الجمهـــوريـــة الجـزائريـــة الديمـقـــراطية الشـعـبيــة

People's Democratic Republic of Algeria

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Department of Telecommunication Systems

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جـــامعة 8 مـــاي 1945- قالمـــة
معهد الاتصالات السلكية واللاسلكية
قسـم أنظمة الاتصالات السلكية واللاسلكية

Lecture Notes

Transmission Media

Designed for students of 3rd year degree in Telecommunications

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2025

Course Outline

Transmission Media

Institute: Institute of Telecommunications.

Department: Telecommunication Systems.

Target Audience: 3rd-year students in Telecom.

Course Title: Transmission Media.

Semester: 5.

Teaching Unit: UED 3.1.

Contact Hours: 22.5 hours (Lectures: 1.5 hours).

Credits: 1.

Coefficient: 1.

Objective:

The objective of this course is to provide students with a comprehensive understanding of the fundamental concepts in transmission media. Concept of Guided and Unguided Transmission Media, Types of Guided Media and Types of Unguided Media.

Prerequisites:

Fundamentals of Telecommunications.

Telecommunications and applications.

Wave Transmission and Propagation.

Course contents:

Chapter I. Transmission media Characteristics

Chapter II. Metallic (copper) conductors

Chapter III. Optical fiber cables

Chapter IV. RF Wireless Transmission

Chapter V. Optical Wireless Transmission

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Course Purpose

Transmission Media

In the world of telecommunication, transmission media are the foundation of any communication system, providing the physical pathways (guided or unguided) for transmitting signals between devices. For guided media, electromagnetic waves are guided along a solid medium, such as copper twisted pair, copper coaxial cable, and optical fiber. For unguided media, wireless transmission occurs through the vacuum, atmosphere, air, or even water, mainly using radio waves, microwaves, infrared and even visible light.

Whether using guided media or unguided media, the choice of transmission media plays a crucial role in the efficiency, reliability, and cost-effectiveness of the telecommunications network. The quality of data transmission is influenced by the characteristics of the transmission media and the type of signal being transmitted.

Therefore, understanding the different types of transmission media and their properties is critical to ensuring efficient and reliable communication, especially in today's highly interconnected world.

The purpose of this course is to offer students a solid foundational knowledge of transmission media. Enrolling in this document can help student understand transmission media and their types and properties in detail, and learn practical applications of different transmission media.

Chapter I

Transmission Media Characteristics

Bandwidth, Transmission impairments, Transmission Line parameters, Transmission Line Equations, Primary and Secondary Constants, Characteristic Impedance, Attenuation constant , Phase shift constant, Propagation Constant Wavelength, Reflection coefficient, Standing wave, Smith chart.

Chapter I: Transmission Media Characteristics

I.1 Introduction

Transmission media characteristics are crucial for understanding how data is transmitted between devices. The characteristics and quality of a data transmission are determined by both the characteristics of the medium and the characteristics of the signal. Guided media are more important in setting limitations, while for unguided media (wireless), the signal's bandwidth is more critical. Data rate and distance are key concerns, influenced by bandwidth, impairments, interference, and the number of receivers.

I.2 Transmission media

I.2.1 Definitions

Transmission Media is a means of establishing a communication medium to send and receive information in the form of electromagnetic signal waves. It functions as a physical path between the sender and the receiver in data communication, and the channel that carries the data from one location to another.

Transmission media are indeed situated below the physical layer in the network model, and they are directly managed and controlled by the physical layer's protocols and hardware.

The transmission media is usually free space, metallic cable, or fiber-optic cable. The information is usually a signal that is the result of a conversion of data from another form. For example, in a copper cable network, bits are available in the form of electrical signals, whereas in a fiber network, bits are available in the form of light pulses.

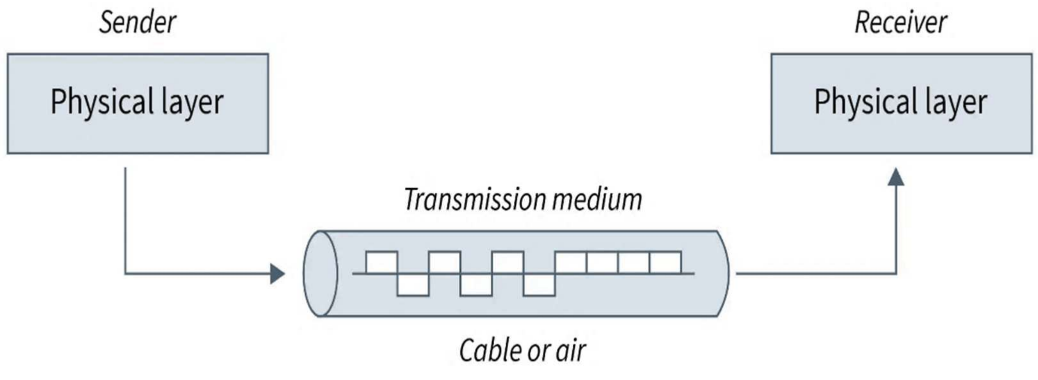


Figure I.1. Transmission media

I.2.2 Types of Transmission media

In telecommunications, transmission media can be divided into two broad categories: guided and unguided media.

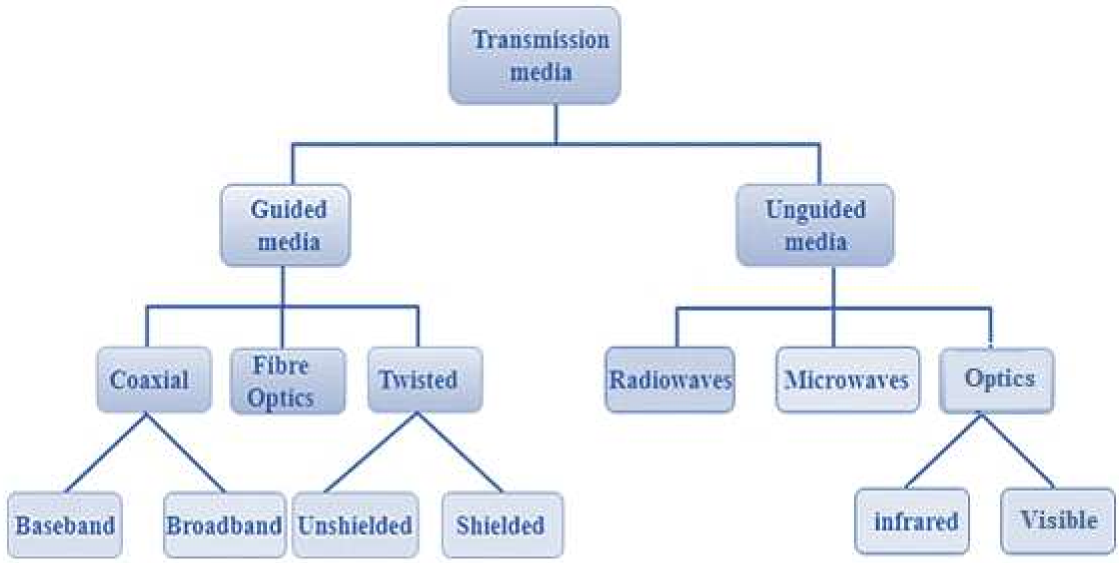


Figure I.2. Types of transmission media

a. Guided media

Guided Transmission media uses a cabling system that guides the signals along a specific path. It is referred to as **wired media**. Sometimes it is also referred to as **bounded media** because it is bounded to a specific limit in the communication network.

Features:

- High Speed
- Secure
- Used for comparatively shorter distances

Types: There are three major types of guided Media

- twisted-pair cable,
- coaxial cable,
- fiber-optic cable.

Out of these twisted-pair cable, coaxial cable transport signals in the form of electric signals and fiber-optic cable transport signals in the form of light.

b. Unguided (wireless) media

Unguided media transport data without using a physical conductor. This type of communication is often referred to as **wireless communication**. It uses wireless electromagnetic signals to send data.

Features:

- The signal is broadcasted through air
- Less Secure
- Used for larger distances

Types: There are three types of Unguided Media

- Radio waves
- Micro waves
- Infrared and visible light.

Figure I.3 depicts the electromagnetic spectrum and indicates the frequencies at which various guided media and unguided transmission techniques operate.

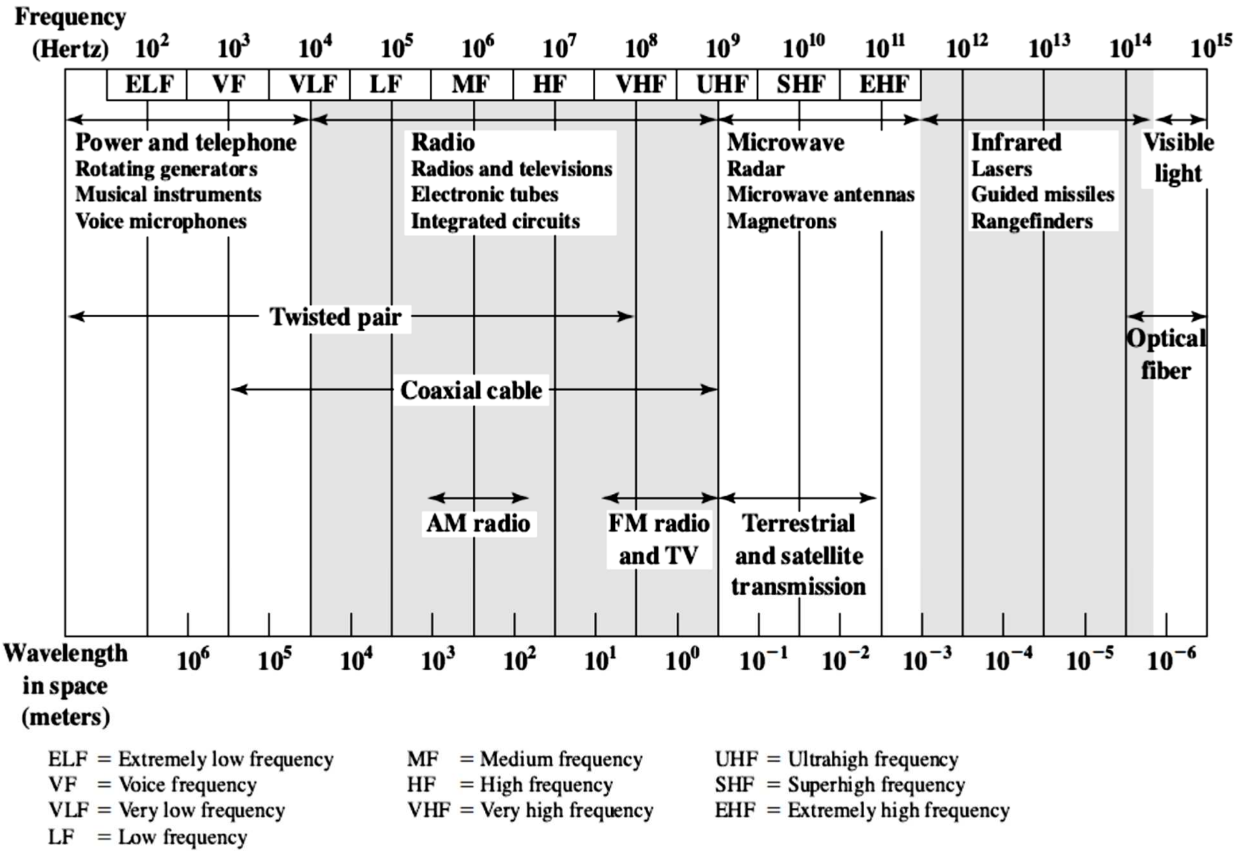


Figure I.3. Electromagnetic Spectrum for Telecommunications

I.3 Design Factors

A number of design factors relating to the transmission medium and the signal need to be considered for designing the transmission media:

I.3.1 Bandwidth

It refers to the data carrying capacity of a channel or medium. Higher bandwidth communication channels support higher data rates.

I.3.2 Transmission impairment

When the received signal is not identical to the transmitted one due to the transmission impairment, the quality of the signals will be destroyed. “What is sent is not what is received”.

For guided media, twisted pair generally suffers more impairment than coaxial cable, which in turn suffers more than optical fiber.

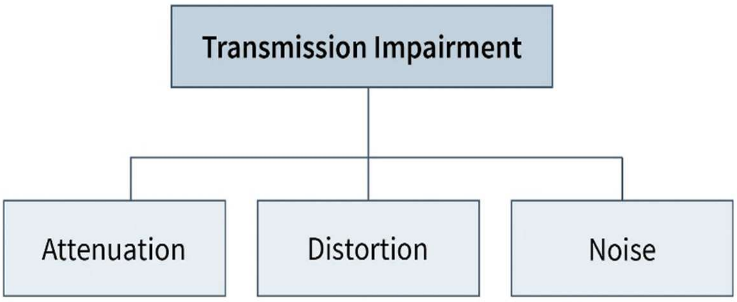


Figure I.4. Transmission impairment

The causes of transmission impairment are:

a. Attenuation: refers to the reduction in the strength or amplitude of a signal as it travels through a medium. It means **loss of energy**. The strength of signal decreases with increasing distance, which causes loss of energy in overcoming resistance of medium.

That is why a wire carrying electric signals gets warm, if not hot, after a while .Some of the electrical energy in the signal is converted to **heat**.

To compensate for this loss, **amplifiers** are used to amplify the signal.

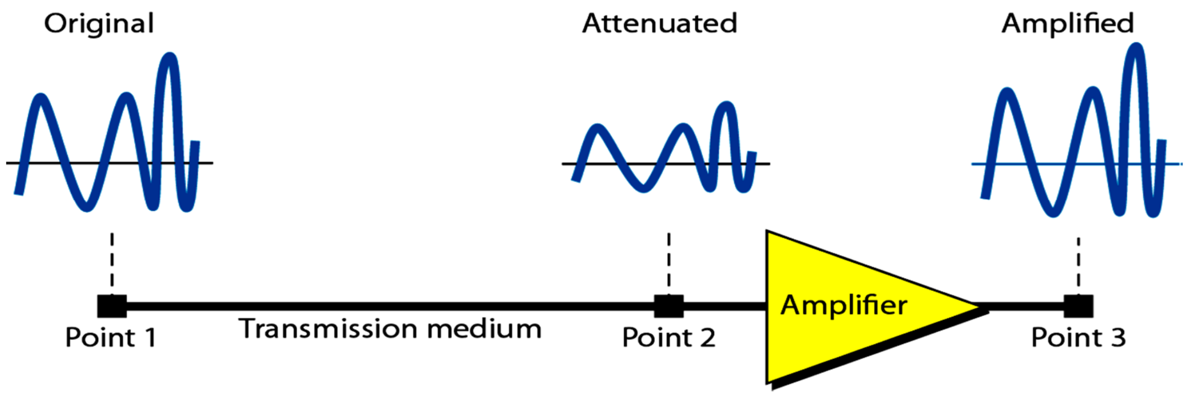


Figure I.5. Attenuation caused by the transmission media

- **Measurement of Attenuation (Decibel)**: to show that a signal has lost or gained strength, engineers use the unit of the decibel. The decibel (dB) measures the relative strengths of two signals or one signal at two different points. Note that the decibel is negative if a signal is attenuated and positive if a signal is amplified.

$$\mathbf{dB} = 10 \log_{10} \frac{P_2}{P_1}$$

Where: Variables P_1 and P_2 are the powers of a signal at points 1 and 2, respectively.

b. Distortion: Distortion occurs when there is **a change in the shape** of the signal. This type of distortion is examined from different signals having different frequencies. Each frequency component has its own propagation speed, so they reach at a different time, which leads to the delay distortion.

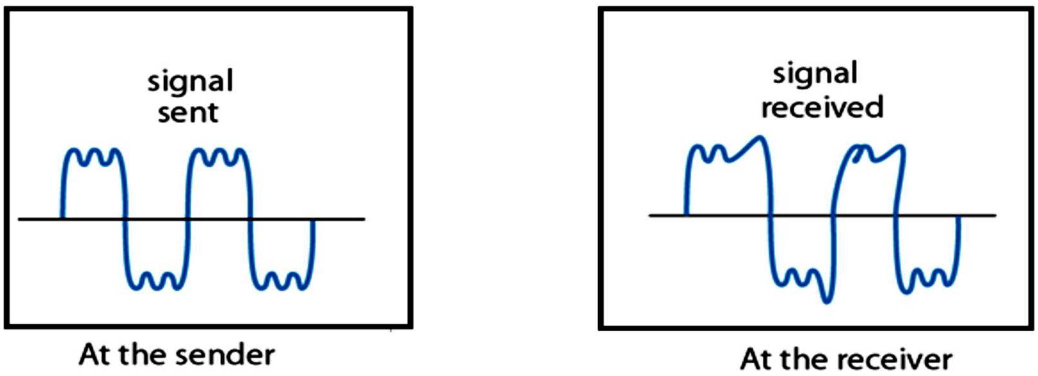


Figure I.6. Distortion caused by the transmission media

c. Noise: When data is travelled over a transmission medium, some **unwanted signal** is added to it, which creates the noise. Several types of noise, such as thermal noise, induced noise, crosstalk, and impulse noise, may **corrupt the signal.**

- **Thermal noise** is the random motion of electrons in a wire, which creates an extra signal not originally sent by the transmitter.
- **Induced noise** comes from sources such as motors and appliances .These devices act as a sending antenna, and the transmission medium acts as the receiving antenna.
- **Crosstalk** is the effect of one wire on the other. One wire acts as a sending antenna and the other as the receiving antenna.
- **Impulse noise** is a spike (a signal with high energy in a very short time) that comes from power lines, lightning, and so on.

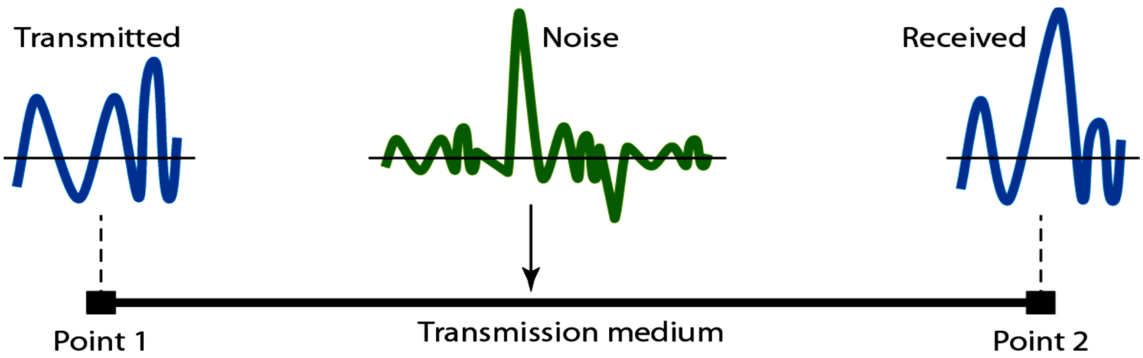


Figure I.7. Noise caused by the transmission media

I.3.3 Interference

Interference from competing signals in overlapping frequency bands can distort or wipe out a signal. Interference is of particular concern for unguided media but is also a problem with guided media. For guided media, interference can be caused by emanations from nearby cables. For example, twisted pairs are often bundled together and conduits often carry multiple cables. Interference can also be experienced from unguided transmissions. Proper shielding of a guided medium can minimize this problem.

I.3.4 Number of receivers

A guided medium can be used to construct a point-to point link or a shared link with multiple attachments. In the latter case, each attachment introduces some attenuation and distortion on the line, limiting distance and/or data rate.

I.4 Representation of transmission line

The simplest form of transmission line is a **pair of parallel conductors** separated by air or any dielectric medium like polyethylene or polyvinyl chloride (PVC).

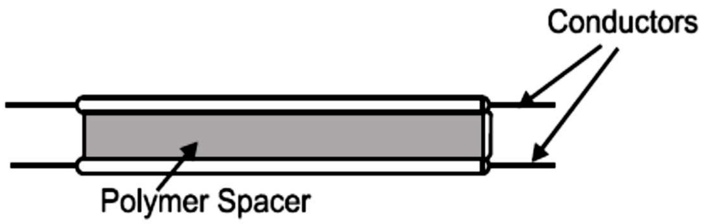


Figure I.8. Transmission Lines (Parallel conductors)

The frequencies of operation lie in the range of **1 GHz** to **300 GHz.** The corresponding wavelengths (λ) are from **0.3 m** to $\mathbf{10^{-3}}$ **m**. At these frequencies, the **inductance** associated with the conductors and **capacitance** between the two conductors cannot be neglected. Since the dielectric between the two conductors has finite conductivity, we also have to consider a **shunt resistance** between the two conductors. All these components are distributed along the length of the transmission line.

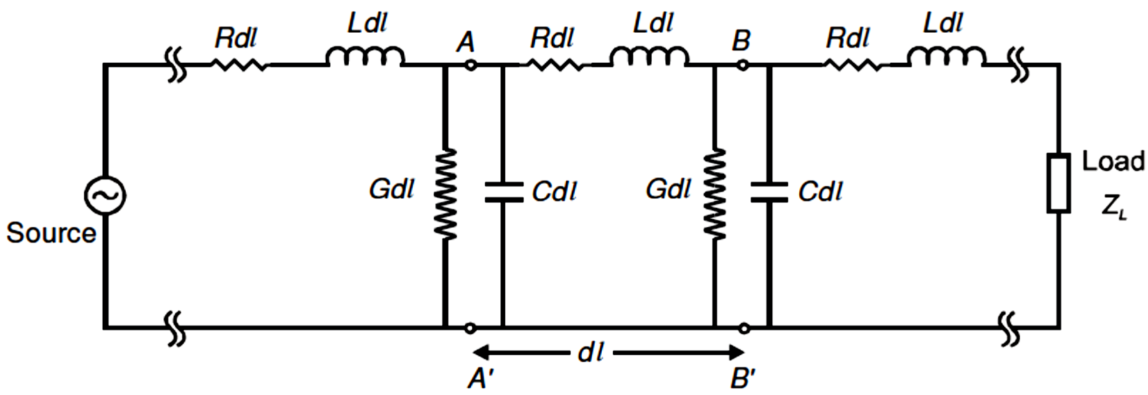


Figure I.9. Lumped component representation of transmission line

Figure I.9 shows equivalent representation of a transmission line in terms of lumped components *R*, *L*, *G* and *C*. Their values are expressed in terms of per unit length.

R is the series resistance per unit length , Ω/m

L is the series inductance per unit length , H/m

G is the shunt conductance per unit length , S/m

C is the shunt capacitance per unit length , F/m

In the short length segment of the transmission line, *dl*, the current and voltage relations are as shown in Figure I.10.

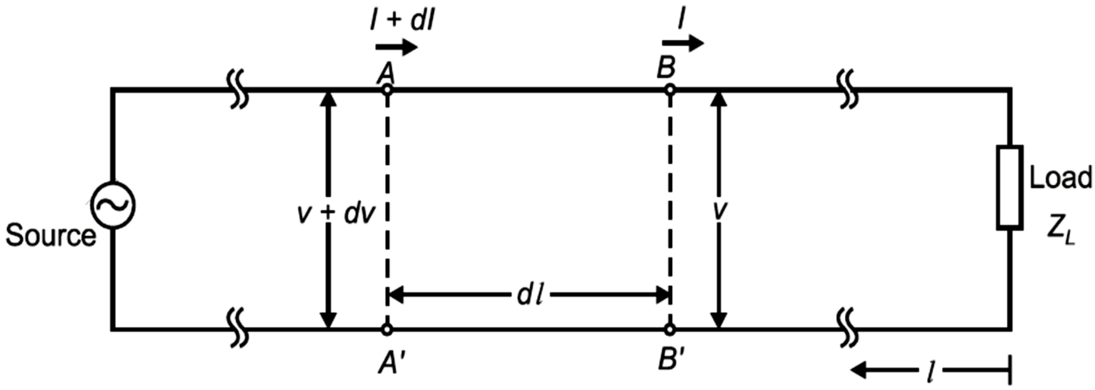


Figure I.10. Current and voltage relations in a short segment of transmission line

I.4.1 Transmission line equations

When there is a line current *I* passing through the transmission line, it produces voltage drop while flowing through the resistance *Rdl* and reactance *jωLdl*. Let the change in the voltage over a short distance *dl* be *dV*. This can be written as:

$$dV = I \times \text{(impedance of length } dl)$$

$$dV = I\,(R + j\omega L)\,dl \tag{I.1}$$

Due to voltage *V* existing between the two conductors, small current *dI* flows through the capacitance *Cdl* and conductance *Gdl*. This current can be expressed as:

$$dI = V \times \text{(admittance of length } dl)$$

$$dI = V\,(G + j\omega C)\,dl \tag{I.2}$$

The power is dissipated due to a current flowing between the two conductors of the transmission line in shunt fashion.

From Equations (I.1) and (I.2) we get:

$$\frac{dV}{dl} = I(R + j\omega L) \tag{I.3}$$

$$\frac{dI}{dl} = V(G + j\omega C) \tag{I.4}$$

We represent:

- The line **impedance** per unit length by $\boldsymbol{Z = (R + j\omega L)}$
- The line shunt **admittance** per unit length by $\boldsymbol{Y = (G + j\omega C)}$

Then the current-voltage (I-V) relations in Equations (I.3) and (I.4) are known as **telegrapher's equations**, and can be represented as:

$$\frac{dV}{dl} = IZ \tag{I.5}$$

$$\frac{dI}{dl} = VY \tag{I.6}$$

Differentiating Equations. (I.5) and (I.6) with respect to dl we get:

$$\frac{d^2V}{dl^2} = \frac{dI}{dl}Z = VYZ \tag{I.7}$$

$$\frac{d^2I}{dl^2} = \frac{dV}{dl}Y = IYZ \tag{I.8}$$

Equations (I.7) and (I.8) are not independent of each other. They are in the form of standard differential equations. Therefore, the solutions of these equations can be written as:

$$V = V_1 e^{\sqrt{ZY}l} + V_2 e^{-\sqrt{ZY}l} \tag{I.9}$$

$$I = I_1 e^{\sqrt{ZY}l} + I_2 e^{-\sqrt{ZY}l} \tag{I.10}$$

Differentiating Equation (I.9) we get

$$\frac{dV}{dl} = V_1\sqrt{ZY}e^{\sqrt{ZY}l} - V_2\sqrt{ZY}e^{-\sqrt{ZY}l} = IZ$$

Rearranging the terms, current I can be written as:

$$I = \frac{V_1\sqrt{ZY}e^{\sqrt{ZY}l}}{Z} - \frac{V_2\sqrt{ZY}e^{-\sqrt{ZY}l}}{Z} = \frac{V_1 e^{\sqrt{ZY}l}}{\sqrt{Z/Y}} - \frac{V_2 e^{-\sqrt{ZY}l}}{\sqrt{Z/Y}}$$

Substituting $\sqrt{Z/Y} = Z_c$ in the above expression, we get

$$I = \frac{V_1 e^{\sqrt{ZY}l}}{Z_c} - \frac{V_2 e^{-\sqrt{ZY}l}}{Z_c} \tag{I.11}$$

Comparing Equations (I.10) and (I.11) we get

$$I_1 = \frac{V_1}{Z_c} \text{ and } I_2 = -\frac{V_2}{Z_c} \tag{I.12}$$

Hence, solutions of Equations (I.5) and (I.6) can be written as

$$V = V_1 e^{\sqrt{ZY}l} + V_2 e^{-\sqrt{ZY}l} = V' + V'' \quad \text{(I.13.a)}$$

$$I = \frac{V_1 e^{\sqrt{ZY}l}}{Z_c} - \frac{V_2 e^{-\sqrt{ZY}l}}{Z_c} = I' + I'' \quad \text{(I.13.b)}$$

Equations (I.13.a) and (I.13.b) are the **transmission line equations**.

These equations can be expressed as the **sum of voltage and currents of two waves.** The wave that is travelling towards receiving end (load end) is called the **incident wave** since it is incident on load. The wave travelling from load to the generator is called the **reflected wave**. It is generated at the load by reflection of incident wave. These two waves are identical in nature but have different directions.

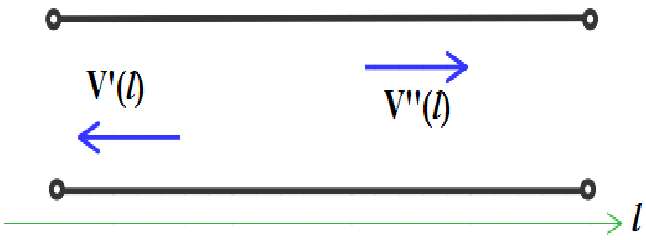


Figure I.11. Incident and reflected waves

a. Incident Wave

It is the wave starting from the source and reaching the load. It consists of voltage component $V' = V_1 e^{\sqrt{ZY}l}$ and current component $I' = \frac{V_1 e^{\sqrt{ZY}l}}{Z_c}$. At every point on the transmission line, current and voltage are in phase and $\frac{\boldsymbol{V'}}{\boldsymbol{I'}} = \boldsymbol{Z_c}$.

b. Reflected Wave

The reflected wave is traveled from the load end to the source end, i.e. in the opposite direction of the incident wave.

The reflected wave consists of following voltage and current components: $V'' = V_1 e^{-\sqrt{ZY}l}$ and $I'' = \frac{V_1 e^{-\sqrt{ZY}l}}{Z_c}$ and everywhere on the transmission line $\frac{\boldsymbol{V'}}{\boldsymbol{I'}} = -\boldsymbol{Z_c}$.

c. Characteristic impedance of the line

The characteristic impedance of the line is defined as $\boldsymbol{Z_c} = \sqrt{\frac{Z}{Y}}$

Hence, we can write

$$\boldsymbol{Z_c} = \sqrt{\frac{R+j\omega L}{G+j\omega C}} \tag{I.14}$$

At the radio frequencies, the inductive reactance is much larger than the resistive component and the capacitive susceptance is much larger than the shunt conductance.

In such cases the characteristic impendence is: $\boldsymbol{Z_c} = \sqrt{\frac{L}{C}}$. This characterizes a **loss-less** transmission line.

In practice, the characteristic impendence is determined by **the geometry, shape** and **spacing of the conductors** as well as **the dielectric constant of the insulator** separating them.

d. Propagation constant of the line

In Equation (I.13), $\gamma = \sqrt{ZY}$ is called the **propagation constant of the line**. $\sqrt{ZY}$ is a complex quantity, which can be represented as

$$\gamma = \sqrt{(R + jL\omega)(G + jC\omega)} = \alpha + j\beta \tag{I.15}$$

Where:

- α is the **attenuation coefficient** that gives measure of decrease in voltage (or current) with length ($e^{-\alpha l}$). The units of α are **Neper**. However, it is a common practice to express the attenuation in dB scale. The relationship between these two units is:

Attenuation (in dB) **= 8.686 α** (in Neper)

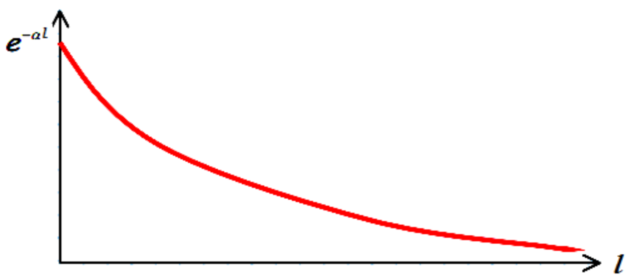


Figure I.12. The attenuation of the line

- β is the **phase shift coefficient** which determines phase angle of the voltage (or current) with distance. The phase angle continuously varies along the length of the line and the length required to obtain a phase shift of 2π radians is defined as the wavelength of the line λ.

Hence $\beta\lambda = 2\pi$ or $\beta = 2\pi/\lambda$

- **The voltage of incident wave $V_1 e^{\gamma l} = V_1 e^{(\alpha + j\beta)l}$** reduces exponentially as the wave travels towards the load. Here αl is the total attenuation of the line of length l. The phase factor **β is positive** in the present case. It means that, as l increases, i.e. as we travel away from the load, the phase position of incident wave advances the phase position at the load end by **βl radians.**

- **The voltage of reflected wave $V_2 e^{-\gamma l} = V_2 e^{-(\alpha + j\beta)l}$** shows that as l increases V'' decreases, i.e. as the wave travels away from the load, its amplitude decreases. The phase of reflected wave drops by β radians per unit distance from the load. That is the reflected wave at distance l away from the load lags the phase position at the load by **βl radians.**

I.4.2 Transmission line parameters

I.4.2.1 Reflection coefficient

When the load impedance connected to the line is equal to the characteristic impedance (Z_c) of the transmission line, **no reflection occurs**. In other cases also, the reflected wave has different amplitude and phase depending on the load value. The incident and reflected waves are related to each other through a transmission line parameter called **reflection coefficient.**

Consider a transmission line terminated in load impedance Z_L as shown in Figure I.13.

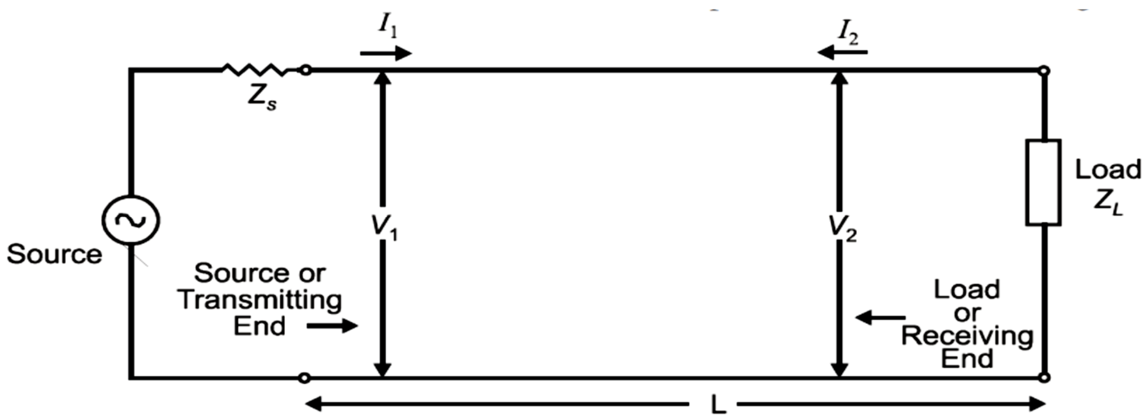


Figure I.13. Transmission line terminated in a load impedance

The reflected wave is generated at the load as a result of reflection of the incident wave by the load impedance. Reflection must satisfy the following conditions.

- For incident wave
- For reflected wave
- Load voltage $V_L = V_1+V_2$ (Sum of incident and reflected voltage at the load, $l = 0$)
- Load current $I_L = I_1+I_2$ (Sum of incident and reflected wave current at $l = 0$)
- Load impedance $Z_L = \frac{V_L}{I_L}$

If the line has a length L, then from Equations (I.13.a) and (I.13.b) the voltage and current at the receiving, (load) end can be expressed in terms of propagation constant as:

$$V_L = V_1 e^{\gamma l} + V_2 e^{-\gamma l} \tag{I.16}$$

$$I_L = \frac{1}{Z_c}(V_1 e^{\gamma l} + V_2 e^{-\gamma l}) \tag{I.17}$$

The ratio of voltage to current at the receiving end is the load impedance

$$Z_L = \frac{V_L}{I_L} = Z_c \frac{V_1 e^{\gamma l} + V_2 e^{-\gamma l}}{V_1 e^{\gamma l} - V_2 e^{-\gamma l}} \tag{I.18}$$

The **reflection coefficient** is defined as $\boldsymbol{\Gamma} = \frac{\boldsymbol{reflected\ voltage}}{\boldsymbol{incident\ voltage}} = \frac{\boldsymbol{reflected\ current}}{\boldsymbol{incident\ current}}$

Hence
$$\Gamma = \frac{V_2 e^{-\gamma l}}{V_1 e^{\gamma l}} \tag{I.19}$$

The **load impedance Z_L** can then be expressed in terms of reflection coefficient as:

$$\boldsymbol{Z_L = Z_c \frac{1+\frac{V_2 e^{-\gamma l}}{V_1 e^{\gamma l}}}{1-\frac{V_2 e^{-\gamma l}}{V_1 e^{\gamma l}}} = Z_c \left[\frac{1+\Gamma}{1-\Gamma}\right]} \tag{I.20}$$

and it can be easily shown that the **reflection coefficient** as:

$$\boldsymbol{\Gamma = \frac{Z_L - Z_c}{Z_L + Z_c}} \tag{I.21}$$

NB:

If the load impedance $\boldsymbol{Z_L}$ and/or characteristic impedance $\boldsymbol{Z_c}$ are complex quantities, then the reflection coefficient is also complex quantity and we can write

$$\boldsymbol{\Gamma = |\Gamma| e^{j\theta}}$$

Where Γ is the magnitude of reflection coefficient and is always less than or equal to one. θ is the phase angle between the incident and reflected voltage at the receiving end. It is usually called **the phase angle of reflection coefficient**.

I.4.2.2 Standing Wave

Just as any AC voltage or current, the two sets of waves, viz. incident and reflected waves add vectorially. As a result of combining these waves, patterns of voltage and current variations are formed on the line. These patterns are stationary with respect to time, and hence they are called **standing waves**.

The general solutions of the transmission line equation consist of two waves travelling in opposite directions with unequal amplitudes given by Equations (I.13.a) and (I.13.b). Equation (I.13.a) can be written as:

$$\begin{aligned} V_s &= V_1 e^{\sqrt{ZY}l} + V_2 e^{-\sqrt{ZY}l} \\ &= V_1 e^{(\alpha+j\beta)l} + V_2 e^{-(\alpha+j\beta)l} \\ &= V_1 e^{\alpha l} e^{j\beta l} + V_2 e^{-\alpha l} e^{-j\beta l} \\ &= V_1 e^{\alpha l}(cos\beta l + jsin\beta l) + V_2 e^{-\alpha l}(cos\beta l - jsin\beta l) \\ &= cos\beta l(V_1 e^{\alpha l} + V_2 e^{-\alpha l}) - jsin\beta l(-V_1 e^{\alpha l} + V_2 e^{-\alpha l}) \end{aligned} \quad \text{(I.22)}$$

Without loss of generality, it can be assumed that $\boldsymbol{V_1 e^{\alpha l}}$ and $\boldsymbol{V_2 e^{-\alpha l}}$ are real. Then the voltage wave equation can be expressed as:

$$\boldsymbol{V_s = V_0 e^{-j\phi}} \quad \text{(I.23)}$$

This equation is called **voltage standing wave equation**, where V_0 represents the amplitude of the standing wave given by:

$$V_0 = [(V_1 e^{\alpha l} + V_2 e^{-\alpha l})^2 cos^2\beta l + (V_2 e^{-\alpha l} + V_1 e^{\alpha l})^2 sin^2\beta l]^{\frac{1}{2}} \quad \text{(I.24)}$$

$$\phi = arctan\left[\left(\frac{V_2 e^{-\alpha l} + V_1 e^{\alpha l}}{V_1 e^{\alpha l} + V_2 e^{-\alpha l}}\right) tan\beta l\right] \quad \text{(I.25)}$$

ϕ being the phase of the standing wave.

The maximum and minimum values of Equation (I.24) can be found by substituting the proper values of β***l*** in the equation. This procedure leads us to the following results:

The maximum voltage amplitude of the standing wave pattern occurs when $\cos^2 \beta l = 1$; or $\beta l = n\pi$ where $n = 0, 1, 2,\ldots$ and it can be expressed as

$$V_{max} = V_1 e^{\alpha l} + V_2 e^{-\alpha l} = V_1 e^{\alpha l}\left(1 + \frac{V_2 e^{-\alpha l}}{V_1 e^{\alpha l}}\right) = V_1 e^{\alpha l}(1 + |\Gamma|) \qquad \text{(I.26)}$$

The minimum amplitude occurs when $\sin^2 \beta l = 1$ or $\beta l = \frac{(2n-1)\pi}{2}$ where $n = 0, 1, 2,\ldots$

The minimum voltage amplitude is:

$$V_{min} = V_1 e^{\alpha l} - V_2 e^{-\alpha l} = V_1 e^{\alpha l}\left(1 - \frac{V_2 e^{-\alpha l}}{V_1 e^{\alpha l}}\right) = V_1 e^{\alpha l}(1 - |\Gamma|) \qquad \text{(I.27)}$$

The voltage and current standing wave patterns for a **loss-less** transmission line are shown in Figure I.14.

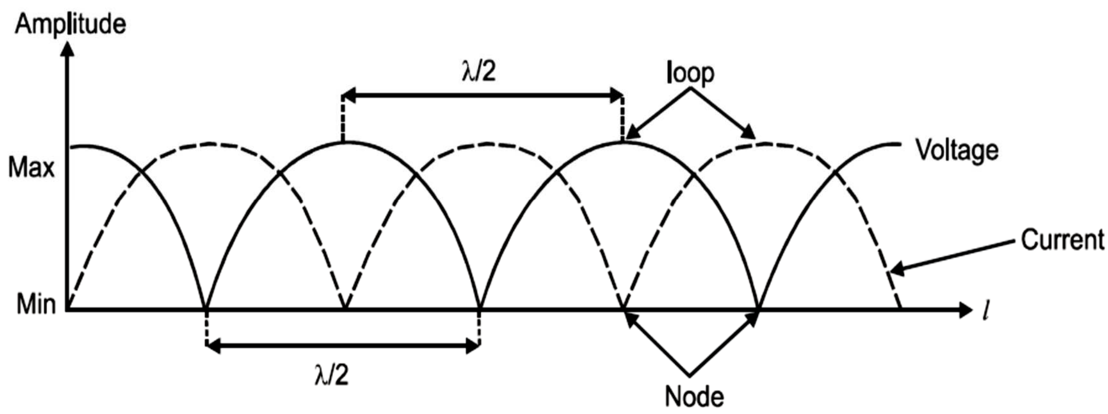


Figure I.14. Standing wave pattern in a loss-less line

The distance between two consecutive maxima or minima is **λ/2**. For a loss-less transmission line the maximum and minimum amplitude of the standing wave remains constant throughout the length of the transmission line. You must have also noticed that, wherever there is voltage maxima, there is current minima and vice-versa, i.e. the voltage and current standing waves are **90°** out of phase along the line.

The points of minimum voltage or current are known as **nodes** while maxima are called the **loops**. Voltage nodes and current nodes are spaced quarter wavelength **(λ/4)** apart.

I.4.2.3 Standing Wave Ratio

The Standing Wave Ratio (**SWR**) is one of the most important parameters used to describe, and to quantify standing wave pattern over a loss-less line. It gives an indication of the amount of mismatch or reflected wave over the line. Note that this parameter is relevant only for loss-less lines.

SWR is defined as the ratio of maximum to minimum voltage in a standing wave pattern over a loss-less line. It can also be defined as the ratio of maximum to minimum current in standing wave pattern. The standing wave ratio **(SWR)** is denoted by ***S***.

$$\boldsymbol{S} = \frac{|\boldsymbol{V_{max}}|}{|\boldsymbol{V_{min}}|} = \frac{|\boldsymbol{I_{max}}|}{|\boldsymbol{I_{min}}|} \tag{I.28}$$

Substituting from Equations (I.26) and (I. 27), we get

$$S = \frac{V_1 e^{\alpha l}(1+|\Gamma|)}{V_1 e^{\alpha l}(1-|\Gamma|)} = \frac{\mathbf{1+|\Gamma|}}{\mathbf{1-|\Gamma|}} \tag{I.29}$$

If we substitute value of **Γ**, we get $\boldsymbol{S} = \frac{\boldsymbol{Z_L}}{\boldsymbol{Z_C}}$

When the load is resistive (R_L) then the SWR takes the following form: $\boldsymbol{S} = \frac{\boldsymbol{R_L}}{\boldsymbol{Z_c}}$

Since **Γ**is always less than or equal to 1 the standing wave ratio is a positive real number which is never less than unity i.e. $S \geq 1$.

The standing wave ratio of a pure travelling wave, i.e. when no reflected wave exists, is **unity** and that for pure standing wave, i.e. incident and reflected wave having equal amplitudes, is **infinite**.

When the standing wave ratio is unity, the transmission line is called **flat line.** The standing wave ratios of voltage and current are identical and are constant throughout the line.

The standing wave ratio is normally defined in terms of voltages and is called **voltage standing wave ratio** (**VSWR**).

Examples:

♦ Z_L= 0 (**Short Circuited Transmission Line**), S= 0 and Γ= -1: total **reflected Wave** (the voltage of reflected wave is 180° out of phase (phase opposition) with respect to incident wave voltage).

♦ $Z_L = \infty$ (**Open ended transmission line**), $S = \infty$ and $\Gamma=1$: total **reflected Wave** (the voltage wave is reflected in-phase with the incident wave).

♦ $Z_L = Z_c$ (**Impedance matching**), $S=1$ and $\Gamma=0$: total incident wave.

♦ $Z_c = 50\Omega$ $Z_L = 75\Omega$, $S=1.5$ and $\Gamma= 0.2$: 20% of incident wave is reflected.

I.4.3 Impedance matching in transmission line

A line is said to be matched to the load when the load accepts all the power that has been placed over the line by generator without any reflections back. Under matched conditions, therefore, the line carry only the forward traveling wave, with no reflected wave. It is shown soon that it can happen only when the load impedance (Z_L) is equal to the characteristic impedance (Z_C) of the line. Mathematically, matched termination imply, $\boldsymbol{Z_L = Z_C}$

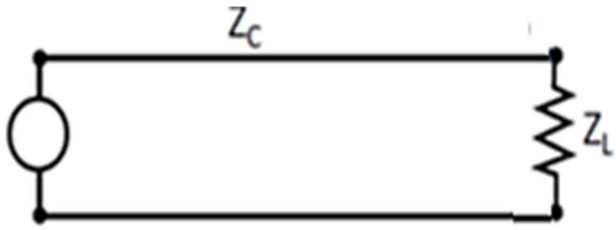


Figure I.15. Impedance Matching

When the line is terminated over impedance, which is different from its characteristic impedance, reflections occur resulting in an inefficient transmission system. Hence, mismatched operation of the line is unwanted and to eliminate or reduce the reflected wave over the line certain measures, called **load matching techniques**, are developed. They are:

- Quarter-wave transformer technique
- Single-stub matching technique
- Double-stub matching technique.

a. Quarter-Wave Transformers

Quarter-wave transmission lines exhibit a special input impedance: $\boldsymbol{Z_{in}\left(\frac{\lambda}{4}\right) = \frac{Z_c^2}{Z_L}}$

We can use this to our advantage by inserting a quarter-wavelength piece of transmission line between the end of the transmission line and the load to change the apparent impedance of the load.

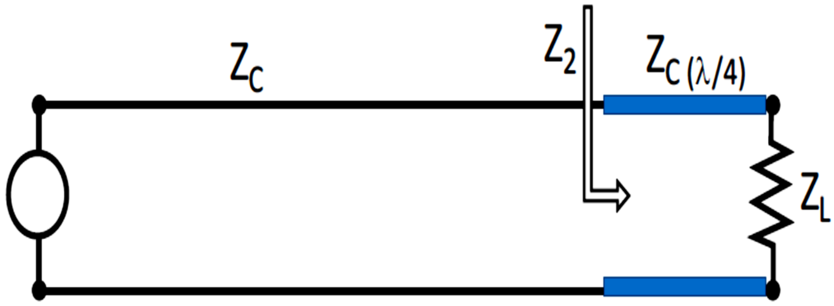


Figure I.16. Impedance Matching with a Quarter-Wave Transformer

Notice that we already know every quantity in this figure except $\boldsymbol{Z_{C(\lambda/4)}}$, which is the characteristic impedance of the short piece of cable we will be adding.

If we look into the wire from the left of the quarter-wave transformer, we will see impedance Z_2, as shown in the Figure I.16. We can calculate Z_2 :

$$Z_2 = Z_{in}\left(l = -\frac{\lambda}{4}\right) = \frac{\left(Z_{c(\lambda/4)}\right)^2}{Z_L}$$

In order for the line to be impedance matched, we must ensure that Z_2, the impedance seen as the load to the main wire, is equal to Z_C:

$$\boldsymbol{Z_c} = \boldsymbol{Z_2} = \frac{\left(Z_{c(\lambda/4)}\right)^2}{Z_L}$$

Solving this equation for $Z_{C(\lambda/4)}$ gives:

$$\boldsymbol{Z_{c(\lambda/4)}} = \sqrt{\boldsymbol{Z_c Z_L}} \qquad \text{(I.30)}$$

The quarter-wave transformer has one substantial shortcoming. **It requires specifying a very precise characteristic impedance for the transformer**, and transmission lines are usually only available in a few pre-determined impedances. This means that a 73.5W transmission line to form a quarter-wave transformer would very likely have to be custom-made, which would be very expensive.

b. Single-Stub Matching technique

The second technique for impedance matching is to insert a single-stub tuner. This tuner will involve inserting a short piece of the very same transmission line we are working with at precisely the correct location and with precisely the correct length. The stub can be either short-circuited or open-circuited, but in practice, it is short-circuited because an open-circuited stub tends to radiate electromagnetic waves. In other words, an open-circuited stub acts like an antenna, which can create all kinds of other problems. Short-circuited stubs do not do this, which is why we use them.

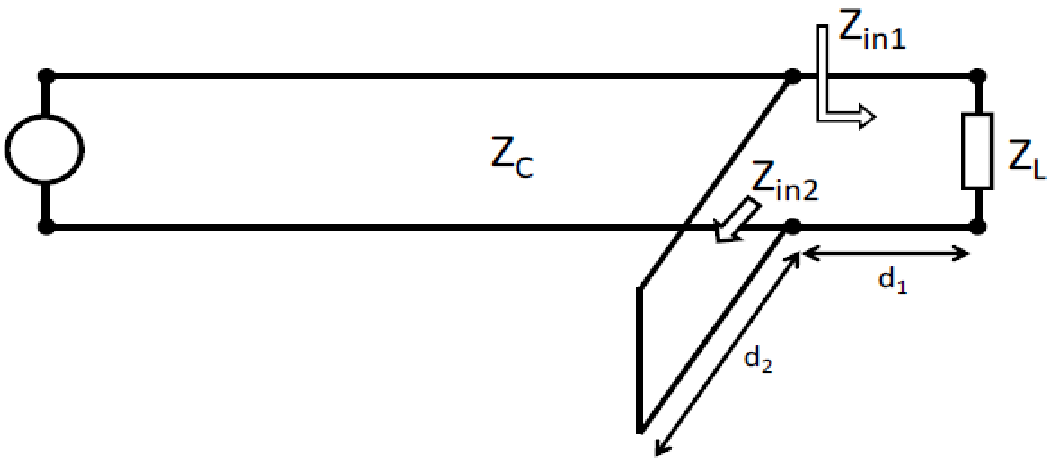


Figure I.17. Impedance Matching with a Single-Stub Tuner

d_1 is the distance from the load where the stub must be placed, and **d_2** is the required length of the stub.

d_1 and d_2 should be selected such that Z_{in1} in parallel with Z_{in2} is equal to Z_C.

I.5 Smith Chart

The Smith chart provides a graphical representation of **reflection coefficient Γ** that permits the determination of quantities such as the **voltage standing wave ratio VSWR** or the terminating impedance. It uses a **bilinear Möbius transformation**, also known as a fractional linear transformation or homographic transformation, projecting the complex impedance plane onto the complex **Γ** plane:

$$\Gamma = \frac{Z-Z_0}{Z+Z_0} \qquad \text{With} \qquad Z = R + jX \tag{I.31}$$

As can be seen in Figure I.18 the half-plane with positive real part of impedance Z is mapped onto the interior of the unit circle of the **Γ** plane.

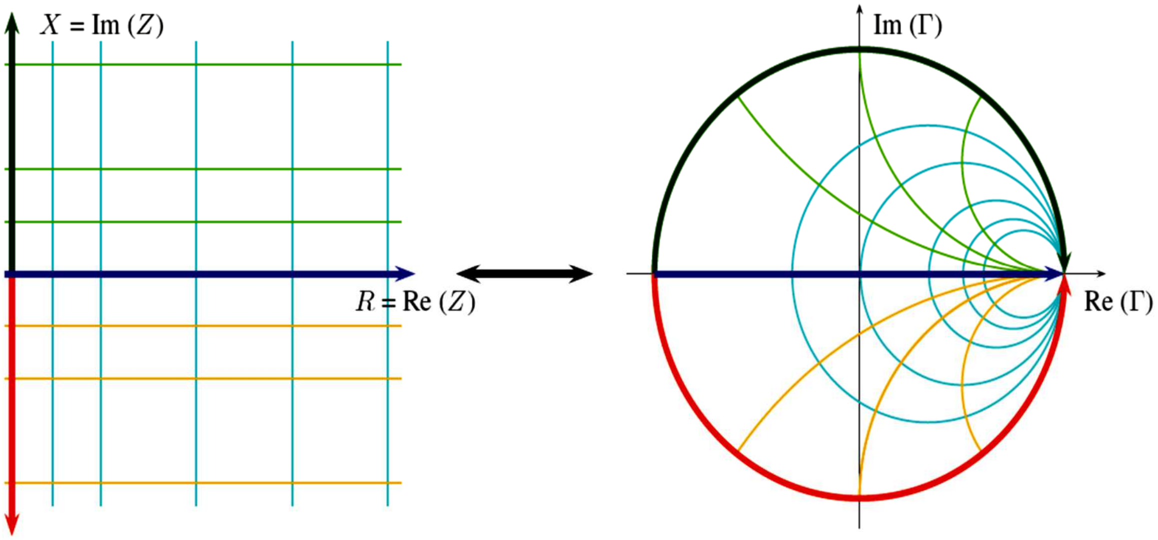


Figure I.18. Illustration of the Moebius transform from the complex impedance plane to the **Γ** plane commonly known as Smith chart

a. Properties of the transformation

In general, this transformation has two main properties:

- Generalized circles are transformed into generalized circles (note that a straight line is nothing else than a circle with infinite radius and is therefore mapped as a circle in the Smith chart);
- Angles are preserved locally.

b. Normalization

The Smith chart is usually normalized to a terminating impedance Z_0 (= real): $Z_0 = \frac{Z}{Z_0}$

This leads to a simplification of the transform:

$$\Gamma = \frac{z-1}{z+1} \quad \Leftrightarrow \quad z = \frac{1+\Gamma}{1-\Gamma} \;.$$

Although Z = 50 is the most common reference impedance (characteristic impedance of coaxial cables) and many applications use this normalization, any other real and positive value is possible. Therefore, it is crucial to check the normalization before using any chart.

Commonly used charts that map the impedance plane onto the **Γ** plane always look confusing at first, as many circles are depicted (Figure I.19).

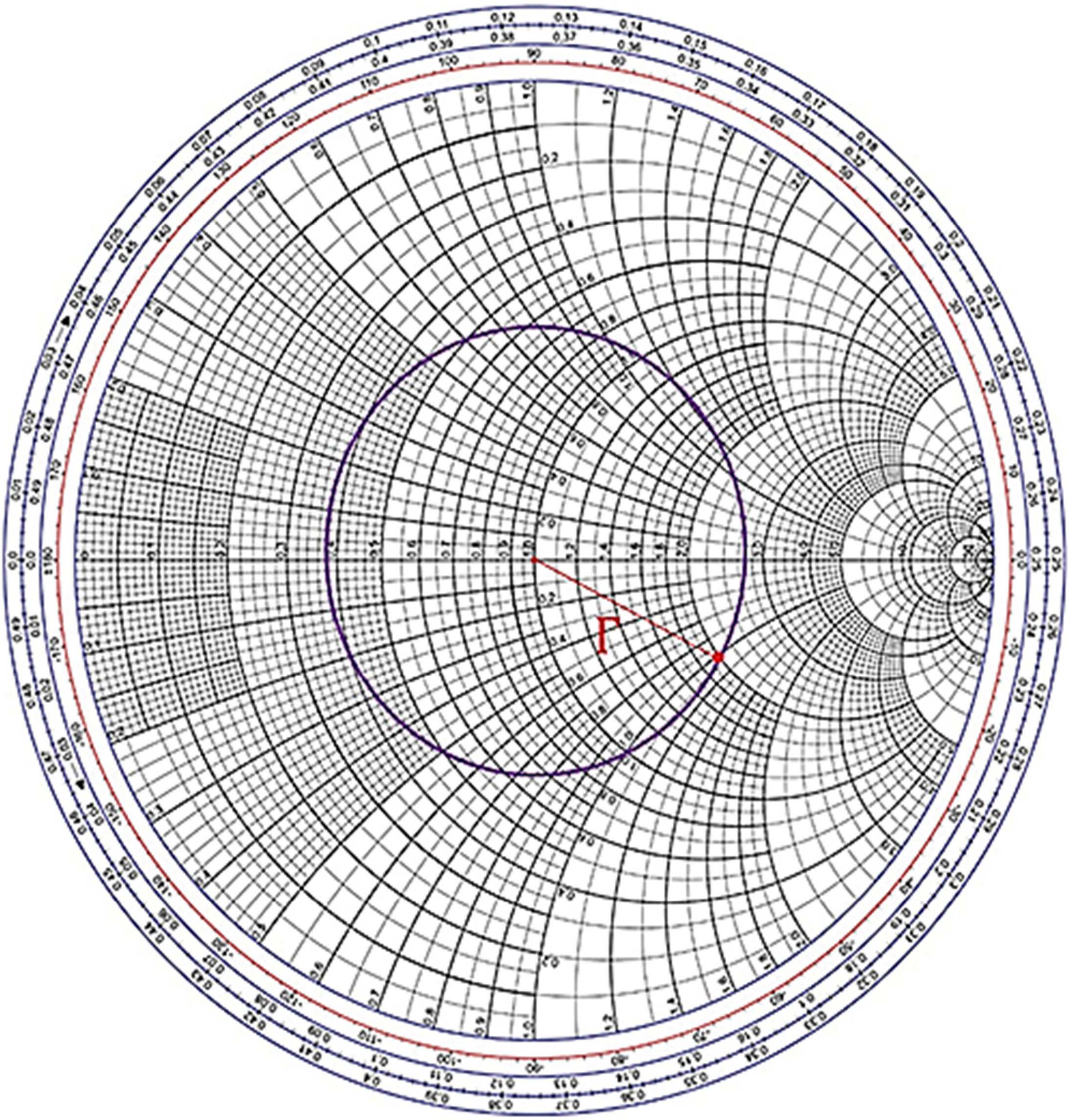


Figure I.19. Example of a commonly used Smith chart

c. Admittance plane

The Möbius transform that generates the Smith chart provides also a mapping of the complex admittance plane ($= \frac{1}{Z}$ or normalized $y = \frac{1}{z}$) into the same chart:

$$\Gamma = -\frac{y-1}{y+1} = -\frac{Y-Y_0}{Y+Y_0} = -\frac{1/Z - 1/Z_0}{1/Z + 1/Z_0} = \frac{Z-Z_0}{Z+Z_0} = \frac{z-1}{z+1} \quad \text{(I.32)}$$

Using this transformation, the result is the same chart, but mirrored at the center of the Smith chart (Figure I.20). Often both mappings, the admittance and the impedance plane, are combined into one chart, which looks even more confusing.

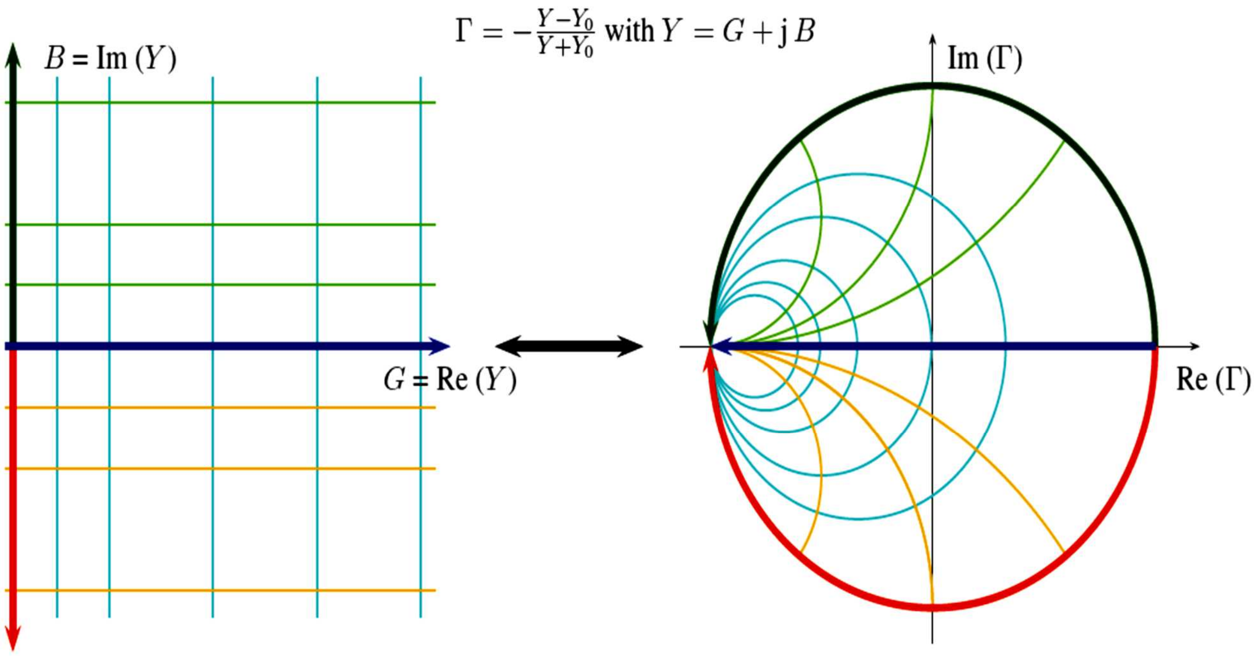


Figure I.20. Mapping of the admittance plane into the **Γ** plane

d. Navigation in the Smith chart

- **Important points:** There are three important points in the chart:
- Open circuit with $\Gamma = 1$, $z \rightarrow \infty$
- Short circuit with $\Gamma = -1$, $z = 0$
- Matched load with $\Gamma = 0$, $z = 1$

They all are located on the real axis at the beginning, the end, and the center of the circle (Figure I.21). The upper half of the chart is **inductive**, since it corresponds to the positive imaginary part of the impedance.

The lower half is **capacitive** as it is corresponding to the negative imaginary part of the impedance.

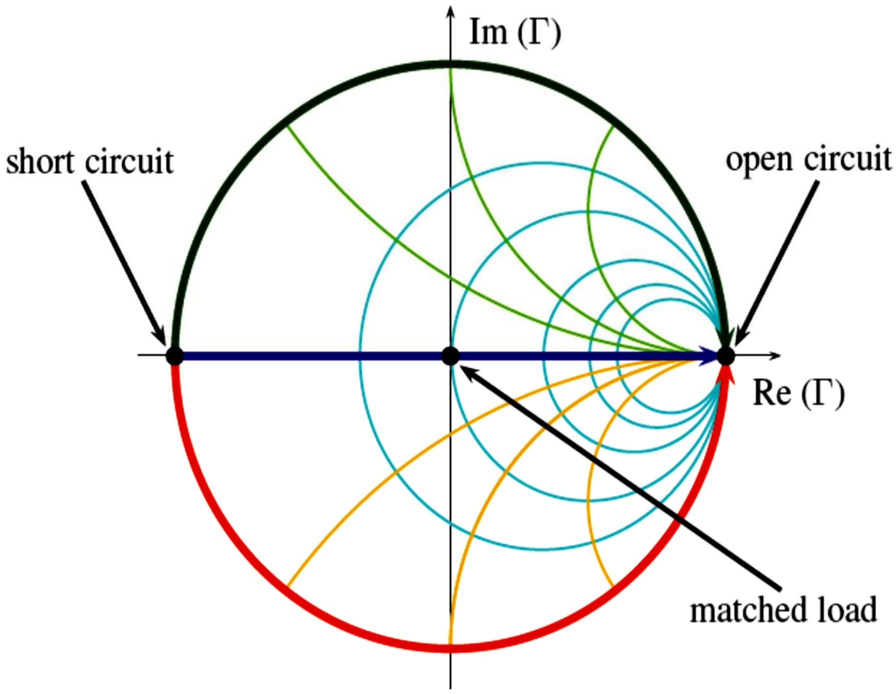


Figure I.21. Important points in the Smith chart

Concentric circles around the diagram center represent constant reflection factors (Figure I.22). Their radius is directly proportional to the magnitude of **Γ**, therefore a **radius of 0.5** corresponds to reflection of **3 dB** (half of the signal is reflected) whereas the outermost circle (**radius = 1**) represents full reflection.

Therefore matching problems are easily visualized in the Smith chart since a mismatch will lead to a reflection coefficient larger than 0.

Power into the load = forward power - reflected power:

$$P = \frac{1}{2}\left(|a|^2 - |b|^2\right) = \frac{|a|^2}{2}\left(1 - |\Gamma|^2\right) \tag{I.32}$$

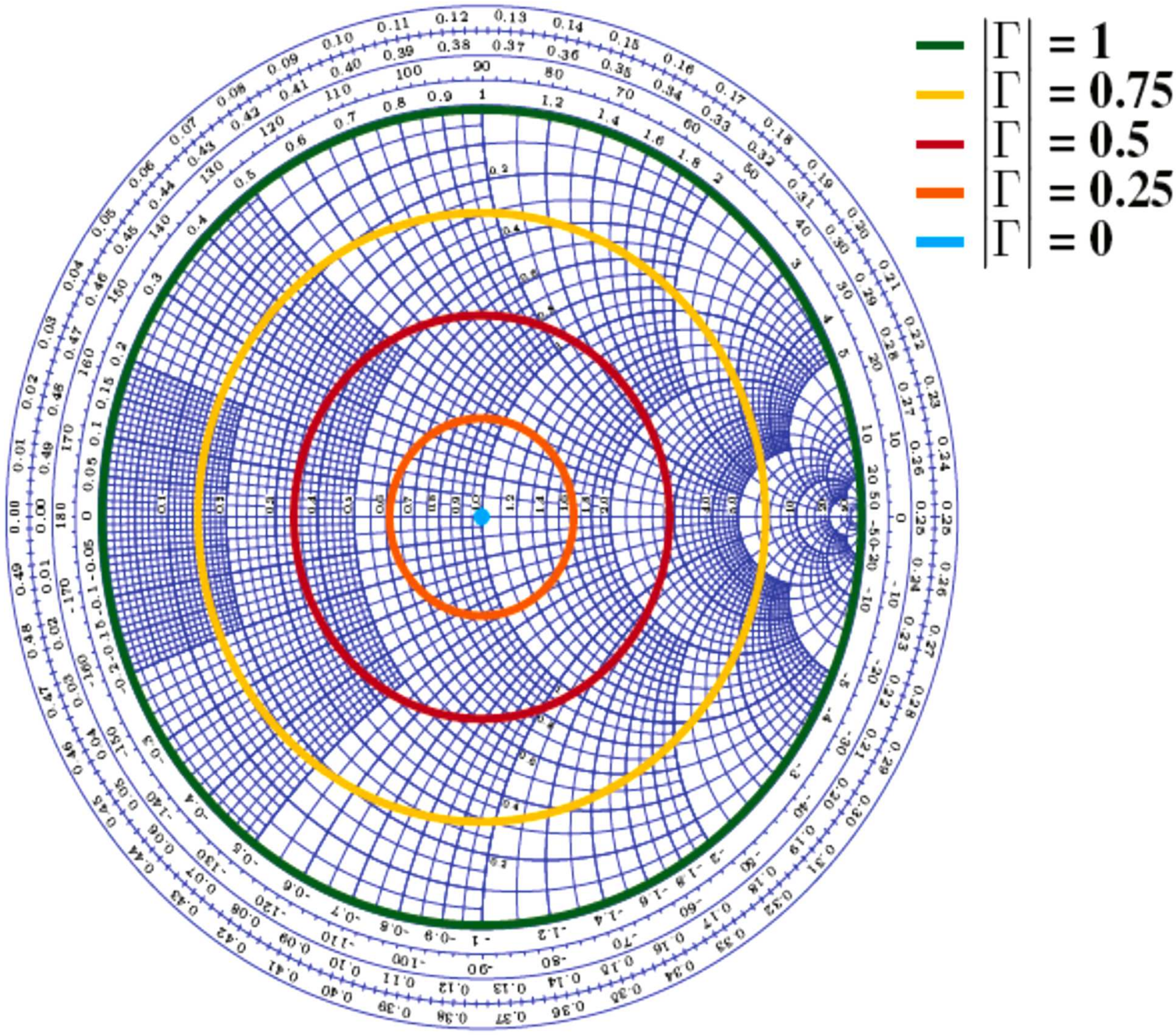


Figure I.22. Illustration of circles representing a constant reflection factor

In Equation (I.32) the European notation is used, where power $= \frac{|a|^2}{2}$. Furthermore, $(1-|\Gamma|^2)$ corresponds to the mismatch loss.

Although only the mapping of the impedance plane to the **Γ** plane is used, one can easily use it to determine the admittance since

$$\Gamma(\frac{1}{z}) = \frac{\frac{1}{z}-1}{\frac{1}{z}+1} = \frac{1-z}{1+z} = \left(\frac{z-1}{z+1}\right) \text{ or } \Gamma(\frac{1}{z}) = -\Gamma(z) \tag{I.33}$$

This can be visualized by rotating the vector of a certain impedance by 180◦ (Figure I.23).

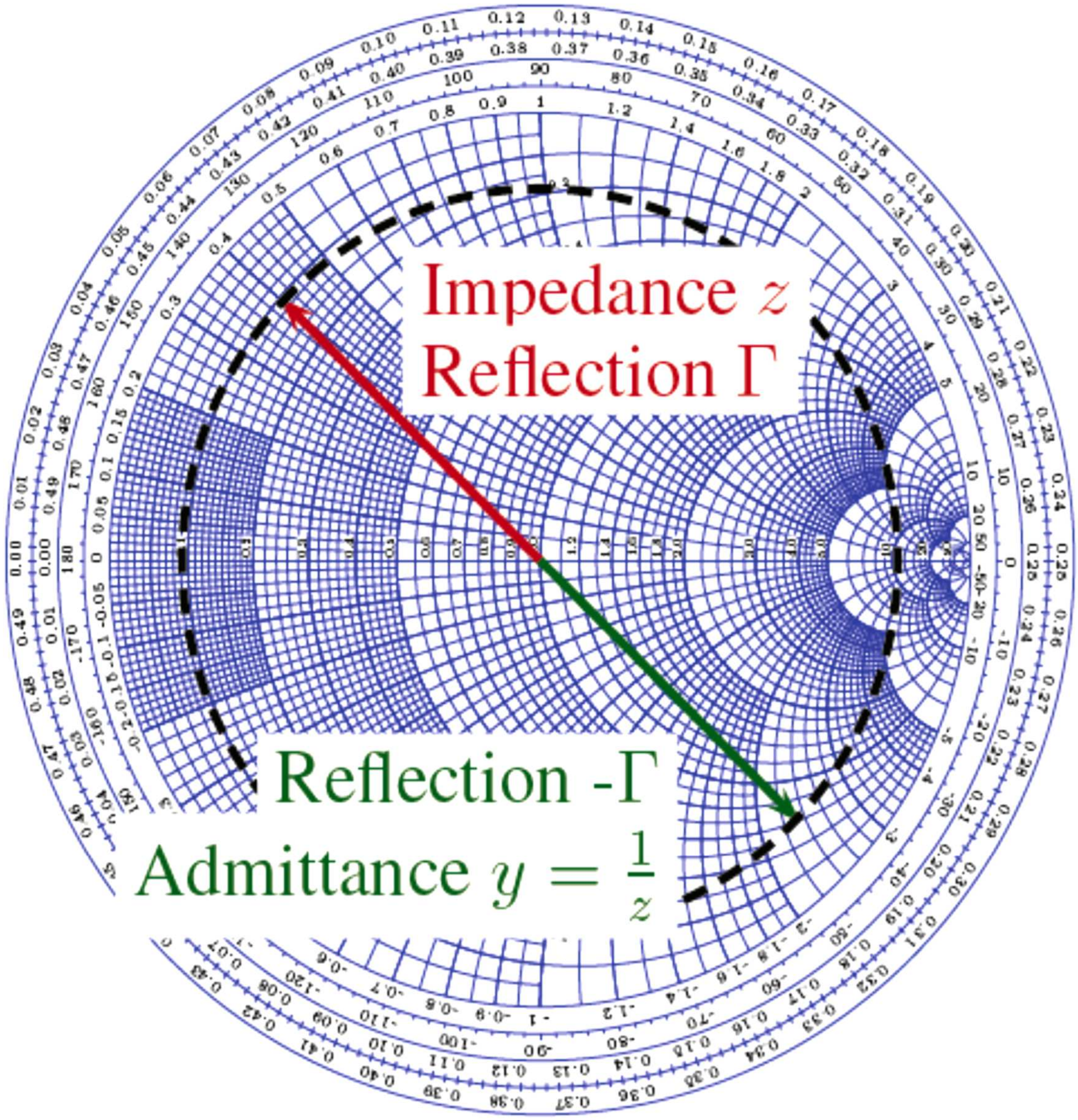


Figure I.23. Conversion of an impedance to the corresponding admittance in the Smith chart

e. Advantages of the Smith chart

- The diagram offers a compact and handy representation of all passive impedances from 0 to ∞.
- Impedances with negative real part such as reflection amplifier or any other active device would show up outside the Smith chart.
- Impedance mismatch is easily spotted in the chart.

- Since the mapping converts impedances or admittances (y = 1/z) into reflection factors and vice versa, it is particularly interesting for studies in the radio frequency and microwave domain. For reasons of convenience, electrical quantities are usually expressed in terms of direct or forward waves and reflected or backwards waves in these frequency ranges instead of voltages and currents used at lower frequencies.
- The transition between impedance and admittance in the chart is particularly easy: $\Gamma(\mathbf{y} = \frac{1}{z}) = -\Gamma(z)$.
- Furthermore, the reference plane in the Smith chart can be moved very easily by adding a transmission line of proper length.
- Many Smith charts have rulers below the complex **Γ** plane from which a variety of quantities such as the return loss can be determined.

Chapter II

Metallic (Copper) conductors

Twisted pair cable

Unshielded Twisted Pair

Shielded Twisted Pair

Foil Twisted Pair

Coaxial cable

Baseband Coaxial cable

Broadband Coaxial cable

Chapter II: Metallic (copper) conductors

II.1 Twisted-Pair Cables

II.1.1 Definition

A twisted pair is the least expensive and most widely used guided transmission medium. It is lightweight, cheap, can be installed easily, and they support many different types of network. It consists of **two conductors** (normally **copper**), each with its own plastic insulation, twisted together. One of the wires is used to carry signals to the receiver, and the other is used only as a ground reference. The receiver uses the difference between the two.

Typically, a number of these pairs are bundled together into a cable by wrapping them in a tough protective sheath (or cable jacket). Over longer distances, cables may contain hundreds of pairs. The twisting tends to decrease the crosstalk interference between adjacent pairs in a cable.

Neighboring pairs in a bundle typically have somewhat different twist lengths to reduce the crosstalk interference. On long-distance links, the twist length typically varies from 5 to 15 cm. The wires in a pair have thicknesses of from 0.4 to 0.9 mm.

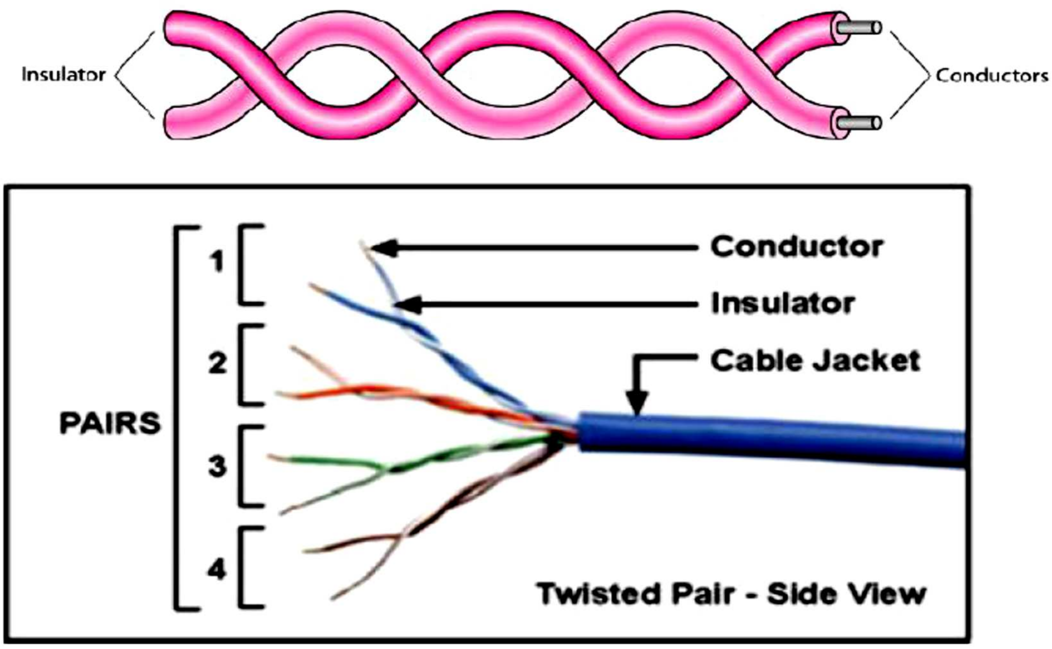


Figure II.1. Twisted pair

The composition of wire colors for four pairs of twisted pairs is shown in Table II.1.

Table II.1. Wire Color Composition for Four Pairs of Twisted Pairs

Pair	Color Code
1	White/Blue//Blue
2	White/Orange//Orange
3	White/Green//Green
4	White/Brown//Brown

II.1.2 Transmission characteristics

- Used to transmit both analog and digital transmission.
- Analog transmission: needs amplifiers every 5 km to 6 km.
- Digital transmission: needs a repeater every 2-3 km.
- Supports only limited distance, limited bandwidth, and limited data rate.
- Susceptible to interference and noise because of its easy coupling with electromagnetic fields.

II.1.3 Types of Twisted Pair cables

Twisted pair comes in two varieties: unshielded and shielded.

II.1.3.1 Unshielded Twisted Pair (UTP)

Unshielded twisted-pair (UTP) cable is the most common type of telecommunication medium in use today. Its usage is most familiar in telephone systems and its frequency range (from **100 Hz** to **5 MHz**) is suitable for transmitting both data and voice.

Usually consists of two copper wires wrapped in individual plastic insulation. The plastic insulation is **color-banded** for identification.

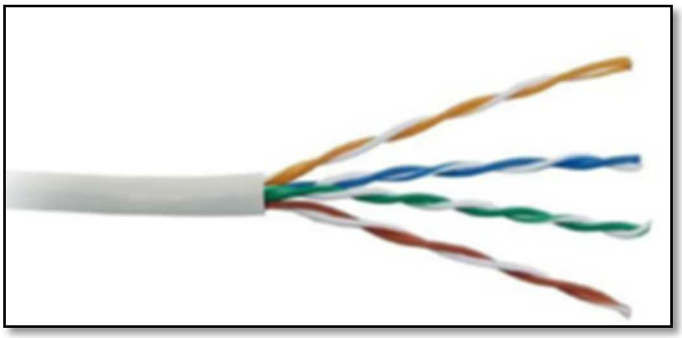


Figure II.2. UTP cables

UTP cables consist of **2** or **4** pairs of twisted cable. Cable with 2 pair use **RJ-11** connector and 4 pair cable use**RJ-45** connector.

a. UTPs categories

The Electronic Industries Association (**EIA**) standards to grade UTP cables by quality. Categories are determined by cable quality, with 1 as lowest and 5 (now 6 and 7) as highest. Each EIA category is suitable for certain uses and not for others (Category 6 and 7 are not EIA standards).

- **Category 1:** The basic twisted-pair cabling used in **telephone systems**. This level of quality is fine for voice but inadequate for data communication.
- **Category 2:** Suitable for voice and for low- speed digital data transmission of up to **4Mbps.**
- **Category 3:** Required to have at least **3-4 twists** per foot, four pairs grouped together in a plastic sheath for protection, and can be used for data transmission of up to **16 Mbps**. It is now the standard cable for most **telephone systems**. Can be used for Ethernet, Fast Ethernet, and token ring.
- **Category 4:** Must also have at least **3 twists** or more per foot as well as other conditions to bring the possible transmission rate from **16 to 20 Mbps**. Used for data and voice transmission. Suitable for Ethernet, Fast Ethernet, Gigabit Ethernet, token ring.
- **Category 5:** Used for voice and data transmission up to **100 Mbps.** Much more tightly twisted - **3 to 4 twists** per inch for less cross talk and better quality signal over longer distances. Suitable for Ethernet, Fast Ethernet, Gigabit Ethernet, token ring, and ATM.
- **Enhanced Category 5** (developing nonstandard cabling): Same as Cat 5 but manufacturing process is refined. Data rates of **1000Mbps**. Suitable for Ethernet, Fast Ethernet, Gigabit Ethernet, token ring, and ATM. Also known as Cat 5E.
- **Category 6:** 250 MHz rating (more than **1 Gbps**). Suitable for Ethernet, Fast Ethernet, Gigabit Ethernet, token ring, and ATM. Also can handle **550 MHz** broadband video.
- **Category 7:** 600 MHz rating. Can achieve higher speeds than Cat6.

Table II.2. UTP categories

Category	*Specification*	*Data Rate (Mbps)*	*Use*
1	Unshielded twisted-pair used in telephone	< 0.1	Telephone
2	Unshielded twisted-pair originally used in T lines	2	T-1 lines
3	Improved CAT 2 used in LANs	10	LANs
4	Improved CAT 3 used in Token Ring networks	20	LANs
5	Cable wire is normally 24 AWG with a jacket and outside sheath	100	LANs
5E	An extension to category 5 that includes extra features to minimize the crosstalk and electromagnetic interference	125	LANs
6	A new category with matched components coming from the same manufacturer. The cable must be tested at a 200-Mbps data rate.	200	LANs
7	Sometimes called *SSTP (shielded screen twisted-pair)*. Each pair is individually wrapped in a helical metallic foil followed by a metallic foil shield in addition to the outside sheath. The shield decreases the effect of crosstalk and increases the data rate.	600	LANs

b. UTP connectors

UTP is most commonly connected to network devices via a type of snap-in plug like that used with telephone jacks.

- The most frequently used in networking applications (LANs) is an **RJ45** (registered jack 45) connector with **8** conductors, one for each wire of **4- twisted pair**.
- Only **4 wires** are used for slower speed LANs (10BaseT), but all are used when the speed is increased (100BaseT).
- For telephones, the registered jack 11 (**RJ-11**) is normally used.

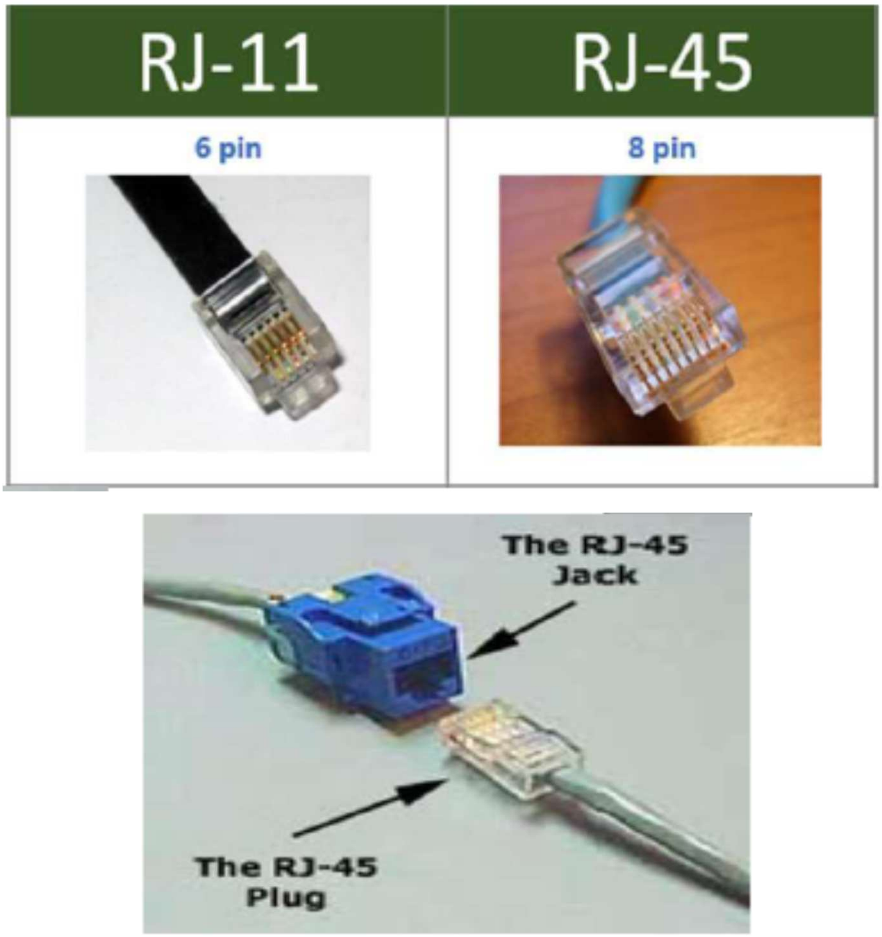


Figure II.3. UTP connectors

c. Advantages and disadvantages of UTP

✓ **Advantages:**

- Installation is easy
- Flexible
- Cheap
- It has high speed capacity,
- 100-meter limit
- Higher grades of UTP are used in LAN technologies like Ethernet.

✓ **Disadvantages:**

- Bandwidth is low when compared with Coaxial Cable
- Provides less protection from interference (EMI).

II.1.3.2 Shielded twisted pair (STP)

The only difference between STP and UTP is that STP cables have a shielding in usually of **aluminum** or **polyeste**r material between the outer jacket and wire.

The shield makes STP less vulnerable to electromagnetic interference (**EMI**), because the shield is electrically grounded.

The metal mesh around the insulated wires eliminates **crosstalk**. Crosstalk occurs when one line picks up some of the other signals traveling down another line.

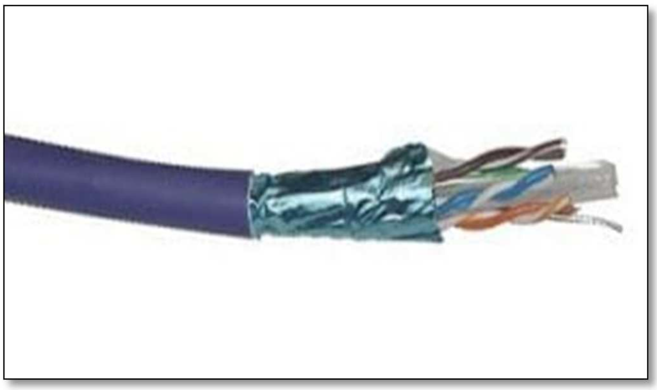


Figure II.4. STP cables

- **Advantages and Disadvantages of STP**

  ✓ **Advantages:**

- Easy to install
- Performance is adequate
- Can be used for Analog or Digital transmission
- Increases the signaling rate
- Higher capacity than unshielded twisted pair
- Eliminates crosstalk

  ✓ **Disadvantages:**

- Difficult to manufacture
- Heavy
- Expensive than UTP

II.1.3.3 Foil Twisted cable (FTP)

FTP cables, also known as **Foil Twisted Pair** cables, have each pair of cables enclosed in its own shielding of foil. It helps FTP cables to protect the cable from **EMI** and **crosstalk**.

FTP cables offer a balance between UTP and STP characteristics, providing protection from EMI and crosstalk without the complexity of installation associated with STP cables. They are suitable for applications that require cable flexibility and electromagnetic interference protection.

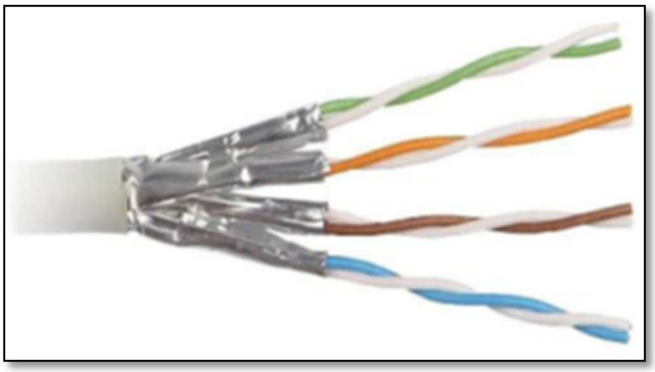
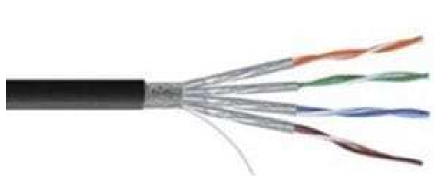


Figure II.5. FTP cables

Table II.3. FTP cable variations

FTP cable	Description	example
S/FTP: Shielded with Foiled Twisted Pairs.	Cable which incorporates a combination of both a foil shield and an overlapped braided shield.	
F/FTP: Foiled with Foiled Twisted Pairs.	Cable which is individually foil pairs and over all foil shield.	
U/FTP: Unshielded with Foiled Twisted Pairs.	Cable which is individually foil shielded pairs without over all foil shield.	

II.1.3.4 Differences between STP, UTP and FTP cables

Key Differences	STP	UTP	FTP
Shielding	Yes	No	Yes
Crosstalk protection	High	Low	High
Grounding requirements	Necessary	No	Necessary
Termination	Difficult and time-consuming	Easier and time-efficient	Difficult and time-consuming
Data Rate	High	Low	High
Cost	Higher	Lower	Higher

II.1.4 Parameters of Twisted Pairs Cables

For twisted pairs (whether it's Category, shielded, or unshielded), users are concerned with parameters such as attenuation, near-end crosstalk, characteristic impedance, etc.

a. Attenuation: - Insertion Loss

Insertion loss measures the amount of energy that is lost as the signal arrives at the receiving end of the cabling link. The insertion loss measurement quantifies the effect of the resistance the cabling link offers to the transmission of the electrical signals. Insertion loss characteristics of a link change with the frequency of the signal to be transmitted; e.g. higher frequency signals experience much more resistance. Stated a different way, the links show more insertion loss for higher frequency signals.

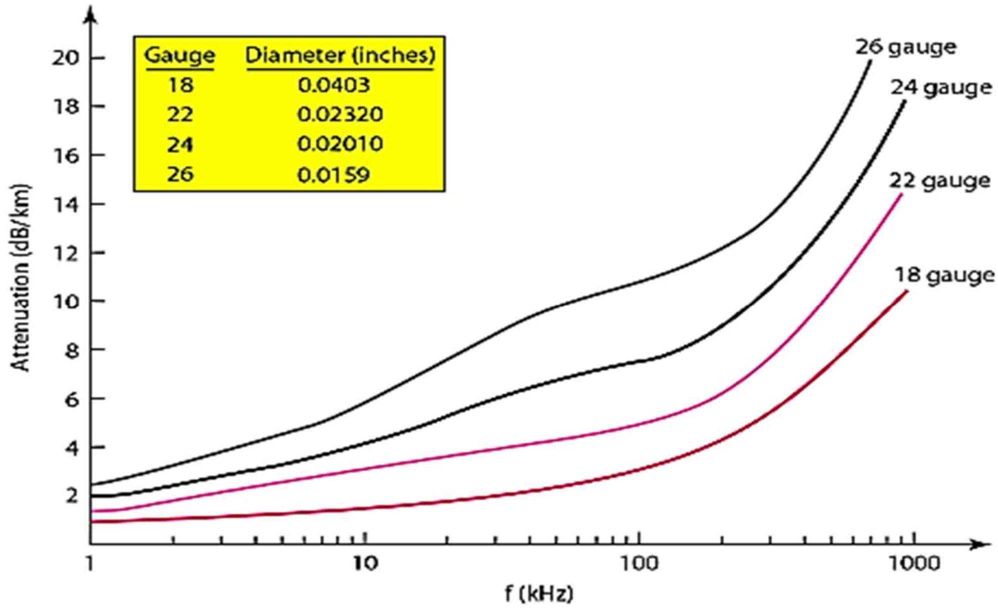


Figure II.6. Attenuation relates to wire gauge and frequency

b. Near-End Crosstalk (NEXT)

One of the most important cable measurements is Near-End Crosstalk (**NEXT**). It is a signal interference from one pair that adversely affects another pair on the same end. Crosstalk occurs between adjacent wire pairs ("pair-to-pair NEXT"). In addition, all other pairs in a UTP cable can also contribute their own levels of both NEXT and Far-End Crosstalk (**FEXT**), multiplying the adverse effects of interference onto a transmitting or receiving wire pair. These compounded levels of interference can prove crippling.

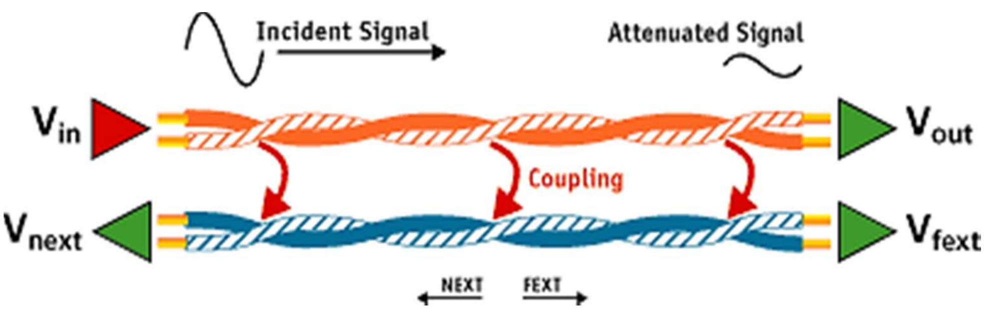


Figure II.7. Crosstalk occurs when signals from one line bleed into another line

✓ **Far-End Crosstalk (FEXT):** FEXT measures an unwanted signal from a pair transmitting on the near end onto a pair at the far end. Full-duplex operation is taken into account where signals are generated simultaneously on both ends.

✓ **Power Sum Near-End Crosstalk (PS-NEXT):** PS-NEXT measures the unwanted signals from multiple pairs at the near end onto another pair at the near end.

✓ **Attenuation-crosstalk ratio (ACR)**: ACR is measured by taking the ratio of a signal from the far end to crosstalk at the near end. Again, higher is better, as it indicates the cable can handle higher data loads and bandwidth.

c. Return Loss :

The impact of incorrect characteristic impedance is more accurately measured and represented by the quantity return loss. Return Loss (RL) is a measure of all reflections that are caused by the impedance mismatches at all locations along the link and is expressed in decibels (dB). Return Loss is of particular concern in the implementation of Gigabit Ethernet.

II.1.5 Twisted-Pairs Cables Applications

By far the most common guided transmission medium for both analog and digital signals is twisted pair.

- It is the most commonly used medium in the telephone network and is the workhorse for communications within buildings.
- These twisted-pair installations were designed to support voice traffic using analog signaling. However, by means of a modem, these facilities can handle digital data traffic at modest data rates.
- Twisted pair is also the most common medium used for digital signaling. For connections to a digital data switch or digital PBX within a building, a data rate of 64 kbps is common.
- Twisted pair is also commonly used within a building for local area networks supporting personal computers. Data rates for such products are typically in the neighborhood of 100 Mbps.
- For long-distance applications, twisted pair can be used at data rates of 4 Mbps or more.
- Twisted pair is much less expensive than the other commonly used guided transmission media (coaxial cable, optical fiber) and is easier to work with.

II.2 Coaxial Cables

II.2.1 Definition

Coaxial cable (or **coax**), like twisted pair, consists of two conductors, but is constructed differently to permit it to operate over a wider range of frequencies (**100 KHz to 500 MHz**). Instead of having two wires, coax has a **central core conductor** (inner conductor) of solid or stranded wire (usually copper) enclosed in an **insulating sheath (dielectric:** PVC, Teflon**)**, which is, in turn, encased in an **outer conductor** of **metal foil**, **braid**, or a combination of the two. The outer metallic wrapping serves both as a shield against noise and as the **second conductor**, which completes the circuit. This outer conductor is also enclosed in an insulating sheath, and the whole cable is protected by a **plastic cover (outer jacket)**.

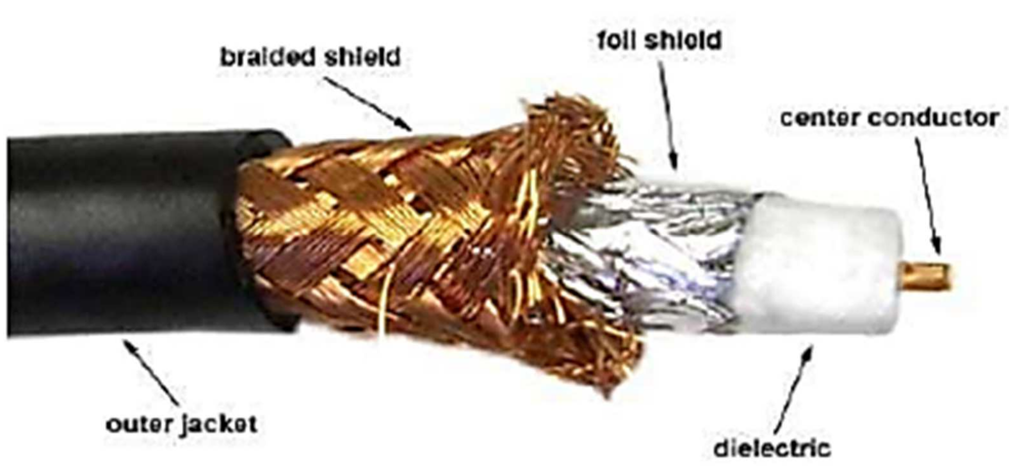


Figure II.8. Coaxial cable

II.2.2 Transmission characteristics

- The construction and shielding of the coaxial cable give it a good combination of high bandwidth and excellent noise immunity.
- The bandwidth possible depends on the cable length. For 1-km cables, a data rate of 1 to 2 Gbps is feasible.
- Superior frequency characteristics compared to Twisted Pair0
- Performance is limited by attenuation & noise.
- For analog signals, amplifiers to be placed at every few km.
- For digital signals, repeaters to be placed at every 1km.

II.2.3 Types of coaxial cables

Two kinds of coaxial cables are widely used: Base band- 50-0hm cable, commonly used for digital transmission. Broad band- 75-0hm cable, commonly used for analog transmission. (Base band means digital and broadband means analog).

II.2.3.1 Baseband Coaxial cable

Baseband Coaxial cable is widely used in Local Area Networks. **10Base 5** (popularly called **Thick** Coax) and **10Base 2** (popularly called **Thin** Coax) are the popular baseband cables used in 802.3 (Ethernet LAN) cabling.

a. Baseband Coaxial (10Base2 Thinnet)

Thinnet cable is a flexible coaxial cable about **0.64 centimeters** (0.25 inches) in diameter.

10Base 2 means that it operates at **10 Mbps**, and can support segments of up to **200 meters**.

Connections to 10Base 2 are made using industry standard **BNC** (bayonet network connector) connector. There are three types: the BNC connector, the BNC T connector, the BNC terminator.

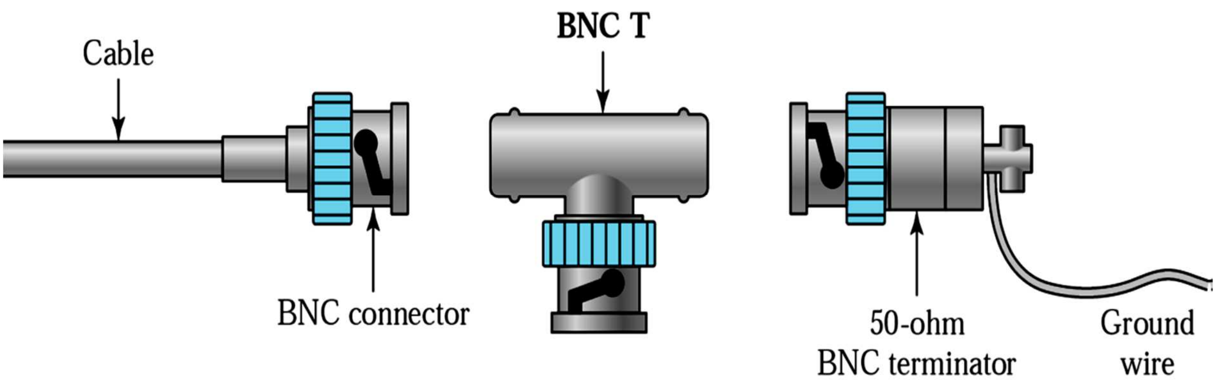


Figure II.9. BNC connectors

- BNC connector pushes on and locks into place with a half turn into a T-connector. Thin Ethernet is much cheaper and easier to install, but it can run for only **200 meters** and can handle only **30 machines** per cable segment.
- Terminators are another type of connectors, which are required for bus topologies where one main cable acts as a backbone with branches to several devices but does not itself terminate in a device.

b. Baseband Coaxial (10Base5 Thicknet)

Thicknet cable is a relatively rigid cable about **1.27 centimeters** (0.5 inches) in diameter.

10Base 5 means that it operates at **10 Mbps**, uses baseband (digital) signaling and can support segments of up to **500 meters**.

Connections to 10Base 5 are generally made using **vampire taps,** in which a pin is carefully forced halfway into the coaxial cable's core. It can support **100 machines** per cable segment.

Thick coaxial cable is awkward to handle and install.

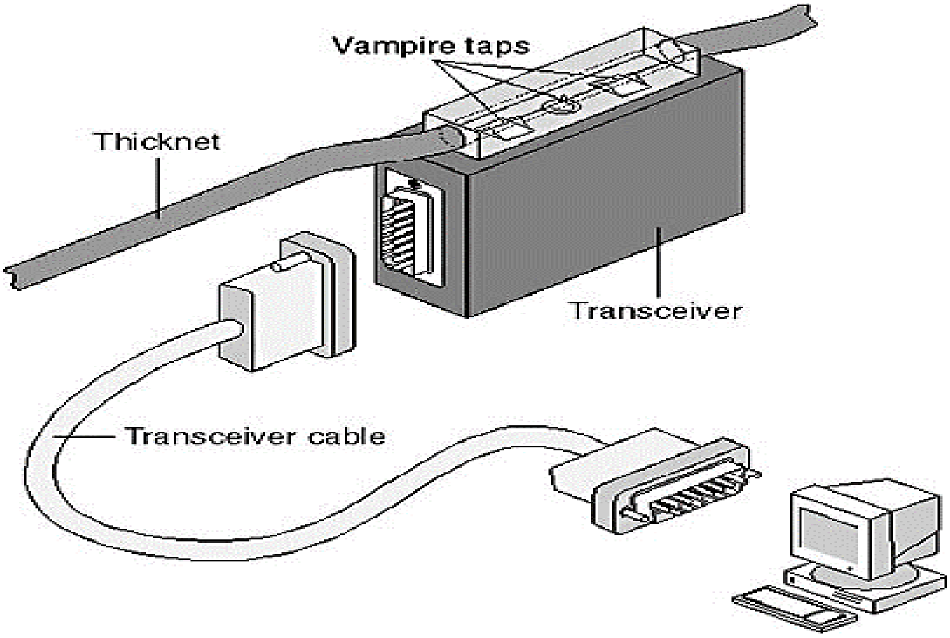


Figure II.10. Thicknet cable transceiver with detail of a vampire tap piercing the core

✓ **Thinnet vs. Thicknet Cable:** Generally, the thicker the cable, the more difficult it is to work with. Thin cable is flexible, easy to install, and relatively inexpensive. Thick cable does not bend easily and is, therefore, harder to install. This is a consideration when an installation calls for pulling cable through tight spaces such as conduits and troughs. Thick cable is more expensive than thin cable, but carry a signal farther.

II.2.3.2 Broadband coaxial cable

Broadband coaxial cable system uses analog transmission on standard cable television cabling.

Coaxial cables are used for connecting television set or digital convertor box to a personal antenna.

The cables can run for nearly **100 km** due to the analog signaling.

Broadband systems are divided up into multiple channels, frequently the **6 MHz** channels used for television broadcasting.

Television and data can be mixed on one cable.

✓ **Applications**

- Cable Television distribution & Cable Modem
- Long-distance telephone transmission

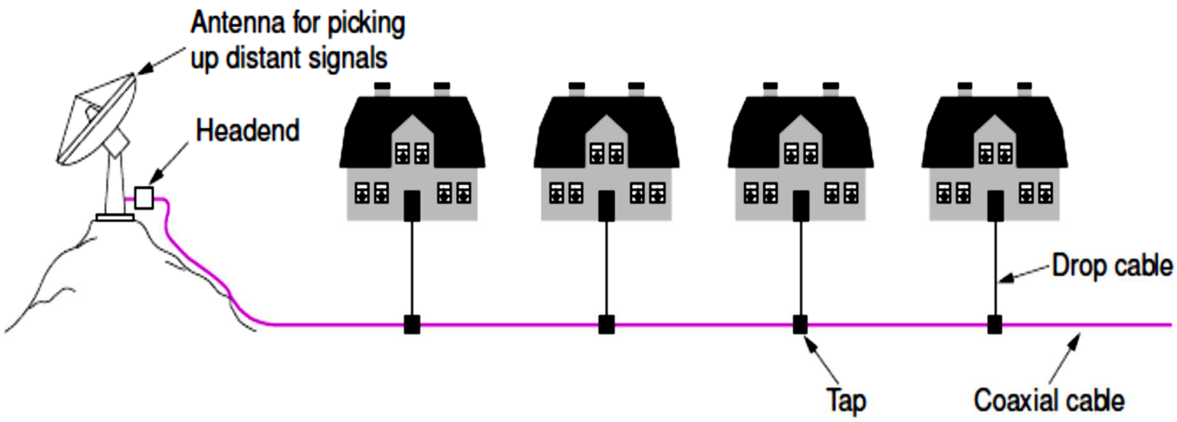


Figure II.11. Broadband coaxial cable for CATV application (Cable Television distribution)

II.2.4 Categories of coaxial cables

Coaxial cables are categorized by radio government rating (**RG: Radio Guide**). Each RG number denotes a unique set of physical specifications. Coaxial Cable RG Numbers are generally just an **indicator of size.**

Coaxial cable standards:

- RG-8, RG-9, RG-11 are used in thick Ethernet.
- RG-58 Used in thin Ethernet.
- RG-59 Used for TV.

Table II.4. Categories of coaxial cables

Category	*Impedance*	*Use*
RG-59	75 Ω	Cable TV
RG-58	50 Ω	Thin Ethernet
RG-11	50 Ω	Thick Ethernet

II.2.5 Performance of coaxial cable: Cable Attenuation

Attenuation is the term given to the loss of signal along a length of cable. With an RF (Radio Frequency) signal, the amount of attenuation is also linked to the frequency of the waveform as much as the resistance and other factors in the cable.

The cable has a resistance to the signal which reduces the voltage (a combination of: the signal travelling the length of the cable, coupling loss though magnetic fields with the shield, return loss from imperfections in the cable, tight bends and adapters joining lengths of cable). A hefty list of issues, all with small effects but all which add up to create a loss, worthy of consideration.

Installing a larger diameter cable could be the first 'go to' answer but cost will also be a factor. A higher quality cable of the same type will generally be a better compromise.

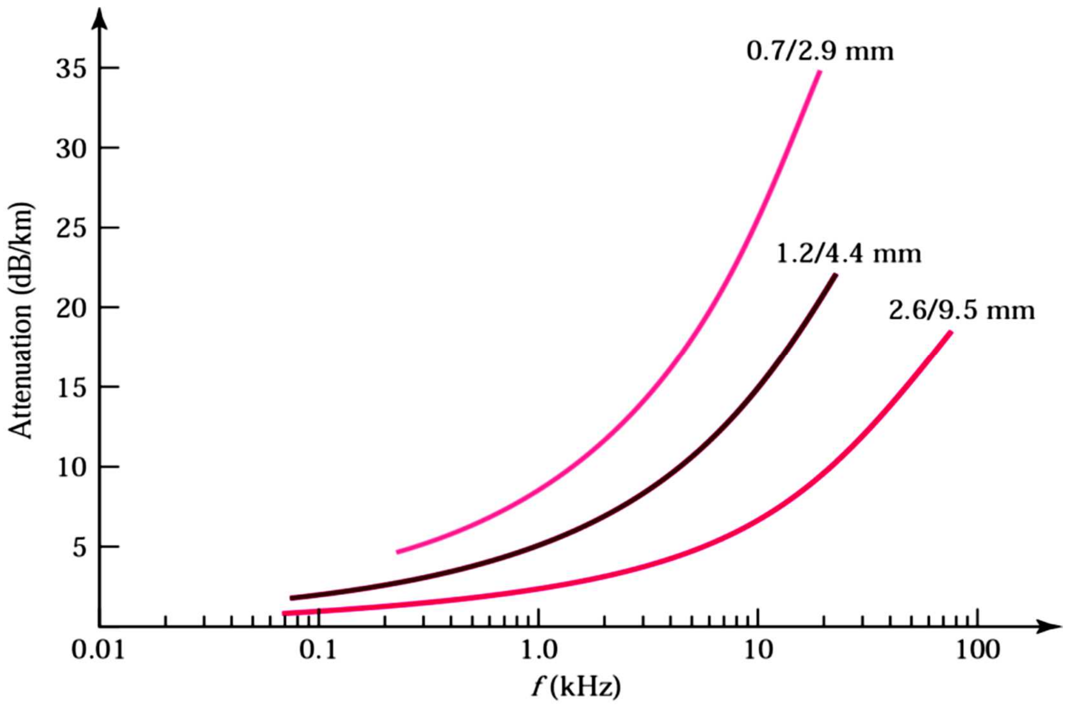


Figure II.12. Attenuation relates to cable size and frequency

II.2.6 Applications of coaxial cable

Coaxial cable is perhaps the most versatile transmission medium and is enjoying widespread use in a wide variety of applications. The most important of these are:

- **Analog telephone network** where a single cable could carry 10,000 voice signals. Later it was used in Digital telephone networks where cable can carry 600 Mbps.

- **Cable TV network**: hybrid network use coaxial cable only at the network boundaries, near the consumer. Cable TV use RG-59.

- **Traditional Ethernet LANs**: 10-base-2 or “Thin Ethernet” uses RG-58 coax cable to transmit data at 10 Mbps with a range of 185 m.10-base-5, or “Thick Ethernet”, uses RG-11 to transmit 10 Mbps with rang of 500 m.

II.2.7 Advantages and Disadvantages of coaxial cables

✓ **Advantages:**

- Can be used over longer distances.
- Support more stations on a shared line than twisted pair.
- Operate over a wider range of frequencies.
- Much less susceptible to interference and crosstalk than twisted pair.

✓ **Disadvantages:**

- It is more expensive as compared to twisted pair cable.
- If any fault occurs in the cable causes the failure in the entire network.

Chapter III

Optical Fiber cables

Optical Fiber Structure

Optical fiber parameters

Optical fiber types

- Single-mode fibers
- Multimode fibers

Optical Fiber applications

Chapter III: Optical fiber cables

III Optical fiber cables

III.1 Optical fiber definition

An optical fiber is a flexible glass or plastic waveguide that can transmit light from one end to the other. Such fibers find wide usage in fiber-optic communications, where they permit transmission over longer distances and at higher bandwidths than electrical cables.

III.2 Optical Fiber Structure

The basic structure of an optical fiber consists of three parts; **the core**, **the cladding**, and **the coating** or **buffer**. The **core** is a cylindrical rod of dielectric material, generally made of glass. The core is described as having a radius of 'a' and an index of refraction $\mathbf{n_1}$. The core is surrounded by a layer of material called the **cladding**. The cladding layer is made of a dielectric material with an index of refraction $\mathbf{n_2}$, less than that of the core material ($\mathbf{n_2 < n_1}$). The cladding is generally made of glass or plastic. The cladding is enclosed in an additional layer called the **coating** or **buffer** that used to protect an optical fiber from physical damage. The material used for a buffer is a type of plastic.

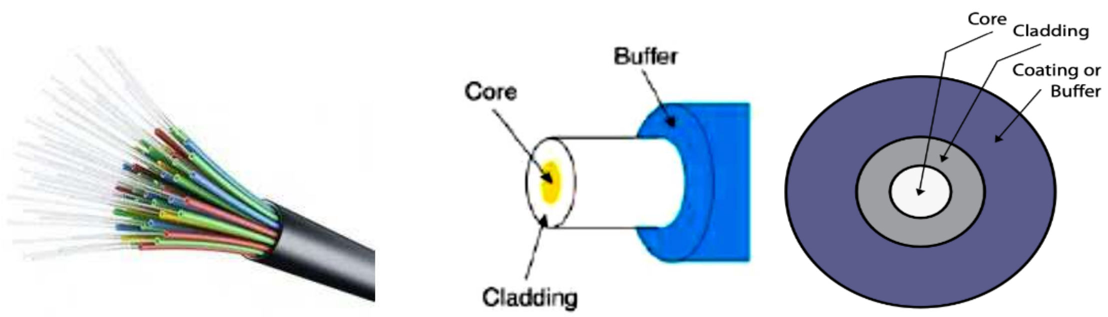


Figure III.1. Basic structure of an optical fiber

III.3 The propagation of light in optical fiber

The light propagates through optical fiber through "**Total internal reflection**".

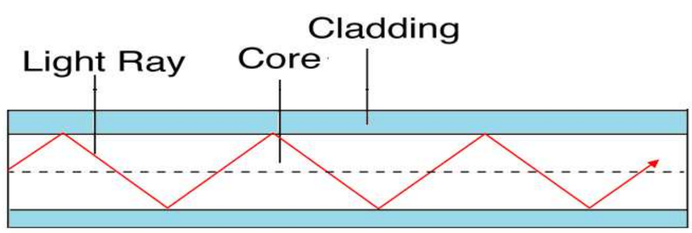


Figure III.2. Total internal reflection through optical fiber

Following are the conditions for total internal reflection:

- The ray of light should be traverse from denser to rarer medium.
- The incident angle should be more than the **critical angle ($\theta i > \theta c$).**

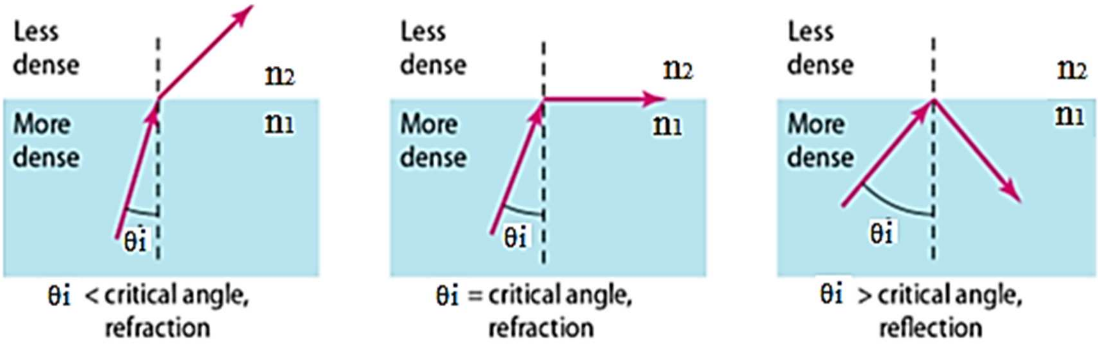


Figure III.3. Propagation of light from rarer to denser medium

If the incident ray exceeds the **critical angle**, the refraction would be turned in to reflection called total internal reflection. The critical angle is used for the mathematical expression to the occurrence of total internal reflection (Figure III.3.b)

$$n_1 \sin\theta_i = n_2 \sin 90^\circ \quad \text{(from Snell's law)}$$

$$\sin\theta_i = \frac{n_2}{n_1} \quad \text{Since, } \sin 90^\circ = 1$$

$$\sin\theta_c = \frac{n_2}{n_1} \quad \text{Since, } \theta_i = \theta_c$$

$$\theta_c = \sin^{-1}\left(\frac{n_2}{n_1}\right)$$

III.4 Optical fiber parameters

III.4.1 Numerical aperture (NA)

Numerical aperture (**NA**) is a light gathering property of optical fiber, which gives the quantity of light that brought into the center of optical fiber in terms of incidence angle. To calculate NA, consider a longitudinal section of fiber as in Figure III.4. Let $\mathbf{n_0}$, $\mathbf{n_1}$, $\mathbf{n_2}$ are the refractive indices of air (outside optical fiber), core and cladding respectively.

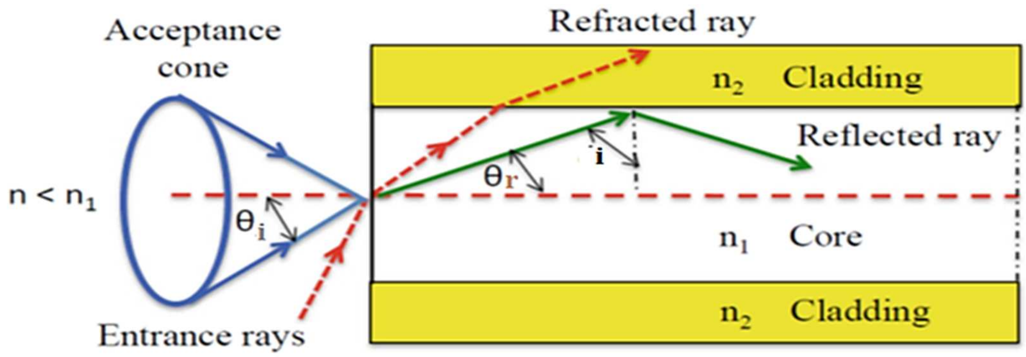


Figure III.4. Fiber acceptance angle

θ_i , θ_r are incidence angle and refracted angle of the light through fiber.

Applying Snell's law at A

$$n_0 \sin\theta_i = n_1 \sin\theta_r$$

$$\sin\theta_i = \frac{n_1}{n_0}\sin\theta_r = \frac{n_1}{n_0}\sqrt{1-\cos^2\theta_r}$$

Applying Snell's law at B

$$n_1 \sin(90-\theta_r) = n_2 \sin 90$$

$$n_1 \cos\theta_r = n_2$$

$$\cos\theta_r = \frac{n_2}{n_1}$$

Substituting (2) in (1)

$$\sin\theta_i = \frac{n_1}{n_0}\sqrt{1-\left(\frac{n_2^2}{n_1^2}\right)} = \frac{n_1}{n_0}\sqrt{\frac{n_1^2-n_2^2}{n_1^2}}$$

$$\sin\theta_i = \frac{1}{n_0}\sqrt{n_1^2-n_2^2}$$

$$\therefore NA = \sin\theta_i = \frac{1}{n_0}\sqrt{n_1^2-n_2^2}$$

Or:

$$\boxed{NA = \sin\theta_i = \sqrt{n_1^2-n_2^2} \qquad \text{(Where } n_0 = 1 \text{ for air)}}$$

III.4.2 Acceptance angle

It is a semi angle that formed by the set of incident rays at the center of fiber, which helps to decide the size of core.

Maximum acceptance angle is that which just gives total internal reflection at the core-cladding interface,

From

$$NA = \sin\theta_i = \sqrt{n_1^2 - n_2^2}$$

$$\sin\theta_i = \sqrt{n_1^2 - n_2^2}$$

$$\theta_i = \sin^{-1}\left(\sqrt{n_1^2 - n_2^2}\right)$$

Replacing

$$\boxed{\theta_a = \sin^{-1}\left(\sqrt{n_1^2 - n_2^2}\right) = \sin^{-1}(NA)}$$

III.4.3 The index difference

Refractive index difference (Δ), in an optical fiber, is a measure of the relative difference in refractive index of the core and the cladding.

$$\Delta = \frac{n_1^2 - n_2^2}{2n_1^2} \quad \rightarrow \quad \Delta = (n_1 - n_2)/n_1$$

III.5 Classification of optical fibers

In the optical fibers, the materials used, refractive index and mode of propagation of light are used for classification as follows:

III.5.1 Material Based optical fibers

The material based classification results to the following types:

- Plastic made fibers.
- Glass made fibers.

The plastic made fibers are obtained from **polymers** of transparent to light, flexibility and interaction less to light etc,. For example poly methyl metha acrylate (PMMA), polyethylene (PE), polystyrene (PS) are used as core materials.

Glass made fiber is also fabricated from flexible glass as core with suitable drawing technique in presence of impurities.

III.5.2 Classification of optical fibers based on refractive index

The types of optical fibre can be classified based on the refractive index are:

- Step index fibres.
- Graded index fibres.

a. Step index

The step index (**SI**) fiber is a cylindrical waveguide core with inner core has a uniform refractive index of n_1 and the core is surrounded by outer cladding with uniform refractive index of n_2. The cladding refractive index (n2) is less than the core refractive index (n1). But there is an abrupt change in the refractive index at the core cladding interface.

The refractive index profile is defined as:

$$n(r) = \begin{cases} n_1 & where\ r < a\ (core) \\ n_2 & where\ r \geq a\ (cladding) \end{cases}$$

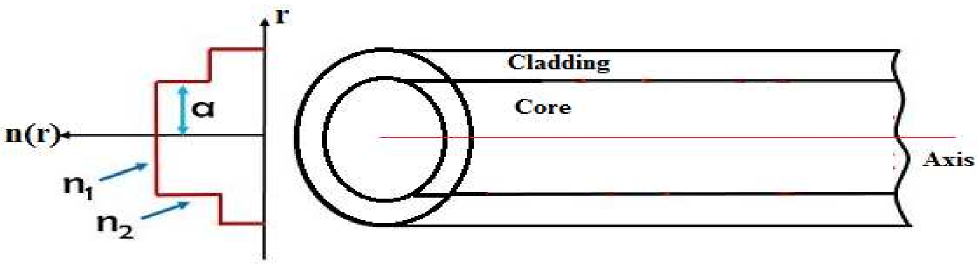


Figure III.5. Step Index fiber profile

b. Graded index

In the graded index **(GRIN)** fiber the refractive index is not uniform within the core, it is highest at the center and decreases smoothly and continuously with distance towards the cladding. Generally, the refractive index profile across the core takes the parabolic nature.

The refractive index variation in the core is giver by relationship:

$$n(r) = \begin{cases} n_1\left(1 - 2\Delta\left(\frac{r}{a}\right)^{\alpha}\right) & \text{when } r < a\ (core) \\ n_1(1 - 2\Delta)^{\frac{1}{2}} \approx n_2 & when\ r \geq a\ (cladding) \end{cases}$$

Where,

r = Radial distance from fiber axis, a = Core radius, and α = Shape of index profile.

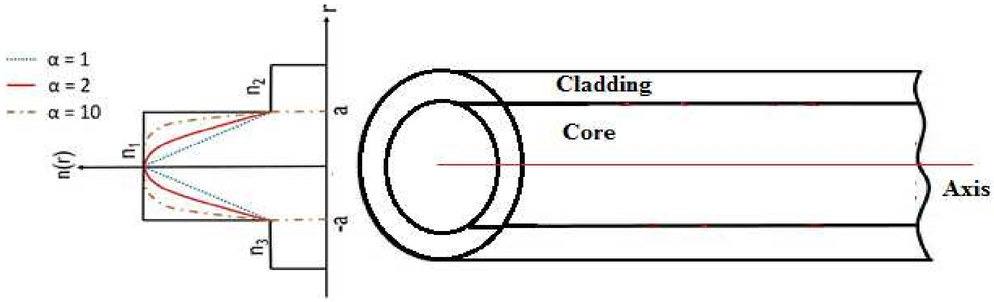


Figure III.6. Graded Index fiber profile

III.5.3 Modes of propagation based optical fiber

Based on modes of propagation of light through core, the following are the types of optical fiber identified:

- Single mode fibres
- Multimode fibres

a. Multimode optical fiber

Multimode is so named because multiple beams from a light source move through the core in different paths. There are two types under multimode transmission: multimode step index and multimode graded index.

- **Multimode Step-Index Fiber**

In multimode step-index fiber, multiple propagation paths exist, each with a different path length and hence time to traverse the fiber. This causes signal elements (light pulses) to spread out in time, which limits the rate at which data can be accurately received.

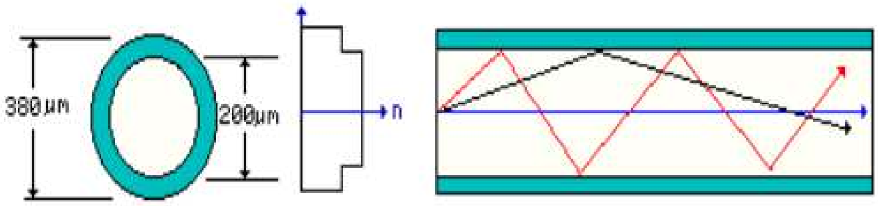


Figure III.7. Multimode step-index fiber

✓ **Characteristics:**

- Core size: 50 or 62.5 µm, cladding 125 µm, (**50/125**),
- Limited bandwidth: < 60 MHz.km.
- Low attenuation: 3 dB/km at 0.85 µm.

- **Multimode graded-index fiber**

For the **graded-index multimode**, the higher refractive index at the center makes the light rays moving down the axis advance more slowly than those near the cladding. Rather than zigzagging off the cladding, light in the core curves helically because of the graded index, reducing its travel distance. The shortened path and higher speed allows light at the periphery to arrive at a receiver at about the same time as the straight rays in the core axis.

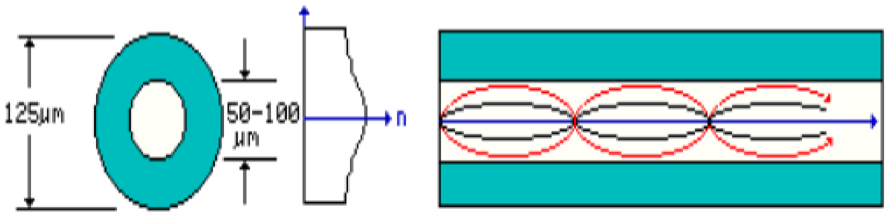


Figure III.8. Multimode graded-index fiber

✓ **Characteristics:**

- Core size: 50 or 62.5 µm, cladding 125 µm, (**50/125**),
- Bandwidth: GHz.km.
- Low attenuation: 3 dB/km at 0.85 µm and 1.5 dB/km at 1.3 µm.

b. Single mode fibers

If the core size is adjusted to allow only one mode of light wave propagation is single mode fiber, whose profile is shown below:

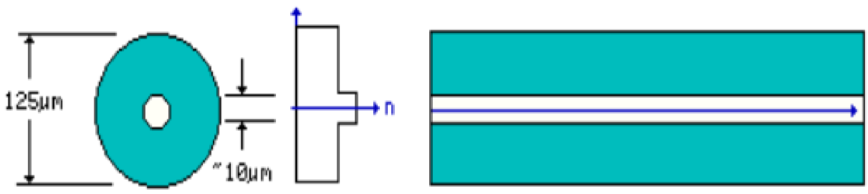


Figure III.9. Single mode fiber

✓ **Characteristics:**

- Core size: 5 to 10 µm, cladding 125 µm (7/125),
- High bandwidth: THz.km.
- Very low attenuation: 0.5 dB/km at 1.3 µm and 0.2 dB/km at 1.5 µm.

Table III.1. Differences between Singlemode and multimode fiber optic cables

Fiber Optic Cable Types	Type	Core Size	1Gb Distance	10 Gb Distance	Wavelength
Multi-mode	OM1	62.5µm	300m	36m	850/1300 nm
Multi-mode	OM2	50µm	550m	86m	850/1300 nm
Multi-mode	OM3	50µm	1000m.	300m.	850/1300 nm
Multi-mode	OM4	50µm	1000m.	550m	850/1300 nm
Single-mode	OS1/OS2	9µm	2Km.	2Km	1300/1550 nm
Single-mode	OS1/OS2	9µm	10km	10km	1300/1550 nm

III.6 Optical fibers modes

In an optical fiber, the normalized frequency, V (also called the **V number**), which determines the number of guided modes, is given by:

$$V = \frac{2\pi a}{\lambda_0}\sqrt{n_1^2 - n_2^2}\,, \quad \rightarrow \quad \boldsymbol{V = \frac{2\pi a}{\lambda}\mathrm{NA}}$$

Where, a = Core radius, and λ = Free space wavelength

- For single-mode operation, it is required that $\boldsymbol{V < 2.405}$
  - The total number of modes in a multimode fiber is given by $N \simeq \frac{V^2}{2}$.

III.7 Performance of optical fibbers

III.7.1 Attenuation

Fiber attenuation results in **pulse power decreasing.** Silica-based glass fibers have losses less than 0.2 dB/km (i.e. 95 % launched power remains after 1 km of fiber transmission). This is essentially the fundamental lower limit for attenuation in silica based glass fibers.

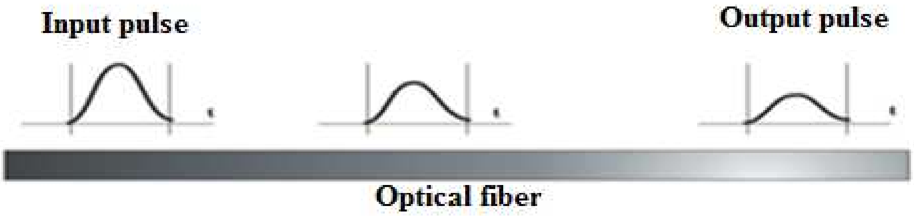


Figure III.10. Power loss along an optical fiber

Attenuation coefficient α is defined as the fractional decrease in the optical power per unit distance. α is in m^{-1}.

$$P_{out} = P_{in}\exp(-\alpha L)$$

Signal attenuation within optical fibers is usually expressed in the logarithmic unit of the decibel. α is in dB.

$$\alpha_{dB} = \frac{1}{L} 10\log\left(\frac{P_{in}}{P_{out}}\right) \qquad \alpha_{dB} = \frac{10}{\ln(10)}\alpha = 4.34\alpha$$

1. Causes of Attenuation

a. Material Losses

Material absorption is a loss mechanism related to both **the material composition** and the **fabrication process** for the fiber. The optical power is lost as heat in the fiber.

✓ Pure silica-based glass has two major intrinsic absorption:

- A **fundamental UV absorption** edge, the peaks are centered in the ultraviolet wavelength.
- A **fundamental infrared and far-infrared absorption** edge, the tail of these absorption peaks may extend into the longer wavelengths of the fiber transmission spectral window.

✓ Major **extrinsic** loss mechanism is caused by absorption due to **water** (as the hydroxyl or OH- ions) introduced in the glass fiber during fiber pulling by means of oxyhydrogen flame. These OH- ions are bonded into the glass structure and have absorption peaks at 1.39 µm.

✓ **1550 nm** window is today's standard **long-haul** communication wavelengths.

b. Rayleigh scattering

Main factor losses in the visible and near infrared.

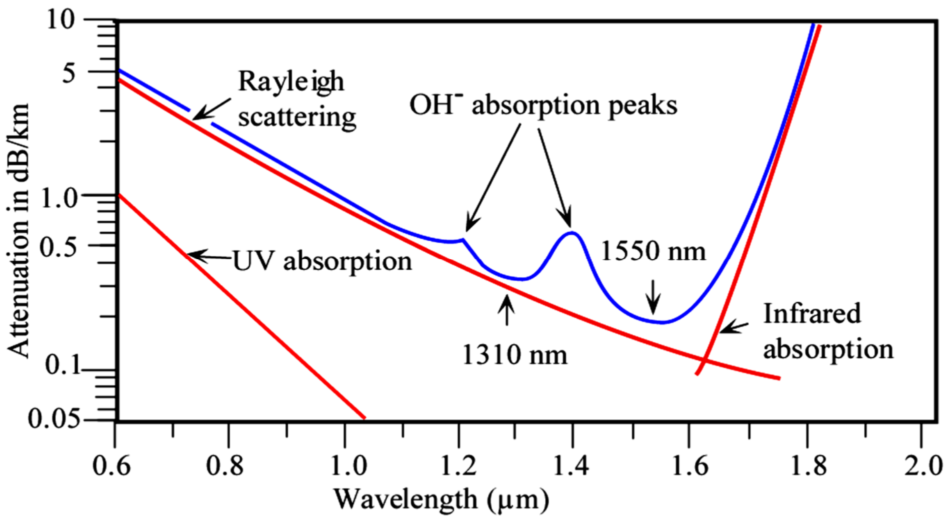


Figure III.11. Attenuation profile of silica fibers

c. Bending Loss

Losses due to curvature and losses caused by an abrupt change in radius of curvature are referred to as 'bending losses'. Exist 2 types of bending losses': **Microbend** and **Macrobend**.

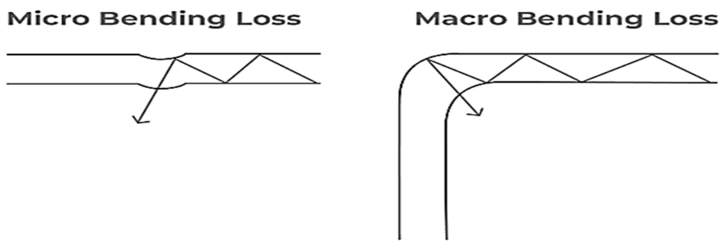


Figure III.12. Bending loss (Microbend and Macroband)

III.7.2 Dispersion in optical fibers

Fiber dispersion results in **optical pulse broadening** and hence digital signal degradation.

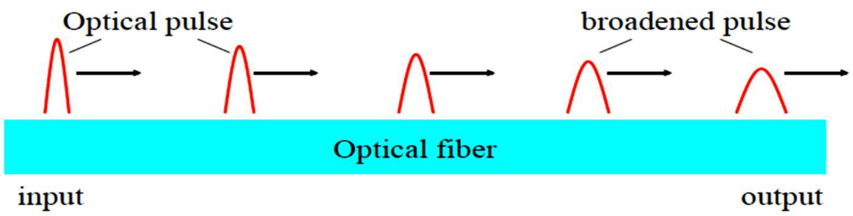


Figure III.13. The spreading of optical pulse along an optical fiber

Pulse broadening limits fiber bandwidth (data rate). An increasing number of errors may be encountered on the digital optical channel as the ISI becomes more pronounced.

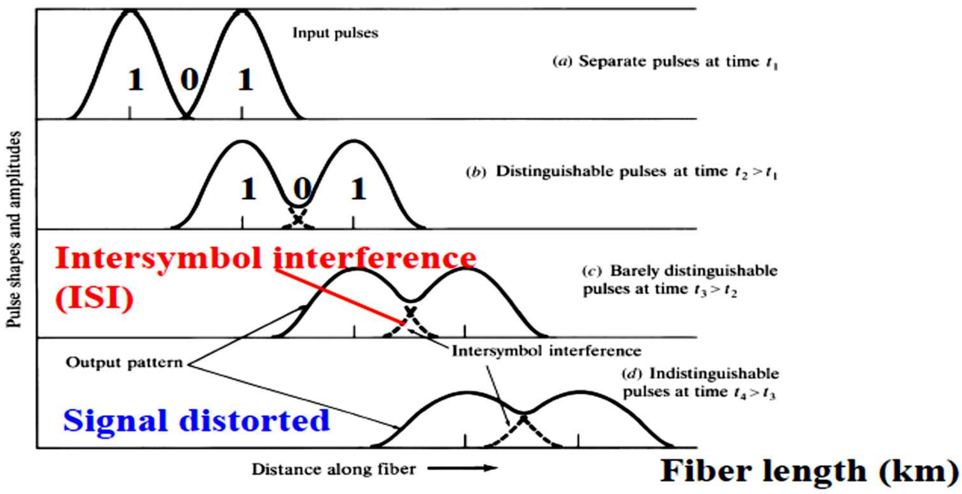


Figure III.14. The spreading of optical pulse along an optical fiber

a. Modal dispersion

When numerous waveguide modes are propagating, they all travel with different velocities with respect to the waveguide axis. Parts of the wave arrive at the output before other parts, spreading out the waveform. This is thus known as **multimode (modal) dispersion**.

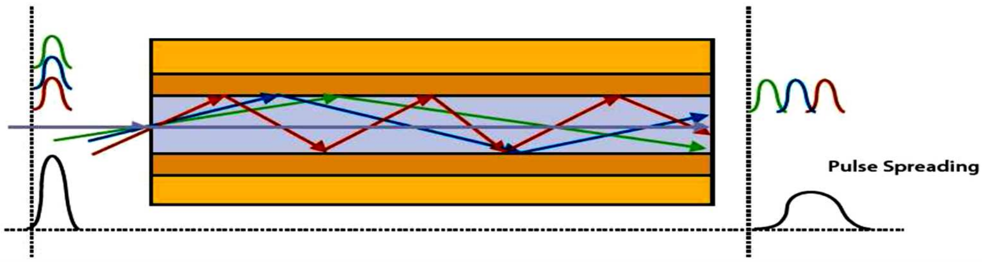


Figure III.15. The spreading of optical pulse due to modal dispersion

- **Modal dispersion** giving by : $\boldsymbol{D_{mod}} = \frac{\boldsymbol{n_1}}{\boldsymbol{c}}\Delta$ **(s/Km)**

$$\Delta\tau_{\text{mod}} \simeq \frac{n_1\Delta}{c}L = \frac{(O.N.)^2}{2cn_1}L$$

- Pulse broadening ratio:

$$\text{BW} \approx \frac{1}{2\Delta\tau_{\text{im}}}$$

- Bite rate :

b. Chromatic dispersion

Chromatic dispersion (CD) is caused by the fact that singlemode glass fibers transmit light of different wavelengths at different speeds. The ratio of the speed of light in a medium to the speed in a vacuum defines the refractive index of the material.

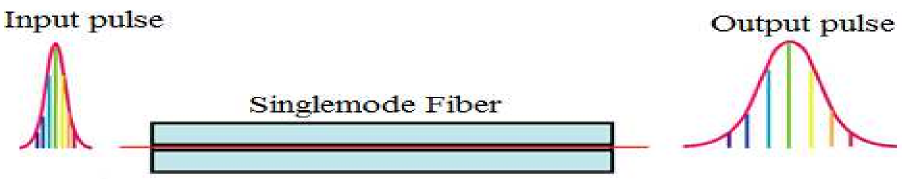


Figure III.16. Chromatic dispersion in fiber caused by longer wavelengths traveling faster

Chromatic dispersion (CD) results in pulse broadening. Pulse broadening occurs because there different spectral components of a pulse, with spectral width of $\Delta\lambda$, travel at different **group velocities.** This is also known as **group velocity dispersion (GVD).**

Hence the pulse broadening due to a differential time delay: $\Delta T = L.D.\Delta\lambda$
Where **D** is called the **dispersion parameter** and is expressed in units of ps/(km/nm).
Consider the maximum pulse broadening equals to the bit time period 1/B, then the **dispersion-limited distance:**

$$L_D = 1 / (D.B.\Delta\lambda)$$

e.g. For D = 17 ps/(km/nm), B = 2.5 Gb/s and $\Delta\lambda$= 0.03 nm => L_D = 784 km.

1. Causes of Chromatic Dispersion:

There are two factors that cause chromatic dispersion: material dispersion and waveguide dispersion.

a. Material dispersion:

Material dispersion is caused by the variation of the index of refraction in a given material, glass in this case, over wavelength (Figure III.17).

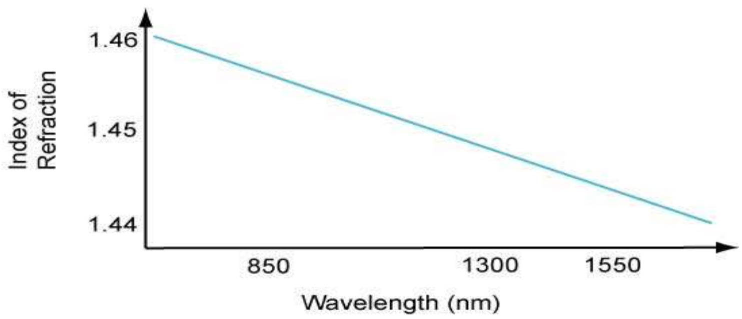


Figure III.17. Material dispersion

b. Waveguide Dispersion:

In singlemode fiber (**SMF**), the wavelength of the light is not that much bigger than the core of the fiber and as a result the light traveling down the fiber actually travels in an area that exceeds the diameter of the core, which we call the "mode field diameter **MFD**" of the fiber. The MFD is a function of the wavelength of the light, with longer wavelengths traveling in a larger MFD. Thus, part of the light is traveling in the geometric core of the fiber and part is traveling in the cladding. Since the core is made of a higher index of refraction glass than the cladding, the light in the cladding travels faster than the light in the core. Longer wavelengths have larger MFD so they suffer more material dispersion.

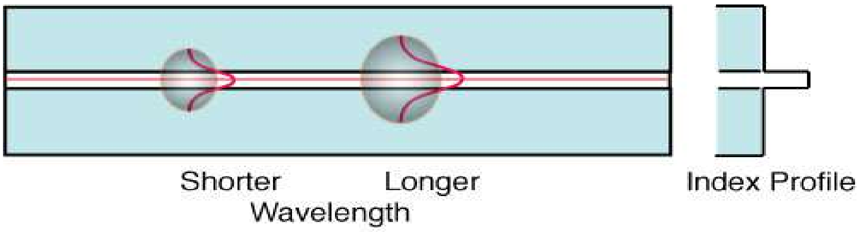


Figure III.18. Waveguide Dispersion

c. Engineered Dispersion in Fibers

Material and waveguide dispersion have opposite variations with wavelength, so careful design of the fiber materials and index profiles allows the fiber to have a "zero dispersion wavelength." On either side of that wavelength, dispersion increases. The importance of chromatic dispersion is a function of the application for the fiber. As a result, different SMFs have been developed for the requirements of specific applications.

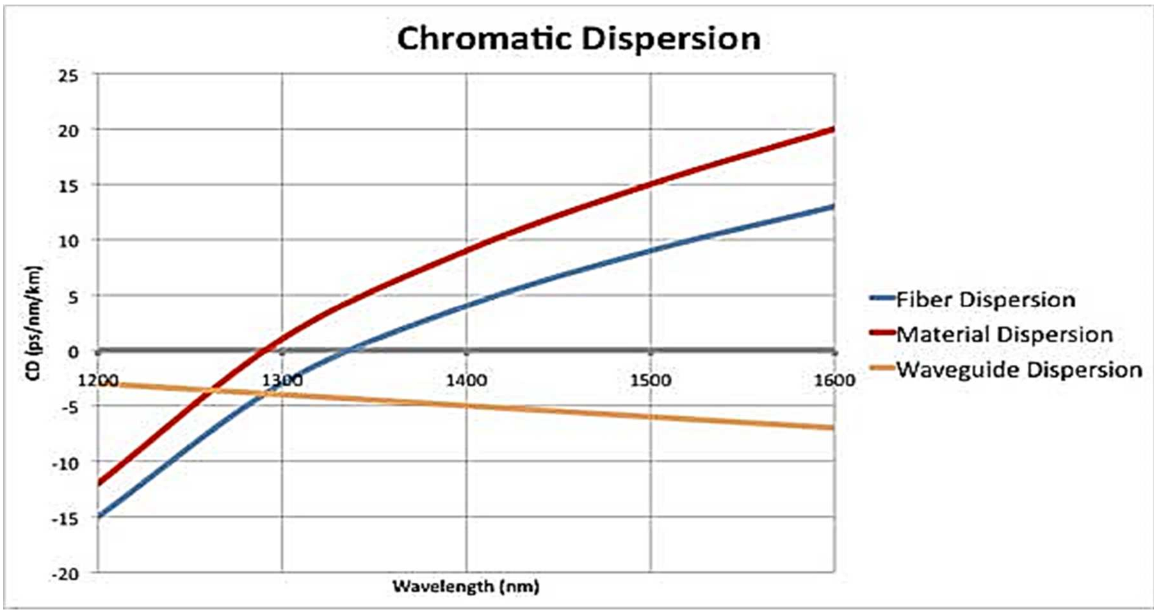


Figure III.19. Engineered dispersion in optical fiber. The fiber dispersion (blue) is a combination of material dispersion (red) and waveguide dispersion (orange)

III.8 Fiber Optic Cable Structures

The generic cable configuration shown in Figure III.20 illustrates some common materials that are used in the optical fiber cabling process. Individual fibers or modules of bundled fiber groupings are wound loosely around the central buffered strength member. A cable wrapping tape and other strength members such as Kevlar then encapsulate and bind these fiber groupings together. Surrounding all is a tough **polyethylene (PE) jacket** that provides crush resistance and handles any tensile stresses applied to the cable so that the fibers inside are not damaged.

The jacket also protects the fibers inside against abrasion, moisture, oil, solvents, and other contaminants. The jacket type largely defines the application characteristics; for example, heavy-duty outside-plant cables for direct-burial and aerial applications have much thicker and tougher jackets than indoor cables that have lower stress environments. Some cable designs might contain optional copper wires for powering in-line equipment. Other cable components can include steel armoring tapes, water-blocking or water-absorbing materials, and optional copper wires for powering in-line equipment, and ripcords that allow the jacket to be cut back easily without damaging the components inside the cable.

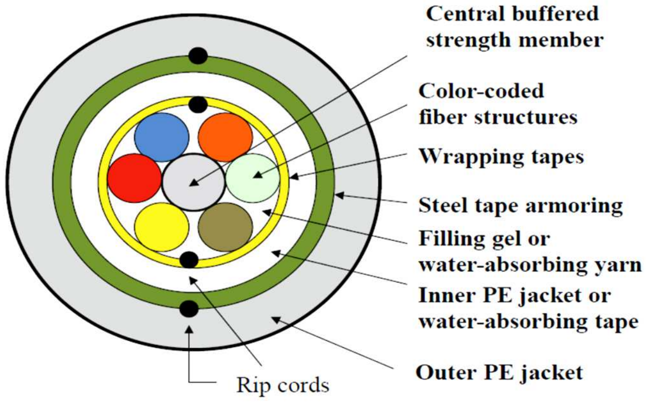


Figure III.20. A typical generic six-fiber cable illustrating some common materials used in the optical fiber cabling process

To distinguish individual fiber strands within a grouping of fibers, each fiber is designated by a separate and distinct jacket color. The **TIA-598-D** Optical Fiber Cable Color Coding standards document prescribes a common set of twelve basic colors. If there are several encapsulated fiber groupings within a cable, then the jacket colors of each fiber grouping follow the same standard color-coding scheme.

The two basic fiber optic cable structures are the **tight-buffered fiber cable** design and the **loose-tube cable** configuration. Cables with tight-buffered fibers nominally are used indoors whereas the loose-tube structure is intended for long-haul outdoor applications. A **ribbon cable** is an extension of the tight-buffered cable. In all cases, the fibers themselves consist of the normally manufactured glass core and cladding, which is surrounded by a protective 250 μm diameter coating.

III.9 Fiber optic connectors

The most popular single fiber connectors are (see Figure III.21):

- **FC-Ferrule Connector:** Although the FC connector is being replaced in many applications (telecom) by LC and SC connectors, it is still used in measurement equipment. The connector has a screw threading and is keyed allowing the ferrule to be angle polished providing low back reflection (light is reflected back to the transmitter, most often at the connector interface due to an index of refraction change).
- **LC-Lucent Connector:** LC connectors are supplanting SC connectors because of their smaller size and excellent design. They are also used extensively on small form-factor pluggable transceivers.
- **SC-Subscriber Connector:** SC connectors also offer a push-pull design (which reduces the possibility of end-face damage when connecting) and provide good packing density. They are still used in telecom applications.
- **ST-Straight Tip Connector:** ST connectors are engaged with a bayonet lock, which is engaged by pushing and twisting the connector. The bayonet interlock maintains the spring-loaded force between the two fiber cores.

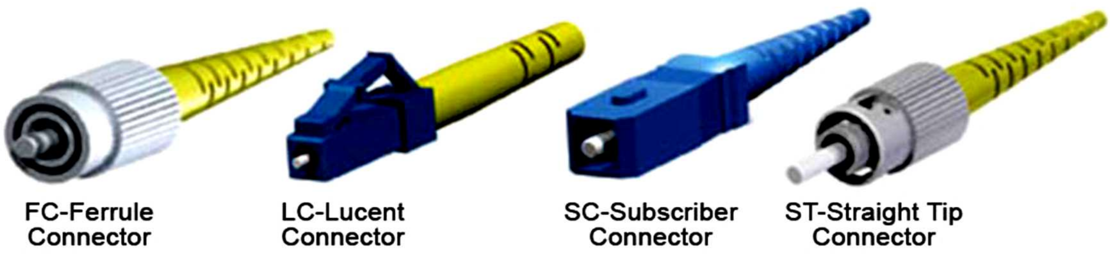


Figure III.21. Fiber optic connectors

III.10 Optical Fiber applications

III.10.1 Optical fiber used in optical communication and networking

- **Long-haul fiber transmission** is becoming increasingly common in the telephone network. Long-haul routes average about 1500 km in length and offer high capacity (typically 20,000 to 60,000 voice channels).These systems compete economically with microwave and have so underpriced coaxial cable in many developed countries that coaxial cable is rapidly being phased out of the telephone network in such countries. Undersea optical fiber cables have also enjoyed increasing use.

- **Metropolitan trunking** circuits have an average length of 12 km and may have as many as 100,000 voice channels in a trunk group. Most facilities are installed in underground conduits and are repeaterless, joining telephone exchanges in a metropolitan or city area. Included in this category are routes that link long-haul microwave facilities that terminate at a city perimeter to the main telephone exchange building downtown.
- **Rural exchange trunks** have circuit lengths ranging from 40 to 160 km and link towns and villages. In the United States, they often connect the exchanges of different telephone companies. Most of these systems have fewer than 5000 voice channels. The technology used in these applications competes with microwave facilities.
- **Subscriber loop circuits** are fibers that run directly from the central exchange to a subscriber. These facilities are beginning to displace twisted pair and coaxial cable links as the telephone networks evolve into full-service networks capable of handling not only voice and data, but also image and video. The initial penetration of optical fiber in this application is for the business subscriber, but fiber transmission into the home will soon begin to appear.
- **Local area networks LAN**, Standards have been developed and products introduced for optical fiber networks that have a total capacity of 100 Mbps to 10 Gbps and can support hundreds or even thousands of stations in a large office building or a complex of buildings.

III.10.2 Optical fibers used in Medical industry

Because of its extremely thin and flexible nature, it is used in various instruments to view internal body parts by inserting into hollow spaces in the body. It is used as lasers during surgeries, endoscopy, microscopy and biomedical research.

III.10.3 Optical fibers used in Industries

These fibers are used for imaging in hard-to-reach places such as they are used for safety measures and lighting purposes in automobiles both in the interior and exterior. They transmit information at lightning speed and are used in airbags and traction control. They are also used for research and testing purposes in industries.

III.10.4 Optical fibers used for Broadcasting

These cables are used to transmit high-definition television signals which have greater bandwidth and speed. Optical Fiber is cheaper compared to the same quantity of copper wires.

Broadcasting companies use optical fibers for wiring HDTV, CATV, video-on-demand and many applications.

III.10.5 Optical fibers used for sensors

Optical fibers are used as sensors by converting physical or chemical changes in their environment into changes in the properties of light that travel through them. These changes are then detected to measure variables like temperature, pressure, strain, and chemical concentrations with high sensitivity.

III.11 Advantages and Disadvantages of Fiber Optics

✓ **Advantages:**

- **Small size and lightweight**: The size of the optical fibers is very small. Therefore, a large number of optical fibers can fit into a cable of small diameter.
- **Easy availability and low cost**: The material used for the manufacturing of optical fibers is Silica glass. This material is easily available. So the optical fibers cost lower than the cables with metallic conductors.
- **No electrical or electromagnetic interference:** Since the transmission takes place in the form of light rays, the signal is not affected due to any electrical or EM Interference.
- **Large Bandwidth**: As the light rays have a very high frequency in GHz range, the bandwidth of the optical fiber is extremely large.
- **Other advantages**: No crosstalk inside the optical fiber cable. Signal can be sent up to 100 times faster.

✓ **Disadvantages:**

- High investment cost
- Need for more expensive optical transmitters and receivers
- More difficult and expensive to splice than wires
- Price
- Fragility
- Affected by chemicals
- Opaqueness
- Requires special skills

Comparison of guided Media

Comparison of Guided Media

Feature	Twisted Pair Cable	Coaxial Cable	Fiber Optic Cable
Bandwidth	Low to medium. Suitable for voice and basic data transmission.	Medium to high. Can handle more data than twisted pair.	Very high. Ideal for high-speed internet, cable TV, and backbone networks.
Signal Type	Uses electrical signals (voltage) to carry data.	Also uses electrical signals but better shielded, so less signal loss.	Transmits data using light pulses, allowing faster and clearer transmission.
Max Distance Without Repeater	Up to 100 meters	Up to 500 meters – 1 km	**Up to 40 km** (Single-mode) **Up to 2 km** (Multi-mode)
Cost	Cheapest among all. Commonly used and easy to produce.	More expensive than twisted pair but still affordable.	Expensive due to materials and installation complexity.
Noise Resistance	Low. Prone to electromagnetic and radio frequency interference (EMI/RFI).	Better noise immunity due to shielding, but still vulnerable over long distances.	Excellent. Immune to EMI, RFI, and other types of interference.
Speed	Up to 1 Gbps (Cat5e/Cat6). Higher categories (Cat6a/Cat7) support higher speeds.	Can support up to 10 Gbps in some configurations.	It can reach terabits per second (Tbps), making it the fastest guided medium.
Installation	Easy to install and maintain. Flexible and lightweight.	Moderate difficulty. Thicker and less flexible than twisted pair.	Difficult and delicate installation. Fibers are fragile and require special handling.
Security	Moderate. Easier to tap or intercept if physical access is available.	Better security due to shielding, but still possible to tap.	Very secure. Hard to tap or intercept without being detected due to light-based data transmission.
Common Use	Telephone lines, LANs, DSL connections.	Cable TV, internet access, CCTV systems.	Internet backbone, long-distance telecom, medical imaging, and high-speed enterprise networks.

Chapter IV

RF Wireless Transmission

Electromagnetic spectrum

Radio-wave Transmission

Microwave Transmission

Satellite Communication

IV RF Wireless Transmission

IV.1 Electromagnetic spectrum

The electromagnetic spectrum is a range of frequencies, wavelengths and photon energies covering frequencies from below **1 Hz** to above **10^{25} Hz**, corresponding to wavelengths, which are a few kilometers to a fraction of the size of an atomic nucleus in the spectrum of electromagnetic waves.

The electromagnetic spectrum is given by radio waves, microwaves, infrared radiation, visible light, ultra-violet radiation, X-rays, gamma rays and cosmic rays in the increasing order of frequency and decreasing order of wavelength. It can be depicted as follows:

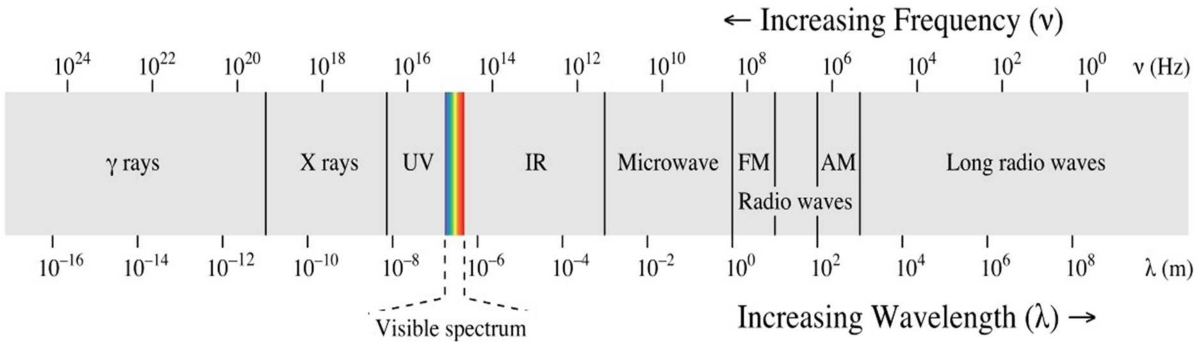


Figure IV.1. Electromagnetic Spectrum

IV.2 Electromagnetic Wave

Electromagnetic waves also called Electromagnetic Radiations are basically defined as super imposed oscillations of an Electric and a Magnetic Field in space with their direction of propagation perpendicular to both of them.

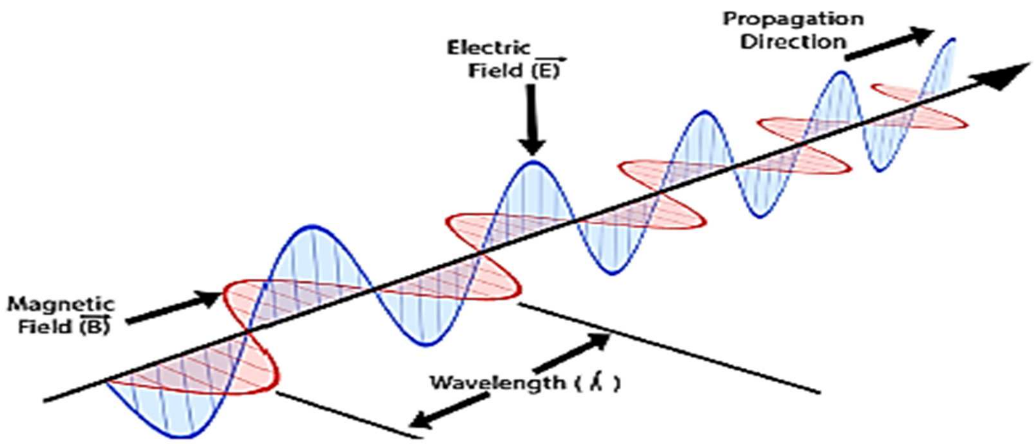


Figure IV.2. Electromagnetic wave

IV.2.1 Electromagnetic Wave Characteristics

1. Wave polarization

Polarization is that property of an electromagnetic wave which describes the time-varying direction and relative magnitude of the electric field.

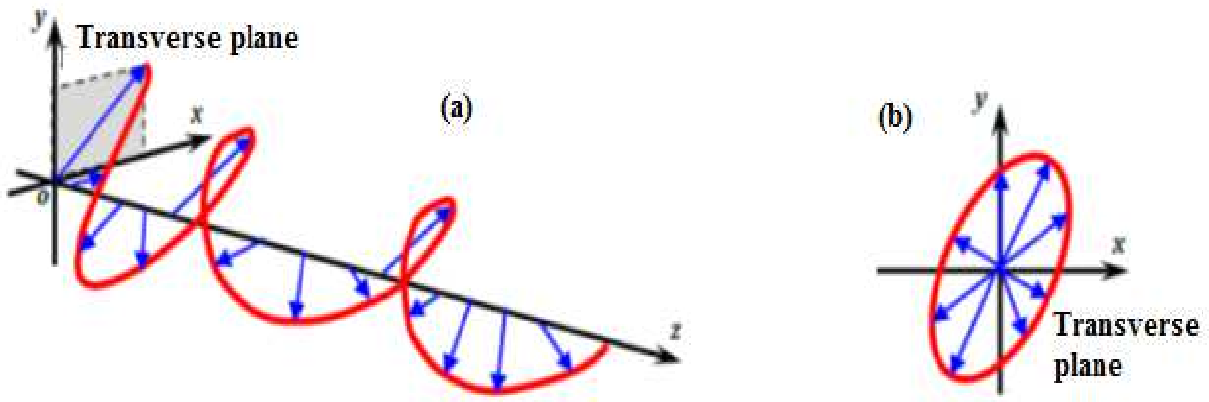


Figure IV.3. Polarization in the (a) propagation plane and (b) transverse plane

- **States of Polarization**

a. Linearly Polarized Wave:

An electromagnetic wave for which the locus of the tip of the electric field vector is a straight line in a plane orthogonal to the wave normal.

- Horizontally linearly polarized wave (H)
- Vertically linearly polarized wave (V)

b. Circularly polarized Wave:

A circularly polarized electromagnetic wave for which the electric field vector, when viewed the wave approaching the observer, rotates in space.

- Left-circular polarization (LCP): vector rotates clockwise
- Right-circular polarization (RCP): vector rotates counterclockwise

c. Elliptically polarized Wave:

In elliptical polarization, the electric field varies in two planes with change in amplitude. In this case, electric field vector is in the form of eclipse in one plane and propagating perpendicular to the direction of the waves (Figure IV.3).

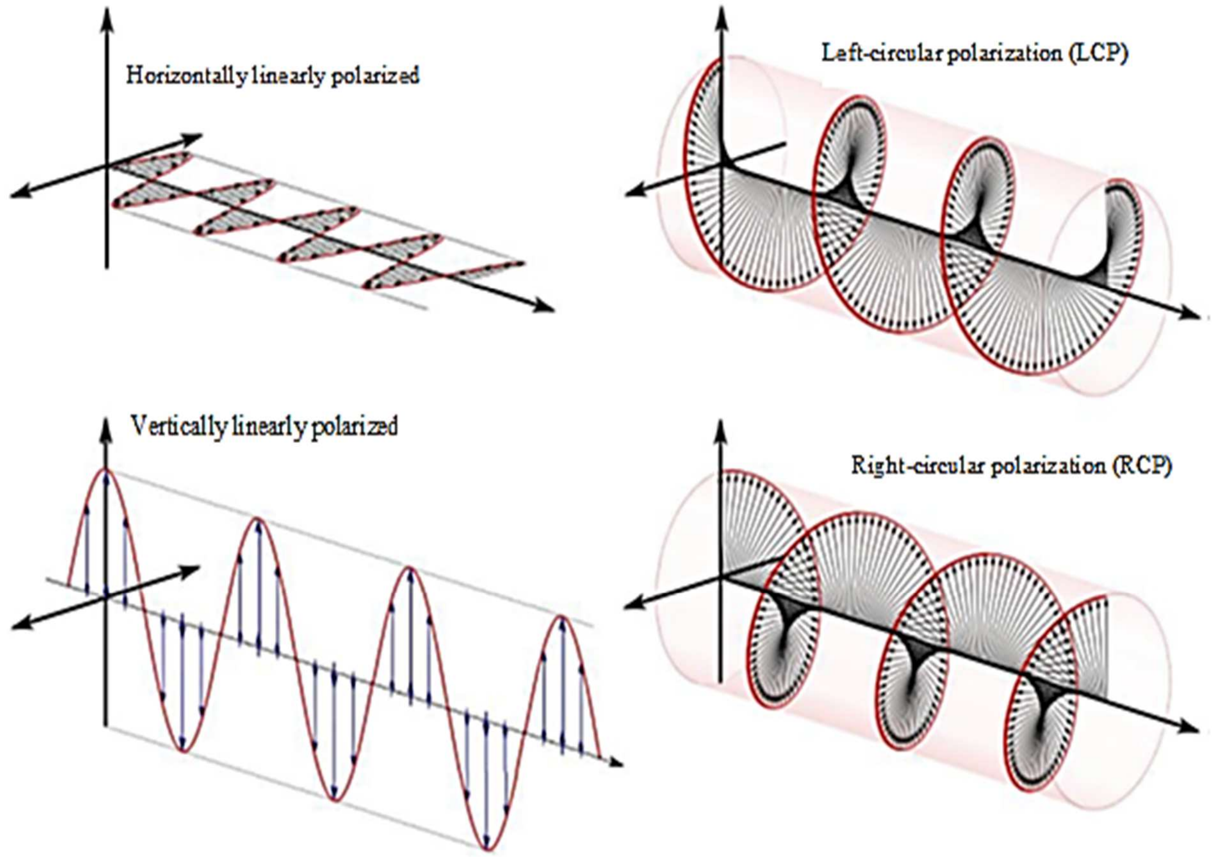


Figure IV.4. States of Polarization

2. The frequency, speed and wavelength

The frequency (f), speed (c), and wavelength (λ) of electromagnetic waves are related as:

$$\boxed{\lambda = \frac{c}{f} \quad \text{or} \quad \lambda = c.T}$$

Where, $c = 3.10^8$ m/s is the speed of light in a vacuum

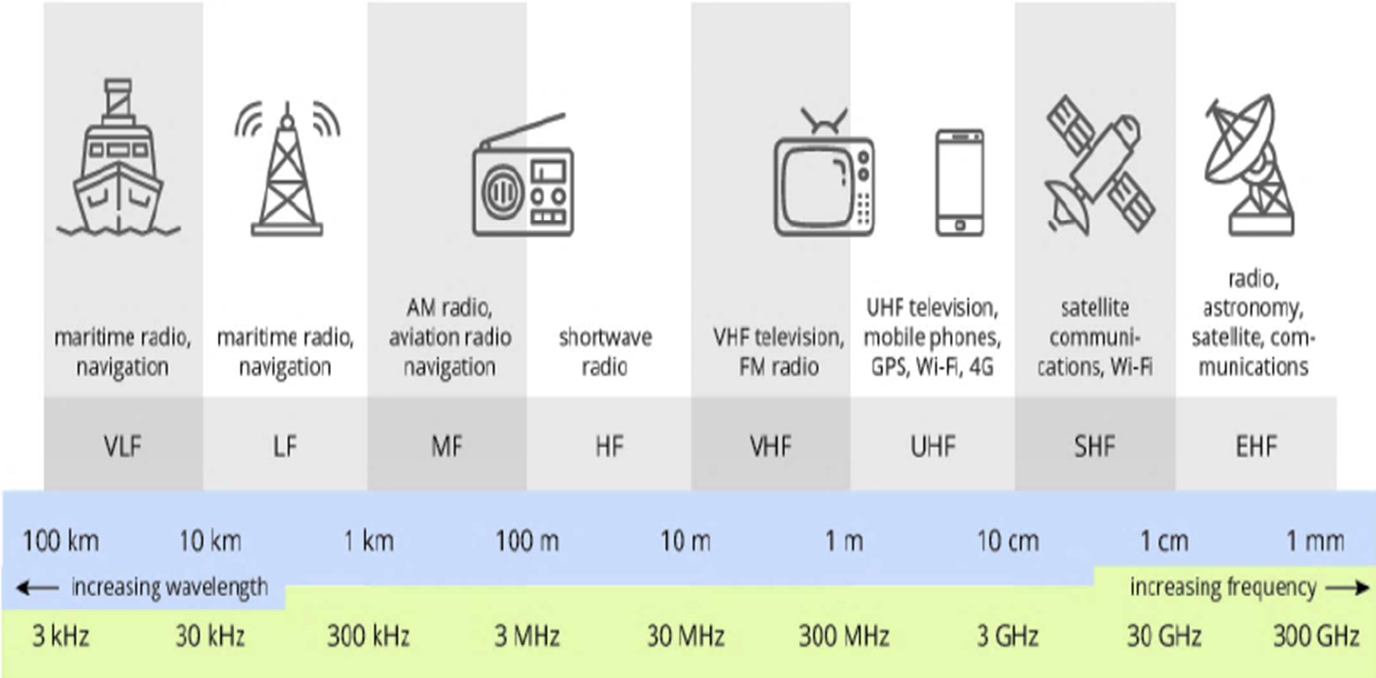
IV.3 Electromagnetic transmission

Electromagnetic transmission in air (Wireless transmissions) can be **radio or microwave** transmission depending on the frequency.

Wireless transmissions are a type of electromagnetic (EM) radiation with wavelengths in the electromagnetic spectrum longer than infrared light. They have frequencies from **300 GHz to as**

low as 3 kHz, and corresponding wavelengths from **1 mm to 100 Km**. Like all other electromagnetic waves, radio waves travel at the speed of light. Radio waves are used for fixed and mobile radio communication, broadcasting, radar and other navigation systems, communications satellites, computer networks and innumerable other applications.

Table IV.1. RF Bands and applications



IV.4 Radio Waves

Waves ranging in frequencies between **3 kHz** and **1 GHz** are called radio waves. Radio waves, for the most part, are **omnidirectional**, meaning that they travel in all directions from the source, so that the transmitter and receiver do not have to be carefully aligned physically. Radio waves, particularly those waves that propagate in the sky mode, can travel long distances. This makes radio waves a good candidate for long-distance broadcasting such as AM radio. The radio wave band is relatively narrow, just under 1 GHz, compared to the microwave band. When this band is divided into sub bands, the sub bands are also narrow, leading to a low data rate for digital communications.

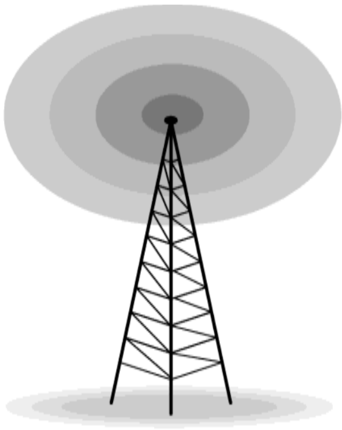


Figure IV.5. Omnidirectional antenna

IV.4.1 Radio Waves Properties

- Can travel long distances
- Can penetrate buildings easily, so they are widely used for communication, both indoors and outdoors.
- The properties of radio waves are frequency dependent.
- At low frequencies, radio waves **pass through obstacles** well, but the power falls off sharply with distance from the source.
- At high frequencies, radio waves tend to travel in straight lines and bounce off obstacles. They are also absorbed by rain.
- At all frequencies, radio waves are subject to interference from motors and other electrical equipment.

IV.4.2 Advantages of Radio Waves

- Radio transmission is mostly utilized for wide area networks and mobile phones.
- Radio waves may penetrate barriers and cover a vast area.
- A greater transmission rate is provided through radio transmission.

IV.4.3 Radio Waves applications

The omnidirectional characteristics of radio waves make them useful for multicasting, in which there is one sender but many receivers. AM and FM radio, television, maritime radio, cordless phones, and paging are examples of multicasting.

IV.4.4 Radio Wave Propagation

In Radio communication systems, we use wireless electromagnetic waves as the channel. The mode of propagation of electromagnetic waves in the atmosphere and in free space may be divided in to the following three categories:

- Ground wave propagation
- Sky wave propagation
- Line of sight (LOS) propagation

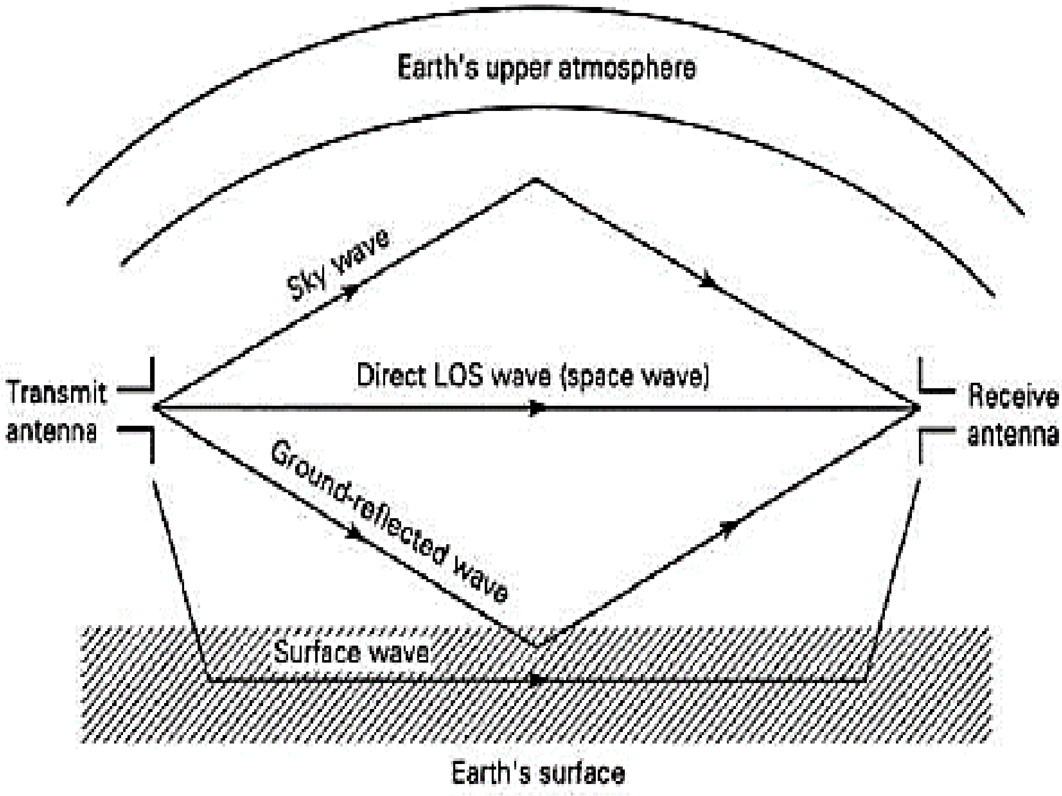


Figure IV.6. Radio Wave Propagation

IV.4.4.1 Ground Wave Propagation

Ground wave propagation is a type of radio propagation, which is also known as a surface wave. Ground wave propagation more or less follows the contour of the earth and can propagate considerable distances, well over the visual horizon. This effect is found in frequencies up to about **2 MHz**. Several factors account for the tendency of electromagnetic wave in this frequency band to follow the earth's curvature.

Electromagnetic waves in this frequency range are scattered by the atmosphere in such a way that they do not penetrate the upper atmosphere.

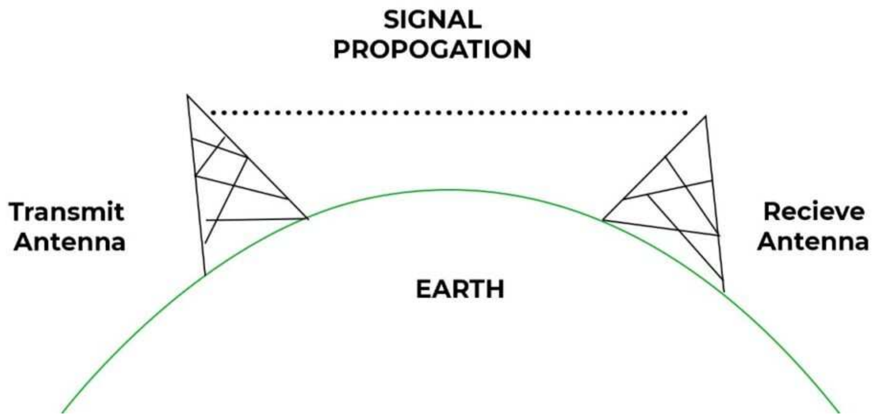


Figure IV.7. Ground wave propagation

Characteristics:

- Follow contour of the earth
- Up to 2 MHz
- Can propagate considerable distances
- Example – AM radio, Military applications
- In the VLF, LF and MF bands the propagation of waves, also called as ground waves follow the curvature of the earth.
- The maximum transmission ranges of these waves are of the order of a few hundred kilometers.

IV.4.4.2 Sky Wave Propagation

In the Frequency range **300 KHz–30 MHz**, long distance communication can be achieved by ionospheric reflection of radio waves back towards the earth.

The sky wave, often called the **ionospheric wave**, is radiated in an upward direction and returned to Earth at some distant location because of refraction from the ionosphere.

This form of propagation is relatively unaffected by the Earth's surface and can propagate signals over great distances. Usually the high frequency (**HF**) band is used for sky wave propagation.

Characteristics:

- Used for the propagation of EM waves with a frequency range of 300 KHz–30 MHz.
- Signal can travel a number of multi-hops back and forth
- Examples – Amateur radio, CB radio, International broadcasts

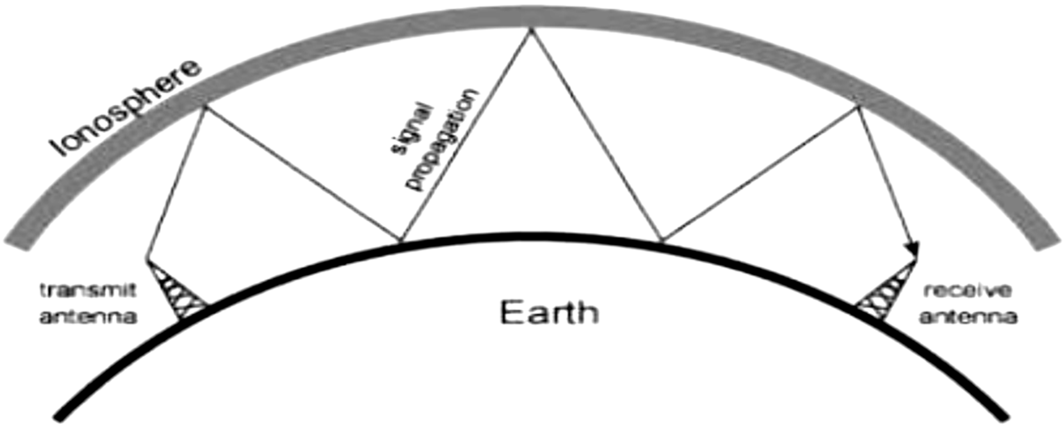


Figure IV.8. Sky Wave propagation

IV.4.4.3 Line of sight (LOS) propagation

At frequencies above **40 MHz**, communication is essentially limited to Line of sight (LOS) paths. At these frequencies, the antennas are relatively smaller and can be placed at heights of many wavelengths above the ground. Because of LOS nature of propagation, direct waves get blocked at some point by the curvature of the earth.

If the signal is to be received beyond the horizon then the receiving antenna must be high enough to intercept the LOS waves.

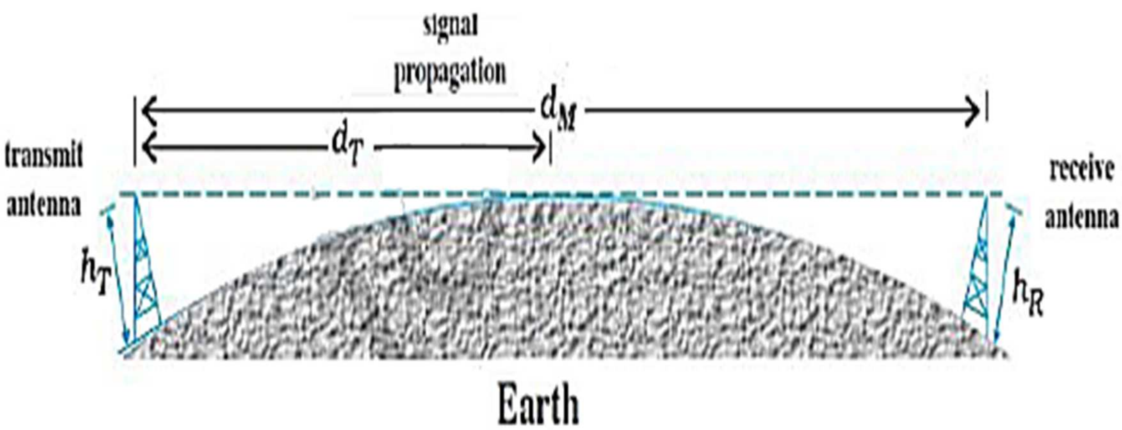


Figure IV.9. LOS propagation

If the transmitting antenna is at a height h_T, then the distance to the horizon d_T is given as

$$d_T = 2Rh_T$$

Where R is the radius of the Earth (approximately 6400 km). d_T is also called the radio horizon of the transmitting antenna.

The maximum LOS distance d_M between the two antennas having heights h_T and h_R above the earth is given by

$$d_M = \sqrt{2Rh_T} + \sqrt{2Rh_R}$$

Where h_R is the height of receiving antenna.

Characteristics:

- Transmitting and receiving antennas must be within line-of sight
- Microwave transmissions
- Above 30 Mhz

IV.5 Microwaves

Microwaves are electromagnetic waves with wavelengths ranging from as long as one meter to as short as one millimeter, or equivalently with frequencies between **2 GHz** and **300 GHz.** As is the case for all EM waves, microwaves travel in a vacuum at the speed of light. The prefix “micro-” in “microwave” is not meant to suggest a wavelength in the micrometer range. It indicates that microwaves are “small” because have shorter wavelengths as compared to waves used in typical radio broadcasting.

IV.5.1 Microwaves properties

The microwave portion of the radio spectrum can be subdivided into three ranges, listed below from high to low frequencies.

- **Extremely high frequency** (**EHF**): in the range of 30 to 300 GHz, is known also as the millimeter band. Above which electromagnetic radiation is considered as far infrared light, also referred to as terahertz radiation.

- **Super high frequency** (**SHF**) : in the range of 3 GHz to 30 GHz, is known also as the centimeter band.

- **Ultra-high frequency** (**UHF**): in the range of 300 MHz and 3 GHz, designates the microwave frequency range, also known as the decimeter band.

IV.5.2 Microwave Transmission characteristics

- **Directional:** Above 100 MHz, the waves travel in straight lines and can therefore be narrowly focused.
- **Parabolic Antennas**: All the energy is concentrated into a small beam using a parabolic antenna.
- **Alignment**: The transmitting and receiving antennas must be accurately aligned with each other.
- **Penetration**: Unlike radio waves at lower frequencies, microwaves do not pass through obstacles well,

a. Advantages of Microwave Transmission

- Microwave transmission is less expensive than cable transmission.
- Because installing cable in terrain is a challenging operation, microwave transmission allows for convenient communication.
- Microwave transmission can be used to communicate across oceans.

b. Disadvantages of Microwave Transmission

- **Eavesdropping**: Eavesdropping makes communication unsafe. Any unauthorized user with his own antenna can capture the signal in the air.
- **Out of phase signal:** Using microwave transmission, a signal can be shifted out of phase.
- **Weather condition**: A microwave transmission is vulnerable to weather conditions. This implies that any environmental disturbance, such as rain or wind, might cause the signal to be distorted.
- **Bandwidth allocation**: In the case of microwave transmission, bandwidth allocation is limited.

IV.5.3 Types of Microwave Transmission

Microwave transmission is used for:

- Terrestrial transmission
- Satellite transmission

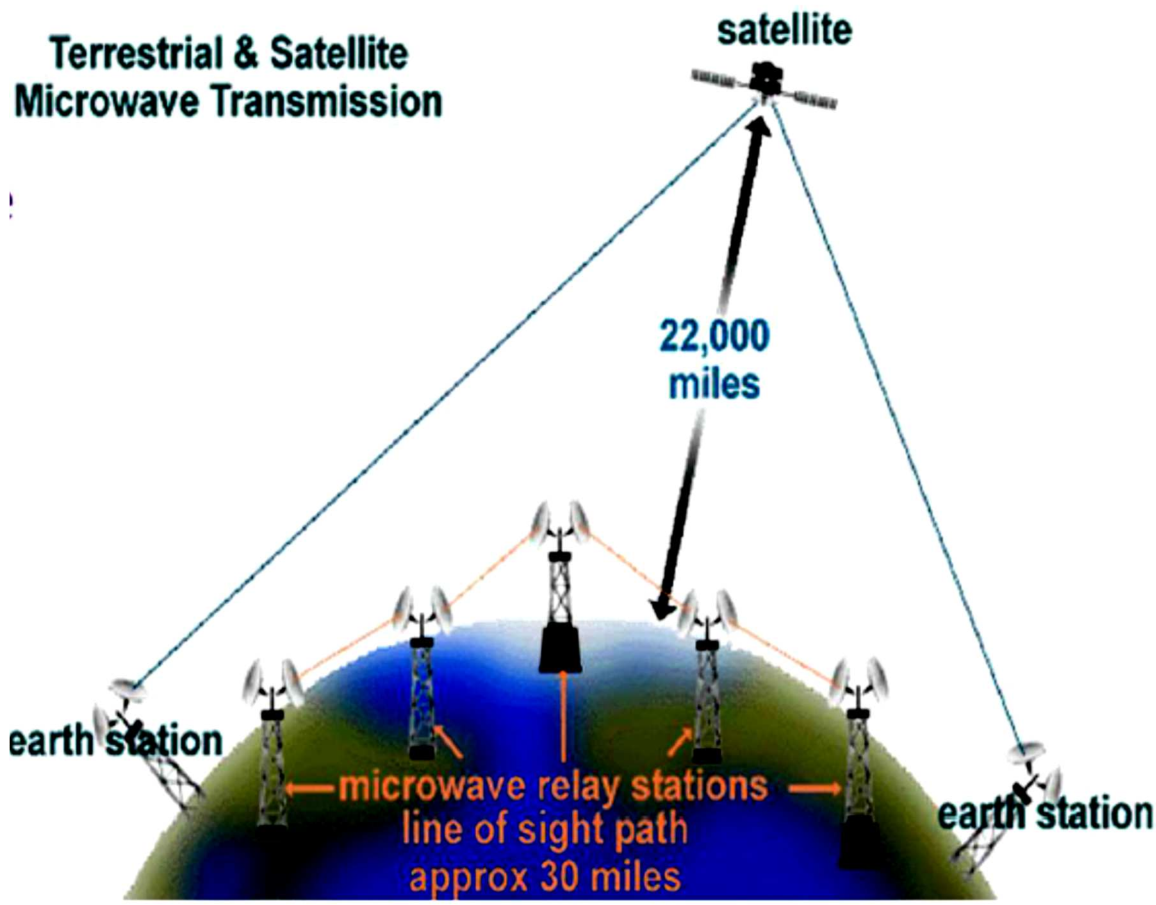


Figure IV.10. Microwave transmission

IV.5.3.1 Terrestrial propagation of microwaves

It is used for long haul telecommunications; commonly used for both voice and television transmission .It support short point-to-point links between buildings, LAN. It only requires far fewer amplifiers or repeaters than coaxial cable over the same distance but requires line-of-sight transmission.

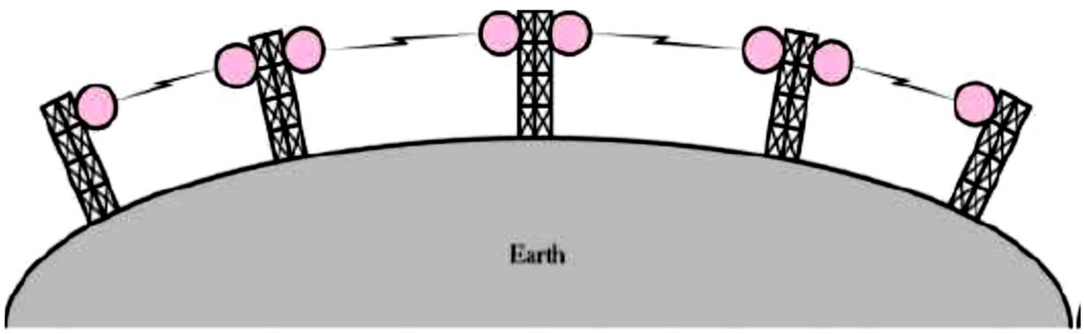


Figure IV.11. Terrestrial propagation of microwaves

It uses a parabolic dish to focus a narrow beam onto a receiver antenna. Typical of size 3m in diameter. Microwave antennas are usually located at substantial heights above ground level to extend the range between antennas. The higher the frequency used, the higher the potential bandwidth and therefore the higher the potential data rate.

a. Parabolic Reflective Antenna: is used in terrestrial **microwave and satellite applications**. A **parabola** is the locus of all points equidistant from a fixed line and a fixed point not on the line. The fixed point is called the **focus** and the fixed line is called the. If a parabola is revolved about its axis, the surface generated is called a **paraboloid**. A cross section through the paraboloid parallel to its axis forms a parabola and a cross section perpendicular to the axis forms a circle.

✓ **Antenna Gain:** Antenna gain is a measure of the directionality of an antenna. **Antenna gain** is defined **as the power output, in a particular direction, compared to that produced in any direction by a perfect omnidirectional antenna (isotropic antenna).**

A concept related to that of antenna gain is the effective area of an antenna. The effective area of an antenna is related to the physical size of the antenna and to its shape.

$$G = \frac{4\pi A_e}{\lambda^2} = \frac{4\pi f^2 A_e}{c^2}$$

G = antenna gain
A_e = effective area
f = carrier frequency
c = speed of light ($\approx 3 \times 10^8$ m/s)
λ = carrier wavelength

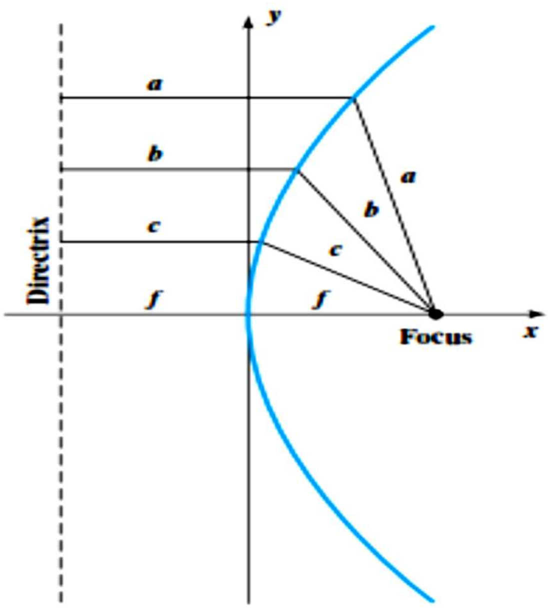


Figure IV.12. Parabolic Reflective Antenna

The most common bands for long-haul telecommunications are the 2 GHz to 6 GHz bands. With increasing congestion at these frequencies, the 11 GHz band is now coming into use. The 12 GHz band is used as a component of cable TV systems. Higher-frequency microwave is being used for short point-to-point links between buildings; typically, the 22 GHz band is used. The higher microwave frequencies are less useful for longer distances because of increased attenuation but are quite adequate for shorter distances.

Table IV.2. Typical Digital Microwave Performance

Band (GHz)	Bandwidth (MHz)	Data Rate (Mbps)
2	7	12
6	30	90
11	40	135
18	220	274

✓ **Characteristics:**

- Since the microwaves travel in a straight line, repeaters are needed periodically.
- The higher the towers are, the further apart they can be.
- Terrestrial microwave with repeaters provides the basis for most contemporary telephone systems worldwide.
- Use Parabolic dish to focus a narrow beam.
- Short distance: It is a low-cost option for short distance travel.
- Long distance: It is costly since a taller tower is required for a longer distance.
- Attenuation: The loss of a signal is referred to as attenuation. It is influenced by ambient factors as well as antenna size.

b. Line-of-sight transmission

1. Free space loss

For any type of wireless communication the signal disperses with distance. Therefore, an antenna with a fixed area will receive less signal power the farther it is from the transmitting antenna. Even if no other sources of attenuation or impairment are assumed, a transmitted signal attenuates over distance (d) because the signal is being spread over a larger and larger area.

$$L = 10 \log\left(\frac{4\pi d}{\lambda}\right)^2 \text{ dB}$$

2. Atmospheric Absorption

An additional loss between the transmitting and receiving antennas is atmospheric absorption. Water vapor and oxygen contribute most to attenuation. A peak attenuation occurs in the vicinity of **22 GHz** due to water vapor. At frequencies below **15 GHz**, the attenuation is less. The presence of oxygen results in an absorption peak in the vicinity of **60 GHz** but contributes less at frequencies below **30 GHz**. Rain and fog (suspended water droplets) cause scattering of radio waves that results in attenuation.

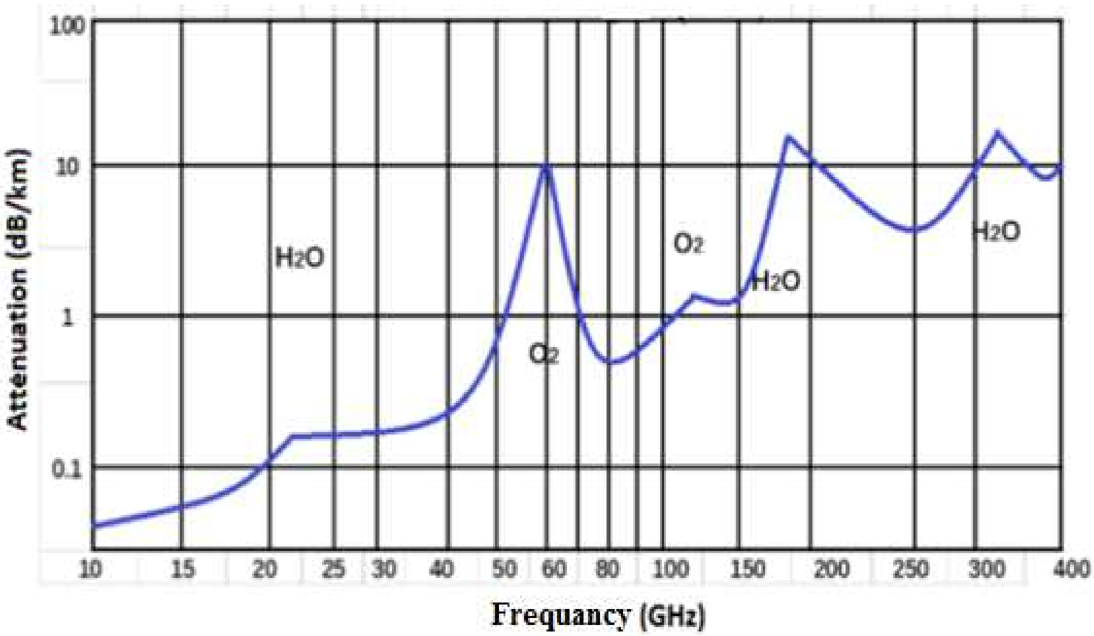
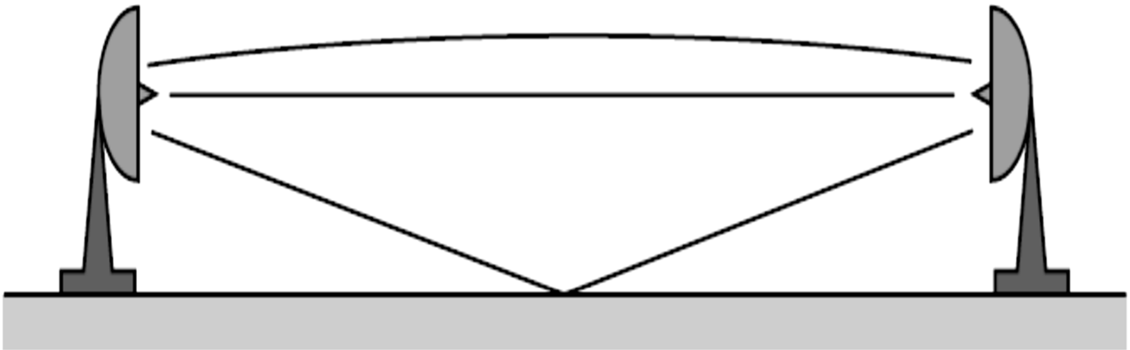


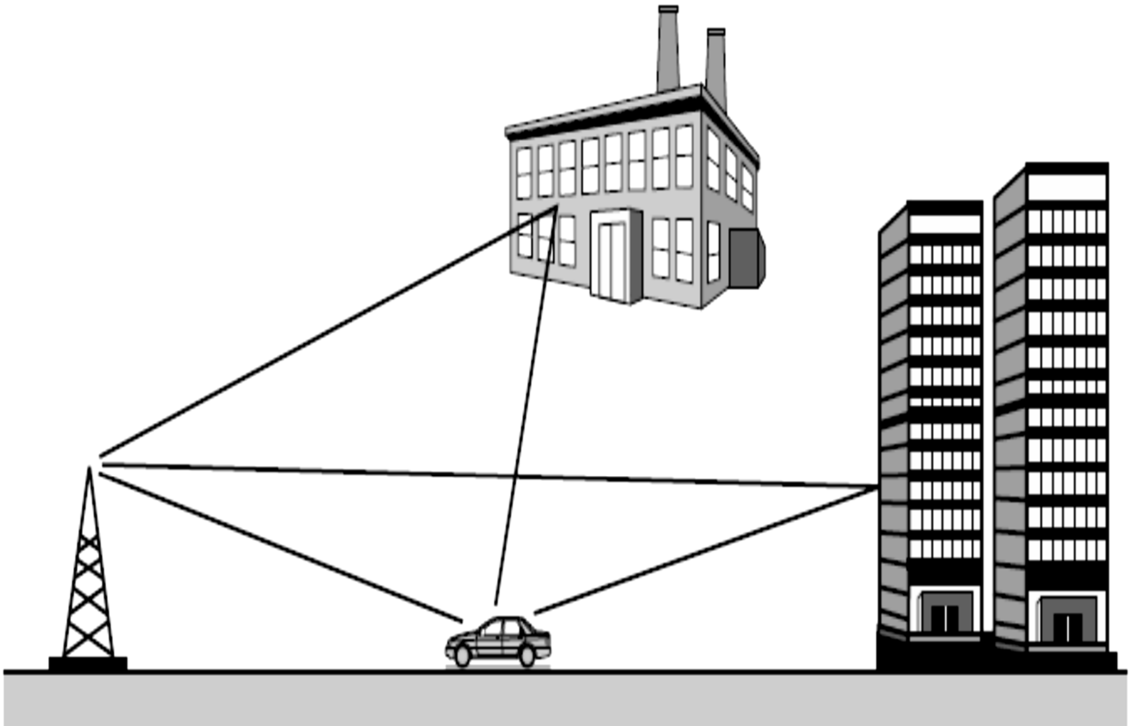
Figure IV.13. Atmospheric Absorption in microwave range

3. Multipath

For wireless facilities where there is a relatively free choice of where antennas are to be located, they can be placed so that if there are no nearby interfering obstacles, there is a direct line-of-sight (LOS) path from transmitter to receiver. This is generally the case for many satellite facilities and for point-to-point microwave. In other cases, such as mobile telephony, there are obstacles in abundance. The signal can be reflected by such obstacles so that multiple copies of the signal with varying delays can be received. In fact, in extreme cases, there may be no direct signal. Depending on the differences in the path lengths of the direct and reflected waves, the composite signal can be either larger or smaller than the direct signal.



(a) Microwave line of sight



(b) Mobile radio

Figure IV.14. Examples of Multipath Interference

Figure IV.14 illustrates in general terms the types of multipath interference typical in terrestrial, fixed microwave and in mobile communications. For fixed microwave, in addition to the direct line of sight, the signal may follow a curved path through the atmosphere due to refraction and the signal may also reflect from the ground. For mobile communications, structures and topographic features provide reflection surfaces.

- **Refraction:**

Radio waves are refracted (or bent) when they propagate through the atmosphere. The refraction is caused by changes in the speed of the signal with altitude or by other spatial changes in the atmospheric conditions. Normally, the speed of the signal increases with altitude, causing radio waves to bend downward. However, on occasion, weather conditions may lead to variations in speed with height that differ significantly from the typical variations. This may result in a situation in which only a fraction or no part of the line-of-sight wave reaches the receiving antenna.

- **Reflection:**

When a wave hits a smooth object that is larger than the wave itself, depending on the media, the wave may bounce in another direction.

As a wave radiates from an antenna, it broadens and disperses. If portions of the wave are reflected, new wave fronts appear from the reflection points.

- **Diffraction :**

Diffraction is the bending and spreading around of an RF signal when it encounters an obstruction.
The waves that encounter the object bend around the object, taking a longer and different path.

IV.5.3.2 Satellite microwaves transmission

a. Definition

A communication satellite is, in effect, **a microwave relay station**. It is used to link two or more ground-based microwave transmitter/receivers, known as **earth stations**, or **ground stations.** The satellite receives transmissions on one frequency band **(uplink**), amplifies or repeats the signal, and transmits it on another frequency **(downlink).** A single orbiting satellite will operate on a number of frequency bands, called **transponder channels**, or simply **transponders**.

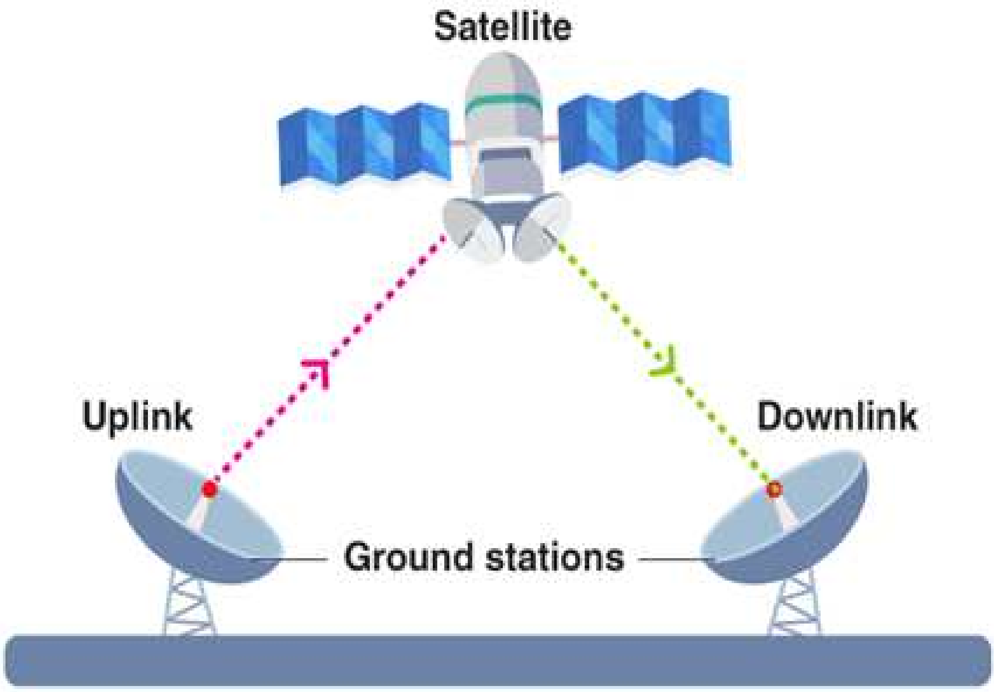


Figure IV.15. Satellite transmission

b. characteristics

- Satellite relays allow microwave signals to span continents and oceans with a single bounce.
- Satellite microwave can provide transmission capability to and from any location on earth, no matter how remote.
- This advantage makes high-quality communication available to undeveloped parts of the world without requiring a huge investment in ground-based infrastructure.
- Satellite are extremely expensive, but leasing time or frequencies on one can be relatively cheap.

c. Satellite orbits

An artificial satellite needs to have an orbit, the path in which it travels around the earth. The orbit can be equatorial, inclined, or polar.

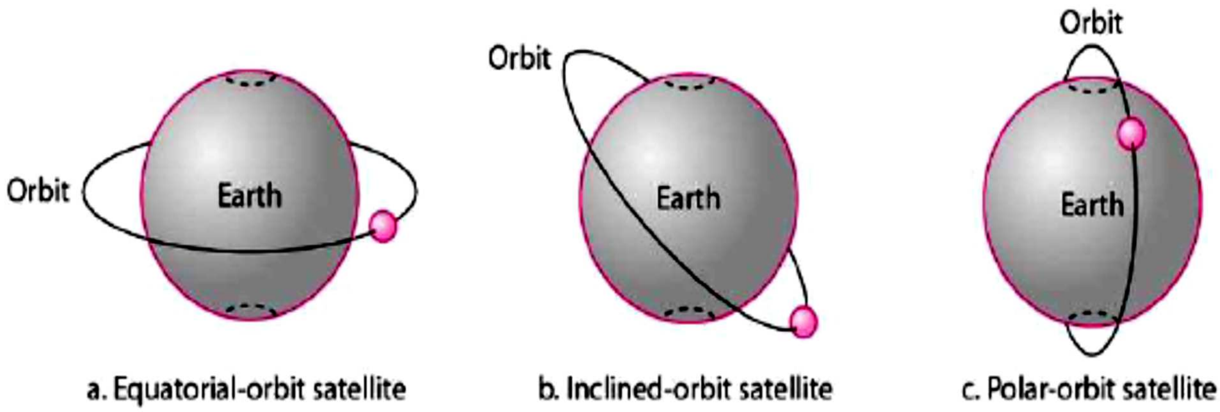


Figure IV.16. Satellite orbits

d. Basics of Satellite Orbits : Elliptical Orbits

➢ **Kepler's Three Laws**

Kepler's First Law: Each planet's orbit about the Sun is **an ellipse**. The Sun's center is always located at one focus of the ellipse. The planet follows the ellipse in its orbit, meaning that the planet-to-Sun distance is constantly changing as the planet goes around its orbit.

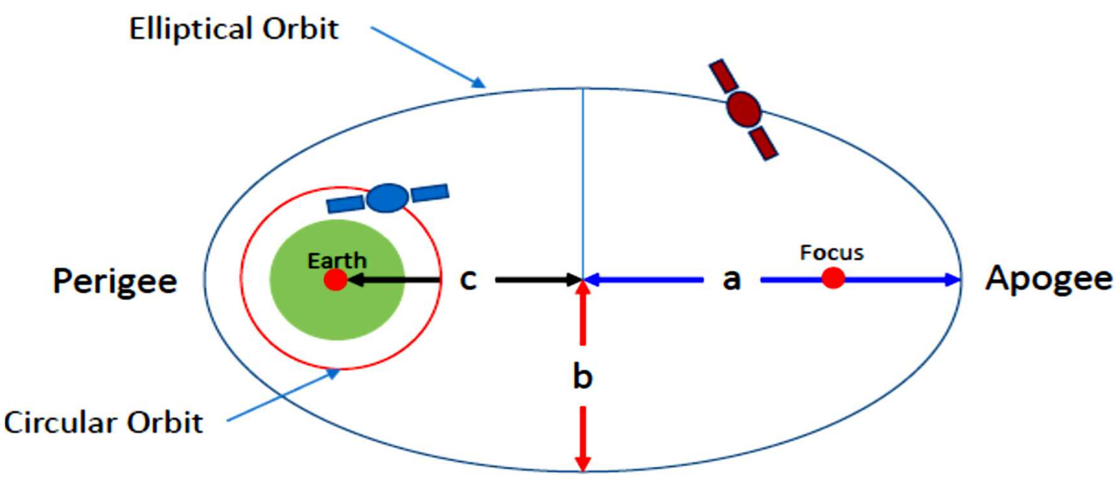


Figure IV.17. Elliptical Orbit

$$a^2 = b^2 + c^2$$

Major Axis = **2a**, Line that contains two foci

Minor Axis = **2b**, Line perpendicular to Major Axis

Distance between the two foci = **2c**

Eccentricity (e): measure of how much a given conic section deviates from being circular**= c/a**,

- **Kepler's Second Law:**

The imaginary line joining a planet and the Sun sweeps out – or covers – equal areas of space during equal time intervals as the planet orbits. Basically, the planets do not move with constant speed along their orbits. Instead, their speed varies so that the line joining the centers of the Sun and the planet covers an equal area in equal amounts of time. The point of nearest approach of the planet to the Sun is called **Perigee**. The point of greatest separation is **Apogee**, hence by Kepler's second law, a planet is moving fastest when it is at **Perigee** and slowest at **Apogee**.

- **Kepler's Third Law:**

The orbital period of a planet, squared, is directly proportional to the semi-major axes of its orbit, cubed. This is written in equation form as $\mathbf{T^2 = a^3}$**.** It implies that the period for a planet to orbit the Sun increases rapidly with the radius of its orbit. Mercury, the innermost planet, takes only **88 days** to orbit the Sun. Earth takes **365 days**, while distant Saturn requires **10,759 days** to do the same.

The orbital period *T* of two point masses orbiting each other in a circular or elliptic orbit is:

$$T = 2\pi\sqrt{\frac{a^3}{GM}}$$

Where: *G* is the gravitational constant, and *M* is the mass of the more massive body.

e. In the special case of perfectly circular orbits, the semimajor axis a is equal to the radius of the orbit, and the orbital velocity is constant and equal to:

$$v_o = \sqrt{\frac{GM}{r}}$$

Where: *r* is the circular orbit's radius in meters,

d. Types of Orbit based on Altitude

- GEO (Geostationary Earth Orbit)
- MEO (Medium Earth Orbit) or ICO (Intermediate Circular Orbit)
- LEO (Low Earth Orbit).

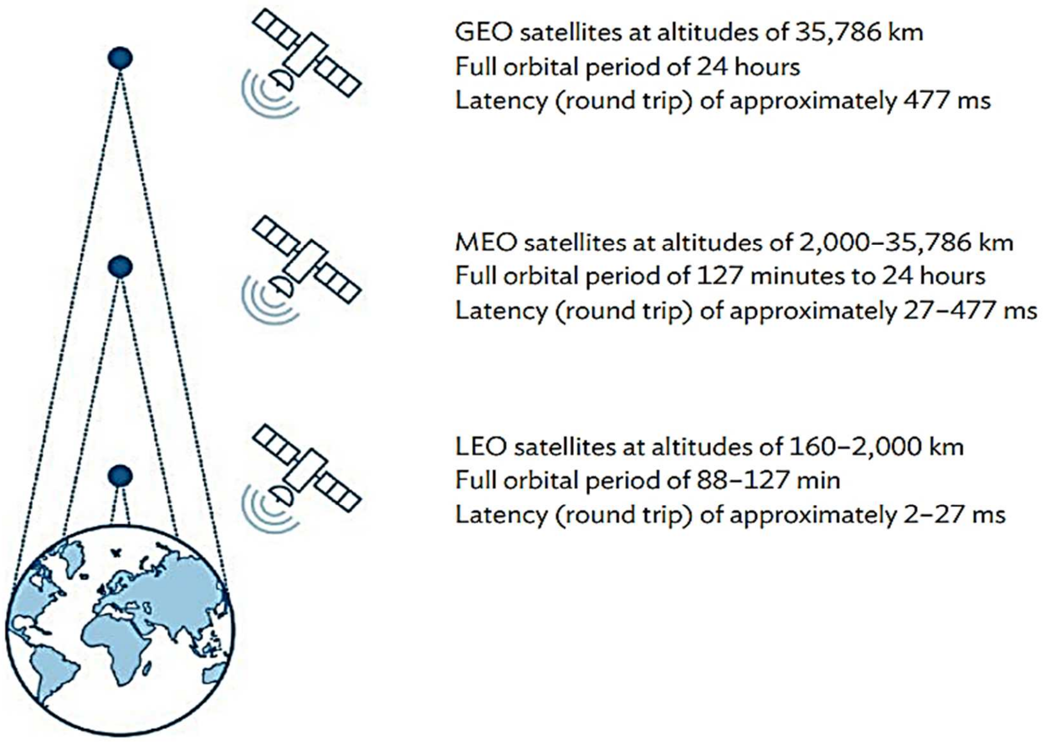


Figure IV.18. Types of orbits

1. Geostationary Earth Orbit (GEO)

GEO lies at and beyond **35,786 km** from Earth's surface. It is a sort of "sweet spot" in which satellite orbit matches the rotation of the Earth.

Application: A satellite in this orbit seems to stay in place over a single longitude, although it may drift north to south. This special, high Earth orbit is known as geosynchronous orbit.

Examples: **GSAT series** of India's indigenously developed communications satellites, used for **digital audio, data, and video broadcasting**.

2. Medium Earth Orbit (MEO)

MEO lies between **2,000 km** to **35780 km** from the surface of the Earth. Two Medium Earth Orbits are the **semi-synchronous orbit** and **the Molniya orbit**. MEO satellites have orbital periods ranging from **2 to 24 hours**.

Application: This is the orbit used by the Global Positioning System (**GPS**) satellites such as **GLONASS** (Altitude of 19,100 km) and **Galileo** (Altitude of 23,222 km).

3. Low Earth Orbit (LEO)

LEO has an altitude between **160 km to 1000 km** above the Earth's surface. Satellites in this orbit take approximately **88 - 127 minutes** to circle Earth.

Applications: This orbit is commonly used for satellite **imaging, Earth observation**, etc., but communicational satellites (in constellations) are also placed in this orbit.

- The **International Space Station (ISS)** is placed in this orbit, traveling about **16 times** around Earth per day.
- A Constellation of **36 communication satellites of OneWeb (Satellite communications company) has been** placed in LEO by ISRO.
- **Earth Observatory satellite- RISAT-2B** (Radar Imaging Earth observation satellite) of ISRO was launched in LEO for the application of the Disaster Management System.

e. Types of Orbit based on Functionality

Based on the various combinations of the above-mentioned factors (Altitude, Eccentricity, Inclination), the most common functional orbits are Geostationary orbit, Polar orbit, Sun-synchronous orbit, Molniya orbit, etc.

1. Geosynchronous Orbit and Geostationary Orbit

A geosynchronous orbit (GEO) is a prograde (in the direction of Earth's rotation), low inclination, high Earth orbit around Earth. A spacecraft in this orbit appears at a constant longitude above the Earth. The geosynchronous orbit is also called the **Clarke orbit,** as it was first popularized by the science fiction author Arthur C. Clarke.

- **Geostationary Orbit:** Geostationary orbit is a particular case of the geosynchronous orbit, with **zero eccentricity** and almost **zero inclination** (latitude), so that the spacecraft in this orbit appears stationary above a point on the Earth.
  - Such maneuvering in orbit is called **station keeping.**
- **Altitude of the Geostationary Orbit:** The Geostationary orbit (or Geosynchronous Orbit) lies exactly **42,164 km** from the Earth's center (**35,786 km** from Earth's surface).

- At this point, the **orbital period of the satellite exactly matches the rotational period of the Earth** (taking 23 hours 56 minutes, and 4 seconds) as it travels at geosynchronous speed (exactly the same speed as the Earth).

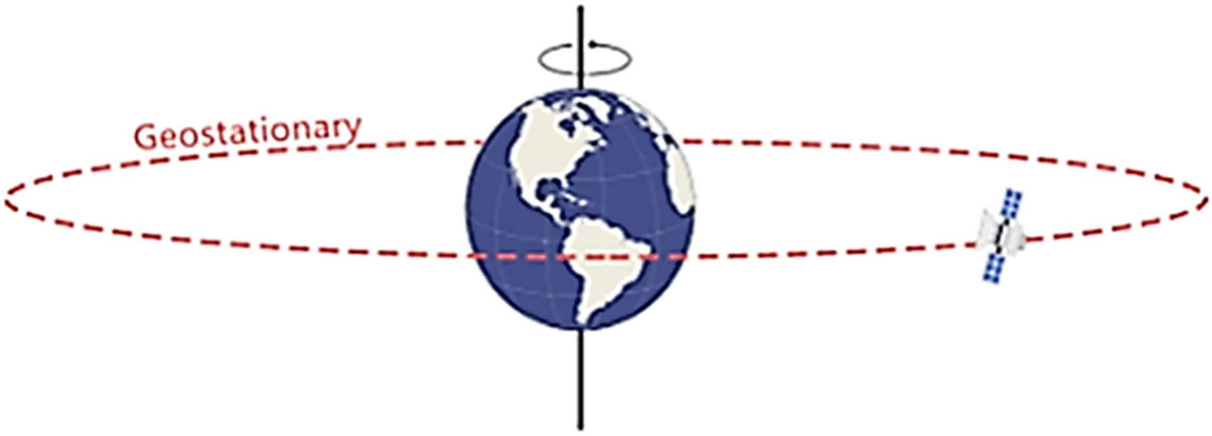


Figure IV.19. Geostationary Orbit

2. Polar Orbit

Polar orbit is a **Low Earth orbit** where satellites travel past Earth from north to south.

Figure IV.20. Polar orbit

- **Altitudes:** The altitudes of the polar orbits range between **200 to 1000 km**. Lower altitudes enable satellites to faster revolution. In polar orbits, satellites can complete **15** to **16** revolutions around the Earth.
- **Inclination:** Inclination of the polar orbits around **90 degrees**, with a deviation ranging from **20** to **30 degrees**.
- **Eccentricity:** Polar orbit follows a **circular shape**; hence, eccentricity is close to zero, hence nearly circular shape.
- **Applications:** Polar orbits have specific characteristics that make them useful for various applications, particularly for **Earth observation** (remote sensing) and scientific research.

    - **Remote sensing**: Such applications generally use nearly polar orbits to attain global coverage. **Example is Cartosat-3**.
    - **Resource management:** Applications such as monitoring crops, forests, and even global security, as done by the **Cartosat series of ISRO.**

3. Sun-synchronous Orbit

It is a particular type of **Polar Orbit**, travelling over the Polar Regions. A typical Sun-synchronous satellite completes **14 orbits a day**, and each successive orbit is shifted over the Earth's surface by around **2875 km** at the equator.

- **Features:** Satellites in this orbit are **synchronous with the Sun,** i.e. they are always in the 'fixed' position relative to the Sun.

    - Hence, in this orbit, the satellite always visits the **same spot at the same local time**. For example, passing Paris every day at exactly the same time in the afternoon.
    - It has constant sun illumination through inclination and altitude.

- **Altitude:** A satellite in a Sun-synchronous orbit would often be at an altitude of between **600** to **800 km**.
- **Applications**: Sun-synchronous can be used for the following purposes:

    - To investigate climate change and **weather patterns,** it enabled scientists to compare images from the same season over several years and deliver consistent information required to study phenomena like **climate change.**

- To help **predict atmospheric disturbance and extreme events like severe cyclonic storms, etc.** For example, **SARAL** (Satellite with ARGOS and ALTIKA) is placed in the Sun-synchronous orbit for oceanographic studies.
- Monitoring **emergencies** like forest fires or flood situations.
- To **accumulate data** on long-term problematic events like deforestation or rising sea levels.
- **Remote sensing applications** in the management of resources

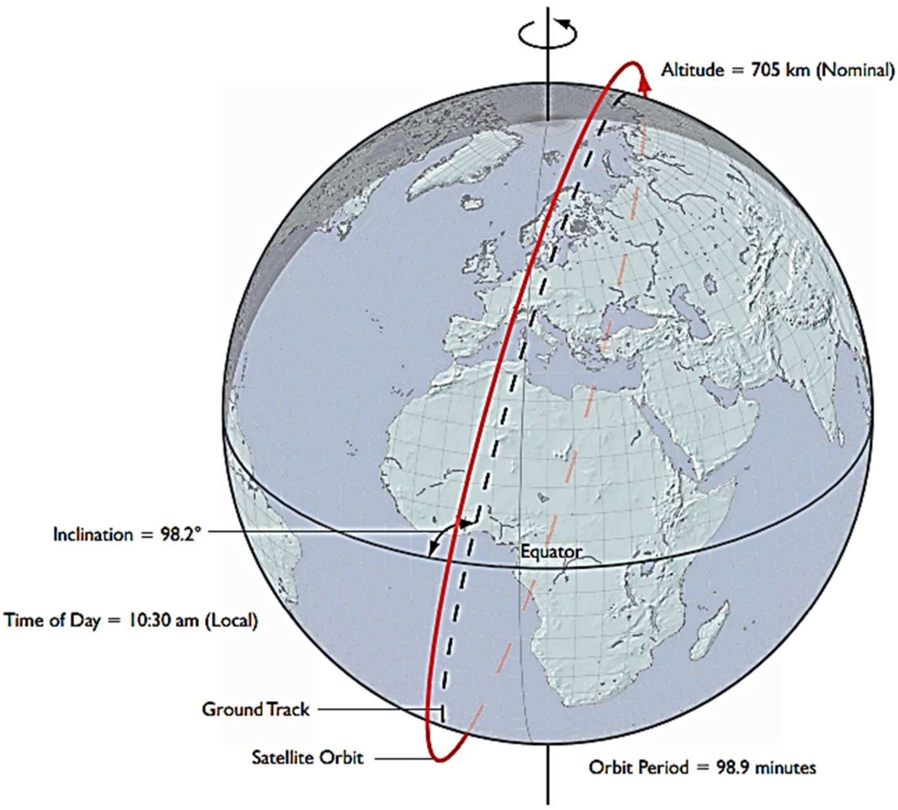


Figure IV.21. Sun-synchronous orbit

4. Molniya Orbit

Molniya Orbit combines **high inclination (63.4°)** with **high eccentricity (0.722)** for better observation and covering larger swaths. It is developed as a **high-latitude (for example, Polar Regions) communication** alternative to geostationary orbits.

The high-altitude portion of the orbit repeats over the same location every day and night.

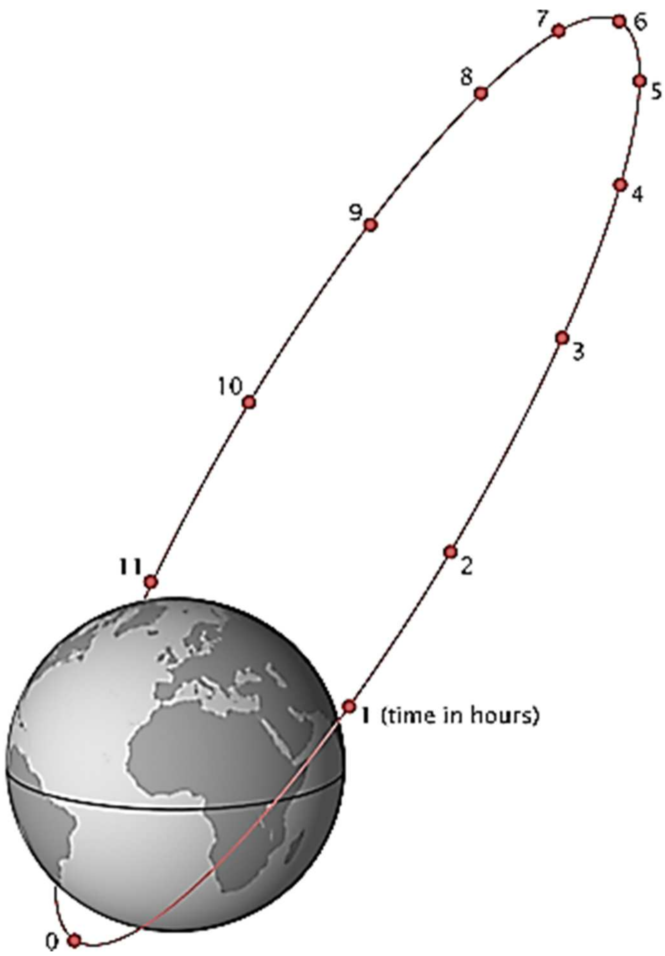


Figure IV.22. Molniya Orbit

- **Applications** of Molniya orbit**:**

- **High latitude observation:** Satellites in this orbit have better capability to observe events and associated phenomena in Polar Regions like the impact of climate change on Polar Regions.
- **Meteorological observation of middle and high latitudes:** Meteorological instruments placed on a satellite in a Molniya orbit improve the temporal frequency of observation of high-latitude phenomena such as polar lows.
- **Communications in the far north or south:** Russian communications satellites and the **Sirius radio satellites** currently use this type of orbit. It is often used by **navigation satellites**, like the European Galileo system.

f. Multiple access schemes

Multiple access schemes differ in the way the satellite transponder resource, which is powered bandwidth during the lifetime of the satellite, is shared among the contenders:

- Frequency division multiple access (FDMA)
- Time division multiple access (TDMA)
- Code division multiple Access(CDMA)

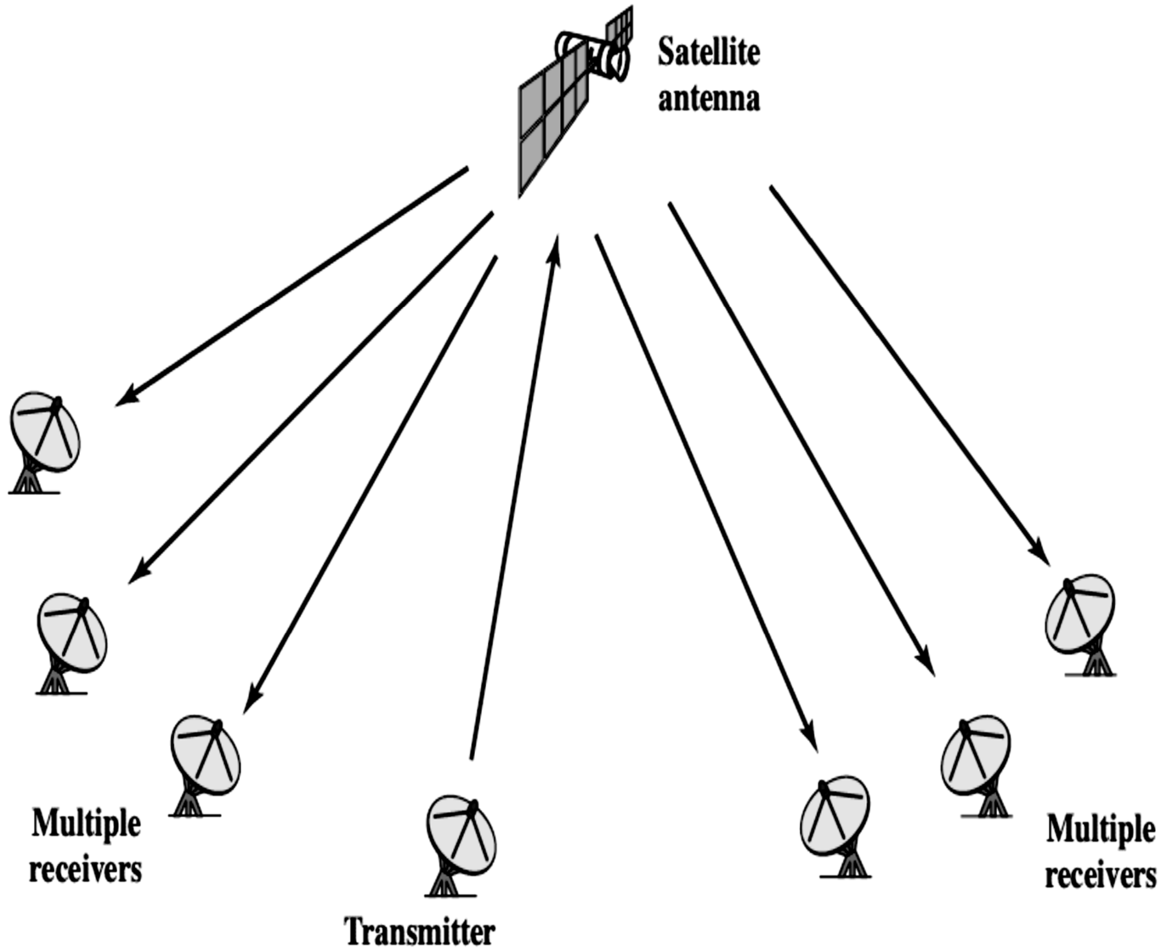


Figure IV.23. Multiple access schemes

1. Frequency division multiple access (FDMA): means allocating a given subband of overall transponder bandwidth, B, to every carrier. The allocated subband, must be compatible with the carrier bandwidth which depends on the bit rate it conveys and the type of modulation and coding.

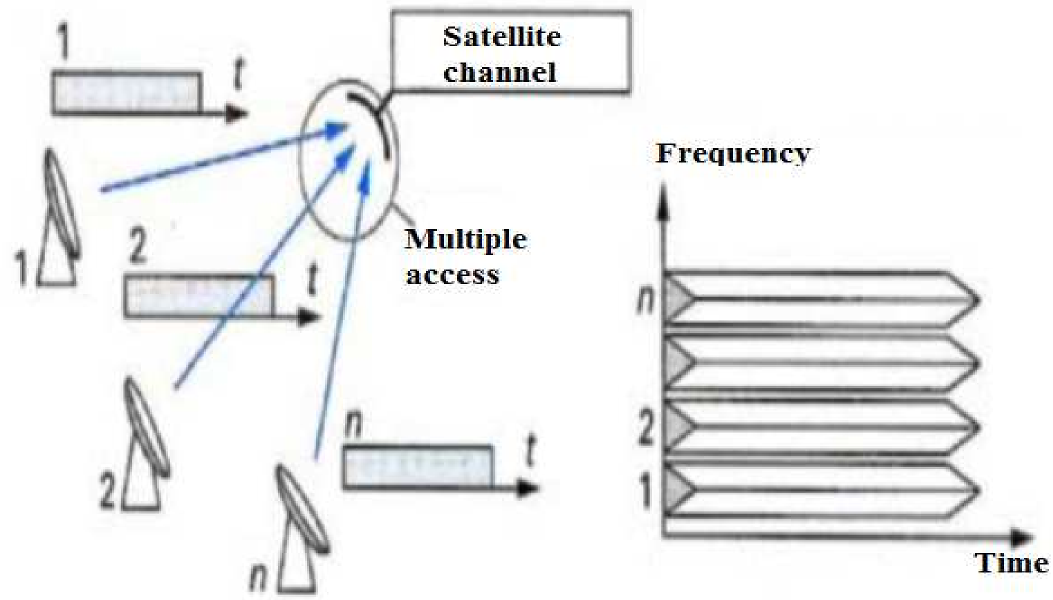


Figure IV.24. Frequency division multiple access (FDMA)

2. Time division multiple access (TDMA) means allocating the overall bandwidth of the transponder, B, to every carrier in sequence for a limited amount of time, called a time slot (n).

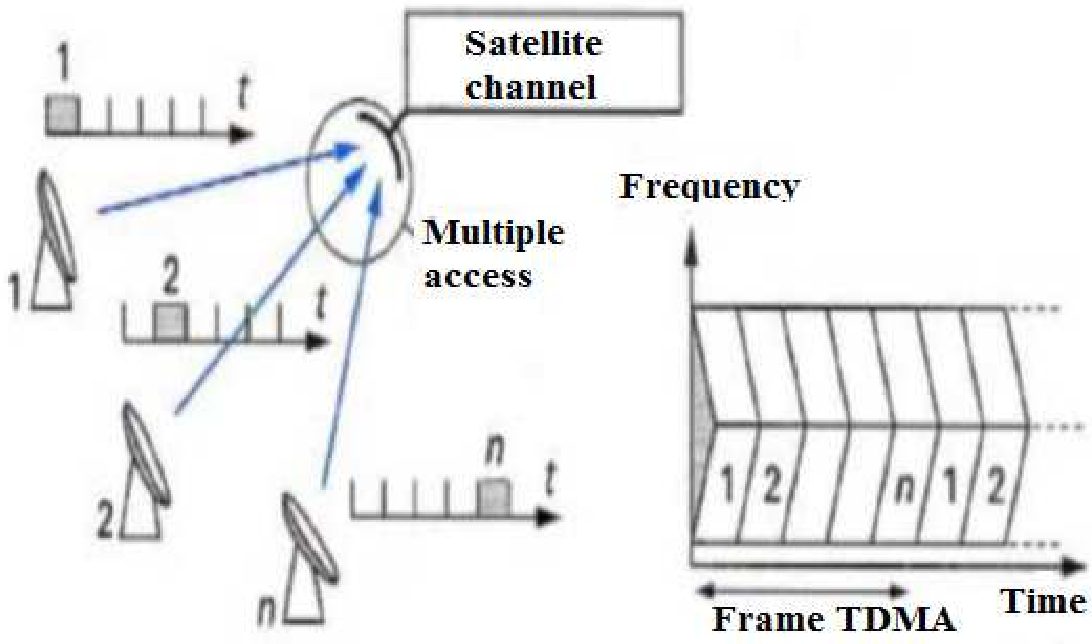


Figure IV.25. Time division multiple access (TDMA)

3. Code division multiple access (CDMA) is a multiple access technique which does not consider any frequency–time partition: carriers are allowed to be transmitted continuously while occupying the full transponder bandwidth, B. Therefore interference is inevitable, but is resolved by using spread spectrum transmission techniques based on the generation of high-rate chip sequences (or 'code'), one for every transmitted carrier. These sequences should be orthogonal so as to limit interference.

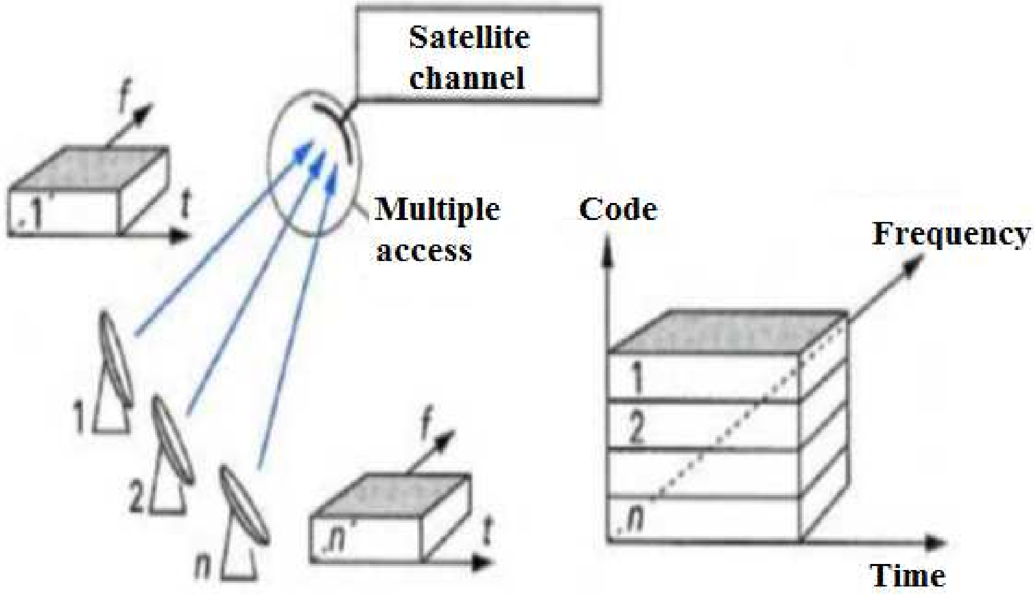


Figure IV.26. Code division multiple access (CDMA)

g. Advantages and disadvantages of Satellite Communication

➢ **Advantages:**

- Installments of circuits are easy.
- The elasticity of these circuits is excellent.
- With the help of satellite communication, every corner of the earth can be covered.
- The user fully controls the network.

➢ **Disadvantages:**

- Initial expenditure is expensive.
- There are chances of blockage of frequencies.
- Propagation and interference.

h. Satellite frequency band

Frequency Band Spectrum	Frequency Range (in GHz)	Satellite Service Type	Applications
L-band	1.518-1.675 GHz	MSS (Mobile Satellite Service)	Civilian mobile communication services and global positioning systems (GPS). (ex: INMARSAT)
S-band	1.97 - 2.69 GHz	MSS (Mobile Satellite Service)	Satellite TV, mobile broadband services, radio broadcasting, and in-flight connectivity.
C-band	3.4GHz - 7.025 GHz	FSS (Fixed Satellite Service)	Data services, unprocessed satellite feeds, and networks for satellite TV. (ex: Telstar)
X-band	7.25 - 8.44 GHz	FSS (Fixed Satellite Service)	Military operations, pulsed radar systems, synthetic operational and wave radars, weather monitoring, air traffic control, maritime traffic regulation, defense surveillance, and the detection of vehicle speeds.
Ku-band	10.7 - 14.5 GHz	FSS (Fixed Satellite Service), BSS (Broadband Satellite Service)	Fixed satellite television data services.
Ka-band	17.3 - 30 GHz	FSS (Fixed Satellite Service), BSS (Broadband Satellite Service)	Two-way broadband services for both mobile and fixed applications, fixed satellite television services, and the deployment of close-range targeting radars within military systems.

Chapter V

Optical Wireless Transmission

Infrared Transmission

Visible Light for wireless transmission

Chapter V: Optical Wireless Transmission

V Optical Wireless transmission

V.1 Introduction

Optical wireless communication (OWC) technologies is based on the use of light waves to transmit data over the air, instead of using radio waves RF like traditional wireless communication systems. More precisely, OWC can be described as a form of optical communication technology that employs light as a propagating medium to enable wireless transmission of data for telecommunications. In this sort of technology, there is no requirement of optical fiber cable where the optical beams are sent through free space. OWC systems use visible or infrared light to transmit data.

Infrared (IR) light is electromagnetic radiation with longer wavelengths than those of visible light, extending from the nominal red edge of the visible spectrum at 0.75 μm to 1 mm. This range of wavelengths corresponds to a frequency range of approximately 0.3 to 400 THz.

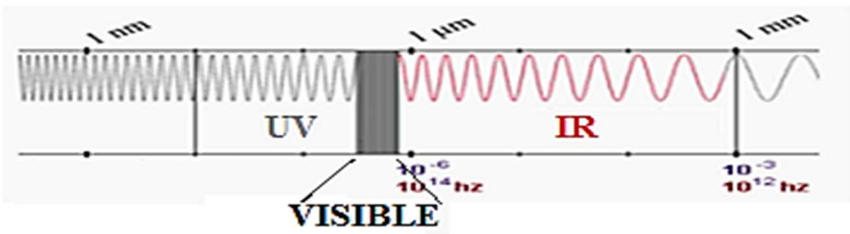


Figure V.1. Optical wave spectrum

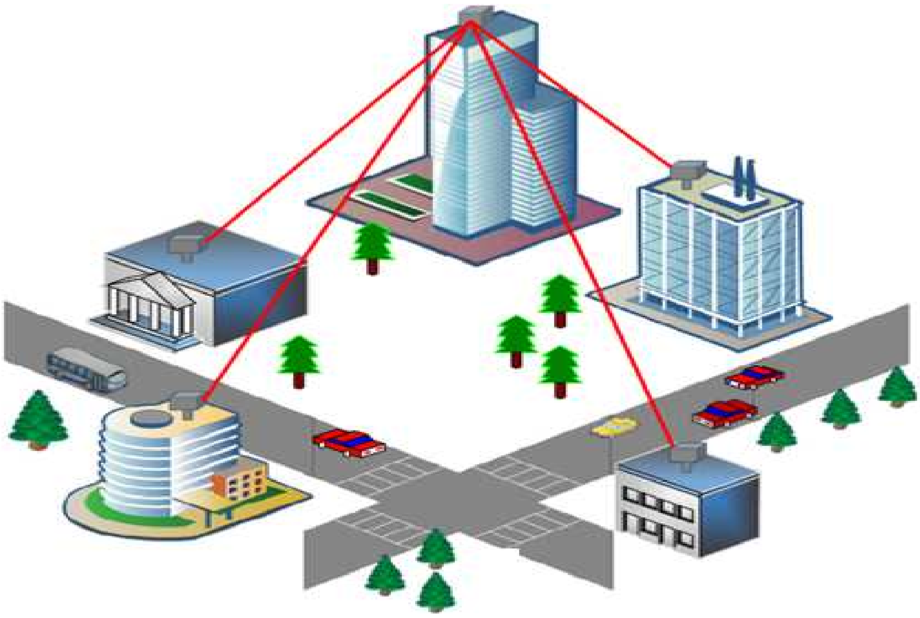
V.2 Infrared Transmission

Infrared transmission links allow the creation of wireless links widely used for atmospheric optical links called as Free Space Optic (**FSO**).

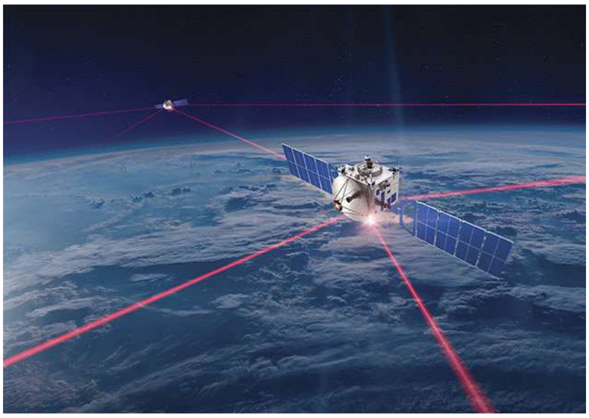
A Free Space Optical transmission system is a wireless form of connection designed for the interconnection of two points, which have a direct line of sight (LOS). The systems operate by taking a standard data or telecommunications signal, and transmitting it through free space. The carrier used for the transmission of this signal is IR.

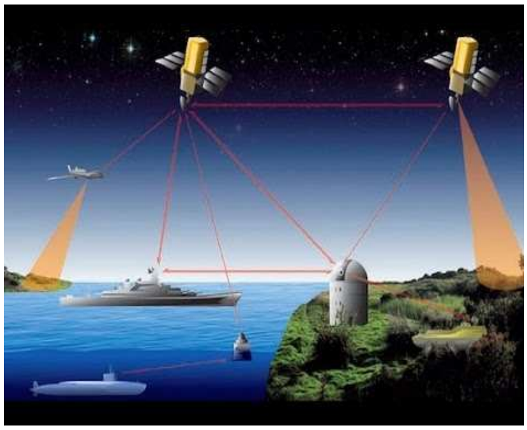
FSO is used for:

- Terrestrial Wireless communications (LAN)
- Earth to satellite communications (ex: observation satellite)
- Satellite to satellite communications,



(a)





(b) (c)

Figure V.2. Example of terrestrial (a), Earth to satellite (b) and Satellite to satellite (c) FSO links.

V.2.1 FSO technology

In FSO system, a high-power laser source (LD) converts data into laser pulses and sends them through a lens system and into the atmosphere. The laser travels to the other side of the link and goes through a receiver lens system and a high-sensitivity photodetector (PD) converts those laser pulses back into electronic data that can be processed. In other words, instead of using an optical fiber as a transmission medium to transmit the laser pulses, FSO uses air as a medium. The laser typically operates at an IR wavelength of 1550nm that is safer on the eye.

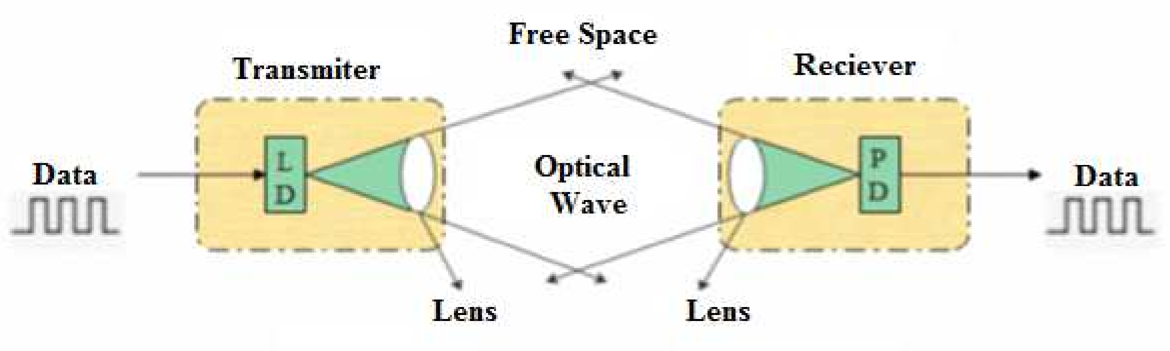


Figure V.3. FSO system diagram.

Figure V.4. FSO transmitter-receiver

a. Advantages of FSO

FSO systems offer a number of unique advantages over its RF counterpart, such as:

- Abundance of unregulated bandwidth (200 THz in the 750–1500 nm range)
- No utilization tariffs
- No multipath fading
- Highly secure connectivity.
- Small, light, compact smaller size components and relatively low cost
- Well-defined cell boundaries and no interchannel interference
- Use one wavelength to cover a large number of cell, therefore no frequency reuse problem as in RF
- No need to dig up roads and is easily installed

- Health-friendly (no RF radiation hazards)
- Lower power consumption
- Immunity to the electromagnetic interference

V.2.2 FSO channel and impediments associated with FSO technology

A number of such impediments (Figure V.5) are listed below:

- **The ambient light sources:** with the spectra well within the receiver bandwidth of silicon photodetectors, thus resulting in the background noise.
- **Obstacles Arising due to different Phenomena**: there are several impediments present, which include: tall trees, skyscrapers and flying birds can obstruct the line of sight (LOS) path thus hindering the communication in case of FSO.
- **Misalignment:** by employing highly directional and narrow beams of light, the changes in mispointing of the transmit beam as well as error due to the tracking of the receiver will introduce signal fading.
- **Scintillation:** The adverse activities carried out by people on earth lead to the emanation of heat from the earth. Hence, as a result, such drastic variation of temperature has a direct impact on the signal, which is received in the FSO system. Due to unexpected amplitude variations, the received signal is a distorted version of the transmitted one and it is popularly known as '**image dancing**'.

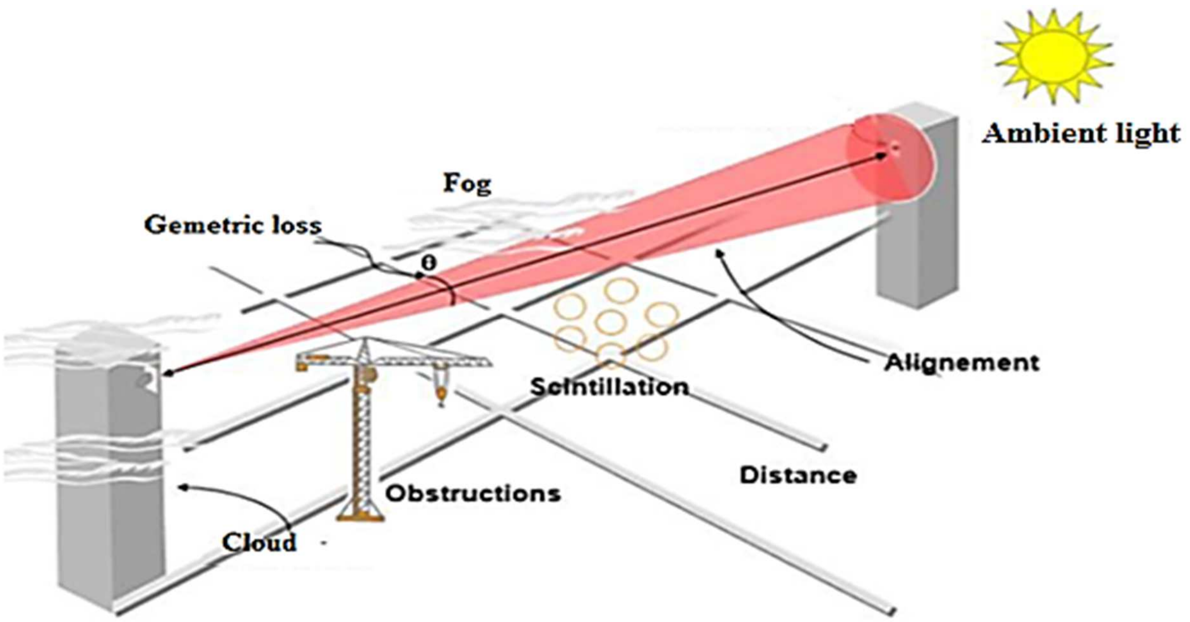


Figure V.5. Different drawbacks associated with FSO channel

- **Atmospheric absorption:** In the terrestrial atmosphere, the water molecules are suspended and imbibe the photon power, which successively decreases the power density of the optical beam. Therefore, it can be asserted that the availability of transmission is directly affected by the absorption.

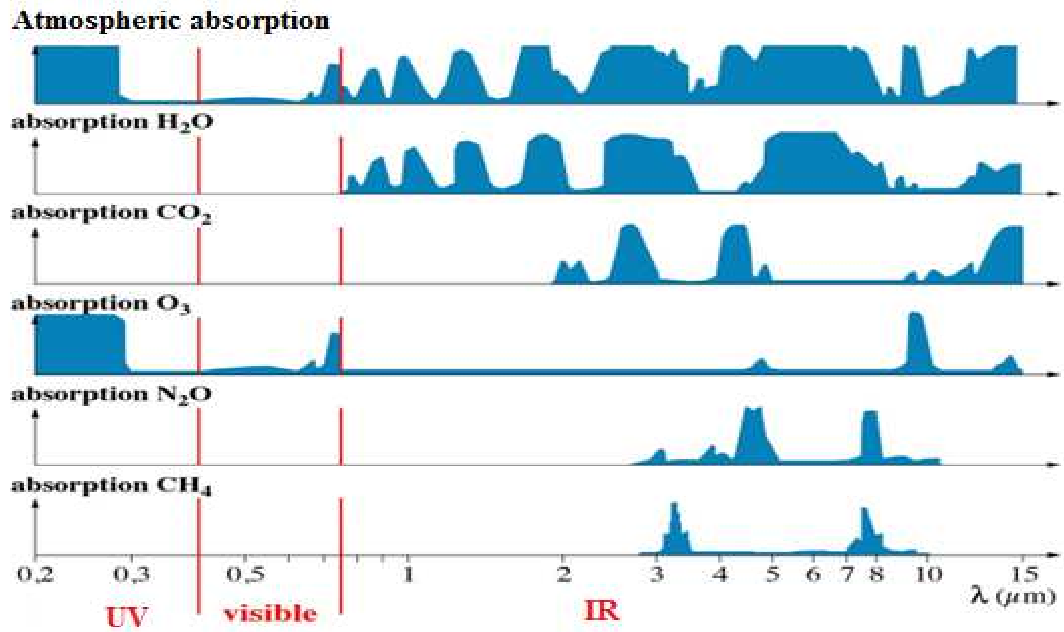


Figure V.6. Atmospheric absorption spectra

The performance of outdoor FSO systems is highly dependent on the operating transmission windows. Longer IR wavelengths are most absorbed by water molecules. Minimal absorption effects at 800–890 nm and 1550 nm.

- **Geometric Loss:** Geometric loss is ably called 'optical beam attenuation'. Generally, this arises due to the spreading of the beam which in turn results in reduction in the power levels of the received signal when the signal is navigated from the transmitting end to the receiving end.

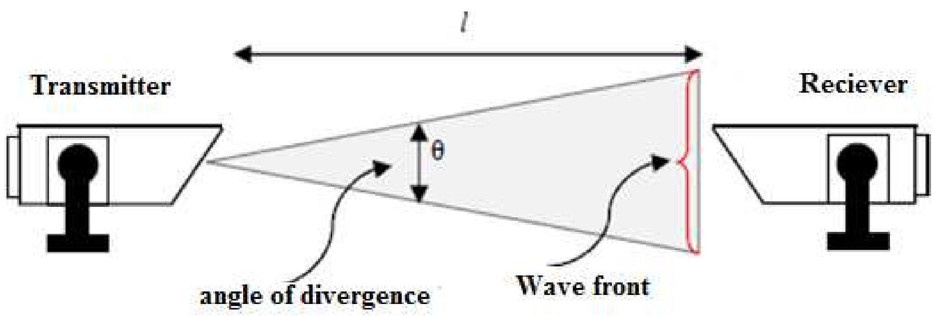


Figure V.7. Geometric loss

Geometric loss of the FSO link (dB) is guiven as:

$$A_{geo} = \frac{S_L}{S_c}$$

With: S_c: is the detection area of the receiver

S_L: is the area of the beam emitted at distance L. Where: $S_L = \frac{\pi}{4}(L.\theta)^2$

θ is the angle of the beam divergence (mrad), and L is the distance between the transmitter and the receiver (km).

- **Atmospheric attenuation**: Heavy rain, fog and haze are the primary weather conditions, which have a direct impact on the FSO link. Due to the adverse atmospheric conditions, the resultant transmitted signal is attenuated.

Atmospheric attenuation γ_{atm} (dB/km) is given as:

$$\gamma_{atm} = \gamma_{\text{clear\_air}} + \gamma_{\text{excess}}$$

Where:

$\gamma_{\text{clear\_air}}$: Atmospheric attenuation for clear whether.

γ_{excess}: Atmospheric attenuation for heavy rain, fog, haze,…

V.2.3 FSO Application Areas

- **Last mile access:** FSO is used to bridge the bandwidth gap (last mile bottleneck) that exists between the end-users and the fiber optic backbone.
- **Optical fiber back-up link:** Used to provide back-up against loss of data or communication breakdown in the event of damage or unavailability of the main optical fiber link.
- **Cellular communication backhaul:** Can be used to backhaul traffic between base stations and switching centers in the third/fourth-generation (3G/4G) networks.
- **Disaster recovery/temporary links:** The technology finds application where a temporary link is needed, be it for a conference or ad hoc connectivity in the event of a collapse of an existing communication network.
- **Multicampus communication network:** FSO has found application in interconnecting campus networks and providing back-up links at fast-Ethernet or gigabit-Ethernet speeds.
- **Difficult terrains:** FSO is an attractive data bridge in instances such as across a river, a very busy street, rail tracks or where right of way is not available or too expensive to pursue.

V.3 Visible Light for wireless transmission

The visible light spectrum is a band of electromagnetic spectrum that can be seen by the human eye. Electromagnetic radiation in this range corresponds to wavelengths from about **380 THz (750 nm)** and **790 THz (380 nm)**. Modern wireless optical communication systems, such as **VLC** (Visible Light Communication) technology are increasingly utilizing this spectrum of visible light as an alternative to RF-based networks.

V.3.1 VLC technology

Visible Light Communication (VLC) is a form of data communication that uses visible light in the electromagnetic spectrum, as a medium to transmit information. It involves modulating light emitted by light-emitting diode (LED) to carry data signals that can be received by a photodetector, after the propagation in VLC channel. The characteristics of these parts have a significant impact on the VLC system.

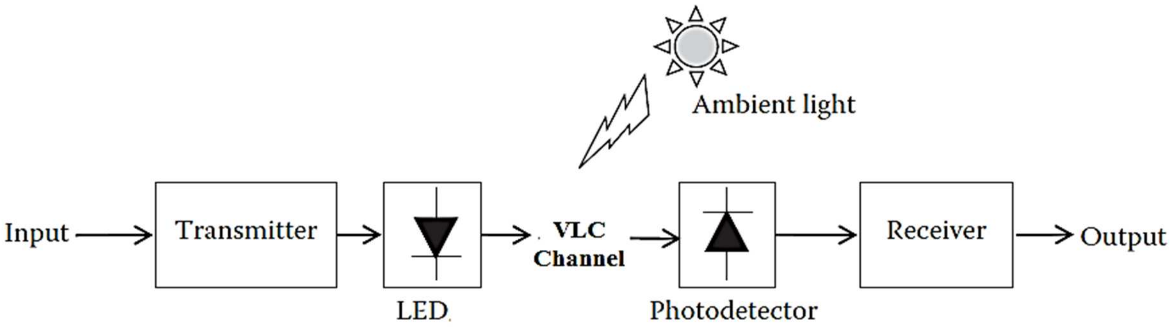


Figure V.9. Basic block diagram of a VLC system

Figure V.10. VLC system using LEDs as a transmitter (https://www.6gflagship.com/visible-light-communication/)

V.3.2 VLC channel configurations

There are numerous ways through which an optical link can be physically configured. These are typically grouped into four system configurations:

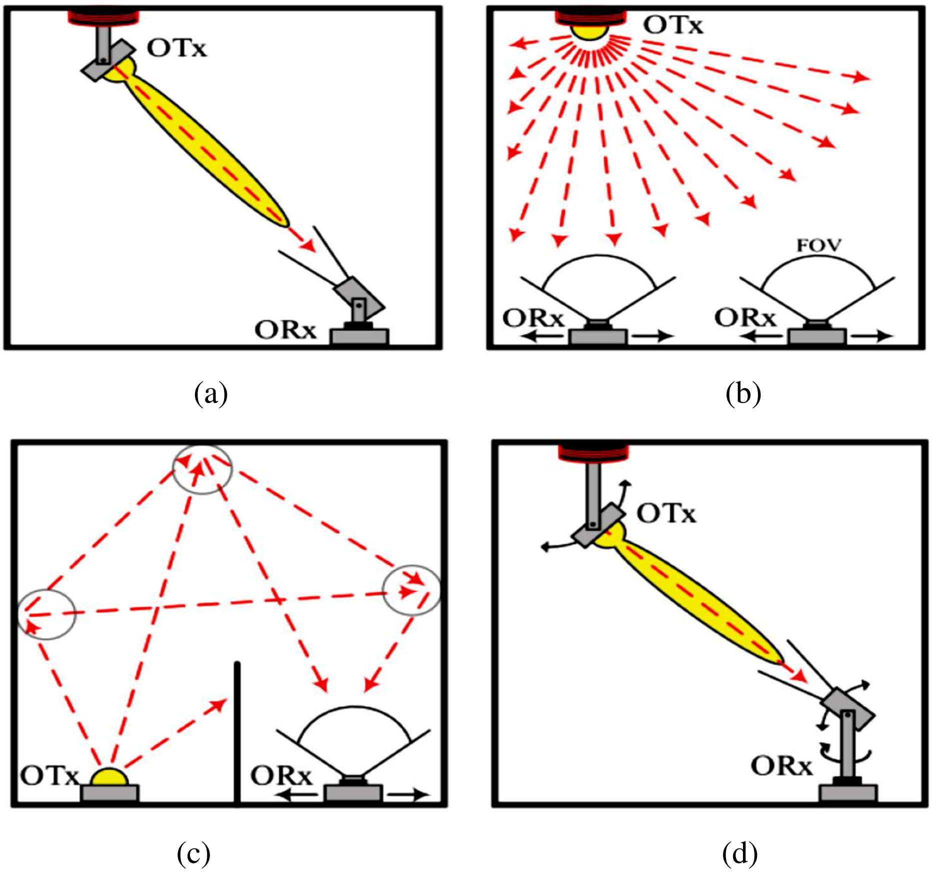


Figure V.11. Link configurations: (a) directed LOS, (b) nondirected LOS, (c) diffuse, and (d) tracked.

a. Directed LOS (Line Of Sight)

- Used for point-to-point communication links
- The LOS link offers the highest data rate over a link span from a few meters to few km.
- LOS links do not suffer from multipath distortion, and noise from the ambient light sources is also rejected when used with a narrow field-of-view (FOV) receiver.
- In LOS, the transmitter/receiver base station is usually mounted to the room ceiling.

- **However,** LOS links cannot support mobile users because of the requirement for alignment of receiver and transmitter modules.

b. Nondirected LOS (NLOS)

- For indoor applications, the NLOS, considered the most flexible configuration, uses wide beam transmitters, wide FOV receivers and scatter from surfaces within the room to achieve a broader coverage area.
- NLOS links are suitable for point to multipoint broadcast applications.
- They offer robustness to shadowing and blockage and require no alignment and tracking.

- **However,** it incur a high optical path loss, and it does give rise to intersymbol interference (ISI). In addition, it ought to be able to operate in environments with intense ambient light levels, thus degrading the link performance.

c. Diffuse configuration (nondirected non-LOS)

- The transmitter points directly towards the ceiling emitting a wide beam.
- The diffuse indoor topology is the most convenient for LAN ad hoc networks since it does not require careful alignment of the transmitter and receiver modules, and is almost immune to blockage of the transmission path.
- It is extremely flexible, and can be used for both infrastructure and ad hoc networks.

- **However,** diffuse links experience high path loss, typically 50–70 dB for a horizontal separation of 5 m.

d. Tracked systems

- The transmitter (Tx)/receiver (Rx) base station is mounted on the ceiling and the mobile stations (MSs) are located at the table-top height.
- The combination of a narrow Tx beam and a receiver with a smaller FOV results in reduced multipath induced ISI and the ambient light interference.

- **However**, mechanical steerable optics are expensive to realize.

V.3.2 .1 LOS propagation model

For indoor VLC systems as shown in Figure V.9, the transmitter, which is based on LEDs, is generally modeled by a **Lambertian pattern**. The receiver of VLC systems usually consists of photodiode (PD), amplifier, optical lens (concentrators) and filter to improve the field of view

(FoV) and the gain of the receiver. Light beams propagate from the LED to the receiver via LOS channel.

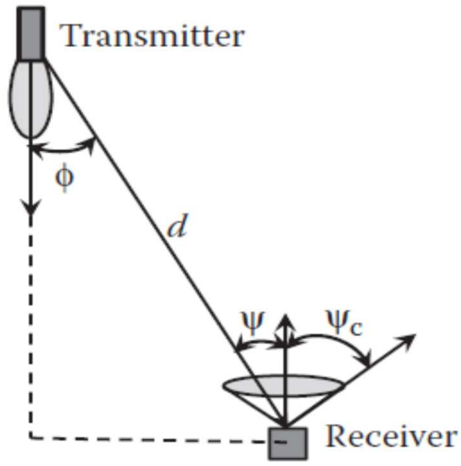


Figure V.12. Geometry LOS propagation model

The received power for LOS channel can be given by the channel transfer function as:

$$H_{LOS}(0) = \begin{cases} \frac{(m+1)A_{PD}}{2\pi d^2}\cos^m(\phi)T_s(\psi)g(\psi)\cos\psi \ , & 0 \le \psi \le \psi_c \\ 0\ , & \psi \ge \psi_c \end{cases}$$

Where d denotes the distance from LEDs to the PD, A_{PD} represents the PD surface area, m is the order of Lambertian model and is given by $m = -\ln 2/\ln(\cos(\theta_{1/2}))$, where $\theta_{1/2}$ is the transmitter half-angle. ψ denotes the incidence half-angle at the PD, ϕ is the irradiance half-angle, ψ_c is the receiver FoV (half-angle), $T_S(\psi)$ is the optical filter gain, $g(\psi)$ is the optical concentrator gain.

The gain of an optical concentrator can be expressed as:

$$g(\psi) = \begin{cases} \frac{n^2}{sin^2\psi} & ,0 \le \psi \le \psi_c \\ 0 & ,\psi \ge \psi_c \end{cases}$$

Where n denotes reflective index of an optical concentrator.

The received power of the LOS link is defined by:

$$P_r = \sum_{LEDs}(P_t . H_{LOS}(0))$$

Where P_t is the transmitted signal power.

V.3.3 VLC Application Areas

a. Indoor VLC Systems

- **Li-Fi:**

One of the most important applications envisioned for VLC is the provision of Light-Fidelity (i.e., optical Wi-Fi. LiFi offers a networked indoor system with bidirectional support for point-to-point (P2P) and multi-point-topoint (MP2P) communications. It also offers the formation of wireless networks and full mobility to users.

- **Indoor localization:**

VLC can provide very efficient indoor location by determining the received signal strength or time of flight. In this kind of applications, VLC is particularly useful, as traditional GPS does not work inside buildings.

- **Interference zone:**

VLC is an ideal solution for providing wireless communications in restricted areas where RF signals are not allowed. Such areas include hospitals, airplanes, and hazardous environments with the risk of explosions such as mines, chemical plants, or oil platforms.

b. Outdoor VLC systems

- **Intelligent Transportation Systems:**

Intelligent Transportation System (ITS) is one particular area where VLC could be very useful. These systems can take advantage of the LED-equipped lighting modules (i.e, traffic lights, headlamps, taillight, rear light) to establish secure and robust communication. These systems creates a connected VLC communication network between vehicles and infrastructure. They offers numerous benefits, including reducing collisions, alerting drivers of traffic lights and speed violations, and warning of roadwork and other hazards.

- **Underwater communication:**

In the underwater environment, radio frequency communication is not effective due to the good conductivity of sea water, which does not allow RF waves to propagate well. In such scenarios, VLC can be used to provide short-range communication between divers and with a base. The various activities include ocean observation, maintenance, and vessel deployment capability.

V.3.4 Advantages and Drawbacks of VLC

✓ **Advantages:**

- **Wide Bandwidth** and High Data Transfer Rates: VLC takes full advantage of the usage of the visible light spectrum, which is between 380 and 780 THz, adding 400 THz off available bandwidth for wireless communications. It can be stated that VLC comes with worldwide, unregulated and almost unlimited bandwidth offering the premises for multi-Gb/s data rates compared with RF, which rarely can provide data rates above 100 Mb/s.
- **Low cost implementation:** VLC uses the visible light for communication, which is in an unlicensed region of the electromagnetic spectrum. Moreover, VLC will rely on existing infrastructures that is already accepted and widespread across the world, thanks to the numerous advantages offered by LED lighting sources.
- **Unrestricted Technology:** RF communication can cause malfunctions of the high precision electronic equipment as the one found in hospitals or in aircrafts. On the other hand, VLC is safe also for the high precision electronic equipment, enabling its usage in such places.
- **Higher security:** Unlike RF waves, the light cannot penetrate through walls, providing VLC with high security against eavesdropping. This makes VLC to be suitable in areas of high security.
- **Safe technology**: The usage of the visible light as a carrier for the data enables VLC to be completely safe for the human health.

✓ **Drawbacks:**

- **Line of sight condition (LOS):** The mandatory LoS condition has a negative effect on mobility and, in some areas, it represents VLC’s greatest disadvantage because an object interposed between emitter and received can block the communication, unless an alternate route is available.
- **Limited transmission range:** VLC cannot compete with RF communications. Even if the VLC transmission range can be increased by optimizing the emitter and receiver parameters, VLC communication range is still significantly shorter than RF communication range.
- **Susceptibility to interference:** VLC is likely to be affected by other illuminating devices such as incandescent or fluorescent light sources. Generally, these light sources produce low frequency noise, which can be removed with a high pass filter. In outdoor applications, the sunlight represents a very strong perturbing factor. However, high intensity optical noise can saturate the receiver, blocking the communication.

Comparison of Unguided Media

Comparison of Unguided Media

Parameter	Radio Waves	Microwaves	Infrared (IR) Waves
Position in EM Spectrum	Lowest frequency, longest wavelength	Between radio and infrared	Between microwaves and visible light
Wavelength Range	~1 mm – 100 km	~1 mm – 30 cm	~700 nm – 1 mm
Frequency Range	3 kHz – 300 GHz	300 MHz – 300 GHz	300 GHz – 430 THz
Energy Level	Lowest	Moderate	Higher than radio/microwaves, lower than visible light
Propagation	Omnidirectional, long-distance, diffracts around obstacles	Line-of-sight or focused beams	Line-of-sight does not penetrate walls well
Penetration	Penetrates buildings and obstacles well	Can penetrate through walls (limited for higher frequencies)	Poor penetration; blocked by most solids
Main Source	Electrical circuits, antennas	Magnetrons, klystrons, oscillators	Thermal radiation from objects, IR LEDs, lasers
Detection	Antennas	Waveguides, dishes	IR sensors, photodiodes, thermal cameras
Typical Applications	AM/FM radio, TV, mobile phones, Bluetooth, satellite communication	Radar, microwave ovens, Wi-Fi, 5G, satellite TV	Remote controls, thermal imaging, night vision, optical fibers
Internet Capability	High (UHF/SHF bands used in Wi-Fi, 4G/5G)	Very high (used in Wi-Fi, 5G, point-to-point links)	High (in optical communication), limited for short-range
Effect of Obstacles	Low to moderate effect	Moderate effect; high frequencies blocked easily	Strongly affected; blocked by walls and fog
Health Impact	Generally safe at low power levels	Safe at moderate levels, excessive exposure may cause heating	Generally safe; can cause heating at high power

Conclusion

Transmission Media

This course on Transmission media is organized into five chapters, each covering important concepts in this field. It is started with the characteristics of the transmission media and channels. Next, It is explored their different types, including guided media and unguided media. In guided media, it is delved into twisted-pair cables, coaxial cable and fiber optic cables. Lastly, it is addressed unguided media including radio wave, microwave and optical wireless transmission (infrared and visible light). This course provides a solid foundation in transmission systems.

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