Chapter 12: Antennas and Wave Propagation

Chapter 12 Objectives

At the conclusion of this chapter, the reader will be able to:

- Describe the characteristics of electromagnetic energy, such as field strength and polarization.
- Describe the characteristics of an isotropic point source.
- Explain the operation of the dipole and Marconi antennas, giving the 3-dimensional field pattern for each one.
- Given manufacturer's data for antenna gain and pattern, describe the performance characteristics of an antenna system.
- Explain the operation of the Yagi-Uda, log-periodic, and other directional antennas; give a typical application for each.
- Describe safety concerns and procedures for working with antenna installations.
- Describe three modes of electromagnetic propagation.
- Explain the interaction between frequency and electromagnetic wave propagation modes.
- Describe the basic principles of satellite communications.
- Calculate the values needed to provide a link budget.

Antennas are a critical part of every RF communication system. Without a proper antenna to launch its energy into space, the most powerful transmitter is useless. A receiver's performance and sensitivity are very dependent on the quality of the attached antenna. Transmitting and receiving antennas are *transducers*. A transducer converts one form of energy into another. A transmitter's antenna converts RF electrical energy into RF electromagnetic energy. The receiver's antenna reverses the process, allowing the recovery of the information on the RF carrier wave sent by the transmitter.

The design of antennas involves a large amount of scientific theory, combined with practical experience, and even a little bit of art. There is no "best antenna" for any application. Often there are many competing designs from various manufacturers, each having been optimized in one or more ways.

12-1 Electrical and Electromagnetic Energy

When RF electrical energy enters a transmitting antenna, an interesting change takes place. The energy is converted into an *electromagnetic wave*, and moves away from the antenna at the speed of light (3×10^8 meters/second). An electromagnetic wave is made up of two parts, an *electric* field, and a *magnetic* field, as shown in Figure 12-1.

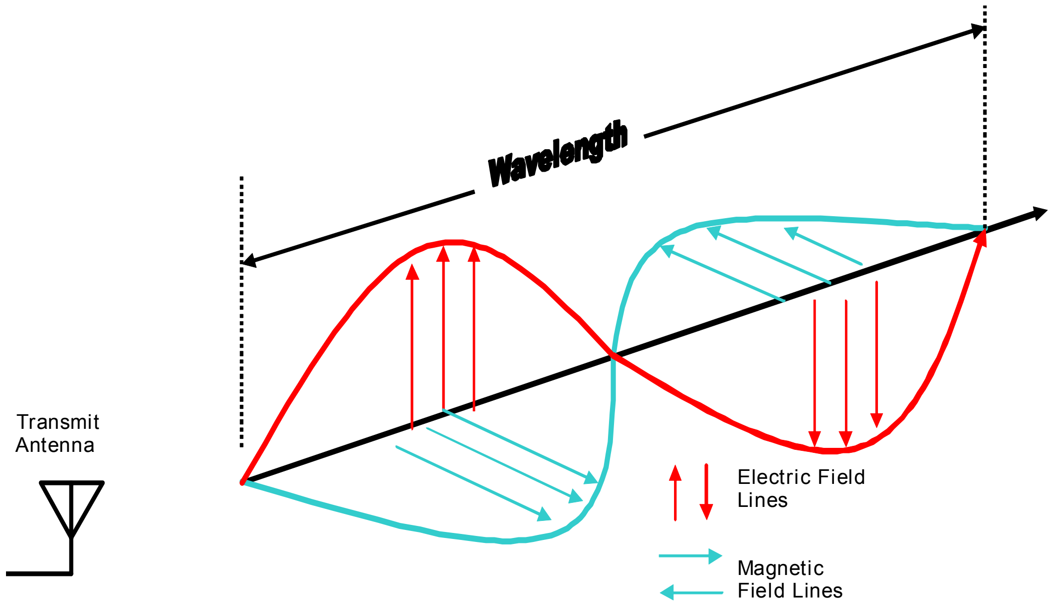

Figure 12-1: An Electromagnetic Wave in Space

The *wavelength* of an electromagnetic wave is the distance the wave travels in one cycle. We can calculate it if we know the velocity (speed) of the wave, and frequency of the wave.

(12-1) $$\lambda = \frac{v}{f}$$

Where v is the velocity (3×10^8 meters/second in free space), and f is the frequency.

Example 12-1

What is the wavelength of a 100 MHz FM broadcast signal in free space?

Solution
Using Equation 12-1, we get:

$$\lambda = \frac{v}{f} = \frac{3 \times 10^8 \, m/s}{100 \, MHz} = \underline{\underline{3 \, meters}}$$

Radio Wave Polarization

The radio wave of Figure 12-1 has two energy fields, the electric and magnetic. These two fields are always at right angles to each other, and they are in phase. The *polarization* of a radio wave simply refers to the orientation of the electric field component.

The electric field lines of Figure 12-1 are straight up and down with respect to the earth's surface, so we refer to this as *vertical polarization*. The transmitting antenna design and orientation controls the polarization of the wave.

We can also build antennas that produce *horizontal polarization*. A horizontally polarized wave has a magnetic field that is vertical, and an electric field that is horizontal.

But that's not all! The radio wave of Figure 12-1 goes straight out into space, never changing its polarization. What if the wave rotated or "corkscrewed" as it traveled outward? This would be an example of *circular* or *elliptical* polarization. And yes, the corkscrew can turn in either a right-hand or left-hand direction.

Polarization of antennas is usually important. If a receiving antenna is designed to pick up vertically polarized energy, then it will not be very sensitive to horizontally polarized signals. In fact, it might not hear them at all!

In general, the polarization of the receiving antenna should match that of the transmitter for best performance.

Circular polarization is often used in satellite communications because the relative orientation of the receiver and transmitter antennas is hard to control. With this type of polarization, both transmitter and receiver must agree on the direction of the wave rotation (right or left hand), or little signal will be received.

The polarization of a radio wave is not set in stone. As a wave makes its way from transmitter to receiver, its polarization can be changed in many ways. *Reflection* from terrain, buildings, and other obstructions can alter polarization drastically. Even waves traveling above ground are affected by the earth's magnetic field, which rotates the wave's polarization. This effect is called *Faraday rotation* and strongly affects radio waves in the HF region (3-30 MHz) that travel over long distances (thousands of miles).

An Ideal Radio Wave Source

In order to calculate and compare the performance of various antennas, we often compare them with a theoretically perfect antenna called an *isotropic point source*. No such antenna really exists. This may sound intimidating, but the idea is really quite simple. *An isotropic point source radiates equally in all directions*. This includes all three dimensions, height, width, and depth.

If you could see the radiation pattern from an isotropic source, it would look like a perfectly round balloon that expands outward at the speed of traveling radio waves (speed of light). If you could freeze this pattern for a moment of time, it might look like Figure 12-2:

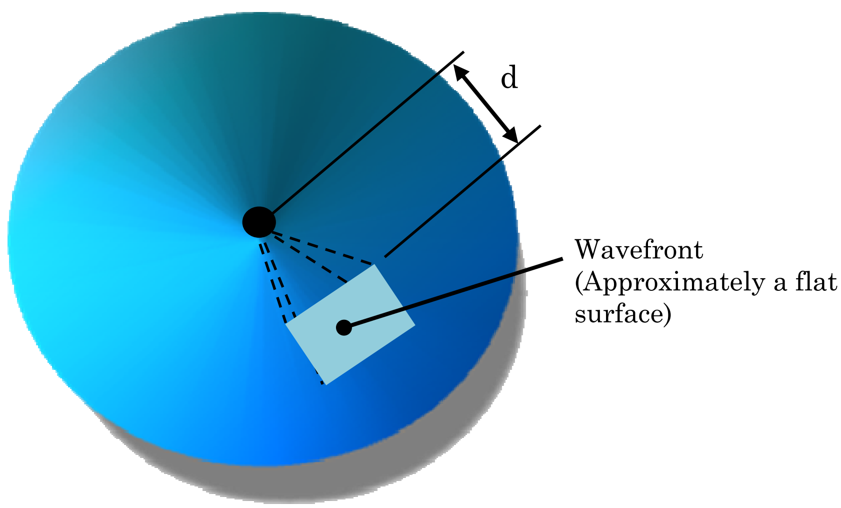

Figure 12-2: The Wavefront From an Isotropic Point Source

Field Intensity of an Electromagnetic Wave

With the appropriate equipment, we can measure the electric and magnetic field strengths or intensities of a radio wave. Because we know about the characteristics of free space, we can also calculate them. An isotropic source is often used as the basis for calculation of field strength. There are two components in a radio wave, and we can calculate both of them:

Electric Field Intensity

$$E = \frac{\sqrt{30Pt}}{d} \quad (12\text{-}2)$$

Where E is the free-space *electric field intensity*, in *volts per meter*, d is the distance from the point source, and Pt is the *isotropic radiated power* (the total power being radiated from the point RF source).

An *electric field* exists any time there is a *difference in potential* between two points in space. The *electric field intensity* indicates how strong this voltage difference is. Although space is essentially an *insulator*, it can still have a voltage drop. (Think about the space between two conducting wires in a circuit; there is an electric field there too, any time there is a difference in potential between the conductors.) The voltage drops on the transmitting antenna are what creates the electric field of the outgoing radio wave.

As the distance from the point source is increased, the electric field decreases in an inversely proportional manner. This makes sense; radio waves get weaker as we move away from the transmitting source.

We can also calculate the strength of the *magnetic* field component:

Magnetic Field Strength

$$H = \frac{\sqrt{Pt}}{68.8d} \quad (12\text{-}3)$$

Where H is the *magnetic field strength* in amperes/meter, Pt is the isotropic radiated power, and d is the distance from the point source. Recall that a magnetic field is created whenever a current flows in a conductor. The currents that flow in a transmitting antenna contribute to the creation of the magnetic field of the radio wave that leaves the antenna. Like the electric field, the magnetic field strength is inversely proportional to the distance from the RF energy source.

Example 12-2

A certain transmitter has an equivalent isotropic radiated power (EIRP) of 100 watts. What are the magnetic and electric field strengths at a distance of 10 meters from the transmitting antenna?

Solution
Equations 12-2 and 12-3 calculate electric and magnetic field strengths:

$$E = \frac{\sqrt{30Pt}}{d} = \frac{\sqrt{30(100\,W)}}{10\,m} = \underline{\underline{5.47\,V/m}}$$

$$H = \frac{\sqrt{Pt}}{68.8d} = \frac{\sqrt{100\,W}}{68.8(10\,m)} = \underline{\underline{0.0145\,A/m}}$$

Having trouble with E and H? Just think of V and I in a conventional AC circuit. E and H are the electromagnetic equivalent of V and I. In fact, Ohm's law can even be used to work problems with them, as we'll soon see.

Power Density and Ohm's Law

Suppose that a certain resistor had a 10 volt drop, and a current of 1 amp. What would the power dissipation of the resistor be? You could use ohm's law to find the answer, since *P=VI=(10V)(1A)=10 watts*.

The electric and magnetic fields of a radio wave combine to form a *power field*. Look at the rectangular area of Figure 12-2. This area is a *wavefront*. The wavefront moves away from the center of the point source at the speed of light, and expands just like the surface of an inflating balloon. The wavefront of the radio wave starts with a fixed amount of power. As the wavefront moves out from the source, that power is spread over a rapidly increasing area. The *power density* of a radio wave is the amount of power that is distributed over an area, and is calculated by the equivalent of Ohm's law:

(12-4) $P = EH$

Where P is the power density, in watts per square meter (W/m^2), E is the electric field intensity in volts/meter, and H is the magnetic field strength in amperes/meter. Notice how the units make sense; volts times amps gives watts, and of course, we now have an *area* in square meters.

By combining the terms and constants in equations 12-2, 12-3, and 12-4, we can get a formula for power density in terms of just transmitted power and distance:

Inverse Square Law

(12-5) $$P = EH = \left(\frac{\sqrt{30Pt}}{d}\right)\left(\frac{\sqrt{Pt}}{68.8d}\right) = \frac{Pt}{12.56d^2} = \frac{Pt}{4\pi d^2}$$

Equation 12-5 shows us that the power density falls off as the *square* of distance. This is one reason why so much amplification has to be performed in radio transmitters and receivers! This is sometimes referred to as the "inverse square law" of power. Equation 12-5 is valid when we are at least several wavelengths away from a transmitting antenna.

Example 12-3

A certain transmitter has an equivalent isotropic radiated power (EIRP) of 5 kW. What are the magnetic, electric field strengths, and power density at distances of (a) 10 meters and (b) 100 meters from the transmitting antenna?

Solution

a) Equations 12-2 and 12-3 calculate electric and magnetic field strengths:

$$E = \frac{\sqrt{30Pt}}{d} = \frac{\sqrt{30(5000W)}}{10m} = \underline{\underline{38.73\,V/M}}$$

$$H = \frac{\sqrt{Pt}}{68.8d} = \frac{\sqrt{5000W}}{68.8(10m)} = \underline{\underline{0.103\ A/m}}$$

$$P = \frac{Pt}{4\pi d^2} = \frac{5000W}{4\pi(10^2)} = \underline{\underline{3.98\,W/m^2}}$$

b) The same procedures are used for the new distance:

$$E = \frac{\sqrt{30Pt}}{d} = \frac{\sqrt{30(5000W)}}{100m} = \underline{\underline{3.873\,V/M}}$$

$$H = \frac{\sqrt{Pt}}{68.8d} = \frac{\sqrt{5000W}}{68.8(100m)} = \underline{\underline{0.0103\ A/m}}$$

$$P = \frac{Pt}{4\pi d^2} = \frac{5000W}{4\pi(100^2)} = \underline{\underline{0.0398\,W/m^2}}$$

Notice that the magnetic and electric field strengths became smaller by a factor of ten, but the power density shrunk one hundred fold!

The Characteristic Impedance of Free Space

The concept of Ohm's law is also quite handy for expressing a quality or property of space known as its *characteristic impedance*. If 10 volts appears across a resistor, and 1 amp flows, then the resistor must be 10 Ω, according to Ohm's law. We can define the *impedance* of space in the same manner:

(12-6) $Z = \frac{E}{H}$

Where Z is the impedance of a medium (like space) in ohms, and E and H are the electric and magnetic field intensities. For any medium, Z is a constant, very much like the characteristic impedance of a transmission line. Different media have varying impedances.

Example 12-4

What is the impedance of free space, given the data from Example 12-3(a)?

Solution
Since Z is just the ratio of E and H, we get:

$$Z = \frac{E}{H} = \frac{38.73V/m}{0.103A/m} = \underline{\underline{376\Omega}}$$

This is *very* close to the theoretical value of ***377 Ω*** that is used by most technicians. This is also very close to ***120π***, which is sometimes used for convenience.

The characteristic impedance of free space is the ratio of electric to magnetic field strengths in radio waves traveling through it. Here's why it's important: You'll recall that a transmission line is used to carry energy from a transmitter, and has its own characteristic impedance, Z_0. A transmission line needs to see a *matched load* at its end, in order to transfer 100% of its energy and avoid reflection.

One way of viewing the functioning of an antenna is as an *impedance matching device*. The antenna accepts the traveling RF wave from the feedline (operating at Z_0) and performs the necessary impedance transformation so that the wave can continue to flow out into space, a medium with an impedance, Z, of 377 Ω. For this to happen, an *impedance transformation* must take place!

If you've ever used a megaphone, you've seen *acoustic* impedance transformation in action. A megaphone helps you to be "louder" at a distance not only because it tends to focus energy in a specific direction, but also because it improves the acoustic impedance match between your voice apparatus (vocal cords, throat, mouth, and nasal passages) and the outside air. All antennas operate in this fashion. They are really just impedance transformers!

Example 12-5

At a distance of 75 miles from a transmitter, the power density is 10 pW/m². What are the electric and magnetic field strengths? What is the EIRP of the transmitter?

Solution
Since Z is just the ratio of E and H, and is known to be 377Ω, we can find the unknowns by using what we already know about Ohm's Law:

$$P = I^2 R \text{ and } I = \sqrt{\frac{P}{R}} \quad \text{(Ohm's Law)}$$

So, remembering that H is analogous to I, and Z is really R, we get:

$$P = H^2 Z \text{ and } H = \sqrt{\frac{P}{Z}} = \sqrt{\frac{10\,pW/m^2}{377\Omega}} = \underline{\underline{163\ nA/meter}}$$

Likewise, we can do the same thing with E:

$$P = \frac{V^2}{R} \text{ and } V = \sqrt{PR} \quad \text{(Ohm's Law)}$$

So,

$$P = \frac{E^2}{Z}\text{ , so } E = \sqrt{PZ} = \sqrt{(10\,pW/m^2)(377\Omega)} = \underline{\underline{61.4\ \mu V/meter}}$$

The most direct way of finding the EIRP is to use Equation 12-5, and solve for Pt. The distance units of *miles* must first be converted to *meters*:

$$d = 75 miles \times \frac{5{,}280\ ft}{1\ mile} \times \frac{1\ meter}{3.28\ ft} = 120{,}732\ meters$$

$$P = \frac{Pt}{4\pi d^2} \text{ so } Pt = EIRP = P(4\pi d^2) = (.01 pW/m^2) 4\pi (120{,}732 m)^2 = \underline{\underline{1.83 watts}}$$

This example demonstrates that everything you know about Ohm's law is useful in electromagnetics. It also shows that a lot can be learned about a transmitter's power output and radiation pattern by remote measurements. The FCC can use this information to verify that broadcasters and other radio spectrum users are operating under correct and

authorized power levels by accurately measuring the field strength from stations at a distance.
In real life, a small signal power like this isn't likely to go 75 miles without being blocked by terrain, or other obstacle! However, in *satellite* applications, a watt or two of power can cover an amazing area and distance, due to the lack of obstructions.
The received field intensities in this example are fairly small, but current receiver technologies are fully capable of recovering signal levels in this range. Remember that noise (both internal and external to the receiver) will be the primary limiting factor in the receiving portion of the process.

Section Checkpoint

12-1 What are the two field components in a radio wave? How are they oriented with respect to each other?
12-2 Explain what is meant by the *polarization* of a radio wave. Give several examples.
12-3 For best signal pickup, how should a receiver's antenna be oriented?
12-4 What is an *isotropic point source*?
12-5 Describe the shape of the radiation pattern from an isotropic point source.
12-6 What are the units of electric and magnetic field intensity?
12-7 Give the analogous (Ohm's law) equivalents for E, H, P, and Z.
12-8 If the distance between a transmitter and receiver is *doubled*, what will happen to the power density P ?
12-9 What does *EIRP* stand for?
12-10 What is the value for the characteristic impedance of space? What two quantities can be divided to find it?

12-2 The Dipole and Marconi Antennas

The *Hertz antenna* or *dipole* is perhaps the simplest and most popular antenna found in communication systems. It consists of nothing more than two conductors fed 180 degrees out of phase. One way of viewing a dipole antennas is as a modified section of transmission line, where the two conductors have been spread apart, resulting in the antenna of Figure 12-3.

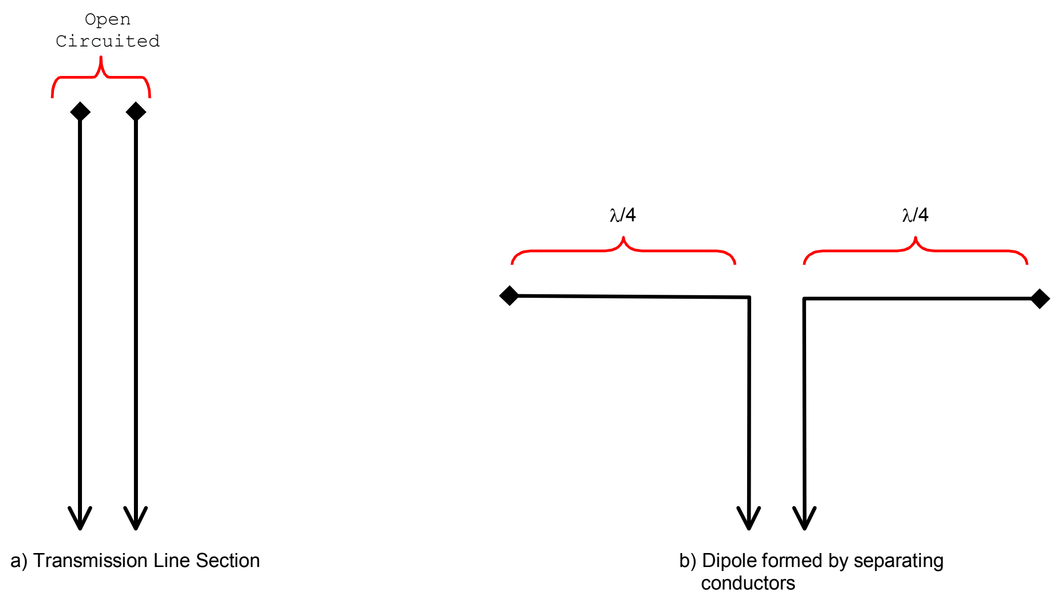

Figure 12-3: A Half-Wavelength Dipole Antenna

Dipole Operating Principle

In a transmission line, an impedance mismatch causes the traveling wave from the generator to *reflect* backward from the point of mismatch. In Figure 12-4, each half of the dipole antenna is treated as a transmission line. The *voltage standing wave pattern* (heavy red line) is developed after many wavefronts pass down the antenna. Note that there is *zero* current at the ends of the antenna (after all, they are open circuited), but a relatively high voltage. Maximum current flows at the feedpoint. Notice the high voltage at the ends of the antenna; depending on the design of the antenna, this voltage can be many times that at the feedpoint.

The ends of a dipole are relatively high impedance points. This is why the voltages are high. The antenna can be easily detuned if the dipole ends are too close to other objects. Also, the high voltages are a potential safety hazard. A transmitting dipole antenna should never be located where persons can touch it.

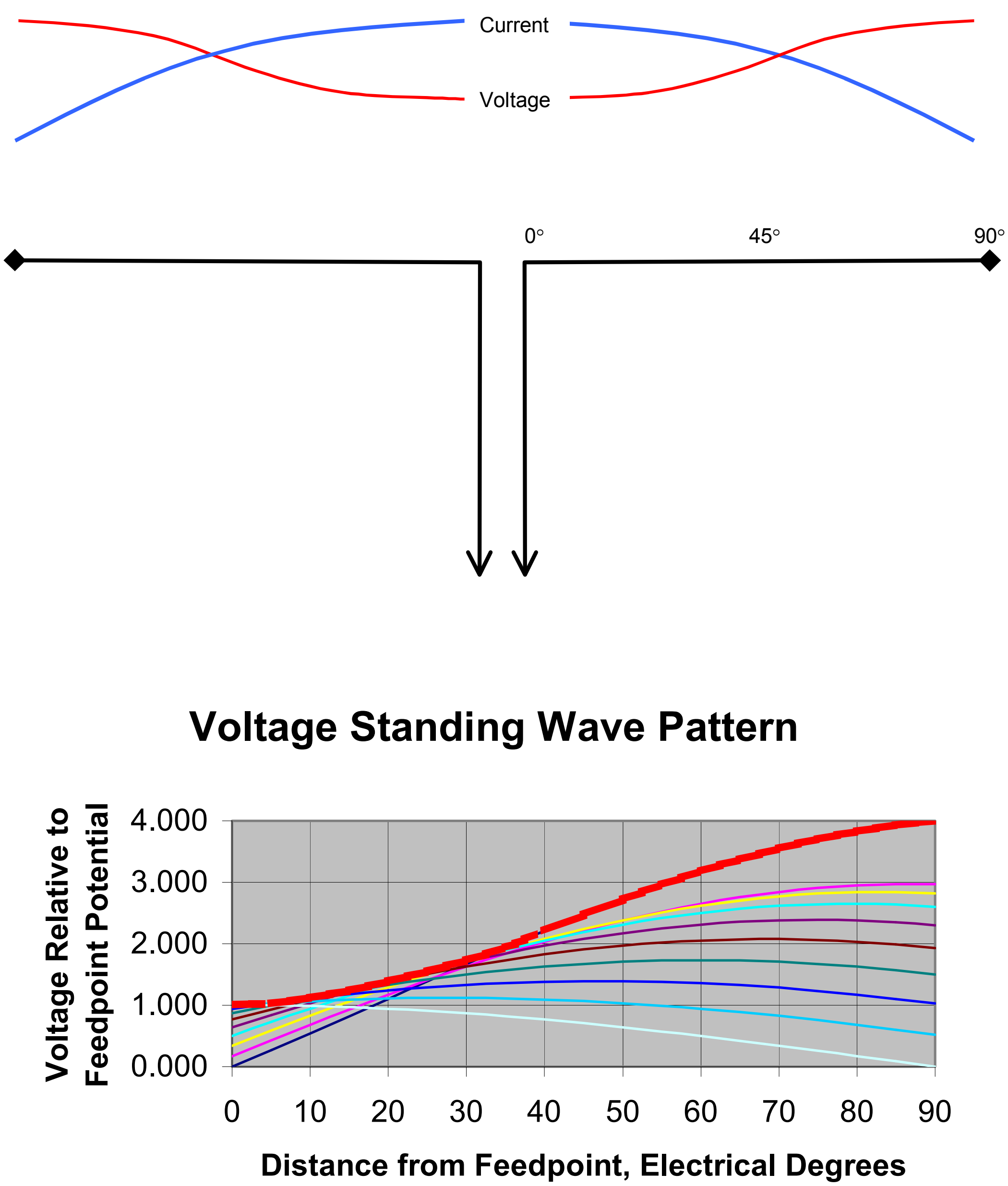

Figure 12-4: Wave Movement on a Dipole, and Resulting Current and Voltage Profile

Consider a wave moving outward on the right-hand side of the dipole of Figure 12-4. The wave travels along the wire, and finds a sudden impedance discontinuity (or bump) at the end of the wire. What do you suppose happens? Right -- the "bump" is an open circuit, which is a severe mismatch! The wave reflects backward toward the generator. But something interesting happens along the way.

You might recall that a quarter-wave section of transmission line can transform a short circuit into an open, and an open circuit into a short. The dipole-half in the figure certainly *looks* like a quarter-wave section of transmission line. So does the input impedance of the right-hand size equal 0 Ω, a short?

The input impedance of each half of the dipole would be a short circuit if there were no loss in the circuit. As both incident and reflected waves move along the dipole wire, *radiation* occurs. Radiation occurs mainly because we separated the two wires of the transmission line in forming the dipole. With the wires separated, their magnetic and electric fields no longer cancel, as they did when they were closely spaced in the transmission line. These fields are now unconfined and free to move out into space as radio waves.

Radiation represents a "loss" in the reflected voltage and current on the dipole. Therefore, the input impedance of the half-dipole is *not* a short circuit; in fact, it comes close to (36.5 + j21.5) Ω. This is why the voltage at the feedpoint is not cancelled, as shown on the graph of Figure 12-4. Of course, this is exactly what we want the antenna to do. We want it to convert the RF electrical energy into electromagnetic wave energy.

The sequence of graphs at the bottom of Figure 12-4 simulates what happens at each end of a dipole. The thin lines represent the result of successive cycles of RF energy traveling towards the end of the dipole wire. These are voltages that are a snapshot in time for a single simulated forward and reflected voltage wave (they're the sum of the forward and incident voltages for a single wavefront). The incident and reflected voltages weaken as they pass down the antenna wire due to the loss of energy by radiation. After many RF wavefronts have been sent down the antenna wire, the standing wave pattern (heavy red line) is developed by summing all of the instantaneous voltage results on the line.

Each half of the dipole presents an identical impedance. Therefore, the total input impedance of a half-wave dipole is just twice that of each side, or about (73 + j43) Ω. Notice that the input impedance is mostly resistive, with a small inductive reactance. By *shortening* the antenna about 5%, most of the inductive reactance is eliminated, leaving an input impedance close to 67 Ω.

For most simple antennas, the element lengths will work out to be 95% of the desired wavelength fraction at resonance. For a dipole antenna, most people use 73 Ω as the input impedance value and forget about the inductive component.

Resistive Antenna Components: Radiation Resistance and Ohmic Loss

There are two resistance components that appear at the input terminals of an antenna, *radiation resistance* and *ohmic loss*. *Radiation resistance is the resistive portion of the input resistance that when excited by an RF current, results in radiated RF energy from the antenna*. Radiation resistance isn't a physical resistor; it represents the ability of the antenna to emit radio waves. Given a constant RF current driving the antenna, a higher radiation resistance will emit a larger radio signal. It is calculated as follows:

$$R_R = \frac{P_R}{I^2} \tag{12-7}$$

where P_R is the total radiated power from the antenna, and I is the feedpoint current. In general, the longer an antenna, the higher its radiation resistance.

The other resistive component of the input impedance, *ohmic loss*, does nothing but generate *heat*. The antenna conductors have a value of resistance determined by the material they're made of, and their physical dimensions. Antenna manufacturers would like to be able to sell units with zero ohmic loss, but that's impossible! Nearby objects and even the earth's surface itself can contribute to ohmic loss, since they can absorb RF energy and convert it to heat.

Example 12-6

A certain antenna radiates 100 W when its feedpoint current is 1.4 A. Find the radiation resistance of the antenna.

Solution

From equation 12-7, we get:

$$R_R = \frac{P_R}{I^2} = \frac{100W}{(1.4A)^2} = \underline{\underline{51\Omega}}$$

Therefore, the portion of the input impedance for this antenna that contributes to radiation (the production of radio wave energy) is $\underline{\underline{51\Omega}}$. Be careful; we're *not* saying that the total input impedance if 51 Ω!

Antenna Efficiency

The *efficiency* of an antenna system is defined as the ratio of power radiated to total power put into the antenna (which is equal to the power loss, plus the radiated power):

$$\text{(12-8)} \quad \eta = efficiency = \frac{P_R}{P_R + P_{LOSS}}$$

No antenna is 100% efficient. However, there is a great difference between different antenna designs. This is partly where the art and science of antenna design meet.

Example 12-7

A certain antenna has a radiation resistance of 51 Ω, and an ohmic (loss) resistance of 10 Ω. If a current of 2 A is driving the antenna, calculate the following:

a) The power radiated
b) The power lost due to heat
c) The total input resistance of the antenna
d) The efficiency of the antenna

Solution
a) By rearranging equation 12-7 to solve for radiated power, we get:

$$P_R = I^2 R_R = (2A)^2(51\Omega) = \underline{\underline{204\ watts}}$$

b) The power lost due to heat can be computed by Ohm's law:

$$P_{LOST} = I^2 R_{LOSS} = (2A)^2(10\Omega) = \underline{\underline{40\ watts}}$$

c) The total input resistance of the antenna is just the sum of the ohmic and radiation components:

$$R_{in} = R_R + R_{LOSS} = 51\Omega + 10\Omega = \underline{\underline{61\Omega}}$$

d) The efficiency is calculated using equation 12-8:

$$\eta = efficiency = \frac{P_R}{P_R + P_{LOSS}} = \frac{204W}{204W + 40W} = 0.836 = \underline{\underline{83.6\%}}$$

This is a good antenna system. 83.6% of the RF energy from the transmitter is converted into electromagnetic energy.

A Shortcut for Efficiency

The efficiency of an antenna can be found without knowing the antenna feedpoint current I by using Ohm's law to simplify Equation 12-8:

$$\eta = efficiency = \frac{P_R}{P_R + P_{LOSS}} = \frac{I^2 R_R}{I^2 R_R + I^2 R_{LOSS}}$$

The common factor I^2 can be cancelled between the numerator and denominator, leaving us with:

$$(12\text{-}9)\quad \eta = efficiency = \frac{R_R}{R_R + R_{LOSS}}$$

Equation 12-9 can be used to find efficiency directly from the resistance values, so it is handy when these are given (or can be measured.)

Dipole Polarization

The *polarization* of an antenna refers to the orientation of the electric field of the radio waves being produced (or received) by it. For a dipole antenna, the polarization is the same as the axis of the conductor.

A dipole strung horizontally produces horizontally-polarized waves. A dipole hung straight up and down produces vertically-polarized output.

Remember that two stations must normally be using the same type of polarization, or severe signal loss will likely result. Antennas used for special purposes often have markings or other instructions as how to mount them, so that proper polarization is achieved.

Dipole Radiation Pattern and Gain

The *radiation pattern* of an antenna is the 3-D distribution of energy leaving the device. You'll recall that an *isotropic point source* is a nonexistent, theoretical antenna that radiates equally well in all directions. The 3-D radiation pattern of an isotropic source can be thought of as a perfect sphere. The RF energy is spread evenly over the entire area of the sphere, so that from any direction, the signal is equal.

Suppose that we take a round balloon, and fill it with water so that it has plenty of room for expansion. The shape of the balloon is like the radiation pattern of the isotropic point source; it is perfectly round. The total amount of water in the balloon is analogous to the *transmitted power* from the isotropic source. How does squeezing the balloon affect the amount of water inside? Since water is relatively incompressible, its volume remains constant as the balloon is compressed. If we squeeze in the center, the sides bulge out; if we try pushing in one end, the other end pops out. *The total amount of water remains the same. Only its distribution is changed.*

The same thing can be said for antennas. Most antennas radiate power better in some directions, and worse in others. The three-dimensional picture of this is called the *radiation pattern* of the antenna. Since it is hard to shown 3-D patterns on the flat pages of books, manufacturers normally show a top and side graph of the antenna's pattern. The pattern for a half-wave dipole is shown in Figure 12-5.

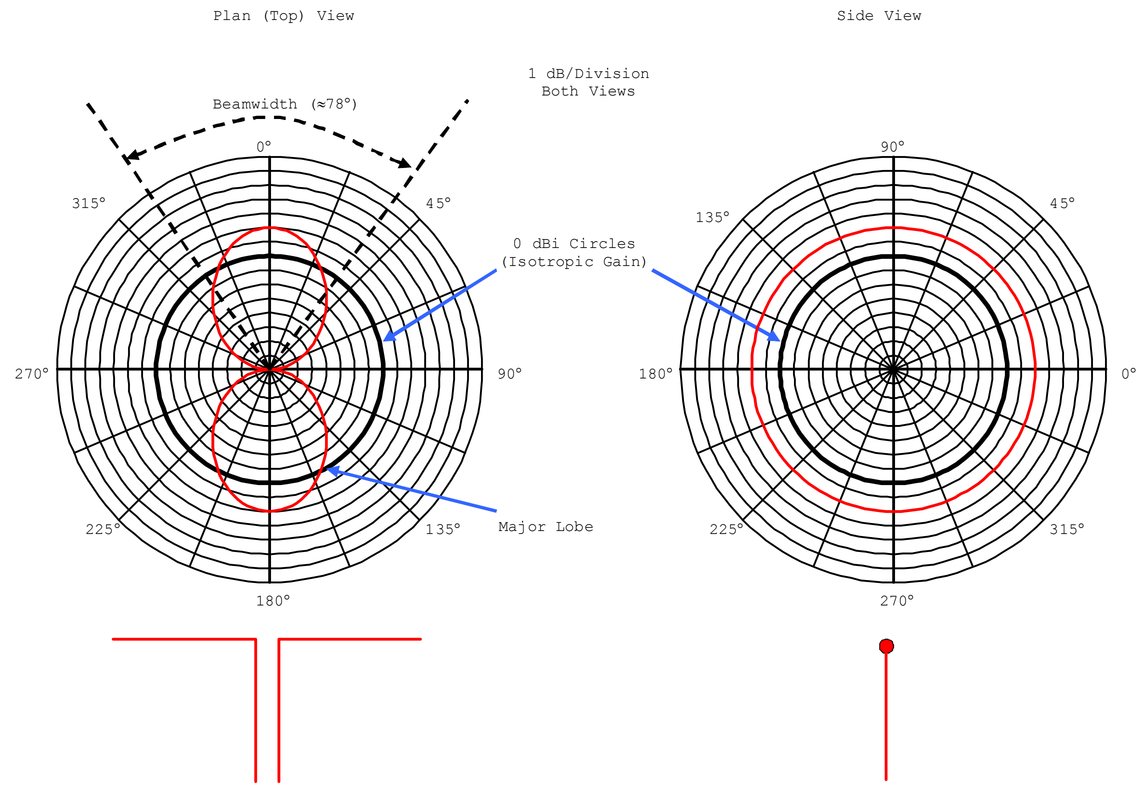

Figure 12-5: The Radiation Pattern of a Dipole Antenna

There are two ways of looking at the radiation pattern, either from the top (the plan view), or from the side. Notice that the graph of each is built out of circles, one inside another. Each circle represents a 1 dB change in field strength (power). The radial lines indicate the *angle* at which the power changes were measured. On both graphs, the bold circle in the middle represents the radiation of an *isotropic* antenna. This *must* be a circle, because an isotropic antenna radiates equally well in all directions. Therefore, we're just looking at the top and side views of a *sphere*. The units on the graphs are *dBi*, which means "decibels of gain with respect to an isotropic source." Recall that the water balloon was a sphere before we squeezed it; when we build an antenna, it usually has *directionality*. It radiates better in some directions, at the expense of radiating *worse* in others.

When we look at it from the top, the *dipole* antenna in Figure 12-5 appears to radiate best from the *sides*, at the 0 and 180 degree marks. Very little radiation comes from the ends. Physically, this is because there is very little *current* flowing near the ends of the dipole. Most of the current flows close to the feedpoint. We would say that a dipole has a gain of approximately +2 dB over an isotropic source in its best direction of radiation. In other words, the gain of a dipole is *2 dBi*. The area of strongest radiation from an antenna is called the *major lobe* of the antenna. The dipole in Figure 12-5 has two major lobes.

The radiation pattern looks quite different from the side; the dot below the right-hand plot of Figure 12-5 represents the *end* of the dipole wire. We're looking into the end of the dipole. This plot shows that the dipole radiates equally well above, below, and left, and right, as far as we can see from the end.

If we mentally put together the two plots of Figure 12-5, we get a 3-D picture of the antenna's radiation. The overall shape is a *donut* when viewed in this way.

Beamwidth

Returning to Figure 12-5, there is a definite range of angles where the antenna radiates most of its energy. The *beamwidth* of an antenna is the angle between the two -3 dB points. The -3dB is measured with respect to the maximum radiation strength in the major lobe of the antenna's pattern. A half-wave dipole has a beamwidth of approximately 78 degrees. This is *somewhat* directional, but it's not effective enough to accurately aim a radio signal at a remote location.

There is a general relationship between *beamwidth* and antenna gain: In general, the more *narrow* the beamwidth of an antenna, the *larger* the gain of the antenna will become. This is why directional antennas are desirable; a highly directional antenna usually has a high gain, and also focuses its energy over a narrow angle, which helps to eliminate interference.

What do you suppose the dipole's radiation pattern will look like if it is placed *vertically*? Just switch the left and right hand graphs of Figure 12-5, and you'll get the answer! (Note that a vertical dipole must be at least one-half wavelength off the ground, because the earth will tend to capacitively "load" the lower dipole conductor if it is too close to ground, which will increase the antenna's loss, as well as distort its radiation pattern.)

Example 12-8

Calculate the length of a 1/2 wavelength dipole for operating on a frequency of 14.150 MHz in the following ways:
a) As a raw 1/2 wavelength figure
b) Taking into account the 95% "fudge factor" for practical antenna construction.

Solution
a) A half-wavelength at this frequency is:

$$\lambda = \frac{v}{f} = \frac{3\times10^8 m/s}{14.150MHz} = 21.2m$$

So 1/2 of this wavelength is (21.2 m / 2) = <u>10.6 meters</u>

b) Because of fringing at the end of the antenna wires (a capacitive effect), a dipole antenna resonates when it is about 95% of the actual 1/2 wavelength length. The *practical* length is therefore:

L=(0.95)(10.16 m) = <u>*10.07 meters*</u>

Note: A popular formula used for a half-wavelength dipole is as follows:

$$L_{feet} = \frac{468}{f_{(MHz)}}$$

This formula returns the length of the antenna in feet, and includes the 95% "fudge factor." The antenna above calculated in this way gives:

$$L_{feet} = \frac{468}{f_{(MHz)}} = \frac{468}{14.150} = \underline{\underline{33.07ft}}$$

This is the same thing as 10.07 meters, which was obtained before.

In order to get an *omnidirectional* pattern, a dipole can be oriented vertically. An *omnidirectional* antenna radiates equally well in all directions (in the horizontal plane, looking from above). Such antennas are popular in broadcast, where a uniform area is to be covered. Using a vertical dipole at the low frequencies of AM broadcast creates a problem, as the next example will demonstrate.

Example 12-9

Calculate the length of a half-wavelength dipole for operating on a frequency of 810 kHz, giving the answer in feet. Give construction details for the device.

Solution
The shorthand formula works best here:

$$L_{feet} = \frac{468}{f_{(MHz)}} = \frac{468}{0.810} = \underline{\underline{577.7\,ft}}$$

This is quite a large antenna! And there's another problem: We can't let the bottom conductor of a vertical dipole get close to the earth, or the earth will capacitively "short out" the dipole's signal. Generally, the bottom of the dipole will be either 1/2λ or 1λ above ground. This is going to be one very tall tower!

This is a good example of why a different antenna, the *Marconi* antenna, is used for AM broadcasting.

The Marconi Antenna

A Marconi antenna is pictured in Figure 12-6. It’s really nothing more than a one-quarter length radiator placed vertically over the earth. The Marconi antenna is fed from the ground, and has a theoretical input impedance of half of a dipole (over perfectly conducting ground), which is about (36.5 + j21.5). When it is shortened 5% (like the dipole), the input impedance becomes approximately 34 Ω.