CHAPTER

2

Radio Frequency and Antenna Fundamentals

CWNA Exam Objectives Covered:

- ❖ Define and explain the basic concepts of RF behavior
  - Gain and Loss
  - Reflection, Refraction, Diffraction, Scattering, and Absorption
  - VSWR
  - Return Loss
  - Amplification and Attenuation
  - Wave Propagation, Free Space Path Loss, and Delay Spread
- ❖ Understand and apply the basic components of RF mathematics
  - Watts and Milliwatts
  - Decibel (dB), dBm, dBi, and dBd
  - SNR and RSSI
  - System Operating Margin (SOM), Fade Margin, and Link Budget
  - Intentional Radiators and EIRP

In This Chapter

CWNA Exam Objectives Covered:

- ❖ Identify RF signal characteristics, the applications of basic RF antenna concepts, and the implementation of solutions that require RF antennas
  - Visual and RF LOS
  - The Fresnel Zone
  - Beamwidth, Azimuth, and Elevation
  - Passive Gain
  - Isotropic Radiators
  - Polarization and Antenna Diversity
  - Wavelength, Frequency, Amplitude, and Phase
- ❖ Explain the applications of basic RF antenna and antenna system types and identify their basic attributes, purpose, and function
  - Omnidirectional, Semidirectional, Highly Directional, and Sectorized Antennas
  - Multiple-Input, Multiple-Output (MIMO) Antenna Systems

Wireless communications must utilize one of two primary media: sound waves or electromagnetic (EM) waves. When one human speaks to another human, the sound waves travel through the air and are interpreted by the receiving human's ears. These sound waves form the most ancient kind of wireless communications. However, sound waves do not provide an effective form of wireless communications over great distances because of the tremendous interference in the sound wave spectrums (frequency ranges) and the massive amounts of power required to send a sound wave over those great distances. Electromagnetic waves, on the other hand, offer a very effective means of wireless communications due to the very structured way the frequencies can be divided and the low amounts of power required to communicate across a vast expanse.

In this chapter, you will first learn about electromagnetic waves and how they can be used for wireless communications. You will then move on to the specific electromagnetic waves that are used within IEEE 802.11–based networks, specifically radio frequency (RF) waves. Next, you will discover the calculations that you can make against RF waves using RF math, and finally, you'll learn about antennas, including both the types of antennas and their functionality.

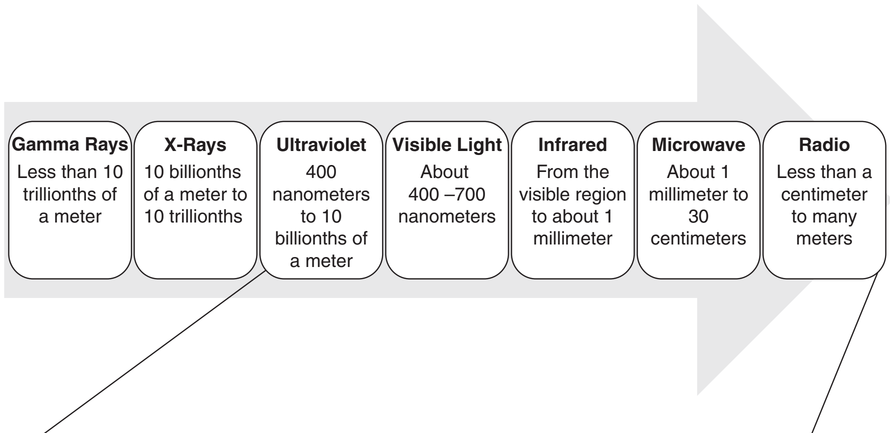
Electromagnetic Waves: A Quick Tour

Simply defined, an *electromagnetic wave* is a fluctuation of energy consisting of electric and magnetic fields. The electric and magnetic fields oscillate or move back and forth at right angles to each other, and the wave moves out from the propagating antenna in a direction related to the shape of the antenna, which you will learn about later. Electromagnetic waves and their uses have been discovered over a lengthy period of time and have required the joint efforts of many dedicated researchers, engineers, and scientists.

History of Electromagnetic Waves

The focus of this book is not on the detailed physics of electromagnetism but is aimed at a higher level of understanding. That higher level is a specific use of electromagnetism: radio waves. There are many good resources that detail the history of wireless communications using electromagnetic waves, including *History of Wireless* by Tapan K. Sarkar et al. (IEEE Press, 2006) and *Energy, Force, and Matter* by P.M. Harman (Cambridge University Press, 2005). However, a quick reminder of how

FIGURE 2.1 Electromagnetic spectrum with wavelengths and example uses



Ultraviolet	Fiber optics, etc.
Infrared	IrDA, remote controls, etc.
Microwave	IEEE 802.11, IEEE 802.16, etc.
Radio	AM radio, twisted pair cabling, etc.

electromagnetic waves have been used will be beneficial and is covered in the next section. Figure 2.1 shows the electromagnetic spectrum and where radio and microwave electromagnetic waves fall.

Early Radio Technologies

Electromagnetic wave–based communications have been utilized for many decades. In fact, radio and television both depend on these electromagnetic waves. Additionally, these electromagnetic waves—or *radio waves*—have been used for purposes such as wireless voice conversations (today, we call these cell phones) and data communications. The military has used wireless communications for many decades, and expensive proprietary equipment has also been available.

You could say that wireless communications over great distance all started with the letter *S*. It was this letter that Guglielmo Marconi transmitted, received, and printed with the Morse inker across the Atlantic in the first decade of the twentieth century. Though Marconi was not the first to communicate over a distance without wires, this event started a greater stirring through the government and business communities that resulted in the many uses of wireless technology we see today.

By the 1920s, radio waves were being used for telecommunications. In fact, the first transatlantic telephone service became available in 1927 from New York to London. Twenty-one years earlier, in 1906, Reginald Fessenden successfully communicated from land to sea over a distance of 11 miles using radio waves to carry voice communications. Bell Laboratories had created a mobile two-way voice-carrying radio wave device by 1924, but mobile voice technology was not really perfected and used widely until the 1940s.

If you are familiar with modems, you are aware that computer data can be transferred over land-based telephone lines using these devices. A modem modulates the binary data into analog signals and demodulates the analog signals into binary data. This allows two computers to talk to each other across these land lines. As you can imagine, the leap to communicating digital data across wireless connections is not a large leap. From the early use of radio technology for broadcasting (radio and television) and voice communications to today's massive data transfer over wireless links, radio wave communications have evolved rapidly.

One of the greatest problems with these early technologies was the proprietary nature of the devices. Just like humans, in order for two devices to communicate with each other, they must share a language. Without standards, each company would create devices that communicated either in ways they thought were best or simply in the only ways their engineers knew how to implement. This resulted in incompatibilities among the different devices. Organizations such as the IEEE, IETF, and ANSI have developed many standards that have helped overcome this hurdle. When it comes to wireless data communications in local area networks (LANs), the IEEE 802.11 standard is the one that started it all.

Fundamentals of Electromagnetic Waves

You will not have to know a great deal about the physics behind electromagnetic waves to pass the CWNA exam or to implement enterprise-class wireless networks. I do, however, hope this overview gives you a desire to learn more. This summary of the fundamentals will also help you to better understand the section "RF Behavior" later in this chapter.

For more information on electromagnetic waves, I suggest the books *How Radio Signals Work* by Jim Sinclair and *Physics Demystified* by Stan Gibilisco. Both books are published by McGraw-Hill (1998 and 2002, respectively).

Waves

The first thing I want to define is a wave. A *wave,* in the realm of physics, can be defined as a motion through matter. Notice I did not say that the wave is a movement of matter, but it is a motion—such as oscillation—through matter or space. Think of the waves in the ocean bobbing up and down. Now imagine a ball placed on top of the waves. The waves pass by and the ball bobs up and down as they pass by, but the ball does not travel with the waves. If you were to investigate even more closely, you would see that the water does not travel with the waves either, but the waves pass through the matter (water).

An electromagnetic wave is an oscillation traveling through space. In the early days of electromagnetic wave study, some thought an invisible medium existed through which the waves traveled. This invisible medium was called the ether. You may recognize this term as it is used today in the word Ethernet, paying homage to this earlier thinking. In fact, electromagnetic waves can travel in a vacuum where all matter has been removed, and because of this, we theorize that they need no material medium to travel. How then do they propagate through space? It is through an interesting relationship, though not fully understood, between electric and magnetic fields.

Electric Fields

An *electric field* is the distribution in space of the strength and direction of forces that would be exerted on an electric charge at any point in that space, according to the *American Heritage Science Dictionary.* In other words, the electric field is the space within which an electrically charged object will feel a pull or a push, depending on whether the charge on the object is unlike (pull) or like (push) that of the pulling or pushing source. Positively charged objects attract negatively charged objects, and negatively charged objects attract positively charged objects. The measurable strength of this attraction is greater when the objects are closer together and lesser when they are farther apart. The electric field represents the space within which this attraction can be detected, although theoretically, the attraction extends infinitely, though it cannot be measured.

Electric fields result from other electric charges or from changing magnetic fields. *Electric field strength* is a measurement of the strength of an electric field at a given point in space and is equal to the force induced on a unit of electric charge at that point.

Magnetic Fields

A *magnetic field* is a force produced by a moving electric charge that exists around a magnet or in free space. Magnetic fields extend out from the attracting center, and the space in which it can affect objects is considered the extent of the magnetic field. A changing magnetic field generates an electric field.

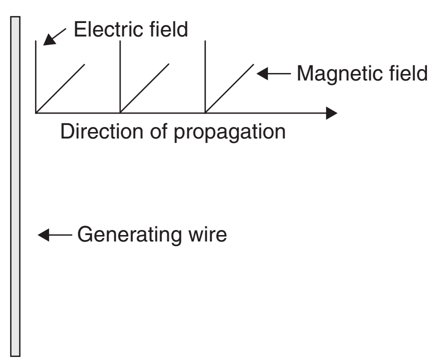
Electromagnetic Waves

Now that you have definitions of electric fields and magnetic fields, you are ready to investigate electromagnetic waves. An electromagnetic wave is a propagating combination of electric and magnetic fields. Remember that a magnetic field can generate an electric field and an electric field can generate a magnetic field. While the analogy is not perfect, consider that a chicken creates an egg that creates a chicken that creates an egg ad infinitum. The alternating current (AC) in the antenna generates a magnetic field around the antenna that generates an electric field that generates a magnetic field ad infinitum.

The electric and magnetic fields are oscillating perpendicular to each other, and they are both perpendicular to the direction of propagation, as is shown in Figure 2.2. You can see that the electric field is parallel to the generating wire (antenna) and the magnetic field is perpendicular to the generating wire. The wave is traveling out from the generating wire.

A very specific form (wavelength and frequency) of these electromagnetic waves is used to communicate wirelessly in IEEE 802.11 networks. This form of wave is a radio frequency wave, often shortened to RF wave. An RF-based system, then, is a system that relies on the phenomenon of electromagnetic wave theory to provide data and voice communications wirelessly.

FIGURE 2.2 Electromagnetic wave propagation direction



RF Characteristics

All RF waves have characteristics that vary to define the wave. Some of these properties can be modified to modulate information onto the wave. These properties are *wavelength, frequency, amplitude,* and *phase.*

Wavelength

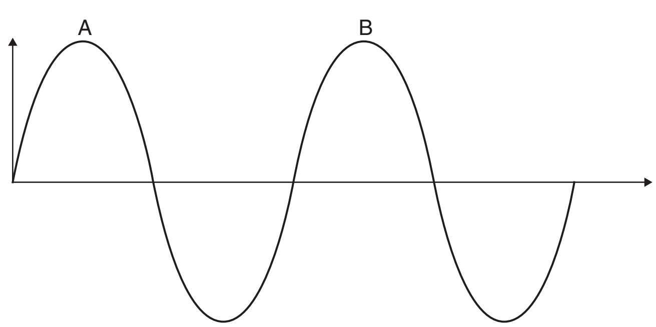
The *wavelength* of an RF wave is calculated as the distance between two adjacent identical points on the wave. For example, Figure 2.3 shows a standard sine wave. Point A and Point B mark two identical points on the wave, and the distance between them is defined as the wavelength. The wavelength is frequently measured as the distance from one crest of the wave to the next.

The wavelength is an important measure of which you should be aware. The wavelength dictates the optimum size of the receiving antenna, and it determines how the RF wave will interact with its environment. For example, an RF wave will react differently when it strikes an object that is large in comparison to the wavelength from when it strikes an object that is small in comparison to the wavelength.

You will learn about frequency next, but it is important you understand that the wavelength and the frequency are interrelated. In fact for a given medium, if you know the wavelength, you can calculate the frequency and if you know the frequency, you can calculate the wavelength.

One of the great discoveries in the history of electromagnetism is that electromagnetic waves travel at the speed of light. Since we know the speed of light to be 299,792,458 meters per second, we also know that this

FIGURE 2.3 Wavelength measurement



is the speed at which electromagnetic waves travel in a vacuum. This was theorized by James Clerk Maxwell and proved through experimentation by Heinrich Hertz.

> You are probably familiar with measurements like 100 megahertz and 3.6 gigahertz. These measurements refer to the number of cycles per second. When we say that the access point is using the 2.45 gigahertz spectrum, we say it is using the spectrum that uses a wave cycle rate of 2,450,000,000 times per second. This measurement is named after Heinrich Hertz and his research in electricity and magnetism. A kilohertz is 1000 hertz or cycles per second. A megahertz is 1,000,000 hertz, and a gigahertz is 1,000,000,000 hertz. A terahertz is one trillion hertz, but these frequencies are not commonly found in today's wireless communications.

Since we know that RF waves travel at the speed of light, we can calculate the frequency when we know the wavelength or the wavelength when we know the frequency. The following formula can be used to calculate the wavelength in meters when the frequency is known:

$$w = 299{,}792{,}458/f$$

Here, w is the wavelength in meters and f is the frequency in *hertz* and the medium is a vacuum. Therefore, the 2.45 GHz spectrum would have a wavelength that is calculated with the following formula:

$$w = 299{,}792{,}458/2{,}450{,}000{,}000$$

The result is 0.123 meters or approximately 12.3 centimeters. This translates to about 4.8 inches. To calculate inches from centimeters, just multiply the number of centimeters by 0.3937. The formal character used to represent a wavelength is the Greek lambda (λ), and the symbol for the speed of light is c. Therefore, the formal representation of the previous formula would be

$$\lambda = c/f$$

The calculation for frequency is just the opposite. You will divide the speed of light by the wavelength in meters to discover the frequency. Keep in mind that the numbers we've been using have been rounded and that impacts the results of the following formula; however, the results are close enough to recognize that a wavelength of 0.123 meters would indicate an RF wave in the 2.45 GHz spectrum:

$$f = 299{,}792{,}458/.123$$

$$f = 2437337056.91$$

Due to the complex number that is the speed of light, this number is often rounded to 300 billion meters per second. While this will change formula results, the findings are close enough for understanding the behavior of RF waves; however, engineers developing RF systems must use more precise measurements. Additionally, formulas like the following simplify matters:

$$\text{Wavelength in inches } (\lambda) = 11.811/f \text{ (in GHz)}$$

$$\text{Wavelength in centimeters } (\lambda) = 20/f \text{ (in GHz)}$$

Because wireless networks use such high frequency ranges, formulas like this make the calculations easier.

While I provide formulas like this, for your reference and use as a WLAN administrator, you will not see these formulas on the CWNA exam. However, my goal is to help you fully understand wireless networking as you journey toward your CWNA certification. For this reason, I will frequently go deeper than the exam requires. I will also point these areas out to you so that you will not have to spend time memorizing facts that you can always reference in this book as you go about your administration tasks.

Frequency

Frequency refers to the number of wave cycles that occur in a given window of time. Usually measured in second intervals, a frequency of 1 kilohertz (KHz) would represent 1000 cycles of the wave in 1 second. To remember this, just keep in mind that a wave cycles frequently and just how frequently it cycles determines its frequency.

Since all electromagnetic waves, including radio waves, move at the speed of light, the frequency is related to the wavelength. In other words, we observe that wavelength, frequency, and medium are interdependent. Higher frequencies have shorter wavelengths, and lower frequencies have longer wavelengths.

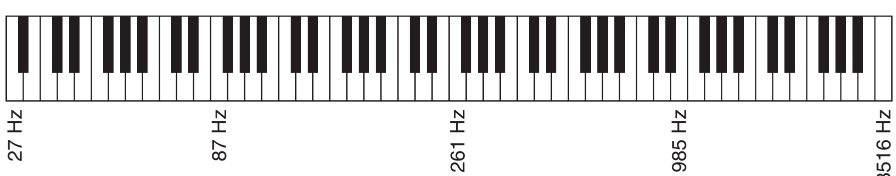
The concept of frequency is used in sound engineering as well as RF engineering. Figure 2.4 shows a piano keyboard and the sound frequencies to which the keys are traditionally tuned. Knowing this can help establish your understanding of frequencies in RF communications; however, you must be clear in your thinking about the differences between sound waves and electromagnetic waves. The two wave types are not the same phenomenon, but they share similar characteristics. Since most people are already somewhat familiar with the behavior of sound waves through life experience, they make a good analogy as a starting point for your understanding of electromagnetic waves.

Remember that an analogy is nothing more than a comparison of the similarities of two different things or concepts. For this reason, you must hold in mind the fact that sound waves are not exactly the same as electromagnetic waves, but that they have similarities that can be used for progressive learning.

With sound waves, the right string that is tightened to the right tension will emit a sound of the appropriate frequency. Sound waves travel much more slowly than electromagnetic waves, at a rate of approximately 344 meters per second or 1100 feet per second through the air. In other words, if you are standing 100 feet (30.5 meters) from the source of the sound, it will take that sound approximately 1/10 of a second to reach you, but that sound's wavelength and frequency cannot be known from this alone.

Looking again at the piano keyboard in Figure 2.4, you can see that Middle C has a frequency of 261 Hz. From this, the wavelength can be calculated by dividing 344 meters by 261 Hz for a wavelength of 1.32 meters or 4.33 feet. In effect, we are saying that there are 261 waves generated in a second and, in any given second, each existing wave travels 344 meters. Now, it is important to note that the lower frequencies still travel at a rate of 344 meters per second; however, there are fewer—though longer—waves in each second. Just like RF waves, lower-frequency sound waves can be

FIGURE 2.4 Sound frequencies on a piano keyboard



perceived at a greater distance due to the mechanism known as the human ear. To show that the other sound waves still exist at the greater distance, you can use an amplifier like that commonly seen along the sidelines at American football games. This device has a larger "receive" space than the human ear, so it is able to "pick up" sound waves that would otherwise be missed.

The impact of frequency usage on wireless local area networks (WLANs) is tremendous. By using different frequencies, you can enable distinct connections or RF links in a given coverage area or cell. For example, an IEEE 802.11g network using channel 1 can exist in the same cell as an IEEE 802.11g network using channel 11. This is because these channels use different frequencies that do not cancel or interfere with each other.

Think of it like a beautiful orchestra. There are many instruments playing on many different frequencies, but together they make wonderful music. Now, consider the sound you get when you walk up to a piano and press the palm of your hand down on six or seven keys simultaneously. Few people call that pleasant music. The sound frequencies are so close together that they just sound like noise. In a similar way, overlapping RF waves will be very difficult, if not impossible, to distinguish from one another. However, consider the melodious sound of the C major chord or the D minor chord. In the same way, multiple IEEE 802.11g networks can work side by side when they are configured to channels 1, 6, and 11 in a cell.

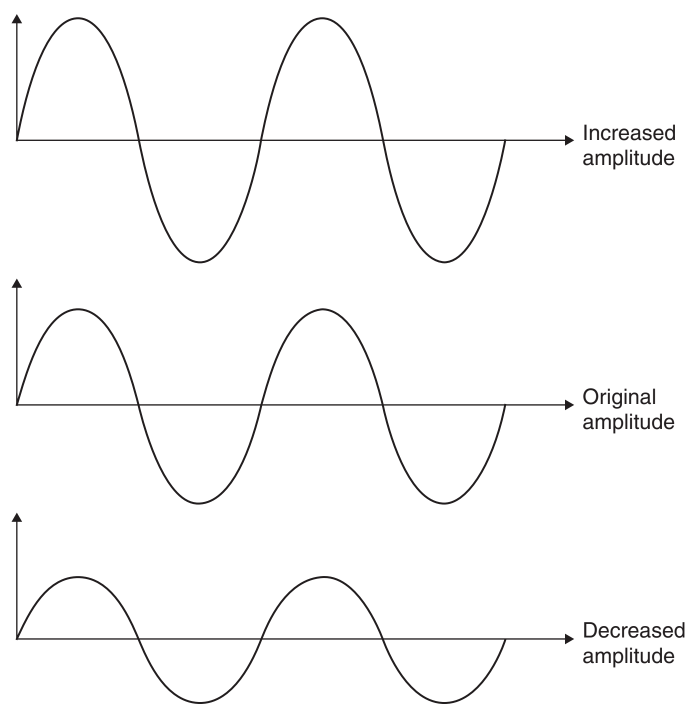
Amplitude

Given the explanation in the preceding section, you might be tempted to think that the volume of sound waves is dependent on the frequency, since lower-frequency waves are heard at a greater distance; however, there is actually another characteristic of waves that impacts the volume. Remember, at greater distances, shorter-wavelength waves are more difficult to detect as the waveform spreads ever wider (though this may be more a factor of the antenna used than of the waveform itself). The characteristic that defines the volume is known as *amplitude.* In sound wave engineering, an increase in amplitude is equivalent to an increase in volume; hence, an amplifier adds to the volume, or makes the sound louder. While the frequency affects the distance a sound wave can travel, the amplitude affects the ability to detect (hear) the sound wave at that distance. RF waves are similar.

An RF wave with greater amplitude is easier to detect than an RF wave with lesser amplitude, assuming all other factors are equal. In other words, in a vacuum, an RF wave will be said to have better quality at a distance if it has greater amplitude. Realize that RF waves travel, theoretically, forever. This being the case, the detectability of the wave is greater at certain distances when the wave starts with a greater amplitude. A wave with a lesser amplitude may not be detectable due to the noise floor. The *noise floor* can be defined as a measure of the level of background noise. In other words, there is a point in space where an RF wave still exists, but it cannot be distinguished from the electromagnetic noise in the environment.

In effect, both the high-amplitude and low-amplitude waves exist at that point, but only the high-amplitude wave can be detected. This means that both waves have traveled the distance, but only the high-amplitude wave is useful. For this reason, in common usage, engineers often say that an increase in amplitude will extend the range of the RF wave. What is meant by this is that the RF wave's useful range has been extended. Figure 2.5 shows an RF signal with original, increased, and decreased amplitudes.

FIGURE 2.5 RF waves at different amplitudes



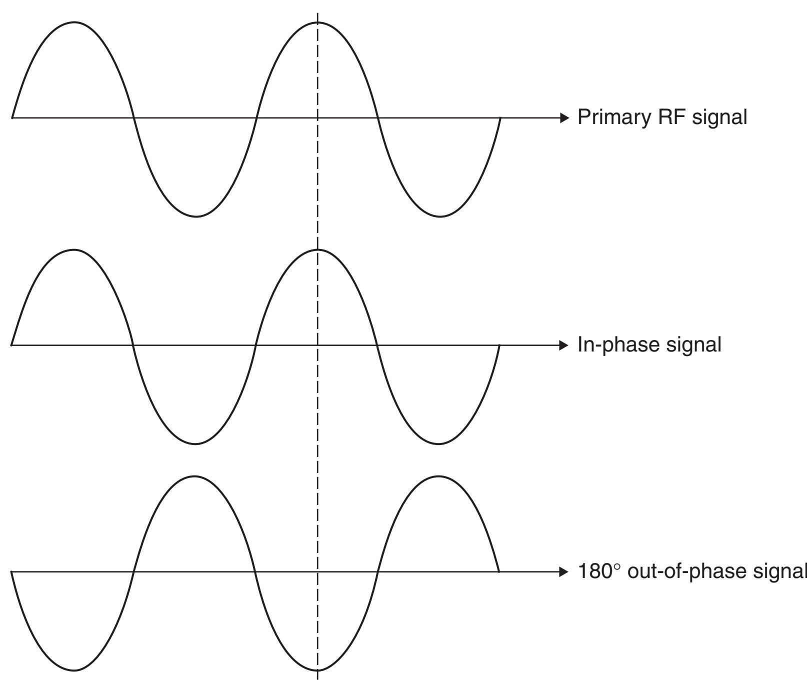
Phase

Unlike wavelength, frequency, and amplitude, *phase* is not a characteristic of a single RF wave but is instead a comparison between two RF waves. If two copies of the same RF wave arrive at a receiving antenna at the same time, their phase state will impact how the composite wave is able to be used. When the waves are in phase, they strengthen each other, and when the waves are out of phase, they sometimes strengthen and sometimes cancel each other. In specific out-of-phase cases, they only cancel each other.

Phase is measured in degrees, though real-world analysis usually benefits only from the knowledge of whether the waves are in phase or out of phase. Two waves that are completely out of phase would be 180 degrees out of phase, while two waves that are completely in phase would be 0 degrees out of phase. Figure 2.6 shows a main wave signal, another in-phase signal, and an out-of-phase signal.

Phase is used for many modern RF modulation algorithms, as you will learn in Chapter 3. When troubleshooting wireless networks, the phase of duplicate RF signals is mostly an implication of reflection or scattering in an area that may cause dead zones due to the out-of-phase signals.

FIGURE 2.6 RF wave phases



RF Behavior

RF waves that have been modulated to contain information are called *RF signals.* These RF signals have behaviors that can be predicted and detected. They become stronger, and they become weaker. They react to different materials differently, and they can interfere with other signals. The following sections introduce you to the major RF signal behaviors and their implications, including

- Gain
- Loss
- Reflection
- Refraction
- Diffraction
- Scattering
- Absorption
- VSWR
- Return Loss
- Amplification and Attenuation
- Wave Propagation
- Free Space Path Loss
- Delay Spread

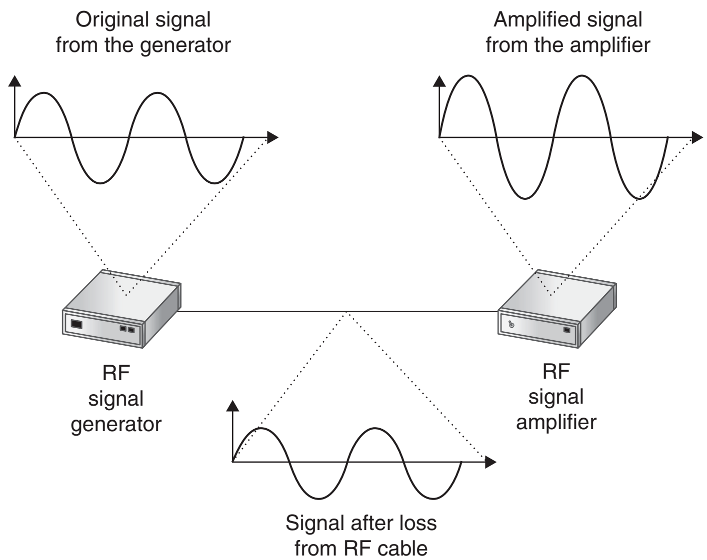
Gain

Gain is defined as *the positive relative amplitude difference between two RF wave signals* (hereinafter known as only RF signals). *Amplification* is an active process used to increase an RF signal's amplitude and, therefore, results in gain. There are two basic types of gain: *active* and *passive.* Both types can be intentional, and passive gain can also be unintentional. Figure 2.7 shows an example of a signal that demonstrates both gain and loss.

Active Gain

Active gain is achieved by placing an amplifier in-line between the RF signal generator (such as an access point) and the propagating antenna. These amplifiers, covered in more detail in Chapter 7, usually measure

FIGURE 2.7 RF signal amplitude gain and loss



the gain they provide in decibel (dB). For example, an amplifier may provide 6 dB of gain to the incoming RF signal. To determine the actual power of the signal after passing through the amplifier, you will have to know the original power of the signal from the RF generator and then perform the appropriate RF math as discussed in the "Basic RF Math" section later in this chapter.

When using any type of intentional gain, you must be careful not to exceed the legal output constraints within your regulatory domain. For example, the FCC in the United States limits the output power at the intentional radiator to 1 watt and at the antenna to 4 watts for point-to-multipoint (PtMP) applications in the unlicensed 2.4 GHz ISM band.

While the concept of the intentional radiator is covered in greater depth later in this chapter, it is mentioned periodically throughout the chapter. For now, consider the following definition: The intentional radiator is the point in the radio system where the system is connected to the antenna. In other words, there are restrictions on the output power at the point where the system connects to the antenna, and then there are restrictions on the output power of the antenna after passive gain.

Passive Gain

Passive gain is not an actual increase in the amplitude of the signal delivered to the intentional radiator, but it is an increase in the amplitude of the signal, in a favored direction, by focusing or directing the output power. Passive gain can be either intentional or unintentional.

Intentional Passive Gain Intentional passive gain is like cupping your hands around your mouth as you yell to someone at a distance. You are directing the sound waves, intentionally, toward that targeted location. You are not increasing your ability to yell louder. If you yell at your loudest without cupped hands, it will not be as detectable at a greater distance as it would with cupped hands. This is intentional passive gain. To experience this, read this paragraph out loud. As you are reading, cup your hands around your mouth and notice how the sound changes (becomes muffled and seems to change tonality). This is because more of the sound waves are traveling out from you and your ears detect the difference. Of course, anyone else in the room with you can tell a difference as well, and they might even think you're a little strange—so be sure you are alone when you perform this test.

Antennas are used to provide intentional passive gain in wireless networks using RF signals. The antenna propagates more of the RF signal's energy in a desired direction than in other directions. The RF signal is said to have gain in that direction. You'll understand this more fully once you've read the section "Isotropic Radiator" later in this chapter.

Unintentional Passive Gain Unintentional passive gain happens because of reflection and scattering in a coverage area. When the RF signal leaves the transmitting antenna, the primary signal travels out from the antenna according to the propagation patterns for which the antenna is designed. However, this signal may encounter objects that cause reflection and scattering, resulting in multiple copies of the same signal arriving at the receiving antenna. If these signals arrive in phase, they can cause the signal strength to actually increase and this would be a form of unintentional passive gain; however, some RF engineers doubt that RF energy, once scattered, is ever joined with other signal paths to produce passive gain of any measurable value.

Loss

Loss is defined as *the negative relative amplitude difference between two RF signals.* Like gain, loss can be either intentional or unintentional (referenced as natural in this section).

Intentional

Due to FCC regulations and the regulations of other regulatory domains, you will have to ensure that the output powers of your wireless devices are within specified constraints. Depending on the radios, amplifiers, cables, and antennas you are using, you may have to intentionally cause loss in the RF signal. This means that you are reducing the RF signal's amplitude, and this is accomplished with an attenuator. Attenuation, the process that causes loss, is discussed in greater detail in the later section "Attenuation."

Natural

In addition to the intentional loss that is imposed on an RF signal to comply with regulatory demands, natural or unintentional losses can occur. This kind of loss happens because of the natural process of RF propagation, which involves spreading, reflection, refraction, scattering, diffraction, and absorption.

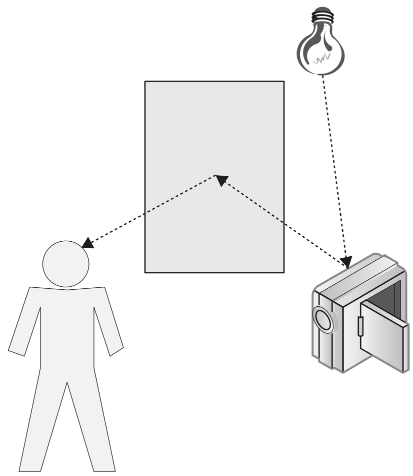
Reflection

When an RF signal bounces off of a smooth, nonabsorptive surface, changing the direction of the signal, it is said to *reflect* and the process is known as *reflection.* This is probably the easiest RF behavior to understand simply because we see it frequently in our daily lives. You can shine a light on a mirror at an angle and see that it reflects off that mirror. In fact, when you look in the mirror, you are experiencing the concept of electromagnetic reflection, which is the same as RF reflection.

Figure 2.8 illustrates this concept. As you can see, the light waves, which are electromagnetic waves similar to RF signals, first reflect off the object and travel toward the mirror. Next, the light waves reflect off the mirror and travel toward your eye. Finally, your eye acts as a focusing device and brings the light waves together at the back of the eye, giving you the sense of sight. However, the important thing to note is that what you are "seeing" is the light reflected off the object into the mirror and off the mirror into your eyes.

RF signals also reflect off objects that are smooth and larger than the waves that carry the signals. Earlier it was noted that the wavelength impacts the behavior of the RF wave as it propagates through space. This is the first example of the relationship of the wavelength and the space through which the wave travels. If the space were empty, there would be no reflection, but since all space we operate in (Earth and its atmosphere)

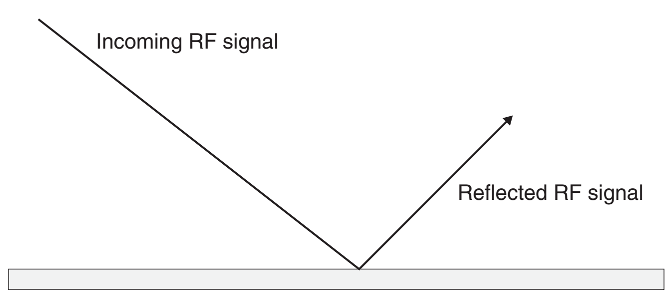
FIGURE 2.8 Illustrating reflection with a mirror



contains some elements of matter, reflection, refraction, scattering, diffraction, and absorption are expected.

Since the object that causes reflection will normally be smooth and larger than the wavelength and since waves used by IEEE 802.11–compliant radios are between 5 and 13 centimeters, it follows that the objects will be greater than 5 centimeters in size (for 5 GHz U-NII bands) or 13 centimeters in size (for the 2.4 GHz ISM band) and smooth. Such objects include metal roofs, metal or aluminum wall coverings, elevators, and other larger smooth objects. Figure 2.9 shows the traditional diagram of RF signal reflection. It is important to remember that reflected signals are usually weaker after reflection. This is because some of the RF energy is usually absorbed by the reflecting material.

FIGURE 2.9 RF signal reflection



Refraction

Refraction occurs when an RF signal changes speed and is bent while moving between media of different densities. Different mediums, such as drywall, wood, or plastic, will have different *refraction indexes.* The refraction index helps in determining how much refraction will occur.

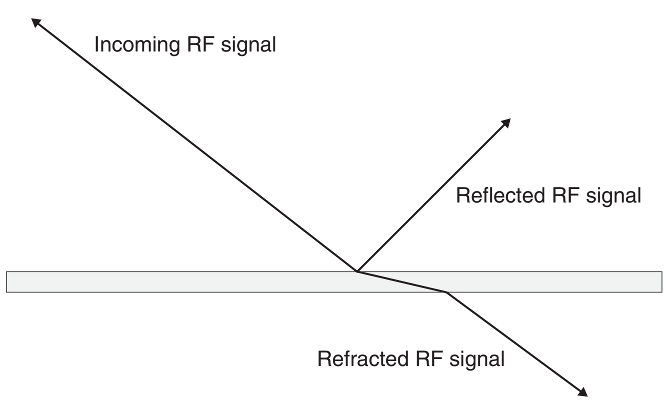
Let's go back to the light reflection analogy for a moment. If you wear glasses, you are wearing a refraction device. The lens refracts, or bends, the light to make up for the imperfect lens in your eye. This allows you to see clearly again because the lacking focus of the eye is corrected by the refraction caused on the lens of the glasses.

Figure 2.10 shows an RF signal being refracted. As you can see, when refraction occurs with RF signals, some of the signal is reflected and some is refracted as it passes through the medium. Of course, as with all mediums, some of the signal will be absorbed as well.

RF signal refraction is usually the result of a change in atmospheric conditions. For this reason, refraction is not usually an issue within a building, but it may introduce problems in wireless site-to-site links outdoors. Common causes of refraction include changes in temperature, changes in air pressure, or the existence of water vapor.

The issue here is simple: if the RF signal changes from the intended direction as it's traveling from the transmitter to the receiver, the receiver may not be able to detect and process the signal. This can result in a broken connection or in increased error rates if the refraction is temporary or sporadic due to fluctuations in the weather around the area of the link.

FIGURE 2.10 RF signal refraction

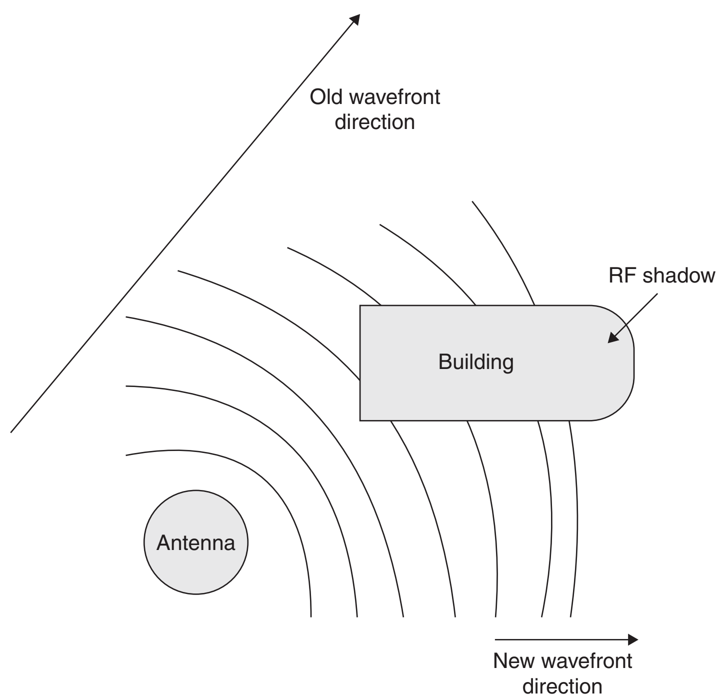


> An excellent experiment can be performed easily that demonstrates the concept of refraction. Take a large clear bowl and fill it with water. Now place a large butter knife into the water at an angle and look through the clear side of the bowl at the knife. What does the knife do? Well, nothing other than enter the water; but what does it appear to do? It appears to bend. This is because the light waves are traveling slower in the water medium and this causes refraction of the light waves. It's not the knife that's bending—because it's not the knife you actually see. It's the light that's bending—because it's the light that you actually see.

Diffraction

Diffraction is defined as a change in the direction and/or intensity of a wave as it passes by the edge of an obstacle. As seen in Figure 2.11, this can cause the signal's direction to change, and it can also result in areas of RF shadow. Instead of bending as it passes into or out of an obstacle, as in the case of refraction, light is diffracted as it travels around the obstacle.

FIGURE 2.11 RF signal diffraction



Diffraction occurs because the RF signal slows down as it encounters the obstacle and this causes the wave front to change directions. Consider the analogy of a rock dropped into a pool and the ripples it creates. Think of the ripples as analogous to RF signals. Now, imagine there is a stick being held upright in the water. When the ripples encounter the stick, they will bend around it, since they cannot pass through it. A larger stick has a greater visible impact on the ripples, and a smaller stick has a lesser impact. Diffraction is often caused by buildings, small hills, and other larger objects in the path of the propagating RF signal.

Scattering

Scattering happens when an RF signal strikes an uneven surface (a surface with inhomogeneities) causing the signal to be scattered instead of absorbed so that the resulting signals are less significant than the original signal. Another way to define scattering is to say that it is multiple reflections. Figure 2.12 illustrates this.

Scattering can happen in a minor, almost undetectable way, when an RF signal passes through a medium that contains small particles. These small particles can cause scattering. Smog is an example of such a medium. The more common and more impactful occurrence is that caused when RF signals encounter things like rocky terrain, leafy trees, or chain link fencing. Rain and dust can cause scattering as well.

Absorption

Absorption is the conversion of the RF signal energy into heat. This happens because the molecules in the medium through which the RF signal is passing cannot move fast enough to “keep up” with the RF waves.

FIGURE 2.12 RF signal scattering

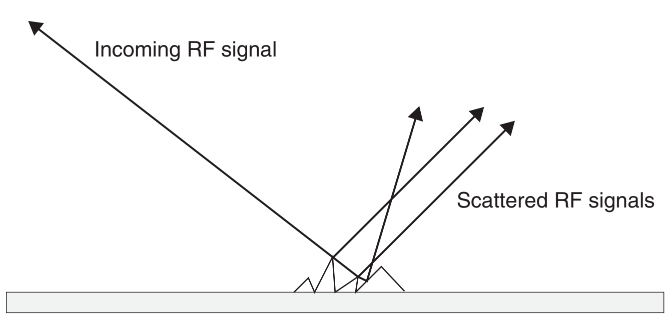
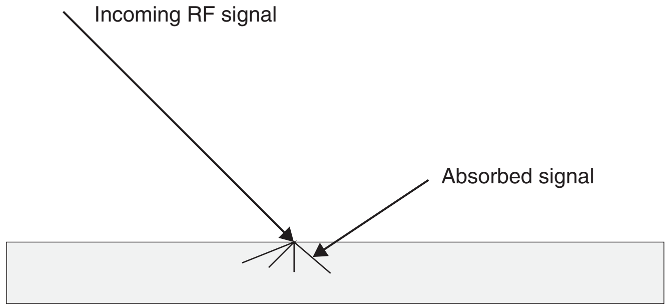


FIGURE 2.13 RF signal absorption



Many materials absorb RF signals in the 2.4 GHz ISM spectrum. These include water, drywall, wood, and even humans. Figure 2.13 shows RF signal absorption.

> Microwave ovens use the 2.45 GHz frequency range to heat food. While your WLAN devices have output power levels from 30 milliwatts to 4 watts, microwave ovens usually have an output power between 700 and 1400 watts. What does this have to do with WLAN engineering? Well, the microwave oven works because RF waves are absorbed well by materials that have moisture (molecular electric dipoles) in them. This absorption converts the RF wave energy into heat energy and therefore heats your food.
>
> If you've ever set up a wireless network in a large auditorium, only to notice that the coverage was less acceptable after the room was filled with hundreds or thousands of people, you've experienced the phenomenon of absorption at first hand. Before the people were in the room, most of the items were reflecting, refracting, scattering, or diffracting the RF signals. People tend to absorb the RF signals instead of reflecting them, causing a reduction in the available signal strength within the coverage area.

Different materials have different absorption rates. Table 2.1 provides a breakdown of some of the more common types of materials and the absorption rates associated with them. When performing a site survey or troubleshooting a communications problem, you should certainly consider the effects of these types of materials.

TABLE 2.1 RF Absorption Rates by Common Materials

Material	Absorption Rate
Plasterboard/drywall	3–5 dB
Glass wall and metal frame	6 dB
Metal door	6–10 dB
Window	3 dB
Concrete wall	6–15 dB
Block wall	4–6 dB

> Earlier, I suggested that you cup your hands in front of your mouth to see the impact this has on sound waves, and I used this as an analogy of intentional passive gain. This total output power was not increased, but it was focused in a specific direction. Let's do another experiment. Begin reading this text aloud. As you continue to read, place your hand over your mouth so that your hand completely covers it and continue reading. If you are reading this with your hand over your mouth, you're experiencing the results of absorption in relation to sound waves. The sound disturbance has great difficulty passing through your hand, and so the sound is muffled. RF signals can be absorbed by materials in a similar manner.

VSWR

Before the RF signal is radiated through space by the antenna, it exists as an alternating current (AC) within the transmission system. Within this hardware, RF signal degradation occurs. All cables, connectors, and devices have some level of inherent loss. In a properly designed system, this loss by attenuation is unavoidable. However, the situation can be even worse if all the cables and connectors do not share the same *impedance* level.

If all cables, connectors, and devices in the chain from the RF signal generator to the antenna do not have the same impedance rating, there is said to be an impedance mismatch. For example, you would not want to use cables rated at 50 ohms with connectors rated at 75 ohms. This would cause an impedance mismatch. Maximum power output and transfer can only be achieved when the impedance of all devices is exactly the same.

TABLE 2.2 VSWR Ratings

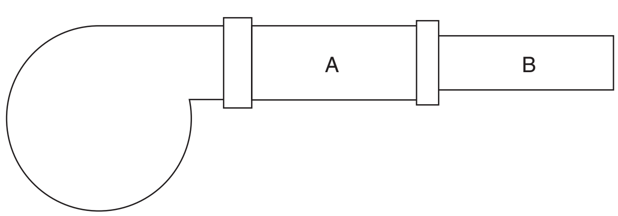
VSWR	Definition
1.0:1	One to one. Exact match. An ideal that cannot be accomplished with current technology.
1.5:1	One point five to one. Good match. Only 4 percent loss in power.
2.0:1	Two to one. Acceptable match. Approximately 11 percent loss in power.
6.0:1	Six to one. Poor match. Approximately 50 percent loss in power.
10:1	Ten to one. Unacceptable match. Most of the power is lost.
∞:1	Infinity to one. Useless to measure, as the mismatch is so great.

Voltage standing wave ratio (VSWR) is a measurement of mismatched impedance in an RF system and is stated as an X:1 (read as "X to one") ratio. Table 2.2 provides a reference for different common VSWR ratings and their meanings.

In a VSWR rating, a lower first number means a better impedance match. Therefore, 1.5:1 is better than 2.0:1. To help with your understanding, think of a series of pipes connected to a water pump as depicted in Figure 2.14. The water pump is analogous to the RF transmitter, and the pipes are analogous to the cables and connectors leading up to the antenna.

Assuming the water pump can pump water at a rate and force equal to pipe A, pipe B will cause a mismatch in impedance because it is a smaller pipe. In other words, pipe B cannot handle the amount of water at the level of pressure that pipe A and the pump can handle. This results in a buildup of pressure in pipe A and within the pump. At this point, two things can happen: the water flowing out of the end of pipe B will be less than the original potential of the water pump or the pipe A and the water

FIGURE 2.14 VSWR analogy using a water pump and pipes



pump may be destroyed in some way. Pipe A could burst, or the seals around the connectors between the water pump and pipe A and between pipe A and pipe B could leak. The water pump itself could begin leaking internally or even overheat and malfunction. As you can see, the least impacting result would be that the water flow is less than what the pump and pip A are capable of. RF systems have similar potentials as you will see in the next section on return loss.

Return Loss

When there is VSWR greater than 1.0:1 (and there always will be), there is some level of power loss due to backward reflection of the RF signal within the system. This energy that is reflected back toward the RF generator or transmitter results in *return loss*. Return loss is a measurement, usually expressed in decibels, of the ratio between the forward current (incident wave) and the reflected current (reflected wave). The results of this return loss will be similar to those in the water pump analogy presented previously. The RF transmitter may be destroyed, as may other components in the RF system, but this would be a worst-case scenario. It is most commonly seen that the output power at the intentional radiator is less than the original potential generated by the RF transmitter.

To minimize VSWR and return loss, you must avoid impedance mismatches. This means you will want to use all equipment (RF transmitters, cables, and connectors) with the same ohm rating. This rating is usually 50 ohms when considering RF systems. If you purchase an entire RF system as a unit from a manufacturer, all the components should have the same ohm rating already. If you build an RF system from scratch, you will have to take the responsibility of ensuring there is no impedance mismatch.

> When discussing VSWR, there are two extreme scenarios that create the ∞:1 value listed in Table 2.2: perfect open and perfect short. A perfect open would mean that someone forgot to connect the end of the cabling to an antenna, and a perfect short would occur if someone shorted out a perfect open with something like a paper clip (though that might hurt). In these cases most of the RF energy is reflected and the VSWR leans toward ∞:1. This, of course, should be avoided if you value your RF equipment.

Amplification

Amplification is an increase of the amplitude of an RF signal. Passive gain, as discussed earlier, is not an amplification of an RF signal up to the intentional radiator. Passive gain is a focusing or directing of an RF signal. Amplification is achieved through active gain and is accomplished with an amplifier.

Many access points contain variable power output settings, and while this capability is not technically an amplifier, these settings will impact the amplitude of the RF signal that is generated. Therefore, the changing of this setting to a higher setting results in a stronger RF signal from the access point.

> Earlier in this chapter, I mentioned that two identical signals arriving at the receiving antenna in phase increases the signal's strength. These two signals would have started as one, but due to reflection, refraction, scattering, and diffraction, they have arrived at the antenna as separate signals. The received signal is stronger than the received signal would have been, had the two signals not combined.

Attenuation

Attenuation is the process of reducing an RF signal's amplitude. This is occasionally done intentionally with attenuators to reduce a signal's strength to fall within a regulatory domain's imposed constraints. Loss is the result of attenuation, and gain is the result of amplification. RF cables, connectors, and devices may have some level of imposed attenuation, and this attenuation is usually stated in decibels and is often stated as loss in decibels per foot—this is also known as insertion loss. Insertion loss is the loss incurred by simply inserting the object (cable, connector, etc.) into the path of the RF signal between the source and the intentional radiator.

Wave Propagation

The way RF waves move through an environment is known as *wave propagation*. Attenuation occurs as RF signals propagate through an environment. When the RF signal leaves the transmitting antenna, it will begin propagation through the local environment and continue on, theoretically, forever. The signal cannot be detected after a certain distance, and this becomes the usable range of the signal. Since the signal could theoretically propagate forever, why is there a point at which it can no longer be detected? This is because attenuation occurs as the signal propagates through the environment. Some of the signal strength is lost through absorption by materials encountered by the RF signal; however, even without any materials in the path of the signal, the amplitude will be lessened. This is due to a phenomenon known as free space path loss.

Free Space Path Loss

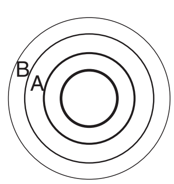
Free space path loss, sometimes called free space loss (FSL) or just path loss, is a weakening of the RF signal due to a broadening of the wave front. This broadening of the wave front is known as signal dispersion. Consider the concentric circles in Figure 2.15 as representing an RF signal propagating out from an omnidirectional antenna. Notice how the wave front becomes larger as the wave moves out from the antenna. This broadening of the wave front causes a loss in amplitude of the signal at a specified point in space.

In other words, if you place a receiving antenna at point B in Figure 2.15, you will detect a weaker signal than if you place a receiving antenna at point A. This broadening of the wave is also called beam divergence. Beam divergence can be calculated by subtracting the beam diameter (D_1) at a greater distance from the beam diameter (D_2) closer to the antenna and then dividing by the distance between these two points (L). The following formula illustrates this:

$$\text{Divergence} = (D_1 - D_2)/L$$

Free space path loss can be understood by thinking of the results you get when blowing bubbles with bubble gum. Either imagine you are blowing a bubble or actually do it. Either way, you will notice that

FIGURE 2.15 Free space path loss demonstrated



the outer shell that forms the bubble boundary becomes thinner as the bubble grows larger. Similarly, RF signals grow weaker as the cell grows larger or the distance becomes greater. The reduction in signal strength is logarithmic rather than linear. For example, a 2.4 GHz signal, such as that used by many IEEE devices, will attenuate by approximately 80 dB in the first 100 meters and then by another 6 dB in the second 100 meters. As you can see, the attenuation becomes much less in the second 100 meters than in the first, and this is due to logarithmic attenuation.

The following formulas are used to calculate free space path loss in dB:

$$LP = 36.6 + (20 \times \log_{10}(F)) + (20 \times \log_{10}(D))$$

where LP is the free space path loss, F is the frequency in MHz, and D is the path length in miles. The result is based on a distance measurement in miles. To get the results based on a distance measurement in kilometers (for example, D is the path length in kilometers), change 36.6 to 32.4, giving you the following formula:

$$LP = 32.4 + (20 \times \log_{10}(F)) + (20 \times \log_{10}(D))$$

For example, assuming you are using the 2.4 GHz ISM spectrum (we'll say 2450 MHz), and the distance you want to evaluate is 2.5 miles, the following equation will result in the free space path loss:

$$36.6 + (20 \times \log_{10}(2450)) + (20 \times \log_{10}(2.5))$$

or

$$36.6 + 67.78 + 8 = 112.38$$

The result is a loss of roughly 112 dB at 2.5 miles. I rounded the numbers in this case. More accurate numbers can be found in Table 2.3, which provides a breakdown of free space path loss attenuation in dB for different distances with both the 2.4 GHz spectrum and the 5 GHz spectrum. The next major section in this chapter, "Basic RF Math," will give you the knowledge you need to calculate an estimate of signal strength in dB after the signal travels this 2.5 miles through free space. There is an element not considered in the free space path loss calculations that will be added at that time: output power. When you know the free space path loss calculation formula and you know the output power, you can estimate the signal power, in dBm, at any point in space. This will be an ideal estimate because weather and other factors can worsen the signal strength in reality.

TABLE 2.3 Free Space Path Loss in dB for 2.4 and 5 GHz Spectrums

Distance (miles)	2.4 GHz	5 GHz
0.5	98.36	104.56
5	104.38	110.58
1.5	107.91	114.10
2	110.40	116.60
2.5	112.34	118.54
3	113.93	120.12
4	116.42	122.62
5	118.36	124.56
10	124.38	130.58

Another method that is simpler to use is the *6 dB rule*. This is an estimation method that is less accurate than the free space path loss formula we've covered, but it provides a quick calculation that is very close to the results that would be provided by the formula. If you look at the 2.4 GHz column in Table 2.3, you will see a pattern that may not stand out at first. Paying close attention to the 1, 2, and 4 mile distances, you can see that there is an increase in dB loss of approximately 6 dB at each of these intervals. You'll also notice that each of these intervals represents a doubling of the distance. Therein lies the 6 dB rule: for every doubling of distance, there is an amplitude loss of approximately 6 dB. Even in the 5 GHz column, you can see that this is true. Though the 5 GHz frequencies attenuate more quickly in the first mile, they follow the 6 dB rule thereafter.

> While the general understanding of free space path loss is usually stated as seen here, it is equally valid to consider a different perspective. This alternate perspective states that the RF signal still travels the farther distance, but that the higher frequencies have shorter wavelengths and therefore shorter optimum antenna sizes. The result is that the smaller antenna has a greater difficulty gathering–sufficient RF energy because of its smaller receiving surface. Think of it like the small receiving surface of the human ear compared to the listening devices used on American football sidelines mentioned earlier. In other words, the argument is that the RF signal may not be attenuating any "faster" but that it attenuated the same and the receiver is the actual locus of the problem rather than the attenuated signal strength.

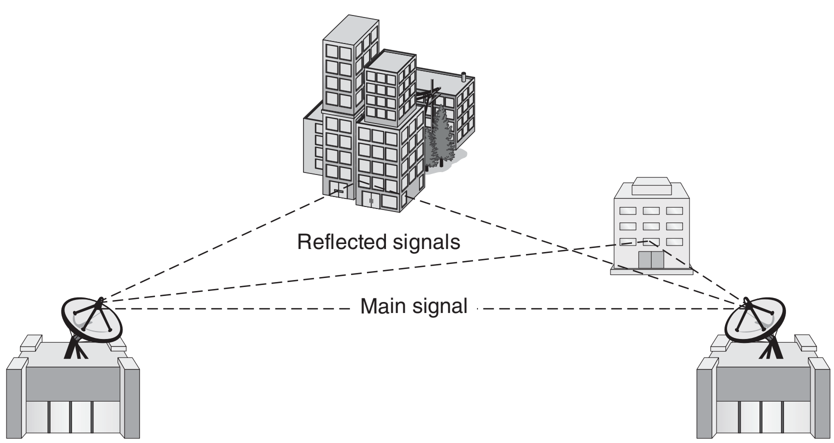
Multipath and Delay Spread

When signals bounce around in an environment through reflection, refraction, diffraction, and scattering, they create an effect known as multipath. *Multipath* occurs when multiple paths of the signal, understood as multiple signals, arrive at the receiving antenna at the same time or within a small fraction of a second (nanoseconds) of each other. Multipath can also occur outdoors when signals reflect off of large objects in the RF link path, as is shown in Figure 2.16.

Multipath occurs very frequently indoors and is so common an occurrence that many access point vendors include multiple antennas for dealing with this phenomenon. Figure 2.16 suggests the potential for multipath indoors. As you can see, file cabinets, walls, desks, and doors—among other things—can cause RF propagation patterns that result in multiple paths arriving at the receiving antenna. In an indoor environment, there is often no direct signal path between the transmitter and the receiver (or the access point and the client station). This means that all signals reaching the client station will have arrived via the RF propagation patterns similar to those in Figure 2.16. Therefore, multipath can become an issue.

The difference in time between the first and second signals arriving at the receiver in a multipath occurrence is known as the *delay spread.* Earlier in this chapter, you learned that signals can be in phase or out of phase. These signals arriving at the receiver with a delay spread of nearly 0 will complement each other and cause signal upfade. In other

FIGURE 2.16 Outdoor multipath



words, the received signal will be stronger at the receiver than it would have been without the multipath occurrence. When the delay spread is greater, so that the signals arrive out of phase, the signal will either be downfaded, corrupted, or nullified. This will be discussed more in Chapter 12.

Basic RF Math

You might be wondering why you have to learn math to implement a network. After all, you've been able to implement wired networks for years with very little math other than counting the number of Ethernet ports needed for your users. Wireless is different. Because the wireless network uses an RF signal, you must understand the basics of RF math in order to determine if the output power of an RF transmitter is strong enough to get a detectable and usable signal to the RF receiver. You had to deal with similar issues with cabling in that you could only use a CAT 5 cable of a particular maximum length, but you didn't really have to calculate anything most of the time. You simply knew you could not span a greater distance than that which was supported by the cabling type.

In order to understand and perform RF math, there are a few basic things you will need to know. First, you'll need to understand the units of power that are measured in RF systems. Second, you'll need to understand how to measure power gains and losses. Third, and finally, you'll need to understand how to determine the output power you will need at a transmitter in order to get an acceptable signal to a receiver. This is true if you are creating a point-to-point connection using wireless bridges or if you are installing an access point in an access role. In both cases, a sufficient signal must reach the receiver listening on the other end of the connection.

Watt

The *watt* (W) is a basic unit of power equal to one joule per second. It is named after James Watt, an eighteenth-century Scottish inventor who also improved the steam engine, among other endeavors. This single watt is equal to one ampere of current flowing at one volt. Think of a water hose with a spray nozzle attached. You can adjust the spray nozzle to allow for different rates of flow. This flow rate is like the amperes in an electrical system. Now, the water hose also has a certain level of water pressure—regardless of the amount that is actually being allowed to flow through the nozzle. This pressure is like the voltage in an electrical system. If you apply more pressure or you allow more flow with the same pressure, either way, you will end up with more water flowing out of the nozzle. In the same way, increased voltages or increased amperes will result in increased wattage, since the watt is the combination of the amperes and volts.

Milliwatt

WLANs do not need a tremendous amount of power to transmit a signal over an acceptable distance. For example, you can see a 7-watt light bulb from more than 50 miles (83 kilometers) away on a clear night with line of sight. Remember, visible light is another portion of the same electromagnetic spectrum, and so this gives you an idea of just how far an electromagnetic signal can be detected. This is why many WLAN devices use a measurement of power that is 1/1000 of a watt. This unit of power is known as a *milliwatt*. 1 W, then, would be 1000 milliwatts (mW).

Enterprise-class devices will often have output power levels of 1–100 mW, while SOHO wireless devices may only offer up to 30 mW of output power. Some wireless devices may support up to 300 mW of output power, but these are the exception to the rule. Ubiquiti Networks develops some devices, such as their 300 mW CardBus wireless adapter and the 600 mW AP-ONE wireless hotspot solution, which is basically an access point with hotspot features and functionality.

For indoor use, it is generally recommended that you transmit at power levels of no more than 100 mW. In most cases, the minimum gain that will be provided by any connected antennas is a 2 dBi gain, which you will read about later. This means that the output power would actually be approximately 160 mW in the propagation direction of this antenna. This usually provides sufficient coverage for indoor WLANs. However, outdoor WLANs may use more power if they are providing site-to-site links or are providing coverage to a large outdoor area as either a public or private hotspot. The FCC limits the total output power from the antenna to 4 W for point-to-multipoint applications in the 2.4 GHz ISM band, and this must be considered when implementing WLAN solutions.

Decibel (dB)

The *decibel* is a comparative measurement value. In other words, it is a measurement of the difference between two power levels. For example, it is common to say that a certain power level is 6 dB stronger than another power level or that it is 3 dB weaker. These statements mean that there has been 6 dB of gain and 3 dB of loss, respectively.

Because a wireless receiver can detect and process very weak signals, it is easier to refer to the received signal strength in dBm rather than in mW. For example, a signal that is transmitted at 4 W of output power (4000 mW or 36 dBm) and experiences −63 dB of loss has a signal strength of 0.002 mW (–27 dBm). Rather than saying that the signal strength is 0.002 mW, we say that the signal strength is −27 dBm.

A decibel is 1/10 of a *bel*. You could equally say that a bel is 10 decibels. The point is that the decibel is based on the bel, which was developed by Bell Laboratories in order to calculate the power losses in telephone communications as ratios. In other words, 1 bel is a ratio of 10:1 between two power levels. Therefore, a power ratio of 200:20 is 1 bel (10:1) and 200:40 is .5 bels (5:1) and 200:10 is 2 bels (20:1). In the end, the decibel is a measurement of power that is used very frequently in RF mathematics.

You may have been asked the same question that I was asked as a child: Would you rather have $1,000,000 at the end of a month or one cent doubled in value every day for a month? Of course, the latter option is worth more than $5,000,000 by the end of the month. This is the power of exponential growth. RF signals experience exponential decay rather than growth as they travel through space. This is also called *logarithmic decay*. The result is a quickly weakening signal. This power loss is measured with decibels.

The decibel is relative where the milliwatt is absolute. The decibel is logarithmic where the milliwatt is linear. To understand this, you'll need to understand the basics of a logarithm or you'll at least need a good tool to calculate logarithms for you, such as a spreadsheet like Microsoft Excel.

A logarithm is the exponent to which the base number must be raised to reach some given value. The most common base number evaluated is the number 10, and you will often see this referenced in formulas as *log10*. For example, the logarithm or log of 100 is 2 with a base of 10. This would be written

$$\log_{10}(100) = 2$$

This is a fancy way of saying $10^2 = 100$, which is a shorthand way of saying $10 \times 10 = 100$. However, knowing the logarithm concept is very important in many RF-based math calculations, though you will not be tested on the complex formulas on the CWNA exam. You will, however, need to be able to calculate simple power level problems. So how will you deal with these problems? Using the rules of 10s and 3s. This system will usually allow you to calculate RF signal power levels without ever having to resort to logarithmic math. Here are the basic rules:

1. A gain of 3 dB magnifies the output power by two.
2. A loss of 3 dB equals one half of the output power.
3. A gain of 10 dB magnifies the output power by 10.
4. A loss of 10 dB equals one-tenth of the output power.
5. dB gains and losses are cumulative.

Now, let's evaluate what these five rules mean and the impact they have on your RF math calculations. First, 3 dB of gain doubles the output power. This means that 100 mW plus 3 dB of gain equals 200 mW of power or 30 mW plus 3 dB of gain equals 60 mW of power. The power level is always doubled for each 3 dB of gain that is added. Rule 5 states that these gains and losses are cumulative. This means that 6 dB of gain is the same as 3 dB of gain applied twice. Therefore, 100 mW of power plus 6 dB of gain equals 400 mW of power. The following examples illustrate this:

$$40 \text{ mW} + 3 \text{ dB} + 3 \text{ dB} + 3 \text{ dB} = 320 \text{ mW}$$

$$40 \text{ mW} \times 2 \times 2 \times 2 = 320 \text{ mW}$$

Both of these formulas are saying the same thing. Now consider the impact of 3 dB of loss. This halves the output power. Look at the impact on the following formula:

$$40 \text{ mW} + 3 \text{ dB} + 3 \text{ dB} - 3 \text{ dB} = 80 \text{ mW}$$

$$40 \text{ mW} \times 2 \times 2/2 = 80 \text{ mW}$$

Again, both of these formulas are saying the same thing. You can see, from this last example, how the accumulation of gains and losses are calculated. Now, rules 3 and 4 say that a gain or loss of 10 results in a gain of 10 times or a loss of 10 times. Consider the following example, which illustrates rules 3, 4, and 5:

$$40 \text{ mW} + 10 \text{ dB} + 10 \text{ dB} = 4000 \text{ mW}$$

$$40 \text{ mW} \times 10 \times 10 = 4000 \text{ mW}$$

As you can see, adding 10 dB of gain twice causes a 40 mW signal to become a 4000 mW signal, which could also be stated as a 4 W signal.

Losses would be subtracted in the same way as the 3 dB losses were; however, instead of dividing by 2 we would now divide by 10 such as in the following example:

$$40 \text{ mW} - 10 \text{ dB} = 4 \text{ mW}$$

$$40 \text{ mW}/10 = 4 \text{ mW}$$

You should be beginning to understand the five rules of 10s and 3s. However, it is also important to know that the 10s and 3s can be used together to calculate the power levels after any integer gain or loss of dB. This is done with creative combinations of 10s and 3s. For example, imagine you want to know what the power level of a 12 mW signal with 16 dB of gain would be. Here is the math:

$$12 \text{ mW} + 16 \text{ dB} = 480 \text{ mW}$$

But how did I calculate this? The answer is very simple: I added 10 dB and then I added 3 dB twice. Here it is in longhand:

$$12 \text{ mW} + 10 \text{ dB} + 3 \text{ dB} + 3 \text{ dB} = 480 \text{ mW}$$

$$12 \text{ mW} \times 10 \times 2 \times 2 = 480 \text{ mW}$$

Sometimes you are dealing with both gains and losses of unusual amounts. While the following numbers are completely fabricated, consider the assumed difficulty they present to calculating a final RF signal power level:

$$30 \text{ mW} + 7 \text{ dB} - 5 \text{ dB} + 12 \text{ dB} - 6 \text{ dB} = \text{power level}$$

At first glance, this sequence of numbers may seem impossible to calculate with the rules of 10s and 3s; however, remember that the dB gains and losses are cumulative, and this includes both the positive gains and the negative losses. Let's take the first two gains and losses: 7 dB of gain and 5 dB of loss. You could write the first part of the previous formula like this:

$$30 \text{ mW} + 7 \text{ dB} + (-5 \text{ dB}) = 30 \text{ mW} + 2 \text{ dB}$$

Why is this? Because +7 plus −5 equals +2. Carrying this out for the rest of our formula, we could say the following:

$$30 \text{ mW} + 7 \text{ dB} + (-5 \text{ dB}) + 12 \text{ dB} + (-6 \text{ dB}) = 30 \text{ mW} + 2 \text{ dB} + 6 \text{ dB}$$

or

$$30 \text{ mW} + 8 \text{ dB} = \text{power level}$$

The only question that is left is this: How do we calculate a gain of 8 dB? Well, remember the rules of 10s and 3s. We have to find a combination of positive and negative 10s and 3s that add up to 8 dB. Here's a possibility:

$$+10 + 10 - 3 - 3 - 3 - 3 = 8$$

If we use these numbers to perform RF dB-based math, we come up with the following formula:

$$30 \text{ mW} + 10 \text{ dB} + 10 \text{ dB} - 3 \text{ dB} - 3 \text{ dB} - 3 \text{ dB} - 3 \text{ dB} = 187.5 \text{ mW}$$

$$30 \text{ mW} \times 10 \times 10/2/2/2/2 = 187.5 \text{ mW}$$

To help you visualize the math, consider the following step-by-step breakdown:

$$30 \text{ mW} \times 10 = 300 \text{ mW}$$

$$300 \text{ mW} \times 10 = 3000 \text{ mW}$$

$$3000 \text{ mW}/2 = 1500 \text{ mW}$$

$$1500 \text{ mW}/2 = 750 \text{ mW}$$

$$750 \text{ mW}/2 = 375 \text{ mW}$$

$$375 \text{ mW}/2 = 187.5 \text{ mW}$$

In the end, nearly any integer dB-based power gain or loss sequence can be estimated using the rule of 10s and 3s. Table 2.4 provides a breakdown of dB gains from 1 to 10 with the expressions as 10s and 3s for your reference. From this table, you should be able to determine the

TABLE 2.4 Expressions of 10s and 3s

Gain in dB	Expression in 10s and 3s
1	+ 10 – 3 – 3 – 3
2	+ 3 + 3 + 3 + 3 – 10
3	+ 3
4	+ 10 – 3 – 3
5	+ 3 + 3 + 3 + 3 + 3 – 10
6	+ 3 + 3
7	+ 10 – 3
8	+ 10 + 10 – 3 – 3 – 3 – 3
9	+ 3 + 3 + 3
10	+ 10

combinations of 10s and 3s you would need to calculate the power gain or loss from any provided dB value. *Always remember that, while plus 10 is actually times 10, plus 3 is only times 2.* The same is true in reverse in that *minus 10 is actually divided by 10 and minus 3 is divided by 2.*

dBm

The abbreviation *dBm* represents an absolute measurement of power where the *m* stands for *milliwatts*. Effectively, dBm references decibels relative to 1 milliwatt such that 0 dBm equals 1 milliwatt. Once you establish that 0 dBm equals 1 milliwatt, you can reference any power strength in dBm. The formula to get dBm from milliwatts is

$$\text{dBm} = 10 \times \log10(\text{Power}_{\text{mW}})$$

For example, if the known milliwatt power is 30 mW, the following formula would be accurate:

$$10 \times \log10(30) = 14.77 \text{ dBm}$$

This result would often be rounded to 15 dBm for simplicity; however, you must be very cautious about rounding if you are calculating a link budget because your end numbers can be drastically incorrect if you've done a lot of rounding along the way. Table 2.5 provides a list of common milliwatt power levels and their dBm values.

TABLE 2.5 mW to dBM Conversion Table (Rounded to Two Precision Levels)

mW	dBm
1	0.00
10	10.00
20	13.01
30	14.77
40	16.02
50	16.99
100	20.00
1000	30.00
4000	36.02

One of the benefits of working with dBm values instead of milliwatts is the ability to easily add and subtract simple decibels instead of multiplying and dividing often huge and tiny numbers. For example, consider that 14.77 dBm is 30 mW as you can see in Table 2.5. Now, assume that you have a transmitter that transmits at that 14.77 dBm and you are passing its signal through an amplifier that adds 6 dB of gain. You can quickly calculate that the 14.77 dBm of original output power becomes 20.77 dBm of power after passing through the amplifier. Now, remember that 14.77 dBm was 30 mW. With the 10s and 3s of RF math, which you learned about earlier, you can calculate that 30 mW plus 6 dB is equal to 120 mW. The interesting thing to note is that 20.77 dBm is equal to 119.4 mW. As you can see, the numbers are very close indeed. While I've been using a lot of more exact figures in this section, you'll find that rounded values are often used in vendor literature and documentation. Figure 2.17 shows a set of power level charts that can be used for simple mW to dBm and dBm to mW conversion.

FIGURE 2.17 dBm to mW conversion

dBm	Watts	dBm	Watts	dBm	Watts
0	1.0 mW	16	40 mW	32	1.6 W
1	1.3 mW	17	50 mW	33	2.0 W
2	1.6 mW	18	63 mW	34	2.5 W
3	2.0 mW	19	79 mW	35	3 W
4	2.5 mW	20	100 mW	36	4 W
5	3.2 mW	21	126 mW	37	5 W
6	4 mW	22	158 mW	38	6 W
7	5 mW	23	200 mW	39	8 W
8	6 mW	24	250 mW	40	10 W
9	8 mW	25	316 mW	41	13 W
10	10 mW	26	398 mW	42	16 W
11	13 mW	27	500 mW	43	20 W
12	16 mW	28	630 mW	44	25 W
13	20 mW	29	800 mW	45	32 W
14	25 mW	30	1.0 W	46	40 W
15	32 mW	31	1.3 W	47	50 W

dBi

The abbreviation *dBi* (the *i* stands for isotropic) represents a measurement of power gain used for RF antennas. It is a comparison of the gain of the antenna and the output of a theoretical isotropic radiator. An *isotropic radiator* is an ideal antenna that we cannot create with any known technology. This is an antenna that radiates power equally in all directions. In order to do this, the power source would have to be at the center of the radiating element and be infinitesimally small. Since this technology does not exist, we call the isotropic radiator the ideal against which other antennas are measured. I'll provide more details about dBi in the later section titled "Isotropic Radiator." For now, just remember that dBi is a measurement of directional gain in power and is not a power reference. In other words, the dBi value must be calculated against the input power provided to the antenna to determine the actual output power in the direction in which the antenna propagates RF signals.

dBd

Antenna manufacturers use both dBi, mentioned previously, and *dBd* to calculate the directional gain of antennas. Where dBi is a calculation of directional gain compared to an isotropic radiator, dBd is a calculation of directional gain compared to a dipole antenna. Therefore, the last *d* in dBd stands for *dipole*. Like dBi, dBd is a value calculated against the input power to determine the directional output power of the antenna.

What is the difference between dBi and dBd, then? The difference is that a dBd value is compared with a dipole antenna, which itself has a gain of 2.14 over an isotropic radiator. Therefore, an antenna with a gain of 7 dBd has a gain of 9.14 dBi. In other words, to convert from dBd to dBi, just add 2.14. To convert from dBi to dBd, just subtract 2.14. To remember this, just remember the formula 0 dBd = 2.14 dBi.

SNR

Background RF noise, which can be caused by all the various systems and natural phenomena that generate energy in the electromagnetic spectrum, is known as the *noise floor*. The power level of the RF signal relative to the power level of the noise floor is known as the *signal-to-noise ratio* or *SNR*.

Think of it like this: Imagine you are in a large conference room. Further, imagine that there are hundreds of people having conversations at normal conversation sound levels. Now, imagine that you want to say something so that everyone will hear you; therefore, you cup your hands around your mouth and yell loudly. You could say that the conversations of everyone else in the conference room constitute a noise floor and that your yelling is the important signal or information. Furthermore, you could say that the loudness of your yelling relative to the loudness of all other discussions is the SNR for your communication.

In WLAN networks, the SNR becomes a very important measurement. If the noise floor power levels are too close to the received signal strength, the signal may be corrupted or may not even be detected. It's almost as if the received signal strength is weaker than it actually is when there is more electromagnetic noise in the environment. You may have noticed that when you yell in a room full of people yelling, your volume doesn't seem so great; however, if you yell in a room full of people whispering, your volume seems to be magnified. In fact, your volume is not greater, but the noise floor is less. RF signals are impacted in a similar way.

RSSI

The *received signal strength indicator (RSSI)* is an arbitrary measurement of received signal strength defined in the IEEE 802.11 standards. There is no absolute rule as to how this signal strength rating must be implemented in order to comply with the IEEE standard other than that it is optional (though I've not encountered a vendor that has not implemented it in client devices), that it should report the rating to the device's driver, and that it should use one byte for the rating, providing a potential range of 0–255.

In reality, no vendors have chosen to use the entire range. For example, Cisco uses a range of 0–100 (101 total values) in their devices, and most Atheros-based chipsets use a range of 0–60 (61 total values). The IEEE does specify an RSSI_MAX parameter, which would be 100 for Cisco and 60 for Atheros. This allows software applications to determine the range implemented by the vendors and then convert the rating value into a percentage. It would not be very beneficial if the client software reported the actual rating to the user. This is because the different ranges used by the different vendors would result in unusual matches. By this I mean that an RSSI rating of 75 in a Cisco client is the same relative rating as an RSSI rating of 45 in an Atheros chipset (assuming they are using similar linear stepping algorithms internally). Therefore, most applications use percentages.

For example, if an Atheros-based client card reported an RSSI of 47, the software application could process the following formula to determine the signal strength in percentage:

$$47/60 \times 100 = 78.3\% \text{ signal strength}$$

How does the software know to use the maximum value of 60? From the RSSI_MAX parameter that is required by the IEEE standard. Symbol, a WLAN hardware manufacturer, for example, uses an RSSI_MAX of 31. This means there is a total of 32 potential values, with 31 of the values actually representing some level of usable signal strength. Most vendors have chosen to use an RSSI of 0 to represent a signal strength less than the receive sensitivity of the device and, therefore, a signal strength that is not usable. In the end, an RSSI of 16 with a Symbol client would be 50 percent signal strength. An RSSI of 50 with a Cisco client would be 50 percent signal strength and an RSSI of 30 with an Atheros client would be 50 percent signal strength. This is why most client software packages report the signal strength in percentage instead of RSSI.

Now, let's make this even more complex. Earlier I said that a Cisco rating of 75 is the same as an Atheros rating of 45, assuming the use of the same linear stepping algorithm. By linear stepping algorithm, I'm talking about the connection between dBm and RSSI rating. For example, one might assume that a dBm of −12 gets an RSSI rating of 100 for Cisco and that a dBm of −12 gets an RSSI rating of 60 for Atheros. In other words, it would make sense to assume that the RSSI_MAX parameter is equal to the same actual dBm signal strength with all vendors; however, since the IEEE leaves it up to the vendors to determine the details of RSSI implementation (mostly because it is an optional parameter anyway), the different vendors often use different dBm signal strengths for their RSSI_MAX parameter. What is the result of this complexity? You may show a 100 percent signal strength for one client device and show a lesser signal strength for another client device from the exact same location. Your assumption may be that the client device with the lesser signal strength is actually providing inferior performance when in fact they are identical.

How can this be? Consider a situation where two vendors use an RSSI_MAX value of 100. However, one vendor (vendor A) equates the RSSI rating of 100 to −12 dBm and the other vendor (vendor B) equates the RSSI rating of 100 to −15 dBm. Now assume that both vendors use a linear stepping scale for their ratings where a decrease in dBm of .7 causes the RSSI rating to drop by 1. This means that, at −15 dBm, vendor B will report 100 percent signal strength, but vendor A will have dropped the RSSI rating 4 times to a value of 96 and report a 96 percent signal strength. You can see how one might assume that vendor B's client is performing better because it has a higher percentage signal strength when, in fact, the two clients simply use a different implementation of the RSSI feature.

Due to these incompatibility issues, RSSI values should only be compared with the values from other computers using the same vendor's devices.

The RSSI rating is also arbitrarily used to determine when to reassociate (roam) and when to transmit. In other words, vendors will decide what the lowest RSSI rating should be before attempting to reassociate to a basic service set (BSS) with a stronger beacon signal. Additionally, vendors must determine when to transmit. To do this, they must determine a clear channel threshold. This is an RSSI value at which it can be assumed that there is no arriving signal and therefore the device may transmit.

Link Budget and System Operating Margin (SOM)

The term *budget* can be defined as a plan for controlling a resource. In a wireless network, the resource is RF energy and you must ensure that you have enough of it to meet your communication needs. This is done by calculating a *link budget* that results in a *system operating margin (SOM)*. Link budget is an accounting of all components of power, gain, loss, receiver sensitivity, and fade margin. This includes the cables and connectors leading up the antenna, as well as the antennas themselves. It also includes the factor of free space path loss. In other words, the many concepts we've been talking about so far in this chapter are about to come together in a way that will help you make effective decisions when building wireless links. You will take the knowledge you've gained of RF propagation and free space path loss and the information related to RF math and use that to perform link budget calculations that result in a SOM.

When creating a financial budget, money management coaches often suggest to their clients that they should monitor how they are currently spending their money. Then they suggest that these individuals create a budget that documents this spending of money. The alternative would be to go ahead and create a financial budget without any consideration for what your expenses actually are. I'm sure you can see that the latter simply will not work. First, you have to know how much money you need to live, and then you design your budget around that knowledge.

Similarly, in WLAN links, you will need to first determine the signal strength that is required at the receiving device and then figure out how you will accomplish this with your link budget. The first calculation you should perform in your link budget is to determine the minimum signal strength needed at the receiver, and this is called the *receive sensitivity.* The receive sensitivity is not a single dBm rating; it is a series of dBm ratings required to communicate at varying data rates. For example, Table 2.6 shows the receive sensitivity scale for a Cisco Aironet 802.11a/b/g CardBus adapter.

There are actually two ways to think of the receive sensitivity: the absolute weakest signal the wireless radio can reliably receive and the weakest signal the wireless radio can reliably receive at a specific data rate. The lowest number in dBm, which is –94 dBm in Table 2.6, is the weakest signal the radio can tolerate. This number is sometimes referenced as the receive sensitivity or the *absolute receive sensitivity.* In more accurate terminology, the receive sensitivity of a card is the complete series or system of sensitivity levels supported by the card.

The receive sensitivity ratings are determined by the vendors. They will place the radio in a specially constructed shielded room and transmit RF signals of decreasing strength. As the RF signal strength decreases, the bit error rate in the receiving radio increases. Once this bit error rate

TABLE 2.6 Cisco Aironet 802.11 a/b/g CardBus Adapter

dBm Power Level	Data Rate
–94 dBm	1 Mbps
–93 dBm	2 Mbps
–92 dBm	5.5 Mbps
–86 dBm	6 Mbps
–86 dBm	9 Mbps
–90 dBm	11 Mbps
–86 dBm	12 Mbps
–86 dBm	18 Mbps
–84 dBm	24 Mbps
–80 dBm	36 Mbps
–75 dBm	48 Mbps
–71 dBm	54 Mbps

reaches a vendor-defined rate, the power level in dBm is noted and the radio is configured to switch down to the next standard data rate. This process continues until the lowest standard data rate for that 802.11-based device (1 or 6 Mbps) can no longer be achieved and this dBm becomes the lowest receive sensitivity rating. In the end, a lower receive sensitivity rating is better because it indicates that the client device can process a weaker signal.

The reason you need to know the receive sensitivity rating is that it is the first of your link budget calculations. The SOM is the amount of received signal strength relative to the client device's receive sensitivity. In other words, if you have a client device with a receive sensitivity of –94 dBm and the card is picking up the wireless signal at –65 dBm, the SOM is the difference between –94 and –65 dBm. Therefore, you would use the following formula to calculate the link budget:

$$\mathrm{SOM} = RS - S$$

where S is the signal strength (the second link budget calculation used to determine the SOM) at the wireless client device and RS is the receive sensitivity of the client device. Plugging in our numbers looks like this:

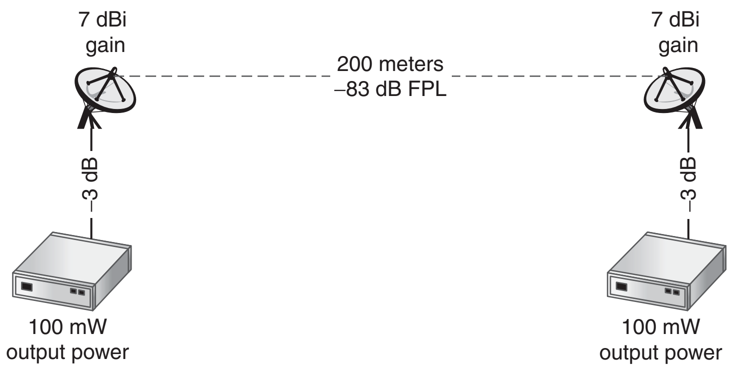
$$\mathrm{SOM} = (-94) - (-65)$$

The resulting SOM is 29 dBm. This means that the signal strength can be weakened by 29 dBm, in theory, and the link can be maintained. There are many factors at play when RF signals are being transmitted, but this number, 29 dBm, will act as a good estimate. You may be able to maintain the link with a loss of 32 dBm, and you may lose the link with a loss of 25 dBm. The link budget is a good estimate but should not be taken as a guarantee for connectivity.

It is rare to calculate the link budget or SOM for indoor connections. This is because most indoor connections are not direct line-of-sight type connections, but instead they reflect and scatter all throughout the indoor environment. In fact, someone can move a filing cabinet and cause your signal strength to change. It can really be that fickle.

Outdoor links are the most common type of links where you will need to create a link budget and determine the SOM. A detailed link budget can be much more complex than what has been discussed here. For example, it may include consideration for Earth bulge, the type of terrain, and the local weather patterns. For this reason, some vendors provide link budget calculation utilities.

FIGURE 2.18 Link budget calculation



Let's consider an actual example of a link budget calculation. Figure 2.18 shows a site-to-site link being created across a distance of 200 meters with IEEE 802.11 bridges. Based on the output power of the bridge, the attenuation of the cables, the gain of the antennas, and the free space path loss, we can calculate the link budget, since the receive sensitivity of both bridges is –94 dBm. The calculations are as follows:

Link budget calculation 1: 100 mW = 20 dBm

Link budget calculation 2: 20 dBm – 3 dB + 7 dBi – 83 dB = –59 dBm

Link budget calculation 3: (–94 dBm) – (–59 dBm) = 35 dBm

SOM = 35 dBm

Fade Margin

Because of the variableness of wireless links, it is not uncommon to "pad the budget" much as a project manager may do for "risk factors" in a project. This padding of the budget is needed because the weather does change and trees grow and buildings are built. These factors, and others, can cause the signal to degrade over time. By including a few extra dB of strength in the required link budget, you can provide a link that will endure longer. This extra signal strength actually has a name, and it is *fade margin.* You do not add to the link budget/SOM dBm value, but instead you take away from the receive sensitivity. For example, you may decide to work off of an absolute receive sensitivity of –80 dBm instead of the –94 dBm supported by the Cisco Aironet card mentioned earlier. This would provide a fade margin of 14 dBm. It would also change our calculations, based on Figure 2.18, to a SOM of 21 dBm.

Intentional Radiator

The *intentional radiator,* in a WLAN transmission system, is the point at which the antenna is connected. The signal originates at a transmitter and may pass through connectors, amplifiers, attenuators, and cables before reaching the antenna. These components amplify or attenuate the signal, resulting in the output power at the intentional radiator before entering the antenna. The FCC sets the rules regarding the power that can be delivered to the antenna and radiated by the antenna. These are two different allowances. The first is for the intentional radiator, and the second is for the antenna element. For example, the FCC allows 1 watt of output power from the intentional radiator and 4 watts of antenna output power in a point-to-multipoint link in the 2.4 GHz ISM band. To understand this, you'll need to understand something called EIRP.

Equivalent Isotropically Radiated Power (EIRP)

The *equivalent isotropically radiated power (EIRP)* is the hypothetical power that is delivered by an intentional radiator to an imaginary isotropic antenna that would produce an even distribution of RF power with the same amplitude actually experienced in the preferred direction of the actual antenna. In other words, it is the output power from the intentional radiator (output power from the transmitter plus any gains or losses leading up to the connection point of the antenna) plus the directional gain provided by the antenna. Therefore, the FCC allows 1 watt of output power from the intentional radiator and then 6 dBi of gain at the antenna to equal 4 watts of total output power in a point-to-multipoint link in the 2.4 GHz ISM band.

FCC Rules for Output Power

The FCC has specified different rules for different link types at different frequencies or bands. Specifically, there are rules for 2.4 GHz point-to-multipoint links in the ISM band and point-to-point links in the same band. Additionally, there are rules for both link types in the 5 GHz U-NII bands. I'll cover both in this section. Sector and phased-array antenna output power levels must also be considered.

The reality of output power rules is actually more complex than most network administrators realize. The general concept that most