CHAPTER 5

THEORY AND TYPES OF ANTENNAS

5.1 Introduction

Antenna is an integral part of wireless communication systems, considered as an interface between transmission line and free space [16]. Antenna converts Electrical signals into Electromagnetic signals and vice versa. It is also defined as a transducer [17].

Antenna has been around the world for more than hundred years. The first successful demonstration of Electromagnetic wave was done by Faraday around 1830’s [74]. He placed a magnet through the coils of a wire attached to a Galvanometer. When he moved the magnet, he was able to produce time varying magnetic field. It in turn, had a time varying Electric Field which was detected by galvanometer. The concept of electromagnetic wave was not known to the world at that time.

In 1886, Hertz developed a wireless communication kit in which an electric spark occurred in the gap of a dipole antenna. He used a loop antenna as a receiver and observed similar effect.

Wireless Communication over long distance was first demonstrated by Marconi. He demonstrated Electromagnetic wave propagation across Atlantic Ocean. His transmitter was placed at Poldhu, UK and his receiver was placed at St. Johns, New Foundland, USA. For a transmit antenna, he used several vertical wires attached to ground. The antennas used in this experiment were of 45 meters height [73]. As operating frequency was in LF range, height of the antennas was longer which put difficulty in installing the antenna. But later on with the introduction of modulation techniques, the height of the antenna became smaller and it was easy to install antennas with manageable height.
In 1906, Columbia University had a wireless station where they used a transmitting aerial cage. This was made up of wires and suspended in the air.

In 1913, the Eiffel Tower was used as an antenna. At that time, communication was carried out at very low frequencies, the antennas had to be very large to radiate or receive properly. The Eiffel Tower fit this bill well, and was used to communicate with the United States Naval Observatory in Arlington, Virginia.

In 1890’s, there were only few antennas in the world. Most of those antennas are placed at the laboratories. They were used to do experiments on Electromagnetic Waves. By World War II, the importance of Antenna was understood by the military people and also by the common man for entertainment purpose. The birth of Radio and later on Television made the industry to think on various antennas. The antenna has become an integral part of common man from that point onwards.

Fig 5.1 Prof. Yagi carrying yagi – uda antenna
Yagi – Uda Antenna is still considered as one of the easiest and efficient directional antennas to construct. It was first developed in 1929 by Shintaro Uda in Japan. The work was presented in English by Yagi, who was Uda’s professor. So, this antenna has been widely known as Yagi – Uda Antenna. A picture of Prof. Yagi carrying the antenna is shown in Fig 5.1.

Horn Antennas are developed in 1939. They operate at UHF and higher frequencies. They have directional radiation pattern with gain ranging 10 to 20 dB. E – plane Horn, H – plane Horn and pyramidal Horn are the types of horn antennas which are vastly used. Horn Antennas have wide bandwidth.

Antenna Arrays were first constructed in 1940’s. Arrays are combination of two or more similar antennas to increase the gain and directivity. By changing the phase of the feeding signal, it is possible to change the direction of radiation pattern of the array. This is known as phased array. Smart antenna which works based on the weighed inputs is also an array antenna. Digital Signal Processing [DSP] algorithms decide the amplitude and phase of the signal, fed to various elements of the array. Phased array and smart antennas are latest additions to the antenna fold.

Corner reflector, Parabolic reflector and Lens antennas are basically known as reflector type antennas. Parabolic Reflector which is considered the best antenna to communicate with the satellites was invented in 1940’s. This antenna has wide bandwidth and very high gain of 30 to 40 dB. Either a horn antenna or a dipole is used as the feed antenna.

The Mobile phone market developed rapidly over the years with cost effectiveness of both mobile phones and service providers. Mobile phones change the life style of common man. Nowadays, almost each and every person is carrying at least an antenna which is integrated in his mobile phone.
The famous Patch Antenna was first fabricated in 1970’s. Their low weight, low cost and smoothness to handle made them hot favorites for the modern applications. Patch antennas are used in mobile phones to make it compact. Planar Inverted ‘F’ Antenna which is also known as ‘PIFA’ was first developed around 1980’s and this has been widely used in Laptops nowadays.

Current research focuses on making antennas smaller, particularly in communications for personal wireless communication devices such as cell phones. A lot of work is being performed on numerical modeling of antennas, so that their properties can be predicted before they are fabricated and tested. Method of Moments, Finite Element Methods, Finite Difference Time Domain method are few numerical techniques used to analyze antennas.

The Current research on antenna also involves meta-materials which are materials having a negative index of refraction. They are also known as Frequency Selective surfaces [FSS] which remove a particular frequency band from their operation.

Small, weight less antennas are used in Radio Frequency Identification [RFID]. This type of antenna is also used at nodes of Wireless Sensor Networks [WSN].

5.2 Basic Antenna Theory

An antenna is made up of simple current carrying conductor which is radiated under certain conditions.

For wire antenna, the basic equation of radiation is expressed as

\[ \mathbf{I} \times \mathbf{L} = \mathbf{Q} \times \mathbf{\dot{v}} \quad (\text{A m/s}) \]  

---  (5.1)
Where,

\[ \vec{I} = \text{time varying current} \]
\[ L = \text{length of antenna element in meter.} \]
\[ Q = \text{charge in the wire.} \]
\[ \dot{\vec{V}} = \text{time change of velocity which equals the acceleration of the charge in m/s}^2. \]

As per equation 5.1, to create radiation, there must be a time varying current or acceleration (or deceleration) of charge. The direction of radiation is perpendicular to the acceleration, and the radiated power is proportional to the square of \((\vec{l} l)\) or \((Q \dot{v})\).

If the antenna is made up of small current elements, the overall effect at a distance point is due to the integration of all the current components. The current density at the antenna results in vector magnetic potential represented as \(A(z)\). The magnetic flux density ‘B’ is found out with the equation

\[ B = \nabla \times A \quad \text{--- (5.2)} \]

Here \(\nabla\) represents curl operation. Once magnetic field is known, the corresponding electric field can be calculated using intrinsic impedance. Thus, the fields of the resultant EM wave can be found out using vector magnetic potential.

5.3 Antenna Parameters

An antenna’s performance is measured with several critical parameters. These are resonant frequency, impedance, gain, radiation pattern, polarization, efficiency and bandwidth. Transmit antennas may also have a maximum power rating and receive antennas differ in their noise rejection properties. All of these parameters can be measured through various techniques.
5.3.1 Resonant frequency

The "resonant frequency" is related to the electrical length of an antenna. Typically an antenna is tuned for a specific frequency and is effective for a range of frequencies that are usually centered on that resonant frequency.

The length of an antenna is designed in terms of wavelength of operation. The frequency and wavelength are related as

\[ \lambda = \frac{C}{f} \] ------ (5.3)

In the above equation, ‘\( \lambda \)’ is the operating wavelength, ‘f’ is the frequency and ‘C’ is the velocity of free space.

For a half wave dipole antenna, the length is ‘\( \lambda/2 \)’. Similarly a monopole antenna has a length of ‘\( \lambda/4 \)’. Thus the wavelength of operation determines the parameters of antenna.

5.3.2 Directivity

‘Directivity’ is considered as the ability of the antenna to focus its energy in a particular direction when it is transmitting and to receive energy better from a particular direction when it is receiving.

Directivity is defined as the ratio of the maximum power density to its average value over a sphere as observed in the far field of an antenna.

If the beam area is smaller, the directivity is larger. For an antenna that radiates over only half a sphere the beam area is \( 2\pi \) steradian and the directivity is 2 [17].
5.3.3 Gain

Gain as a parameter measures the efficiency of a given antenna. Gain and directivity of an antenna are related with antenna efficiency factor.

\[ G = kD \quad --- (5.4) \]

Where, ‘G’ is the gain of the antenna,

‘D’ is the directivity of the antenna

‘k’ is the antenna efficiency factor, \(0 \leq k \leq 1\).

Gain can be measured by comparing the maximum power density of the antenna under test \([P_{\text{max(test)}}]\) with a reference antenna of known gain \([P_{\text{max(ref)}}]\) [17].

\[ G = \left[ \frac{P_{\text{max(test)}}}{P_{\text{max(ref)}}} \right] \times G_{\text{(ref)}} \quad --- (5.5) \]

High-gain antennas have the advantage of longer range and better signal quality, but must be aimed carefully in a particular direction. Low-gain antennas have shorter range, but the orientation of the antenna is relatively inconsequential. For example, a dish antenna on a spacecraft is a high-gain device that must be pointed at the planet to be effective, whereas a typical Wi-Fi antenna in a laptop computer is low-gain, and as long as the base station is within range, the antenna can be in any orientation in space.

The gain is measured with reference to a dipole [dBd] or a theoretical isotropic radiator [dBi]. In practice, the half-wave dipole is taken as a reference instead of the isotropic radiator. The gain is then given in dBd (decibels over dipole). 0 dBd is equated as 2.15 dBi.
5.3.4 Radiation pattern

The radiation pattern of an antenna is a graph which shows the variation in actual field strength of electromagnetic field at all points which are at equal distances from the antenna. If the radiation is expressed in terms of field strength (E), it is known as ‘field pattern’. If it is given in power, then it is denoted as ‘power pattern’.

Radiation pattern is generally a three dimensional one. They are following spherical coordinate system. Certain methods are followed to represent radiation pattern into two dimensional patterns. Two dimensional patterns are drawn as elevation and azimuthal patterns, vertical and horizontal patterns, ‘E’ plane and ‘H’ plane patterns.

5.3.5 Impedance

Antenna as a transmitter is connected at the last part of a communication system. Antenna provides a series resistance to the communication network. This resistance is known as the radiation resistance. For a dipole, radiation resistance is 73 Ω.

As signal from source travels through different parts of the communication system, it may encounter differences in impedance. At each interface, depending on the impedance match, some fraction of the wave's energy will reflect back to the source, forming a standing wave in the transmission line. The ratio of maximum power to minimum power of the wave can be measured and is called the standing wave ratio (SWR). A SWR of 1:1 is ideal. It means the entire power is radiated through antenna. Practically, part of transmitted power gets reflected back into the transmission line and is measured as SWR. A SWR of 1.5:1 is considered to be acceptable. Matching impedances at each interface reduces SWR and maximize power transfer through each part of the communication system.
5.3.6 Efficiency

Efficiency of an antenna is defined as the ratio of power actually radiated to the total input power into the antenna terminals.

\[
\text{Efficiency} = \frac{R_r}{R_r + R_l} \tag{5.6}
\]

Where, ‘\(R_r\)’ is the radiation resistance,

‘\(R_l\)’ is the ohmic loss resistance of antenna conductor.

Radiation in an antenna is caused by radiation resistance. Ohmic loss resistance usually results in heat rather than radiation, and reduces efficiency.

5.3.7 Bandwidth

The bandwidth of an antenna is the range of frequencies over which it is effective. It is centered on the resonant frequency. The bandwidth of an antenna may be increased by several techniques, including using thicker wires, replacing wires with cages to simulate a thicker wire, tapering antenna components and combining multiple antennas into a single assembly.

5.3.8 Polarization

The polarization of an antenna is defined as the orientation of the electric field (E-plane) of the EM wave with respect to the direction of EM wave. There are two types of polarizations available. They are linear and elliptical. A special case of elliptical polarization is known as circular polarization. Elliptical polarization has its sense as ‘right handed’ and ‘left handed’. To communicate signal effectively, both transmitter and receiver should have the same polarization.
5.4 Transmission and Reception

Antenna exhibits same properties when it works as transmitter as well as receiver. If an antenna has a gain of 6 dB when it works as transmitting antenna, it has the same 6 dB gain even when it works as receiver. Thus Antenna is said to have reciprocity property.

5.5 Types of Antennas

Based on the structure of antennas, they classified into the following types:

i. Wire Antennas – Dipole, Loop
ii. Aperture Antennas – Horn Antenna
iii. Reflector Antennas – Parabolic and Corner reflector antennas
iv. Array Antennas – Yagi - Uda
v. Patch Antennas – Micro strip antenna

Depends on the radiation pattern, antennas are generally fall into two categories:

i. Directional
ii. Omni directional.

Omni directional antennas radiate RF energy equally in all horizontal directions which covers 360 degrees. It is also called ‘Non-Directional’ as it does not prefer any direction. Fig. 5.2 shows an omni directional antenna and fig 5.3 gives the radiation pattern of omni directional antenna. The radiated signal has equal strength in all directions.
Fig 5.2. Omni Directional Antenna for WLAN.

Fig 5.3. Omni Directional Radiation Pattern
5.5.1 Wire Antennas

Dipole is one of the simplest examples of directional antennas. The dipole is also known as ‘Half Wave Dipole’ as the physical length of the antenna is half of the wavelength of operation. The diagram of a half way dipole is shown below.

![Diagram of a half wave dipole antenna](image)

Fig. 5.4. The structure of the dipole

The frequency and wavelength of a signal are related as

\[ f = \frac{C}{\lambda} \]  \hspace{1cm} (5.7)

Where ‘\( \lambda \)’ is the wavelength, ‘\( C \)’ is the velocity of free space \([3 \times 10^8 \text{ m/sec}]\) and ‘\( f \)’ is the frequency of operation. For a frequency of 300 MHz, the wavelength is 1 meter. The half wavelength is 0.5 meter. This is the length of the dipole antenna which can operate at 300 MHz.

Half wave dipole antenna has half cycle of current distribution. Maximum of the current is at the perpendicular direction and the current reduces to ‘zero’ at both the edges of
antenna. So, the radiation pattern of a dipole is having maxima at the perpendicular direction and the minima at the antenna axis ends.

The radiation pattern of the dipole is known as ‘cardiod’ shape. The two dimensional vertical cut of this three dimensional pattern is called as ‘Figure of Eight’ pattern. The radiation pattern of a half wave dipole is shown in the following diagram as a three dimensional case. The corresponding two dimensional diagram is also given below.
The picture of ‘Dipole antenna’ is shown in fig 5.7. The dipole can be fixed either horizontally or vertically with respect to ground. In both the cases, the radiation pattern is the same. The maximum remains in the perpendicular direction to the antenna axis. But depending on whether antenna is placed horizontally or vertically the direction of the main beam will change. The dipole placed vertical with respect to the ground is shown in the diagram given below.

The angle ‘θ’ is measured from ‘z’ axis and the angle ‘φ’ is measured from ‘x’ axis. The variation of angle ‘θ’ by keeping another angle ‘φ’ at zero degree gives elevation pattern. Similarly by varying the angle ‘φ’ and keeping ‘θ’ at 90° gives azimuthal pattern. These patterns are two dimensional patterns drawn based on actual three dimensional radiation pattern of the antenna.
5.5.2 Aperture Antenna

‘Aperture’ means a small opening. The antenna is fed with such a small gap. The Horn antenna is considered as a perfect aperture antenna. Depending on the orientation of this antenna, it is known as ‘E-Plane Horn’, ‘H-Plane Horn’ and ‘Pyramidal Horn’. Horn antennas have greater directivity and narrower bandwidth. Horn antenna is used as the test antenna in the calculation of gain in standard gain measurement method. The picture of a horn antenna is given in fig 5.8.
5.5.3 Reflector Antenna

The antennas which can have higher gain by reflecting EM waves on a surface are known as ‘Reflector Antenna’. Depending on the shape of surface, this antenna is classified such as parabolic reflector antenna. This antenna is used for satellite reception and has been used for satellite Television signal reception. ‘Direct to Home [DTH] Service’ is also utilizing this antenna. At the focal point of this antenna, a feed antenna is placed. Dipole or horn antenna is used as feeder for this antenna [17]. To increase efficiency of this antenna, feeder is placed at the back side of reflector. This is known as ‘Cassegrain feed’. Similarly the feeder is placed at one end is known as ‘Offset feed’. This antenna acts as excellent microwave reflector and concentrates signal in a particular direction. So, this antenna can provide better directivity. An image of parabolic reflector is given in fig 5.9.
Fig 5.9 Parabolic Reflector Antenna
5.5.4 Array Antenna – Yagi Antenna

The most easiest and efficient directional antenna is the ‘Yagi – Uda’ Antenna. It is named after its inventors Prof. Uda and Prof. Yagi. This antenna has been successfully used for VHF band terrestrial home Television reception.

The directivity is increased by increasing the number of directors which are known as ‘Parasitic Elements’ as they are not directly fed. Only the dipole or folded dipole is directly fed. There is one reflector which used to reflect EM signal. A sample yagi array is given in the following diagram.

Fig 5.10 Three Element Yagi Array
The yagi array consists of at least three elements. The dipole or the folded dipole is at which the signal is fed. The length of the dipole is $0.5 \lambda$ with respect to the frequency of operation. The element on the left to the dipole in the above diagram is at $0.55 \lambda$. The spacing between the dipole and the reflector is $0.3 \lambda$. The element on the right of the dipole is known as ‘Director’. It has the length of $0.45 \lambda$. The spacing between the dipole and the director is $0.25 \lambda$. [17].

![Three Dimensional Radiation Pattern of Yagi antenna](image)

The above figure shows the radiation pattern of a yagi antenna. The major lobe of yagi antenna is at towards directors. EM signal is reflected by ‘reflector’ and it travels towards directors. There are also some side lobes and back lobes. These are radiating energy in unwanted direction. So, these lobes are to be reduced as much as possible so that the maximum of the energy is directed in the desired direction.
5.5.5 Micro strip patch antenna

The concept of ‘Microwave Integrated circuits’ was developed around 1970’s. But this field didn’t develop into an emerging field till the introduction of VLSI concepts. After late 1980’s, this field has lot of development. ‘Planar antennas’ are introduced based on this concept. Transmission lines were developed based on dielectric substrate materials. The width and length of the conducting lines are designed based on the operating frequency and the dielectric constant of the substrate material.

Micro strip antenna has few advantages such as low profile, easy to fabricate, easy to feed, easy to use as an array and hemispherical radiation pattern with moderate directivity of 6 to 8 dB. Micro strip antennas also possess some disadvantages such as low bandwidth and low efficiency. The diagram of a rectangular micro strip patch antenna is shown below.

A dielectric substrate with a known dielectric constant is selected as the base. On one side of this substrate, a thin conductor is placed throughout the entire length. This is called as the ‘Ground Plane’. On the other side of the substrate, a conducting patch element is placed. The length and width of this patch are determined based on frequency of operation and relative permittivity of substrate. Though the patch is generally in
rectangular shape, it may be of any shape. Coaxial feed, micro strip feed, aperture feed and proximity feed are few types of feeds used for micro strip antenna.

![Fig. 5.13 Electric flux lines of micro strip](image)

The electric flux lines start from the patch and travel towards the ground plane. In this process, some flux lines are traveling through the free space and the remaining through the dielectric material. So, an effective dielectric constant is to be calculated for any micro strip patch. The dominant mode of operation of micro strip is given as ‘Quasi TEM’ or Impure TEM. The magnetic flux lines form closed loops around the conducting patch [26].

![Fig 5.14 Radiation Pattern of Micro strip patch antenna](image)
The radiation pattern of a micro strip antenna is unidirectional and its major beam is perpendicular to the plane of the antenna. As the other side of the dielectric material, ground plane is placed, antenna cannot radiate in that direction. The entire energy is directed in the perpendicular direction to the plane of the antenna. But this antenna can provide only narrow beam width radiation pattern. Generally, this antenna can operate with less amount of power.

Micro strip antenna is simple and easy to design and construct. It is having smaller shape and weight compared to other antennas which makes this antenna as an important one. This antenna can be compact and conformal. So, this antenna can be placed at any bends, rough walls and even at glass. With these advantages, almost the work on modern antennas narrowed down into the work on micro strip or its related antennas.

5.6 Conclusion

Antennas are generally classified into wire, aperture, reflector, array and patch antenna. In this chapter, basic antenna theory and various parameters of antenna are presented. The types of antennas and their radiation pattern are also discussed.

Directional antennas such as yagi array radiates EM wave in a particular direction. If any directional antenna is used as AP of WLAN, security can be improved. The design and fabrication of WLAN antenna which enhance security of WLAN is to be discussed in the next chapter.