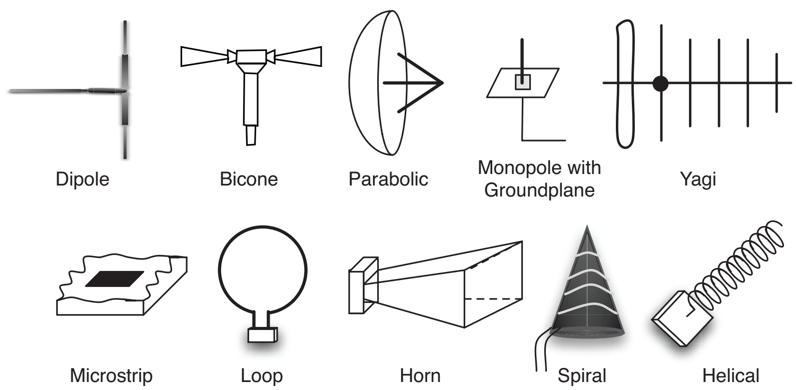

Figure 13.2 Some antenna types.

13.2 ANTENNAS

As the name implies, wireless communication systems include a wireless link—normally as the last link from the network to the user. Communications over the wireless link for the systems we will study takes place via radio waves over the air. A typical radio communication system consists of the following components. The information source signal (audio, data or video) is first passed through various signal processing functions which appropriately filter and code the signal (e.g., bandlimiting signal, A/D conversion, error control coding, vocoding, etc.). Next the signal is modulated to the carrier frequency—resulting in the information signal being shifted in the frequency domain to the appropriate radio channel (see Chapter 14). The amplifier/antenna combination transmits the signal obeying specifications for bandwidth and power limits. After the signal propagates through the air to the receiver, the receiver antenna must couple the desired signal to the receiver, the receiver must filter/remove noise, demodulate, decode and amplify the information signal. For two way communication each end of the wireless link must have both a transmitter section and a receiver section. This combination of a transmitter and receiver is called a *transceiver*.

To transmit the radio signal over the air and recover it from the air, the transceiver needs antennas. Antennas are transducers that convert an electrical signal flowing on a guided medium (wire) into an electromagnetic wave that can propagate over an unguided medium (air or free space). They also perform the reverse task of capturing an electromagnetic radiation and converting it into an electrical signal on a guided medium. This process is possible because there is a coupling between accelerated charges in a medium and electromagnetic radiation as discussed in the Appendix on *Maxwell's Equations*. Acceleration of charges is created either by a time-varying current or by changes in the shape of the path along which charges move (making charges move along a curved conductor). Aperture sources where EM fields are created across an aperture can also serve as sources of radiation.

Any conductor or dielectric can serve as an antenna, but the shape, size, and material characteristics impacts the properties of the antenna. These properties can make an antenna either very well suited or competely unsuitable for the application at hand. For example, the impedance of an antenna needs to be matched to both that of the transmission line or guided medium on one side and the unguided medium on the other side[1] to efficiently convert the energy in the signal from one form to the other. Impedance matching is also necessary to prevent reflections of signals back to where it originated. Depending on the application, the transmission frequencies of interest and directionality of transmission, the structure of the antenna needs careful design. Figure 13.2 shows some schematics of antenna types.

Consider the dipole antenna as an example. The vertical dipole antenna consists of a single radiating element split into two sections as shown in Figure 13.2. It is common to have the two sections be of length equal to $\frac{\lambda}{4}$ for a total length of $\frac{\lambda}{2}$. The antenna is then called a half-wave dipole and has a good impedance match to a coaxial cable. This antenna is also omnidirectional and has found to be useful in wireless communication systems where the transmitter cannot remained pointed at the receiver (e.g., cell phones and broadcast TV). The quarter-wave monopole with a ground plane (see Figure 13.2) consists of a radiating element of length $\frac{\lambda}{4}$ mounted on a metallic plate. Qualitatively speaking, the plate acts as a reflector and if we think of it as a mirror, an image of the radiating element is created on the other side. Thus we could envisage this as being equivalent to a half-wave dipole antenna. Other antennas shown in Figure 13.2 have their own specific characteristics the discussion of which is left to books dedicated on antenna design [1].

The dimensions of an antenna are measured in units of the wavelength λ of the carrier frequency of interest. In fact, a lot of the distance measurements related to antennas are expressed in λs. We illustrate this usage with an example of the terms "near-field" and "far-field" of an antenna. The EM fields created by an antenna can be demarcated into two regions—one close to and the other far away from the antenna. The so-called near-field or *Fresnel Region* is around one λ near the antenna. The far-field or *Fraunhofer Region* is several λs away from the antenna. The physical dimension of an antenna is represented by a number d where d is the diameter of the smallest sphere that completely encloses the antenna. Then, the boundary between the near and far-fields is defined as the sphere of radius $R = \frac{2d^2}{\lambda}$. The reason for demarcating these regions is as follows. In the near-field, the properties of the antenna are difficult to determine. Here, the fields are usually reactive and not radiating in nature. Reactive fields are quasi-static fields similar to the fields generated by inductors (or electric motors) and tend to store energy locally they rather than radiate it as waves. There is a complicated coupling between the physical objects, the current or voltage and the created EM fields. In the far-field, radiation dominates over coupling. Radiation in the far-field is similar to plane-wave propagation and allows us to simplify the characteristics of an antenna. Fortunately, the far-field is the region of interest for most applications since we want to use an antenna for communicating across distances larger than a few λs.

Example. Compute the far-field of a half wavelength dipole antenna for a 1 GHz carrier. Let us suppose that the physical dimension of the antenna is λ. So the radius of the sphere

1 The characteristic impedance of air is $120\pi\,\Omega$.

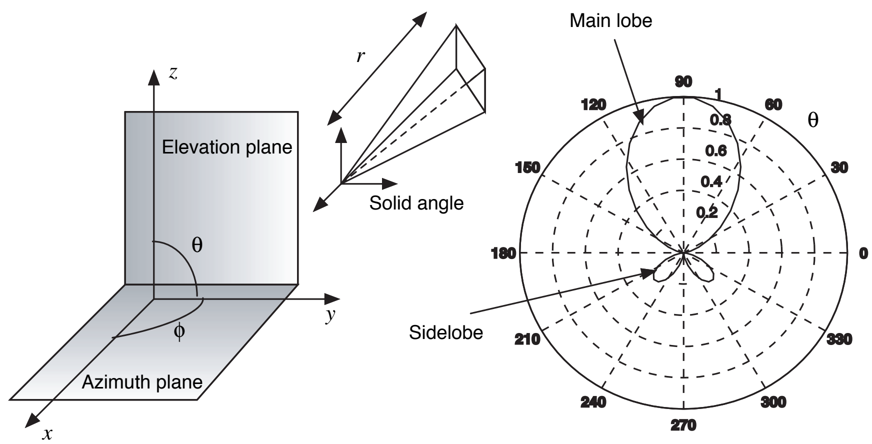

Figure 13.3 Spherical coordinates, solid angle and example antenna pattern.

that separates the near and far fields is $R = \frac{2(\lambda)^2}{\lambda} = 2\lambda$. For a 1 GHz carrier, the wavelength is $\lambda = \frac{3\times10^8}{10^9} = 0.3$ m. The far-field starts at 0.6 m.

Antenna Pattern and Directivity. In the far field of an antenna, we are often interested in the power delivered in a specific direction as this allows us to place antennas for best coverage over a given region. It also allows us to design and choose antennas to deliver power only in certain directions thereby reducing the power wasted in other directions (which may also interfere with other signals in those directions).

The *radiation pattern* or *antenna pattern* of any antenna is a directional function of the relative distribution of power or intensity in the far-field. It is a three dimensional plot (often shown as two two-dimensional plots) of the relative power as a function of the spherical coordinates θ and ϕ. Since it is a plot of the relative power, it is independent of distance from the antenna. The θ direction is called the *elevation plane* and the ϕ direction is called the *azimuth plane*. Figure 13.3 shows the two planes and an example antenna pattern in the elevation plane. The radiation patterns for transmission and reception are usually the same for a given antenna. This is called *reciprocity* and it holds for most antennas of interest.

Example. An omnidirectional antenna, such as a dipole radiates energy uniformly over ϕ. The radiation pattern is written as $G(\theta, \phi)$ as it denotes the *gain* (or loss) in power in a given direction. The function G is usually normalized to the maximum value G_{max} and expressed in dB. Two special cases of radiation patterns are important. In the first case, called an *isotropic antenna*, $G(\theta, \phi) = 1$. The radiation pattern is a sphere with unit gain in all directions - that is the radiation propagates equally in all directions. This is an ideal antenna that is not physically realizable. However it is useful as a benchmark to evaluate the properties of other antennas. In the second case, called an *omnidirectional antenna*, $G(\theta, \phi) = G(\theta)$. This means that the radiation pattern has the same value in the

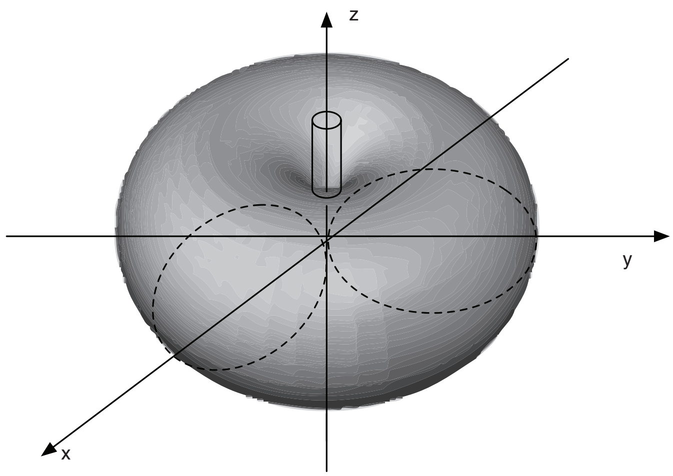

Figure 13.4 Omnidirectional antenna with a donut shaped pattern.

azimuthal plane for all values of ϕ. The radiation pattern depends only on θ. Half-wave dipole antennas and quarter-wave monopoles with a ground plane are good examples of omnidirectional antennas. In such cases, the antenna pattern is donut shaped as shown in Figure 13.4. The gain along the x-y plane is 2.15 dB with respect to an isotropic antenna.

Antenna gains are usually expressed relative to the isotropic or omnidirectional antennas. If the gain is relative to an isotropic antenna, it is written in units of dBi. If it is relative to the dipole antenna, it is written in units of dBd. The gain in dBi is 2.15 + the gain in dBd as explained by the following example.

Example. Consider a Yagi antenna that has a specification of a gain of 18 dBi. What this means is that the power measured at any point (in the specified direction in the far-field) will be 18 dB larger than that from an isotropic antenna placed at the same point as the Yagi with the same overall transmit power. The specification of the Yagi antenna could also have been expressed as 15.85 dBd. In this case, the meaning of this term is that the power with the Yagi antenna will be 15.85 dB larger than the power with a half-wave dipole antenna. As discussed above, the gain in dBi is 2.15 + the gain in dBd.

If we want to transmit a signal in a particular direction, we would want the antenna to ideally radiate with the same gain over specified angle and not radiate at all in other directions (that is have $G = 1$ for a range of θ and ϕ and $G = 0$ elsewhere). However, a real antenna will not have such characteristics. Note that the antenna pattern in Figure 13.3 does not have the same value for a range of directions. It radiates power in unwanted directions through *sidelobes*. These radiations are useless and often create interference in addition to reducing the efficiency in the desired direction. The ratio of the power in the main lobe to the power in a lobe created in the back of the antenna is called the *front-to-back ratio*. This ratio should be made as large as possible to improve the efficiency. Also, the mainlobe does not have a uniform gain. It is common to define the *beamwidth* of an antenna like the bandwidth of a signal—by considering the points where the relative power radiated is 3 dB below the maximum. Formally, the antenna beamwidth is the angle of coverage where the radiated power is 3 dB below that at the peak of the beam.

The *directivity* of an antenna provides a quantitative description of how much gain is there in a given direction. It is the ratio of the maximum radiation intensity in any given direction to the average radiation density and is given by:

$$D = \frac{G_{max}}{\frac{1}{4\pi} \iint\limits_{4\pi} G(\theta, \phi)\, d\Omega} \tag{13.1}$$

Here $d\Omega$ refers to the *solid angle* in the direction specified by θ and ϕ (see Figure 13.3). In terms of the spherical coordinates, it is $d\omega = \sin(\theta)\, d\theta\, d\phi$. It can be shown that a sphere is made of 4π steradians which are the units of the solid angle (which is why the integral is over 4π).

Example. The directivity of the isotropic antenna can be computed easily. The maximum gain in any direction is 1. So, the directivity is:

$$D_{iso} = \frac{1}{\frac{1}{4\pi} \int_0^{\pi} \int_0^{2\pi} \sin\theta\, d\phi\, d\theta} = \frac{4\pi}{2\pi \int_0^{\pi} \sin\theta\, d\theta} = 1 \tag{13.2}$$

The *effective area* of an antenna is a measure of its ability to capture energy from a radiating field and convert it into signal power on the guided medium. This is also called the *effective aperture* or *receiving cross-section*. You can think of it as a quantity that measures the efficiency of the antenna. The physical area of the antenna has only a *very small* impact on the effective area. We will not go into the details of analyzing the effective area of antennas, but we will mention a result that we will use later in considering free-space loss in Section 13.3.2. For an antenna that has its impedance matched to the transmission line, it is possible to show that the effective area is given by:

$$A_e = \frac{\lambda^2 D}{4\pi} \tag{13.3}$$

where D is the directivity. The effective area of an isotropic antenna is $A_e = \frac{\lambda^2}{4\pi}$.

Antenna Arrays and Beamforming. In many cases, the antenna radiation pattern and directivity are not suitable for the application at hand. For example, it may be necessary to have focussed narrow radiation patterns for high gains in certain directions and almost no transmission in other directions. A single antenna may not be capable of providing such an antenna pattern. However, it is possible to combine several antennas that are fed from the same source (or lead to the same sink) in a manner that can provide the required radiation pattern, gain and directivity. Such combinations of antenna elements are called antenna arrays. Usually, all the antenna elements are of the same type (for example, all dipole elements) although this is not necessary. The arrangement of the antenna

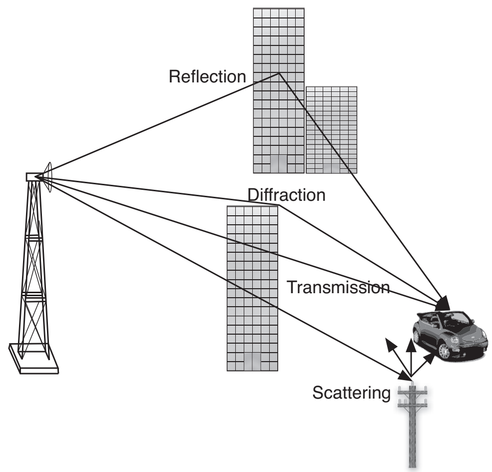

Figure 13.5 Mechanisms of radio propagation.

elements follows some geometric pattern (example, linearly spaced elements, elements on a rectangular grid or elements placed on a circle) to achieve the requirements. The spacing of antenna elements is once again measured in fractions or multiples of λ. In recent years, it has been possible to electronically shift the phases and amplitudes of signals entering the antenna elements to *steer* the beams created by arrays dynamically without mechanically moving the antenna itself. The interested reader is referred to [1] and [2] for a detailed mathematical treatment of antennas and antenna arrays.

13.3 RADIO PROPAGATION

In electrical wires and fiber optic lines we have well defined models for the attenuation of a signal as it propagates along the media. This is not true for the wireless environment, it is fairly difficult to understand the nature of electromagnetic wave propagation in complex environments. Maxwell's equations, discussed in Appendix B can only be solved for simple geometries and material with homogeneous properties. Hence approximations, empirical characterization and statistical models are necessary to predict radio wave propagation in all cases. In Section subsec:radpropmechanisms, we describe elementary mechanisms of propagation qualitatively. Different types of fading are discussed in the other two subsections.

13.3.1 Mechanisms

Radio waves suffer attenuation and dispersion like light waves. At frequencies greater than 500 MHz, radio wave propagation can be approximated as ray propagation in a manner similar to optics (see Chapter 12). There are three basic mechanisms by which a radio