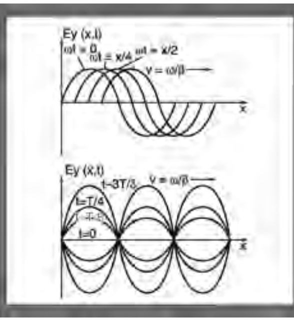
Chapter 1



Basics of Wave Propagation

Topics in this chapter include:

- Introduction
- Definition and broad categorization
- Wave classification
- Wave environment
- Modes of wave propagation
- Noise
- Ray and mode concepts
- Wave applications

1–1 Introduction

Modern radio engineering is one of the most powerful tools in spreading the scientific and technical knowledge and the fruits of its progress among the masses. It has penetrated all branches of national and international economy, science, industry, culture and our everyday life. One of its most important applications involves long-distance communication by means of electromagnetic waves.

The electromagnetic spectrum encompasses a frequency range from a small fraction of a hertz to 10^{20} Hz and even more. The term *radio wave* is arbitrarily applied to electromagnetic waves in the frequency range from 0.001 to 10^{16} Hz. In terms of wavelength, the lower limit of radio waves propagated in free space (or vacuum) is 3×10^{11}m and the upper limit is 3×10^{-8} m. The frequencies down to a few thousandth of a hertz are involved in some natural phenomena. Such frequencies, for example, are generated by fluctuations of the solar electron proton stream as it penetrates the earth's atmosphere. These waves are closely related to magneto-hydro-dynamic waves (mechanical waves produced by the ion plasma of the atmosphere). Lightning discharges also produce these waves. The frequency of 0.001 Hz is an arbitrary limit, which may go down with further advances in scientific knowledge. The lower limit of the frequencies used by transmitters is normally set to be 10^3 Hz. On the higher side, radio wave spectrum presently extends to the limit of 10^{16} Hz.

It is customary to divide the entire radio spectrum into bands on decimal basis, with bands named according to the frequency or wavelength they encompass. This division of radio waves (included in Table 1–2) helps not only in the study of characteristics of waves but also in identifying different applications and the design of transmitters, receivers, antennas (or channels in case of guided waves). The UHF and SHF, sometimes also referred as microwave and millimetric wave, are further classified into sub-bands as given in Table 1–2.

The waves longer than 10^5m (sub-audio and audio waves) have little or no commercial usage and are employed solely in research. The waves having wavelengths between 10^3–10^5 m, find applications in sub-marine and mine communication, since they can penetrate deeper into water and earth. Besides, the waves having extremely high frequencies (or extremely short wavelengths) of terra hertz (THz) range are now gaining ground in optical communication systems owing to their high bandwidth capability, very high speed and several other significant advantages.

1–2 Definition and Broad Categorization

1–2a Basic Definition

An electromagnetic wave can be conceived in terms of electric and magnetic field vectors **E** and **H.** These vectors obey the mathematical relations $\nabla^2 E = \mu\varepsilon\partial^2 E/\partial t^2$ and $\nabla^2 H = \mu\varepsilon\partial^2 H/\partial t^2$ respectively. Study of these wave equations leads to the following definition:

"If a physical phenomenon that occurs at one place at a given time is reproduced at other places at later times, the time delay being proportional to the space separation from the first location, the group of phenomena constitutes a wave. The term *wave* also has an entirely different usage, viz, a recurring function of time at a point, as in the expression of sinusoidal voltage wave. A wave, however, may not necessarily be a repetitive phenomenon in time."

Depending on the nature and location of space encountered, some or all the characteristics of a propagating wave may get altered. The possible phenomena which may lead to characteristic modifications may include reflection, refraction, diffraction, absorption and the rotation of plane of polarization. These are mainly due to variation of media parameters (σ, ε and μ) on the way or the shape and characteristics of obstructing objects. The paths to be adopted by the electromagnetic waves to arrive at the destination (normally, a receiving antenna) may thus differ from situation to situation. These may also depend on the heights of transmitting and receiving antennas, the angle of launch of electromagnetic energy into the space, the frequency of operation, the polarization and other factors. In view of variations, factors, applications and situations, electromagnetic waves can be classified in a number of ways (as subsequently discussed). But before that, the wave study may broadly be categorized as under.

1–2b Guided Waves

These include the waves guided by manmade structures such as parallel wire pairs, coaxial cables, wave-guides, strip lines, optical fibers, etc. Guided waves have a very large sphere of applications for signal and data communication. Long haul telephone trunk lines such as Trans-Atlantic-coaxial cables, wire pairs and cables used in local area networks (LAN), closed circuit TV, interconnections used for providing Internet services, cable networks used by cable TV operators and networking of computers located in the same room, building, locality or campus. These are only a few applications where waves are guided through transmission structures.

1–2c Unguided Waves

These include waves propagating in the terrestrial atmosphere, over and along the earth and in outer space. Unguided radio waves also find many and extremely important applications in science and engineering and the sphere of these applications is increasing day by day. These include the transmission of information over short and long distances through telegraphy and telephony, radio broadcast, television, mobile communication, satellites, radars, telecontrol, radio location, radio navigation, remote sensing and distance measurements by radio means. Unguided propagation is also used in geophysics, in the study of upper atmosphere, radio astronomy, study of activities of sun, stars and nebulae inside and outside our galaxy. The most common features of all (guided or unguided) waves are that they all employ a radio circuit or link, consisting of a transmitter, a receiver and a propagation medium. The order of distances involved between transmitting and receiving points may vary from very small to very large. Table 1–1 illustrates the probable distances between

Table 1–1 Probable physical distances between processors

Sl. No.	Inter-processor distances	Processor located in the same:	Example
1	$\leq$ 0.1 m	Circuit board	Data flow in machines
2	1 m	System	Multi-processor
3	10 m	Room	
4	100 m	Building	Local network
5	1 km	Campus	
6	10 km	City	Long haul network
7	100 km	Country	
8	$\geq$ 1000 km	Country, Continent, Planet	Interconnection of long haul networks

transmitters and receivers (or processors). These distances may be quite short located in the same circuit board or may be quite large as in different continents or even planets.

From the above, it is evident that the study of different aspects of wave propagation is immensely important and useful for any student of the communication stream of engineering and for those working in communication-related industries. These aspects may include various modes of propagation, the types and basis of classification of radio waves, the environment faced by the propagating wave, the characteristics exhibited by waves therein and the applications of waves in different ranges of frequency.

1–3 Classification of Electromagnetic Waves

The energy generated by a transmitter is fed to a transmitting antenna which in turn radiates the same into the space. This radiated energy travels all through the space and this mode of travel is termed as electromagnetic wave. Basic definition of the wave along with its governing equations has been given earlier in Section 1–2a.

1–3a General Classification

Plane wave In phasor form, a plane wave is defined as one for which the equiphase surface is a plane.

Uniform plane wave If the equiphase surface is also an equiamplitude surface, the wave is called a uniform plane wave. A uniform plane wave progressing in the direction z (say), will have no E_z component. It, however, may have E_x and/or E_y component(s), i.e., in a uniform plane wave E is entirely transverse. In a uniform plane wave, E and H are at right angles (orthogonal) to each other.

Non-uniform plane wave In a non-uniform plane wave, the equiphase and equiamplitude surfaces are neither same nor they are parallel. Also, in a non-uniform plane wave, E and H need not necessarily be orthogonal.

Slow wave When the phase velocity normal to the equiphase surfaces is less than the velocity of light 'c', the wave is referred to as a slow wave. In certain microwave devices (e.g., TWT) special structural shapes are employed to slow down the speed of the wave.

Forward wave A wave traveling in an assigned direction from the point of origin is called forward wave provided there is no hindrance to cause reflection?

Backward wave The backward wave is, in general, a reflected wave which results, when a forward wave strikes a reflecting surface. The reflection of a wave may be total or partial depending upon the conductivity and roughness of the surface it strikes. The reflection also occurs in transmission lines when it is terminated in impedance other than the characteristic impedance of the line. The word transmission line generally encompasses parallel wire lines, coaxial cables, waveguides or an optical fibre.

Traveling wave When a wave is progressing only in one direction and there is no reflected wave present, it is called a traveling wave. In such a wave, the maximas or minimas of E and H at different time instants appear at different space locations as illustrated in Fig. 1–1 (a) and (c).

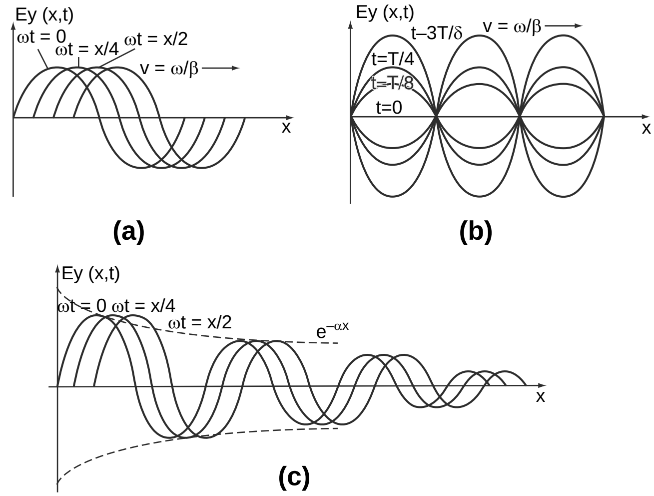


Figure 1–1 Variation of E with space parameter x in (a) traveling wave, (b) standing wave, and in (c) traveling wave with attenuation.

Standing wave If both forward and reflected waves are simultaneously present, they combine to result in a wave called standing wave. Such a wave does not progress and maximas or minimas (of E and H) for different time instants will appear at the same space location but with varying magnitudes. The traveling and standing waves are illustrated in Fig. 1–1(b).

Surface wave If a wave is supported by some kind of surface between two media, it is called a surface wave. In other words, a surface wave is one that propagates parallel to the interface and decays vertically to it. Ground waves may be composed of surface waves (originating from antennas located near to the ground) and space waves (originating from elevated antennas). In case of strip lines, the wave travels as a surface wave.

Trapped wave Sometimes a surface wave is also called a trapped wave because it carries its energy within a small distance from the interface. This wave does not radiate except at discontinuities, such as the termination of the structure. A traveling wave carried by a two-wire line with discontinuities placed at regular intervals along the line is a surface wave. The ducting phenomenon in space wave mode of propagation also amounts to trapping of the wave within its lower and upper bounds.

Leaky wave When discontinuities are densely placed along the line, making it a continuous perturbing structure, another type of traveling wave results and is a called a leaky wave. There is some leakage of energy mainly from the top bounds of the duct.

1–3b Classification Based on Orientation of Field Vector

A wave may also be classified according to the polarization or time-varying behavior of the electric field vector **E** at some fixed point in space. A wave may be polarized *along x/y* direction or it may be *linearly*, *circularly* or *elliptically polarized*. Further, the circularly or elliptically polarized wave may have a *left-hand* or a *right-hand sense*.

Besides, if in a wave **E** is parallel to the boundary surface or perpendicular to the plane of incidence (i.e., a plane containing the incidence ray and the normal to the surface), the wave is termed *horizontally polarized*. In case **E** is perpendicular to the boundary surface or parallel to the plane of incidence, it is called *vertically polarized*. These waves originate from the horizontal and vertical antennas respectively with reference to the surface of the earth. However, it is seen that, whereas **E** of a horizontally polarized wave is horizontal, **E** of a vertically polarized wave is not wholly vertical but has some horizontal component. More appropriate designations, therefore, are *perpendicular* and *parallel polarization*, to indicate that **E** is perpendicular or parallel to the plane of incidence.

1–3c Classification Based on the Presence of Field Components

The wave propagating between two parallel planes or waveguides assumes altogether a different nomenclature, namely, *transverse electric* (TE) or **H** *wave* and *transverse magnetic* (TM) or **E** *wave*. In a transverse electric wave, **E** has no component in the direction the wave progresses, and in a transverse magnetic wave, **H** has no component in the direction of propagation. Thus, in an H wave, E is entirely transverse, whereas in E wave H is entirely transverse. A special case, which results from TM wave, only in case of parallel planes, is that of *transverse electromagnetic (TEM)* also termed as **EH** or **HE** *wave*. In a TEM wave, **E** and **H** both are transverse and there is no component of **E** or **H** in the direction the wave progresses. The use of TEM waves is mainly confined to the parallel plane / parallel wire transmission line. Since the cutoff, i.e., the lowest limit of frequency for a TEM wave is zero, it is best suited where low frequency transmission is involved such as power lines. The other two (TE and TM) modes of propagation are commonly used in waveguides and coaxial cables in view of their high cutoff frequencies. The nomenclature of E wave, H wave, EH / HE wave is more frequently used for waves propagating in optical fibers while TE, TM and TEM terminology is generally assigned to waves traveling between parallel planes and in wave guides.

1–3d Classification Based on Modes of Propagation

In case of long distance unguided waves, the communication link may be established through *ground waves*, *space waves* or *sky waves*. The selection of a particular mode depends on frequency range and applications. Table 1–2 shows modes of wave propagation used in different ranges of frequencies. As evident from the table, in some of the ranges more than one mode of propagation is employed. Figure 1–2 illustrates the above and the ranges in which the waves (i) are vertically or horizontally polarized, (ii) follow curved or straight line paths, (iii) are fully absorbed/reflected, and partly absorbed/reflected by different layers of the ionosphere, and (iv) penetrate in earth and water.

Table 1–2 Modes of radio wave propagation$^{\chi}$

Sl. No.	Frequency band	Short range	Long range Day	Long range Night
1	ELF	Ground and ionospheric waves	Ionospheric wave	Ionospheric wave
2	VLF			
3	LF			
4	MF	Ground wave	Ground	
5	HF		Ionospheric	
6	VHF		Ionospheric, Tropospheric, Direct	Ionospheric wave Tropospheric wave, Direct wave
7	UHF		Tropospheric wave, Direct wave	Tropospheric wave, Direct wave
8	SHF			
9	EHF	Direct wave	Direct wave	Direct wave
10	Optical band			

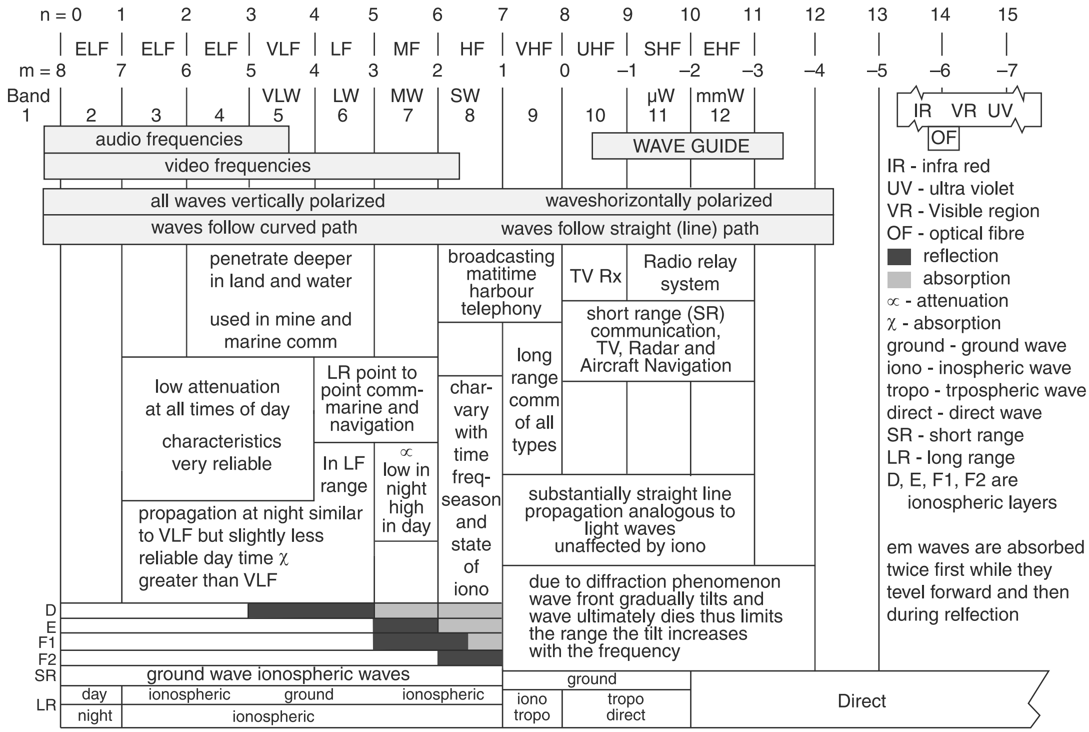


Figure 1–2 Wave characteristics in different frequency bands.

1–4 Wave Environment

The study of wave propagation requires a complete understanding of the nature and characteristics of media, which a wave may encounter during the course of its travel. An electromagnetic wave is visualized in terms of the variations of electric and magnetic field quantities with space and time. These quantities are susceptible to the changes in media parameters (ε, μ, and σ). Thus the media require an in-depth study and must be classified so as to spell the true nature of variations in space and time. The following terminology is normally used to define a media.

Homogeneous/non-homogeneous media A homogeneous medium is one for which ε, μ and σ are constant throughout the medium. If either of these parameters (ε, μ and σ) has different values at different locations, the media is called heterogeneous or non-homogeneous.

Isotropic/anisotropic media A medium is isotropic if ε (or μ) is a scalar constant, so that **D** and **E** (or **B** and **H**) have the same direction everywhere. If either of the media parameters varies with the space parameters, **D** and **E** (or **B** and **H**) will have different orientations and such a media is termed as anisotropic/non-isotropic.

Source-free region A source-free region is one in which no impressed voltages or currents (i.e., no generators) are present.

Though the above classification is also valid in case of wave propagation but in view of different propagation modes altogether different nomenclature is used in connection with the waves. These are as given below.

Troposphere It is a region containing atmosphere and almost all weather phenomena including cloud formation takes place here. It extends from the earth's surface to nearly 8 to 10 km at poles, 10 to12 km for moderate latitudes and 16 to 18 km at the equator. With the exception of water vapour content which strongly depend on weather conditions and sharply decrease with height, the percentage of gas components does not vary with height. The temperature of troposphere decreases with height at an average rate of 6 degree/km. There may be a lot of turbulence because of variations in temperature, pressure and density. These conditions have a profound effect on the propagation of radio waves. The upper boundary of the troposphere is called *tropopause* which is a narrow region of constant temperature.

Stratosphere This region is located between the troposphere and ionosphere and extends from upper limit of troposphere to the lower limit of ionosphere. The temperature throughout this region is almost constant and there is little water vapor present. In this region matter is partly ionized. Because it is relatively calm region with little or no temperature change, the stratosphere has almost no effect on radio waves.

Ionosphere This region extends from limits of stratosphere to nearly 400 to 500 km into space and is the most important region of the earth's atmosphere for long-distance point-to-point communication. In this region, matter is totally ionized. Since the existence of the ionosphere is directly related to the radiations emitted from the sun, the movement of the earth about the sun or change in the sun's activity results in variations in the ionosphere. These variations are generally categorized in accordance with their occurrence and can be termed as regular and irregular. The regular variations more or less occur in cycles and, therefore, can be predicted with reasonable accuracy. The irregular ones are the result of abnormal behaviour of the sun and cannot be predicted. Both regular and irregular variations affect the radio wave propagation to the tune of their severity. The regular variations can be divided into daily, 27-day, seasonal and 11-year variations.

The daily variations are the result of ultraviolet energy radiated by the sun. It results in the formation of four cloud-like layers of electrically charged gas atoms called *ions* through a process called *ionization*. The high-energy ultraviolet light waves of differing frequency emanated from the sun enter the atmosphere and strike neutral gas atoms to make some of their electrons free. The atoms from which the electrons are librated become positively charged and are called *positive ions*. The ultraviolet rays of higher frequency penetrate deeper than those of the lower frequency. Thus, higher frequency rays result in the formation of lower ionized layers whereas the lower frequencies form the upper layers. The ion density contents of these ionized layers are determined by the location of the sun or more specifically its elevation angle. In view of the frequent change in the sun's location, the height and thickness of the ionized layers keeps on changing with the time of the day and the seasons of the year. It is to be noted that the ionization process is not a stable phenomenon. The freed electrons and the positive ions keep on colliding with each other. In the process some of them recombine and the positive ions return to their original neutral state. Like ionization, the recombination process also depends on the time of day. Between early morning and late afternoon, the ionization process dominates since the radiation from sun in this period is more intense. During this period, the ionized layers have the greatest density and have maximum influence on the wave propagation. From late afternoon to early morning the recombination process dominates and results in reduction of layer densities. Further details about the referred four layers are incorporated with the discussion of sky wave propagation.

Besides the four ionized layers, there are certain belts containing ionized particles and are capable of influencing wave propagation. These radiation belts called Van Allen Belts (VAB) occupy the outer region of the ionosphere and are referred as VAB-1, VAB-2 and VAB-3, girdling the earth and consisting of the charged particles trapped by the terrestrial magnetic field, having the shape of magnetic lines of force. Within these radiation belts, the charged particles are in oscillatory and rotational motion along and around the magnetic lines of force. Some more details related to these belts are as below.

VAB-1 The inner belt is situated in the interval of geomagnetic latitudes between $\pm$ (35° to 40°). In the plane of the geomagnetic equator, it begins at an altitude of about 600 km in the Western Hemisphere and 1600 km in the Eastern Hemisphere and extends out to a distance of about an earth radius. Protons with an energy of 10^8 electron volts and electrons with an energy of 10^6 electron volts occupy the inner zone. These particles are presumably produced by the decay of the neutrons emitted by the earth's atmosphere under the action of cosmic rays.

VAB-2 The outer belt begins at an altitude of about 20,000 km in the plane of the geomagnetic equator and extends out to a distance of seven earth radii. This belt has the shape of a horseshoe and comes within 300 to 1,500 km of the earth's surface in the interval of geomagnetic latitudes between $\pm$ (55° to 70°). The outer part of this belt appears to be filled with particles of solar origin energies from a few tens of kilo-electron volts to mega electron volts.

VAB-3 The third radiation belt occurs in the interval of distances from 55,000 to 75,000 km (8.5 to 11.5 earth radii). It is filled with electrons of relatively low energies, but greater than 200 electron volts. Its size depends on the extent of geomagnetic disturbances.

In case of ground waves, the environment nearer to the earth's surface and the roughness of the earth surface and the electrical properties of the earth are of prime importance. In case of ionospheric (sky) wave propagation, the structure and characteristics of the ionospheric layers; their hourly, seasonal and yearly variations and effect of sunspots and other solar activities are of importance. For space waves, the refractive index profiles (which depend on temperature, pressure and humidity, etc.) are the decisive factors for proper establishment of communication. If the destination of a wave is a geo-synchronous satellite, Moon, a planet or any other object far removed from earth, the wave may have to pass through the Van Allen belts which are related with solar activity and the earth's magnetic field. Thus, before establishing a communication link, the distance to the destination and the hazards to be faced by the wave are to be systematically explored.

1–5 Different Modes of Wave Propagation

The energy radiated from a transmitting antenna may travel all through space with (or without) alteration in its characteristics, after refraction due to variation of media parameters on the way or after reflection from obstructing objects including earth surface to arrive at the receiving antenna. The path to be adopted by the electromagnetic waves to arrive at the receiver will not only depend on the characteristics of the space between the two antennas and the angle of launch of the energy into the space but will also be affected by many other factors. Figure 1–3 illustrates many possible propagation paths.

The wave (marked 1) adopts a *straight-line path* in free space and is sometimes referred as *direct wave (DW)*. The wave (marked 2) adopts a *curved path* in view of refraction phenomena in the atmosphere. The wave (marked 3) reflected or scattered in the troposphere is termed as *tropospheric wave*. This mode of propagation is the result of irregularities of troposphere, which extends to nearly 10 to 15 km from the earth surface. The communication utilizing the tropospheric waves is called *tropospheric communication*. The wave (marked 4) reaching the receiver after getting refracted and reflected from the ionosphere, is called *ionospheric or sky wave (SKW)*. This is sometimes also referred as ionospherically reflected or ionospherically scattered wave. This mode of propagation is used for *beyond the horizon communication* or very long distance communication and is operated in high frequency (HF) range. This mode is also employed in over-the-horizon (OTH) radars. The wave (marked 5)

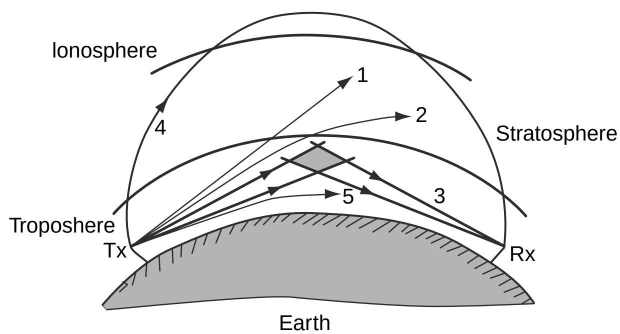


Figure 1–3 Different modes of wave propagation.

propagating over paths near the earth's surface is often referred as *ground wave (GW)*. Ground (surface) waves are vertically polarized and exist if antennas are close to earth. All *broadcast signals in daytime* are ground waves. Beside broadcasting, these are also used for *ground wave radars*.

In view of the Sommerfeld analysis, the ground wave is divided into two parts, namely, the surface wave (SUW) and the space wave (SPW). The space wave predominates at larger distances above the earth, whereas the surface wave is more significant near the earth's surface.

Space wave is made up of the direct wave (comprising the signal reaching the receiver through the straight path from the transmitter) and the ground reflected wave (containing the signal arriving at the receiver after reflection from the surface of the earth). Such waves are used for beyond-the-horizon communication. Space waves are the only means of communication beyond the 30-MHz range. A surface wave also includes the energy received as a result of diffraction around the earth's surface and reflection from the upper atmosphere.

1–6 Wave Applications

The electromagnetic waves encompass a variety of applications ranging from radio and TV broadcast to radars and satellites. Some of the wave applications along with the frequency range of communication systems are illustrated in Figs. 1–2 and 1–4.

One of the most important applications of wave propagation is related to the time and frequency standards. Almost for all space vehicles, aircrafts and ships, for their takeoff, landing/docking, parking and for transmitting and receiving messages and commands, it is necessary that an accurate time schedule is observed. This requires an accurate measurement of time and frequency. The propagation time from one point to another for a VLF wave can be very accurately measured and the variations therein, can be predicted and compensated up to a great extent. The diurnal variations obtained at the NWC station in Australia operating at 22 kHz are about 50 μs. Thus, the time standard can be obtained up to 50 μs accuracy. Since the propagation delay varies less if observed at the same time every day, the measurement accuracy can be further improved by applying correction factors for the time of day. The measurement of stable propagation delay automatically leads to the

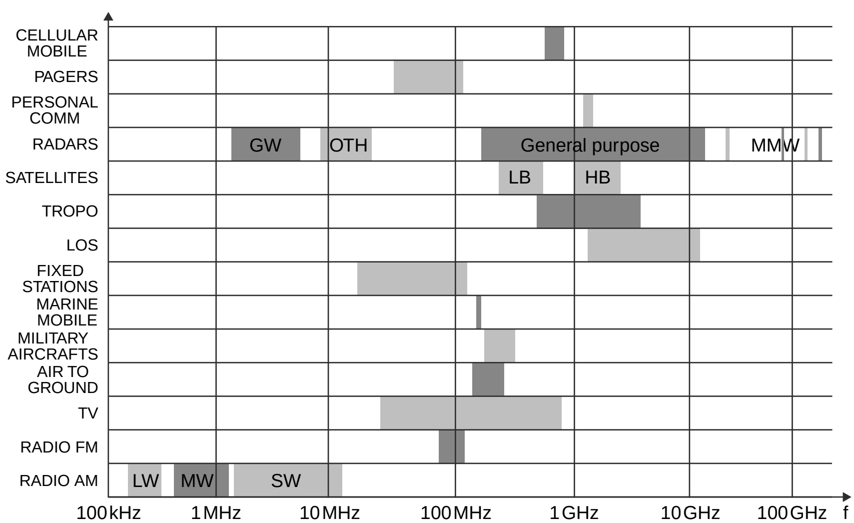


Figure 1–4 Communication Services through Un-guided waves.

stable measurement of frequency. A VLF transmitter transmitting power of the order of MW, at an accurately monitored frequency and modulation can provide time and frequency standards for across the globe as far as 10,000 km.

1–7 Noise

Noise is the classical limitation of electronic devices and communication systems. The noise and distortions limit the range of processing and detection devices, measurement techniques and make the results erroneous. Noise can be defined as an *unwanted electromagnetic signal*. With addition of noise, the amplitude and/or the phase of the desired signal may get altered. Noise can be broadly categorized as internal and external. *Internal noise* occurs due to random motion of electrons in most of the electronic devices. Due to the involvement of a very large number of such electrons and independency of their motion, variations in current flow are bound to exist. These random variations can be only statistically accounted. In the context of wave propagation, the internal noise is relatively of lesser significance. *External noise* is of greater significance and requires a little more attention **i**n the scenario of wave propagation. The external noise generally includes manmade interference, atmospheric noise, cosmic noise and thermal noise**.** These constituents are briefly described below.

Manmade interference Electrical motors, home appliances, induction heaters, automobile ignition and other industrial and household electrical plants are the major contributors to this type of noise. It is stronger in big cities. The vertically polarized waves, nearer to the earth, are more likely to be affected by manmade interference since such interference, by nature, is mainly vertically polarized. Therefore, in applications, viz., TV and FM broadcasting horizontally polarized waves are generally preferred in order to discriminate from vertically polarized interference.

Atmospheric noise It is also called *precipitation static*. Its main cause is the natural occurrence of lightning flashes. About 100 lightning discharges occur every second around the globe, mostly in tropical belts of the continents.

Cosmic noise It is the main source of interference in metric waves and is a result of emissions from various radio sources from in and outside our galaxy and from the sun. The quantum of impact of the sun depends on its quite and disturbed states.

Thermal noise The re-radiation of the energy, absorbed by water vapour (at about 22 GHz) and oxygen molecules (at about 60 GHz), is the major cause of thermal noise.

1–8 Ray and Mode Concepts

In the subsequent chapters, the terms ‘ray’ and ‘mode’ are frequently used. *Ray* is defined as the perpendicular drawn to an equiphase plane and the term ‘*mode*’ was introduced in Section 1–3. There are mainly two methods of analyzing the wave phenomena. These are referred as ‘ray theory’ and ‘mode theory’. *Ray theory* is applicable only if the distance between two reflecting layers is several wavelengths long; while for shorter distances, *mode theory* is normally employed. When using ray theory, a surface wave needs to be separately taken into account, whereas it is not necessary in mode theory. The surface wave that is of importance is the *Norton surface wave*. The attenuation of the surface wave as a function of distance is strongly dependent on the ground conductivity. Effects of ionosphere are relatively un-important. At VLF, waves can be analyzed either by ray theory or mode theory. In fact, ray theory would be valid only at the upper edge of the VLF range or in the LF range. In ray theory, the phases and amplitudes of all rays that can reach a given observation point from a given origination point are calculated. If the receiver is very far (>2000 km) from the transmitter then the number of hops (i.e., number of times the wave gets reflected) becomes very large and mode theory calculations are preferred.

The modes of propagation in the earth–ionosphere cavity are similar to the modes of propagation between parallel conducting plates. The ionosphere and the earth both act as good reflectors especially in the lower VLF range. For rigorous treatment of the problem, one must assume a spherical earth and take appropriate models of electron and collision frequency variations with height. To understand mode theory, the problem can be simplified by assuming the earth to be flat and the ionosphere to begin abruptly at a height h above the earth. Effective reflection coefficients (in general, complex quantities) for both parallel and perpendicular polarization at ground and at lower edge of ionosphere can be calculated. The simplest mode of propagation is the TEM mode with zero cutoff frequency. For TE and TM modes, the cutoff frequencies are much higher. TEM mode is dominant only at frequencies below 1 kHz. At higher frequencies, losses are too high.