4

Antennas & Transmission Lines

The transmitter that generates the RF[1] power to drive the antenna is usually located at some distance from the antenna terminals. The connecting link between the two is the ***RF transmission line***. Its purpose is to carry RF power from one place to another, and to do this as efficiently as possible. From the receiver side, the antenna is responsible for picking up any radio signals in the air and passing them to the receiver with the minimum amount of distortion, so that the radio has its best chance to decode the signal. For these reasons, the RF cable has a very important role in radio systems: it must maintain the integrity of the signals in both directions.

There are two main categories of transmission lines: cables and waveguides. Both types work well for efficiently carrying RF power at 2.4GHz.

Cables

RF cables are, for frequencies higher than HF, almost exclusively coaxial cables (or ***coax*** for short, derived from the words "of common axis"). Coax cables have a core ***conductor*** wire surrounded by a non-conductive material called ***dielectric,*** or simply ***insulation***. The dielectric is then surrounded by an encompassing shielding which is often made of braided wires. The dielectric prevents an electrical connection between the core and the shielding. Finally, the coax is protected by an outer casing which is generally made

1. Radio Frequency. See chapter two for discussion of electromagnetic waves.

from a PVC material. The inner conductor carries the RF signal, and the outer shield prevents the RF signal from radiating to the atmosphere, and also prevents outside signals from interfering with the signal carried by the core. Another interesting fact is that the electrical signal always travels along the outer layer of the central conductor: the larger the central conductor, the better signal will flow. This is called the "skin effect".

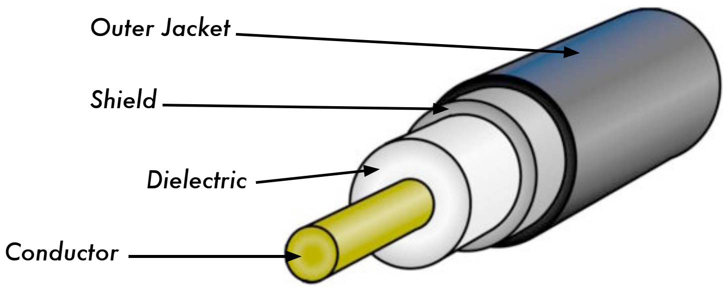

Figure 4.1: Coaxial cable with jacket, shield, dielectric, and core conductor.

Even though the coaxial construction is good at containing the signal on the core wire, there is some resistance to the electrical flow: as the signal travels down the core, it will fade away. This fading is known as ***attenuation***, and for transmission lines it is measured in decibels per meter (***dB/m***). The rate of attenuation is a function of the signal frequency and the physical construction of the cable itself. As the signal frequency increases, so does its attenuation. Obviously, we need to minimize the cable attenuation as much as possible by keeping the cable very short and using high quality cables.

Here are some points to consider when choosing a cable for use with microwave devices:

1. "The shorter the better!" The first rule when you install a piece of cable is to try to keep it as short as possible. The power loss is not linear, so doubling the cable length means that you are going to lose much more than twice the power. In the same way, reducing the cable length by half gives you more than twice the power at the antenna. The best solution is to place the transmitter as close as possible to the antenna, even when this means placing it on a tower.

2. "The cheaper the worse!" The second golden rule is that any money you invest in buying a **good quality** cable is a bargain. Cheap cables are intended to be used at low frequencies, such as VHF. Microwaves require the highest quality cables available. All other options are nothing but a dummy load[2].

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2. A dummy load is a device that dissipates RF energy without radiating it. Think of it as a heat sink that works at radio frequencies.

3. Always avoid RG-58. It is intended for thin Ethernet networking, CB or VHF radio, not for microwave.

4. Always avoid RG-213. It is intended for CB and HF radio. In this case the cable diameter does not imply a high quality, or low attenuation.

5. Whenever possible, use ***Heliax*** (also called “Foam”) cables for connecting the transmitter to the antenna. When Heliax is unavailable, use the best rated LMR cable you can find. Heliax cables have a solid or tubular center conductor with a corrugated solid outer conductor to enable them to flex. Heliax can be built in two ways, using either air or foam as a dielectric. Air dielectric heliax is the most expensive and guarantees the minimum loss, but it is very difficult to handle. Foam dielectric heliax is slightly more lossy, but is less expensive and easier to install. A special procedure is required when soldering connectors in order to keep the foam dielectric dry and uncorrupted. LMR is a brand of coax cable available in various diameters that works well at microwave frequencies. LMR-400 and LMR-600 are a commonly used alternative to Heliax.

6. Whenever possible, use cables that are pre-crimped and tested in a proper lab. Installing connectors to cable is a tricky business, and is difficult to do properly even with the proper tools. Unless you have access to equipment that can verify a cable you make yourself (such as a spectrum analyzer and signal generator, or time domain reflectometer), troubleshooting a network that uses homemade cable can be difficult.

7. Don’t abuse your transmission line. Never step over a cable, bend it too much, or try to unplug a connector by pulling directly the cable. All of those behaviors may change the mechanical characteristic of the cable and therefore its impedance, short the inner conductor to the shield, or even break the line. Those problems are difficult to track and recognize and can lead to unpredictable behavior on the radio link.

Waveguides

Above 2 GHz, the wavelength is short enough to allow practical, efficient energy transfer by different means. A waveguide is a conducting tube through which energy is transmitted in the form of electromagnetic waves. The tube acts as a boundary that confines the waves in the enclosed space. The skin effect prevents any electromagnetic effects from being evident outside the guide. The electromagnetic fields are propagated through the waveguide by means of reflections against its inner walls, which are considered perfect conductors. The intensity of the fields is greatest at the center along the X dimension, and must diminish to zero at the end walls because the existence of any field parallel to the walls at the surface would cause an infinite current to flow in a perfect conductor. Waveguides, of course, cannot carry RF in this fashion.

The X, Y and Z dimensions of a rectangular waveguide can be seen in the following figure:

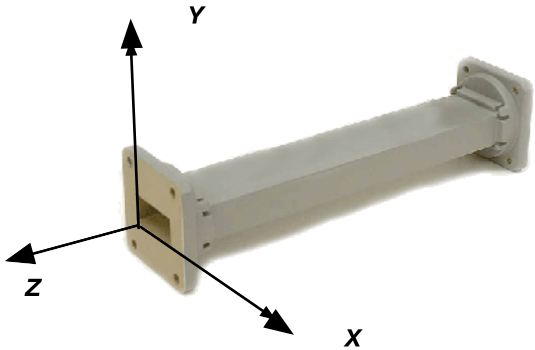

Figure 4.2: The X, Y, and Z dimensions of a rectangular waveguide.

There are an infinite number of ways in which the electric and magnetic fields can arrange themselves in a waveguide for frequencies above the low cutoff frequency. Each of these field configurations is called a ***mode***. The modes may be separated into two general groups. One group, designated ***TM*** (Transverse Magnetic), has the magnetic field entirely transverse to the direction of propagation, but has a component of the electric field in the direction of propagation. The other type, designated ***TE*** (Transverse Electric) has the electric field entirely transverse, but has a component of magnetic field in the direction of propagation.

The mode of propagation is identified by the group letters followed by two subscript numerals. For example, TE 10, TM 11, etc. The number of possible modes increases with the frequency for a given size of guide, and there is only one possible mode, called the ***dominant mode***, for the lowest frequency that can be transmitted. In a rectangular guide, the critical dimension is X. This dimension must be more than 0.5 λ at the lowest frequency to be transmitted. In practice, the Y dimension usually is made about equal to 0.5 X to avoid the possibility of operation in other than the dominant mode. Cross-sectional shapes other than the rectangle can be used, the most important being the circular pipe. Much the same considerations apply as in the rectangular case. Wavelength dimensions for rectangular and circular guides are given in the following table, where X is the width of a rectangular guide and r is the radius of a circular guide. All figures apply to the dominant mode.

Type of guide	Rectangular	Circular
Cutoff wavelength	**2X**	**3.41r**
Longest wavelength transmitted with little attenuation	**1.6X**	**3.2r**
Shortest wavelength before next mode becomes possible	**1.1X**	**2.8r**

Energy may be introduced into or extracted from a waveguide by means of either an electric or magnetic field. The energy transfer typically happens through a coaxial line. Two possible methods for coupling to a coaxial line are using the inner conductor of the coaxial line, or through a loop. A probe which is simply a short extension of the inner conductor of the coaxial line can be oriented so that it is parallel to the electric lines of force. A loop can be arranged so that it encloses some of the magnetic lines of force. The point at which maximum coupling is obtained depends upon the mode of propagation in the guide or cavity. Coupling is maximum when the coupling device is in the most intense field.

If a waveguide is left open at one end, it will radiate energy (that is, it can be used as an antenna rather than as a transmission line). This radiation can be enhanced by flaring the waveguide to form a pyramidal horn antenna. We will see an example of a practical waveguide antenna for WiFi later in this chapter.

Cable Type	Core	Dielectric	Shield	Jacket
RG-58	0.9 mm	2.95 mm	3.8 mm	4.95 mm
RG-213	2.26 mm	7.24 mm	8.64 mm	10.29 mm
LMR-400	2.74 mm	7.24 mm	8.13 mm	10.29 mm
3/8” LDF	3.1 mm	8.12 mm	9.7 mm	11 mm

Here is a table contrasting the sizes of various common transmission lines. Choose the best cable you can afford with the lowest possible attenuation at the frequency you intend to use for your wireless link.

Connectors and adapters

Connectors allow a cable to be connected to another cable or to a component of the RF chain. There are a wide variety of fittings and connectors designed to go with various sizes and types of coaxial lines. We will describe some of the most popular ones.

BNC connectors were developed in the late 40s. BNC stands for Bayonet Neill Concelman, named after the men who invented it: Paul Neill and Carl Concelman. The BNC product line is a miniature quick connect / disconnect connector. It features two bayonet lugs on the female connector, and mating is achieved with only a quarter turn of the coupling nut. BNC's are ideally suited for cable termination for miniature to subminiature coaxial cable (RG-58 to RG-179, RG-316, etc.) They have acceptable performance up to few GHz. They are most commonly found on test equipment and 10base2 coaxial Ethernet cables.

TNC connectors were also invented by Neill and Concelman, and are a threaded variation of the BNC. Due to the better interconnect provided by the threaded connector, TNC connectors work well through about 12GHz. TNC stands for Threaded Neill Concelman.

Type N (again for Neill, although sometimes attributed to "Navy") connectors were originally developed during the Second World War. They are usable up to 18 Ghz, and very commonly used for microwave applications. They are available for almost all types of cable. Both the plug / cable and plug / socket joints are waterproof, providing an effective cable clamp.

SMA is an acronym for SubMiniature version A, and was developed in the 60s. SMA connectors are precision, subminiature units that provide excellent electrical performance up to 18 GHz. These high-performance connectors are compact in size and mechanically have outstanding durability.

The ***SMB*** name derives from SubMiniature B, and it is the second subminiature design. The SMB is a smaller version of the SMA with snap-on coupling. It provides broadband capability through 4 GHz with a snap-on connector design.

MCX connectors were introduced in the 80s. While the MCX uses identical inner contact and insulator dimensions as the SMB, the outer diameter of the plug is 30% smaller than the SMB. This series provides designers with options where weight and physical space are limited. MCX provides broadband capability though 6 GHz with a snap-on connector design.

In addition to these standard connectors, most WiFi devices use a variety of proprietary connectors. Often, these are simply standard microwave connectors with the center conductor parts reversed, or the thread cut in the opposite direction. These parts are often integrated into a microwave system using a short jumper called a ***pigtail*** that converts the non-standard connector into something more robust and commonly available. Some of these connectors include:

RP-TNC. This is a TNC connector with the genders reversed. These are most commonly found on Linksys equipment, such as the WRT54G.

U.FL (also known as ***MHF***). The U.FL is a patented connector made by Hirose, while the MHF is a mechanically equivalent connector. This is possibly the smallest microwave connector currently in wide use. The U.FL / MHF is typically used to connect a mini-PCI radio card to an antenna or larger connector (such as an N or TNC).

The ***MMCX*** series, which is also called a MicroMate, is one of the smallest RF connector line and was developed in the 90s. MMCX is a micro-miniature connector series with a lock-snap mechanism allowing for 360 degrees rotation enabling flexibility. MMCX connectors are commonly found on PCMCIA radio cards, such as those manufactured by Senao and Cisco.

MC-Card connectors are even smaller and more fragile than MMCX. They have a split outer connector that breaks easily after just a few interconnects. These are commonly found on Lucent / Orinoco / Avaya equipment.

Adapters, which are also called coaxial adapters, are short, two-sided connectors which are used to join two cables or components which cannot be connected directly. Adapters can be used to interconnect devices or cables with different types. For example, an adapter can be used to connect an SMA connector to a BNC. Adapters may also be used to fit together connectors of the same type, but which cannot be directly joined because of their gender. For example a very useful adapter is the one which enables to join two Type N connectors, having socket (female) connectors on both sides.

Figure 4.3: An N female barrel adapter.

Choosing the proper connector

1. "The gender question." Virtually all connectors have a well defined gender consisting of either a pin (the "male" end) or a socket (the "female" end). Usually cables have male connectors on both ends, while RF devices (i.e. transmitters and antennas) have female connectors. Devices such as directional couplers and line-through measuring devices may have both male and female connectors. Be sure that every male connector in your system mates with a female connector.

2. "Less is best!" Try to minimize the number of connectors and adapters in the RF chain. Each connector introduces some additional loss (up to a few dB for each connection, depending on the connector!)

3. "Buy, don't build!" As mentioned earlier, buy cables that are already terminated with the connectors you need whenever possible. Soldering connectors is not an easy task, and to do this job properly is almost impossible for small connectors as U.FL and MMCX. Even terminating "Foam" cables is not an easy task.

4. Don't use BNC for 2.4GHz or higher. Use N type connectors (or SMA, SMB, TNC, etc.)

5. Microwave connectors are precision-made parts, and can be easily damaged by mistreatment. As a general rule, you should rotate the outer sleeve to tighten the connector, leaving the rest of the connector (and cable) stationary. If other parts of the connector are twisted while tightening or loosening, damage can easily occur.

6. Never step over connectors, or drop connectors on the floor when disconnecting cables (this happens more often than what you may imagine, especially when working on a mast over a roof).

7. Never use tools like pliers to tighten connectors. Always use your hands. When working outside, remember that metals expand at high temperatures and reduce their size at low temperatures: a very tightened connector in the summer can bind or even break in winter.

Antennas & radiation patterns

Antennas are a very important component of communication systems. By definition, an antenna is a device used to transform an RF signal traveling on a conductor into an electromagnetic wave in free space. Antennas demonstrate a property known as ***reciprocity***, which means that an antenna will maintain the same characteristics regardless if whether it is transmitting or receiving. Most antennas are resonant devices, which operate efficiently over a relatively narrow frequency band. An antenna must be tuned to the same frequency band of the radio system to which it is connected, otherwise the reception and the transmission will be impaired. When a signal is fed into an antenna, the antenna will emit radiation distributed in space in a certain way. A graphical representation of the relative distribution of the radiated power in space is called a ***radiation pattern***.

Antenna term glossary

Before we talk about specific antennas, there are a few common terms that must be defined and explained:

Input Impedance

For an efficient transfer of energy, the ***impedance*** of the radio, antenna, and transmission cable connecting them must be the same. Transceivers and their transmission lines are typically designed for 50Ω impedance. If the antenna has an impedance different than 50Ω, then there is a mismatch and an impedance matching circuit is required. When any of these components are mismatched, transmission efficiency suffers.

Return loss

Return loss is another way of expressing mismatch. It is a logarithmic ratio measured in dB that compares the power reflected by the antenna to the power that is fed into the antenna from the transmission line. The relationship between SWR and return loss is the following:

$$\text{Return Loss (in dB)} = 20\log_{10} \frac{SWR}{SWR-1}$$

While some energy will always be reflected back into the system, a high return loss will yield unacceptable antenna performance.

Bandwidth

The ***bandwidth*** of an antenna refers to the range of frequencies over which the antenna can operate correctly. The antenna's bandwidth is the number of Hz for which the antenna will exhibit an SWR less than 2:1.

The bandwidth can also be described in terms of percentage of the center frequency of the band.

$$\text{Bandwidth} = 100 \times \frac{F_H - F_L}{F_C}$$

...where F_H is the highest frequency in the band, F_L is the lowest frequency in the band, and F_C is the center frequency in the band.

In this way, bandwidth is constant relative to frequency. If bandwidth was expressed in absolute units of frequency, it would be different depending upon the center frequency. Different types of antennas have different bandwidth limitations.

Directivity and Gain

Directivity is the ability of an antenna to focus energy in a particular direction when transmitting, or to receive energy from a particular direction when receiving. If a wireless link uses fixed locations for both ends, it is possible to use antenna directivity to concentrate the radiation beam in the wanted direction. In a mobile application where the transceiver is not fixed, it may be impossible to predict where the transceiver will be, and so the antenna should ideally radiate as well as possible in all directions. An omnidirectional antenna is used in these applications.

Gain is not a quantity which can be defined in terms of a physical quantity such as the Watt or the Ohm, but it is a dimensionless ratio. Gain is given in reference to a standard antenna. The two most common reference antennas are the ***isotropic antenna*** and the ***resonant half-wave dipole antenna***. The isotropic antenna radiates equally well in all directions. Real isotropic antennas do not exist, but they provide useful and simple theoretical antenna patterns with which to compare real antennas. Any real antenna will radiate more energy in some directions than in others. Since antennas cannot create energy, the total power radiated is the same as an isotropic antenna. Any additional energy radiated in the directions it favors is offset by equally less energy radiated in all other directions.

The gain of an antenna in a given direction is the amount of energy radiated in that direction compared to the energy an isotropic antenna would radiate in the same direction when driven with the same input power. Usually we are only interested in the maximum gain, which is the gain in the direction in which the antenna is radiating most of the power. An antenna gain of 3dB compared to an isotropic antenna would be written as **3dBi**. The resonant half-wave dipole can be a useful standard for comparing to other antennas at one frequency or over a very narrow band of frequencies. To compare the dipole to an antenna over a range of frequencies requires a number of dipoles of different lengths. An antenna gain of 3dB compared to a dipole antenna would be written as **3dBd**.

The method of measuring gain by comparing the antenna under test against a known standard antenna, which has a calibrated gain, is technically known as a ***gain transfer*** technique. Another method for measuring gain is the 3 antennas method, where the transmitted and received power at the antenna terminals is measured between three arbitrary antennas at a known fixed distance.

Radiation Pattern

The ***radiation pattern*** or ***antenna pattern*** describes the relative strength of the radiated field in various directions from the antenna, at a constant distance. The radiation pattern is a reception pattern as well, since it also describes the receiving properties of the antenna. The radiation pattern is three-dimensional, but usually the measured radiation patterns are a two-dimensional slice of the three-dimensional pattern, in the horizontal or vertical planes. These pattern measurements are presented in either a ***rectangular*** or a ***polar*** format. The following figure shows a rectangular plot presentation of a typical ten-element Yagi. The detail is good but it is difficult to visualize the antenna behavior in different directions.

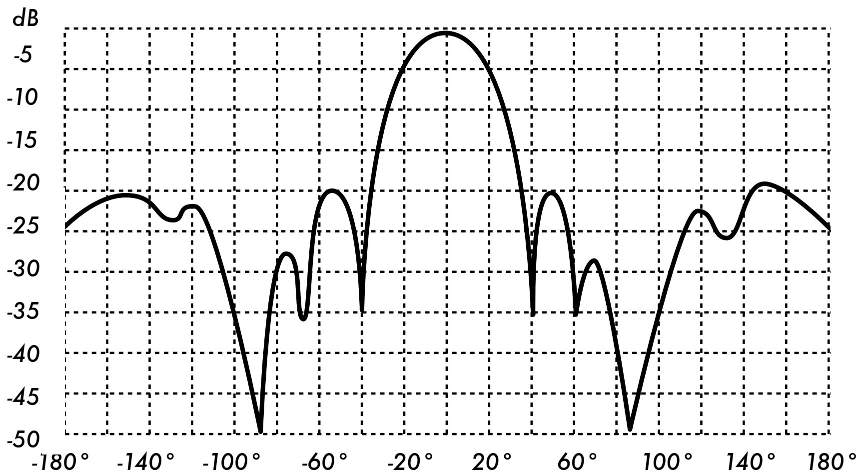

Figure 4.4: A rectangular plot of a yagi radiation pattern.

Polar coordinate systems are used almost universally. In the polar-coordinate graph, points are located by projection along a rotating axis (radius) to an intersection with one of several concentric circles. The following is a polar plot of the same 10 element Yagi antenna.

Polar coordinate systems may be divided generally in two classes: ***linear*** and ***logarithmic***. In the linear coordinate system, the concentric circles are equally spaced, and are graduated. Such a grid may be used to prepare a linear plot of the power contained in the signal. For ease of comparison, the equally spaced concentric circles may be replaced with appropriately placed circles representing the decibel response, referenced to 0 dB at the outer edge of the plot. In this kind of plot the minor lobes are suppressed. Lobes with peaks more than 15 dB or so below the main lobe disappear because of their small size. This grid enhances plots in which the antenna has a high directivity and small minor lobes. The voltage of the signal, rather than the power, can also be plotted on a linear coordinate system. In this case, too, the directivity is enhanced and the minor lobes suppressed, but not in the same degree as in the linear power grid.

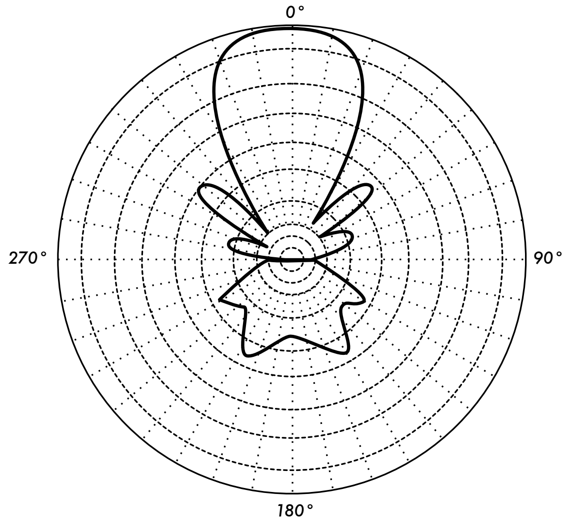

Figure 4.5: A linear polar plot of the same yagi.

In the logarithmic polar coordinate system the concentric grid lines are spaced periodically according to the logarithm of the voltage in the signal. Different values may be used for the logarithmic constant of periodicity, and this choice will have an effect on the appearance of the plotted patterns. Generally the 0 dB reference for the outer edge of the chart is used. With this type of grid, lobes that are 30 or 40 dB below the main lobe are still distinguishable. The spacing between points at 0 dB and at -3 dB is greater than the spacing between -20 dB and -23 dB, which is greater than the spacing between -50 dB and -53 dB. The spacing thus correspond to the relative significance of such changes in antenna performance.

A modified logarithmic scale emphasizes the shape of the major beam while compressing very low-level (>30 dB) sidelobes towards the center of the pattern.

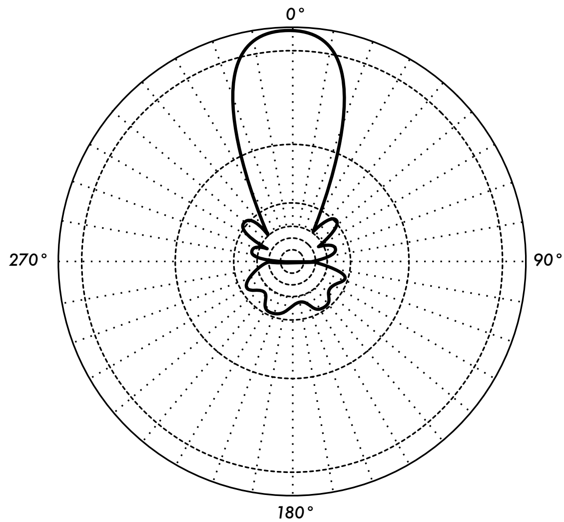

Figure 4.6: The logarithmic polar plot

There are two kinds of radiation pattern: ***absolute*** and ***relative***. Absolute radiation patterns are presented in absolute units of field strength or power. Relative radiation patterns are referenced in relative units of field strength or power. Most radiation pattern measurements are relative to the isotropic antenna, and the gain transfer method is then used to establish the absolute gain of the antenna.

The radiation pattern in the region close to the antenna is not the same as the pattern at large distances. The term near-field refers to the field pattern that exists close to the antenna, while the term far-field refers to the field pattern at large distances. The far-field is also called the radiation field, and is what is most commonly of interest. Ordinarily, it is the radiated power that is of interest, and so antenna patterns are usually measured in the far-field region. For pattern measurement it is important to choose a distance sufficiently large to be in the far-field, well out of the near-field. The minimum permissible distance depends on the dimensions of the antenna in relation to the wavelength. The accepted formula for this distance is:

$$r_{min} = \frac{2d^2}{\lambda}$$

where r_{min} is the minimum distance from the antenna, d is the largest dimension of the antenna, and λ is the wavelength.

Beamwidth

An antenna's ***beamwidth*** is usually understood to mean the half-power beamwidth. The peak radiation intensity is found, and then the points on either side of the peak which represent half the power of the peak intensity are located. The angular distance between the half power points is defined as the beamwidth. Half the power expressed in decibels is -3dB, so the half power beamwidth is sometimes referred to as the 3dB beamwidth. Both horizontal and vertical beamwidths are usually considered.

Assuming that most of the radiated power is not divided into sidelobes, then the directive gain is inversely proportional to the beamwidth: as the beamwidth decreases, the directive gain increases.

Sidelobes

No antenna is able to radiate all the energy in one preferred direction. Some is inevitably radiated in other directions. These smaller peaks are referred to as ***sidelobes***, commonly specified in dB down from the main lobe.

Nulls

In an antenna radiation pattern, a ***null*** is a zone in which the effective radiated power is at a minimum. A null often has a narrow directivity angle compared to that of the main beam. Thus, the null is useful for several purposes, such as suppression of interfering signals in a given direction.

Polarization

Polarization is defined as the orientation of the electric field of an electromagnetic wave. Polarization is in general described by an ellipse. Two special cases of elliptical polarization are ***linear polarization*** and ***circular polarization***. The initial polarization of a radio wave is determined by the antenna.

With linear polarization, the electric field vector stays in the same plane all the time. The electric field may leave the antenna in a vertical orientation, a horizontal orientation, or at some angle between the two. ***Vertically polarized*** radiation is somewhat less affected by reflections over the transmission path. Omnidirectional antennas always have vertical polarization. With ***horizontal polarization***, such reflections cause variations in received signal strength. Horizontal antennas are less likely to pick up man-made interference, which ordinarily is vertically polarized.

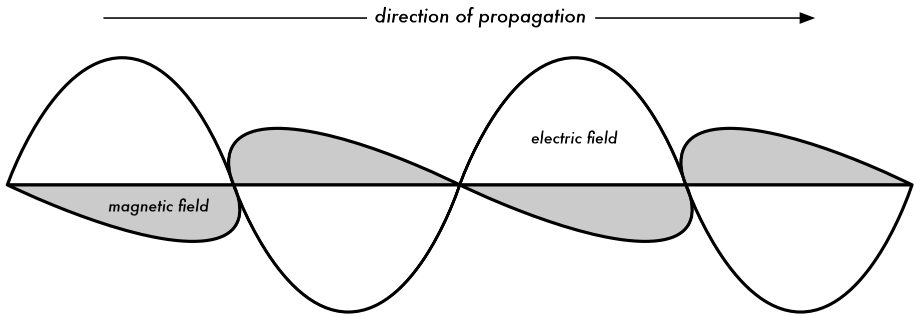

Figure 4.7: The electrical sine wave moves perpendicular to magnetic wave in the direction of propagation.

In circular polarization the electric field vector appears to be rotating with circular motion about the direction of propagation, making one full turn for each RF cycle. This rotation may be right-hand or left-hand. Choice of polarization is one of the design choices available to the RF system designer.

Polarization Mismatch

In order to transfer maximum power between a transmit and a receive antenna, both antennas must have the same spatial orientation, the same polarization sense, and the same axial ratio.

When the antennas are not aligned or do not have the same polarization, there will be a reduction in power transfer between the two antennas. This reduction in power transfer will reduce the overall system efficiency and performance.

When the transmit and receive antennas are both linearly polarized, physical antenna misalignment will result in a polarization mismatch loss, which can be determined using the following formula:

$$\text{Loss (dB)} = 20 \log (\cos \theta)$$

...where θ is the difference in alignment angle between the two antennas. For 15° the loss is approximately 0.3dB, for 30° we lose 1.25dB, for 45° we lose 3dB and for 90° we have an infinite loss.

In short, the greater the mismatch in polarization between a transmitting and receiving antenna, the greater the apparent loss. In the real world, a 90° mismatch in polarization is quite large but not infinite. Some antennas, such as yagis or can antennas, can be simply rotated 90° to match the polarization of the other end of the link. You can use the polarization effect to your advantage on a point-to-point link. Use a monitoring tool to observe interference from adjacent networks, and rotate one antenna until you see the lowest received signal. Then bring your link online and orient the other end to match polarization. This technique can sometimes be used to build stable links, even in noisy radio environments.

Front-to-back ratio

It is often useful to compare the ***front-to-back ratio*** of directional antennas. This is the ratio of the maximum directivity of an antenna to its directivity in the opposite direction. For example, when the radiation pattern is plotted on a relative dB scale, the front-to-back ratio is the difference in dB between the level of the maximum radiation in the forward direction and the level of radiation at 180 degrees.

This number is meaningless for an omnidirectional antenna, but it gives you an idea of the amount of power directed forward on a very directional antenna.

Types of Antennas

A classification of antennas can be based on:

- **Frequency and size**. Antennas used for HF are different from antennas used for VHF, which in turn are different from antennas for microwave. The wavelength is different at different frequencies, so the antennas must be different in size to radiate signals at the correct wavelength. We are particularly interested in antennas working in the microwave range, especially in the 2.4 GHz and 5 GHz frequencies. At 2.4 GHz the wavelength is 12.5cm, while at 5 GHz it is 6cm.
- **Directivity.** Antennas can be omnidirectional, sectorial or directive. ***Omnidirectional antennas*** radiate roughly the same pattern all around the antenna in a complete 360° pattern. The most popular types of omnidirectional antennas are the ***dipole*** and the ***ground plane***. ***Sectorial antennas*** radiate primarily in a specific area. The beam can be as wide as 180 degrees, or as narrow as 60 degrees. ***Directional*** or ***directive antennas*** are antennas in which the beamwidth is much narrower than in sectorial antennas. They have the highest gain and are therefore used for long distance links. Types of directive antennas are the Yagi, the biquad, the horn, the helicoidal, the patch antenna, the parabolic dish, and many others.
- **Physical construction.** Antennas can be constructed in many different ways, ranging from simple wires, to parabolic dishes, to coffee cans.

When considering antennas suitable for 2.4 GHz WLAN use, another classification can be used:

- **Application**. Access points tend to make point-to-multipoint networks, while remote links are point-to-point. Each of these suggest different types of antennas for their purpose. Nodes that are used for multipoint access will likely use omni antennas which radiate equally in all directions, or sectorial antennas which focus into a small area. In the point-to-point case, antennas are used to connect two single locations together. Directive antennas are the primary choice for this application.

A brief list of common type of antennas for the 2.4 GHz frequency is presented now, with a short description and basic information about their characteristics.

1/4 wavelength ground plane

The 1⁄4 wavelength ground plane antenna is very simple in its construction and is useful for communications when size, cost and ease of construction are important. This antenna is designed to transmit a vertically polarized signal. It consists of a 1⁄4 wave element as half-dipole and three or four 1⁄4 wavelength ground elements bent 30 to 45 degrees down. This set of elements, called radials, is known as a ground plane. This is a simple and effective antenna that can capture a signal equally from all directions. To increase the gain, the signal can be flattened out to take away focus from directly above and below, and providing more focus on the horizon. The vertical beamwidth represents the degree of flatness in the focus. This is useful in a Point-to-Multipoint situation, if all the other antennas are also at the same height. The gain of this antenna is in the order of 2 - 4 dBi.

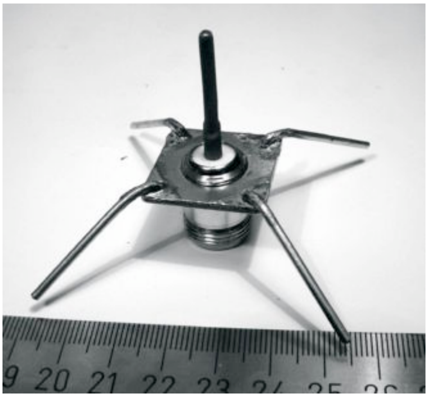

Figure 4.8: Quarter wavelength ground plane antenna.

Yagi antenna

A basic Yagi consists of a certain number of straight elements, each measuring approximately half wavelength. The driven or active element of a Yagi is the equivalent of a center-fed, half-wave dipole antenna. Parallel to the driven element, and approximately 0.2 to 0.5 wavelength on either side of it, are straight rods or wires called reflectors and directors, or simply passive elements. A reflector is placed behind the driven element and is slightly longer than half wavelength; a director is placed in front of the driven element and is slightly shorter than half wavelength. A typical Yagi has one reflector and one or more directors. The antenna propagates electromagnetic field energy in the direction running from the driven element toward the directors, and is most sensitive to incoming electromagnetic field energy in this same direction. The more directors a Yagi has, the greater the gain. As more directors are added to a Yagi, it therefore becomes longer. Following is the photo of a Yagi antenna with 6 directors and one reflector.

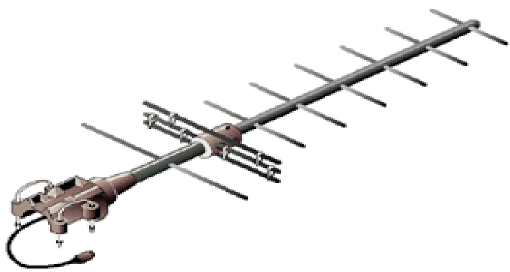

Figure 4.9: A Yagi antenna.

Yagi antennas are used primarily for Point-to-Point links, have a gain from 10 to 20 dBi and a horizontal beamwidth of 10 to 20 degrees.

Horn

The horn antenna derives its name from the characteristic flared appearance. The flared portion can be square, rectangular, cylindrical or conical. The direction of maximum radiation corresponds with the axis of the horn. It is easily fed with a waveguide, but can be fed with a coaxial cable and a proper transition. Horn antennas are commonly used as the active element in a dish antenna. The horn is pointed toward the center of the dish reflector. The use of a horn, rather than a dipole antenna or any other type of antenna, at the focal point of the dish minimizes loss of energy around the edges of the dish reflector. At 2.4 GHz, a simple horn antenna made with a tin can has a gain in the order of 10 - 15 dBi.

Figure 4.10: Feed horn made from a food can.

Parabolic Dish

Antennas based on parabolic reflectors are the most common type of directive antennas when a high gain is required. The main advantage is that they can be made to have gain and directivity as large as required. The main disadvantage is that big dishes are difficult to mount and are likely to have a large windage.

Dishes up to one meter are usually made from solid material. Aluminum is frequently used for its weight advantage, its durability and good electrical characteristics. Windage increases rapidly with dish size and soon becomes a severe problem. Dishes which have a reflecting surface that uses an open mesh are frequently used. These have a poorer front-to-back ratio, but are safer to use and easier to build. Copper, aluminum, brass, galvanized steel and iron are suitable mesh materials.

Figure 4.11: A solid dish antenna.

BiQuad

The BiQuad antenna is simple to build and offers good directivity and gain for Point-to-Point communications. It consists of a two squares of the same size of 1⁄4 wavelength as a radiating element and of a metallic plate or grid as reflector. This antenna has a beamwidth of about 70 degrees and a gain in the order of 10-12 dBi. It can be used as stand-alone antenna or as feeder for a Parabolic Dish. The polarization is such that looking at the antenna from the front, if the squares are placed side by side the polarization is vertical.

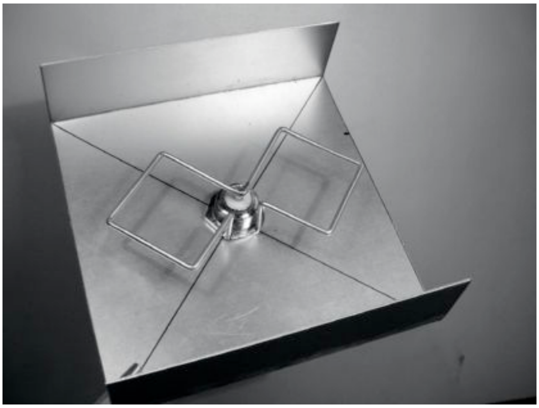

Figure 4.12: The BiQuad.

Other Antennas

Many other types of antennas exist and new ones are created following the advances in technology.

- Sector or Sectorial antennas: they are widely used in cellular telephony infrastructure and are usually built adding a reflective plate to one or more phased dipoles. Their horizontal beamwidth can be as wide as 180 degrees, or as narrow as 60 degrees, while the vertical is usually much narrower. Composite antennas can be built with many Sectors to cover a wider horizontal range (multisectorial antenna).
- Panel or Patch antennas: they are solid flat panels used for indoor coverage, with a gain up to 20 dB.

Reflector theory

The basic property of a perfect parabolic reflector is that it converts a spherical wave irradiating from a point source placed at the focus into a plane wave. Conversely, all the energy received by the dish from a distant source is reflected to a single point at the focus of the dish. The position of the focus, or focal length, is given by:

$$f = \frac{D^2}{16 \times c}$$

...where D is the dish diameter and c is the depth of the parabola at its center.

The size of the dish is the most important factor since it determines the maximum gain that can be achieved at the given frequency and the resulting beamwidth. The gain and beamwidth obtained are given by:

$$\text{Gain} = \frac{(\pi \times D)^2}{\lambda^2} \times n$$

$$\text{Beamwidth} = \frac{70\ \lambda}{D}$$

...where D is the dish diameter and n is the efficiency. The efficiency is determined mainly by the effectiveness of illumination of the dish by the feed, but also by other factors. Each time the diameter of a dish is doubled, the gain is four times, or 6 dB, greater. If both stations double the size of their dishes, signal strength can be increased of 12 dB, a very substantial gain. An efficiency of 50% can be assumed when hand-building the antenna.

The ratio f / D (focal length/diameter of the dish) is the fundamental factor governing the design of the feed for a dish. The ratio is directly related to the beamwidth of the feed necessary to illuminate the dish effectively. Two dishes of the same diameter but different focal lengths require different design of feed if both are to be illuminated efficiently. The value of 0.25 corresponds to the common focal-plane dish in which the focus is in the same plane as the rim of the dish.

Amplifiers

As mentioned earlier, antennas do not actually create power. They simply direct all available power into a particular pattern. By using a ***power amplifier***, you can use DC power to augment your available signal. An amplifier connects between the radio transmitter and the antenna, and has an additional lead that connects to a power source. Amplifiers are available that work at 2.4GHz, and can add several Watts of power to your transmission. These devices sense when an attached radio is transmitting, and quickly power up and amplify the signal. They then switch off again when transmission ends. When receiving, they also add amplification to the signal before sending it to the radio.

Unfortunately, simply adding amplifiers will not magically solve all of your networking problems. We do not discuss power amplifiers at length in this book because there are a number of significant drawbacks to using them:

- **They are expensive**. Amplifiers must work at relatively wide bandwidths at 2.4GHz, and must switch quickly enough to work for Wi-Fi applications. These amplifiers do exist, but they tend to cost several hundred dollars per unit.
- **You will need at least two**. Whereas antennas provide reciprocal gain that benefits both sides of a connection, amplifiers work best at amplifying a transmitted signal. If you only add an amplifier to one end of a link with insufficient antenna gain, it will likely be able to be heard but will not be able to hear the other end.
- **They provide no additional directionality.** Adding antenna gain provides both gain and directionality benefits to both ends of the link. They not only improve the available amount of signal, but tend to reject noise from other directions. Amplifiers blindly amplify both desired and interfering signals, and can make interference problems worse.
- **Amplifiers generate noise for other users of the band.** By increasing your output power, you are creating a louder source of noise for other users of the unlicensed band. This may not be much of an issue today in rural areas, but it can cause big problems in populated areas. Conversely, adding antenna gain will improve your link and can actually decrease the noise level for your neighbors.
- **Using amplifiers probably isn't legal.** Every country imposes power limits on use of unlicensed spectrum. Adding an antenna to a highly amplified signal will likely cause the link to exceed legal limits.

Using amplifiers is often compared to the inconsiderate neighbor who wants to listen to the radio outside their home, and so turns it up to full volume. They might even "improve" reception by pointing their speakers out the window. While they may now be able to hear the radio, so must everyone else on the block. This approach may scale to exactly one user, but what happens when the neighbors decide to do the same thing with their radios? Using amplifiers for a wireless link causes roughly the same effect at 2.4GHz. Your link may "work better" for the moment, but you will have problems when other users of the band decide to use amplifiers of their own.

By using higher gain antennas rather than amplifiers, you avoid all of these problems. Antennas cost far less than amps, and can improve a link simply by changing the antenna on one end. Using more sensitive radios and good quality cable also helps significantly on long distance shots. These techniques are unlikely to cause problems for other users of the band, and so we recommend pursuing them long before adding amplifiers.

Practical antenna designs

The cost of 2.4GHz antennas has fallen dramatically since the introduction of 802.11b. Innovative designs use simpler parts and fewer materials to achieve impressive gain with relatively little machining. Unfortunately, availability of good antennas is still limited in many areas of the world, and importing them can be prohibitively expensive. While actually designing an antenna can be a complex and error-prone process, constructing antennas from locally available components is very straightforward, and can be a lot of fun. We present four practical antenna designs that can be built for very little money.

USB dongle as dish feed

Possibly the simplest antenna design is the use of a parabola to direct the output of a USB wireless device (known in networking circles as a ***USB dongle***). By placing the internal dipole antenna present in USB wireless dongles at the apex of a parabolic dish, you can provide significant gain without the need to solder or even open the wireless device itself. Many kinds of parabolic dishes will work, including satellite dishes, television antennas, and even metal cookware (such as a wok, round lid, or strainer). As a bonus, inexpensive and lossless USB cable is then used to feed the antenna, eliminating the need for expensive coaxial cable or heliax.

To build a USB dongle parabolic, you will need to find the orientation and location of the dipole inside the dongle. Most devices orient the dipole to be parallel with the short edge of the dongle, but some will mount the dipole perpendicular to the short edge. You can either open the dongle and look for yourself, or simply try the dongle in both positions to see which provides more gain.

To test the antenna, point it at an access point several meters away, and connect the USB dongle to a laptop. Using the laptop's client driver or a tool such as Netstumbler (see chapter six), observe the received signal strength of the access point. Now, slowly move the dongle in relation to the parabolic while watching the signal strength meter. You should see a significant improvement in gain (20 dB or more) when you find the proper position. The dipole itself is typically placed 3 to 5 centimeters from the back of the dish, but this will vary depending on the shape of the parabola. Try various positions while watching your signal strength meter until you find the optimum location.

Once the best location is found, securely fix the dongle in place. You will need to waterproof the dongle and cable if the antenna is used outdoors. Use a silicone compound or a piece of PVC tubing to seal the electronics against the weather. Many USB-fed parabolic designs and ideas are documented online at *http://www.usbwifi.orcon.net.nz/* .

Collinear omni

This antenna is very simple to build, requiring just a piece of wire, an N socket and a square metallic plate. It can be used for indoor or outdoor Point-to-MultiPoint short distance coverage. The plate has a hole drilled in the middle to accommodate an N type chassis socket that is screwed into place. The wire is soldered to the center pin of the N socket and has coils to separate the active phased elements. Two versions of the antenna are possible: one with two phased elements and two coils and another with four phased elements and four coils. For the short antenna the gain will be around 5dBi, while the long one with four elements will have 7 to 9 dBi of gain. We are going to describe how to build the long antenna only.

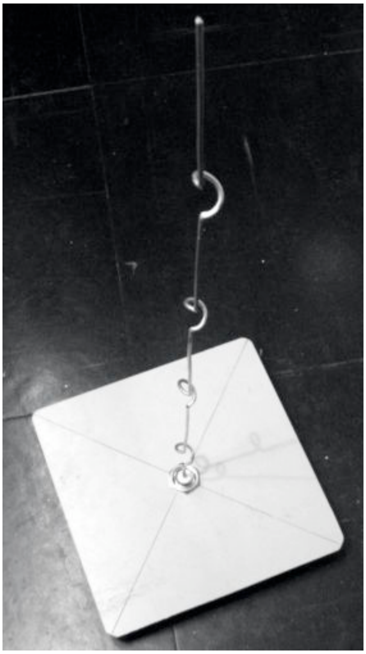

Figure 4.13: The completed colinear omni

Parts list

- One screw-on N-type female connector
- 50 cm of copper or brass wire of 2 mm of diameter
- 10x10 cm or greater square metallic plate

Figure 4.14: 10 cm x 10 cm aluminum plate.

Tools required

- Ruler
- Pliers
- File
- Soldering iron and solder
- Drill with a set of bits for metal (including a 1.5 cm diameter bit)
- A piece of pipe or a drill bit with a diameter of 1 cm
- Vice or clamp
- Hammer
- Spanner or monkey wrench

Construction

1. Straighten the wire using the vice.

Figure 4.15: Make the wire as straight as you can.

2. With a marker, draw a line at 2.5 cm starting from one end of the wire. On this line, bend the wire at 90 degrees with the help of the vice and of the hammer.

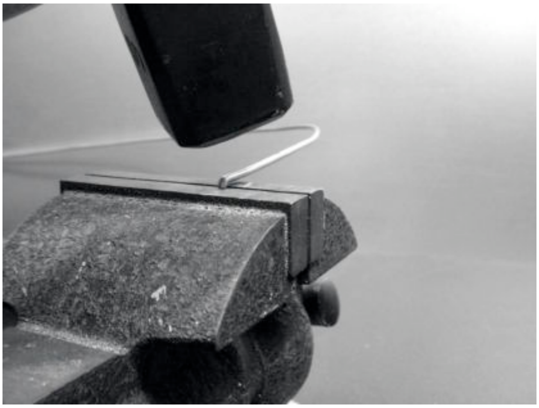

Figure 4.16: Gently tap the wire to make a sharp bend.

3. Draw another line at a distance of 3.6 cm from the bend. Using the vice and the hammer, bend once again the wire over this second line at 90 degrees, in the opposite direction to the first bend but in the same plane. The wire should look like a ‘Z’.

Figure 4.17: Bend the wire into a "Z" shape.

4. We will now twist the 'Z' portion of the wire to make a coil with a diameter of 1 cm. To do this, we will use the pipe or the drill bit and curve the wire around it, with the help of the vice and of the pliers.

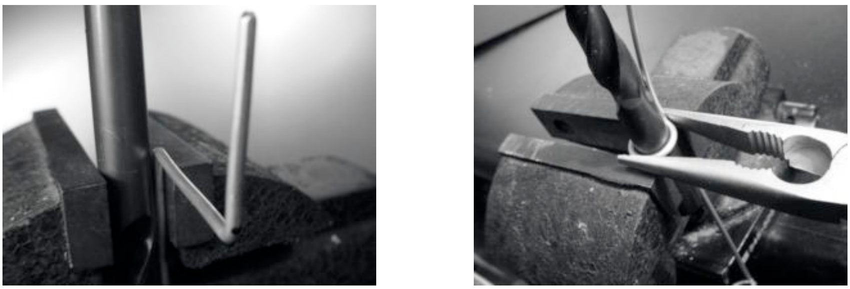

Figure 4.18: Bend the wire around the drill bit to make a coil.

The coil will look like this:

Figure 4.19: The completed coil.

5. You should make a second coil at a distance of 7.8 cm from the first one. Both coils should have the same turning direction and should be placed on the same side of the wire. Make a third and a fourth coil following the

same procedure, at the same distance of 7.8 cm one from each other. Trim the last phased element at a distance of 8.0 cm from the fourth coil.

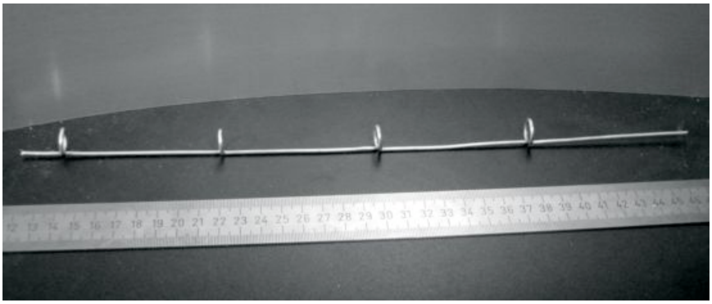

Figure 4.20: Try to keep it as straight possible.

If the coils have been made correctly, it should now be possible to insert a pipe through all the coils as shown.

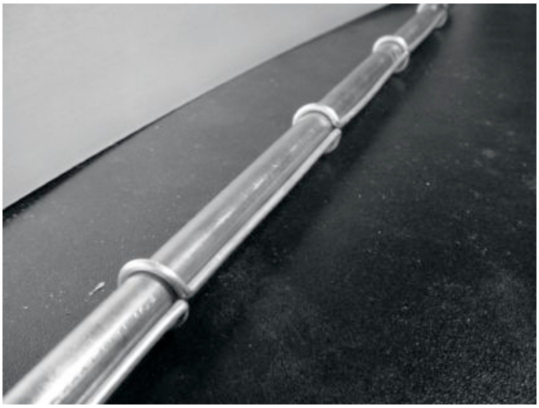

Figure 4.21: Inserting a pipe can help to straighten the wire.

6. With a marker and a ruler, draw the diagonals on the metallic plate, finding its center. With a small diameter drill bit, make a pilot hole at the center of the plate. Increase the diameter of the hole using bits with an increasing diameter.

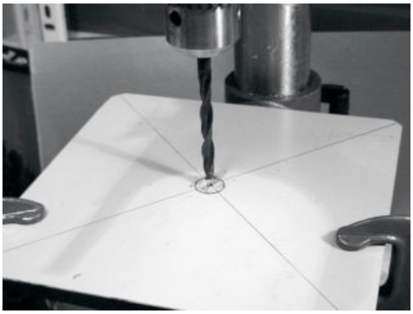


Figure 4.22: Drilling the hole in the metal plate.

The hole should fit the N connector exactly. Use a file if needed.

Figure 4.23: The N connector should fit snugly in the hole.

7. To have an antenna impedance of 50 Ohms, it is important that the visible surface of the internal insulator of the connector (the white area around the central pin) is at the same level as the surface of the plate. For this reason, cut 0.5 cm of copper pipe with an external diameter of 2 cm, and place it between the connector and the plate.

Figure 4.24: Adding a copper pipe spacer helps to match the impedance of the antenna to 50 Ohms.

8. Screw the nut to the connector to fix it firmly on the plate using the spanner.

Figure 4.25: Secure the N connector tightly to the plate.

9. Smooth with the file the side of the wire which is 2.5 cm long, from the first coil. Tin the wire for around 0.5 cm at the smoothed end helping yourself with the vice.

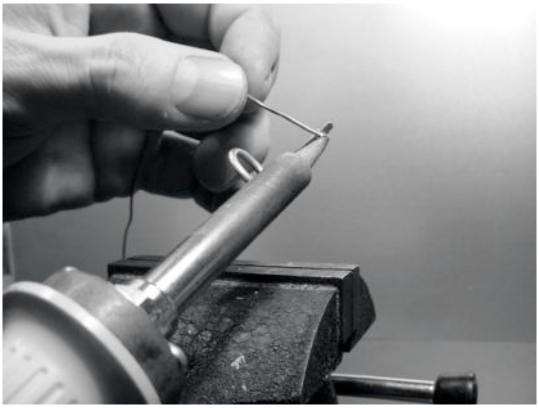

Figure 4.26: Add a little solder to the end of the wire to "tin" it prior to soldering.

10. With the soldering iron, tin the central pin of the connector. Keeping the wire vertical with the pliers, solder its tinned side in the hole of the central pin. The first coil should be at 3.0 cm from the plate.

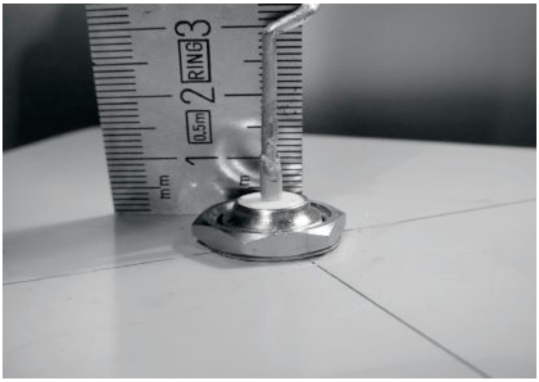

Figure 4.27: The first coil should start 3.0 cm from the surface of the plate.

11. We are now going to stretch the coils extending the total vertical length of the wire. Using the use the vice and the pliers, you should pull the cable so that the final length of the coil is of 2.0 cm.

Figure 4.30: Stretching the coils. Be very gentle and try not to scrape the surface of the wire with the pliers.

12. Repeat the same procedure for the other three coils, stretching their length to 2.0 cm.

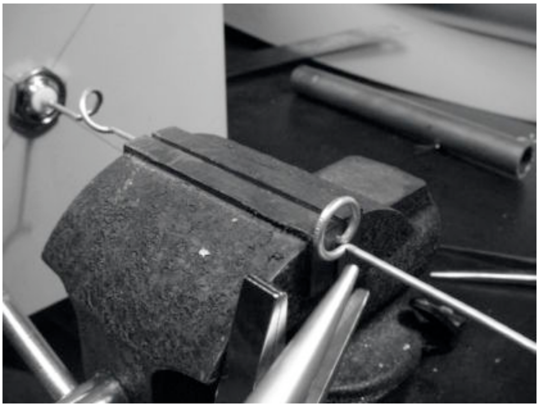

Figure 4.29: Repeat the stretching procedure for all of the remaining coils.

13. At the end the antenna should measure 42.5 cm from the plate to the top.

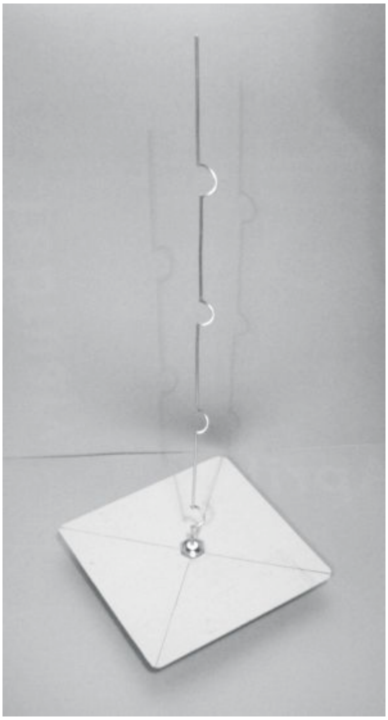

Figure 4.30: The finished antenna should be 42.5 cm from the plate to the end of the wire.

14. If you have a Spectrum Analyzer with Tracking Generator and a Directional Coupler, you can check the curve of the reflected power of the antenna. The picture below shows the display of the Spectrum Analyzer.

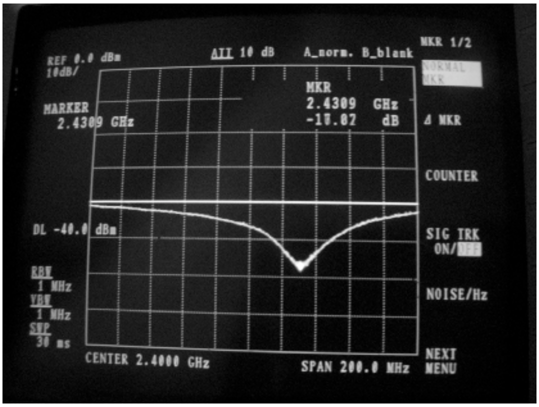

Figure 4.31: A spectrum plot of the reflected power of the collinear omni.

If you intend to use this antenna outside, you will need to weatherproof it. The simplest method is to enclose the whole thing in a large piece of PVC pipe closed with caps. Cut a hole at the bottom for the transmission line, and seal the antenna shut with silicone or PVC glue.

Cantenna

This antenna, sometimes called a Cantenna, uses a tin can as a waveguide and a short wire soldered on an N connector as a probe for coaxial-cable-to-waveguide transition. It can be easily built at just the price of the connector, recycling a food, juice, or other tin can. It is a directional antenna, useful for short to medium distance point-to-point links. It may be also used as a feeder for a parabolic dish or grid.

Not all cans are good for building an antenna because there are dimensional constraints:

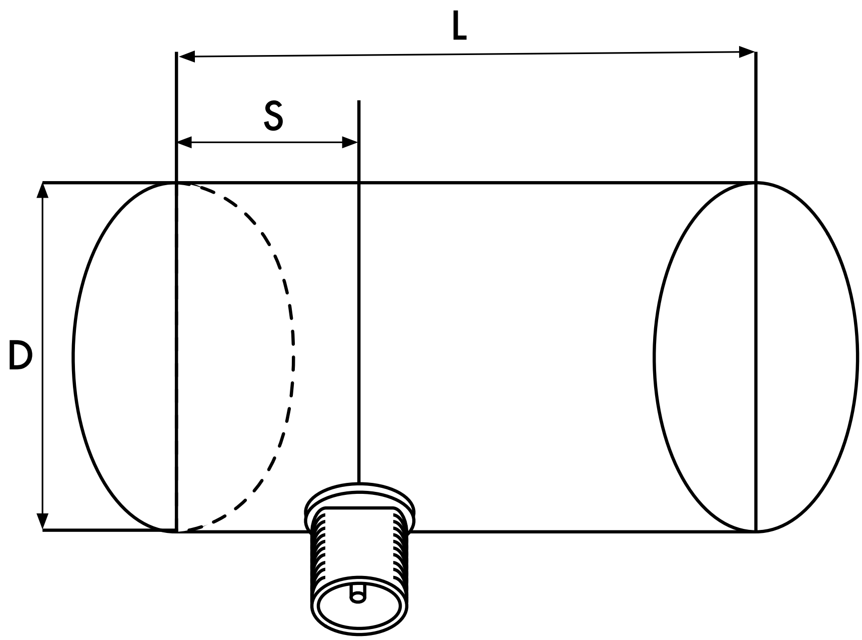

Figure 4.32: Dimensional constraints on the cantenna

1. The acceptable values for the diameter D of the feed are between 0.60 and 0.75 wavelength in air at the design frequency. At 2.44 GHz the wavelength λ is 12.2 cm, so the can diameter should be in the range of 7.3 - 9.2 cm.

2. The length L of the can preferably should be at least 0.75 λ_G , where λ_G is the guide wavelength and is given by:

$$\lambda_G = \frac{\lambda}{\mathrm{sqrt}(1 - (\lambda / 1.706D)^2)}$$

For D = 7.3 cm, we need a can of at least 56.4 cm, while for D = 9.2 cm we need a can of at least 14.8 cm. Generally the smaller the diameter, the longer the can should be. For our example, we will use oil cans that have a diameter of 8.3 cm and a height of about 21 cm.

3. The probe for coaxial cable to waveguide transition should be positioned at a distance S from the bottom of the can, given by:

$$S = 0.25\ \lambda_G$$

Its length should be 0.25 λ, which at 2.44 GHz corresponds to 3.05 cm.

The gain for this antenna will be in the order of 10 to 14 dBi, with a beam-width of around 60 degrees.

Figure 4.33: The finished cantenna.

Parts list

- one screw-on N-type female connector
- 4 cm of copper or brass wire of 2 mm of diameter
- an oil can of 8.3 cm of diameter and 21 cm of height

Figure 4.34: Parts needed for the can antenna.

Tools required

- Can opener
- Ruler
- Pliers
- File
- Soldering iron
- Solder
- Drill with a set of bits for metal (with a 1.5 cm diameter bit)
- Vice or clamp
- Spanner or monkey wrench
- Hammer
- Punch

Construction

1. With the can opener, remove carefully the upper part of the can.

Figure 4.35: Be careful of sharp edges when opening the can.

The circular disk has a very sharp edge. Be careful in handling it! Empty the can and wash it with soap. If the can contained pineapple, cookies, or some other tasty treat, have a friend serve the food.

2. With the ruler, measure 6.2 cm from the bottom of the can and draw a point. Be careful to measure from the inner side of the bottom. Use a punch (or a small drill bit or a Phillips screwdriver) and a hammer to mark

the point. This makes it easier to precisely drill the hole. Be careful not to change the shape of the can doing this by inserting a small block of wood or other object in the can before tapping it.

Figure 4.36: Mark the hole before drilling.

3. With a small diameter drill bit, make a hole at the center of the plate. Increase the diameter of the hole using bits with an increasing diameter. The hole should fit exactly the N connector. Use the file to smooth the border of the hole and to remove the painting around it in order to ensure a better electrical contact with the connector.

Figure 4.37: Carefully drill a pilot hole, then use a larger bit to finish the job.

4. Smooth with the file one end of the wire. Tin the wire for around 0.5 cm at the same end helping yourself with the vice.

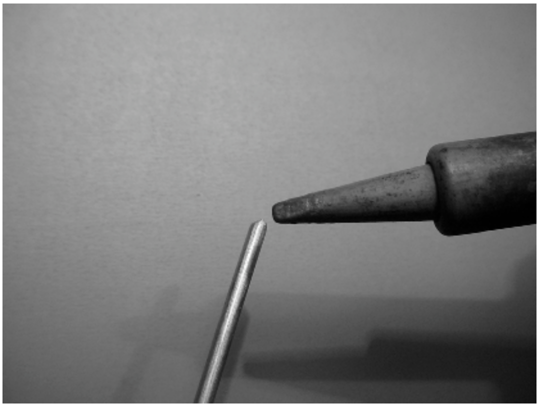

Figure 4.38: Tin the end of the wire before soldering.

5. With the soldering iron, tin the central pin of the connector. Keeping the wire vertical with the pliers, solder its tinned side in the hole of the central pin.

Figure 4.39: Solder the wire to the gold cup on the N connector.

6. Insert a washer and gently screw the nut onto the connector. Trim the wire at 3.05 cm measured from the bottom part of the nut.

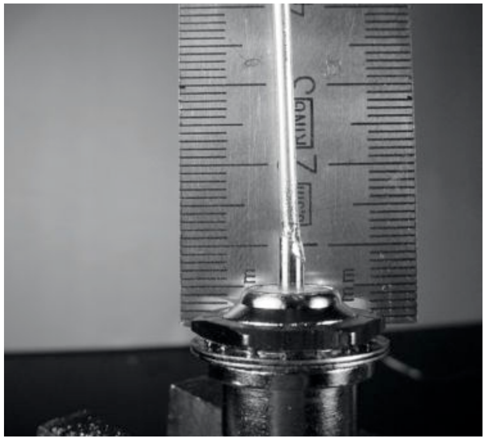

Figure 4.40: The length of the wire is critical.

7. Unscrew the nut from the connector, leaving the washer in place. Insert the connector into the hole of the can. Screw the nut on the connector from inside the can.

Figure 4.41: Assemble the antenna.

8. Use the pliers or the monkey wrench to screw firmly the nut on the connector. You are done!

Figure 4.42: Your finished cantenna.

As with the other antenna designs, you should make a weatherproof enclosure for the antenna if you wish to use it outdoors. PVC works well for the can antenna. Insert the entire can in a large PVC tube, and seal the ends with caps and glue. You will need to drill a hole in the side of the tube to accommodate the N connector on the side of the can.

Cantenna as dish feed

As with the USB dongle parabolic, you can use the cantenna design as a feeder for significantly higher gain. Mount the can on the parabolic with the opening of the can pointed at the center of the dish. Use the technique described in the USB dongle antenna example (watching signal strength changes over time) to find the optimum location of the can for the dish you are using.

By using a well-built cantenna with a properly tuned parabolic, you can achieve an overall antenna gain of 30dBi or more. As the size of the parabolic increases, so does the potential gain and directivity of the antenna. With very large parabolas, you can achieve significantly higher gain.

For example, in 2005, a team of college students successfully established a link from Nevada to Utah in the USA. The link crossed a distance of over 200 kilometers! The wireless enthusiasts used a 3.5 meter satellite dish to establish an 802.11b link that ran at 11Mbps, without using an amplifier. Details about this achievement can be found at *http://www.wifi-shootout.com/*

NEC2

NEC2 stands for ***Numerical Electromagnetics Code*** (version 2) and is a free antenna modeling package. NEC2 lets you build an antenna model in 3D, and then analyzes the antenna's electromagnetic response. It was developed more than ten years ago and has been compiled to run on many different computer systems. NEC2 is particularly effective for analyzing wire-grid models, but also has some surface patch modeling capability.

The antenna design is described in a text file, and then the model is built using this text description. An antenna described in NEC2 is given in two parts: its ***structure*** and a sequence of ***controls***. The structure is simply a numerical description of where the different parts of the antenna are located, and how the wires are connected up. The controls tell NEC where the RF source is connected. Once these are defined, the transmitting antenna is then modeled. Because of the reciprocity theorem the transmitting gain pattern is the same as the receiving one, so modeling the transmission characteristics is sufficient to understand the antenna's behaviour completely.

A frequency or range of frequencies of the RF signal must be specified. The next important element is the character of the ground. The conductivity of the earth varies from place to place, but in many cases it plays a vital role in determining the antenna gain pattern.

To run NEC2 on Linux, install the NEC2 package from the URL below. To launch it, type **`nec2`** and enter the input and output filenames. It is also worth installing the **`xnecview`** package for structure verification and radiation pattern plotting. If all went well you should have a file containing the output. This can be broken up into various sections, but for a quick idea of what it represents a gain pattern can be plotted using xnecview. You should see the expected pattern, horizontally omnidirectional, with a peak at the optimum angle of takeoff. Windows and Mac versions are also available.

The advantage of NEC2 is that we can get an idea of how the antenna works before building it, and how we can modify the design in order to get the maximum gain. It is a complex tool and requires some research to learn how to use it effectively, but it is an invaluable tool for antenna designers.

NEC2 is available from Ray Anderson's "Unofficial NEC Archives" at *http://www.si-list.org/swindex2.html*

Online documentation can be obtained from the "Unofficial NEC Home Page" at *http://www.nittany-scientific.com/nec/* .