Chapter 15
ANTENNAS

15-1 Introduction and Objectives

An antenna is a device that provides the transition from a guided electromagnetic wave on a transmission line to an electromagnetic wave propagating in free space. An antenna is used both at the transmitting end or source of radiation and at the receiving end, where the radiation is converted from an electromagnetic wave propagating in free space back to an electromagnetic wave being guided by a transmission line.

After completing this chapter, the reader should be able to

1. Describe an antenna and its functions.
2. Describe an isotropic antenna and its characteristics.
3. Define antenna directivity and gain.
4. Describe antenna radiation patterns.
5. Define radiation intensity.
6. Describe the near field and far field regions surrounding an antenna.
7. Define the 3-dB beamwidth, sidelobes, and front-to-back ratio of an antenna.
8. Define antenna efficiency and illumination efficiency.
9. Define and determine the effective area of an antenna.
10. Describe the capture area of an antenna.
11. Define polarization and describe the differences between linear, elliptical, and circular polarization.
13. Describe the difference between self-impedance and mutual impedance of an antenna.
15. Describe the properties of a half-wave dipole antenna.
16. Describe the properties of a quarter-wave monopole antenna.
17. Discuss the functions of a ground plane.
18. Describe the properties of a waveguide horn antenna.
19. Describe the properties of a parabolic reflector antenna.
20. Determine the effective area, isotropic gain, and the 3-dB beamwidth of a parabolic reflector antenna.
15-2 General Discussion

An antenna serves two basic functions. First, it is an impedance matching device that matches the characteristic impedance of the transmission line to the intrinsic impedance of free space. This matching is necessary to prevent unwanted reflections back to the source or load. Second, the antenna is designed to direct the electromagnetic radiation in the desired direction. Some representative antenna types are shown in Figure 15-1.

Isotropic Point Radiator

In the analysis of complex antenna systems, reference is frequently made to a fictitious ideal isotropic point radiator. This hypothetical antenna would radiate power equally well in all directions in a volume sense. This means that this antenna would have an omnidirectional pattern in all planes. All real antennas have some directivity. This means that the intensity of the radiation will vary with the orientation. Depending on the application, it may be desirable to have a broad pattern or one that is aimed in a particular direction.

Radiation Pattern

The radiation pattern is a plot of the relative strength or intensity of the antenna radiation as a function of the orientation in a given plane. The quantity used in specifying the relative strength may be the power density or basic electromagnetic quantities such as the electric field intensity (in volts/meter) or the magnetic field intensity (in amperes/meter). More often, it is the power density in decibel form.

Antenna Gain

The term antenna gain refers to the ratio of the power density at a particular location from an antenna with directivity to the power density from an ideal isotropic antenna radiating the same power. The antenna most often used is the hypothetical isotropic point radiator. However, some antenna gain measurements utilize a "real-life" antenna such as the dipole for the reference.

The term "gain" may be confusing to someone studying antennas for the first time since an antenna does not "create" energy or power and it is a passive device. Yet the concept of "gain" might imply that the output power is greater than the input power. What actually happens is that the power that would be radiated equally well in all directions if the antenna were an isotropic radiator is focused or beamed in a much more limited range of directions, and the resulting power density in this limited range can be much greater than for the completely omnidirectional antenna. In simple terms, power is taken away from some directions and added to the power in other directions, and the result is an effective gain in the direction of maximum radiation.

Reciprocity

There is a basic property of an antenna called the reciprocity theorem, which is useful in studying radiation properties. Basically, it states that the properties of the antenna used for transmission will be same as when used for reception. The most obvious interpretation of this theorem is that of the radiation pattern, which will have the same form when used for reception as for transmission.

In discussing this theorem, some have interpreted it as saying that if one trades a particular transmitting antenna with a particular receiving antenna, the received signal strength will be the same. This is taking the theorem too far. In realistic terms, the transmitting antenna must be constructed to handle a much larger power level than at the receiver, and trading the antennas could have disastrous results. The best interpretation is to assume similar field patterns and impedance properties of a given antenna used in the two different modes.
Power Density

The relative strength of a signal radiating from an antenna can be specified or measured in terms of its power density. The power density concept is illustrated in Figure 14-2. Assume that an imaginary surface in the shape of a sphere is formed such as to completely enclose the antenna, which is located at the center. At any point on the imaginary sphere, the power density is the electromagnetic power per unit area radiating through an infinitesimal unit of area. Note that the direction of propagation is perpendicular to the surface area at a given point. As in Chapter 14, we will use the symbol \( p_d \) to represent the power density, and it is measured in watts per square meter (W/m\(^2\)).

The actual power passing through a closed surface can be determined by integrating the power density over the surface area. By conservation of energy, this value of power must equal the actual power radiated by the antenna if the medium is lossless.

Assume an ideal isotropic point radiator transmitting power \( P \). The power density \( p_d \) on the surface of the sphere of radius \( r \) will be equal at all points and will be

\[
p_d = \frac{P}{4\pi r^2} \tag{15-1}
\]

Radiation Intensity

Another quantity of interest, particularly in radio astronomy, is the radiation intensity. The radiation intensity will be denoted by \( U \) and it is defined as the power per solid angle. A solid angle is a property of a sphere and is measured in steradians (sr). There are \( 4\pi \) steradians in a sphere and the radiation intensity on any surface surrounding the sphere is given by

\[
U = \frac{P}{4\pi} \tag{15-2}
\]

The units of radiation intensity are watts/solid angle or watts/steradian (W/sr).

An important point is that radiation intensity is independent of the radius. It is this property that allows astronomers to make deductions about stars that are thousands of light-years away.

Comparing (15-1) and (15-2), the relationship between power density and radiation intensity is

\[
U = r^2 p_d \tag{15-3}
\]
**Example 15-1**

The power density 10 km from a transmitting antenna is 0.06 \( \text{W/m}^2 \). Determine the radiation intensity.

**Solution**

The radiation intensity can be determined from (15-3) as follows:

\[
U = r^2 p_d = (10^4)^2 \times (6 \times 10^{-8}) = 6 \text{ W/sr}
\]  

(15-4)

**Example 15-2**

The radiation intensity from a transmitting antenna is 50 \( \text{W/sr} \). Determine the power density of a receiving antenna located 25 km from the transmitting station.

**Solution**

Rearranging equation (15-3), we find that the power density is

\[
p_d = \frac{U}{r^2} = \frac{50}{(2.5 \times 10^4)^2} = 8 \times 10^{-8} \text{ W/m}^2 = 0.08 \mu \text{W/m}^2
\]  

(15-5)
15-3 Electromagnetic Radiation From an Antenna

Time-varying voltages and currents in an antenna produce time-varying electric and magnetic fields that travel radially away from the antenna at a velocity determined by the medium in which the electromagnetic fields are propagating. There are two distinct regions of electric and magnetic fields surrounding an antenna. These two regions, referred to as the near field and far field, are defined by the distance from the antenna as a function of the frequency of the electromagnetic radiation and size of the antenna. The fields in the far field are transverse fields; i.e., the electric and magnetic field intensities are transverse to the direction of propagation. This condition, which was introduced in the preceding chapter, is referred to as plane wave propagation.

Both transverse and radial electric and magnetic field intensities exist in the near field region. The boundary between the near and far fields is an arbitrary sphere surrounding the antenna whose radius $R_\| is$

$$R_\| = \frac{2D^2}{\lambda}$$  \hspace{1cm} (15-6)

where $\lambda$ is the wavelength of the radiation and $D$ is the physical linear dimension of the antenna. The radiation patterns that describe the radiation intensity of the antenna as a function of angle are usually patterns for the far field.
Example 15-3

Determine the distance from a 100-MHz half-wavelength dipole to the boundary between the near field and the far field.

Solution

The reader can verify that the wavelength \( \lambda \) at 100 MHz is 3 m. Therefore, the length of the dipole is 1.5 m. The distance to the far field can then be determined from (15-6).

\[
R_f = \frac{2D^2}{\lambda} = \frac{2(1.5)^2}{3} = 1.5 \text{ m} \tag{15-7}
\]

For a dipole, the distance to the far field is the length of the dipole.

Example 15-4

A parabolic reflector antenna with a diameter of 18.3 m operates at 2.3 GHz for space communications. Determine the far field distance for this antenna.

Solution

The reader can verify that the wavelength at 2.3 GHz is 0.13 m. The distance to the far field can be determined as

\[
R_f = \frac{2D^2}{\lambda} = \frac{2(18.3)^2}{0.13} = 5.15 \times 10^3 \text{ m} = 5.15 \text{ km} \tag{15-8}
\]

The preceding analysis shows that the far-field distance for a high-gain antenna can be very large. The measurement of the far field radiation pattern for a large antenna operating at a high frequency can be a difficult task.
15-4 Radiation Patterns

In general, the radiation pattern of an antenna is a three-dimensional plot of the relative strength or radiation intensity of an antenna as a function of the coordinate systems. The spherical coordinate system is often used to describe the pattern mathematically. In the spherical coordinate system, the three variables are $\rho$, $\theta$, and $\phi$. The quantity $\rho$ is the distance from the origin to a point and it represents the relative radiation intensity in this case. The quantity $\theta$ is the angle with respect to the z-axis, and $\phi$ is the angle with respect to the x-axis of the projection of $\rho$ in the x-y plane. See Figure 15-3 for an illustration.

Since it is difficult to present three-dimensional information, typically the radiation patterns are shown as a pair of two-dimensional plots. The first plot shows the radiation intensity as a function of the angle in the plane of the electric field intensity vector and the second plot shows the radiation intensity as a function of the angle in the plane of the magnetic field. The plot in the plane of the electric field is called the E plane pattern and the plot in the plane of the magnetic field is called the H plane pattern. The E plane and H plane are orthogonal to each other and are referred to as the principal plane patterns. Normally these are the only two patterns taken in an antenna measurement facility to describe the radiation patterns of an antenna.

Typical E and H plane Plots

Consider a simple half-wave dipole antenna aligned with the y-axis with the center at the origin. A typical E plane radiation pattern for a half-wave dipole antenna is shown in Figure 15-4(a). This plane is the y-z plane in this case. A typical H plane radiation pattern for a half-wave dipole is shown in Figure 15-4(b). This plane is the x-z plane for the orientation given. Note that the pattern is omnidirectional in the H plane.

Gain Functions

Radiation patterns are often normalized to the maximum gain $G_{max}$ by dividing the gain $G(\theta, \phi)$ as a function of the two angles by the maximum gain to obtain the normalized gain. The normalized gain will be represented as $g(\theta, \phi)$ and it is

$$g(\theta, \phi) = \frac{G(\theta, \phi)}{G_{max}} \quad (15-9)$$

This means that the normalized maximum gain is 1, and the gain at other angles is less than 1. Since normalized antenna patterns cover a significant dynamic range, typically from 1 down to $10^{-4}$ or less, antenna radiation patterns are normally plotted in decibels on a linear scale, usually on a polar plot. However, some applications require the use of a rectangular plot. The normalized decibel gain is

$$g_{dB}(\theta, \phi) = 10\log[g(\theta, \phi)] \quad (15-10)$$

Figure 15-5 illustrates two normalized antenna radiation patterns of a standard gain horn antenna. A polar plot is shown in (a) and a rectangular plot is shown in (b).
15-5 Antenna Beamwidths and Sidelobes

An ideal antenna would have a radiation pattern whose normalized gain is 1 over the desired angular beamwidth and 0 at all other angles. A more realistic antenna radiation pattern is shown in Figure 15-6.

Beamwidth

The antenna beamwidth is defined as the included angle between the -3 dB points on the normalized gain pattern. Therefore, the power gain at the edges of the antenna beamwidth is 1/2 of the on-axis or maximum gain.

Lobes

The main lobe is the antenna beam defined between the first null on either side of the maximum gain angle. Typically for high-gain antennas, the null-to-null beamwidth is 2.5 times the 3-dB beamwidth.

An antenna will usually radiate some power in undesired directions. The radiation pattern of Figure 15-6 has several sidelobes. The levels of the sidelobes determine how much power is radiated in these undesired directions. If the antenna is a receiving antenna, the sidelobes will determine the levels of undesired signals that could be received.

Backlobe

Another undesired part of the radiation pattern when single direction transmission is desired is the backlobe. A quality factor called the front-to-back ratio is important in these cases. As shown back in Figure 15-4, the absolute value of the front-to-back ratio of a dipole is 1, which in decibel form would be 0 dB. A dipole cannot tell if the signal is coming from the front or back of the antenna.
15-6 Directivity and Antenna Gain

There are two commonly employed terms used to describe the radiation characteristics of an antenna: directivity and antenna gain. Directivity is a characteristic of the radiation pattern of an ideal lossless antenna while the antenna gain includes the ohmic losses of the antenna physical structure.

Directivity

The directivity $D$ of an antenna is defined from the radiation pattern as

$$D = \frac{U_{\text{max}}}{U_0} = \frac{\text{maximum radiation intensity}}{\text{average radiation intensity}}$$

(15-11)

where $U_0$ represents the average radiation intensity. If numerator and denominator of (15-11) are multiplied by $4\pi$ and divided by $r^2$, the following form can be developed;

$$D = \frac{4\pi U_m}{4\pi U_0} = \frac{4\pi U_m}{P_T} = \frac{U_m}{P_T / 4\pi} = \frac{U_m / r^2}{P_T / 4\pi r^2} = \frac{P_{d,\text{max}}}{P_T / 4\pi r^2}$$

(15-12)

Therefore, the directivity is

$$D = \frac{\text{maximum power density}}{\text{power density from an isotropic radiator}}$$

(15-13)

The directivity does not take into consideration the ohmic losses in the antenna since it is based on the radiation pattern only.

Antenna Gain

Antenna gain is defined as the ratio of the maximum radiation intensity $U_{\text{max}}$ to the maximum radiation intensity $U_{\text{ref}}$ from a reference antenna with same power input to the antenna.

$$G = \frac{U_{\text{max}}}{U_{\text{ref}}}$$

(15-14)

The difference between directivity and gain is that directivity is referenced to the power radiated by the antenna, while gain is referenced to the power delivered by the transmission line to the antenna. Therefore, gain is always less than or equal to directivity, the difference being the power dissipated in the antenna ohmic losses.

Normally, antenna gain is expressed as a power ratio and is usually specified in decibels as

$$G_{\text{dB}} = 10 \log G$$

(15-15)

The value of gain depends on the gain of the reference antenna. It is important to know what reference has been used for the antenna gain. Two of the common references are as follows:
1. a lossless isotropic antenna, in which the radiation intensity is uniform over the sphere surrounding the antenna, i.e., all 4π steradians

2. a reference dipole

The lossless isotropic antenna is a theoretical concept and has never been realized in practice, while the dipole is readily available.

Antenna measurements of gain are usually referenced to a standard dipole for low-gain antennas or to a standard-gain horn for higher-gain antennas. Accurate theoretical calculations of the gain referenced to a lossless isotropic antenna are possible for both the standard dipole and the standard-gain horn. The absolute gain of a standard half-wave dipole with respect to an isotropic radiator is 1.643 or 2.16 dB

**Antenna Efficiency**

The antenna efficiency \( \eta_a \) is a measure of the power dissipated in the ohmic losses of the antenna. It is the ratio of the total power radiated from the antenna to the power delivered to the antenna from the transmission line. The antenna efficiency can be determined from the directivity and gain of an antenna as follows:

\[
\eta_a = \frac{G}{D}
\]

where \( D \) and \( G \) are the absolute values of directivity and gain.

**Assumed Reference and dBi**

Although dipoles and horns are often used as references in measuring antenna pattern, most basic developments utilize gain with respect to the **isotropic radiator**. Many references use the term dBi as the abbreviation of the decibel gain with respect to the isotropic radiator. While this practice has many supporters, this author believes it is misleading since the practice of adding a letter to dB implies a reference that has units, but the gain of an isotropic radiator has no units since it is dimensionless. Hence, the practice in this text will be to simply use dB for antenna gain with the understanding that the isotropic radiator is the basis for comparison.
**Example 15-5**

An antenna is transmitting 200 W of power. The maximum power density at a distance of 10 km is 3.184 mW/m². Determine the directivity of the antenna.

**Solution**

The power from an isotropic antenna can be determined from (15-1) to be

\[
p_d = \frac{P_r}{4\pi r^2} = \frac{200}{4\pi (10^4)^2} = 0.1592 \text{ µW/m}^2
\]

(15-17)

The directivity can be determined from (15-13) as

\[
D = \frac{3.184 \times 10^{-3}}{0.1592 \times 10^{-6}} = 20,000
\]

(15-18)

The corresponding value in decibels will be denoted as \( D_{\text{db}} \) and it is

\[
D_{\text{db}} = 10 \log D = 10 \log 20,000 = 43.01 \text{ dB}
\]

(15-19)

**Example 15-6**

An antenna with a directivity of 16 dB is transmitting a power of 1 kW. Determine the maximum power density at a distance of 50 km from the antenna.

**Solution**

A decibel directivity of 16 dB is equivalent to an absolute directivity of

\[
D = 10^{16/10} = 10^{1.6} = 39.81
\]

(15-20)

Rearranging (15-12) yields

\[
p_{d,\text{max}} = D \left( \frac{P_r}{4\pi r^2} \right) = 39.81 \left( \frac{1000}{4\pi (50 \times 10^3)^2} \right) = 1.267 \text{ µW/m}^2
\]

(15-21)

**Example 15-7**

An antenna has an efficiency of 95% and the directivity is 33 dB. Determine the antenna gain in dB.

**Solution**

The absolute directivity is

\[
D = 10^{33/10} = 1995.26
\]

(15-22)

The antenna gain is

\[
G = \eta_a D = (0.95)(1995.26) = 1895.5
\]

(15-23)

The antenna gain in decibels is

\[
G_{\text{db}} = 10 \log 1895.5 = 32.78 \text{ dB}
\]

(15-24)
15-7 Effective Area of an Antenna

An electromagnetic wave propagating in free space must be "captured" by an antenna if it is to serve any communication purpose. The antenna performs the function of converting the power density of electromagnetic radiation incident on the antenna into a voltage across and a current flowing into the transmission line. The antenna has an effective area by which the power density in watts per unit of area is multiplied to obtain power in watts delivered to the load. The effective area is also referred to as the capture area of the antenna.

The effective area is not necessarily the physical area of the antenna, although it may be close to the physical area for certain types, e.g., for the parabolic reflector antenna. It can be shown by an advanced development in antenna theory that the effective area \( A_e \) is directly proportional to the gain of the antenna, where the gain is referenced to an isotropic antenna. The effective area is given by

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

(15-25)

**Example 15-8**

Determine the effective area of a 5-GHz antenna whose gain with respect to an isotropic antenna is 15 dB.

**Solution**

The wavelength of a 5-GHz antenna can be determined as

\[
\lambda = \frac{c}{f} = \frac{3 \times 10^8}{5 \times 10^9} = 0.06 \text{ m} = 6 \text{ cm}
\]

(15-26)

The absolute antenna gain is

\[
G = 10^{\frac{G_{\text{iso}}}{10}} = 10^{1.5} = 31.623
\]

(15-27)

Substitution of (15-26) and (15-27) into (15-25) yields

\[
A_e = \frac{\lambda^2}{4\pi} G = \frac{(6 \times 10^{-2})^2}{4\pi} (31.623) = 9.059 \times 10^{-3} \text{ m}^2
\]

(15-28)
15-8 Polarization

By definition, the polarization of an electromagnetic wave propagating in free space is the orientation of the electric field intensity vector relative to the surface of the earth. There are two basic types of polarization: linear and elliptical. In linear polarization, the electric vector does not change orientation as it travels away from an observer. In elliptical polarization, the electric vector rotates as it travels away from an observer, and the tip of the electric vector traces an ellipse.

Linear Polarization

Linear polarization can be divided into two classifications: vertical and horizontal, both of which are illustrated in Figure 15-7. In horizontal polarization, shown in Figure 15-7(a), the electric vector is parallel to the earth's surface. In vertical polarization, shown in Figure 15-7(b), the electric vector is perpendicular to the earth's surface.

Circular Polarization

The most common form of elliptical polarization is that of circular polarization, and it occurs when the tip of the rotating electric vector traces a circle in space as it travels away from the observer. Two classifications of circular polarization are right-hand circular and left-hand circular. Figure 15-8 illustrates the two forms. In right-hand circular polarization, the electric vector rotates in a clockwise direction as the electric vector travels away from the observer as shown in Figure 15-8(a). In left-hand circular polarization, the electric vector rotates in a counterclockwise direction, as shown in Figure 15-8(b).

An antenna transmits vertical, horizontal, right-hand (RH) circular, or left-hand (LH) circular polarization depending on the antenna design and orientation. There is a significant loss of approximately 30 dB if the transmitting antenna has one form of linear polarization and the receiving antenna has the other linear form. This loss also occurs if one antenna is circularly polarized with one sense (RH or LH) and the receiving antenna is circularly polarized with the other sense (LH or RH). This characteristic is used to provide polarization diversity in communication systems. Two channels of information can be sent over the same physical path in which one uses vertical polarization while the other uses horizontal polarization.

A linear polarized transmitting antenna can be combined with a circular polarized receiving antenna, or vice versa, and there will be only a 3-dB loss. This combination is used where the orientation of a linear polarized antenna can change significantly, such as on a missile or spacecraft.
15.9 Antenna Impedance and Radiation Resistance

In order to account for the power absorbed and subsequently radiated by an antenna, it acts like an impedance to a source providing power to it. The antenna may appear to be nothing more than some wires at dc (e.g., a dipole), but when it is excited by an appropriate ac source, it acts like a complex impedance. This impedance can be measured by an appropriate RF bridge excited with a signal source at the frequency at which the measurement is desired.

Antenna Impedance

Antenna impedance is the ac impedance of an antenna measured at its input terminals. It is the ratio of the phasor voltage at the feed point (input) of the antenna divided by the phasor current flowing into the antenna at the same point. It is a function of frequency and can be complex with both a real (resistive) part and an imaginary (reactive) part. Ideally, the antenna should be purely resistive at the frequency of operation and equal to the characteristic impedance of the line connected to it.

Self and Mutual Impedances

If an antenna is isolated from ground and any other surrounding objects, this impedance is the self-impedance of the antenna. It usually consists of a self-resistance and a self-reactance. However, at resonance, the reactive part of the antenna impedance approaches zero, and the antenna impedance has only a real or resistive component. When other antennas, objects, or ground is near the antenna, the currents flowing in these objects have an influence on the antenna impedance. The antenna impedance is then determined both by the self-impedance of antenna and by a mutual impedance between the antenna and the nearby objects.

Radiation Resistance

An antenna radiates electromagnetic energy. The amount of this energy leaving a sphere surrounding the antenna per unit of time is the power radiated by the antenna $P_{\text{rad}}$. This resistance, called the radiation resistance $R_{\text{rad}}$ of the antenna, can be determined from

$$R_{\text{rad}} = \frac{P_{\text{rad}}}{I_{\text{rms}}^2} \quad (15-29)$$

where $I_{\text{rms}}$ is the rms value of the antenna current magnitude at the input terminals of the antenna. The radiation resistance is the real part of the complex antenna impedance of a lossless antenna. If the antenna has ohmic losses that dissipate power as heat, this antenna ohmic loss is usually represented by an additional resistance in series with the radiation resistance, and the sum of the two resistance is equal to the real part of the antenna impedance.

Example 15.9

An antenna has an rms current of 3 A flowing into the antenna, and it is transmitting 1 kW of power. Determine the radiation resistance of the antenna.

Solution

The radiation resistance is determined from (15-29).

$$R_{\text{rad}} = \frac{P_{\text{rad}}}{I_{\text{rms}}^2} = \frac{1000}{3^2} = 111.1 \ \Omega \quad (15-30)$$
15-10 Dipoles

One of the simplest and most commonly used antennas is the half-wave dipole, formed from a two-wire parallel transmission line as shown in Figure 15-9(a). Starting with an open-ended line, which has a voltage maximum at the open end and a voltage minimum $\lambda/4$ back from the open end, the two conductors are bent $90^\circ$ from the transmission line as illustrated in Figure 15-9(b). The theoretical length of the antenna is $\lambda/2$. The diameter $d$ of the wires is assumed to be much smaller than the length, and the spacing $D$ at the feed point must be small compared with the length.

Input Impedance of Dipole

A voltage minimum and a current maximum occur at the feed point, which means that the impedance is a minimum at that point. The actual value of the impedance of the half-wave dipole is $73 + j42.5 \ \Omega$. The reactive component can be eliminated by tuning the antenna, which is accomplished by shortening the length by about 5% from $0.5\lambda$ to $0.475\lambda$, corresponding to approximately 95% of the theoretical length. This deviation from the theoretical situation is primarily due to end effects. Thus, when properly tuned, the half-wave dipole has an impedance of $73 \ \Omega$ resistive, which for a lossless dipole is the radiation resistance of the antenna.

The dipole is a balanced antenna and must, therefore, be fed by a balanced transmission line. Since the most common transmission line providing the best impedance match is coaxial cable, a balun must be used to properly connect a coaxial cable to a dipole. Several types of baluns are available for connecting between the balanced antenna and the unbalanced line.

Radiation Patterns

The $E$ plane and $H$ plane radiation patterns of the half-wave dipole were shown in Figure 15-4 as examples of patterns and the reader should refer back to that figure for the discussion that follows. The $E$ plane pattern is like a doughnut with two maxima broadside to the dipole and a null at both ends of the dipole. The 3-dB beamwidth is $78^\circ$. The isotropic power gain or directivity for a lossless $\lambda/2$ dipole is $1.643$ or $2.16 \ \text{dB}$. As shown in Figure 15-4(a), the polarization of the dipole is parallel to the dipole. The $H$ plane pattern is illustrated in Figure 15-4(b) and is a uniform circular pattern with a constant gain for an angle of $360^\circ$ about the dipole.

Effective Area

The effective area of a dipole can be determined from the isotropic gain and is

$$A_e = \frac{\lambda^2}{4\pi} G = \frac{\lambda^2}{4\pi} (1.463) = 0.13\lambda^2 \quad (15-31)$$

Folded Dipole

A variation of the $\lambda/2$ dipole is the folded dipole, which is shown in Figure 15-10. The most common balanced transmission line used at RF frequencies is the 300-$\Omega$ twin lead, which has been used extensively in the TV and FM industries. A folded dipole is constructed from a $\lambda/2$ length of 300-$\Omega$ twin lead. The feed point is at the middle of one of the conductors. The ends of the two conductors are connected. The combination of the 73-$\Omega$ self-impedance of the dipole and the mutual impedance from the parallel conductor connected at both ends increases the antenna impedance of the folded dipole to 280 $\Omega$. Therefore, the folded dipole is a balanced 280-$\Omega$ antenna, which closely matches the 300-$\Omega$ twin-lead balanced transmission line.
Example 15-10

Determine the effective area of a dipole at 98 MHz.

Solution

The wavelength at 98 MHz is

\[ \lambda = \frac{c}{f} = \frac{3 \times 10^8}{98 \times 10^6} = 3.061 \text{ m} \quad (15-32) \]

The effective area of a dipole can be determined from (15-31).

\[ A_e = 0.13\lambda^2 = 0.13(3.061)^2 = 1.218 \text{ m}^2 \quad (15-33) \]
15-11 Antennas Above a Ground Plane

A ground plane is a uniform surface beneath an antenna, which will be considered as a perfect conductor. In actual situations, a good ground plane can be constructed from good conductors, or at some frequencies, the earth acts as a good ground plane.

Reflected Wave at Perfect Conductor Surface

Electromagnetic fields cannot exist in a perfect conductor, and any wave incident upon a perfect conductor will be reflected. Figure 15-11 illustrates this situation. To satisfy the boundary condition that no tangential component of electric field can exist there, the reflected wave will be shifted in phase by 180°.

The radiation patterns and antenna impedances of an antenna above a ground plane are different from that of the antenna without the presence of the ground plane. A concept known as image theory is used to determine the characteristics of an antenna above a ground plane. The reflected wave is like a direct wave from an identical antenna located within the ground plane the same distance from the boundary as the real antenna is above the ground plane. This situation is illustrated in Figure 15-11. The image antenna is similar to an image formed in a mirror at optical frequencies.

Monopole Antenna

An important and commonly used antenna is the \( \frac{\lambda}{4} \) monopole antenna on a ground plane as shown in Figure 15-12(a). This is an unbalanced antenna since the feed point is between the monopole and ground, and it has vertical polarization. The radiation resistance is 36.5 \( \Omega \), and the antenna impedance has a reactive component of \( j21 \Omega \). When the monopole is located close to the ground plane, the image antenna forms a dipole as shown in Figure 15-12(b). The \( E \) plane radiation pattern is that of a \( \lambda/2 \) dipole with only one-half of the pattern above the ground plane as shown.

The ground plane can be achieved either by a grounded metal disc or by radial wires as shown in Figure 15-13. The roof of a vehicle such as a car or truck can form a ground plane for a \( \lambda/4 \) monopole. The radiation pattern tilts upward as the ground plane becomes smaller and less of a perfect conductor. The maximum gain for a monopole above a semi-infinite perfect ground plane is directly along the ground plane as shown in Figure 15-13(b). Figure 15-13(c) illustrates the \( E \) plane radiation pattern for a \( \lambda/4 \) monopole over a finite-size, nonideal ground plane.

Some vertical monopole antennas are longer than \( \lambda/4 \). When the length exceeds \( \frac{5\lambda}{8} \), the radiation pattern forms multiple lobes, and the main lobe is at an angle above the ground plane. At a height of one wavelength, the main lobe is above a 45° angle to the ground plane. One of the reasons for making the antenna longer is to increase the radiation resistance, thereby increasing the power radiated for the same antenna current. Large antenna currents have disadvantages because the power lost in the ohmic resistance of the antenna wires and transmission lines feeding the antenna increases.
15-12 Horns

The open end of a microwave waveguide can transmit or receive electromagnetic radiation as an antenna. However, the sudden change from the impedance of the waveguide to the impedance of free space reflects energy back to the source due to the impedance mismatch. This problem can be overcome by flaring the four walls of the waveguide to provide a gradual transition from the waveguide impedance to free-space impedance. This structure is referred to as a wave-guide horn.

Classification of Horns

There are three basic types of waveguide horns: (a) the $E$ plane sectional horn, (b) the $H$ plane sectional horn, and (c) the pyramidal horn. These three types are illustrated in Figure 15-14.

The directivity of a waveguide horn is a function of the frequency, aperture size, and flare length in both the $E$ plane and the $H$ plane dimensions. The procedures for these calculations are beyond the scope of this text but can be found in advanced antenna texts.

The radiation patterns for a typical pyramidal horn were shown in Figure 15-5 in both a polar plot and a rectangular plot. The gain of a standard-gain horn antenna usually varies from approximately 15 dB at the lower end of a waveguide band to 17.5 dB at the upper end of the band.

The 3-dB beamwidth of the horn is a function of the aperture size. The larger the horn dimension in the flare direction, the narrower the 3-dB beamwidth. Therefore, a sectional horn produces a fan-shaped beam, narrow in one plane and broad in the other plane. The $E$ plane sectional horn produces a narrow beam in the $E$ plane and a wide beam in the $H$ plane. An $H$ plane sectional horn produces a narrow beam in the $H$ plane and a wide beam in the $E$ plane. A pyramidal horn produces a narrow beam in both planes.

The larger the aperture of a horn, the narrower the beamwidths will be and, therefore, the higher the directivity. Horns have good efficiency, and high isotropic gains can be achieved by constructing horns with a large aperture. This requires a long antenna because the flare must be gradual to provide good impedance matching. Therefore, a large, high-gain horn becomes not only heavy but very expensive to construct. To overcome this problem, a different type of aperture antenna, the parabolic reflector antenna, is used, and its properties will be discussed in the next section.
15-13 **Parabolic Reflector Antennas**

The surface generated by the revolution of a parabola about its axis is a *paraboloid*. The paraboloid has a focal point such that any plane wave electromagnetic radiation incident upon the paraboloid surface will be directed to the focal point. Conversely, if an isotropic radiator is placed at the focal point, it will radiate a spherical wave, a portion of which will be reflected by the paraboloid reflector surface into a plane wave. The plane wave exists over an area equal to the projection of the parabolic reflector, which is a circle with a diameter $D$, as illustrated in Figure 15-15(a).

The *parabolic reflector antenna* is shown in Figure 15-15(b). It consists of a parabolic reflector whose surface is a paraboloid and a primary antenna located at the focal point. The purpose of the primary antenna is to illuminate the reflector with a uniform electromagnetic wave. If an isotropic antenna were used as a primary antenna, it would provide a uniform illumination over the reflector surface. However, it would also radiate and receive radiation from all other directions. This phenomenon is referred to as *antenna spillover* and is a problem because the antenna could receive undesired radiation from other sources. An ideal primary antenna would have uniform gain over the subtended angle of the reflector and zero gain outside of this solid angle. A pyramidal horn antenna is a good primary antenna for the parabolic reflector antenna. It is usually designed such that the gain at the edges of the paraboloid is approximately 10 dB below the peak on-axis gain of the horn. The effect of the nonuniform illumination is taken into account by the *illumination efficiency* $\eta_I$. The effective area of the parabolic reflector antenna is

$$A_e = \eta_I A_p$$  \hspace{1cm} (15-34)

where $A_p$ is the projected physical aperture of the parabolic reflector and is given by

$$A_p = \frac{\pi D^2}{4}$$  \hspace{1cm} (15-35)

### Parabolic Reflector Antenna Gain

The gain of a parabolic reflector antenna can be determined with (15-25), (15-34), and (15-35). Rearranging (15-25) and substituting (15-34) and (15-35) into (15-25) yield

$$G = \frac{4\pi A_e}{\lambda^2} = \frac{4\pi}{\lambda^2} \left( \frac{\eta_I \pi D^2}{4} \right) = \eta_I \left( \frac{\pi D}{\lambda} \right)^2$$  \hspace{1cm} (15-36)

The illumination efficiency $\eta_I$ usually varies between 0.55 and 0.75.

### Parabolic Reflector Beamwidth

The 3-dB beamwidth, expressed in radians, for most parabolic reflector antennas is

$$\theta_{3dB} = 1.2 \frac{\lambda}{D} \text{ rad}$$  \hspace{1cm} (15-37)

This bandwidth is commonly expressed in degrees and is

$$\theta_{3dB} = 70 \frac{\lambda}{D} \text{ degrees}$$  \hspace{1cm} (15-38)
Example 15-11

An 11-GHz parabolic reflector has a physical diameter of 15 m. The illumination efficiency is 70\%. Determine the (a) effective area, (b) the gain in dB (relative to an isotropic radiator), and (c) the 3-dB beamwidth.

Solution

The wavelength at 11 GHz is

\[
\lambda = \frac{3 \times 10^8}{11 \times 10^9} = 0.02727 \text{ m} \tag{15-40}
\]

(a) The physical area is

\[
A_p = \frac{\pi D^2}{4} = 176.7 \text{ m}^2 \tag{15-41}
\]

The effective area is determined from (15-35) and (15-36).

\[
A_e = \eta_e A_p = 0.7 \times 176.7 = 123.7 \text{ m}^2 \tag{15-42}
\]

(b) The gain is

\[
G = \frac{4\pi A_e}{\lambda^2} = \frac{4\pi (123.7)}{(2.727 \times 10^{-2})^2} = 2.09 \times 10^6 \tag{15-43}
\]

The decibel gain is

\[
G_{\text{dB}} = 10 \log 2.09 \times 10^6 = 63.2 \text{ dB} \tag{15-44}
\]

(c) The 3-dB beamwidth in degrees can be determined from (15-38).

\[
\theta_{3\text{dB}} = 70 \frac{\lambda}{D} = 70 \left( \frac{0.02727}{15} \right) = 0.1273 \text{ degrees} \tag{15-45}
\]
PROBLEMS

15-1 The power density 5 km from a transmitting antenna is 3.5 \( \text{W/m}^2 \). Determine the radiation intensity.

15-2 The power density 60 km from a transmitting antenna is 0.6 \( \text{W/m}^2 \). Determine the radiation intensity.

15-3 The radiation intensity from a transmitting antenna is 20 W/sr. Determine the power density at a receiving antenna located 5 km from the transmitter.

15-4 The radiation intensity from a transmitting antenna is 1.5 W/sr. Determine the power density at a receiving antenna located 20 km from the transmitter.

15-5 Determine the distance from an 88-MHz half-wavelength dipole to the boundary between the near field and the far field.

15-6 Determine the distance from a 156-MHz half-wavelength dipole to the boundary between the near field and the far field.

15-7 A parabolic reflector antenna with a diameter of 12 m operates at 6.4 GHz for space communications. Determine the far field distance for this antenna.

15-8 A parabolic reflector antenna with a diameter of 2 m operates at 3.9 GHz for space communications. Determine the far field distance for this antenna.

15-9 An antenna is transmitting 10 W of power. The maximum power density at a distance of 2 km is 4 mW/m\(^2\). Determine the directivity of the antenna in dB.

15-10 An antenna is transmitting 250 W of power. The maximum power density at a distance of 1 km is 0.5 mW/m\(^2\). Determine the directivity of the antenna in dB.

15-11 An antenna with a directivity of 23 dB is transmitting a power of 1.5 kW. Determine the maximum power density at a distance of 10 km from the antenna.

15-12 An antenna with a directivity of 6 dB is transmitting a power of 0.5 kW. Determine the maximum power density at a distance of 5 km from the antenna.

15-13 An antenna has an efficiency of 92%. If the directivity is 46 dB, determine the antenna gain in dB.

15-14 An antenna has an efficiency of 94%. If the directivity is 13 dB, determine the antenna gain in dB.

15-15 Determine the effective area of a 2.3-GHz antenna whose isotropic gain is 43 dB.

15-16 Determine the effective area of a 1-GHz antenna whose isotropic gain is 7 dB.

15-17 An antenna has a current of 5 A flowing into the input, and it is transmitting 2.5 kW of power. Determine the radiation resistance of the antenna.

15-18 An antenna has a current of 2.5 A flowing into the input, and it is transmitting 0.8 kW of power. Determine the radiation resistance of the antenna.

15-19 A 6.4-GHz parabolic reflector antenna has a physical diameter of 15 m. The illumination efficiency is 65%. Determine the following: (a) the effective area, (b) the gain in dB, and (c) the 3-dB beamwidth in degrees.
15-20 A 4-GHz parabolic reflector antenna has a physical diameter of 1.5 m. The illumination efficiency is 70%. Determine the following: (a) the effective area, (b) the gain in dB, and (c) the 3-dB beamwidth in degrees.

15-21 Determine the effective area of a half-wave dipole at 3.9 MHz.

15-22 Determine the effective area of a half-wave dipole at 54 MHz.