ENGINEERING @ SP

Singapore Polytechnic

ET0153

SATELLITE AND OPTICAL COMMUNICATION

(Version 1.1)

School of Electrical & Electronic Engineering

Engineering @ SP

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we prepare our learners to be
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for the transformation of Singapore

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A caring community of inspired learners committed to serve with mastery.

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- Self-Discipline
- Personal Integrity
- Care & Concern
- Openness
- Responsibility
- Excellence

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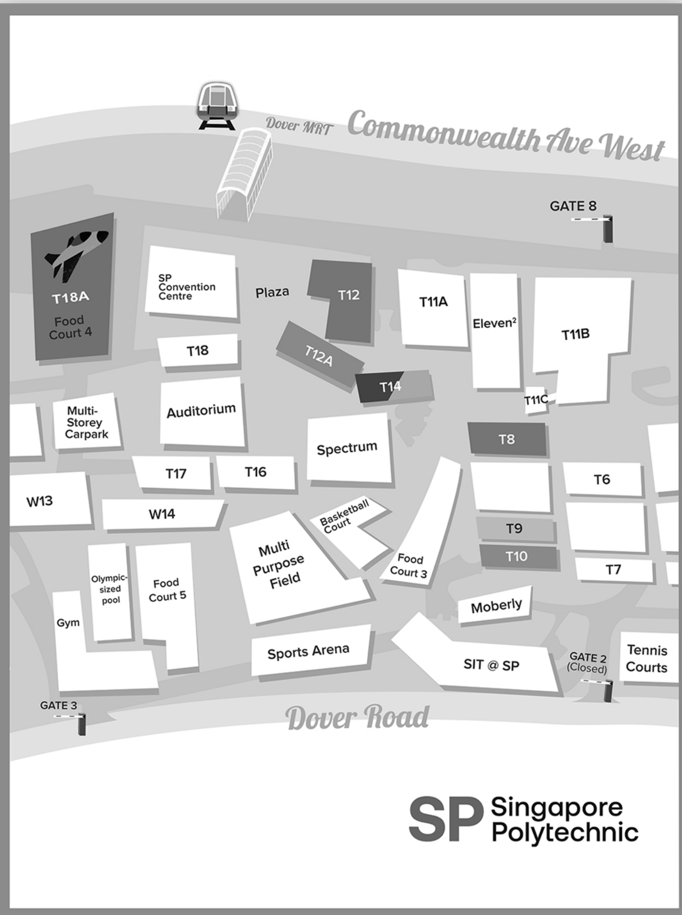
Singapore Polytechnic

SP | SCHOOL OF ELECTRICAL & ELECTRONIC ENGINEERING

Industry-Collaborated TECH HUB



T18A

Aerospace Engineering Hub

Diploma in Aerospace Electronics

Themed Project : Unmanned Aircraft Applications
Facilities : A320 Flight Simulator
Industries : Aerospace, Air Transport
Industry Partners : AIRBUS, Rolls-Royce
Industry Co-location Lab : ST Engineering Aerospace

T9 level 3 & T14 level 3

5G & AIoT Technology Hub

Diploma in Computer Engineering

Themed Project : Smart Facility Management
Facilities : AIoT Nerve Centre, 5G Garage
SP Connected Solutions Lab
Industries : ICT & Media, Smart City
Industry Partners : ADVANTECH, CONTEC, D'CRYPT, ENVISION, HUAWEI, LINGJACK DiGiTaL, unabiz
Industry Co-location Lab : BOSCH, ERICSSON, Singtel

T14 level 3

Technology to Business Hub

Diploma in Engineering with Business

Themed Project : Technology To Business Venture
Facilities : IdeaBox, T2B Hub
Industries : Entrepreneurship & Start-up
Industry Co-location Lab : SPgroup, GEX VENTURES
APOL, BevEat, BitsGreat, MEMORY ARK, OCTOPUS8, Jackdat, REAL IMPACT, SMARTDB, TOP TASTE, Vaster

T10 level 3

Robotics, Automation & Control Hub

Diploma in Electrical & Electronic Engineering

Themed Project : Smart Workflow Solution for I4.0
Autonomous Mobile Robot/Robocup
Facilities : SP-SICK Smart Sensor Lab, SP-Rexroth I4.0 Innovation Lab
Industries : Logistics, Electronics (Manufacturing), Electronics & Chemicals (Manufacturing)
Industry Partners : ABB, BECKHOFF, LKH PRECICON, SEW EURODRIVE, Weidmüller, ZEBRA
Industry Co-location Lab : rexroth A Bosch Company, SICK Sensor Intelligence.

T8 level 2 & T12 level 1

Power & Sustainable Energy Hub

Themed Project : Net-zero Renewable Energy Vertical Farming
Facilities : High Voltage Training, LE & LET Training, Energy Efficiency Lab
Industries : Energy & Power
Industry Partners : CHNT, ebmpapst, sembcorp, SUNLIGHT A CHNT COMPANY

T12/T12A level 2

Semicon & Electronics Hub

Themed Project : Artificial Intelligence of Things using FPGA
Facilities : Nanofab & IC Design Labs, Infineon Innovation Lab
Industries : Semiconductor & Electronics
Industry Partners : SSIA
Industry Co-location Lab : ADVANTEST, Infineon

T12 level 6

Biomedical Engineering Hub

Themed Project : Engaging Rehabilitation with Data Visualisation & Analytics
Facilities : Biomedical Engineering Lab
Industries : Healthcare
Industry Partners : GE Healthcare, GOLD LITE, Khoo Teck Puat Hospital, NATIONAL INSTRUMENTS

T8 level 2 & T12 level 1

Autonomous & Transportation Systems Hub

Themed Project : 5G-enabled Autonomous Safety Vehicle
Autonomous Underwater Vehicle
Facilities : RSS Lab for RTT Training, Siemens Digital Experience Centre,
SP-TIBCO Adv Mfg Analytics Lab
Industries : Smart Transport, Land Transport
Industry Partners : ST Engineering Land Systems, SMRT, SIIX, SUTD, GreenPower
Industry Co-location Lab : SIEMENS Ingenuity for life, TIBCO

CONTENTS

Module Overview

1 Introduction

This is a 60 hours, 4 credit units module which consists of 15 hours lectures and supported by 22.5 hours of tutorial sessions designed to help students in understanding the concepts. To further reinforce the concepts taught, students will spend 22.5 hours in the laboratory, experimenting on key topics.

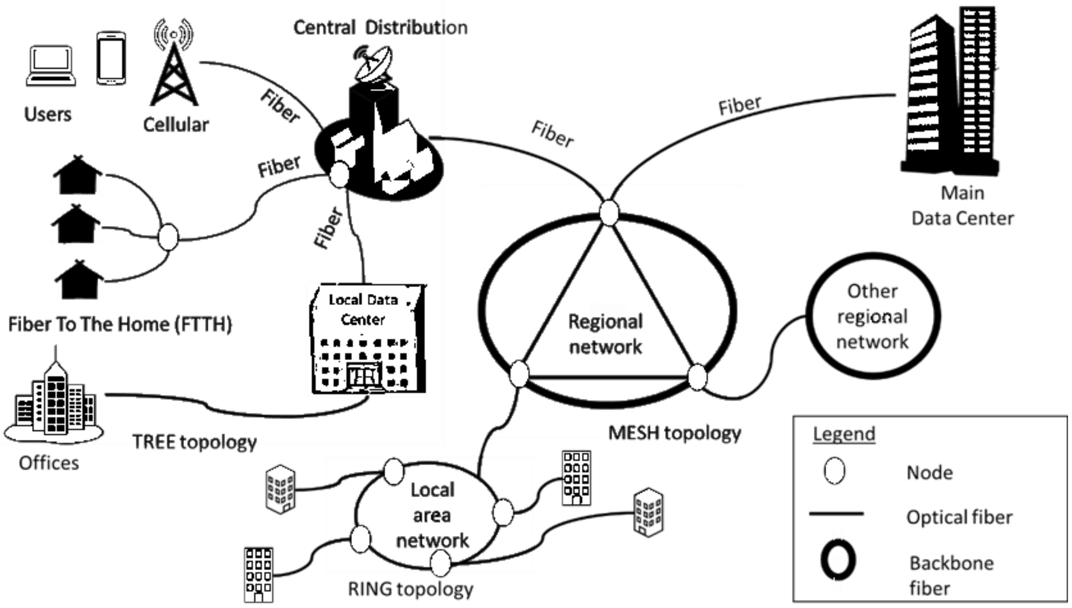
2 Module Aims

This module will cover the following objectives:

- To equip students with a basic knowledge of satellite communications as well as to give them practical experience in satellite communication applications.
- To equip students with a basic understanding of optical fiber communication systems and various components/devices used.
- To provide students with working knowledge in planning, operating and maintaining optical communication systems.

SATELLITE & OPTICAL COMMUNICATION

Satellite Communication
wireless *broadcast service*



Optical Fiber Communication
wireline *point to point link*

CHAPTER 1

INTRODUCTION TO OPTICAL COMMUNICATION

CHAPTER OBJECTIVES:

1. Know the basic principles of optical communications
2. Know the basic principles of optical communications

Learning outcomes

At the end of the chapter, the students will be able to:

- ☑ Describe the development of optical communications.
- ☑ Define the electromagnetic spectrum and identify the optical spectrum by wavelength.
- ☑ Describe the functions of the fundamental components of optical communication link.
- ☑ State the advantages of optical communication link over conventional communication systems
- ☑ Define refractive index, modes, Snell’s law, critical angle, total internal reflection related to light wave propagation in optical fibers
- ☑ Analyse reflection and refraction of light propagation within optical fibers
- ☑ Explain the various modes of propagation in optical fibers
- ☑ Analyse numerical aperture, acceptance angle & acceptance cone for optical fibers

CHAPTER 1 Introduction to Optical Communication

INTRODUCTION

Before optical fibers, most electronic communication was carried by copper cables, whether twisted pairs, coaxial cables, or copper waveguides. With the growth of internet, gaming, online shopping, video and social media, the demand for more bandwidth eventually led to the investigation and development of optical fibers as a communication link.

In optical fiber communication, light replace the electrical signals. An optical fiber is a transparent rod usually made of pure glass or clear plastic. A strand of fiber is about the diameter of a human hair but it is able to carry light signals from transmitter to receiver over long distances.

The numerous advantages of optical fiber from low loss to high data rates and signal security make it a preferred choice especially for the telecommunication industry. Experts and analysts expect the optical fiber communication industry to grow tremendously following the deployment of 5G across the globe with billions of dollars invested in optical fiber infrastructure. .

In order to appreciate optical fiber as the preferred method of communication among the various industries, it is beneficial to know the history of fiber development and useful to review the advantages and the various areas of application provided by this optical fiber

1.1 DEVELOPMENT

The history of the development of fiber optic technology centers on applications in the communication industry and on government-sponsored research, which is focused almost exclusively on communication. The major advances have started as early as the 1970s and 1980s. The important milestones are listed here.

YEAR	MAJOR ADVANCES
1930	Willis Lamb, Jr., experimented with light guided in a glass fiber
1951	A group of researchers in the US. Demonstrated the transmission of an image through a bundle of glass fibers
1953	Narinder Sing Kapany developed fibers with cladding
1960s	Theodore Maiman demonstrated the first laser and invented the semiconductor laser
1970s	Corning Class Company produced low-loss fibers (under 20dB/km)
1980s	American Telephone & Telegraph (AT&T) began the major fiber optic communication link between Boston in Massachusetts and Richmond in Virginia Corning Glass Company commercially introduced single-mode fibers with high bandwidth and low loss (1981) Companies like AT&T installed long-distance fiber optic communication links using single-mode fibers (1983) The first erbium-doped optical fiber amplifier was made at the University of Southampton (1987)
1990s	Steve Alexander from MIT Lincoln labs introduced the world's first commercial DWDM (dense wave-division multiplexing) system which greatly increased the capacity of the fiber hundred fold.
2000s	Gigabit capable Passive Optical Networks (G-PON) was standardized by Telecommunication Standardisation Sector of the International Telecommunication Union (ITU-T)
2010s	10 Gigabit capable Passive Optical Networks were standardised by ITU-T World First 0.14-dB/km Ultra-low Loss Optical Fiber by Takemi HASEGAWA

YEAR	MAJOR ADVANCES
	Super-C-band transmission with 6–THz optical bandwidth was demonstrated by Huawei Technologies (2019)
2020s	With the global launched of 5G, optical fiber will be the preferred medium for wired transmission with its high speed, high data rates, immunity to interference, low loss etc.

Since the early stages of development, fiber communication has promised extremely high data rates, which means large masses of data may be transmitted quickly. It also had the potential for transmission over long distances without the need to amplify and retransmit along the way.

In year 2018, researchers at Sumitomo produced the world first 0.14-dB/km Ultra-low Loss Optical Fiber. This development means that transmission over a distance of more than 100 km is now possible. New, high-intensity, long-life semiconductor lasers, optical amplifiers has further increased the transmission distance.

The enormous bandwidth of optical fibers results in a great reduction in the size and weight of data cables. The introduction of coarse wave-division multiplexing (CWDM) and dense wave-division multiplexing (DWDM) by MIT Lincoln labs, optical fibers have expanded the fiber bandwidth enormously.

1.2 ADVANTAGES

ADVANTAGES	DESCRIPTION
Wide Bandwidth	Able to carry large amounts of information
Low transmission loss	Loss down to 0.14 dB/km! Needs fewer repeaters than coaxial systems. Reduce cost and increase reliability.
Small size and light weight	Being about the same diameter as a human hair fiber is much smaller than copper cable. Fibers can be installed in cable ducts that have no room for copper cables and hundreds of fibers will take up the same space as one piece of coaxial cable.
Immune to interference	Optical fibers carry signals as light and not effected by electromagnetic interference (EMI) which is becoming a major problem for communications systems working in the electrical frequency range
Low Crosstalk	Fibers do not generate external electromagnetic fields, light in one fiber will not induce crosstalk in adjacent fiber.
Greater safety	A spark, from electrical communication system, can spell disaster in certain industrial environments. Oil refineries, flour mills & chemical plants are capable of exploding if a spark is generated in wrong place. Fiber only transmits light, cannot generate such a spark, it is safe to use in hazardous environments.
Signal security	It is difficult for someone to tap an optical fiber. This is because the light does not radiate outside the fiber and any tapping into the fiber would be detected because of the associated power loss.
Abundant raw materials	Glass is made from silicon which is an abundant and easily extracted element. Copper is relatively rare & difficult to mine.

1.3 APPLICATIONS

Optical fiber are used in a variety of industrial applications. Some common applications are listed in the table below.

INDUSTRY	APPLICATION
Telecommunications	Telephone systems are made easier with the use of optical fiber as a means conveying signals over a long distance to connect intercity calls or international calls. Connections are faster. Conversation are clear without any significant lag on either side.
Cable Television (CATV)	Service providers are increasingly using optical fiber to connect homes to services. With its wide bandwidth and speed, it is ideal for transmitting signals for HDTV.
Medical	Increasing use in the fields of medicine and research. It can be used as light guides to light up the surgery area within the body, or as an imaging tool in non-intrusive surgical methods such as endoscopy.
Automobiles	Besides being used for aesthetically lighting up the interior and exterior of the car, it is also used in safety applications such as traction control and airbags.
Military	Fiber optic offer high data security which is suited for military applications such as hydrophones for seismic and SONAR uses.
Networks	Networks connecting users and servers, networks connecting computers in building are made easier and faster with the use of optical fibers.

1.4 ELECTROMAGNETIC SPECTRUM

The electromagnetic spectrum is used in a variety of ways. Figure 1.1 lists typical uses of the spectrum.

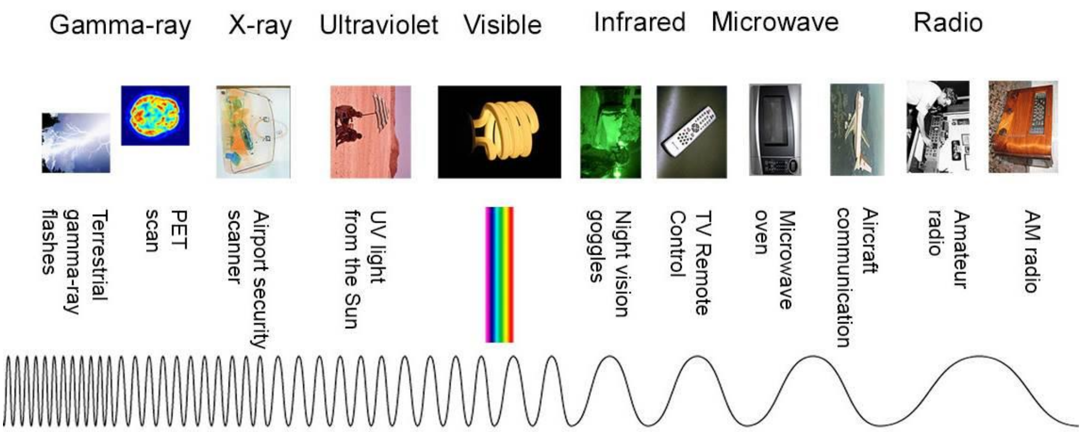


Figure 1.1 (courtesy of NASA)

The fundamental nature of all electromagnetic radiation is the same. It can be viewed as photons or waves and travels at the speed of light (c), which is approximately 300,000 km/s.

The electromagnetic spectrum can be expressed in several ways and these three views are compared in Figure 1.2.

- As length of a wave - wavelength (λ) of an electromagnetic field.
- As energy of a photon (eV) of an electromagnetic field.
- As oscillation frequency (f) of an electromagnetic field.

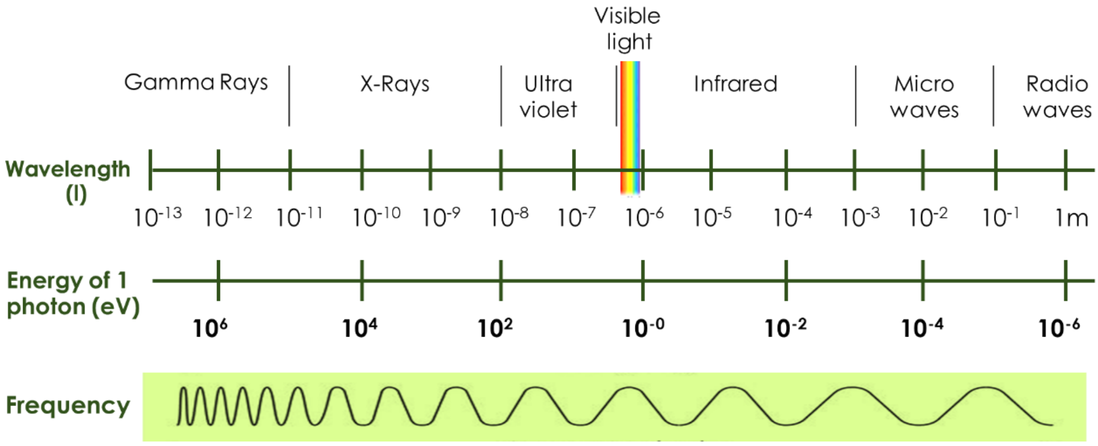


Figure 1.2 The electromagnetic spectrum

In radio communication, frequency is used most. Frequency is measured in Hertz (Hz), with Megahertz (MHz or 106 Hz), Gigahertz (GHz or 109 Hz). The optical world talks in wavelength, which is measured in meters(m), micrometers (μm or 10^{-6} m), and nanometers (nm or 10^{-9} m). Photon energy can be measured in many ways, but the most convenient here is in electron volts (eV) i.e. energy that an electron gains in moving through 1V electric field.

1.5 THE OPTICAL SPECTRUM

The communication signals on a piece of optical fiber are in the form of light energy. "Light" is only a small part of the spectrum of electromagnetic radiation. Light waves vary in frequency from 300 GHz in the far infrared region to 30000THz in the extreme ultraviolet region. Because the optical frequencies are large it is generally more convenient to work in wavelength. It is easy to convert between wavelength and frequency using the following equation:

$$\lambda = \frac{c}{nf} \text{ (m)}$$

Where: c is the speed of light in a vacuum, 3 x 10^8 m/s
n is the refractive index of the material in which light is travelling (1 for air)
f is the frequency of the light wave in Hz.
λ is the wavelength of the light wave in m.

While the optical spectrum covers a large range of frequencies, fiber optic communication systems only use a small number of wavelengths. In fact most optical systems will use 850nm, 1300nm or 1550nm. These wavelengths are all in the INFRARED part of the spectrum and are invisible to the human eye.

1.6 COMPONENTS OF OPTICAL FIBER COMMUNICATION LINK

An optical fiber transmission link is comprised of the elements shown in figure 1.3.

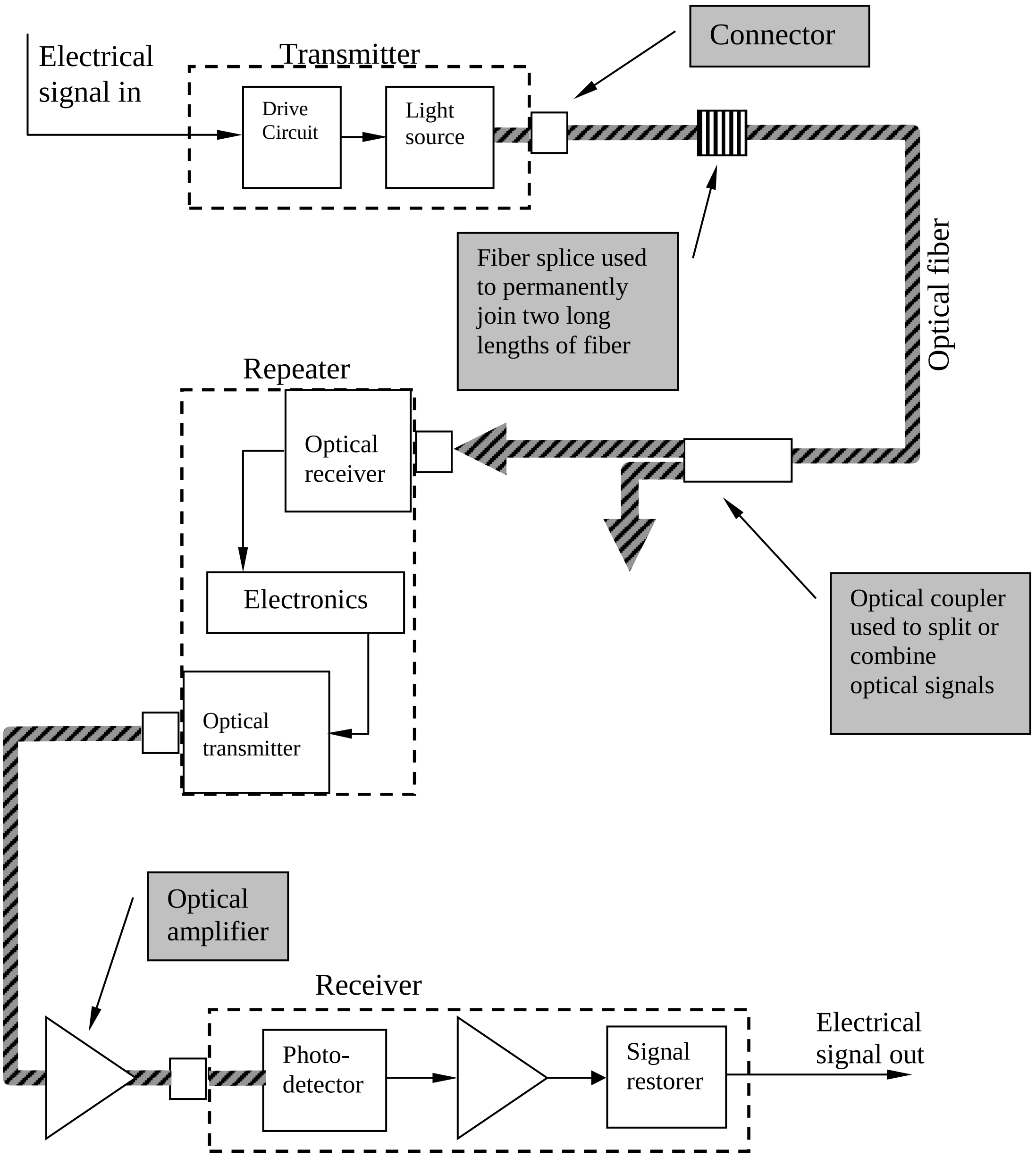


Figure 1.3 Typical Optical Fiber Transmission Link

The major parts of the optical fiber communication link are:

- A transmitter consisting of a light source and its associated circuitry.
- An optical fiber that will be in cased inside a cable. The cable will provide mechanical & environmental protection to the optical fiber(s) contained inside.
- A receiver consisting of a photodetector plus amplification and signal restoring circuitry.

Additional components include optical connectors, splices, optical couplers, repeaters or optical amplifiers to amplify optical signal.

1.7 LIGHT WAVE FUNDAMENTALS

Before we study how light behaves inside the fiber, it is useful to be familiar with the basic properties of light.

1.7.1 REFLECTION

When a ray of light is incident on a flat reflecting surface the ray will be reflected from the surface and the angle of incidence is equal to the angle of reflection. This situation is shown in figure 1.4.

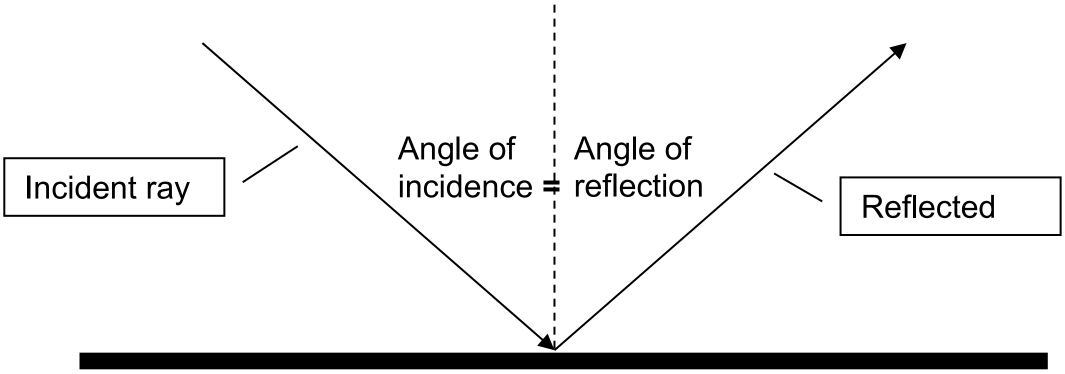


Figure 1.4 Reflection from a smooth surface

1.7.2 REFRACTION

Light is an electromagnetic wave, hence, the speed at which it travels is determined by the electrical and magnetic properties of the material in which it travels. If the light travels in different materials then the light will change speed and will bend in a different direction. This bending is known as refraction.

The speed of light in a material is determined by the following equation: $v = \frac{c}{n}$ (m/s)

Where v is the velocity of the light ray,

c is the velocity of light in free space 3×10^8 m/s

n is the refractive index of the material in which the light is travelling.

Figure 1.5 shows how light is bent when travelling between two different materials. To calculate the angle of refraction θr, use **Snell's Law**: $\mathbf{n_a \sin\theta_i = n_b \sin\theta_r}$

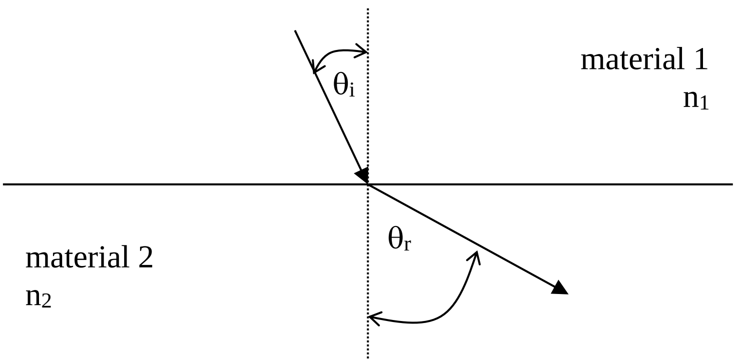


Figure 1.5 Refraction

1.7.3 CRITICAL ANGLE

Consider what happens if θi is increased. Eventually θr will reach 90^0 and the angle θi that gives θr = 90^0 is known as the critical angle (θc) as illustrated in Fig 1.6 (a).

If θi is increased beyond θc then the light is no longer refracted into the second material n_2. Instead the light is Totally Internally Reflected in the first material n_1. This situation is shown in figure 1.6 (b).

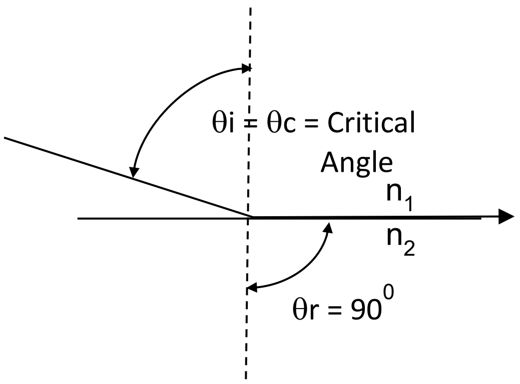


Fig 1.6 (a) Critical Angle

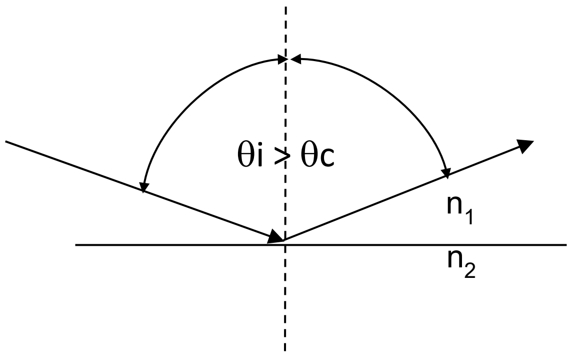


Fig 1.6 (b) Total Internal Reflection (TIR)

Applying Snell's law to figure 1.6(a), the value of the critical angle can be determined by:

Snell's law: $n_1 \sin \theta_c = n_2 \sin 90^0$

$$\sin \theta_c = \frac{n_2}{n_1}$$

Critical Angle: $$\boxed{\theta_c = Sin^{-1} \frac{n_2}{n_1}}$$

1.7.4 ACCEPTANCE CONE & ANGLE

Any light entering the fiber from within the acceptance cone will be guided down the fiber.

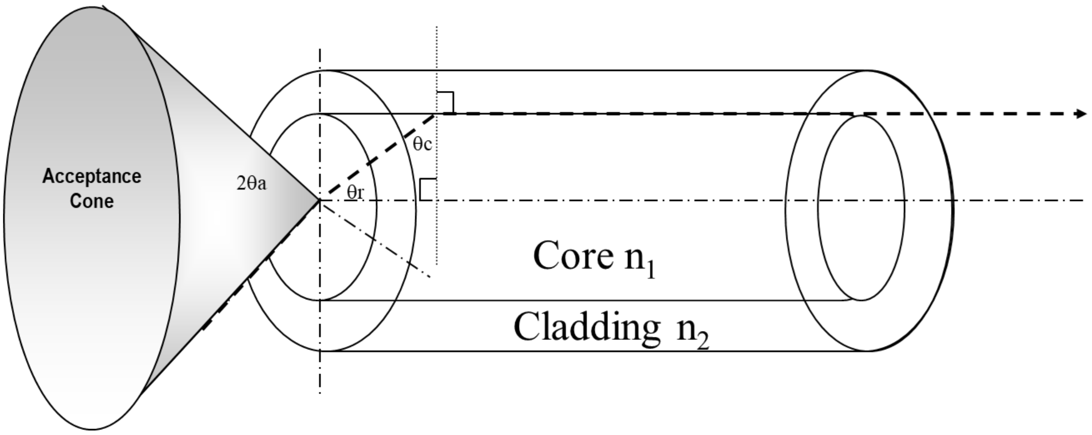


Figure 1.7 (a) Acceptance cone

The acceptance angle θa is measured from the axis of the optical fiber to the boundary of the acceptance cone. This means the Acceptance cone is equal to 2 times the acceptance angle.

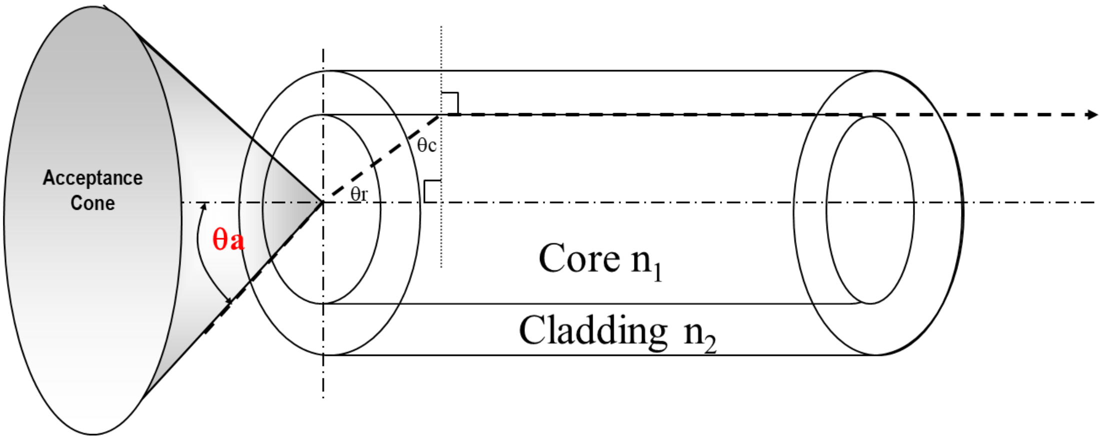


Figure 1.7 (b) Acceptance angle θa

1.7.5 MODES

Any Light ray entering the fiber at an angle less than the acceptance angle θa will travel to the end of the fiber. Modes refer to the different paths of the light rays as it enters the fiber.

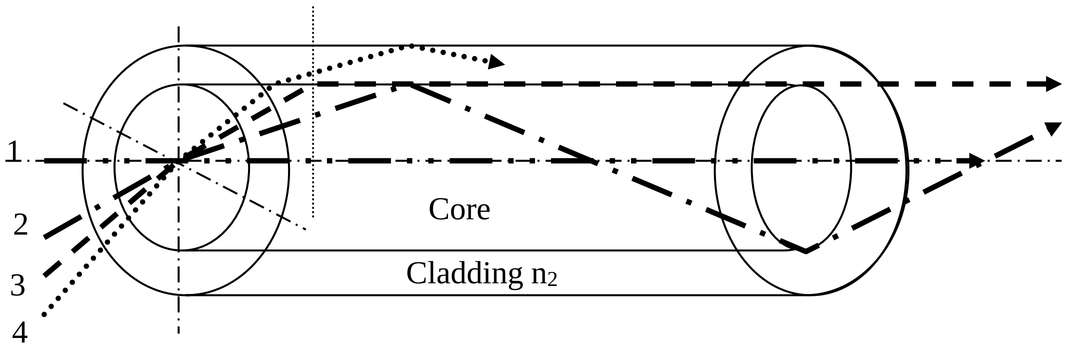


Figure 1.8 Various modes of propagation in optical fibers

Mode 1 Enters at the axis and travels to the end of the fiber.
It will arrive first because it travels the shortest distance.

Mode 2 Enters at an angle to the axis.
As it enters the fiber it is refracted towards the axis and hits the core cladding interface at an angle > θc. Hence the mode is guided down the fiber by total internal refection in the core.

Mode 3 Special case. The mode enters the fiber at an angle, θa, to the fiber axis. Once inside the fiber it is refracted towards the axis and hits the core cladding interface at an angle θc (the critical angle) thus the angle of refraction in the core is 90^0 and the mode travels to the fiber end along the interface between the core and the cladding.

Mode 4 Enters the fiber at an angle > θa and is refracted towards the axis.
The ray strikes the core cladding interface at an angle < θc and is refracted into the cladding. Because the cladding is has higher attenuation than the core light in the cladding is quickly lost and does not reach the fiber end.

From the above you can see that light entering the fiber at an angle < θa will travel down to the far end of the fiber, which is what we want for fiber optic transmission.

Whereas, light entering the fiber at an angle > θa is lost.

1.7.6 NUMERICAL APERTURE (NA)

Numerical aperture of the fiber defines the light gathering ability of the fiber. Numerical aperture NA can be found by using Snell's law.

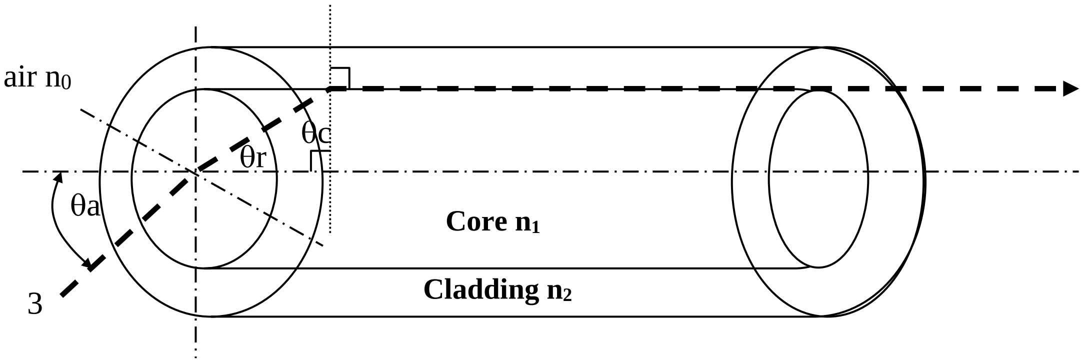


Figure 1.9 Mode that enters at θa

First apply Snells' law to the air core interface: $n_0 Sin\theta a = n_1 Sin\theta r$

but $\theta r = 90 - \theta c$. Then: $noSin\theta a = n_1 Sin(90 - \theta c)$

$noSin\theta a = n_1 Cos\theta c$

$$n_0 Sin\theta_a = n_1\sqrt{Cos^2\theta_c}$$
$$n_0 Sin\theta_a = n_1\sqrt{1 - Sin^2\theta_c}$$

But $Sin\theta_c = \dfrac{n_2}{n_1}$ Then: $$n_0 Sin\theta_a = n_1\sqrt{1 - \frac{n_2^2}{n_1^2}}$$

Then we have: $$n_0 Sin\theta_a = \sqrt{n_1^2 - n_2^2}$$

The term Sin θa is known as the **Numerical Aperture** of the fiber.

Usually light enters the fiber from the air so n_0 is usually 1.

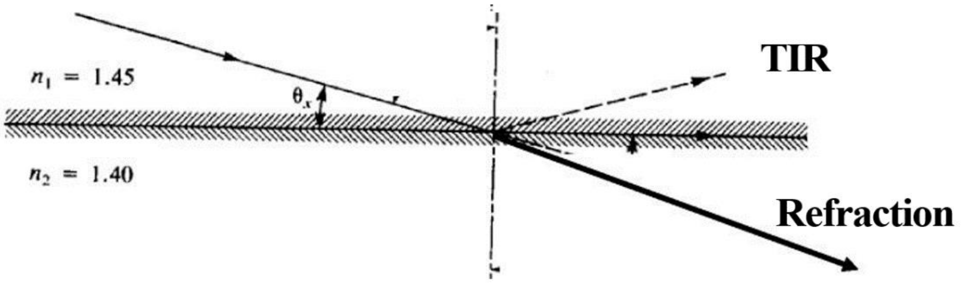
Then: $$\boxed{NA = Sin(\theta a) = \sqrt{n_1^2 - n_2^2}}$$

This is another way of calculating the NA by using only the fiber constants n_1 and n_2.

TUTORIAL 1

1. Discuss why optical fiber is the preferred transmission link.

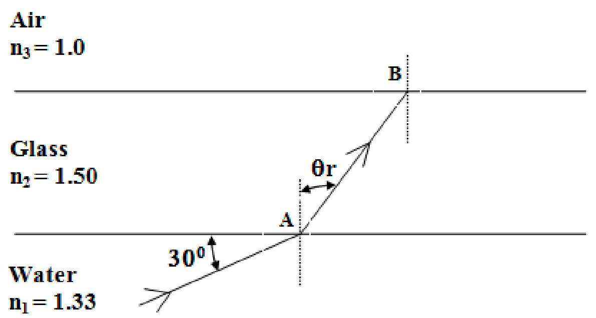
2. Two layers of glass are placed on top of each other as shown below.



The light is travelling from top glass (n_1= 1.45) to bottom glass (n_2= 1.40).

(a) State the two conditions for which Total Internal Reflection (TIR) will take place.
(b) Find the range of angle θ_x for which total internal reflection (TIR) takes place.
(c) If the top glass is removed and replaced by air (n_1 = 1.0). The light is now travelling from air to glass. Find the new range of angle θ_x for which total internal reflection (TIR) takes place.

3. A light beam travels from medium 1 (water, n_1 = 1.33) to medium 2 (glass, n_2 = 1.50) at an angle 30^0 with the glass surface, as shown in figure below:



(a) Find the angle of refraction (θ_r) at A in the glass.
(b) Calculate the critical angle (θ_c) for the glass at glass-air interface (B).
(c) Sketch the light beam path in medium 3 (air, n_3 = 1.0), after striking glass-air interface at point B. Give reasons to support your answer.

4.A step index fiber has n_{core} = 1.41 and n_{clad} = 1.37. Find :
(a) The numerical aperture, NA.
(b) The acceptance angle.
(c) The acceptance cone angle.
(d) If a light beam enters the fiber core at an angle of 20^0 with fiber axis, can the light propagate in fiber core and reach the other end of fiber?
Give reason to support your answer.

TUTORIAL GUIDE 1

Q1. Read Chapter 1 and summarise the "most important" at section 1.2.

Q2a. Study and apply section 1.7.3.
Q2b. $0 < \theta_x < 15.1^o$ c) Study and apply section 1.7 – 1.7.4.

Q3. a) $\theta_r = 50.16^0$ b) $\theta_c = 41.81^0$
c) Study and apply section 1.7.3.

Q4. (a) Study and apply section 1.7.6, NA = 0.33
(b) $\theta_a = 19.5^o$

(c) $\theta_{cone} = 39^o$

(d) Study and apply section 1.7.4. Hint: $\theta_i > \theta_a$ ($20^o > 19.5^o$)

CHAPTER 2

OPTICAL FIBER CABLE CHARACTERISTICS

CHAPTER OBJECTIVES:

1. Understand the operating characteristics of optical fibers

Learning outcomes

At the end of the chapter, the students will be able to:

- ☑ Explain the structure of optical fiber.
- ☑ Explain the types of optical fiber and its characteristics.
- ☑ Explain the dispersion of light in optical fibers and interpret the effects of dispersion in relation to data rate & bandwidth of optical communication system.
- ☑ Analyse the factors contributing to attenuation (loss) of light within optical fibers.
- ☑ List the various kinds of connectors and splicing techniques used in fiber joining.

CHAPTER 2: Optical Fiber Cable Characteristics

OPTICAL FIBER STRUCTURE

Figure 2.1 shows the construction of a typical optical fiber.

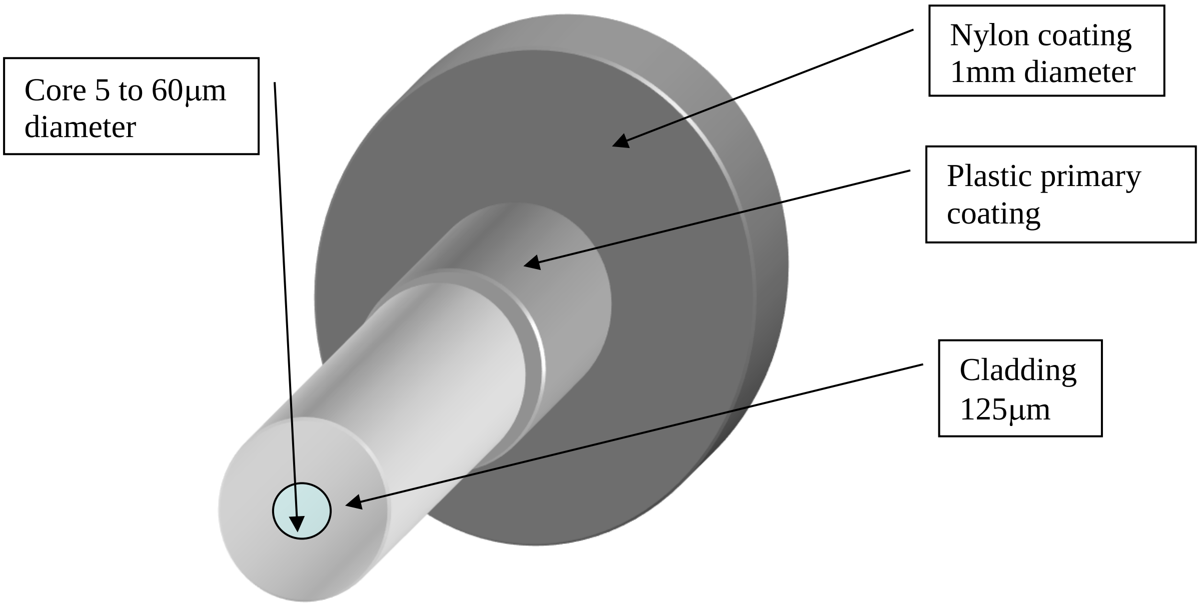


Figure 2.1 Optical fiber structure

- The optical fiber is made up of two layers called the core and the cladding, usually made of a single strand of glass.
- Refractive index of the inner core (n_c) is higher than that of the surrounding cladding (n_{cl}).
- The core guides the light waves; the cladding keeps the light waves within the core and provides some strength to the core.
- Plastic fibers are also available, however, plastic fibers have much higher loss than glass and are only used for short distance, low data rate fiber links.
- The core and cladding structure is very weak mechanically and subject to chemical attack by moisture. Thus bare fiber is normally given a plastic primary coating (buffer) and further protected by a 1mm or 3mm diameter nylon jacket (patch cord).

2.1 TYPES OF FIBER

Fiber optic cable is classified according to the number of modes it supports and the way in which the refractive index of the core changes across the core. The main types of fiber are: Step index multimode, Graded index multimode and single (mono) mode.

2.2 REFRACTIVE INDEX PROFILE

Refractive index profile is the variation of refractive index in the fiber core.

A refractive index profile diagram shows how the refractive index of the core varies across the core diameter.

Step index multimode fiber

Core refractive index maintains at constant value of n_1, reduce to a step value of n_2 in cladding.

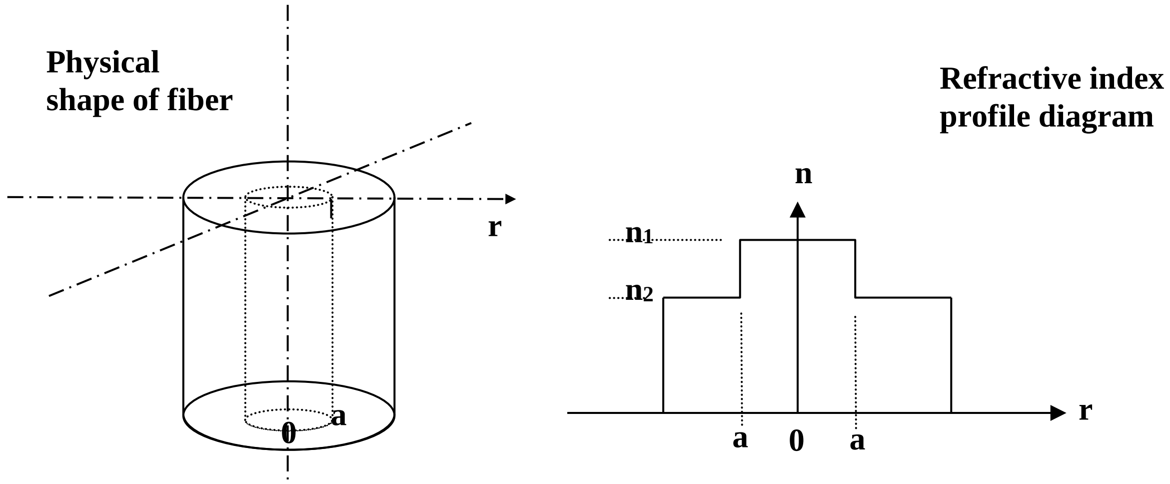


Figure 2.2a Step index multimode fiber

Graded index multimode fiber

Core refractive index, n_1 varies in a certain way across the fiber diameter as shown in figure 2.2b.

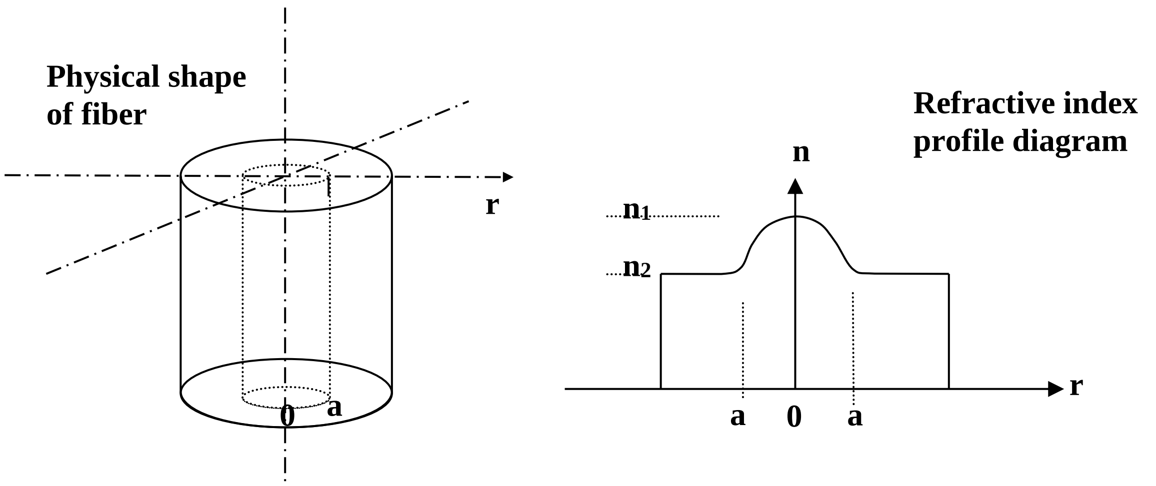


Figure 2.2b Graded index multimode fiber

This variation is usually parabolic but can be other shapes. An equation that gives variation of refractive index across the graded index multimode fiber core is given below:

$$n(r) = n_1 \sqrt{1 - 2\Delta \left(\frac{r}{a} \right)^{\alpha}}$$

Where: n_1 is the refractive index of the core at the centre of the fiber.

Δ is the relative refractive index difference between axial index n_1 and cladding index n_2.

$$\Delta = \frac{n_1^2 - n_2^2}{2n_1^2}$$

a is the radius of the fiber core

α is a factor that determines the shape of refractive index profile.

Figure 2.3 shows how the profile varies for various values of α.

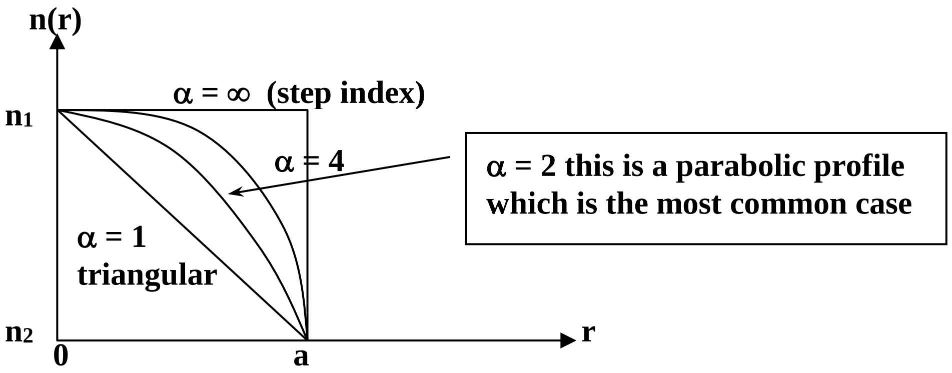


Figure 2.3 Variation of refractive index profile with α

<u>Single mode fiber</u>

Similar to step index multimode fiber structure, the core refractive index maintains at a constant value of n_1 and reduce to a step value of n_2 in cladding. However, single mode fiber core diameter is made much smaller than step index multimode fiber, only one mode can propagate in the fiber.

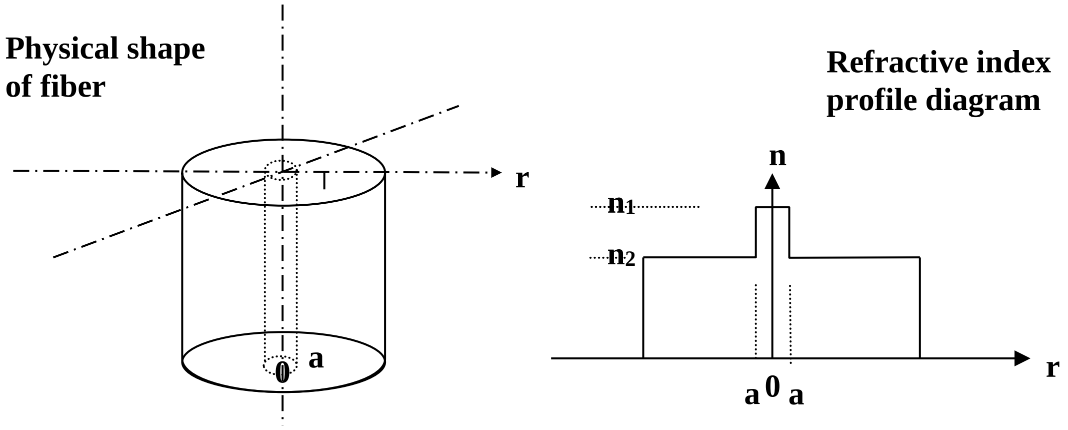
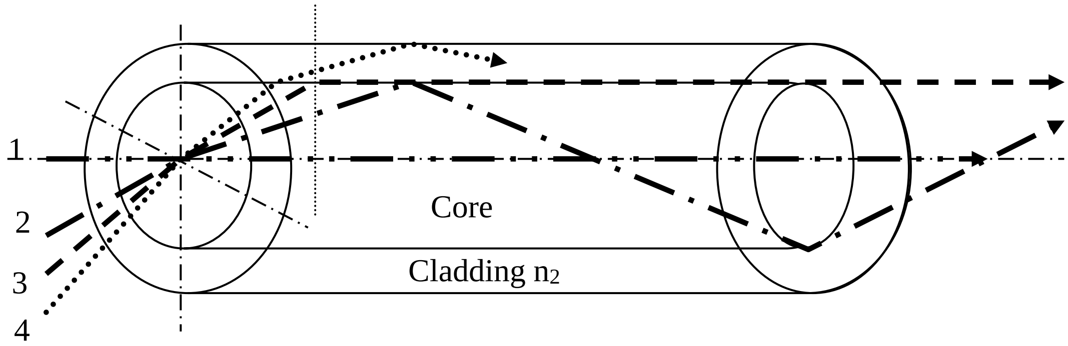


Figure 2.4 Step index single mode fiber

2.3 LIGHT PROPAGATION IN OPTICAL FIBER

Step index multimode fiber

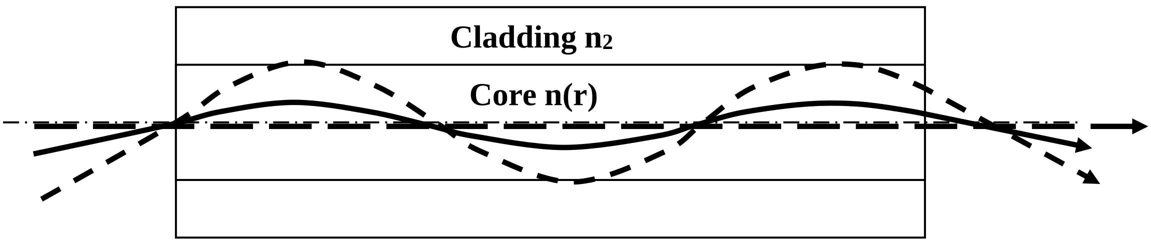
Light travel in a straight **zigzag** path in the fiber core before reaching fiber end.



2.5 Light propagation in step index multimode fiber

Graded index multimode fiber

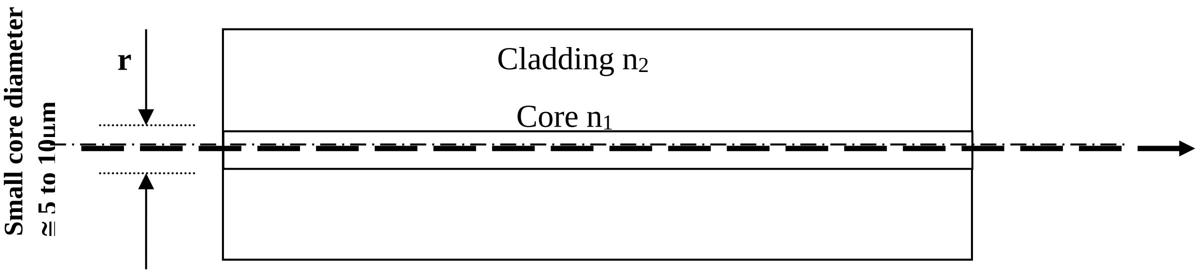
Because the refractive index of the core is continually varying, light is constantly being refracted by different amounts and travels down the fiber along a **curved** path.



2.6 Light propagation in graded index multimode fiber

Single mode fiber

Core diameter is made so small that only one light path can propagate to the fiber end.



2.7 Light propagation in single mode fiber

2.4 MODES IN OPTICAL FIBER

All light energy entering the fiber, with an angle within the acceptance cone, does not travel down the fiber in one big chunk. Instead it splits up and travels to the end of the fiber along an integer number of paths. The light energy in each of these paths is known as a **mode**.

Step index multimode fiber

The approximate number of modes in a step index multimode fiber is given by the following equation:

$$\boxed{M = \frac{V^2}{2}}$$

Where: $V = \frac{\pi d}{\lambda}(NA)$

V is the normalised frequency
λ is the wavelength of the light source
d is the diameter of the fiber

Graded index multimode fiber

The approximate number of modes in a graded index multimode fiber is given by the following equation:

$$\boxed{M = \frac{V^2}{4}}$$

Where: $V = \frac{\pi d}{\lambda}(NA)$

Single mode fiber

Theoretically, only one mode is present in the fiber. How small must the core be before the fiber has only one mode? The answer to this is given by the following equation:

For single mode operation $\boxed{a \le \frac{2.405\lambda}{2\pi\sqrt{n_1^2 - n_2^2}}\ (\mathrm{m})}$ or $\boxed{a \le \frac{2.405\lambda}{2\pi NA}\ (\mathrm{m})}$

Where:
a = core radius
λ = source wavelength
n_1 = core refractive index
n_2 = cladding refractive index

The factor 2.405 is equivalent to V, which is the normalised frequency

Week 2 endWe

2.5 DISPERSION IN OPTICAL FIBER

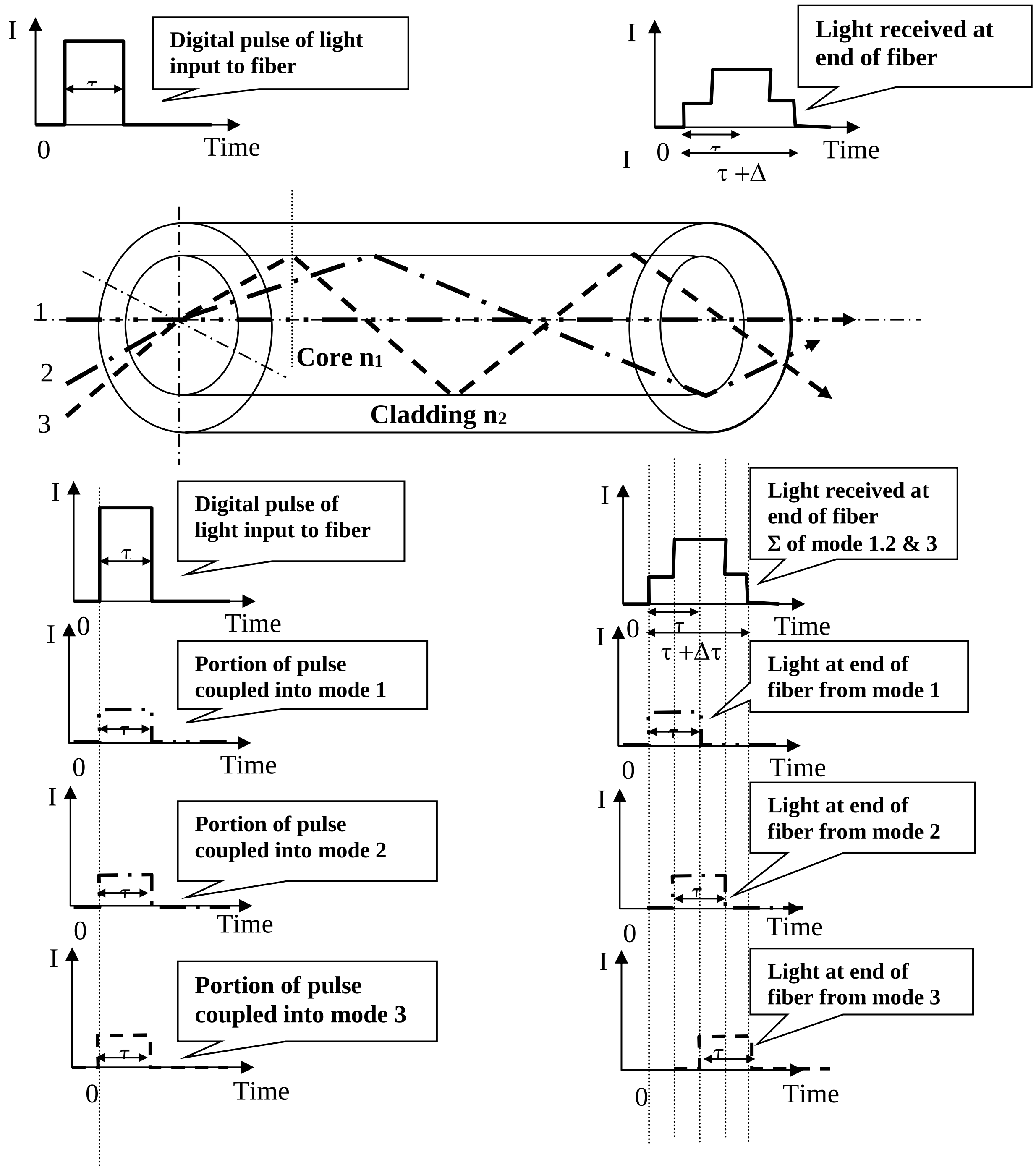
Dispersion is the enemy of bandwidth. If an optical link has high dispersion then its bandwidth will be low. If the designer can produce an optical link with very low dispersion then it will support a high bandwidth and high data rate.

There are three types of dispersion that affect optical fiber. These are: **Modal dispersion, Material dispersion** and **Waveguide dispersion.**

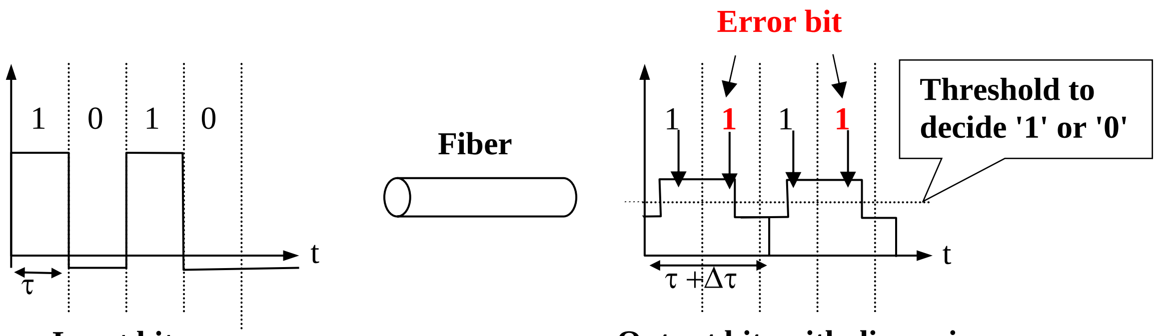
2.5.1 MODAL DISPERSION

Modal dispersion or **intermodal dispersion** is due to the fact that different modes in the fiber arrive at the fiber end at different times. When the light energy splits between the modes each mode carries exactly the same message down the fiber. Each mode has the same speed, $v = c/n_1$. Mode **1** will arrive first because it travels the shortest distance. **Mode 2** to arrive at the fiber end and followed by **mode 3**.

When these modes are combined in the receiver and the total output pulse has **spread out** in time. It has gone from being τ seconds wide to being $\tau + \Delta\tau$ seconds wide. The quantity $\Delta\tau$ is the **modal dispersion**.



If a digital data stream is sent down the fiber. An example is shown in figure below:



Input bits **Output bits with dispersion**

Modal dispersion causes the bits to spread out in time. If modal dispersion is large compared with the bit width, τ, bit errors will be generated. The time difference between the fastest and slowest mode arriving at the end of the fiber, Δτ is given by:

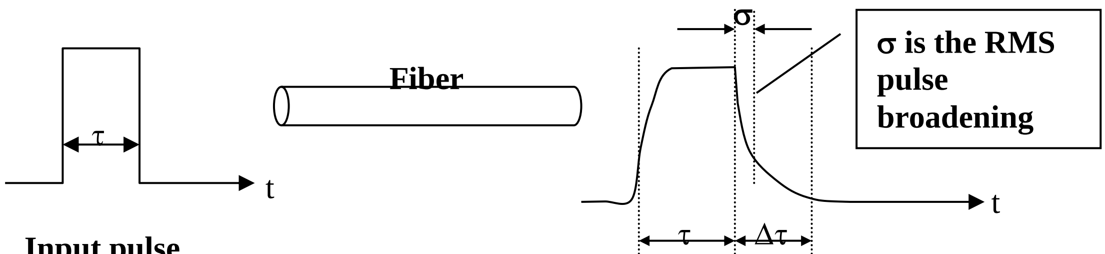
$$\Delta\tau = \frac{Ln_1}{c}\left(\frac{n_1 - n_2}{n_2}\right)$$

<u>Example</u>:   Given n1 = 1.479, n2 = 1.457 and L = 1km

$$\Delta\tau = \frac{1.479\times 1\times 10^3}{3\times 10^8}\left(\frac{1.479}{1.457} - 1\right)$$

$$\Delta\tau = 74.44\,ns$$

The actual shape of the output pulse after dispersion is shown in figure below:



Input pulse **Output pulse**

For bandwidth of the fiber, we don't use, Δτ, the total pulse broadening. Instead we use σ which is the RMS pulse broadening.

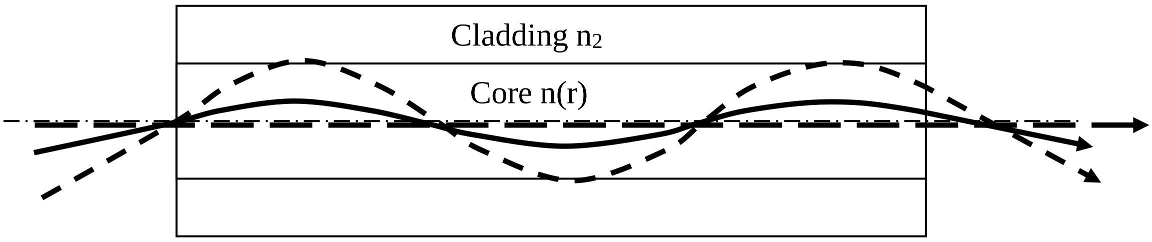
<u>Modal dispersion for **step index multimode fiber** σ</u> is given by: $\sigma = \frac{n_1 L\Delta}{\sqrt{12}c}$

Taking the same fiber in the previous example with; n_1 = 1.479, n_2 = 1.457, L = 1km.

$$\Delta = \frac{n_1^2 - n_2^2}{2n_1^2} = \frac{1.479^2 - 1.457^2}{2\times 1.479^2} = 0.0148 \qquad \sigma = \frac{1.479\times 1\times 10^3\times 0.0148}{\sqrt{12}\times 3\times 10^8} = 21.012\,ns$$

Hence, the bandwidth of the multimode fiber is : $B = \frac{0.35}{\sigma}$ B = <u>16.66 MHz</u>

Modal dispersion in graded index multimode fiber
The bandwidth of step index fiber is quite poor. For high bandwidth applications, graded index fiber gives much more improvement than step index fiber.



Light propagation in multimode graded index fiber

The modes entering at an angle to the axis travel faster as they move towards the cladding because they see a reducing core refractive index. Thus the higher order modes will catch up with the lower order modes (the ones travelling close to the fiber axis) because they travel faster. The result is that all modes will arrive at the end of the fiber at almost the **same time** and modal dispersion is greatly reduced.

σ for **graded index** multimode fiber with parabolic refractive index is: $\sigma = \dfrac{n_1 L \Delta^2}{\sqrt{48}c}$

Compare this with σ for **step index** multimode fiber, $\sigma = \dfrac{n_1 L \Delta}{\sqrt{12}c}$

For step index fiber modal dispersion is proportional to Δ, but for graded index fiber modal dispersion is proportional to Δ^2 which is a big improvement.

Taking the previous example $n_1 = 1.479$, $n_2 = 1.457$, L =1km then:

$$\sigma = \frac{1.479 \times 1 \times 10^3 \times 0.000219}{\sqrt{48} \times 3 \times 10^8} = 0.1558\,\text{ns}$$

$$B = \frac{0.35}{\sigma} = \frac{0.35}{0.1558 \times 1 \times 10^9}$$

B = 2.246 GHz

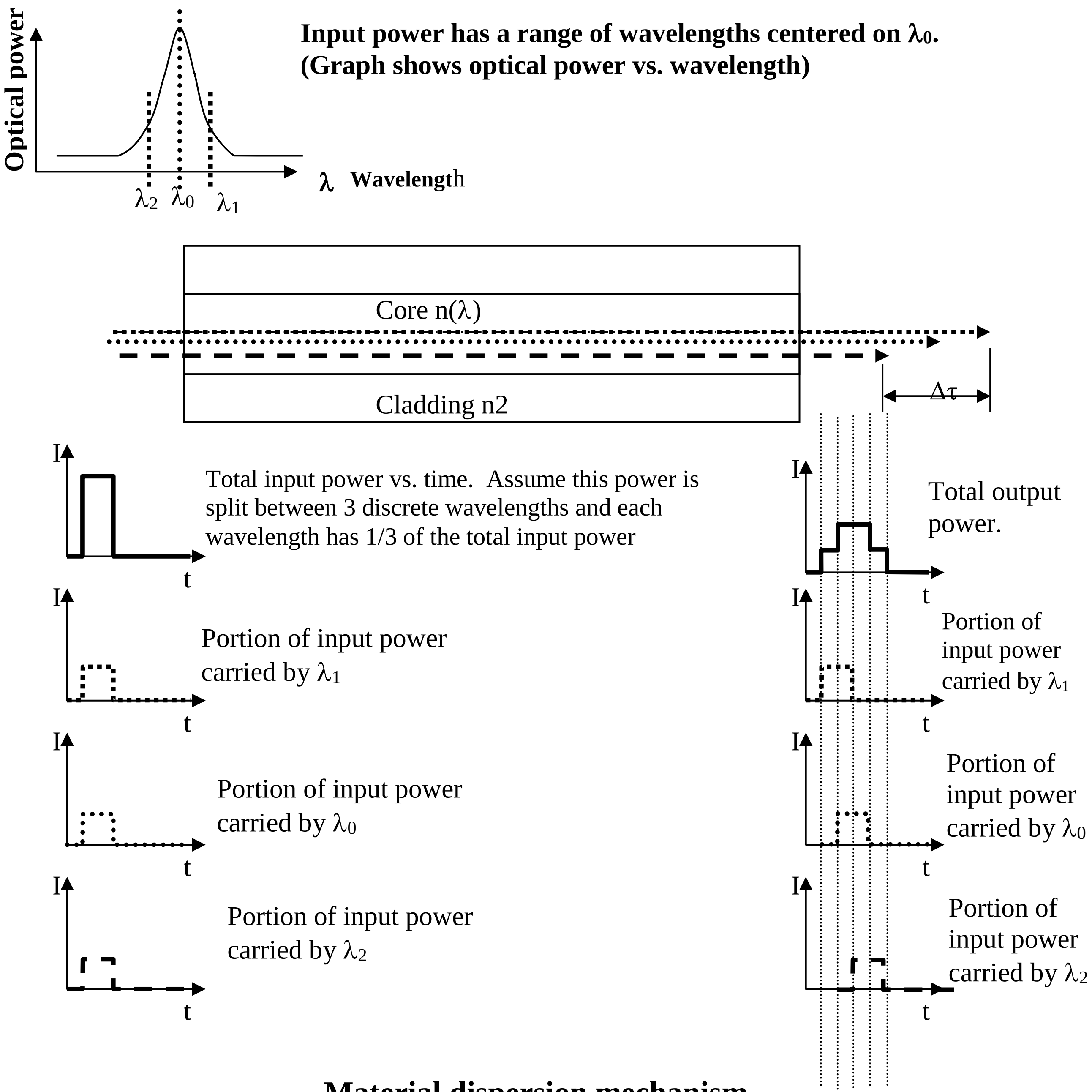
As you can see, the graded index multimode fiber has much better bandwidth than the step index multimode fiber.

Modal dispersion in **single mode fiber**
As only one mode exists, in single mode fiber, there is **no modal dispersion**. Single mode fiber has the highest bandwidth of all the fiber types.

2.5.2 MATERIAL DISPERSION

Material dispersion is due to different wavelength (colours) of light travelling at different speeds in the fiber core. It is of smaller magnitude than modal dispersion but it still has limiting effect on fiber bandwidth. Unlike modal dispersion, material dispersion cannot be eliminated but with careful design it can be reduced to a very low level.

In the figure below, only one mode of light is travelling down the fiber so **no modal dispersion** exists. But the light in the mode is made up of a range of wavelengths (colours). Each wavelength travels at a different speed down the fiber. When the light is received at the end of the fiber it has **spread out in time**.



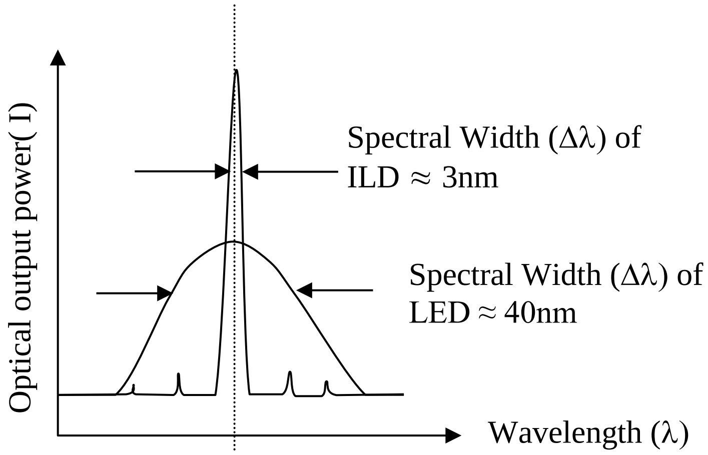
Material dispersion mechanism

The speed of light in the fiber core = $\frac{c}{n(\lambda)}$, where n(λ) is the refractive index of the fiber core.

Because n(λ) is a function of λ, the input light pulse spreads out in time as it travels down the fiber. At the fiber output all the light contributes to the receiver output giving a pulse that has **spread out in time**.

2.5.3 DESIGNING FOR MINIMUM MATERIAL DISPERSION

Material dispersion cannot be eliminated but it can be minimised. Light emitting diodes (LED's) have a much wider line width than injection laser diodes (ILD) as shown in figure below :

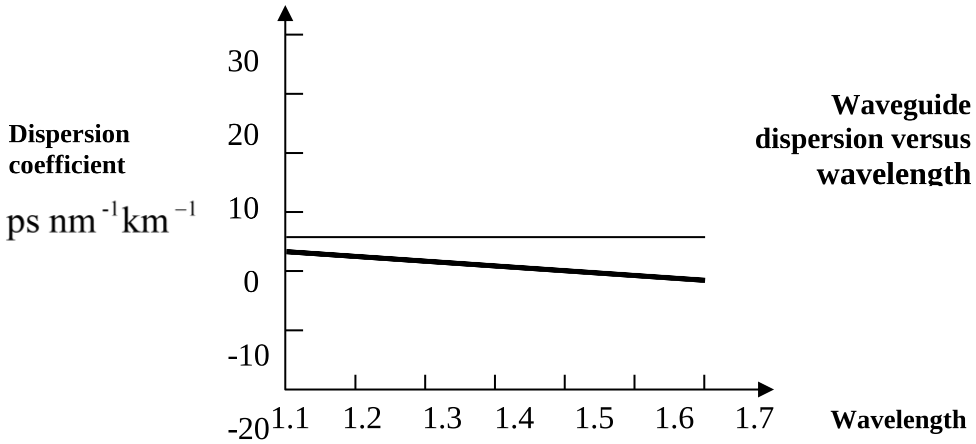


Optical output Power of ILD and LED

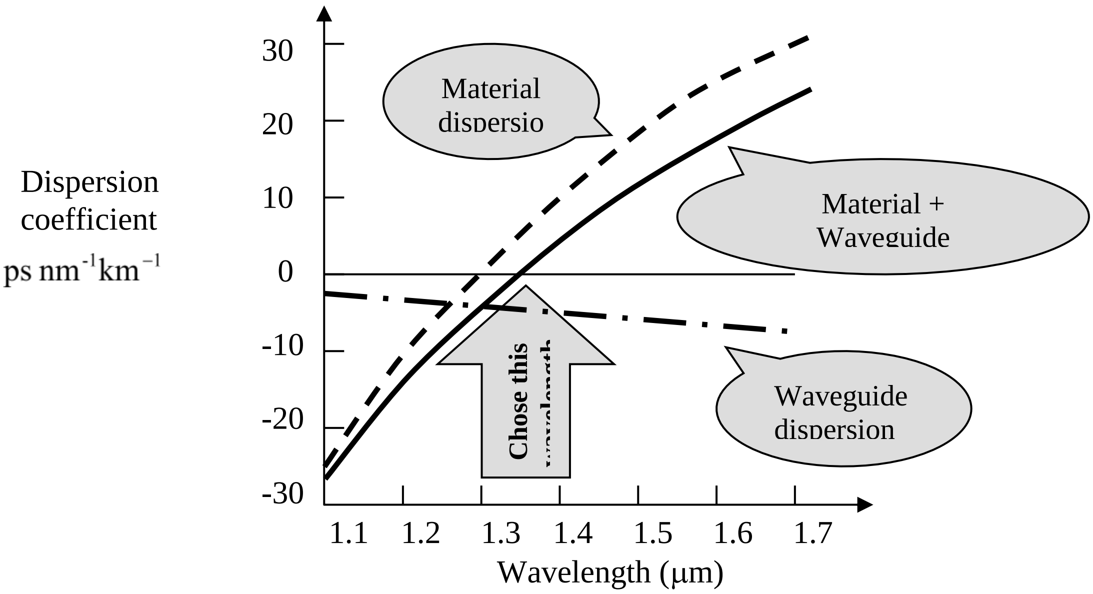
Material dispersion is reduced if an ILD is used instead of an LED. Material dispersion is also found to be lowest in the 1300 nm region. If the source is chosen to operate at this λ then material dispersion can be reduced to a very low level providing the source has a narrow line width.

2.5.4 WAVEGUIDE DISPERSION

It is **much smaller** than modal dispersion and can be ignore in multimode fibers. For single mode fibers designed to operate with low material dispersion, waveguide dispersion becomes significant. Waveguide dispersion depends on the normalised frequency. Figure below shows how the waveguide dispersion parameter varies with wavelength.



If the fiber system is to be designed for **maximum bandwidth** performance, the operating wavelength can be chosen such that material dispersion and aveguide dispersion cancel each other out. This is shown in figure below:



Wavelength for minimum dispersion in single mode fiber.

With the use of a narrow line width source and choosing the correct wavelength single mode fiber systems can have bandwidth in excess of **15 GHz.km**.

2.5.5 BANDWIDTH LENGTH PRODUCT & DISPERSON

Calculations for the dispersion and bandwidth of a fiber system can be quite time consuming. To make the calculation of fiber bandwidth easier, for **multimode fiber**, manufactures give a bandwidth length product figure.

This figure tells the designer the bandwidth of a 1km length of fiber. If the fiber is longer or shorter than 1km the bandwidth can be found from the following equation:

$$\boxed{\text{Bandwidth} = \frac{\text{Bandwidth length product}}{\text{L}}}$$

For example is a step index fiber has a bandwidth length product of 10MHz.km, what is the bandwidth of 500m of the fiber?

$$B = \frac{10\times10^6 \times 1\times10^3}{500} = \underline{\underline{20MHz}}$$

As you can see the calculation becomes very simple.

2.5.6 SUMMARY

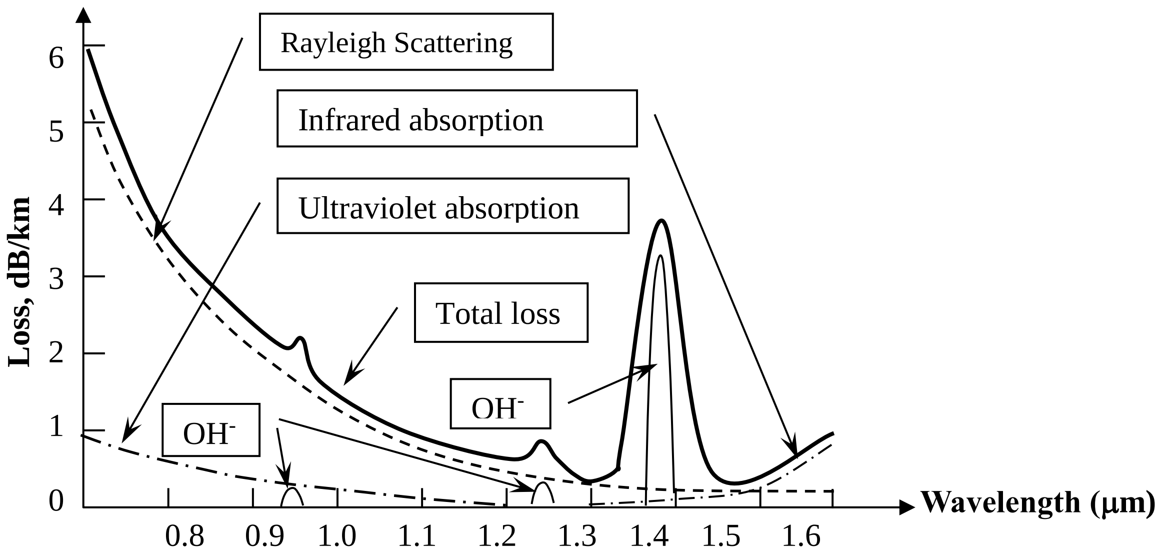
A comparison between fiber types is given in the following table. The choice of fiber will be a trade-off between system requirements and cost. Most modern communications systems tend to use single mode fiber. This is because they can support higher bandwidths if required to do so in the future. If multimode fiber systems were installed, they would need to be replaced if the bandwidth requirement rose above 2GHz.km.

Fiber type	Dispersion type	Bandwidth	Cost
Multimode step index	Modal and Material. Modal dispersion very high	Low 10 to 20 MHz.km	Low.
Multimode graded index	Modal and material	High > 2GHz.km	Medium.
Step index singlemode	Material and waveguide	Very high > 15GHz.km	Medium to High (components such as connectors, sources and receivers cost more than multimode but the fiber itself is not much more costly).

Comparison between fiber types.

2.6 ATTENUATION IN OPTICAL FIBER

Attenuation is the loss of optical power as the light travels down the fiber - measured in dB/km. It ranges from 300dB/km for plastic fiber to around 0.2dB/km for single mode fiber. Attenuation varies with wavelength as shown in figure below:



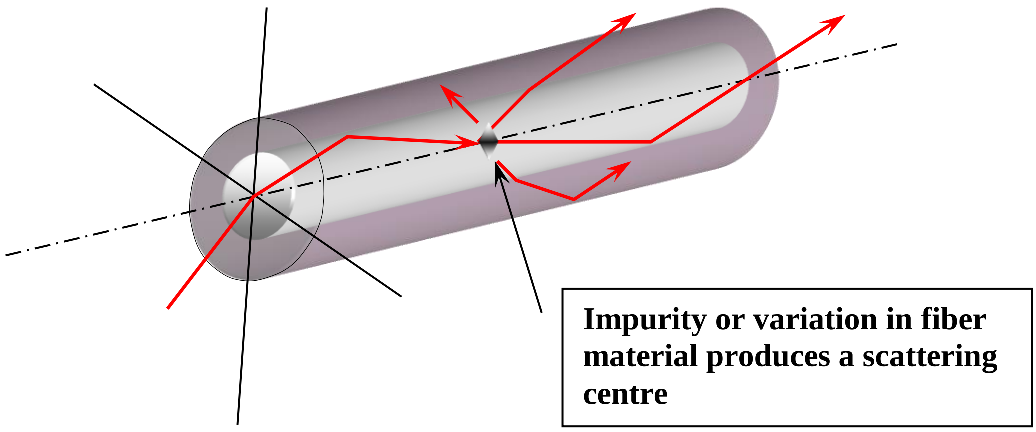
Windows are low loss regions, where fibers carry light with **little attenuation**. The first generation of optical fibers operated in the first window, around 850 nm. Modern optical fibers operate around either 1300 nm or 1550 nm.

Attenuation in a fiber has two main causes:
1. Scattering
2. Absorption

The scattering and absorption losses contribute to the overall attenuation of the fiber.

2.6.1 SCATTERING

Scattering is the loss of optical energy due to imperfections in the fiber and the basic structure of the fiber. Scattering does just what the term implies, it scatters the light in all directions as shown in figure below:



Scattering in an optical fiber.

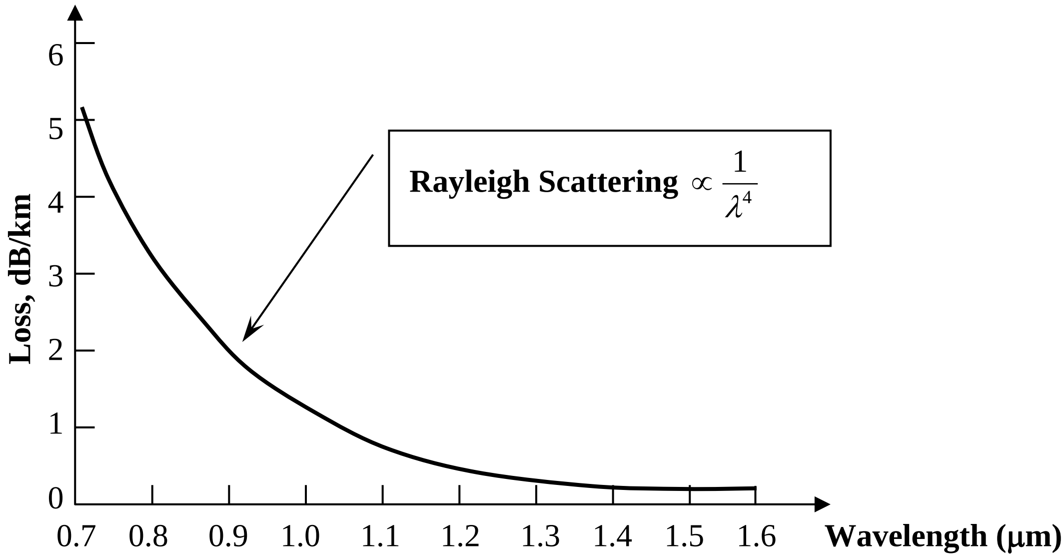
Scattering in the fiber is a natural by-product of manufacturing. It comes from two sources:

- Variations in material density which is caused by variation of refractive index over distances.
- Compositional variation which is due to the bubbles of gas or unreacted material in the fiber core

When light rays propagating down the core strikes one of these impurities, they will be scattered. Some rays escape through the cladding and result in a loss of light power in the wanted direction. This type of scattering is referred to as **Rayleigh scattering** and is inversely proportional to the forth power of the wavelength.

$$\text{Rayleigh Scattering} \propto \frac{1}{\lambda^4}$$

Rayleigh scattering decreases rapidly at longer wavelengths as shown in the graph below:



Rayleigh scattering loss as a function of wavelength

2.6.2 ABSORPTION

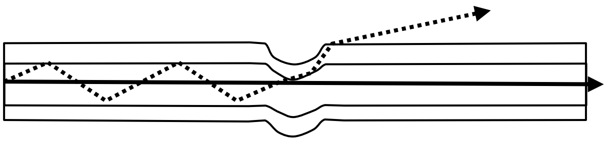
Absorption is the process by which impurities (such as OH^- water ions and heavy metal ions e.g. Chromium, Cobalt, Manganese, Copper etc.) in the fiber absorb optical energy and dissipate it as a small amount of heat. High loss regions in a fiber result from water bands, where OH^- ions significantly absorb light. To maintain low loss, manufacturers must hold these ions to < 1ppb.

2.6.3 BENDING LOSS

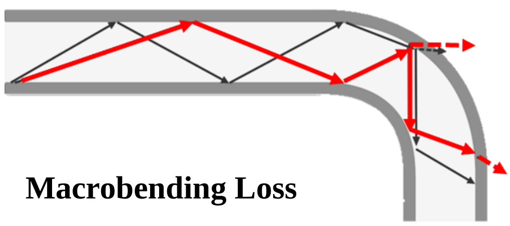
There are two types of bending losses: Microbend and Macrobend.

MICROBENDING LOSS

Microbending loss is loss resulting from a microbend, which is a small radius bend in the fiber, as shown in figure below. Microbending is caused by errors in buffer, jacket fabrication or poor installation practice.



Microbending Loss



Macrobending Loss

MACROBENDING LOSS

Any bending of the fiber will alter the angle at the core cladding interface, and cause some loss of light from the higher order modes. However, providing the bend radius is large compared with the diameter of the fiber this loss should be very small. Manufacturers will specify a minimum bend radius for their fiber.

2.6.4 MISALIGNMENT LOSS

The misalignments are induced by the connector and bad end surface preparation. The connector body, the alignment mechanism and housing, are constructed with parts that are manufacture within certain tolerances.

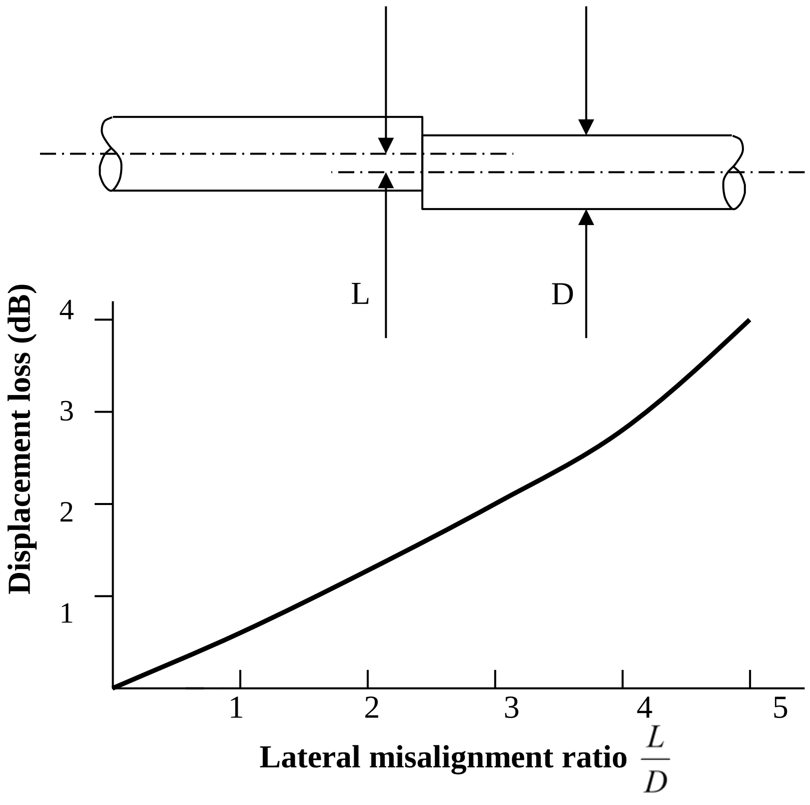
Therefore, the fibers guided by the connector are not necessarily perfectly aligned and thus an optical transmission loss is induced at the junction, even if the joining fibers are identical.

The three major misalignments between joining fibers are:

a. Lateral displacement.
b. End separation.
c. Angular misalignment.

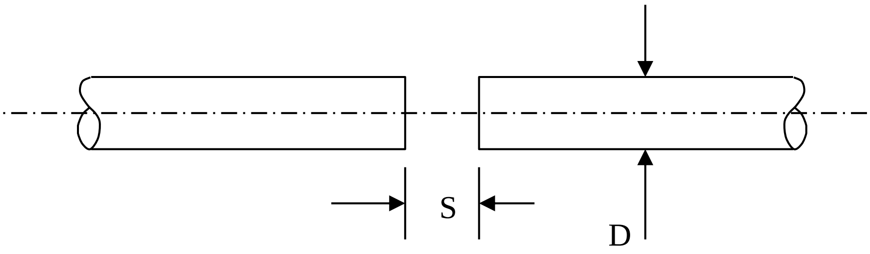
<u>LATERAL DISPLACEMENT</u>

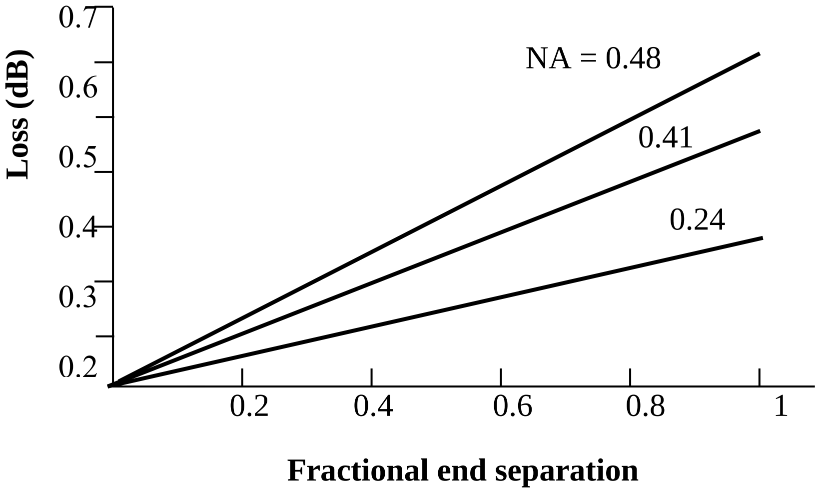
Lateral displacement refers to the condition in which the two joining fibers are laterally offset from one another such that a portion of the light emitted from one fiber is not captured by the receiving fiber. This is shown in figure below:



END SEPARATION

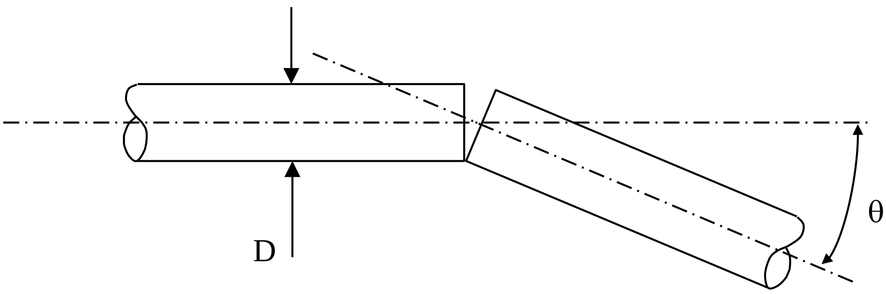
End separation refers to the condition when a finite distance separates the two joining fiber ends, such that the portion of the light divergent from the transmitting fiber is not captured by the receiving fiber. This situation is shown in figure below:

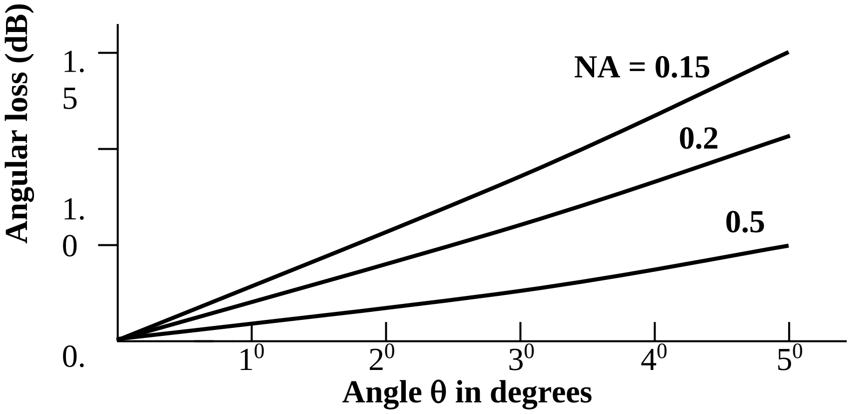




ANGULAR MISALIGNMENT

The case of angular Misalignment refers to the condition where the two joining fibers are tilted at an angle to each other. This configuration together with the loss characteristics is shown in fgure below:





2.7 CONNECTORS & SPLICING TECHNIQUES

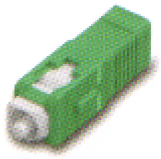
There are two ways of joining optical fibers: Permanently using a splice **or** temporary using a removable connector.

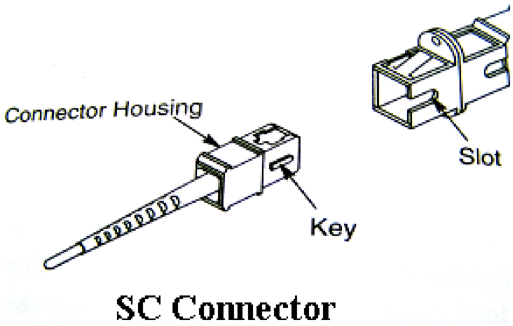
OPTICAL CONNECTORS

Connectors are usually used between the fiber and transmitter or between fiber and receiver, so that components can easily be replaced.

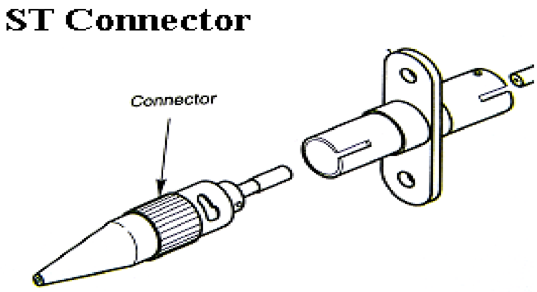
It is important that connectors maintain proper fiber alignment otherwise the optical loss could be unacceptably high. The standard connector types for fiber are SC, ST & FC as shown in below:

SC Connector: Square cross-section allows high packing density on patch panels.





ST Connector: Round cross-section latched into place by twisting it to engage a spring-loaded bayonet socket.



FC Connector: Screw-on type connector with optical losses similar to SC & ST

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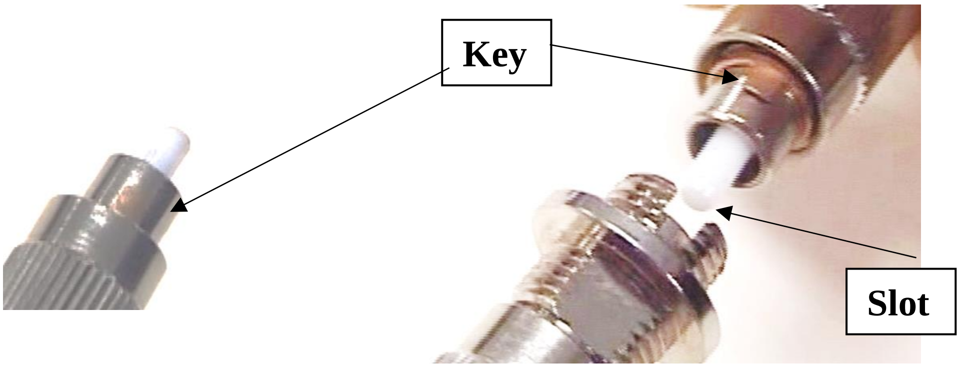
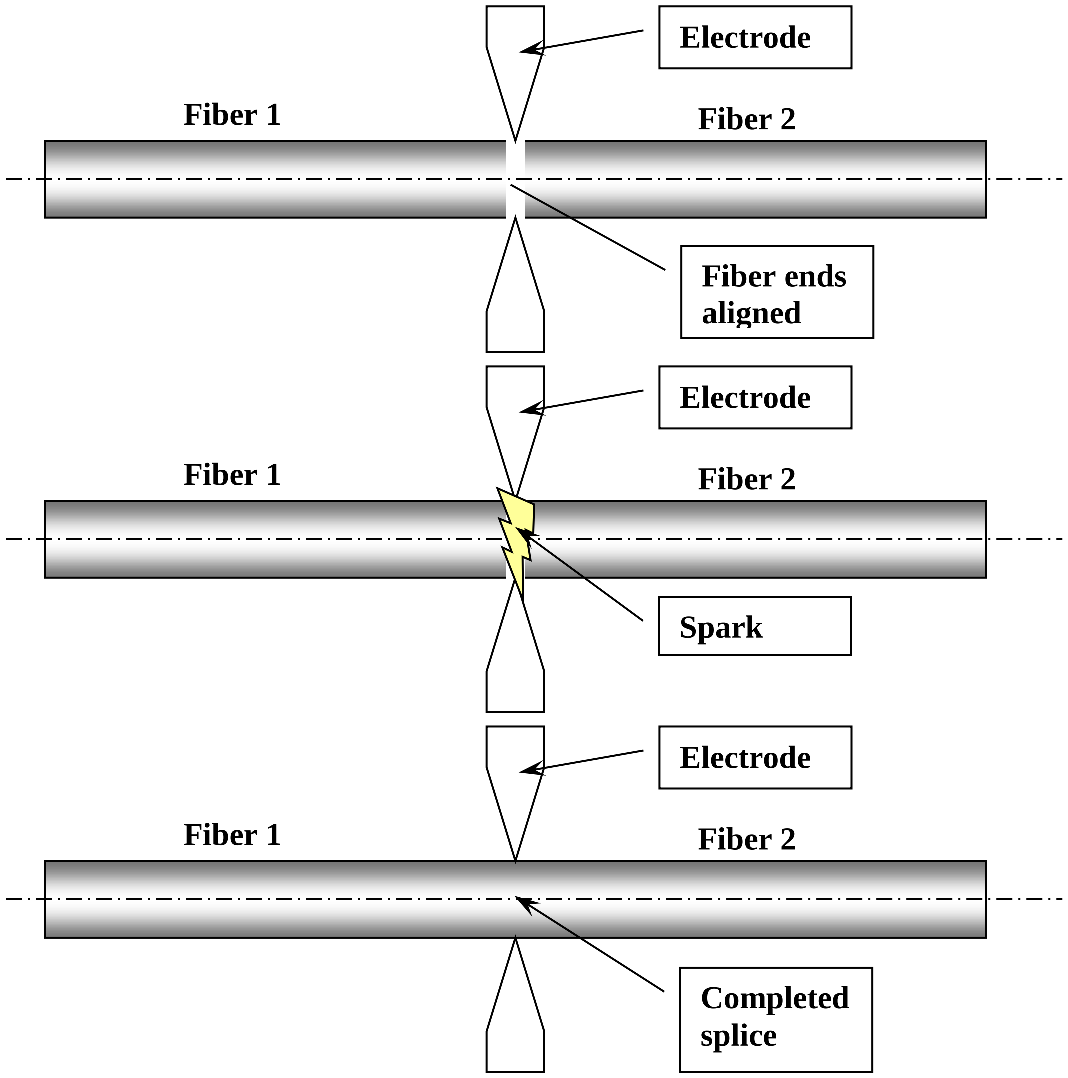


OPTICAL FIBER SPLICES

If the required fiber link length is longer than the length of fiber on a single drum, then it is necessary for two or more lengths of fiber to be joined. It is unlikely that these lengths of fiber will need to be disconnected, so it is usual to join them with a **permanent** splice rather than a de-mountable connector.

Splices can be **mechanical** or **fusion type**.

A **fusion splice** is made with a machine that first aligns the fiber ends, melts them with a spark, so that they fuse together. This process is illustrated in figure below:



Stages 1, 2 and 3 of the fusion splicing process

A **mechanical splice** is made with joining two fiber ends either by clamping them within a structure or by gluing them together.

In general, mechanical splicing requires less costly capital equipment but has higher loss than fusion splices.

TUTORIAL 2

1. How is the data rate and bandwidth of the fiber related to :
   (a) Total dispersion of the fiber.
   (b) Number of modes in the fiber.
   (c) Fiber core diameter.

2. State THREE advantages to operate at 1310nm wavelength in optical fiber link.

3. What kind of dispersion is dominant in :
   (a) Multimode step-index fiber.
   (b) Multimode graded-index fiber.
   (c) Single mode fiber.

4. A fiber has a specified NA of 0.22 and n_{core} = 1.4. Find the time difference between the fastest and slowest modes arriving at the end of a 500 m length fiber.

5. A graded index parabolic profile fiber has n_1 = 1.46, n_2 = 1.42, core diameter of 50μm and operate with λ = 800nm.
   (a) Sketch the refractive index profile of the fiber.
   (b) Find the refractive index at a point where r = 20μm.
   (c) Calculate the number of modes in the fiber.
   (d) Calculate the bandwidth of a 1 km long fiber.

6. A fiber has n_1 = 1.40, n_2 = 1.39 and operate at λ = 1300nm. Find the largest core diameter for which the fiber will become single mode.

7. (a) State the two main causes of attenuation in an optical fiber.
   (b) Name the loss mechanism which is wavelength dependent and state its relationship with the wavelength.
   (c) Define the term “Low-loss Windows”. Name the THREE wavelengths for the low-loss windows used in optical communication links.

TUTORIAL GUIDE

1. Study and apply section 2.5.1.

2. Study and apply section 2.5.2 – 2.5.4.

3. Study and apply section 2.51 – 2.5.6.

4. $\Delta\tau = 28.7(ns)$

5. (a) Study and apply section 2.1 – 2.2.

   (b) $n(20\mu m) = 1.435$

   (c) $M = 1110$ (modes)

   (d) $BW = 683.6(MHz)$

6. d_{max} =5.96 (μm)

7. Study and apply 2.6 – 2.6.2.

CHAPTER 3

OPTICAL DEVICES & MEASUREMENT TECHNIQUES

CHAPTER OBJECTIVES:

- Understand the operating characteristics of optical devices & measurement techniques used in optical communication link.

Learning outcomes

At the end of the chapter, the students will be able to:

☑ Explain the principles of light emission.

☑ Explain the operating characteristics of Light Emitting Diode (LED) and Laser Diode (LD).

☑ Compare & contrast the advantages & disadvantages of LED & LD devices.

☑ Explain the principles of photo detection.

☑ Explain the operating characteristics of PIN Photodiode (PIN) and Avalanche Photodiode (APD).

☑ Compare & contrast the advantages & disadvantages of PIN & APD devices.

☑ Describe the test equipment and measurement techniques used in optical communication systems.
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CHAPTER 3: Optical Devices & Measurement Techniques

LIGHT

Light may be modelled as a wave or a particle according to the duality principle.

For explaining how light propagates down an optical fiber, it is easier to consider light as an electromagnetic wave. However, it is more convenient to think of light as a stream of tiny particles called Photons when studying the generation of light by LED/ILD, or the reception of light by photodetectors PIN/APD.

3.1 PHOTON

Photon is a tiny particle of energy. It takes zillions of photons to make up one beam of light. Each photon has an associated wavelength. This means that the photons are vibrating as they travel out from the source.

If a photon stops moving it ceases to exist because its rest mass is zero. When the photon ceases to exist, the energy in that photon must be transferred to another particle as energy must be conserved.

An important equation linking energy of a photon E to its wavelength is given below:

$$\boxed{E = E_2 - E_1 = hf = \frac{hc}{\lambda} \text{ (J)}}$$

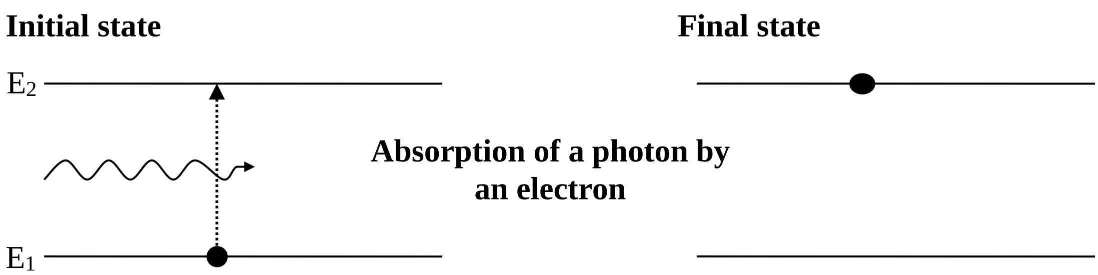
Where: E is the energy of the photon, h is Plank's constant 6.626×10^{-34} Js
f is the frequency of the photon , λ is the wavelength of the photon
c is the speed of light in a vacuum 3×10^{8} m/s

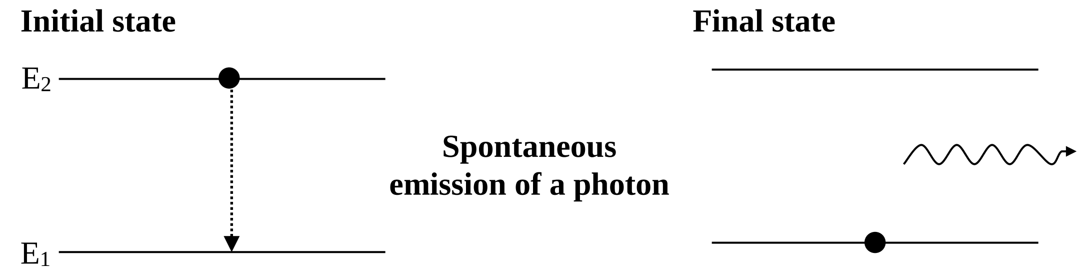
If E is expressed in electron volts then the above equation becomes:

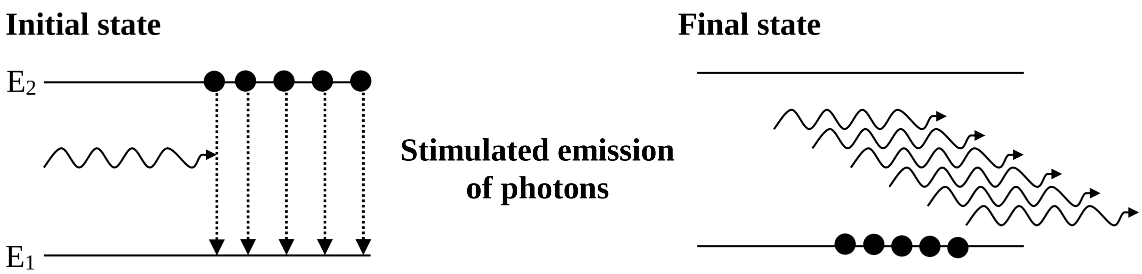
$$\boxed{E = \frac{1.24}{\lambda} \text{ (eV)}}$$

3.1.1 PHOTON-ELECTRON INTERACTIONS

To understand how photons of light are generated or received within a semiconductor you should understand the three basic interactions between photons and electrons these are shown in figure below:







Photon - electron interactions

3.1.2 ABSORPTION OF A PHOTON

This is the process by which an **optical detector** works. If the photon has the same energy as the bandgap (E2 -E1) then it is possible for the kinetic energy of the photon to be absorbed by an electron.

When this happens the electron gains the photons kinetic energy and moves to a higher energy level. The kinetic energy that was in the photon is now the potential energy in the electron. The photon no longer exists. It is said to have been absorbed by the electron.

3.1.3 SPONTANEOUS EMISSION OF A PHOTON

This is the process by which a **light emitting diode** (LED) works. An electron in an excited energy level within a material, sees an opportunity to fall back to a lower energy level.

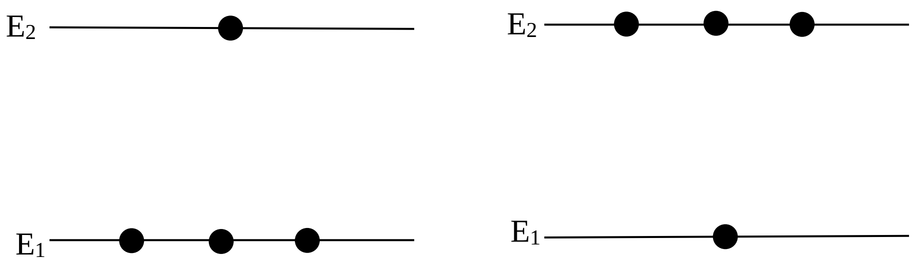
When the electron falls to the lower energy level, it losses some potential energy. This potential energy creates a photon which is emitted from the material. It is not possible to predict exactly when the electron will move to the lower energy level so light emitted by spontaneous emission will be non-coherent. That is the phase and frequency of the photons emitted from a source are not closely related.

3.1.4 STIMULATED EMISSION OF A PHOTON

This is the process by which a **laser diode** works. If it is possible to get many electrons into the higher energy level without them falling to a lower level and spontaneously emitting photons.

When a photon enters the material it will cause all the electrons to fall to the lower energy level at the same time. When this happens a stream of photons will be created which have the same phase and frequency i.e. the light emitted from the material is coherent. This kind of emission does not happen naturally.

It is quite difficult to get a lot of electrons to stay in the higher energy level long enough for stimulated emission. When this is achieved it is called a population inversion because there are usually more electrons in the lower energy level as illustrated below:



Natural state with more electrons in the lower energy level

More electrons in the higher energy level. Population Inversion

Population inversion

3.2 OPTICAL SOURCES

The two commonly used light sources for optical fiber communication systems are:

- LEDs (Light Emitting Diodes)
- ILDs (Injection Laser Diodes)

The choice of either LEDs or ILDs for a system depends on such factors as cost, optical power output, spectral width, speed, temperature sensitivity, coupling efficiency, lifetime etc.

Cost: ILDs cost about 10 times more than LEDs.
ILD requires more complex drive circuitry, hence increase in system cost.

Power Output: For the same driving power, the optical output power of an ILD is in general higher than that of a LED. Thus an ILD is better suited for long distance communications.

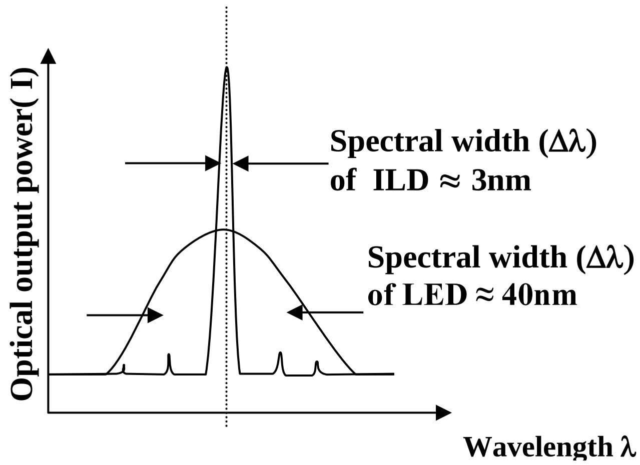
Coupling Efficiency: Emission from an ILD is much more directional than from a LED, therefore an ILD has higher coupling efficiency than a LED.

Temperature Sensitivity: ILDs are extremely sensitive to temperature changes, thus they require more complex drive circuitry to stabilise their output power against temperature variations.

Lifetime: The lifetime of an optical source is taken to end when the peak output power is reduced by 50% or 3dB. ILDs operating at higher power have sorter lifetimes than LEDs. Lifetime for ILDs ranges from 10^4 to 10^5 hours and the lifetime for LEDs ranges from 10^6 to 10^7 hours.

Spectral Width: Range of wavelengths emitted by an optical source. The spectral width of a laser is much narrower than that of a LED as shown in figure below.

Typical values are 3nm for an ILD and 40 nm for LED. ILD sources produces smaller material dispersion in the fiber, capable of higher transmission rates than LED.



Speed (or rise-time): The source must turn on and off fast enough to meet the bandwidth requirements of the system.

Source speed is specified by rise and fall times.

Laser have a rise time of less than 1ns, while slower LEDs have rise times of 2 to 20ns.

A rough approximation of bandwidth for a given rise time is:

$$\boxed{BW = \frac{0.35}{t_r}\ (\mathrm{Hz})}$$

For example, a rise time of 3.5ns allows 100MHz operation.

3.2.1 LIGHT EMITTING DIODES (LEDS)

A light emitting diode is a PN junction semi-conductor device that emits light when forward biased. As current starts flowing in the circuit and a free electron meets a free hole, the electron can recombine with the hole. The energy lost in the transition is converted to optical energy in the form of a **photon**

The photon energy and frequency are related by the formula $E_g = hf$ and the radiated frequency is given by the equation:

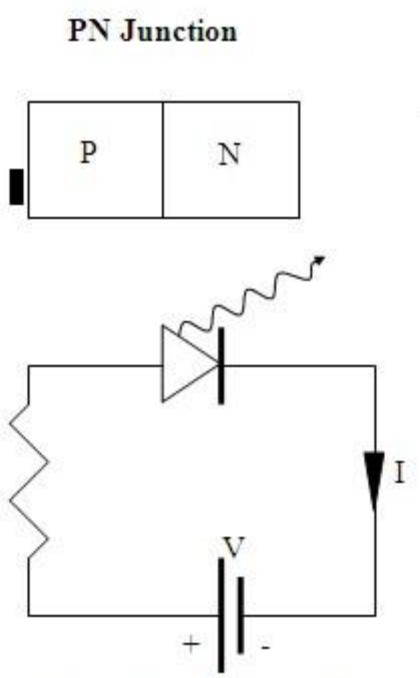
$$\boxed{\lambda = \frac{hc}{E_g} \text{ (m)}}$$

Where: h = Plank's constant = 6.62×10^{-34} Js
c = velocity of light in free space = 3×10^{8} m/s

If the bandgap energy is expressed in **electron volts (eV)** & the wavelength in **micrometers (μm)** then the above equation becomes:

$$\boxed{\lambda = \frac{1.24}{E_g}}$$

Different material will have different band gap energies and will emit light of different wavelengths (colours).

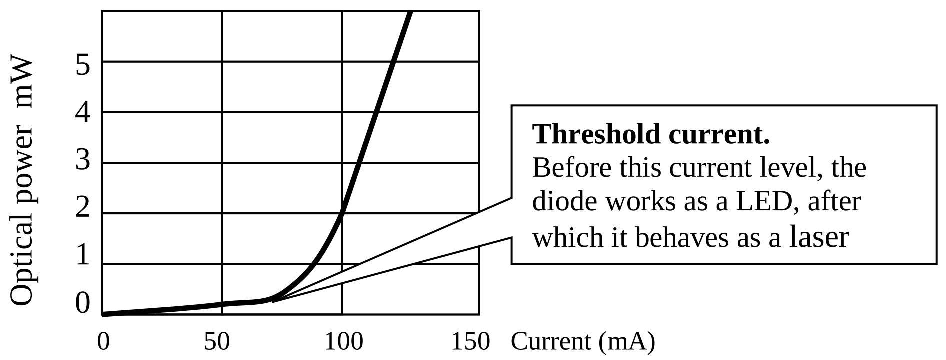


Circuit with forward bias voltage applied to LED

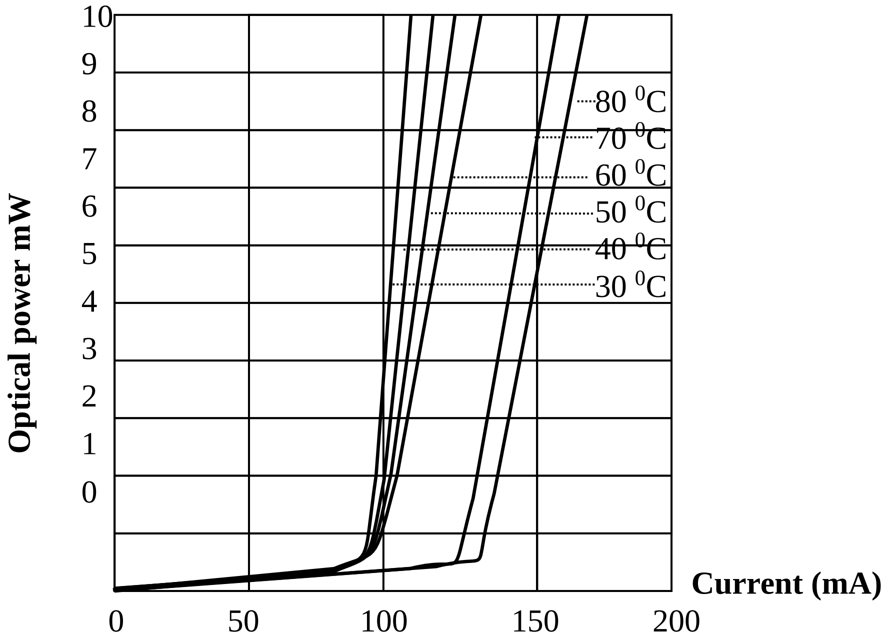
3.2.2 LASER DIODES

The word "LASER" is an acronym, which stands for Light Amplification by Stimulated Emission of Radiation. Difference between a laser diode and a light emitting diode is that the laser diode produces its light output by stimulated emission of photons, whereas, a light emitting diode produces its light output by spontaneous emission of photons.

To achieve stimulated emission of photons the laser diode must have a large number of charge carriers in the active region so that when a photon comes along it will stimulate the emission of more photons. This is achieved by injecting a large amount of current into the device. The point at which the current becomes large enough for the laser to start lasing is known as the **threshold of lasing** as shown in the graph of laser output versus input current.



Laser diodes are more temperature sensitive than LED, as shown in figure below. Thermoelectric cooling and negative feedback DC bias control circuits are normally needed to overcome temperature drift problems.



Power variations due to temperature changes in the laser diode

3.2.3 ADVANTAGES & DISADVANTAGES OF ILD VERSUS LED

<u>ADVANTAGES</u>

1. ILD's have a more directional radiation pattern, it is easier to couple their light into optical fiber. This reduces coupling losses & allows smaller fibers to be used.

2. Radiant output power from a ILD is greater than that from a LED.
   This allows ILD's to provide a higher output power and used for systems that operate over longer distances.

3. ILD's can be used at higher bit rates.

4. ILD's have smaller spectral width, which reduces material dispersion.

<u>DISADVANTAGES</u>

1. ILD's are more expensive than LED's.

2. ILD's have a shorter lifetime than LED's.

3. ILD's are more temperature dependant than LED's.

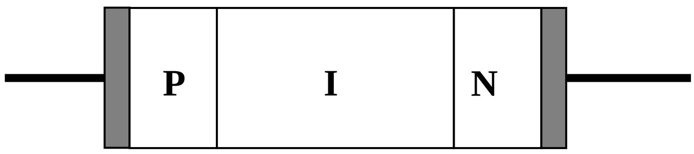
3.3 OPTICAL DETECTORS

Optical detector works on the process of **absorption of a photon by an electron.**
If the photon has the same energy as the bandgap (E_2 -E_1), then it is possible for the kinetic energy of the photon to be absorbed by an electron. When this happens, the electron gains the photons' kinetic energy and moves to a higher energy level. This allows electrons to move freely and produce current.

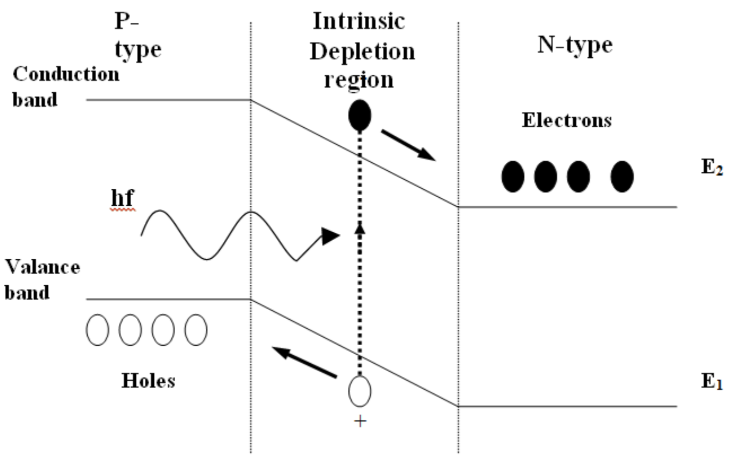
There are two types of photodetectors used in fiber optic systems: PIN & APD.

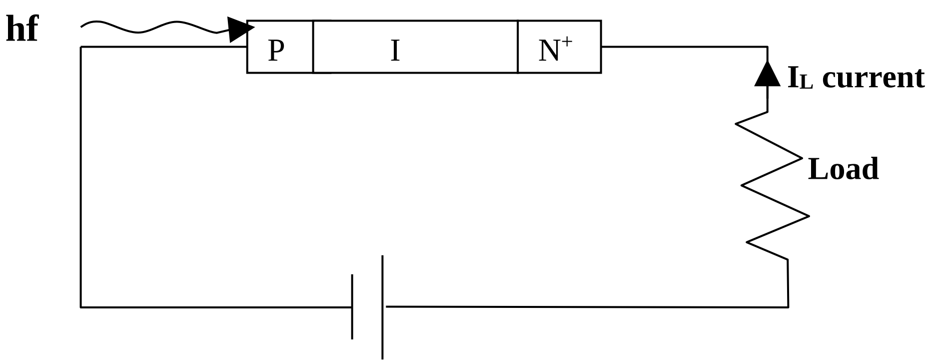
3.3.1 PIN DIODE

PIN stands for P-type Intrinsic N-type. Structure of PIN diode is shown below:



The I region of the semiconductor is actually not totally intrinsic but rather very lightly doped N-type. It is made long to allow deep light penetration into the device.This gives each photon a berter chance of being absorbed by an electron. This process is shown in the energy level diagram below:





PIN photodiode <u>Reverse biasing</u> circuit

To understand how the PIN detector works, consider the above energy level diagram & biasing circuit :

- Diode is **reverse biased** so no current will flow in the external circuit (apart from a small current, due to minority carriers, called the dark current).

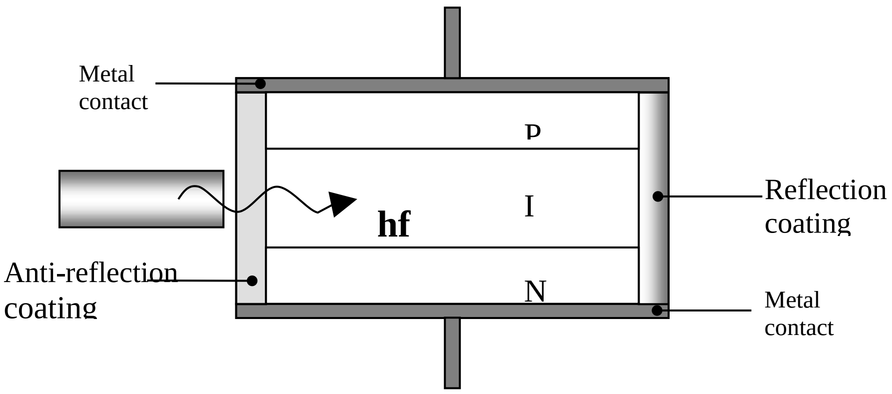
- When a photon of enteres the diode, if it has the correct energy, it may be absorbed by an electron in the depletion region of the PIN.

- If the photon is absorbed by an electron, the electron will be raised into the conduction band, leaving a hole in the valance band.

- These carriers will be pulled into the external circuit due to the applied voltage and cause a current to flow in the external circuit.

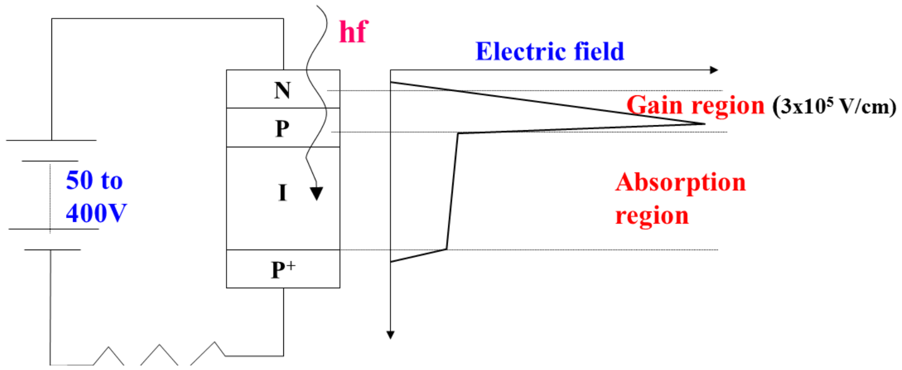
- The amount of current in the external circuit will be proportional to the number of **electrons** entering the PIN photodiode.
  i.e. reverse biased PIN covert an optical signal back into an electrical signal.

Figure below shows a side illuminated PIN diode structure :



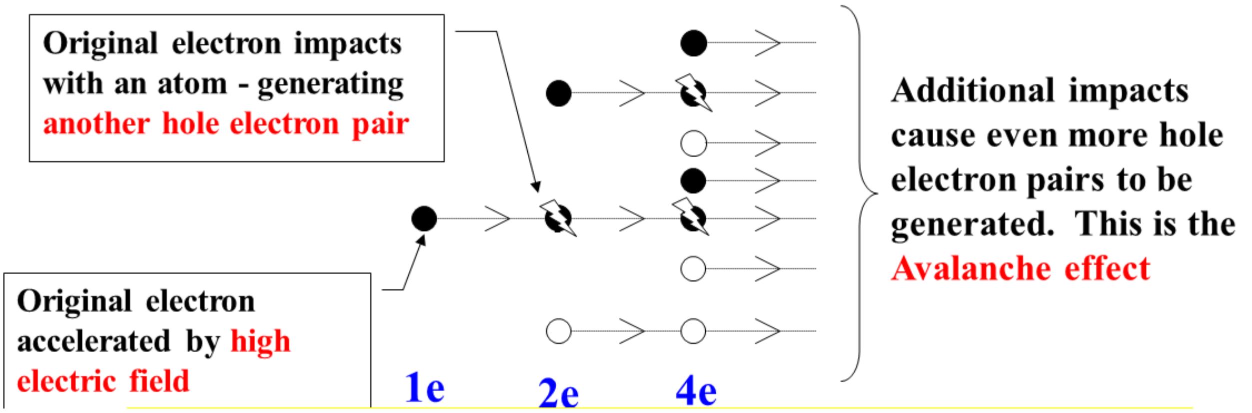
3.3.2 AVALANCHE PHOTODIODE (APD)

These devices have a more complicated structure than PIN photodiodes, but they are more sensitive and can receive lower levels of light. To understand how an APD works consider Figure below:



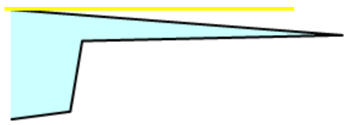
Electric field distribution across the reverse biased APD

- APD needs a **high** reverse biase voltage.
- Reverse biase voltage causes electric field distribution shown in above figure
- Electric field in the gain region is very high, in the order of $3x10^5$ V/cm.
- This gives the holes and electrons, generated by incoming photons, sufficient energy to **excite** new hole-electron pairs.
- This is called **impact ionisation**.
  The process is illustrated in the following figure.
- Carrier multiplication can be as large as 10000 times, unlike the PIN where, at best, on photon generates one electron.
- This device has gain, hence APD is much more sensitive than the PIN.



Electrons gain sufficient energy through this high gain region

\- High electric field in gain region +



3.3.3 IMPORTANT CHARACTERISTICS OF LIGHT DETECTORS

The most important characteristics of light detectors are:

- **Responsivity**
  This is a measure of the conversion efficiency of a photodetector.
  It is the ratio of output current to input optical power - units Amperes / Watt.

  R = (Output current generated) / (Input optical power) (A/W)

  Responsivity is generally given for a particular wavelength.

- **Quantum efficiency**
  The number of generated electrons divided by the number of incident photons.

  η = (number of electrons collected) / (number of incident photons)

- **Dark Current**
  This is the leakage current that flows through the photodiode with no light input. Dark current is caused by minority carriers in the diode.

- **Transit time (or response time)**
  Response time is the time required for a photodiode to respond to optical inputs and produce an external current. The response time is usually specified as a rise time and or fall time measured between **10% and 90%** points of amplitude.

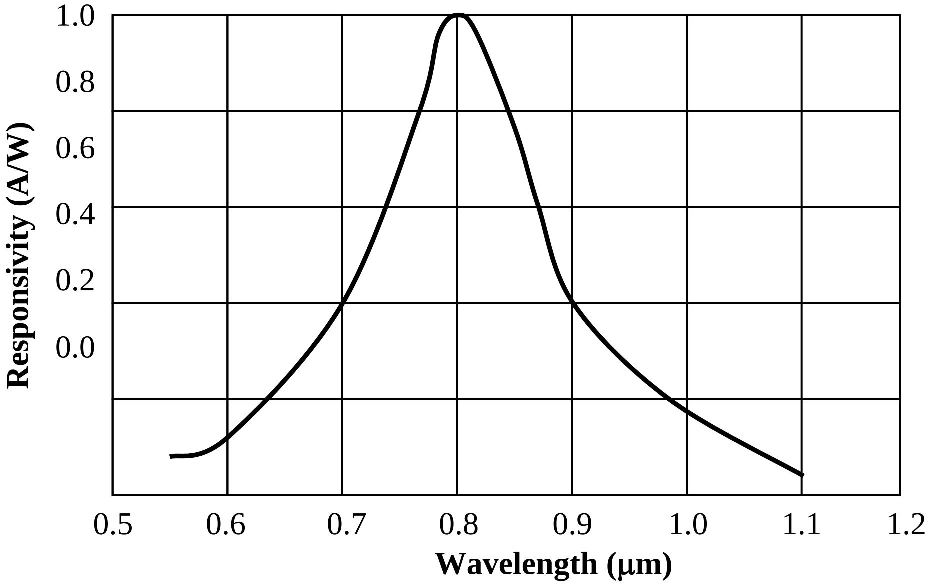
  Rise times range from 0.5ns to tens of ns and is influenced by the bias voltage. Higher voltages bring faster rise times. A pin diode may have a rise time of 5ns at 15V and 1ns at 90 V.

  The response time of the photodiode relates to its usable bandwidth.

  Bandwidth can be approximated from rise time: $\boxed{BW = \frac{0.35}{t_r}}$

- **Sensitivity (or minimum detectable power)**
  The sensitivity of a detector determines the lowest level of incident optical power that the detector can handle.

- **Spectral Response**
  It determines range of wavelengths over which a detector is usable. Figure below is a plot of responsivity versus wavelength for a detector that would be used in an 800nm optical link. Clearly this detector would be of little use in a 1300nm or 1550nm link.



The spectral response of a photodetector

3.3.4 CALCULATIONS OF QUANTUM EFFICIENCY & RESPONSIVITY

Quantum efficiency $\eta = r_e / r_p$	η = (number of electrons collected/sec) / (number of incident photons/sec) = (Electron rate $\mathbf{r_e}$) / (Photon rate $\mathbf{r_p}$)
Responsivity $R = I_p / P_o$	R = (Output current generated) / (Input optical power) $\mathbf{R = \eta\lambda e / hc}$
Electric Current I_p	I_p = total electric charges per sec (coulomb per sec) =(Number of electrons per sec) x (Electric charges) A **=** (Electron rate) x (Electric charge) = $(\mathbf{r_e})$ x (e)
Optical power P_o	P_o = total optical energy per sec (Joules per sec) = (Number of photons per sec) x (Energy of one photon) **=** (Photon rate) x (Energy of one photon) = $(\mathbf{r_p})$ x (hc/λ)
Photon rate r_p	$r_p = P_o / (hc/ \lambda) = P_o\lambda) / hc$
Electron rate r_e	$r_e = \eta r_p = \eta(P_o\lambda) /(hc$
Output current I_p	$I_p = (r_e)(e) = [\eta(P_o\lambda) /(hc)]\ (e)$
Responsivity	$R = I_p / P_o = [\eta(P_o\lambda) /(hc)]\ (e) / P_o = \mathbf{[\eta(\lambda) /(hc)]\ (e)}$

<u>EXAMPLE 1</u> (the solution is available in the BB teaching slides)
When 3 x 10^{11} photons per sec with wavelength of 0.85 μm are incident on a photodiode, on average 1.2 x 10^{11} electrons per sec are collected at the terminals of the device. Determine:

(i) Quantum efficiency.
(ii) Incident optical power on the photodiode.
(iii) Output current generated at the photodiode terminals.
(iv) Responsivity of the photodiode.

<u>EXAMPLE 2</u> (the solution is available in the BB teaching slides)
A photodiode has quantum efficiency of 65% when photons of energy 1.5 x 10^{-19} J each are incident upon it.

Determine: (i) The operating wavelength of the photodiode.
(ii) The responsivity of the photodiode.
(iii) The incident optical power, if a photocurrent of 2.5 μA is detected at the photodiode terminals.

3.3.5 PERFORMANCE REQUIREMENTS OF PHOTODETECTORS

- High sensitivity.
- High responsivity.
- Sufficient bandwidth or speed of response.
- Relatively immune to temperature variations.
- Low noise (i.e. small dark current)

Noise generated by the photodetector and its associated circuitry is one main factor limiting the sensitivity of the receiver.

3.3.6 APD VERSUS PIN PHOTODIODES

- An APD costs 5 to 10 times more than a PIN diode.
- APD offers higher sensitivity and higher responsivity. APD typically has a responsivity of 75 A/W, whereas, PIN has a typical responsivity of 0.5 A/W.
- Speed of PIN diodes and APD are comparable, however, for long distance links, APD is preferred because of higher gain.
- APD needs higher operating voltage (400V compared with 40V for PIN).
- APD produces more noise (internally generated noise due to avalanche multiplication)
- APD is more sensitive to temperature variations, needs special temperature stabilising circuitry.
- APD has higher receiving sensitivity, more suitable for long distance links. PIN is useful in short haul links where low cost is an important factor.

3.4 MEASUREMENT TECHNIQUES

Measurements on fiber cable installation may be done by the two commonly used methods:

- Measurement of cable attenuation or loss
- Optical fiber evaluation by Optical Time Domain Reflectometer (OTDR)

3.4.1 MEASUREMENT OF CABLE ATTENUATION

Attenuation is the most important property of passive optical components. It is always a function of wavelength although the wavelength sensitivity varies widely.

In fibers, the variation with wavelength is large. However, in some other components it is negligibly small.

Attenuation is measured by comparing input and output levels, P_{in} and P_{out}, respectively. It is given in decibels by:

$$\textbf{ATTENUATION (dB)} = \mathbf{-10 \log (P_{out} / P_{in})}$$

The negative sign is added to give attenuation a positive value, because the output power is always lower than the input power for passive devices.

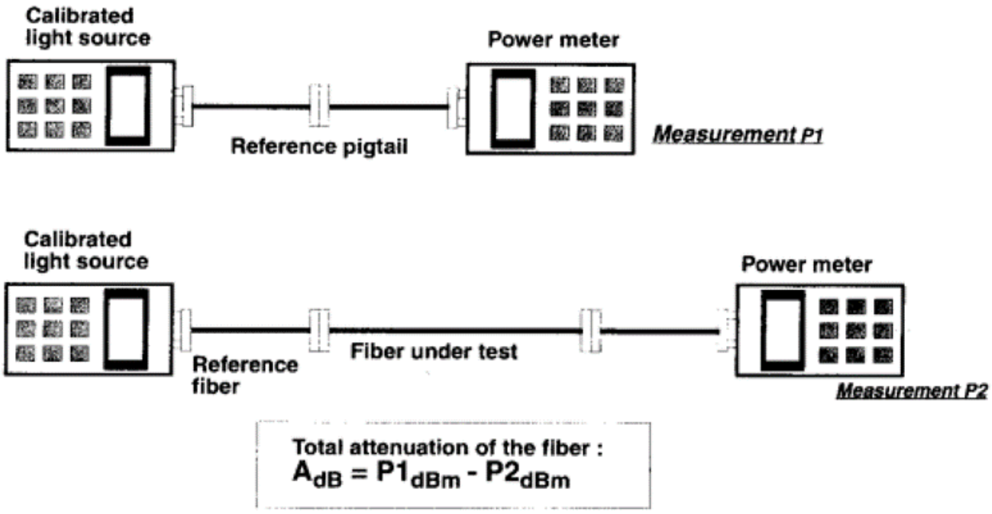
Two methods are commonly used to measure attenuations:

1) Insertion loss measurement
2) Cut back measurement

INSERTION LOSS TECHNIQUE

Insertion loss technique is a non-destructive method to measure the attenuation across a fiber, a passive component or an optical link.

With the substitution method, the output from a source and a Reference fiber is measured directly before another measurement is performed with the fiber to be measured.



The difference between the two results gives the attenuation of the fiber.

$$\textbf{ATTENUATION (dB)} = 10 \log (P_1 / P_2)$$

$$\textbf{ATTENUATION (dB)} = P_1\,(dBm) - P_2\,(dBm)$$

The purpose of the first or “reference” measurement is to cancel out as far as possible the losses caused by the various patch cables.

CUT BACK TECHNIQUE

This technique gives the most accurate measurement, but it is also destructive and cannot be applied in the field. This is the reason why it is not used during installation and maintenance.

Testing with the cutback method requires first measuring attenuation of the length of fiber under test, then cutting back a part of the length from the source end, and measuring attenuation of this part of cable.

The difference of the two values gives the attenuation of the cut fiber.

Link losses are sometimes measured in each direction and averaged to improve confidence in the measurements.

3.4.2 OPTICAL FIBER EVALUATION BY OPTICAL TIME REFLECTOMETER (OTDR)

Use of Optical Time Domain Reflectometer (OTDR) is another way to measure attenuation of fiber.

An OTDR (Optical Time Domain Reflectometer) is a fiber optic tester characterizing fibers and optical networks. The aim of this instrument is to detect, locate and measure events at any location in the fiber link.

One of the main benefits of the OTDR is that it can fully test fiber from only one end, as it operates like a one dimensional radar system. The OTDR is similar to an accurate radar as its resolution can be between 6 cm and 40 meters.

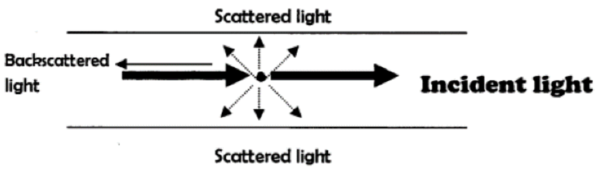
PRINCIPLES OF OTDR

The OTDR's ability to characterize a fiber is based on detecting small signals returned back to the OTDR in response to injection of a large signal, much like a "radar". In this regard, the OTDR depends on two types of optical phenomena:

1) Rayleigh Backscattering   2) Fresnel Reflections.

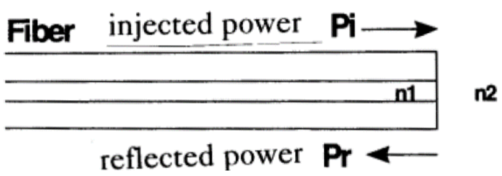
The major difference between these two phenomena are:

1) Rayleigh scattering is intrinsic to the fiber material itself and is present along the entire length of the fiber. If Rayleigh scattering is uniform along the length of the fiber, then discontinuities in the Rayleigh backscatter can be used to identify anomalies in transmission along the fiber length.



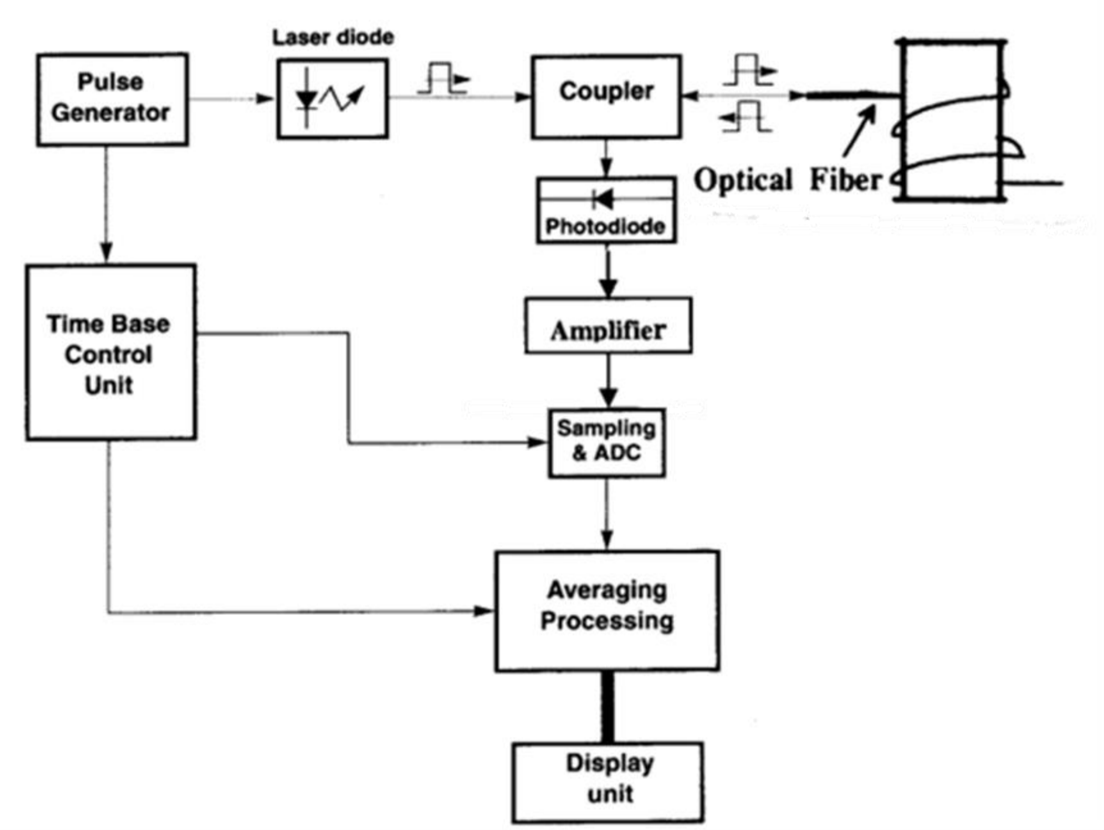
Rayleigh scattering

2) Fresnel reflections are "point" events and occur only where the fiber comes in contact with air or another media such as at a mechanical connection/splice or joint

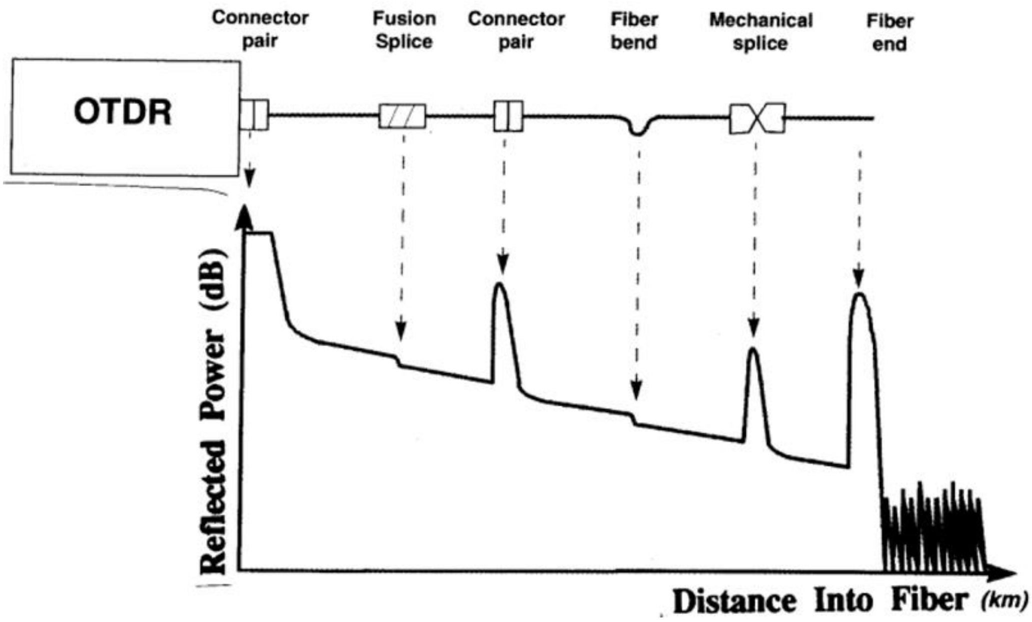


Fresnel Reflections

OTDR BLOCK DIAGRAM



The OTDR injects light energy into the fiber through a laser diode and pulse generator. The returning light energy is separated from the injected signal using a coupler and fed to the photodiode. The optical signal is converted to an electrical value, amplified, sampled and then displayed on a screen. The display shows a vertical scale in dB and an horizontal scale in km (or feet), and plots numerous acquisition points which represent the backscatter "signature" of the fibers under test.

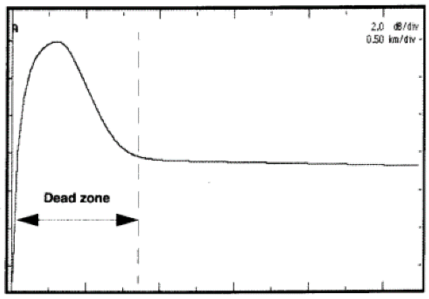


DEAD ZONE

The OTDR is designed to detect backscattering level all along the fiber link. It measures backscattered signals which are much smaller than the signal sent to the fiber. The component which receive those values is the photodiode. It is designed to receive a given level range.

When there is a strong reflection, then power received by the photodiode can be more than 4000 times higher than the backscattered power and can saturate the photodiode. The photodiode requires time to recover from the saturated condition; during this time, it will not detect the backscatter signal accurately.

The length of fiber which is not fully characterized during the recovery period is termed the dead zone. This effect is similar to the one when you are driving a car at night, and that another car's headlights dazzle your vision momentarily.



OTDR dead zone example

OTDR MEASUREMENTS

The following features can be observed on the OTDR display:

- Reflective events (by Fresnel reflections) where a discontinuity in the fiber causes an abrupt change in the refractive index are either caused by breaks, connectors junctions, mechanical splices or the un-terminated end of fiber. Connector loss can be around 0.5dB and mechanical splices can range from O.1dB up to 0.2dB

- Non reflective events occur where there are no discontinuities in the fiber and generally are produced by fusion splices or bending losses. Typical values would be from 0.02dB up to 0.1 dB depending on the splicing equipment and operator.

- A continuous return of pulse is observed, which is due to Rayleigh scattering of the probe pulse travelling in the forward direction. The observed signal represents the two-way travel time through the device under test. The fiber’s loss in dB/km is given by the slope of the curve.

After determining the travel time of a light pulse, the OTDR can calculate the distance (fiber length or fault location) D according to the following equation:

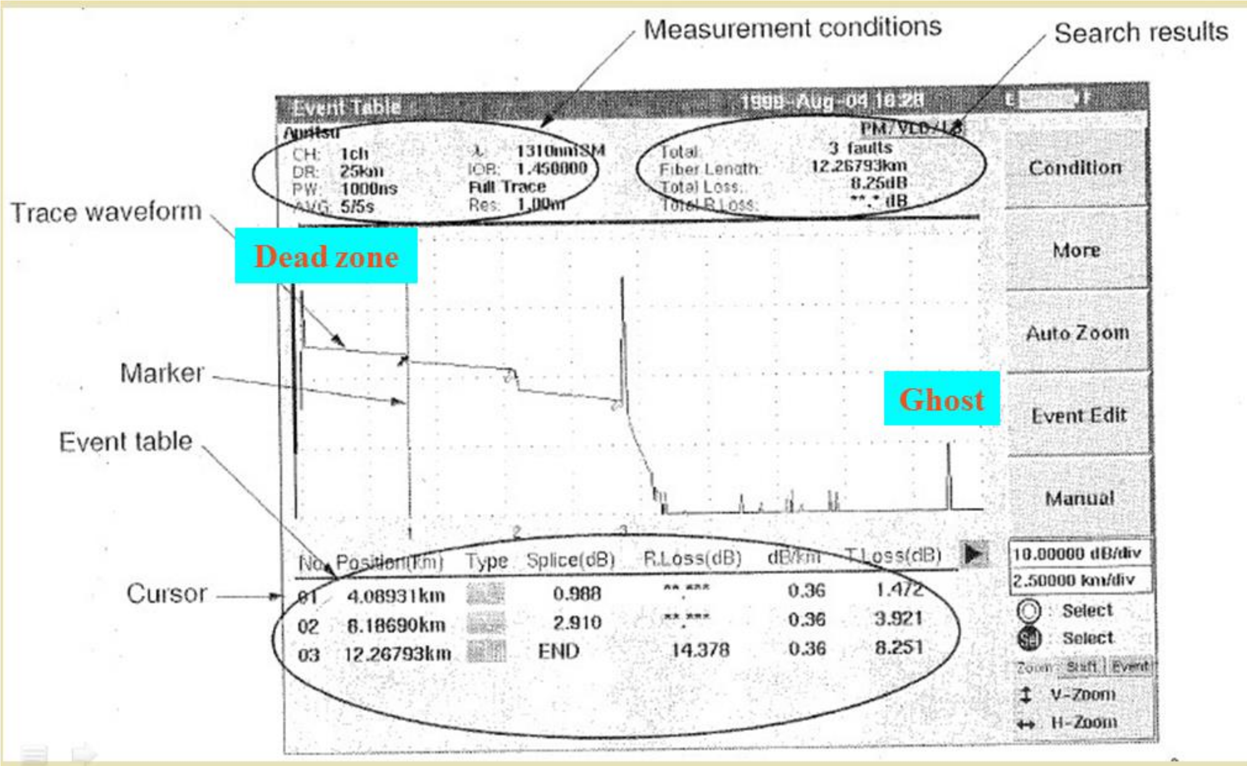
$$D = \frac{ct}{2n}$$

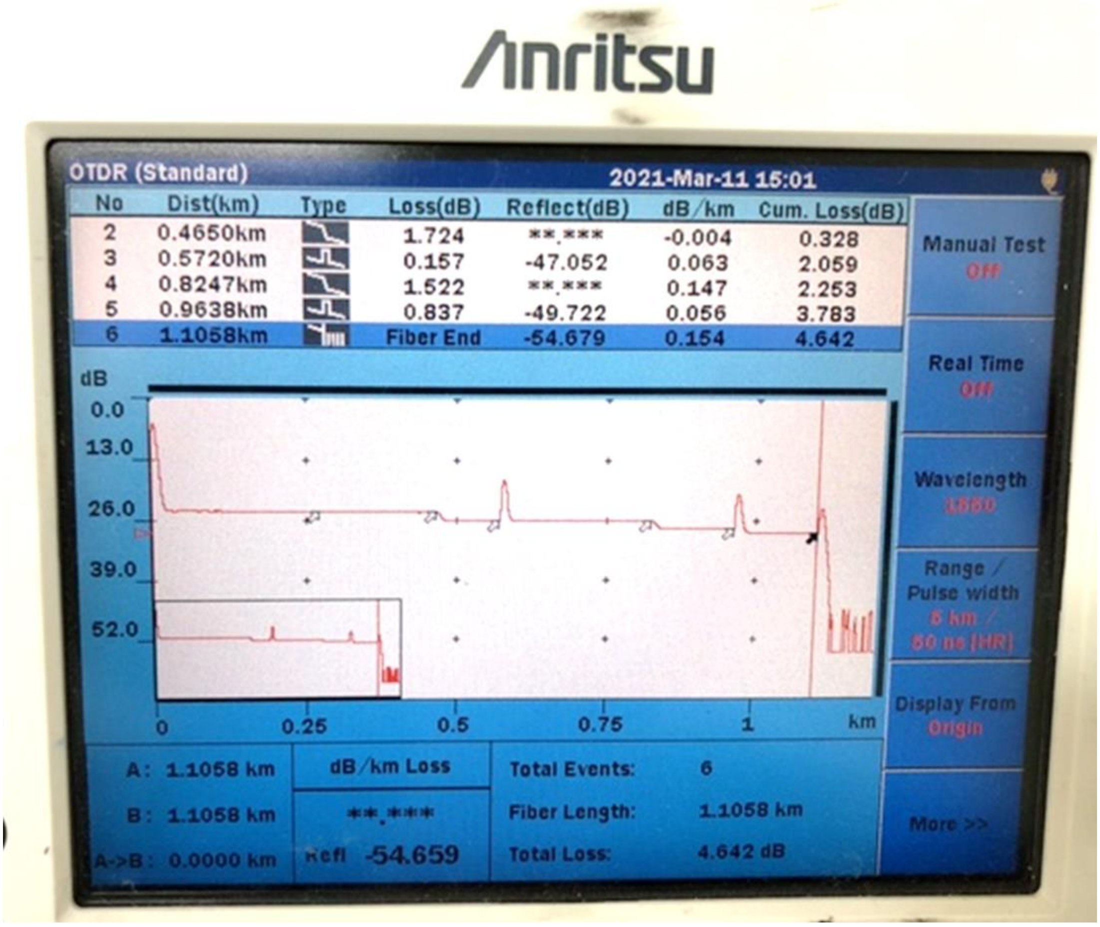
Where D = Distance to the defect or end of fiber
c = Speed of light in vacuum (3x108 m/s)
t = Round-trip travel time between the launched pulse and the return pulse
n = Reflective index of the fiber core

The following measurements can be performed by an OTDR.

1) For each event Distance location & loss
2) For each section of fiber Section length, section loss in dB & dB/km
3) For the complete terminated system: Link length & link loss in dB

TYPICAL OTDR TRACE





TUTORIAL 3a

1. State the **three** differences between spontaneous and stimulated emission.

2. Define the term "Population Inversion". Explain why it is important to optical radiation in ILD.

3. Avalanche Photodiode (APD) is more sensitive than the PIN Photodiode (PIN) due to carrier multiplication. Name the process occurred in APD and hence state the TWO factors which lead to carrier multiplication to be as large as 10,000 times.

4. An ILD material has a band gap of 1.3eV :
   (a) Find the wavelength and frequency of peak emission.
   (b) Find the band gap energy in Joules.

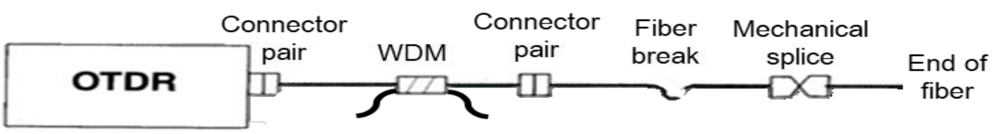
5. A PIN photodiode on average generate one electron-hole pair per two incident photons at a wavelength of 900nm. If 27.8μw of optical light incident on the photodiode and assuming that all the electrons are collected at the photodiode terminal.
   (a) Calculate the maximum possible bandgap energy in eV.
   (b) Calculate the quantum efficiency of the photodiode.
   (c) Estimate the Photon rate and Electron rate.
   (d) Calculate its responsivity at 900nm.

TUTORIAL 3b

6. State the two methods commonly used to measure fiber attenuations. Give one advantage for using each method.

7. Attenuation measurement using cutback technique is performed on a 1.5 km length of optical fiber at wavelength of 850nm. The measured optical output power from 1.5km length is 50.1 μw. When the fiber is cut back to a 200.0 m length, the measured optical output power is 385.4 μw.
   (a) Express the optical power of 50.1 μw and 385.4 μw in dBm.
   (b) Determine the attenuation per km of the fiber at a wavelength of 850nm.
   (c) If the 850nm source is replaced by a 1550nm source, will the fiber attenuation be reduced? Give reason to support your answer.

8.



An OTDR is used to locate the fracture point in an optical fiber cable with a core refractive index of n = 1.5. If an optical pulse is launched into the fiber and the pulse echo takes 2 μs to return back to the OTDR.
   (a) Determine the distance of the cable fracture point from the OTDR
   (b) Sketch the OTDR display and indicate clearly label all events & fracture distance
   (c) State the advantage of using WDM devices in an optical communication link. Give four differences between CWDM and DWDM.

TUTORIAL GUIDE 3

1) Study and apply section 3.1 -3.1.4.

2) Study and apply section 3.1.4.

3) Study and apply section 3.3.2.

4) a) λ = 954 (nm). f = 3.15×10^{14} (Hz).
(b) $E_g = 2.084 \times 10^{-19}$ (J)

5) (a) Max possible bandgap energy : $E_g = 1.38(eV)$
(b) Quantum efficiency η = 50%
(c) Photon rate : $r_p = 1.252 \times 10^{14}$ (photons / sec)
Electron rate : $r_e = 6.26 \times 10^{13}$ (electrons / sec)
(d) Responsivity : R = 0.362 (A/W)

6) Study and apply section 3.4 – 3.4.1.

7) (a) $P_{1.5km}$ = -13 dBm. P_{2m} = -4.14 dBm.
(b) 6.82 (dB/km)
(c) Answer may be found at page 31

8) 200m

CHAPTER 4

OPTICAL FIBER COMMUNICATION SYSTEMS & NETWORK

CHAPTER OBJECTIVES:

- Understand the various practical aspects of designing optical fiber communication systems & network

Learning outcomes

At the end of the chapter, the students will be able to:

☑ Describe the transmission formats used in optical comm. System

☑ Analyse system budgeting through the use of rise time & power budgets for point-to-point optical fiber links

☑ Explain the general topology and role of WDM devices in the optical fiber network

CHAPTER 4 Optical Fiber Communication Systems & Network

4.1 TRANSMISSION FORMATS

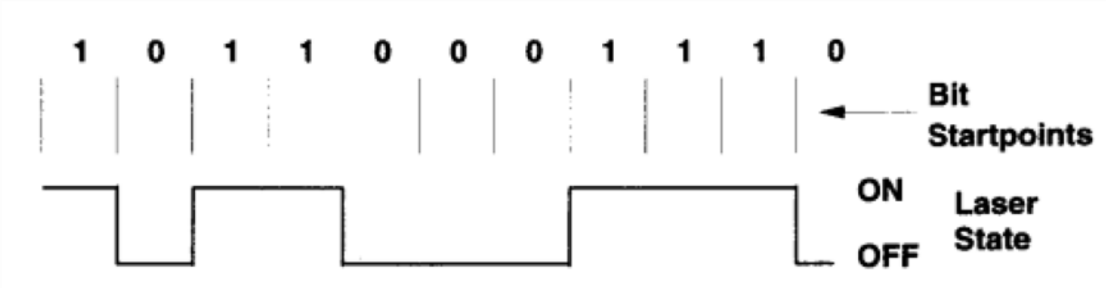
Most current optical transmission systems encode the signal as a sequence of light pulses in a binary form. “One” represents the presence of light, “zero” represents the absence of light. This is called “On-Off-Keying” (OOK).

The simplest coding system used in optical communication system is Non-Return-to-Zero (NRZ).

In NRZ coding, every “on” or “off” state occupies a full bit time.

Hence the signal bandwidth is equal to half of its bit rate. i.e. BW = BR / 2.

The typical NRZ bit pattern is shown as follow:

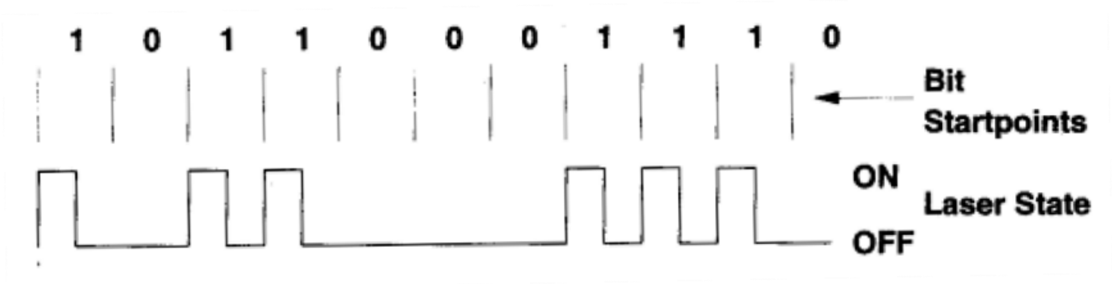


The other coding format used in optical communication system is Return-to-Zero (RZ). In RZ coding, the signal returns to the zero state every bit time.

Every “on” or “off” state occupies only half a bit time.

Consequently, the signal bandwidth is equal to its bit rate. i.e. BW = BR.

The typical RZ bit pattern is shown as follow:



4.2 OPTICAL COMMUNICATION SYSTEM BUDGETING

In the designing of an optical fiber communication system, it is important to select the components that will function together to yield a working system complete with a safety measure in place to counter aging of the components.

Here are some practical questions for consideration:

- Is there enough power arriving at the receiver?
- Are components rise-time within system bandwidth requirement, S/N ratio, BER?
- Are repeaters required? What is the safety margin to use?
- What type of fiber is best suited for the application?
- Which multiplexing technique is best suited for the particular application?
- What is the cost?

In order to ensure that the assembled system meets the desired system performance, two analysis are usually carried out. They are:

- Link power budget analysis (or loss budgeting)
- System rise time budget analysis (or rise time budgeting)

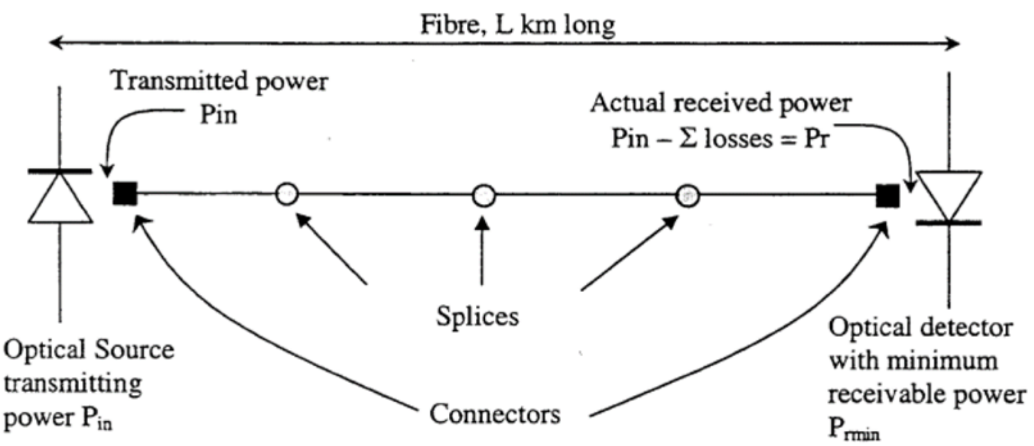
4.2.1 Link Power Budget Analysis

The process of performing a link power budget analysis is to evaluate all aspects of power requirement to ensure that the system will function properly. This means all signal losses incurred in the system must be less than the maximum losses allowable for the system.

Here are the steps to perform a link power budget analysis:

(a) Determine the power being launched into the fiber from the transmitter (Pin).
(b) Determine the minimum power required at the detector (Prmin) needed to establish a specific S/N ratio or BER. This is the sensitivity of the chosen detector.
(c) Calculate the power loss in the connectors, splices, fiber and any additional safety margin to compensate for expected component aging,
(d) Check to see if the difference between the results of steps (a) and (b) is larger than the total losses obtained in step (c). If necessary select different components or modify the system requirements (or specification).

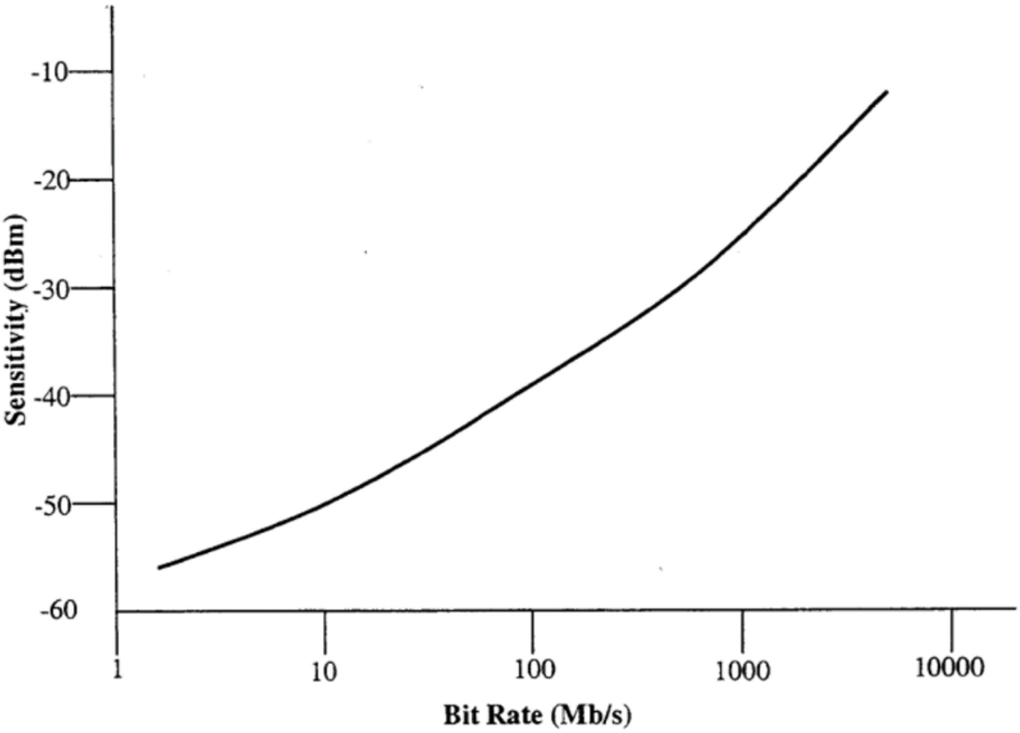
Figure below shows an optical power loss model for a point to point link.



Optical power loss model for an optical fiber link

The key to optical power budgeting is making sure that there is sufficient power at the optical detector. Optical detector manufacturers will quote a sensitivity for their detectors. Detector sensitivity depends on the required Bit Error Rate (BER) and the required bit rate. The optical power arrived at the detector must be greater than the sensitivity of the detector.

A graph of sensitivity for BER of 10^{-9} is shown in figure below. It is the sensitivity level that is equal to the minimum power required. Because sensitivity depends on bit rate and BER, the same detector will have different sensitivities for different applications.



Sensitivity versus bit rate for an InGaAs APD

When doing power budget calculations, the sensitivity may be given or it may be obtained from a graph like the one in above figure. Once the sensitivity is found, the next step is to work out the sum of all the losses for the optical link. It is necessary to add a safety margin to the sum of losses to allow for component aging.

If the optical link is to function correctly, the transmitted power minus the sum of the losses and safety margin must be larger than the sensitivity of the detector.

$$P_{r\min} \le P_{in} - \sum Connector\ Loss - \sum Splice\ Loss - \sum Fiber\ Loss - System\ Safety\ Margin$$

$$P_{r\min} \le P_{in} - \sum Connector\ Loss - \sum Splice\ Loss - \alpha L - System\ Safety\ Margin$$

α is the fiber loss per km, L is the fiber length in km. Safety Margin is usually 3 to 6 dB.

Alternatively, we can express Power Budgeting as:

$$P_{in} - P_{r\min} \geq \sum Connector\ Loss + \sum Splice\ Loss + \alpha L + System\ Safety\ M\arg in$$

If power budget fails, it means that there is insufficient power to "drive" the detector. The designer must consider making the following choices:

- Change to a more sensitive light detector (receiver)?
- Choose lower loss components – optical fiber?
- Choose a more powerful light source (transmitter)?
- If all fails, consider the use of a repeater or optical amplifier in the link.

It is usually impractical make the link shorter or reduce the bit rate, because it must go from point a to point b, and provide the customer with the specified performance.

EXAMPLE 1 (the solution is available in the BB teaching slides)

Determine the maximum transmission distance for a link with the following specifications:

Data rate:	20 Mb/s (NRZ signal)
BER:	10^{-9}
Wavelength:	850 nm
Detector sensitivity:	-42 dBm
Power launched from LED source:	50 μw
Connector loss:	1 dB per connector
Safety margin:	6 dB
Fiber attenuation (α):	3 dB/km
Number of splicing:	6
Average splice loss:	0.2 dB per splice

4.2.2 SYSTEM RISE-TIME BUDGET ANALYSIS

The power budget analysis ensures that sufficient power is available throughout the link to meet application demands. But we also have to make sure that all of the components in the optical link operate fast enough to meet the bandwidth requirements of the application.

The rise time budget is used to determine the dispersion limitation on Bandwidth or Data rate of an optical link. As we have seen in the previous chapter, both sources and detectors have a certain response time. The response time limits the bandwidth or data rate of the devices. Similarly, material and modal dispersion in the fiber limit the bandwidth or data rate of the fiber.

When the bandwidth (BW) of a component is specified, its rise time τr can be approximated using, the formula:

$$\tau_r = \frac{0.35}{BW}$$

For example, a fiber is specified with a bandwidth length product of 500MHz.km and the fiber link is 2km long, then:

BW = 500 / 2 = 250 MHz

= 1.4ns

When all the individual rise times have been found, the total system rise time can be found from the equation:

$$\tau_{sys} = 1.1\sqrt{\tau_f^2 + \tau_s^2 + \tau_d^2}$$

Where: τsys is the actual system rise time.
τf is the fiber rise time.
τs is the source (or transmitter) rise time.
τd is the detector (or receiver) rise time.

Fiber rise time is composed of material and modal dispersion: $\tau_f = \sqrt{\tau_{\mathrm{mod}al}^2 + \tau_{material}^2}$

Factor 1.1 allows for 10% degradation of system rise time due to component aging. In a typical application, the rise time budget can also be used to find the required rise time for an individual component, such as the source, fiber or detector by transposing the rise time equation to solve for the unknown rise time.

That is, for a given system rise time, the component rise time is calculated from:

$$\tau_s = \sqrt{\left(\frac{\tau_{sys}}{1.1}\right)^2 - \tau_f^2 - \tau_d^2}$$

EXAMPLE 2 (the solution is available in the BB teaching slides)
A 20MHz optical transmission system operates over 2km using a fiber that has a 400MHz.km bandwidth length product. The detectors rise time is l0 ns. What is the rise time required for the source?

Solution] *Hint: Here we will use the equation* $\tau_s \le \sqrt{\left(\frac{\tau_{sys}}{1.1}\right)^2 - \tau_f^2 - \tau_d^2}$

τ_s *is less than or equal to the sum on the right hand side of the equation, because the system rise time,* ***τ_{sys}*** *is actually the maximum allowable rise time derived from the performance specification (20MHz optical link in this case).* ***τ_{sys}*** *may be more than the actual system rise time if the components used have a faster rise time.*
Now to find τ_s, we must find ***τ_{sys}*** *and* ***τ_f***

Fiber BW:

Fiber rise time (τ_f):

Actual system rise time (τ_{sys}):

Then $\tau_s \le$ ____________________

EXAMPLE 3 (the solution is available in the BB teaching slides)
A system is designed to operate at 20Mb/s (NRZ signal). The system has the following component rise time parameters:

Source rise time:	15ns
Detector rise time	14ns
Fiber modal dispersion rise time	21ns
Fiber material dispersion rise time	3.9ns

Determine if the system will operate satisfactorily.

[Solution]
Hint: We must compare the system rise time from the specification (20 Mb/s) with the actual system rise time (found from the component rise time values) and see if the actual system rise time is less than or equal to the specified system rise time. If it is, then the system will function correctly.

4.3 PRACTICAL DESIGN CONSIDERATION

It is important that both power and rise time budget analysis must be considered when designing practical optical communication link.

Separate calculations must be carried out to determine maximum link length for power and rise time analysis. The practical maximum link length will be the smaller of the two calculations.

If the practical maximum link length is equal to that obtained from power budget analysis, then the link is said to be **Power limited**.

If the practical maximum link length is equal to that obtained from rise time budget analysis, then the link is said to be **Rise time limited**.

<u>EXAMPLE 4 (Solution is available in the BB teaching slides)</u>

It is desired to transmit a 20 Mb/s NRZ signal at a BER of 10^{-9} through an optical fiber link, which has the following system specifications:

Transmitter	Receiver
Output power = 100 μw	Sensitivity at 10^{-9} BER = -30 dBm
Source rise time = 15 ns	Detector rise time = 14 ns
Connector loss = 1 dB	Connector loss = 1 dB

System margin of 6 dB is to be reserved.

Optical Fiber
Modal dispersion = 10 ns/km
Material dispersion = 4 ns/km
Attenuation = 3 dB/km
Splice loss is negligible

(a) Determine the maximum link length for this fiber optic link.
(b) If the fiber optic link is operating between 2 locations 70 km apart, estimate the number of repeaters required.

4.4 OPTICAL FIBER NETWORK

Optical Fiber network offers high speed wireline with immunity to interference, high bandwidth and high performance suitable for long-haul networks. Signal can travels on fiber for 40 miles without losing signal strength compared to 300 feet for copper wireline.

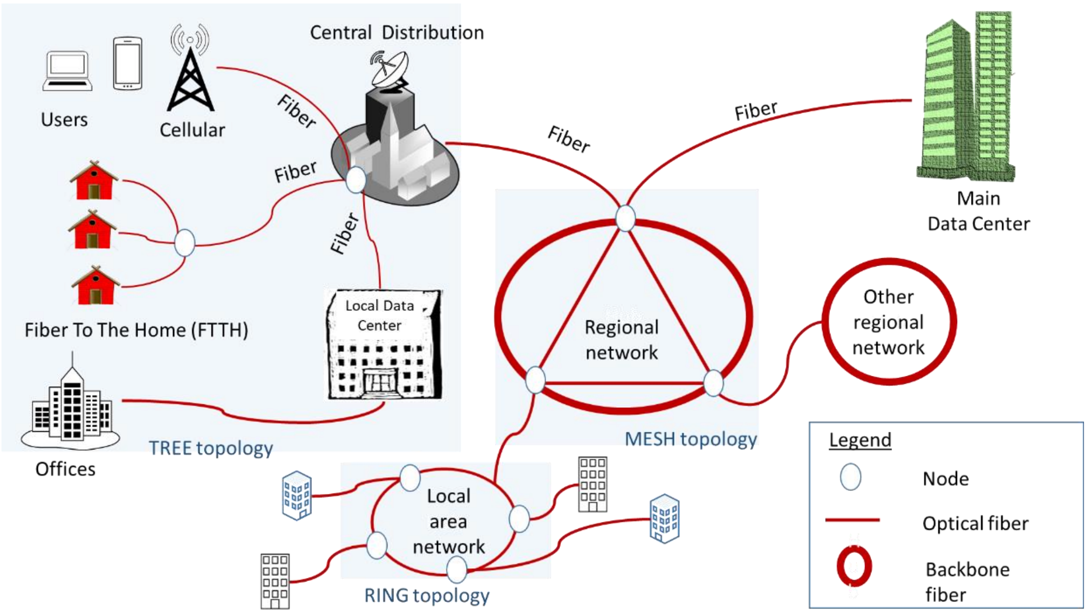
Over the past decade, businesses have switched to optical fiber technology in a wide range of applications from major telecommunication backbone infrastructure to broadband distribution and general data networking.

The limitation to optical fiber networks lies in the fact that it lacks mobility because it is not wireless. This explained why telecommunication industry have been using optical fiber networks in the backbone applications while their wireless network of 4G and 5G bridge the short distances for their mobile users.

It is useful to examine the general topology and fiber components used in the optical fiber network as it is the wireline supporting most telecommunication infrastructure.

4.4.1 OPTICAL FIBER NETWORK TOPOLOGY

The general network topology refers to how various elements on the network are connected in relation to each other. For example in the telecommunication industry, the network topologies are usually ring, mesh, tree and star. A backbone network is used to provide paths for the exchange of information between different sub-networks such as local users access network, other regional network, global network etc.



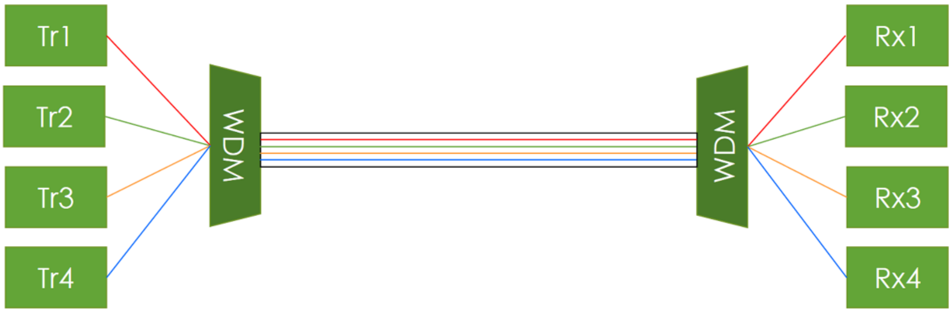
Optical fiber telecommunication network

In network design it is important to consider the merits and drawbacks of the various topologies.

Star topology	In star, a central hub is used to connect the various nodes in the network. The merits of star are easy to manage and maintain as it is easier to detect faults or remove parts. The drawback is the dependency on the central hub. If the central hub fails, it disables the whole network. It is usually used in access network like FFTH
Tree topology	A tree network is made up of two or more star network and the information traffic will flow in a hierarchical step. Though tree topology is cheaper, it is less robust as the network will be disconnected in the event of a faulty element e.g. the central hub.
Ring	Every network node is connected to two neighbouring nodes in such a way that all connections form a ring. The merit of ring is that the data may be routed the other way in the event of a fiber cut or faulty element.
Meshed	This type of topology is usually used in small networks with few nodes as each node is connected to several other nodes. This point to point connection can be changed according to the application. This makes it reliable as in the case of failure of one node, others can be used as alternative path that will allow network traffic to continue. Most backbone network uses mesh topology.

4.4.2 WDM FIBER NETWORK

WDM is a technique in optical fiber transmission where multiple light wavelengths are used to send data over a single optical fiber. It is one of the most widely used technology for high-capacity optical communication systems.



Unidirectional WDM fiber transmission system

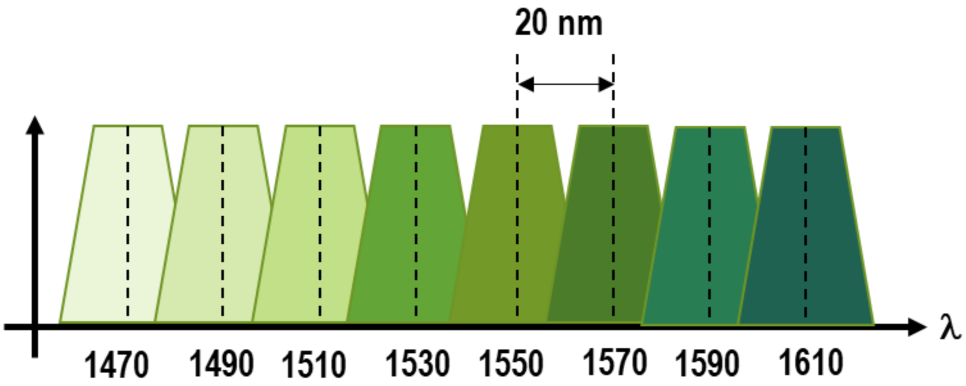
WDM fiber transmission system uses multiple optical transmitters, each emitting light at a different wavelength. Every wavelength carries an individual signal that does not interfere with other wavelengths. These signals are multiplexed by the WDM and transmitted over a single optical fiber. At the receiver side the signals are de-multiplexed by the WDM and sent to multiple receivers.

In the late 1980s, WDM technology provided a great expansion in the information carrying capacity of a single optical fiber from 1 signal to 8 signals.

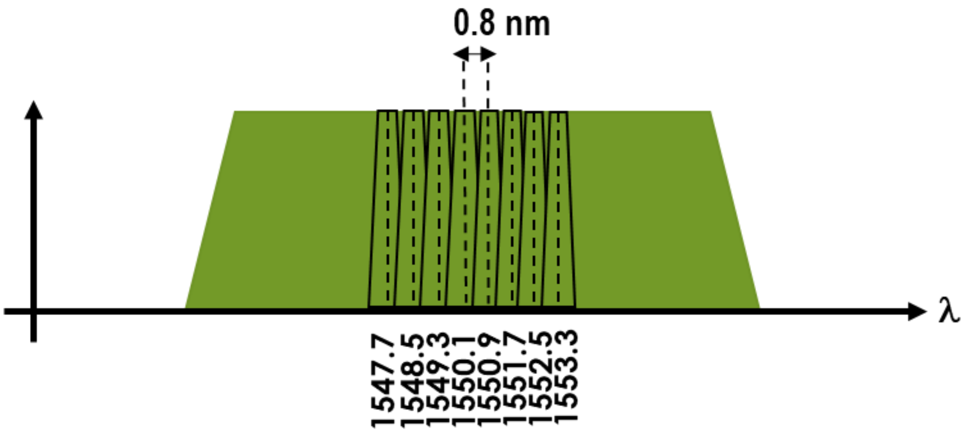
There are two types of WDM commonly used in the telecommunication industry.

COARSE WAVE DIVISION MULTIPLEXING (CWDM)

CWDM is commonly deployed in short distance point-to-point enterprise networks and telecom access networks.



DENSE WAVE DIVISION MULTIPLEXING (DWDM)



DWDM is able to support longer distance and hence used for interconnecting data centers and for financial services networks. The difference between CWDM and DWDM is the frequency or wavelength spacing between two adjacent signals or channels. In terms of wavelength, CWDM uses 20nm spacing in the spectrum grid of 1271nm to 1611nm. DWDM uses as narrow as 0.4 or 0.8 nm spacing with wavelengths from 1525 to 1565nm and 1570nm to 1610 nm..

Both CWDM and DWDM are using WDM technology. CWDM can carry up to 18 signals with different wavelengths while DWDM is able to transmit up to 160 wavelengths. It is easy to see why the market favor DWDM as it is able to offer a dramatic increase in the optical fiber bandwidth.

Traditionally installing new optical fiber was the norm for industry when faced with high demand on their optical fiber infrastructure. However it was also a costly technique as deploying a new optic fiber could easily translate to about $70K per mile with much of the cost going into the labor-intensive of digging, laying and construction.

DWDM is more costly and complex than CWDM. However, the ever increasing demand for more bandwidth has fuelled DWDM's development and expanded its market demand which in turn led to higher production hence lowering cost.

DWDM is an effective and cost friendly technology to expanding the bandwidth of existing networks because of its ease of use, scalability and reliability. However, CWDM still has price advantage for short distance and lower data rates below 10GHz.

TUTORIAL 4

1. A 7.5 km optical fiber link that operates at 10 Mbps with a 10^{-9} BER is designed with the following components:

   Optical fiber, in rolls of 1km, with an attenuation of 2 dB/km.
   Splices with loss of 0.8 dB per splice; End connectors with a loss of 2 dB per connector.
   A GaAlAs LED source operating at 850 nm & capable of coupling 50 µW into fiber. A Si PIN detector having -47 dBm sensitivity at the system operating wavelength.

   (a) Determine the total number of the splices used in the optical fiber link.
   (b) Determine the total system losses and the available safety margin.
   (c) If the safety margin required by the optical link is only 6 dB, determine the required PIN detector sensitivity.

2. An optical fiber link is required to cover a distance of 25 km.

   The following data for the system components are given:
   - The fiber has an attenuation of 0.5 dB/km.
   - Fiber modal dispersion is 20ns/km, material dispersion is 0.2ns/km.
   - 24 splices with a loss of 0.5dB per splice.
   - 2 connectors with 1dB loss each.
   - 1310 nm ILD transmitter with an output power of 2dBm.
   - 1310 nm APD detector with a rise-time of 2ns.

   (a) If a system safety margin of 9 dB is to be reserved, determine the required sensitivity of the receiver.
   (b) The ILD source has a rise time of 6ns, determine the system bit rate of the optical fiber link operating with NRZ signal.

3. It is desired to transmit a 10 Mbps (RZ) digital signal at a BER of 10^{-9} through an optical fiber link, which has the following system specifications:

Transmitter	Receiver
Output Power= 100 µW	Sensitivity at 10^{-9} BER = -48 dBm
Source rise time = 15 ns	Detector rise time = 14 ns
Connector loss = l dB	Connector loss = 1 dB

   Fiber
   Modal dispersion rise time = 10 ns/km; Material dispersion rise time = 4 ns/km
   Attenuation = 3 dB/km; Splice loss is negligible
   A safety margin of 6 dB is to be reserved.

   (a) Determine the maximum link distance.
   (b) Is the system power or rise time limited?

4. An optical fiber system has the following system parameters:

ILD transmitter power :	-3 dBm
Fiber loss : .	2 dB/km
Connector loss at each end of the link :	l dB
Sensitivity of the PIN receiver : (at 140 Mbs, NRZ and 10^{-9} BER)	-50 dBm
Required safety margin :	3 dB
ILD transmitter rise time :	2 ns
Fiber dispersion :	5 ns/km
PIN receiver rise time :	1 ns

(a) Estimate the maximum permissible link length, without repeater, when operating at 140 Mbps NRZ (BER = 10^{-9}).
(b) If the ILD transmitter power is increased to 0dBm, can the transmission distance be increased without degrading the system performance ? Why?
(c) If the optical fiber system is to operate over a link length of 50 km, determine the total number of repeaters required.

5. State the advantage of using WDM devices in an optical communication link. Give four differences between CWDM and DWDM.

TUTORIAL GUIDE 4

1a) 7

1b) Σ Losses = 24.6 (dB)
SM 9.4 (dB)

1c) P_{rmin} = -43.6 (dBm)

2a) P_{rmin} = -33.5 (dBm)

2b) BR_{sys} = 1.272 (Mbps)

3a) L_p = 10 (km) – power budget
L_{rt} = 2.26 (km) – risetime budget

3b) Study and apply section 4.3.

4a) L_p = 21 (km) – power budget
L_{rt} = 3.96 / 5 = 0.792 (km) – risetime budget

4b) Study and apply section 4.3.

4c) 63

5 Study and apply section 4.4.2.

CHAPTER 5

INTRODUCTION TO SATELLITE COMMUNICATION

CHAPTER OBJECTIVES:

- Know the development and basic principles of satellite communications

Learning outcomes

At the end of the chapter, the students will be able to:

- ☑ Describe the development of satellite communications.
- ☑ Describe the development of satellite services and the telecommunication services provided by satellites.
- ☑ Describe the types of satellite orbits.
- ☑ Compare the advantages and disadvantages of the various types of satellite.
- ☑ Analyse and derive the orbital period and velocity of the satellite.

CHAPTER 5 Introduction to Satellite Communication

INTRODUCTION

Communication satellites are man-made space vehicles that orbit Earth, providing a multitude of communication functions to a wide variety of consumers including military, government, private and commercial subscribers.

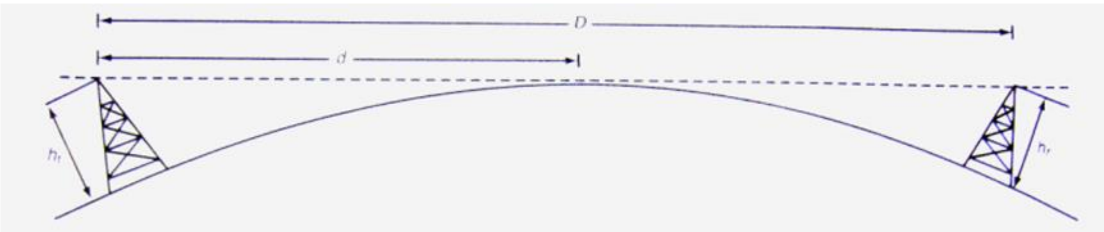
Communication satellite is like a microwave repeater in the sky that consists of receiver, transmitter, amplifier, filter, antenna, and other electronic communication circuits.

Satellite system consists of one or more satellite space vehicles, a ground base to monitor and control the operation of the system, and a user network of earth stations that provides the interface facilities for the transmission and reception of terrestrial communication traffic through the satellites.

5.1 HISTORICAL DEVELOPMENT

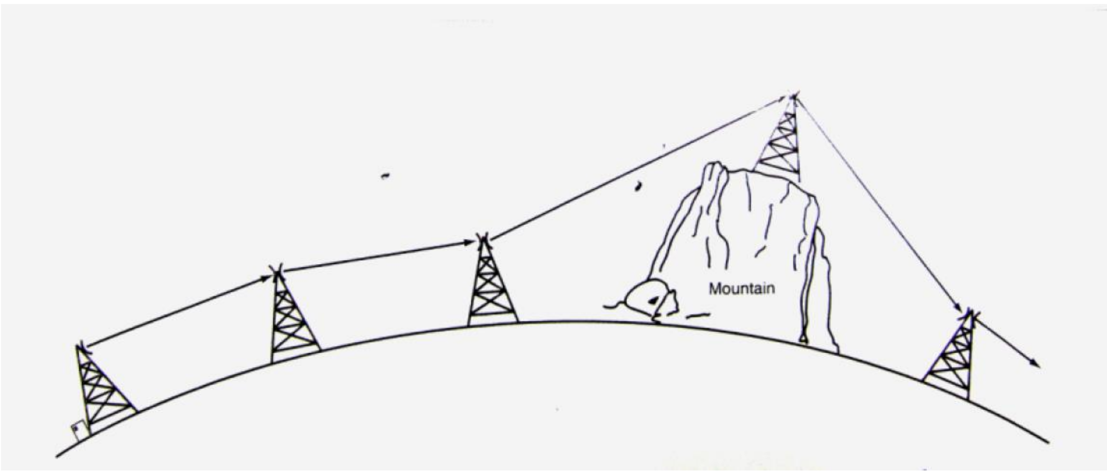
World demand for communications facilities carrying many different types of real-time and non-real-time signals such as voice, data and video has been growing very rapidly during the past few decades. The continuing increasing demand and resulting large amount of worldwide communication traffic naturally calls for communications links with very large transmission bandwidth.

Before the era of communication satellites, long distance transmission of information relied principally on microwave and sub-oceanic cable links. Microwave links provide large usable bandwidth and their performance is generally good. The major constraint is that the system operates on the principle of Line Of Sight (LOS) where the transmitting and receiving antennas must "see" one another. Line Of Sight (LOS) communication, the maximum distance (Dmax) for the transmitting and receiving antennas to "see" one another is about 80km.



To transmit signals beyond the horizon, repeater stations are required. The normal distance between repeaters is between 50km to 80km depending upon terrain. However having many repeaters means high operating and maintenance cost.

The normal distance between repeater stations is between 50km to 80km depending upon terrain



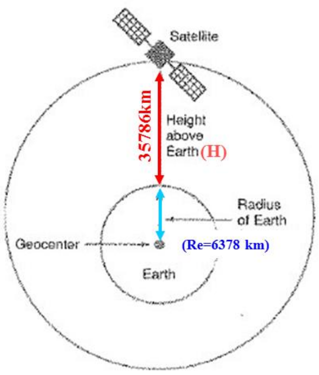
The biggest problem, however, is that global communication inevitably requires transmission over large expanses of sea and ocean. Microwave links are obviously unable to overcome this constraint.

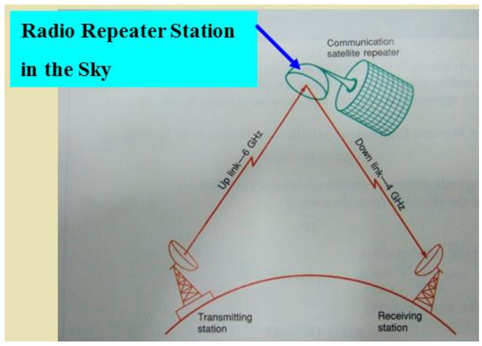
Sub-oceanic coaxial cables solved the problem to some extent. However, they had several limiting factors such as high cost, high signal attenuation (required many repeaters), and limited bandwidth. Most importantly the number of cables being laid in the oceans just could not keep up with the global demand for communication bandwidth.

In 1945 Arthur C Clarke suggested an answer to the problem in a famous article he wrote for Wireless World. He showed that a satellite with a circular orbit at a correct altitude of 35 786 km (known as a GEOSTATIONARY orbit) would make one revolution every 24 hours i.e. it would rotate at the same angular velocity as the Earth.

An observer looking at such a geostationary satellite would see it as always being fixed at the same point in the sky.

This satellite would be used as a radio repeater station in the sky.





Clarke also showed that **three** geostationary satellites, powered by solar energy, could provide world-wide communications for all possible types of services.

Figure 5.1 illustrates how three satellites can provide world-wide communications.

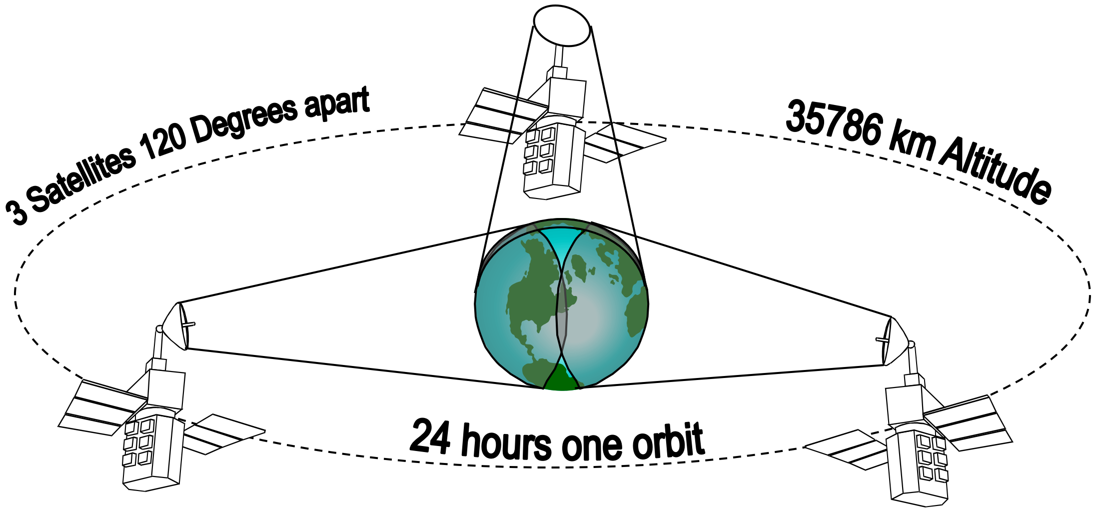


Figure 5.1 Three geostationary satellites providing worldwide coverage

Clarke's vision became reality 20 years later when International Telecommunications Satellite Organisation (INTELSAT), established in 1964, launched the Early Bird (INTELSAT 1) in April 1965. By the year 2000 hundreds of geostationary satellites will in geostationary orbit providing international telecommunications services.

In recent years sub-oceanic cables containing **fiber optics** with huge bandwidth have been competing with fixed satellite services. It looks as though these cables will gradually replace satellites in providing fixed services.

It is, however, most unlikely that fiber optics can replace satellites in providing broadcast services and of course impossible for optical fiber cables to provide mobile services.

5.2 COMMUNICATION SATELLITES

International telecommunications services (that is the transmission of voice, video and data around the world) are provided by satellite organisations.

5.2.1 INTERNATIONAL SATELLITE ORGANISATIONS

The majority of international satellite communications are provided by international organisations. These organisation allow groups of countries to share the costs and resources of satellite communications networks. In addition to international satellite organisations there are also regional satellite organisations that own and operate satellites.

INTELSAT

The first supplier of satellite communications services, formed in 1964, is now providing reliable, high quality international and domestic service to over 200 countries world-wide.

It has membership over 140 countries, uses a network of 20 geostationary satellites to provide communications services to the entire world.

INTELSAT Satellites
Since the Early Bird satellite (INTELSAT 1) was launched in 1965 there has been nine generations of INTELSAT satellites.

Each successive generation has had increased capacity which has led to a dramatic decrease in the cost per voice circuit. This increase in capacity has been achieved as a result of the increase in the power of the satellites, frequency reuse techniques and channel multiplication techniques.

INTELSAT Services
Telephony and Television channels - INTELSAT provides two-way telephone circuits and TV channels broadcasting services worldwide.

INMARSAT

The International Maritime Satellite Organisation, was founded in 1979 by a group of maritime nations to provide improved communication from ship to ship and from ship to shore.

There are 82 member countries having over 4000 ship terminals registered under their flags. INMARSAT is also developing aeronautical and land based mobile satellite communications systems.

INMARSAT Satellites
There are now three generations of Inmarsat mobile communications satellites, each one more powerful and versatile than the last. The latest is the Inmarsat-3 series.

INMARSAT Services
Telephony and Telegraphy - INMARSAT provides automatic calling from ship to shore and semiautomatic calling from shore to ship.

Telex - Fully automatic Telex is offered in both directions.

Data Transmission - Data transmission is available at speeds upto 56 kbps.

Distress (SOS) - SOS alerts are virtually instantaneous via a Rescue Co-ordination Centre using priority connections in the satellite.

Aeronautical / land communications - A full range of communications services will be offered to aircraft / truck, including telephony for passengers.

INMARSAT Earth Stations
Land based, called Coast Earth Stations(CES), owned by the individual countries telecommunications administration & have antennas of 10 to 15m diameter.

Ship/Aeronautical/Truck based, called Small Earth Stations (SES), have antenna of less than 1m in diameter.

INTERSPUTNIK

The International Organization of Space Communications was established in 1971 according to an intergovernmental Agreement of November 15, 1971. At that time INTERSPUTNIK had nine member countries.

At present, the INTERSPUTNIK membership includes 23 states.

In late 80’ INTERSPUTNIK started commercial operation of its global satellite system. INTERSPUTNIK has been leasing Gorizont- and Express-series communications satellites and Gals DBS from the Russian Federation.

At the end of 1997 the Organization used 31 transponders on seven geostationary satellites located in the orbital arc from 14W to 142.5E. INTERSPUTNIK provides a complete range of satellite services: TV, voice traffic, data, video conferencing, VSAT, etc.

EUTELSAT

It was created in 1977 and formally established in 1985. The initial membership of 17 countries now stands at 44.

EUTELSAT uses 11 satellites in orbit and a further six under construction, it is the largest satellite operator in Europe.

EUTELSAT satellites carry international and domestic public fixed and mobile telecommunications (telephony, telegraphy, telex, fax, data, videotext, TV and radio transmissions services).

The Organization can also offer specialised telecommunications services (radio-navigation services, broadcasting satellite services, space research services, meteorological services and remote-sensing of earth resources).

5.2.2 NATIONAL SATELLITE NETWORKS

Many countries use satellites to provide some or all of their national (domestic) telecommunications services. Some of these counties own and operate satellites while others lease transponder space on satellites belonging to neighbouring countries or international organisations.

AUSTRALIA

Australia, being a very large but sparsely populated country, uses satellites to provide economic countrywide telecommunications. It can reach isolated small communities.

AUSSAT is Australia's domestic satellite operating organisation. It provides a full range of services including:

- Low power direct broadcast for radio and television.
- Telephony, voice and data for mining and oil exploration.
- Computer and data services for businesses, etc.

SINGAPORE

Singapore's first satellite (ST-1) was launched in 1998 from French Guiana Space Centre at a total cost of S$398 million.

The satellite was built by French company (Matra MarconiSpace) and the launcher was made by European rocket maker (Arian space).

The 3,200 kg satellite is owned jointly by Singapore Telecom and Chunghwa Telecom International of Taiwan. It provides telecommunications and broadcasting services over South East Asia and India.

The ST-1 satellite specifications are as follows :

- Weight : 3200 kg
- Dimension (H x L x W) : 5m x 1.7m x 2.5m
- Solar panel fully extended length : 32.3m
- Lifespan : 12 years minimum
- Location : 88^0 E Longitude
- Transponder : 30 Ku band & 14 C band

Further to the successful commercial operation of SingTel's ST-1 satellite since year 1998, SingTel had since launched another brand new satellite named ST-2 in 2012.

The ST-2 satellite specifications are as follows:

Customer	ST-2 Satellite Ventures Private Limited
Prime contractor	Mitsubishi Electric Corporation
Mission	Telecommunications
Mass	Total mass at lift-off 5078.8 kg Dry mass 1986.3 kg
Stabilization	3-axis stabilized
Dimensions	2.9 x 3.2 x 6.6 m
Span in orbit	31.6 m
Platform	MELCO DS2000
Payload	Ku-band and C-band transponders
On-board power	11816 W (end of life)
Life time	15 years minimum
Orbital position	88° East
Coverage area	Central Asia, South-East Asia, India sub-continent Middle East and Mediterranean Sea.

ST-2 provides high quality C-band and Ku-band satellite transponders to support product offerings such as Transponder Lease, Maritime VSAT, VSAT, Satellite IP and Broadcasting.

SINGAPORE SATELLITE EARTH STATIONS

Sentosa satellite earth station: (1st earth station in Singapore, established in 1970)

- Inmarsat (Inmarsat C)
- Iridium Support
- BGAN Support
- I-SAT Phone Support

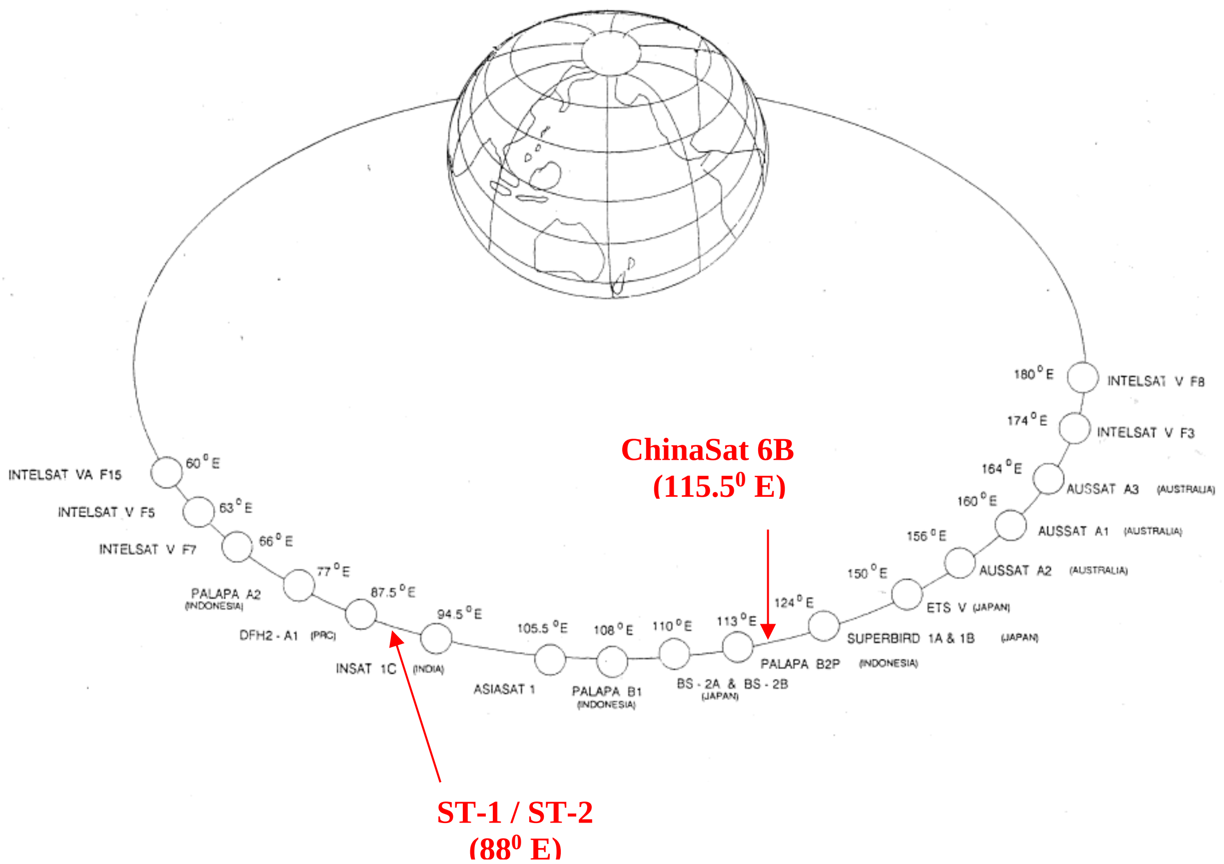
Bukit Timah satellite earth station (1985)

- Broadcast
- Playout and IPTV Iridium Support
- MVSAT
- Hub services

Seletar satellite earth station (1993)

- Mainly for control & monitoring of ST-1 / ST-2 satellites
- Inmarsat (Inmarsat C)
- User housing services

5.2.3 SATELLITES OVER ASIA



5.3 SATELLITE ORBITS

Satellites orbits can be generally classified as **circular** or **elliptical** orbits as shown in Fig 5.2.

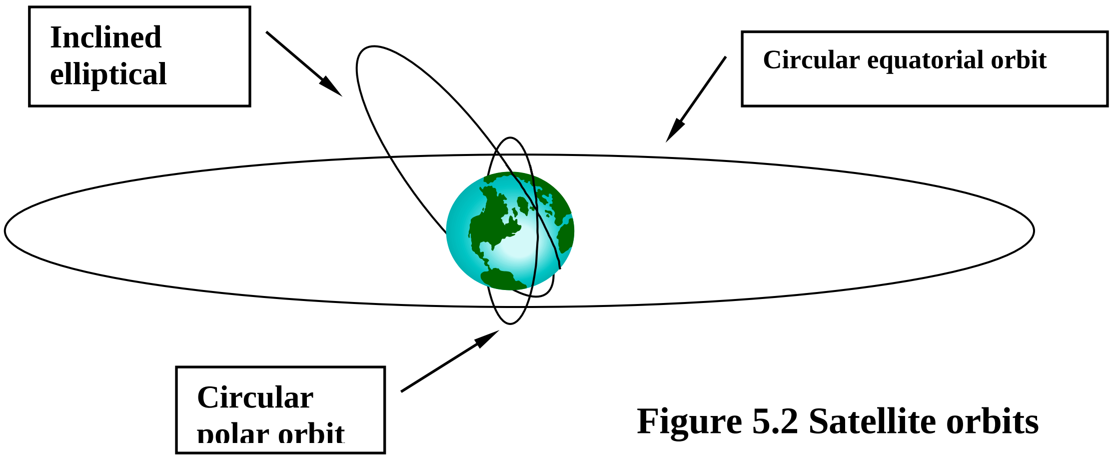


Figure 5.2 Satellite orbits

The satellites in satellite communication systems are classified based on their altitudes:

- Orbital satellites – LEO (Low Earth Orbit) & MEO (Medium Earth Orbit) satellites.
- Geostationary satellite – GEO (Geostationary Earth Orbit) satellite.

5.3.1 ORBITAL SATELLITES

Orbital satellites are satellites with circular or elliptical trajectory launched at low or medium altitude and making several revolutions per day around the Earth.

Satellites in Low Earth Orbit (LEO) orbit close to the Earth (160 to 500 km in height) travel at faster speed, approximately 28000 km per hour. At this speed, it takes approximately one and a half hours to rotate around the entire Earth. Consequently, the time that the satellite is in LOS (Line Of Sight) of a particular earth station is only fifteen minutes or less per orbit.

Satellites in Medium Earth Orbit (MEO) orbit at a medium altitude (10,000 to 20,000 km in height) have a rotation period of five to twelve hours and remain in LOS of a particular Earth station for two to four hours per orbit.

DISADVANTAGES

- Rotate around the Earth in a low altitude elliptical or circular pattern with an angular velocity greater than that of the Earth, hence do not remain stationary to any particular point on Earth. They can only be used when available, and several such satellites are needed to establish communications links.

- Need for complicated and expensive tracking equipment at the earth stations. Each earth station must locate the satellite as it comes into view and then lock its antenna onto the satellite and track it as it passes overhead.

ADVANTAGE

Propulsion rockets are not required on board the satellites to keep them in accurate orbits.

5.3.2 GEOSTATIONARY SATELLITES

High altitude satellites (35,786km in height) launched on a circular orbit (Geostationary Earth Orbit – GEO) travel at approximately 11,000 km/hour and have a period of 24 hours (23 hours 56 minutes 4.09 seconds to be precise), exactly the same as that of the Earth. These satellites also orbit above the equator in the same direction as the Earth's rotation.

For a terrestrial observer, a geostationary satellite is, therefore, **immobile** in the sky. A geostationary satellite permits coverage of a zone equal to about 40 % of the Earth's surface and its immobility in the sky makes it possible for the earth station antennas to point in a fixed direction.

A single geostationary satellite is able to link-up earth stations up to 17000 km apart. Global coverage of the Earth, **excluding Polar Regions**, can be achieved with 3 geostationary satellites.

<u>ADVANTAGES</u>

- Since geostationary satellites remain in a fixed position in respect to a given point on Earth, available to all earth stations, within their footprint, 100% of the time.
- (The footprint of a satellite covers all earth stations that have a line of sight - LOS path to it and lie within the radiation pattern of the satellites antennas).
- As satellite remains stationary with respect to a given earth station, expensive tracking equipment is not required at the earth stations.
- There is no need to switch from one satellite to another as they orbit overhead. Consequently, there are no breaks in transmission.
- High-altitude geostationary satellites can cover a much larger area of the earth than their low altitude counterparts.
- The effects of Doppler shift are negligible.

<u>DISADVANTAGES</u>

- Require sophisticated propulsion devices on board to keep them in a fixed orbit.
- Higher altitudes of geostationary satellites introduce much longer propagation delay times. Round trip propagation delay between two earth stations through a geostationary satellite is 500 to 600 ms.
- Require higher transmit powers and more sensitive receivers because of the longer distances and greater path losses. The earth stations also require high power transmitters, large directional antennas and highly sensitive low-noise receivers.
- High-precision spacemanship is required to place a geostationary satellite into orbit and keep it there. Also, propulsion engines are required on board the satellites to keep them in the correct orbit.
- Polar regions of the Earth’s surface are not covered by geostationary satellites.

5.4 VELOCITY OF A SATELLITE IN GEOSTATIONARY ORBIT

A satellite in orbit comes under the influence of two forces, the centrifugal force Fc and the gravitational force Fg as shown in figure 5.3.

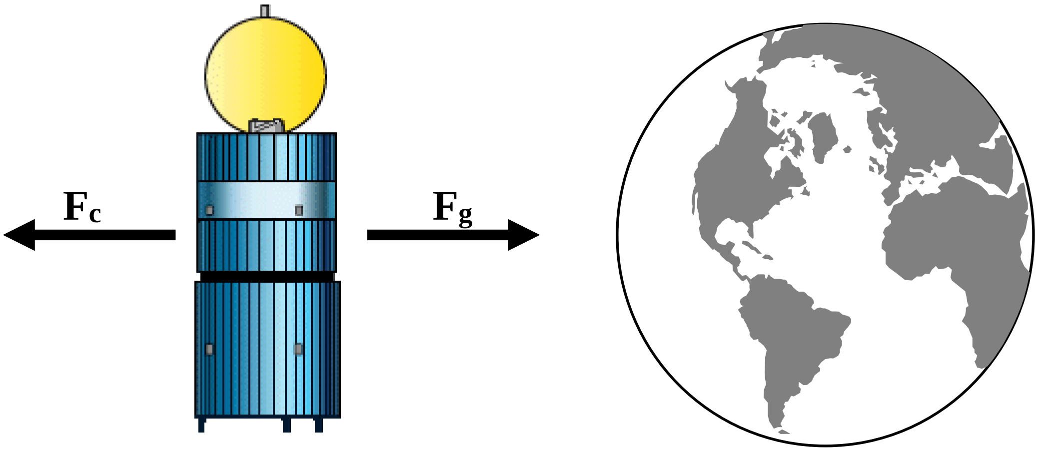


Figure 5.3 Forces acting on a geostationary satellite.

Once launched, a satellite remains in orbit because the centrifugal force caused by its rotation around the earth is counterbalanced by the Earth's gravitational pull.

The closer to the Earth the satellite rotates the greater the gravitational pull and the greater the velocity required to keep it from being pulled to Earth.

The centrifugal force is:

$$F_c = m_s \frac{v^2}{r}$$

where: m_s= the satellite's mass in kg
v = the velocity of the satellite in m/s
r = orbit radius (from Earth's centre) in m

The gravitational force is:

$$F_g = \frac{Gm_e m_s}{r^2}$$

where: G = gravitational constant = $6.673 \times 10^{-11} Nm^2kg^{-2}$
m_e= mass of Earth = 5.975×10^{24}kg

For the satellite to stay in a circular orbit of radius r (from centre of Earth), the two forces must be equal, i.e.

$$\frac{m_s v^2}{r} = \frac{Gm_e m_s}{r^2}$$

or

$$v = \sqrt{\frac{Gm_e}{r}}$$

<u>EXAMPLE 1</u> (Solution is available in the BB teaching slides)
A small communication satellite having mass 100 kg is in circular orbit at an altitude of 10,355 km. If the Earth has a radius of 6378 km and mass of 5.975×10^{24} Kg , the gravitational constant $G = 6.673 \times 10^{-11}$ $Nm^2 Kg^{-2}$

(a) Identify the type of satellite in use.

(b) Find the velocity of the satellite and its period of rotation.

(c) How many times can a ground earth satellite station receive its transmission per day?

TUTORIAL 5

1. Define the term “geostationary satellite”.
   State the FOUR conditions for a satellite to become a geostationary satellite.

2. Explain how THREE satellites can be used to provide worldwide communications.

3. Name 3 main international satellite organisations and 3 national satellite organisations.
   Which satellite organisation is responsible for the mobile satellite communications?

4. It is impossible for long distance / sub-oceanic fiber optics cables to replace satellite communication services completely. Give TWO reasons to support the statement.

5. The altitude of GPS satellite is 20,200 km. Find its period of rotation in hours

TUTORIAL GUIDE 5

1) Read section 5.3 for the definition. Study section 5.1 and extract
   the criteria that define geostationary

2) The answer may be found at section 5.1.

3) The answer may be found at section 5.2 – 5.2.2.

4) The answer may be found at page 77.

5) 11.98 hrs.

CHAPTER 6

SATELLITE EARTH STATION SUBSYSTEMS & MULTIPLE ACCESS TECHNIQUES

CHAPTER OBJECTIVES:

- Understand the subsystems of a typical communication satellite / Earth Station
- Understand the various multiple access techniques used in satellite communications.

Learning outcomes

At the end of the chapter, the students will be able to:

- ☑ Six on board subsystems on the Geostationary Communications Satellite.
- ☑ Five major subsystems in an Earth Satellite station.
- ☑ Frequency Division Multiple Access (FDMA)
- ☑ Time Division Multiple Access (TDMA)

CHAPTER 6 Satellite / Earth Station Subsystems & Multiple Access Techniques

COMMUNICATION SATELLITE SUBSYSTEMS

Geostationary communications satellites require six on board subsystems as shown in figure 6.1.

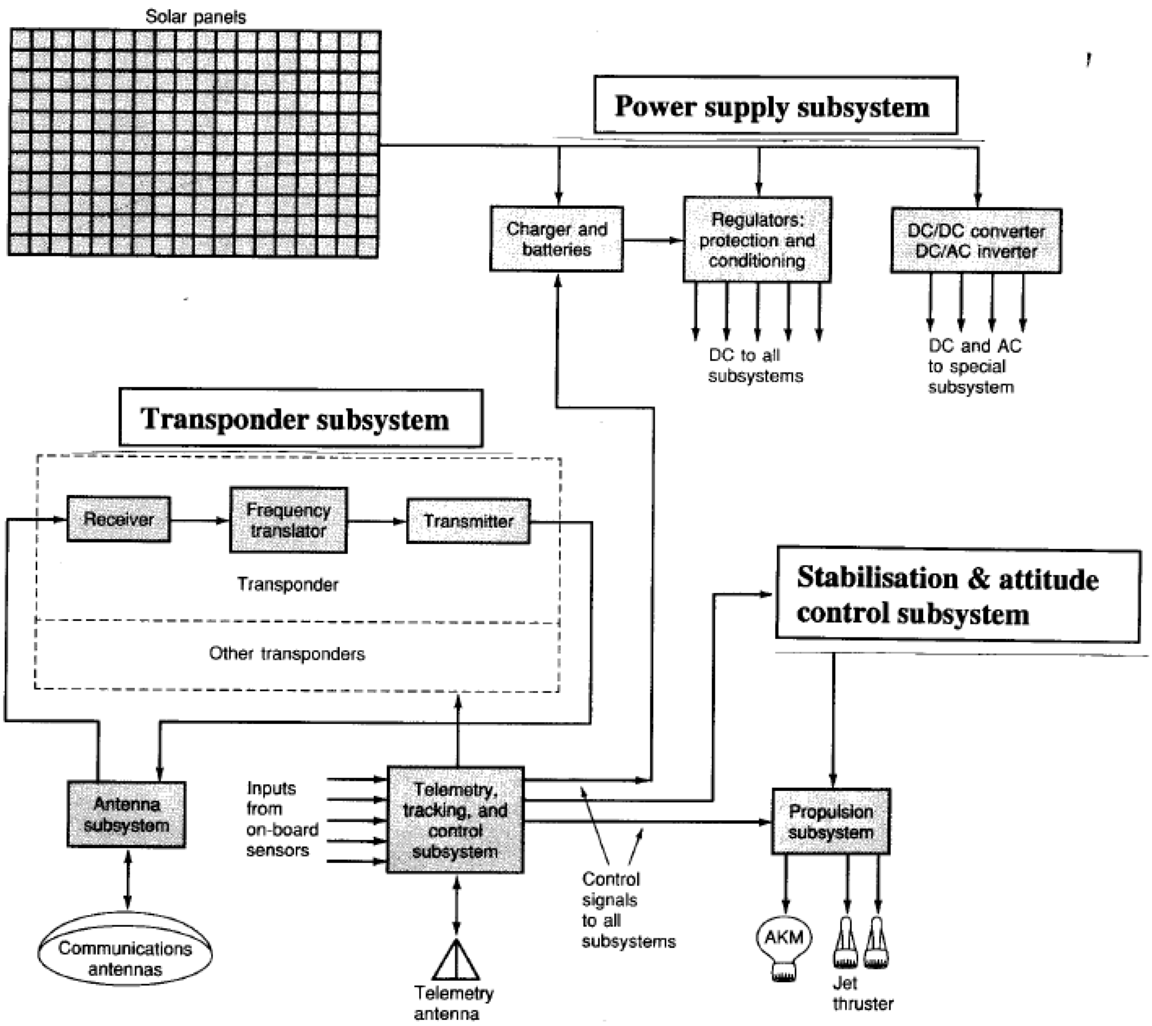


Figure 6.1 General block diagram of a communication satellite

The six subsystems are:

- Antenna subsystem.
- Transponder subsystem.
- Power supply subsystem
- Stabilisation and attitude control subsystem
- Command telemetry and control subsystem.
- Propulsion subsystem.

We will only discuss the first three subsystems in detail in the next sections.

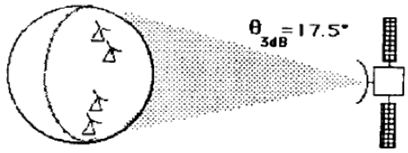
6.1 ANTENNA SUBSYSTEM

Most communications satellites contain several antennas.
The purpose of these antennas is: -

- To receive signals from transmitting Earth stations.
- To transmit signals to receiving Earth stations.

Numerous antennas are generally required because of various satellite requirements. For examples, one antenna may be used for communication relay purposes, while another antenna is dedicated to the telemetry, tracking and control functions.

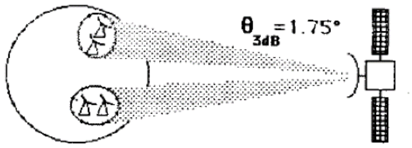
Omnidirectional antennas have wide beams (e.g. 17.5^0 beam width) for earth coverage,



Highly directional gain antennas with narrow beams (e.g. 1.75^0 beam width) for densely populated regions.

Figure 6.2 Coverage by Omnidirectional & Multiple narrow-beam antennas

Figure 6.2 shows the antenna coverage by omnidirectional and multiple narrow-beam antennas.



Satellites with multiple narrow-beam antennas give higher EIRP (Effective Isotropic Radiated Power). Also, different beams of the same frequency can be directed to different geographical areas.

This is called frequency reuse and can greatly increase the information carrying capacity of the satellite.

6.1.1 FREQUENCY REUSE

It is a technique that allows two sets of transponders to operate on the same frequency, thus doubling channel capacity. The two transponder systems, while operating on exactly the same frequencies, are isolated from one another by the use of special antenna techniques.

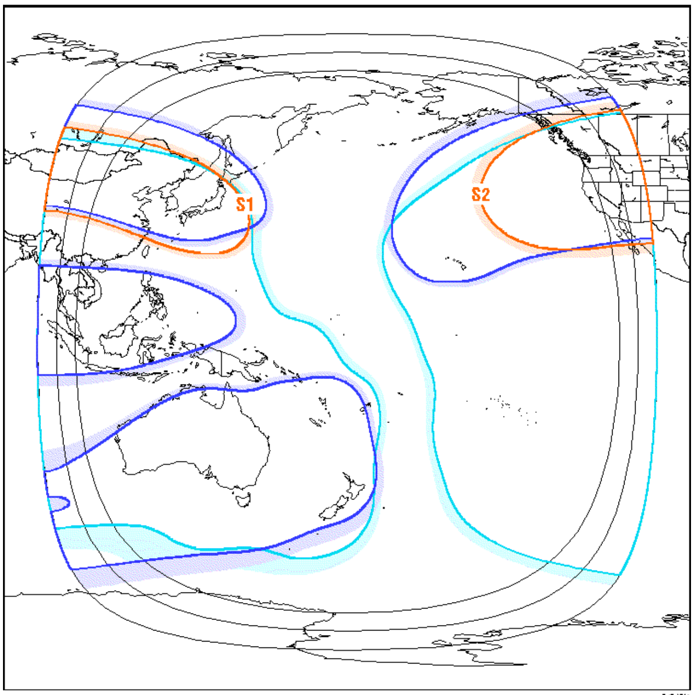
Two methods are employed in satellite transponders when using frequency reuse technique:

- Use antennas of different polarization to prevent interference between two transponder systems using same frequency. Antennas with either vertical / horizontal polarization or right-hand / left-hand circular polarization are used.

- Use highly directional spot-beam antennas to focus the downlink signal to specific areas of the Earth. By using such antennas on the spacecraft, the signals can be confined to a particular area. In this way, different earth stations can use the same frequencies. They do not interfere with one another because of the highly directional antennas.

6.1.2 SHAPED AND CONTOURED BEAMS ANTENNAS

IS-802 at 174°E



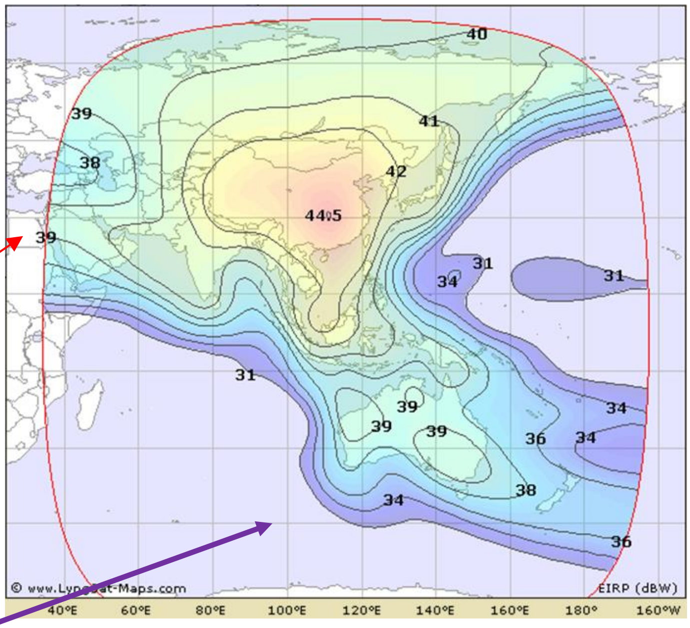
	Beam Peak	Extended 2 dB Contour
Hemi	40.2	34.5 - 32.5 dBW
Zone	42.8	34.5 - 32.5 dBW
Ku-Spot: 1	52.6	44.0 - 42.0 dBW
2	51.6	44.0 - 42.0 dBW

For satellite communications, the use of antennas producing circular or elliptical beams is often inefficient.
Because power will be wasted on areas of the ocean where there are no people living.

Figure on the left shows a shaped beam coverage map for an INTELSAT VIII spacecraft.

For this reason many satellites have antennas producing shaped and contoured beams that will direct most of the available power over the desired areas.

CHINASAT 6B BEAM COVERAGE



RED enclosure shows
Conventional coverage
(40% - Geostationary satellite)

Shaded area shows
Shaped & contoured beam coverage
(Directed to smaller area with higher EIRP)

Figure 8.3
Shaped and contoured

6.2 TRANSPONDER SUBSYSTEM

The transponder is the electronic equipment that takes in the incoming received signal and performs the necessary processing on the signal and then sends it out to the transmit antenna in a form suitable for retransmission. To do this the transponder has to perform several functions.

6.2.1 TRANSPONER FUNCTIONS

The transponder receives the incoming signal, from the transmitting earth station, amplifies it, changes its frequency and amplifies it again before retransmission to the receiving earth stations. Transponders may also perform other functions such as on board processing and switching of the signal. A typical up-link frequency plan is shown in figure 6.3

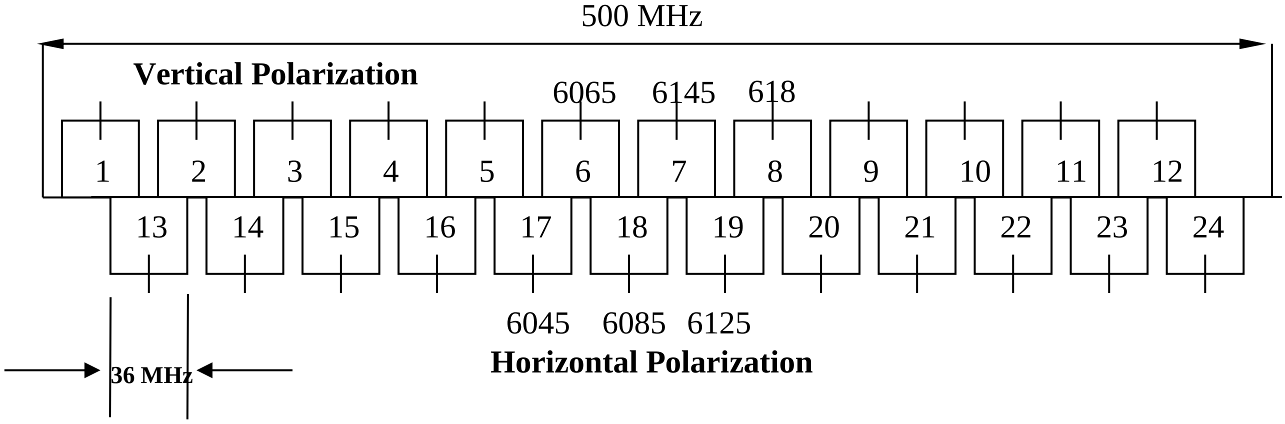


Figure 6.3 Typical uplink frequency & polarization plan for C-band Transponder System.

<u>AMPLIFICATION</u>

The satellite power gain is due to the gain of the receiving and transmitting antenna on the satellite and the Gain of the Transponder. It is found in practice that transponders need to provide a gain of 110 to 130dB.

<u>FREQUENCY TRANSLATION</u>

A satellite transponder has to change the frequency of the incoming up-link signal to a lower frequency for retransmission on the down link. This is necessary, if transponder simply amplified and retransmitted the same signal, part of the powerful output signal would leak back to the input of the transponder causing it to oscillate.

With the frequency changed, any leakage signal from the transponder output, arriving back at the transponder input, can be filtered out before it reaches the amplifier.

<u>ON BOARD PROCESSING</u>

In future, satellites will not be used simply as repeaters in the sky. They will be required to perform on board processing of the signal before it is retransmitted.

For example the signal may be demodulated to baseband and switched in a time and space just like a modern digital telephone exchange on the Earth.
With digital transmission, error correction could be carried out before the signal is retransmitted from the satellite.

On board processing will help improve the efficiency of communications satellites.

SWITCHING

Some satellites with multi beam operation need the signal arriving on the uplink side of a transponder to be switched to a different transponder for the down link.
This switching can be done in the transponder system.

6.2.2 TRANSPONDER BLOCK DIAGRAM

In order to explain how the various parts of the transponder are used to achieve the required result consider the transponder block diagram in figure 6.4

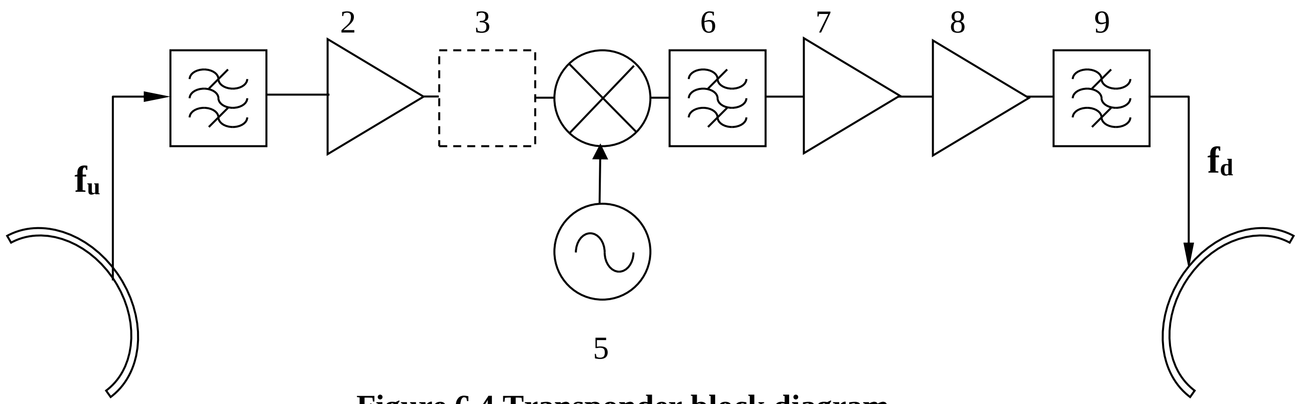


Figure 6.4 Transponder block diagram

The transponder is conveniently split into nine blocks. These blocks are: -

1. Input filter
2. Low noise amplifier
3. Demultiplexer*
4. Mixer
5. Local oscillator
6. Post mixer filter
7. Channel amplifier
8. Power amplifier
9. Output filter (output multiplexer)*

* Multiplexers and demultiplexer are only required in multichannel transponders.

INPUT FILTER

It is used in the transponder to band limit input noise and to prevent lower frequency transponder output signal, fd, from getting back in at the input and causing oscillation. On most communications satellites, the input filter is a microwave cavity constructed from plated aluminium or invar.

LOW NOISE AMPLIFIER (LNA)

It is important that the first amplifier in the transponder should have a very low noise figure so that the weak input signal is not swamped by noise.

Transponder needs an overall gain of approximately 120 dB.

This is a very large amount of gain for one stage of amplification and may be difficult to obtain at the higher uplink frequencies.

For this reason the low noise amplifier is designed to give a gain of about 40 dB. After this any further amplification will not significantly affect the overall noise performance of the transponder and will be easier to achieve at the lower down link frequency.

DEMULITPLEXER

In multichannel transponders it may be acceptable for a number of carriers to share the input filter and the low noise amplifier.

However, as the power of the signal increases intermodulation distortion will become too large. To efficiently use the equipment a bank of filters (known as a demultiplexer) is used after the low noise amplifier. This multiplexer will split the carriers after low noise amplifier, into single carriers for frequency conversion and power amplification.

LOCAL OSCILLATOR

The local oscillator generates a frequency, fo, which is used in the frequency translation process. Frequency translation is necessary to prevent the transponder from oscillation.

MIXER

The mixer is used to mix the incoming signal with the local oscillator frequency. This produces a signal with the incoming frequency plus the local oscillator frequency and the incoming frequency minus the local oscillator frequency i.e. f_u+f_o and f_u-f_o.

POST MIXER FILTER

It is usual for communications satellite to down link information at a lower frequency than it was up linked. Hence, the difference frequency output from the mixer is the one chosen for transmission i.e. $f_{in}-f_o$.

The job of the post mixer filter is to remove the $f_{in}+f_o$ frequencies. Because loss of signal power is not so critical after the first low noise amplifier the post mixer filter can also be used to provide some group delay equalisation.

CHANNEL AMPLIFIER

The signal will still require and amplification of about 80dB at this point in the transponder. As this is such a large power gain the amplification is usually split between two output amplifiers.

The first of these output amplifiers is the channel amplifier. The channel amplifier will have a gain of about 40dB and as its efficiency is not critical it can also be used to provide gain control. The channel amplifier will usually be made in the same technology as the low noise amplifier, however, high gain is more important than low noise at this stage in the transponder.

HIGH POWER AMPLIFIER

The high power amplifier provides the last 40dB of gain. It is vitally important that the high power amplifier does this as efficiently as possible so as not to waste the limited power available for the satellites.

Unfortunately high power amplifiers will be most efficient near saturation where their linearity is poor. This non-linear amplification will inevitably lead to spectral spreading of the signal.

OUTPUT FILTER (MULTIPLEXER)

For a multi-channel transponder, the output filter will be replaced by a bank of filters called the output multiplexer. As loss must be kept to a minimum after the high power amplifier, the output filter must be designed to give as low a loss as possible and in the case of a multiplexer the signal must be combined in a waveguide manifold.

6.3 POWER SUPPLY SUBSYSTEM

Everything on board operates electrically or has electrical components in it. The primary power supply for all communications satellites is provided by solar cell arrays.

A secondary power supply, made up of Nickel-cadmium (NiCd) or Nickel-hydrogen (NiH) batteries, is also provided in the power supply subsystem as backup power source for solar cell arrays.

The solar cell panels generate a direct current (DC) which is used to operate the various components of the satellite.

The basic DC voltage from the solar cell panels is then conditioned in various ways :

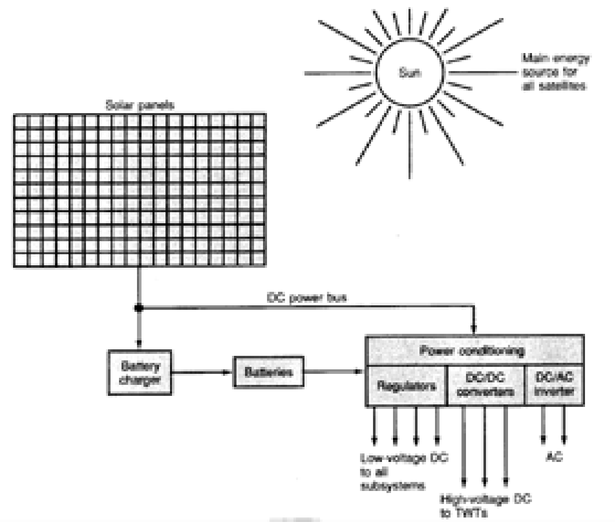


Fig 6.5 Block diagram of the Power Supply Subsystem

- By regulators to provide low voltage DC to all subsystems.
- By special DC-to DC converters to translate low DC voltage to the higher DC voltages required by the TWTs.
- By special DC-to-AC inverters to provide high AC voltages.

At times, when the satellite goes into an eclipse or when the solar cell panels are not properly positioned to the sun, the batteries take over temporarily and keep the satellite operating.

6.3.1 SOLAR CELLS

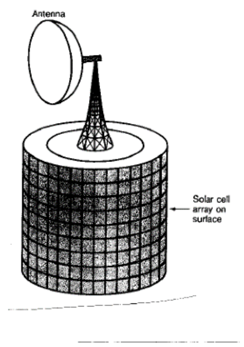
The solar cell panels are large arrays of photocells connected in various series and parallel circuits to create a powerful source of DC voltage.

Two basic satellite configurations as shown in earlier Figure 6.6 a & b, spin and three-axis stabilized satellite, use different arrangement of solar cells on the satellite body.

In a spin stabilised satellite, the body is cylindrical and the solar cells are mounted around the body as shown in Figure 6.6a.

In a three axis stabilised satellite, the solar cells are mounted on wing like structures.

They stand out from the body of the satellite as shown in Figure 6.6b.



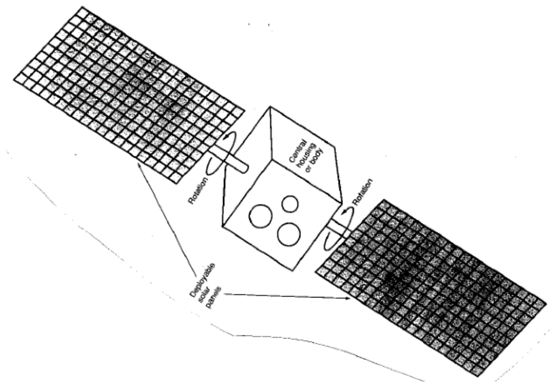


Figure 6.6a Spin stabilised b) Three axis stabilised satellite

6.3.2 ECLIPSE

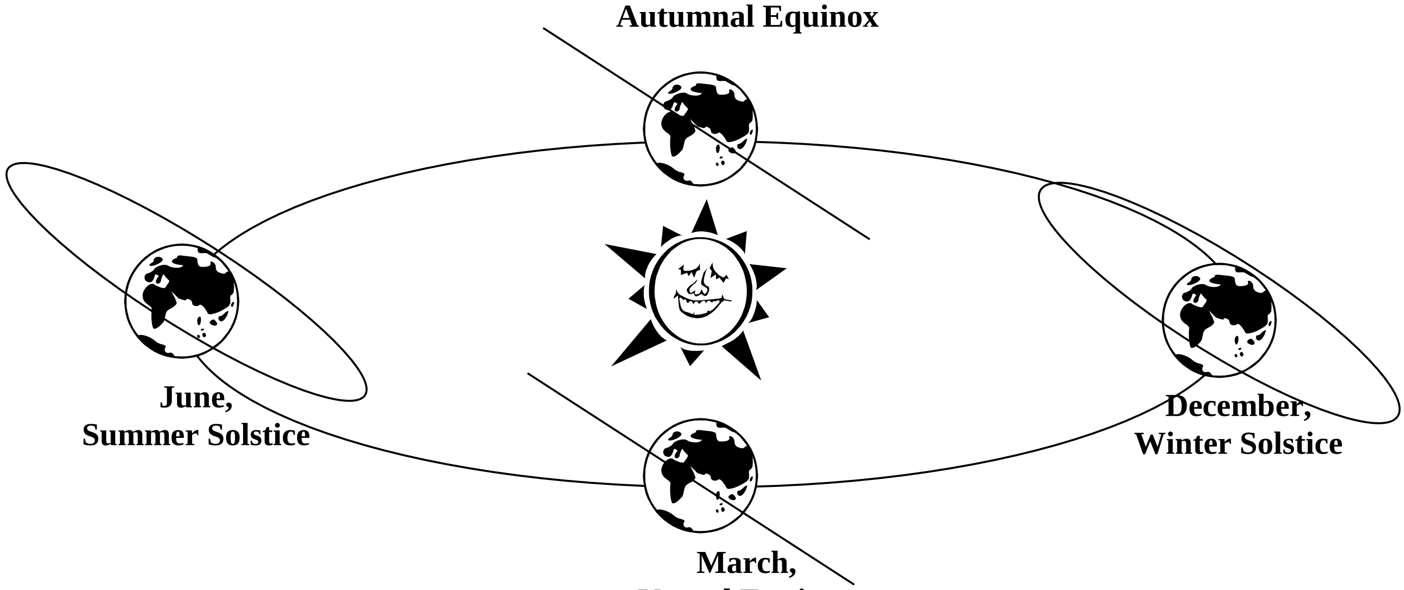
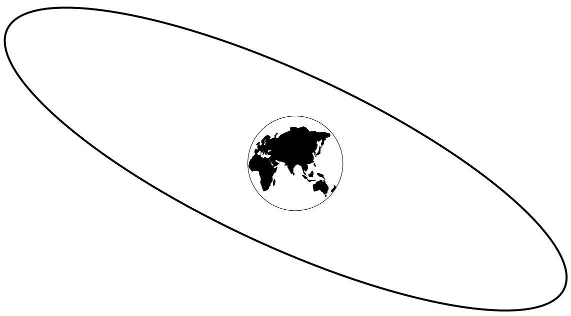


Figure 6.7 Attitude of Earth on its yearly orbit around the Sun

To see why the satellite is eclipsed, consider what the earth looks like from the Sun :

The two diagrams below illustrate this for Summer solstice and Autumnal equinox. You can produce your own diagrams for the Winter Solstice and the Vernal equinox..



June the Summer Solstice.
The satellite is illuminated by the Suns rays regardless of where it is in orbit. Batteries are not needed because 24 hours of sunlight.

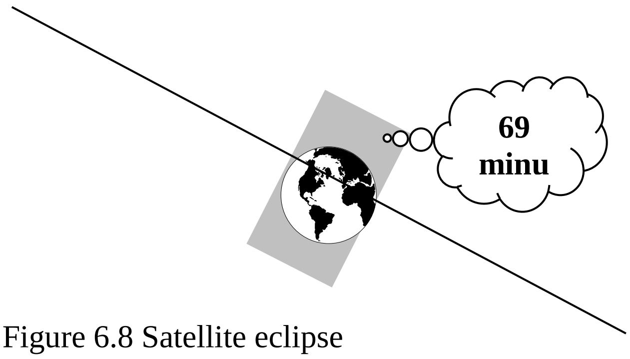


Figure 6.8 Satellite eclipse

September the Autumnal Equinox
The satellite goes behind the Earth for a maximum of 69 minutes. During this time the satellite is said to be eclipsed and batteries are needed.

6.4 STABILISATION & ATTITUDE CONTROL SUBSYTEM

The two functions of this system are:

- To keep the satellite stable in the sky.
- To keep its antennas/solar cell panels pointing in the correct direction i.e. towards earth/sun.

6.4.1 REFERENCE AXIS

The attitude (position) of a satellite in geostationary orbit is measured with respect to the pitch, roll and yaw axis as shown in figure 6.9.

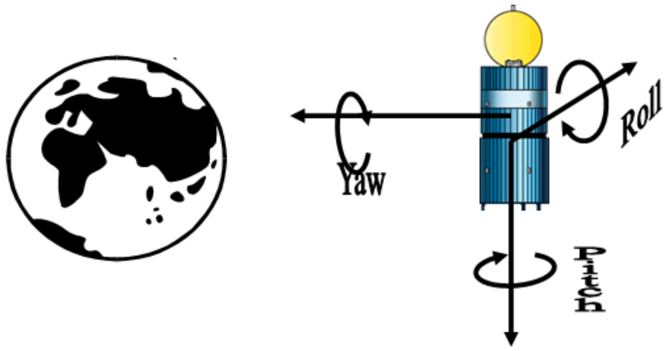


Figure 6.9 Pitch, Roll and Yaw axis co-ordinates.

6.4.2 STABILISATION

Spin stabilised satellites are kept in a stable position by gyroscopic stiffness which is achieved by spinning the body of the satellite.

The antennas and some or all of the electronic systems must be despun to keep the antennas pointing at Earth's surface.

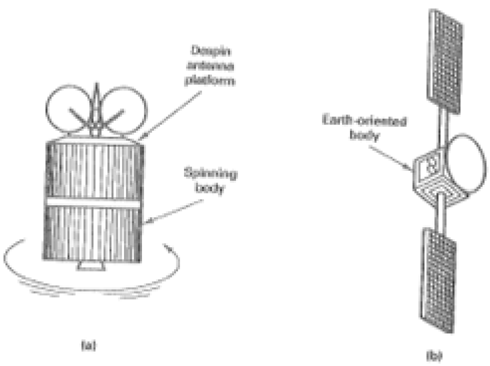


Figure 6.10 Spin & Three axis stabilized satellite

Three axis stabilised satellites are kept in a stable position by one or more momentum wheels or three reaction wheels inside the satellite body. This allows for the use of fully illuminated solar cell arrays fixed to the side of satellite body.

6.4.3 ATTITUDE CONTROL

The attitude control system requires sensors to measure the satellites attitude (orientation), attitude actuators (momentum & reaction wheels) and thrusters to correct the attitude of the satellite. In addition it must interface with the satellites telemetry system.

6.5 PROPULSION SUBYSTEM

It consists of the apogee kick motor (AKM) that puts the satellite into final orbit, one or more liquid or solid propellant rockets / jet thrusters that could be used for positioning and control the attitude of a satellite or remove the satellite from orbit. It is also operated by the on-board computer in response to the command and control subsystem.

6.6 TELEMETRY< TRACKING & COMMAND SUBSYSTEM

The purpose of the telemetry, tracking and command (TT&C) subsystem is to monitor the condition of the satellites various system, track the satellites position and to send commands to the satellite.

For instance the command system may send a command to the satellite to switch to a redundant TWT amplifier if the telemetry system has detected that a TWT amplifier is about to fail. Orbital adjustment manoeuvres are also carried out in response to commands from the earth station

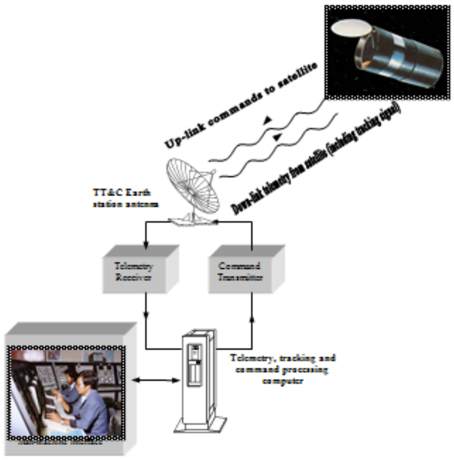


Figure 6.11 Block diagram of a TT&C system

<u>SATELLITE EARTH STATION SUBSYSTEMS</u>

The earth station or ground station is the terrestrial base of satellite communication system. The earth station communicates with the satellites to carry out the designated mission.

Like the satellite, the earth station is made up of a number of different subsystems.
The subsystems generally correspond to those on board the satellite.

However, most of the subsystems are larger and much more complex.

An earth station consists of 5 major subsystems:

- Antenna subsystem.
- Receive subsystem.
- Transmit subsystem.
- Ground Communications Equipment (GCE) subsystem.
- Power supply subsystem.

Note that the telemetry, control and tracking subsystem only exists in the control earth station.

A general block diagram of an earth station is shown in figure 6.12.

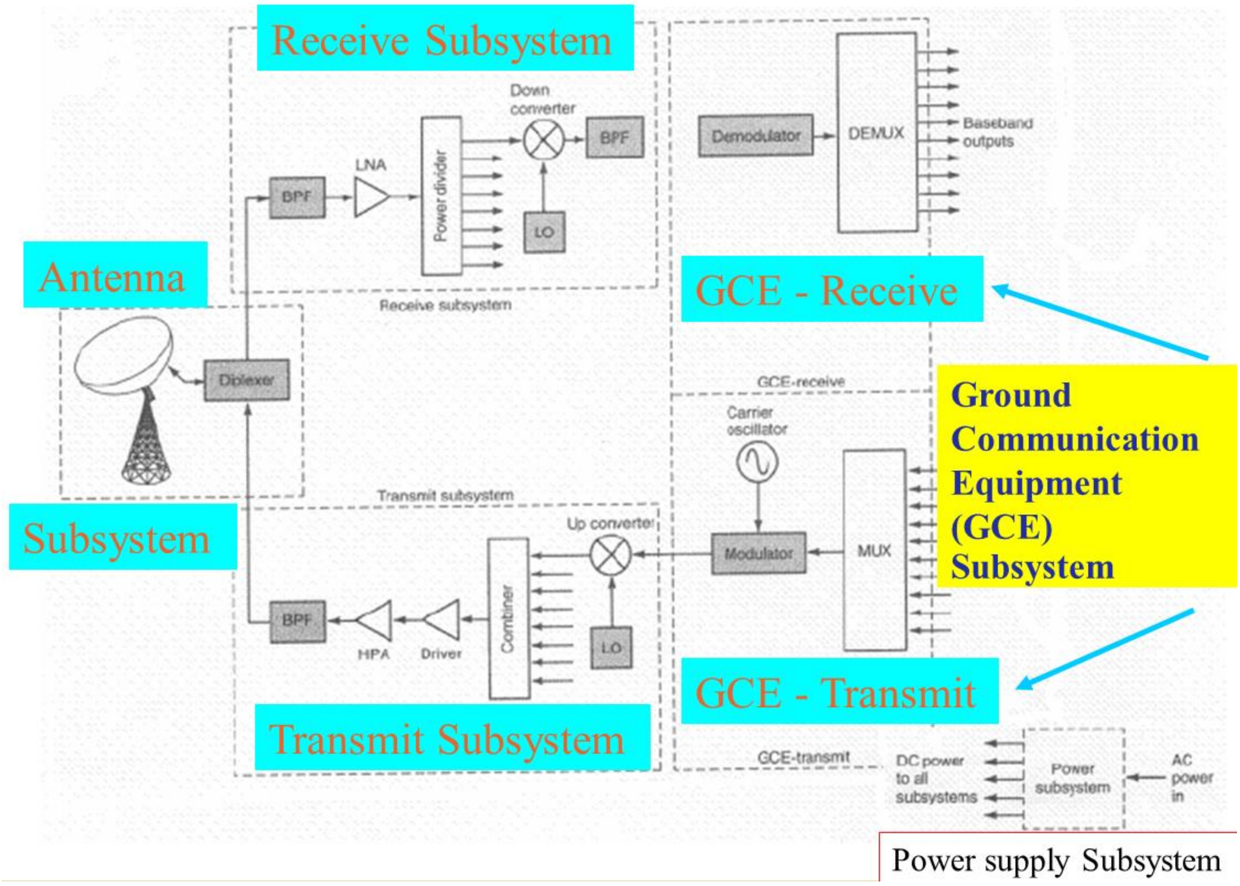
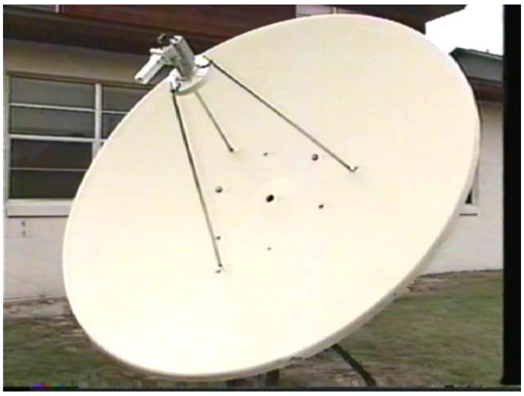


Figure 6.12 General block diagram of an earth station

6.7 ANTENNA SUBSYSTEM

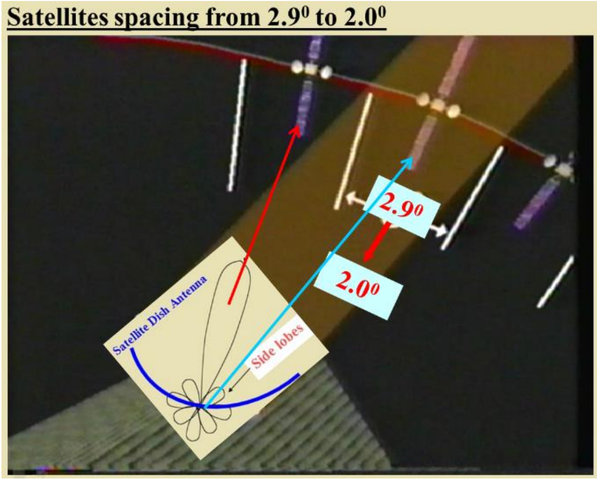
The antenna subsystem consists of the parabolic reflector, feed horn, tracking system and the related mounts. All earth stations have a relatively large parabolic dish antenna that is used for sending and receiving signals to and from the satellites. Typically the same antenna is used for both transmitting and receiving.




Parabolic reflector ranges in size from 30 m, for an INTELSAT standard A antenna, down to > l m for a Television Receive Only system (TVRO). The choice of antenna size will depend on its application.

6.7.1 ANTENNA PERFORMANCE PARAMETERS

Earth station antennas accessing satellites are controlled by international organisation, such as INTELSAT, have to meet strict performance criterion. For the satellite system to work properly, transmissions from Earth stations cannot be allowed to interfere with satellites adjacent to the satellite for which the transmission is intended.



The minimum spacing between geostationary satellites originally set, by international agreement, at 2.9^0.

Due to the increased demand on the geostationary space segment, the minimum spacing has now been reduced to 2.0^0.

As a result of the spacing between geostationary satellites, sidelobe radiation pattern become one of the most important performance characteristics of an earth station.

The three important performance characteristics for antenna are:
- Side lobe radiation pattern
- Figure of merit (G/T)
- Cross Polar Interference (XPI)

<u>ANTENNA SIDELOBE RADIATION PATTERN</u>

The maximum permitted sidelobe pattern for the antenna in transmitting mode is given by the equation:

$$S(\theta) = 32 - 251og_{10}(\theta) \quad \text{dBi} \qquad \text{for } 2.9^0 \text{ spacing}$$
$$S(\theta) = 29 - 251og_{10}(\theta) \quad \text{dBi} \qquad \text{for } 2.0^0 \text{ spacing}$$

Where $S(\theta)$ = The maximum permitted amplitude of sidelobes.
θ = The angle from the boresight in degrees.

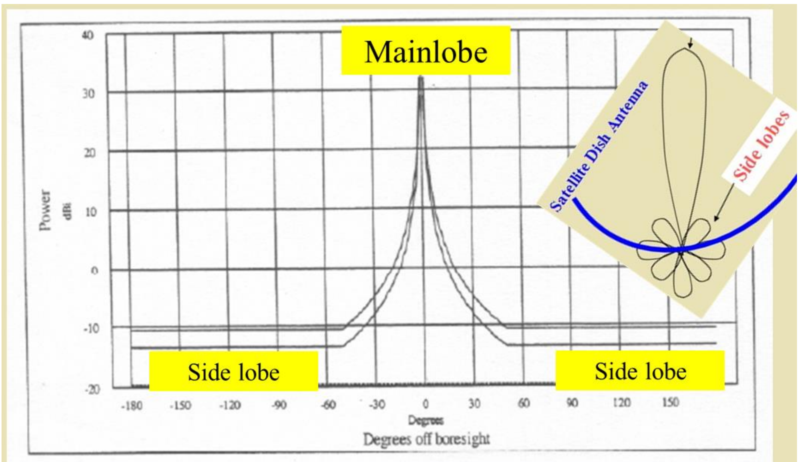


Figure 6.13 Graph of maximum sidelobe amplitude for S(θ)=32-251og(θ) and S(θ)=29-251og(θ)

Figure 6.13 shows the maximum limits of the two sidelobe patterns (for 2.0^0 & 2.9^0 spacing). These limits on the sidelobe radiation pattern are not easy to obtain, even for large antennas.

For large antennas with a diameter of 400λ to 600λ, the $S(\theta)=29-251og(\theta)$ sidelobe pattern can reasonably be obtained.

For antennas from 100 λ to 400 λ, special design techniques (such as shaped reflectors or offset feeds) are required to produce the $S(\theta)=29-251og(\theta)$ specification.

For antennas with diameters < 100λ, the $S(\theta)=29-251og(\theta)$ specification is virtually impossible to achieve. For antennas in this size range, the maximum sidelobe envelope is specified with the antenna diameter taken into account.

The sidelobe equation for antennas with D< 100λ becomes

$$S(\theta) = 52 - 10\log(D/\lambda) - 251og(\theta) \quad \text{dBi}$$

Where D is the diameter of the antenna.
λ is the wavelength of the transmitted signal.

FIGURE OF MERIT (G/T)

For the satellite link, the antenna should be as efficient as possible in providing a high gain G, without adding significantly to the noise temperature T. This is particularly important in receive mode because weak incoming signals can easily be lost in noise.

CROSS POLAR INTERFERENCE & CROSS POLAR DISCRIMINATION

Most communications satellite systems employ frequency reuse techniques to make more efficient use of the available bandwidth. This is done by transmitting the same frequency twice with different polarisations.

INTELSAT sets the cross polar interference for a satellite link at 30 dB. This means that the earth station antenna must have a cross polar discrimination of about 31 dB.

6.7.2 TYPES OF EARTH STATION ANTENNA

The main types of antennas used in communications satellite earth stations are:

- Axisymmetric single reflector type
- Offset single reflector type
- Axisymmetric dual reflector cassegrain type
- Axisymmetric dual reflector gregorian type
- Offset dual reflector cassegrain type
- Offset dual reflector gregorian

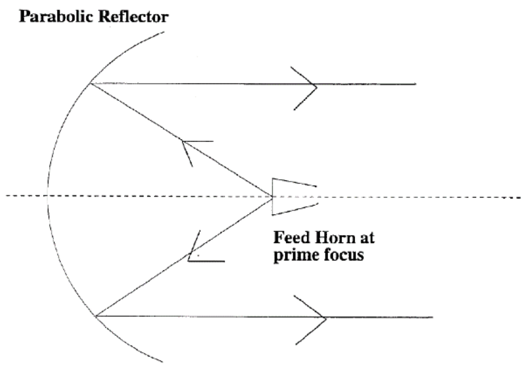
AXISYMMETRIC SINGLE REFLECTOR TYPE ANTENNA

This is the simplest form of satellite antenna. It is made from an axisymmetric parabolic reflector with the feed horn positioned at its **prime focus**.

Advantage of this type of antenna is its simplicity and are extensively used for antennas up to 3m in diameter.

For antennas above this size, long runs of waveguide from the feed horn to the receiver make it unattractive.

As with all axisymmetric antenna, the blocking of antenna by the feed horn reduces the antennas efficiency and makes the required sidelobe pattern difficult to achieve.

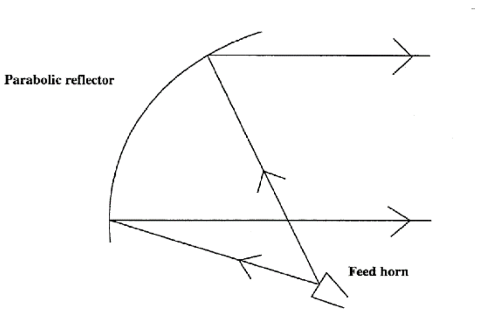


Axisymmetric single reflector antenna

OFFSET SINGLE REFLECTOR TYPE ANTENNA

This type of antenna has a more complicated geometry than the axisymmetric single reflector antenna.

It is more efficient and produces a much improved side lobe radiation pattern because the feed horn does not block the reflector aperture.



Offset single reflector type antenna

DUAL REFLECTOR AXISYMMETRIC CASSEGRAIN & GREGORIAN TYPE ANTENNAS

When antennas get above a certain size, it is no longer practical to have the feed system positioned at the focus of the main reflector.

Dual reflector systems are used for **larger antennas**. The feed and associated transmitting & receiving electronics can be positioned at back of the main reflector.

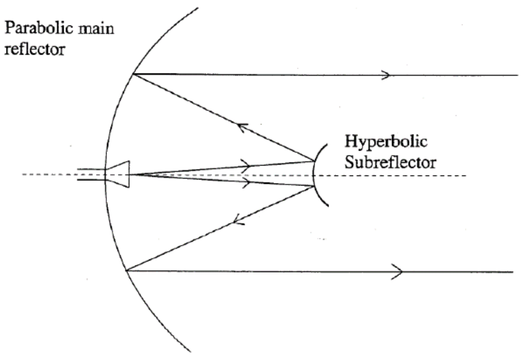
The feed horn and associated electronics can be fixed in a stationary position on the ground.

The two types of dual reflector axisymmetric antennas used are:

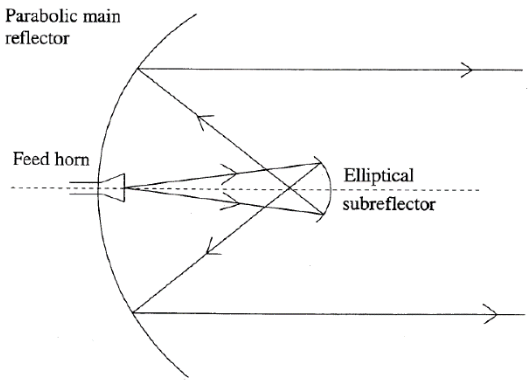
- Cassegrain in which sub reflector is a section of a hyperboloid situated at focus of the main reflector.
- Gregorian in which sub reflector is a section of an ellipsoid situated outside focus of the main reflector.

RF performance of the two types is very similar. Both types suffer from the problem of reduced efficiency & poor sidelobe radiation patterns due to antenna blocking by sub reflector.

Advantage of this type of antenna is the relatively simple geometry.



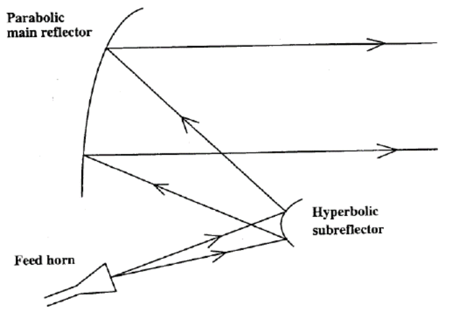
Dual Reflector Cassegrain type



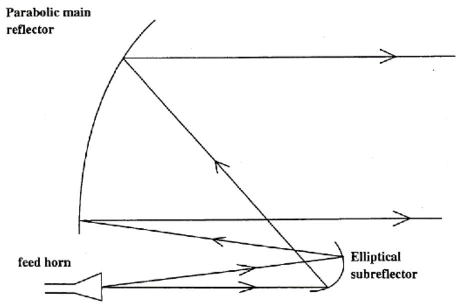
Dual Reflector Gregorian type

OFFSET DUAL REFLECTOR CASSEGRAIN & GREGORIAN TYPE ANTENNAS
Dual reflector antennas can also be the offset type. Either the cassegrain or gregorian configuration can be used.

They have greater efficiency and better sidelobe radiation patterns than the axisymmetric type. However, they have a more complex geometry.



Dual Reflector Cassegrain type



Dual Reflector Gregorian type

6.7.3 The feed horn and primary feed system

Feed horn used in the majority of satellite earth stations will be of the hybrid mode corrugated conical horn type.

This particular mode of operation is chosen because the radiation pattern is nearly symmetrical in the E and H-plane, has low sidelobes and low cross-polarisation.

Most modern satellite communications systems make more efficient use of the available bandwidth with frequency reuse techniques. Signals of the same frequency are used twice.

Different signals of the same frequency are separated by having different polarisations The feed system is hence required to separate signals in frequency and in polarisation.

6.7.4 ANTENNA TRACKING SYSTEM

Very large antennas, such as an INTELSAT standard A antenna, have very narrow beam widths. They must point towards the satellite with an accuracy of 0.01^0.
This is achieved using closed loop tracking system.

Smaller antennas have much wider beam widths and do not generally need a closed loop tracking system. Occasional manual adjustment will usually being sufficient.

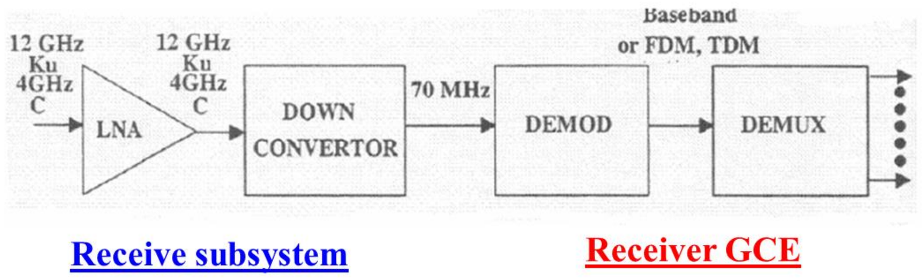
Commonly used tracking systems are:

- Step tracking
- Monopulse tracking
- Conical scan tracking
- Programmed tracking
- Electronic beam tracking

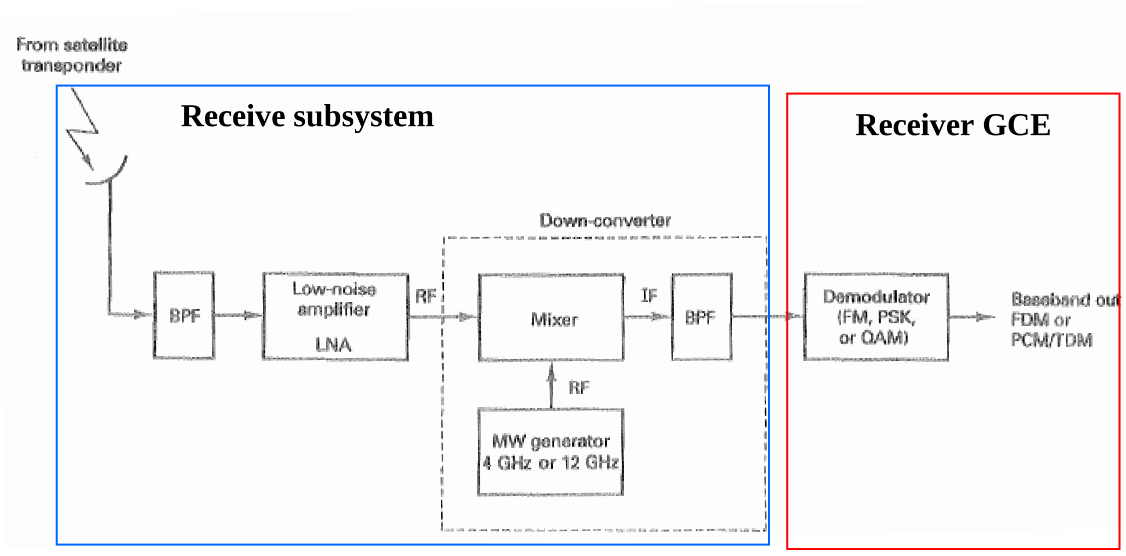
6.8 RECEIVER EQUIPMENT

The receiver equipment consists of the following one and half subsystems:

- Receive subsystem
- Receiver GCE subsystem



Receiver equipment block diagram



The receive subsystem consists of the Low Noise Amplifier (LNA), down converters.

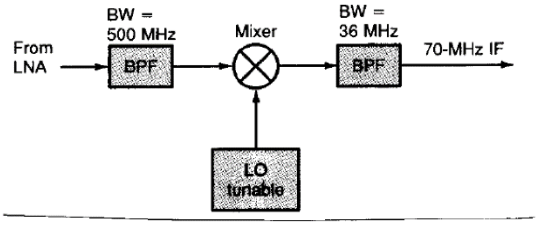
The purpose of receive subsystem is to amplify the down link satellite signal and translate it to a suitable Intermediate Frequency (IF).

In Receiver GCE, the IF signal is demodulated and de-multiplexed to generate back the original baseband signals.

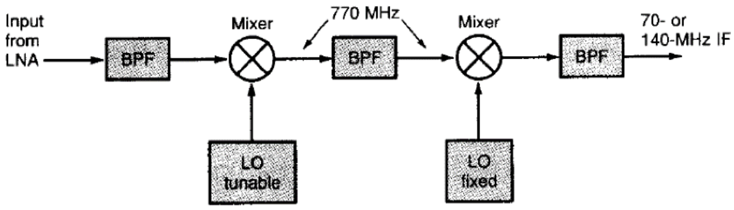
LOW NOISE AMPLIFIER (LNA)
When down-link signal reaches receiver, it is very weak and almost buried in noise.
The first amplifier in the receiver must add very little noise and provide very high gain to the signal.

It must be an amplifier with a very low noise temperature, e.g. 20K at 4GHz and are highly reliable, compact and relatively cheap.

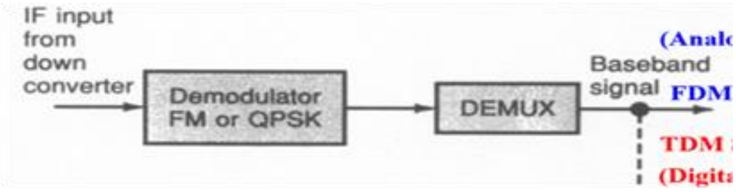
DOWN CONVERTER
Down converter's function is to translate the RF frequency of the signal carrier down to the required IF frequency for demodulation processes. The most commonly used IF is 70MHz.



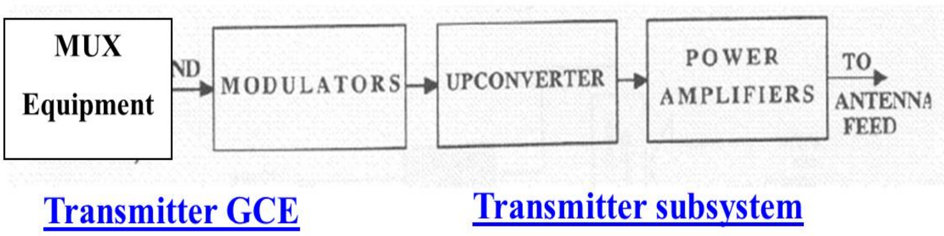
Either single conversion or dual conversion down converters are used in the earth station receivers.



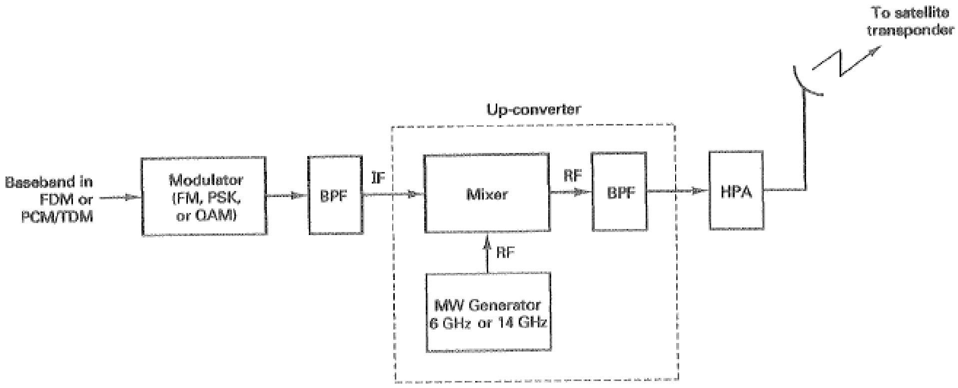
DEMODULATOR & DEMULTIPLEXER (DEMUX)
The 70 MHz IF signals are demodulated and demultiplexed into original baseband signals in the Receiver GCE subsystem.



6.9 Transmitter equipment
The transmitter equipment consists of the following one and half subsystems:
- Transmit subsystem
- Transmitter GCE subsystem



Transmitter equipment block diagram



The transmit subsystem consists of the up converters and the power amplifiers.

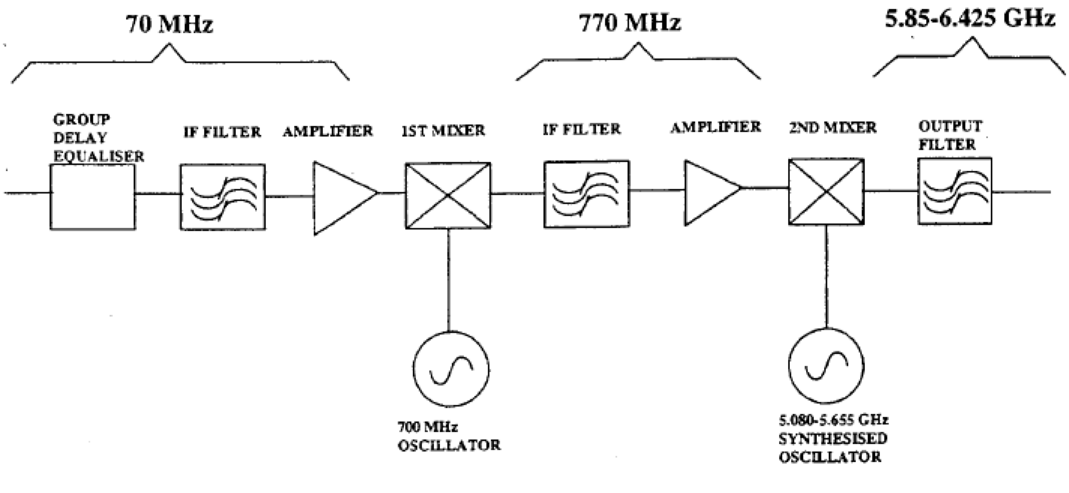
The purpose of the transmit subsystem is to convert the IF signals, up to the final up-link microwave frequencies.

The high power amplifier generate the high power signals and applied to the antenna.

<u>UP CONVERTER</u>

The purpose of the up converter is:

- To chance the frequency of the incoming IF signal from the modulator, from 70 MHz to 6 GHz for C band, 14 GHz for Ku band transmission.
- To provide group delay equalisation & the required filtering of the signal.



It is important that the up converter has good linearity to prevent large amounts of intermodulation distortion from appearing in the RF signal.

POWER AMPLIFIERS

The power amplifier must boost the signal to a sufficiently high power for the signal to be transmitted to satellite without it being swamped in noise at satellite receiver.

The output RF power required from an earth station depends on the type of service provided and the number of carriers transmitted. The types of power amplifiers used in satellite earth stations are:

- Travelling wave tube amplifiers (TWTA).
- Reflex klystrons.
- Solid state power amplifiers (SSPA).

MULTIPLEXER (MUX) & MODULATOR

Transmitter GCE subsystem consists of multiplexer and modulator.

The function of the modulator is to superimpose the baseband signal on an IF carrier and ready for up conversion and transmission.

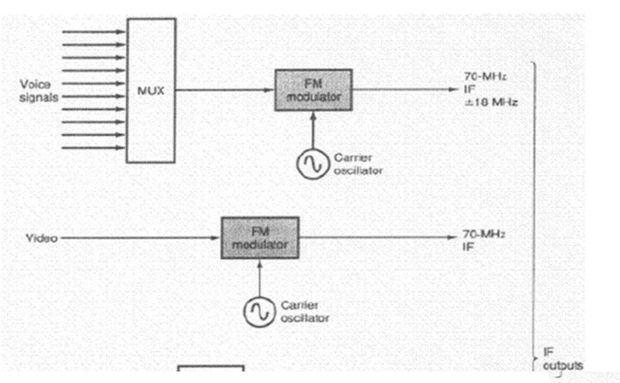
The type of modulation depends on whether the baseband signal is analogue or digital.

For analogue transmission, FM is the most commonly used form of transmission.

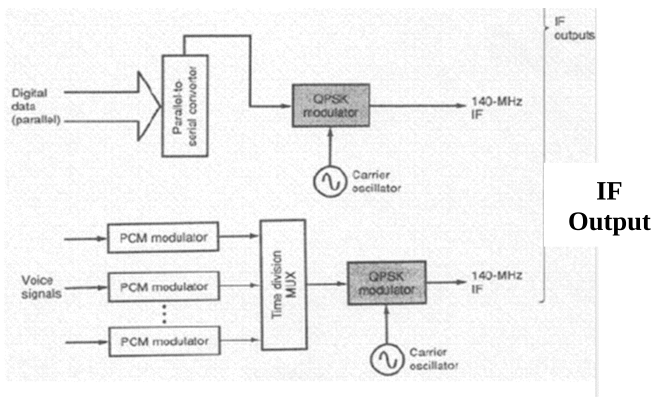
Quadrature phase shift keying (QPSK) is the most commonly used form of modulation in digital transmission schemes.

For an analogue system, individual signals **IF Output** equency division multiplexed (FDM).

For a digital system, individual signals are time division multiplexed (TDM).



Analogue Transmission



Digital Transmission

6.10 POWER SUPPLY SUBSYSTEM

The power supply subsystem furnishes all the power to the equipment.
The primary sources of power are the standard AC power lines. The subsystem operates power supplies which distribute a variety of DC voltages to the equipment. It also consists of emergency power sources, such as diesel generators, batteries and inverters to ensure continuous operation during power failures.

6.11 TRANSMISSION TECHNIQUES USED IN SATELLITE COMMUNICATIONS

Both analogue and digital modulations are used in satellite communications.
Although digital modulation is starting to take over from analogue modulation, analogue modulation is still widely used in satellite communication systems.

6.11.1 ANALOGUE MODULATION

Frequency division multiplex / Frequency modulation (FDM/FM) systems, Single channel per carrier / Frequency modulation (SCPC/FM) systems and Television / Frequency modulation (TV/FM) systems are the common systems used analogue modulation technique.

<u>FDM/FM</u>

In FDM/FM, telephone voice channels are first single sideband suppressed carrier (SSBSC) modulated and then assembled in a frequency division multiplex by shifting them in frequency. Each channel is allowed to occupy a 4 KHz frequency slot.
When the multiplexing has been done, the group of multiplexed voice channels is made to frequency modulate one carrier. The carrier is then transmitted to the satellite. The single carrier may contain as many as 900 voice channels.

<u>SCPC/FM</u>

In SCPC/FM systems, a single voice channel is modulated onto a FM carrier and transmitted to the satellite. The satellite transponder will carry many SCPC/FM channels each being assigned a different frequency slot inside the transponder.
The multiplexing is hence done in the satellite instead of in the earth station GCE equipment as in FDM/FM.

<u>TV/FM</u>

For TV transmission, the required bandwidth is so large that only one or two TV channels can be fitted into a transponder. The baseband composite video signal will have several carriers, with FM modulated sound above the video signal. The sound and video are FM modulated onto a carrier and then transmitted to the satellite.

6.11.2 DIGITAL MODULATION

In digital modulation, the digital bits are made to modulate a RF carrier in amplitude, frequency or phase. Some types of digital modulation vary a combination of these variables. Satellite communication systems commonly use Quadrature Phase Shift Keying (QPSK) digital modulation scheme.

6.12 SATELLITE MULTIPLE ACCESS TECHNIQUES

The concept of multiple access involves systems that make it possible for multiple earth stations to interconnect their communication links through **single transponder**.

There are four types of multiple access systems, namely:

- Frequency Division Multiple Access (FDMA)
- Time Division Multiple Access (TDMA)
- Code Division Multiple Access (CDMA)
- Space Division Multiple Access (SDMA)

FDMA and TDMA are the most widely used multiple access techniques.
We will only be discussing these two techniques in this module.

6.12.1 FREQUENCY DIVISION MULLTIPLE ACCESS (FDMA)

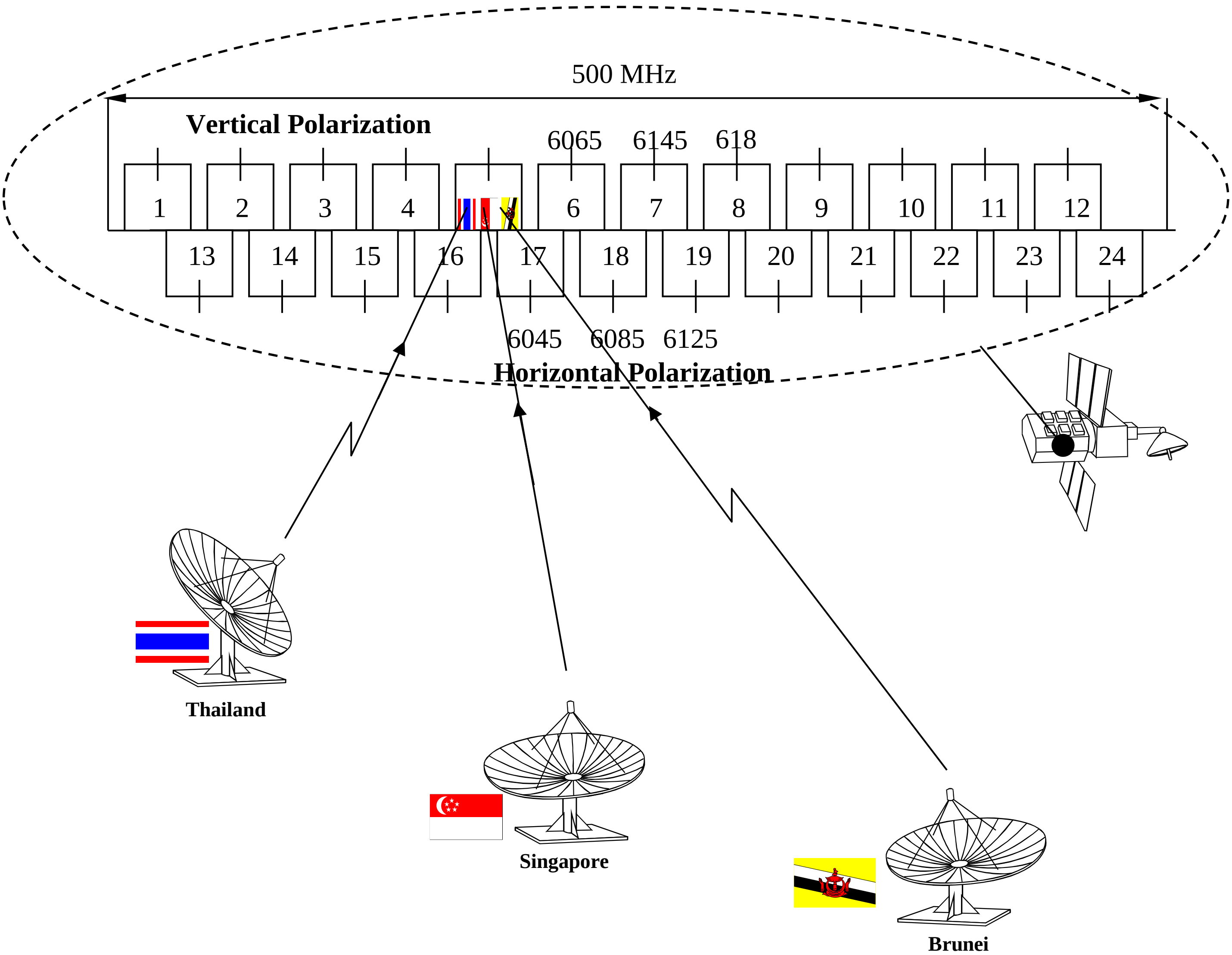


Figure 6.13 3 satellite earth stations sharing a transponder with FDM

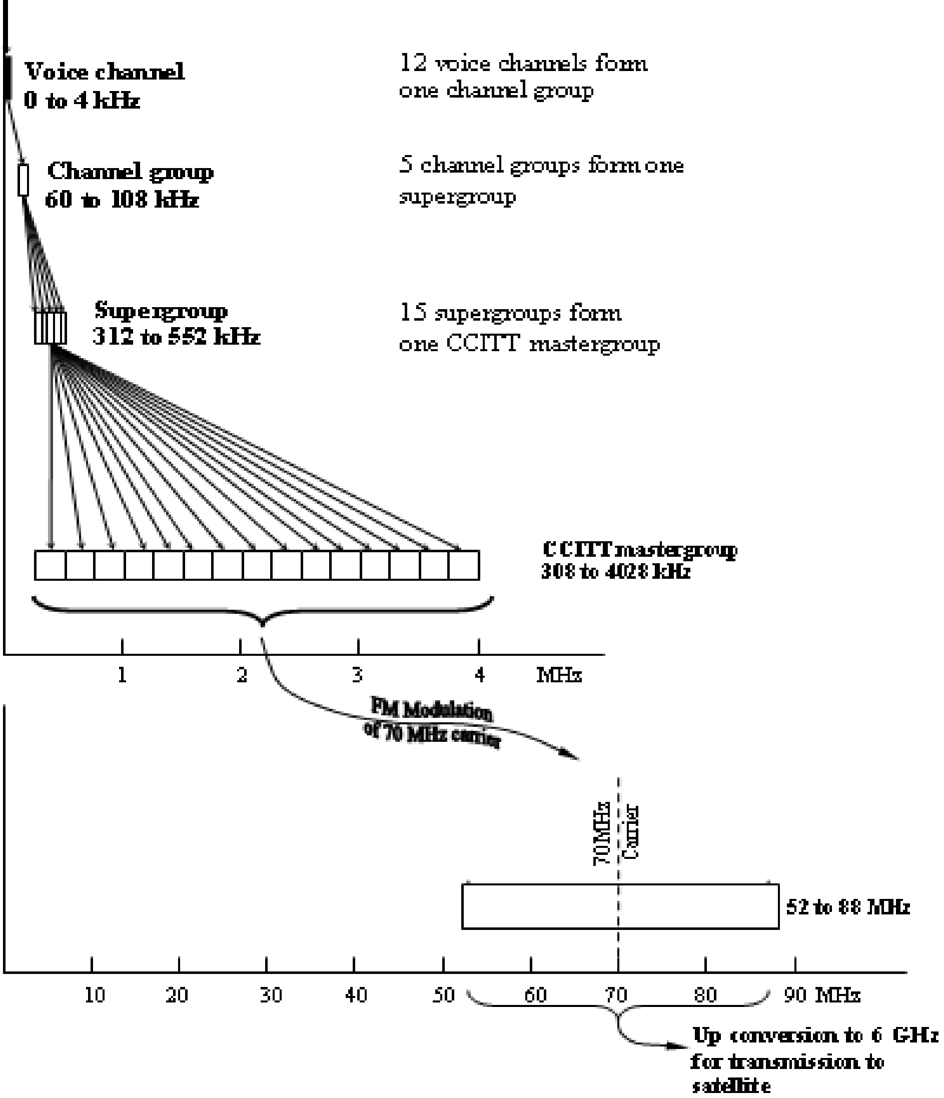
The FDMA system channelizes a transponder using multiple carriers.
The transponder bandwidth (e.g. 36 MHz for an INTELSAT IV transponder) is further divided into smaller bandwidth subdivisions (can be as small as a single voice channel) in the same way as FDM (Frequency Division Multiplexing).

The original FDMA method using **Multiple Channels Per Carrier (MCPC)** was derived from terrestrial frequency division multiplex systems. Each frequency carrier corresponds to a bandwidth subdivision and is assigned to a specific earth station.
An earth station may be assigned more than one carrier within a multi-carrier transponder. These frequency carrier assignments to earth station are fixed.

Figure 6.13 shows how the telecommunication companies of various ASEAN countries could access a single transponder using FDM.

INTELSAT uses this FDMA method for most services.
In this method, the transmitting earth station frequency-division multiplexes (FDM) several SSB carrier telephone channels into one carrier baseband assembly, which in turn frequency modulates (FM) a carrier for transmission to satellite. Hence the technique is referred to as **FDM/FM/FDMA**.

Figure 6.14 Frequency Division Multiplexing (FDM/FM)



In Figure 6.14, 900 voice channels are transmitted using FDM/FM/FDMA.

Block of 12 voice channels multiplexed to form one “group” in CCITT terminology.
5 of these channel groups are further multiplexed into a “supergroup”. A “master group” is formed from 15 supergroups, containing in all 900 telephone channels.

A master group occupies a bandwidth of about 4 MHz (308 to 4028 MHz). This band is used to frequency modulate a 70 MHz carrier using a high enough modulation index to occupy the 36 MHz bandwidth of the transponder.

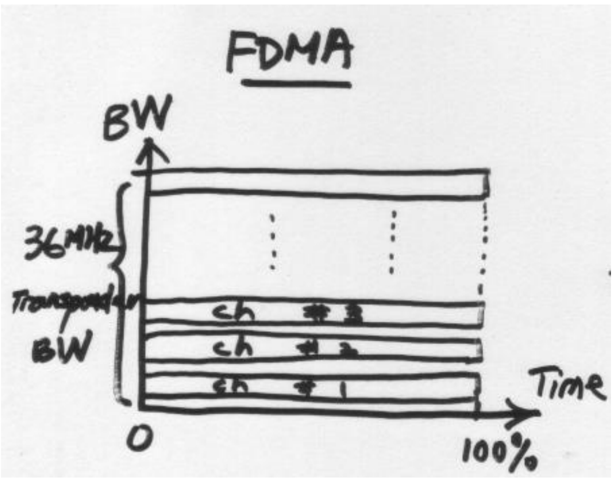
Each INTELSAT transponders can carry such a block of voice channels. Another type of FDMA system employs a single **voice channel per carrier** (**SCPC**). A composite SCPC spectrum consists of many RF carriers in adjacent frequency slots, occupying the transponder bandwidth, each carrier being modulated with information from a single voice or data source.

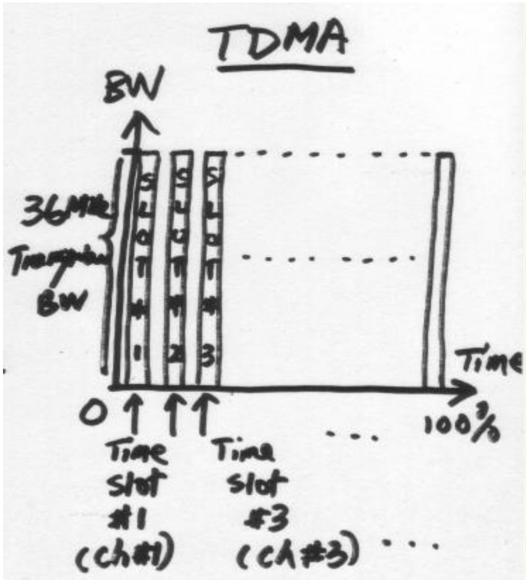
No multiplexing is involved except within transponder bandwidth, where frequency division is used to channelize individual RF carriers, each supporting the information from a single channel.

The carrier frequencies for SCPC in the satellite transponder may either be preassigned to individual channel units or used exclusively by that channel unit, or they may be demand assigned.

6.12.2 TIME DIVISION MULTIPLE ACCESS (TDMA)

TDMA method is based on the same principle as Time Division Multiplexing (TDM).





FDMA : Each earth station has its own pre-assigned carrier frequencies in a multi-carrier transponder.

TDMA : Each earth station has its own pre-assigned, non-overlapping time slot to access the transponder using the same carrier frequency.

In other words, each earth station, instead of using a portion of the bandwidth exclusively, takes turn to use all the available bandwidth in given time slots to transmit a high-speed burst of bits.

Hence, TDMA is characterised by the use of a single digitally modulated carrier per transponder, where the bandwidth associated with the carrier is typically the full transponder bandwidth.

Clearly, timing requirements that must be met in such a system are crucially stringent.

A typical TDMA configuration is shown in Figure 6.15.

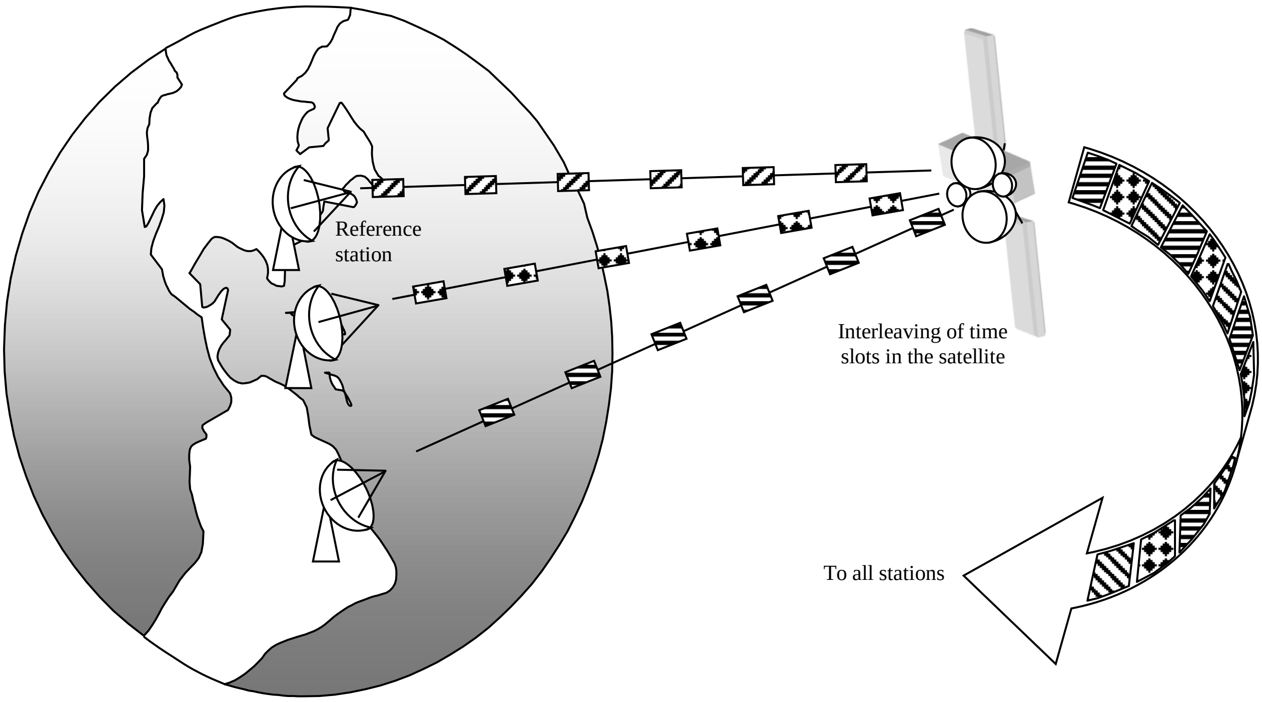


Figure 6.15 A typical TDMA configuration

The transponder is time-shared by each earth station transmitting its traffic information in bursts of the digital carrier at common frequency and data rate.

The high-speed bursts must be transmitted at the correct time so that bursts from all stations arrive sequentially at the satellite.

To properly control the interleaving of bursts from multiple earth stations, a TDMA system uses a frame organisation.

The frame structure of a typical TDMA system comprising frame format, burst format and preamble format as shown in Figure 6.16.

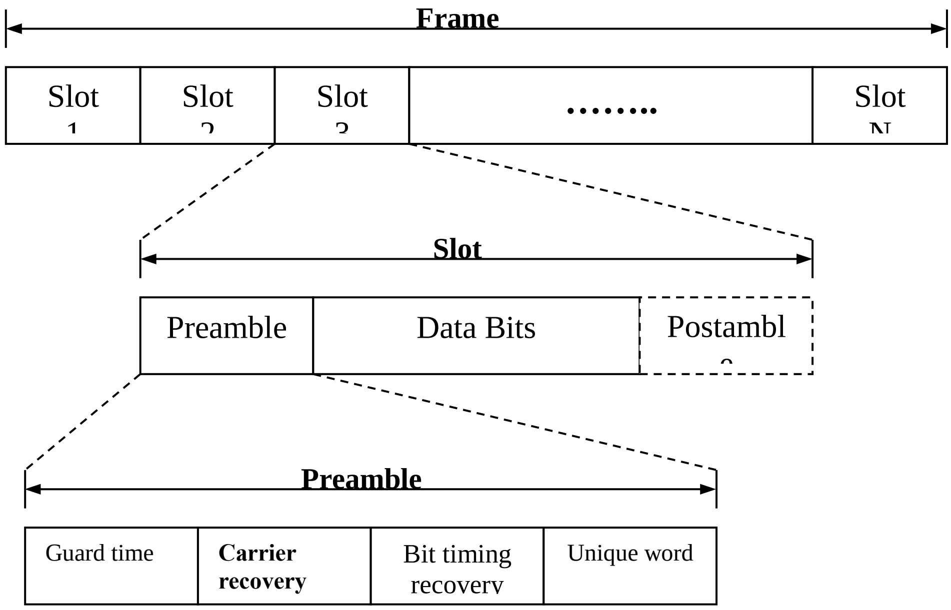


Figure 6.16 TDMA frame and burst format

During the time slot assigned to an earth station within each frame, the burst is subdivided into:

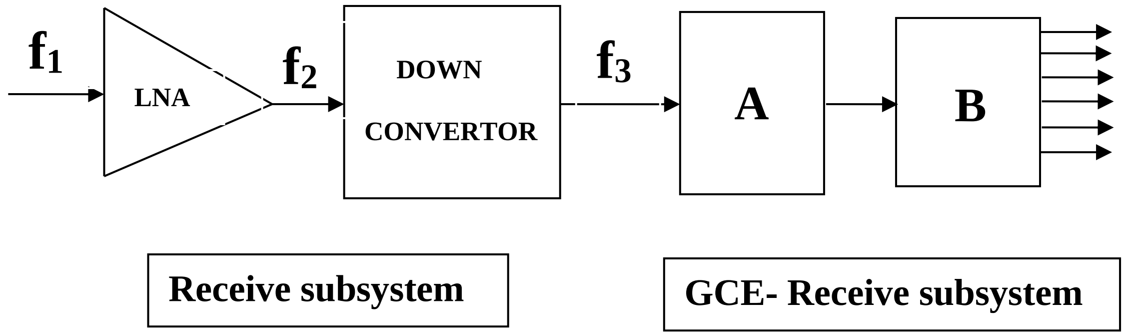
- Preamble (or header) for received synchronisation & station identification purposes.
- Data information addressed to various destination earth stations.
- Postamble to identify end of transmission. (Many systems are designed to operate without a postamble).

A reference burst is normally required at the beginning of each frame to provide timing information for the acquisition and synchronisation of bursts.

TUTORIAL 6a

1. (a) State two main functions of the satellite transponder.
   (b) Explain how the above two functions are achieved in the transponder subsystem.

2. The following block diagram shows Receive & GCE-Receive subsystems of the satellite earth station:



   (a) Name Box A and B in the above block diagram.
   (b) If the subsystems operate at Ku-band, identify the frequency values of f_1, f_2 and f_3.
   (c) State the functions of LNA and Down Converter in the satellite earth station.
   (d) Sketch a single conversion Down Converter, indicate clearly the IF frequency.

3. Comment on the earth satellite station dish antenna used in the following situations. Can the dish antenna be allowed for communication with the satellites? Give reason to support your answer.

   (a) An INTELSAT standard A antenna with diameter > 100λ is used to communicate with satellites at spacing of 2.0^0. The measured sidelobe radiation pattern at 5^0 from the antenna boresight is found to be 12.5 dBi.
   (b) The earth satellite station has an antenna with a diameter of 40λ and is used to communicate with certain geostationary satellites. The measured sidelobe radiation level is found to be 15.5 dBi at 5^0 from its boresight.

4. (a) State the main advantages and disadvantages of TDMA systems as compared to the FDMA systems.
   (b) Explained why system timing is so important for a TDMA system.

TUTORIAL 6b

1. The use of frequency reuse technique in satellite communication is to:
   (a) Increase the transmitting power of the satellite.
   (b) Increase the coverage area of the satellite.
   (c) Increase the information carrying capacity of the satellite.
   (d) Increase the line of sight (LOS) of the satellite.

2. Three axis stabilized satellites are kept in a stable position by:
   (a) Spinning the body of the satellite.
   (b) Momentum wheels inside the satellite body.
   (c) Reaction wheels inside the satellite body.
   (d) Both momentum wheels and reaction wheels inside the satellite body.

3. The satellite subsystem that converts uplink to downlink frequencies is the:
   (a) Transponder subsystem.
   (b) Power supply subsystem.
   (c) Command, telemetry and control subsystem.
   (d) Antenna subsystem

4. Which of the following component is not part of a transponder subsystem :
   (a) LNA.
   (b) Mixer.
   (c) Modulator.
   (d) HPA.

5. Under which of the following situations, satellites need to use battery power :
   (a) The vernal equinox.
   (b) The satellite goes into an eclipse.
   (c) The solar cell panels not properly positioned to the sun.
   (d) All of the above.

6. The function of TWTA in the satellites earth stations is :
   (a) To translate the signal frequencies.
   (b) To reduce the system noise.
   (c) To boost the signal to a sufficient high power.
   (d) To modulate the baseband signals.

7. Which of the following type of dish antenna is not used in earth station:
   (a) Axisymmetric dual reflector type.
   (b) Single reflector type.
   (c) Dual reflector cassegrain type.
   (d) Dual reflector gregorian type.

8. Which one of the following parameter is not the important performance characteristics of earth station antenna :
   (a) Figure of merit (G/T).
   (b) Sidelobe radiation pattern.
   (c) Cross Polar Interference (XPI).
   (d) FSPL.

9. For dual conversion Down Converters in earth satellite station, the two IF frequencies are:
   (a) 6/4 GHz.
   (b) 6/4 MHz.
   (c) 70/770 MHz.
   (d) 12/14 GHz.

10. The receive GCE system in an earth satellite station performs what functions?
   (a) Demodulation and demultiplexing.
   (b) Modulation and multiplexing.
   (c) Up conversion.
   (d) Down conversion.

11. The LNA of the earth satellite station is located in the:
   (a) Receive subsystem.
   (b) Receive GCE subsystem.
   (c) Transponder subsystem.
   (d) Transmit subsystem.

12. The Down Converter (DC) in part of:
   (a) Transmit GCE subsystem.
   (b) Receive GCE subsystem.
   (c) Transmit subsystem.
   (d) Receive subsystem.

13. The modulation normally used with digital data is:
   (a) AM.
   (b) FM.
   (c) SSB.
   (d) QPSK.

14. In FDM/FM/FDMA, the transponder's 36 MHz bandwidth can carry a maximum of ________ voice channels:
   (a) 900.
   (b) 800.
   (c) 90.
   (d) 80.

TUTORIAL GUIDE 6a

1a&b) Answer may be found by reading section 6.2.1 – 6.2.2.

2a-d) Answer may be found by reading section 6.8.

3a) 11.53 (dBi)

3b) 18.51 (dBi)

4a-b) Answer may be found by reading section 6.12 – 6.12.2.

TUTORIAL GUIDE 6b

1 Answer may be found by reading page 90

2 Answer may be found by reading section 6.3.1.

3 Answer may be found by reading section 6.2.1.

4 Answer may be found by reading section 6.2.1

5 Answer may be found by reading section 6.3.2.

6 Answer may be found at page 107

7 Answer may be found at page 102-103

8 Answer may be found by reading section 6.7.1

9 Answer may be found by reading section 6.8

10 Answer may be found by reading section 6.8.

11 Answer may be found by reading section 6.8.

12 Answer may be found by reading section 6.8.

13 Answer may be found at page 108

14 Answer may be found at page 109-113

CHAPTER 7

SATELLITE LINK POWER BUDGET ANALYSIS & APPLICATIONS

CHAPTER OBJECTIVES:

- Evaluate the satellite uplink & downlink.
- Discuss on the satellite applications

]

Learning outcomes

At the end of the chapter, the students will be able to:

☑ Explain the frequency bands used in satellite communication

☑ Explain propagation delay problem & attenuation in satellite communication.

☑ Explain the receiver noise and carrier-to-noise ratio.

☑ Analyse the satellite uplink & downlink power budget.

☑ Analyse the combined uplink & downlink carrier-to-noise ratio.

☑ Explain the Direct Broadcast Satellite (DBS) and TVRO services.

☑ Explain the Global Positioning Satellite (GPS) system.

CHAPTER 7 Satellite Link Power Budget Analysis & Applications

SATELLITE LINK CONSIDERATION

An important consideration in the geostationary satellite communications system is the **propagation delay** and **attenuation of signals** experienced when linking two earth stations.

Propagation delay is particularly noticeable during telephone conversations using analogue satellite link. It may cause synchronisation problems in digital satellite communications.

Careful selection of frequency bands will minimise attenuation of signal when propagating in the air and interference to the nearby microwave stations.

Uplink & Downlink power budget analysis is used to ensure that sufficient power is transmitted to compensate for the large signal loss in the air due to long transmission distance, so that satisfactory carrier-to-noise can be achieved.

7.1 FREQUENCY BANDS USED IN SATELLITE COMMUNICATION

The most common carrier frequency bands used for satellite communications are 4/6 and 12/14 GHz bands. These are known as the C and Ku bands respectively.

The first number is the down-link (transponder to earth station) frequency and the second number is the up-link (earth station to transponder) frequency. Different up-link and down-link frequencies are used to prevent signal interference.

The selection of suitable operating frequencies depends on the following factors:

- Size and gain of antenna
- Bandwidth allocation
- Atmospheric attenuation or losses
- Various sources of noise
- Effects of rainfall, fog etc.

C BAND (4/6 GHz)

In this band, the effect of the ionosphere on wave propagation is negligible. There is little absorption by atmospheric gases and water vapour. From the consideration of different types of loss and noise, 4/6 GHz band can provide high quality transmission. The 4/6 GHz band is used extensively by commercial satellite communications service providers.

One problem with the use of the 4/6 GHz band is the increasing use of this band in large urban areas for terrestrial microwave links. There is the problem of interference between satellite links and terrestrial microwave links occurred.

By far the most serious is the interference caused by a transmitting earth station signal being picked up by a nearby terrestrial microwave receiver. As an earth station must transmit a high power signal to make up the large transmission distance loss. Some of the signal spilled out in the sidelobe radiation may cause substantial interference with a microwave receiver. Hence a transmitting earth station working in the 4/6 GHz band should **not** be located in large urban areas.

KU BAND (12/14 GHz)
12/14 GHz band offers the advantages of greater antenna gains on both the up-link and down-link than those of the 4/6 GHz band for antennas of the **same size**.

In addition, its earth station antennas can operate in any large city centre without causing interference to nearby terrestrial microwave links.

The improvement in antenna gain could be used to allow the earth station and the satellite antennas to be made smaller and cheaper. For the same size antenna, the beamwidth is less than the 4/6 GHz band, thus lessening the interference effects.

However, the disadvantage of the higher frequency is the increase in signal loss and noise under poor weather conditions with heavy rain fog or clouds.

7.2 PROPAGATION DELAY & ATTENUATION

The propagation (time) delay of the geostationary satellite communications system is about 0.5 sec, experienced when linking two earth stations.

EXAMPLE 1
A geostationary satellite is located 38000 km from the transmitting earth station A and 42000 km from receiving earth station B. Calculate the round trip echo delay.

[Solution]
Distance traveled in round trip = 2 (38000 + 42000) = 160000 km
Round trip echo delay = 160 000 / 3 x 10^5 = 533 ms (0.533 sec)

Since the distance between satellite and earth station varies somewhat with the satellite's elevation angle from the earth station, the propagation delay also varies.

The CCITT has established a standard of maximum delay of 0.6 s so that communications involving two successive hops with satellite are not recommended.
The angle of elevation is the angle formed between the plane of a wave radiated from an earth station antenna and the horizon, or the angle subtended at the earth station antenna between the satellite and the earth's horizon.

The **smaller** the angle of elevation, the **greater** the distance a propagated wave must pass through the earth's atmosphere. As with any wave propagated through the earth's atmosphere, it suffers absorption and may also be severely contaminated with noise. Consequently, if the angle of elevation is too small and the distance of the wave is too long, the wave may deteriorate to a degree that it provides inadequate transmission.

Generally, 5^0 is considered as the minimum acceptable angle of elevation.

Figure 7.1 shows how the angle of elevation affects signal strength of a propagated wave due to normal atmospheric absorption, absorption due to thick fog and absorption due to heavy rain.

It can be seen that 12/14 GHz band is more severely affected than the 4/6 GHz band. This is due to the smaller wavelengths associated with the higher frequencies. Also, at elevation angles less than 5^0, the attenuation increases rapidly.

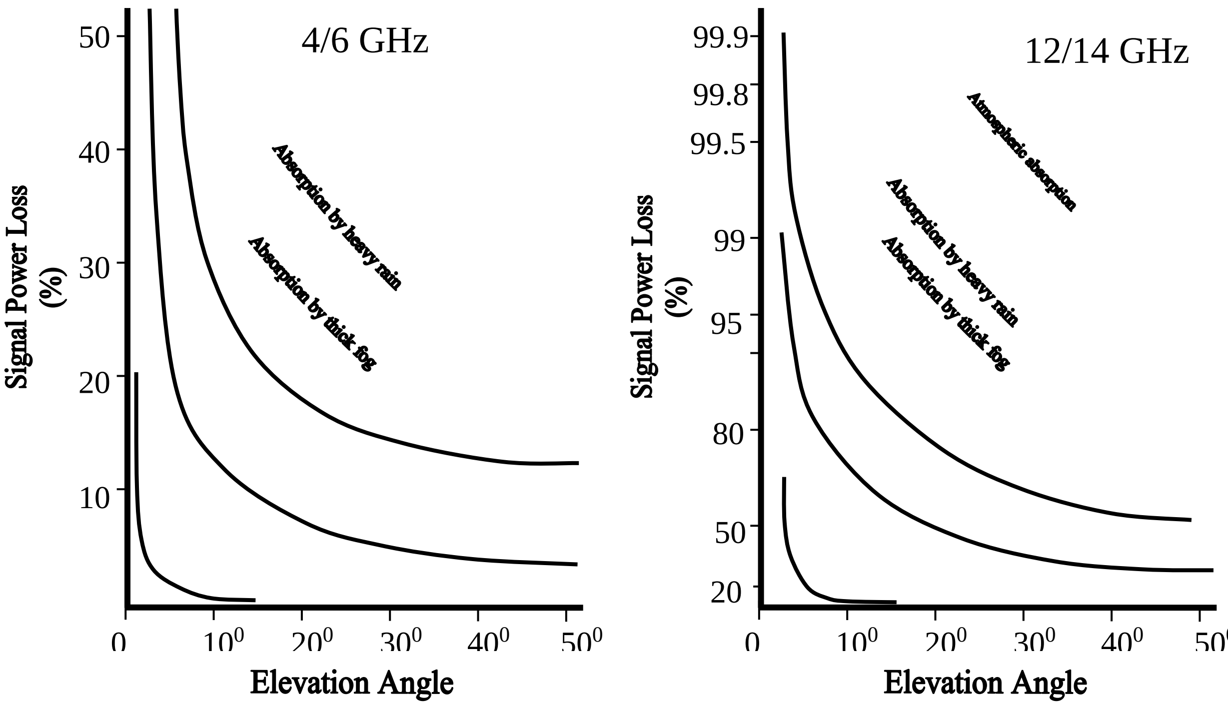


Figure 7.1 Signal loss due to absorption at various elevation angles

7.3 RECEIVER NOISE & CARRIER-TO-NOISE RATIO

As the satellite is placed high up in space in its geostationary orbit, the link distance between an earth station and the satellite could easily exceed 40000 km. Thus the path loss is extremely large, in addition to other losses due to such factors as rainfall, cloud, fog, feeder systems, etc.

To compensate for high signal attenuation, an earth station must supply very high power of several kilowatts, and must use very large antennas.

The up-link power budget is not much of a problem, unlike the down-link budget due to the limitation on the size and weight of a satellite. Power transmitted from the satellite is limited.

Furthermore, there are guidelines limiting the RF signals reaching the earth's surface in order not to produce too severe an interference to other ground communications systems.

Consider the simplified earth satellite communications link shown in figure 7.2.

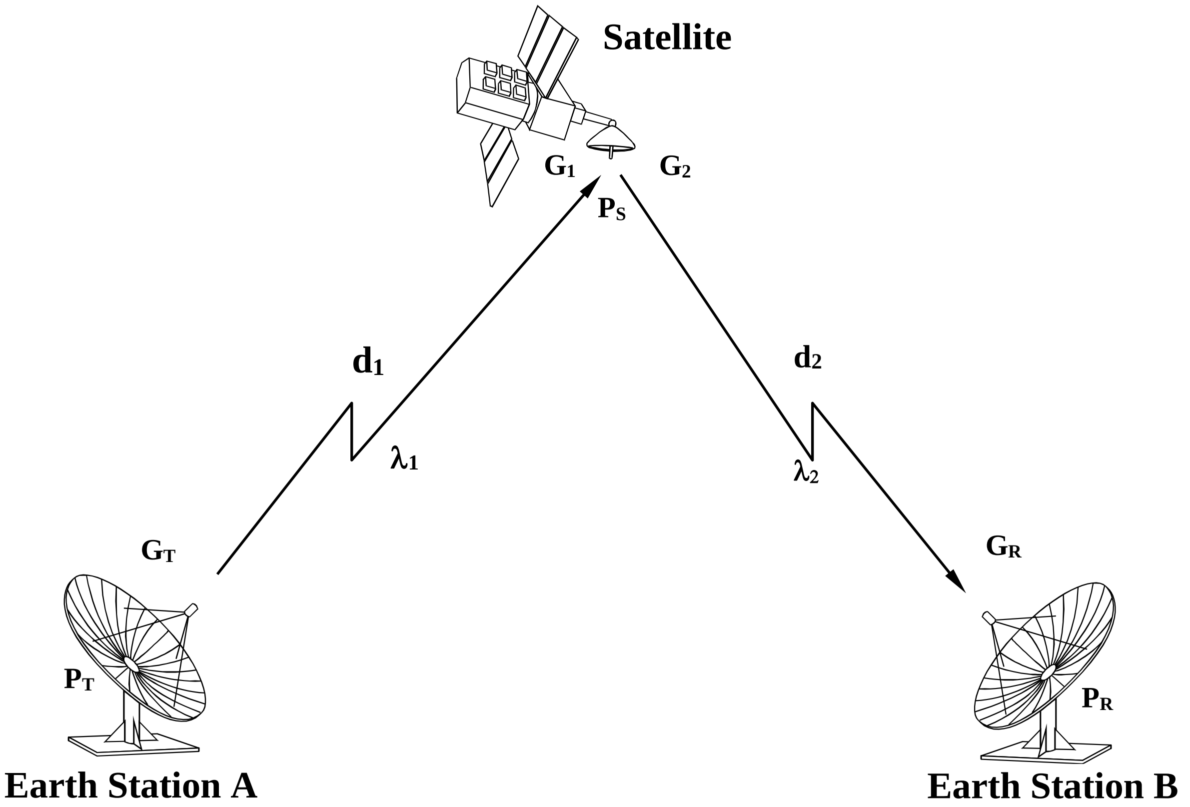


Figure 7.2 Satellite communications link

Let the various parameters be defined as follows:-

G_T, G_1, G_2, G_R	= Antenna gains.
P_T	= Power transmitted from source earth station.
P_R	= Power received by destination earth station.
d_1, d_2	= distance of up-link and down-link.
P_S	= Power transmitted from satellite transponder.
λ_1, λ_2	= Carrier signal wavelength for up-link and down-link.

The carrier signal power, C, received in a line of sight (LOS) link is given by:-

$$C = P_T G_T G_R \left(\frac{\lambda}{4\pi d} \right)^2$$

Effective Isotropic Radiated Power (EIRP) is the total signal power radiated from the antenna to the air which is $P_T G_T$.

The factor $(4\pi d / \lambda)^2$ is termed Free Space Path Loss (FSPL) and expressed in dB.

If the units are in MKS (m/kg/sec) :

$$L_{dB} = 20 Log \left(\frac{4\pi d}{\lambda} \right)$$

If the distance of up-link and down-link (d) in km and carrier signal frequency (f) in MHz :

$$L_{dB} = 32.44 + 20Log[d(km)] + 20Log[f(MHz)]$$

Thus, the received carrier power in dBW is:-

$$(C)_{dBW} = (P_T)_{dBW} + (G_T)_{dB} + (G_R)_{dB} - (L)_{dB}$$

Generally the capability of a communications link is measured in terms of its signal to noise ratio (S/N). A quantity often used to state the quality of a satellite channel is the carrier to noise density ratio (C/N_0) defined as the ratio of received carrier power (C) to noise density (N_0).

The total noise power, N, is usually quoted in terms of its equivalent temperature T, such that N = KTB
where

K = 1.38x10-23 J/K is Boltzmann's constant
B = System bandwidth

Equivalent noise temperature T is a hypothetical value that can be calculated but cannot be measured. T is often used rather than noise figure because it is a more accurate method of expressing the noise contributed by a receiver when evaluating its performance. Essentially, equivalent noise temperature is the noise present at the input of a device plus the noise added internally by the device. This allows us to analyse the noise characteristics of a device by simply evaluating an equivalent noise temperature.

T is a very useful parameter when evaluating the performance of a satellite system.
Typically, equivalent noise temperatures of the receivers used in satellite transponders are about 1000K. For earth station receivers the equivalent noise temperatures are between 20 and 1000K.

Equivalent noise temperature is generally more useful when expressed as a log ratio with units of dB K, as T(dBK) = 10 log T.

Thus the noise density per Hz of bandwidth is:-

$$N_0 = \frac{N}{B} = KT$$

Hence,

$$\frac{C}{N_0} = \frac{P_T G_T G_R}{KT}\left(\frac{\lambda}{4\pi d}\right)^2$$

The link carrier-to-noise density ratio expressed in dBHz:-

$$\left(\frac{C}{N_0}\right)_{dBHz} = (P_T)_{dBW} + (G_T)_{dB} + \left(\frac{G_R}{T}\right)_{dB} - (L)_{dB} - 10\log K$$

7.4 SATELLITE UPLINK & DOWNLINK POWER BUDGET ANALYSIS

$$\left(\frac{C}{N_0}\right)_{dBHz} = \left(P_T\right)_{dBW} + \left(G_T\right)_{dB} + \left(\frac{G_R}{T}\right)_{dB} - \left(L\right)_{dB} - 10\log K$$

7.4.1 CARRIER-TO-NOISE DENSITY RATIO

For up-link system, **carrier-to-noise density ratio equation** is:-

$$\left(\frac{C}{N_0}\right)_{dBHz} = \left(P_T\right)_{dBW} + \left(G_T\right)_{dB} + \left(\frac{G_1}{T_S}\right)_{SAT\,(dB/K)} - \left(L_u\right)_{dB} - 10\log K$$

For down-link, **carrier-to-noise density ratio equation** is:-

$$\left(\frac{C}{N_0}\right)_{dBHz} = \left(P_S\right)_{dBW} + \left(G_2\right)_{dB} + \left(\frac{G_R}{T}\right)_{ES\,(dB/K)} - \left(L_d\right)_{dB} - 10\log K$$

L_u and L_d are the free space up-link and down link path losses.

FIGURE OF MERIT (G/T)

$(G/T)_{dB/K}$ = 10 log (G/T) =10 log (G) - 10 log (T) = G(dB) - 10 log (T)

G is the gain of the receiving antenna & T is the equivalent noise temperature of the receiver system, is known as the Gain-to-Noise Temperature ratio (in dB/K) or **Figure of Merit** of the receiver system (at Satellite Transponder or Earth Station).

$(G/T)_{ES}$ is the G/T ratio of the Earth Station receiving system,
$(G/T)_{SAT}$ is the G/T ratio of the Satellite transponder receiving system.
Note that the unit is in dB/K.

The **quality or efficiency** of a satellite or an earth station is often specified in terms of G/T ratio or Figure of Merit.

The larger the gain of the receiving antenna and the smaller the noise introduced, the larger will be the G/T ratio and hence the better the efficiency of the system.

EXAMPLE 2

Calculate the FSPL in dB for the up-link and down-link respectively of a 4/6 GHz.
If EIRP of the satellite is 22 dBW, what is the power received by the earth station B whose antenna gain is 60 dB?
What is the power transmitted by satellite transponder with an antenna gain of 14 dB? The up-link distance is 38000km and the down-link distance is 42000km.

Solution (Solution is available in the BB teaching slides)

EXAMPLE 3

A 12/14 GHz communication satellite in geostationary orbit is 35860 km above an earth station. The earth station transmits an output power of 2 kW using a 64 dB gain antenna. If the atmospheric loss is 0.6 dB and the satellite G/T is -5.3 dB/K, calculate the C/N_0 at the satellite transponder input.

Solution (Solution is available in the BB teaching slides)

7.4.2 CARRIER-TO-NOISE RATIO

$$N_0 = \frac{N}{B} \qquad \frac{C}{N} = \frac{C}{N_0 B} \qquad \left(\frac{C}{N}\right)_{dB} = \left(\frac{C}{N_0}\right)_{dB} - 10\log B$$

Satellite carrier-to-noise ratio can be expressed in full equation:

$$\left(\frac{C}{N}\right)_{dB} = \left(P_T\right)_{dBW} + \left(G_T\right)_{dB} + \left(\frac{G_R}{T}\right)_{dB} - \left(L\right)_{dB} - 10\log K - 10\log B$$

For the up-link, Carrier-to-noise ratio equation is:-

$$\left(\frac{C}{N}\right)_{dB} = \left(P_T\right)_{dBW} + \left(G_T\right)_{dB} + \left(\frac{G_1}{T_S}\right)_{SATdB} - \left(L_u\right)_{dB} - 10\log K - 10\log B$$

For down-link, Carrier-to-noise ratio equation is:-

$$\left(\frac{C}{N}\right)_{dB} = \left(P_S\right)_{dBW} + \left(G_2\right)_{dB} + \left(\frac{G_R}{T}\right)_{ESdB} - \left(L_d\right)_{dB} - 10\log K - 10\log B$$

L_u and L_d are the free space up-link and down link path losses.

<u>EXAMPLE 4</u>
If the one of the transponders on the satellite in Example 3 is carrying a television signal which takes up the entire 36MHz transponder bandwidth.
Calculate the C/N ratio of the signal at the satellite transponder input.

Solution (Solution is available in the BB teaching slides)

7.4.3 OVERALL CARRIER-TO-NOISE RATION

The **overall** carrier-to-noise ratio combines the effect of both up-link and down-link carrier-to-noise ratios using the follows equation:

$$\left(\frac{C}{N}\right)_{Total}^{-1} = \left(\frac{C}{N}\right)_{Up}^{-1} + \left(\frac{C}{N}\right)_{Down}^{-1} \quad \text{With all values as RATIOS not dB's}$$

<u>EXAMPLE 5</u>

The C/N contribution from the uplink side of a satellite system was found to be 22dB and the contribution from the downlink side was found to be 17dB. What is the overall C/N ration for the satellite link?

Solution (Solution is available in the BB teaching slides)

EXAMPLE 6

A regional satellite communication system using 4/6 GHz band has the following parameters:

Satellite

Transponder overall gain: 90 dB
Transponder bandwidth: 36 MHz
Transponder peak output power: 6.3W
Transponder input noise temperature: 500K
Antenna gain : 22 dB (Receive)
20 dB (Transmit)

Earth Station

Antenna gain: 60.0 dB (Receive)
61.3 dB (Transmit)
System equivalent noise temperature: 100K
Uplink path distance: 38,000 Km
Downlink path distance: 42,000 Km

Determine (i) Uplink frequency.
(ii) Downlink G/T in dBK^{-1}.
(iii) (a) Input power level at the satellite transponder.
(b) Transmitter output power at Earth station.
(iv) Overall C/N ratio for a 10 MHz bandwidth signal.

Solution (Solution is available in the BB teaching slides)

7.5 SATELLITE APPLICATIONS

Satellite applications are conventionally limited to **communication** related applications. However, more non-communication related satellite applications are getting popular. For examples, weather satellites (NOAA, MTSAT) are used to weather forecasting.

The following non-communication related satellite applications will be discussed in the subsequent paragraphs:

- Direct Broadcast by Satellite (DBS) and TeleVision Receive Only (TVRO)
- Navigation by satellites.

7.5.1 DIRECT BROADCAST BY SATELLITES (DBS)

A DBS satellite is one which is specifically designed to provide television, radio and other services at a high power level, so that its broadcasts can be received by individuals with very small TVRO antennas.

Current DBS systems in Europe and Japan allow the reception of high quality television and radio with parabolic dish antennas of less than 30cm in diameter or with small flat plate antennas.

7.5.2 TVRO SYSTEM

In the mid 1970's, amateurs found that it was possible to receive the broadcasts on much smaller home-made dishes working, only in receive mode.

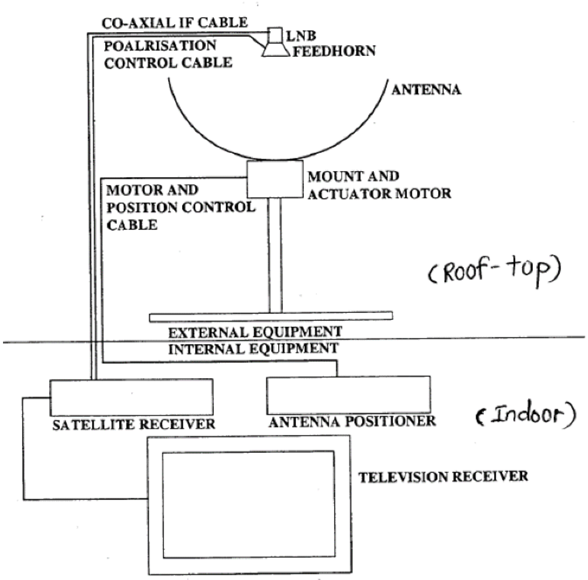
Individuals can receive television broadcast from around the world in their own homes with the use of a small inexpensive dish and the associated receiving electronics.

These systems are known as TeleVision Receive Only (TVRO) systems, and their function is to receive audio & video signals with **no transmission**.

<u>ELEMENTS OF A TVRO SYSTEM</u>

A TVRO system consists of the following elements:

- Parabolic antenna.
- Feedhorn capable of receiving signals of various polarities.
- Low noise block converter (LNB) LNA & down converter integrated into one box of electronics and mounted directly onto the feedborn.
- Polar or Azimuth-Elevation mounting
- Actuator motor.
- Positioner.
- Satellite receiver.
- Television receiver.



TVRO ANTENNA MOUNTINGS

There are two types of TVRO antenna mountings commonly in use, namely:

- Azimuth elevation mount or fixed mount.
- Polar mount.

Azimuth elevation mount is designed to remain fixed on a single satellite.

Polar mount is designed to enable its antenna to be moved to look at any visible geostationary satellites.

The dish alignment of a multi-satellite system (polar mount) is more complicated than the alignment of a single satellite system (azimuth elevation mount).

TVRO IN SINGAPORE

Presently there are no DBS services available in Singapore, so it is still necessary to have quite a large sized antenna to receive satellite television here.

There is, however, quite a lot of satellite televisions can be received in Singapore, with the correct sized dish, and lots more will become available as new satellites are launched in the coming years of this decade.

Examples of broadcasting satellites available at Singapore site:

- CHINASAT 6B
- THAICOM
- PALAPA, etc

Internet searching for the available TVRO satellites in Asia & South Pacific Region

Go to the web site http://www.lyngsat.com/asia.html, to obtain the TVRO satellites available in this region :

116.0°E	Koreasat 6	120302
115.5°E	ChinaSat 6B	111026
113.0°E	Koreasat 5	120308
	Palapa D	120321
110.5°E	ChinaSat 5B *(incl. 0.5°)*	
110.5°E	ChinaSat 10	110821

80.0°E	Express AM2	120321
	Express MD1	120217
78.5°E	Thaicom 5	120326
76.5°E	Apstar 2R	120314
75.0°E	ABS 1	120326
74.9°E	ABS 1A *(incl. 4.7°)*	
74.0°E	Insat 3C	110909
	Insat 4CR	120321

Colour codes on this regional index: no data/L/S/Ka band C band C & Ku band Ku band moving

Example : Satellite “ChinaSat 6B” is located at 115.5^0 E, operating at C band (pink shaded area)

Further searching on “ChinaSat 6B” will show the following information on this satellites :

Shandong TV using C band transponder with **Vertical Polarized Frequency (3834 V)**
CCTV using C band transponder with **Horizontal Polarized Frequency (3840 H)**

………………etc.

LyngSat

ChinaSat 6B at 115.5°E

3834 V	Shandong TV	A	DVB-S	5400-3/4 1 - 32		1-3 33 C	C 0 5.5	T Kameda 070922
	Shandong News Channel	A S F		11		257 C		
	Shandong Economy Channel	A S F		12		258 C		
	Shandong Literature Channel	A S F		13		259 C		
	Shandong Life Channel	A S F		14		260 C		
	Shandong Traffic Channel	A F		15		261 C		
	Shandong City FM	A F		16		262 C		
3840 H	CCTV	A	DVB-S	27500-3/4		2184-3	C 0 5.5	E Chua 070806
	CCTV 1	A F		301	512	650 C		
	CCTV 2	A F		302	513	660 C		
	CCTV 7	A F		303	514	670 C		
	CCTV 10	A F		304	515	680 C		
	CCTV 11	A F		305	516	690 C		
	CCTV 12	A F		306	517	700 C		
	CCTV 15	A F		307	518	710 C		
3846 V	Shanxi TV	A	DVB-S	5950-3/4 1 - 160		0-1 80 C	C 0 5.5	Anonymous 090122
	Shanxi News Radio	A F		1		81 C		

7.5.3 NAVIGATION BY SATELLITES

The newest and most useful satellite application is the satellite-based navigation system. Two main satellite-based navigations are in operation today.

- Global Positioning System (GPS) of the USA
- Global Navigation Satellite System (GLONASS) of Russia.

The GPS navigation system employs a constellation of 24 satellites and ground support facilities to provide the three-dimensional position, velocity and timing information to all the users worldwide 24 hours a day.

The GLONASS system comprises 21 active satellites and provide continuous global services like the GPS.

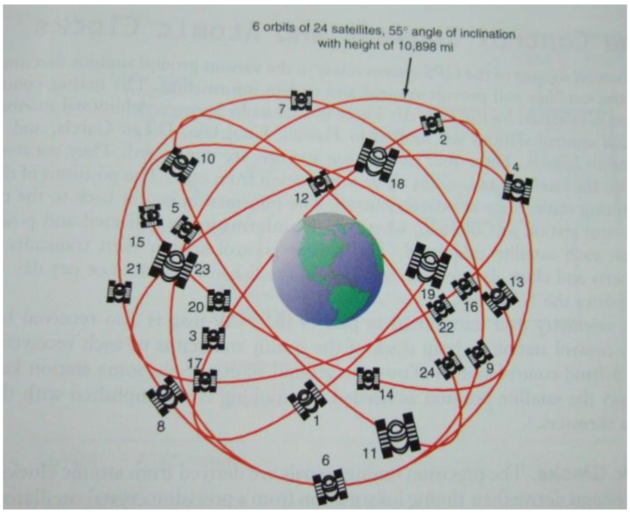
Only the GPS navigation system will be discussed in detail subsequently.

GLOBAL POSITIONING SYSTEM (GPS)

The GPS consists of three segments, namely the space segment, control segment and user segment. All three segments work in an integrated manner to ensure proper functioning of the system.

Space Segment

The space segment is a network of 24 Medium Earth Orbit (MEO) satellites plus 4 in-orbit spares spaced equally around the world in overlapping patterns.



- Satellites are placed in 6 orbital planes, with 4 satellites in each plane.
- Satellites orbit in circular orbits at an altitude of 20,200 km, inclined at 55^0 to the equator.
- Orbital period is around 12 hours.
- 4 to 10 satellites to be visible to all receivers anywhere in the world.
- All GPS satellites equipped with atomic clocks having a very high accuracy of the order of a few ns.
- Each satellite transmits signals, synchronized with each other on two microwave frequencies of 1575.42 MHz (L1) and 1227.6 MHz (L2).

Control Segment

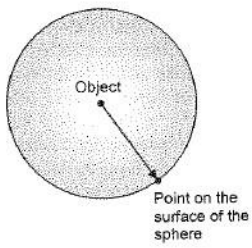
The control segment comprises a worldwide network of 5 monitor stations, 4 ground antenna stations and a master control station. These stations upload tracking information to GPS satellites as well as receive satellite telemetry data.

User Segment

The user segment includes all military and civilian GPS receivers intended to provide position, velocity and time information.

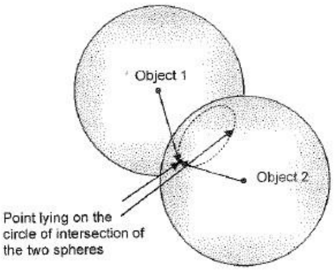
WORKING PRINCIPLES OF GPS

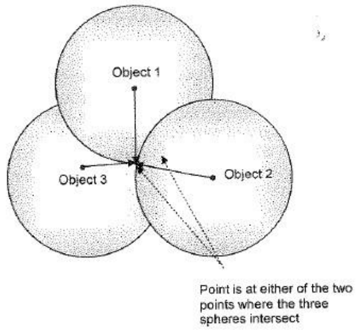
The basic principle of operation of the GPS is that the location of any point can be determined if its distance is known from four objects or points with known positions.



- If distance of a point is known from **one object**, then it lies anywhere on a sphere with the object as the centre, having a radius equal to the distance between the point & object.
- If distance of a point is known from **two object**, then it lies anywhere on the circle formed by the **intersection of two such spheres**.

- Distance from the **third object** can be found if it is known that the point is located at any of the **TWO positions** where the three spheres intersect.

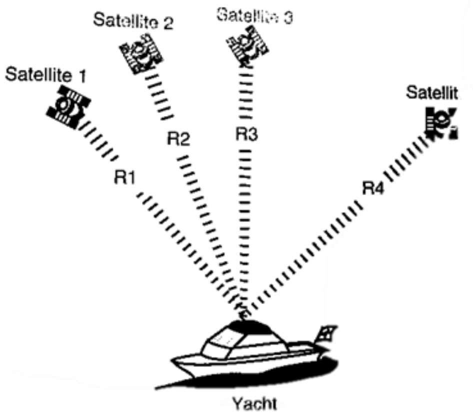




- Information from the fourth object reveals the **EXACT position** of the point as it is located at the point where the four spheres intersect.

- Fundamental concept behind GPS is to make simultaneous distance measurements from three (or four) satellites to compute the position of any receiver.

- GPS receiver calculates its distance from the GPS satellites by timing the journey of the signal from the satellite to the receiver. i.e. measuring time interval (Δt) between transmission of the signal from satellite and its reception by the GPS receiver.



- Velocity of propagation is known (speed of light, 3 x 10^8m/s), the relative path lengths (Pseudorange) can be computed in the receiver microprocessor by :

  Pseudorange = c Δt

- 4 simultaneous equations are then solved by GPS receiver processor to determine 3 variables (Latitude, Longitude, and Altitude) of the GPS receiver.

$$(x_1 - U_x)^2 + (y_1 - U_y)^2 + (z_1 - U_z)^2 = (\mathrm{PR}_1 \pm \mathrm{EC})^2$$
$$(x_2 - U_x)^2 + (y_2 - U_y)^2 + (z_2 - U_z)^2 = (\mathrm{PR}_2 \pm \mathrm{EC})^2$$
$$(x_3 - U_x)^2 + (y_3 - U_y)^2 + (z_3 - U_z)^2 = (\mathrm{PR}_3 \pm \mathrm{EC})^2$$
$$(x_4 - U_x)^2 + (y_4 - U_y)^2 + (z_4 - U_z)^2 = (\mathrm{PR}_4 \pm \mathrm{EC})^2$$

Where x_n, y_n, z_n = the n^{th} satellite coordinates;
U_x, U_y, U_z = GPS Receiver coordinates
PR_n = Pseudorange of the Receiver from n^{th} satellite coordinates
EC = error correction

APPLICATIONS OF SATELLITE NAVIGATION SYSTEMS

Military forces around the world use these systems for the following diverse applications:

- Navigation systems are invaluable tools for soldiers to navigate their way in unfamiliar enemy territory. They are replacing the conventional magnetic compass.

- Navigation satellites are used to track potential targets before they are declared hostile to be engaged by various weapon platforms.

- Navigation satellites are used to guide bombers and missiles to targets and position artillery for precise fire event in adverse weather conditions. Cruise missile commonly used by the USA with multi-channel GPS receivers to determine accurately their location constantly while in flight.

- Navigation satellites proved invaluable for determining the location of casualties during operations.

- Navigation satellites systems augment the collection of precise data necessary for quick and accurate map updates.

Satellite navigation systems have become commonplace for civilian applications:

- Mapping and construction.
- Saving lives and property.
- Vehicle tracking and navigation.
- Environment monitoring.
- Precise timing information.

TUTORIAL 7

1 (a) Define the term "Free Space Path Loss (FSPL)".
(b) Elaborate the two factors affecting the FSPL in satellite communication links.
(c) Compute the difference in the total (up and down links) path loss in dB between a 4/6 GHz and a 12/14 GHz satellite communication system.
Which is better from the path loss point of view?

2. (a) Define the terms "Effective Isotropic Radiated Power (EIRP)" & "Figure of Merit".
(b) Write down their mathematical expressions.
(c) Explain how they can be used to improve the quality of the uplink / downlink of the satellite communications link.

3. On a 4 GHz satellite down-link path, the earth station has an antenna with 60 dB gain, a total antenna and receiver effective noise temperature of 70 K. The satellite is at 36000 km above the earth station, and has an effective radiated power (EIRP) of 20 dBW.

(a) Calculate the "Figure of Merit" of the earth satellite station.
(b) If the transmit antenna gain of the satellite is 8dB, calculate the output power sent out by the satellite transponder in dBw & watt.
(c) Calculate the carrier to noise density ratio at the earth station receiver.

4. In a C band satellite uplink path, the slant range between the ground station and the satellite is 42,000 km and the EIRP of earth station is 45 dBW. Other losses along the path account for another 3dB. If the Figure of Merit of the satellite is 11 dB/K, calculate the C/N in dB for a system bandwidth of 36 MHz.

5. A Ku band satellite has the following parameters:

	Uplink	Downlink
EIRP	98 dBw	41 dBw
G/T	-5.3 dBK^{-1}	38 dBK^{-1}
FSPL	208 dB	206 dB
Other losses	7.6 dB	1.0 dB

(a) Calculate the round trip echo delay in ms.
(b) Determine the earth satellite station transmitter output power in kw, if the antenna gain is 64 dB.
(c) Determine the overall C/N ratio for a 36 MHz bandwidth signal.
(d) Without changing the link distance, suggest a way to reduce the FSPL of this link.

6. (a) Describe how the satellite constellations are formed in the space segment of the Global Positioning System.
(b) Briefly explain the principle of operation of Global Positioning System.

TUTORIAL GUIDE 7

1a-b)	Answer may be found by reading section 7.3.
1c)	16.9 dB
2a-c)	Answer may be found at page 125 Example 2 (BB)
3a)	41.55 (dB/K)
3b)	15.85 (watt)
3c)	94.55 dBHz
4	5.4 dB
5a)	550.5ms
5b)	2.51 kW
5c)	23.87 dB
6	Answer may be found by reading section 7.5.3.

LASER SAFETY

IT IS IMPERATIVE THAT YOU READ AND UNDERSTAND THE FOLLOWING SAFETY INFORMATION BEFORE ATTEMPTING ANY OF THE EXPERIMENTS DETAILED HERE. IF YOU HAVE ANY QUERIES PLEASE CONSULT YOUR LECTURER OR TSO.

Operational Hazard - Semiconductor Laser Diode

- The Laser Diode source emits infrared radiation at 1310nm and 1550nm which is **invisible to the human eye and may cause eye damage** if the output beam is viewed directly.

- When in use, **never stare at the optical output port of the Laser Diode** when its dust cap is removed to connect an optical fiber and always replace the device dust cap when the fiber is removed.

- Always leave the dust caps for the fiber patchcords in position until ready to make a connection and never stare at the end of a fiber patchcord connected to the Laser Diode output port or point the fiber end at yourself or anyone else in your vicinity before making a connection.

- Never use external optics (i.e. collimating lenses) to view the Laser Diode emission at close range.

- The output power of the Semiconductor Laser Diode is less than 2mW conforms to all applicable standards of DHHS regulations 21 CFR 1040.10 and 1040.11 and falls within international safety Class 3B.

Optical Communication Experiment 1

Bandwidth measurement of an optical fiber link

1. OBJECTIVES

☑ To determine the bandwidth of an optical fiber link through frequency response measurement

☑ To determine the bandwidth of an optical fiber link through system rise-time measurement

2. MATERIALS NEEDED

☑ Variable DC Power Supply
☑ Optical fiber system kit
☑ Oscilloscope
☑ Function generator
☑ Semi-log scale graph paper

3. INTRODUCTION

A complete optical fiber system may be assembled using three components: optical source, optical detector and an optical fiber. In order to ensure that the assembled system meets the desired system performance, both the power budget and rise-time budget must be satisfied.

The power budget is to ensure that there is sufficient power available throughout the link to meet application demands. The rise-time budget is to ensure that the link operate fast enough to meet the bandwidth requirements of the application.

The system bandwidth is determined by the rise-time of the light source, detector and the optical fiber.

The system rise-time t_r is related to the system bandwidth as follows: $\tau_r = 0.35 / BW$

In this experiment, you will determine the bandwidth of an optical fiber link by measuring the system frequency response & rise-time.

4. PROCEDURES & RESULTS

Part 1: Frequency Response Measurement

1. The optical fiber system kit provides a printed circuit board with a piece of Plastic Fiber as the optical link between the optical transmitter and receiver.

2. Connect the Function Generator to the optical transmitter Input. Set the Function Generator to Sinewave.

3. Connect the optical receiver Output to Channel 1 of the oscilloscope.

4. Switch on the DC power supply and set the supply voltage to 9V. Connect it to the optical fiber system kit power DC supply points.

5. Set the frequency of the Function Generator to 1.0 KHz. Press MEASURE and observe the output signal Vpp value on the oscilloscope Channel 1 as you slowly increase the frequency of the sinewave from 1 kHz, until you observe the output sinewave has reaches a maximum value.

6. Now slowly adjust the input signal amplitude by turning the Variable Resistor Knob (on the optical fiber system kit) such that the output signal on Channel 1 is showing an undistorted sine wave with signal level exactly at 6.0 Vpp.

7. **Now maintain the setting on the input signal amplitude and use this level throughout the whole experiment**.

There are TWO methods which can be used to estimate the bandwidth of the optical link.

METHOD 1

8. Vary the input signal frequency on the function generator from 100 Hz to 100 KHz. **Channel 1 should display undistorted sinewave output signal throughout the measurements.** Complete the following table:

Input Signal Frequency (Hz)	**Output Signal Level (Volt pp)**	**Input Signal Frequency (Hz)**	**Output Signal Level (Volt pp)**
100		4,000	
200		5,000	
300		10,000	
400		15,000	
500		16,000	
700		18,000	
800		20,000	
900		30,000	
1,000		50,000	
2,000		75,000	
3,000		100,000	

10. Plot the output signal level (in linear vertical scale) vs input frequency (in horizontal log scale) on a semi-log scale graph paper.

11. From the graph determine the bandwidth of the optical link using the 3 dB voltage point which is 0.707 of the maximum output signal level. Record the results.

Voltage at 3dB point V_{3dB}	
Frequency $F_{(low)}$	
Frequency $F_{(high)}$	
Bandwidth, BW $=F_{(high)} - F_{(low)}$	

METHOD 2

12. Increase the frequency of the sine wave from 1.0 KHz until the output voltage level of undistorted sine wave reached the **maximum** value**, i.e. 6.0 Vpp.** Record the frequency at V_{max}.

13. Continue to increase the frequency at the Function Generator until the output signal voltage Vpp is equal to the voltage at the 3dB point i.e. Vpp = V_{3dB} . Record the frequency value as $F_{(high)}$.

14. Now DECREASE the frequency at the Function Generator until the output sinewave signal reaches V_{3dB} value again. Record the frequency as $F_{(low)}$.

Frequency at V_{max}	
Frequency $F_{(low)}$	
Frequency $F_{(high)}$	
Bandwidth, BW $=F_{(high)} - F_{(low)}$	

Part 2 : Rise-Time Measurement

1. Use the same setup in Part 1. Change the Function Generator to “Square-wave” and set the frequency to 9 KHz.

2. Observe the output waveform on Channel 1. Measure the system rise-time on the oscilloscope. (Note: rise-time is defined as the time it takes for the output voltage to go from 10% to 90% of its maximum value).

System rise-time τ_r	
Bandwidth BW = $0.35 / \tau_r$	

5. DISCUSSION

1. From the graph, observe the frequency response at input signal operating frequencies below 50Hz and above 50 KHz. What is the characteristics of the optical fiber link?

2. Compare the system bandwidth measured using method 1 and method 2. Comment on the results.

3. Does the system bandwidth calculated from the rise-time measurement agree with the system bandwidth using the frequency response measurement? Explain why.

4. List down the 3 optical components used in the optical fiber link.

5. Suggest 4 ways to improve on the system bandwidth of the optical link.

---- END ---

Optical Communication Experiment 2

Attenuation measurement of an optical fiber link

1. OBJECTIVES

☑ To measure the optical power loss using insertion loss method

☑ To determine the loss and attenuation coefficient of the optical fiber.

2. MATERIALS NEEDED

☑ Attenuator box
☑ FC connector
☑ Optical fiber patch (2 pcs),
☑ Optical power meter
☑ Laser source

3. INTRODUCTION

Attenuation is the major source of signal degradation in optical fiber communication systems. It impose limits on the maximum link length of the optical communication system. Attenuation in optical communication system is mainly caused by the optical signal loss in the fiber and the connectors.

Insertion loss is the loss in transmitted light power when an optical device is inserted in the light path. The insertion loss measurement technique will be used to estimate the attenuation of an optical fiber and connector in an optical link. An optical fiber loss is measured as the optical power loss in dB at any point along the fiber length relative to the input power.

Attenuation of optical fiber or attenuator box is given by: **Attenuation (dB) = $10\log_{10} (P_1 / P_2)$**
P_1 is power measured with the optical fiber patch or reference fiber patch.
P_2 is power measured with the attenuator box or the Fiber under Test (FUT).

The attenuation for a given link length, L, of an optical fiber is then simply αL (dB).

Attenuation (dB) = $\alpha L = 10\log_{10} (P_1 / P_2)$

α is the **Attenuation coefficient of the fiber (dB/km), $\alpha = [10\log_{10} (P_1 / P_2)] / L$**

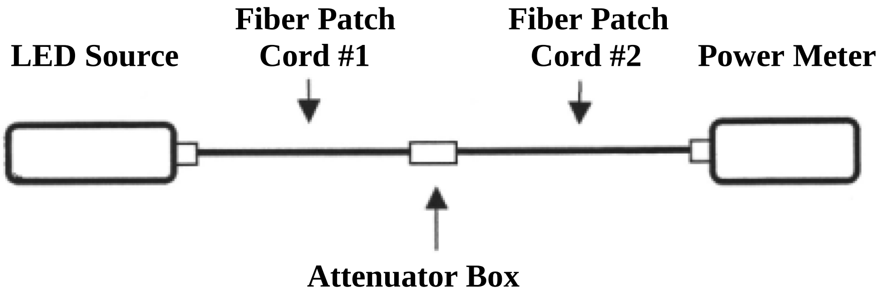
4. PROCEDURES & RESULTS

<u>Part 1: Attenuation box loss measurement by insertion loss method</u>

1. Connect the LED source to the optical power meter using short fiber patch cord #1 and short fiber patch cord #2.

2. Record down the power meter readings using 1550nm and 1310nm sources.

3. Insert the **Attenuator Box** between the two fiber patch cords.



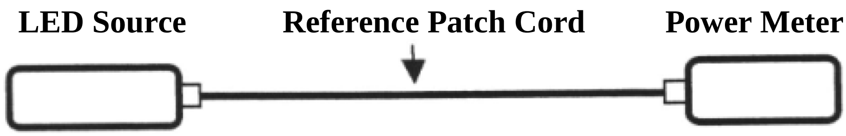
4. Record down the power meter readings using 1550nm and 1310nm sources.

LED Source	Power measured using two fiber patch cords (μW)	Power measured using two fiber patch cords and Attenuator Box (μW)
1310 nm		
1550 nm		

5. Determine the optical power loss (attenuation) of the attenuator box at 1550nm and 1310nm wavelengths using the above measured data.

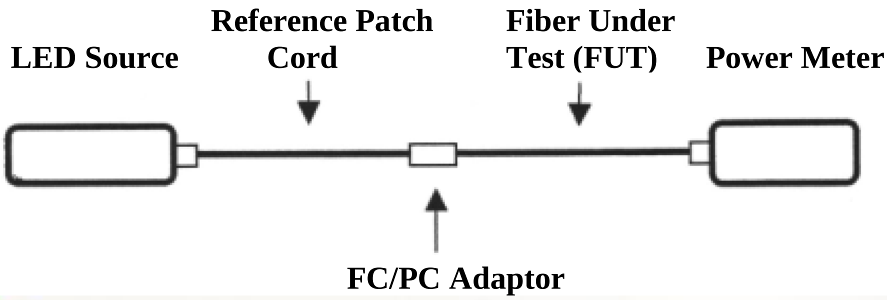
Part 2: Optical fiber Loss Measurements by insertion loss method

1. Connect the LED source to the optical power meter using short fiber patch cord #1 (Reference Fiber).



2. Record down the power meter readings using 850nm and 1310nm sources.

3. Insert the Fiber Under Test (FUT) between the fiber patch cord #1 (Reference Fiber) and the optical power meter.



4. Record down the power meter readings using 850nm and 1310nm sources.

LED Source	Power measured using Reference Fiber (μW)	Power measured using FUT and Reference Fiber (μW)
850 nm		
1300 nm		

5. If the length of the optical fiber (FUT) is 250m, determine the optical loss (attenuation) and the fiber attenuation coefficient (α) of the optical fiber at 850nm and 1300nm wavelengths using the above measured data.

6. Complete the following summary table and answer the following questions.

	Attenuation (dB)	Attenuation coefficient (dB/km)
850 nm		
1300 nm		

5. DISCUSSIONS

1. Compare the Attenuator Box loss using 1550nm and 1310nm LED source. Are they the same? Comment on the results.

2. Compare the optical fiber loss at 850nm and 1310nm. Are they the same? If not the same, give reasons to explain the difference in values.

3. Comment on the accuracy of the insertion loss measurement technique.

The insertion loss technique is more practical for field work. However measurement uncertainty is compromised by connector loss uncertainty. It is commonly used in field situations where acceptable measurement performance is obtained regardless of connector performance.

---- END ---

Optical Communication Experiment 3

Optical Fiber network analysis using OTDR

1. OBJECTIVES

☑ To perform OTDR investigations of network section.

☑ To identify and measure losses associated with the nature and location of faults or components degradation.

2. MATERIALS NEEDED

☑ OTDR
☑ Optical Network Analyser
☑ Optical fiber patch

3. INTRODUCTION

Optic fiber cables are increasingly deployed across the world to support the ever growing bandwidth demand by online users. In optical fiber networks, signal losses may occur in the fiber itself, or occurs at splices, connectors and within components, such as couplers and wavelength division multiplexers. Consequently, checking for losses in an optical network is essential in order to ensure proper functioning of the optical network throughout its lifetime.

Optical time domain reflectometry (OTDR) is the Industry Standard for measuring the loss characteristics of an optical fiber network. It is used to monitor the network status and to locate faults and degrading components. OTDR measures the loss for individual components of the fibre cable. OTDT can identify and measure the loss of individual components like splices or couplers, and measures the length of the optical cable and provide the location of the fault.
In operation, an OTDR launches pulses of light into the line fiber of an optical network and monitors the backscatter signal as a function of time relative to the launch time. As the pulse propagates down the fiber, it becomes weaker with increasing distance due to power loss, and the measured backscatter signal decreases accordingly.

The rate of signal decrease for a continuous section of fiber represents the fiber losses and any abrupt drops correspond to losses from the presence of components, terminations or faults which can be readily identified in the OTDR trace events. Figure 1 below shows the readily identified features on the OTDR signal referred to as events.

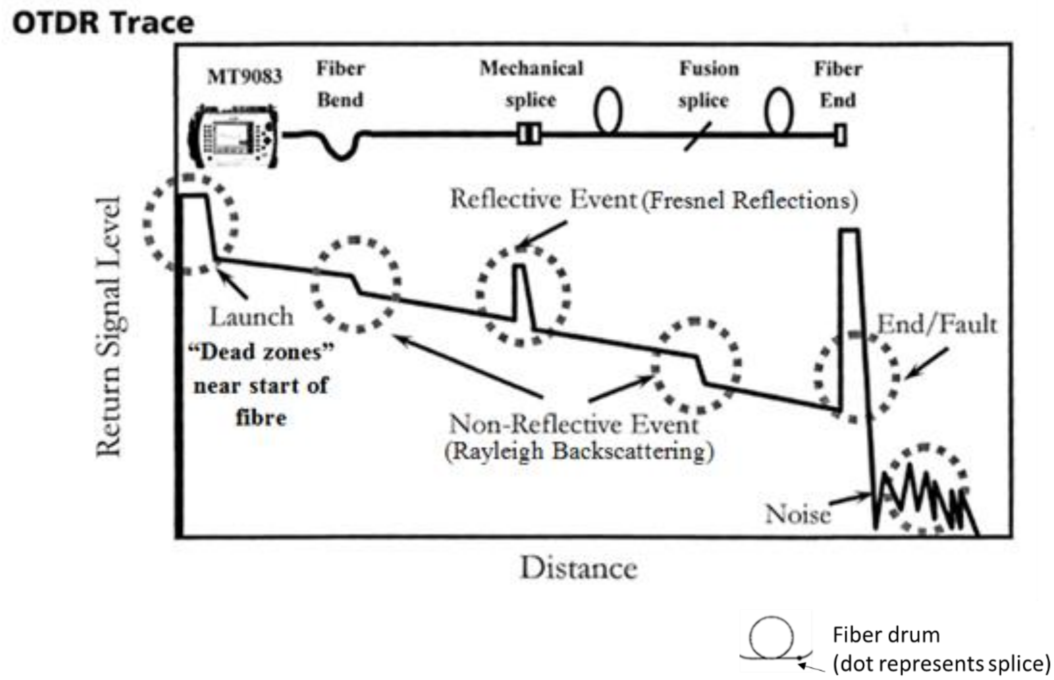


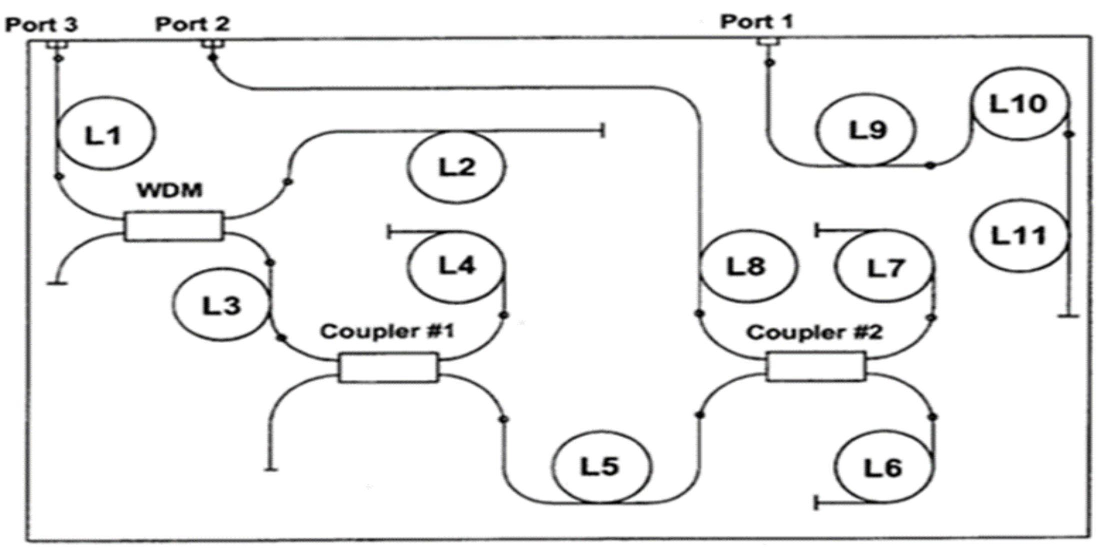
Figure 1 <u>An illustration of OTDR Events</u>

The following measurements may be performed by an OTDR:

For each event: Distance location & loss
For each section of fiber: Section length, section loss in dB & dB/km
For the complete terminated system: Link length & link loss in dB

4. PROCEDURES & RESULTS

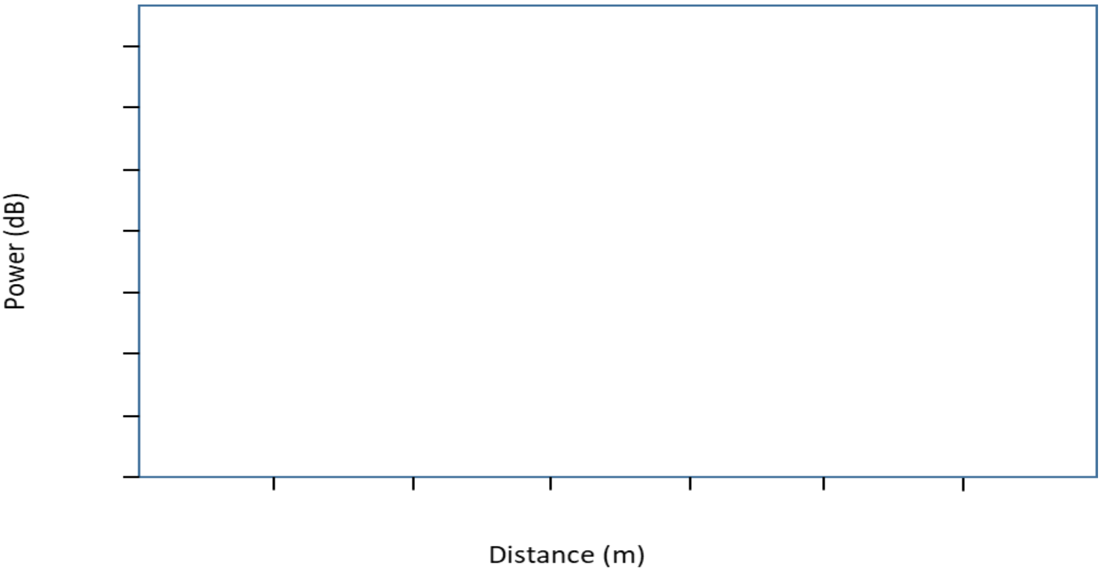
A single mode optical fiber network unit with 3 input ports is provided for investigation:



Part 1 : Investigation of connector and splice losses

Port 1 of the network unit is the input to a short length of fiber containing an average splice and a bad splice.

1. Connect the short fiber patch cord output at the OTDR to Port 1.
2. Set the OTDR wavelength to 1550nm.
3. Press the START button to begin acquiring the trace for this network at Port 1.
4. Sketch the OTDR trace.



5. Record the readings for the trace events in the Table below.

Event	**Type**	**Distance(m)**	**Loss(dB)**
Dead zone			
Splice 1			
Splice 2			
End of fiber			

5. Determine the total link distance and total signal loss.

6. Switch the wavelength to 1310nm and repeat the measurements. Comment on any differences observed between the two wavelengths.

Part 2: Investigation of a network section containing a fused fiber coupler

Port 2 of the network unit is linked to a length of fiber containing a fused fiber coupler which has a specified coupling ratio at 1550nm.

1. Connect the OTDR to Port 2 via the patch cord. Select OTDR Standard test.
2. Set the OTDR wavelength to 1550nm and acquire the OTDR trace of this network.
3. Record the measurements in the table below.

Event	Type	Distance(m)	Signal Loss(dB)

4. Switch the wavelength to 1310nm and repeat measurements. What is the Coupler insertion loss at 1550nm and 1310nm?

5. Compare and comment on the overall link loss at 1550nm and 1310nm.

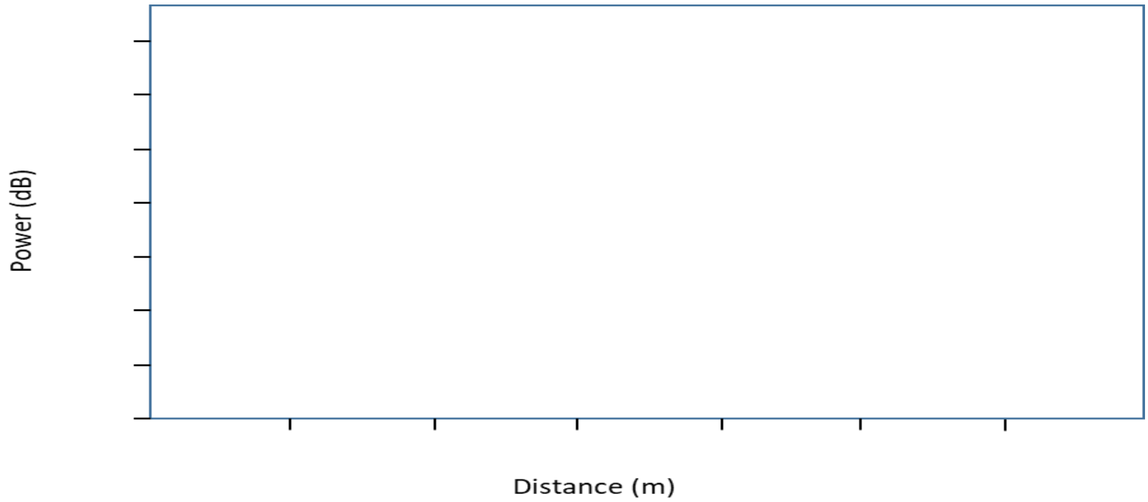
Part 3: Investigation of a simple network section

Port 3 of the network unit is linked to a length of fiber containing a wavelength division multiplexer (WDM) and two fused fiber coupler which has a specified coupling ratio at 1550nm.

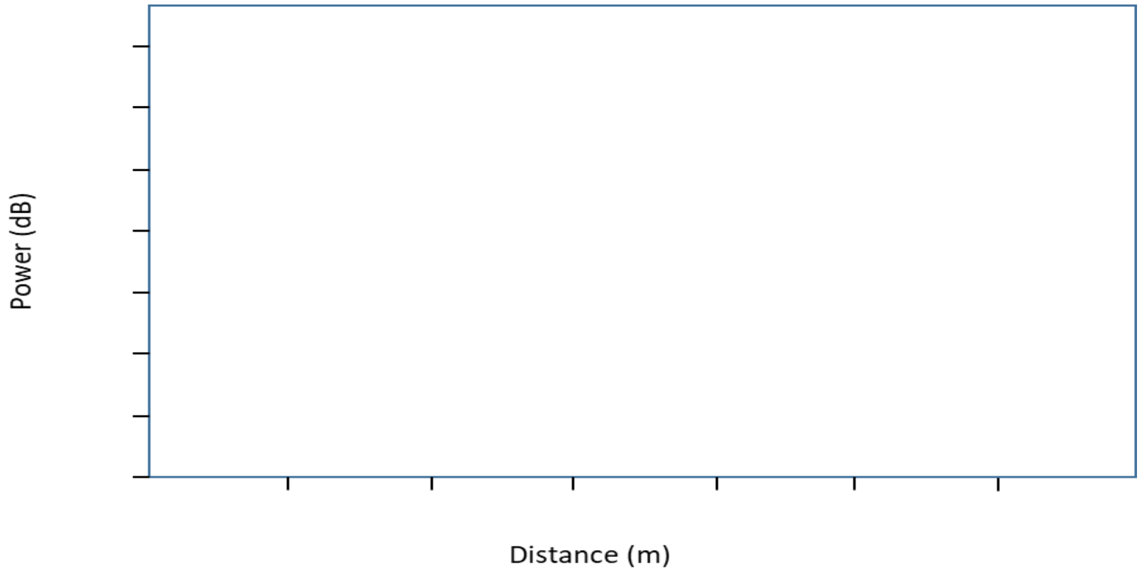
1. Connect the OTDR to Port 3 via the patch cord.

2. Set the OTDR wavelength to 1310nm and acquire the OTDR trace of this network.

3. Sketch the OTDR trace.



4. Switch the wavelength to 1550nm and sketch the OTDR trace.



5. DISCUSSIONS

Q1. What are the two operating wavelengths of the WDM?

Q2. Compare and comment on any visible differences observed between the OTDR traces of the two wavelengths for Port 3

Satellite Communication Experiment 1

Application of Geostationary Satellites – Broadcasting

1. OBJECTIVES

- ☑ To become familiar with the operation of a multi-satellite TVRO station.
- ☑ To assess signal quality of a TVRO signal received from a geostationary satellite.
- ☑ To estimate the signal to noise ratio (S/N) for a FM modulated TV signal.

.

2. MATERIALS NEEDED

- ☑ Satellite TV Spectrum Analyser r
- ☑ Television + remote control
- ☑ Satellite Receiver/Antenna Positioner + remote control

3. INTRODUCTION

Broadcasting satellites are geostationary satellites at 35,786 km altitude and located at fixed location to provide video (TV), voice (Radio) & data services to the TVRO users. The use of TVRO (TV Receiving Only) systems is becoming widespread throughout Asia, There are quite a lot of satellite televisions broadcasting channels that can be received in Singapore as can be seen in the picture below: Koreasat, Chinasat, Palappa, Thaicom etc.

116.0°E	Koreasat 6	120302
115.5°E	ChinaSat 6B	111026
113.0°E	Koreasat 5	120308
	Palapa D	120321
110.5°E	ChinaSat 5B *(incl. 0.5°)*	
110.5°E	ChinaSat 10	110821

80.0°E	Express AM2	120321
	Express MD1	120217
78.5°E	Thaicom 5	120326
76.5°E	Apstar 2R	120314
75.0°E	ABS 1	120326
74.9°E	ABS 1A *(incl. 4.7°)*	
74.0°E	Insat 3C	110909
	Insat 4CR	120321

Colour codes on this regional index: no data/L/S/Ka band C band C & Ku band Ku band moving

It is important for Technologists to know how to assess signal quality of these systems. A picture seen as being acceptable by one person may be seen as a poor quality picture by another person
Two of the most important parameters used to assess picture quality are C/N and S/N. Generally if the C/N is >10dB and the S/N is >40dB then a good quality television picture will result.
This experiment shows how C/N is measured using a spectrum analyzer and how S/N can be estimated from the carrier to noise ratio.

The relationship between C/N and S/N

For AM the S/N is equal to the C/N. For a TVRO system to produce a signal of >40dB C/N ratio at the receiver would be impossible. Hence FM must be used for TV transmitter over satellite in order to obtain the required S/N from a much lower C/N ratio signal.

Measurement of analog and digital satellite TV channels

The received signal is measured at the input to the satellite receiver in the Intermediate Frequency (IF) line from the Low Noise Block Converter.

The Satellite TV Spectrum Analyzer used in this experiment is the **PRODIG-5 TV Explorer**.

 **TV Mode**  **Measurements**

 **Spectrum Analyser Mode**

 **Digital/Analog measurement mode**

 **Auto ID / Explorer function**

Measurement mode

For analog channels : Carrier level, frequency, C/N.
For digital channels : Carrier power, frequency, C/N, BER(VBER & CBER).

Spectrum analyser mode

It allows user to discover the signals present in the frequency band of the selected satellite quickly and easily to make measurements at the same time

TV mode

It demodulates the currently tuned video signal and display the TV picture on the monitor.

Estimating S/N

S/N can be measured directly from the baseband video signal using the appropriate filter and weighting network. The equation link S/N to C/N in TVRO system is given by:

S/N = C/N + FM Improvement Factor, OR **S/N = C/N + 35**

TVRO System setup

Study the diagram in the left.

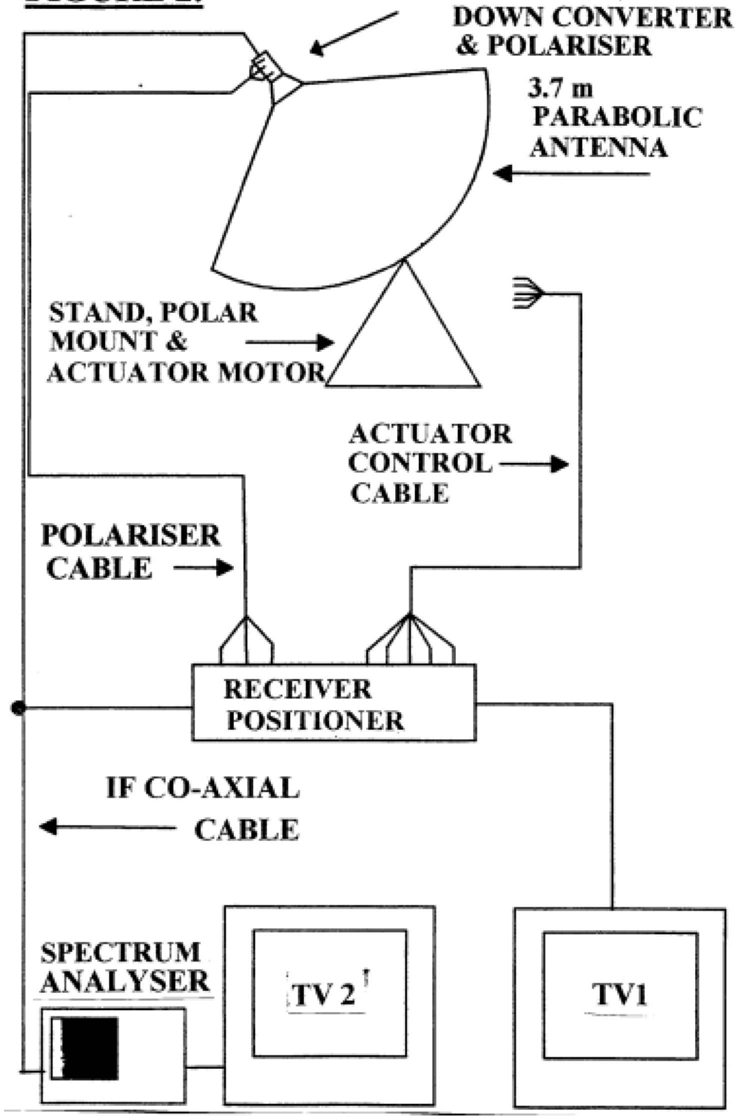
Identify the following items in the TVRO system :

- Parabolic dish (at rooftop)
- TVRO receiver
- PRODIG-5 TV Explorer
- LCD TV set.

Referring to the satellite dish next to the setup, identify the following components on the dish :

- Parabolic dish
- Feed horn
- Low Noise Amplifier (LNA)
- Down Converter (DC)

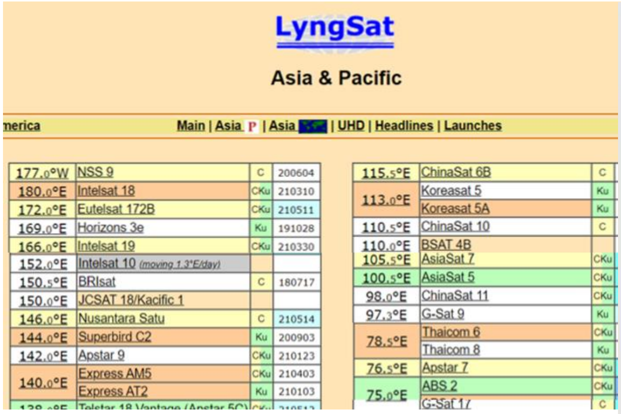
FIGURE 2.

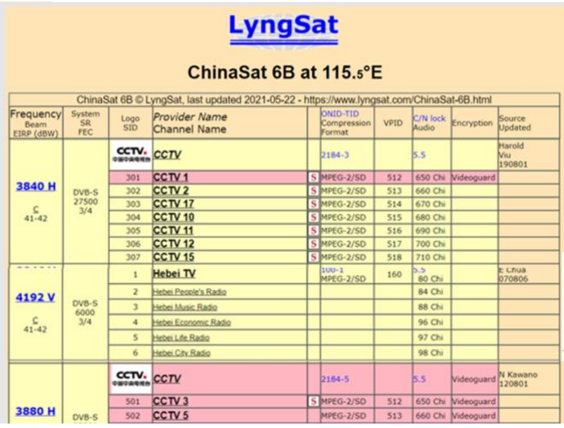


4. PROCEDURES & RESULTS

1. Switch on the TVRO receiver equipment and the Satellite TV Spectrum Analyser and set it to to "Spectrum Analyzer" mode to show the spectrum on the screen.

2. Go to the web site http://www.lyngsat.com/asia.html, to obtain the TVRO satellites available in Asia & South Pacific Region





4. Click on the Satellite and complete the table below:

Satellite Name	Satellite Location	Frequency Band (C/Ku)	Any 2 Horizontal Polarized Frequencies	Any 2 Vertical Polarized Frequencies
Chinasat 6B	115.5^{0}E	C	CCTV 3840H/3880H	Hebei 4192V…etc.
Asiasat 7				
ST2 (Singapore)				
Thaicom 6				

5. Use the remote control to move to **CHINASAT** and press **SELECT**. The dish should now move to the CHINASAT satellite and tune to Chinasat 6B Horizontal Polarized Channel 3840H.

6. Go to the web site http://www.lyngsat.com/asia.html, select Satellite **Chinasat 6B** and look at the CCTV 3840 MHz as shown below :

ChinaSat 6B © LyngSat, last updated 2021-05-22 - https://www.lyngsat.com/ChinaSat-6B.html										
Frequency Beam EIRP (dBW)	System SR FEC	Logo SID	*Provider Name* Channel Name		ONID-TID Compression Format	VPID	C/N lock Audio	Encryption	Source Updated
3840 H C 41-42	DVB-S 27500 3/4	CCTV	*CCTV*		2184-3		5.5		Harold Viu 190801
		301	**CCTV 1**	S	MPEG-2/SD	512	650 Chi	Videoguard	
		302	**CCTV 2**	S	MPEG-2/SD	513	660 Chi		
		303	**CCTV 17**	S	MPEG-2/SD	514	670 Chi		
		304	**CCTV 10**	S	MPEG-2/SD	515	680 Chi		
		305	**CCTV 11**	S	MPEG-2/SD	516	690 Chi		
		306	**CCTV 12**	S	MPEG-2/SD	517	700 Chi		
		307	**CCTV 15**	S	MPEG-2/SD	518	710 Chi		

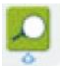
7. Determine the Intermediate Frequency (IF) carrier using the following equation:

   IF carrier (MHz) = *LO carrier – RF carrier (*LO carrier is fixed at 5150 MHz)

   IF carrier (MHz) = 5150 – 3840 = 1310 (MHz)

8. Press the Prodig-5 TV Explorer Spectrum  button located at the middle of the TV Explorer.

9. The display screen will show the satellite spectrum measurements (Frequency, Power, C/N and VBER). Set the frequency value to "1310 MHz".

10. Press the Auto Identification  button located at the middle of the TV Explorer.

11. When the signal is digital, it analyses the modulation type (for Satellite signal - QPSK) and all associated parameters (Frequency, C/N, Power, CBER & VBER) are displayed.

12. Fine-tune the IF frequency by rotating the tuning dial to obtain **Highest** C/N ratio.

13. You can view the TV picture of digital channels (NOT analog) on the monitor by pressing the TV  button.

14. Press the Measurements  button at the middle of the TV Explorer again. Record down the Carrier power (dBm), BER, C/N Ratio in the table below.

RF Carrier (Freq Tp)	IF Carrier Frequency (MHz)	IF Carrier Power (dBm)	BER (VBER)	C/N Ratio (dB)	Estimated S/N Ratio (dB)
3840 H					

Note: IF carrier (MHz) = LO carrier – RF carrier

15. To review all TV /Radio / Data channels in the same IF carrier, press the "Left/Right Arrow key" to view each channel.

RF Carrier (Freq Tp)	Channel Name	Channel Numbers (SID)	Bit Rate (bps)	
			Video	Audio
3840 H	***Video***			
	CCTV 1			
	CCTV 2			
	CCTV 17			
	CCTV 10			
	CCTV 11			
	CCTV 12			

16. Go to the web site http://www.lyngsat.com/asia.html, select Satellite **Chinasat 6B** and look at the Row with Frequency 4192V as shown below :

RF Carrier (Freq Tp)	IF Carrier Frequency (MHz)	IF Carrier Power (dBm)	BER (VBER)	C/N Ratio (dB)	Estimated S/N Ratio (dB)
4116 H					

Note: IF carrier (MHz) = LO carrier – RF carrier

RF Carrier (Freq Tp)	Channel Name	Channel Numbers (SID)	Bit Rate (bps)	
			Video	Audio
4116 H				

5. DISCUSSIONS

1. At the TVRO site, carrier signals received from **different satellites** have different measured levels. Analyse the factors that could result in the different measured values.

   Hints: Use the following **satellite link power budget expression** to analyse.

   $$(C)_{dBw} = (P_T)_{dBw} + (G_T)_{dB} + (G_R)_{dB} - (L)_{dB}$$

2. At the TVRO site, carrier signals received from the **same satellite** have different measured levels. Analyse the factors that could result in the different measured values.

   Hints: Use the following **satellite link power budget expression** to analyse.

   $$(C)_{dBw} = (P_T)_{dBw} + (G_T)_{dB} + (G_R)_{dB} - (L)_{dB}$$

3. Are the TVRO broadcasting satellites in Geostationary or Orbital orbits? Give reason to support your answer.

4. Name the different types of baseband signals carried by the TVRO broadcasting satellites.

5. What parameters should be used to assess the quality of analogue & digital TV channels?

---- END ---

Satellite Communication Experiment 2

Radiation Pattern Measurements of Dish Antenna

1. OBJECTIVES

☑ To investigate the gain and directivity of the dish antenna.

☑ To estimate the gain of the dish antenna using dipole.

☑ Estimate the sidelobe radiation level of the Dish Antenna

2. MATERIALS NEEDED

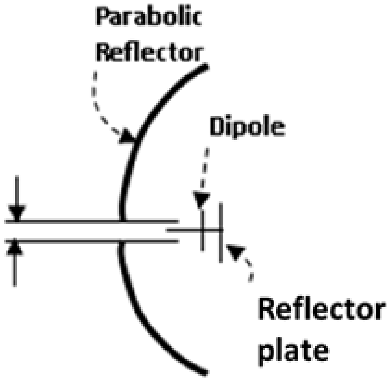
☑ Parabolic dish

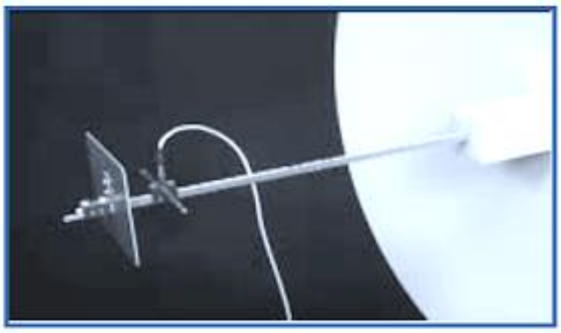
☑ Dipole

☑ Antenna Modelling System + PC

3. INTRODUCTION

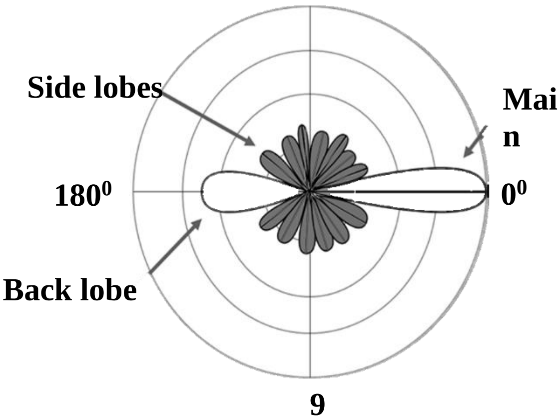
In this lab setup, a simple dipole with reflector plate is to perform the task of the feed horn. It is located at the focus of a 60cm parabolic dish. The dipole is just a half-wave conductor that that divided a feeder from a receiver or transmitter. A dish is a passive reflector that focuses energy from a source into one direction, much as a parabolic mirror focuses light.



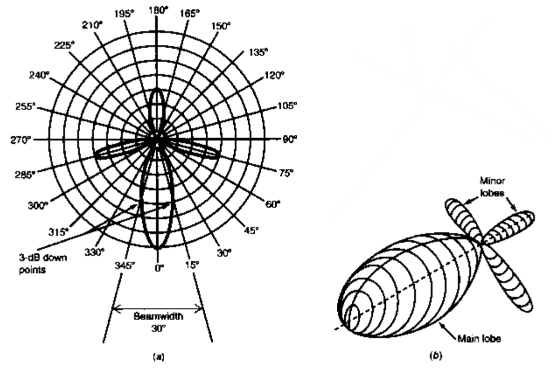


Radiation pattern

The energy radiated by the antenna is represented as the radiation pattern of the antenna. Theoretical radiation pattern and the practical polar plot of the Dish antenna is shown in Figures below.



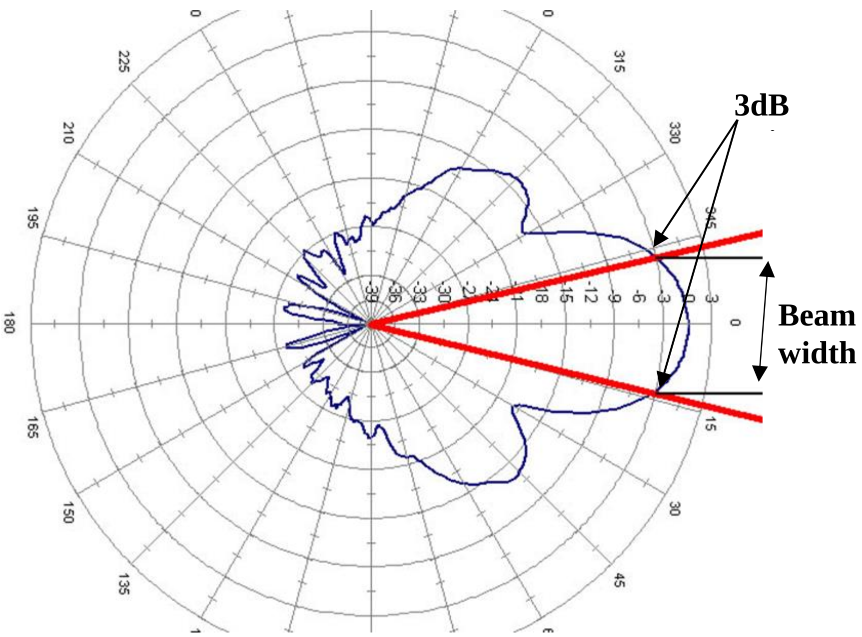
Radiation pattern



Practical Polar Plot of Dish antenna

Beamwidth

Beam width is the angular width between **half-power points** of the main lobe of the antenna radiation pattern, i.e., the angle subtended by the 3dB points on the radiation pattern of the antenna. It is an indication of the **directivity** of an antenna.



Beam width measurement of Dish Antenna

Gain

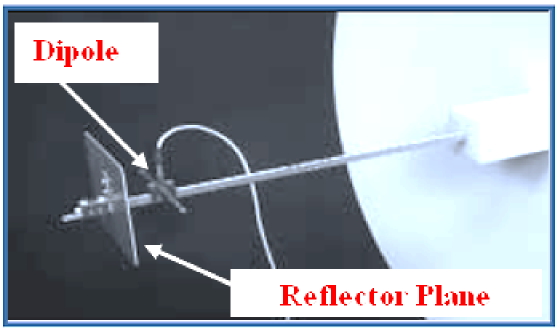
Gain in a transmitting antenna, gain represents the antenna’s ability to convert input power to radio waves. In a receiving antenna, gain represents the antenna’s ability to convert radio waves into electrical power.

Antenna gain and beam width are inversely proportional. The higher the gain of an antenna, the smaller the area coverage and this is actually the measured beam width. Higher antenna gain may not always be advantageous. It depends on the coverage area required.

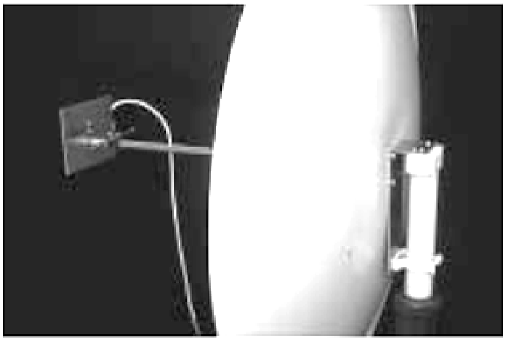
4. PROCEDURES

Part 1 Radiation pattern & Beam Width of Dish Antenna

1. Identify the Dish Antenna. Mount Dish Antenna with the boom assembly on top of the Generator Tower and position the dipole **horizontally** on the boom assembly at a distance of 5cm spacing between the reflector plane and dipole as shown in Figures below :



Dish Assembly Front View



Dish Assembly Rear View

2. Position the receiving antenna array **horizontally** and point it to the transmitting dipole antenna.

3. On the screen menu, select Polar plot and set the frequency value to **“1500 MHz”**.

4. Press “ENTER” and quickly move away from the Dish antenna setup. The boom assembly will rotate 360^0. A Polar Plot of the radiation pattern will be display on the screen.

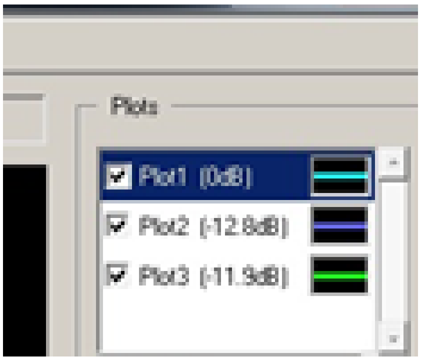
2. Set the scale to min:-15dB and Max: 0dB.

3. Print out the radiation pattern of the dish antenna on the Colour HP Printer.

6. Draw the 3 dB curve on the printed graph (at -3 dB circle). Estimate the beam width of the dish antenna on the polar plots from the print out:

Dish antenna **BEAM WIDTH** = ________

Part 2 Estimate the gain of the Dish Antenna using Dipole



1. Re-position and align the dipole and receiving antenna.

2. Press “C” to change from a 35 dB range to a 70dB range.

3. Press “S” to superimpose a new plot of dish antenna on the original dipole polar plot at 1500 MHz.

4. Record down the differential value in dB shown on the screen. This gives the gain of the dish antenna over the dipole antenna at 1500MHz.

   Gain of the dish antenna over dipole = _____________ dB (dB relative to dipole antenna)

5. As the gain of the dipole relative to isotropic antenna is 2.15 dBi

   Hence, the dish antenna has a gain of _________dBi (dB relative to isotropic antenna).

Part 3 Estimate the sidelobe radiation level of the Dish Antenna

1. The sidelobe radiation level (in dBi) of the dish antenna can be determined using the plotted radiation pattern of the dish antenna and the calculated dish antenna gain.

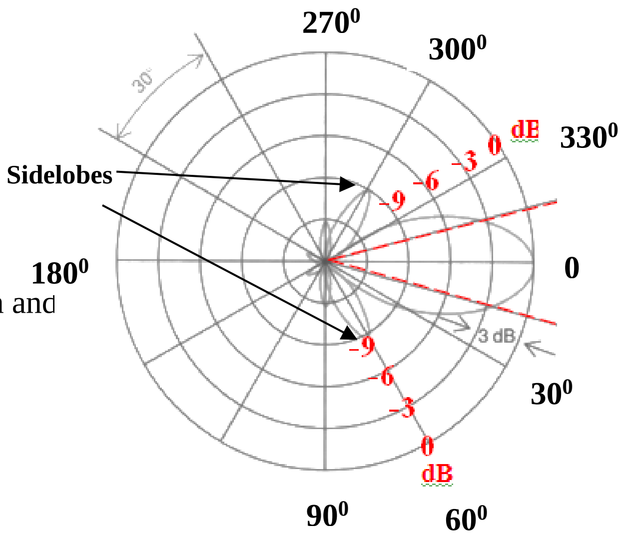
2. Assume that the plotted radiation pattern of the dish antenna is shown in Figure below.

   <u>EXAMPLE</u>
   If the calculated gain of the dish antenna is G = 7(dBi), The nearest sidelobe is located at 300^0 or 60^0 from the boresight (max gain) of the dish antenna.

   Hence the radiation level of the sidelobe will be:

   e.g. $S(60^0 \text{ or } 300^0) = G\ (\text{dBi}) - 9\ (\text{dB})$

   $= 7 - 9 = -2\ (\text{dBi})$



4. Now use your plotted dish antenna radiation pattern and the calculated dish antenna gain value to determine the nearest sidelobe radiation level in dBi.

---- END ---

Satellite Communication Experiment 3

Application of Global Position System – GPS

1. OBJECTIVES

☑ To understand how GPS locate a position.

☑ To understand the basic navigation information provided by a GPS.

☑ To perform “on road” tracking using the NEO-M8P.

2. MATERIALS NEEDED

☑ PC installed with u-center_v20.10.exe

☑ GPS modules NEO-M8P and Pro Micro Arduino board

☑ Map set of compass or string with pens/pencils and thumb tacks

3. INTRODUCTION

There are GPS satellites (31 satellites) orbiting the earth operated by US Defence agency. These satellites are in circular Medium Earth Orbit (MEO) at an altitude of 20,200 km. GPS satellites are always sending out radio signals that can be used in five main applications: Locating a position, Tracking, Navigation, Mapping and Timing.

The two most common applications are the tracking of locations and navigation. Tracking of people, valuables, keeping watch over elderly, monitoring delivery trucks, and catching criminals are some familiar usages. Navigation is widely used by the transport industry for planning routes, and by unmanned aerial vehicles (UAVs) for resource mapping and aerial surveying.

Locating a position on earth uses two basic mathematical concepts:

i) Trilateration, which is the positioning from three distances.

ii) Distance = Rate × Time, which is the relationship between distance travelled, rate (speed) of travel and amount of time spent traveling

The first concept, trilateration, determines your position by knowing the location of orbiting GPS satellites and the distance from those satellites to your position on earth. However, to measure the distance from your position up to the satellites, we estimate the distance by using the second concept, relating distance with rate and time.

4.0 PROCEDURE

Part 1 <u>How GPS locate a position.</u>

1. Calculate the distance of the four satellites (A, B, C, D) to your location on the ground using the timing received from the satellites A to D shown in the tale below:

	Satellite A	Satellite B	Satellite C	Satellite D
Timing received, t sec	0.00988783s	0.00663206s	0.00502010s	0.00398925s
Distance = c x t m/s C is $3x10^8$ m/s				
SCALED DISTANCE (cm) =Distance/(3500x100)				

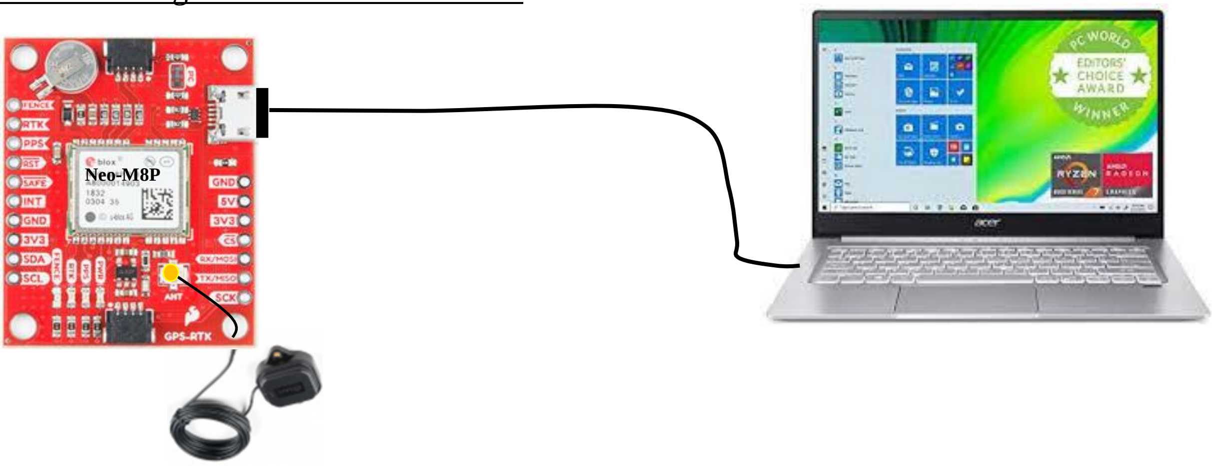
Note: We are using scaled distance (1:3500) so your location will be just an estimate.

2. The position of the satellites are marked on the Map shown below. <u>For each satellite</u>, take the compass with the SCALED DISTANCE fixed as radius and draw a Circle on the Map. If the circle is too big, then just the biggest Arc will do.

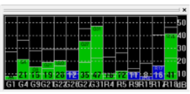
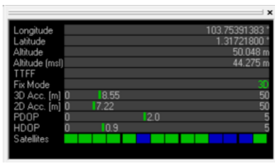
3. Repeat step 2 for Satellite B. Notice how the circle or Arc A and B intersects each other at two points. The area within these two points are your possible location.

2. Continue drawing the circle or arc for Satellite C and D, observing how your location is getting more precise each time. Notice there should only be one place on the map where all your series of arcs and circles intersect each other. This is where your location is.

Part 2: Basic navigation information for GPS

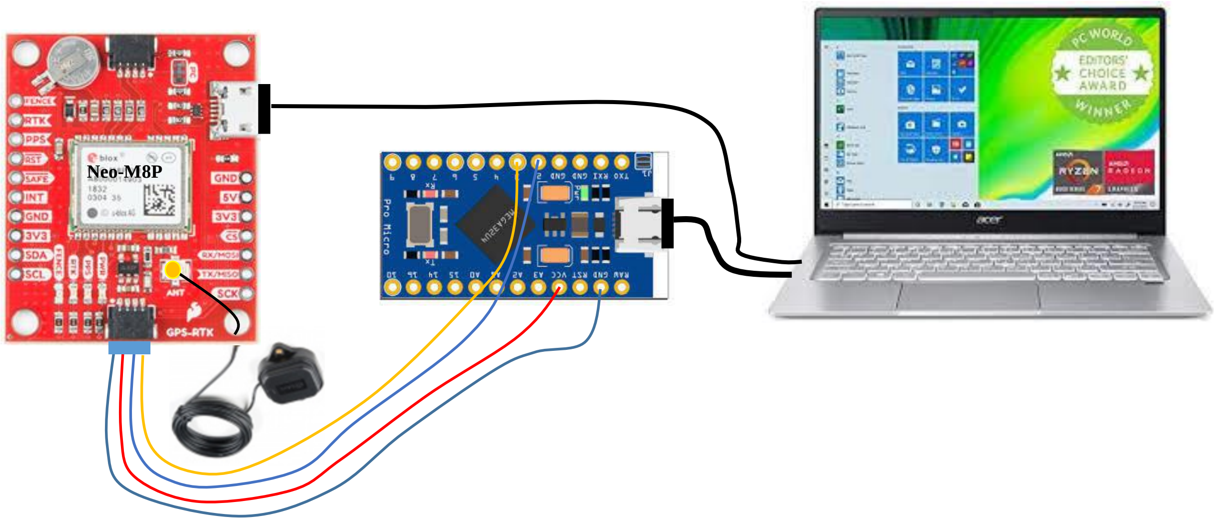


1. Connect the GPS Neo-M8P to the Laptop and launch U-center. Observe and record the following information in the table below:

Sky view  It shows the position of each visible satellite (1-31) in graphic sky view format. If a satellite is not currently being tracked (e.g. satellite signal blocked by building or obstruction), it will be displayed differently on screen.	How many satellites are in communication link with GPS Neo-M8P? ____
Satellite Bar Graph  It displays the signal quality of each visible satellite graphically. The satellite numbers (1-31) are represented along the horizontal axis (bottom of the graph) and the signal quality (10 –weakest to 50 -strongest) is represented along the vertical axis.	How many satellites are of strength greater than >30? ____
Location coordinates  Altitude – vertical height above earth surface Positional DOP : <4 – very good Horizontal DOP:< 3 – very good	Latitude :____________________ Longitude:____________________ Altitude :____________________

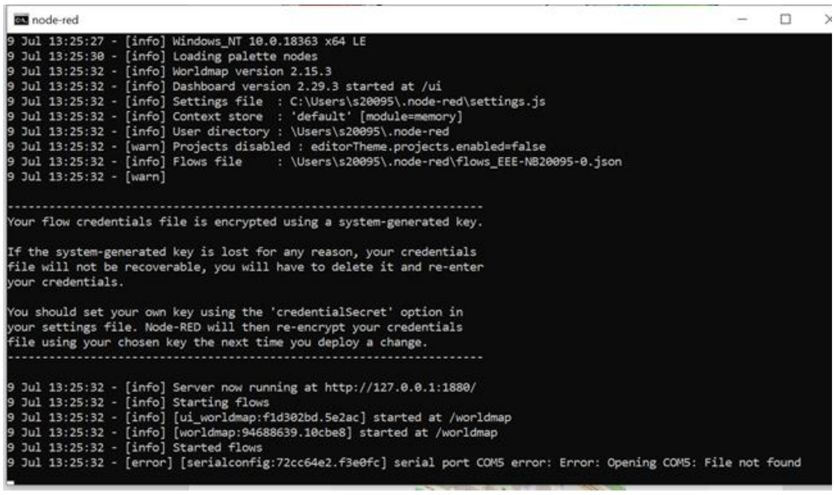
Part 3: Tracking of location by GPS

1. Connect GPS Neo-M8P to the Arduino board as shown in the diagram below. This setup will allow the GPS to track your location and present your position on the map.



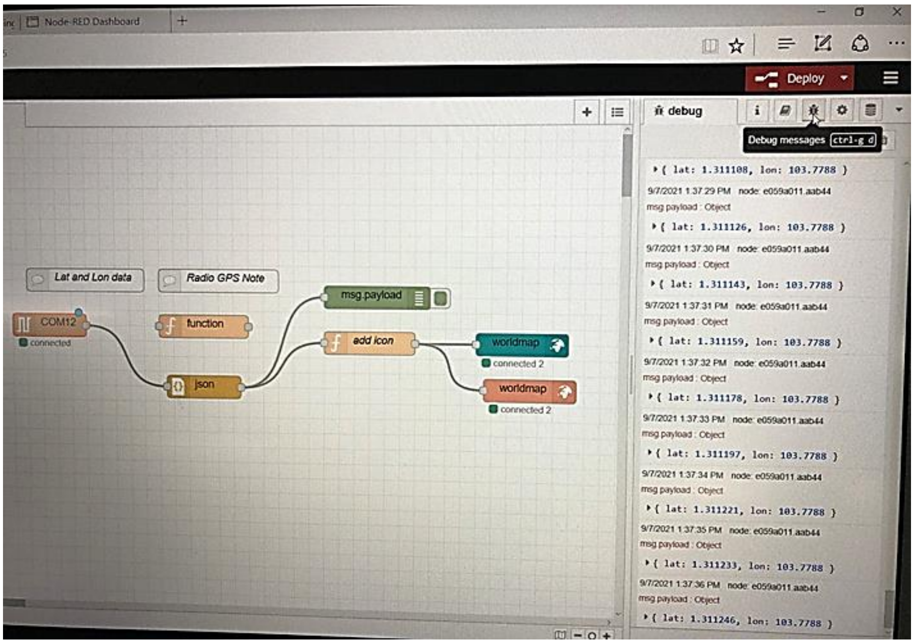
2. Press Window-R and type cmd to launch command prompt. At command prompt, type

   C:\users > **node-red**.

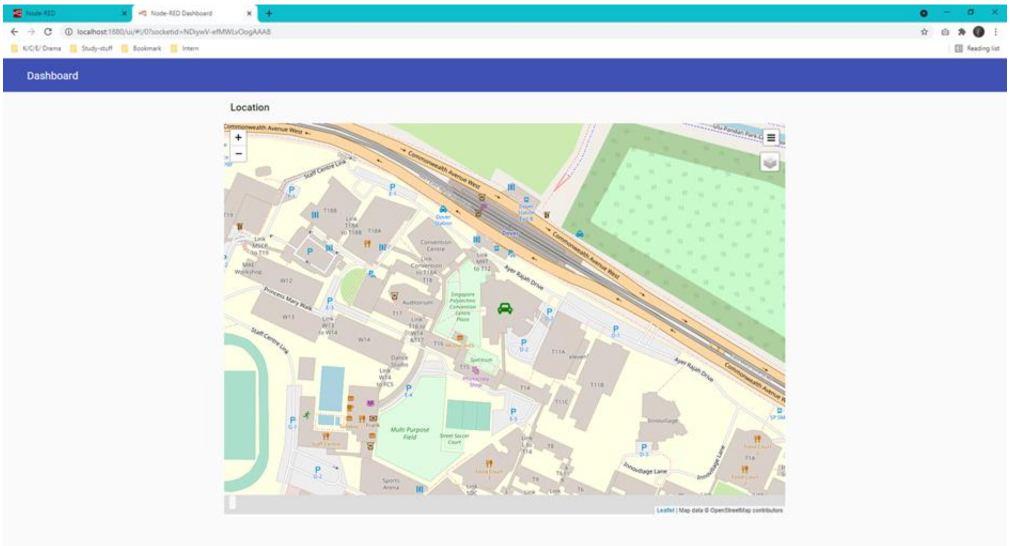


3. Launch the internet explorer and enter **Localhost:1880.**

4. Click on Com12. Check that the baudrate is 57600. Click Done. Click Deploy. Click on Debug messages to view the latitude and longitude.



5. Press CTRL+SHIFT – M to see your location on the map. Is it accurate?



6. Observe how the car position change on the map as you shift the antenna. Can you explain why?

____

____

5.0 DISCUSSION

Q1. Give three reasons how GPS may show the wrong position.

____

____

____

Q2. Discuss why 3 or 4 satellites are needed to determine a position.

____

____

____

Q3. Discuss the accuracy of position provided by the GPS.

____

____

____

Appendix Parameters used to specify practical antennas

The following parameters are used to specify practical antennas :
- Decibels
- Radiation pattern
- Bandwidth
- Beamwidth
- Gain
- Effective Isotropic Radiated Power (EIRP)
- Polarisation

1 Decibel (dB)

The unit Decibel is a logarithmic unit. It is used in a number of ways.

Used to express power gain and attenuation in dB

Power gain expressed : G(dB) = 10 log G(ratio) or $G(ratio) = 10^{dB/10}$

Power loss expressed : L(dB) = 10 log L(ratio) or $L(ratio) = 10^{dB/10}$

Used to express power levels in dBm or dBw

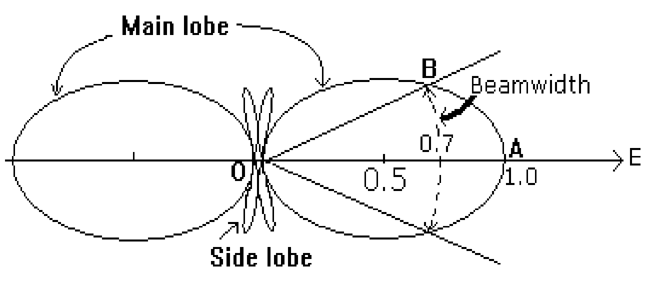
Power level expressed : P(dBm) = 10 log P(mw) or P(dBw) = 10 log P(w)

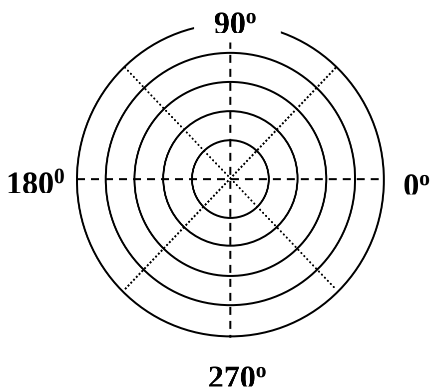
Power level expressed : $P(mw) = 10^{dBm/10}$ or $P(w) = 10^{dBw/10}$

Notes : dB, dBm and dBw can be added or subtracted accordingly.
dBm + dB = dBm, or dBm – dB = dBm
dBw + dB = dBw, or dBw – dB = dBw
dBm – dBm = dB, or dBw – dBw = dB

2 Radiation Pattern(Polar Diagram)

The **radiation pattern** of an antenna is known as its **polar diagram**. It is a graphical representation (using polar coordinates) of the manner in which either the **electric field**, or the **power density** varies at EQUAL distances from the antenna in a particular plane.
Since P is proportional to E^2 there is a corresponding difference in the shapes of their respective polar diagrams.





A typical radiation pattern

Above figure shows E field polar diagram of **a directional antenna** in the plane containing the antenna axis. The radiation pattern has **2 main lobes and 4 sidelobes**.

The maximum field strength is OA.

The field strength at direction OB is 0.7 times the maximum field strength (0.707 x OA).
At some directions, like 90^o & 270^o, field strengths are zero, these are known as null points.

3 Beamwidth

In above Figure, angular width between **half-power points** of the main lobe of the antenna radiation pattern, i.e., the angle subtended by the 3dB points on the radiation pattern of the antenna.

It is a **measure of the directivity** of an antenna. It is the angle within which the power intensity **exceeds half the maximum power intensity**. In terms of the electric field strength it becomes the angle within which the E field exceeds $0.707E_{(max)}$.

4 Bandwidth

It is defined as the difference between the frequencies at which the received power is -3dB of its maximum value, in the direction of maximum radiation. Within the frequency range, the operation of the antenna is satisfactory.

5 Antenna Gain

The **maximum directive gain** (also called the antenna gain) of an antenna is defined as the ratio of the maximum power density produced by the test antenna at a point in the direction of maximum radiation to the maximum power density that would be radiated at the same point by a reference antenna.

$$\text{i.e. } G = \frac{\text{Maximum Power density from the test antenna}}{\text{Maximum Power density from reference antenna.}}$$

(Where **input power** to both antennas is the **same**).

Notes : G is expressed in **dBi** if reference antenna is an isotropic antenna (isotropic antenna)

G is expressed in **dB_d** if reference antenna is a $\lambda/2$ dipole ($\lambda/2$ dipole antenna).

It can be shown that the gain of a $\lambda/2$ dipole relative to the isotropic antenna is : **1.64 or $0\ dB_d = 10\log(1.64) = 2.15$dBi**.

6 Effective Isotropic Radiated Power (EIRP)

The EIRP of an antenna is the power that **an isotropic radiator** would have to radiate to produce the same field strength at a particular point in the direction of maximum radiation.

Numerically, the EIRP of an antenna is equal to the *product* of the effective power input to the antenna P_T and the gain G of the antenna measured with respect to an isotropic radiator, i.e, the effective isotropic radiated power

EIRP = $(P_T)(G)$ in watt or EIRP = P_T(dBw) + G(dB) in dBw

Example

An antenna with a gain of 20dBi connects to a transmitter with output of 1.kW.
Hence the **effective power input** to the antenna is1kW, calculate the EIRP of the antenna.

[Soln] Because 20 dB is equivalent to a power ratio of 100, hence G = 100
EIRP = P_T G = 1kw x 100 = 100kw.

Alternatively, 1kw is equivalent to a power of 10[log(1000)] = 30 (dBw)

Hence, P_T = 30 (dBw) and, EIRP = P_T(dBw) + G(dB) = 30 + 20 = 50(dBw)

which is **equivalent to 100kW**

7 Polarisation

The orientation of the electric field component of the radiated EM wave is called its polarisation. If the direction remains constant with time at a fixed point in space, the field is said to be **linearly polarised**. The terms **vertical, horizontal and slant** polarisation are frequently used to denote linear polarisation with the appropriate orientations.

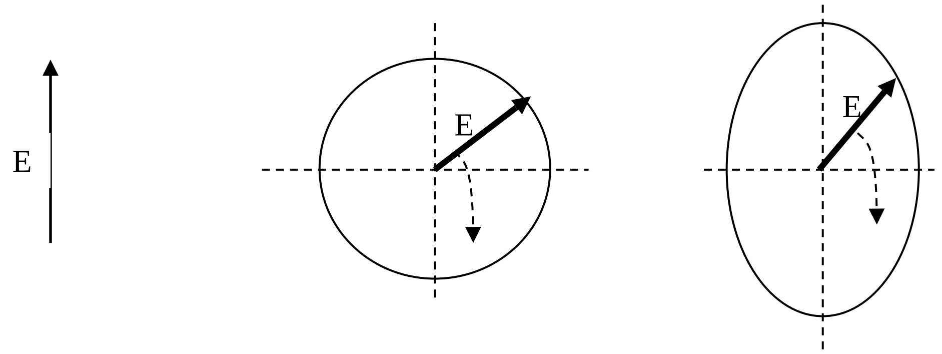
For example, if a dipole antenna is positioned vertically with respect to the earth's surface then it will radiate vertically polarised EM waves.

An antenna is said to be horizontally (or vertically) polarised if the antenna is positioned horizontal (or vertical) with respect **to** the earth's surface.

For **circular polarisation** the **E field vector has constant magnitude** but its direction, in the plane perpendicular to the velocity of propagation, **rotates smoothly through 360 degrees per wavelength of propagation**.

An antenna is said to be **Left-Hand (or Right-Hand) Circular Polarised** if the E field vector rotates anticlockwise (or clockwise) smoothly through 360 degrees per wavelength of propagation.

For **elliptical polarisation** the tip of the electric field vector traces an ellipse as it rotates 360 degrees per wavelength of propagation.



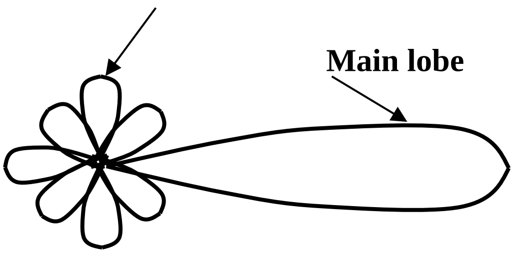
Polarization of waves

8 Radiation Dish antenna

Directional antennas provide greater efficiency of power transmission. With omnidirectional antennas, the transmitted power radiates out in all directions. Only a small portion of the power is received by the desired station, the rest of the radiated power is in effect wasted.

When the antenna is made directional, e.g. satellite dish antenna, the transmitted power can be focused into a narrow beam directed towards the desired stations.

Satellite dish antennas are designed to be unidirectional to send or receive signals in **one direction only**. Figure belowshows the directivity pattern of a highly directional antenna. The large loop represents the **mainlobe** which has maximum radiation or reception in this direction. The 7 smaller patterns or loops radiate power in different directions from the mainlobe are called **sidelobes**. These sidelobes are undesirable and must be minimized through various antenna design.

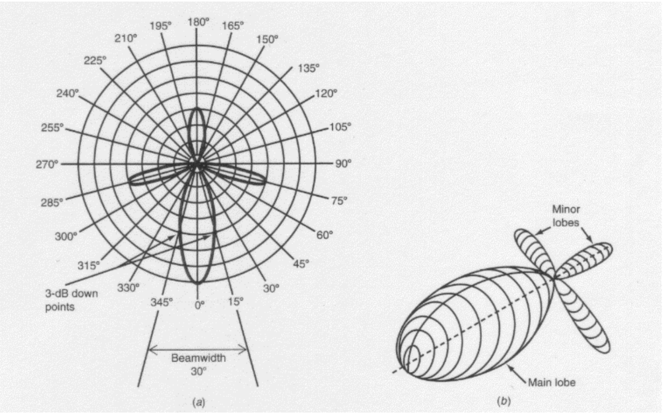


Radiation Pattern of Unidirectional Antenna

For a good directional antenna, mainlobe must be as high and as narrow as possible in order to put more power in the desired direction, sidelobes must be as little and as low as possible in order to eliminate power waste in other directions.

The beamwidth of a half-wave dipole antenna is about 78^0, this is not a highly directional antenna. The narrower the beamwidth, the better the directivity and the more highly focused the signal. Some of the large satellite dish antennas at earth stations can have beamwidth as narrow as 1^0 or less.

Figure below shows the polar plots of **highly directional antenna (satellite dish)**.



Polar plots – Horizontal and 3-D Radiation Pattern of a Highly Directional Antenna.

Glossary for SATCOM chapters

Low Earth Orbit (LEO) : A satellite orbit with an orbit height of around 150 – 500 km above the surface of Earth. These orbits have lower orbital periods, shorter propagation delays and lower propagation losses.

Medium Earth Orbit (MEO) : A satellite orbit with an orbit height of around 10,000 - 20,000 km above the surface of Earth.

Geostationary Earth Orbit (GEO) : A satellite orbit with an orbit height at 35,786 km above the surface of Earth. This height makes the orbital velocity equal to the speed of rotation of Earth, thus making the satellite look stationary from a given point on the surface of the Earth.

Footprint : The area of coverage of a satellite which covers all earth stations that have a line of sight (LOS) path to it and lie within the radiation pattern of the satellites antennas.

Beamwidth : Defined with respect to the antenna radiation pattern, it is the angular separation between the half power point ($0.5P_{max}$ / 3 dB point) or the 0.707 voltage point (at $0.707E_{max}$).

Effective Isotropic Radiated Power (EIRP) : Product of the transmitter power and the antenna gain, i.e. total effective power sent out by the antenna.

Frequency Division Multiple Access (FDMA) : A multiple access technique in which different earth stations are able to access the total available bandwidth in satellite transponder by virtue of their different carrier frequencies, thus avoiding interference among multiple signals.

Multi-Channel Per Carrier (MCPC) : This is a type of FDMA where the earth stations frequency multiplexes several channels into one carrier baseband assembly, which then frequency modulate an RF carrier and transmits it to the satellite transponder

Single Channel Per Carrier (SCPC) : This is a type of FDMA in which each signal channel modulates a separate RF carrier which is then transmitted to the transponder.

Time Division Multiple Access (TDMA) : Each of the multiple earth stations accessing a given satellite transponder transmits one or more data bursts. The satellite thus receives at its input a set of bursts from large number of Earth stations.

Figure of merit (G/T) : It measures the quality of a satellite receiver or Earth station receiver. A high G/T implies that the receiving end (satellite or Earth station) has high antenna gain or low receiver noise.

Cross polar interference (XPI) : It indicate how good the separation between different polarisations at the same frequency the receiving end can achieved.
A minimum cross polar interference for a satellite link must be at least 30 dB or more.

Constants & Formulas Sheet

Gravitational constant $G = 6.673 \times 10^{-11}\ Nm^2 Kg^{-2}$

Mass of Earth $M_e = 5.975 \times 10^{24}$ Kg , Radius of Earth = 6378 km

Boltzmann's constant $k = 1.38 \times 10^{-23}$ J/K

Speed of light $c = 3 \times 10^8$ m/s

Plank's constant $h = 6.626 \times 10^{-34}$ Js

Electron charge $e = 1.602 \times 10^{-19}$ C

$$v = \sqrt{\frac{Gm_e}{r}}$$

$$S(\Theta) = 52 - 10\log_{10}\left(\frac{D}{\lambda}\right) - 25\log(\Theta) \quad dBi$$

For D < 100λ

$$S(\Theta) = 29 - 25\log_{10}(\Theta) \quad dBi$$

For 2.0^0 spacing

$$S(\Theta) = 32 - 25\log_{10}(\Theta) \quad dBi$$

For 2.9^0 spacing

$$L_{dB} = 20\log\left(\frac{4\pi d}{\lambda}\right) = 32.44 + 20\log[d] + 20\log[f]$$

$$(C)_{dBw} = (P_T)_{dBw} + (G_T)_{dB} + (G_R)_{dB} - (L)_{dB}$$

$$\left(\frac{C}{N_0}\right)_{dBHz} = (P_T)_{dBW} + (G_T)_{dB} + \left(\frac{G_R}{T}\right)_{dB} - (L)_{dB} - (L_o)_{dB} - 10\log K$$

$$\left(\frac{C}{N}\right)_{dB} = \left(\frac{C}{N_0}\right)_{dBHz} - 10\log B \qquad \left(\frac{C}{N}\right)_{Total}^{-1} = \left(\frac{C}{N}\right)_{Up}^{-1} + \left(\frac{C}{N}\right)_{Down}^{-1}$$

$$n_1 Sin\Theta_i = n_2 Sin\Theta_r$$

$$NA = Sin\Theta_a = \sqrt{n_1^2 - n_2^2}$$

$$v = \frac{c}{n}$$

$$\Delta = \frac{n_1^2 - n_2^2}{2n_1^2}$$

$$\sigma = \frac{n_1 L \Delta}{c\sqrt{12}}$$

$$\sigma = \frac{n_1 L \Delta^2}{c\sqrt{48}}$$

$$V = \frac{\pi d}{\lambda}(NA)$$

$$M = \frac{V^2}{2}$$

For step-index multimode

$$M = \frac{V^2}{4}$$

For graded index multimode

$$\Delta\tau = \frac{Ln_1}{c}\left(\frac{n_1 - n_2}{n_2}\right)$$

$$n(r) = n_1\sqrt{1 - 2\Delta\left(\frac{r}{a}\right)^{\alpha}}$$

$$a \leq \frac{2.405\lambda}{2\pi\sqrt{n_1^2 - n_2^2}}$$

$$B = \frac{0.35}{\sigma}$$

$$B = \frac{0.35}{t_{sys}}$$

$$f = \frac{c}{\lambda}$$

$$\lambda = \frac{hc}{E_g}$$

$$\lambda = \frac{1.24}{E_g}$$

$$R = \frac{\eta\lambda e}{hc}$$

$$I_p = (r_e)(e)$$

$$P_o = (r_p)(hc/\lambda)$$

$$t_f = \sqrt{t_{modal}^2 + t_{material}^2}$$

$$t_{sys} = 1.1\sqrt{t_f^2 + t_s^2 + t_d^2}$$

$$D = \frac{ct}{2n}$$

Engineering @ SP

The School of Electrical & Electronic Engineering at Singapore Polytechnic offers the following full-time courses.

1. Diploma in Aerospace Electronics (DASE)

The Diploma in Aerospace Electronics course aims to provide students with a broad-based engineering curriculum to effectively support a wide spectrum of aircraft maintenance repair and overhaul work in the aerospace industry and also to prepare them for further studies with advanced standing in local and overseas universities.

2. Diploma in Computer Engineering (DCPE)

This diploma aims to train technologists who can design, develop, setup and maintain computer systems; and develop software solutions. Students can choose to specialise in two areas of Computer Engineering & Infocomm Technology, which include Computer Applications, Smart City Technologies (IoT, Data Analytics), Cyber Security, and Cloud Computing.

3. Diploma in Electrical & Electronic Engineering (DEEE)

This diploma offers a full range of modules in the electrical and electronic engineering spectrum. Students can choose one of the six available specialisations (Biomedical, Communication, Microelectronics, Power, Rapid Transit Technology and Robotics & Control) for their final year.

4. Diploma in Energy Systems & Management (DESM)*

The Diploma in Energy Systems & Management course aims to equip students with the knowledge and expertise in three specialisations: clean energy, power engineering and energy management, so as to design clean and energy efficient systems that will contribute to an economically and environmentally sustainable future.

5. Diploma in Engineering Systems (DES)*

The Diploma in Engineering Systems course aims to provide students with a broad-based engineering education to support activities and future challenges requiring interdisciplinary engineering systems capabilities. The course leverages on the experience and expertise of two schools, namely the School of Electrical & Electronic Engineering and the School of Mechanical & Aeronautical Engineering.

6. Diploma in Engineering with Business (DEB)

Diploma in Engineering with Business provides students with the requisite knowledge and skills in engineering principles, technologies, and business fundamentals, supported by a strong grounding in mathematics and communication skills, which is greatly valued in the rapidly changing industrial and commercial environment.

7. Common Engineering Program (DCEP)

In Common Engineering Program, students will get a flavour of electrical, electronic and mechanical engineering in the first semester of their study. They will then choose one of the 7 engineering courses specially selected from the Schools of Electrical & Electronic Engineering and Mechanical & Aeronautical Engineering.

*Course is applicable only for AY2018 intake and earlier

School of Electrical & Electronic Engineering

More than 60 Years of solid foundation	8 Tech Hubs	Unique PTN Scheme	SP-NUS SP-SUTD Programmes	More than 35,000+ Alumni

SP Singapore Polytechnic

Electives offered by SP

SCHOOL OF
ELECTRICAL & ELECTRONIC ENGINEERING

All SP students, including EEE students are free to choose electives offered by ANY SP schools, subject to meeting the eligibility criteria.

Like all schools, School of Electrical and Electronic Engineering offers electives for:

- EEE students only
- *and* for all SP students

EEE students are required to complete 3 electives, starting from Year 2 to Year 3 (one elective per semester).

Electives Choices for All SP students

Mod Code	Module Title
EP0400	Unmanned Aircraft Flying and Drone Technologies
EP0401	Python Programming for IoT*
EP0402	Fundamentals of IoT*
EP0403	Creating an IoT Project*
EP0404	AWS Cloud Foundations
EP0405	AWS Academy Cloud Architecting
EP0406	Fundamentals of Intelligent Digital Solutions
EP0407	Technology to Business
EP0408	Cybersecurity Essentials

Certificate in IoT (Internet of Things)

* A certificate in IoT would be awarded if a student completes the 3 modules: EP0401, EP0402 and EP0403

Electives Choices for EEE students

Mod Code	Module Title
EM0400	Commercial Pilot Theory
EM0401	Autonomous Electric Vehicle Design
EM0402	Artificial Intelligence for Autonomous Vehicle
EM0403	Autonomous Mobile Robots
EM0404	Smart Sensors and Actuators
EM0405	Digital Manufacturing Technology
EM0406	Linux Essential
EM0407	Advanced Linux
EM0408	Linux System Administration
EM0409	Rapid Transit System
EM0410	Rapid Transit Signalling System
EM0412	Data Analytics
EM0413	Mobile App Development
EM0414	Client-Server App Development
EM0415	Machine Learning & Artificial Intelligence
EM0416	Solar Photovoltaic System Design
EM0417	Introduction to Energy Efficiency
EM0418	Integrated Building Energy Management System
EM0419	Digital Solutioning Skills
EM0423	Independent Study 1