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Deploying License-Free Wireless Wide-Area Networks

Best practices for planning and deployment of broadband WWANs

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Deploying License-Free Wireless Wide-Area Networks

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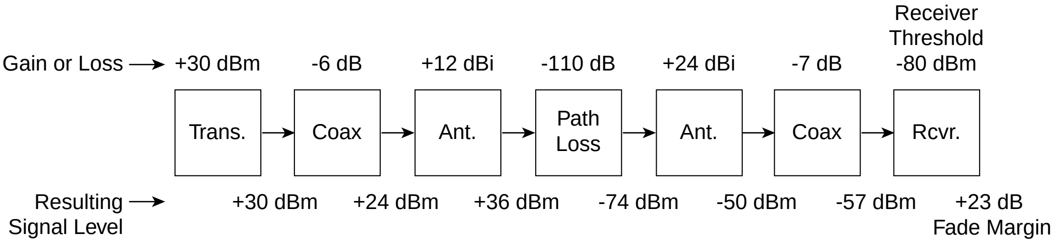

Fade Margin = (Signal Arriving at Receiver) - (Receiver Threshold)
= -57 dBm - (-80 dBm)
= -57 dBm + 80 dBm
Fade Margin = +23 dB

Correction for Figure 2-25 on Page 52

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Tim Barnard

Chapter 2. Understanding Wireless Fundamentals

This chapter describes the wireless fundamentals that underlie the successful design, deployment, operation, support, and expansion of wireless wide-area networks (WANs). This book focuses on the application of these fundamentals in license-free wireless networks; however, these same wireless principles apply to licensed wireless networks and to all wireless signals.

Wireless Propagation

Wireless propagation is the total of everything that happens to a wireless signal as the signal travels from Point A to Point B. Although invisible to your eyes, the wireless signal interacts with everything that it comes near or passes through, including trees, hills, buildings, bodies of water, the earth's atmosphere, people, vehicles, and so on. The better you understand these interactions, the more easily and more successfully you will be able to deploy wireless WANs. First, it is important for you to understand how wireless signals are created.

Wireless communication is possible because changes in the electron flow within a wire cause changes in the magnetic fields and in the electric fields that surround the wire. Magnetic fields and electric fields are invisible, but you can see the results of their presence. If you have ever used a magnet to attract a piece of iron or steel, you have seen the result of a magnetic field. If you have ever seen a bolt of lightning, you have seen the effect of an electric (or electrostatic) field.

When electron streams change direction rapidly within a wire or antenna, the electrostatic and magnetic fields around the wire or antenna change at the same rapid rate. These rapidly changing fields are called electromagnetic waves. The electromagnetic waves do not simply stay near the antenna; they travel away at nearly the speed of light—186,000 miles per second (300,000,000 meters per second). The changing electron flow within the antenna has been transformed into electromagnetic (wireless) waves traveling away from the antenna.

TIP

Keep a mental picture of a moving wave in your mind; it is not a spot or a line; it is a wave. If you drop a rock into a pond, the waves spread out from the point where the rock hit the water. If you place an antenna in free space, the wireless waves spread out from the antenna. Wireless waves pass through air, space, people, and objects. If you can visualize electro-magnetic waves traveling away from an antenna and radiating outward, you will be off to an excellent start toward successfully deploying wireless

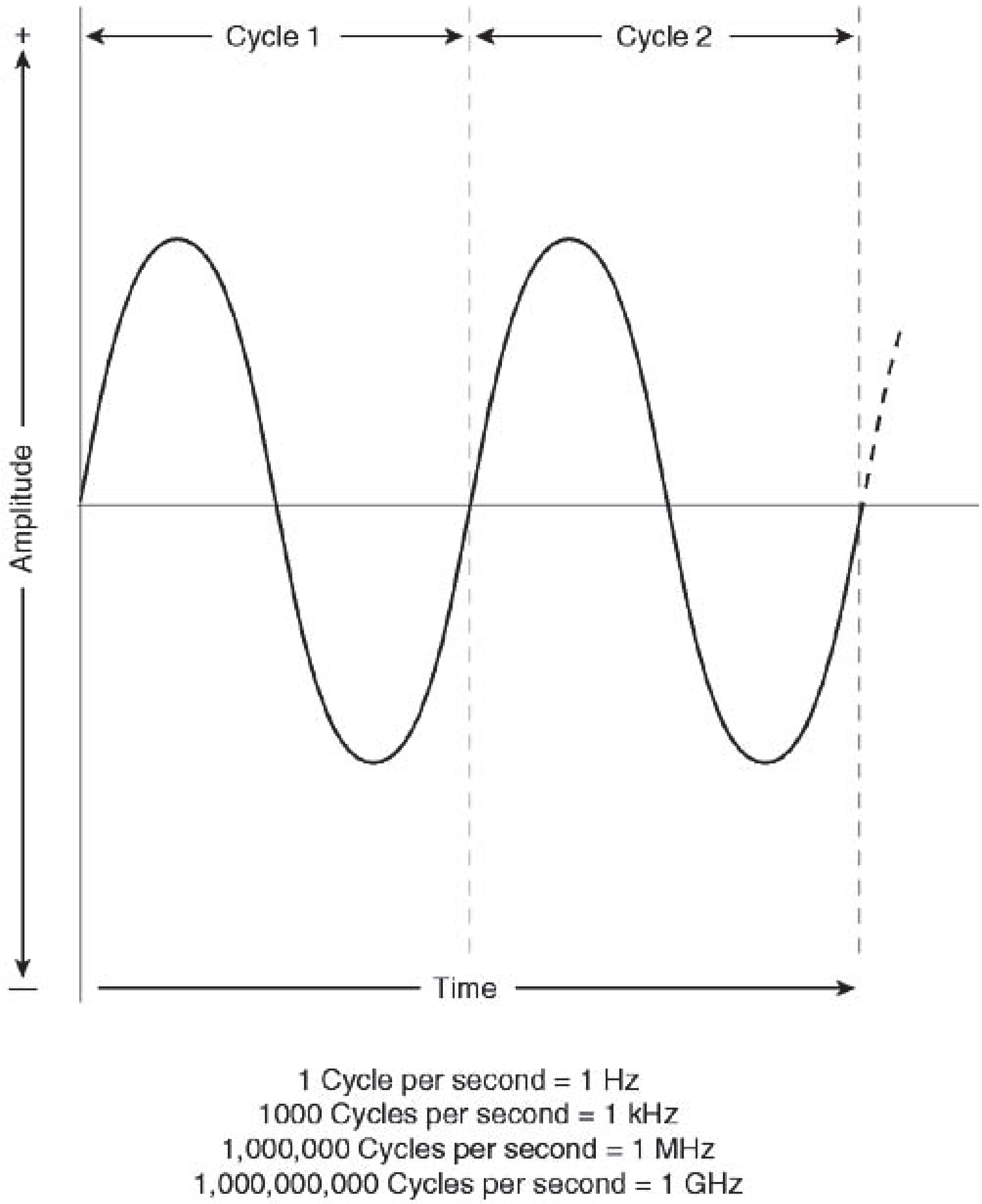
Wireless Frequency

As an ocean wave travels, its height changes; as the front of the wave approaches you, the height increases. When the crest passes you, the height of the wave decreases. The height decreases further as the trough passes you. Finally, the height of the sea is back to the level where it was before the wave appeared. You have just experienced one complete up-down-up wave cycle. Without changes in the wave height, there would be no wave cycle or wave.

Changes in the electron flow in an antenna cause the same changes in the electromagnetic fields around the antenna. Another word for electron flow in a wire is *current*. Without changes in the antenna current, there would be no change in the electromagnetic fields around the antenna; therefore, there would be no useable wireless signal moving outward, away from the antenna. The number of times each second that the current in the antenna goes through one complete positive-negative-positive change-cycle is the same as the *frequency* of the wireless waves that radiate outward from the antenna. If you drew a graph of the current flow in the antenna, the resulting graph would be a sine wave. The positive distance (above the centerline) and the negative distance (below the centerline) represent the *amplitude,* or strength, of the current. The greater the amplitude of the current, the stronger the radiated electromagnetic waves.

Figure 2-1 shows two complete cycles of positive-negative-positive current flow in an antenna. If there are 100 complete cycles in one second, the frequency of the current flow (and the frequency of the resulting wireless wave) is 100 cycles per second. Around 1960, the term *cycles per second* was replaced with the term *Hertz* (abbreviated Hz). The frequency of this wireless wave is 100 Hz.

Figure 2-1. Antenna Current Alternating Between Positive and Negative



Wireless signals cycle back and forth so quickly—millions of times each second—that the following abbreviations are used to specify their frequency:

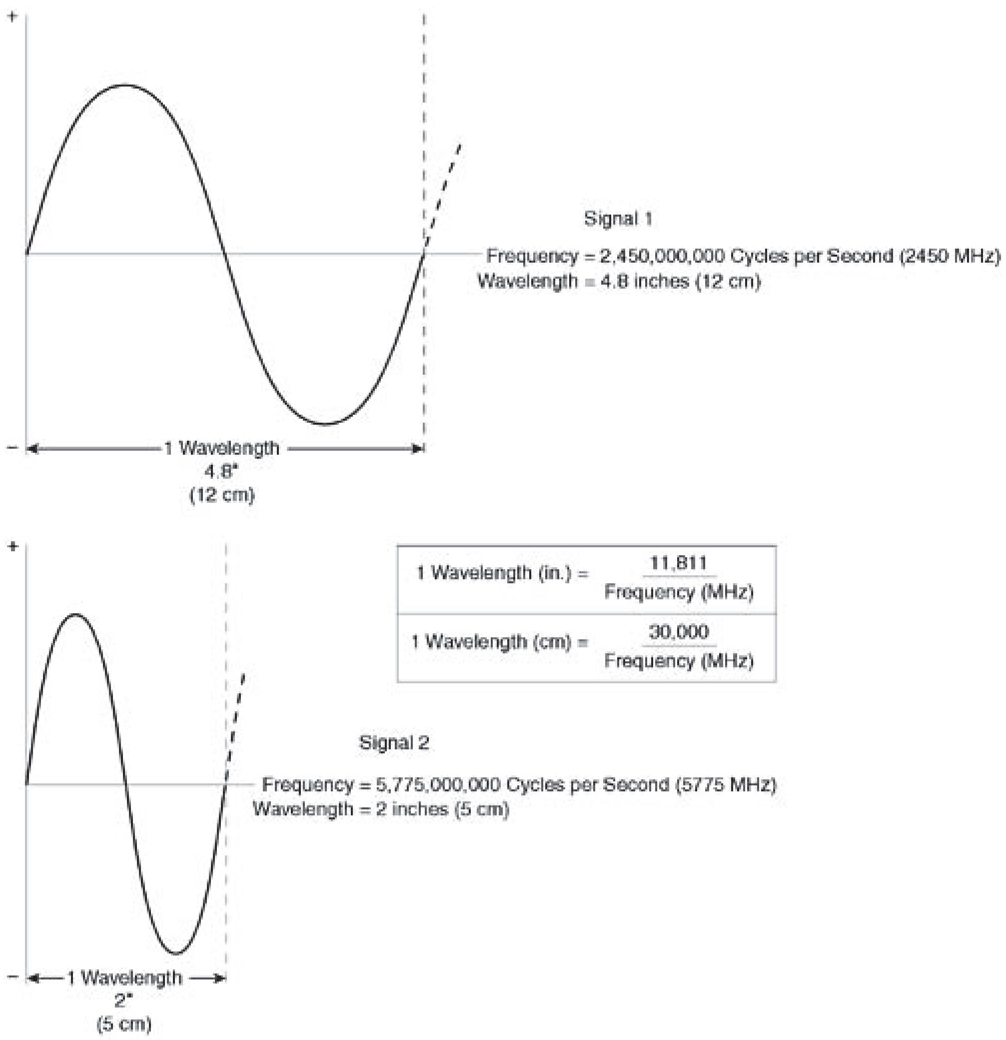
- Kilohertz (kHz): Thousands of cycles per second
- Megahertz (MHz): Millions of cycles per second
- Gigahertz (GHz): Billions of cycles per second

Wireless Wavelength

It is important to be able to visualize the physical size of a wireless signal because the physical size of each signal determines how that signal interacts with its environment and how well it is propagated from antenna to antenna within the wireless network. The signal's physical size also determines how large or how small the antennas that transmit and receive the signal must be; the smaller the signal size, the smaller the antenna.

Figure 2-2 shows two wireless signals on two different frequencies—2.45 GHz and 5.775 GHz. All wireless signals travel through the air at the same speed. That speed is the speed of light, which is 186,000 miles per second (300,000,000 meters per second). The distance that a radio signal travels during a single cycle is called the *wavelength* of that signal. Higher-frequency waves have higher-frequency waves is shorter than for lower-frequency waves.
less time to travel during a single cycle than lower-frequency waves, so the wave-length for

Figure 2-2. Physical Size (Wavelength) of Wireless Waves

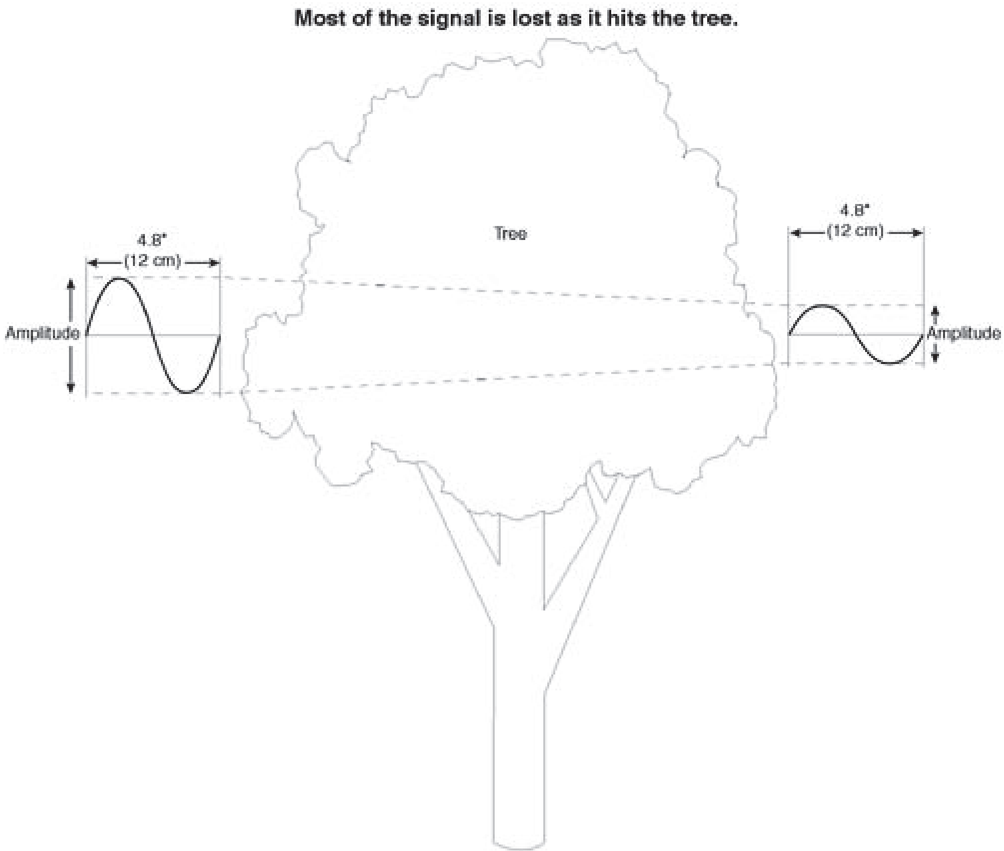


In Figure 2-2, each cycle of Signal 1 (2.45 GHz) has time to travel 4.8 inches (12 cm). Therefore, Signal 1's wavelength is 4.8 inches (12 cm). Signal 2 is changing more rapidly; each cycle of Signal 2 has time to travel only 2 inches (5 cm). Therefore, the wavelength of Signal 2 is only 2 inches (5 cm). There is a corresponding physical wavelength for every wireless frequency. The lower the frequency, the longer the wavelength; the higher the frequency, the shorter the wavelength.

Attenuation

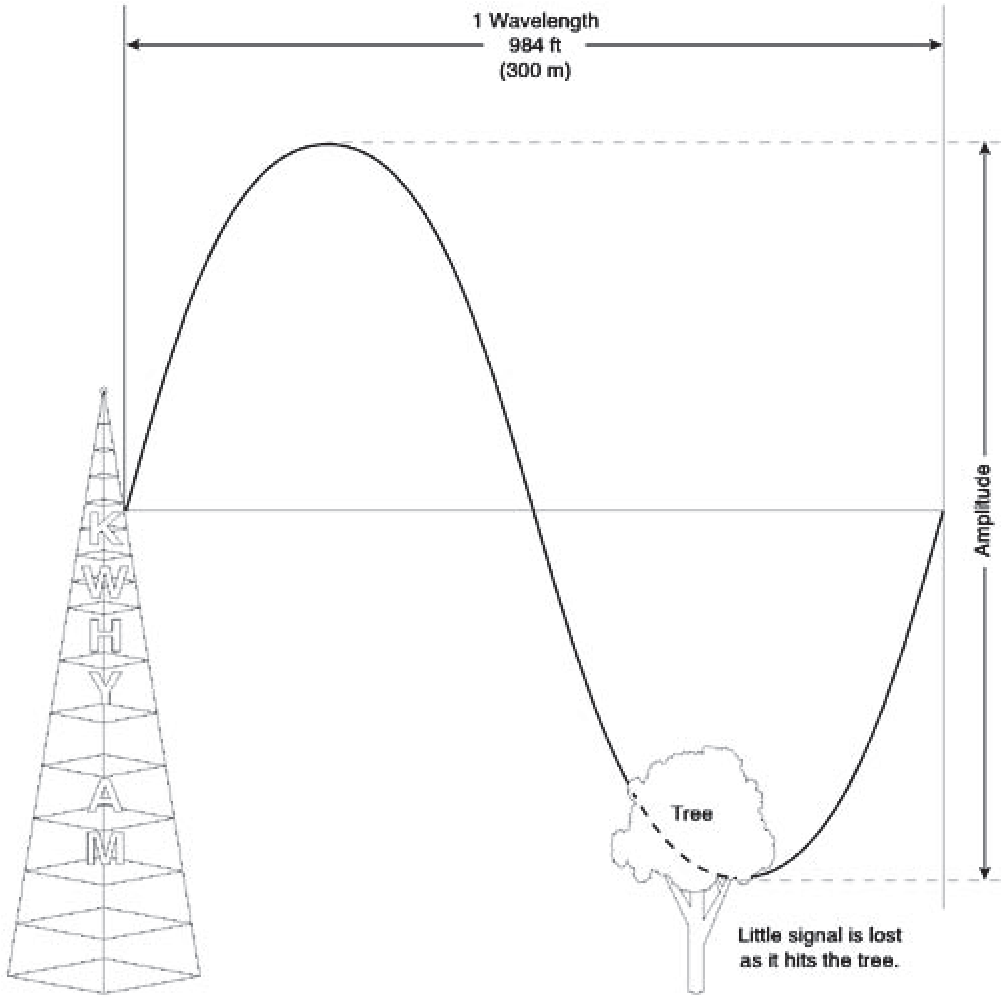
Attenuation is the loss in amplitude that occurs whenever a signal travels through a wire, through free space, or through an obstruction. Figure 2-3 shows a 2.45-GHz (2450 MHz) signal as it encounters a tree. The signal is attenuated; that is, its amplitude is reduced. The amount of signal that emerges on the other side of the tree is much less than the amount of signal that entered the tree. Often, after colliding with an object, the signal strength remaining is too small to make a reliable wireless link.

Figure 2-3. Attenuation of a 4.8-inch (5-cm) Signal by a Tree



In addition, the shorter the wavelength of a wireless signal, the more it is attenuated when it encounters an object. The longer the wavelength of a wireless signal, the less it is attenuated when it encounters an object. Figure 2-4 shows a signal in the AM radio broadcast band at a frequency of 1000 kHz (1 MHz).

Figure 2-4. Attenuation of a 984-ft (300-m) Signal by a Tree



When this signal encounters a tree, the wavelength of the signal (984 ft/300 m) is so much greater than the size of the tree that the amplitude of the signal remains almost unchanged.

NOTE

A sharp-eyed reader will look at Figure 2-4 and says "Sure, the amplitude is still large after the collision. The amplitude of the AM broadcast signal was a lot larger than the amplitude of the 2.4-GHz signal to begin with." Well, sharp-eyed reader, you are correct. Yes, the AM broadcast signal had higher amplitude (more power) to begin

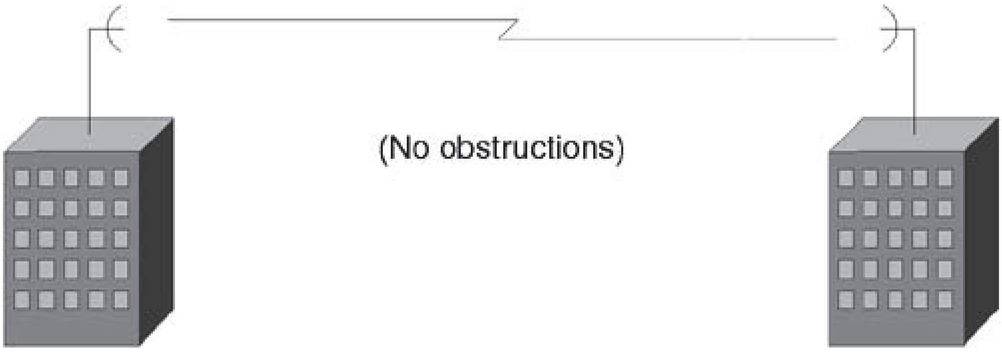
here's the point. Even if the AM broadcast signal started out with 4W, a lot more of it would*still* be left over after encountering the tree, compared to the remaining 2.4-GHz

wavelength of the 2.4-GHz signal, and the tree is many times smaller than the physical wavelength of the 1000-kHz KWHY-AM signal.

Free-Space Waves

A free-space wave is a signal that propagates from Point A to Point B without encountering or coming near an obstruction, as in Figure 2-5.

Figure 2-5. Free-Space Wave



The signal arrives at its destination with as much amplitude as possible because the amplitude is not reduced by attenuation from objects. The only amplitude reduction that occurs is the normal reduction due to the signal being propagated through free space. A signal path like this, with no obstructions, is an ideal wireless scenario.

Reflected Waves

When a wireless signal encounters an obstruction while traveling from Point A to Point B, two things normally happen:

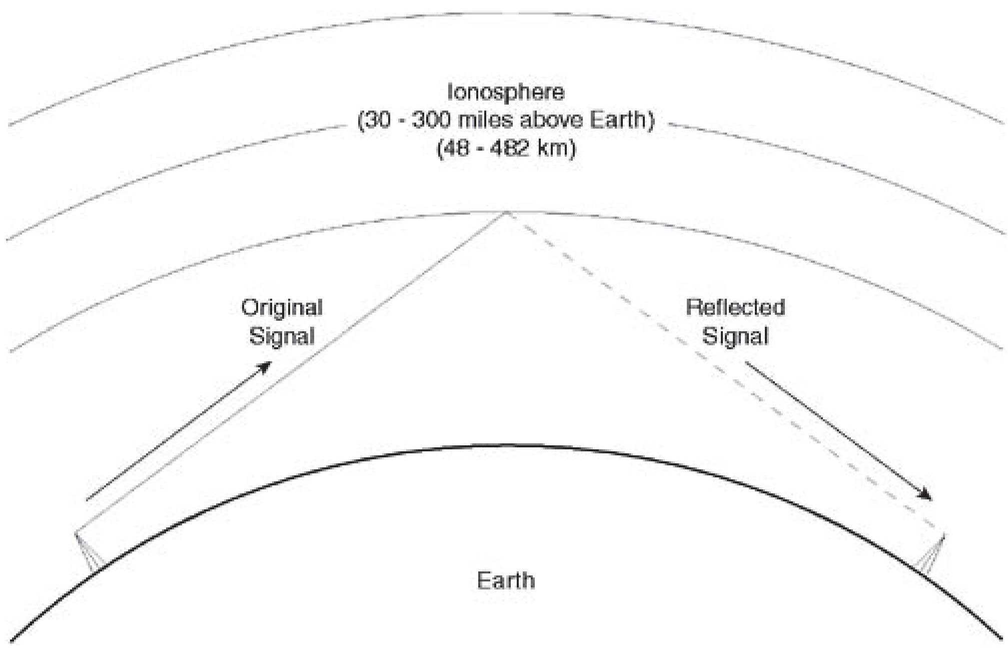
- **Attenuation—** In general, the shorter the wavelength of a signal, relative to the size of the obstruction, the more the signal is attenuated.
- **Reflection—** The shorter the wavelength of the signal relative to the size of the obstruction, the more likely it is that some of the signal will be reflected off the obstruction.

The following sections describe two types of reflected waves. One of these two types occurs at microwave frequencies and is important to your understanding of microwave propagation. You might already be familiar with the first type of reflected waves: sky waves.

Sky Waves

The first type of reflected waves is sky waves. Sky waves generally occur at short wave frequencies, where wavelengths range from 328 to 33 feet (100 to 10 m). Sky waves often reflect off the ionosphere—layers of ionized particles that exist from 30 to 300 miles (48 to 482 km) above the Earth, as shown in Figure 2-6.

Figure 2-6. Sky Wave: Reflected Signal at Non-Microwave Frequencies

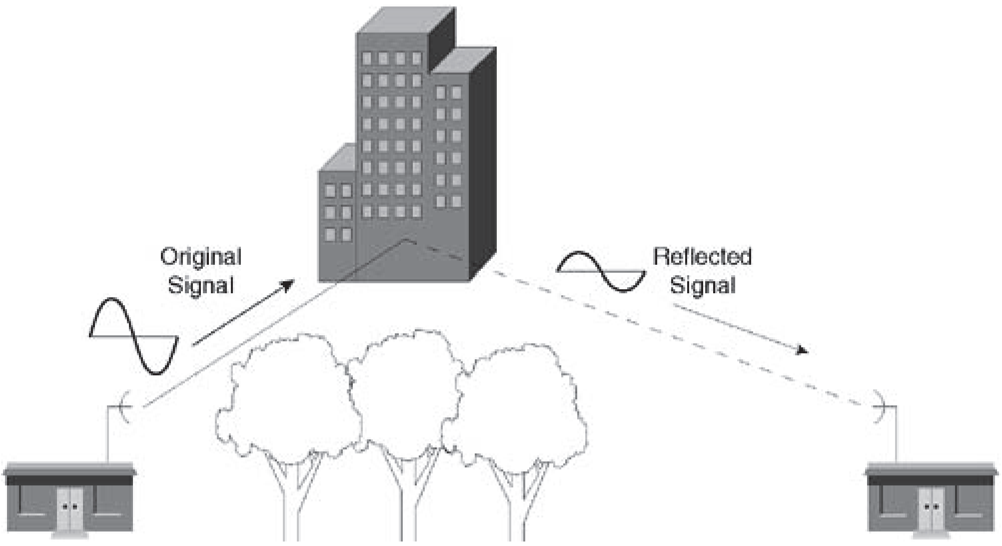


from stations located in other countries, thousands of miles away. Sky waves sometimes also make it possible for you to receive AM broadcast stations at night that are hundreds or thousands of miles away. Ionospheric reflection, however, seldom occurs at microwave frequencies.

Microwave Reflections

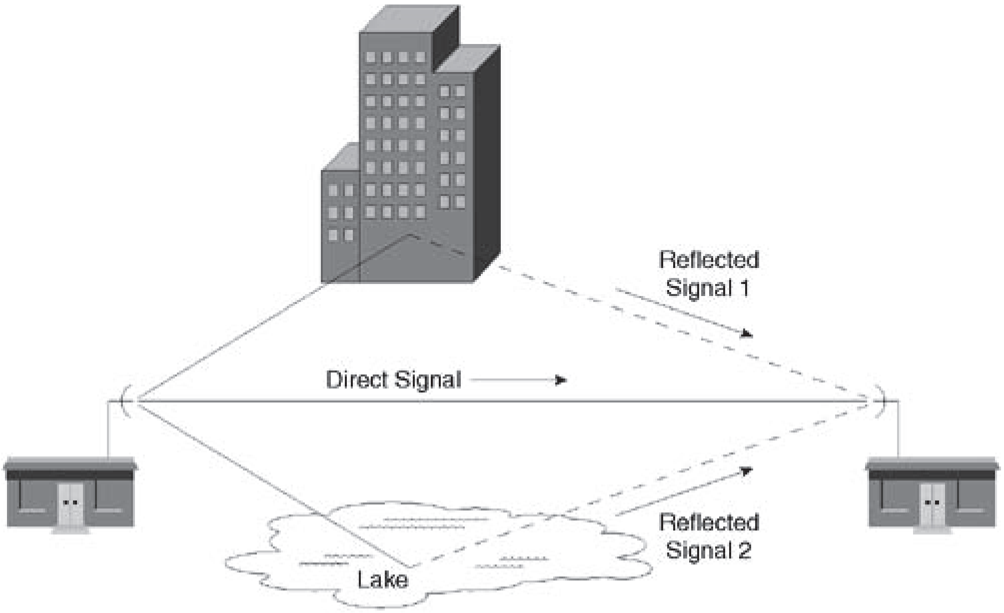
Microwave signals have frequencies between 1000 MHz (1 GHz) and 30 GHz and a physical wavelength from approximately 12 in. (30 cm) down to less than 1 in. (2.5 cm). Microwave signals reflect off of objects that are larger than their wavelength, such as buildings, cars, flat stretches of ground, and bodies of water. Figure 2-7 illustrates microwave reflection off of a building.

Figure 2-7. Microwave Signal Reflection



Each time a microwave signal is reflected, its amplitude is reduced. Microwave reflection can be an advantage or a disadvantage. The advantage is that sometimes the reflection (or *bounce*) off of a building or water tank allows a microwave link to work even though obstructions, such as the trees in Figure 2-7, block the direct wave. The disadvantage of microwave reflection is that a phenomenon called multipath can occur.

Fig 2-8. Microwave signal with Multiple Reflections

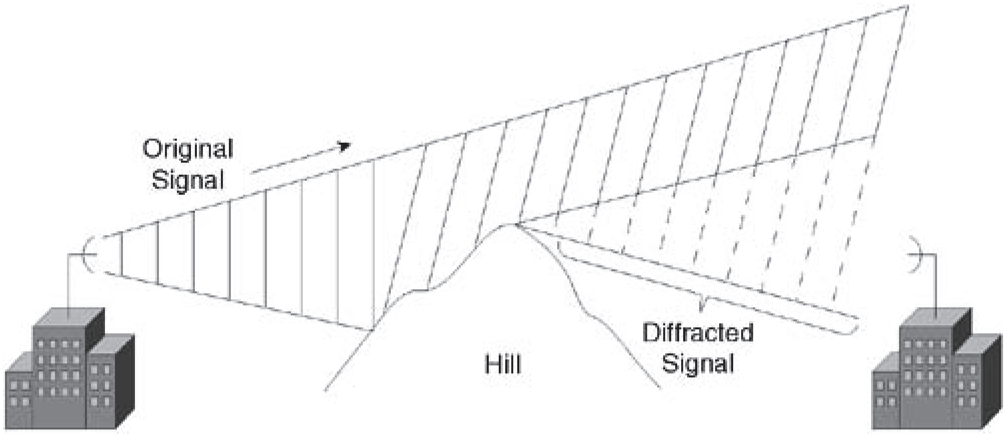


Reflected Signals 1 and 2 follow slightly longer paths than the direct signal; therefore, they arrive slightly later than the direct signal. These reflected echoes sometimes cause problems at the receiver by partially canceling the direct signal, effectively reducing its amplitude. The link throughput slows down because the receiver needs more time to either separate the real signal from the reflected echoes or to wait for missed packets to be retransmitted. Multipath is a significant problem for designers of microwave networks. Methods that you can use to minimize the effects of multipath are discussed later in the book.

Diffraction

Diffraction of a wireless signal occurs when the signal is partially blocked or obstructed by a large object in the signal's path, as shown in Figure 2-9.

Figure 2-9. Signal Diffraction Around an Obstruction



intercepts the hilltop, the signal is diffracted, causing part of the signal energy to bend slightly around the hilltop.

The diffracted signal energy is usually attenuated so much that it is too weak to provide a reliable microwave connection. In a few cases, however, the diffracted signal, although weakened, might still be strong enough to allow a connection to be made to a nearby location that would otherwise be blocked.

TIP

Always try to obtain an unobstructed path between the microwave antennas that you set up. Do not plan to use a diffracted signal in place of a direct signal because most of the time, the diffracted signal is too weak to provide a reliable link.

Weather and Other Atmospheric Effects

Microwave signals must pass through the earth's atmosphere (unless you are communicating from spacecraft to spacecraft, which is a not-too-distant possibility). The earth's atmosphere is a dynamic environment consisting of regions of constantly changing temperatures, pressures, water vapor, and weather. These changes affect the passage and the propagation of microwave signals. Understanding these propagation changes helps you design reliable wireless WANs.

Precipitation

Rain, snow, hail, fog, and sleet are all forms of precipitation—water or water vapor—that is present in the air. As you evaluate the effect that each form of precipitation has on your wireless WAN, keep in mind that the physical size of a wireless signal plays a big role in determining how that signal interacts with the precipitation that it encounters.

Rain, Snow, and Hail

One cycle of a wireless signal at 2.45 GHz has a wavelength of 4.8 in. (12 cm); one cycle at 5.7 GHz has a wavelength of 2 in. (5 cm). Compared to the size of a raindrop—even a big raindrop in a heavy downpour—these wireless signals are quite a bit larger than the raindrops. As a result, the raindrops do not significantly attenuate these signals. At higher wireless frequencies (at or above 10 GHz), where the signal wavelength decreases to less than 1 inch (3 cm), rain, partially melted snow, and partially melted hail *do* start to cause significant attenuation.

Rain can, however, have other effects on the operation of a wireless system. Wherever a tiny hole exists anywhere in an antenna system, rain usually finds it and gets inside the system. After the rain is inside, the water degrades the performance of the system. Eventually, the system fails completely and the antenna cabling must be replaced. Rain can also make surfaces (such as buildings and leaves) more reflective, increasing multipath fading.

TIP

This is another reason to use nonobstructed paths between your antennas. If you try to "blast through" trees, you are just setting yourself up to have problems.

Ice

Ice buildup on antenna systems impacts the operation of wireless WANs in two different ways:

- Reducing system performance
- Physically damaging the antenna system

A thick buildup of ice on a microwave antenna changes the performance of the antenna and the performance of the wireless link degrades.

Ice buildup also adds substantial extra weight, which increases the chance of antenna system failure, especially under windy conditions. A heavier than normal antenna might bend under the extra weight or might even fall from the antenna tower. Ice can also fall from a higher antenna onto a lower one, damaging the lower antenna or antenna cable.

NOTE

nimize problems in snow and ice-prone areas, many commercial microwave antennas are protected with radomes that are designed to cover the antenna. Some radomes also have heaters to melt ice buildups. If you are located in an area that has heavy winter icing conditions, you might want to consult with a local two-way radio shop to see what methods it uses to reduce icing problems on its antenna systems.

Wind

Wind can have a significant impact on the reliable operation of wireless WAN systems. The force from a moderate or heavy wind pushes against both the antenna and the tower or mast that holds the antenna in position. Under this force, several things could happen:

- The antenna could turn on the mast or tower, causing signal levels to decrease as the aim of the antenna changes.
- The tower or mast could sway or twist, changing the aim of the antenna and causing signal levels to decrease or to vary.
- An antenna or tower that has not been properly designed, installed, guyed, or maintained could fail in a strong wind—potentially causing physical injury or property damage.

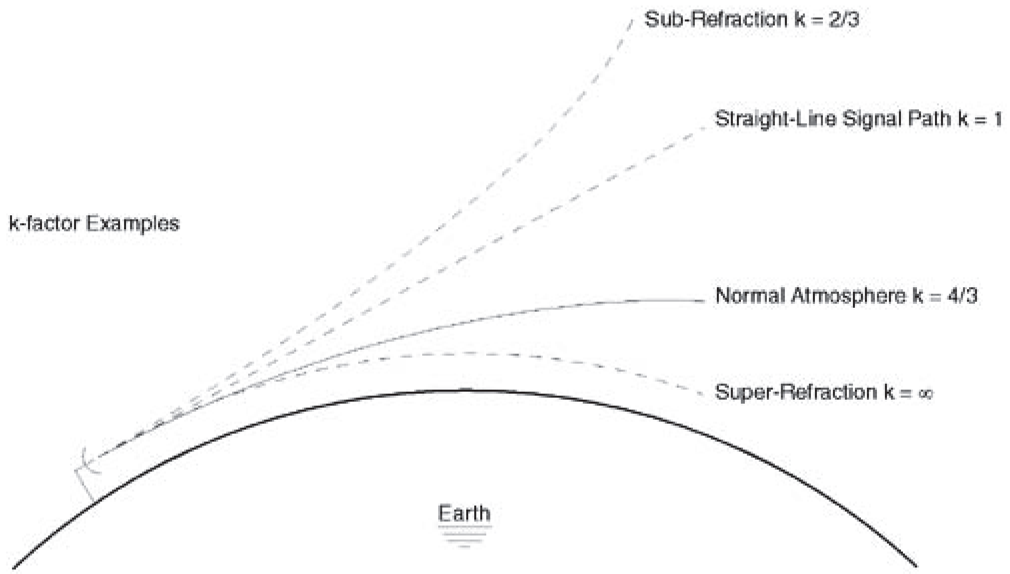
NOTE

Safety is priority one in the design, installation, and operation of a wireless WAN systems. Please pay special attention to the safety sections and notes throughout this book. Give them special attention as you design and install your wireless systems.

Refraction

The changes in temperature, pressure, and water vapor content in the atmosphere play a significant role in the propagation of microwave signals—refracting (or bending) the signals. The refractivity of the atmosphere changes depending on the height above ground. The refractivity is usually largest at low elevations, closest to the surface of the earth. The refractivity is usually smallest the higher you go above the earth. This refractivity change (called the refractivity gradient or *k-factor*) usually causes microwave signals to curve downward slightly toward the earth, as shown in Figure 2-10.

Figure 2-10. Signal Refraction in the Atmosphere



The k-factor can change frequently, such as from hour to hour, from day to night, from weather pattern to weather pattern, or from season to season. Different regions of the earth have slightly different average k-factors. A k-factor of 1 indicates no bending; a signal radiated under this condition travels in a straight line.

A k-factor higher than 1 means that microwave signals bend slightly downward, toward the earth. In most regions, *the median k-factor is 4/3*. A k-factor of 4/3 has the effect of making the radio horizon farther away than the visual horizon. In other words, the length of the microwave path is increased by approximately 15 percent. At times, weather conditions can temporarily cause the k-factor to become infinite. When this occurs, the amount of signal bending equals the curvature of the earth. This effect is called *super-refraction,* or *ducting*. Ducting causes a microwave signal to be propagated for hundreds of miles or until the atmospheric conditions change enough for the ducting to stop.

Changes in the k-factor are a common cause of fading on microwave paths. Sometimes, due to atmospheric conditions, the k-factor is less than 1; for example, the k-factor could be 2/3. This condition, called *subrefraction*, has the effect of bending the microwave signal path upward, away from the earth. Subrefraction reduces signal levels, causing fading at the distant receiver. Over longer microwave paths, the k-factor might be different at different points along the path.

Working with Wireless Power

- Working with wireless WANs requires knowing how to work with wireless power. Following are facts about wireless power:
- Power can be either increased (a power gain) or decreased (a power loss).
- Power can be relative, for example, twice as much power or 1/2 as much power or Power can be absolute, for example, 1 watt or 4 watts.
- Both absolute and relative power are always referenced to initial power level, either to a relative power level or to an absolute power level.
- Wireless WAN power levels become very small, very quickly after leaving a transmitting antenna.
- Wireless WAN power does not decrease linearly with distance; it decreases inversely as the square of the distance increases. Here are some examples:

    - If we double the distance of a wireless link, we don't have 1/2 of the original power reaching the end of the new link; we receive only 1/4 of the original power.

    - If we triple the distance of a link, we receive only $1/9^{th}$ of the original power.

    - If a new link is 5 times longer than an existing link, we receive only $1/25^{th}$ of the power that arrived at the receiver of the original link.

- Wireless power calculations are done in dB, for the following reasons:

    - dB values are logs—that is, they increase and decrease not linearly but logarithmically, just like the way that wireless power increases or decreases.

    - dB values can be used to conveniently represent very small power levels, like the levels of wireless power that arrive at a receiver.

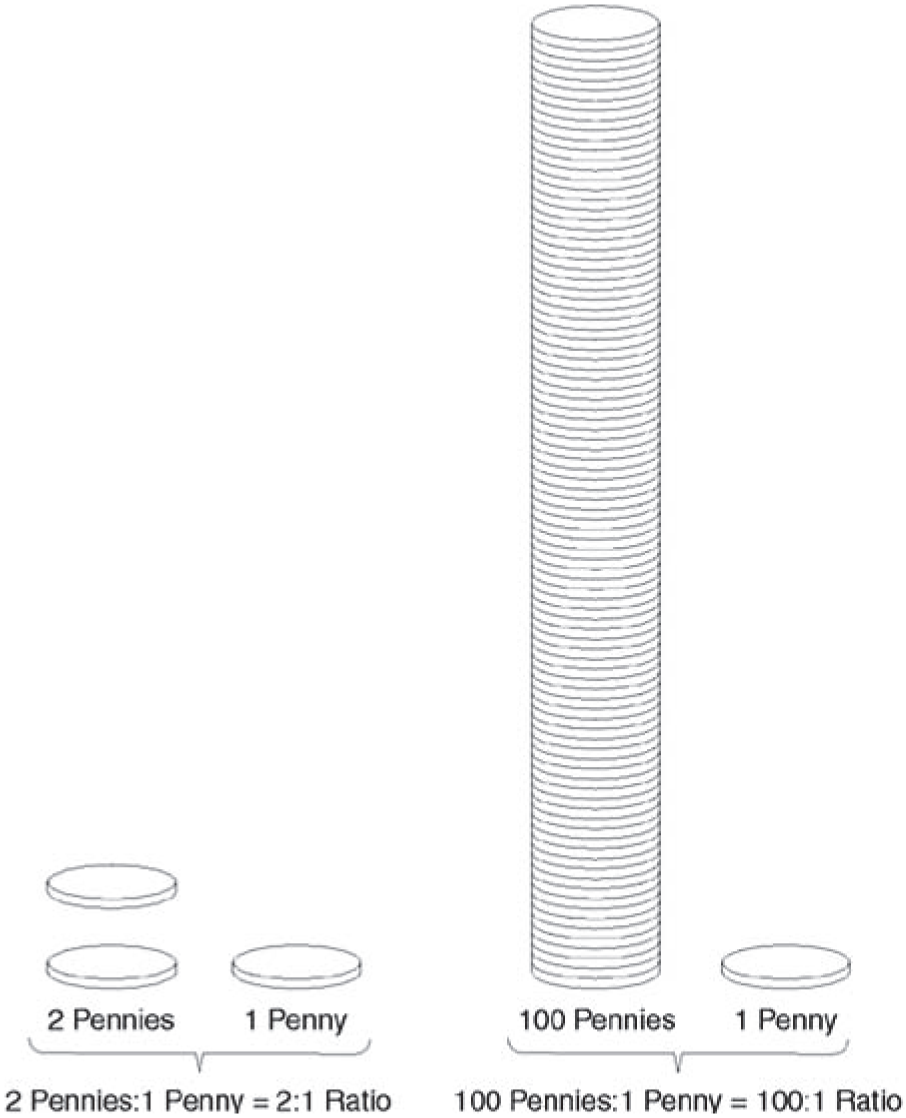
    - Although they are logarithmic, dB values can be added and subtracted together (with each other) using just regular (linear) math. For example: 3 dB plus 3 dB equals 6 dB.

The following sections help you become comfortable using dB to calculate relative power levels and dBm to calculate absolute power levels. Later, you will also use dBi to calculate and compare antenna gains relative to the reference level of an isotropic antenna.

Ratios

Every db value is a *ratio*. This section explains ratios. A ratio is a comparison between two quantities. Ratios use a colon (:) to divide the two quantities. Figure 2-11 uses pennies to show two examples of ratios.

Figure 2-11. Penny Ratios

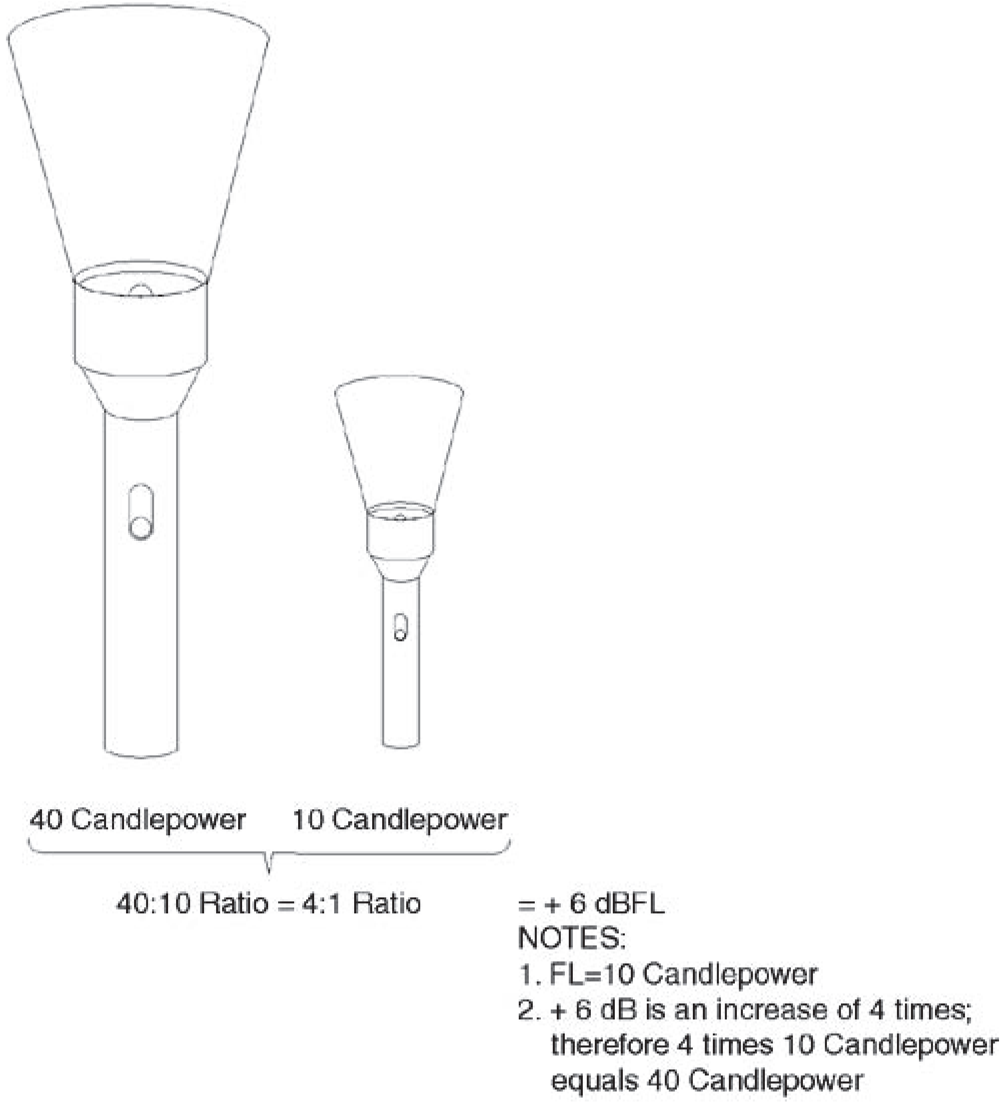


The first example is a ratio of two-to-one (2:1), and the second example is a ratio of 100:1. The first example shows a pile with two pennies next to a pile with one penny—a ratio between the piles of two pennies to one penny, or 2:1. The second example shows a pile with 100 pennies next to a pile with one penny—a ratio of 100:1.

Power Ratios

Figure 2-12 uses two flashlights to show an example of a power ratio.

Figure 2-12. Flashlight Power Ratios



The flashlight on the left has a power of 40 candlepower (as bright as 40 candles). The flashlight on the right is 10 candlepower. The power ratio, 40 candlepower to 10 candlepower, is 4:1.

NOTE

If you look closely, you'll also notice that the 40 candlepower flashlight beam travels only twice as far as the 10 candlepower beam. Hmmm… four times the power travels only twice the distance? Yes, that is correct. The reason for this will be discussed more at the end of this chapter. You will also see how to quickly and easily determine if you can double the distance of a wireless link. (HINT: Do you have four times the power?)

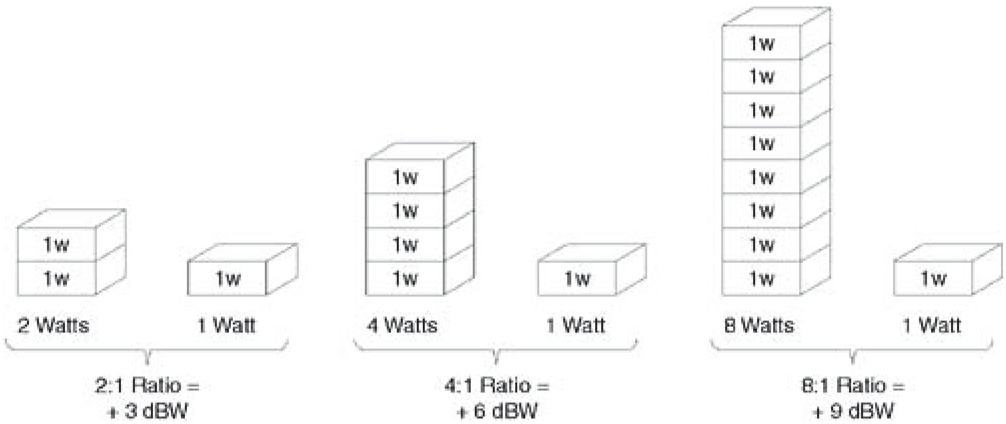
All power ratios use some quantity as their initial reference point. The flashlight example in Figure 2-12 uses the 10-candlepower level (the smaller flashlight) as the reference point. This 10-candlepower level is abbreviated "FL". + 6 dBFL now means 6 dB (or 4 times) larger than the

10 candlepower reference level, or 40 candlepower (the larger flashlight). As long as the abbreviation (FL) and the power level (10 candlepower) are defined and communicated, then FL can be used indefinitely as a reference level.

Wireless Power Ratios

Figure 2-13 shows examples of three wireless power ratios; each uses 1 Watt (1 W) of power as their reference point. The 1-Watt reference point is abbreviated by the "W," the third letter in "dBW." If, for example, you were told that a transmitter had an output of +3 dBW, you would know that the output power was twice (3 dB means two times) greater than (the + sign indicates a power gain) 1 Watt (indicated by the "W") or a total of 2 Watts output.

Figure 2-13. Power Ratios in dBW (Relative to 1W)



dBm

The most common dB power reference level when working with wireless WANs is dBm. The "m" in dBm stands for 1 milliwatt. A milliwatt is 1/1000 of a watt. There are 1000 mW in 1Watt. 1 milliwatt is 0 dBm. Positive dBm values (such as +30 dBm) indicate power levels greater than 1 mW. Negative dBm values (such as –20 dBm) indicate power levels less than 1 mW.

This is a good place to reaffirm that all absolute-power decibel values contain three things:

- A sign (+ or –) to indicate whether the value is above or below the absolute reference level
- The logarithmic value that represents the ratio of the two powers, in decibels
- The reference-power level, such as the "m" meaning 1 mW

Table 2-1 shows some of the most common wireless power levels (above and below 1 mW).

Table 2-1. Power Ratios in dBm (Relative to 1 mW)

Power Level Relative to 1 mW (0 dBm)	Level (+ or – dBm)	Power (Watts)	Power Abbreviation
4000 times more than 0 dBm	+36 dBm	4Watts	4W (4000 mW)
1000 times more than 0 dBm	+30 dBm	1Watt	1W (1000 mW)
Two times more than 0 dBm	+3 dBm	2 milliwatts	2 mW
0 dBm Reference Level	**0 dBm**	**1 milliwatt**	**1 mW**
1/2 of 0 dBm	–3 dBm	1/2 milliwatt	0.5 mW
1/1000 of 0 dBm	–30 dBm	1/1000 milliwatt	0.001 mW
1/4000 of 0 dBm	–36 dBm	1/4000 milliwatt	0.00025 mW

dBm Calculations and Reference Chart

It is possible to calculate a power gain or a power loss in decibels by using the following formula:

dB = 10log(P2/P1)

This says that the power ratio (in decibels) between any two power levels is equal to 10 times the log of the ratio of the two power levels. For example, if you have a transmitter with a power output of 100 mW and you add an amplifier with a power output of 400 mW, the increase in power level (in decibels) is calculated as follows:

The initial power level (P1) is 100 mW.

The new power level (P2) is 400 mW.

The ratio P2/P1 is 400/100, or 4.

The log of 4 (use a calculator here) is .602.

Ten times .602 is 6.02 or, rounding this off, 6 dB.

The power has increased (P2 was greater than P1), so the final decibel value has a + sign (+6 dB) to indicate that there is a four-times relative power gain.

Going the other way, here is an example of a power loss:

The power output of the same 100-mW transmitter suddenly drops down to 25 mW. P1 is 100 mW and P2 is 25 mW.

The ratio P2/P1 is 25/100 (1/4, or .25).

The log of .25 is –0.602.

Ten times (−0.602) is −6.02, or, rounding off, −6 dB.

The power has decreased (P2 was less than P1), so the final dB value has a − sign (−6 dB) to indicate a power reduction down to 1/4 of the original value.

When you need to convert a power in watts to an absolute power in dBm, use the following formula:

dBm = 10log (Power in watts) + 30

This says that the power ratio in dBm equals 10 times the log of the power in watts plus 30. For example, if you have a transmitter with 1W of output power, the output power in dBm is as follows:

The log of 1 is 0. (Check it on your calculator.)

Ten times 0 is also 0.

Add 30 and the answer is +30 dBm.

1W of power is equal to +30 dBm.

It is usually easier and quicker to use the following reference table (Table 2-2) to find dBm levels; however, from time to time, you should practice using the formulas to keep sharp on how dBm ratios work.

Table 2-2. Decibel (dB) Reference Chart

Power Level (dBm) (Relative to 0 dBm or 1 mW)	**Power Loss (Relative to 0 dBm or 1 mW)**	**Power Gain (Relative to 0 dBm or 1 mW)**	**Comments**
−104	40 percent of 1 ten-billionth of 1 mW		
−100	1 ten-billionth of 1 mW		
−85	3 billionths of 1 mW		Threshold where most receivers start working
−40	1/10,000 of 1 mW		
−30	1/1000 of 1 mW		
−20	1/100 of 1 mW		
−13	1/20 of 1 mW		
−10	1/10 of 1 mW		
−9	1/8 of 1 mW		
−6	1/4 of 1 mW		
−3	1/2 of 1 mW		

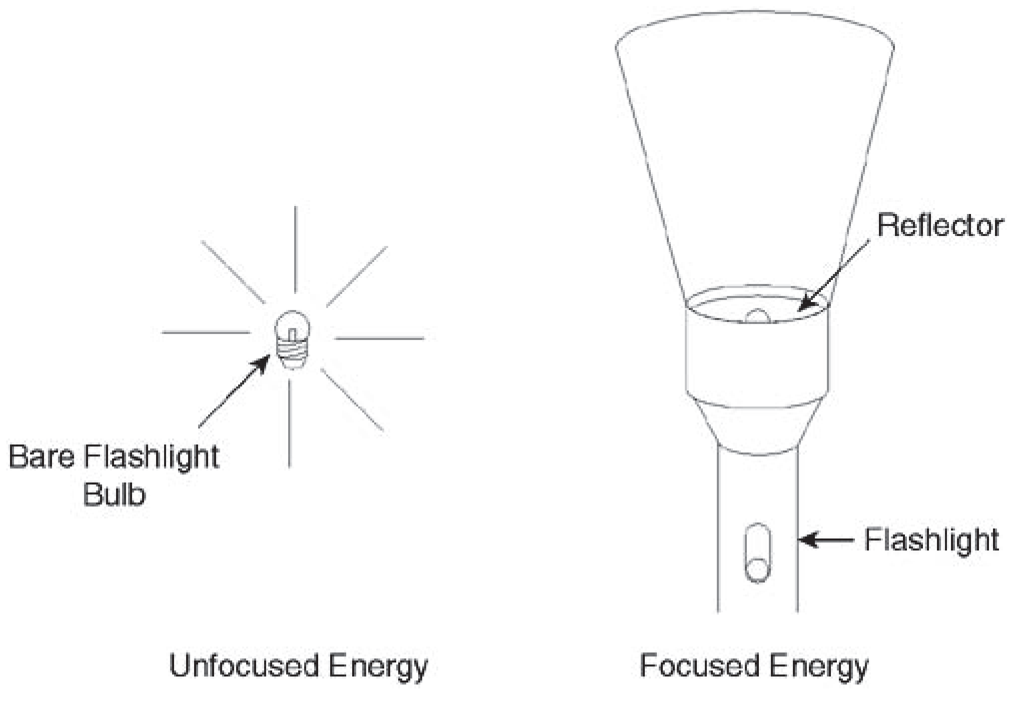
0 dBm	No Power Loss	No Power Gain	0 dBm Reference Level (1 mW)
+ 3		2 times 1 mW	
+ 6		4 times 1 mW	
+ 9		8 times 1 mW	8 mW
+ 10		10 times 1 mW	10 mW
+ 13		20 times 1 mW	20 mW
+ 16		40 times 1 mW	40 mW
+ 20		100 times 1 mW	100 mW
+ 30		1000 times 1 mW	1W
+ 40		10,000 times 1 mW	10W
+ 85		316,000,000 times 1 mW	316 kW (316 kilowatts)
+ 100		10 billion times 1 mW	10 MW (10 megawatts)

Antenna Characteristics

Antennas are the most important part of every wireless WAN. Every WAN covers a wide area. Without an antenna, wireless power travels only a short distance, perhaps a few dozen feet. To successfully deploy license-free wireless WANs, you need to understand the key concepts of antenna directivity and antenna gain.

Antenna Directivity

Antennas radiate wireless power—that is, antennas accept wireless signal energy from the transmission line connected to a transmitter and launch that wireless energy into free space. Antennas focus the wireless energy like a flashlight reflector focuses the light from the flashlight bulb.Figure 2-14 compares the energy radiated from a bare, unfocused flashlight bulb to the focused energy radiated from a flashlight bulb with a reflector behind it.



Notice that in Figure 2-14, the flashlight bulb on the left radiates light energy in all directions. There is no focusing element, and no direction receives more light than any other direction. The light energy radiated from the unfocused flashlight bulb is similar to the wireless energy radiated from a theoretical isotropic antenna. An isotropic antenna radiates wireless energy equally in all directions and does not focus the energy in any single direction.

In contrast to the bare flashlight bulb, the flashlight on the right has a reflector behind the bulb. The reflector focuses the light into a beam that comes out the front of the flashlight. The flashlight does not amplify the power or the total amount of light from the flashlight bulb. The flashlight simply focuses the light so that all of it travels in the same direction. By focusing the light, the flashlight provides more *directivity* (beam-focusing power) for the light energy. Similarly, an antenna provides directivity for the wireless energy that it focuses. Depending on their design, construction, and orientation, antennas focus and radiate their energy more strongly in one favored direction. When they are receiving, antennas focus and gather energy from their favored direction and ignore most of the energy arriving from all other directions.

Antenna Radiation Patterns

Antennas exhibit directivity by radiating most of their power in one direction—the direction of their major (or main) lobe. They radiate only a small amount of power in other directions—the directions of their minor (or side) lobes. Figure 2-15 shows a top view of a directional antenna.

Figure 2-15. Horizontal Radiation Pattern of a Directional Antenna

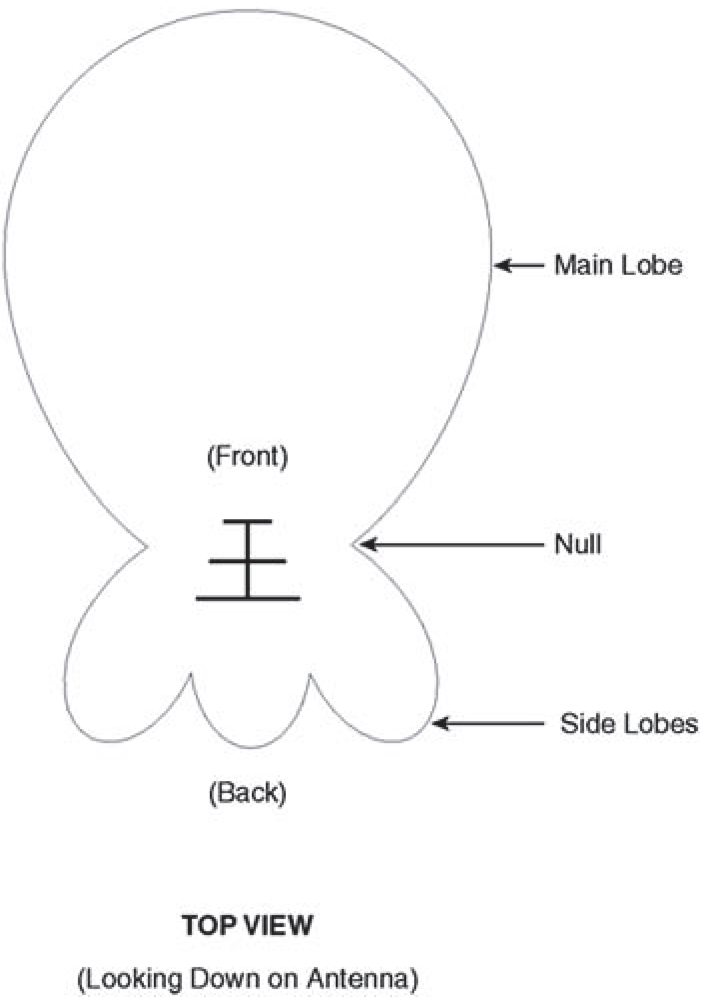


Figure 2-15 illustrates the horizontal radiation pattern of the antenna. It shows both the main and the side lobes. A main lobe exists toward the front of the antenna and several side lobes exist toward the back of the antenna. *Nulls*—areas where no power is radiated—exist to the sides of the antenna.

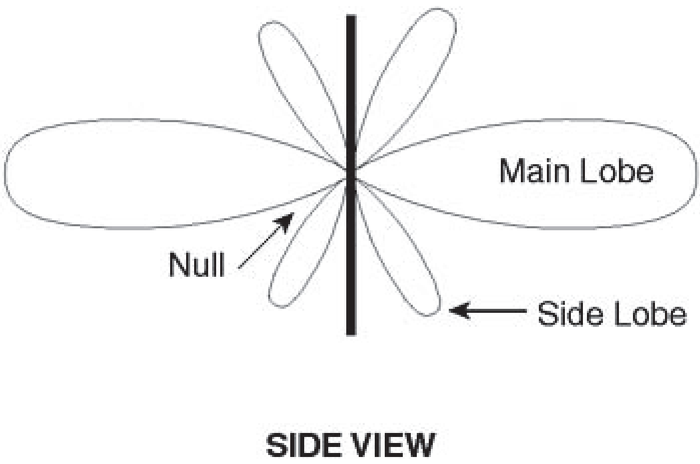
All antennas provide the same directivity on both transmit and receive. An antenna radiates transmitter power in the favored direction(s) when transmitting. The antenna gathers signals coming in from the favored direction(s) when receiving.

NOTE

When receiving, antenna directivity not only gathers incoming signals from the favored direction, but it also reduces noise, interference, and unwanted signals coming in from other directions. Keep this important point in mind as you select antennas for your networks; use antenna directivity to reduce noise coming from unwanted directions.

Figure 2-16 shows another view of antenna directivity: the vertical radiation pattern, when you look at an antenna from the side.

Figure 2-16. Vertical Radiation Pattern of an Omnidirectional Antenna



This view shows an omnidirectional antenna with main and side lobes in the vertical direction. An omnidirectional antenna radiates equally well in all horizontal directions around the antenna but has a main lobe in the vertical direction. This main lobe surrounds the antenna like a doughnut.

Antenna Gain

Measuring the power in the main lobe of an antenna and comparing that power to the power in the main lobe of a reference antenna determines the *gain* of an antenna. Antenna gain is measured in decibels, either in dBi or in dBd.

If the reference antenna is a dipole, the measured antenna gain is in dBd. The "d" in dBd means that the gain is measured relative to the gain of a dipole reference antenna.

If the reference antenna is an isotropic antenna, the antenna gain is measured in dBi. The "i" in dBi means that the gain is measured relative to an isotropic reference antenna.

NOTE

Chapter 5, "Selecting Antenna Systems," defines and discusses isotropic antennas and dipole antennas in more detail. For now, the important point to remember is that your wireless WAN uses antennas that have more directivity (and therefore more gain) than either a simple dipole or an isotropic antenna.

Antenna Spillover

Now that you are familiar with the horizontal and vertical directivity of antennas, there is one more point to keep in mind. Wireless power never stops exactly on a sharp line like the main and the side lobe drawings show. Wireless power tapers off—it declines gradually rather than suddenly. In other words, some transmitter power and some receive capability exist outside of the main and side lobes of each antenna.

Antenna Beamwidth

Beamwidth—the width of the main beam (main lobe) of an antenna—measures the directivity of the antenna. The smaller the beamwidth in degrees, the more the antenna focuses power into its main lobe. The more power in the main lobe, the further the antenna can communicate. Beamwidth is specified in two dimensions:

- Horizontal beamwidth around the antenna
- Vertical beamwidth above and below the antenna

Figure 2-17 shows an example of the horizontal pattern of a directional antenna. This antenna has one main lobe that extends outward from the front of the antenna.

Figure 2-17. Horizontal Beamwidth Showing Half-Power Points

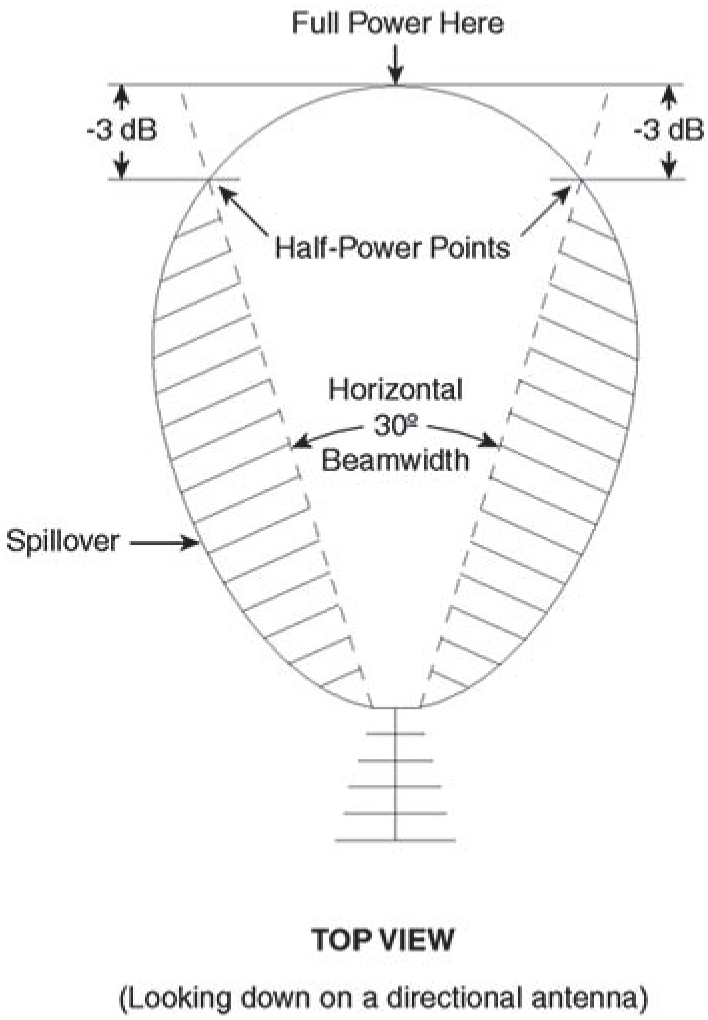
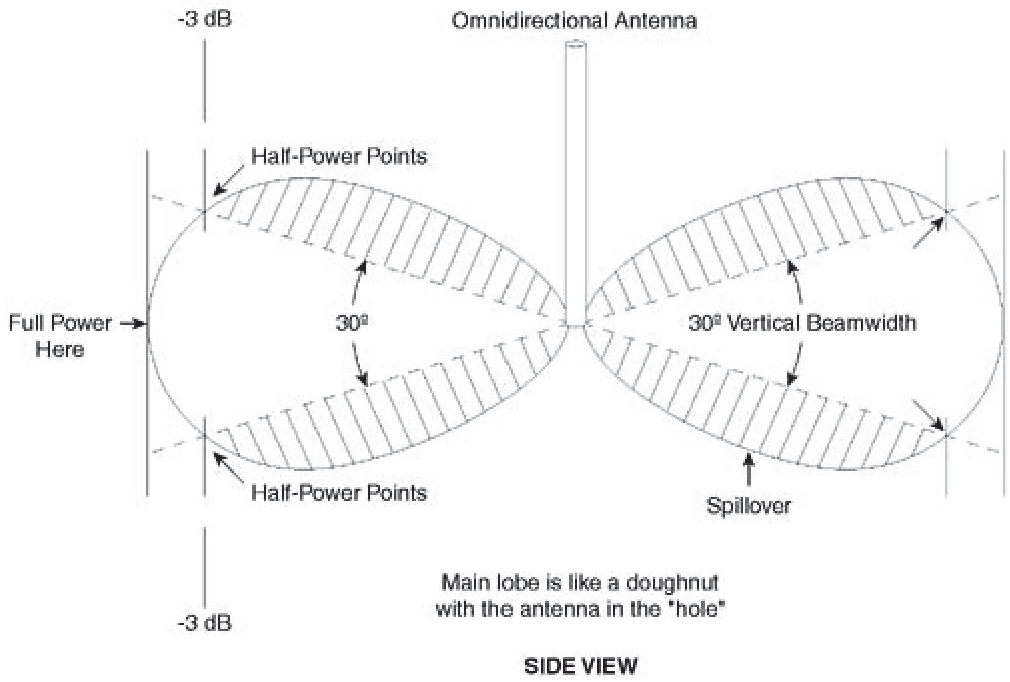


Figure 2-18 shows an example of the vertical pattern of an omnidirectional antenna. This antenna has one main lobe extending outward in all directions (like a doughnut) from the antenna. The antenna sticks up like a pencil through the center of the doughnut.

Figure 2-18. Vertical Beamwidth Showing Half-Power Points



Remember from the discussion of wireless spillover that wireless power does not stop and start exactly along a straight line but declines gradually with distance; therefore, a consistent method is needed to define the width of the main lobe. This method is visible in Figures 2-17 and 2-18. The smooth outlines of the main lobes show the approximate intensity of the wireless power at various distances away from the antenna, but the dotted lines inside the smooth lines enclose most of the power of the main lobe. These dotted lines pass through the *half-power points*—the points on each side of the center of the main lobe where the wireless power is one-half as strong as it is at the center of the lobe. The angle between the two dotted lines defines the horizontal or vertical beamwidth of the antenna.

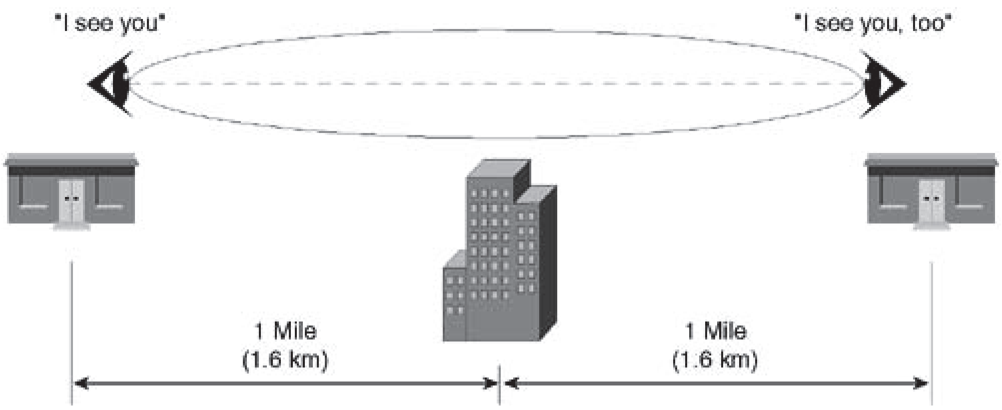
Obtaining Wireless Line-of-Sight Paths

When a wireless signal encounters an obstruction, the signal is always attenuated and often reflected or diffracted. With outdoor wireless WANs, the attenuation from these encounters is usually so great that not enough signal remains to be detected at the other end of the link. When you design a wireless WAN link, it is important to work to achieve a wireless *line-of-sight (LOS)* path. This is a path that has no obstructions to significantly block, diffract, absorb, or attenuate the wireless signal. A wireless LOS path typically requires a visual LOS path plus additional path clearance to account for the spreading of the wireless signal. The following paragraphs describe visual and wireless LOS paths and help you understand how a wireless LOS path is different from a visual LOS path.

Visual LOS Path

If you can see from one antenna to the other, you have a visual LOS path, as shown in Figure 2-19. You might or might not have an unobstructed wireless LOS path.

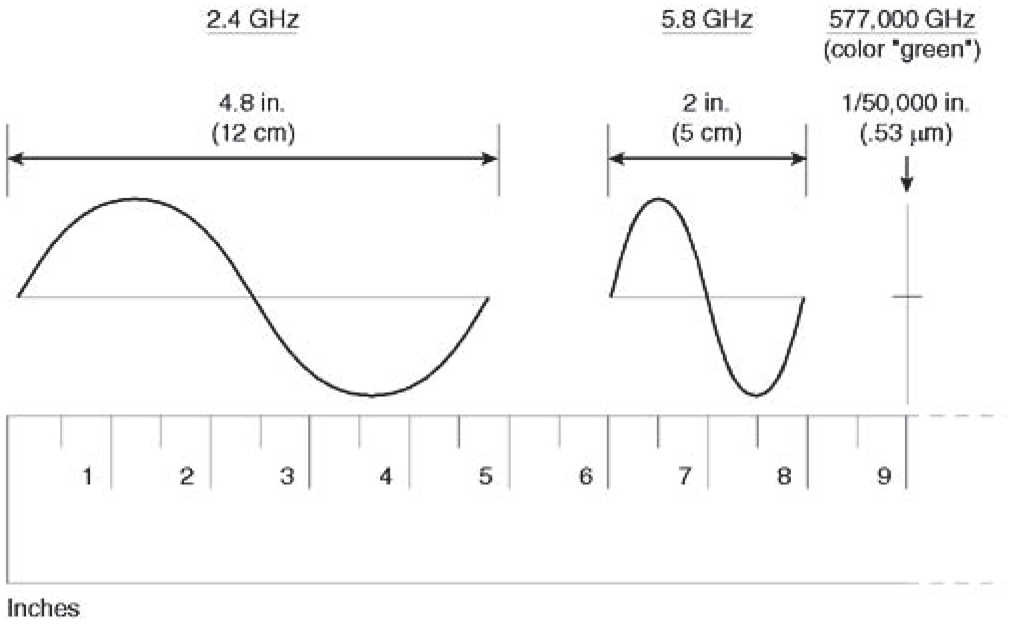
Figure 2-19. Visual LOS Path



Difference Between Visual and Wireless LOS Paths

How can there be a difference between the visual and the wireless LOS paths? There is a difference because of the vast difference between the wavelength of a wireless wave and the wavelength of a visible light wave. Figure 2-20 shows this physical wavelength difference.

Figure 2-20. Difference between Wireless Wavelength and Visible Wavelength



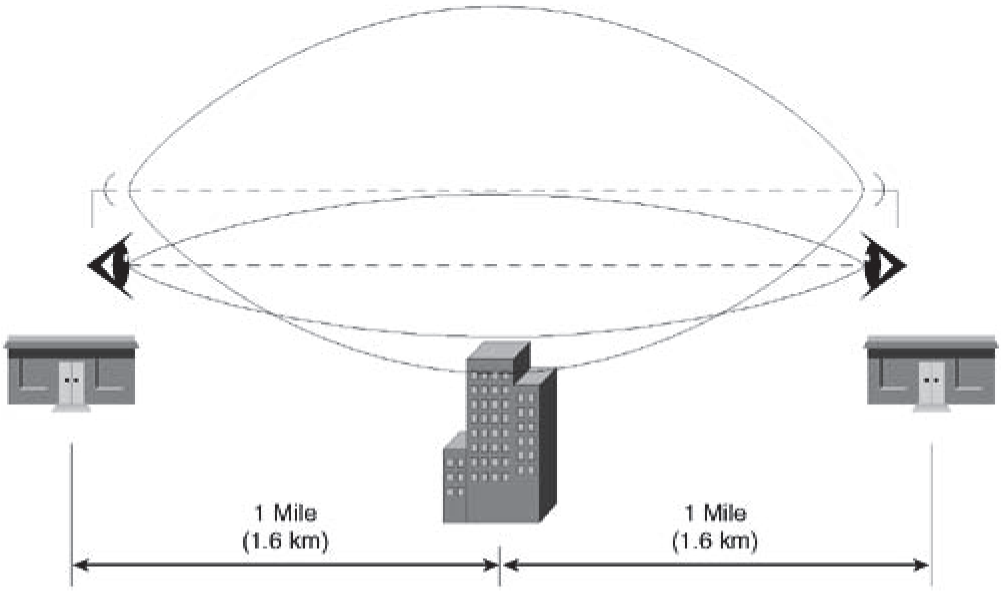
The 2.4-GHz signal has a wavelength of 4.8 in. (12.5 cm). The 5.8-GHz wireless signal has a wavelength of 2 in. (5.3 cm). The light wave, which is green, has a wavelength of 1/50,000 of an inch (.53 micrometers), which is much shorter than either of the wireless signals. The wavelength of the green light wave is only approximately 1/100,000 as long as the wavelength of the 5.8-GHz wireless signal.

NOTE

A lightwave is similar to a wireless wave. Both lightwaves and wireless waves are forms of electromagnetic radiation. Although there is a substantial size difference between the wavelength of light and the wavelength of wireless, they both obey the same laws of physics as they propagate. You might want to think of wireless signals as lightwaves that the eye cannot see.

The shorter the wavelength of an electromagnetic wave, the less clearance it needs from the objects that it passes as it travels from Point A to Point B. The less clearance a wave needs, the closer the wave can pass to an obstruction without experiencing an additional loss in signal strength. The next section shows you how to calculate how close a wave can come to an obstruction without experiencing additional attenuation. This clearance distance is called the *Fresnel zone*. For now, look at the waves in Figure 2-21. Both a green lightwave and a 2.4-GHz wireless wave are traveling the same path and passing by the same building.

Figure 2-21. Visual and Wireless LOS Paths



The short wavelength of the green light wave needs to clear the building only by a fraction of an inch to avoid being attenuated. All of the green light wave easily clears the building. The longer-wavelength 2.4-GHz wireless wave has a larger Fresnel zone and needs to clear the building by quite a few feet to avoid being attenuated. The next section provides more information about calculating the necessary Fresnel zone clearance.

Fresnel Zone

The concept of the Fresnel zone (pronounced "frA-nel"; the "s" is silent) provides a method of calculating the amount of clearance that a wireless wave (or a light wave) needs from an obstacle to ensure that the obstacle does not attenuate the signal. Figure 2-22 shows two ways to calculate the Fresnel zone clearance.

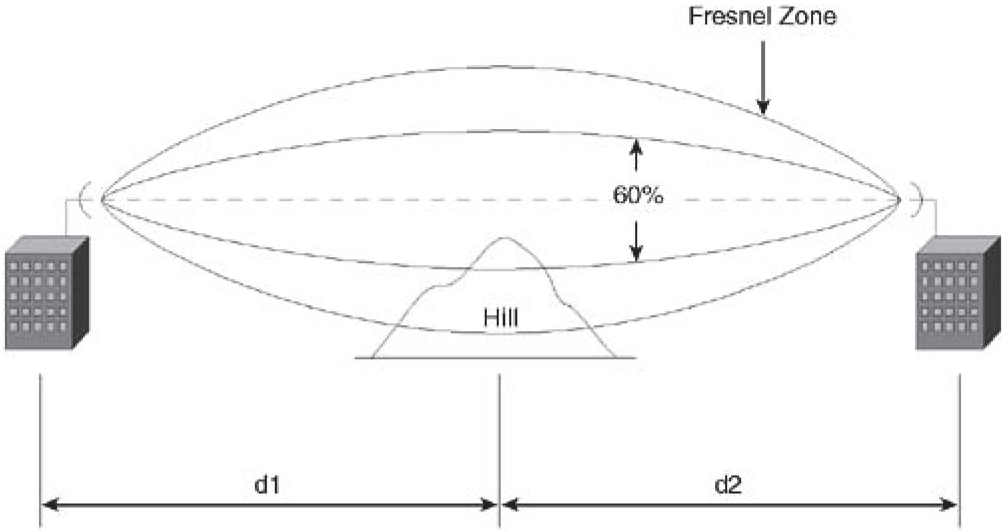
Figure 2-22 - Fresnel Zone Calculations

To calculate Fresnel Zone diameter in either English or Metric units:

$$\text{diam} = \sqrt{\frac{\lambda(d1)(d2)}{(d1+d2)}} \qquad \lambda = \text{wavelength}$$

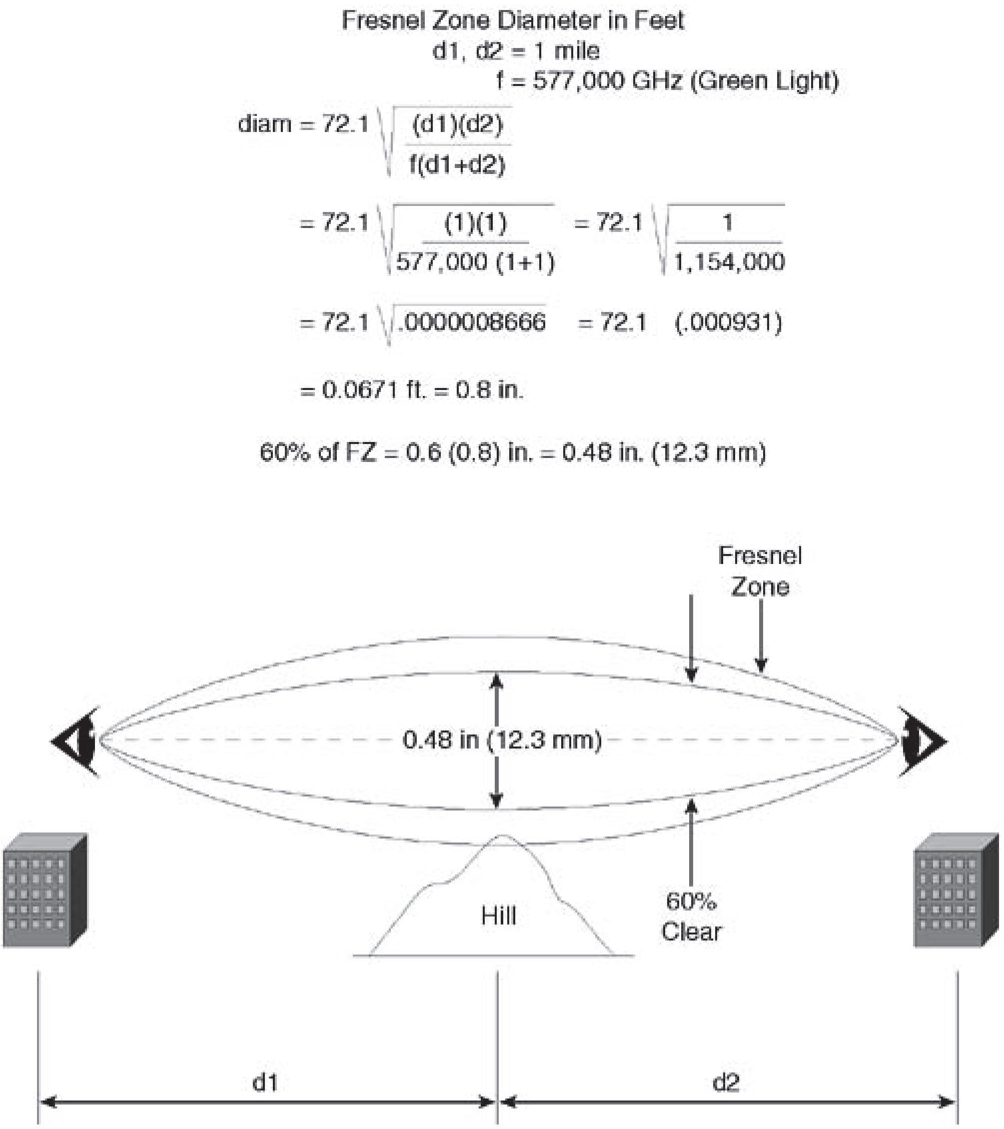
To calculate Fresnel Zone diameter in English units:

$$\text{diam (ft.)} = 72.1\sqrt{\frac{(d1)(d2)}{f(d1+d2)}} \qquad d1,\ d2 = \text{miles},\quad f = \text{GHz}$$



The amount of Fresnel zone clearance is determined by the wavelength of the signal, the total path length, and the distance to the obstacle. The Fresnel zone is always widest in the middle of the path, between the two antennas. At least 60 percent of the calculated Fresnel zone must be clear to avoid significant signal attenuation. In Figure 2-22, the top of the hill extends so far into the Fresnel zone that 60 percent of the Fresnel zone is not clear; therefore, part of the signal will be attenuated. Figure 2-23 shows the calculation of Fresnel zone clearance for a green light wave over a two-mile path with a hill located at the middle of the path.

Figure 2-23. Fresnel Zone Clearance for a Green Light



[Figure 2-24](#) shows the calculation of Fresnel zone clearance for a 2.4-GHz signal over the same two-mile path.

Figure 2-24. Fresnel Zone Clearance for 2.4GHz

Fresnel Zone Diameter in Feet

$d1, d2 = 1$ mile

$f = 2.4$ GHz

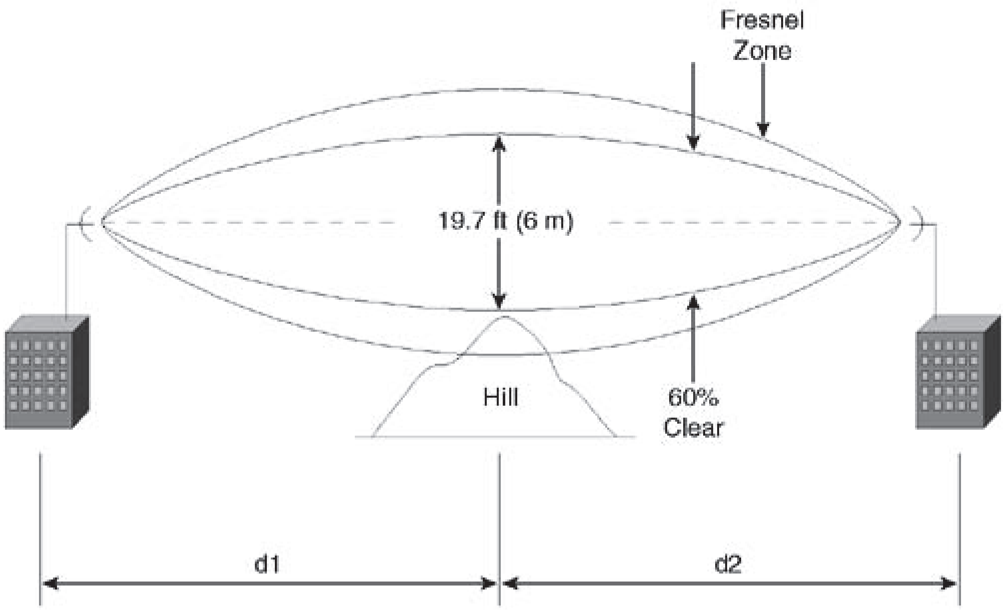
$$\text{diam.} = 72.1\sqrt{\frac{(d1)(d2)}{f(d1+d2)}}$$

$$= 72.1\sqrt{\frac{(1)(1)}{2.4\,(1+1)}} \quad = 72.1\sqrt{\frac{1}{4.8}}$$

$$= 72.1\sqrt{.208} \quad = 72.1\ (.456)$$

$$= 32.9 \text{ ft.}$$

60% of FZ = 0.6 (32.9) ft. = 19.7 ft. (6m)



The green light wave in Figure 2-23 must have a clear Fresnel zone diameter that is at least 0.48 in. (1.22 cm), or 60 percent of the calculated Fresnel zone diameter, to avoid being partially attenuated. The required clearance above the hill (the radius of the calculated 60 percent Fresnel zone diameter) is one-half of the diameter, so the green light wave must clear the hill by one-half of 0.48 in., or by 0.24 in. (0.61 cm).

The 2.4-GHz wireless wave in Figure 2-24 must have a clear Fresnel zone diameter that is at least by 19.7 ft (6 m), or 60 percent of the calculated Fresnel zone diameter, to avoid being partially attenuated. The required clearance above the hill (the radius of the calculated 60 percent Fresnel zone diameter) is one-half of the diameter, so the wireless wave must clear the hill by one-half of 19.7 ft, or by 9.85 ft (3 m).

You can see from Figures 2-23 and 2-24 how a visual LOS path can exist that allows you to see from Point A to Point B with no attenuation, whereas a wireless wave traveling the same path *will* experience significant additional attenuation. Many times in your life, you have heard the expression, "Seeing is believing." Figures 2-23 and 2-24 provide a graphic example that, when you are working with wireless, "Seeing is *not* believing." In other words, just because you can see to the other end of a wireless path, do not believe that you have a clear LOS wireless path.

The clear, visual LOS path does *not* mean that you have an attenuation-free wireless path. You must calculate the size of the Fresnel zone and confirm that the clearance above any obstacle(s) is at least equal to one-half of 60 percent of the Fresnel zone diameter.

Wireless Link Budget

A wireless link budget calculation totals the signal gains, subtracts the signal losses over the length of a wireless link, and predicts whether the signal level that arrives at the receiver will be high enough for the link to work reliably. If the link budget predicts that the link will *not* work reliably, you can examine the gain of each link budget element to see which elements to change and by how much to get the link to work.

NOTE

The following link budget discussion explains the link budget elements as if the signal path went only one way: from Transmitter A to Receiver B. Wireless WAN links in the real world operate in both directions—with a transmitter and a receiver at each end of every link. Therefore, your two-way wireless links have two link budgets—one in each direction. Due to differences in transmitter power or receiver sensitivity, the link budgets in each direction can be different.

The individual link budget elements are as follows:

- Transmitter power output
- Transmitter antenna system coaxial cable (transmission line) loss
- Transmitting antenna gain
- Free-space path loss
- Receiving antenna gain
- Receiver antenna system transmission line loss
- Receiver sensitivity threshold

Transmitter Output Power

The transmitter generates power and delivers it to the transmitter output connector. This power level is specified in dBm—decibels referenced to 1 mW. Typical transmitter output powers range from 10 mW (+10 dBm) to 1W (+30 dBm). Transmitter output power adds to the link budget.

Transmitter Antenna System Transmission Line Loss

The transmitter antenna system coaxial cable or transmission line carries power from the transmitter output connector to the transmitting antenna. Some power is lost in the cable (and in the cable connectors and lightning arrestor) during this process. The smaller the diameter of the cable and the shorter the wireless wavelength (the higher the frequency), the more power that is lost. Typical power losses at 2.4 GHz are 7 dB for each 100-ft length of 3/8-in. diameter cable. The total transmission line loss is subtracted from the link budget.

TIP

Always design your wireless links to minimize the length of the antenna cables. Place the transmitter and the receiver as close as possible to the antenna. By doing this, you maximize the distance and the reliability of your wireless links.

Transmitting Antenna Gain

The transmitting antenna receives power from the transmission line. The antenna focuses and concentrates this power and radiates it toward the distant receiver. This focusing ability results in an effective power gain in the direction of the antenna's main lobe. For 2.4-GHz antennas, gains typically range from +6 dBi to +24 dBi. The transmitting antenna gain adds to the link budget.

Free-Space Path Loss

You must pay a price to use the magic of wireless. That price is that most of the wireless energy that leaves your transmitting antenna is lost—gone forever. Only a tiny fraction of the transmitted energy ever arrives at the receiving antenna. How much of the energy actually arrives? If you have a 2.4-GHz signal that travels 1 mile, your receiving antenna catches less than 1 ten billionth of the energy that you radiated from your transmitting antenna. All the energy that is lost (remember that there is no wire present) is called the *free-space path loss*. The longer the wireless path and the shorter the wavelength of the wireless signal, the higher the free-space path loss. The free-space path loss can be calculated using the following formula:

$$PL = 96.6 + 10 \log(d^2) + 10 \log(f^2) \text{ dB}$$

where f is the frequency in GHz and d is the distance in miles.

If you prefer to use metric units to compute the free-space path loss, here is the formula:

$$PL = 92.4 + 20 \log(f) + 20 \log(d) \text{ dB}$$

where f is the frequency in GHz and d is the distance in km.

Table 2-3 shows several examples of free-space path loss for the 2.4-GHz and 5.7-GHz frequency bands.

Table 2-3. Examples of Free-Space Path

	Free-Space Path Loss at 1 Mile (1.6 km)	Free-Space Path Loss at 2 Miles (3.2 km)
2.4 GHz	104 dB	110 dB
5.7 GHz	112 dB	118 dB

Wireless Is Magic!

If you stop and think about wireless signals for a minute, you will probably agree with the statement, "*Wireless is magic.*" You know—invisible energy waves that carry voices, pictures, and information almost instantly through the air, through you, and even through interplanetary space at distances of thousands, and sometimes millions of miles. Only a tiny fraction of the transmitted energy ever arrives at the receiving end, and yet wireless works! Wireless has seemed like magic to me since I was 10 years old.

Receiving Antenna Gain

The receiving antenna works like the transmitting antenna to concentrate energy, but in reverse. The receiving antenna gathers and concentrates the small amount of power that reaches it at the far end of a wireless link. Think for a moment about the catcher in a game of baseball. The receiving antenna works a lot like the catcher's glove. The larger the glove, the easier it is for the catcher to grab the ball that the pitcher throws. The larger your receiving antenna, the easier it is for the antenna to grab the incoming signal—and the more signal that the antenna grabs. The more signal the antenna receives, the more gain that is added to the link budget.

Receiver Antenna System Transmission Line Loss

The receiving antenna system transmission line carries power from the receiving antenna to the receiver input. Just like with the transmitter antenna system transmission line, some power is lost in the cable during this process. This cable loss subtracts from the link budget.

Receiver Sensitivity Threshold

Each receiver has a *threshold level*—a minimum level of signal where the receiver just starts to operate. The receiver cannot detect signals below this threshold. The receiver antenna system (receiving antenna plus transmission line) must deliver a signal that is at or above this threshold for the wireless link to begin to operate. A typical threshold for an 11-Mbps 2.4-GHz wireless link receiver is around –85 dBm. The smaller (the more negative) this number is, the more sensitive the receiver is. For example, a receiver that has a threshold of –90 dBm is more sensitive than a receiver that has a threshold of –85 dBm.

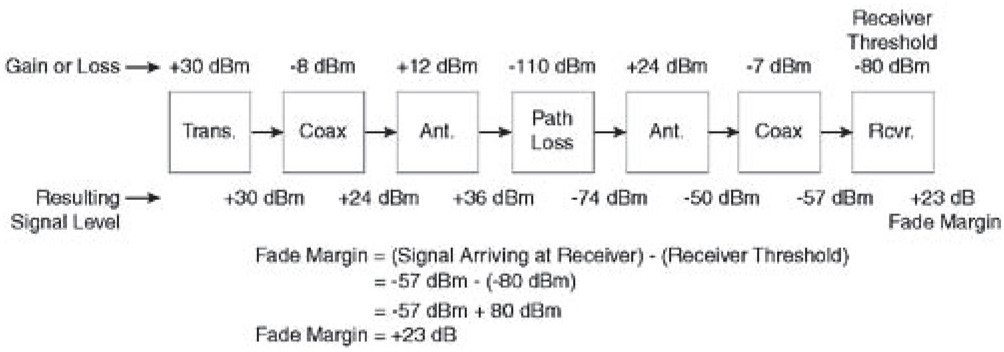
NOTE

There is a tradeoff between receiver sensitivity and receiver data rate. Generally, the higher the data rate of the receiver, the less sensitive the receiver is. For example, a receiver that has a threshold of −85 dBm at a data rate of 2 megabits per second (2 Mbps) might have a threshold of only −80 dBm at a data rate of 11 Mbps. If you compare the sensitivities of two different receivers, be sure you compare them at the same data rate (or bandwidth) setting.

Fade Margin

The reason for calculating a wireless link budget is to design and build a reliable wireless link. Microwave signals normally interact with many objects in their environment, as discussed throughout this chapter. Therefore, fading is a normal condition for all microwave links. To overcome the effects of this fading and to provide reliable service, every microwave link needs a certain amount of extra signal, over and above the minimum receiver threshold level. This extra signal is called the *fade margin*. Another term sometimes used for this extra signal is *system-operating margin (SOM)*. Most wireless equipment manufacturers recommend a minimum fade margin of at least +10 dB to ensure reliable link performance. In general, the longer the link, the more fluctuation in signal levels and the greater the fade margin needs to be. Figure 2-25 shows a sample link budget calculation, including the calculated fade margin.

Figure 2-25. Link Budget and Fade Margin Calculations



By calculating the fade margin, you can predict the reliability of a wireless link. The 2-mile long link shown in Figure 2-25 has a fade margin of +23 dB. +23 dB is 13 dB more than the 10 dB fade margin needed to make this link perform reliably; therefore, you can conclude that this link is going to deliver excellent reliability.

TIP

It is important that you measure the fade margin of every link that you install. Even though the calculated fade margin might be 10 dB or more, it is possible that installation mistakes or local noise conditions could reduce the performance of your real-world links. After you measure the fade margin, you can be sure that the link will operate reliably. Chapter 7, "Installing Outdoor Wireless Systems," covers the fade margin measurement process in detail.

Doubling the Link Distance

Doubling the distance of a wireless link requires four times more signal power, not twice the power like intuition would suggest. Wireless signal power declines as the square of the distance covered. Doubling the distance of the wireless link requires 2^2, or four times, the power. Four times the power is +6 dB (as shown in Figure 2-13).

After you have measured the fade margin on a link, you can predict how far the link can be extended. For example, the fade margin on the 2-mile 2.4-GHz link in Figure 2-25 is +23 dB. Doubling the distance requires four times (+6 dB) more power. Starting from the 2-mile fade margin of +23 dB and subtracting 6 dB leaves a remaining fade margin of +17 dB. This is 7 dB more than the minimum required fade margin of 10 dB; therefore, you can double the distance of this link to 4 miles and still have a reliable link. Of course, these figures are true only if both the 2-mile and the 4-mile link have unobstructed wireless LOS paths.

If you calculate or measure a fade margin of less than 10 dB (or whatever value of fade margin the manufacturer of your equipment recommends), you need to increase the power or reduce the loss of one or more of the system elements shown in Figure 2-25. You can increase the transmitter power, reduce the transmission line loss, use a larger antenna, or use a more sensitive receiver. Any of these improvements will increase the fade margin and improve the reliability of your link.

Tips for Planning Long Wireless Links

The longer a wireless link, the more important it is to properly design and plan the link so that it will provide you with reliable performance. The following sections provide some reminders to help you plan longer, reliable wireless links. Consider your links that are longer than about 7 miles (11 km) to be long links.

Antenna Height

As you know, the earth is curved. The distance to the radio horizon is 7.75 miles (12.5 km) for an antenna that is mounted 30 ft (9 m) above the ground, assuming a k-factor of 4/3.

Longer link distances require that you mount your antennas higher above the ground to extend your radio horizon. You can calculate the distance in miles to the radio horizon by multiplying 1.415 times the square root of the height of your antenna (in feet) above the ground. You can calculate the distance in kilometers to the radio horizon by multiplying 4.124 times the square root of the height of your antenna (in meters) above the ground.

Fresnel Zone

You know that a wireless wave needs a clearance (Fresnel) zone from objects that it passes close to. You also know that the size of this Fresnel zone is largest in the middle of a wireless path and that the Fresnel zone size increases both with longer distances and with higher frequencies.

The longer your link, the higher above the earth your antennas need to be mounted so that the part of your wireless wave closest to the earth can maintain an adequate Fresnel zone clearance above the earth.

Atmospheric Refraction (k-Factor)

You have learned that the k-factor varies depending on the temperature, the water vapor, and the barometric pressure of the atmosphere. The k-factor is usually greater than 1, bending microwave signals around the earth and extending the radio horizon beyond the visual horizon by approximately 15 percent. Sometimes, however, the k-factor can be less than 1, causing microwave signals to bend away from the Earth and causing the radio horizon to be closer than the visual horizon.

The longer a wireless link, the more regions of the atmosphere the wireless wave passes through and the more frequently the k-factor changes. These k-factor changes result in more frequent changes in your wireless path and more frequent fading. You need to allow a higher fade margin.

Link Budget

You remember that a reliable wireless link requires each receiver to receive a signal that fits both of the following conditions:

- Is above the receiver threshold
- Is high enough above the threshold to fade (usually at least 10 dB) and still remain above the threshold

The transmitter power, transmission line loss, antenna gain, and receiver sensitivity might need to be adjusted to maintain an adequate fade margin. The longer your wireless link, the more variation in signal strength and the more fade margin you need.

A rule-of-thumb that I like to use is to add 1 decibel of additional fade margin (above the original 10 dB) for every additional mile beyond 10 miles of link distance.

Long-Link Strategies

To successfully design, plan, install, and test long links, consider doing some (or all) of the following:

- Get help from wireless equipment vendors to select equipment and antenna systems with appropriate fade margins.
- Consult advanced wireless engineering textbooks (see the books in Appendix B, "Wireless Hardware, Software, and Service Provider Organizations").
- Consult with people (both paid and unpaid) who have more hands-on wireless experience than you do.
- Install the links carefully; pay particular attention to mounting the antennas firmly and aligning them correctly.
- Allow more time to test longer wireless links before placing them into service.
- Monitor your long links to be sure that they are providing reliable service.
- Enjoy the journey. Although long wireless links require you to spend more time and energy to do it right, the rewards for you in personal satisfaction are substantial and long lasting. Have fun with wireless—after all, whether you realize it or not, wireless is having fun with you.

Review Questions

1: How does the wavelength of a wireless signal change as the frequency of the signal increases?

2: When a 2.4-GHz signal encounters an obstruction, what happens?

3: Does ionospheric reflection occur at microwave frequencies?

4: How is wireless power measured?

5: In the abbreviation dBm, what does the "m" stand for?

6: If 1Watt equals +30 dBm, then 2W equals how many dBm?

7: The main lobe of a non-isotropic antenna radiates power in which direction?

   A. In one horizontal direction

   B. In two horizontal directions

   C. Equally in all horizontal directions

   D. Both A and C

8: If you can stand at one antenna and see the antenna at the other end of a wireless link, do you have a line-of-sight wireless path?

9: Tripling the distance on an unobstructed wireless link requires increasing the power how many times?