EC8701 ANTENNAS AND MICROWAVE ENGINEERING

L	T	P	C
3	0	0	3

OBJECTIVES:

- To enable the student to understand the basic principles in antenna and microwave system design
- To enhance the student knowledge in the area of various antenna designs.
- To enhance the student knowledge in the area of microwave components and antenna for practical applications.

UNIT I INTRODUCTION TO MICROWAVE SYSTEMS AND ANTENNAS 9

Microwave frequency bands, Physical concept of radiation, Near- and far-field regions, Fields and Power Radiated by an Antenna, Antenna Pattern Characteristics, Antenna Gain and Efficiency, Aperture Efficiency and Effective Area, Antenna Noise Temperature and G/T, Impedance matching, Friis transmission equation, Link budget and link margin, Noise Characterization of a microwave receiver.

UNIT II RADIATION MECHANISMS AND DESIGN ASPECTS 9

Radiation Mechanisms of Linear Wire and Loop antennas, Aperture antennas, Reflector antennas, Microstrip antennas and Frequency independent antennas, Design considerations and applications.

UNIT III ANTENNA ARRAYS AND APPLICATIONS 9

Two-element array, Array factor, Pattern multiplication, Uniformly spaced arrays with uniform and non-uniform excitation amplitudes, Smart antennas.

UNIT IV PASSIVE AND ACTIVE MICROWAVE DEVICES 9

Microwave Passive components: Directional Coupler, Power Divider, Magic Tee, attenuator, resonator, Principles of Microwave Semiconductor Devices: Gunn Diodes, IMPATT diodes, Schottky Barrier diodes, PIN diodes, Microwave tubes: Klystron, TWT, Magnetron.

UNIT V MICROWAVE DESIGN PRINCIPLES 9

Impedance transformation, Impedance Matching, Microwave Filter Design, RF and Microwave Amplifier Design, Microwave Power amplifier Design, Low Noise Amplifier Design, Microwave Mixer Design, Microwave Oscillator Design

TOTAL: 45 PERIODS

OUTCOMES:

The student should be able to:

- Apply the basic principles and evaluate antenna parameters and link power budgets
- Design and assess the performance of various antennas
- Design a microwave system given the application specifications

TEXTBOOKS:

1. John D Krauss, Ronald J Marhefka and Ahmad S. Khan, "Antennas and Wave Propagation: Fourth Edition, Tata McGraw-Hill, 2006. (UNIT I, II, III)
2. David M. Pozar, "Microwave Engineering", Fourth Edition, Wiley India, 2012.(UNIT I,IV,V)

REFERENCES:

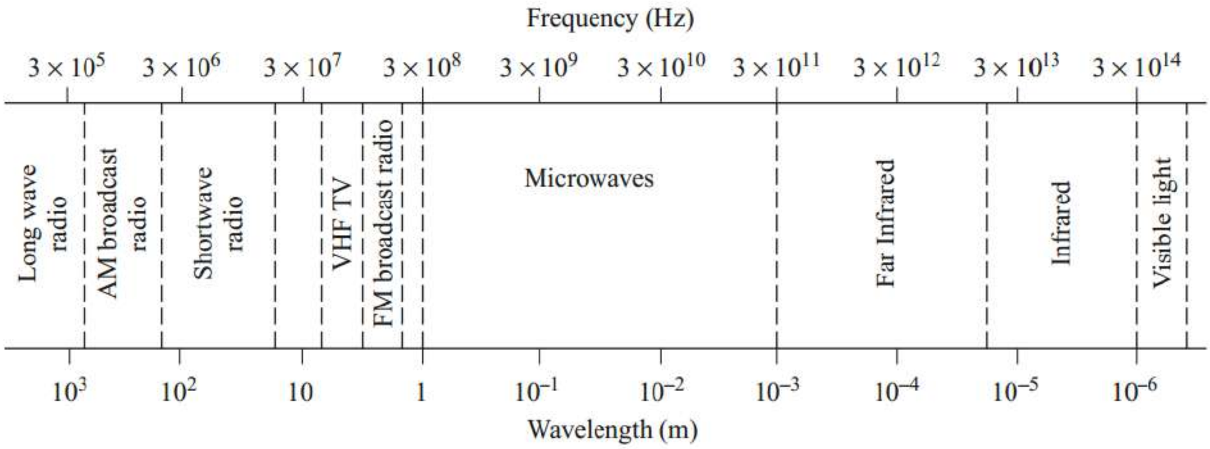
1. Constantine A.Balanis, “Antenna Theory Analysis and Design”, Third edition, John Wiley India Pvt Ltd., 2005.
2. R.E.Collin, "Foundations for Microwave Engineering", Second edition, IEEE Press, 2001

1.1 Microwave Spectrum and Bands, Historical Background

Microwaves are a type of electromagnetic radiation, as are radio waves, ultraviolet radiation, X-rays and gamma-rays. Electromagnetic radiation is transmitted in waves at different wavelengths and frequencies. This broad range of wavelengths is known as the electromagnetic spectrum (EM spectrum).

Loosely speaking, the fields of microwave and RF engineering together encompass the design and implementation of electronic systems utilizing frequencies in the electromagnetic spectrum from approximately 100 MHz to over 1000 GHz. The term microwave is typically used to describe electromagnetic waves with frequencies between 3 GHz and 300 GHz, with a corresponding electrical wavelength between $\lambda=c$[1]$/f$ = 10 cm and λ=1 mm, respectively in free space[2]. The boundary between "RF" and "microwave" is somewhat indistinct.

Electromagnetic waves with wavelengths ranging from 1 to 1mm are called millimeter waves. The infrared radiation spectrum comprises electromagnetic waves with wavelengths in the range 1µm (10^{-6} m) upto 1mm. Beyond the infrared range is the visible optical spectrum, the ultraviolet spectrum, and finally x-rays.



Several different classification schemes are in use to designate frequency bands in the electromagnetic spectrum.

As a matter of convention, the ITU divides the radio spectrum into different bands, each covering a decade of frequency or wavelength.

Frequency Band	Designation	Example uses
3–30 Hz	Extremely low frequency (ELF)	Submarine communication
30–300 Hz	Super low frequency (SLF)	Submarine communication
300–3000 Hz	Ultra low frequency (ULF)	Submarine communication
3–30 kHz	Very low frequency (VLF)	Submarine communication
30–300 kHz	Low frequency (LF)	AM longwave broadcasting, RFID
300–3000 kHz	Medium frequency (MF)	AM (medium-wave) broadcasts
3–30 MHz	High frequency (HF)	Shortwave broadcasts, aviation communications, RFID,
30–300 MHz	Very high frequency (VHF)	FM, television broadcasts
300–3000 MHz	Ultra high frequency (UHF)	TV broadcasts, mobile phones, wireless LAN, Bluetooth
3–30 GHz	Super high frequency (SHF)	microwave devices/communications, wireless LAN
30–300 GHz	Extremely high frequency (EHF)	microwave remote sensing

Each of these bands has a traditional name. This is just a naming convention and is not related to allocation; the ITU further divides each band into subbands allocated to different uses.

[1] $c = 3.00\times10^{8}$ m/s.

[2] Free space is characterized by the electrical medium parameters: permittivity (ε_o) = 8.854 x 10^{-12} Farad/m, permeability (μ_o) = $4\pi\times10^{-7}$ Henry/m.

Typical Frequencies	
AM broadcast band	535–1605 kHz
Short wave radio band	3–30 MHz
FM broadcast band	88–108 MHz
VHF TV (2–4)	54–72 MHz
VHF TV (5–6)	76–88 MHz
UHF TV (7–13)	174–216 MHz
UHF TV (14–83)	470–890 MHz
US cellular telephone	824–849 MHz
	869–894 MHz
European GSM cellular	880–915 MHz
	925–960 MHz
GPS	1575.42 MHz
	1227.60 MHz
Microwave ovens	2.45 GHz
US DBS	11.7–12.5 GHz
US ISM bands	902–928 MHz
	2.400–2.484 GHz
	5.725–5.850 GHz
US UWB radio	3.1–10.6 GHz

IEEE MICROWAVE FREQUENCY BANDS

Designation	Frequency range in gigahertz
HF	0.003– 0.030
VHF	0.030– 0.300
UHF	0.300– 1.000
L band	1.000– 2.000
S band	2.000– 4.000
C band	4.000– 8.000
X band	8.000– 12.000
Ku band	12.000– 18.000
K band	18.000– 27.000
Ka band	27.000– 40.000
Millimeter	40.000–300.000
Submillimeter	>300.000

Historical Background

Microwave engineering is often considered a fairly mature discipline because the fundamental concepts were developed more than 50 years ago, and probably because radar, the first major application of microwave technology, was intensively developed as far back as World War II. However, recent years have brought substantial and continuing developments in high-frequency solid-state devices, microwave integrated circuits, and computer-aided design techniques, and the ever-widening applications of RF and microwave technology.

- The foundations of modern electromagnetic theory were formulated in 1873 by James Clerk Maxwell[3],
    - Maxwell (13 June 1831 – 5 November 1879) predicted theoretically the existence of electric and magnetic fields associated with electromagnetic wave propagation.

[3] Maxwell noticed that electrical fields and magnetic fields can couple together to form electromagnetic waves. Neither an electrical field (like the static which forms when you rub your feet on a carpet), nor a magnetic field (like the one that holds a magnet onto your refrigerator) will go anywhere by themselves. But, Maxwell discovered that a CHANGING magnetic field will induce a CHANGING electric field and vice-versa. An electromagnetic wave exists when the changing magnetic field causes a changing electric field, which then causes another changing magnetic field, and so on forever. Unlike a STATIC field, a wave cannot exist unless it is moving.
He added the displacement current term to Ampère's circuital law and this enabled him to derive the electromagnetic wave equation. Displacement current isn't really current. It's a way of describing how the change in electric field passing through a particular area can give rise to a magnetic field, just as a current does. *Maxwell actually developed a set of 20 simultaneous equations, with 20 variables to explain electromagnetic radiation*, and they included terms for both fields and potentials.

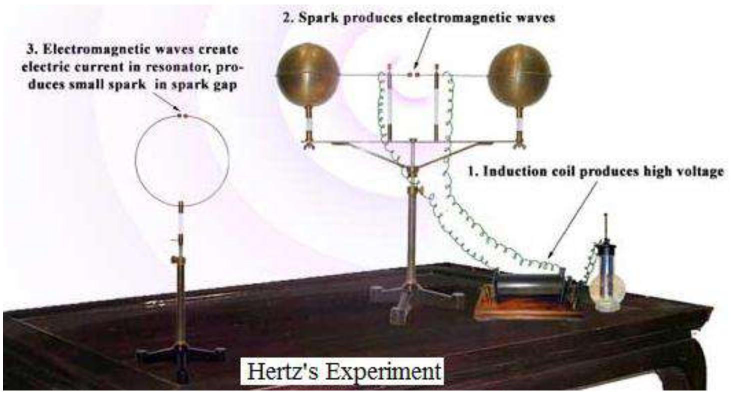
- He hypothesized, solely from mathematical considerations, electromagnetic wave propagation and the idea that light was a form of electromagnetic energy.

- Maxwell’s formulation was cast in its modern form by Oliver Heaviside[4] during the period from 1885 to 1887. Heaviside (18 May 1850 – 3 February 1925) was a reclusive genius whose efforts removed many of the mathematical complexities of Maxwell’s theory, introduced vector notation, and provided a foundation for practical applications of guided waves and transmission lines.
- Heinrich Hertz (22 February 1857 – 1 January 1894), a German professor of physics who understood the theory published by Maxwell, carried out a set of experiments during the period 1887–1891 that validated Maxwell’s theory of electromagnetic waves.
  - The first clearly successful attempt to generate and detect electromagnetic radiation using some form of electrical apparatus was made by Hertz in 1887.

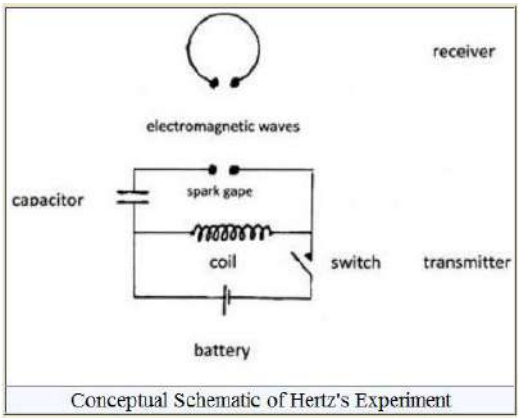
    For his radio wave transmitter he used a high voltage induction coil, a condenser (capacitor, Leyden jar) and a spark gap - whose poles on either side are formed by spheres - to cause a spark discharge between the spark gap’s poles oscillating at a frequency determined by the values of the capacitor and the induction coil. This first radio waves transmitter is basically, what we call today, an LC oscillator.

    To prove there really was radiation emitted, it had to be detected. Hertz used a piece of copper wire bent into a circle, with a small brass sphere on end. He added a screw mechanism so that the spares could be moved very close in a controlled fashion. This "receiver" was designed so that current oscillating back and forth in the wire would have a natural period close to that of the "transmitter" described above. The presence of oscillating charge in the receiver would be signaled by sparks across the (tiny) gap between the sphere.

    In this experiment Hertz confirmed Maxwell’s theories about the existence of electromagnetic radiation.



Hertz's Experiment

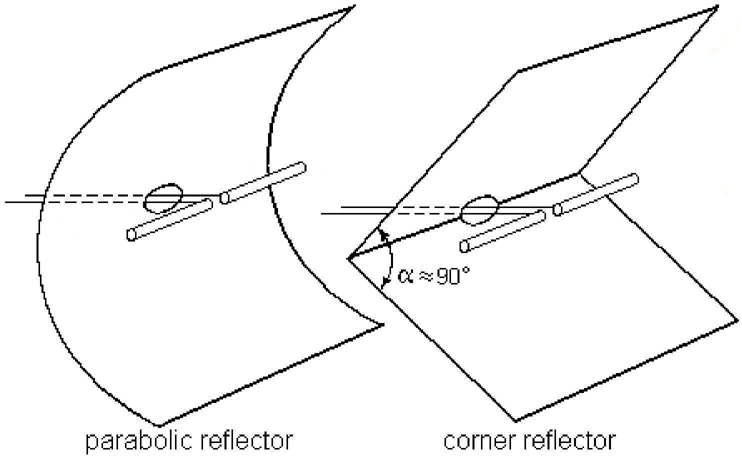


Conceptual Schematic of Hertz's Experiment

  - During experiments Hertz also noted that electrical conductors reflect the waves and that they can be focused by concave reflectors. In this way he invented parabolic antenna and perform experiments with it. He used cylindrical parabolic reflectors fed by spark-excited dipole antennas at their focus for both transmitting and receiving during his historic experiments.
- William Thompson developed the waveguide theory for propagation of microwaves in a guided structure in around 1893.
- In 1897-1899, Sir Oliver Lodge (12 June 1851 – 22 August 1940) established the mode properties of propagation of EM waves in free space and in a hollow metallic tube known as the waveguide.

[4] Using a new notation, *Heaviside simplified Maxwell’s original equations to the four*, using only terms for fields that we employ to this day. At first those equations were referred to by various combinations of the names of Maxwell, Heaviside, and Heinrich Hertz, who was the first to demonstrate Maxwell’s waves. However, for all his otherwise brilliance, Albert Einstein referred to them as Maxwell’s equations in his 1940 monograph “Considerations Concerning the Fundamentals of Theoretical Physics.” The name stuck, and Heaviside faded from public view. (Hertz at least had a unit named after him.)

- The first horn antenna was constructed in 1897 by Indian radio researcher Jagadish Chandra Bose (30 November 1858 – 23 November 1937) in his pioneering experiments with microwaves. Bose's horn operated in the millimetre wave range and his horn and waveguide were circular. Horn antennas are still considered to be useful feeds for reflector antennas.
- Microwave vacuum tube klystron was invented by Russel and Varian Brass in 1937. The klystron was the first significantly powerful source of radio waves in the microwave range. Conventional vacuum tubes are not efficient sources of currents at microwave frequencies.
- John D. Kraus (June 28, 1910 – July 18, 2004) invented corner reflector antenna for electromagnetic wave transmission in 1938. A corner reflector antenna is a type of directional antenna used at VHF and UHF frequencies. They are widely used for UHF television receiving antennas.

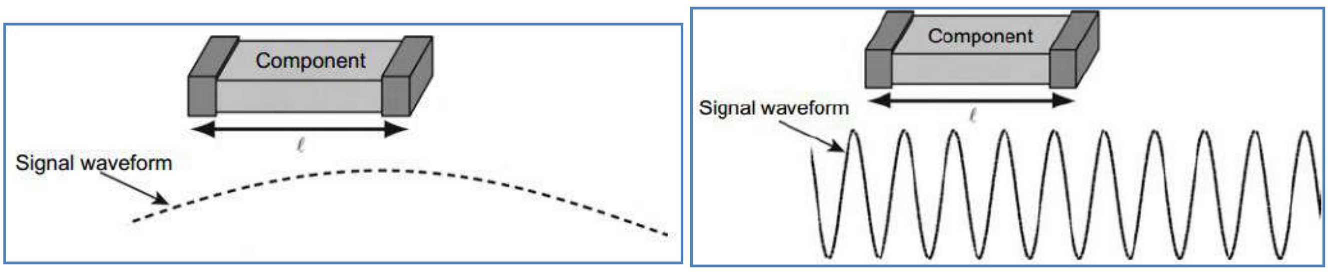


- Rudolf Kompfner (May 16, 1909 – December 3, 1977) intentioned microwave travelling wave tube (TWT) in 1944. TWT is a specialized vacuum tube that is used in electronics to amplify RF signals in the microwave range.
- Percy Spencer (July 19, 1894 – September 8, 1969) invented the modern microwave oven for domestic cooking in 1946.
- Microstrip antenna was first theorized by G. A. Deschamps in 1953. But it didn't become practical until the 1970s when it was developed further by Robert E. Munson using low-loss soft substrate materials.

1.2 Limitations of conventional circuit theory, concepts at microwave frequencies

The most fundamental characteristic that distinguishes conventional circuit analysis from microwave engineering is directly related to the frequency (and thus the wavelength, λ) of the electronic signals being processed. In free space, $\lambda = c/f$, where f is the frequency of the signal and c is the speed of light.

For low-frequency circuits (with a few special exceptions such as antennae), the signal wavelength is much larger than the size of the electronic system and circuit components being examined. In contrast, for a microwave system the sizes of typical electronic components are often comparable to (i.e., within approximately 1 order of magnitude of) the signal wavelength.



As illustrated in above figure, for components much smaller than the wavelength (i.e., $l<\lambda/10$), the finite velocity of the electromagnetic signal as it propagates through the component leads to a modest difference in phase at opposite ends of the component. For components comparable to or larger than the wavelength, however, this end-to-end phase difference becomes increasingly significant.

This gives rise to a reasonable working definition of the two design areas based on the underlying approximations used in design. Since in conventional circuit, the circuit components and interconnections are generally small compared to a wavelength, they can be modeled as lumped elements for which Kirchoff's voltage and current laws apply at every instant in time. It means the description or analysis of such circuits may be adequately carried out in terms of loop currents and node voltages without consideration of propagation effects assuming that the current (and voltage) at any given instant has the same value at every point in the element. The time delay between cause and effect at different points in these circuits is so small compared with the period of the applied signal as to be negligible. In practice, a rule of thumb for the applicability of a lumped-element equivalent circuit is that the component size should be less than $\lambda/10$ at the frequency of operation.

As the frequency is raised to a point where the wavelength is no longer large compared with the circuit dimensions, propagation effects can no longer be ignored. So for microwave frequencies for which component size exceeds approximately $\lambda/10$, the finite propagation velocity of electromagnetic waves can no longer be as easily absorbed into simple lumped-element equivalent circuits. For these frequencies, the time delay associated with signal propagation from one end of a component to the other is an appreciable fraction of the signal period, and thus lumped-element descriptions are no longer adequate to describe the electrical behavior. In this case phase differences within element become significant; at a given instant the current at one point in the element may be passing through its maximum value, while at another point it is zero. A distributed-element model is required to accurately capture the electrical behavior. *The time delay associated with finite wave propagation velocity that gives rise to the distributed circuit effects is a distinguishing feature of the mindset of microwave engineering*.

The extension of conventional circuit theory to microwave system is further complicated by the use of circuit elements such as waveguides, in which voltages and currents are not uniquely defined. The analysis of these elements must be approached from the point of view that they serve to guide electromagnetic waves; attention is centered on electric and magnetic fields rather than on voltage and current.

In addition to material properties, some physical effects are significant at microwave frequencies that are typically negligible at lower frequencies. For example, radiation losses become increasingly important as the signal wavelengths approach the component and interconnect dimensions. For conductors and other components of comparable size to the signal wavelengths, standing waves caused by reflection of the electromagnetic waves from the boundaries of the component can greatly enhance the radiation of electromagnetic energy.

Unique characteristics of microwaves

1. Short wavelengths
2. More bandwidth (directly related to data rate).
   Eg. TV bandwidth = 6 MHz
   At 60 MHz (VHF), 10% BW for 1 Channel
   At 60 GHz (U-Band) 1% BW for 100 channels
   A 1% bandwidth at 600 MHz is 6 MHz, which (with binary phase shift keying modulation) can provide a data rate of about 6 Mbps (megabits per second), while at 60 GHz a 1% bandwidth is 600 MHz, allowing a 600 Mbps data rate.
3. Small antenna size with large antenna gain[5].

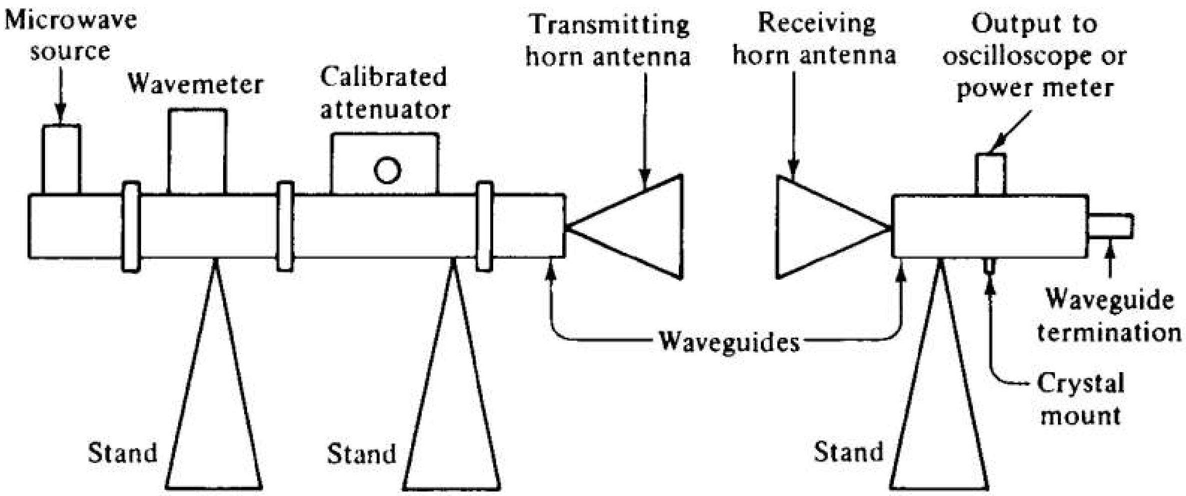
[5] $Antenna\ gain, G \propto A/\lambda^2$, A - Physical aperture area of antenna, λ - wavelength

Antenna gain is proportional to the electrical size of the antenna. At higher frequencies, more antenna gain can be obtained for a given physical antenna size.

4. Travel by line of sight propagation through ionosphere with negligible absorption and reflection.
   Microwave signals travel by line of sight and are not bent by the ionosphere as are lower frequency signals. Satellite and terrestrial communication links with very high capacities are therefore possible, with frequency reuse at minimally distant locations.
5. Reflection from metallic surfaces.
6. Microwave heating
7. Molecular, atomic and nuclear resonance.
   Various molecular, atomic, and nuclear resonances occur at microwave frequencies, creating a variety of unique applications in the areas of basic science, remote sensing, medical diagnostics and treatment, and heating methods.

Typical microwave system

A typical microwave system normally consists of a transmitter subsystem (including a microwave generator, waveguides, wavemeter, attenuator and a transmitting antenna) and a receiver subsystem (including a receiving antenna, waveguide, a microwave amplifier, and a receiver).



Typical microwave system

Therefore, a first course on microwave engineering should include three major areas of study.

i. Microwave Transmission Lines and waveguides
ii. Microwave circuit elements
iii. Microwave sources, amplifiers and detectors

Basic microwave concepts

Microwave Transmission

The principle of microwave transmission is based upon the same fundamental laws of electromagnetism, but it cannot be derived extending either low frequency radio or high frequency optical concepts.

For instance conventional two conductor line cannot be used for microwave transmission. If microwave power is fed to these pair of conductor line where dimensions of line are comparable to the wavelength of the propagating signal, it leads to a series of interesting effects that fall outside the scope of problems examined by classical theory of ling transmission line.

Therefore one has to use hollow metal tubes called waveguides. The energy propagation in these structure is basically a reflection phenomenon. The waveguide transmission of microwave is associated with a number of interesting problems such as coupling of power from generator to line, exciting of waves in a waveguide etc.

Microwave circuit elements

The conventional circuit elements such as resistors, inductors and capacitors do not respond well at microwave frequencies. We still can construct energy dissipating (resistors) and storing (capacitors and inductors) elements at microwave frequencies but their geometrical shape will be quite different. A section of microwave line (distributed parameters) offers reactances varying from $-\infty$ to $+\infty$ if its length is suitably chosen.

Similarly, conventional resonant and anti-resonant circuits are replaced by resonant microwave line sections known as resonant cavities.

When a number of such microwave circuit elements are connected together, we have a microwave circuit.

Generation and amplification of microwave

The operation of conventional vacuum tubes and solid state devices is limited by transit time effects. However, the frequency range of operation of those devices can be extended to the lower edge of microwave spectrum at the cost of power output and noise characteristics.

To exploit this frequency region number of new principles of operation such as velocity modulation, interaction of space charge waves with electromagnetic fields were proposed. It involves transfer of power from a source of direct voltage to a source of alternating voltage by means of a density-modulated stream of electrons resulting in the development of klystron, magnetron and travelling-wave tube.

Reed diode and IMPATT was developed using interaction of the impact ionization avalanche and the transit time of charge carriers. Quantum mechanical tunneling was used to develop tunnel diode. Transferred electron techniques were used to develop transfer electron devices.

The solid-state devices used for microwave generation and amplification exploit the negative resistance characteristics.

1.3 Applications of Microwaves

a) Microwave communication systems

Because of the increase in bandwidth microwaves are extensively used to carry voice (4 KHz bandwidth), digital data, television signals (6 MHz bandwidth) or telephonic traffic etc over long distances links on the ground (ground communication) or deep-space spacecraft (space communication).

- Direct broadcast satellite television (DBST)
- Personal communication systems (PCSs)
- Wireless local area computer networks (WLANs)
- Global positioning satellite (GPS)

b) Radar Systems

Microwave are widely used for radar because extremely narrow microwave beam could be produced by the microwave antennas.

- Air and marine navigation
- Detection and tracking of aircraft, missiles, spacecraft
- Missile guidance

c) **Radiometry/ Radio-astronomical research**

Radiometry is to gather information about a target solely from the microwave portion of the black body radiation that is either emits directly or reflects from surrounding.

Astronomical use

- Planetary mapping
- Solar emission mapping
- Measurement of cosmological background radiation

Remote sensing use

- Measurement of soil moisture
- Snow cover/ice cover mapping
- Developing atmospheric temperature and humidity profiles

d) **Industrial applications**

- Microwave oven
- Microwave drying machines are used in textile and paper industries.
- Non- destructive testing of metals such as thickness measurements.

e) **Biomedical applications**

- The exact location of deep cancerous tissue can be known by means of microwave radiometers.
- Microwave diathermy machines are used to remove rheumatic pains by producing heat inside the muscle without affecting the skin.
- Microwave radiations are used for cancer therapy, hyperthermia. Hyperthermia therapy is a type of medical treatment in which body tissue is exposed to slightly higher temperatures to damage and kill cancer cells or to make cancer cells more sensitive to the effects of radiation and certain anti-cancer drugs.

f) **Basic and Applied Research**

- Microwave and radio frequency spectroscopy for structural analysis.
- Microwave absorption spectra provide information about molecular structure and energy levels.

CHAPTER 2

Physical Concept of Radiation

All truths are easy to understand once they are discovered;
The point is to discover them

— Galileo Galilei

2.1 INTRODUCTION

For wireless communication systems, the antenna is one of the most critical components. A good design of the antenna can relax system requirements and improve overall system performance. A typical example is TV for which the overall broadcast reception can be improved by utilizing a high performance antenna. An antenna is the system component that is designed to radiate or receive electromagnetic waves. In other words, the antenna is the electromagnetic transducer which is used to convert, in the transmitting mode, guided waves within a transmission line to radiate free-space waves or to convert, in the receiving mode, free-space waves to guided waves. In a modern wireless system, the antenna must also act as a directional device to optimize or accentuate the transmitted or received energy in some directions while suppressing it in others. The antenna serves to a communication system the same purpose that eyes and eyeglasses serve to a human. The history of antennas dates back to James Clerk Maxwell who unified the theories of electricity and magnetism, and eloquently represented their relations through a set of profound equations best known as *Maxwell's Equations.* His work was first published in 1873. He also showed that light was electromagnetic and that both light and electromagnetic waves travel by wave disturbances of the same speed. In 1886, Professor Heinrich Rudolph Hertz demonstrated the first wireless electromagnetic system. He was able to produce in his laboratory at a wavelength of 4 m a spark in the gap of a transmitting $\lambda/2$ dipole which was then detected as a spark in the gap of a nearby loop. It was not until 1901 that Guglielmo Marconi was able to send signals over large distances. He performed, in 1901, the first transatlantic transmission from Poldhu in Cornwall, England, to St. John's, Newfoundland. His transmitting antenna consisted of 50

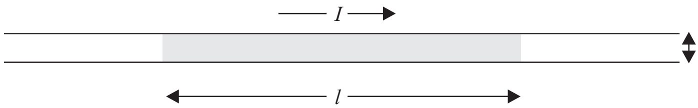


Fig. 2.1

movement. The acceleration due to change in direction is called centripetal acceleration. Since a current is the rate of change of charge, and a time varying current corresponds to acceleration or deceleration of charges, which is the required condition to radiate electromagnetic waves.

Consider a current '*I*' be flowing in an extremely thin wire. From the fundamental equation of current

$$I = \frac{q}{t}$$

where q is the charge moved through the length l of the wire in time t

$$I = \frac{q}{t} \times \frac{l}{l} = \frac{q}{l} \times \frac{l}{t}$$

$I = \rho_l v$ where ρ_l is the linear charge density and v is the drift velocity of charge

Differentiating the above equation with respect to time

$$\frac{dI}{dt} = \rho_l \frac{dv}{dt} = \rho_l a\ ,$$

here a is the acceleration of charge

or $$\boxed{l\,\frac{dI}{dt} = l\rho_l a} \qquad (2.1)$$

This equation is the basic relation between current and charge and is known as fundamental equation of electromagnetic radiation.

2.2.2 Radiation From Single Wire

The conducting wire can radiate electromagnetic energy if there is:

- oscillating current in wire
- steady current in curved, bent, discontinuous, terminated, or truncated wire as shown in figure 2.2

Consider a pulse source is applied to the end of the wire and the other end is connected to the ground via load as shown in figure 2.3.

The free electrons are accelerated from the source end and are retarded at the load end due to the build-up of the electrons there. The electromagnetic radiations are produced at the ends and along the length of the wire. Since the magnitude of acceleration or retardation is not uniform throughout, as a result there is a broad frequency spectrum (frequency is proportional to acceleration or retardation of electric charge). The band width depends upon the pulse width.

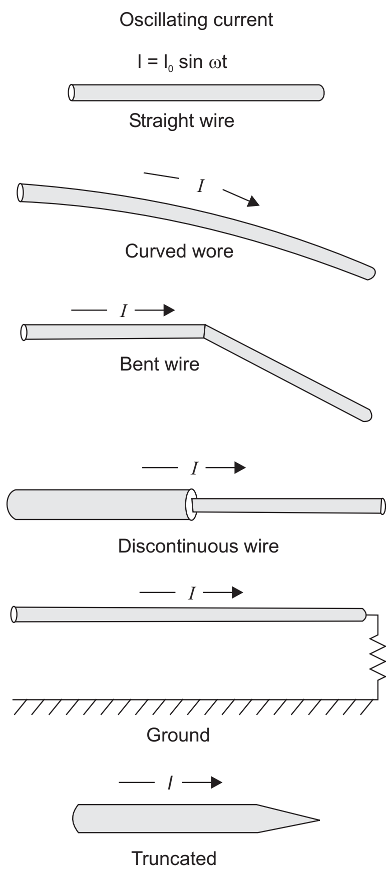


Fig. 2.2

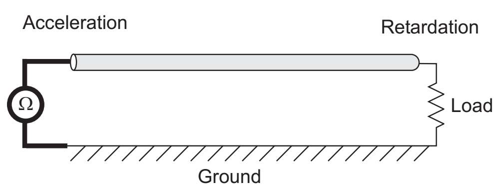
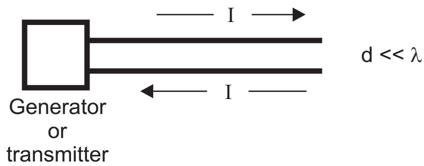


Fig. 2.3

For AC current, ideally there is single frequency of radiation. The moving charge through curved or bent wire experiences centripetal acceleration, which also produces radiation. For discontinuous wire impedances change rapidly at the point of discontinuity which is also responsible for radiation.

2.2.3 Radiation from Two Wires

Consider two straight conducting wires connected through generator or transmitter as shown in figure 2.4. The AC current in the two wires is same but their directions



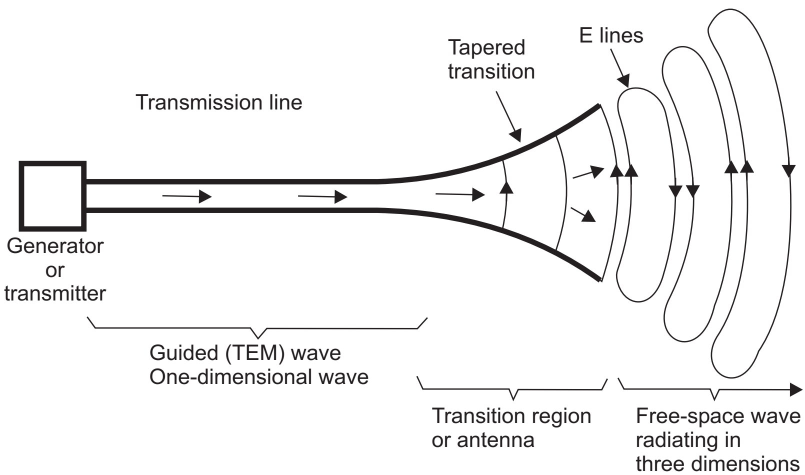


Fig. 2.4

are opposite. If the separation between the conductors is very small as compared to the wavelength, then the electromagnetic fields of both the wires cancel each other and as a result there is no net radiation. However when the open end of the wires are tapered which results in the increased separation between the wires, secondly the directions of currents in the two wires now are not exactly opposite which results in no net cancelling of electromagnetic fields and the structure starts radiating.

2.2.4 Radiation from Dipole

If the transition region of the two conductor wires is bent through 90° as shown below in figure 2.5, the two currents become exactly parallel to each other. This

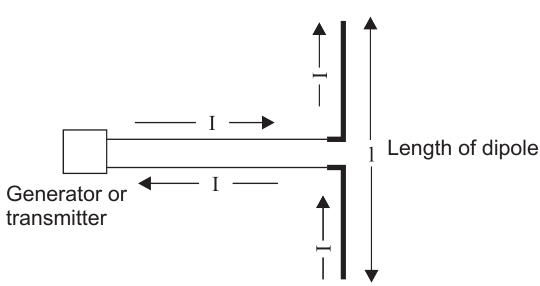


Fig. 2.5

the next quarter period, the original field line travels additional distance of $\lambda/4$ and the total distance becomes $\lambda/2$, simultaneously the charge on the dipole becomes zero. This can be thought of as being neutralized by the appearance of opposite charges. The field lines by this opposite charges are shown dashed (anti-clockwise sense). Since there is no net charge on the dipole and the existence of such-line is only possible when they form closed loops. These closed loops propagate away resulting in electromagnetic radiation.

2.3 CURRENT DISTRIBUTION ON THIN WIRE ANTENNA

Consider two wire transmission line which is open at load side. The source sends traveling current wave in the wires. The current at the each end reflects back with phase change of 180°. The incident and reflected current combine to produce a standing wave pattern of sinusoidal form as shown in figure 2.7. If the separation between the lines is very small as compared to wavelength, there will not be any radiation. If the open end region is bent to 90°, the currents in the two vertical sections become in the same direction as shown in figure 2.8, so corresponding

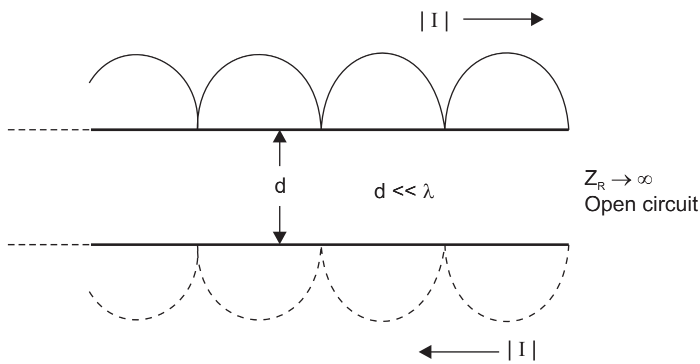


Fig. 1.7

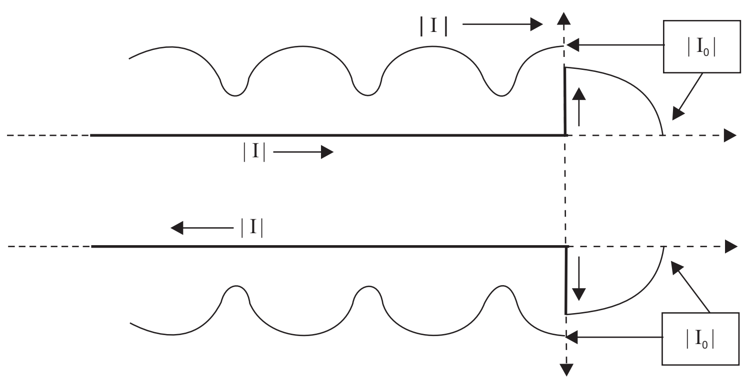
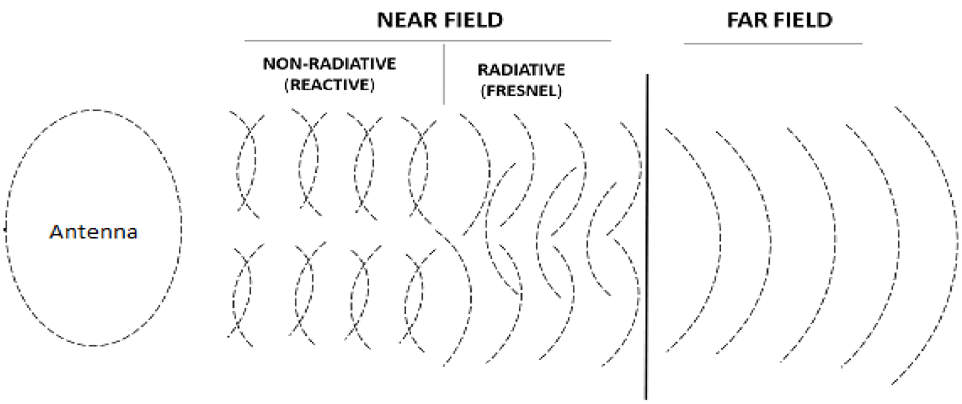


Fig. 2.8

Near and Far Field Region



When a signal from a transmitter is applied to an antenna, it sends out electromagnetic waves in to free space. The EM field characteristics vary as a function of distance from the antenna. They are broadly divided into two regions, the near-field region, and the far field region.

The **Near Field Region** is the region right next to the antenna. It is defined by the following equation:

$$Near\ Field\ Region < \frac{2D^2}{\lambda}$$

Where D = Maximum linear dimension of the antenna

λ = Wavelength of the EM Waves

In this region, the fields are sort of unpredictable and therefore no measurements are usually made in this region.

This region is further divided into two parts:

Reactive Near Field: This is the region that is adjacent to the antenna. In this region, the E-Field and H-Field are 90 degrees out of phase with each other and are therefore reactive. To radiate or propagate the E/H fields need to be orthogonal (perpendicular) and in phase with each other.

$$Reactive\ Near\ Field\ Region\ <\ 0.62\sqrt{\frac{D^3}{\lambda}}$$

Where D = Maximum linear dimension of the antenna

λ = Wavelength of the EM Waves

Radiative Near Field: This region is also known as the Fresnel Region. It is the region between the reactive near field and the far field. This is the region where the EM fields start to transition from reactive to radiating fields. However, since they have not completely transitioned, the shape of the radiation pattern still varies with distance.

$$0.62\sqrt{\frac{D^3}{\lambda}} < \boldsymbol{Radiative\ Near\ Field\ Region} < \frac{2D^2}{\lambda}$$

Where D = Maximum linear dimension of the antenna

λ = Wavelength of the EM Waves

The **Far Field Region** is the region that comes after the near radiative near field. In this region, the EM fields are dominated by radiating fields. The E and H-fields are orthogonal to each other and to the direction of propagation as with plane waves. The far-field region is represented by the following equation:

$$Far\ Field\ Region > \frac{2D^2}{\lambda}$$

Where D = Maximum linear dimension of the antenna

λ = Wavelength of the EM Waves

Antennas are usually used to transfer signals at large distances which are considered to be in the far-field region. One condition that must be met when making measurements in the far field region is that the distance from the antenna must be much greater than the size of the antenna and the wavelength.

The fields surrounding an antenna are divided into 3 primary regions:

- Reactive Near Field
- Radiating Near Field or Fresnel Region
- Far Field or Fraunhofer Region

The far field region is the most important, as this determines the antenna's radiation pattern. Since antennas are used to communicate wirelessly from long distances, this is the region of operation for most antennas. We will start with the Far Field.

Far Field (Fraunhofer) Region

The far field is the region far from the antenna, as you might suspect. In this region, the radiation pattern does not change shape with distance (R). Although the E- and H- fields still die off as 1/R, the power density dies off as 1/R^2. The far field is dominated by radiated fields, with the E- and H-fields orthogonal to each other and the direction of propagation, as with plane waves.

If the maximum linear dimension of an antenna is D and the wavelength is λ , then the following 3 conditions must all be satisfied to be in the far field region:

$$R > \frac{2D^2}{\lambda} \qquad \textbf{[Equation 1]}$$

$$R >> D \qquad \textbf{[Equation 2]}$$

$$R >> \lambda \qquad \textbf{[Equation 3]}$$

The first and second equation above ensure that the power radiated in a given direction from distinct parts of the antenna are approximately parallel (see Figure 1). This helps ensure the fields in the far-field region behave like plane waves. Note that >> means "much much greater than" and is typically assumed satisfied if the left side is 10 times larger than the right side.

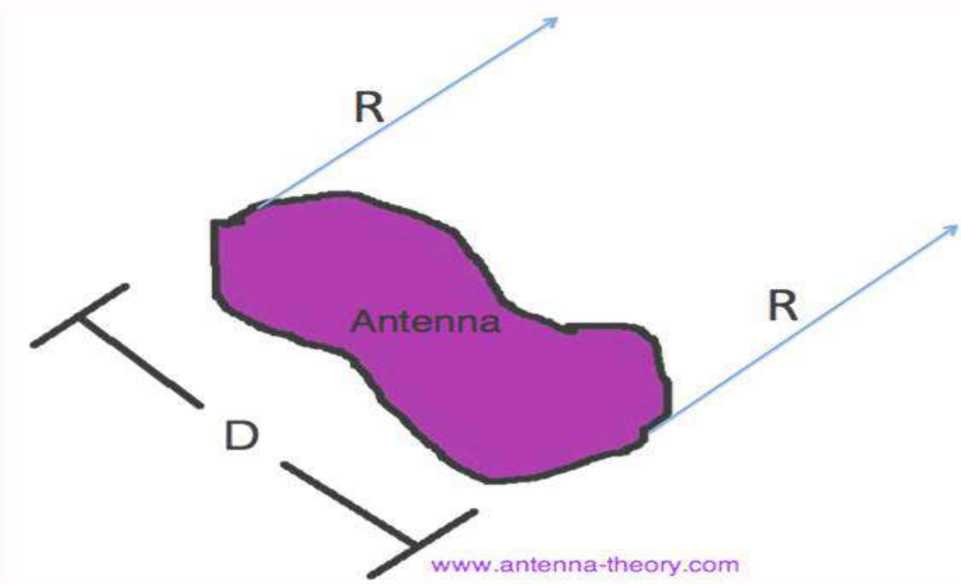


Figure 1. The Rays from any Point on the Antenna are Approximately Parallel in the Far Field.

Reactive Near Field Region

In the immediate vicinity of the antenna, we have the reactive near field. In this region, the fields are predominately reactive fields, which means the E- and H- fields are out of phase by 90 degrees to each other (recall that for propagating or radiating fields, the fields are orthogonal (perpendicular) but are in phase).

Radiating Near Field (Fresnel) Region

The radiating near field or Fresnel region is the region between the near and far fields. In this region, the reactive fields are not dominate; the radiating fields begin to emerge. However, unlike the Far Field region, here the shape of the radiation pattern may vary appreciably with distance.

The region is commonly given by:

fresnel region for antennas

Note that depending on the values of *D* and the wavelength, this field region may or may not exist.

Finally, the above can be summarized via the following diagram:

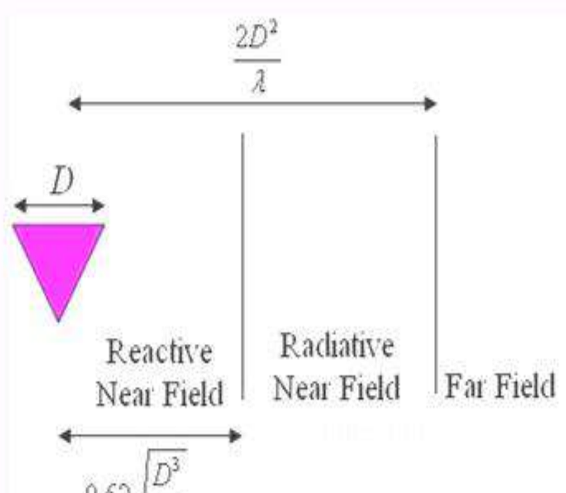
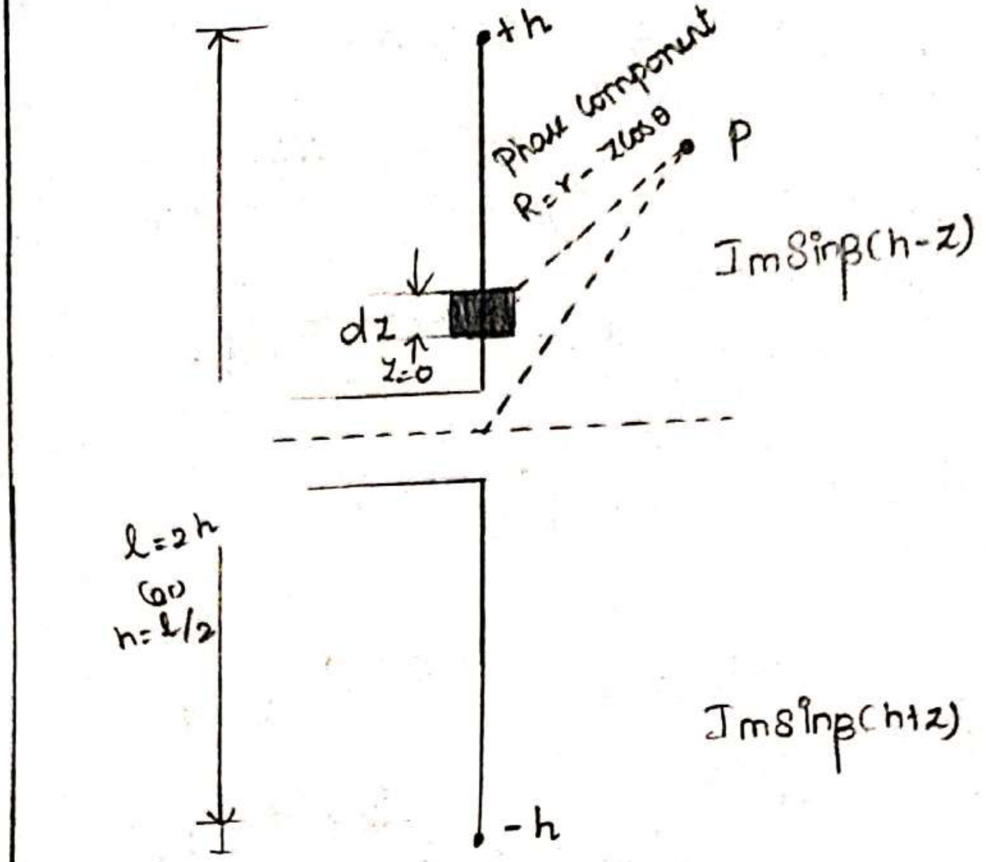


Figure 2. Illustration of the Field Regions for an Antenna of Maximum Linear Dimension *D*.

Half Wave Dipole Antenna :-



Magnetic Vector potential

$$dA_z = \frac{\mu}{4\pi} \frac{I dz\, e^{-j\beta R}}{R}$$

R → Phase Component.

Total Vector potential due to all such a Elements

$$\int dA_z = \int_{-h}^{0} \frac{\mu}{4\pi} \frac{I dz e^{-j\beta R}}{R} + \int_{0}^{h} \frac{\mu}{4\pi} \frac{I dz e^{-j\beta R}}{R}$$

Replace $I = I_m \sin\beta(h+z)$

$I = I_m \sin\beta(h-z)$

$$\int dA_z = \int_{-h}^{0} \frac{\mu}{4\pi} I_m \sin\beta(h+z) \frac{e^{-j\beta R}}{R} dz$$

$$+ \int_{0}^{h} \frac{\mu}{4\pi} I_m \sin\beta(h-z) \frac{e^{-j\beta R}}{R} dz$$

$$\int dA_z = \frac{\mu}{4\pi}\int_{-h}^{0}\frac{I_m \sin\beta(h+z)\, e^{-j\beta R}}{R}dz + \frac{\mu}{4h}\int_{0}^{h}\frac{I_m \sin\beta(h-z)\, e^{-j\beta R}}{R}dz$$

Substitute $R = r - z\cos\theta$ & $R = r$

$$A_z = \frac{\mu}{4\pi}\int_{-h}^{0}\frac{I_m \sin\beta(h+z)\, e^{-j\beta(r - z\cos\theta)}}{r}dz +$$

$$\frac{\mu}{4\pi}\int_{0}^{h}\frac{I_m \sin\beta(h-z)\, e^{-j\beta(r - z\cos\theta)}}{r}dz$$

$$e^{-j\beta(r - z\cos\theta)} = e^{-j\beta r} e^{+j\beta z\cos\theta}$$

$$A_z = \frac{\mu I_m e^{-j\beta r}}{4\pi r}\int_{-h}^{0}\sin\beta(h+z)\, e^{+j\beta z\cos\theta}dz +$$

$$\frac{\mu I_m e^{-j\beta r}}{4\pi r}\int_{h}^{0}\sin\beta(h-z)\, e^{+j\beta z\cos\theta}dz$$

Substitute $l = 2h$ $\quad h = l/2 = \lambda/4 = \pi/2 - h$

$$\therefore \beta = \frac{2\pi}{\lambda}$$

$$\sin\beta(h+z) = \sin\beta(h-z)$$

$$\sin\beta(h+z) = \sin[\beta h - \beta z]$$

$$= \sin\left[\frac{2\pi}{\lambda}\cdot\lambda/4 + \beta z\right]$$

$$\sin\beta(h+z) = \sin\left[\beta z + \pi/2\right]$$

$$\sin\beta(h+z) = \cos\beta z$$

$$A_z = \frac{\mu I_m e^{-j\beta r}}{4\pi r}\left[\int_{-h}^{0}\cos\beta z\, e^{+j\beta z\cos\theta}dz + \int_{0}^{h}\cos\beta z\, e^{j\beta z\cos\theta}dz\right]$$

Change of limit, so in power we obtain -ve

$$A_z = \frac{\mu I_m e^{-j\beta r}}{4\pi r}\left[\int_0^h \cos\beta z\left[e^{+j\beta z\cos\theta} + e^{-j\beta z\cos\theta}\right]dz\right]$$

20

$$\left(\because e^{j\theta} + e^{-j\theta} = \cos\theta\right)$$

$$A_z = \frac{\mu I_m e^{-j\beta r}}{4\pi r}\int_0^h \cos\beta z \; 2\cos(\beta z\cos\theta)\; dz$$

$$A_z = \frac{\mu I_m e^{-j\beta r}}{4\pi r}\int_0^h \cos\{\beta z(1+\cos\theta)\} + \cos\{\beta z(1-\cos\theta)\}\; dz$$

$$\because \quad 2\cos\alpha\cos\beta = \cos(\alpha-\beta) + \cos(\alpha+\beta)$$

$$A_z = \frac{\mu I_m e^{-j\beta r}}{4\pi r}\left[\frac{\sin(\beta z(1+\cos\theta))}{\beta(1+\cos\theta)} + \frac{\sin\beta z(1-\cos\theta)}{\beta(1-\cos\theta)}\right]_0^{\lambda/4}$$

λ:

Since W.K.T $h = z = \lambda/4$

$$A_z = \frac{\mu I_m e^{-j\beta r}}{4\pi r\beta}\left[\frac{(1-\cos\theta)\sin\beta z(1+\cos\theta) + (1+\cos\theta)\sin\beta z(1-\cos\theta)}{(1-\cos^2\theta)}\right]$$

$$A_z = \frac{\mu I_m e^{-j\beta r}}{4\pi r\beta}\left[\frac{(1-\cos\theta)\sin[\beta z + \beta z\cos\theta] + (1+\cos\theta)\sin[\beta z - \beta z\cos\theta]}{1-\cos^2\theta}\right]$$

$$\beta z = \frac{2\pi}{\lambda}\cdot\lambda/4 = \pi/2$$

Substitute $\beta z = \pi/2$ in above equation

$$A_z = \frac{\mu I_m e^{-j\beta r}}{4\pi r\beta}\left[\frac{(1-\cos\theta)\sin(\pi/2 + \pi/2\cos\theta) + (1+\cos\theta)\sin(\pi/2 - \pi/2\cos\theta)}{1-\cos^2\theta}\right]$$

$$A_z = \frac{\mu I_m e^{-j\beta r}}{4\pi\beta r}\left[\frac{(1-\cos\theta)\cos\left(\frac{\pi}{2}\cos\theta\right) + (1+\cos\theta)\cos\left(\frac{\pi}{2}\cos\theta\right)}{\sin^2\theta}\right]$$

W.k.T $= \sin(90+\theta)$

$\Rightarrow \cos\theta$

$1-\cos^2\theta = \sin^2\theta$

$$A_z = \frac{\mu I_m e^{-j\beta r}}{4\pi\beta r}\left[\frac{\cos\left(\frac{\pi}{2}\cos\theta\right)\left[(1-\cancel{\cos\theta}) + (1+\cancel{\cos\theta})\right]}{\sin^2\theta}\right]$$

$$\boxed{A_z = \frac{\mu I_m e^{-j\beta r}}{\cancel{4}_{2}\pi\beta r}\left[\frac{\cancel{2}^{1}\cos\left(\frac{\pi}{2}\cos\theta\right)}{\sin^2\theta}\right]} \longrightarrow (1)$$

formula $= \nabla\times A = \mu H$

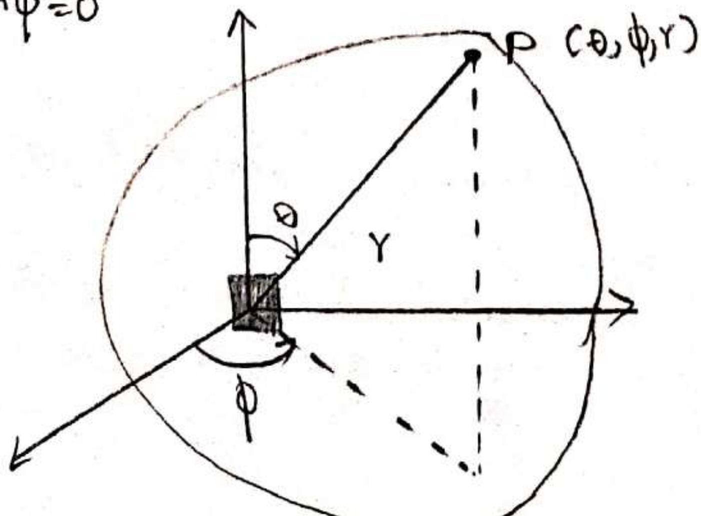
$\mu H_\phi = (\nabla\times A)_\phi$

$= \frac{1}{r}\left[\frac{\partial}{\partial r}(A_\theta \cdot r)\right]$

$A_r = A_z\cos\theta$

$A_\theta = -A_z\sin\theta$

$A_\phi = 0$



$$\mu H_\phi = \frac{1}{r}\left[\partial/\partial r\,(A_\theta \cdot r)\right]$$

$$= \frac{1}{r}\left[\partial/\partial r\,(-A_z \sin\theta \cdot r)\right]$$

$$\mu H_\phi = -\frac{\sin\theta}{r}\left[\partial/\partial r\,(A_z \cdot r)\right]$$

$$= \frac{1}{r}\left[\partial/\partial r\,(A_\theta \cdot r)\right] - \partial/\partial\theta\,(A_r)$$

$$= \frac{1}{r}\left[\partial/\partial r\,(-A_z \sin\theta \cdot r)\right] - \partial/\partial\theta\,(A_z \cos\theta]$$

$$\mu H_\phi = \frac{1}{r}\left[\partial/\partial r\left[\frac{-\mu I_m e^{-j\beta r}}{2\pi\beta r}\left(\frac{\cos(\pi/2\cos\theta)}{\sin^{\cancel{2}}\theta}\cdot \sin\cancel{\theta}\cdot r\right)\right]\right.$$
$$\left.-\frac{\partial}{\partial\theta}\left[\frac{\mu I_m e^{-j\beta r}}{2\pi\beta r}\left(\frac{\cos(\pi/2\cos\theta)}{\sin^2\theta}\cdot\cos\theta\right)\right]\right]$$

$$\left[\because \partial/\partial\theta = 0\right]$$

$$\mu H_\phi = \frac{1}{r}\left[\partial/\partial r\left[-\frac{\mu I_m e^{-j\beta r}}{2\pi\beta \cancel{r}}\left(\frac{\cos(\pi/2\cos\theta)}{\sin\theta}\,\cancel{r}\right)\right]\right]$$

$$\cancel{\mu} H_\phi = \frac{(-)\cancel{\mu} I_m \cos(\pi/2\cos\theta)}{2\pi\beta r\sin\theta}\left[\partial/\partial r\left[e^{-j\beta r}\right)\right]$$

$$H_\phi = \frac{(-) I_m e^{-j\beta r}(-j\cancel{\beta})}{2\pi\cancel{\beta} r} \times \frac{\cos(\pi/2\cos\theta)}{\sin\theta}$$

$$\boxed{|H_\phi| = \frac{I_m}{2\pi r}\,\frac{\cos(\pi/2\cos\theta)}{\sin\theta}\ A/m^2} \longrightarrow A$$

$$\left|\frac{E_\theta}{H_\phi}\right| = \eta = 120\pi = \sqrt{\mu_0/\varepsilon_0} = 377\,\Omega$$

$$|E_\theta| = \eta\,|H_\phi|$$

Scanned with CamScanner

$$|E_\theta| = \eta \frac{I_m}{2\pi r} \frac{\cos(\pi/2 \cos\theta)}{\sin\theta}$$

$$= \cancel{120\pi}^{60} \frac{I_m}{\cancel{2\pi} r} \frac{\cos(\pi/2 \cos\theta)}{\sin\theta}$$

$$|E_\theta| = \frac{60 I_m}{r} \frac{\cos(\pi/2 \cos\theta)}{\sin\theta} \ v/m$$

$$\boxed{\therefore |E_\theta| = \frac{60 I_m}{r} \frac{\cos(\pi/2 \cos\theta)}{\sin\theta} \ v/m} \longrightarrow B$$

Power radiated:-

$$P = VI = E_\theta H_\phi$$

$$P_{max} = \left[\frac{\cancel{60}^{30} I_m}{r} \frac{\cos(\pi/2 \cos\theta)}{\sin\theta}\right] \cdot \left[\frac{I_m}{\cancel{2}\pi r} \frac{\cos(\pi/2 \cos\theta)}{\sin\theta}\right]$$

$$P_{max} = \frac{30 I_m^2}{\pi r^2} \left[\frac{\cos(\pi/2 \cos\theta)}{\sin\theta}\right]^2$$

$$P_{max} = \frac{30 I_m^2}{\pi r^2} \frac{\cos^2(\pi/2 \cos\theta)}{\sin^2\theta}$$

$$\boxed{\therefore P_{max} = \frac{30 I_m^2}{\pi r^2} \frac{\cos^2(\pi/2 \cos\theta)}{\sin^2\theta} \ w/m^2}$$

Power radiated $W = \oint P_{max} \cdot ds$

$$W = \int_0^{\pi/2} \frac{30 I_m^2}{\pi r^2} \frac{\cos^2(\pi/2 \cos\theta)}{\sin^2\theta} \, ds.$$

$$ds = 2\pi r^2 \sin\theta \, d\theta$$

$$W = \int_0^{\pi/2} \frac{30 I_m^2}{\cancel{\pi r^2}} \frac{\cos^2(\pi/2 \cos\theta)}{\sin^{\cancel{2}}\theta} \, 2\cancel{\pi r^2} \cancel{\sin\theta} \, d\theta$$

$$W = 60 I^2 m \int_0^{\pi/2} \frac{\cos^2(\pi/2 \cos\theta)}{\sin\theta} d\theta$$

$$= 60 I^2 m \int_0^{\pi/2} \frac{1}{2} \left[\frac{1 + \cos(\pi\cos\theta)}{\sin\theta} \right\} d\theta$$

$$= 60 I^2 m \cdot I$$

$$\therefore I = \frac{1}{2} \int_0^{\pi/2} \left\{ \frac{1 + \cos(\pi\cos\theta)}{\sin\theta} \right\} d\theta$$

$$W = 60 I^2 m \cdot I \qquad I = 1.219$$

$$W = 60 I^2 m \cdot (1.219)$$

$$W = 73.140 I^2 m \simeq 73 \Omega$$

$$\boxed{\text{Radiation Resistance } R_{rad} = 73 \Omega}$$

$\lambda/2$ Antenna:- It is a linear antenna whose length is $\lambda/2$ and the current distribution is sinusoidal. It is usually centre field.

Scanned with CamScanner

Half-wave Dipole

* linear antenna.
* length is $\lambda/2$.
* current distribution is assumed to be sinusoidal
* usually centre-fed.

Quarter-wave Monopole

* linear antenna.
* length is $\lambda/4$.
* current distribution is assumed to be sinusoidal.
* fed at one end w.r.to earth.

Antenna fundamentals & characteristics:-

Definition :- Em Waves

A Wave is a carrier of Energy (or) Information which is function of a time as well as space.

Antenna:-

→ An Antenna (or) Aerial is one (or) more Electrical conductors of a specific length that radiates Em Waves Generated by a transmission (or) that collect radiowaves at receiver.

→ Antenna must be always Excited only with the help of current sources.

→ An Antenna is transducer, an impedance matching device, the radiator and a sensor of Em Waves. It is an Essential device (or) Element in all types of communication and radar systems. It can be considered as a source of Em Waves.

FREQUENCY SPECTRUM OF EM WAVES:-

• Em Waves produced by the antenna have a wide range of frequencies the Wavelength (λ) of the Em Wave depends on its Velocity and frequency.

∴ the relationship between c and f is given by

$\lambda = c/f$ where c = Velocity of light ; f = frequency

$$\boxed{c = 3\times10^{8}\ m/s}$$

Band Name	Frequency Range	λ
(i) ELF [Extreme low frequency]	30-300 Hz	10mm-100km
(ii) VLF [Very low frequency]	3-30 kHz	100km-10km
(iii) LF [low frequency]	30-300 kHz	10km-1km
(iv) MF [Medium frequency]	300-3000 kHz	1km-100m
[v] HF [High frequency]	3MHz-30MHz	100m-10m
[vi] VHF [very high frequency]	30MHz-300MHz	10m-1m
[vii] UHF [ultra high frequency]	300-3000MHz	1m-10m
(viii) SHF [super high freq]	3-30 GHz	10-1cm
[ix] EHF [Extreme high freq]	30-300 GHz	km-1mm

IEEE Specified Radar Band:-

Band Name	Frequency Range	(λ) cm
L	1-2	30-15
S	2-4	15-7.5
C	4-8	7.5-3.75
X	8-12	3.75-2.5
ku	12-18	2.5-1.67
k	18-27	1.67-1.11
ka	27-40	1.11-0.75

Antenna Parameters:-

16m 1) Radiation Intensity

2m 2) Radiation Pattern

3) Gain

4) Half power Beam Width [HPBW]

5) Directive Gain

6) Directivity

7) Antenna Efficiency

8) Effective Area

9) Lobe

10) Effective length & Height

11) Radiation Resistance

1) Radiation Intensity:-

It is defined as the power radiated In a given direction per Unit solid angle. The unit is Watt/steridian

It is denoted by Letter "U" (or) Φ (or) R.I

Formula:- $R.I = r^2 P = \frac{r^2 E^2}{\eta_0}$ w/sr

P = power radiator in Watts

E = Electric field strength in V/m

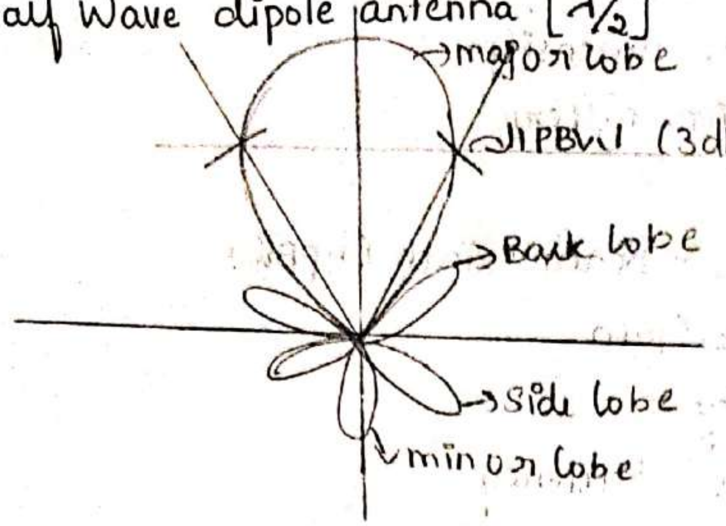
η_0 = Intrinsic Impedance of the medium in Ω [$Z_0 = 50\Omega$ or 73Ω]

r = radius of the sphere in m

2) Radiation Pattern:-

It is a 3D-quantity and graphical representation of Radiation in actual fied strength measured at the point around the antenna which all are at the Equal distance from antenna.

Eg:- Half Wave dipole antenna [$\lambda/2$]



[Refer Book (3D diagram)]

formula:-

field pattern $E_\theta(\theta, \phi_n) = \dfrac{E_\theta(\theta, \phi)}{E_\theta(\theta, \phi_{max})}$

E_θ = θ component of Electric field as a function of θ and ϕ

E_ϕ = ϕ component of Electric field as a function of θ and ϕ

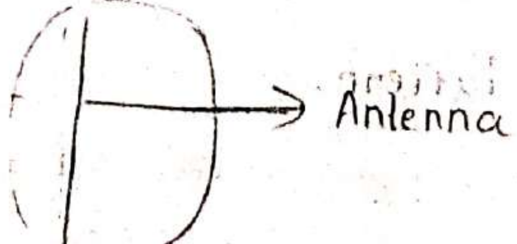
Power pattern $P(\theta, \phi)_n = \dfrac{S(\theta, \phi)}{S(\theta, \phi)_{max}}$

$S \Rightarrow$ poynting vector $\qquad \dfrac{S(\theta,\phi)}{S(\theta,\phi)_{max}}$

$E = \sqrt{E_\theta^2 + E_\phi^2}$

TYPES of Radiation pattern:-

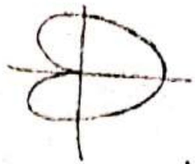
1) omni directional (or) Broad cast Radiation Pattern



2) pencil beam radiation pattern 

3) fan beam radiation pattern

4) Cardiod Radiation pattern



5) figure of 8 radiation pattern

6) Shape beam radiation pattern (Any shape)

3] LOBE :-

It is the portion of radiation pattern bounded by the Region of relatively weak radiation intensity

Types of lobe :-

(i) Major lobe
(ii) Minor lobe
(iii) Back lobe
(iv) Side lobe.

Comparison of Antenna & Transmission line:-

Antenna	Transmission line
RLC (ie) [Resistor, Inductor, capacitor) Varied.	RLC Not Varied
Its radiates Em Waves	It does not radiate (ie) radiation is no more

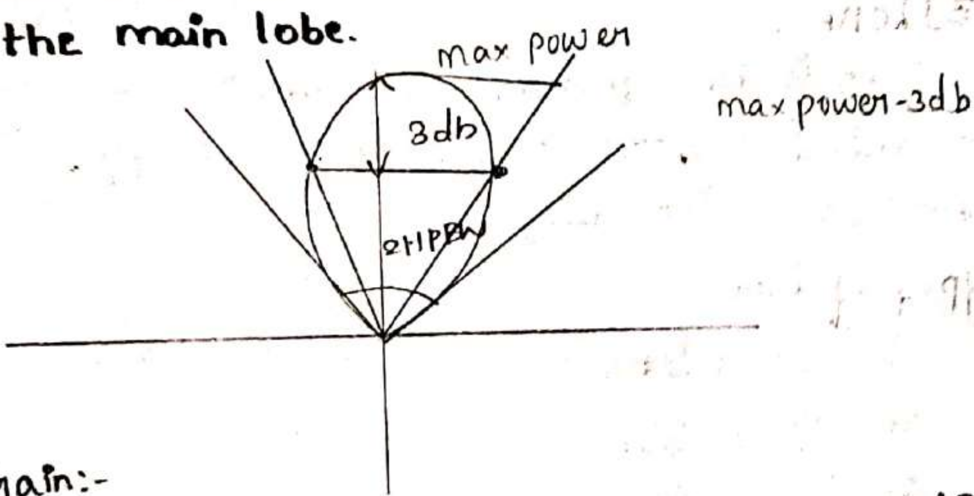
4] Isotophic Radiator:-

It radiates the field strength (or) Power in all direction Equally.

This is the Omni directional antenna

5] Half Power Beam Width [HPBW]

It is the angular width b/w the two points which are at 3db from the maximum power radiated half of the Power radiated in the main lobe.



6] Gain:-

It is the ratio b/w maximum radiation intensity from the test antenna & maximum radiation Intensity from the isotophic antenna

It relates the Performance of test and reference antenna.

$$\text{Gain} = \frac{\text{Max. R.I from test antenna}}{\text{Max. R.I from Reference antenna}}$$

Formula:-

$$G(\theta, \phi) = 4\pi \frac{u(\theta, \phi)}{P_{in}}$$

$4\pi \Rightarrow$ Sphere

$u(\theta, \phi)$ = radiation intensity

P_m = maximum power.

7) Directive Gain:-

It is the Gain of an antenna in a particular direction. It defines the Extend to which the antenna concentrates its radiated Energy in a particular direction.

Directive gain is represented as G_d

$$G_d = \frac{\text{R.I of test antenna in Particular Direction}}{\text{Avg radiated Power in that direction}}$$

Formula:-

$$G_d = \frac{\phi(\theta,\phi)}{\phi_{avg}} = \frac{\Phi(\theta,\phi)}{\Phi_{avg}} = \frac{\phi(\theta,\phi)}{\frac{W_r}{4\pi}} = \frac{4\pi\,\Phi(\theta,\phi)}{W_r}$$

where $\Phi_{avg} = \frac{W_r}{4\pi}$

$W_r \Rightarrow$ Angular frequency.

8) Power gain:-

It is the ratio between Radiated Power density in a particular direction from test antenna to the Radiated Power density in a particular direction from Reference antenna.

It is represented as G_p

$$G_p = \frac{\text{R.P.D in a P.D from Test antenna}}{\text{R.P.D in a P.D from Reference antenna}}$$

Formula:-

$G_p = \eta_0 G_d$ $\quad \eta_0 = 1$ (intrinsic impedance) where

$G_p = G_d$ $\quad \eta = \frac{R_r}{R_r + R_L}$

R_r → Radiation Resistance

R_L → Load Resistance

9] Directivity:-

It is the ratio of radiation Intensity in a Given direction from the antenna to the Radiation intensity avg overall direction

(or) It is the ratio of the maximum radiation Intensity to the avg radiation Intensity

$$(gd)_{max} = D \approx \text{Directivity}$$

$$D \text{ in db} = 10\log_{10}[gd]_{max}$$

$$D = \frac{4\pi}{\Omega_A}$$

" omega(ω) (or) Ω

$$D = \frac{Max.R.I}{Avg\ R.I}$$

Where $D = \frac{4\pi Ae}{\lambda^2}$

10] Antenna Efficiency:-

It is the ratio of the radiated power to the input power.

$$\eta = \frac{\text{power radiated}}{\text{Total power Input}}$$

"

Antenna efficiency

$$e_0 = e_r e_c e_d$$

Where

e_0 = Total antenna Efficiency

e_r = Reflection Efficiency

e_c = Conditional Efficiency

e_d = dielectric "

Scanned with CamScanner

11] Effective Area (or) Effective Aperture (or) Capture Area:-

Area Overwhich the antenna Extracts Energy from the Travelling Em Waves.

It is represented as Ae

$$A_e = \frac{\text{Power Radiated by test Antenna}}{\text{poynting Vector of Incident Wave.}}$$

$$A_e = \frac{D\lambda^2}{4\pi}$$

The relationship b/w Directivity & Effective Area is

$$D = \frac{4\pi A_e}{\lambda^2}$$

TYPES OF APERTURE:-

(i) Scattering Aperture

(ii) Loss Aperture

(iii) Collecting Aperture

(iv) physical Aperture

(i) Scattering Aperture:-

It is represented as A_s

$$\alpha = \frac{A_e}{A_{e\,max}}$$

$$A_s = \frac{I^2_{rms} \cdot R_r}{P}$$

Scattering ratio (β):

$$\beta = \frac{A_s}{A_e}$$

(ii) Loss Aperture :-

It is denoted as R_r & R_e Values.

$$A_e = \frac{I^2_{rms} \cdot R_e}{P}$$

(iii) Collecting Aperture :-

It is denoted as A_c

$$A_c = A_e + A_s + A_e$$

$$= I^2_{rms} R_L + I^2_{rms} R_r + I^2_{rms} R_l$$

Where

R_L = Loss

R_l = load.

(iv) physical Aperture :-

It depends on physical size (or) shape of an antenna.

$$A_p = \frac{A_{e(max)}}{\gamma}$$

$\gamma \rightarrow$ Absorption Ratio.

EFFECTIVE HEIGHT :-

It is denoted as h_e

It represents the effectiveness of the antenna, for receiving antenna,

$$h_e = \frac{\text{Voltage induced in the receiving terminal of an antenna}}{\text{Incident Electric field Intensity}}$$

formula :- $h_e = \frac{V}{E}$ m^2 (or) λ

The relationship between Effective Area and Effective height is

$$A_{e\,max} = \frac{h_e^2 Z_0}{4 R_r}$$

EFFECTIVE LENGTH :-

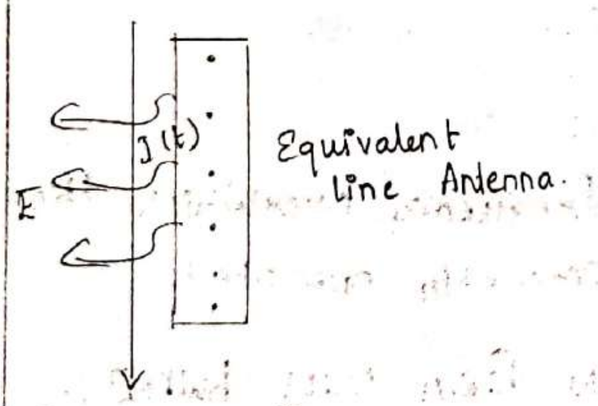
It is an length of an equivalent linear antenna that has same current [I[C]] at all points along its length that radiates the same E [Electric field Intensity]

It is Used to indicate the Effectiveness of antenna as a radiator (or) receiver of Em Energy.

Formula :-

$$\text{Effective length} = l_e = \frac{2}{I[C]} \int_0^{l/2} I(z)\, dz$$

$$l_e = 2\sqrt{\frac{A_e R_r}{Z_0}}$$



RADIATION RESISTANCE :-

It is a hypothetical Resistance that would dissipate an amount of power Equal to the radiated power.

Formula :-

$R \to$ Low freq

$Z \to$ high freq

$$R_r = \frac{\text{Power Radiated}}{I_{rms}^2} \qquad \boxed{R_r = 73.2\,\Omega}$$

ANTENNA IMPEDANCE (Or) INPUT IMPEDANCE:-

It is defined as the ratio of input Voltage to input Current.

It is denoted as Z.

Formula:-

$$Z = \frac{V_i}{I_i} \ \Omega$$

Complex quantity

Z is the Complex quantity so it can be written as

$$Z = R_a + jX_a$$

The Reactive path X_a Results from fields surrounding the antenna.

The Resistance Path R_a is given as

$$R_a = R_l + R_r$$

where

$R_l \Rightarrow$ loss in antenna

$R_r \Rightarrow$ radiation Resistance

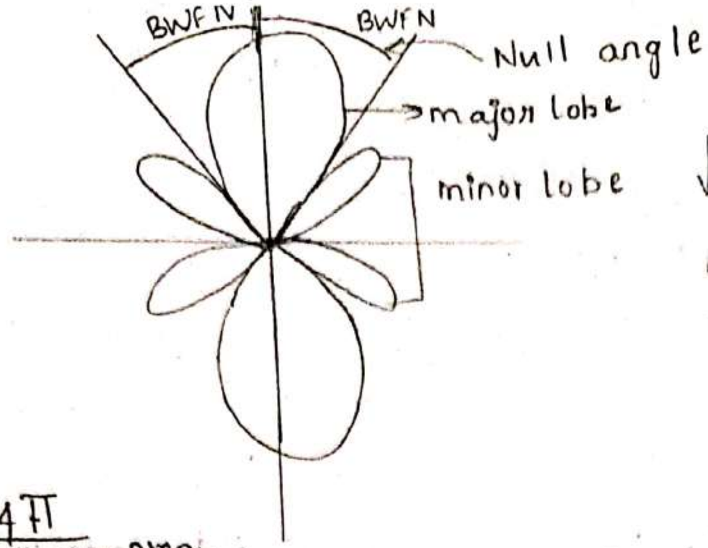
BEAM WIDTH:-

Range of frequency Over Which the antenna can be Efficiently operated.

BEAM WIDTH BETWEEN FIRST NULL [BWFN]:-

Amount of Power spends in the main Lobe aswell as side lobe.

If more side lobes are available it is not Efficient antenna.



$$\downarrow A_e \uparrow = \downarrow \uparrow \frac{D\lambda^2}{4\pi}$$

$$D = \frac{4\pi}{\Omega_A} \rightarrow \text{Area}$$

Major lobe Area can be calculated with Beam width.

Major lobe Area = HPBW in horizontal direction × HPBW in vertical direction.

$$B = \theta_E \times \theta_H$$

$$D = \frac{4\pi}{\theta_E \times \theta_H}$$

ANTENNA BANDWIDTH :-

Range of frequencies overwhich the antenna maintain its characteristics & parameters like gain, SWR, polarization, Directivity and so on, without considerable change.

$$BW = \frac{\text{Resonant freq.}}{\text{Quality factor}} = \frac{\omega_r}{Q}.$$

FRONT TO BACK RATIO [FBR] :-

The Ratio of Radiated power in the desired direction to the Radiated power in the opposite direction.

$$FBR = \frac{\text{r.p in the direction}}{\text{r.p in the Opp direction}}$$

for Directional antenna FBR changes with respect to frequency.

for increasing FBR add the antenna arrays, lens antenna and Reflectors.

[predefined length, predefined height placing nearby)

POLARISATION:-

The Orientation of electric field (or) H field of an antenna.

TYPES:-

(i) Linear → 3 types (i) horizontal

(ii) Vertical

(iii) Theta.

(ii) Circular

(iii) Elliptical

[sense of rotation]

BEAM AREA (Or) BEAM SOLID ANGLE:-

It is denoted by Ω_A

In polar 2d coordinates an incremental Area dA on the surface of a sphere is the product length of $rd\theta$, in the θ direction [latitude] and $r\sin\theta d\phi$ in the ϕ direction [longitude]

dA = Beam solid Angle (or) Beam Area

$dA = (rd\theta)(r\sin\theta d\phi)$

$dA = r^2 d\Omega$

$\sin\theta d\theta d\phi \Rightarrow$ Beam solid Angle.

Antenna Noise Temperature

Antenna Temperature (T_A) is a parameter that describes how much noise an antenna produces in a given environment. This temperature is not the physical temperature of the antenna. Moreover, an antenna does not have an intrinsic "antenna temperature" associated with it; rather the temperature depends on its gain pattern and the thermal environment that it is placed in. Antenna temperature is also sometimes referred to as **Antenna Noise Temperature**.

To define the environment (and hence give the full definition of antenna temperature), we will introduce a temperature distribution - this is the temperature in every direction away from the antenna in spherical coordinates. For instance, the night sky is roughly 4 Kelvin; the value of the temperature pattern in the direction of the Earth's ground is the physical temperature of the Earth's ground. This temperature distribution will be written as $T(\theta,\phi)$. Hence, an antenna's temperature will vary depending on whether it is directional and pointed into space or staring into the sun.

For an antenna with a radiation pattern given by $R(\theta,\phi)$, the noise temperature is mathematically defined as:

$$T_A = \frac{1}{4\pi}\int_0^{2\pi}\int_0^{\pi} R(\theta,\phi)T(\theta,\phi)\sin\theta d\theta d\phi$$

This states that the temperature surrounding the antenna is integrated over the entire sphere, and weighted by the antenna's radiation pattern. Hence, an isotropic antenna would have a noise temperature that is the average of all temperatures around the antenna; for a perfectly directional antenna (with a pencil beam), the antenna temperature will only depend on the temperature in which the antenna is "looking".

The noise power received from an antenna at temperature T_A can be expressed in terms of the bandwidth (B) the antenna (and its receiver) are operating over:

$$P_{TA} = KT_AB$$

In the above, K is Boltzmann's constant (1.38 * 10^-23 [Joules/Kelvin = J/K]). The receiver also has a temperature associated with it (T_R), and the total system temperature (antenna plus receiver) has a combined temperature given by $T_{sys} = T_A + T_R$. This temperature can be used in the above equation to find the total noise power of the system. These concepts begin to illustrate how antenna engineers must understand receivers and the associated electronics, because the resulting systems very much depend on each other.

A parameter often encountered in specification sheets for antennas that operate in certain environments is the ratio of gain of the antenna divided by the antenna temperature (or system temperature if a receiver is specified). This parameter is written as G/T, and has units of dB/Kelvin [dB/K].

Finally, note that many RF engineers like to use the term Noise Figure (or Noise Factor, NF) to describe systems. This is the ratio of the input SNR (signal to noise ratio) to the output SNR. Basically, all RF devices (like mixers and amplifiers) add some noise. Antenna temperature doesn't really relate to a Noise Figure, as the signal level power input varies greatly with the desired signal's direction of arrival, while the noise added is a constant.

Link Power Budgetting : Calculation/Measurement Of Receiver G/T

Link Power Budgetting

9.Calculation of receiver G/T

1. <u>Antenna elevation angle (deg)</u> Antenna elevation effects the antenna noise temperature. Antenna noise temperature decreases with increase of elevation.

2. <u>Antenna noise temp</u> Antenna noise temperature is the sum of all noise sources at the antenna.

3. <u>Increase in Antenna noise due to rain</u> Rain effects the antenna noise temperature. It increases the antenna noise temperature.

4. <u>LNA noise temp</u> LNA means Low Noise Amplifier. LNA noise temperature means noise temperature of LNA.

5. <u>System noise temp (k)</u> It is the sum of all noise temperatures at the receiving antenna

System noise temperature (k) = antenna noise temperature + increase in antenna noise due to rain + LNA noise temperature (k).....[13]

Example : Calculate system noise temperature of a satellite having noise temperature 25 K increase in antenna noise due to rain =0 K LNA noise temperature = 50 K

Solution:

System noise temperature = antenna noise temperature + increase in antenna noise due to rain + LNA noise temperature

= 25 + 0 + 50 = 75

6. <u>Receiver G/T (dB/k)</u> Receiver G/T is the Figure of merit at the receiver antenna.

Receiver G/T (dB/K) = Receiver Antenna gain-10 log(system noise temperature) (dB/k).....[14]

Example : Calculate Receiver G/T (dB/K) of a satellite having antenna gain 41.33 , over all receiver noise temperature = 75 K

Solution:

Receiver G/T (dB/K) = Receiver Antenna gain - 10 log(system noise temperature)

= 41.33- 10 log(75)

=22.579 (dB/K)

Link Power Budgetting : Calculation/Measurement Of Link Margin

Link Power Budgetting

10.Calculation of link margin

1. <u>Down link rain attenuation</u> Rain fall introduces attenuation by absorption and scattering of signal energy, and the absorptive attenuation introduces noise.

Effective noise temp of rain as

$T_{rain} = T_A(1-(1/A))$

Where T_{rain} is known as apparent absorber temperature. It is a measured parameter, which is a function of many factors, including physical temperature of rain, and scattering effect of the rain, and the scattering effect of the cell on the thermal noise incident up on it. The value of the apparent absorber temperature lies between 270 and 290 K .

Total sky noise temperature is the clear sky temperature plus the rain temperature

$T_{Sky} = T_{cs} + T_{RAIN}$

Where T_{cs} is the clear-sky noise temperature

2. <u>Receiver antenna pointing loss</u> When a satellite link is established, the ideal situation is to have the earth station and satellite antennas aligned for maximum gain. There are two possible sources of off axis loss , one at the satellite and one at the earth station . The off axis loss at the satellite is taken in to account by designing the link for operation on actual satellite antenna contour. The off axis losses at the earth station is referred to as the antenna pointing loss.

Antenna pointing losses are usually only a few tenths of a decibel.

3. <u>Eb/No required for BER of $1/10^7$</u> It is Signal to noise ratio required to achieve Bit Error Ratio of 1 error bit per 10^7 message bits.

4. <u>Down link C/N_0 (dB Hz)</u> It is the down link carrier to noise ratio. It can be calculated as follows.

Down link C/N_0(dB Hz) = Satellite operating EIRP - Downlink path loss - Down link rain attenuation - Receiving antenna pointing loss + Receiver G/T +228.6. ....[15]

Example : Calculate Down link C/N_o(dB Hz) for the Satellite operating EIRP =-6.23 dB W, Downlink path loss =195.74 dB, Down link rain attenuation=0 dB, Receiving antenna pointing loss = 0.70 dB, Receiver G/T =22.58(dB/K)

Solution:

Down link C/N_o(dB Hz) = Satellite operating EIRP - Downlink path loss - Down link rain attenuation - Receiving antenna pointing loss + Receiver G/T +228.6.

= -6.23-195.74-0-0.70+22.58+228.6

= 48.51 dB Hz

5. **<u>Over all Down link C/No (dB Hz)</u>** It is the some of carrier to noise ratio at the down link and carrier to noise ratio at the up link. It can be calculated as follows

Over all Downlink(C/N_o) (dB Hz)= -10*LOG $(10^{-(C/N_o)U}+10^{-(C/N_o)D})$.......[16]

Here,

$(C/N_o)_U$ = Up link C/N ratio.

$(C/N_o)_D$ = Downlink C/N ratio.

It is the effective C/N ratio of the total system (Transmitter & receiver)

Example : Find over all carrier to noise ratio of the satellite Up link C/N ratio = 61.95, Downlink C/N ratio= 48.51

Solution:

Over all Downlink(C/N_o) (dB Hz)= -10*LOG $(10^{-(C/N_o)U}+10^{-(C/N_o)D})$

= 48.32

6. **<u>Available Eb/N_o</u>** It is the ratio of signal to noise ratio of the system. It can be calculated as follows.

Available Eb/N_O = over all downlink (C/N_o) / Input data rate

Available Eb/N_O (dB)= Over all downlink (C/N_o)(dB) - Input data rate (dB)

= Over all downlink(C/N_o)(dB) - 10log (input data rate in KB*10_3)........[17]

Example : Find Available Eb/N_O (dB) for the satellite Over all downlink (C/N_o)(dB) =48.32, Input data rate (dB)= 9.6 KB/S.

Solution:

Available Eb/N_O (dB)= Over all downlink (C/N_o)(dB) - 10log (input data rate in KB*10_3)

= 48.32-10 log(9.6 * 10^3)

= 8.63 dB

7. <u>Available link margin</u> It is the Difference between 'Available Eb/N_0' and 'Eb/N_0 required for BER of $1/10^7$ in dB.

Available link margin = Available Eb/N_0(dB) - Eb/N_0 required for BER of $1/10^7$ (dB)......[18]

Example : Find Available link margin for the satellite Available Eb/N_0(dB) =8.63 and Eb/N_0 required for BER of $1/ 10^7$ (dB) = 6.5.

Solution:

Available link margin = Available Eb/N_0(dB) - Eb/N_0 required for BER of $1/10^7$ (dB)

$= 48.32-10 \log(9.6 * 10^3)$

$= 8.63-6.5 = 2$ dB.

Impedance Matching

In general, the transmission line will transform the impedance of an antenna, making it very difficult to deliver power, unless the antenna is matched to the transmission line. Consider the situation shown in Figure 2. The impedance is to be measured at the end of a transmission line (with characteristic impedance Z0) and Length L. The end of the transmission line is hooked to an antenna with impedance ZA.

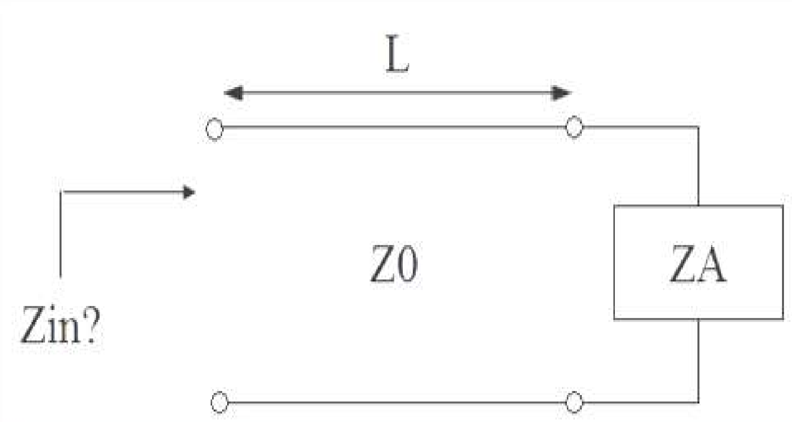


Figure 2. High Frequency Example.

It turns out (after studying transmission line theory for a while), that the input impedance Zin is given by:

$$Z_{in} = Z_0 \frac{ZA + jZ_0 \cdot \tan(\frac{2\pi f}{c}L)}{Z_0 + jZA \cdot \tan(\frac{2\pi f}{c}L)}$$

This is a little formidable for an equation to understand at a glance. However, the happy thing is:

If the antenna is matched to the transmission line (ZA=ZO), then the input impedance does not depend on the length of the transmission line.

This makes things much simpler. If the antenna is not matched, the input impedance will vary widely with the length of the transmission line. And if the input impedance isn't well matched to the source impedance, not very much power will be delivered to the antenna. This power ends up being reflected back to the generator, which can be a problem in itself (especially if high power is transmitted). This loss of power is known as *impedance mismatch*. Hence, we see that having a tuned impedance for an antenna is extremely important. For more information on transmission lines, see the transmission line tutorial.

VSWR

We see that an antenna's impedance is important for minimizing impedance-mismatch loss. A poorly matched antenna will not radiate power. This can be somewhat alleviated via impedance matching, although this doesn't always work over a sufficient bandwidth (bandwidth is the next topic).

A common measure of how well matched the antenna is to the transmission line or receiver is known as the Voltage Standing Wave Ratio (VSWR). VSWR is a real number that is always greater than or equal to 1. A VSWR of 1 indicates no mismatch loss (the antenna is perfectly matched to the tx line). Higher values of VSWR indicate more mismatch loss.

As an example of common VSWR values, a VSWR of 3.0 indicates about 75% of the power is delivered to the antenna (1.25 dB of mismatch loss); a VSWR of 7.0 indicates 44% of the power is delivered to the antenna (3.6 dB of mismatch loss). A VSWR of 6 or more is pretty high and will generally need to be improved.

The parameter VSWR sounds like an overly complicated concept; however, power reflected by an antenna on a transmission line interferes with the forward travelling power - and this creates a standing voltage wave - which can be numerically evaluated by the quantity Voltage Standing Wave Ratio (VSWR). For more information, see the page on VSWR and VSWR Specifications.

Friis Transmission Equation

On this page, we introduce one of the most fundamental equations in antenna theory, the **Friis Transmission Equation**. The Friis Transmission Equation is used to calculate the power received from one antenna (with gain *G1*), when transmitted from another antenna (with gain *G2*), separated by a distance *R*, and operating at frequency *f* or wavelength lambda. This page is worth reading a couple times and should be fully understood.

Derivation of Friis Transmission Formula

To begin the derivation of the Friis Equation, consider two antennas in free space (no obstructions nearby) separated by a distance *R*:

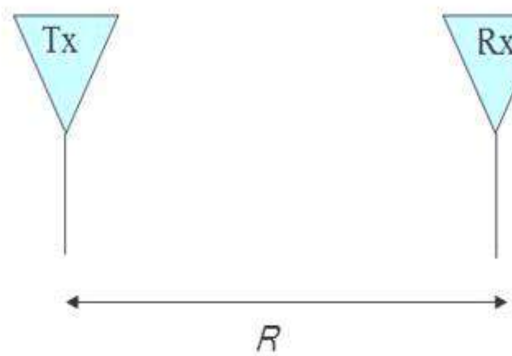


Figure 1. Transmit (Tx) and Receive (Rx) Antennas separated by *R*.

Assume that P_T Watts of total power are delivered to the transmit antenna. For the moment, assume that the transmit antenna is omnidirectional, lossless, and that the receive antenna is in the far field of the transmit antenna. Then the power density *p* (in Watts per square meter) of the plane wave incident on the receive antenna a distance *R* from the transmit antenna is given by:

$$p = \frac{P_T}{4\pi R^2}$$

If the transmit antenna has an antenna gain in the direction of the receive antenna given by G_T, then the power density equation above becomes:

$$p = \frac{P_T}{4\pi R^2} G_T$$

The gain term factors in the directionality and losses of a real antenna. Assume now that the receive antenna has an effective aperture given by A_{ER}. Then the power received by this antenna (P_R) is given by:

$$P_R = \frac{P_T}{4\pi R^2} G_T A_{ER}$$

Since the effective aperture for any antenna can also be expressed as:

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

The resulting received power can be written as:

$$P_R = \frac{P_T G_T G_R \lambda^2}{(4\pi R)^2} \qquad \textbf{[Equation 1]}$$

This is known as the ***Friis Transmission Formula***. It relates the free space path loss, antenna gains and wavelength to the received and transmit powers. This is one of the fundamental equations in antenna theory, and should be remembered (as well as the derivation above).

Another useful form of the Friis Transmission Equation is given in Equation [2]. Since wavelength and frequency *f* are related by the speed of light *c* (see intro to frequency page), we have the Friis Transmission Formula in terms of frequency:

$$P_R = \frac{P_T G_T G_R c^2}{\left(4\pi R f\right)^2} \qquad \textbf{[Equation 2]}$$

www.antenna-theory.com

Equation [2] shows that more power is lost at higher frequencies. This is a fundamental result of the Friis Transmission Equation. This means that for antennas with specified gains, the energy transfer will be highest at lower frequencies. The difference between the power received and the power transmitted is known as *path loss*. Said in a different way, Friis Transmission Equation says that the path loss is higher for higher frequencies.

Finally, if the antennas are not polarization matched, the above received power could be multiplied by the Polarization Loss Factor (*PLF*) to properly account for this mismatch. Equation [2] above can be altered to produce a generalized Friis Transmission Formula, which includes polarization mismatch:

$$P_R = (PLF) \cdot \frac{P_T G_T G_R c^2}{\left(4\pi R f\right)^2} \qquad \textbf{[Equation 3]}$$

Noise Characterization of Receiver

Noise Characterization of a Receiver

We can now analyze the noise characteristics of a complete antenna–transmission line–receiver front end, as shown in Figure 14.14. In this system the total noise power at the output of the receiver, N_o, will be due to contributions from the antenna pattern, the loss in the antenna, the loss in the transmission line, and the receiver components. This noise power will determine the minimum detectable signal level for the receiver and, for a given transmitter power, the maximum range of the communication link.

The receiver components in Figure 14.14 consist of an RF amplifier with gain G_{RF} and noise temperature T_{RF}, a mixer with an RF-to-IF conversion loss factor L_M and noise temperature T_M, and an IF amplifier with gain G_{IF} and noise temperature T_{IF}. The noise effects of later stages can usually be ignored since the overall noise figure is dominated by the characteristics of the first few stages. The component noise temperatures can be related to noise figures as $T = (F - 1)T_0$. From (10.22) the equivalent noise temperature of the receiver can be found as

$$T_{\mathrm{REC}} = T_{\mathrm{RF}} + \frac{T_M}{G_{\mathrm{RF}}} + \frac{T_{\mathrm{IF}} L_M}{G_{\mathrm{RF}}}. \tag{14.27}$$

The transmission line connecting the antenna to the receiver has a loss L_T, and is at a physical temperature T_p. So from (10.15) its equivalent noise temperature is

$$T_{\mathrm{TL}} = (L_T - 1)T_p. \tag{14.28}$$

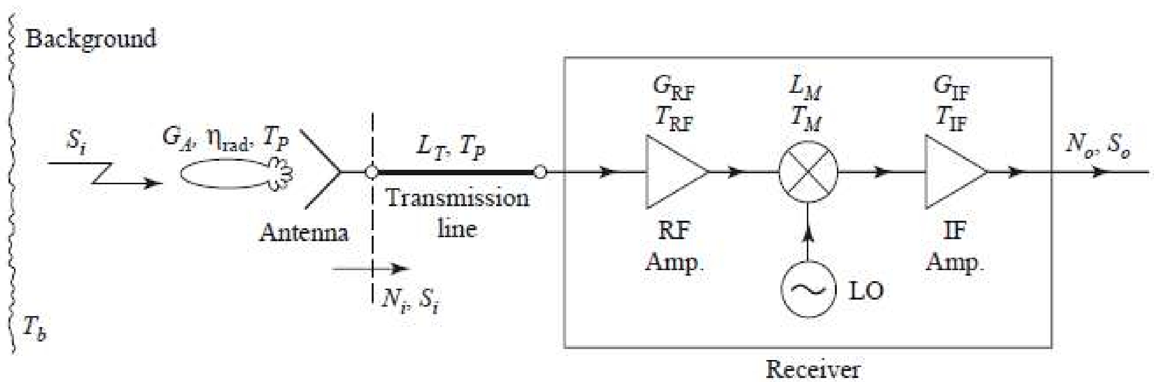


FIGURE 14.14 Noise analysis of a microwave receiver front end, including antenna and transmission line contributions.

Again using (10.22), we find that the noise temperature of the transmission line (TL) and receiver (REC) cascade is

$$\begin{aligned} T_{\mathrm{TL+REC}} &= T_{\mathrm{TL}} + L_T T_{\mathrm{REC}} \\ &= (L_T - 1)T_p + L_T T_{\mathrm{REC}}. \end{aligned} \tag{14.29}$$

This noise temperature is defined at the antenna terminals (the input to the transmission line).

As discussed in Section 14.1, the entire antenna pattern can collect noise power. If the antenna has a reasonably high gain with relatively low sidelobes, we can assume that all noise power comes via the main beam, so that the noise temperature of the antenna is given by (14.18):

$$T_A = \eta_{\mathrm{rad}} T_b + (1 - \eta_{\mathrm{rad}}) T_p, \tag{14.30}$$

where η_{rad} is the efficiency of the antenna, T_p is its physical temperature, and T_b is the equivalent brightness temperature of the background seen by the main beam. (One must be careful with this approximation, as it is quite possible for the noise power collected by the sidelobes to exceed the noise power collected by the main beam, if the sidelobes are aimed at a hot background. See Example 14.3.) The noise power at the antenna terminals, which is also the noise power delivered to the transmission line, is

$$N_i = kBT_A = kB[\eta_{\mathrm{rad}} T_b + (1 - \eta_{\mathrm{rad}}) T_p], \tag{14.31}$$

where B is the system bandwidth. If S_i is the received power at the antenna terminals, then the input SNR at the antenna terminals is S_i/N_i. The output signal power is

$$S_o = \frac{S_i G_{\mathrm{RF}} G_{\mathrm{IF}}}{L_T L_M} = S_i G_{\mathrm{SYS}}, \tag{14.32}$$

where G_{SYS} has been defined as a system power gain. The output noise power is

$$\begin{aligned} N_o &= (N_i + kBT_{\mathrm{TL+REC}})\, G_{\mathrm{SYS}} \\ &= kB(T_A + T_{\mathrm{TL+REC}}) G_{\mathrm{SYS}} \\ &= kB[\eta_{\mathrm{rad}} T_b + (1 - \eta_{\mathrm{rad}}) T_p + (L_T - 1) T_p + L_T T_{\mathrm{REC}}] G_{\mathrm{SYS}} \\ &= kBT_{\mathrm{SYS}} G_{\mathrm{SYS}}, \end{aligned} \tag{14.33}$$

where T_{SYS} has been defined as the overall system noise temperature. The output SNR is

$$\frac{S_o}{N_o} = \frac{S_i}{kBT_{SYS}} = \frac{S_i}{kB[\eta_{rad}T_b + (1 - \eta_{rad})T_p + (L_T - 1)T_p + L_T T_{REC}]}. \qquad (14.34)$$

It may be possible to improve this SNR by various signal processing techniques. Note that it may appear to be convenient to use an overall system noise figure to calculate the degradation in SNR from input to output for the above system, but one must be very careful with such an approach because noise figure is defined only for $N_i = kT_0B$, which is not the case here. It is often less confusing to work directly with noise temperatures and powers, as we did above.