of and derivation of the parameters that are used in calculating loss budgets.

8.2.1 Definition of parameters

- **Transmitter power**
  The accepted method for measuring transmitted power out of an optical light source is a *de facto* arrangement, where a piece of fiber approximately 2 m in length is attached to the light source and the output power is measured at the end of the fiber. Using this method accounts for mismatches between the fiber and the light source such as fiber core/light source size and NA differences and any other sources of power loss at the source to fiber interface. An optical transmitter specification is therefore generally specified with a matching cable size and type.

- **Minimum transmit power**

  The manufacturer will generally quote the minimum transmit power that can be expected from the light source over its operating lifetime. This figure should be used in the calculations to ensure that the calculated loss budget is within the acceptable limits.

  The output power figure that is specified will be either peak power or average power and will be specified in dBms. The important point to remember here is to use the same power measurement type (peak or average) for the transmitter and receiver in the calculations. If the measurement types are different, then the loss budget figures could be incorrect by 3 dB or more.

- **Receiver sensitivity**

  For a particular optical detector, the manufacturer will quote the minimum level of signal power that is required at the receiving end of the fiber to activate the receiver. This minimum allowable receive signal level is referred to as the receiver sensitivity. The quoted receiver sensitivity will be the minimum receive signal level that is required to provide a data output from the receiver with a worst bit error rate (BER) of 10^{-9} or 10^{-12}.

  There are two important points to be noted concerning receiver sensitivity. As the data rate increases, a receiver will require an increase in the minimum input power (receiver sensitivity) to maintain the same BER. Secondly, if the data rate remains the same and the transmitter input level drops only slightly, the bit error rate can increase significantly. For example, if the received signal level drops 1 dB below the receiver sensitivity the bit error rate could drop to 10^{-6}.

- **System gain**

  The system gain is a figure that represents the total available optical power between the optical source and the optical detector. Therefore, the system gain can be represented as the numerical difference between the transmitter output power and the receiver sensitivity.

- **System losses**

  Losses to the optical signal (attenuation) over a fiber optic link are caused by natural fiber attenuation, splicing losses, connector losses, coupling losses, dispersion losses, losses due to component aging and variations over time of environmental losses. (For example, temperature, physical stress, damaged fibers.)

- **Safety margin**

  The component losses due to aging and variations over time of the environmental losses are not directly calculable and are accounted for by leaving a safety margin in the design. This margin also helps to account for small design errors and for additional splices that may be required at a later date if the cable is broken.

  Manufacturers also sometimes specify a figure referred to as the receiver power penalty. This is a power safety margin figure that is to compensate for jitter, bandwidth limitations, dispersion and clock recovery problems that may be encountered by the receiver and reduce its effective receiver sensitivity. This power margin should also be covered by the system safety margin.

  The author recommends that the designed safety margin be somewhere between 5 and 10 dB.

- **Dynamic range**

  The receiver detector will have a maximum limit to the signal power that it can receive without going into distortion. The difference between the maximum power that it can receive and the receiver sensitivity is referred to as the dynamic range.

  When designing a system, it is important that the dynamic range of the receiver is not exceeded. Sufficient attenuation must be available in the fiber route to ensure that it does not occur. In some cases, it may be required to insert additional attenuation into the fiber section.

- **Transmitter to fiber coupling loss**

  Coupling from LEDs into fibers results in a significant amount of the power from the LED being lost because the LED has a very large surface area compared to the surface area of the fiber core. For example, an LED coupled to a 50 μm core diameter fiber will lose about 15 dB of the transmitted power to coupling loss. If the LED is producing 0 dBm.

  (1 mW) of output power, then only –15 dBm (32 μW) of power is getting into the core of the fiber for transmission. Losses from an LED into a single mode fiber are significantly higher (approximately 35 dB) and are therefore almost never used as a combination.

  Lasers generally have a surface area that is much smaller than the core of a singlemode fiber and therefore, the coupling losses are relatively small. Several milliwatts of power can be coupled into a singlemode fiber from a laser.

  As mentioned earlier, the manufacturer will generally specify the output power of an optical source as the power that is available after several meters of fiber and not the power directly from the source itself.

- **Fiber to receiver coupling losses**

  For both singlemode and multimode fibers, the detectors have a much larger surface area than the optical fiber cores and therefore, there is only a very small coupling loss incurred (mostly due to internal Fresnel reflection).

- **Link loss budget**

  If the safety margin is subtracted from the system gain, the remaining figure is the link loss budget. This figure represents the maximum amount of signal loss available during the design process for cable attenuation, splicing losses and connector losses. Some manufacturers will provide a link loss budget figure with their transmitter and receiver equipment which will take into account safety margin and system gain. This concept is illustrated in Figure 8.4.

- **Fade margin**

  Given that the length of the cable run is known, then the total known loss can be calculated (for connectors, splices, cable length). If this figure is subtracted from the link loss budget, then there should be a positive value. This is known as the fade margin and it represents the amount of unused system gain.

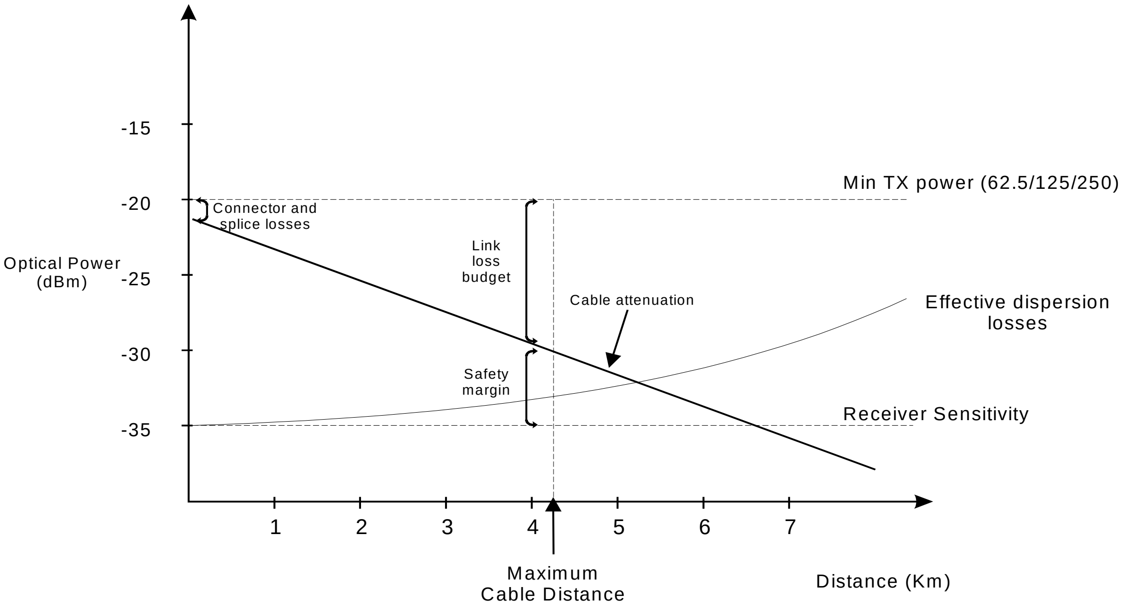


Figure 8.4
Illustration of link loss budget and safety margin

8.2.2 Methodology for loss budget calculations

The following is a step by step approach to designing the power loss budget of a fiber optic link:

- **Power into fiber**
  Generally, the transmitter power that is quoted by the manufacturer is the power into the fiber. If not, then the coupling loss must be determined.

  * Power into fiber (dBm) = TX power (dBm) – coupling loss (dB)

- **Calculate the system gain**
  Subtract the receiver sensitivity, for a given bit error rate from the minimum transmit power. Both values must be in the same type of units (the most common being dBm) and must be of the same measurement type (average power or peak power). The system gain will then be represented in decibels.

  * System gain (dB) = TX power (dBm) – RX sens. (dBm)

- **Determine the safety margin**
  Either calculate the safety margin or allow a suitable figure. The safety margin is represented in decibels.

  * Safety margin (dB) = Environmental factor (dB) + Aging factor (dB)
  + Dispersion factor (dB) + Jitter factor (dB) +
  Repair factor (dB) + Design error margin (dB)

- **Calculate the link loss budget**
  Determine the maximum allowable loss for the end-to-end optic fiber cable link section by subtracting the safety margin from the system gain.

  * Link loss budget (dB) = System gain (dB) – Safety margin (dB)

- **Calculate the total connector losses**
  Calculate the total connector losses in a link section of optic fiber by multiplying the number of connectors in that section by the loss per connector (in dBs).

  Total Connector Losses (dB) = Connector Loss (dB) × number of connectors

- **Calculate the total splice losses**
  Calculate the total splice losses in a link section of optic fiber by multiplying the number of splices by the loss per splice (in dBs).

  * Total Splice Losses (dB) = splice loss (dB) × number of splices

- **Calculate other possible losses**
  Calculate other losses to the system by adding together losses due to passive components in the optic fiber route. For example: passive stars, combiners, splitters, etc.

- **Calculate the maximum allowable cable attenuation**
  Each section of fiber link should be analyzed to determine the maximum allowable fiber optic cable attenuation. This is calculated by subtracting the connector losses, splice losses and other losses from the link loss budget.

  *Allowable cable attenuation (dB) = Link loss budget (dB) – Connector losses (dB) – Splice losses (dB) – other losses (dB)

- **Calculate the maximum normalized cable attenuation**
  For each section of optic fiber, determine the maximum allowed decibels per kilometer (dB/km) attenuation rating. This calculated figure is then compared to the manufacturer's attenuation figures to determine which cables are suitable for each section. The figure is calculated by dividing the maximum allowable cable attenuation by the total cable length.

  $$\text{* Max. norm. cable atten. (dB/km)} = \frac{\text{(max. allowable cable atten.(dB))}}{\text{(total cable length (km))}}$$

- **Choose the required fiber grade**
  Once the maximum normalized cable attenuation figure has been calculated, choose the appropriate fiber optic cable grade to match. The fiber grade (db/km) should be equal to or less than that calculated earlier in this section.

- **Calculate the fiber loss for each cable section**
  Calculate the expected signal attenuation from each section of optic fiber, by multiplying the cable length for a section by the specified normalized cable attenuation of the chosen cable.

* Fiber loss (dB) = fiber length (km) × norm. cable atten. (dB/km)

- **Calculate the received signal level**
  Determine the power level of the signal at the end of the fiber that is entering the receiver. This is calculated by subtracting all the losses along the cable section from the transmit power into the fiber.

  *Received signal level (dBm) = transmit power (dBm) – fiber loss (dB) – connector losses (dB) – splice losses (dB) – other losses (dB)

- **Check dynamic range**
  Ensure that the receive signal level at the end of the fiber section does not exceed the maximum permitted signal level allowed into the receiver. This is calculated by adding the dynamic range to the receiver sensitivity and ensuring that the receive signal level is less than this result.

  * Received signal level (dBm) < Receiver sensitivity (dBm) + Dynamic range (dB)

8.2.3 Example calculation

The specifications for the system are as follows:

light source	LED
fiber type	50/125/250 graded
operating wavelength	850 nm
minimum TX power into fiber (average)	–17 dBm
receiver sensitivity	–40 dBm
dispersion margin	0.5 dB
jitter factor	0.2 dB
dynamic range	14 dB
connector loss	0.8 dB
splice loss (mechanical)	0.5 dB
number of connectors	4
number of splices	3
section in length	3.48 km

Following is the procedure that was discussed in section 8.2.2:

a) power into fiber = –17 dBm

b) system gain = (–17 dBm) – (–40 dBm) = 23 dB

c) Let :

environmental factor = 1 dB
aging factor = 2 dB
repair factor = 1 dB
design error factor = 2 dB

and :

dispersion factor = 0.5 dB
jitter factor = 0.2 dB

therefore:
safety margin = 1 + 2 + 1 + 2 + 0.5 + 0.2 = 6.7 dB

d) link loss budget = 23 dB – 6.7 dB = 16.3 dB

e) total connector losses = 4 × 0.8 dB = 3.2 dB

f) total splice losses = 3 × 0.5 dB = 1.5 dB

g) no. of other losses

h) maximum allowable cable attenuation = 16.3 – 3.2 – 1.5 = 11.6 dB

i) maximum normalized cable attenuation = 11.6 dB/3.48 km = 3.33 dB/km

j) Using the result in (i) as a reference, the cable chosen was a Belden model 227417, which has a maximum normalized attenuation of 3 dB/km and a bandwidth of 600 MHz.km at 850 nm.

k) Fiber loss = 3.48 km × 3 dB/km = 10.44 dB

l) Received signal level = –17 dBm – 10.44 – 3.2 – 1.5 = – 32.14 dBm

m) Check dynamic range – 32.14 dBm < (– 40 dBm + 14 dB) = – 26 dBm

8.3 Design bandwidth calculations

The next requirement in fiber optic system design is to determine whether the link system has sufficient bandwidth to support the data speed requirement of the system. As the greater majority of fiber optic links are used for digital transmission, this discussion will look at the bandwidth requirements for standard digital transmission.

8.3.1 Time response

The simplest method of evaluating the bandwidth requirements of a transmission link system is to examine and compare the time responses of the signal and the transmission system. This avoids (some mathematicians would argue ‘incorrectly’) the requirement to analyze the system and the signals from a frequency perspective, which can become quite complex.

The light signal that emanates from the transmitter will be in the form of a square wave. If it is a non return to zero (NRZ) waveform then it will have a signal period equal to one bit period. Therefore for a data transmission rate of R and a pulse duration of T:

$$T = 1/R$$

This is illustrated in Figure 8.5 below.

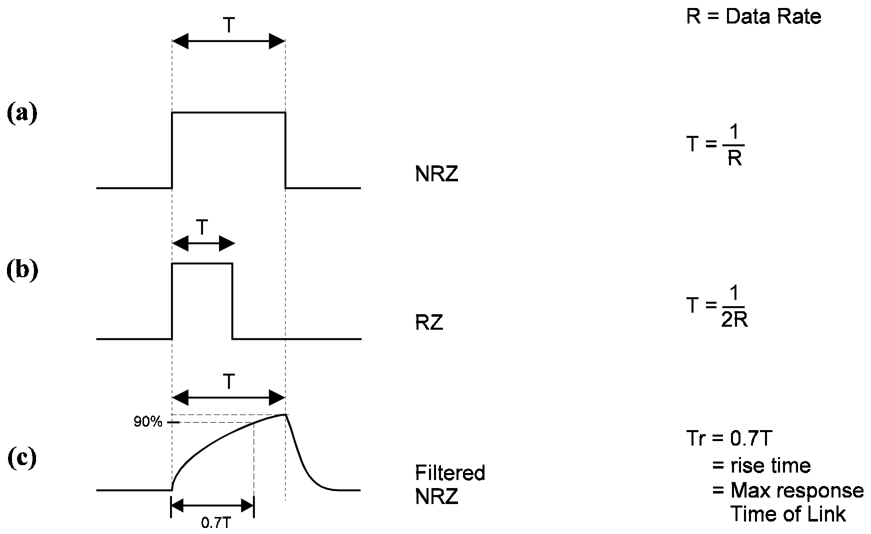


Figure 8.5
Illustration of pulse duration and time response

For example, if the signal has a period of 1 μs (1 × 10^{-6} seconds) then the data transmission rate is 1 Mbps for an NRZ signal.

In theory, the link system (the link system includes the transmitter, receiver and optic fiber cable) time response must be faster (shorter response period) than the signal response time (signal rise time) for the signal to pass through it successfully. The fiber optic link can be conceptualized as a low pass filter, whose cutoff frequency must be higher than the highest frequency component of the signal that is attempting to pass through it. If the transmission link system time response is too slow, then the pulses coming out of the receiving end of the link system will have their rise times slowed down by the system response time and will be overlapping each other.

The low pass filtering effect of the link system on the square input pulse produces a curved pulse at the receiver output as illustrated in Figure 8.5 (like the charging and discharging of a low pass filter or capacitor). In order to define a limit to the time response of the link system, an often used rule of thumb is to assume the worst case (slowest response time of the system). It means, where the pulse coming out of the receiver has risen to either equal to or greater than 90% of the input pulse amplitude in 70% of the input pulse period. That is, the rise time of the link system should be no more than 70% of the input pulse duration.

$$T_r = 0.7T = 0.7/R$$

where:

T_r is the system rise time
T is the input pulse period

The allowable rise time then becomes the maximum allowable link system time response. For example, if the link system is required to be able to transmit a data rate of 1 Mbps, where the pulse duration of the input signal for an NRZ pulse is 1 μs, the required link system maximum time response is:

$$0.7 \times 1\ \mu s = 0.7\ \mu s$$

The 0.7 µs time response represents a fiber link system minimum bandwidth requirement of 1/(0.7 µs) = 1.43 MHz to successfully transmit the 1 Mbps signal.

If the signal is a return to zero signal, then the pulse period is half that of the non return to zero signal. This is illustrated in Figure 8.5b. The required system link time response is:

$$T_r = (0.7 \times T)/2 = 0.35\ T = 0.35/R$$

8.3.2 Overall system time response

To calculate the overall time response for a fiber optic transmission link system, take the square root of the sum of the squares of the time response of each individual component. This is represented as:

$$T_s = \sqrt{\Sigma(T_i^2)}$$

where:

T_s = the system time response
T_i = time response of each individual component

The only components that affect the time response of a system to any degree are the transmitter, receiver and the length of optic fiber. Passive devices such as couplers, stars, connectors and splices do not cause any noticeable effect to the system time response. Therefore, the system time response becomes:

$$T_s = \sqrt{\Sigma\ (T_t^2 + T_r^2 + T_f^2)}$$

where:

T_t = time response of the transmitter
T_r = time response of the receiver
T_f = time response of the optic fiber

8.3.3 Optical fiber time response

The optical fiber rise time T_f is affected by two factors; modal dispersion and chromatic dispersion. The total effect of both dispersions is found by using the sum of squares formula on the separate time responses that result from each dispersion.

The time response that is caused by modal dispersion is given by:

$$T_{fm} = Dm \times L$$

where:

T_{fm} = time response from modal dispersion (ns)
Dm = modal dispersion (ns/km)
L = fiber length (km)

To determine a value for modal dispersion, we can assume that the maximum bandwidth of a fiber correlates directly to the minimum modal dispersion that can be attained from that fiber.

The supplier will normally quote the 3 dB bandwidth of the fiber. In that case, a rule of thumb formula is used to calculate *Dm* is:

$$Dm = \frac{350}{\text{Bandwidth}\,(3\,\text{dB})}$$

where the bandwidth is in MHz /km.

If the supplier provides a figure for 'modal bandwidth,' it is simply a matter of inverting this value:

$$Dm = \frac{1}{\text{Bandwidth}\,(\text{Modal})}$$

Another method is the calculation modal pulse spreading using the following formula:

$$T_{\mathrm{p}} = \frac{(NA)^2(L)}{(2N \times C)}$$

Where:

NA = Numerical aperture
L = Length
N = RI of core
$C = 3 \times 10^8$

Optical pulse spreading can be converted into electrical rise time through the following:

$$T_{\mathrm{fm}} = 0.44\ \mathrm{Tps}$$

The first of the two methods is preferred because it is being calculated from an actual measured figure provided by the supplier, of a complete 1 km length of the cable. The second method is based on many assumptions and tends to give rather spurious results.

The time response that is caused by chromatic dispersion is given by:

$$T_{\mathrm{fc}} = D_{\mathrm{c}} \times \Delta\lambda \times L$$

where:

T_{fc} = time response from chromatic dispersion (ps)
D_{c} = chromatic dispersion (ps/nm-km)
$\Delta\lambda$ = spectral spread (range of wavelengths) of the optical source (nm)
L = length of fiber optic cable (km)

The manufacturer in the optical fiber specification provides the chromatic dispersion figure.

Therefore the time response T_{f} of the fiber is given by:

$$T_{\mathrm{f}} = \sqrt{}\Sigma(T_{\mathrm{fm}}^2 + T_{\mathrm{fc}}^2)$$

For multimode fibers, note that modal dispersion is the significant problem and chromatic dispersion to a lesser extent but for singlemode fibers, modal dispersion becomes negligible and chromatic dispersion becomes the major factor.

8.3.4 Transmitter and receiver time response

The time responses for the optical transmitters and receivers are provided in the manufacturers' specification sheets. For LED transmission systems, which are generally short distance, the source and detector time responses are slow compared to the optical fiber time response. For example, a typical time response for a transmitter is approximately 6 ns and for a detector, approximately 10 ns. Over 1 km of fiber the time response may only be 2 ns.

For laser transmitters and receivers, the time responses are generally less than 0.5 ns and for a singlemode fiber, the time response would generally be significantly less than 0.01 ns over a 1 km link.

8.3.5 Example of bandwidth calculation

A fiber optic transmission system has the following specifications:

light source	LED
spectral spread of LED	45 nm
fiber type	50/125/250 graded
operating wavelength	850 nm
bandwidth (3 dB)	600 Mha-km
chromatic dispersion	110 ps/(nm-km)
NA	0.2
section length	3.48 km
transmitter rise time	6 ns
receiver rise time	9 ns
signal type	NRZ

a) The first step is to calculate the modal dispersion for the fiber using the first rule of thumb formula.

$$Dm \frac{350}{600} = 0.58 \text{ ns/km}$$

b) Calculate the time response caused by modal dispersion:

$$\begin{aligned} T_{fm} &= Dm \times L \\ &= 0.58 \times 3.48 \\ &= 2.02 \text{ ns} \end{aligned}$$

c) Calculate the time response due to chromatic dispersion for the fiber:

$$\begin{aligned} T_{fc} &= Dc \times \Delta\lambda \times L \\ &= 110 \times 45 \times 3.48 \\ &= 17226 \text{ ps} = 17.226 \text{ ns} \end{aligned}$$

d) Calculate the overall time response for the fiber:

$$\begin{aligned} T_f &= \sqrt{\Sigma}(T_{fm}^2 + T_{fc}^2) \\ &= \sqrt{\Sigma}\,((2.02)^2 + (17.226)^2) \\ &= 17.34 \text{ ns} \end{aligned}$$

e) Calculate the overall time response of the link system.

$$T_s = \sqrt{\Sigma}(T_t^2 + T_r^2 + T_f^2)$$
$$= \sqrt{\Sigma}((6)^2 + (9)^2 + (17.34)^2)$$
$$= 20.44 \text{ ns}$$

f) The figure calculated in (e) represents the minimum time response from a signal that would successfully pass down the link system. That is, the 20.44 ns is the fastest time response that is possible from the link system. The signal must have a slower time response than the system to pass through it successfully. Therefore, to calculate the maximum data rate that the link system can support, this time response figure shall be a minimum of 0.7 of the pulse duration of the digital signal.

$$T_s = 0.7\text{T} = 0.7/R \left(T = \frac{1}{R} \right)$$
$$20.44\ 10^{-9} = 0.7\,T = 0.7/R$$

where:

$T = 29.2 \times 10^{-9} = 1/\text{R}$
$R = 34.25$ Mbps (NRZ)
$R = 17.12$ Mbps (RZ)

With the maximum data speed calculated for this link segment, it can now be determined if this matches the requirements of the proposed technology. For example, this link would be suitable for an Ethernet FOIRL. It is also worth noting from the figures used in (d) and (e) that the major limiting factor here is the chromatic dispersion. This is more significant than modal dispersion because an LED is being used at 850 nm, which has a very wide spectral width and high chromatic dispersion at the 850 μm wavelength, over a relatively long distance. If an LED operating at 1300 nm (which is closer to the zero dispersion wavelength with a chromatic dispersion approximately 5 ps/nm/km) then modal dispersion would become the major limiting factor. It would be so if laser were to be used (which has a spectral width of approximately 3 nm) or the link were operating over a shorter distance, (but of course, the modal dispersion will also be very low due to the very small number of modes emitted by a laser).

9

Testing of fiber optic systems

Introduction

Once a fiber optic link system has been installed, it is vital that the link be thoroughly tested to ensure that it would perform to the design specifications. The testing of the fiber optic system, both during installation and then for system commissioning is a mandatory part of the project. The commissioning tests that are performed will determine if the final installed fiber optic cable is continuous and stable, whether any damage has been caused to the cable during installation, whether the losses calculated during the design stage due to splices, connectors, fiber length, etc, are correct and whether the final installed system is operating to an acceptable level of performance.

If the system has been carefully designed and then correctly installed, the commissioned test results should generally provide better performance figures than the designed parameters (assuming that a conservative design approach was taken). On rare occasions, the link will perform worse than designed. This may be due to unexpected excess bending losses. The link will also undergo deterioration in performance during its lifetime, which should have been accounted for in the design process. The safety margin to account for these unpredictable losses will also be confirmed during the commissioning tests.

This chapter examines the requirements for testing fiber optic cables and optical transmitter and receiver equipment. The first part of the chapter examines the fundamental concepts that are specific to taking optical measurements. The second part of the chapter examines in detail the main fiber optic tests that are normally performed on pre-installed and final installed fiber optic cables and equipment. Finally, a number of other less common tests associated with performance of final installed systems are discussed.

9.1 Fundamental concepts of optical measurement

9.1.1 Optical power

The fundamental unit of measure used in fiber optics is light power. As with electric power, optic power is measured in watts.

Light has similar properties to electricity. Light energy like electric energy is theoretically in the form of a sinusoidal wave. Therefore, the basis of the mathematical formulas that are used for calculating power related measurements with electric power could also be used for calculating power related measurements with optical power.

The following analogies apply to optical measurements:

- Power is a measure of the rate of transfer of energy (where energy is measured in joules 'Q'). That is:

  $$P = \mathrm{d}Q/\mathrm{d}t$$

- Power is a measure of voltage (V) and current (I). A light wave has an electric field and a magnetic field, which is analogous to the voltage field and the current field in electrical energy. Therefore:

  For electric energy:

  $$P = VI$$

  For light energy:

  $$D = \varepsilon E$$
  $$B = \mu H$$
  $$S = EH$$

  Where:

  D = Electric flux density
  B = Magnetic flux density
  E = Electric field intensity
  H = Magnetic field intensity
  ε = Permitivity of the medium
  μ = Permeability of the medium
  S = Energy density (watts/square meter)

- Light energy is directly proportional to the square of the amplitude of the electromagnetic wave. Power in electrical energy is directly proportional to the square of the voltage or current amplitudes.

  $$P = V^2/R$$
  $$= I^2R$$

In the case of light energy, the resistance would in effect, be the permeability and permitivity of glass.

For light, the total energy Q is given by:

$$Q = NQ_\mathrm{p}$$

where:

Q_p is the energy of a single photon
N is the number of photons

Therefore:

$$\text{Power} = \frac{\mathrm{d}(NQ_\mathrm{p})}{\mathrm{d}t}$$

Light power measurements are generally performed and specified in decibel units. The discussion in section 2.3 concerning decibel measurements also applies to optic measurements.

The signal that emanates from an optic transmitter will be in the form of pulses. The level of power that it is transmitting is continually varying. The measurement of this power can be as an instantaneous peak or as an average. In general, the measurement and specification of optic power is as an average power. This is illustrated in Figure 9.1.

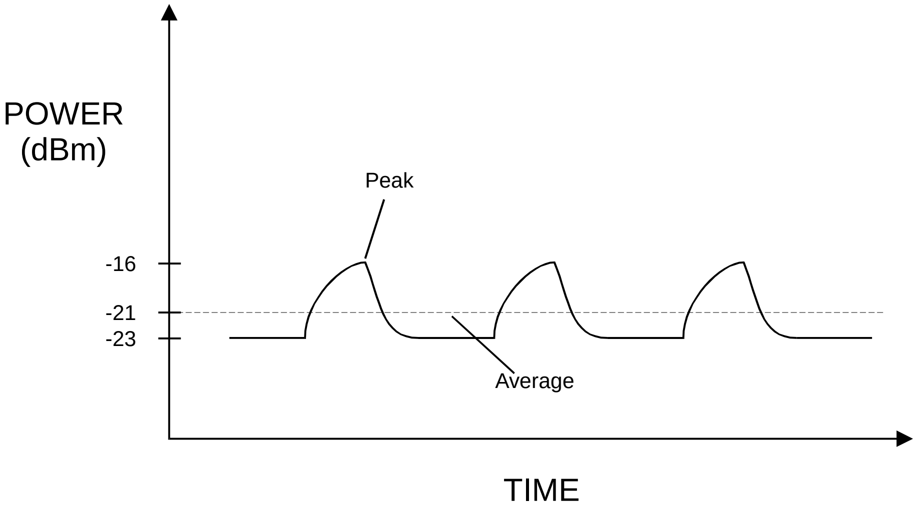


Figure 9.1
Power for received optical waveform

Power is also directly proportional to the frequency of the electromagnetic wave and inversely proportional to the wavelength of the electromagnetic wave (as $C = \lambda \times f$). Light is theoretically in the form of tiny particles called photons, which are emitted from atoms as electrons move up and down various energy layers that surround atoms. As frequency increases (that is wavelength decreases), there is a proportional increase in the energy in the photon. This, in effect, means that it takes more energy to excite an electron to produce a high frequency photon than to produce a low frequency photon. Therefore, as the measurement of optical power is the measure of the flow of photons per unit time, optical power is directly proportional to frequency and inversely proportional to wavelength. This relationship is described in Planck's law:

$$Q = h \times f$$

where Q is the energy in the photon and h is Planck's constant.

9.1.2 Power measurement

Different materials that are used to manufacture light detectors are sensitive to different wavelengths. For example, silicon detectors respond strongly to 850 nm wavelengths while indium gallium arsenide (InGaAs) detectors respond strongly to 1300 nm and 1550 nm wavelengths. Therefore, light detectors that are used for power measurement purposes have to be calibrated for the frequency they are to measure.

Detectors will only provide a linear response over a limited dynamic range of input signal level. Therefore, they must be calibrated for a particular application and the anticipated range of powers at the end of the fiber optic cable into detector.

The response time of a detector in a light meter is very slow when compared to the speed of the incoming pulses. Therefore, most optical power meters are calibrated for measuring average power.

9.1.3 Optical and electrical bandwidth

Bandwidth is specified in two different forms, optical and electrical. Optic bandwidth refers to the highest modulation frequency at which the output of the optical system has dropped by 3 dB compared to the lower frequency optical responses. Because of the optical to electrical conversion process in an optical detector, a 3 dB drop in the optical power results in a 6 dB drop in the electric power reading. The measurement of electric bandwidth uses the same rule as optic bandwidth; the electric bandwidth is where the frequency response has dropped by 3 dB. Therefore when it is required to measure optic bandwidth, it must be remembered that the detector will show 6 dB drop in electric power. Power measurement equipment will compensate for this and show the correct optic power. The measurement process for optic bandwidth is discussed in section 9.3.3.

9.2 Standard fiber optic tests

The testing of fiber optic equipment and cables is generally carried out before and after the system is installed. The following section examines the main tests that are carried out on fiber optic systems.

9.2.1 Component testing

Testing of the transmitting and receiving equipment is not commonly carried out before installation, mainly because of the extra costs and test equipment involved. However, although these components would have been tested by the vendor, it is recommended that they are tested again before installation, as for high integrity performance.

There are two main tests that are performed on the transmitting and receiving equipment. The first is to test the transmitter output power. The transmitter is connected to a short piece of reference fiber about 2 m long. The reference fiber must be the same type and size as the fiber that the transmitter has been designed to interface to and that is intended to be installed in the system. A power meter is connected to the other end of the fiber and the power figure noted. This figure should be within ±5% of the power into the fiber figure provided by the supplier for that transmitter. This test is illustrated in Figure 9.2.

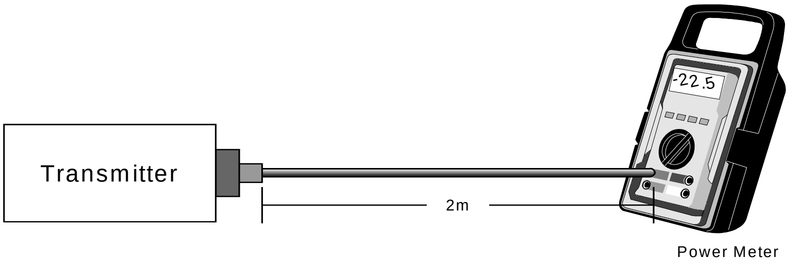


Figure 9.2
Power into fiber level check for a transmitter

The second test is to check the receiver. This is performed by connecting the transmitter and receiver to a reference fiber, which provides the required attenuation so that the received signal level is down to the receiver sensitivity level for a BER of $10^{-9.}$ This should be matching with the level quoted by the manufacturer in the receiver specification (the received signal level can be checked with a power meter). A BER tester is then connected to the transmitter and receiver and the BER is tested for a minimum period of at least 30 minutes. This will confirm that the receiver performs to the manufacturers' specification and that it will perform satisfactorily in the system for which, it has been designed. This test is illustrated in Figure 9.3.

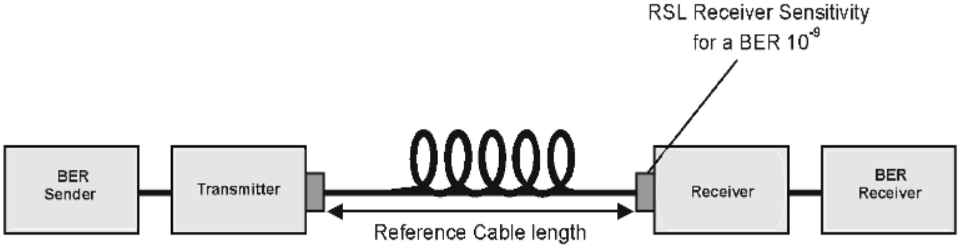


Figure 9.3
Testing of the receiver

9.2.2 Continuity testing

The most fundamental aspect of all fiber optic cable tests that can be performed is to carry out a continuity test. The continuity test simply checks that the fiber is continuous from one end to the other. A light beam is inserted from a light source in one end of the fiber and is observed coming out of the other end of the fiber. This test provides no information about the condition of the fiber other than there are no complete breaks along the fiber length. Initially, it was performed by flashing a powerful torch beam down the end of the fiber and observing the light coming out of the other end. This worked fine for multimode fibers with large core diameters over distances up to five hundred meters approximately. But it was not reliable in respect of very long distances.

Although this test is very basic, it is an extremely handy tool available to quickly locate the correct fibers at the other end of a link. The size of the continuity fiber tester is generally that of a pen and can be carried in the breast pocket. It is used extensively in metropolitan and campus area networks.

There is specific test equipment available that can be used as a continuity tester. The device has a fiber optic transmitter with a suitable fiber optic connector that transmits a 650 μm visible red light. This will transmit visible light over several kilometers and can be used for such applications as continuity testing, finding fractures in fibers or bad splices by observing light that may be leaking out and for identifying fibers at the end of a cable that has many fibers in it. It can also be used for identifying fibers along the route of a cable (where it is required to break into a cable for a system extension) by bending the fiber and watching the light leaking out of the bend. This type of fiber optic test has limited application, as it is of no use in finding faults with buried cables or aerial cables.

As a word of caution, the user should not look into fiber groups at the end of cables if any fibers on the system at any location are connected to lasers. The infrared light from lasers cannot be seen by the human eye but will cause permanent eye damage. Before trying to locate fibers by using a continuity tester, ensure that all live equipment is disconnected.

9.2.3 Insertion loss testing

One of the most common tests that is carried out on a fiber optic system is to measure the attenuation of a length of a fiber. This figure will allow most elements of the system design to be verified.

Most of the insertion loss testing is carried out with a power source and a power meter. Firstly, the power meter is calibrated to the power source by connecting the two instruments together with a short piece of optic fiber approximately 2 m in length. Generally, the power source is set to transmit a level of –10 dBm and the power meter is then adjusted accordingly to read –10 dBm. Ensure that the level used to calibrate the power meter is within the dynamic range of the power meter.

There are four important points to check before commencing insertion loss testing. Firstly, ensure that the optic fiber type used for calibration purposes is the same optic fiber type that is to be tested for insertion loss. Secondly, the power meter and the power source must operate at the wavelength that the installed system equipment is to use. Thirdly, the power meter and source must also use the same source and detector types (LED or laser) that the transmitter and receiver in the installed system are to use. Fourthly, to avoid possible incorrect calibration, ensure that the same connectors are used for calibration as are used in the installation.

Once the power meter has been calibrated, then the power meter and source are taken into the field and connected to the installed cable. The level that is read at the meter can be used to calculate the insertion loss through the cable section under test. This will include the losses caused by the optic fiber, splices and the connectors. The test procedure is illustrated in Figure 9.4.

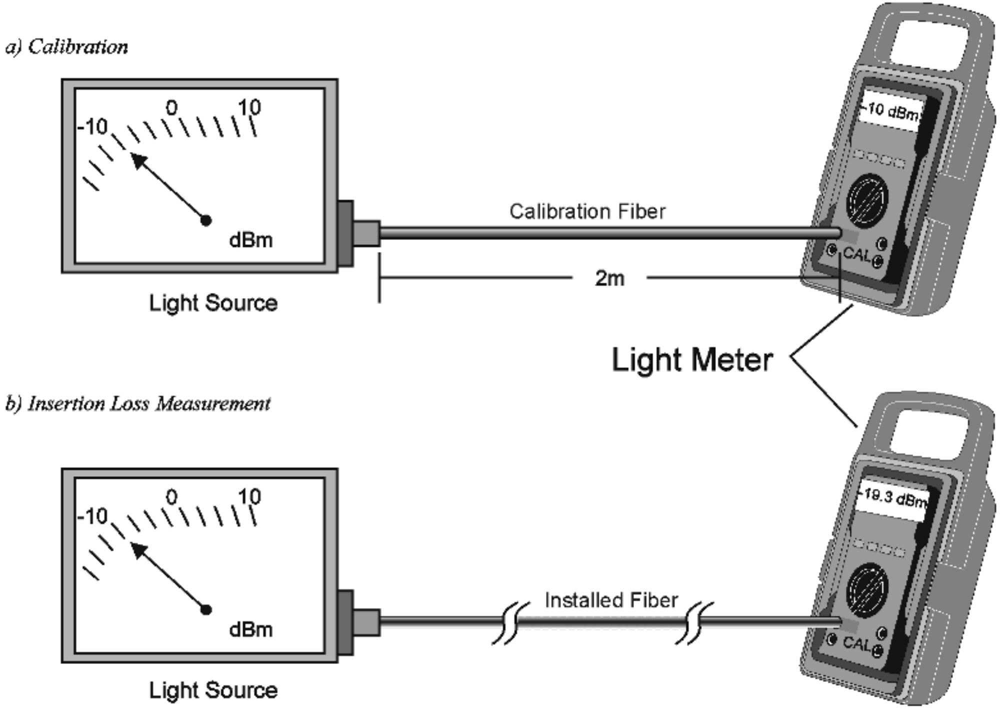


Figure 9.4
Insertion loss measurement

If the power source and the power meter are calibrated in watts, then the formula for converting the loss figure to decibels is:

$$\text{Attenuation (dB)} = -10 \text{ Log } (P_o/P_i)$$

Where:

P_o is power out of the fiber
P_i is power into the fiber

To calculate the insertion loss, subtract the dBm reading at the power meter from the input power source value. For the example, the insertion loss shown in Figure 9.4 is 9.3 dB.

It is recommended that the insertion loss measurement be performed in both directions of an installed cable. The losses measured in each direction tend to vary because connectors and splices sometimes connect unevenly. The core diameter of fibers would also tend to vary slightly, causing similar variation in the insertion losses. For example, if the core diameters of two fibers spliced together are 49.5 μm and 50.5 μm, light waves traveling from the thinner diameter fiber into the thicker diameter fiber would all enter the thicker diameter fiber. For the light traveling from the thicker diameter fiber into the thinner diameter fiber, a small amount will be lost around the edges of the interface between the two cores. A mismatch of this type could account for a difference in insertion loss in the two directions of 0.2 dB.

If the equipment transmitter is to be used as the power source, the first requirement is to configure the transmitter to send a 50% duty cycle signal into the fiber. The transmitter should be modulated with a continuous on/off NRZ signal (101010101010 etc), which would provide a true averaging signal at the power meter. The power meter must then be calibrated as discussed above and the insertion loss of the chosen fiber measured. If possible, it is worthwhile to carry out the insertion loss test with the transmitter in addition to using a separate power source to confirm that there is not a large variation in the measured insertion loss figures.

Insertion loss measurements should be performed on every fiber in a cable in both directions, whether the fibers are planned for use or not.

9.2.4 Optical time domain reflectometers

The most commonly used and best recognized method of analyzing the state of a fiber optic link is to test it with an optical time domain reflectometer (OTDR). The OTDR sends a short pulse of light down the fiber and measures and records the light energy that is reflected back up the fiber. A reflection may be caused by a connector, splice, crack, impurities, or a break in the fiber. By measuring the time it takes for the reflected light to return to the source and knowing the refractive index of the fiber, it is possible to calculate the distance to the reflection point.

Impurities in the glass will cause a continuous low level reflection as the light travels through the glass fiber. This is referred to as backscatter. The correct technical term of this is Rayleigh scattering, which was discussed in Chapter 3. The strength of the backscatter signal received at the source gradually drops, as the pulse moves away from the source. This is seen on an OTDR as a near linear drop in the received reflected signal and the slope of this linear drop is the attenuation of the fiber (dB per km). Figure 9.5 illustrates a typical reflection curve for an OTDR and notes the backscatter.

Generally, an OTDR will not provide accurate readings of irregularities and losses in the fiber for the first 15 m of the cable. This is because the pulse length and its rise time from the OTDR are comparatively large when compared to the time it takes for the pulse to travel the short distance to the point of reflection within this 15 m and back. To overcome this problem, a reel of cable is inserted between the OTDR and the link to be tested. When reading the OTDR screen, the first length of cable is ignored and is referred to as the deadband.

With reference to the OTDR plot in Figure 9.5, the Y axis of the plot shows the relative amplitude of the light signal that is reflected back to the source and the X axis represents time. The time base is directly translated and displayed as distance by the OTDR.

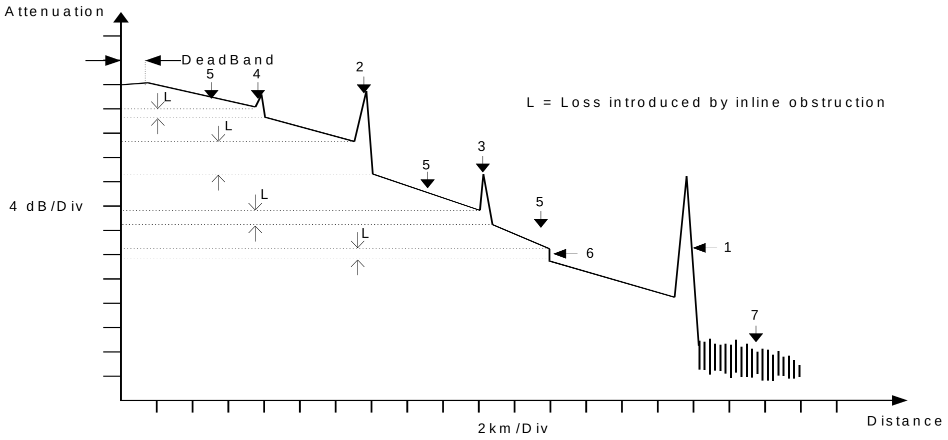


Figure 9.5
Trace from an OTDR

The sudden peaks that appear along the slope are the points where reflections have occurred and the light that has reflected back to the source is stronger than the backscatter. There are five main reflection points illustrated in Figure 9.5. In their order of decreasing magnitude, they are:

1. Reflection from the unterminated end of the fiber
2. Reflection from a connector
3. Reflection from a splice
4. Reflection from a hairline crack in the fiber
5. Backscatter

After each of the reflections, the slope of the attenuation curve drops suddenly. This drop represents the loss introduced by the connector, splice or imperfection in the fiber.

Point (6) noted in Figure 9.5 illustrates a splice where the cores of fibers are well matched for light traveling in the direction away from the source. This splice has no reflection but just a loss introduced by the splice. The type of drop at point (6) in the attenuation curve could also be caused by a sharp bend in the fiber where light escapes out of the fiber at the bend and is not reflected back. Some types of faults in the fiber will also cause similar results.

Point (7) noted in Figure 9.5 shows the noise floor of the instrument. This is the lowest sensitivity of received signal that the device can accept. Measurements made close to this level are not very accurate.

OTDR testing can provide very accurate fault analysis over almost any length of fiber. It is important that the deadband roll of cable is always inserted between the OTDR and the link before making the measurement. On the better quality instruments, a resolution of 1 m for fault location and .01 dB for in line losses can be obtained. Some instruments will operate with a range up to 400 km.

In general, OTDRs are relatively easy to use and special analysis software packages are available for downloading the test results and carrying out detailed analysis if required. The unfortunate downside with OTDR technology is that it is generally very expensive. Even small, reduced feature units could be prohibitively expensive.

Care should be taken when interpreting the results from an OTDR. Where different fibers are joined together, this connection may represent a change in refractive index, core size, modal properties and/or material properties of the fiber. For example, after a splice or connector, the OTDR may display what appears to be a signal gain on the screen. What has probably occurred is that the light has entered a fiber with greater impurities and there has been an increase in backscatter.

The OTDR test should be carried out on every optical fiber in a cable while it is still on the reel before installation, to insure that faulty fibers are not installed. The results of these tests should be stored in memory or as a print out. These pre-installation tests are generally carried out when the custody of the cable is passed from one party to the next; for example, when the cable is handed from the purchasing party to the installation contractor.

Once the cable has been installed, the OTDR tests should be carried out again on every optical fiber. The results of the as installed tests can then be compared to the pre-installation test results to determine whether the fibers have been damaged or poorly installed.

The results of the pre-installation and the post-installation tests should be kept as part of the commissioning documentation. If there is a fault with the system at a later date, then the commissioning test results can be used to help determine where the faults are located. For high integrity longer distance systems, it is worth carrying out an audit of the system after a number of years of operation, performing the OTDR tests again, and comparing them to the commissioning test results to measure any deterioration in the cabling system since installation.

The OTDR can be used for providing accurate attenuation measurements assuming that the OTDR is of a high quality and is regularly calibrated.

Since the OTDR would only provide relative measurements, the wavelength at which it operates is not important. Distance readings, splice losses, and connector losses are not affected by the small changes in wavelength associated with lasers and LEDs.

Also, tests should always be carried out in both directions. Certain types of faults will show up in one direction but not in the other. An example of this would be a mismatch in core diameters. It was noted in the previous section that the loss of a connector or splice might be different when measured from each direction into the optic fiber. If the connector and splice losses are different in each direction, then an average of the two figures can be taken.

Some fiber optic cables are constructed so as to enable to lay them in a helical fashion around the center of the cable. In this case, the length of the cable is not going to be the length of the fibers. This difference will make it inherently difficult to determine the distance to faults. To overcome this problem, the manufacturer will generally provide a ratio of fiber length to cable length. The ratio is then used to calculate the exact cable distance to the fault from the OTDR distance reading. In the absence of such a ratio, an OTDR measurement is performed on a known length of cable (generally 1 km) and the ratio is calculated as below:

$$\text{Fiber/cable ratio} = \frac{\text{Length of fiber in 1 km of cable}}{\text{1 km}}$$

$$\text{Distance to fault} = \frac{\text{OTDR distance reading}}{\text{Fiber/Cable ratio}}$$

9.2.5 The cold clamp

One of the major problems associated with OTDR measurements is that the distance to the fault along the cable and the physical distance to the fault measured along the ground can often be very different. This is generally because the cable is often coiled up at splicing and pulling points along the path to allow for repairs and extensions to the system. It can be very difficult to determine exactly how much this difference between cable length and physical distance actually is.

An Australian telecommunications carrier, Telstra, in conjunction with an Australian optical fiber test equipment manufacturer, Kingfisher, have developed a technique for introducing a temporary fault into the cable to find relative position. The system consists of an open clamp that is fixed around the cable and into which liquid nitrogen is poured. The 'cold clamp' (as it is referred) introduces attenuation at that point of between 0.2 and 1 dB. The OTDR will then locate the induced fault distance, and then the real fault can be precisely located and fixed.

9.2.6 Bit error rate testing

BER is a measure of the performance of a data communications link. The BER is determined by attaching BER test instruments to the transmitter and to the receiver and then having the transmitter send a pseudo random pattern of bits through the fiber optic link system and measuring the number of bits that are incorrect when they come out of the receiver (the BER instrument attached to the receiver also knows the pseudo random bit code). The test is carried out for a predetermined period of time, which is used as a base reference for the BER figure. The BER is then calculated by adding the total number of bits that were in error and dividing by the total number of bits that were sent over the specified period of time:

$$\text{BER} = \frac{\text{errored bits}}{\text{total bits}}$$

For fiber optic link systems, the BER test is generally carried out for a period of 30 minutes or 1 hour (for example, compared to microwave radio links where it is generally carried out for 24 hours, 48 hours or longer).

For most fiber optic link systems, it is recommended that a residual BER (the background BER when the system is available for normal operation) of 10^{-9} be the minimum that is acceptable (that is, one bit in error for every billion that are transmitted). If a graph is plotted for a standard fiber optic transmission system of the BER versus the received signal strength at the detector, it can be seen that the BER remains relatively flat until the received signal level approaches the receiver sensitivity and then it drops very sharply. This is illustrated in Figure 9.6.

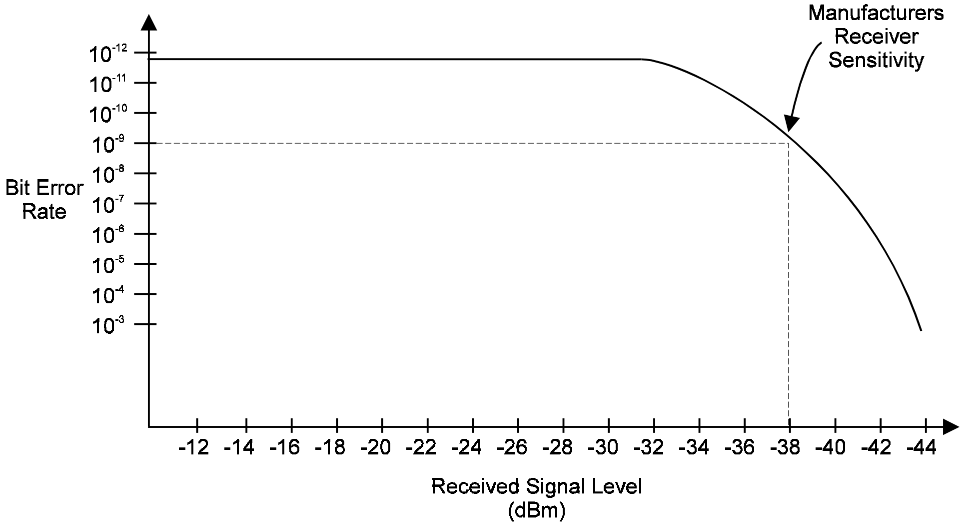


Figure 9.6
BER vs received signal level for standard optical transmission system

Also illustrated in this graph is the fact that the background BER to be expected is normally around 10^{-12} on a fiber optic link.

As a rule, BER testing is carried out only in fiber optic systems that require high integrity operation. For link distances greater than 2 km and for transmission rates greater than 100 Mbps, it is a standard recommended test.

The BER is generally related to another link system measurement referred to as 'availability.' This is defined as the percentage of time that a link is available for uninterrupted use over a period of 12 months for a minimum specified BER (generally 10^{-9} or 10^{-12} for a fiber optic link). The time that the link is not available for use is referred to as an outage. As it is impossible to perform a BER test over a link for a 12-month period (because the link is required for its designed purpose of transmitting information), the availability figures are generally theoretically calculated using the safety margin as the basis of the calculations in order to determine the link's availability.

For example, the performance required may be that the link has an availability of 99.99% for any 12-month period, with respect to a maximum BER of 1×10^{-9}.

This means the system shall not have outages over a 12-month period. The total outage is greater than (365 days × 24 hours/day × 60 minutes/hour × 0.01%), 53 minutes where an outage is considered to be more than 1 bit in error for every million bits transmitted.

Another example with less stringent parameters (for example, on a copper cable or radio link) may be a performance requirement with an availability of 99.85% for the worst performing month of any year with respect to a maximum BER of 1×10^{-3}.

This means that the system shall not have outages in the worst performing month that total greater than (31 days × 24 hours/day × 60 minutes/hour × 0.15%) 1 hour, 7 minutes where an outage is considered to be more than 1 bit in error for every 1000 bits sent.

International standard

Where measuring BER for high-speed data circuits over telephony links, the international standard requires that the BER be tested over the 64 kbps components of the high-speed link (often 2 Mbps). Unavailability is then defined as periods of time when the BER in each second exceeds 10^{-3} for a period of 10 consecutive seconds or longer at a data rate of 64 kbps. If the BER exceeds 10^{-3} for only nine consecutive seconds, the link is considered to still be available.

Other terms used for these types of links are severely errored seconds where the BER exceeds 10^{-3} for one complete second (i.e. a second with more than 64 bits in error in them) and errored seconds where there are one or more bits in error in a second.

Fiber optic transmission systems should have extremely high availability figures. A figure of 99.99% (outage of 53 minutes per year in total) or better should be easily achievable for a fiber system. The reason that the availability figures are so good is that the optic fiber is not affected by external noise, interference, or most other environmental effects as are copper cable and radio communications systems. However, due to Rayleigh scattering, dispersion, changing temperatures, jitter in fast systems and other unpredictable effects the BER will never theoretically reach 100%.

9.2.7 Time domain measurements (eye diagrams)

It is also important to analyze the data communications signal in real time. The most effective method of doing this is to analyze the digital pulses at the output of the receiver in the time domain. The time base characteristics of a signal can provide a wealth of useful information about the quality and performance of the transmission system.

The parameters of a digital pulse that can be measured include period, duty cycle, settling time, pulse width, rise time, fall time, overshoot, undershoot, preshoot and settling time. By comparing the shapes and time domain parameters of continuous sequential pulses, it is possible to measure other parameters such as noise, jitter, general pulse quality (referred to as masks) and over what distance the pulse is expected to last (referred to as the extinction ratio).

The instrument that is taking the measurement in the time domain must have a relatively fast transient response (time response) compared to the pulse it is measuring in order to make accurate measurements of the pulse parameters. For the instrument to accurately measure fast optical input signals, the instruments impulse response must generally be at least four times faster than the signal it is to measure.

For those who are mathematically minded, it is also worth noting that the frequency response of the measuring instrument can be determined from the impulse response by taking its Fourier transform. The reverse of this is also true, where the impulse response can be determined by taking the inverse Fourier transform of the frequency response.

The measurement of BER requires the transmission of a pseudo random bit pattern. This bit pattern can also be used for a useful time domain measurement. By overlapping the output light waveforms of successive pseudo random bits and displaying the signals on a storage oscilloscope, a pattern referred to as an eye diagram is formed. A typical eye diagram is illustrated in Figure 9.7.

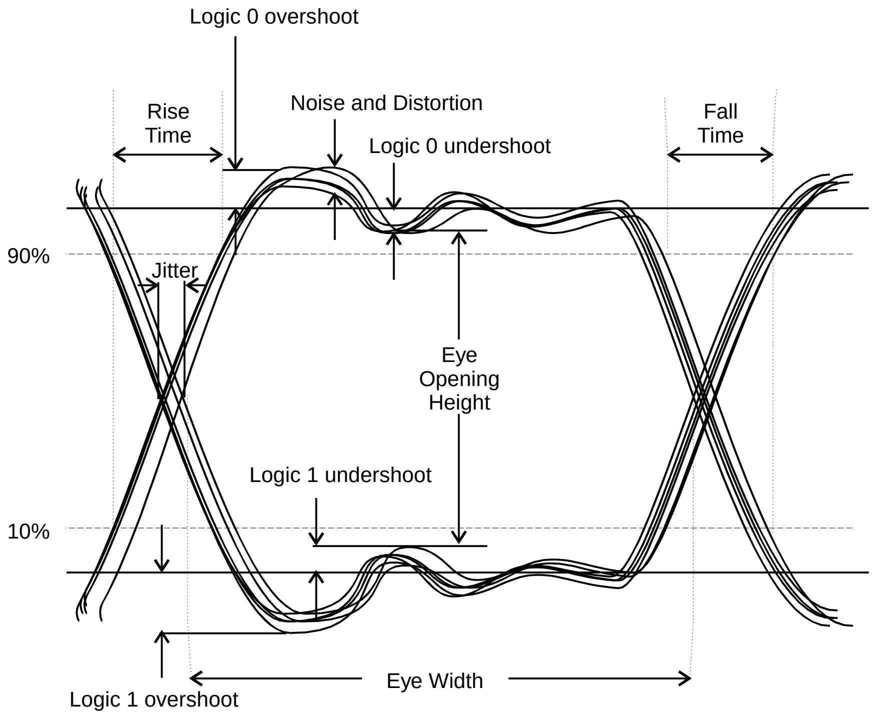


Figure 9.7
Eye diagram

An eye diagram provides an indication of how easy, or difficult, it will be for the receiver to distinguish between a logic 1 and a logic 0. Because the time of arrival and the shape of each successive pulse is going to vary, the eye diagram will form with thick lines. The more noise that is in the fiber transmission system, the greater the variation in the amplitude of the eye lines. The greater the variation in the difference between the time of arrival of each consecutive pulse, the greater the variation in the width of the eye lines (referred to as jitter).

A number of important measurements can be made from the eye.

- The more open the eye is, the easier it is to distinguish between a logic 1 and a logic 0.
- The eye diagram opening width (the time between logic 1 to logic 0 and logic 0 to logic 1 line crossings) shows the time interval over which the signal may be sampled without error due to intersymbol interference.
- The eye opening height measures the noise margin in the receiver output.
- The width of the eye lines where they cross at the corners of the eye is a measure of the jitter in the transmission system. Jitter is caused by variations in the laser turn on and turn off times, pulse distortion by the optical fiber, and noise. Jitter is expressed in pecoseconds, degrees or as a percentage of the bit interval.
- The thickness of the pulse lines at the top and the bottom of the eye is proportional to noise and distortion in the transmission system.
- The transition time of the signal from the top (logic 0) to the bottom (logic 1) and vice versa in the eye pattern indicates the rise and fall times of the

transmission system. These are generally measured between the 10% and the 90% marks.

- The rise and fall times are important for estimating the system's sensitivity to sample timing. The slower the signal rise and fall times the more sensitive the system is to timing errors.
- To provide maximum noise immunity in the system, the best time to sample the signal is when the eye diagram opening height is at a maximum.

9.3 Other fiber optic tests

The fiber optic tests that were discussed in the previous section are the most common that are carried out on installed fiber optic transmission systems. The tests that are discussed in this section are the more esoteric tests that are generally carried out in laboratory environments only or on very high reliability, long distance, high data rate telecommunications systems belonging to public carriers.

9.3.1 Wavelength measurement

This measurement is used to measure the central operating wavelength and the range of wavelengths (spectral spread) that are being emitted from an optical source. The wavelength (and spectral spread) is specified by the equipment manufacturer or by the particular application that the equipment is to be used for.

The techniques that are used to measure wavelength are based on the fact that different light wavelengths travel at different speeds through, around and off matter. The two most common methods for measuring wavelengths are with equipment that uses a prism or a diffraction grating. Light will travel at different speeds through a glass prism and will diffract at different angles off a diffraction grating. This is illustrated in Figure 9.8.

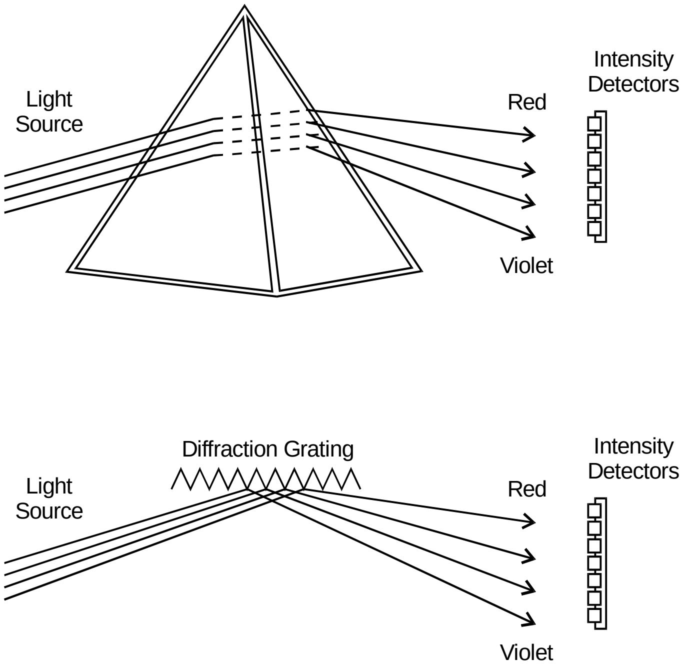


Figure 9.8
Measurement of light wavelengths

9.3.2 Dispersion measurement

Chapter 3 of the book discussed the three types of dispersion in optical fibers. Modal dispersion, which is the significant dispersion type in multimode fibers and material and waveguide dispersion (together referred to as chromatic dispersion), which are the significant dispersion types in singlemode fibers.

To measure each dispersion type individually requires very sophisticated laboratory equipment. Therefore, this level of testing is generally left to the manufacturers and for research and development purposes. However, it is comparatively easy to measure the total dispersion in the fibers. This is achieved by comparing the input optical signal shape to the output signal shape and measuring the spread of the output optical signal compared to the input signal in nanoseconds. This type of measurement is performed using optical probes and good quality oscilloscopes. The measurement setup is shown in Figure 9.9.

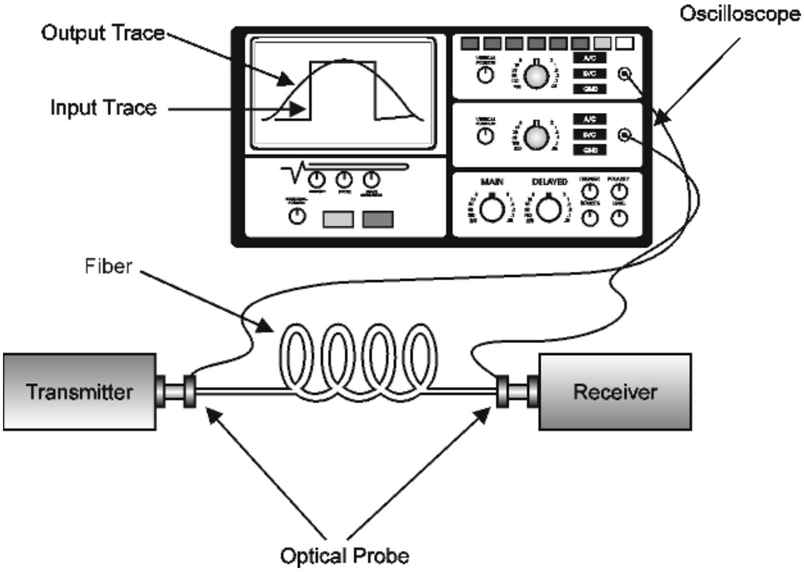


Figure 9.9
Measurement of total dispersion

9.3.3 Bandwidth measurement

The method used to measure bandwidth in an optic fiber is the same as the method used to measure bandwidth in copper cables or in radio and microwave links.

The system test configuration consists of an analog optical coherent transmitter that is attached to the input of a 1 km length of fiber and is modulated with a variable frequency oscillator. The analog optical transmitter provides a constant sinusoidal output amplitude. An optical power meter is attached to the end of the fiber and is used to monitor the output power.

The bandwidth of an optic fiber is when the received signal level has dropped by 3 dB. This represents the limits of the frequency bandwidth of operation.

The variable frequency oscillator is increased in frequency until the amplitude of the signal at the output of the fiber has dropped by 3 dB. The equipment configuration and a graph of the received level output is illustrated in Figure 9.10.

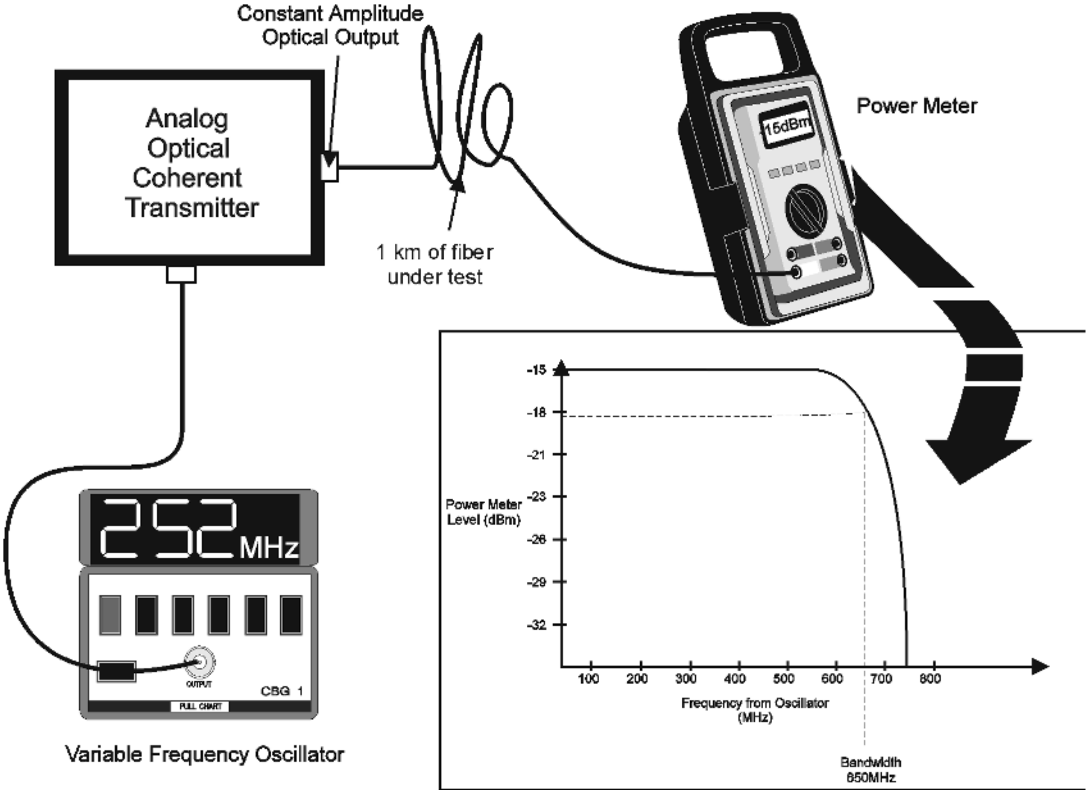


Figure 9.10
Measuring the bandwidth of an optical fiber

Bandwidth testing is often carried out on long distance (50 km or more) telecommunications fibers after installation is complete.

9.3.4 Phase measurement

Due to various forms of dispersion that occur in fibers, the light waves arrive at the receiver at different times. As light is of a sinusoidal nature in its characteristic form, there will be adding and subtracting of the waveforms at the receiver. When two waves arrive in phase, they add (constructive) and when they arrive out of phase, they subtract (destructive). This is referred to as phase distortion and is seen as interference zones across the face of the receiving detector; that is, constructive or destructive zones across the face of the receiver.

To measure the phase distortion the light output is amplified, enlarged, and placed across a series of light detectors, which detect the intensity of the light in each of the zones. The measured intensity of each of the zones is used to calculate the phase distortion of the received signal. This is illustrated in Figure 9.11.

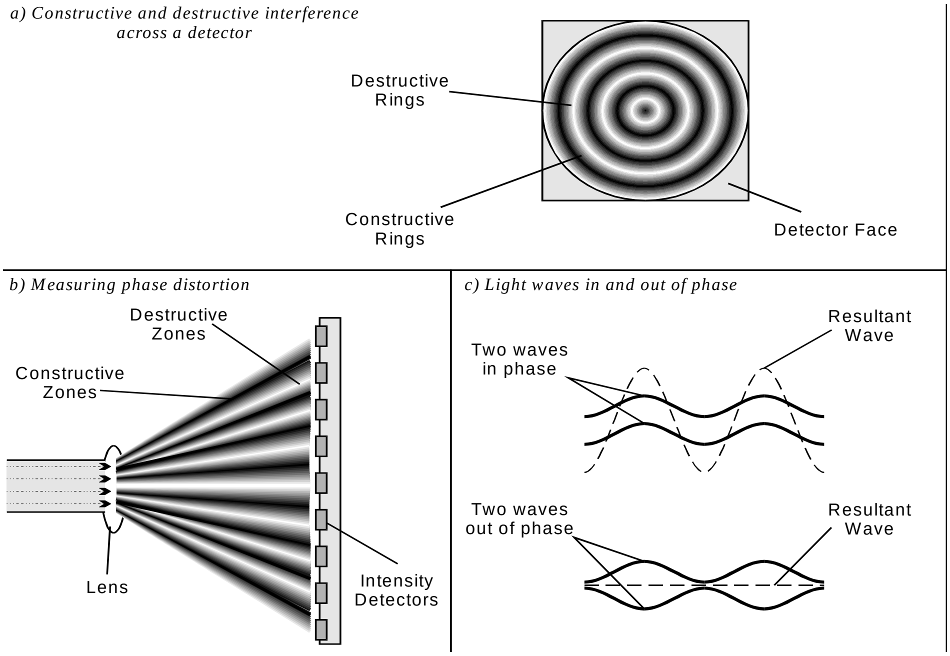


Figure 9.11
Measurement of phase distortion

9.3.5 Polarization measurement

In Chapter 2, it was explained how the light is constructed of an electric field and a magnetic field and the polarization of the light is determined by the electric field. When the light consists of waves, which are all, polarized in the same plane, then the system is said to be linearly polarized or coherent (coherent actually means of the same phase, wavelength and polarization). If the electric field is moving in a circular pattern as it moves through the fiber, then it is said to be circularly polarized. If the electric field orientation of each light ray is purely random, then the light is said to be unpolarized.

Some fiber optic communications systems are polarization sensitive. These are generally the more sophisticated systems but in such cases, the degree of polarization must be measured.

Measurement of polarization is quite simple. Firstly, the intensity of the light signal is measured coming from the fiber. Then a polarization filter is placed in front of the fiber and the intensity is measured again. If the light in the fiber is linearly polarized, there should be no drop in the intensity. If the light is partially polarized, there will be a proportional drop in the intensity.

9.3.6 Miscellaneous measurements

Other parameters of a fiber that are measured in the laboratory are the number and type of modes that are operating in a fiber, the numerical aperture and therefore the acceptance angle and refractive index of the fiber, the final core diameter of the fiber and the wavelength characteristics of the fiber.

Most of these parameters are measured using very sophisticated instruments that measure the distribution and intensity of light over an area as it leaves the fiber. Another approach is to project the light over surfaces that are at varying distances from the fiber end and to compare the intensity variations against different distances.

10

Technologies that use optical fibers

Introduction

Fiber optic systems are being used in many new technologies to take advantage of the unique properties of optical fibers.

These include:

- Wide bandwidths
- Low loss
- Noise immunity
- Galvanic isolation
- Low power levels
- Light weight

The wide bandwidths, low loss, and low noise characteristics of fiber optic systems (particularly digital systems) have enabled them to be used for high-speed communications systems.

These include long-distance digital communications systems providing world-wide telephone and data links as well as LAN/MAN/WAN systems.

Fiber optic cables are being used increasingly in industrial applications in areas where the older copper cable technology is more difficult or dangerous to use. Examples here include the use of fiber optic cables to control high current industrial machinery in the presence of high levels of electromagnetic interference caused by their operation. Other industrial processes involve high voltages, such as power stations, power transmission lines, electric traction systems etc. Fiber optic systems here provide safe, cost-effective communications and control capabilities in this difficult environment. Some industrial areas need to operate in the presence of flammable/explosive hazards. Here, intrinsic safety is vital. Copper cables in such environments need to have special equipment to ensure the energy in the circuits is restricted to be incapable of igniting the atmosphere, in the event of a cable circuit breakage. The energy levels in the fiber optic communications and control cables meet these requirements directly.

Fiber optic cables are also being used increasingly in applications where its lightweight is an additional advantage. This includes use in the control systems of aircraft, ships and even automobiles.

The way in which the light in the fiber optic cables themselves is changed by their environment can be monitored for use in many sensor applications, such as measurement of: pressure, temperature, stains, magnetic fields, acceleration etc. Fiber optic technology is also being used to make very reliable gyroscopes, which have no moving parts!

Other technologies involve the use of bundles of fibers, for purposes of illumination or imaging such as endoscopes.

10.1 Communications systems

10.1.1 Analog systems

As discussed in Chapter 2, signals can be transmitted in analog or digital form. Analog transmission requires signals, which are varied in a continuous manner to convey their information. In order to transmit information in an analog form over a fiber optic cable, we need to modify some property of the light to represent the analog information. We use a modulator for this purpose to vary one or more of the light's frequency, amplitude, or phase.

Transmission of very wide bandwidth analog signals over a fiber is made difficult because the attenuation characteristics of the fibers do not offer uniform properties over a wide range of wavelengths. The glass fibers shown in Figure 3.9 illustrate this. Optical fibers show low attenuation only in the three narrow operating windows around 850 nm, 1300 nm and 1550 nm. For this reason, long distance high bandwidth systems are more suited to digital transmission as discussed in the next section.

However, short distance transmission can make use of analog transmission with applications such as closed-circuit television and cable television distribution systems.

10.1.2 TV modulators

Standard analog television signals require a bandwidth of about 6 MHz. Modulators are available for the transmission of analog TV signals at 850 and 1300 nm. For longer distances, the 1300 nm wavelengths are preferred because the cable has far less attenuation. Optical amplifiers are expensive, so most systems utilize single hops without intermediate amplification. The optical system design process described in Chapter 8 is used to ensure the analog signal arriving at the receiver has adequate strength to operate reliably.

10.1.3 Cable TV

Another example of analog optical transmission technology can be found in some cable television networks. For example, in Australia, the pay-TV network is being installed using combined fiber and coaxial cable analog network, as shown in Figure 10.1. Here, the studio head-end multiplexes the TV signals in the frequency range from 50 MHz to 550 MHz. The fiber backbone network operates at the 1300 nm wavelength, generally without amplifiers. Bi-directional signals are provided on two fibers. The customer distribution is made by sending the RF signals over the coax network, with amplifiers every 500 m. The single coax is able to transmit backward signals from the customers into the fiber network, for control purposes and later for interactive services.

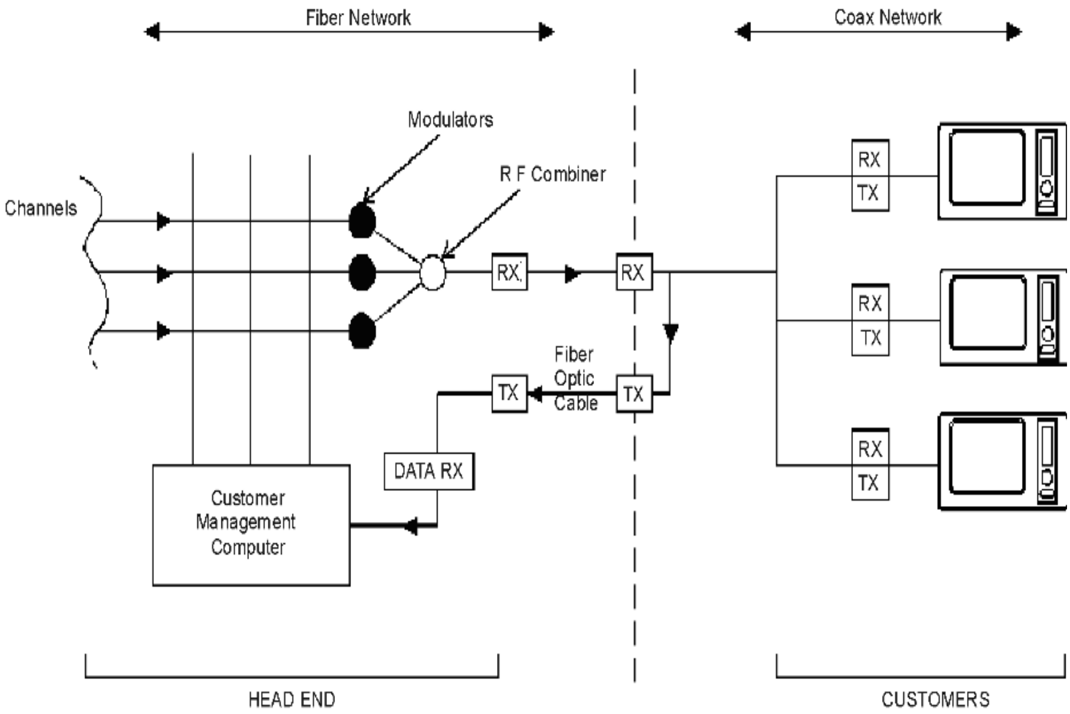


Figure 10.1
Cable TV application

10.1.4 Digital systems

Digital fiber optic systems have considerable advantages for long distance transmission. The digital signals are simply on/off pulses of light and they can be detected and near perfect pulses regenerated at regular intervals along the transmission system. Providing this is always done before the signal-to-noise ratio deteriorates, then the received signals have no accumulated noise and are near perfect replicas of the transmitted signals. The fiber system brings with it the low losses, high noise immunity and, with dielectric cables, protection against high voltages, such as lightning strikes.

10.1.5 Undersea cables

All undersea transmission cables are being installed with digital fiber optic technology. As an example of current technology, there are undersea cables that travel for many thousands of kilometers between countries with distances between repeaters of 120 km and that they carry data rates of 800 Gbps per single fiber.

10.1.6 HDTV

High definition television (HDTV) is a technology that requires the high bandwidth of fiber optic systems to operate. HDTV has an analog bandwidth of 27 MHz and results in data rates of the order of 600 Mbps to 1 Gbps when digitized. Conventional TV by comparison has a 6 MHz bandwidth and can be digitized with data rates about 100 Mbps. With data compression techniques, these transmission requirements can be reduced to about 150 Mbps and 34 Mbps respectively. Higher compression rates are possible but these tend to degrade the picture quality. Digital television is now available over the free to air services, but is slow in coming home via cable.

10.2 Local area network applications

Local area networks (LAN) provide high speed connections between computer systems allowing the users to share data or other resources such as printers. Various architectures limit the physical size of the LAN, but in each case, the cabling system is limited to within the owner's property. Circuits required to leave the site, crossing public property, need to be provided by a telecommunications circuit provider and constitute a MAN or WAN, as discussed in section 10.3.

A brief discussion of various types of LAN technologies using fiber optic cables now follows.

10.2.1 FOIRL

This is the fiber optic inter-repeater link specification. This was developed as part of the IEEE 802.3 CSMA/CD (Ethernet) standard. This enabled the copper-based coaxial cable and twisted pair Ethernet segments to be extended by the use of fiber optic cable. This allows link segments between repeaters of up to 2000 m at the standard Ethernet data rate of 10 Mbps.

10.2.2 10BaseF

This standard is based on a star topology using wiring hubs. It consists of three architectures as illustrated in Figure 10.2. These are:

10BaseFL

The fiber link segment standard that is basically an upgrade to the existing fiber optic inter repeater link (FOIRL) standard to 3 km. Note that this is a link between two repeaters in a network, and cannot have any nodes connected to it.

10BaseFP

A star topology network based on the use of a passive fiber optic star coupler. Up to 33 ports are available per star, and each segment has a maximum length of 500 m. The passive hub is completely immune to external noise and is an excellent choice for noisy industrial environments.

10BaseFB

A fiber backbone link segment in which data is transmitted synchronously. It is designed only for connecting repeaters, and for repeaters to use this standard, they must include a built in transceiver. This reduces the time taken to transfer a frame across the repeater hub. The maximum link length is 2 km, although up to 15 repeaters can be cascaded, giving great flexibility in network design.

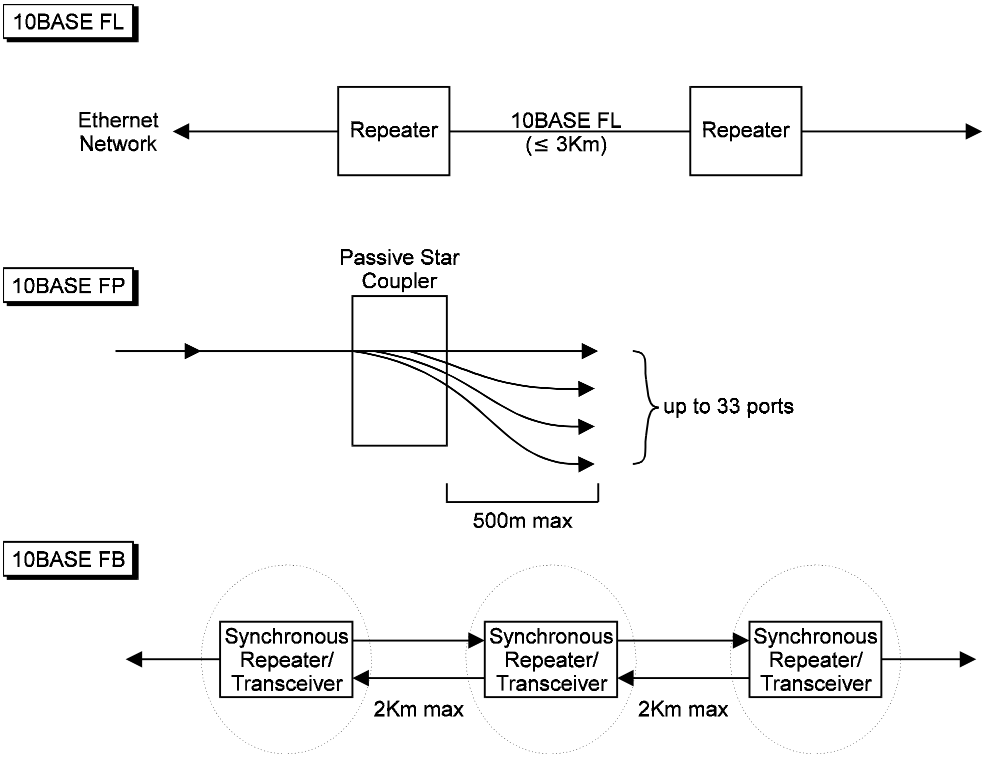


Figure 10.2
10BaseF architectures

100BASE-TX

This is a 100 Mbps LAN technology, which can utilize fiber optic cable. It is supported by David Systems, DEC, Grand Junction Networks, Intel, National Semiconductor, SUN Microsystems, SynOptics and 3COM and seeks to combine two standards:

- The Ethernet MAC (IEEE 802.3)
- The FDDI physical media dependent (ANSI Standard X3T9.5)

This uses the unchanged MAC layer of IEEE 802.3 operating at 100 Mbps. The maximum (1518 octets) and minimum (64 octets) frame sizes remain unchanged. The times for transmission naturally are reduced by a factor of 10 times, so for example, the interframe gap of 96 bit times shrinks to 0.96 microseconds.

Essentially, the approach is to use a three level code. This allows for four bit combinations for every signal change. Hence, for a 31.25 MHz baseband signal, this allows for a 125 Mbps signaling bit stream providing a 100 Mbps throughput (4 B/5B encoder). The MAC outputs an NRZ code. This code is then passed to a scrambler, which ensures that there are no invalid groups in its NRZI output. The NRZI converted data is passed to the three level code block and the output is then sent to the transceiver.

The three level code, or MLT-3 as it is called, changes the voltage between three voltage levels, 0, +1, +2 volts. This results in a lower frequency signal. Noise tolerance is not high because of the multilevel coding system; hence, data grade (category 5) cable is required.

Two pairs of category 5 wire, RJ-45 connectors and a hub are requirements for 100BASE-X. These factors and a maximum distance of 100 m between concentrators make for a very similar architecture to 10BASE-T. The total network span is 250 m. 100

BASE-TX also supports the use of IBM type 1 cable (2-pairs STP) and optical fiber. Costs are of the order of two to three times that of standard 10 Mbps cards.

100 VG-AnyLAN

This is another 100 Mb/s LAN technology, which can use fiber optic cable. It was developed by Hewlett Packard and IBM and is supported by Proteon, AT&T, Ungermann-Bass. The name ‘AnyLAN’ indicates that it has been designed to operate with both Ethernet and token ring frames. Note that it will not accommodate both of these at the same time.

The key advance here is to provide demand priority media access in message frames to ensure that more important messages such as multimedia full motion video frames get to their destination node quicker. Subject to study by the IEEE 802.12 committee for universal application.

A node sends messages to the hub using four pairs of wires. The hub then passes the messages onto the destination node. The hub services higher priority messages first; if all messages are of the same priority, they are serviced in a standard round robin arrangement.

A two level NRZ output is used, and five data bits are packaged into six transmit bits. Four pairs of unshielded twisted cable are used in half-duplex (i.e. transmit or receive once at a time). Category 3 wire is used due to the lower frequency signaling rate with parallel transmission of data over four pairs of wires.

Future implementations of this are being developed for 2-pair category 5 UTP or STP and also for fiber optic cable.

Gigabit Ethernet

The 802.3z standard defines the gigabit Ethernet media access control layer functionality as well as three different physical layers; 1000BaseLX and 1000BaseSX that use fiber and 1000Base CX that uses copper.

IBM originally developed these physical layers for the ANSI fiber channel systems and used 8B/10B coding to reduce the bandwidth required to sending the high speed signals.

A further standard, 1000Base-TX, has been developed to provide service over four pairs of cat 5 cable.

1000Base-SX uses 850 nm diodes and operates over distances up to approximately 500 meters.

1000Base-LX uses 1300 nm lasers and can operate up to distances of 80 km, depending on the type of laser used.

10 gigabit Ethernet

The fundamentals of the 10 GB Ethernet standard were completed in 2002 by the IEEE in association with the 10GEA (10 GB Ethernet Alliance). Companies are now in process of releasing products.

There are a number of fundamental differences between 1 Gbps Ethernet and 10 Gbps Ethernet. The differences include:

- 1 GE has standards for operating with copper and fiber while (at this stage) 10 GE is standardized for fiber only.
- 10 GE has been designed for direct attachment to SONET and SDH networks.
- 1 GE uses 8B/10B coding while a new coding scheme has been developed for 10 GE.

- 1 GE can operate in CSMA/CD (half-duplex) mode or in full-duplex mode, while 10 GE can only operate in full-duplex.

Fiber distributed data interface

This is a high speed token ring based system that uses fiber optic cable as the medium. It is based on an American National Standards Institute (ANSI) standard X3T9.5, which has now been adopted as the ISO 9314 standard. The standard includes physical layer, MAC layer and station management (SMT) specifications, and so is broadly analogous to the IEEE standards in its relationship to the OSI model.

The FDDI standard specifies two physical rings that simultaneously send data in opposite directions (referred to as dual, counter rotating rings). This is to enhance the reliability of the network, with bypass switches automatically rerouting frames in the event of cable or station faults as shown in Figure 10.3.

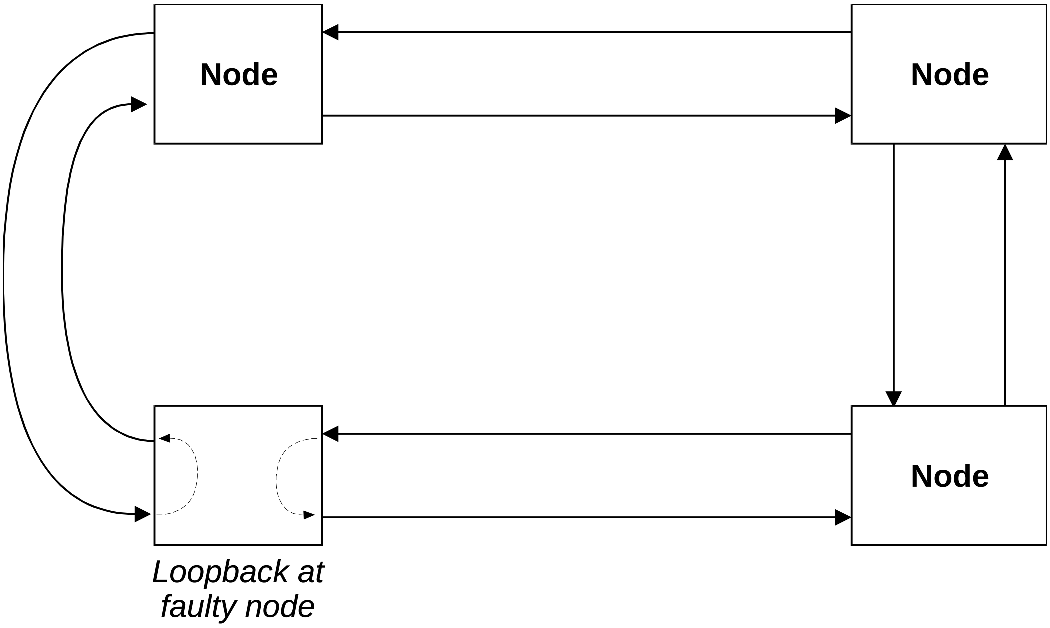


Figure 10.3
FDDI dual ring architecture

The basic fiber cables used for FDDI have dual core with polarized connectors at each end to prevent the transmit and receive fibers from being interchanged and bringing down the whole network. Multimode fiber is usually specified with a core diameter of 62.5 micrometers operating at 1300 nm, giving repeater spacing of 2 km. Singlemode cable can also be used to give repeater spacings of up to 60 km using singlemode cable of 8 micrometers.

FDDI uses four-bit of five-bit (4B/5B) encoding, where each four bits of data are encoded into a five cell code word or symbol. This enables a 100 Mbps data rate to be provided with a 125 MHz clock rate. The symbols are chosen so that no more than three consecutive zeros are transmitted in each symbol to ensure adequate clock transitions for synchronizing the receivers.

One FDDI ring can be up to 200 km in length and it can have up to 1000 stations attached to it. In practical terms, since nodes need to be visited twice under ring failure conditions, this then means that the primary ring can be up to 100 km with 500 stations.

FDDI networks can be used for the following applications:

- As a backbone network, providing a high speed network to which other networks can connect
- As a back end, or 'computer room' network, to connect mainframes, minicomputers and peripherals
- As a front end, or a high-speed LAN, connecting high-speed workstations

10.3 MAN and WAN applications

10.3.1 SONET and SDH

Synchronous optical networks (SONET) and synchronous digital hierarchy (SDH) use synchronous operation of the transmission nodes on a network, usually fiber optic cable. Synchronous transmission networks facilitate the dropping and inserting of channels at various points in the network and make possible the provision of bandwidth on demand. A comparison of the use of synchronous and asynchronous methods of transmission channel drop-and-insert capabilities is shown in Figure 10.4.

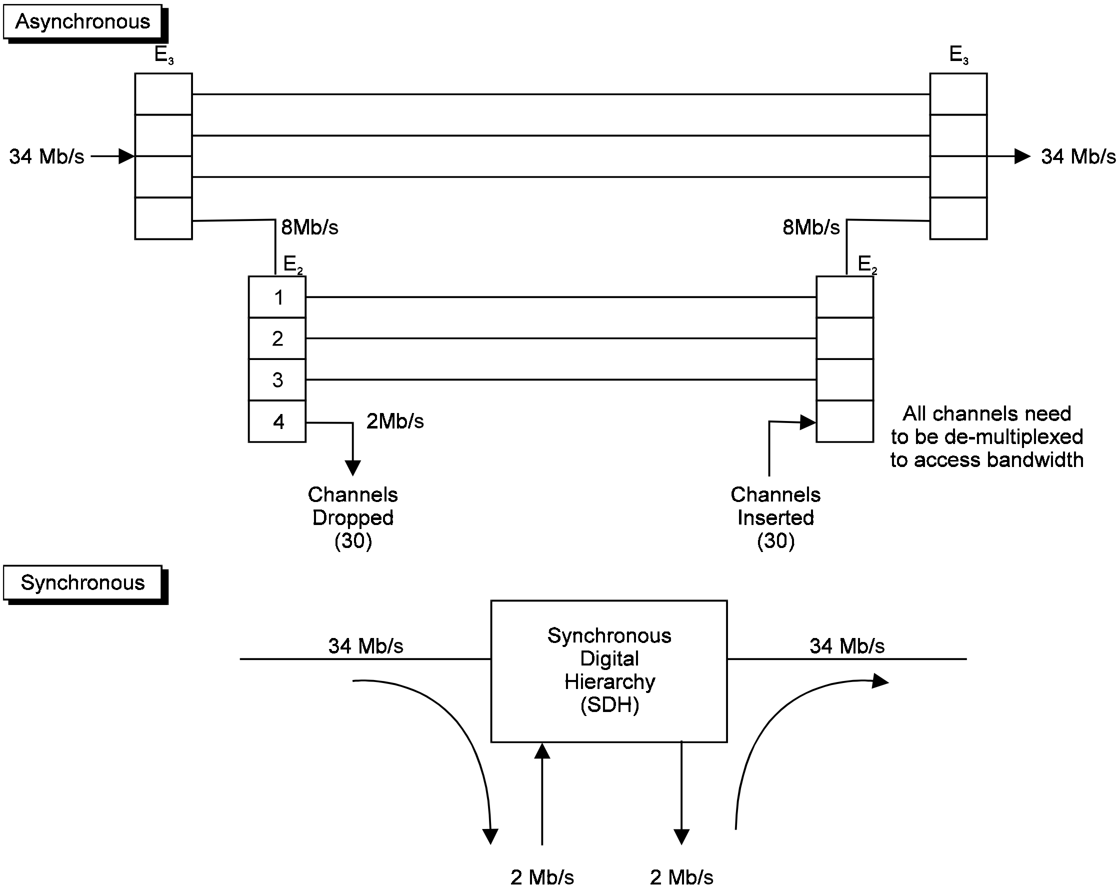


Figure 10.4
Drop-and-insert topologies

It can be seen that the synchronous network enables individual channels to be accessed by their particular time slots. This requires relatively little hardware. The asynchronous networks, by comparison, require hardware to demultiplex all the channels down to the level at which the new channels are to be inserted, then to re-multiplex them back up to the high-speed data stream.

The basic building block of the SONET signal hierarchy is the synchronous transport signal – level 1 (STS-1). This has a bit rate of 51.84 Mbps and includes the overhead to carry a clear T3 (44.736 Mbps) signal or a combination of lower order multiplexed signals. The optical carrier (OC) signals are shown in Table 10.1. The OC-1 signal is obtained by scrambling the STS-1 signal to avoid long strings of ones and zeros to ensure the receivers can recover the clock signals.

Optical carrier level	Line rate Mbps
OC-1	51.84
OC-3 (STM 1)	155.52
OC-9	466.56
OC-12 (STM 4)	622.08
OC-18	933.12
OC-24	1244.16
OC-36	1866.24
OC-48 (STM 16)	2488.32
OC192 (STM 64)	9953.28

Table 10.1
Optical carrier (OC) signals

Designed to accommodate the SONET data rates, ATM is now available at the rate up to OC192.

Synchronous digital hierarchy (SDH) provides technology to integrate the North American and European digital multiplexing schemes into a single high-speed data stream. North American networks are built around the T1 (1.544 Mbps) 24 channel m-law digital multiplexing hierarchy, compared with the E1 (2.048 Mbps) 30 channel A-law multiplexing of European networks. The digital multiplexing hierarchies are shown in Table 10.2. SDH allows the ability to mix these different multiplexing hierarchies in the same system. Table 10.1 shows the equivalent SDH (STM nn) to SONET (OC nn) configurations.

Multiplex order	Bit rate Mbps	Channels	Multiplex order	Bit rate Mbps	Channels
T1	1.544	24	E1	2.048	30
T2	6.312	96	E2	8.448	120
T3	45	672	E3	34	480
T4	91	1344	E4	140	1920
T5	274	4032	E5	565	7680

Table 10.2
Digital multiplex hierarchies

10.3.2 B-ISDN

Broadband ISDN is the name for various sets of integrated standards for high speed data transport and switching using short data cells. These include frame relay, ATM and fiber channel.

As discussed earlier, compressed HDTV signals require data rates in the range 92 to 200 Mbps. B-ISDN is standardized on data rates of 155 Mbps and 622 Mbps to handle such signals. Modern electronic publishing requires very high resolution images. For example, a glossy magazine page can require 2400 dots per inch and a palette comprising 16 million colors. Such images can total 100 MB per page. With electronic publishing, such image files need to be moved easily from designer to customer to printer.

The reference architecture for B-ISDN is shown in Figure 10.5. This indicates various functional units in a network, the interfaces between them, and the functions carried out by each unit.

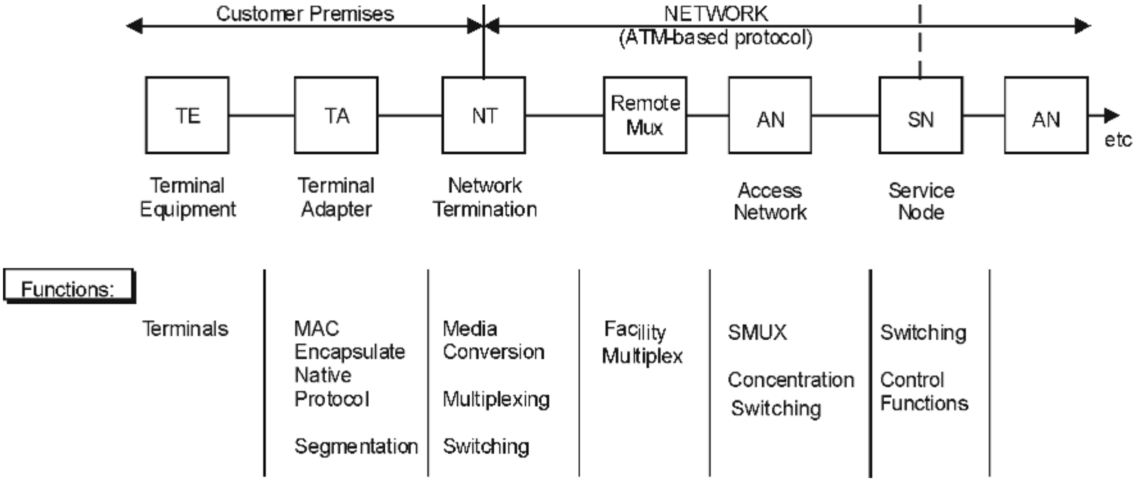


Figure 10.5
B-ISDN reference architecture

10.3.3 Asynchronous transfer mode (ATM)

ATM is one of the B-ISDN standards and it provides a high bandwidth low delay packet switching service. ATM meets the varied requirements for the transport of data, video and voice at differing speeds. While this was developed for wide area networks, it is also very attractive for local area networks requiring high bandwidth. ATM-based LANs are often called local ATM (LATM).

ATM overcomes many of the problems experienced with the current LAN technologies:

- **Shared access security**
  Because conventional LANs have only one path shared by all users, security problems can arise since it is easy to eavesdrop on other users' data. ATM systems use much higher speed virtual circuits, where the common channel is only allocated to the user the time it takes for the individual cells to cross the network. Since each cell only contains 48 bytes of data, such extensive fragmentation and random arrival times of the cells comprising one message makes eavesdropping more difficult.

- **Line speed requirements**
  The use of fiber optic systems enables higher data rates to be achieved. Sending a greater or lesser number of cells can meet the individual user's line speed requirements.
- **Network latency**
  Traditional LAN systems such as Ethernet, token ring and FDDI use access control techniques to allow one user exclusive access to the media at a time, to avoid conflicts between transmitting stations. As data throughput increases, it requires larger packets to be transmitted, and therefore other stations have to wait longer before they can send their messages. In addition, as the usage of the system increases, users need to wait for a free transmission time on the system. In contrast, ATM systems use very short cells (53 byte) multiplexed onto a common transmission system called *virtual path.* At 155 Mbps the cell length is 2.7 microseconds. This can be the maximum delay for time sensitive, real-time data.
- **Network routing**
  With the current LAN and WAN technologies, specialized devices such as bridges and routers, are required to interconnect networks. ATM technology will use the same virtual circuit interconnection processes for local networks or long-distance connections over common carrier systems. This will make the distance between the devices transparent to the applications.

ATM provides a very fast scaleable network. Designed to accommodate the SONET and SDH data rates, ATM is now available at the OC 192 rates of 10 Gbps.

10.3.4 Frame relay

Frame relay is a fast packet switching technology for use on WAN links. It has evolved from the link access protocol for the D channel (LAPD) developed by the CCITT for use on the ISDN D channel (16 kbps).

Frame relay is a more simplified protocol than ATM, and achieves faster speeds than the packet switch X25 protocol by reducing the protocol overhead. Frame relay requires a very reliable communications system such as fiber optic cable, enabling it to operate with less error checking. It checks the frame at the physical layer of the OSI model, reduces the data link layer functions, and eliminates the network layer. Higher layer protocols need to recover from any transmission problems due to the absence of these lower layer functions.

Frame relay operates with virtual circuits, which are logical channels established between the end user (DTE) and the frame relay network (DCE). Virtual circuits are assigned data link connection identifiers (DLCI) when the DTE is attached to the frame relay network. Multiple and/or permanent virtual circuits can be established between DTE and DCE. The frame relay configuration is shown in Figure 10.6.

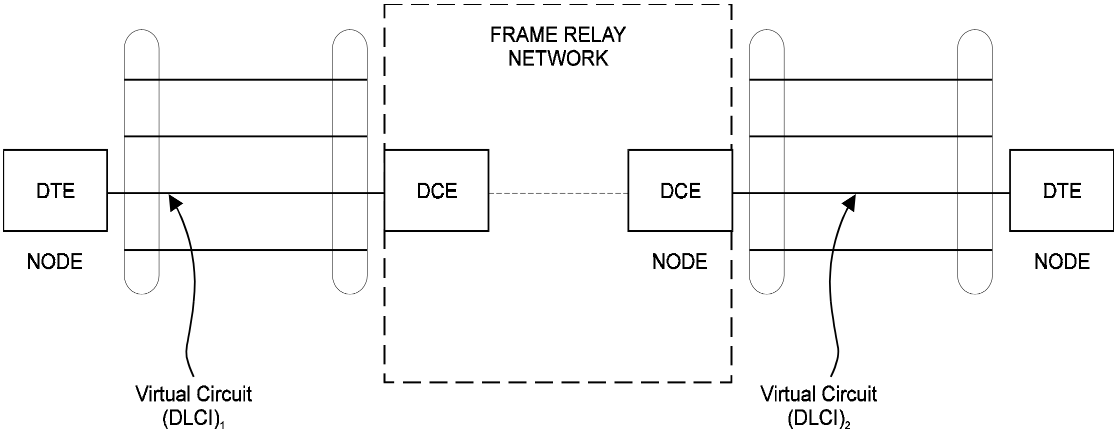


Figure 10.6
Frame relay network

When a frame enters the frame relay network via the DCE, the DLCI is examined and a lookup table consulted to determine the correct outgoing link. If any errors are detected in the frame or if a lookup table entry cannot be found for the frame, the frame is simply discarded. The higher layer protocols at each end of the link need to sort out the problem.

10.3.5 Fiber channel

Fiber channel is an interface technology allowing transfer of very large amounts of data at high speed and with little delay. Fiber channel provides a point-to-point logical channel for the transfer of data between a buffer in a source node and an equivalent buffer at the destination. Generally, the node only needs to manage the connection between itself and the switch. This can be provided using the following topologies as illustrated in Figure 10.7.

- **Point-to-point**
  This channel uses bi-directional point-to-point links connecting the NPorts of a pair of nodes.
- **Fabric**
  This channel uses an entity called fabric, which can comprise one or more switches to provide bi-directional links between its FPorts. The fabric carries out the routing, error detection, correction and the flow control functions.
- **Loop**
  The arbitrated loop is defined in the FC-AL standard (X3.272). This topology interconnects the LPorts at the nodes with one unidirectional channel. The protocol enables an LPort to continuously arbitrate to access the medium to transmit to another LPort.

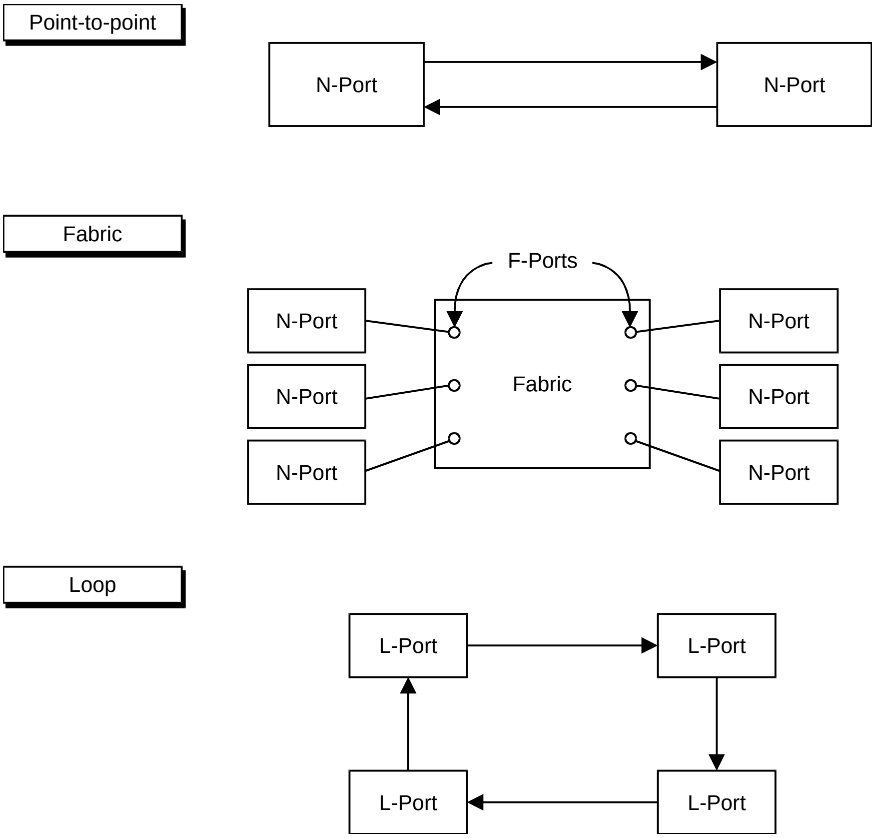


Figure 10.7
Fiber channel topologies

The fiber channel architecture is made of five protocol layers (FC-0 to FC-4). The fiber channel physical and signaling interface (FC-PH) covers layers FC-0 to FC-2 and is described in ANSI X3.230.

- **FC-0**
  This layer describes the physical characteristics of the link connections. Allows transmission over 10 km links of singlemode fiber, 2 km on multimode fiber and up to 50 m on coaxial cables. Singlemode fibers use 1300 nm wavelengths while multimode fibers use 780 and 1300 nm.
- **FC-1**
  This layer describes the transmission protocol, covering the coding and decoding of messages, special characters and error control. This uses an 8B/10B code format where each 8-bit data byte is coded as a 10-bit word. The user node data rates and corresponding channel data rates are shown as Table 10.3.

User data rate (Mbps)	Channel data rate (Mbps)
12.5	132.6
25	256.6
50	531.2
100	1062.5

Table 10.3
Fiber channel and user data rates

- **FC-2**
  This layer defines how data is transferred between nodes and specifies the frame formats, frame sequences and communications protocols. A variable sized frame is used, which can be up to 2148 bytes carrying up to 2048 user data bytes. Each frame has an overhead of 36 bytes for addressing and control purposes. Large frames need to be fragmented into a series of frames.
- **FC-3**
  This layer provides communications services for higher layer protocols. These can include the delivery of multicast and broadcast messages.
- **FC-4**
  This layer provides a protocol convergence layer so the fiber channel node appears to provide the lower layer services that the higher layer protocols require. This may include buffering, synchronization, translation etc. FC-4 mappings are provided for many common protocols including IEEE 802.2 (LLC), Internet protocol (IP) and ATM.

10.4 Sensors

There are various ways fiber optics can be used as sensors. Opto/electronic sensors are widely used to detect objects by looking for the presence or absence of the light coming from a source. This can be supplemented by the use of fibers to enable the sources and/or detectors to be located in more appropriate locations, either to facilitate access or to move the devices away from electrical or other hazards. The basic fiber optic proximity sensor is shown in Figure 10.8.

Fibers can also be used in other sensor applications such as level sensors for flammable liquids. The basic arrangement is shown in Figure 10.9. Here, a pair of fibers is used to get the light to the sensor and detect whether the light is directed back into the collecting fiber. This occurs if the prism at the end of both fibers is not immersed in the liquid. When the prism is immersed, the liquid prevents the total internal reflection occurring and so, the light is no longer detected at the collecting fiber.

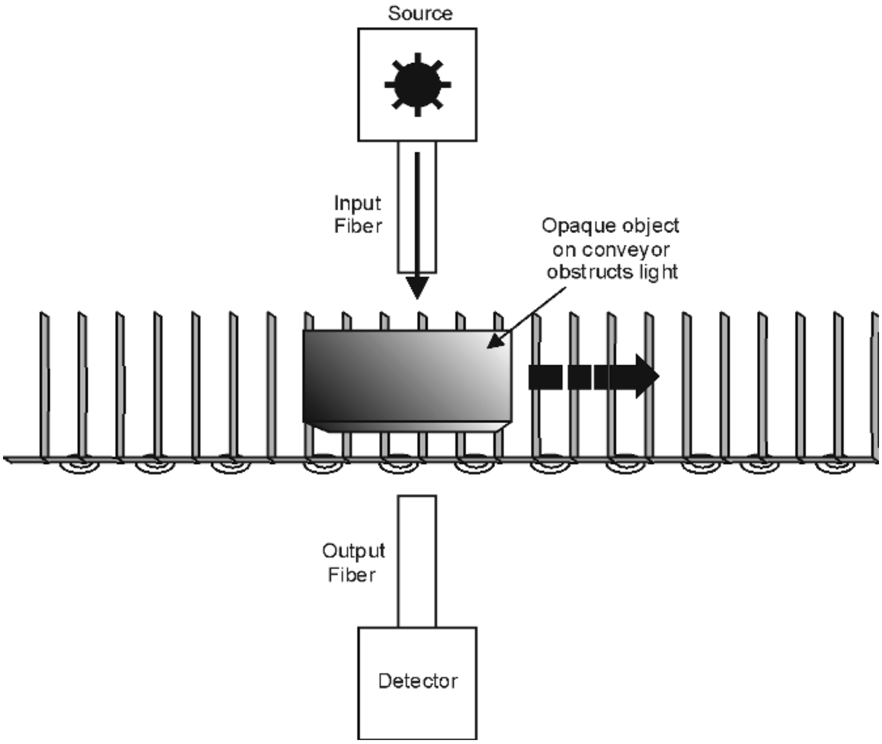


Figure 10.8
Basic fiber optic proximity sensor

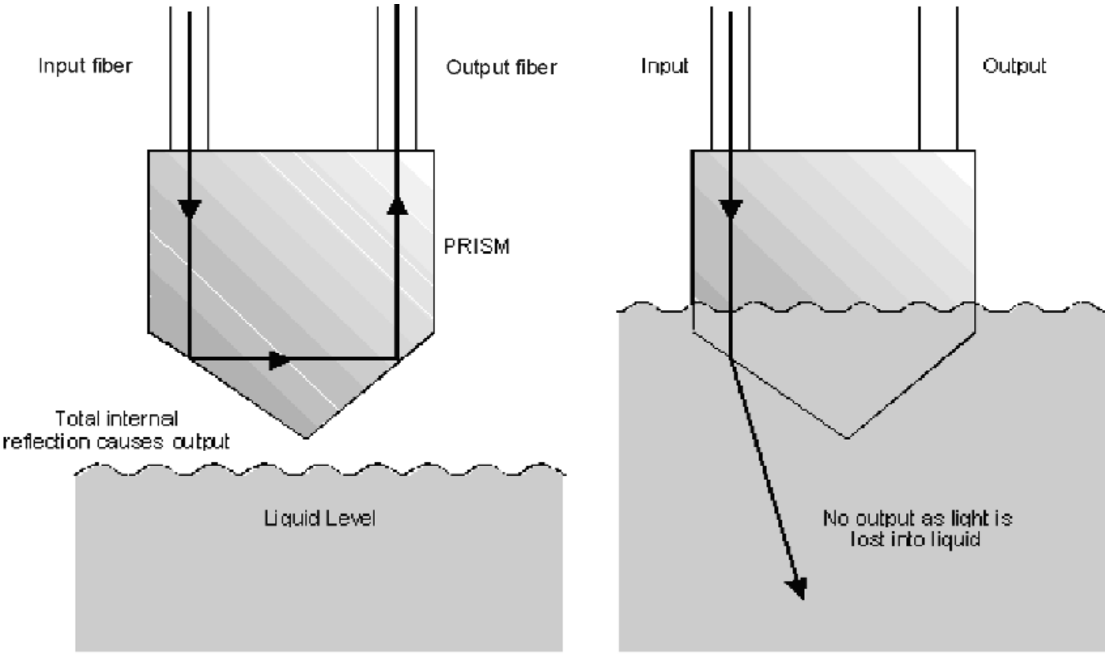


Figure 10.9
Liquid level sensor

10.4.1 Environmental sensors

The way in which the light in the fiber optic cables themselves is changed by their environment can be monitored for use in many sensor applications such as measurement of: pressure, temperature, stains, magnetic fields, acceleration etc. Such applications rely on the very small changes to the light passing through the fiber, which are caused by the external environmental changes. For example, pressure or temperature can be measured by monitoring the loss in a fiber, which is subjected to microbending forces by the external pressure. Magnetic field strength can be measured by monitoring the length of a fiber, which can be moved by the magnetic field. Similarly, acceleration can be measured by determining how much a fiber supporting a weight stretches under acceleration. These sensor applications were generally developed for military applications and most are not cost effective at present.

10.4.2 Fiber optic gyroscopes

Fiber optic technology is also being developed to make very reliable gyroscopes, which have no moving parts! These work on the principle of sending a beam of light in opposite directions through a multiple-turn loop of singlemode fiber optic cable. If the loop is stationary, both beams arrive at the same time. If the loop of circumference *C* is rotated at a distance *d* as shown in Figure 10.10, one beam travels distance *C* + *d* and the other travels *C* – *d*. The small difference can be measured by interference effects in the single mode cable. These are being enthusiastically developed as relatively low-cost gyroscopes for the future.

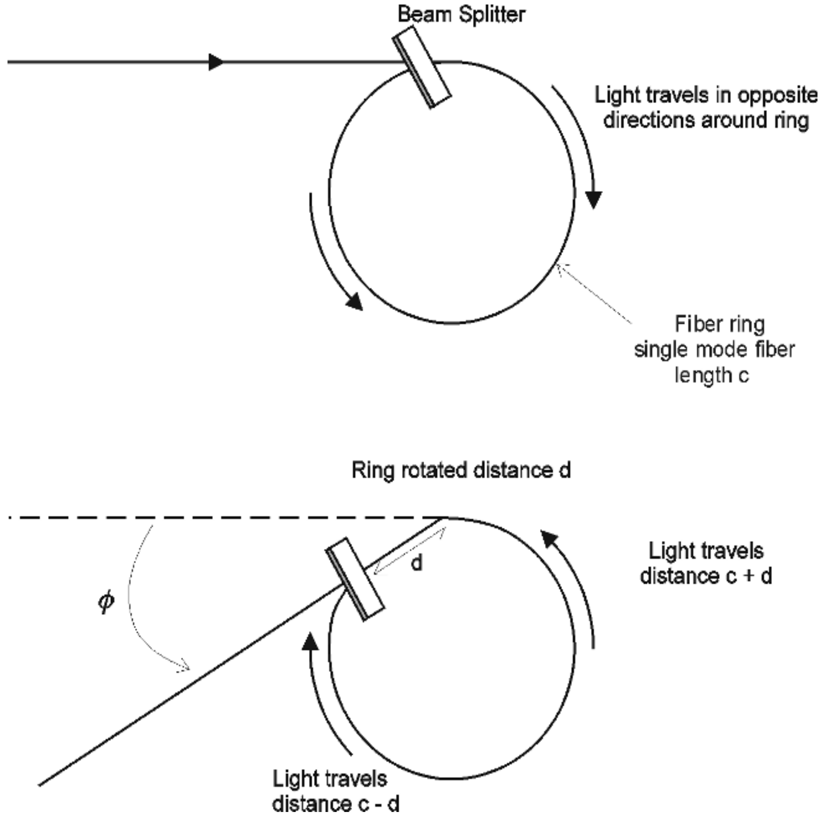


Figure 10.10
Fiber optic gyroscopes

10.5 Bundled fiber applications

Bundles of fibers are often used for non-communication applications, for purposes of illumination or imaging such as medical endoscopes. A bundle of fibers can collect much more light than a single fiber and is more reliable than a single fiber. For illumination purposes, the fibers can be randomly arranged in the bundle, with the individual fibers being as large as 100 mm.

For imaging applications, such as medical endoscopes, the fibers are carefully arranged so that they have the same relationship at both ends of the bundle. This enables images to be transmitted through the bundle and produces what is known as a ‘coherent’ bundle. High-resolution fiber bundles can comprise individual fibers as small as 3µm, and may contain as many as 20 000 fibers.

Appendix A

Glossary

10BASE2	IEEE 802.3 (or Ethernet) implementation on thin coaxial cable (RG58/Au)
10BASE5	IEEE 802.3 (or Ethernet) implementation on thick coaxial cable
10BASEF	IEEE 802.3 (or Ethernet) implementation on fiber optic cable
10BASET	IEEE 802.3 (or Ethernet) implementation on unshielded 22 AWG twisted pair cable
Absorption	loss of optical power caused by unwanted impurities in waveguide material
Acceptance angle	the angle over which, the core of the optical fiber will accept the incoming light – *see* Numerical aperture (NA)
All dielectric cable	cable made entirely of insulating (dielectric) materials
Analog	a continuous real-time phenomenon where the information values are represented in a variable and continuous waveform
Angstrom (A)	unit of length of 0.1 nm or 10^{-10} meter – used for measuring wavelength but not part of the SI system of units

ANSI	American National Standards Institute – the principal standards development body in the USA
Armor	layer providing mechanical protection to the exterior of a cable, usually metallic
AS	Australian Standard
ASCII	American Standard Code for Information Interchange – a universal standard for encoding alphanumeric characters into 7 or 8 binary bits, drawn up by ANSI to ensure compatibility between different computer systems
Asynchronous	communications where characters can be transmitted at an arbitrary, unsynchronized point in time and where the time intervals between transmitted characters may be of varying lengths – communication is controlled by start and stop bits at the beginning and end of each character
ATM	asynchronous transmission mode
Attenuation	the decrease in the magnitude of strength (or power) of a signal – in cables, generally expressed in dB per unit length
Attenuator	circuit element, which reduces the level of signals passing through it, by introducing attenuation
Avalanche photodiode	semiconductor photo-detector in which, the detected photocurrent is amplified by creating an avalanche of other electrons
AWG	American Wire Gauge
Backscattering	scattering of light in the direction opposite to its direction of travel
Balanced circuit	a circuit so arranged that the impressed voltages on each conductor of the pair are equal in magnitude but opposite in polarity with respect to ground
Bandwidth	the range of frequencies available expressed as the difference between the highest and lowest frequencies is expressed in hertz (or cycles per second) – also, used as an indication of capacity of the communications link

Base address	a memory address that serves as the reference point – all other points are located by offsetting in relation to the base address
Baseband	Baseband operation is the direct transmission of data over a transmission medium without the prior modulation on a high frequency carrier band
Baud	unit of signaling speed derived from the number of events per second (normally bits per second) – however, if each event has more than one bit associated with it, the baud rate and bits per second are not equal
BERT/BLERT	Bit Error Rate/Block Error Rate Testing – an error checking technique that compares a received data pattern with a known transmitted data pattern to determine transmission line quality
Bifringent	having refractive index which changes according to the polarization of the light
Bipolar	a signal range that includes both positive and negative values
BIT (Binary Digit)	derived from ‘BInary DigiT,’ a one or zero condition in the binary system
BITS per sec (BPS)	unit of data transmission rate
Block sumcheck	this is used for the detection of errors when data is being transmitted – it comprises a set of binary digits (bits), which are the modulo 2 sum of the individual characters or octets in a frame (block) or message
BNC	bayonet type coaxial cable connector
Branching element	devices, such as optical couplers, to passively distribute the optical signal power to a number of other devices
Bridge	a device to connect similar sub-networks without its own network address – used mostly to reduce the network load
Broadband	a communications channel that has greater bandwidth than a voice grade line and is potentially capable of greater transmission rates – opposite of baseband – in wide band operation, the data to be transmitted are first modulated on a high frequency carrier signal –

	they can then be simultaneously transmitted with other data modulated on a different carrier signal on the same transmission medium
Broadcast	a message on a bus intended for all devices which requires no reply
BS	British Standard
BSC	Bisynchronous Transmission – a byte or character oriented communication protocol that has become the industry standard (created by IBM) – it uses a defined set of control characters for synchronized transmission of binary coded data between stations in a data communications system
Buffer	an intermediate temporary storage device used to compensate for a difference in data rate and data flow between two devices (also called a spooler for interfacing a computer and a printer)
Burst mode	a high-speed data transfer in which the address of the data is sent followed by back-to-back data words while a physical signal is asserted
Bus	a data path shared by many devices with one or more conductors for transmitting signals, data or power
Byte	a term referring to eight associated bits of information; sometimes called a ‘character’
Capacitance	storage of electrically separated charges between two plates having different potentials – the value is proportional to the surface area of the plates and inversely proportional to the distance between them
Capacitance (mutual)	the capacitance between two conductors with all other conductors, including shield, short-circuited to the ground
Cascade	two or more electrical circuits in which the output of one is fed into the input of the next one
CCITT	Consultative Committee International Telegraph and Telephone – an international association that sets worldwide standards (e.g. V.21, V.22, V.22bis) – now incorporated into the International Telecommunications Union (ITU)

Character	letter, numeral, punctuation, control figure or any other symbol contained in a message
Characteristic impedance	the impedance that, when connected to the output terminals of a transmission line of any length, makes the line appear infinitely long – the ratio of voltage to current at every point along a transmission line on which there are no standing waves
Chromatic dispersion	spreading of the light pulse caused by the differences in speed of propagation of the various wavelengths making up the pulse
Cladding	layer of lower refractive index material surrounding core of fiber, which serves to confine light within the core
Clock	the source(s) of timing signals for sequencing electronic events e.g. synchronous data transfer
Closed loop	a signal path that has a forward route for the signal, a feedback network for the signal and a summing point
Coherent bundles	fibers assembled in a bundle having the same arrangement at both ends so they can transmit images
Collision	the situation when two or more LAN nodes attempt to transmit at the same time
Common carrier	a private data communications utility company that furnishes communications services to the general public
Common mode signal	the common voltage to the two parts of a differential signal applied to a balanced circuit
Contention	the facility provided by the dial network or a data PABX, which allows multiple terminals to compete on a first come, first served basis for a smaller number of computer posts
Core	the central region of an optical fiber used for light transmission.
Coupler	a device which connects several fibers together so that the light is divided between the fibers
CPU	Central Processing Unit

CRC	Cyclic Redundancy Check – an error-checking mechanism using a polynomial algorithm based on the content of a message frame at the transmitter and included in a field appended to the frame – at the receiver, it is then compared with the result of the calculation that is performed by the receiver – also referred to as CRC-16
Critical angle	the angle at which light undergoes total internal reflection
Cross talk	a situation where a signal from a communications channel interferes with an associated channel's signals
CSMA/CD	Carrier Sense Multiple Access/Collision Detection – when two situations transmit at the same time on a local area network, they both cease transmission and signal that a collision has occurred – each then tries again after waiting for a predetermined time period – this forms the basis of the IEEE 802.3 specifications
Cutback technique	method of measuring the attenuation of a fiber by comparing the loss of a long segment with that of a shortened section
Cutoff wavelength	the shortest wavelength, which can be transmitted on a singlemode fiber
Dark current	the noise current generated by an unilluminated photodiode
Data link layer	this corresponds to layer 2 of the ISO reference model for open systems interconnection – it is concerned with the reliable transfer of data (no residual transmission errors) across the data link being used
Data integrity	a performance measure based on the rate of undetected errors
Data reduction	the process of analyzing a large quantity of data in order to extract some statistical summary of the underlying parameters
Datagram	a type of service offered on a packet-switched data network – a datagram is a self-contained packet of information that is sent through the network with minimum protocol overheads

Decibel (dB)	a logarithmic measure of the ratio of two signal levels where dB = $20\log_{10}V1/V2$ or where dB = $10\log_{10}P1/P2$ and where V refers to voltage or P refers to power – note that it has no units of measure
Decoder	a device that converts a combination of signals into a single signal representing that combination
Default	a value or setup condition assigned, which is automatically assumed for the system unless otherwise explicitly specified
Delay distortion	distortion of a signal caused by the frequency components making up the signal having different propagation velocities across a transmission medium
DES	Data Encryption Standard
Detector	a device, which generates an electrical signal when illuminated by light
Dielectric	nonconductive
Dielectric constant (E)	the ratio of the capacitance using the material in question as the dielectric, to the capacitance resulting when the material is replaced by air
Digital	a signal, which has definite states (normally two)
DIN	Deutsches Institut Für Normierung
Diode laser	a semiconductor diode, which produces laser light
DIP	acronym for dual in line package referring to integrated circuits and switches
Direct memory access	a technique of transferring data between the computer memory and a device on the computer bus without the intervention of the microprocessor – also abbreviated to DMA
Directional coupler	a coupling device which separates the light traveling in different directions
Dispersion	the variation of the signal delay in an optical fiber, which results in the spreading out of the pulses
Dispersion-shifted fiber	Optical fiber designed to have its nominal zero dispersion point at 1550 nm rather than 1300 nm

DPI	Dots per Inch
Driver software	a program that acts as the interface between a higher level coding structure and the lower level hardware/firmware component of a computer
DSP	Digital Signal Processing
Duplex	the ability to send and receive data simultaneously over the same communications line
Duplex cable	cable containing two fibers
Duplex connector	connector mechanically linking a pair of fibers
EDAC	Error Detection and Correction
Edge emitting diode	a LED, which emits light from the edge of the layers, producing a more confined beam than the conventional surface emitting LEDs
EIA	Electronic Industries Association – a standards organization in the USA, specializing in the electrical and functional characteristics of interface equipment
EISA	Enhanced Industry Standard Architecture
EMI/RFI	Electromagnetic Interference/Radio Frequency Interference – ‘Background noise’ that could modify or destroy data transmission
EMS	Expanded Memory Specification
Emulation	the imitation of a computer system performed by a combination of hardware and software that allows programs to run between incompatible systems
Enabling	the activation of a function of a device by a defined signal
Encoder	a circuit which changes a given signal into a coded combination for purposes of optimum transmission of the signal
EPROM	Erasable Programmable Read Only Memory – non volatile semiconductor memory that is erasable in an ultra violet light and reprogrammable
Erbium-doped fiber amplifier	optical amplifier for 1550 nm region using fibers doped with the rare earth element erbium

Error rate	the ratio of the average number of bits that will be corrupted to the total number of bits that are transmitted for a data link or system
ESD	Electrostatic Discharge
Ethernet	name of a widely used LAN, based on the CSMA/CD bus access method (IEEE 802.3) – ethernet is the basis of the TOP bus topology
Evanescent waves	light guided through the cladding of an optical fiber rather than its core
FCC	Federal Communications Commission
FCS	Frame Check Sequence – general term given to the additional bits appended to a transmitted frame or message by the source to enable the receiver to detect possible transmission errors
FDDI	Fiber Distributed Data Interface – a standard for a 100 Mbps fiber optic local area network
Feedback	a part of the output signal being fed back to the input of the amplifier circuit
Ferrule	tubular connector component for holding and aligning fiber
FIFO	First in, First Out
Firmware	a computer program or software stored permanently in PROM or ROM or semi-permanently in EPROM
Flame retardancy	the ability of a material not to propagate flame once the flame source is removed
Floating	an electrical circuit that is above the earth potential
Flow control	the procedure for regulating the flow of data between two devices, preventing the loss of data once a device's buffer has reached its capacity
Frame	the unit of information transferred across a data link – typically, there are control frames for link management and information frames for the transfer of message data
Frequency	refers to the number of cycles per second

Frequency domain	the displaying of electrical quantities versus frequency
Full-duplex	simultaneous two way independent transmission in both directions (4 wire) – see Duplex
G	giga (metric system prefix – 10^9)
GaAlAs	gallium aluminum arsenide
GaAs	gallium arsenide
Gallium aluminum arsenide (GaAlAs)	a semiconductor material used for LEDs, diode lasers and photo detectors
Gallium arsenide (GaAs)	a semiconductor material used for LEDs, diode lasers and other electro-optical components
Gateway	a device to connect two different networks, which translates different protocols
Graded index fiber	fiber having a refractive index profile, which progressively changes with distance from the fiber axis
Ground	an electrically neutral circuit having the same potential as the earth – a reference point for an electrical system also intended for safety purposes
Group index	the velocity of propagation of light pulses in a fiber is determined by the group index $n_g = n - \lambda dn \backslash d\lambda$
Half-duplex	transmissions in either direction, but not simultaneously
Half power point	the point in a power versus frequency curve, which is half the power level of the peak power (also called the 3 dB point)
Hamming distance	a measure of the effectiveness of error checking – the higher the Hamming distance (HD) index, the safer is the data transmission
Handshaking	exchange of predetermined signals between two devices establishing a connection
Hard-clad silica fiber	an optical fiber having a hard plastic cladding around a silica core

Harmonic distortion	distortion caused by the presence of harmonics in the desired signal
HDLC	High Level Data Link Control – the international standard communication protocol defined by ISO to control the exchange of data across either a point-to-point data link or a multidrop data link
HDTV	High-definition television
Hertz (Hz)	a term replacing cycles per second as a unit of frequency
Hex	hexadecimal
Hydrogen losses	increased fiber attenuation caused by the absorption of light in hydrogen molecules, which have diffused into the glass matrix
IEC	International Electrotechnical Commission
IEE	Institution of Electrical Engineers
IEEE	Institute of Electrical and Electronic Engineers – an American based international professional society that issues its own standards and is a member of ANSI and ISO
Impedance	the total opposition that a circuit offers to the flow of alternating current or any other varying current at a particular frequency – it is a combination of resistance R and reactance X, measured in ohms
Index matching gel	a gel or fluid, which has a refractive index close to that of glass, used at mechanical fiber joints to reduce reflective losses due to refractive index discontinuities
Index profile	curve showing the variation of refractive index over the cross-section of the optical fiber
Index of refraction	refractive index – the ratio of the speed of light in a vacuum to the speed of light in an optically dense medium, usually given abbreviation ‘n’
Indium gallium arsenide (InGaAs)	semiconductor material used for lasers, LEDs and optical detectors

Indium gallium arsenide phosphide (InGaAsP)	semiconductor material used for lasers, LEDs and optical detectors
Inductance	the property of a circuit or circuit element that opposes a change in current flow, thus causing current changes to lag behind voltage changes – it is measured in henrys
Infrared	wavelengths of light between 700 and 1000 nm – these wavelengths are invisible but can be felt as heat
InGaAs	Indium gallium arsenide
InGaAsP	Indium gallium arsenide phosphide
Injection fiber	fiber inserted between an optical source and another fiber
Injection laser diode (ILD)	a semiconductor diode laser
Insertion loss	the attenuation introduced by inserting an optical component in an optical transmission system
Insulation resistance (IR)	resistance offered by insulation to an impressed DC voltage, tending to produce a leakage current though the insulation
Integrated optics	optical devices, which are formed on a single substrate, similar to integrated electronic circuits
Intensity	power per unit solid angle
Interface	a shared boundary defined by common physical interconnection characteristics, signal characteristics and measurement of interchanged signals
Interrupt	an external event indicating that the CPU should suspend its current task to service a designated activity
Interrupt handler	the section of the program that performs the necessary operation to service an interrupt when it occurs
Intrinsic losses	splice losses caused by differences between the fibers being spliced
IP	Internet protocol

Irradiance	power density at a surface, measured in w/cm^2
ISA	Industry Standard Architecture (for IBM personal computers)
ISB	Intrinsically Safe Barrier
ISDN	Integrated Services Digital Network – the new generation of world-wide telecommunications network that utilizes digital techniques for both transmission and switching – it supports both voice and data communications
ISO	International Standards Organization
ISR	Interrupt Service Routine – *see* Interrupt handler
ITU	International Telecommunications Union
Jumper	a wire connecting one or more pins on the one end of a cable only
Junction laser	semiconductor diode laser
k (kilo)	this is 2^{10} or 1024 in computer terminology, e.g. 1 kb = 1024 bytes
Kevlar	an aramid fiber material used for cable strength members – trademark of the Dupont Company
LAN	Local Area Network – a data communications system confined to a limited geographic area typically about 10 km with moderate to high data rates (100 kbps to 50 Mbps) – some type of switching technology is used, but common carrier circuits are not used
Large core fiber	fiber with a core typically exceeding 200 micrometers
Laser	acronym for light amplification by stimulated emission of radiation – semiconductor diode lasers are the common light sources for higher speed fiber optic systems
LCD	Liquid Crystal Display – a low power display system used on many laptops and other digital equipment
Leased (or private) line	a private telephone line without inter-exchange switching arrangements
LED	Light emitting diode

Light	electromagnetic radiation visible to human eye (400 to 700 nm), commonly used to include the invisible near-infrared wavelengths applied in many fiber optic systems
Light emitting diode (LED)	semiconductor diode, which emits incoherent light from the junction between p- and n-doped materials when forward biased
Line driver	a signal converter that conditions a signal to ensure reliable transmission over an extended distance
Line turnaround	the reversing of transmission direction from transmitter to receiver or vice versa when a half duplex circuit is used
Link layer	layer two of the ISO/OSI reference model – also known as the data link layer
Longitudinal modes	transmission modes along the length of a waveguide
Loop resistance	the measured resistance of two conductors forming a circuit
Loopback	type of diagnostic test in which the transmitted signal is returned on the sending device after passing through all, or a portion of, a data communication link or network – a loopback test permits the comparison of a returned signal with the transmitted signal
Loose tube	a tubular structure, which protects and isolates one or more cabled fibers from external forces – often filled with waterproofing gel for external use
Loss	attenuation of a signal, normally measured in dB
Loss budget	summation of total gains and attenuation in an optical fiber system
m	Meter – metric system unit for length
M	Mega – metric system prefix for 10^6
MAP	Manufacturing Automation Protocol – a suite of network protocols originated by General Motors, which follow the seven layers of the OSI model – a reduced implementation is referred to as a mini-MAP

Margin	additional allowance for attenuation in system
Mark	equivalent to a binary 1
Master/slave	bus access method whereby the right to transmit is assigned to one device only, the master, and all the other devices, the slaves may only transmit when requested
Material dispersion	dispersion of non-monochromatic pulses caused by the change of the material's refractive index with wavelength
Mbps	megabits per second
Mechanical splice	splice where fibers are joined mechanically by clamping or crimping
Microbending	microscopic axial bends in fibers, which increase loss
Micrometer	one-millionth of a meter (μm)
MIPS	Million instructions per second
MMS	Manufacturing Message Services – a protocol entity forming part of the application layer – intended for use specifically in the manufacturing or process control industry – enables a supervisory computer to control the operation of a distributed community of computer-based devices
Modal dispersion	dispersion caused in multimode cables by the differences in propagation times of different modes
Mode	discrete optical waves, which can propagate in an optical waveguide or cavity – the modes have different field patterns and propagation velocities
Mode field diameter	the diameter of the one mode of light which propagates in a monomode fiber, typically slightly larger than the core diameter
Mode stripper	device, which removes high-order modes from a multimode fiber to standardize measurement conditions
Modem	modulator–demodulator – a device used to convert serial digital data from a transmitting terminal to a signal suitable for transmission over a telephone

	channel or to reconvert the transmitted signal to serial digital data for the receiving terminal
Monomode fiber	singlemode fiber
MTBF	Mean Time Between Failures
MTTR	Mean Time To Repair
Multidrop	a single communication line or bus used to connect three or more points
Multimode distortion	the signal distortion caused by modal dispersion
Multiplexer (MUX)	a device used for division of a communication link into two or more channels either by using frequency division or time division
n-Region	semiconductor material doped to produce an excess of electrons as charge carriers
NA	numerical aperture
Nanometer	si system unit of length, 10^{-9} meter
Nanosecond	one-billionth of a second, 10^{-9} second
Narrowband	a device that can only operate over a narrow band of frequencies
National electric code	a US wiring code which specifies safety standards for copper and fiber optic cables
Near infrared	part of the spectrum just beyond the visible wavelengths into the infrared
Near-field radiation	distribution of the power density (irradiance) over an emitting surface
Network	an interconnected group of nodes or stations
Network architecture	a set of design principles including the organization of functions and the description of data formats and procedures used as the basis for the design and implementation of a network (ISO)
Network layer	layer 3 in the ISO/OSI reference model, the logical network entity that services the transport layer responsible for ensuring that data passed to it from

	the transport layer is routed and delivered throughout the network
Network topology	the physical and logical relationship of nodes in a network; the schematic arrangement of the links and nodes of a network typically in the form of a star, ring, tree or bus topology
NMRR	Normal Mode Rejection Ratio
Node	a point of interconnection to a network
Noise	a term given to the extraneous electrical signals that may be generated or picked up in a transmission line – if the noise signal is large compared with the data carrying signal, the latter may be corrupted resulting in transmission errors
Noise effective power (NEP)	the optical input power required by a detector to generate an electrical signal equivalent to the inherent electrical noise
Non-linearity	a type of error in which the output from a device does not relate to the input in a linear manner
NRZ	Non-Return to Zero – a digital coding technique in which the signal level is low for a ‘0’ bit and high for a ‘1’ bit, and does not return to zero between consecutive ‘1’ bits
NRZ	Non-Return to Zero – pulses in alternating directions for successive 1 bits but no change from existing signal voltage for 0 bits
NRZI	Non-Return to Zero Inverted
Numerical aperture	the sign of the maximum possible angle over which the fiber can accept light
OHM (Ω)	unit of resistance such as a constant current of one ampere that produces a potential difference of one volt across a conductor
Operating lifetime	period of time over which a continuously operating component, such as a laser diode, will retain its parameters within a prescribed range
Optical amplifier	a device, which amplifies an optical signal directly without needing to convert it to an electrical signal

Optical isolation	two networks with no electrical continuity in their connection because an optoelectronic transmitter and receiver has been used
Optical loss test set	an optical light source and power meter calibrated to work together
Optical receiver	device for converting optical signals to electrical signals
Optical time domain reflectometer (OTDR)	an instrument for measuring fiber transmission performance by sending a short pulse into the fiber and observing the backscattered light
Optical waveguide	a structure, which can guide light, comprising an optically transparent core surrounded by a cladding of lower refractive index
Optical waveguide connector	component used for the non-permanent connection and disconnection of optical waveguides, usually having greater insertion loss than a splice
OSI	Open Systems Interconnection
p-Region	semiconductor type in which the dominant electron carriers are holes
Packet	a group of bits (including data and call control signals) transmitted as a whole on a packet switching network. Usually smaller than a transmission block
Pad	Packet Assembler/Disassembler – an interface between a terminal or computer and a packet switching network
Parallel transmission	the transmission model where a number of bits is sent simultaneously over separate parallel lines – usually unidirectional such as the Centronics interface for a printer
Peak power	highest instantaneous power level in a pulse
Peripherals	the input/output and data storage devices attached to a computer e.g. disk drives, printers, keyboards, display, communication boards etc.
Photodetector	a light detecting device

Photodiode	a diode, which absorbs light and releases the charge carriers to an external circuit as a photocurrent
Photon noise	see Quantum noise
Photonic	devices which work using photons (cf ‘electronic’ devices which use electrons)
Photons	quanta of electromagnetic radiation – light waves are considered to be either waves or photons
Physical layer	layer one of the ISO/OSI reference model, concerned with the electrical and mechanical specifications of the network termination equipment
Pig-tail	short length of optical fiber used to connect optical devices – usually, permanently connected to a component such as a laser diode
Pin photodiode	photodiode with an intrinsic (i) depletion layer separating its pn junction – has high quantum efficiency but no internal current gain – used for fiber-optic receivers
Planar waveguide	waveguide fabricated in a flat material such as a thin film
Plastic clad silica (PCS) fiber	a step-index multimode fiber comprising a silica core surrounded by a lower refractive index plastic cladding
PLC	Programmable Logic Controller
Plenum cable	cable made with a flame retardant jacket material to meet the US electrical code requirements (UL 910) for low smoke emission to allow installation in air spaces
Point-to-point	a connection between only two items of equipment
Polarization	alignment of the electric field component of an electromagnetic wave – light is polarized if all the light waves have the same electric field alignment
Polling	a means of controlling devices on a multipoint line – a controller will query devices for a response
Port	a place of access to a device or network, used for input/output of digital and analog signals

Preform	a cylindrical rod of glass from which the optical fibers are drawn – the refractive index profile of the preform is transferred into the fiber
Presentation layer	layer 6 of the ISO/OSI reference model, concerned with negotiation of a suitable transfer syntax for use during an application – if this is different from the local syntax, the translation to/from this syntax
Primary coating	the plastic coating applied to the cladding surface of an optical fiber, especially glass, during manufacture to preserve the integrity of its surface
Protocol	a formal set of conventions governing the formatting, control procedures and relative timing of message exchange between two communicating systems
Protocol entity	the code that controls the operation of a protocol layer
PSDN	Public Switched Data Network – any switching data communications system, such as Telex and public telephone networks, which provides circuit switching to many customers
PSTN	Public Switched Telephone Network – this is the term used to describe the (analog) public telephone network
PTT	Post, Telephone and Telecommunications Authority
Pulse dispersion	the broadening of pulses as they travel along an optical fiber – caused by variations in the lengths of the paths taken by the light rays and/or variation of the propagation velocity of the light in the fiber
Quantum efficiency	the fraction of photons striking a photodetector which release charge carriers (electron-hole pairs) in the photocurrent
Quantum noise	the signal-dependent noise component produced by the statistical fluctuations of the quantized photons and electrons
Quaternary	a semiconductor material made of four elements such as InGaAsP
R/W	read/write
Radiance	density of the radiant power relative to the emitting area and solid angle – nominal units are W/cm^2sr

Radiant intensity	power density in the far field of an optical source – nominal units are W/sr
Radiation hardened	devices, which are insensitive to the effects of nuclear radiation, normally used for military applications
RAM	Random Access Memory – semiconductor read/write volatile memory – data is lost if the power is turned off
Rays	straight lines used to represent the path taken by light
Receiver sensitivity	the optical power needed by a receiver to achieve low error transmissions – usually quoted as the mean optical power (W or dBm) at which a BER of 10^{-9} is achieved
Receiver	device used to detect optical signals and convert them into electrical signals
Recombination	process in a semiconductor in which an electron and a hole combine to release energy, sometimes as light emission
Refraction	the bending of light as it crosses the boundary between materials of different refractive index
Refractive index	ratio of the velocity of light in a vacuum to that in an optically dense material, abbreviation n
Refractive index contrast (Δ)	the normalized refractive index difference, $\Delta = (n_1^2 – n_2^2)/2n_1^2$, often approximated to $(n_1 – n_2)/n_1$
Refractive index difference	the difference between the maximum refractive index in the core of an optical fiber n_1 and the refractive index in the cladding n_1
Refractive index profile	the change of refractive index with distance from the axis of an optical fiber
Regenerator	a receiver-transmitter pair used in a digital transmission system to detect a weak incoming signal and regenerate the original signal from it for onward transmission
Repeater	an amplifier, which regenerates the signal and thus expands the network
Resistance	the ratio of voltage to electrical current for a given circuit measured in ohms

Response time	the elapsed time between the generation of the last character of a message at a terminal and the receipt of the first character of the reply – it includes terminal delay and network delay
Responsivity	ratio of the output of a detector to its input, often measured in microamperes per microwatt
Return to zero (RZ)	digital coding technique in which the signal is low for a logical 0 bit and high for a logical 1 bit during the first half of the bit interval, then always it returns to zero for the second half of the bit
RFI	Radio Frequency Interference
Ribbon cable	a cabling structure where multiple fibers are assembled in parallel, then embedded in plastic to form a flat ribbon-like construction – allows modular installation and automated jointing of multiple fibers
Ring	network topology commonly used for interconnection of communities of digital devices distributed over a localized area, e.g. a factory or office block – each device is connected to its nearest neighbors until all the devices are connected in a closed loop or ring – data are transmitted in one direction only – as each message circulates around the ring, it is read by each device connected in the ring
Rise time	the time required for a waveform to reach a specified value from some smaller value
RMS	Root Mean Square
ROM	Read Only Memory – computer memory in which data can be routinely read but written to only once using special means when the ROM is manufactured – a ROM is used for storing data or programs on a permanent basis
Router	a linking device between network segments which may differ in layers 1, 2a and 2b of the ISO/OSI reference model
RS	Recommended Standard (e.g. RS-232-C) – newer designations use the prefix EIA (e.g. EIA-RS-232-C or just EIA-232-C)
RTU	Remote Terminal Unit – terminal unit situated remotely from the main control system

SAA	Standards Association of Australia
Scattering	principal cause of attenuation in an optical waveguide. Produced by microscopic density changes in the glass, which deflect a small part of the guided light out of the waveguide
SDH	Synchronous Digital Hierarchy
SDLC	Synchronous Data Link Control – IBM standard protocol superseding the bisynchronous standard
Semiconductor laser	a laser in which injection of current into a semiconductor diode produces light by recombination of electrons and holes at the junction between the p- and n-doped regions
Serial transmission	the most common transmission mode in which information bits are sent sequentially on a single data channel
Session layer	layer 5 of the ISO/OSI reference model, concerned with the establishment of a logical connection between two application entities and with controlling the dialog (message exchange) between them
Sheath	the outer protective layer of a cable
SI units	Système Internationale d’Unites – the standard international system of metric units
Signal to noise ratio	the ratio of signal strength to the level of noise
Silica glass	glass made mostly of silicon dioxide SiO_2, used for most common fibers
Simplex transmissions	data transmission in one direction only
Single-frequency laser	a laser, which emits a narrow enough range of wavelengths to be considered as a single frequency
Singlemode fiber	monomode fiber – small diameter optical waveguide in which only the fundamental mode can propagate
Singlemode laser	laser operating in one transverse or one horizontal mode only – note a laser operating in a single transverse mode typically does not operate in a single longitudinal mode as well

Single-polarization fibers	optical fibers designed to carry light in one polarization only
Slew rate	this is defined as the rate at which the voltage changes from one value to another
SNA	Systems Network Architecture
SNR	Signal to Noise Ratio
Soliton	pulses, which can retain their pulse shape after traveling very long distances in fiber optic system – utilize self-phase modulation to counteract dispersion effects.
Sonet	synchronous optical network – a standard for synchronous fiber optic transmission forming part of the B-ISDN standard
Space	absence of signal – this is equivalent to a binary 0
Splice	a permanent connection between two optical fibers
Splitting ratio	the ratio of power distributed among the output ports of an optical coupler
Spontaneous emission	occurs when there are too many electrons in the conduction band of a semiconductor – when an electron drops spontaneously into the valence band it emits a photon
Standing wave ratio	the ratio of the maximum to minimum voltage (or current) on a transmission line at least a quarter-wavelength long (VSWR refers to voltage standing wave ratio)
Star	a type of network topology in which there is a central node that performs all switching (and hence routing) functions
Star coupler	optical component for transferring the optical input power to multiple outputs
Step-index monomode fiber	optical fiber with a constant refractive index across a small diameter core and sharply reduced refractive index in the cladding – small diameter core carries light in only one mode
Step-index multimode fiber	optical fiber with a constant refractive index across a large diameter core and sharply reduced refractive

	index in the cladding – large diameter core carries light in multiple modes
Stimulated emission	occurs where photons in a semiconductor stimulate available excess charge carriers to recombine, and emit light identical in wavelength and phase with the incident light
STP	Shielded Twisted Pair
Submarine cable	cable designed for installation underwater
Surface-emitting diode	a simple, inexpensive LED structure, which emits light in a wide angle from its flat surface
Switched line	a communication link for which the physical path may vary with each usage, such as the public telephone network
Synchronization	the co-ordination of the activities of several circuit elements
Synchronous digital hierarchy	international version of SONET, enabling different data rates to be accessed in synchronous transmission schemes
Synchronous transmission	transmission in which data bits are sent at a fixed rate, with the transmitter and receiver synchronized – synchronized transmission eliminates the need for start and stop bits
T coupler	an optical coupling device with three parts – gives one output for two inputs, or vice versa
TCP	Transmission Control Protocol
TDR	Time Domain Reflectometer – this testing device enables the reflections user to determine cable quality with providing information and distance to cable defects
Temperature rating	the maximum, and minimum temperature at which an insulating material may be used in continuous operation without loss of its basic properties
Ternary compounds	silicon compounds made of three elements, such as GaAsP

Threshold current	the minimum driving current required in a laser diode to maintain laser action – this is strongly temperature dependent
TIA	Telecommunications Industry Association
Tight buffer	a material tightly surrounding a fiber providing physical protection, allowing the fiber to connect directly to components
Time domain	the display of electrical quantities versus time
Time sharing	a method of computer operation that allows several interactive terminals to use one computer
Token ring	collision free, deterministic bus access method as per IEEE 802.2 ring topology
TOP	Technical Office Protocol – a user association in USA which is primarily concerned with open communications in offices
Topology	physical configuration of network nodes, for example, bus, ring, star, tree
Total internal reflection	total reflection of light, incident at less than a critical angle, occurring at an interface to a material of lower refractive index
Transceiver	a combination of transmitter and receiver
Transient	an abrupt change in voltage of short duration
Transmission line	one or more conductors used to convey electrical energy from one point to another
Transport layer	layer 4 of the ISO/OSI reference model, concerned with providing a network independent reliable message interchange service to the application oriented layers (layers 5 through 7)
Transverse modes	transmission modes, which are across the width of a waveguide
Trunk	a single circuit between two points, both of which can be switching centers or individual distribution points – a trunk usually handles many channels simultaneously

Twisted pair	a data transmission medium, consisting of two insulated copper wires twisted together – this improves its immunity to interference from nearby electrical sources that may corrupt the transmitted signal
Unbalanced circuit	a transmission line in which voltages on two conductors are unequal with respect to ground e.g. a coaxial cable
Ultraviolet	electromagnetic waves shorter in wavelength than the visible spectrum (10–400 nm)
UTP	Unshielded Twisted Pair
Velocity of propagation	the speed of an electrical signal down a length of cable compared to speed in free space expressed as a percentage
VFD	Virtual Field Device – a software image of a field device describing the objects supplied by it e.g. measured data, events, status etc., which can be accessed by another network
Visible light	wavelengths of electromagnetic radiation between 400 and 700 nm, visible to the human eye
Volatile memory	an electronic storage medium that loses all data when power is removed
Voltage rating	the highest voltage that may be continuously applied to a wire in conformance with standards of specifications
VT	Virtual Terminal
WAN	Wide Area Network
Waveguide	a structure which guides electromagnetic waves along its length – optical fibers are optical waveguides.
Waveguide couplers	a coupler in which light is transferred between planar waveguides
Waveguide dispersion	the contribution to the chromatic dispersion caused by the light traveling at different speeds in the core and cladding of a single mode fiber
Wavelength	the distance a wave travels in oscillating through a complete cycle – wavelengths of light are typically

	measured in units of nanometers (10^{-9} m) or micrometers (microns) (10^{-6} m)
Wavelength-division multiplexing	process for multiplexing signals by transmitting them at different wavelengths in the same waveguide
Word	the standard number of bits that a processor or memory manipulates at one time – typically, a word has 16 bits
X.21	CCITT standard governing interface between DTE and DCE devices for synchronous operation on public data networks
X.25	CCITT standard governing interface between DTE and DCE device for terminals operating in the packet mode on public data networks
X.25 Pad	a device that permits communication between non X.25 devices and the devices in an X.25 networks
X.3/X.28/X.29	a set of internationally agreed standard protocols defined to allow a character oriented device, such as a visual display terminal, to be connected to a packet switched data network