

Antenna Concepts and Building a "Coffee Can" Antenna

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Whether your wireless system is a simple home office setup or a large-scale outdoor wireless network, the antenna system is the most important, but often most overlooked, aspect of the system. The antenna system is often the “make or break” factor for a successful wireless transmission. Poor antenna selection or design can lead to frustration and intermittent connectivity problems. This translates into poor throughput performance and frustrated wireless users.

In this article, we explore the important issues surrounding antenna selection for any 2.4 or 5 GHz unlicensed wireless system. You’ll get all the information you need to achieve the best performance possible. We’ll examine many types of commercially available antennas, and you’ll see how you can build your own antenna as an alternative, using inexpensive materials from the local hardware store.

Topics in this Article:

- ◆ Before You Start: Basic Concepts and Definitions
- ◆ Building a Waveguide “Coffee Can” Antenna
- ◆ The Future of Antennas

At the conclusion of this article, you should:

- ◆ Understand the different decibel (dB) measurements and how to use them correctly
- ◆ Understand the Federal Communications Commission (FCC) rules and power output requirements for operation in the 2.4 and 5 GHz bands
- ◆ Understand the different types of antennas and use Figures of Merit (FOMs) to determine the best choice
- ◆ Understand the “3 dB” rule and its importance in determining system performance
- ◆ Understand “wavelengths” and use a formula to determine how long an antenna needs to be for a given frequency
- ◆ Determine system performance requirements using the link budget calculation
- ◆ Estimate the “fresnel zone” to determine antenna height and orientation
- ◆ Understand how different building materials can affect performance
- ◆ Be aware of safety precautions such as lightning arrestors, proper grounding techniques, and building code adherence

Before You Start: Basic Concepts and Definitions

Before you can install and/or construct any antenna, there are several terms and calculations with which you should be familiar. While a degree in physics is not necessary, a basic understanding

of physics is helpful.

An antenna is simply a passive transducer that radiates energy (*gain*) into space. Antennas do not actually amplify the signal; they simply change the shape of the energy pattern being radiated. You should be able to select or construct a basic antenna for your use once you understand the basics of antenna design, construction, and operation.

The decibel is the most important unit of measurement when looking at antenna performance. The decibel (or dB) is the basic unit used for radio frequency (RF) power measurement. Table 10.1 lists decibel power levels in relation to wattage levels.

Table 10.1 Transmit Power in Decibels

Watts	Decibels
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1/1000	0 dB
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1/100	10 dB
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1/10	20 dB
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1/4	24 dB
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1/2	27 dB
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1	30 dB
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2	33 dB
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5	37 dB
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We use decibel measurements because signal strengths vary logarithmically, not linearly. A logarithmic scale allows simple numbers to represent large variations in signal levels. You'll see it's also very useful in calculating system gains and losses. In the following sections, we've included brief definitions of all the terms we'll be using in this article:

- ♦ **↓dB** Decibel. The basic unit of measurement that represents the ratio of two signal levels.
- ♦ **dBm/dBW** Decibel milliWatt. This measurement is used to represent power, with 0 dBm defined as 1 milliWatt. For larger signals, there is also dBW, a reference to 1W. Small signals are represented as negative numbers, (for example, -95 dBm). When referencing commercial Wi-Fi devices, power output is normally given in dBm. Many WLAN PCMCIA cards and some Access Points (APs) have a power output of +17dBm (50mW). There is also usually a Receive Signal Sensitivity Indicator (RSSI) measurement listed in dBm (for example, -95dBm).

- ♦ **dBd** Decibel dipole. The output power (gain) an antenna has over a dipole antenna at the same frequency. A dipole (two-pole) antenna is a ½ wave antenna used as a reference against all other antennas. It is a reference known as 0 dBd (zero decibel referenced to dipole). The dBd measurement is usually used only with antennas below 1 GHz.
- ♦ **dBi** Decibel isotropic. This measurement is used for antennas above 1 GHz .A dipole antenna has 2.14 dB higher gain than the 0 dBi dipole reference. If antenna gain is given in dBd, not dBi, add 2.14 to convert to the dBi rating.

NEED TO KNOW...RF POWER

There are several basic rules that you should know when working with antennas, RF power, and expected signal strength. The “3 dB” rule is perhaps the most important rule when dealing with RF (signal) power. It states that for every 3 dB increase in level, the power is *doubled*. For every 3 dB decrease, the power is cut in half. Similarly, every 10 dB increase in level is 10 times the power, and every 10 dB decrease in level results in 1/10 the power. This is sometimes referred to as the “rule of 3s and 10s.”

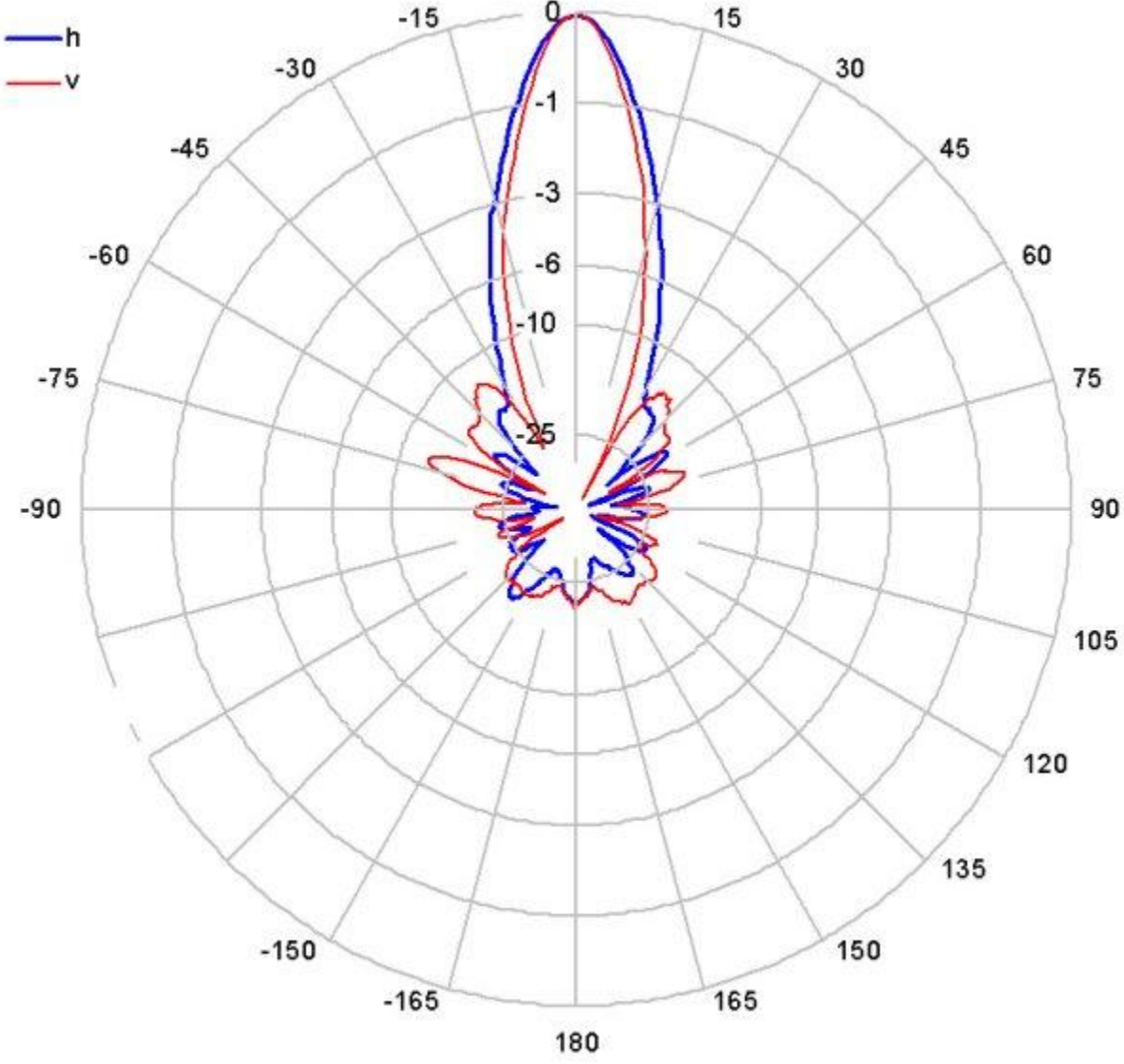
Once you understand the different decibel measurements, it is easy to understand Figures of Merit (FoMs) when working with antennas. FOMs are attributes that describe an antenna’s performance characteristics. The FoMs are listed as part of every antenna’s specifications. Important FoM attributes like *gain* and front-to-back ratio are listed in dB or dBm. There are many other RF terms and figures that use decibel reference and values (these terms are explained in greater detail later in this article). Once you are familiar with FoMs in general, it will be easy to recognize the important features of antennas and choose the best antenna for your application.

Effective Isotropic Radiated Power (EIRP) is defined as the power found in the *main* lobe of the antenna relative to an Isotropic radiator with 0 dB of gain. The EIRP is calculated by taking the antenna gain (in dBi) plus the power (in dBm) inbound from the transmitter. For example, a 9dBi antenna fed with 26 dBm of power would have an EIRP of 35 dBm.

$$9 \text{ dBi} + 26 \text{ dBm} = 35 \text{ dBm} (3.2\text{W})$$

The chart on the left in Figure 10.1, known as a *Smith* chart, shows the propagation area of a Yagi antenna (image on the right of the figure). A Smith chart is included with any antenna specification and represents the radiation pattern of the antenna. It also shows the front-to-back ratio, and the “side lobes,” which are the smaller, less powerful radiation patterns on each side of the main lobe.

Figure 10.1 Representation of a Unidirectional Yagi Antenna Radiation Pattern



The top pattern represents the main lobe and transmit gain. The lower pattern the back lobe. The difference (in dB) between the front and back lobe is called the front-to-back ratio.

A WORD ABOUT ANTENNA GAIN AND COVERAGE

Since the EIRP is in the *main* antenna lobe only, antenna selection is critical.

When using a high-gain omni antenna (8–12 dBi), the propagation angle is very flat and narrow. Placing the antenna too high will cause the main lobe to pass over the intended target antenna. The irony here is that height is required to clear obstructions, a.k.a. Line-of-Sight, from the Wireless Point of Presence (WiPoP) path to the receivers. Higher gain omni antennas have a flatter, “pancake” shape, while lower gain omni antennas tend to have a wider “donut” shaped pattern.

It may be necessary to use a unidirectional antenna and “down tilt” that concentrates the energy (signal) in a more focused area. Unidirectional antennas direct energy in one direction by radiating the entire signal in a concentrated area instead of 360 degrees like an omni. Table 10.2 lists antenna types and associated values in dBi (gain). Figures 10.2 through 10.6 are images of these antenna types.

Table 10.2 Typical Antenna Types and Gain Values for Off-the-Shelf Antennas

Antenna Type Gain (dBi as we’re dealing with >1GHz) Freq.

Unity gain Omni 0 dBi

Low Gain Omni 2–6 dBi

High Gain Omni 8–12 dBi

4 x 6” Panel (Unidirectional) 7 dBi

Small Yagi 10 dBi

8”– 10” Panel (Uni) 13 dBi

12” Panel (Uni) 16 dBi

Long Yagi 16 dBi

18” Parabolic Dish 19 dBi

18” Diagonal Mesh/Grid Antenna 21 dBi

24” Diagonal Mesh/Grid Antenna 24 dBi

Figure 10.2 8 dBi Omni



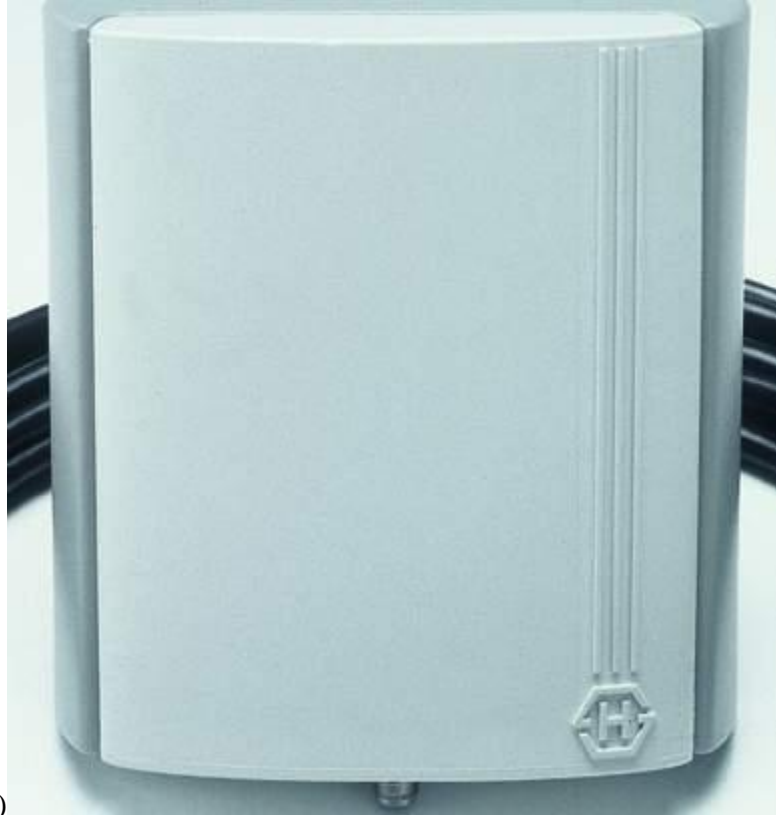


Figure 10.3 8 dBi Uni (Panel)



Figure 10.4 Large Omni

Figure 10.5 24" x 36" Mesh Grid Antenna (21 dBi)



Figure 10.6 Yagi (12 dBi)

NOTE... INTERESTING ANTENNA

An interesting antenna type has been developed by cantenna.com. This “super cantenna” resembles a Pringles can antenna, is linearly polarized, and features a gain of 12 dBi and a beam width of 30 degrees. You can learn more about this innovative, low-cost product at www.cantenna.com.



Federal Communications Commission

A common misconception when using ‘unlicensed’ equipment is that there are no rules covering the operation of such equipment. While there are no license requirements, the FCC does have some regulations with respect to the maximum power output levels when using unlicensed equipment. Part 15 of the FCC’s rules for radio equipment lists the specific power requirements. We discuss the pertinent limitations in this section.

The FCC has relaxed the rules on EIRP limits for Point-to-Point (PtP) systems. This has increased the choices of antennas and extended the range of PtP systems. The EIRP for a 2.4–2.5 GHz PtP system is now 36dBm (an amazing 4 watts!) We must calculate a link budget to determine the total EIRP, and remain in FCC compliance. The FCC allows *only* 30 dBm (1W) EIRP for Point-to-Multipoint (PtMP) communications. This limits the antenna choices and makes the calculation of system output very important. However, for most off-the-shelf commercial equipment using attached antennas, the output is 50–200 mW. This coupled with a 6 dBi antenna is well below FCC limits. Using the previous charts and remembering the rules will help you calculate power levels and remain in compliance. A good rule to remember for 2.4 GHz PtP systems is that for every 3 dBi of antenna gain over 6 dBi, the transmitter power output must be reduced by 1 dB. For 2.4 GHz PtMP, every 3 dBi of antenna gain over 6 dBi must be met with a 3 dB reduction in transmitter power.

The 5 GHz band has various output power limits. The limits depend upon the sub-band within the 5 GHz band in which you’re operating. The lower portions of the 5 GHz unlicensed band are between 5.15 and 5.25 GHz The output for these devices is fixed at a maximum of 50 mW. The 5.25–5.35 GHz middle sub-band has a power limit of 250 mW.

The 5.725–5.825 GHz upper band is normally used for high bandwidth (T-1 > OC-3) transmissions associated with microwave radio. This band has most recently been adopted by many Wireless Internet Service Providers (WISPs) as a high data rate “backhaul” solution. This removes congestion from the 2.4 GHz (DSSS) frequency band and allows much more bandwidth (users) to be concentrated for transmission.

The Link Budget is the calculation of the losses and gains (in dB) for the complete RF system, and is determined using a simple formula that combines all the power and gain figures for both sides of a link.

$$\text{Link Budget} = P(t) + \text{TX}(G) + \text{Rx}(G) + \text{Rx} - \text{Path Loss}$$

Where:

- $P(t)$ = power of transmitter (e.g., 17 dBm)
- $\text{TX}(G)$ = transmit antenna gain (e.g., 6 dBi)
- $\text{RX}(G)$ = receive antenna gain (e.g., 6 dBi)
- Rx = Receive Sensitivity of receiver

The numbers are the *gain* figures used in a link budget. We will also look at the loss or attenuation levels—caused by cables, connectors, and so forth—that *must* also be factored into the final Link Budget calculation. (A good online calculator can be found at www.beagle-ears.com/afar-www/v01/RF_calc.htm.)

Path loss, the amount of loss in dB that occurs when a radio signal travels through free space (air), is also known as Free Space Loss (FSL). FSL can be calculated using the following formula:

$$\text{FSL (isotropic)} = 20\text{Log}_{10} (\text{Freq in MHz}) + 20\text{Log}_{10} (\text{Distance in Miles}) + 36.6$$

Additional factors you should consider when determining your link’s requirements:

- **Radiation pattern/propagation angle** The propagation angle is given in degrees and denotes how much area in degrees an antenna broadcasts its signal. Example: Vertical angle = 45 degrees, Horizontal angle = 7 degrees. Search the Internet for various antenna manufacturers to find examples of Smith charts that represent various propagation angles.
- **↓Polarity** All antennas have a “pole” (short for polarity), which can be horizontal, vertical, or circularly polarized. Polarity indicates the angle of the RF wave’s propagation in reference to an H/V/C plane. You *must* insure that all Wi-Fi systems you want to communicate with have antennas on the same pole. The difference in H/V poles (if for example, one antenna is horizontally polarized and the other is vertically polarized) is a loss of 30 dB.

- ♦ **Vertical/horizontal beam width** This is the angle of the RF “beam” referenced to the horizontal or vertical plane. Typically, the higher the gain, the more focused (narrow) the beam. Example: A 24 dBi antenna commonly has an 18-degree beam width, vs. a 9 dBi antenna, which will have a 45- to 60-degree beam width.
- ♦ **Fresnel zone** The Fresnel zone is the propagation path that the signal will take through the air. The Fresnel zone can be determined using the following formula. The Fresnel zone is important when installing Line-of-Site equipment, because if the Fresnel zone or any part of it is obstructed, it will have a direct and negative effect on the system connectivity.

Fresnel Zone Calculation = $72.1 * \text{SqrRoot}(\text{Dst1Mi} * \text{Dist2Mi} / \text{Freq (in GHz)}) * \text{Distance-in-Miles}$

You can find a good online Fresnel zone calculator at www.radiolan.com/fresnel.html.

- ♦ **↓Front-to-back ratio** An antenna’s front-to-back ratio is typically given in dB and denotes how much signal is projected behind the antenna, relative to the signal projected in front of the antenna (in the main lobes). The lower the front-to-back ratio, measured in dB, the better. The reason is that you don’t want excessive signal propagating from the rear of the antenna.
- ♦ **Link Margin** The Link Margin, sometimes called System Operating Margin (SOM), is the minimum difference between the received signal (in dBm) and the sensitivity of the receiver required for error-free operation. In many systems, this is also referred to as the Signal-to-Noise-Ratio (SNR).

Table 10.3 Fade Margins for Various Link Distances

Distance (Miles)	Conservative Fade Margin (dB)
0.5	4.2
1	7.5
2	10.8
3	12.75
4	14.1
5	15.2
10	18.5
15	20.4

In many newer radios, a Signal to Noise Ratio (SNR) specification is used instead of the RSSI reading/measurement. Motorola's 5 GHz Canopy system requires only 3 dB SNR to achieve connectivity, while Alvarion's EasyBridge 5.8 GHz system expects a minimum 10 dB SNR for connectivity. Several good Web sites provide calculators for Fresnel Zone, Fade Margin, and Path Loss:

- ♦ www.zytrax.com/tech/wireless/calc.htm
- ♦ www.dataradio.com/mso/tsan002rf.xls
- ♦ www.andrew.com/products/antennas/bsa/default.aspx?Calculators/qfreespace.htm

NEED TO KNOW...THE BIGGER THEY ARE, THE FARTHER THEY CALL

Size does matter! It may be necessary to increase the size of your antenna if you find that you can't quite get the desired distance or throughput from your link. Remember the "6 dB" rule when thinking about antennas (size), propagation distance, and path loss. The rule states that each time you double the distance from transmitter to receiver, the signal level decreases by 6 dB.

Attenuation in Cables, Connectors, and Materials

Attenuation is the reduction in signal due to cable length, connectors, adapters, environment, or building materials. Often, indoor wireless systems will suffer extreme attenuation due to metal cross members or rebar within walls. It is important to consider the type of building materials used for either indoor systems or systems where client antennas are mounted indoors while AP antennas are outdoors at a distance. It is also important to take the figures for cable and connector loss into account when calculating your link budget.

Table 10.4 lists common building materials and the expected loss in dB.

Table 10.4 Attenuation Factors for Various Materials

Material Attenuation Factor/dB Loss

Plasterboard wall 3 dB

Glass wall with metal frame 6 dB

Cinder block wall 4 dB

Office window 3 dB

Metal door 6 dB

Metal door in brick wall 12.4 dB

The most common cables used in unlicensed wireless include:

- ♦ **RG-58** Commonly used for pigtails and is not recommended for long runs. Loss at 2.4 GHz per 100 feet = 24.8 dB.
- ♦ **LMR 195** Identical in gauge to RG 58, but with less loss. Loss at 2.4 GHz per 100 feet = 18.6 dB.
- ♦ **LMR 400** Used most commonly for antenna runs over 6 feet. Loss at 2.4 GHz per 100 feet = 6.6 dB.
- ♦ **LMR 600** The best, but also the most expensive cable. Loss at 2.4 GHz per 100 feet = 4.3 dB.

The loss quoted for any cable specification is generally per 100 feet. The loss factor is important to remember when installing outdoor systems. For both cables and connectors, the loss factor is commonly listed as “insertion loss.” A good online cable loss calculator can be found at www.timesmicrowave.com/cgi-bin/calculate.pl.

Figures 10.7 through 10.11 are examples of connector types used in unlicensed wireless systems. In most cases, it is assumed that the loss per connector is between .2 and 1.0 dB. Many people use .5 dB of loss per connector as a general rule of thumb. If a connector is suspect and produces more loss, it is either of poor design or is faulty.

Figure 10.7 “N” Type

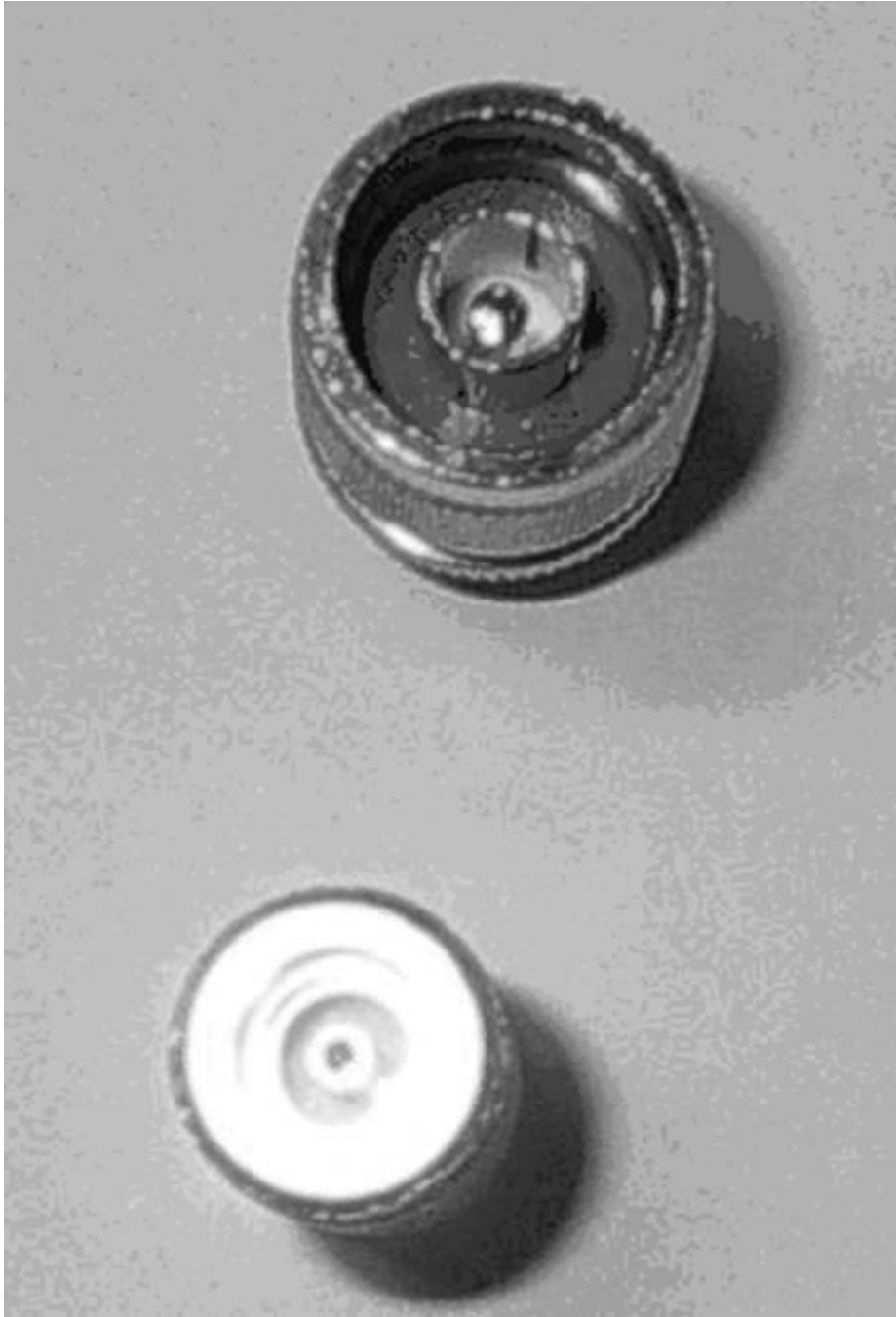




Figure 10.8 SMA

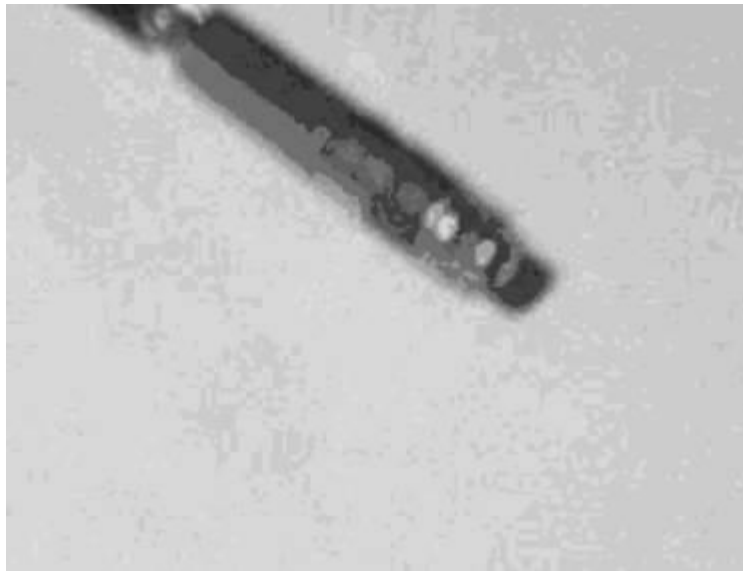


Figure 10.9 MMCX



Figure 10. 10 TNC

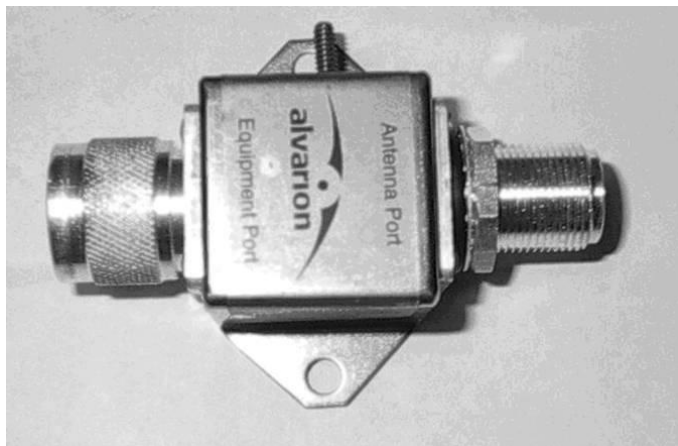


Figure 10.11 Reverse Polarity (R/P) TNC

System Grounding and Lightning Protection

Since an antenna is a metal object with a corresponding wire connection and is elevated several feet in the air, it unfortunately makes an excellent lightning rod. It is always recommended that you use both an earth ground and a lightning arrester when installing antennas outdoors. The earth ground should be connected to the antenna mast and the antenna tower to ground electrical charges (lightning). It is also recommended to use a lightning arrester to protect radio equipment. The insertion loss of a good lightning arrester is commonly a maximum of 1.5 dB.

Figure 10. 12 Common Lightning Arrester for 2.4 GHz

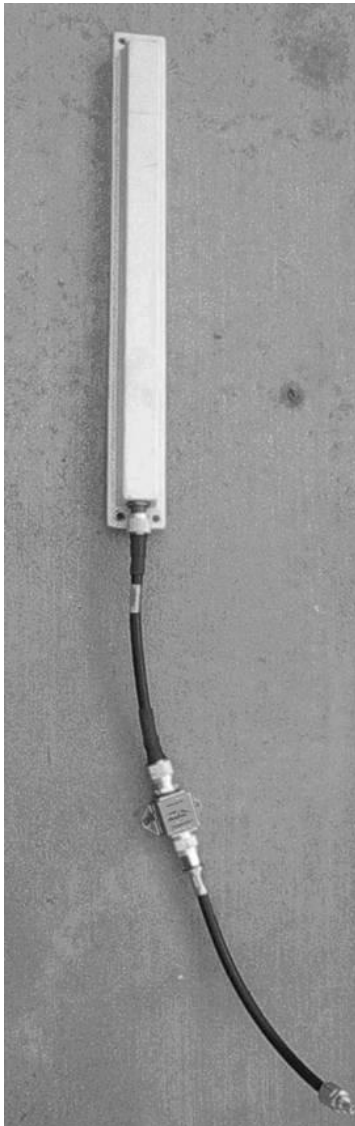


WARNING: HARDWARE HARM

The labeling on the lightning arrestor denotes the antenna port connection and the equipment (radio) port connection. Connecting the device in reverse may result in damage to equipment and systems. It is also quite probable that the system will not work or performance will be severely degraded.

The lightning arrestor should be located between the radio equipment and the antenna. Figure 10.13 is an example of a small unidirectional antenna with jumper plus a lightning arrestor and pigtail assembly. This could be mounted on a pole, on the side of an eave, or in conjunction with an outdoor box containing the radio.

Figure 10.13 Lightning Arrestor Mounting Scenario



WARNING: HARDWARE HARM

It is always recommended that proper grounding techniques and lightning protection devices be used when installing any antenna system outdoors. Always use caution when installing antennas, especially when using extended masts or building tower sections. It should be prominently displayed on or near all outdoor antenna installations.

Building a Coffee Can Antenna

If you'd rather not purchase antennas from one of the many vendors available, there are many Do-It-Yourself designs available. For those of you who are interested in experimenting, we'll start with building a coffee can antenna. The coffee can antenna hack we'll be describing here will provide up to 11 dBi of gain at 2.4 GHz.

Preparing for the Hack

Before constructing any antenna, there are two important formulas you need to know. The first is a Frequency/Wavelength formula. For our purposes, we'll use Megahertz instead of Gigahertz.

This tells us the wavelength for our coffee can antenna. For example, if we use 2.45 GHz (the middle of 2.4 GHz band), we get a wavelength of $= .4016$ feet ($984/2450$).

The materials required for this hack are:

- Garden-variety coffee can as shown in Figure 10.14 (Folgers or Maxwell House will do). The best cans will be 3 to 3.5 inches in diameter, as long as possible.
- 1.2" brass rod or 12-gauge solid core electrical wire
- Type "N" bulkhead connector
- Four very small nuts and bolts (long enough to extend through the connector and can)

Figure 10.14 Coffee Can



Performing the Hack

To perform the hack:

1. Drill a ½" hole, for the type "N" connector.

If your can has a 3" diameter, the hole should be 3.75" from the bottom of the can.

If your can has a 3.25" diameter, the hole should be 2.5" from the bottom of the can.

If your can has a 3.5" diameter, the hole should be 2.07" from the bottom of the can.

If your can has a 3.75" diameter, the hole should be 1.85" from the bottom of the can.

If your can has a 4" diameter, the hole should be 1.72" from the bottom of the can.

2. Tin the bulkhead connector by applying a light coat of solder to the "inside" center pin (the opposite side of where the cable is connected).

3. Cut a brass rod 1.2" in length and solder the connector to the brass rod. You can also use solid 12-gauge electrical wire. Figure 10.15 shows "helping hands," which can be useful when you need an extra set of hands for soldering. Figure 10.16 shows a completed element.

4. Insert the bulkhead connector into the can (the wire/rod portion goes in the can; the other side, where the cable attaches, goes outside the can). Use the four bolts/nuts to secure the connector in place. You may need to drill some small pilot holes in the can to put the bolts through. Figure 10.17 shows a completed coffee can antenna.

Figure 10.15 “Helping Hands” Helpful when Soldering Wire and Connectors



Figure 10. 16 The Completed “Waveguide” Element

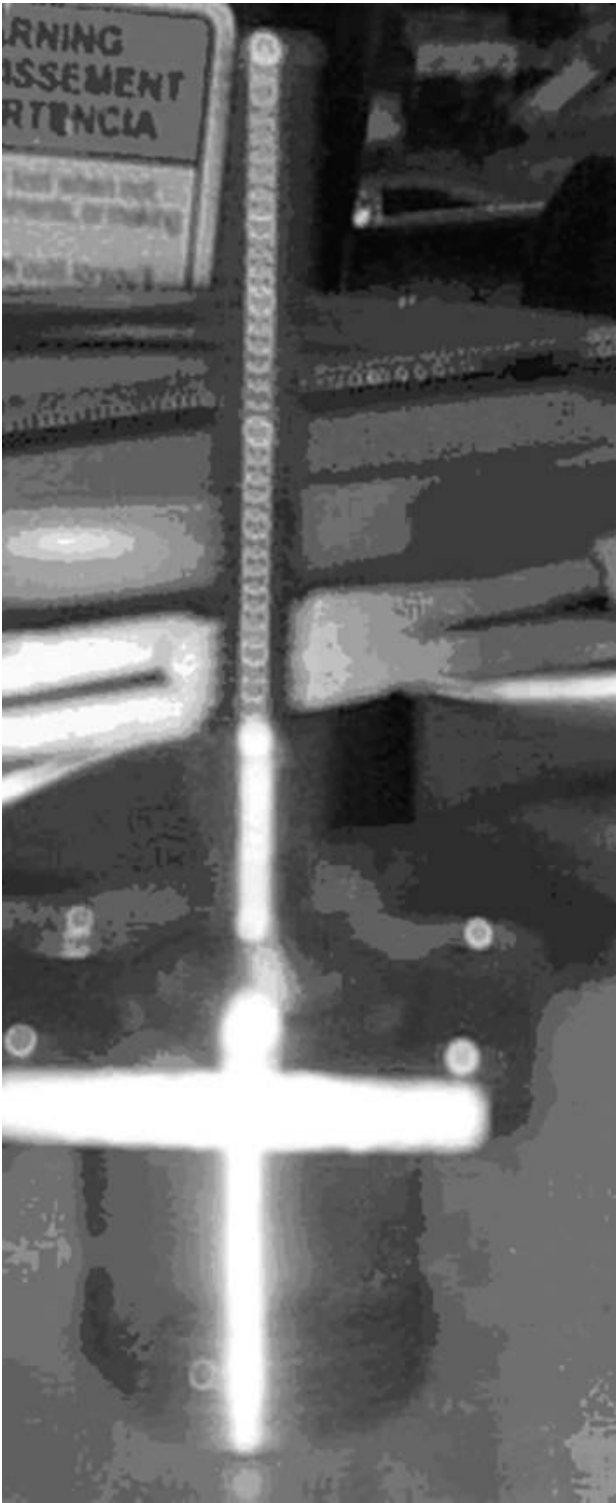
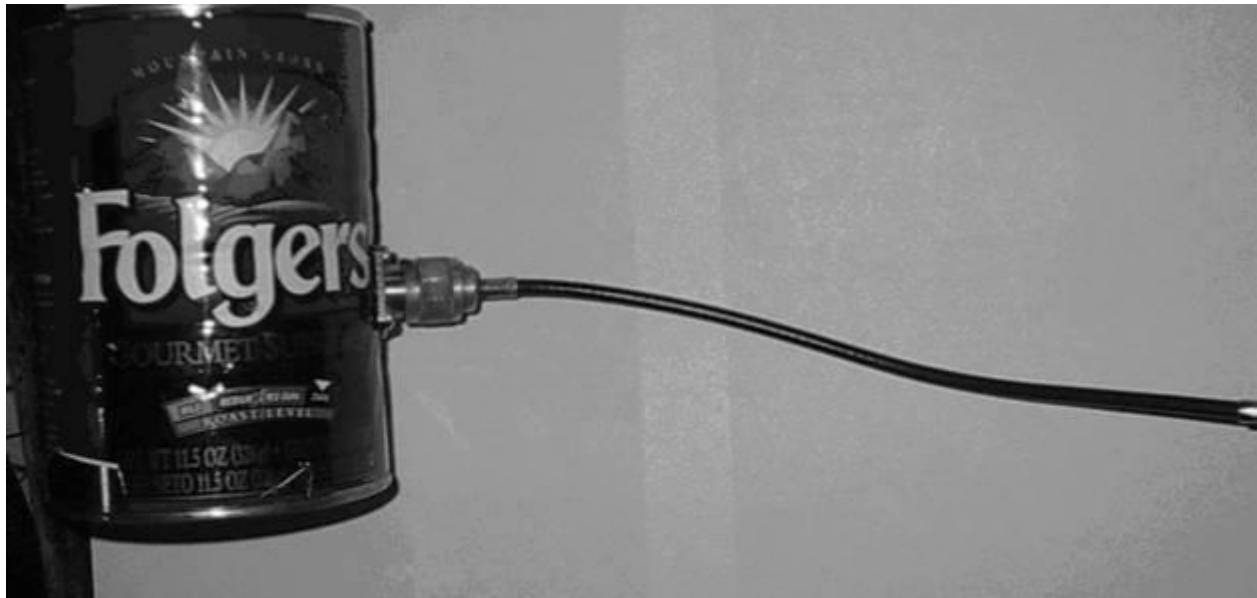


Figure 10. 17 The Completed Coffee Can Antenna



The coffee-can side of the pigtail is an “N” connector, while the other side (for connecting to the radio) is an SMA connector. Various types of connectors may be used depending on the connector interface required by the PC card or subscriber unit.

NEED TO KNOW...SAVE THE JUMPER/PULL THE PIGTAIL

It is important to remember that most wireless APs will require a short cable commonly referred to as a “pigtail” to interface between the antenna and the AP. This cable is usually 3”–6” in length with connectors on each end. There are several types of connectors used on commercial APs and client cards. It is also sometimes necessary to use a short “jumper” cable between the lightning arrestor or outdoor enclosure and the antenna. These cables should be 6” to 10”. Figure 10.18 shows a complete antenna plus arrestor assembly. Figure 10.19 shows a 6” N-to-N jumper used between the antenna and lightning arrestor.

Figure 10.18 A Common 10" Pigtail with "N" Connector and MMCA (PCMCIA) Connector



Figure 10.19 A 6" N-to-N Jumper Used between the Antenna and Lightning Arrestor



Under the Hood: How the Hack Works

Lightning arrestors are basically voltage “redirectors” that really do not eliminate all electrical charges. However, the standard $\frac{1}{4}$ wave stub lightning arrestors from PolyPhaser are the best

