CHAPTER

1

ANTENNAS

1.1 INTRODUCTION

An antenna is defined by Webster's Dictionary as "a usually metallic device (as a rod or wire) for radiating or receiving radio waves." The *IEEE Standard Definitions of Terms for Antennas* (IEEE Std 145-1983)* defines the antenna or aerial as "a means for radiating or receiving radio waves." In other words the antenna is the transitional structure between free-space and a guiding device, as shown in Figure 1.1. The guiding device or transmission line may take the form of a coaxial line or a hollow pipe (waveguide), and it is used to transport electromagnetic energy from the transmitting source to the antenna, or from the antenna to the receiver. In the former case we have a transmitting antenna and in the latter a receiving antenna.

A transmission-line Thevenin equivalent of the antenna system of Figure 1.1 in the transmitting mode is shown in Figure 1.2 where the source is represented by an ideal generator, the tramission line is represented by a line with characteristic impedance Z_c, and the antenna is represented by a load Z_A [$Z_A = (R_L + R_r) + jX_A$] connected to the transmission line. The Thevenin and Norton circuit equivalents of the antenna are also shown in Figure 2.19. The load resistance R_L is used to represent the conduction and dielectric losses associated with the antenna structure while R_r, referred to as the *radiation resistance,* is used to represent radiation by the antenna. The reactance X_A is used to represent the imaginary part of the impedance associated with radiation by the antenna. This is discussed more in detail in Sections 2.13 and 2.14. Under ideal conditions, energy generated by the source should be totally transferred to the radiation resistance R_r, which is used to represent radiation by the antenna. However, in a practical system there are conduction-dielectric losses due to the lossy nature of the transmission line and the antenna, as well as the due to reflections (mismatch) losses at the interface between the line and the antenna. Taking into account the internal impedance of the source and neglecting line and reflection (mismatch) losses, maximum power is delivered to the antenna under *conjugate matching.* This is discussed in Section 2.13.
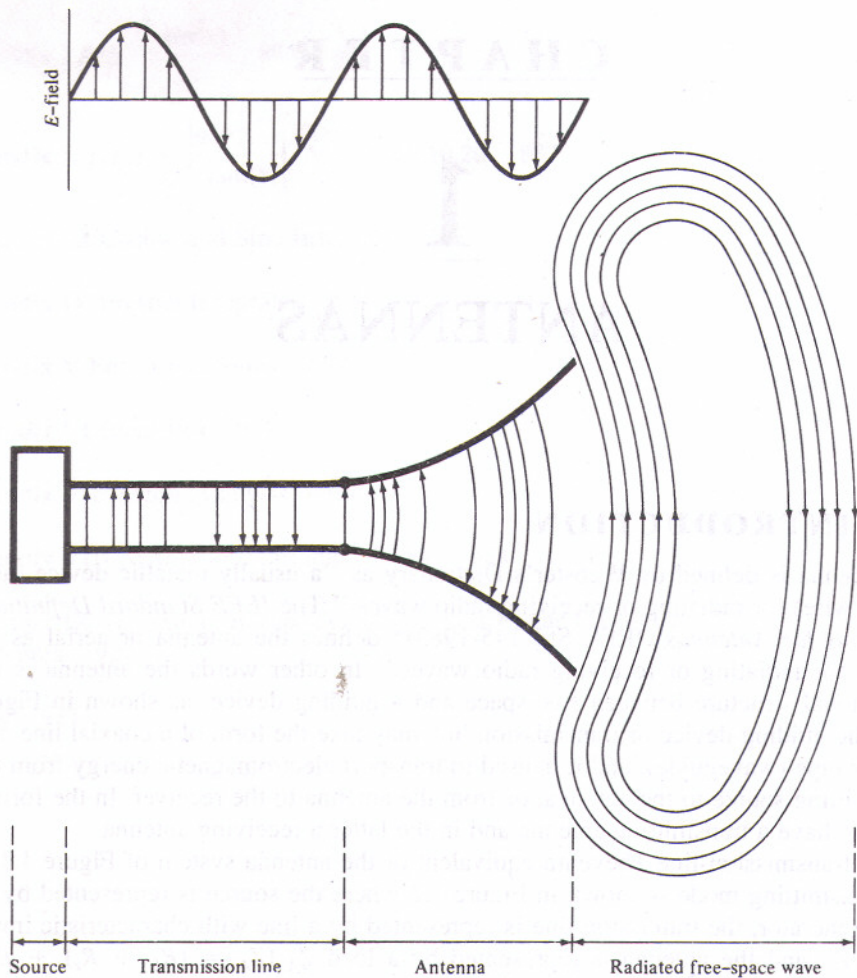
Figure 1.1   Antenna as a transition device.

The reflected waves from the interface create, along with the traveling waves from the source toward the antenna, constructive and destructive interference patterns, referred to as *standing waves*, inside the transmission line which represent pockets of energy concentrations and storage, typical of resonant devices. A typical standing wave pattern is shown dashed in Figure 1.2, while another is exhibited in Figure 1.15. If the antenna system is not properly designed, the transmission line could act to a large degree as an energy storage element instead of as a wave guiding and energy transporting device. If the maximum field intensities of the standing wave are sufficiently large, they can cause arching inside the transmission lines.

The losses due to the line, antenna, and the standing waves are undesirable. The losses due to the line can be minimized by selecting low-loss lines while those of the antenna can be decreased by reducing the loss resistance represented by R_L in Figure 1.2. The standing waves can be reduced, and the energy storage capacity of the line minimized, by matching the impedance of the antenna (load) to the characteristic impedance of the line. This is the same as matching loads to transmission lines, where
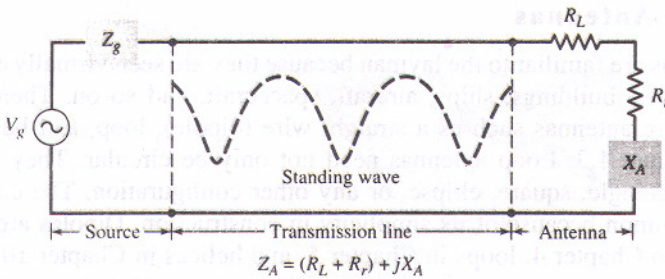
Figure 1.2   Transmission-line Thevenin equivalent of antenna in transmitting mode.

the load here is the antenna, and is discussed more in detail in Section 9.8. An equivalent similar to that of Figure 1.2 is used to represent the antenna system in the receiving mode where the source is replaced by a receiver. All other parts of the transmission-line equivalent remain the same. The radiation resistance R_r is used to represent in the receiving mode the transfer of energy from the free-space wave to the antenna. This is discussed in Section 2.13 and represented by the Thevenin and Norton circuit equivalents of Figure 2.20.

In addition to receiving or transmitting energy, an antenna in an advanced wireless system is usually required to *optimize* or *accentuate* the radiation energy in some directions and suppress it in others. *Thus the antenna must also serve as a directional device in addition to a probing device.* It must then take various forms to meet the particular need at hand, and it may be a piece of conducting wire, an aperture, a patch, an assembly of elements (array), a reflector, a lens, and so forth.

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. The antenna serves to a communication system the same purpose that eyes and eyeglasses serve to a human.

The field of antennas is vigorous and dynamic, and over the last 50 years antenna technology has been an indispensable partner of the communications revolution. Many major advances that occurred during this period are in common use today; however, many more issues and challenges are facing us today, especially since the demands for system performances are even greater. Many of the major advances in antenna technology that have been completed in the 1970s through the early 1990s, those that were underway in the early 1990s, and signals of future discoveries and breakthroughs were captured in a special issue of the *Proceedings of the IEEE* (Vol. 80, No. 1, January 1992) devoted to Antennas. The introductory paper of this special issue [1] provides a carefully structured, elegant discussion of the fundamental principles of radiating elements and has been written as an introduction for the nonspecialist and a review for the expert.

1.2   TYPES OF ANTENNAS

We will now introduce and briefly discuss some forms of the various antenna types in order to get a glance as to what will be encountered in the remainder of the book.

1.2.1 Wire Antennas

Wire antennas are familiar to the layman because they are seen virtually everywhere—on automobiles, buildings, ships, aircraft, spacecraft, and so on. There are various shapes of wire antennas such as a straight wire (dipole), loop, and helix which are shown in Figure 1.3. Loop antennas need not only be circular. They may take the form of a rectangle, square, ellipse, or any other configuration. The circular loop is the most common because of its simplicity in construction. Dipoles are discussed in more detail in Chapter 4, loops in Chapter 5, and helices in Chapter 10.

1.2.2 Aperture Antennas

Aperture antennas may be more familiar to the layman today than in the past because of the increasing demand for more sophisticated forms of antennas and the utilization of higher frequencies. Some forms of aperture antennas are shown in Figure 1.4. Antennas of this type are very useful for aircraft and spacecraft applications, because they can be very conveniently flush-mounted on the skin of the aircraft or spacecraft. In addition, they can be covered with a dielectric material to protect them from hazardous conditions of the environment. Waveguide apertures are discussed in more detail in Chapter 12 while horns are examined in Chapter 13.

1.2.3 Microstrip Antennas

Microstrip antennas became very popular in the 1970s primarily for spaceborne applications. Today they are used for government and commercial applications. These antennas consist of a metallic patch on a grounded substrate. The metallic patch can take many different configurations, as shown in Figure 14.2. However, the rectangular and circular patches, shown in Figure 1.5, are the most popular because of ease of
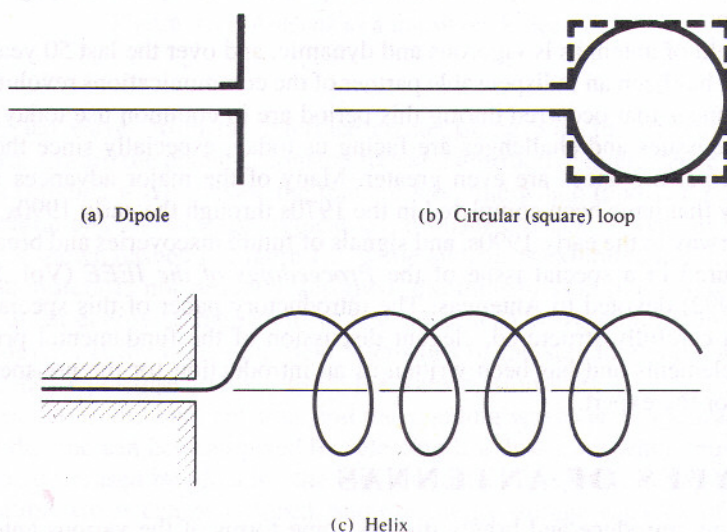
(a) Dipole   (b) Circular (square) loop

(c) Helix

Figure 1.3   Wire antenna configurations.

(a) Pyramidal horn

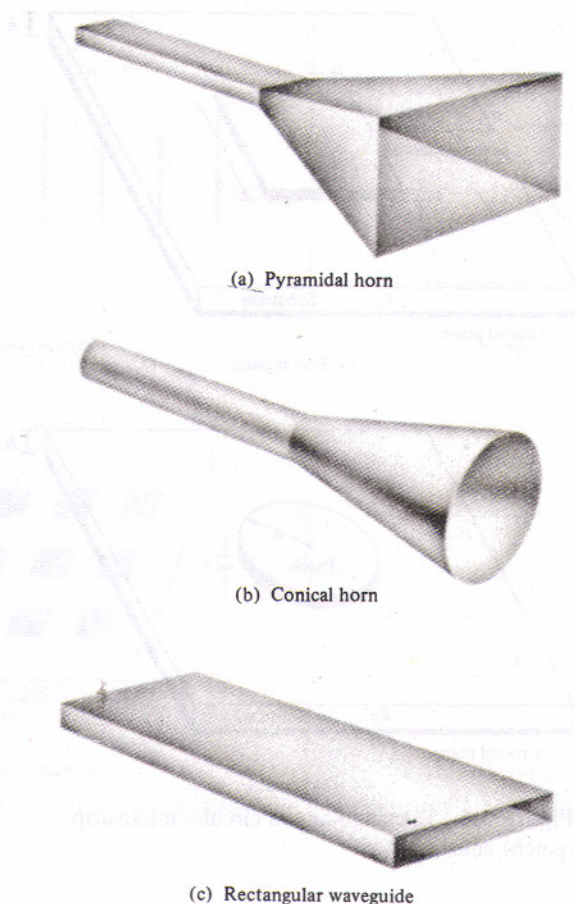(b) Conical horn

(c) Rectangular waveguide

Figure 1.4   Aperture antenna configurations.

analysis and fabrication, and their attractive radiation characteristics, especially low cross-polarization radiation. The microstrip antennas are low-profile, comformable to planar and nonplanar surfaces, simple and inexpensive to fabricate using modern printed-circuit technology, mechanically robust when mounted on rigid surfaces, compatible with MMIC designs, and very versatile in terms of resonant frequency, polarization, pattern, and impedance. These antennas can be mounted on the surface of high-performance aircraft, spacecraft, satellites, missiles, cars, and even handheld mobile telephones. They are discussed in more detail in Chapter 14.

1.2.4 Array Antennas

Many applications require radiation characteristics that may not be achievable by a single element. It may, however, be possible that an aggregate of radiating elements in an electrical and geometrical arrangement (*an array*) will result in the desired radiation characteristics. The arrangement of the array may be such that the radiation from the elements adds up to give a radiation maximum in a particular direction or directions, minimum in others, or otherwise as desired. Typical examples of arrays
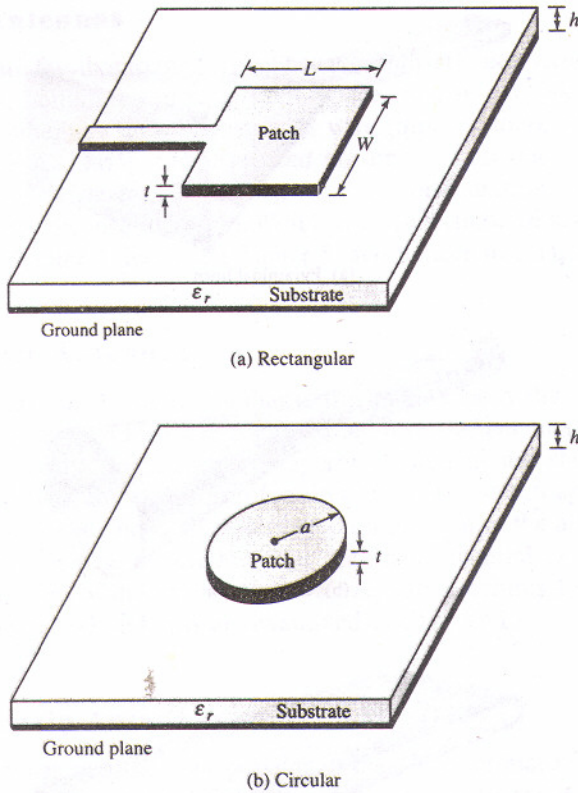
(a) Rectangular

(b) Circular

Figure 1.5   Rectangular and circular microstrip (patch) antennas.

are shown in Figure 1.6. Usually the term *array* is reserved for an arrangement in which the individual radiators are separate as shown in Figures 1.6(a–c). However the same term is also used to describe an assembly of radiators mounted on a continuous structure, shown in Figure 1.6(d).

1.2.5 Reflector Antennas

The success in the exploration of outer space has resulted in the advancement of antenna theory. Because of the need to communicate over great distances, sophisticated forms of antennas had to be used in order to transmit and receive signals that had to travel millions of miles. A very common antenna form for such an application is a parabolic reflector shown in Figures 1.7(a) and (b). Antennas of this type have been built with diameters as large as 305 m. Such large dimensions are needed to achieve the high gain required to transmit or receive signals after millions of miles of travel. Another form of a reflector, although not as common as the parabolic, is the corner reflector, shown in Figure 1.7(c). These antennas are examined in detail in Chapter 15.
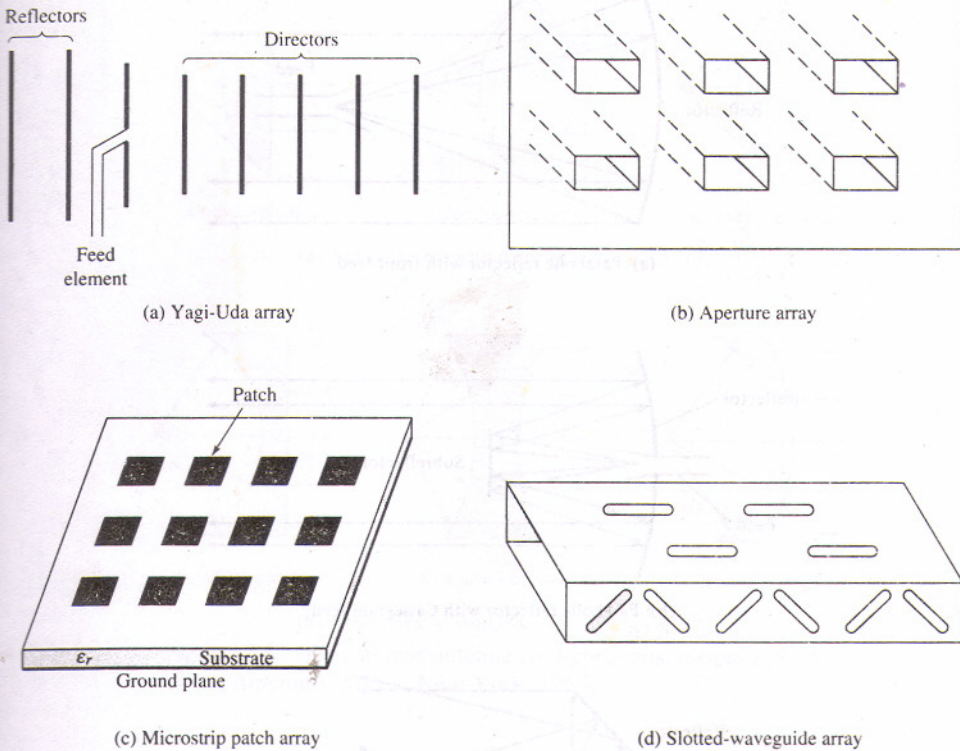
(a) Yagi-Uda array

(b) Aperture array

(c) Microstrip patch array

(d) Slotted-waveguide array

Figure 1.6 Typical wire, and aperture and microstrip array configurations.

1.2.6 Lens Antennas

Lenses are primarily used to collimate incident divergent energy to prevent it from spreading in undesired directions. By properly shaping the geometrical configuration and choosing the appropriate material of the lenses, they can transform various forms of divergent energy into plane waves. They can be used in most of the same applications as are the parabolic reflectors, especially at higher frequencies. Their dimensions and weight become exceedingly large at lower frequencies. Lens antennas are classified according to the material from which they are constructed, or according to their geometrical shape. Some forms are shown in Figure 1.8 [2].

In summary, an ideal antenna is one that will radiate all the power delivered to it from the transmitter in a desired direction or directions. In practice, however, such ideal performances cannot be achieved but may be closely approached. Various types of antennas are available and each type can take different forms in order to achieve the desired radiation characteristics for the particular application. Throughout the book, the radiation characteristics of most of these antennas are discussed in detail.

1.3 RADIATION MECHANISM

One of the first questions that may be asked concerning antennas would be "how is radiation accomplished?" In other words, how are the electromagnetic fields generated
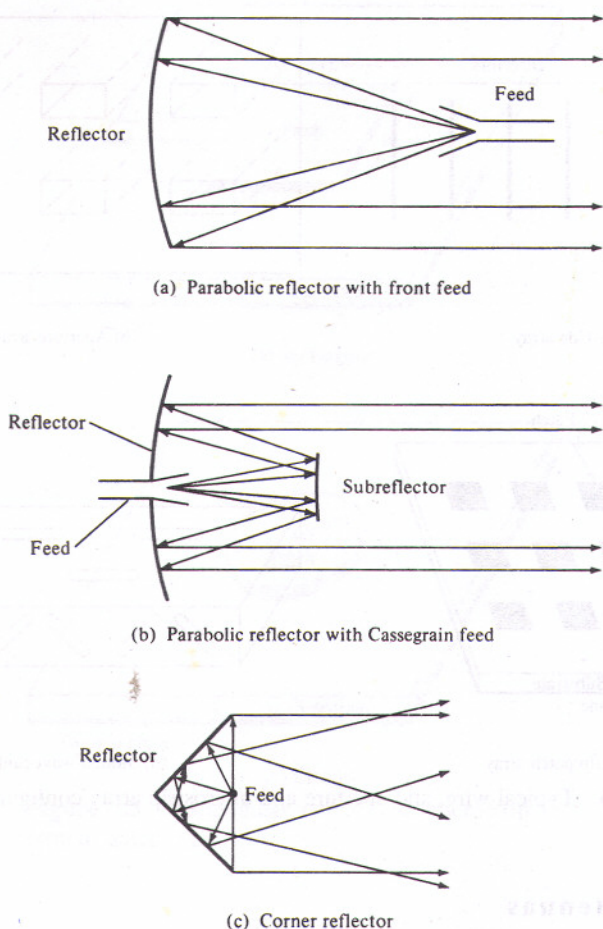
(a) Parabolic reflector with front feed

(b) Parabolic reflector with Cassegrain feed

(c) Corner reflector

Figure 1.7   Typical reflector configurations.

by the source, contained and guided within the transmission line and antenna, and finally "detached" from the antenna to form a free-space wave? The best explanation may be given by an illustration. However, let us first examine some basic sources of radiation.

1.3.1 Single Wire

Conducting wires are material whose prominent characterisic is the motion of electric charges and the creation of current flow. Let us assume that an electric volume charge density, represented by q_v (coulombs/m^3), is distributed uniformly in a circular wire of cross-sectional area A and volume V, as shown in Figure 1.9. The total charge Q within volume V is moving in the z direction with a uniform velocity v_z (meters/sec). It can be shown that the current density J_z (amperes/m^2) over the cross section of the wire is given by [3]

$$J_z = q_v v_z \qquad (1\text{-}1a)$$

(a) Lens antennas with index of refraction $n > 1$

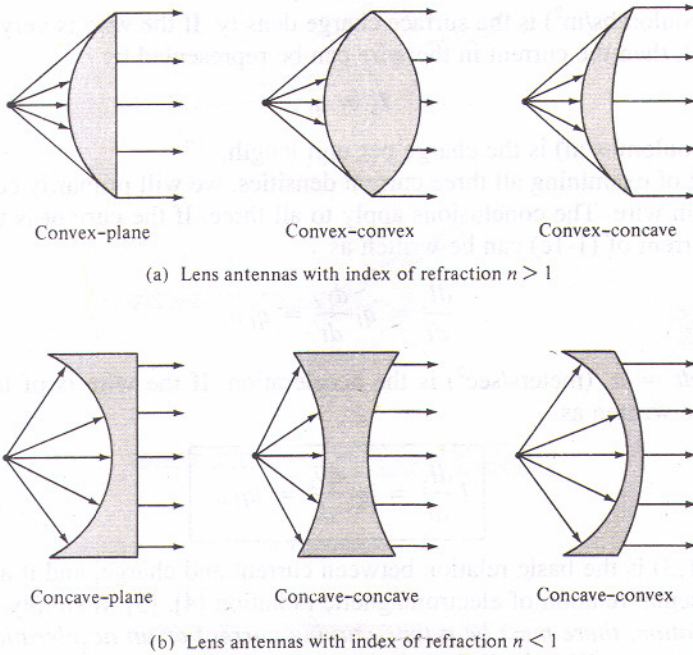(b) Lens antennas with index of refraction $n < 1$

Figure 1.8 Typical lens antenna configurations. (SOURCE: L. V. Blake, *Antennas*, Wiley, New York, 1966).

If the wire is made of an ideal electric conductor, the current density J_s (amperes/m) resides on the surface of the wire and it is given by
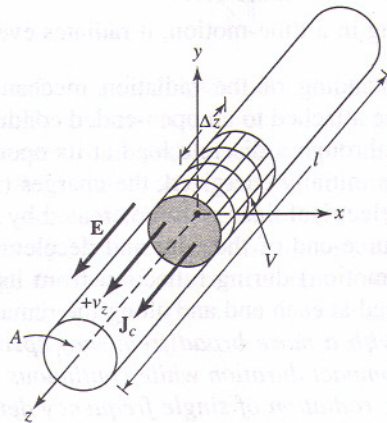
$$J_s = q_s v_z \tag{1-1b}$$

Figure 1.9 Charge uniformly distributed in a circular cross section cylinder.