Understanding Antenna Specifications and Operation

Application Note AN-00501

Introduction

The antenna is probably the most overlooked part of an RF design. The range, performance, and legality of an RF link are critically dependent upon the antenna. However, it is often left until the end of the design and expected to fit into whatever space is left, no matter how unfavorable to performance that location may be. Many of these designs will have to ultimately accept degraded performance or go through multiple redesigns.

The antenna is one of the most complicated aspects of RF design. With so many interdependent variables, application becomes as much art as science. Engineers delving into RF design for the first time can quite easily confuse or misinterpret the meaning of antenna specifications and how to apply them. For instance, the gain of an antenna is very different from the gain of an amplifier. The most common misconception may be that the radiation pattern on a monopole antenna's data sheet will be that of the antenna on the final product. In actuality, the radiation pattern for a quarter-wave monopole antenna is so critically dependent on the design and layout of the product that manufacturers' gain specifications and radiation pattern plots have little use except to ascertain potential antenna performance.

Since voluminous texts have been written about each of the many antenna styles, it is unnecessary to cover them all here. This article will focus only on those styles which are commonly used in low-power handheld products: dipole and monopole whips. These styles cover a wide range of available antennas and are among the most common to be implemented incorrectly. With that in mind, there are several rules of thumb that can be applied to antenna designs. These rules are less "how to design an antenna" and more "how to design with an antenna."

Antenna Fundamentals

An antenna is a device that converts electric currents into electromagnetic waves and vice versa. It can be considered a complex RLC network. At some frequencies, it will appear as an inductive reactance and at others as a capacitive reactance. At a specific frequency, both of the reactances will be equal in magnitude but opposite in influence and thus cancel each other. At this specific frequency, the impedance is purely resistive and the antenna is said to be resonant.

Here is where the physical meets the theoretical. Resonance will occur at whole number multiples or fractions of the frequency of interest. These frequencies correspond to a wavelength. That wavelength is the required antenna length. That length is what must be incorporated into the final product, either embedded inside the enclosure or externally attached to the device. The frequency of the electromagnetic waves is related to the wavelength by the following equation:

$$\lambda = \frac{c}{f}$$

where
f = frequency in hertz (Hz)
λ = wavelength in meters (m)
c = speed of light (299,792,458 m/s)

As can be seen by the equation, the higher the frequency, the shorter the wavelength and the smaller the antenna. For example, the wavelength for 433.92MHz is 0.69m (2.27ft) and the wavelength for 916MHz is 0.33m (1.07ft). 433.92MHz is a popular frequency for remote keyless entry (RKE) systems such as car keyfobs, but obviously there is no way that a 2.27-foot antenna is going to fit into a keyfob.

Fortunately for everyone who wants to carry their keys in their pocket, there are ways to make the antenna smaller. Since resonance will occur at whole number fractions (½, ⅓, ¼, etc.) of the fundamental frequency, shorter antennas can be used to send and recover the signal. As with everything in engineering, there is a tradeoff. Reducing the antenna's size will have some impact on the efficiency and impedance of the antenna, which can affect the final performance of the system.

A half-wave dipole antenna has a length that is one-half of the fundamental wavelength. It is broken into two quarter-wave lengths called elements. The elements are set at 180° from each other and fed from the middle. This type of antenna is called a center-fed half-wave dipole. It shortens the antenna length by half.

HALF-WAVE DIPOLE ANTENNA (HERTZ)

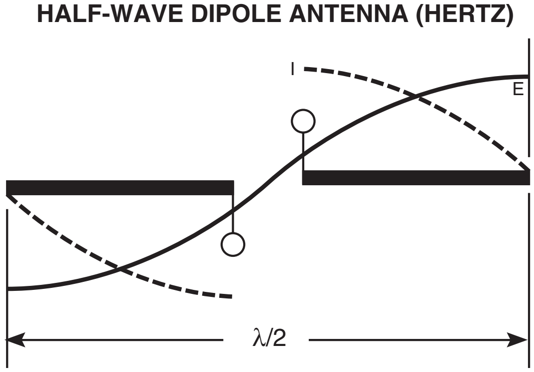

Figure 1: A Half-Wave Dipole Antenna

A method for making the antenna even smaller is to use one of the quarter-wave elements of a dipole and allow the ground plane on the product's PCB to serve as a counterpoise, in essence, creating the other quarter-wave element.

Since most devices have a circuit board anyway, using it for half of the antenna can make a lot of sense. Generally, this half of the antenna will be connected to ground and the transmitter or receiver will reference it accordingly. This style is called a quarter-wave monopole and is the most common antenna on today's portable devices.

Another way to reduce the size of the antenna is to coil the element. This is where the straight wire is coiled or wrapped around a non-conductive substrate to create what is called a helical element (Figure 3). This has the advantage of making the overall length shorter, but it will also reduce the antenna's bandwidth. Just as with an inductor, the tighter the coil, the higher the Q, so the smaller the bandwidth. Where a straight antenna may have a bandwidth of 100MHz, a helical may only have a bandwidth of 10MHz. This becomes more pronounced as the frequency gets lower, since the coils typically get closer together to maintain a specific overall length.

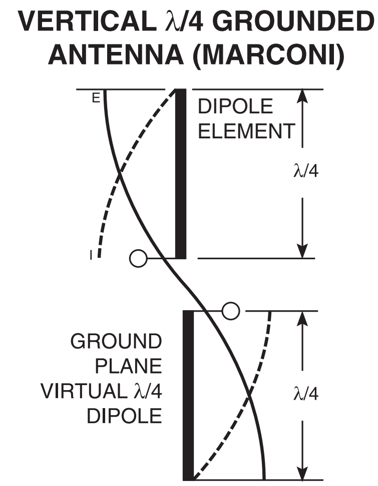

Figure 2: A Quarter-Wave Monopole Antenna

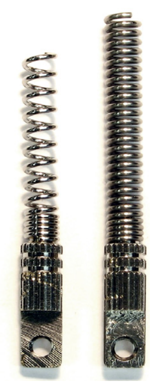

Figure 3: 916MHz (L) and 315MHz (R) Helical Antennas

Antenna Specifications

If antennas are the least understood RF component, then antenna specifications are the least understood of all RF components. For instance, many designers look for radiated test data without really understanding what they are looking at or how it relates to the performance of their product. For this reason, let's examine the most common antenna specifications.

Impedance

The impedance of an antenna is the real resistance and imaginary reactance that appears at the terminals of the antenna. Because there are inductive and capacitive elements to an antenna, this will change with frequency. It will also be affected by objects that are nearby, such as other antennas, the components on a circuit board, and even the user of the device.

An antenna will have two types of resistance associated with it. Radiation resistance converts electrical power into radiation. Ohmic resistance is loss on the antenna's structure that converts electrical power into heat. The radiation resistance should be much higher than the ohmic resistance, though both are important to the antenna's efficiency. Generally, the radiation resistance at the terminals of a dipole antenna in free space (isolated from anything conductive) is 73-ohms. A monopole antenna will be half of this, or 36.5-ohms.

The reactance is power that is stored in the near field of the antenna. This reactance combined with the real resistance make up the antenna's impedance. Both values are affected by objects in the near field and will vary down the antenna's length. The specifics of this are beyond the scope of this document, but can be found in most antenna literature.

These values are important because, in any system, maximum power transfer will occur when the source and load impedances match. If they are different, called a mismatch, then some of the power sent to the antenna will be reflected back into the load or lost as heat. This will lower the efficiency of the system, lowering range, increasing power requirements, and shortening battery life.

Industry convention for RF is an impedance of 50-ohms. Most IC manufacturers will have matched their products to 50-ohms or will provide a circuit designed to match their product to a 50-ohm load. Likewise, antenna manufacturers frequently design and characterize antennas at 50-ohms.

VSWR

The Voltage Standing Wave Ratio (VSWR) is a measurement of how well an antenna is matched to a source impedance, typically 50-ohms. It is calculated by measuring the voltage wave that is headed toward the load versus the voltage wave that is reflected back from the load. A perfect match will have a VSWR of 1:1. The higher the first number, the worse the match and the more inefficient the system. Since a perfect match cannot ever be obtained, some benchmark for performance needs to be set. In the case of antenna VSWR, this is usually 2:1. At this point, 88.9% of the energy sent to the antenna by the transmitter is radiated into free space and 11.1% is either reflected back into the source or lost as heat on the structure of the antenna. In the other direction, 88.9% of the energy recovered by the antenna is transferred into the receiver. As a side note, since the ":1" is always implied, many data sheets will remove it and just display the first number.

VSWR is usually displayed graphically versus frequency, as shown in Figure 4. The lowest point on the graph is the antenna's center frequency. The VSWR at that point denotes how close to 50-ohms the antenna gets. The space between the points where the graph crosses the specified VSWR typically defines the antenna's bandwidth.

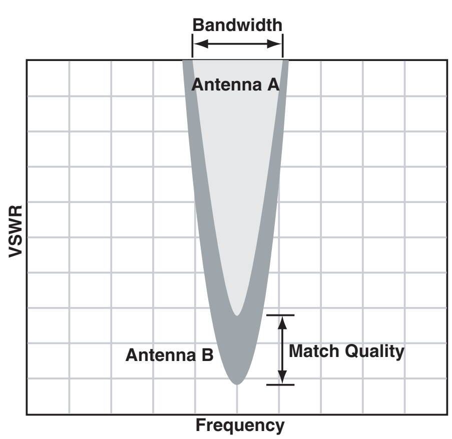

Figure 4: VSWR Graph

Directivity, Efficiency and Gain

True antenna performance can only be determined by measuring the amount of energy that the antenna radiates into free space. This is not an easy task given all of the variables associated with radiated measurements, but that is for another time. When the radiated power is measured around the antenna, a shape emerges called the radiation pattern (Figure 5). This is the most direct measurement of an antenna's actual performance.

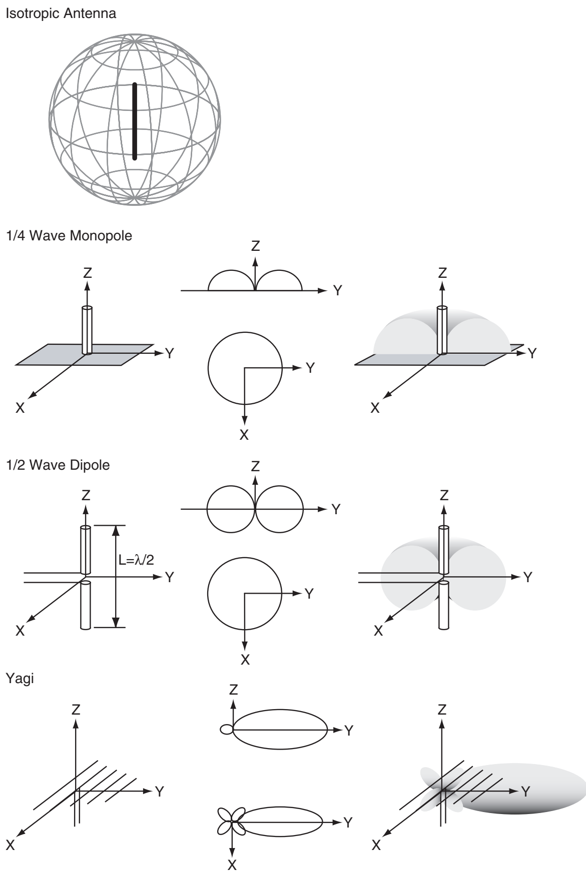

Figure 5: Example Radiation Patterns

Antenna radiation patterns can take many interesting shapes, particularly when presented graphically in their real-world three-dimensional state. The adjoining diagram shows shapes typical of the most popular antenna types. For a dipole antenna, the pattern looks like a doughnut. For a monopole antenna on a ground plane, cut that doughnut in half along the edge and set it on the plane with the antenna sticking up through the middle. The Yagi's directivity can be clearly seen, although that term and the value of these types of plots will become even more apparent as directivity, efficiency and gain are discussed.

After the radiated energy surrounding an antenna is measured, the data is often turned into a radiation pattern plot. This plot graphically presents the way in which the radio frequency energy is distributed or directed by the antenna into free space. An antenna radiation pattern plot is an important tool that allows rapid visual assessment and comparison of antennas. The antenna's radiated performance, and thus the corresponding plot, will be influenced by the test jig or product on which the antenna is mounted. This makes the comparison of plots coming from different manufacturers difficult. In addition, the plot for a specific design will likely vary from that of a reference design. Pattern plots typically consist of a polar coordinate graph, though Cartesian coordinate graphs are also used. Polar plots are easier to visualize, as they show the radiated power 360° around the antenna under test. Generally, a logarithmic scale is used, which allows a range of data to be conveniently shown on the same plot. Two plots are created, one in the horizontal axis and one in the vertical axis. Together, these give a picture of the three dimensional shape of the radiation pattern as shown in Figure 6.

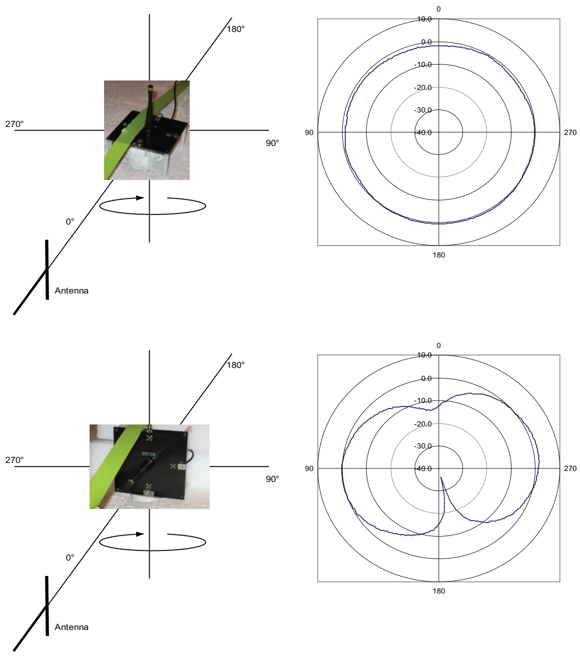

Figure 6: Polar Plots of an Antenna Radiation Pattern

An antenna's radiation pattern and specifications related to it often need a point of comparison or reference. Most frequently, a theoretical antenna called an isotropic antenna or isotropic radiator is used for this purpose (Figure 7). The term "iso" means the same and "tropic" means direction. Thus isotropic describes an antenna which radiates electromagnetic energy the same in all directions. The isotropic antenna and its perfect spherical pattern are only theoretical and do not actually exist, but the model serves as a useful conceptual standard against which "real world" antennas and their specifications can be compared. Now it is time to take a closer look at some of the most important radiated specifications and what they mean.

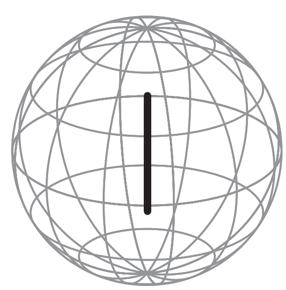

Figure 7: Isotropic Radiation Pattern

There are three radiated specifications that are of primary interest: efficiency, directivity and gain.

Often these terms are talked about in the context of an antenna's transmitted signal. It is somewhat easier to visualize these concepts by thinking of radiated power, but it should be recognized they apply directly to reception as well.

Efficiency is a measurement of how much energy put into the antenna actually gets radiated into free space rather than lost as heat on the antenna's structure or reflected back into the source. The antenna's impedance and VSWR at the center frequency play a big role in this measurement.

Directivity measures how much greater an antenna's peak radiated power density is in a particular direction than for a reference radiator with the same source power. It is the ratio of the power density in the pattern maximum to the average power density at a uniform distance from the antenna. In short, it is a comparison of the shape of the radiation pattern of the antenna under test to a reference radiation pattern. Most commonly, the reference would be the perfect spherical pattern of the isotropic model described earlier. The units of this measurement are decibels relative to isotropic, or dBi. A dipole antenna is also sometimes used as a reference, in which case the units be stated in dBd (meaning decibels relative to dipole). A dipole has a gain of 2.15dB over isotropic or dBi = dBd + 2.15dB. When comparing gains, it is important to note whether the gain is being expressed in dBd or dBi and convert appropriately.

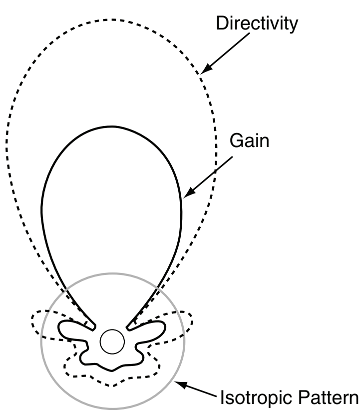

Figure 8: Directivity and Gain

Gain can be a confusing specification. Most engineers are familiar with the term in reference to amplifiers, where gain is a measure of how much an amplifier increases the input signal. But there is a significant difference between an amplifier's gain and an antenna's gain. The amplifier puts energy into the system, making it an active device. An antenna cannot put energy into the system, so it is a passive device. Gain is commonly misinterpreted as an increase in output power above unity. Of course, this is impossible, since the radiated power would be greater than the original power introduced to the antenna.

Directivity and gain are closely related. Gain is the directivity of the antenna reduced by the losses on the antenna, such as dielectric, resistance and VSWR. In other words, it is the product of directivity and efficiency. Gain is the most direct measurement of an antenna's real performance. As such, it is one of the most important specifications.

A simple way to understand directivity or gain is to think of a focusable light source. Assume the light output is constant and focused over a wide area. If the light is refocused to a spot, it appears brighter because all of the light energy is concentrated into a small area. Even though the overall light output has remained constant, the concentrated source will produce an increase in lux at the focus point compared to the wide source. In the same way, an antenna that focuses RF energy into a narrow beam can be said to have higher directivity (at the point of focus) than an antenna that radiates equally in all directions. In other words, the higher an antenna's directivity, the narrower the antenna's pattern and the better its point performance will be.

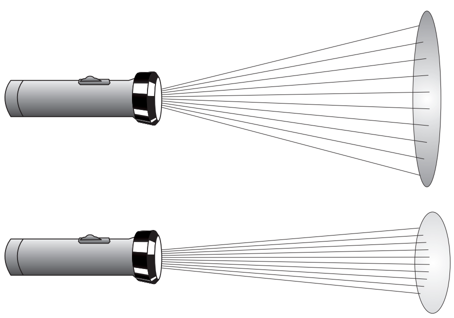

Figure 9: Light Gain