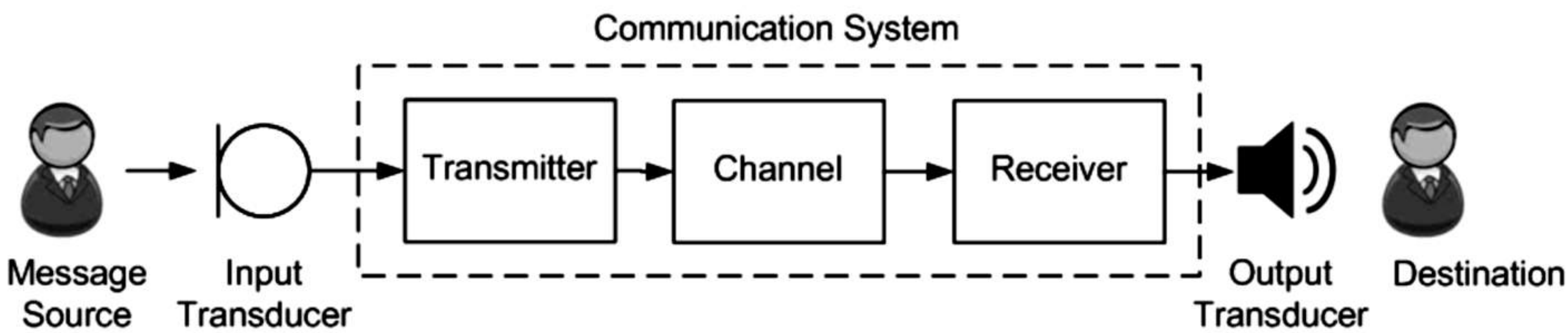
Introduction

to

Electronics & Communication Engineering

What is communication

- Communication or, more specifically, telecommunication refers to the transmission of messages over a long distance.
- Model of a communication system



A brief timeline

- **Prehistoric Era:** Fires, beacons, smoke signals, communication drums, horn, etc.
- **6th century BC:** Mail
- **5th century BC:** Pigeon post
- **4th century BC:** Hydraulic semaphore (Greece)
- **490 BC:** Heliographs
- **15th century:** Maritime flag semaphore
- **1672:** First acoustic telephone by Robert Hooke
- **1790:** Optical telegraphs

A brief timeline

- **1838:** Electrical telegraph by Samuel B. Morse
- **1858:** First trans-Atlantic telegraph cable
- **1876:** Telephones by Alexander Graham Bell
- **1877:** Acoustic phonograph by Thomas Alva Edison
- **1880:** Telephony via light-beam (photophones) by A.G. Bell
- **1886 onwards:** Radio (wireless) communication
  - In 1893 Tesla successfully transmitted radio waves

A brief timeline

- Since the early days of human civilization, communication systems evolved continuously from prehistoric age to modern day civilization.
- Prehistoric age Communication – smoke signals, drum beats
- Non-electrical means of communication – carrier pigeons, semaphore, acoustic phonograph, etc.
- Electrical (electro-mechanical) telecommunication systems – telegraphy and telephony. This marks the starting of actual telecommunication engineering.

Telegraphy system

- Samuel B. Morse developed the first telegraph system in 1838; the first message in history was transmitted on May 24, 1844 at 8:45 a.m. when Morse in Washington telegraphed to Vail in Baltimore, "What Hath God Wrought."

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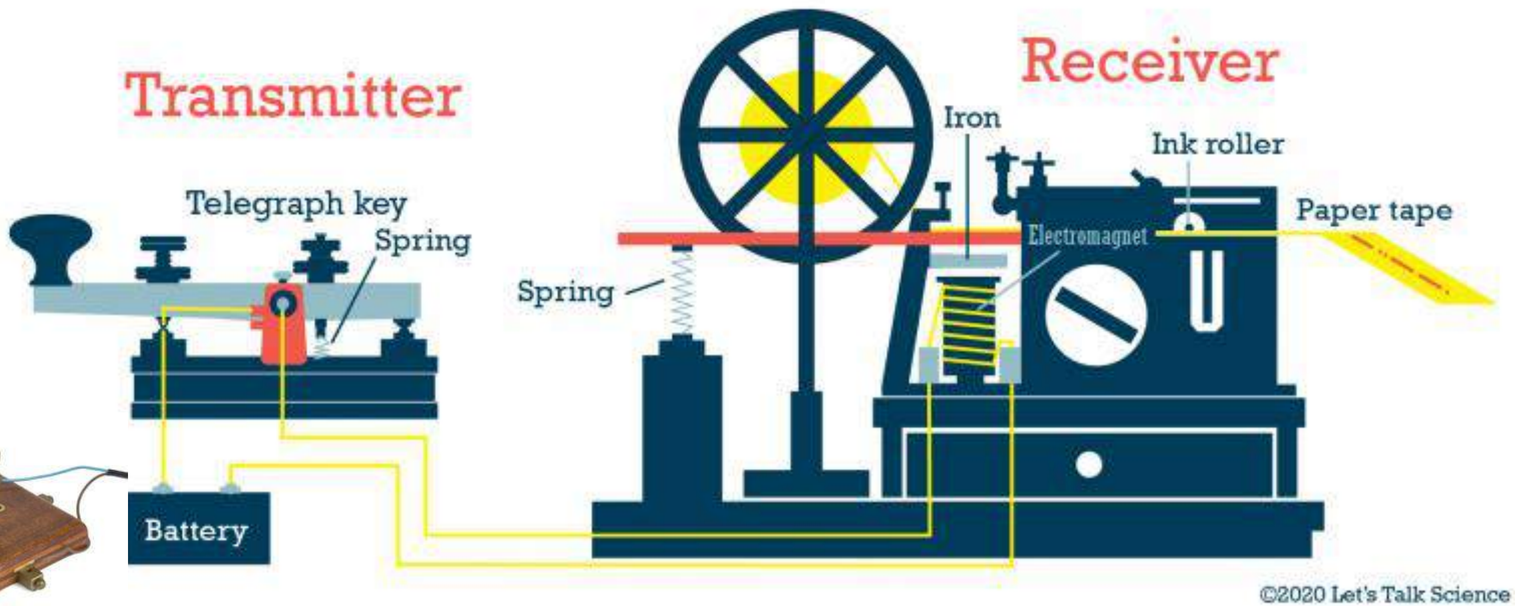
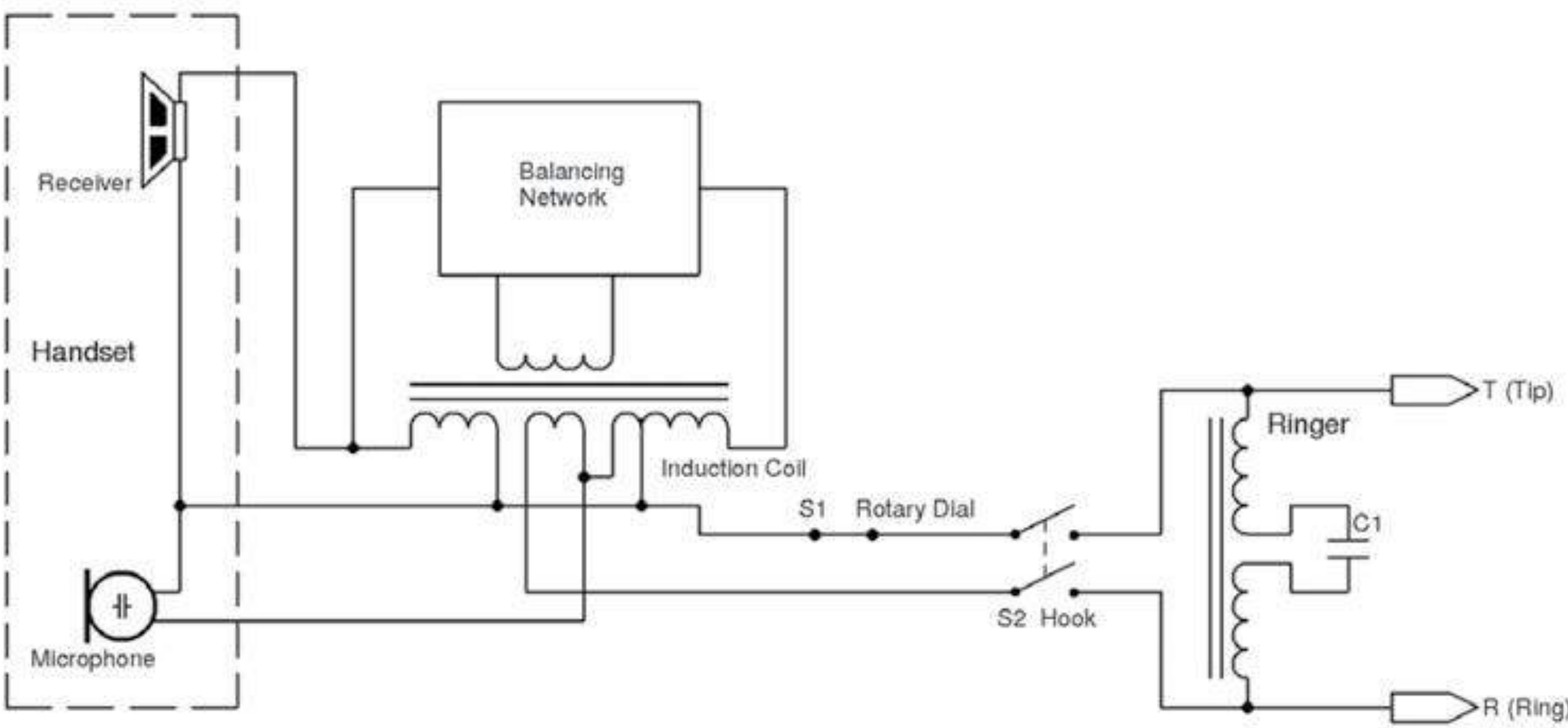


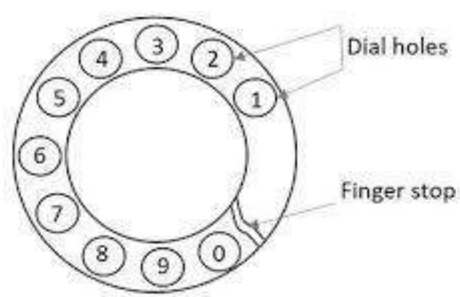
Telephone system

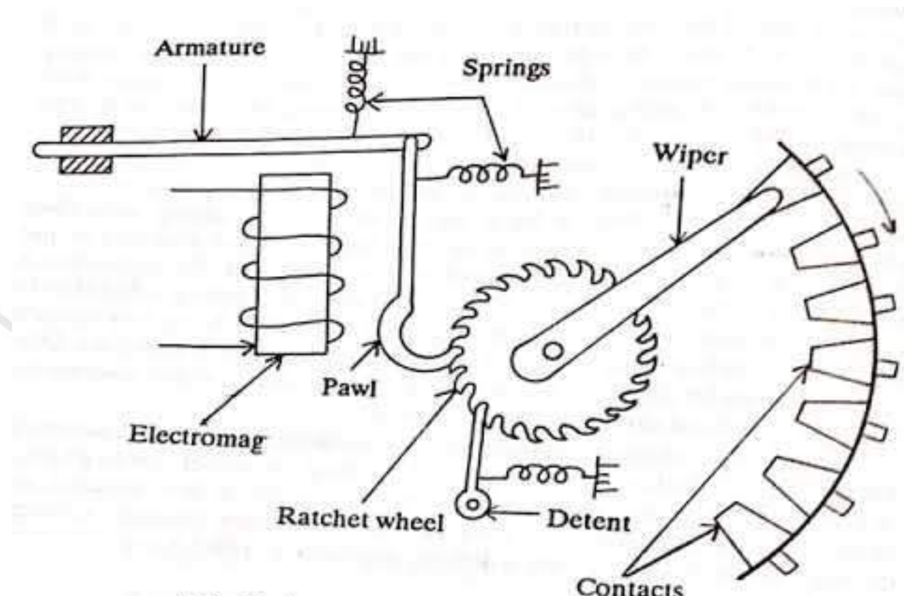
- Telephone invented by Alexander Graham Bell in March 1876.



Telephone system – Dialling in the old days

- Electromechanical dialling – how it works

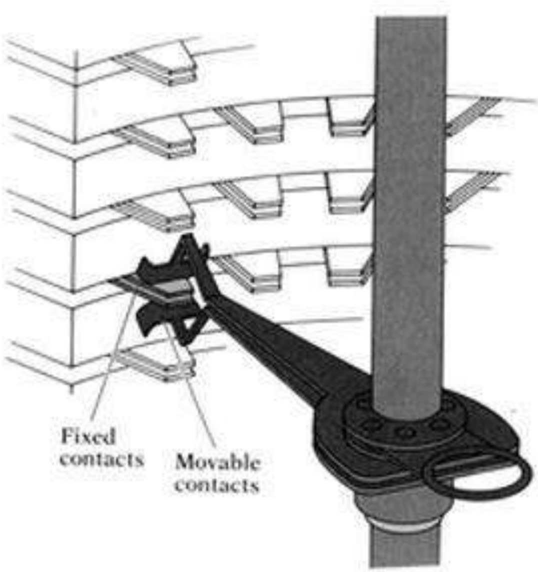


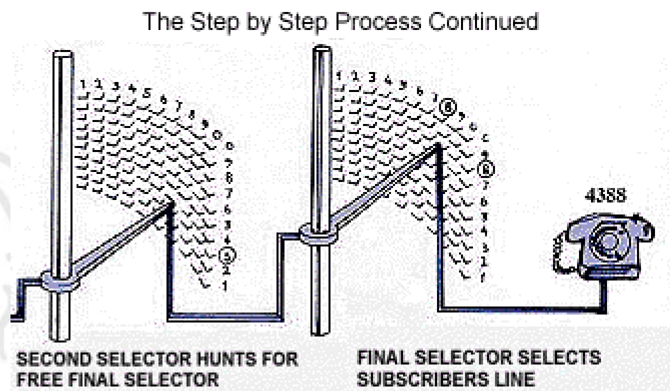


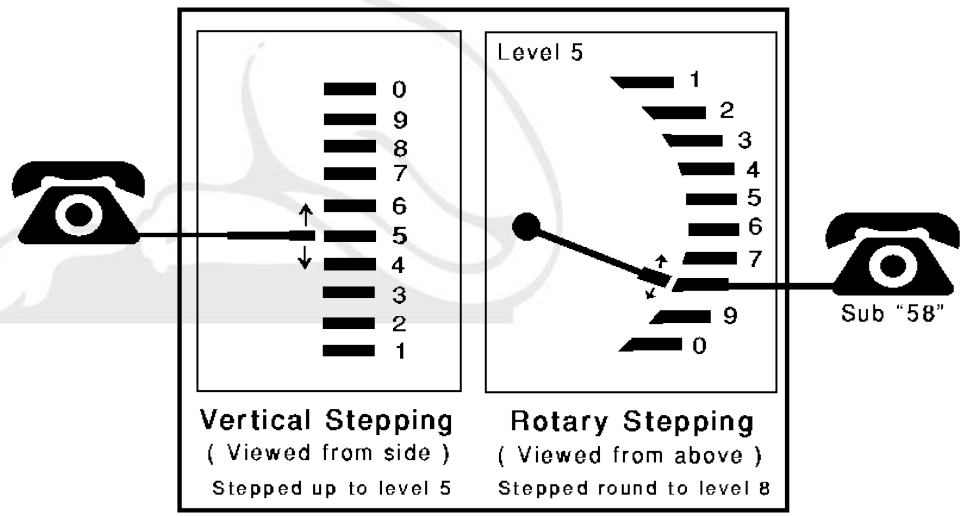
(a) Drive mechanism of a rotary switch

Telephone system – Establishing a call

- Electromechanical dialling – how it works







Telephone system – Hierarchical call setup

- Each subscriber's telephone set is connected to local central office by a simple two-wire cable forming the local loop.
- All such local central offices within a larger geographical region are further connected to each other through a toll office located centrally within that region.
- The toll offices, in turn, are connected to each other through intermediate switching offices, thereby forming a hierarchical structure of interconnections.
- The three major components of a telephone system are –
  - (i) local loops connecting the subscribers to the network,
  - (ii) trunks connecting the switching offices, and
  - (iii) switching offices where calls are redirected from one trunk to another.

Telephone system – Transmission cable

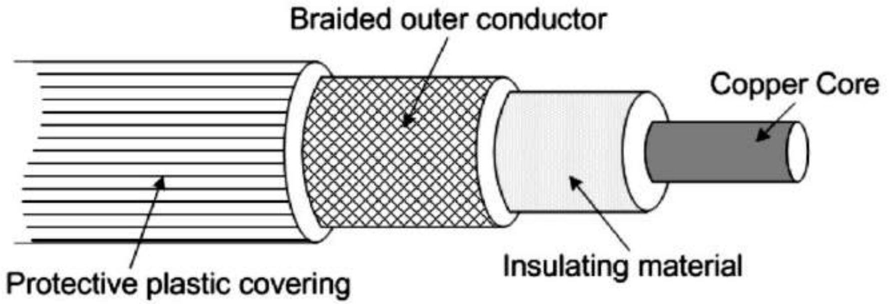
- Sound waves (voice: 20 Hz to 3.4 kHz) converted into electrical wave by microphone, travels over wires to another phone and converted back to sound waves by speaker.
- Single wires with ground returns – susceptible to noise.
- Two-wire cable – Since both the wires in a pair are generally affected by same amount of external noise, the difference in voltage between the two wires is hardly affected by noise providing better immunity to channel noise.
- However, still suffers from signal leakage since parallel wires make a fine antenna that radiates electromagnetic energy
- Twisted pair cable – prevent radiation loss during transmission by nullifying the waves from different twists.

Telephone system – Transmission cable

- Multiple pairs of twisted cables bundled together by wrapping them in a tough protective insulating sheath for exchange to exchange connection.
- Cross-talk interference between neighbouring pairs in a bundle is reduced by having different twist lengths for different pairs.
- However, highly susceptible to external interference, offers high attenuation and generally has a very narrow transmission bandwidth.
- There are two basic types of twisted pair cables – unshielded and shielded.

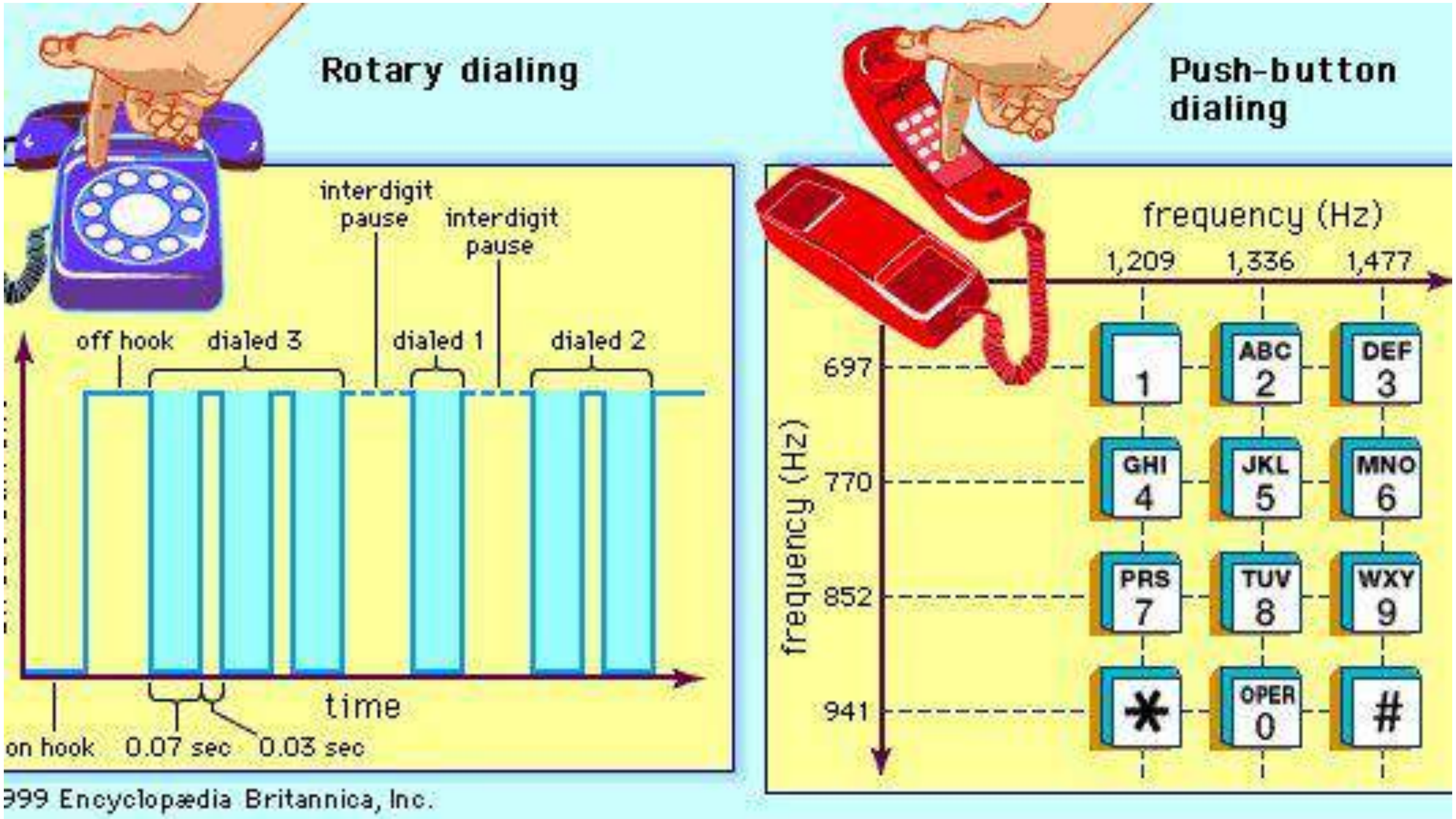
Telephone system – Transmission cable

- Unshielded twisted-pair is the ordinary wire and so is the cheapest, easy to work with and install and, hence, used commonly for local telephone networks.
- In shielded cable, there is metallic shielding on every individual twisted pair in a bundle as well as well as around the entire bundle; inner layer of shielding prevents crosstalk between adjacent cable-pairs, the outer layer shielding makes the cable less susceptible to external interference.
- Coaxial cable – better shielding and greater bandwidth.



Telephone system – a shift in paradigm

- Dialling – from electromechanical to modern day tone dialling



Pioneering works on Radio Communication

- Radio waves were first identified and studied by German physicist Heinrich Hertz in 1886 – unit of frequency is named after him as hertz (Hz).
- In 1893, Tesla successfully transmitted radio waves – unit of magnetic field intensity or magnetic flux density named after him as tesla (T).
- Marconi built the radio system in 1897 and patented it.
- However, the actual man behind this invention is Sir Jagadish Chandra Bose; we Indians are unfortunate that the credit for this invention did not go to Bose since he was more interested in academics – to know the science behind radio waves – and not interested in patenting his work and make money.

Pioneering works on Radio Communication

- In November 1895, Sir J.C. Bose presented a public demonstration at Town Hall in Calcutta, where he sent an electromagnetic wave across 75 feet, passing through two intervening walls to remotely ring a bell and to explode some gunpowder.
- This is the first millimeter-wave communication system in the world, developed more than 125 years ago.

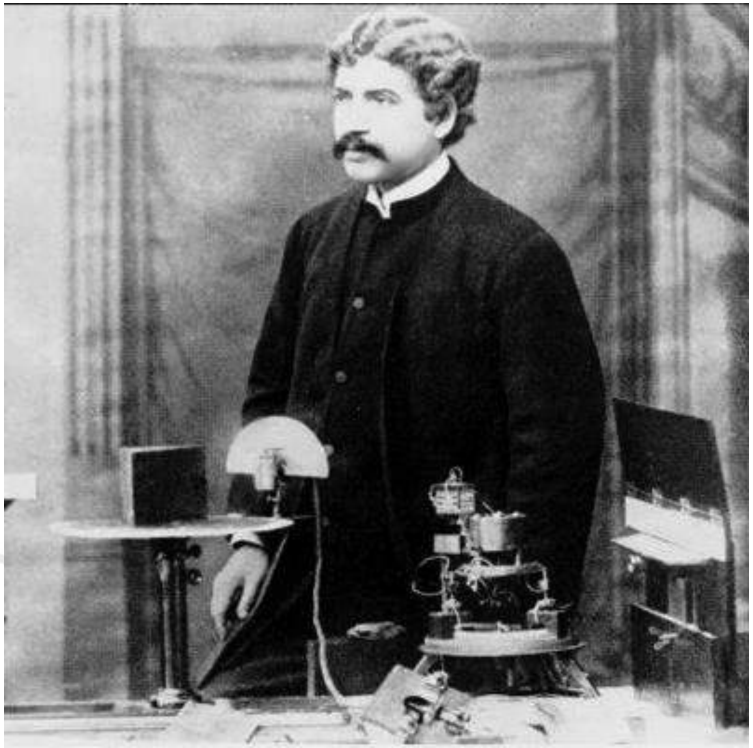
- For his communication system, Bose pioneered in making all millimeter-wave components – spark-gap transmitter, dielectric lens, coherer, horn antenna, polarizer, and cylindrical diffraction grating.

Pioneering works on Radio Communication

- At the same time, Popov in Russia was doing similar experiments, but even till December 1895, he was still trying to do remote signalling with radio waves.
- Bose had great reluctance in getting his research contribution patented and was against any commercialization of science. Rather he wished that his work be used by others for the benefit of mankind.
- Marconi, in fact, used the ‘Mercury Coherer’, the radio wave receiver invented by Bose, to build an operational two-way radio in 1897 and patented it.
- So, undoubtedly Sir J.C. Bose is the pioneer in the field of millimetre-wave and microwave physics.

Pioneering works on Radio Communication

- In recognition to this, on 14th September 2012, his pioneering experimental work in millimetre-band radio was recognized as an IEEE Milestone in Electrical and Computer Engineering,
- Subsequently, the name of Sir J.C. Bose was included in the Hall of fame along with Marconi and Popov.



- Acharya Jagadish Chandra Bose is regarded as the father of modern day wireless telecommunication.

Pioneering works on Radio Communication

- Bose’s pioneering work on mm-wave propagation with certain polarizing crystals (1896-98) lead to the development of ‘**solid-state** detector for electrical disturbances’, published in a seminal paper in the Proc. of the Royal Society, London in January 1897.
- He named this radio wave detecting device as ‘electric eye’ or ‘artificial eye’ as it was transforming the electromagnetic radiation impinging on it into an electrical signal.
- This device was named by Oliver Lodge and others in his time as ‘Coherer’,
- This may be regarded as the first ever solid-state ‘Diode’.

Pioneering works on Radio Communication

- J. C. Bose also invented many other useful solid-state detector devices for ‘wireless’ waves in this period, known as ‘self-restoring coherers’.
- In 1901, the very first semiconductor device "*cat whiskers*” was invented by Bose. It was a point-contact semiconductor rectifier used for detecting radio waves.
- Marconi used this solid-state detector for his Trans-Atlantic Radio Communication experiment.
- However, it was only through the sage advice and insistence of his long-term friend, Swami Vivekananda that J.C. Bose was prevailed upon to patent his unique invention of ‘Detector for Electrical Disturbances’, calling it *cat whiskers,* in U.S. in1904 as a one-time gesture.

Pioneering works on Radio Communication

- So, Sir J.C. Bose not only developed the first ever wireless telecommunication system but also contributed in solid-state electronics as well.
- In the words of Sir Nevill Mott, Nobel Laureate in 1977,
  - "J.C. Bose was at least 60 years ahead of his time. In fact, he had anticipated the existence of P-type and N-type semiconductors."

Electromagnetic wave – Basics

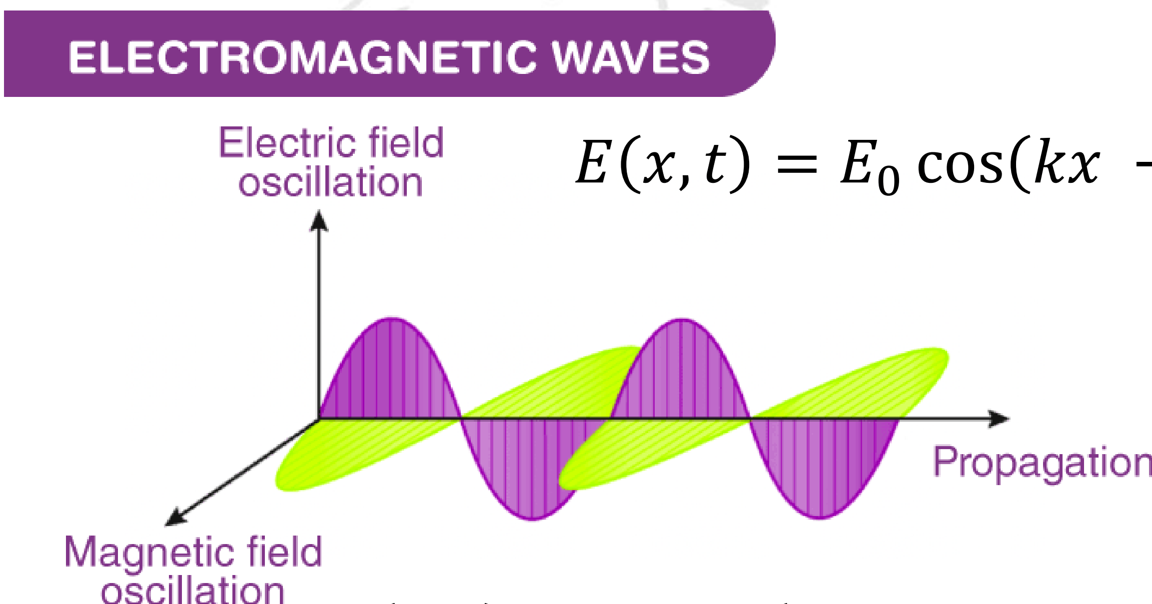
- Electromagnetic radiations are composed of electromagnetic waves that are produced when an electric field comes in contact with the magnetic field.
- In other words, electromagnetic waves are the composition of oscillating electric and magnetic fields.
- Generally, an electric field is produced by a charged particle. A force is exerted by this electric field on other charged particles along the direction of the field.
- The Magnetic field is produced by a moving charged particle. A force is exerted by this magnetic field on other moving particles; direction of the force always perpendicular to the direction of their velocity and therefore only changes the direction of the velocity, not the speed.

Electromagnetic wave – Basics

- So, the electromagnetic field is produced by an accelerating charged particle.
- Electromagnetic waves are nothing but electric and magnetic fields travelling through free space with the speed of light *c*.
- If accelerating charged particle is that oscillates about an equilibrium position with frequency *f*, then it produces an electromagnetic wave with frequency *f*.
- The wavelength λ of this wave is $\lambda = c / f$.
- Electromagnetic waves transfer energy through space.
- Electromagnetic waves are solutions of Maxwell's equations, which are the fundamental equations of electrodynamics.

Electromagnetic wave – Basics

- The EM wave consists of time-varying electric and magnetic fields which are perpendicular to each other and are also perpendicular to the direction of propagation of waves.
- Therefore, electromagnetic waves are transverse in nature.



$$E(x,t) = E_0 \cos(kx - \omega t + \varphi)$$

$$B(x,t) = B_0 \cos(kx - \omega t + \varphi)$$

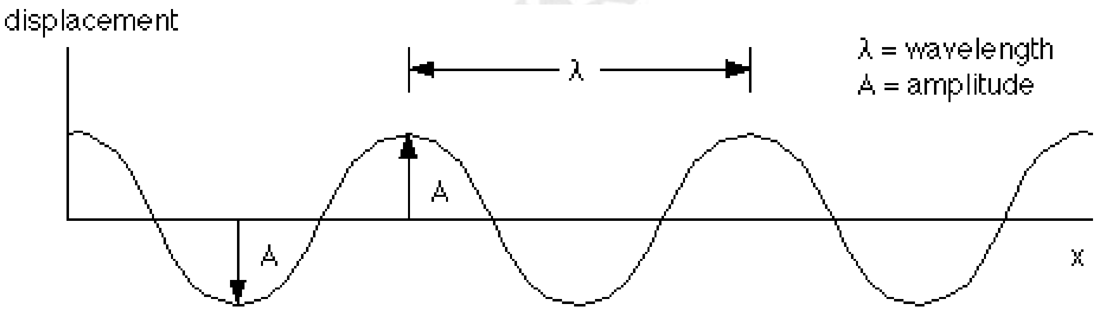
Electromagnetic wave – Basics

- General equation for wave motion:

$$y(x,t) = A\cos(\omega t - kx) = A\cos(kx - \omega t)$$

$$y(x,t) = A\cos(kx - \omega t) = A\cos\frac{2\pi}{\lambda}(x - ct)$$

- Differential equation for wave motion: $$\frac{\partial^2 y}{\partial x^2} = \frac{1}{c^2}\frac{\partial^2 y}{\partial t^2}$$



A snapshot of a transverse periodic wave at a particular time

Electromagnetic wave – Basics

- Maxwell's four equations in free space:

$$\vec{\nabla}.\vec{E} = 0$$ Gauss' Law for electrostatics for charge free space

$$\vec{\nabla}.\vec{B} = 0$$

$$\vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$ Faraday's Law of Electromagnetic Induction

$$\vec{\nabla} \times \vec{B} = \mu_0 \epsilon_0 \frac{\partial \vec{E}}{\partial t}$$ Maxwell's modification to Ampere's Law

- Gauss' Law: $\vec{\nabla} . \vec{E} = \frac{\rho}{\epsilon}$
- Modified Ampere's Law: $\vec{\nabla} \times \vec{B} = \mu\left(\vec{J} + \epsilon \frac{\partial \vec{E}}{\partial t}\right)$

Electromagnetic wave – Basics

- Taking curl on both sides of the 3rd equation:

$$\vec{\nabla} \times \left(\vec{\nabla} \times \vec{E}\right) = \vec{\nabla} \times \left(-\frac{\partial \vec{B}}{\partial t}\right)$$

$$\Rightarrow \quad \vec{\nabla}.\left(\vec{\nabla}.\vec{E}\right) - \vec{E}(\vec{\nabla}.\vec{\nabla}) = -\frac{\partial}{\partial t}\left(\vec{\nabla} \times \vec{B}\right)$$

$$\Rightarrow \quad 0 - \nabla^2 \vec{E} = -\frac{\partial}{\partial t}\left(\vec{\nabla} \times \vec{B}\right)$$

$$\Rightarrow \quad \nabla^2 \vec{E} = \frac{\partial}{\partial t}\left(\mu_0 \epsilon_0 \frac{\partial \vec{E}}{\partial t}\right)$$

- Similarly, from 4th equation we get: $\nabla^2 \vec{B} = \mu_0 \epsilon_0 \frac{\partial^2 \vec{B}}{\partial t^2}$

Electromagnetic wave – Basics

- Now, for free space:
  - Permittivity: $\epsilon_0 = \frac{1}{4\pi \times 9 \times 10^9}$ farad / m
  - Permeability: $\mu_0 = 4\pi \times 10^{-7}$ weber / ampere-m
- Therefore, $\mu_0 \, \epsilon_0 = {}^{1}/_{c^2}$
- So, the EM wave equations are:

$$\nabla^2 \vec{E} - \frac{1}{c^2}\frac{\partial^2 \vec{E}}{\partial t^2} = 0$$

$$\nabla^2 \vec{B} - \frac{1}{c^2}\frac{\partial^2 \vec{B}}{\partial t^2} = 0$$

- Compare these with the general equation for wave equations.

Electromagnetic wave – Basics

- So, by solving the wave equations (taking only the real part of the solution), we get the wave equations as:

$$E(x,t) = E_0 \cos(kx - \omega t + \varphi)$$

$$B(x,t) = B_0 \cos(kx - \omega t + \varphi)$$

- The direction of propagation of the electromagnetic wave is given by vector cross product of the electric field and magnetic field, called Poynting vector.

$$\vec{P} = \vec{E} \times \vec{H}$$

- This is the direction of power flow

Transmission Line

- Guided medium for transmission of radio waves:
  - Transmission lines
  - Waveguides

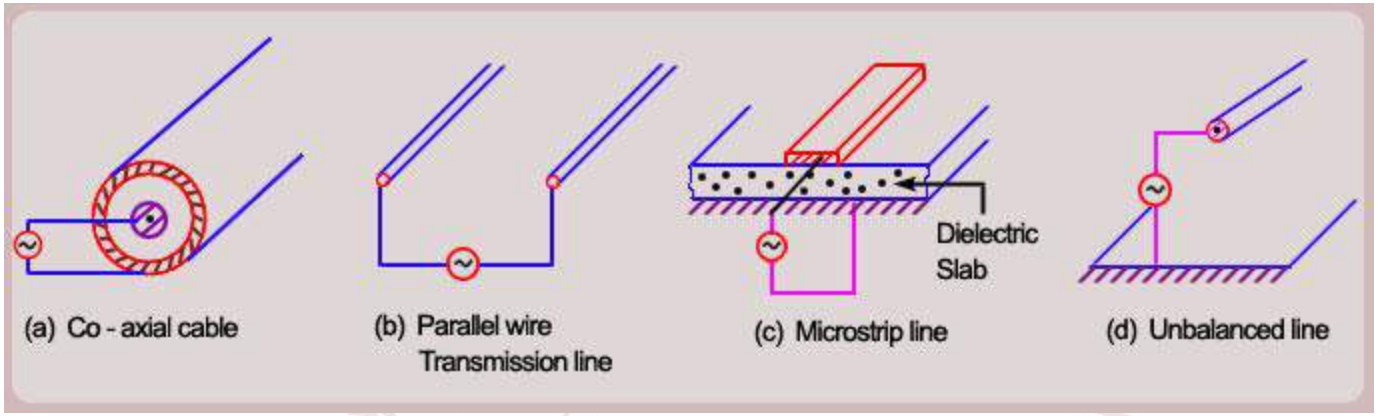
- As the name suggests, transmission line is a structure that transports electrical energy from one point to another.

- A transmission line consists of two linear conductors separated by a distance.

- When an electrical source is applied between the two conductors, the line gets energized and the electrical energy flows along the length of the conductors.

Transmission Line

- Transmission line may be of any of the following forms:

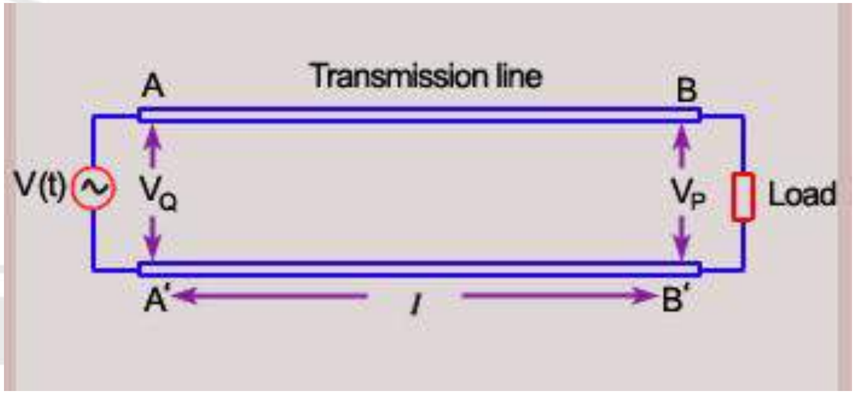


- **Microstrip Line:** Thin metallic strip on one side of a dielectric substrate and ground plane on the other side.
- Majority of the fields are confined in the dielectric substrate.
- Usually found in printed circuit boards at high frequencies.

Transmission Line

- If the two conductors are symmetric around the ground, then the line is called the balanced line, otherwise the line is an un-balanced line.
- Co-axial cable, microstrip line and single-conductor line are un-balanced lines; twin (parallel) wire is a balanced line.
- Delay (transmit time) between source and load points:
- $t_r = \frac{l}{c} = \frac{l}{f\,\lambda} = \frac{l\,T}{\lambda}$

Assuming vel. of the wave same as light

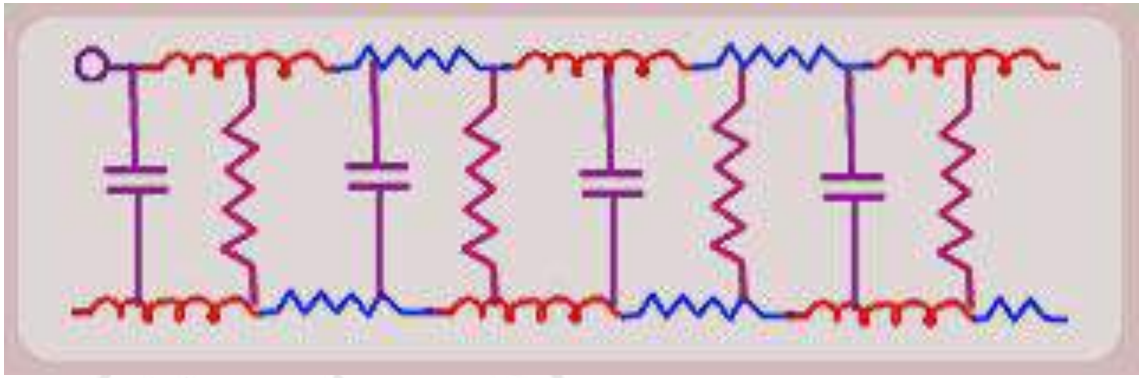


- We will like to have $t_r \ll T$
- So, large λ (small f) desired.
- That means, on the other hand, this delay effect becomes significant at higher frequencies

Transmission Line

- A conductor carrying a current has magnetic field and consequently has flux linkage. The conductor therefore has inductance distributed along the length of the conductor.
- Similarly the two conductors form a parasitic capacitor having capacitance distributed along the length of the conductor.
- For non-ideal conductors there is resistance along the length of the line.
- Also if the medium separating the conductors is non-ideal, there is leakage current through the medium which can be accounted for by placing equivalent conductance between the conductors distributed along the length of the conductor.

Transmission Line



- So, there is voltage drop along the conductor due to resistance and inductance effect while current reduces due to conductance and capacitance effect.

$$\lim_{\Delta x \to 0} \frac{\Delta V}{\Delta x} \equiv \frac{dV}{dx} = -(R + j\omega L)I$$

$$\lim_{\Delta x \to 0} \frac{\Delta I}{\Delta x} \equiv \frac{dI}{dx} = -(G + j\omega C)V$$

Transmission Line

- From these we get, $\frac{d^2V}{dx^2} = -(R+j\omega L)\frac{dI}{dx} = -(R+j\omega L)[-(G+j\omega C)V = \gamma^2 V$
- Similarly, $\frac{d^2I}{dx^2} = \gamma^2 I$ where $\gamma = \sqrt{(R+j\omega L)\,(G+j\omega C)} = \alpha + j\beta$

  is called the propagation constant.
- General solutions to the above differential equations give

$$V(t) = V^+.\exp\{j\omega t - \gamma x\} + V^-.\exp\{j\omega t + \gamma x\}$$

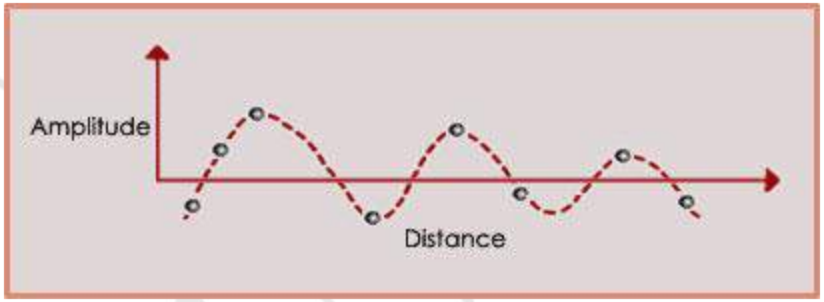
$$I(t) = I^+.\exp\{j\omega t - \gamma x\} + I^-.\exp\{j\omega t + \gamma x\}$$

$$V(t) = V^+.\exp\{-\alpha x\}.\exp\{j\omega t - j\beta x\} + V^-.\exp\{\alpha x\}.\exp\{j\omega t + \beta x\}$$

$$I(t) = I^+.\exp\{-\alpha x\}.\exp\{j\omega t - j\beta x\} + I^-.\exp\{\alpha x\}.\exp\{j\omega t + \beta x\}$$

Transmission Line

- So, these equations give voltage and current at any point on the conductor as a function of combined space and time, what we know as "wave motion".
- That means, Voltage and the Current exist in the form of waves on a transmission line. Both waves have two components:
  - Forward travelling wave
  - Backward travelling wave



- The waves decay exponentially along the direction of propagation; α is the 'attenuation constant' (unit: neper/m).
- $\beta = 2\pi/\lambda$ gives phase change per unit length and hence called 'phase constant' of the line (unit: radian/m).

Transmission Line

- The ratios of forward / backward voltage and current waves are given as

$$\frac{V^+}{I^+} = \frac{R + j\omega L}{\gamma} = \sqrt{\frac{R + j\omega L}{G + j\omega C}} = Z_0$$

$$\frac{V^-}{I^-} = -\frac{R + j\omega L}{\gamma} = -\sqrt{\frac{R + j\omega L}{G + j\omega C}} = -Z_0$$

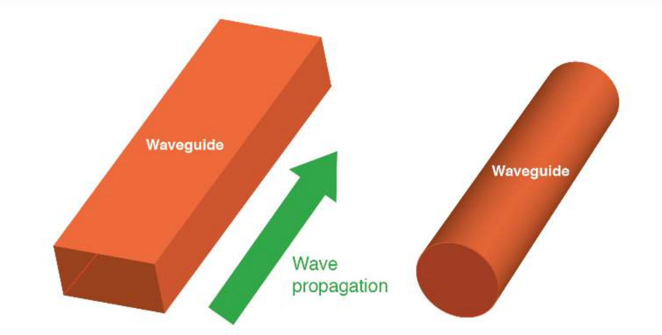
- Z_0 is called the characteristic impedance of the line.
- For high frequency, inductance and capacitance effect plays significant role → phase constant will increase → transmission delay will increase, as said earlier.
- In a lossless line $R = 0$ and $G = 0$. Then $\alpha = 0$.

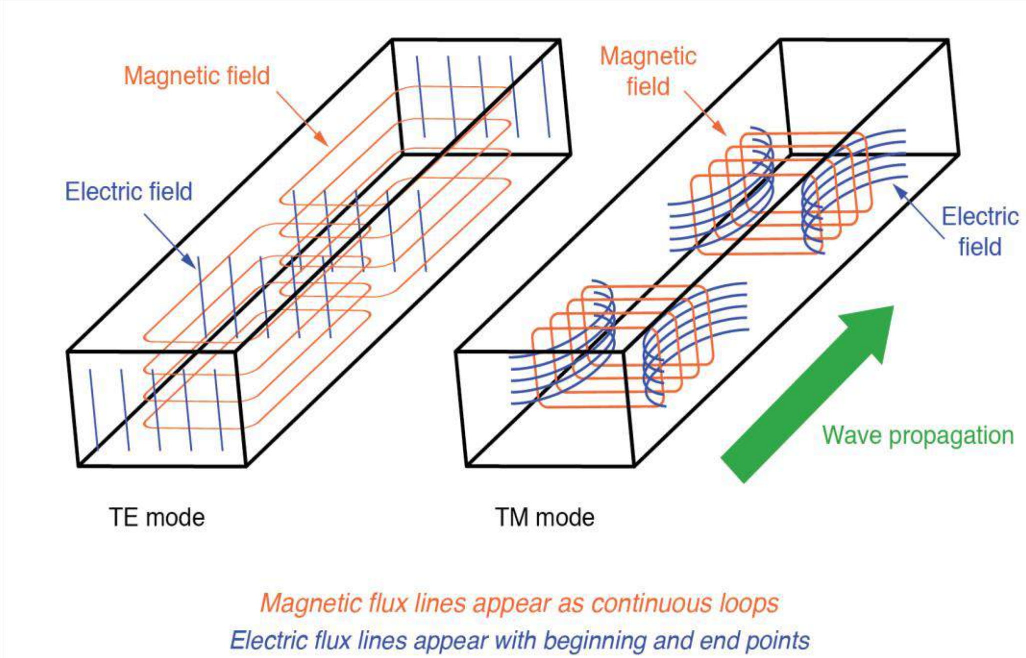
Wave Guides

- Wave Guide is a structure which can guide or transport Electro Magnetic Energy with minimal loss.
- Two types of wave guide in structure:
  - **Metallic Wave Guide**: used in high frequency, microwaves and millimeter waves. Hollow rectangular or circular wave guides fall in this category.
  - **Dielectric Wave Guide**: used at sub-millimeter wavelengths and optical frequencies. Optical fibres fall in this category.
- Parallel wave guide is formed by two infinite parallel conducting planes; the EM energy is confined between the planes and moves in a direction parallel to the planes.

Wave Guides

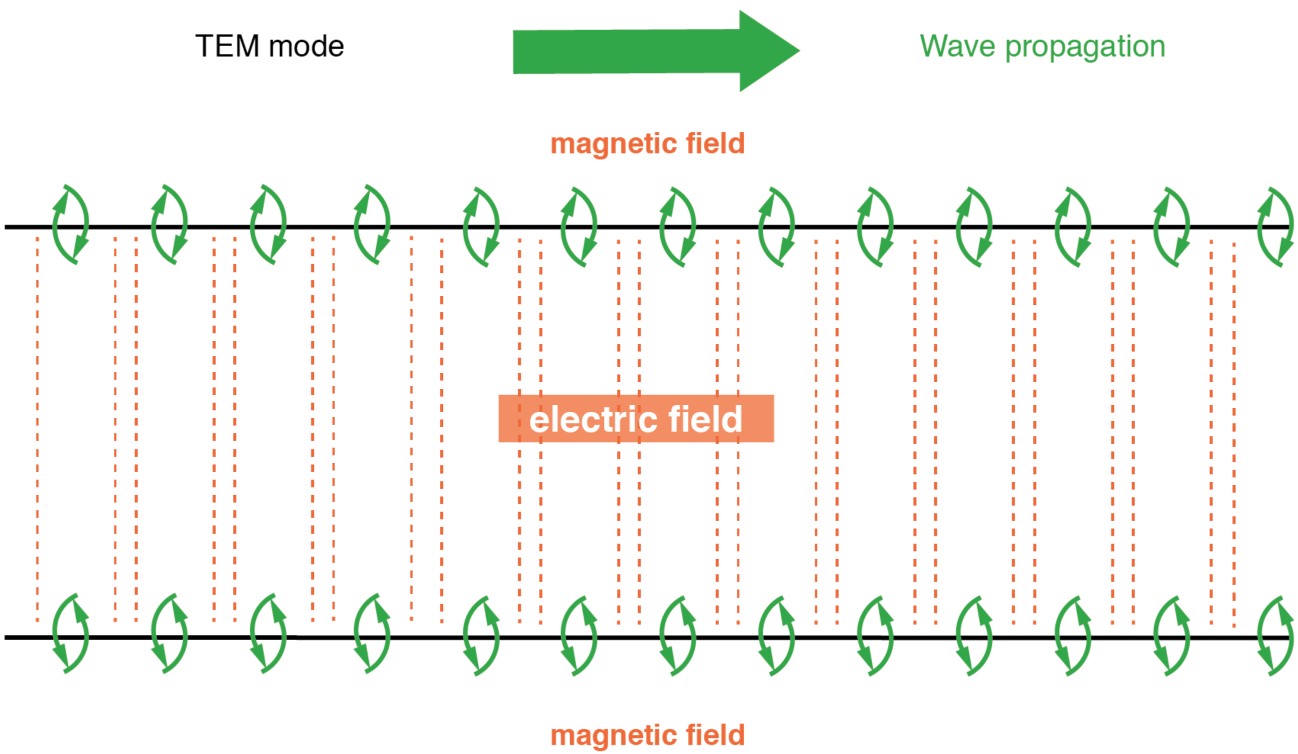
- The electro magnetic waves which can exists between the parallel planes can be of three types
  - Transverse Electric Fields (TE mode)
  - Transverse Magnetic FIelds (TM mode)
  - Transverse EM Fields (TEM mode)





Wave Guides

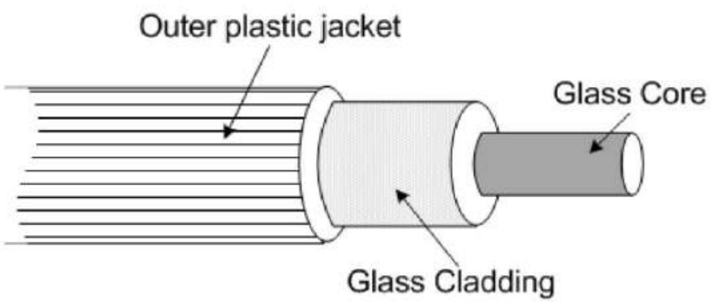
- TEM Mode:

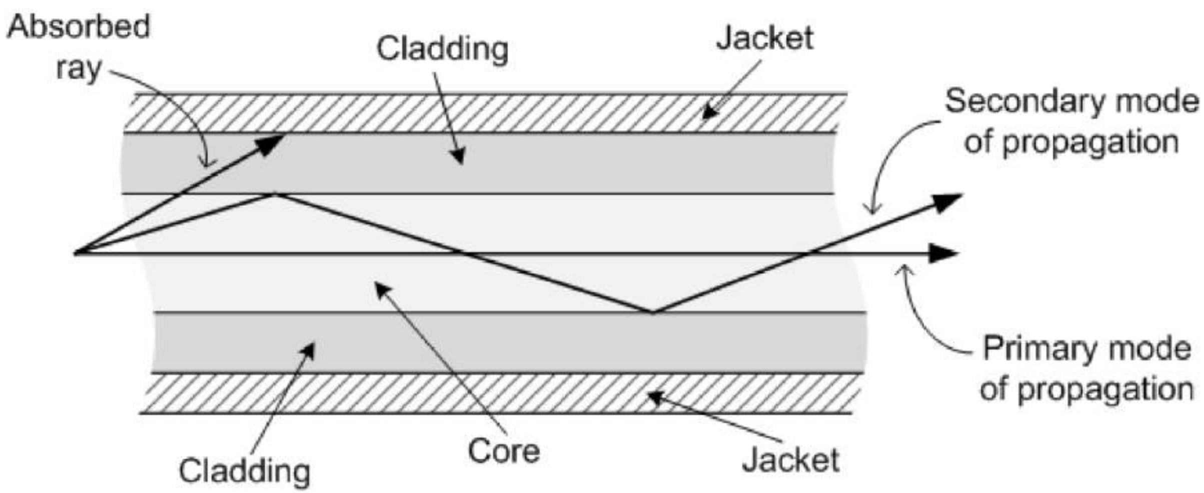


Both field planes perpendicular (transverse) to direction of signal propagation.

Optical Fibres

- Three bands of light waves in the near-IR part of spectrum centered at 850 nm, 1300 nm and 1550 nm are used.
- Photo-diode and photo-detectors used as transducers at two ends.
- Total internal reflection used for light propagation



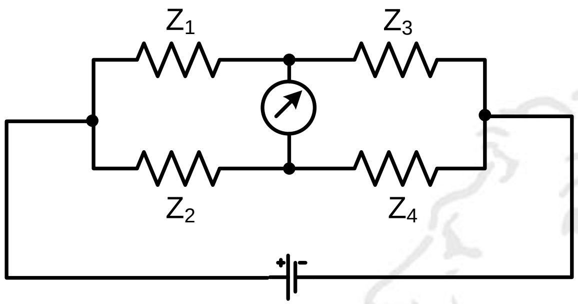


Modes of transmission

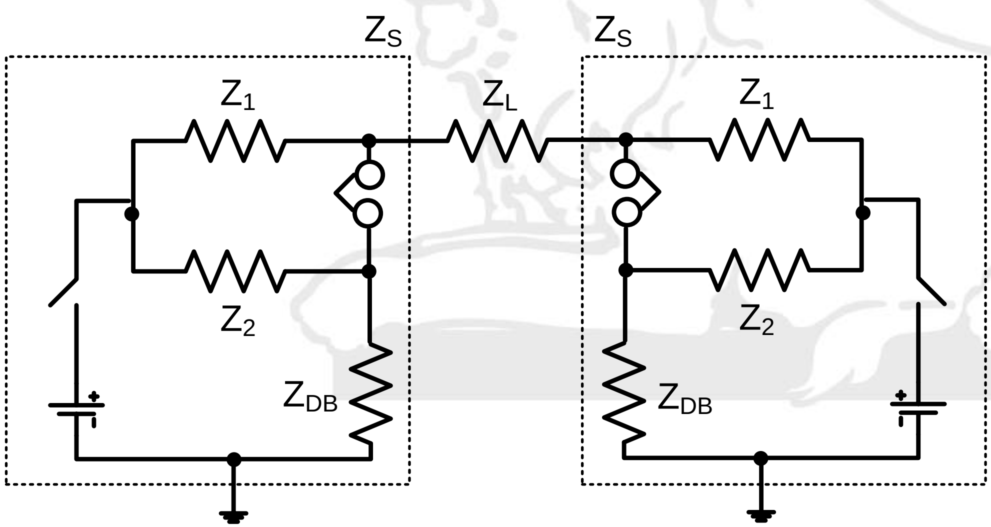
- Different classes of communication systems based on the modes of transmission:
  - **Simplex:** one-way, e.g. the first form of telegraphy system, TV broadcasting, pager, keyboard to CPU.
  - **Semi-duplex:** two-way but not simultaneously, e.g. old-days' telegraphy system, walkie-talkie.
  - **Duplex:** – two-way simultaneously, e.g. latest telegraphy system, present day telephony, mobile phone.
  - **Diplex:** two messages transmitted simultaneously but only in one-direction (diplex telegraphy developed by Thomas A. Edison)
  - **Quadruplex:** somewhat like duplexed diplex (quadruplex telegraphy developed by Thomas A. Edison)

Duplex Telegraphy and Telephony

- One example of duplex system using bridge.



Condition for no current through the galvanometer: $\frac{Z_1}{Z_2} = \frac{Z_3}{Z_4}$



Here, $Z_3 = Z_L + Z_S$

and $Z_4 = Z_{DB}$

Duplex balance Z_{DB} taken such that $\frac{Z_1}{Z_2} = \frac{Z_L + Z_S}{Z_{DB}}$

Issues in question

- Is it possible to transmit telegraph and telephonic (voice) signals over a long distance without much attenuation?
  - No, attenuation will be there due to R and G of the cable and also radiation loss.
  - So, needs to install intermediate relay stations to boost the signal power.
- Can we transmit telegraph and telephonic (voice) signals over a long distance wirelessly without the use of cable?
  - Research in radio waves showed that it is possible to transmit high frequency radio waves wirelessly over a long distance – this led to the invention of radio system.

Issues in question

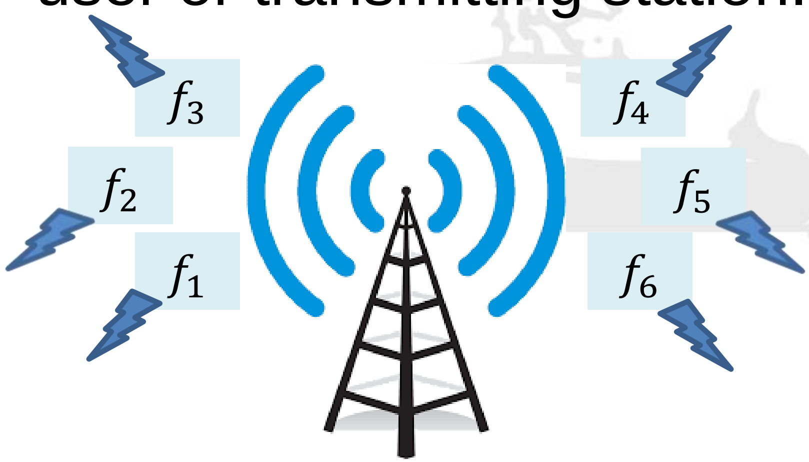
- Even point-to-point communication over a long distance via guided medium may use radio wave communication.
- How to take care of cross-talk in wireless communication?
- Can we do 2-way transmission over the same dedicated line connecting a pair of users?
- Can we multiplex multiple pairs of users over a single line?
- Answer to all these questions is Multiplexing.
- How can we translate the low frequency telegraph and telephonic (voice) signals to high frequency radio waves?
- This can be done by a process called Modulation.

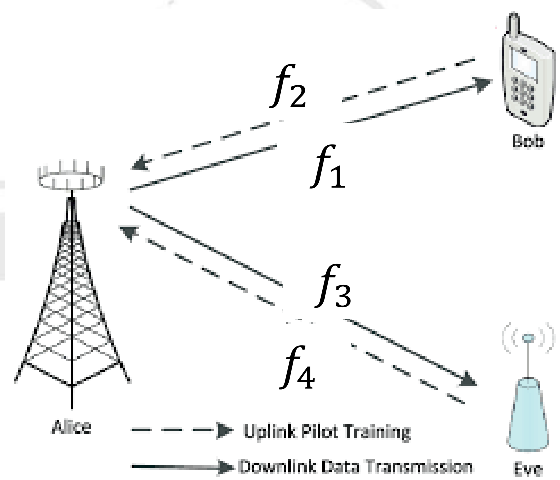
Multiplexing

- Multiplexing – sharing of channels among multiple signals for economy and maximum utilization of the communication networks.
- Some multiplexing schemes:
  - Frequency Division Multiplexing (FDM)
  - Time Division Multiplexing (TDM)
  - Code Division Multiple Access (CDMA)
  - Orthogonal Frequency Division Multiplexing (OFDM)
  - Non-Orthogonal Multiple Access (NOMA)

Frequency Division Multiplexing (FDM)

- The inherent bandwidth of a transmission medium is generally much greater than that needed for a single signal.
- FDM can be employed to take advantage of this in sending multiple signals over a single medium .
- The available bandwidth of the transmission medium is divided into a number of narrower frequency bands (subbands), each of these subbands is allocated to each user or transmitting station.



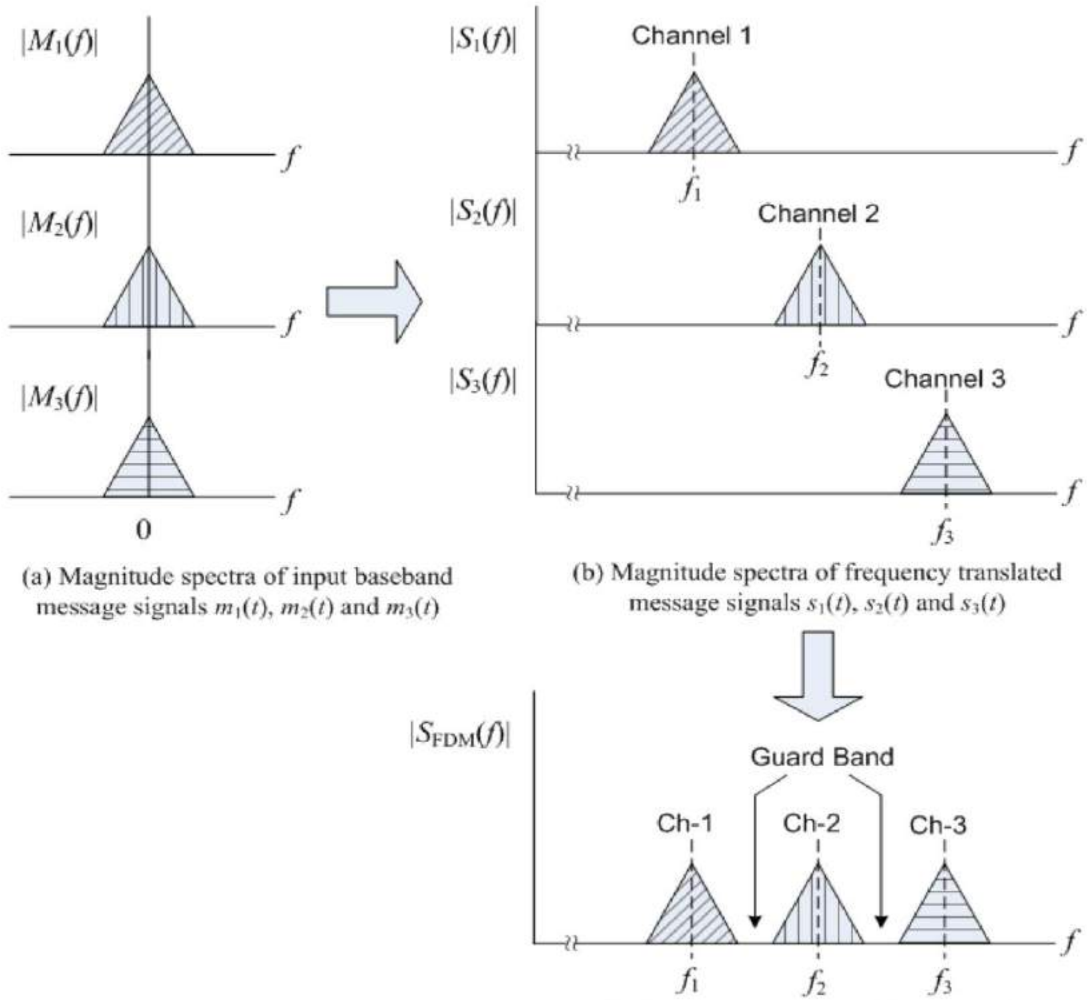


Frequency Division Multiplexing

- **How?** A carrier signal of appropriate frequency (center frequency of the sub-band allocated to a transmitting station or user) is **modulated** by the signal originated at that particular station.
- The message is thus inserted within the sub-band allocated to that station in the form of modulated wave carrying the signal information.
- A sufficient amount of separation (guard band) between the sub-bands is generally allowed so as to avoid any interference between the adjacent channels.

Frequency Division Multiplexing

- Any arbitrary signal can be expressed as the sum of many sinusoids of different frequencies and amplitudes.
- Spectrum of a signal – plot of amplitude vs. frequency.



(a) Magnitude spectra of input baseband message signals $m_1(t)$, $m_2(t)$ and $m_3(t)$

(b) Magnitude spectra of frequency translated message signals $s_1(t)$, $s_2(t)$ and $s_3(t)$

(c) Magnitude spectrum of the composite multiplexed signal $s_{FDM}(t)$

Frequency Division Multiplexing

- This scheme has been used in radio and TV broadcasting, in multiplexing calls over a telephone line and continues to be used in present day cellular networks and satellite communication.
- FDM is also utilized in fiber-optic transmission systems, where it is customarily referred to as wavelength division multiplexing (WDM).
- When multiple users share a physical communication channel using frequency division multiplexing, it is called frequency division multiple access (FDMA).

Amplitude Modulation (AM)

- The basic purpose of modulation is to translate baseband (low frequency) message signal to a higher frequency band.
- This frequency translation serves two purposes
  - High freq. (radio wave, mm wave, microwave) comm.
  - Simultaneous transmission of a number of message signals over a common channel using FDM,
- Consider simple single-tone message signal with freq. f_m.
- When two cosines with $f_m \ll f_c$ are multiplied:

$$s(t) = m(t) \times c(t) = A_m \cos(2\pi f_m t + \varphi) \times A_c \cos(2\pi f_c t)$$

$$= \frac{1}{2} A_c A_m \left[\cos\{2\pi(f_c - f_m)t - \varphi\} + \cos\{2\pi(f_c + f_m)t + \varphi\}\right]$$

Amplitude Modulation (AM)

- So, we get message signal translated from lower frequency f_m to two higher frequencies $(f_c - f_m)$ and $(f_c + f_m)$.
- This is the **modulation** process that we do at transmitter; carrier signal $c(t)$ modulated by message signal $m(t)$.
- At receiver, we multiply the received modulated signal $s(t)$ again by the same carrier signal:

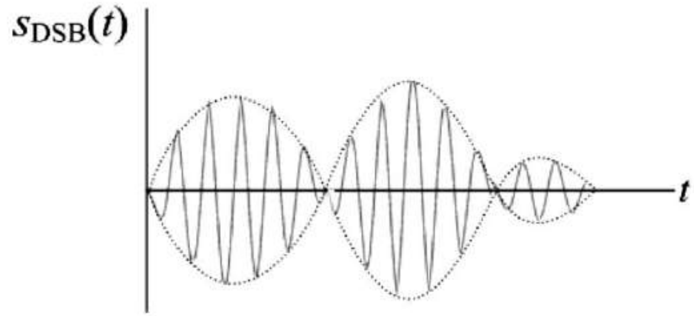
$$v(t) = s(t)\ \times c(t) = \ \frac{1}{2}A_c^2 A_m \cos(2\pi f_m t + \varphi)$$

$$+\frac{1}{4}A_c^2 A_m\,[\cos\{2\pi(2f_c - f_m)t - \varphi\}\ + \cos\{2\pi(2f_c + f_m)t + \varphi\}]$$

- Next, pass $v(t)$ through a low-pass filter (LPF) with cut-off frequency just more than f_m; the original message (amplified by a factor $\frac{1}{2}A_c^2$) is retrieved. This is **demodulation** process.

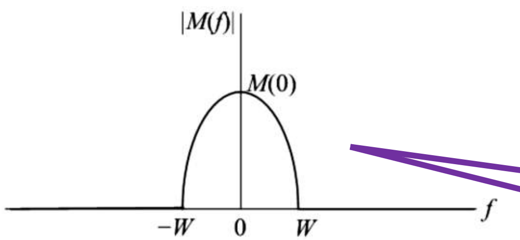
Amplitude Modulation (AM)

- Generalizing to arbitrary multi-tone signal with $f_{m,max} = W \ll f_c$:

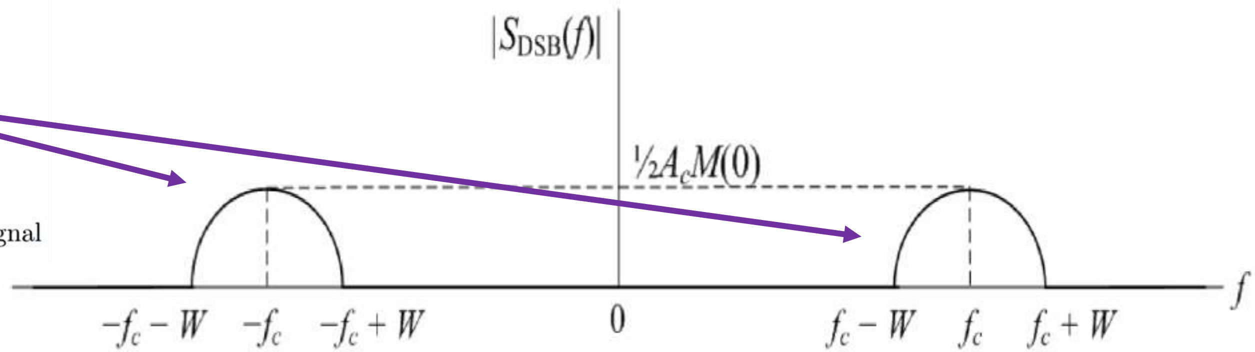


$$s_{\mathrm{DSB}}(t) = A_c m(t) \cos 2\pi f_c t$$

$$\rightleftharpoons S_{\mathrm{DSB}}(f) = \frac{A_c}{2}\left[M\left(f + f_c\right) + M\left(f - f_c\right)\right]$$



Magnitude spectrum of baseband message signal



This is Double-sideband-suppressed-carrier (DSBSC) type amplitude modulation

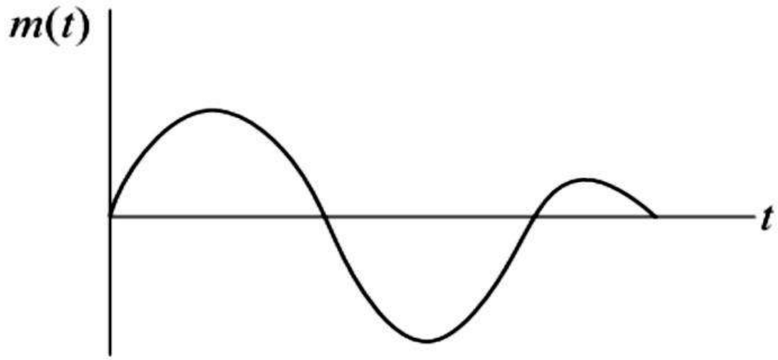
Amplitude Modulation (AM)

- Now, let us modify the modulation scheme by scaling the DSBSC signal and adding the carrier signal to it:

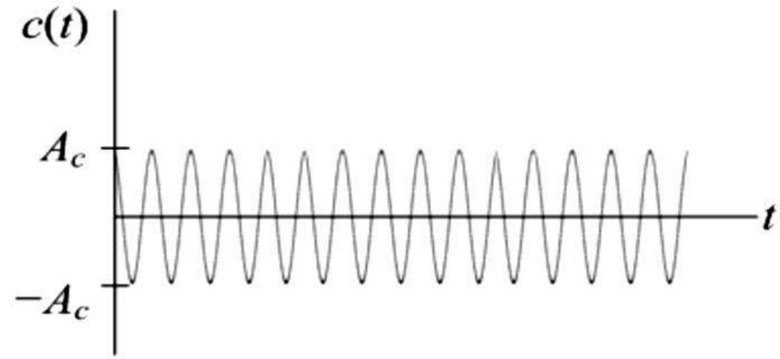
$$s_{\mathrm{AM}}(t) = A_c\left[1 + k_a m(t)\right]\cos 2\pi f_c t$$

- k_a = amplitude sensitivity of the modulator
- This is the Double-sideband-full-carrier (DSBFC) type amplitude modulation or simply the general amplitude modulation scheme.
- Obviously, this will demand more transmission power compared to DSBSC.
- **Then why use it?**

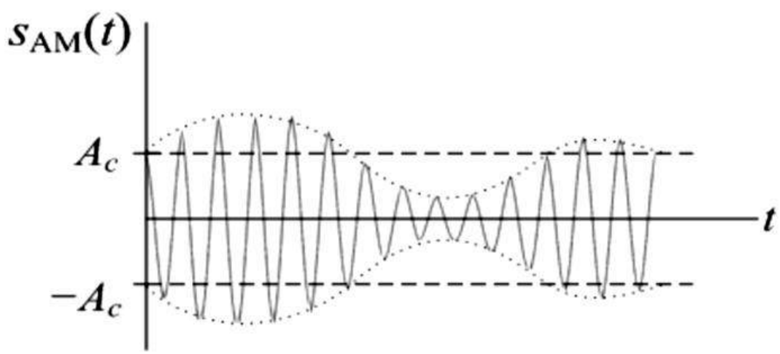
Amplitude Modulation (AM)



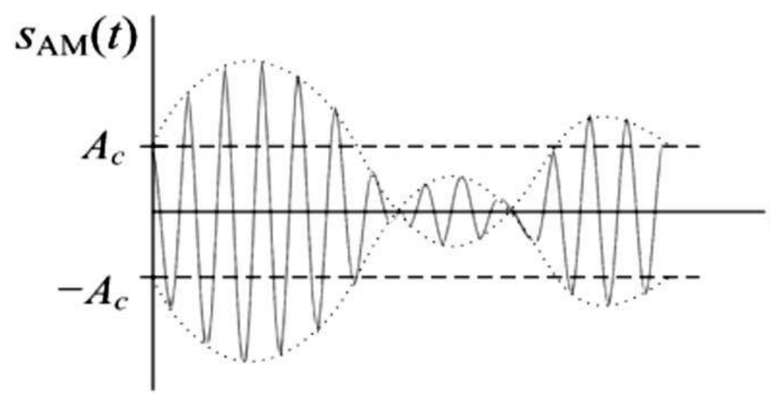
(a) Message signal



(b) Carrier signal



(c) AM wave for $\mu < 1$



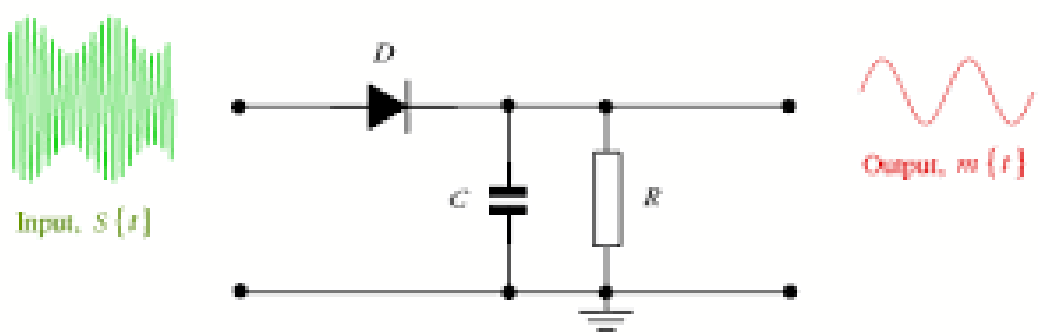
(d) AM wave for $\mu > 1$

Amplitude Modulation (AM)

- The parameter μ is called modulation index, $\mu = |k_a \, m_{max}|$
- So, the maximum and minimum amplitudes of the modulated wave possible are

$$s_{AM,max} = A_c\,(1+\mu) \quad \text{and} \quad s_{AM,min} = A_c\,(1-\mu)$$

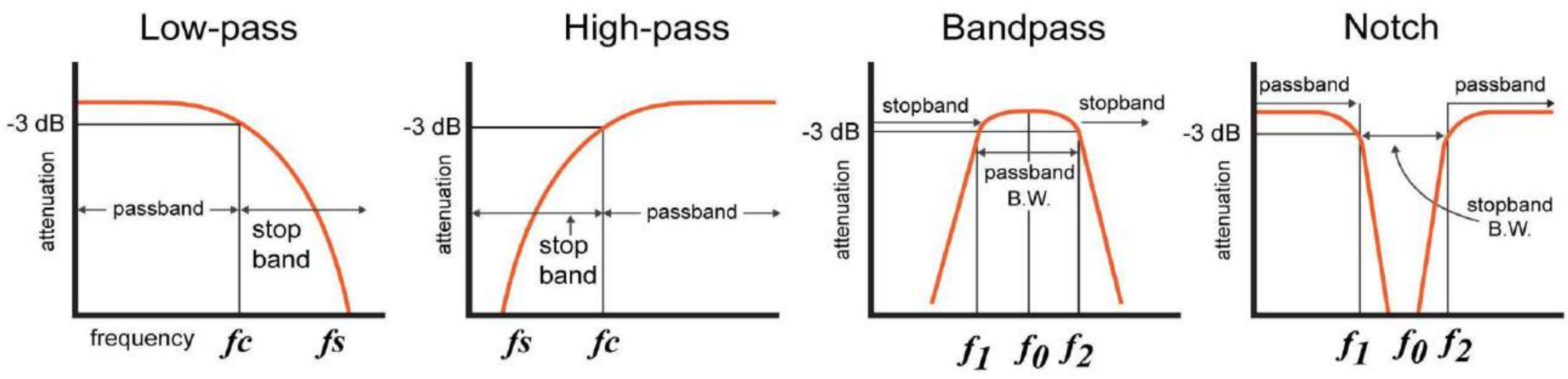
- Hence, for $0 < \mu \leq 1$ (i.e. max. 100% modulation) we have upper envelope of the modulated wave always non-negative.
- This may be useful in doing demodulation simply by envelope detection (by low-cost diode rectification)



Amplitude Modulation (AM)

- Disadvantage with both DSBFC and DSBSC modulation techniques is that the transmission bandwidth is double ($2W$) the actual bandwidth (W) of the message signal; particularly bad in large BW messages such as TV transmission.
- For real signals, the two sidebands (on two sides of the carrier frequency f_c) are symmetric.
- So, no need to transmit both the sidebands → accordingly, select any one of the two sidebands (either lower or upper sideband) by bandpass filtering and transmit only that sideband → this is single-sideband (SSB) modulation.
- SSB may be either with full-carrier or suppressed-carrier.
- Problem with SSB is that it requires filtering by ideal filter with sharp cut-off at f_c, practically not possible.

Amplitude Modulation (AM)



- So, SSB may be modified by including some part of the adjacent sideband, though redundant → this is Vestigial sideband (VSB) modulation (commonly used in TV transmission).
- Disadvantage of all the different types of AM is that AM signal is highly prone to noise.

Angle Modulation

- In amplitude modulation, any change in amplitude during transmission will result in distortion in the message recovered after demodulation in the receiver.
- Channel noise are generally additive in nature and hence, will alter the amplitude of AM modulated wave → an AM signal is highly prone to noise.
- This may be taken care of by modulating the angle (frequency or phase) of the carrier signal in accordance with the message signal while the amplitude of the carrier signal is maintained constant.
- Angle modulation schemes provide good immunity to noise but at the cost of increased bandwidth – better noise immunity can be achieved by increasing transmission BW.

Angle Modulation

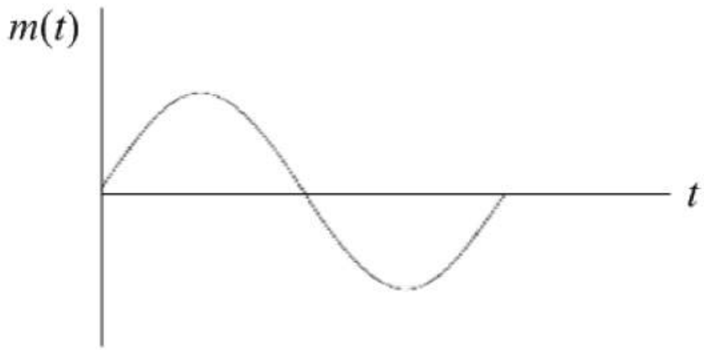
- There are two forms of angle modulation –
  - phase modulation (PM) and
  - frequency modulation (FM).

$$s_{\mathrm{PM}}(t) = A_c \cos\left[2\pi f_c t + k_p m(t)\right]$$

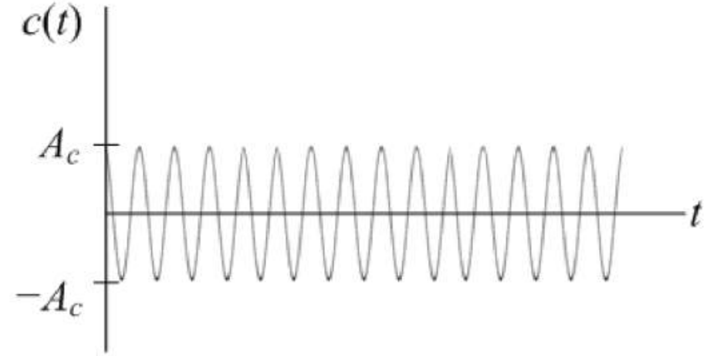
$$s_{\mathrm{FM}}(t) = A_c \cos\left[2\pi \left(f_c + k_f m(t)\right) t\right]$$

- k_p and k_f represent the phase sensitivity and the frequency sensitivity of the modulators, respectively.

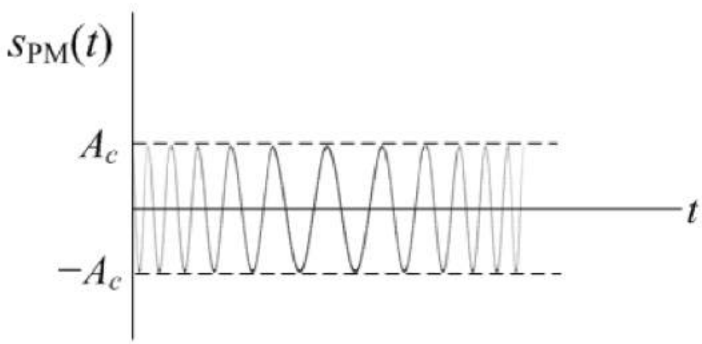
Angle Modulation



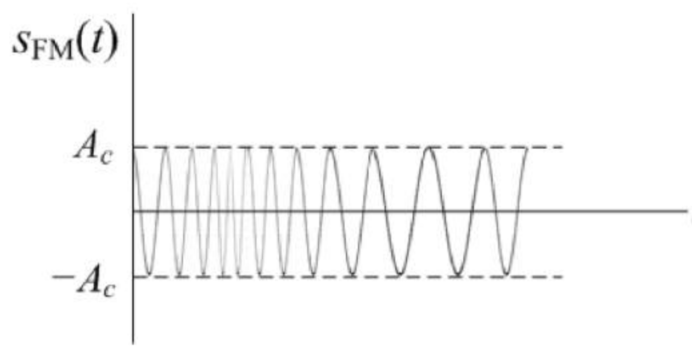
(a) Sinusoidal message signal



(b) Carrier signal



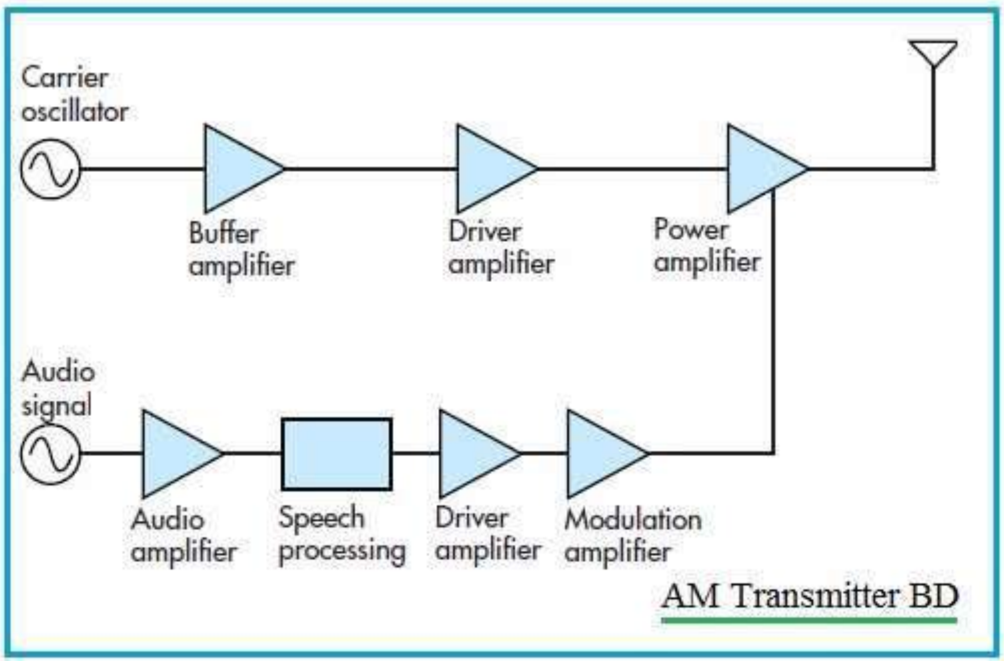
(c) Phase modulated wave



(d) Frequency modulated wave

Radio Transmitter System

- **Oscillators** are electronic circuits that generates sinusoidal signal of a particular frequency to which the oscillator is tuned – high frequency microwaves are generated in special microwave tube oscillators (klystron, magnetron, gyrotron), and solid-state oscillators (Gunn diode, PIN diode).



Antenna

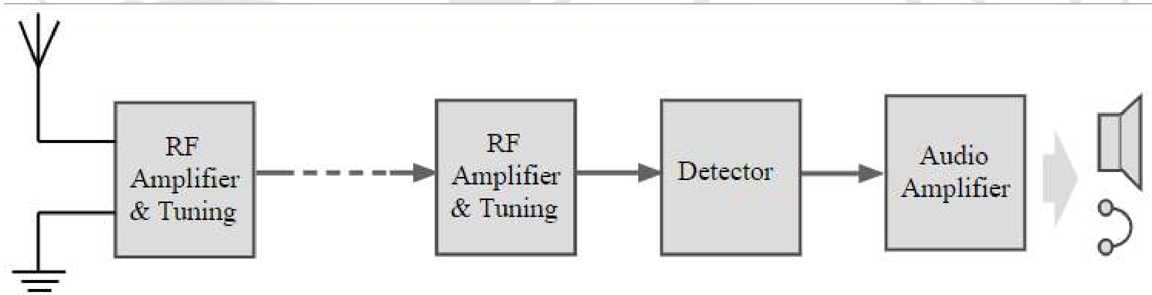
- An antenna is a device that serves as interface between the electric circuit and space, designed to transmit and/or receive electromagnetic waves within a certain frequency range according to its size, shape and form.
- Every wireless communication device must contain at least one antenna.
- Generally composed of metals (mainly copper or aluminum), antennas can convert an electric current into electromagnetic radiation and vice versa.
- The simplest type of antenna consists of two metal rods, known as a **dipole**, while one common type of antennas is the **monopole** antenna, consisting of a single rod placed vertical to a large metal board forming the ground plane.

Antenna

- A transmission antenna carries an electric current whose intensity fluctuates over time and converts it into radiofrequency radiation that propagates in space.
- A receiving antenna performs the reverse process – it receives radiofrequency radiation and converts it into electric currents in an electric circuit connected to the antenna.
- One important attribute of an antenna is its **directionality**. In communication between two fixed targets, a directional antenna is used to direct the transmission energy to the receiver exclusively. In case of mobile transmitter or receiver, omni-directional antenna is used that transmits / receives EM waves uniformly in all directions.

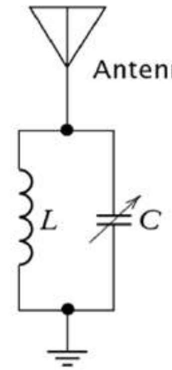
Radio Receiver System

- Signal received by the receiving antenna is to be demodulated in the receiver – either by simple envelope detection or by multiplying with carrier signal generated by a local oscillator (LO) in the receiver (in AM) or by using phase detector with carrier signal as reference signal (in FM).
- But, a general purpose radio receiver is designed to receive signals from multiple channels (radio broadcast stations).
- So, antenna is first connected to a tuning circuit followed by an LO (if not using envelope detector), both tuned to desired radio station frequency f_s (carrier freq. of that station).



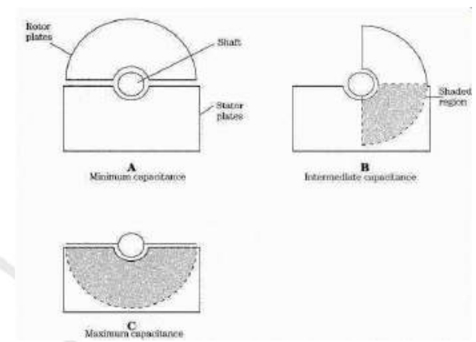
Radio Receiver System

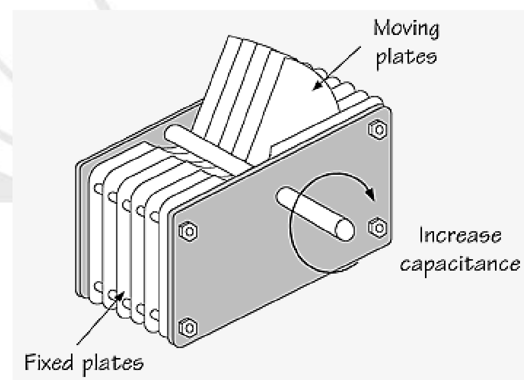
- The tuning circuit (also called tank circuit) selects signal in a small band with centre frequency f_s to which it is tuned.
- Multiple stages of tuning circuits generally used for better selectivity – this is Tuned Radio Frequency (TRF) receiver in use till 2nd / 3rd decade of 20th century.
- However, tuning TRF receiver took a little while as each stage needed to be adjusted separately. Later ganged tuning capacitors were introduced, but by this time the superheterodyne receiver was becoming more widespread.



Resonating Freq.

$$f_s = \frac{1}{2\pi\sqrt{LC}}$$



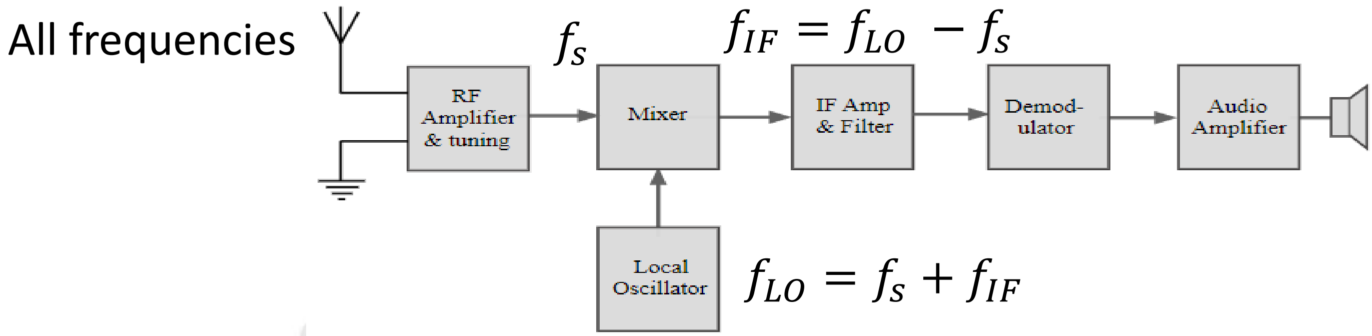


Radio Receiver System

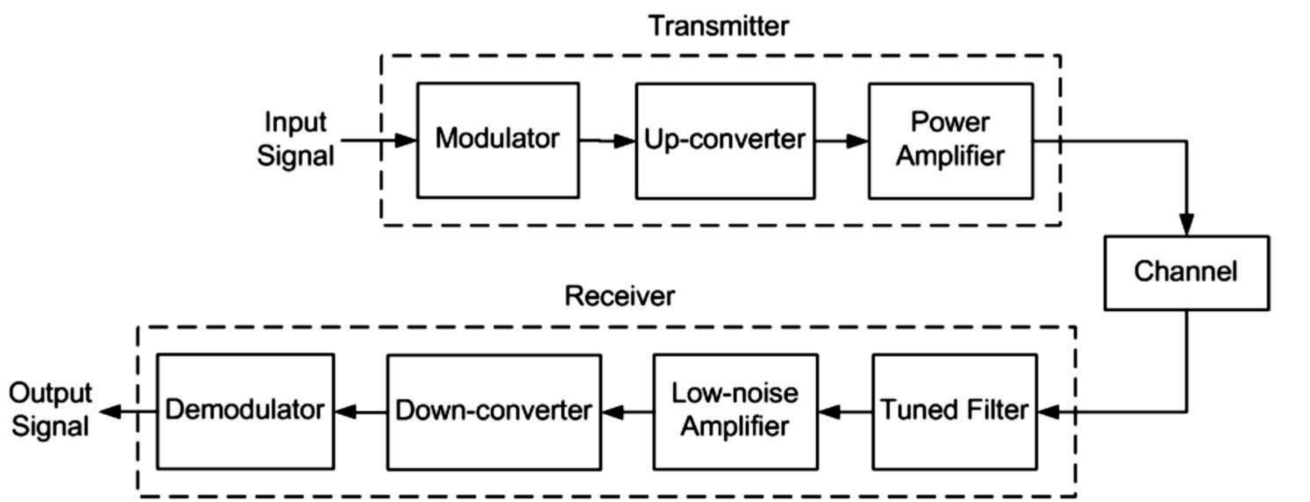
- One problem with tuned circuit is that the selectivity is not uniform over the frequency band – selectivity at higher frequencies is poorer than that at lower frequencies.
- So, 2 stages employed – this is **superheterodyne** receiver.
  - In 1st stage signal of desired frequency f_s is selected and then down-converted to a fixed frequency f_{IF} called intermediate frequency (IF); tank circuit and LO accordingly tuned.
  - In 2nd stage filtering is done again and then demodulated. Thus, 2nd stage circuitry is fixed irrespective of radio station selected → uniform overall performance for all radio stations.

Analog Communication System

- Super-heterodyne receiver block diagram

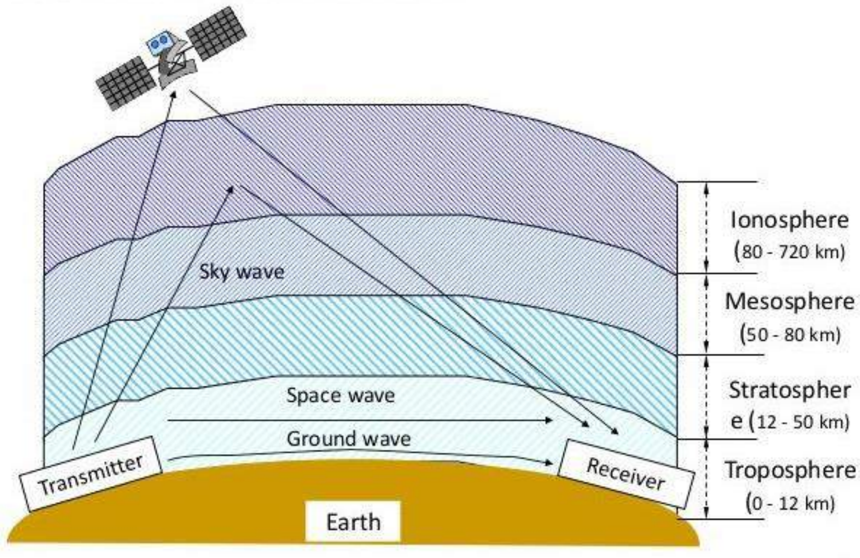


- Basic elements of an analog communication system



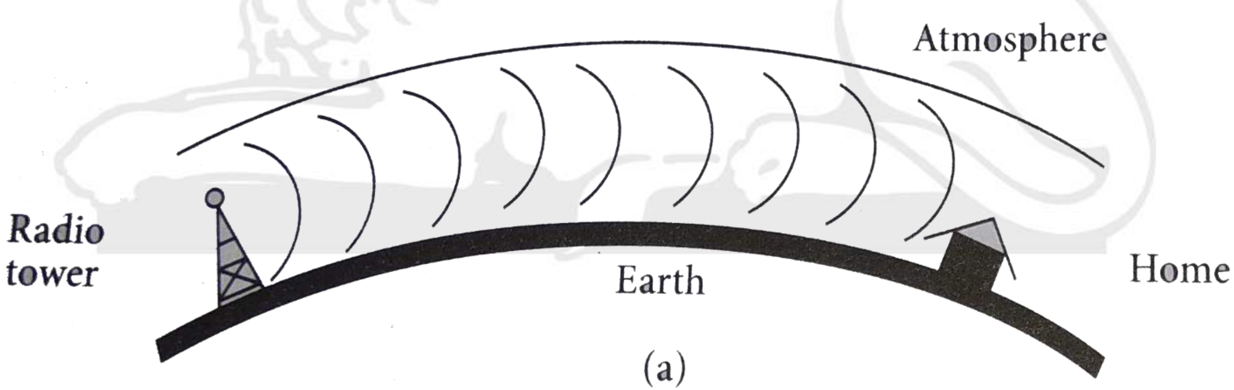
EM Wave Propagation

- How to choose the value of carrier frequency?
  - Distance and/or location of the transmitter-receiver pair
  - Intended system of communication
- EM wave propagation modes in atmosphere and free space:
  - Ground wave propagation
  - Line of sight propagation
  - Skywave propagation



Ground wave propagation

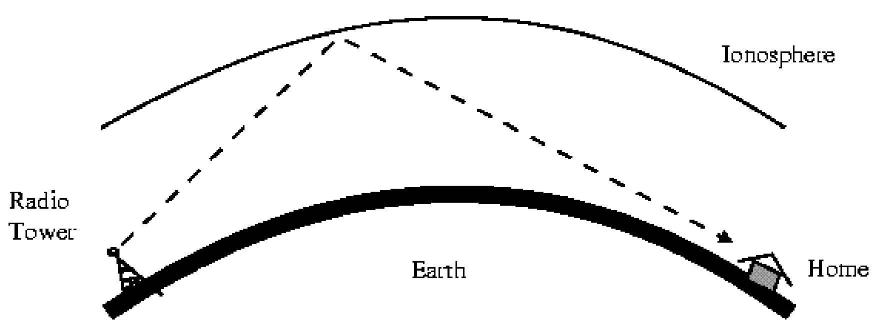
- In ELF (Extremely low frequency upto 3 kHz), VLF (Very low frequency upto 30 kHz), LF (Low frequency upto 300 kHz) and medium wave (MW upto 3 MHz) frequency bands, the Earth and the ionosphere act as a wave-guide for electromagnetic wave propagation.
- EM wave travels following the contour of the earth.
- Gets attenuated very fast and so cannot travel long distance

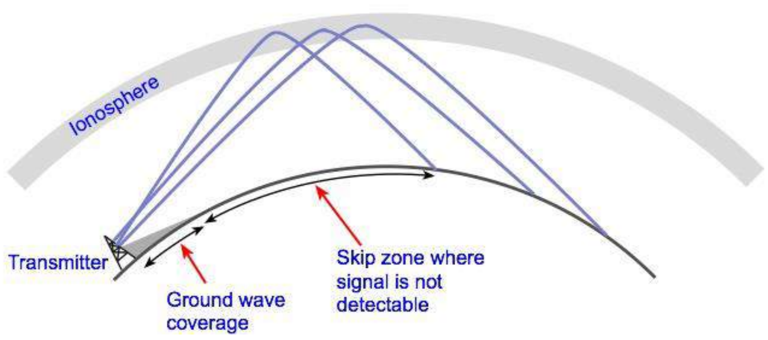


(a)
Ground wave

Skywave propagation

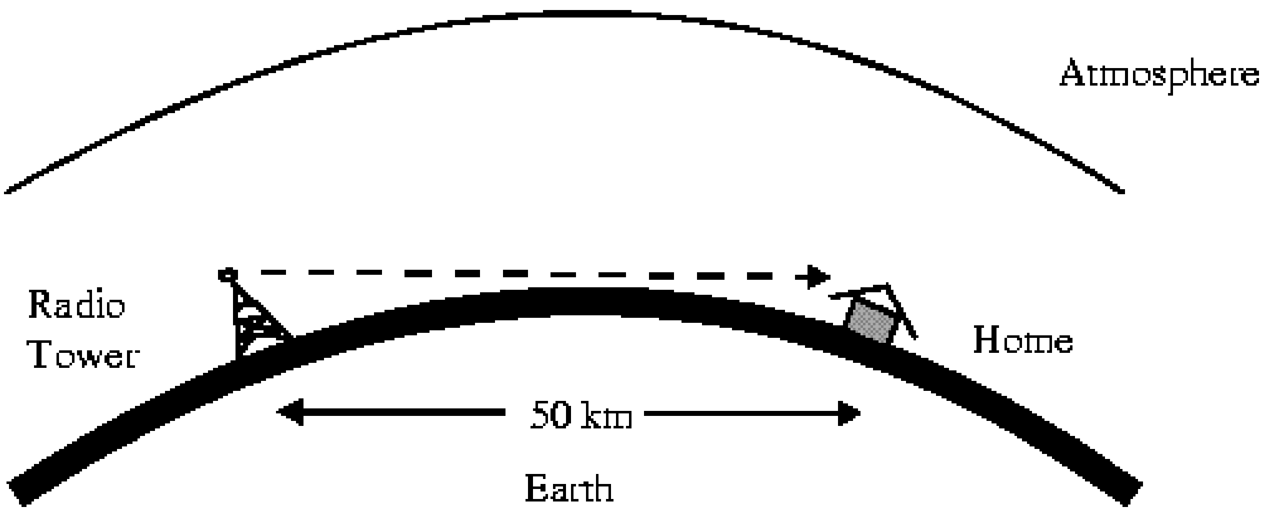
- Skywave propagation is preferred when the wave has to travel a longer distance, even on the other side of the globe.
- Short-waves (3 to 30 MHz) are projected onto the sky and are reflected from the ionosphere (reflected by the charged particles in ionosphere) back to the Earth.
- Here the waves transmitted from one place can be received by many receivers and so good for broadcasting.





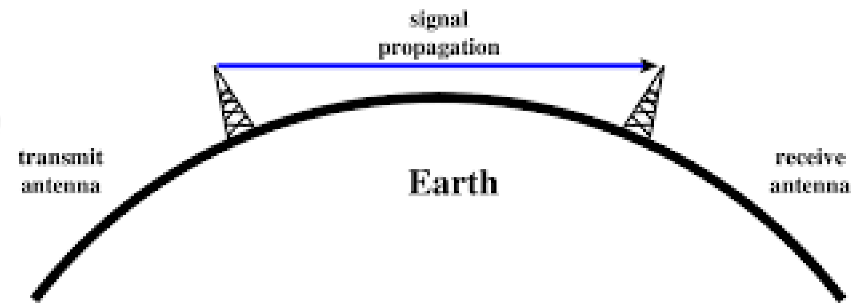
Line of sight propagation

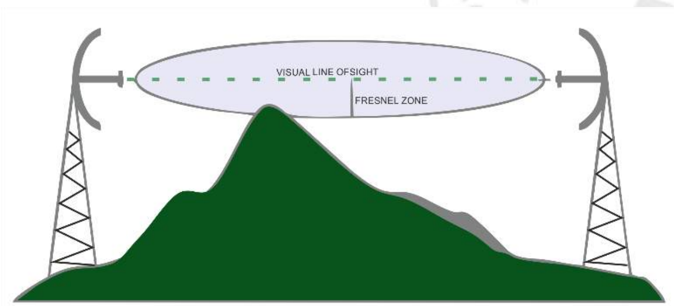
- Used for transmission of VHF (Very high frequency 30 to 300 MHz), UHF (Ultra high frequency upto 3 GHz) and Microwaves (above 3 GHz).
- The wave travels directly in a straight line to the distance up to which a naked eye can see.

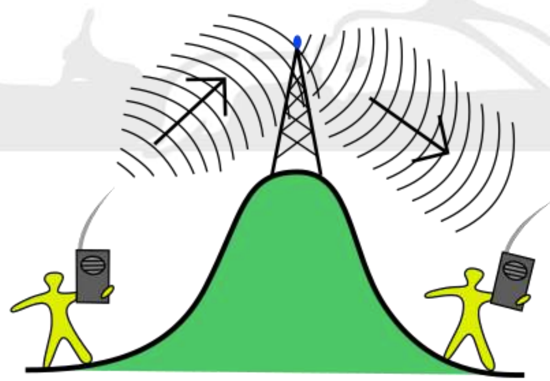


Line of sight propagation

- The line-of-sight propagation is not possible if there occurs any obstacle in its transmission path, or on the other side of the globe.
- Solution is to use extremely tall antenna towers or in-between relay antennas.

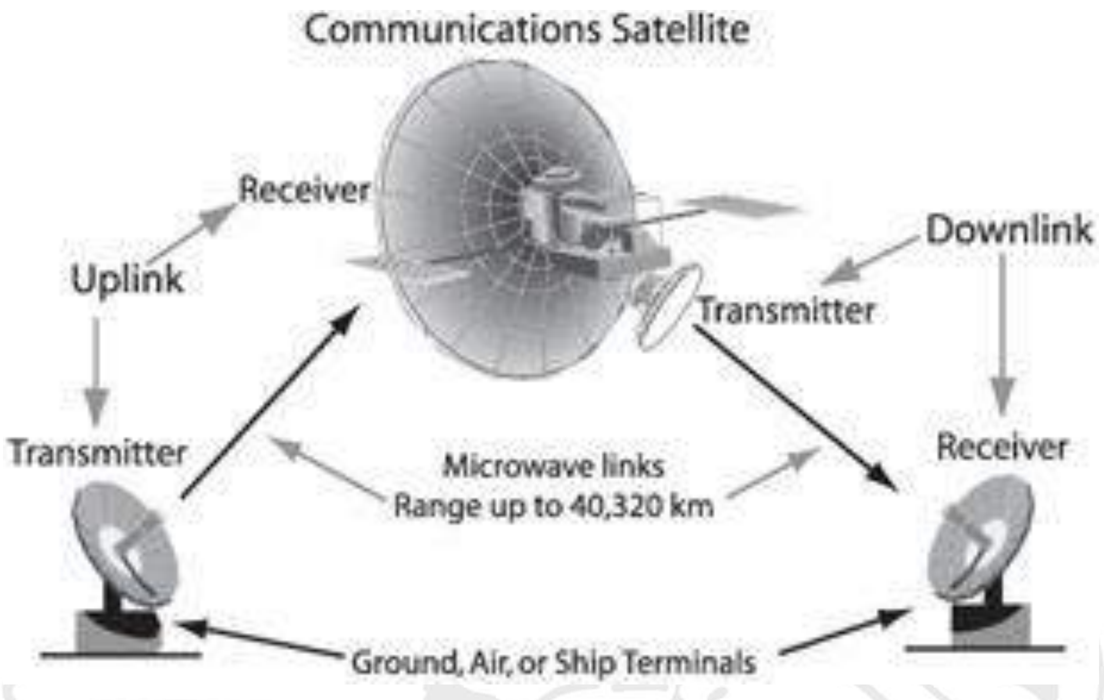






Satellite Communication System

- Better and recent days' solution is satellite communication.



- Artificial satellites that provide communication and other related services to a variety of consumers is called a communication satellite or *comsat* in short.

Satellite Communication System

- A communication satellite is essentially a microwave repeater in the sky that receives communication signals from a transmitting station on the Earth and relays it back to one or more receivers on the Earth.
- Satellite communication systems provide means for relaying of telephone signals, broadcasting of television signals, communication links to remote locations, direct-to-home television distribution and GPS (global positioning system).
- A satellite communication system consists of one or more satellite space vehicles, a ground-based control station on the Earth, and a network of user Earth stations that communicates with each other via transmission and reception of communication signals through satellite system.

Satellite Communication System

- Communication satellites are generally placed in geostationary orbit so that their positions in sky are fixed w.r.t. Earth. So, antenna on the Earth can be pointed in fixed directions towards the satellites without the need for tracking the positions of the satellites.
- A transponder attached to satellite, one transponder per channel, receives signal from transmitting antenna on Earth, amplifies it and then relays back to the Earth.
- The uplink (Earth-to-satellite) and the downlink (satellite-to-Earth) use different frequencies to avoid any interference.
- The geographical area on the Earth's surface covered by the downward antenna beam is referred to as footprint. A communication satellite is generally equipped with multiple antennas to have a larger footprint area.

Applications of Radio waves in ISM

- Industrial – Scientific – Medical (ISM) applications:

  “Operation of equipment or appliances designed to generate and use locally radio frequency energy for industrial, scientific, medical, domestic or similar purposes, excluding applications in the field of telecommunications”

- Microwave oven for domestic cooking; industrial heating using induction or microwave heating; heat therapy for relaxation or healing or killing cancer tissues.

- Wi-fi and Bluetooth for non-telecomm uses in domestic and industry; contactless smart cards, keyless entry systems, RFID, drone control, wireless surveillance, etc.

Signal Types in Communication

- **Signal**: function of one or more independent variables.
  – Sound wave, light wave, mechanical vibration, etc. all are different signals but non-electrical signals.
- Electrical signals: Voltage (or current) as a function of time or space; can be represented as function of freq. (spectrum) by time/spatial to frequency domain mathematical transform
  – 1D time domain $s(t) \rightleftharpoons$ 1D frequency domain $S(f)$
  – 2D spatial domain $s(x, y) \rightleftharpoons$ 2D frequency domain $S(u, v)$
- Examples: ECG, EEG, 2D ECG, USG, MRI, CT-scan, seismic images, etc.
- In electrical communication systems, we are concerned with messages in the form of electrical signals which are functions of time (and also frequency).

Signal Types in Communication

- Broad classification of communication signals:
  - Analog: continuous-time and continuous-amplitude
  - Digital: discrete-time, discrete-amplitude and binary coded
- **Message signals:**
  - Text message: telegraphic signals, nowadays emails, file transfers using ftp, etc.
  - Speech and/or audio: telephonic signals, radio broadcasting, TV sound, mobile phones, etc.; voice BW = 3.4 kHz, audio BW = 20 kHz
  - Image and/or video: TV pictures (BW = 5 MHz), videophone, image and video downloads, etc.; BW of video signals of decent quality is in the range of 4.2 MHz.

Progress in the last century

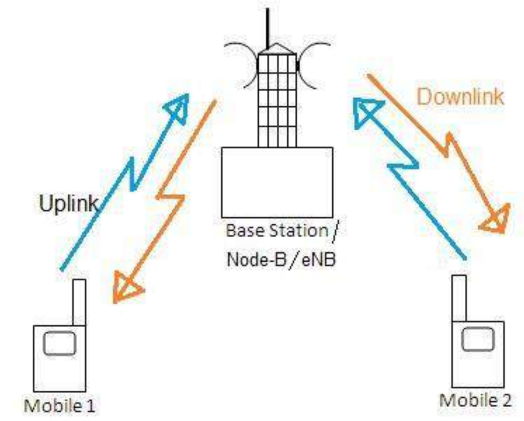
- **1915:** First North American transcontinental telephone call
- **1927:** Television
- **1927:** First U.K.-U.S. radio-telephone service
- **1930:** First experimental videophones
- **1946:** Limited-capacity mobile telephone service for automobiles
- **1962:** Commercial telecommunications satellite
- **1964:** Fiber-optic telecommunications
- **1969:** Computer networking

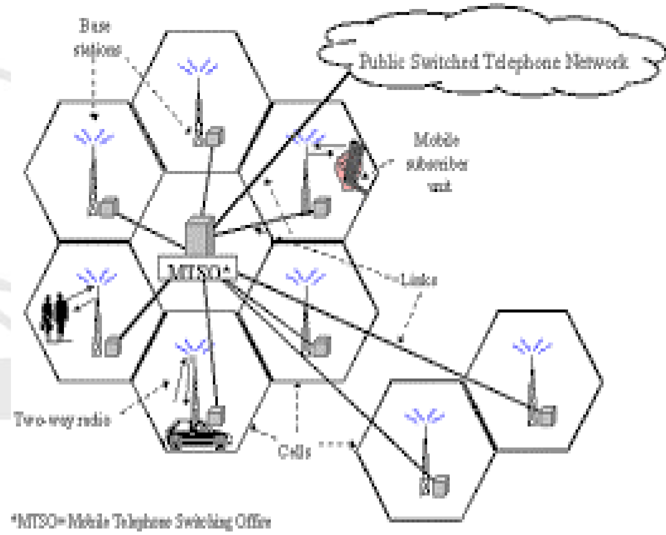
Progress in the last century

- **1973:** First modern-era mobile phone
- **1979:** INMARSAT ship-to-shore satellite communications
- **1981:** First mobile phone network (Japan)
- **1982:** SMTP email
- **1983:** Internet (ARPANET) and Transmission Control Protocol/Internet Protocol (TCP/IP) became standard.
- **1998:** Mobile satellite hand-held phones
- **2003:** VoIP Internet telephony

Mobile Phone System

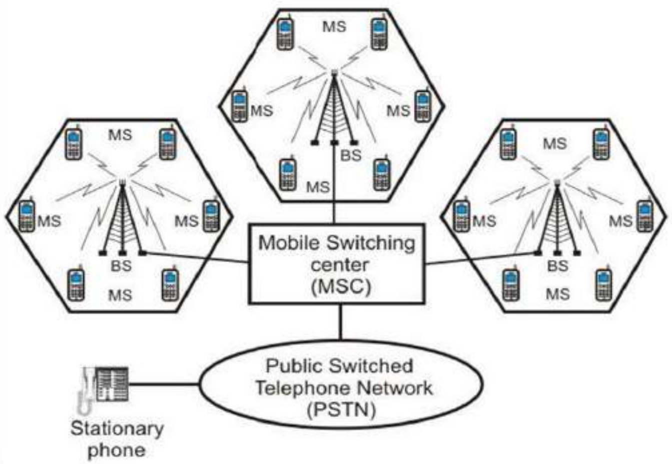
- A geographical area is divided into smaller regions called **cells**, each having a **base station**.
- The base station of every cell uses a set of frequencies that are shared by all mobile users within that cell
- The frequencies used in a cell are reused in other nearby cells, but not in its adjacent cells to avoid intercell interference.
- Thus, a large population in a region is catered by dividing the area into numerous smaller-sized cells thereby permitting more frequency reuse.



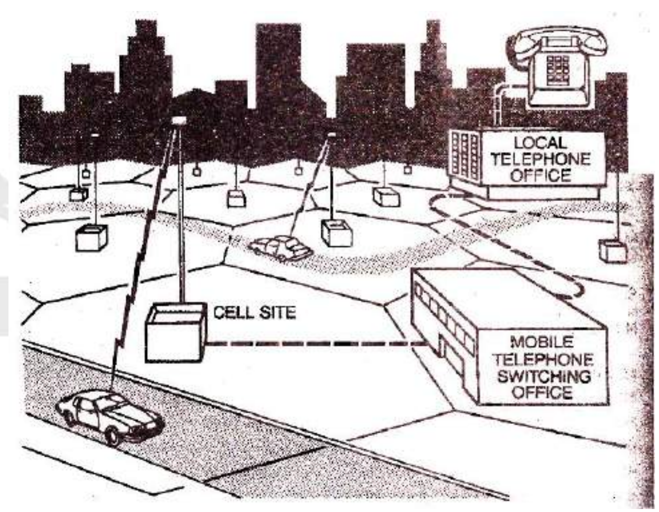


Mobile Phone System

- Frequency allotment done by mobile switching centre to which all base stations in a region are connected
- A user moving in a particular cell communicates to the base station.
- The base station connects to the mobile switching centre which in turn connects caller to called party through base station of the cell within which the called party is located.
- The mobile switching centre assigns new frequency to a user leaving a cell and entering a new adjacent cell, a process called **handoff**.



Schematic diagram of a cellular telephone system

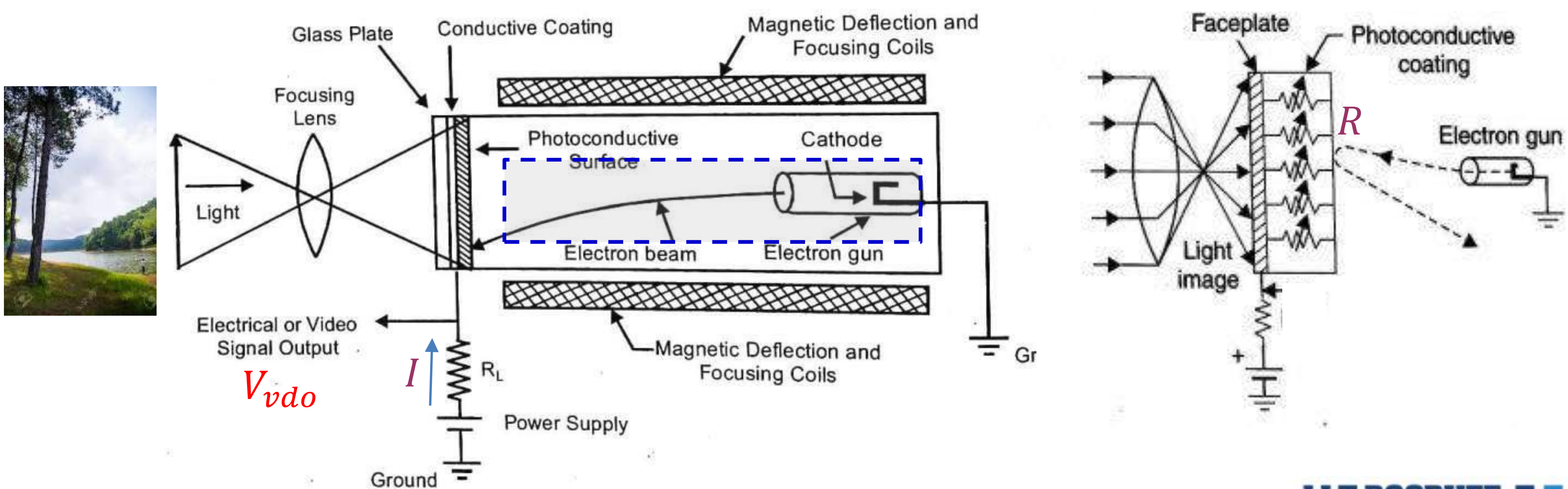


Television System

- Video signal $V_{vdo} = V_{supply} - IR_L = V_{supply}\frac{R}{R_L + R}$, where R is the resistance of the photoconductive coating at that point:

  more bright → less R → higher I → lower V_{vdo}

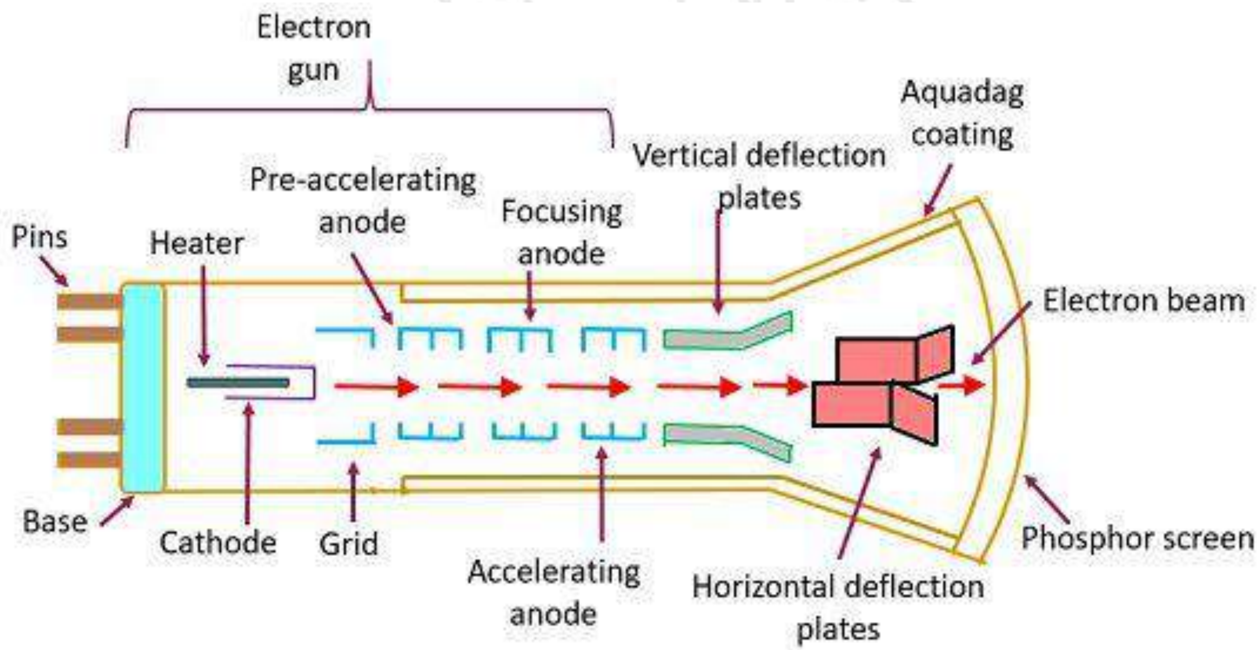
- As electron beam scans photo-plate (bottom-up, right-left order), video signal inversely proportional to brightness of the projected scene is generated and transmitted.

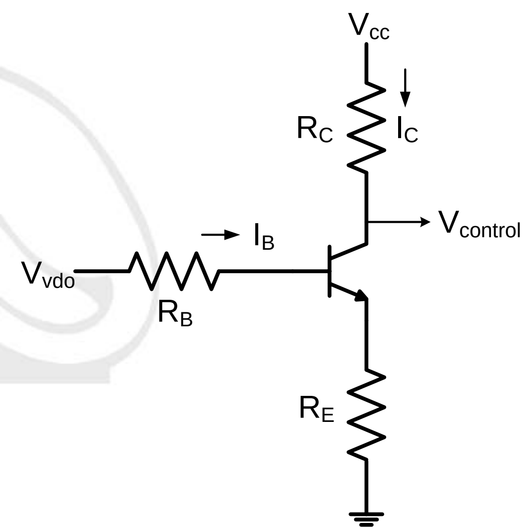


Television System

- Electron beam scans screen in top-bottom, left-right order
- Illumination at a point on phosphor screen proportional to the intensity of electron beam controlled by the control voltage applied to the grid which is proportional to scene brightness.

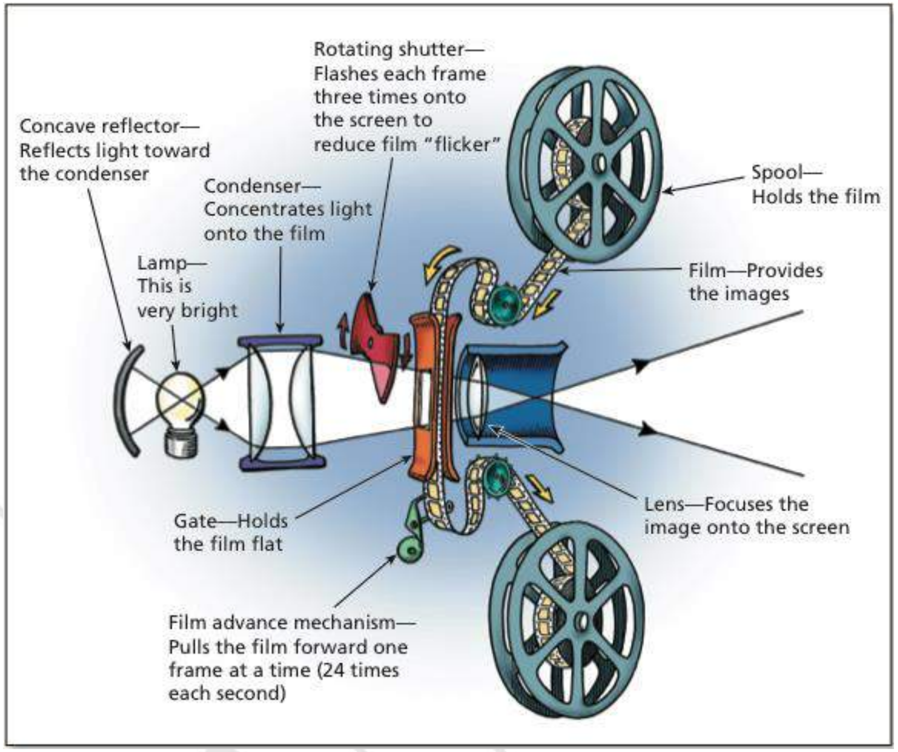
$$V_{control} = V_{CC} - \beta I_B R_C = V_{CC} - K V_{vdo} R_C = I R_L \propto \text{Brightness}$$





Television System

- Persistence of vision = one-sixteenth (1 / 16) of second.
- In movies, 24 frames of a moving scene projected in one second; actually the same scene is projected 3 times to reduce noticeable flickering caused by blanks in-between frames.



- In our TV system (PAL system), we use 25 frames / sec, each in turn is split into 2 **interlaced fields** (odd and even) ⇒ 50 fields / sec in line with power line frequency 50 Hz.
- NTSC system uses 30 frames / sec ⇒ 60 fields / sec

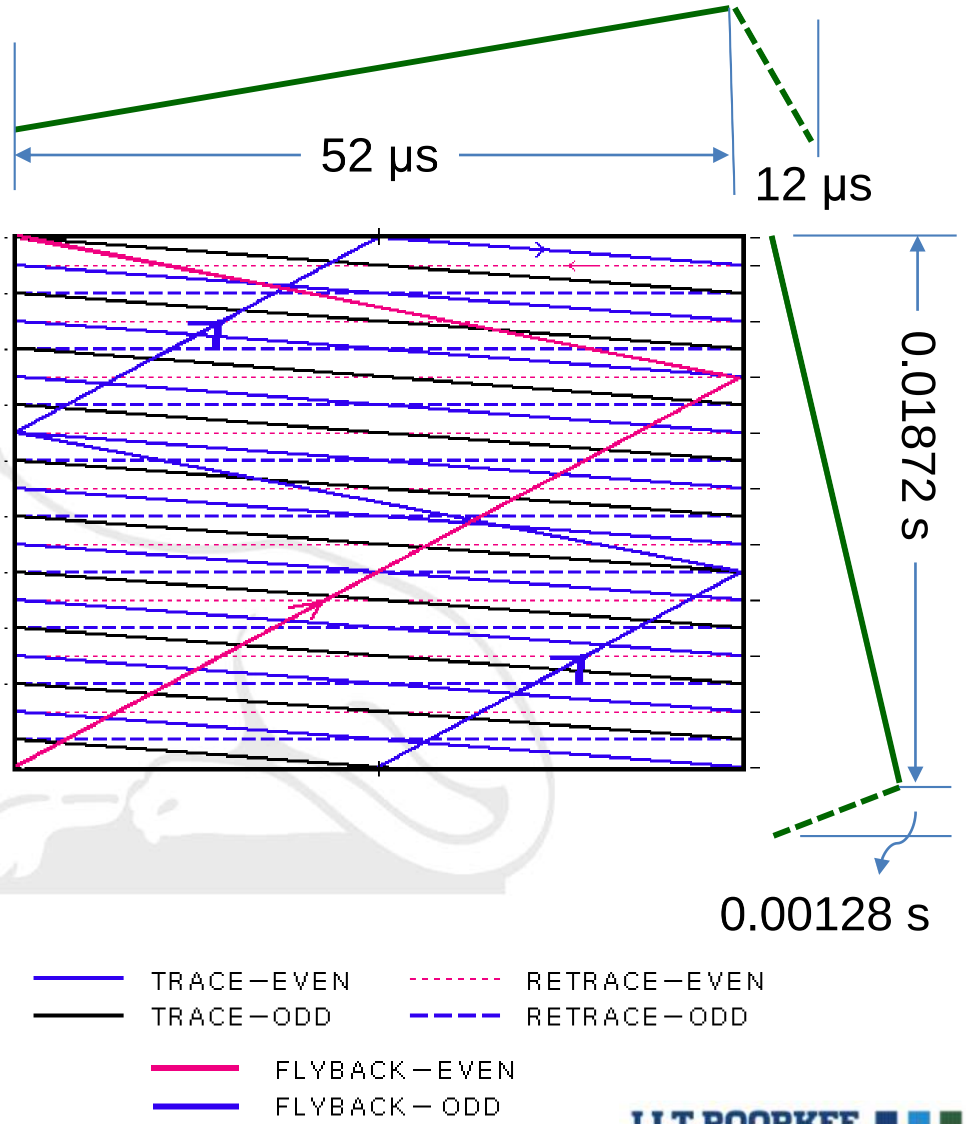
Television System

- One frame time = 0.04 sec.
- 625 lines per frame

  ⇒ one line time 64 μs = 52 μs visible line time + 12 μs blanking during horizontal retrace.

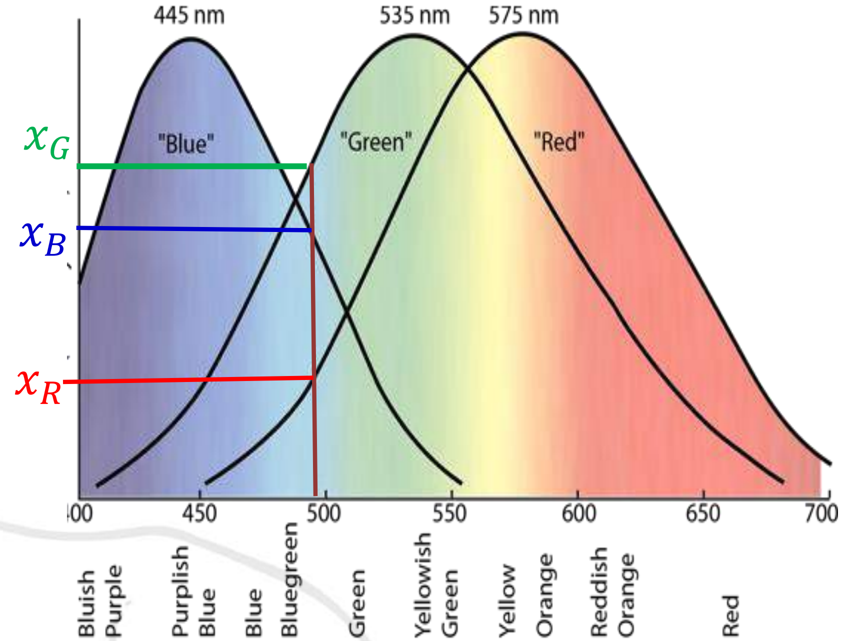
- 312.5 lines per field = 292.5 visible lines + 20 blanked lines during vertical retrace (flyback)

  ⇒ field duration 0.02 sec = 0.01872 sec visible field + 0.00128 sec blank



Television System

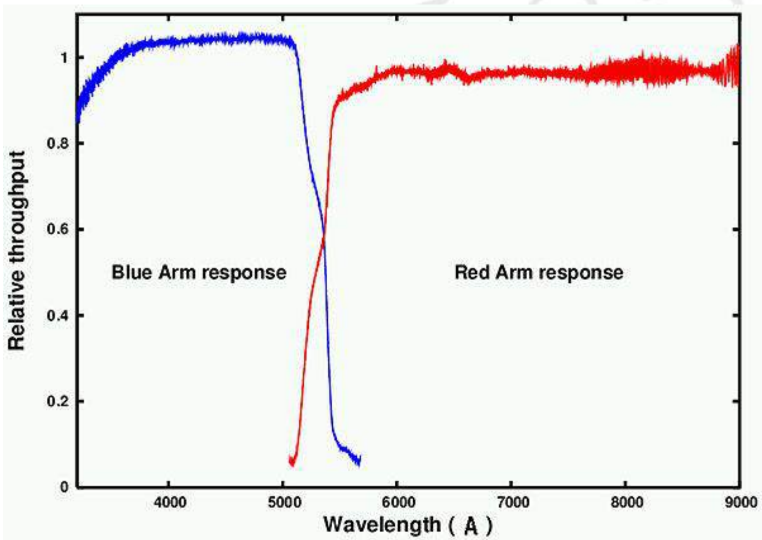
- Perception of color: 3 types of cone cells in our retina respond differently to 3 different spectra of visible light centred roughly around RED, GREEN and BLUE.



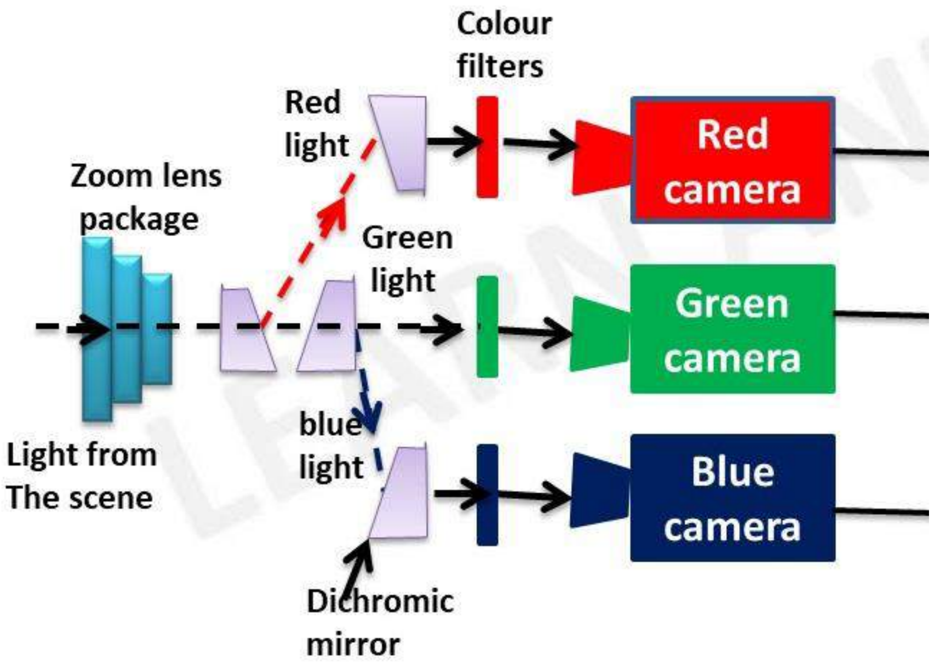
- The relative proportion of their responses $x_R : x_G : x_B$ give the sensation of color.
- Perception of the corresponding color is created by stimulating the cone cells in the same proportion – pure RED, GREEN and BLUE lights of different intensities in the same proportion give a mixed impression of <u>more-or-less</u> the same color.

Television System

- Dichroic mirror reflects a particular band of light and allows all lights outside that band to pass through.



- Response of the color filters somewhat like that of cone cells in human.

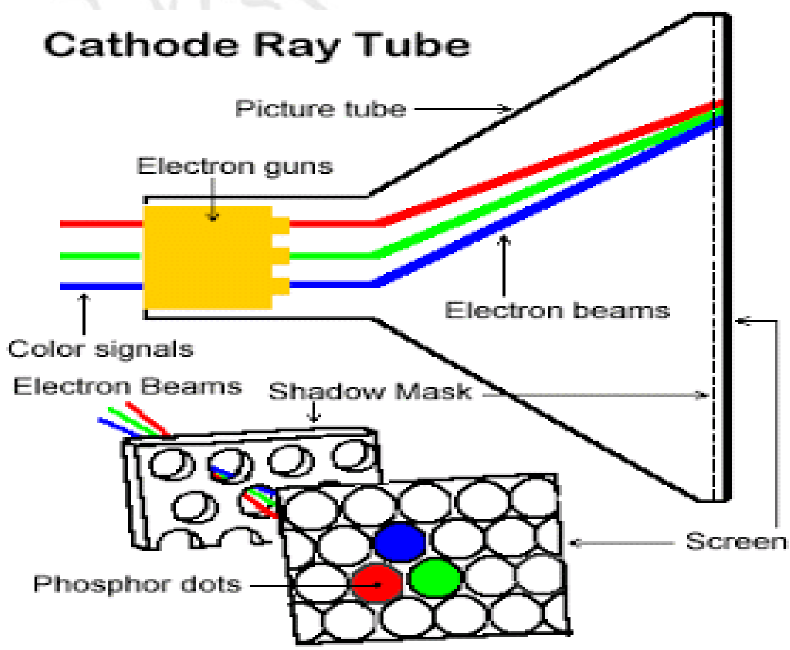


- Transmits composite signal:

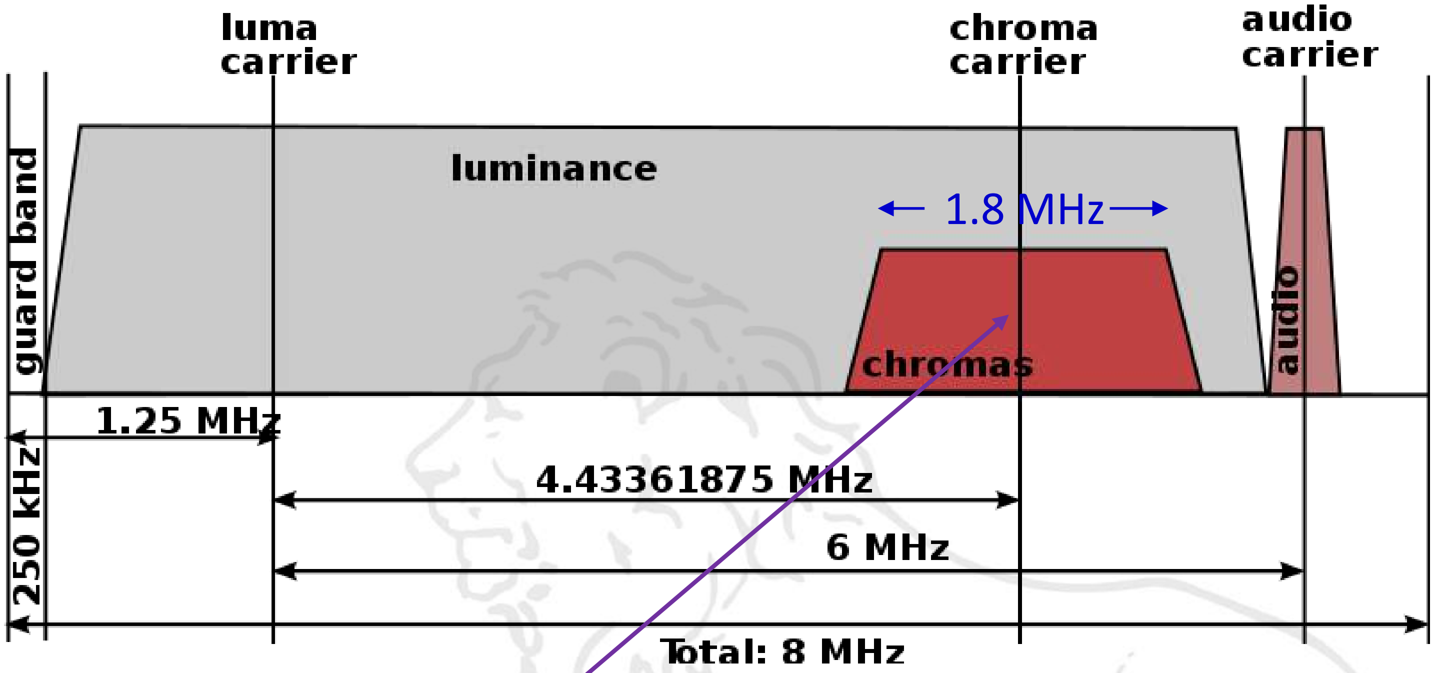
$$Y = 0.3R + 0.59G + 0.11B$$
$$U = 0.493\,(B - Y)$$
$$V = 0.877\,(R - Y)$$

Television System

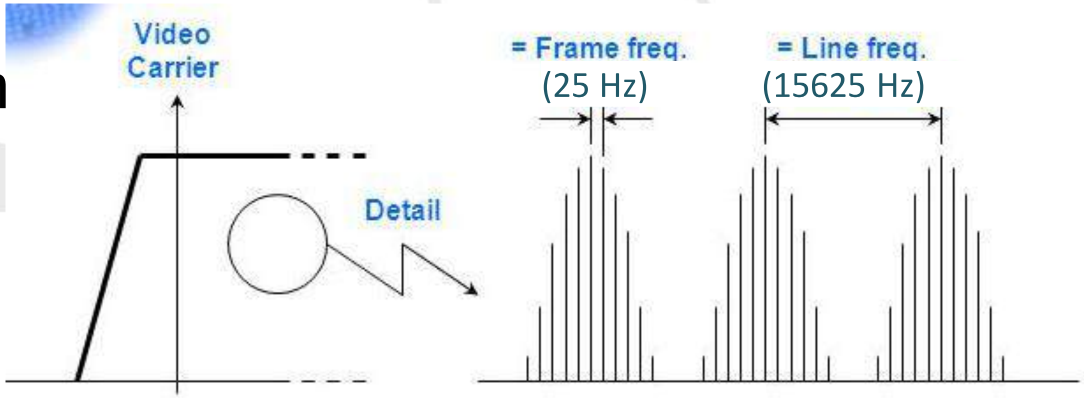
- Received YUV signals are transformed back to RGB format
  - Then, why unnecessarily have extra hardware to convert RGB to YUV in Tx and then YUV to RGB in Rx?
- RGB signals from 3 electron guns projected on 3 closely placed phosphor dots that emit Red, Green and Blue colors respectively.



Television System



U and V carrying chrominance information (hue and saturation) are quadrature amplitude modulated



The Digital Era

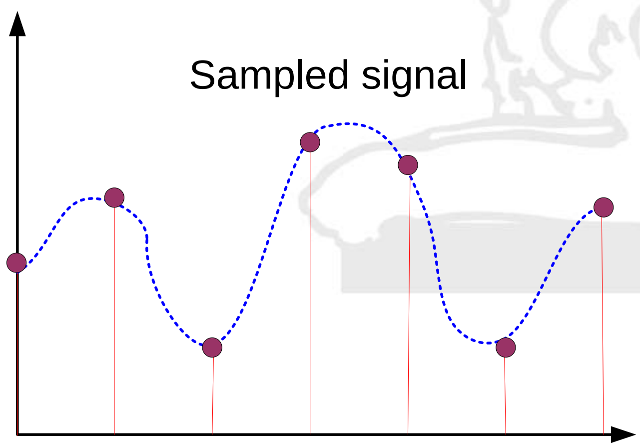
- Communication systems were primarily developed for voice transmission and later, with the invention of television system, for image and video transmission.
- Real-world voice, image and video signals are analog in nature that are continuous both in time and amplitude.
- Accordingly, since the earlier days of telecommunication, analog system has been the primary technology platform.
- Voice digitization and transmission started to evolve in the late 1950s due to certain advantages.
- Digital communication technology has gradually taken over from analog technology during the second half of the 20th century and the trend still continues.

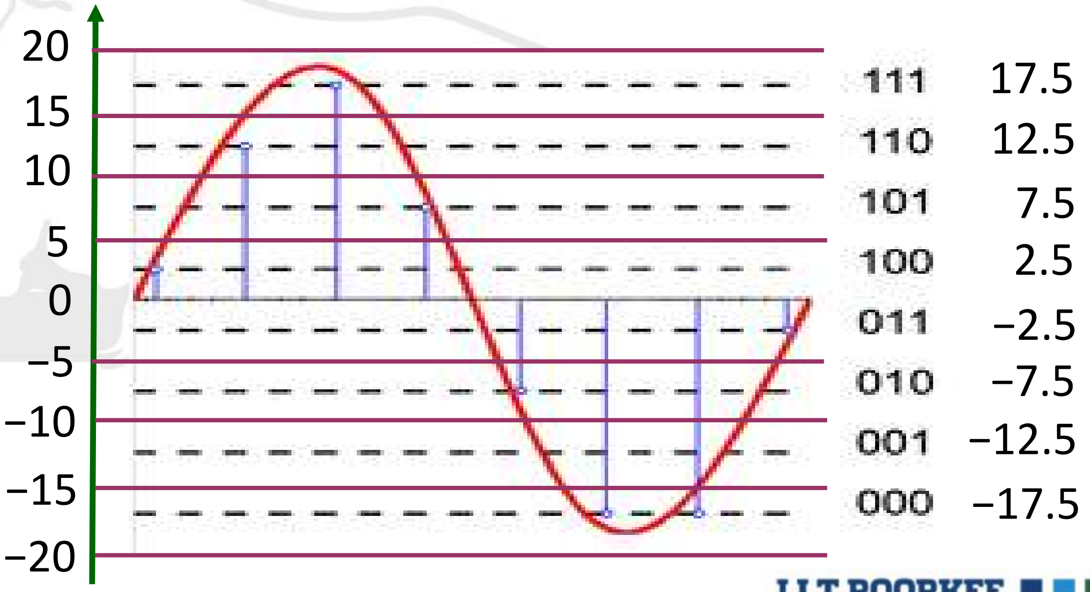
The Digital Era

- **Advantages** of digital communication:
  - Immunity to noise
  - Data integration
  - Error detection and correction capability
  - Easy processing like data compression, encryption, etc.
  - Use of modern technology – VLSI, DSP, etc.
  - Easy multiplexing by TDM
- **Disadvantages**:
  - Signal distortion to some extent due to quantization noise
  - More bandwidth required for transmission
  - Needs proper bit, character and frame synchronization
  - Extra processing – A/D at transmitter and D/A at receiver

Digital Communication Technique

- Signal digitization – signal value at every instant to be binary coded in the form of a string of bits. Steps involved are:
  - **Sampling** – Signal discretized in time
  - **Quantization** – Samples discretized in amplitude for convenience in binary coding
  - **Binary encoding** with corresp. quantization level index





Digital Communication Technique

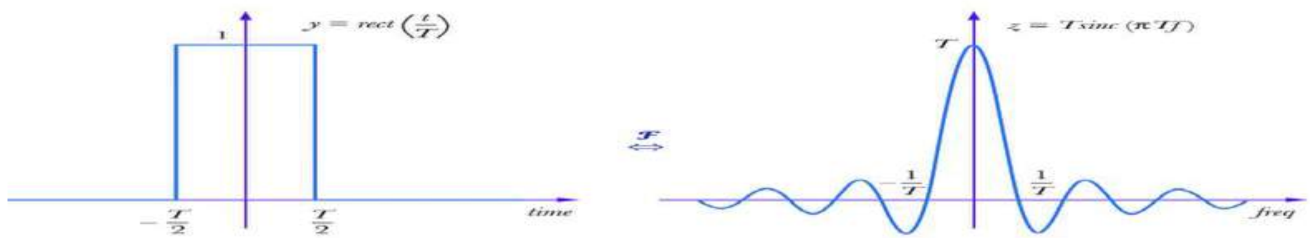
- Text messages: composed of discrete characters; total 128 characters – 7 bits required + 1 extra bit used for error detection by even parity check.
- By Shanon’s sampling theorem:
  - Sampling rate ≥ 2 times maximum frequency present in the signal (Nyquist rate).
- Speech signal: max. frequency 3.4 kHz → standard sampling rate = 8 kHz and each sample quantized to 256 levels ⇒ transmission rate 64 kbps or 8 kBps
- Audio signal sampled at more than 40 kHz rate and quantized at 12 or 13 bits per sample.

Digital Communication Technique

- Digital image: Image made of closely spaced dots called pixel (picture element) defined by the intensity value as function of 2D space $I(x, y)$; for color image each pixel defined by RGB intensity values.
- Video signal sampled → every sample is a pixel.
- For sampling of TV signal at 15 MHz (minimum sampling rate = 10 MHz), each line will have 780 pixels; so total pixels in a frame is 780 × 585 pixels.
- Standard TV resolution: 640 × 480 pixels
- HDTV has much more number of pixels:
  - 1280 × 720, 1366 × 768, 1920 × 1080, or 3840 × 2160

Digital Communication Technique

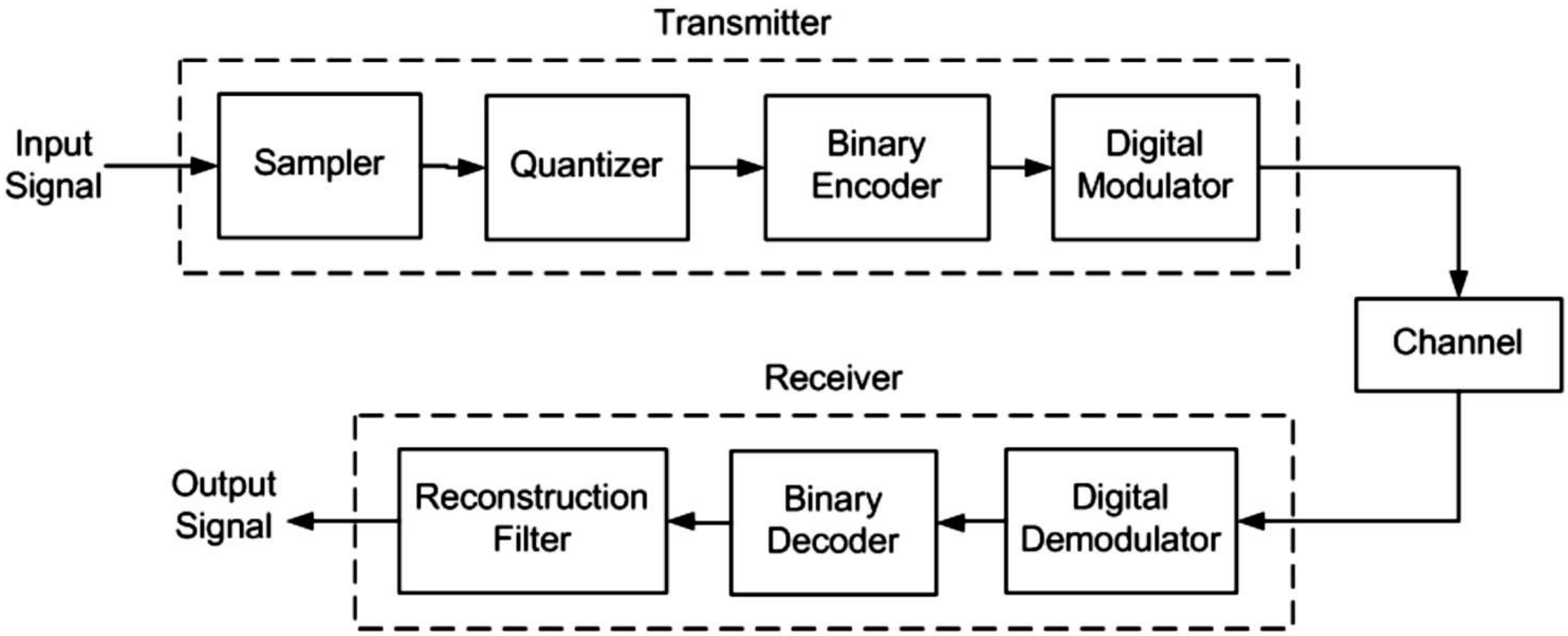
- Bits may be transmitted directly – baseband communication; but requires very large BW channel, otherwise there will be problem of inter-symbol interference (ISI).



- So, better to modulate a high frequency carrier wave (continuous-time) by bit string – passband communication.
  - Binary-Phase-Shift keying (BPSK)
  - Frequency-Shift Keying (FSK)
  - Quadri-Phase-Shift Keying (QPSK)
  - Quadrature Amplitude Modulation (QAM)

Digital Communication Technique

- Basic elements of a digital communication system:



Time division multiplexing (TDM)

- In TDM the entire channel is available to all users but periodically for a restricted interval of time.
- Samples and/or data symbols from several sources are time interleaved and then transmitted over a single communication channel.
- Interleaving may be: Bit interleaving, byte (8 bits representing one ASCII character or one sample of digitized speech/audio/image/video signal) interleaving, packet interleaving or frame interleaving.