Chapter 2
Transmission Media and Propagation Mechanisms

2.1 Introduction

Signals generated by the source need to be transported to the destination over a communication's channel. A communication channel can be described by its bandwidth, attenuation and the propagation delay. As the signal is attenuated while propagating through the channel, it must be regenerated after a certain distance to maintain signal quality. In general, a communication channel is the physical path between transmitter and receiver and is established through transmission lines in tandem. The transmission links include guided and unguided media such as two-wire lines, co-axial cables, microwave radio, optical fibers and satellites.

2.2 Wired Media: Twisted Pair

Twisted pair cable (Fig. 2.1) is a wire line channel which can be classified as Shielded Twisted Pair (STP) and Unshielded Twisted Pair (UTP). It is least expensive and most widely used wired media. Due to twisting, interference and crosstalk are reduced. The applications of twisted pair cable are

- Data connection especially in PSTN local loop analog links (within an office building, each telephone is also connected to a twisted pair)
- Local area networks supporting personal computers
- In high-speed transmission, although these are quite limited in terms of the number of devices and geographic scope of the network.

The bandwidth of a twisted pair cable varies with the type of wire pair used and its length. Therefore, the use of twisted pair is limited in distance, bandwidth and data rate. For point-to-point analog signaling, a bandwidth of up to 1 MHz is possible for twisted pair and a number of voice channels can be accommodated within this

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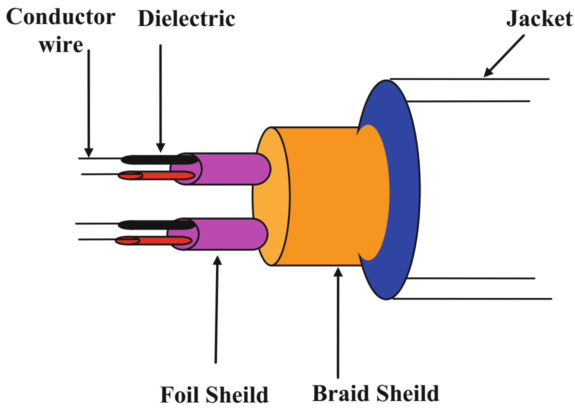

Fig. 2.1 Structure of twisted pair cable

available bandwidth. Coaxial cable, like twisted pair, consists of two conductors, but is constructed differently to permit it to operate over a wider range of frequencies. However, its loss increased drastically with the increased frequency. Thus equalizer is required. Equalization tends to adjust the frequency response. With the introduction of fiber optic cable, with its much greater bandwidth and comparatively flat frequency response, the coaxial cable becomes obsolete though it is also extensively used in cable television plants, especially in the “last mile”.

2.3 Wired Media: Optical Fiber

An optical fiber is a dielectric waveguide capable of transporting light waves. The optical fiber media is used for high speed data transmission. The primary material for the construction of optical fiber is nonmetallic and non-conductive. There is no electromagnetic radiation from the optical fibers due to waveguide transmission with optical flux contained within the fiber waveguide (Fig. 2.2).

Optical fiber is a long, thin strand of very pure glass about the diameter of 2–125 μm. Optical fibers are assembled together called optical cables and used to transmit light signals over long distances. The propagation through optical fibers is entirely based on the principle of total internal reflection. This is explained in the following picture.

2.3.1 Structure of an Fiber Optic Cable

Typical optical fibers consist of the core, cladding and buffer or coating. The core is the innermost part of the fiber, which guides light. It is generally made of glass. The core is surrounded with cladding. The cladding has optical properties different from

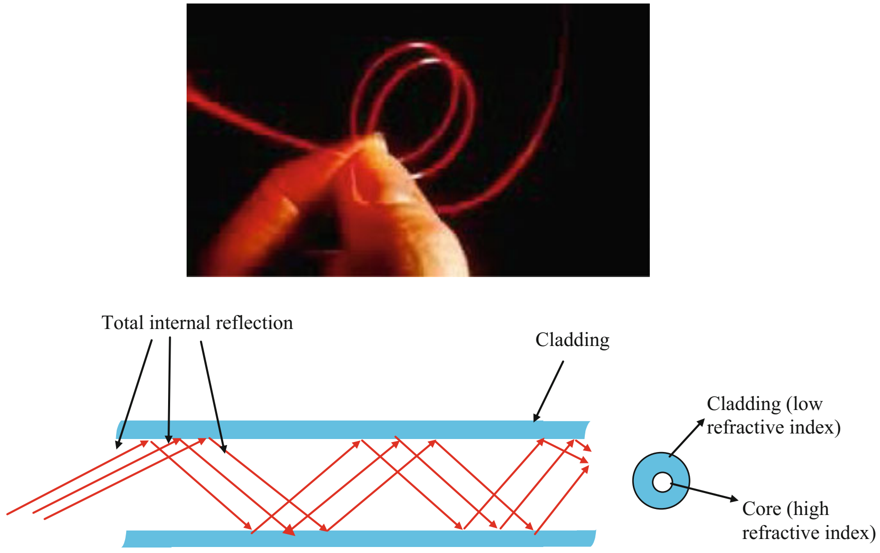

Fig. 2.2 Propagation of light through optical fiber

those of the core, light in the core strikes the interface between the core and cladding and confine light that would otherwise escape the core. The outermost part surrounding the cladding is the jacket.

For the most common optical glass fiber include 1550 nm single mode fibers and 850 or 1300 nm multimode fibers. Multimode fiber has larger core diameter than the single mode fiber and the three most common core diameter sizes are 9 µm (single mode), and 50 or 62.5 µm (multimode). The most common cladding diameter is 125 µm. The material of buffer coating is soft or hard plastic such as acrylic, nylon and with diameter ranges from 250 to 900 µm. The buffer coating provides mechanical protection and has bending flexibility for the fiber (Fig. 2.3).

2.3.2 Propagation Modes of Fiber Optic Cable

The light waves are propagating through optical fiber in different modes. Modes define the way the light waves travel across the fiber. The waves can have the same mode but have different frequencies. It depends on the variation in refractive index that shapes the core. The variations in refractive index create boundary conditions that dictate traveling of light waves through the fiber, like the walls of a tunnel effect that create sounds echo inside.

The variation of material composition of the core gives rise to the two commonly used fiber types. In the first type, the refractive index of the core is constant throughout and undergoes an abrupt change at the cladding boundary. This is called

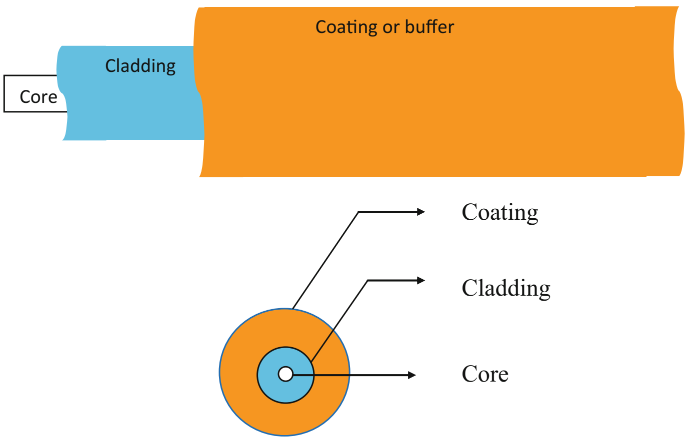

Fig. 2.3 Structure of optical fiber

step-index fiber. In the second type, the refractive index of the core is varied as a function of radial distance from the center of the fiber. This type is called graded-index fiber. Both the step-index and graded-index fibers can be further classified into single mode and multimode.

Fibers that support many propagation paths or transverse modes are called multimode fibers. It has a wider core diameter. Light waves travel at slightly different velocity in a multimode fiber. Therefore, pulse arrives at the end of fiber at slightly different times which causes pulse to spread out in time. On the other hand, some fibers have narrow core diameter that can support only one mode. Light wave travels through the center of the core as a straight line. These fibers are single mode fibers. This is illustrated in the following picture (Fig. 2.4).

2.3.3 *Calculation of Number of Modes in a Fiber*

Modes are sometimes expressed by numbers. Single mode fibers support only the lowest-order mode, assigned the number 0 (zero) and multimode fibers support higher-order modes. The number of modes that can propagate through a fiber depends on the fiber's numerical aperture (or acceptance angle) as well as on the diameter of its core and the wavelength of the light. For a step-index multimode fiber, the number of such modes, Nm, is approximated by

$$N_m = 0.5\left(\frac{\pi D \times NA}{\lambda}\right)^2 \tag{2.1}$$

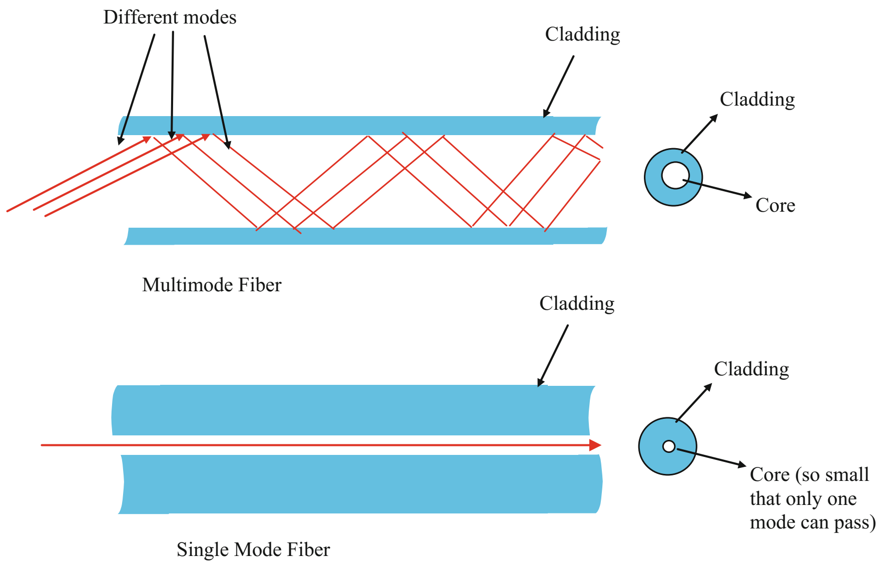

Fig. 2.4 Single mode and multimode Fiber

where, D is the core diameter, λ is the operating wavelength NA is the numerical aperture (or acceptance angle). The above equation is only an approximation and does not work for fibers carrying only a few modes.

Problem 2.1
A step-index fiber has a normalized frequency, V = 26.6 at a 1300 nm wavelength. If the core radius is 25 μm, let us find the numerical aperture and total number of modes entering the fiber.

Solution

$V = \frac{\pi D}{\lambda} NA$

$$NA = \frac{V \times \lambda}{\pi D} = \frac{26.6 \times 1300 \times 10^{-3}}{3.1416 \times 2 \times 25}$$

$NA = 0.220$

2.3.4 Optical Fiber Index Profile

The Index profile is the distribution of refractive indices across the core and the cladding of the fiber. In the case of step index profile, the core has one uniform refractive index and a sharp decrease in refractive index at the core-cladding interface so that the cladding is of lower refractive index. For a graded index profile,

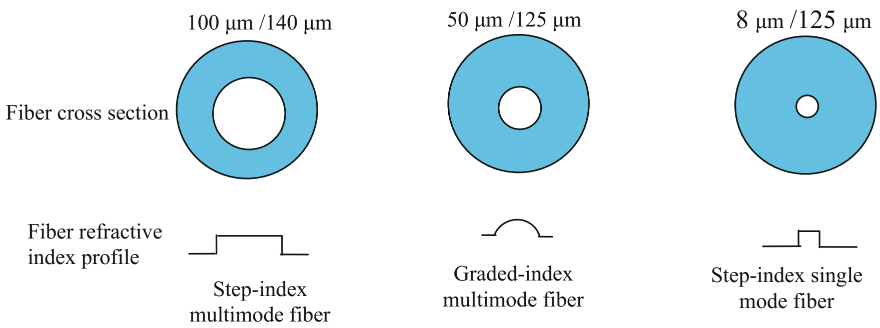

Fig. 2.5 Optical fiber index profile

refractive index varies steadily as a function of radial distance from the optical axis of the fiber. The graded-index profiles include power-law index profiles and parabolic index profiles. The following figure shows some common types of index profiles for single mode and multimode fibers (Fig. 2.5).

2.3.5 *Optical Fiber's Numerical Aperture (NA)*

Numerical aperture is a measure of the acceptance angle of fiber. The propagation of light through multimode optical fiber occurs if enters the fiber within acceptance angle of the fiber. For step-index multimode fiber, the acceptance angle is determined only by the indices of refraction of core, the cladding and the medium:

$$NA = n\sin\theta_{\max} = \sqrt{n_f^2 - n_c^2} \tag{2.2}$$

where, n denotes the refractive index of the medium, n_f is the refractive index of the fiber core, n_c is the refractive index of the cladding (Fig. 2.6).

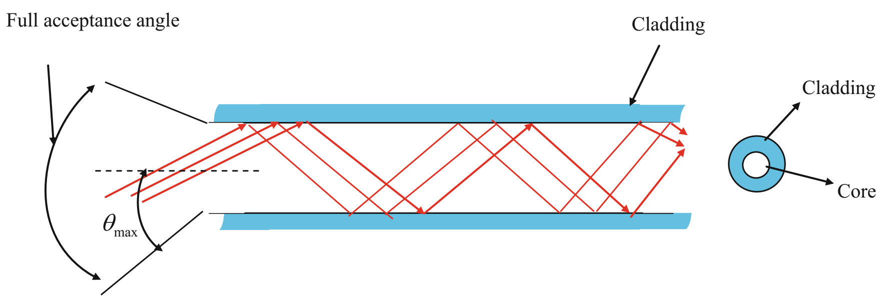

Fig. 2.6 Numerical aperture

2.4 Wireless Media

Wireless communication has a rapid progress in the last decade, and many types of wireless systems have flourished, and often later on, these are vanished. For example, television transmission, in its early days, was broadcast by wireless radio transmitters, which are being swapped by cable transmission. Likewise, the telephony system, point-to-point microwave circuits are being restored by optical fiber. In the first example, wireless technology happened to obsolete due to wired distributed network; in the second case, wired technology (optical fiber) take over the older technology. The opposite example is true in today's telephony, where wireless (cellular) technology is replacing to some extent the use of the wired telephone network. The point of these examples is that the modern communication has given us some options in different situations to select whether wireless or wire technologies and the choice often changes when new technologies become available.

There are different propagation phenomena of wireless communication such as reflection, diffraction and scattering that create the problem challenging and exciting which is not as significant as in wireline communication. The first phenomenon is fading which is due to the rapid fluctuations of signal strengths. The effect of small-scale multipath fading is attenuation while for larger-scale fading are path losses and shadowing. The wireless users communicate over free space and the interference is significant between transmitters communicating with a common receiver (e.g., uplink of a cellular system), between signals from a single transmitter to multiple receivers (e.g., downlink of a cellular system), or between different transmitter–receiver pairs (e.g., interference between users in different cells).

The propagation at LF band is due to ground wave which provides stable transmission over distances up to about 1500 km. This band is used for long-wave sound broadcasting. In the MF and HF bands, sky wave predominates and these bands are used for sound broadcasting and long distance communication to ships and aircraft.

2.5 Transmission Impairments

In any communications system, the received signal can differ from the transmitted signal due to various transmission impairments. Transmission impairments cause the signal quality degradation for analog signals, and bit errors is introduced for digital signals, for example a binary 1 is converted into a binary 0 or vice versa.

Attenuation

Attenuation is the falls off signal strength with the distance during propagation over the transmission medium. For guided media, this is usually exponential and is normally expressed as a constant number of decibels per unit distance. For unguided media, attenuation is a more complex function of distance. In microwave (and radio frequencies), the loss can be expressed as:

$$L = 10\log\left(\frac{4\pi d}{\lambda}\right)^2 dB, \tag{2.3}$$

where, d is the distance and λ is the wavelength, in the same units. Thus loss varies as the square of the distance.

To overcome attenuation, the transmitted signal strength need to be increased so that the received signal have sufficient strength to detect the signal and the signal must maintain a level sufficiently higher than the noise to be received without error. The attenuation problem is dealt with the use of amplifiers or repeaters. Techniques are also available for equalizing attenuation across a band of frequencies. For voice-grade telephone lines, loading coils are used that change the electrical properties of the line which smooth out attenuation effects. Another approach is to use amplifiers that amplify high frequencies more than lower frequencies.

Delay Distortion

Delay distortion happens due to the signal velocity through a guided medium. For a bandlimited signal, the velocity is likely to be highest near the center frequency and decrease towards the edges of the band. Thus different frequency components of a signal will arrive at the receiver from different directions with different times, creating phase shifts between the different frequencies component. Delay distortion is critical for digital data, because some of the signal components of one bit position will spread out into other bit positions, causing intersymbol interference. This is a major limitation to achieve maximum bit rate over a transmission channel [1].

Noise

For any communication system, the received signal consists of the transmitted signal which is modified by the transmission impairments, plus additional unwanted signal, referred to as noise, that are added anywhere between transmission and reception. Noise is a major issue in communication system performance. Thermal noise cannot be purged and therefore places an upper bound on communication system performance; and. is mainly important for satellite system. Thermal noise is generated from the thermal agitation of electrons in all electronic devices and transmission media and is a function of temperature. Thermal noise is evenly spread across the bandwidths usually used in communication systems and hence is often referred to as white noise.

Intermodulation noise is generated due to transmission of signals at different frequencies sharing the same transmission medium. Due to the intermodulation noise, the signals are produced at a frequency that is the sum or difference of the two original frequencies or multiples of those frequencies, thus probably create interference with services at these frequencies. It is produced by nonlinearities in the transmitter, receiver, and/or intervening transmission medium.

2.6 Data Transmission

The successful transmission of data mainly depends on two factors: the quality of the signal being transmitted and the characteristics of the transmission medium. There are a variety of impairments that can distort or corrupt a signal. The chief impairments are attenuation, delay distortion, noise. For digital transmission these impairments limit the data rate. Data rate is the maximum rate at which data can be transmitted over a given communication channel, under given conditions. There are four parameters that are related to one another—data rate, bandwidth, noise and bit error rate and determine channel capacity.

- Data rate, in bits per second (bps), at which data can be transmitted
- Bandwidth depends on the nature of the transmission medium, expressed in cycles per second, or Hertz
- Noise, average level of noise exists over the communications bandwidth
- Error rate is the rate of error, at which errors occur, where the error was the reception of 1 when a 0 was transmitted or the reception of a 0 when a 1 was transmitted.

All the transmission channels are of limited bandwidth due to the physical properties of the transmission channel or intentionally limited the transmission bandwidth to prevent interference from other sources. The ultimate goal is to make an efficient use of available bandwidth as much as possible. For digital data, this means that we would like to get as high data rate as possible at a particular error rate for a given bandwidth. The main constraint on achieving this high data rate is noise.

2.6.1 Nyquist Information Capacity

Nyquist showed that the theoretical minimum bandwidth needed for the baseband transmission of R_s symbols per second without ISI is $R_s/2$ Hz. If the transmitted signals are binary (two voltage levels), then the data rate that can be supported by B Hz is 2B bps. However, signals with more than two levels (i.e. multi-level signaling) can be used; that is, each signal element can be represented by more than one bit. For example, if eight possible voltage levels are used as signals, then each signal element can be represented by using three bits. With multilevel signaling, the Nyquist formulation becomes

$$r_b = 2B_T \log_2(L), \tag{2.4}$$

where, L is the number of discrete signal or voltage levels. Thus, for a given bandwidth, the data rate can be increased by increasing the number of voltage levels. However, this imposes an augmented burden on the receiver, as it must differentiate one of L possible signal elements. Noise and other impairments on the transmission channel will limit the practical value of L. However, there is absolute maximum of information capacity that can be transmitted in a channel. This is called as (Shannon's) channel capacity, which is given in the next section.

2.6.2 Shannon Capacity

There is a relationship among data rate, noise, and error rate. Due to the presence of noise, one or more bits can be corrupted i.e. efficient transmission is controlled by noise. If the data rate is increased, then the bits become "shorter" so that more bits are affected by a given pattern of noise. Mathematician Claude Shannon developed a formula relating these.

Shannon's result is that the maximum channel capacity, in bits per second, complies with the equation shown below. C is the capacity of the channel in bits per second and B is the bandwidth of the channel in Hertz. For a channel with received signal power, S additive white noise with received noise power, N. The Shannon formula represents the theoretical maximum that can be achieved. In practice, however, only much lower rates are achieved, in part because formula only assumes white noise (thermal noise).

$$C = B\log_2(1 + S/N)\,\text{bps} \tag{2.5}$$

For a certain level of noise power, the ability to receive data correctly in the presence of noise depends on the signal strength. The signal-to-noise ratio (SNR, or S/N) is an important parameter that sets an upper bound on the achievable data rate. Typically, this value of S/N ratio is measured at the receiver, because it is at this point that an attempt is made to process the signal to recover the data. For the convenience, this ratio is often reported in decibels. This expresses the amount, in decibels, that the intended signal exceeds the noise level. A high SNR will mean a high-quality signal and a low number of required intermediate repeaters.

However, Shannon theory does not tell you how to design real communication systems. Shannon theory predicted a maximum modem speed of 32 Kbps in 1949. Today, we have 56 Kbps modems.

Problem 2.2
A mobile communication system uses a radio channel of bandwidth 30 kHz. with an intended capacity of 180 Kbps. What signal to noise ratio is required to achieve this capacity (considering AWGN)?

Solution

Given,

Channel Capacity, C = 180 Kbps = 180×10^3 bps
Channel Bandwidth, B = 30 kHz = 30×10^3 Hz
Find SNR = ?

According to Sahnnon's Channel Capacity,
The theoretical bit rate, $C = B \times \log_2(1 + SNR)$
$180 \times 10^3 = 30 \times 10^3 \log_2(1 + SNR)$
$1 + SNR = 2^6$
$SNR = 2^6 - 1$
$SNR = 63$
$SNR_{dB} = 18.06$ dB (ans).

2.7 Wireless Propagation

A radio signal radiated from antenna propagates through atmosphere in a path between transmitter and receiver. There are two different waves (ground wave and sky wave) of carrying messages from the transmitter to a receiver. The ground wave is used for short-range communications with high frequencies and at low power, and for long-range communications at low frequencies and with very high power. Daytime reception from most commercial radio stations operating in the medium frequency (MF) band is carried by the ground wave.

The sky wave is used for long-range, high frequency communications. Due to varying ionospheric conditions, the daylight frequencies for sky wave propagation are somewhat higher thin at night.

2.7.1 Ground Wave Propagation

The ground wave consists of two separate components called the space wave and the surface wave. The classification of ground wave components lies in whether the component wave is traveling along the surface of the earth or over the surface. One factor is that the electromagnetic wave induces a current in the earth's surface which slows the wave front near the earth, causing the wavefront tilt downward and hence follows the earth's curvature. The other factor is diffraction due to the presence of obstacles (Fig. 2.7).

2.7.2 Sky Wave Propagation

The sky wave, often referred to as the ionospheric wave, is radiated in an upward direction and it returns to the earth at some distant place. The return point is due to refraction from the ionosphere. The sky wave travels through a number of hops, bouncing back and forth between the ionosphere and the earth's surface. This form of propagation is relatively unaffected by the earth's surface and is capable the HF Band (3–30 MHz) is used in sky wave propagation (Fig. 2.8).

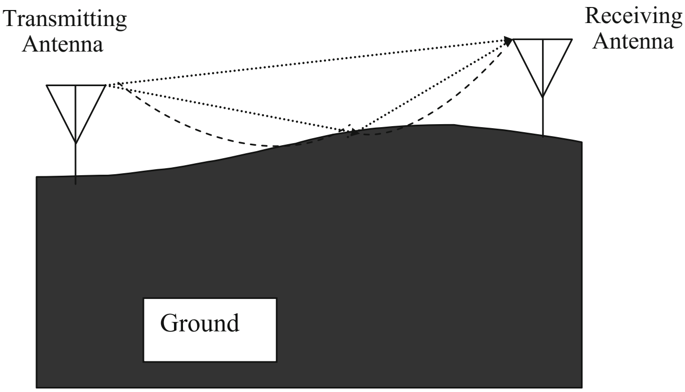

Fig. 2.7 Schematic diagram of ground wave propagation

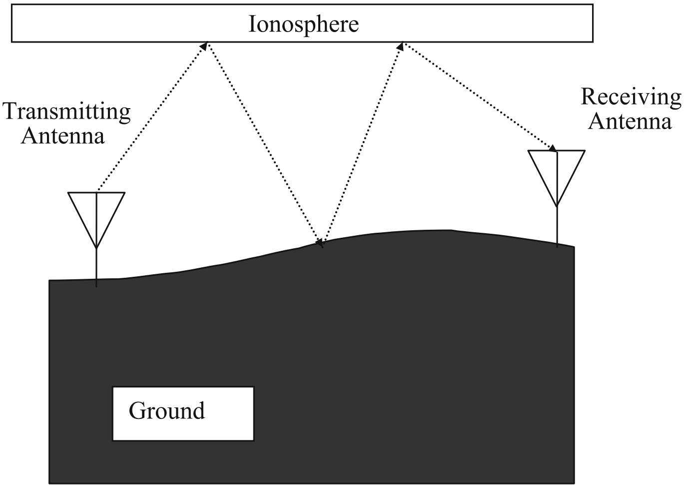

Fig. 2.8 Schematic diagram of sky wave

The critical frequency is the limiting frequency at or below which a radio wave is reflected by an ionospheric layer. Radio waves which are higher than the critical frequency of a given ionized layer will pass through the layer and be lost unless refracted by an upper, more densely ionized layer operating with a higher critical frequency. Radio waves of frequencies lower than the critical will be refracted back to the earth. The critical frequency can be determined using the following formulae:

Critical Frequency, $f_c = 9\sqrt{N}$; where, N is equal to the number of electrons per cubic meter.

Problem 2.3
Calculate the critical frequency if the maximum electron density (N_{max}) of the layer used is 4×10^{11} electrons/m^3.

Solution

$$F_{crit} = 9\sqrt{N_{max}} = 9\sqrt{4 \times 10^{11}} = 5.693\,\text{MHz}\,(\text{Ans})$$

2.8 Propagation Mechanism

Electromagnetic waves propagate through environments where they are reflected, scattered, and diffracted by walls, terrain, buildings, and other objects. The ultimate details of this propagation can be obtained by solving Maxwell's equations with boundary conditions that express the physical characteristics of these obstructing objects. The reflection, diffraction and scattering mechanisms are briefly explained in this section. Reflection occurs when a propagating electromagnetic wave strikes upon an object which has large dimension in compare to the wavelength of the propagating wave. Reflections occur from the surface of the earth and from buildings and walls.

Diffraction occurs due to the presence of obstacle in between the transmitter and receiver that has large scale irregularities (edges) such as hills, trees, or buildings. It allows radio signals to propagate behind the obstacles. The amount of loss depends on the shape of terrain elevations, the electrical characteristics of the ground, the frequency of operation and the extent of Fresnel zone obstruction between the transmitter and receiver.

Scattering occurs when the medium through which the wave travels consists of objects with dimensions that are small compared to the wavelength, and where the number of obstacles per unit volume is large. Scattered waves are produced by rough surfaces, small objects, or by other irregularities in the channel.

In wireless communication, a line-of-sight (LOS) path seldom exist due to the presence of different obstacles between transmitter and receiver. Even if, there are no other sources of attenuation in case of LOS transmission, the transmitted signal can realize attenuation as the signal is being dispersed over distance. This form of attenuation is called free space loss. To calculate the free space loss, consider a signal transmitted through free space to a receiver located at distance d from the transmitter.

$$P_r(d) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2 L}, \tag{2.6}$$

$$Path\,loss = 10\log_{10}\frac{P_t}{P_r} = -10\log_{10}\left[\frac{G_t G_r \lambda^2}{(4\pi)^2 d^2 L}\right]$$

where, $P_r(d)$ is the received signal power at distance d from the transmitter, P_t is transmitted power, G_t and G_r are transmitter and receiver antenna gains respectively, λ is the wavelength and L is the system loss factor. The received power is proportional to $1/d^2$ or d^{-2} but in real life measurement the received power signal level tends to follow a d^{-n} curve, where n is the number typically between 2 and 6, referred to as the *path loss exponent*.

2.9 Sample Questions

1. What are the primary functions of transmission systems?
2. What is attenuation?
3. Define channel capacity.
4. What key factors affect channel capacity?
5. A digital signaling system is required to operate at 9600 bps.
6. If a signal element encodes a 4-bit word, what is the minimum required bandwidth of the channel?
7. Repeat question (6) for the case of 16 bit words.
8. Define channel capacity. A channel with an intended capacity of 20 Mbps and the bandwidth of 3 MHz is given. Calculate the required signal to noise ratio to achieve this capacity. Assume white thermal noise.
9. What is the difference between guided media and unguided media?
10. What is the difference between shielded and unshielded twisted pair cable?
11. Describe the components of optical fiber cable.
12. Distinguish between the terms ground wave and sky wave used in radio wave propagation.
13. What is the difference between diffraction and scattering?

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