APPLICATION NOTE AN-00500
Antennas:
Design, Application, Performance

Introduction

This application note is intended for designers who are incorporating RF into Part 15-compliant designs. It is designed to give the reader a basic understanding of an antenna's function, operational characteristics, and evaluation techniques. It will also briefly touch on design considerations for the three most common low-power antenna styles, the whip, helical and loop trace.

What is an antenna?

A RF antenna is defined as a component that facilitates the transfer of a guided wave into, and the reception from, free space. In function, the antenna is essentially a transducer that converts alternating currents into electromagnetic fields or vice versa. The physical components which make up an antenna's structure are called *elements*. From a coat hanger to a tuned Yagi, there are literally hundreds of antenna styles and variations that may be employed.

Receive and transmit antennas are very alike in characteristics; in many cases virtual mirror images of each other. However, in many Part 15 applications it is often advantageous to select different characteristics for the transmitter and receiver antennas. For this reason, we will address each separately.

The transmitter antenna

The transmitter antenna allows RF energy to be efficiently radiated from the output stage into free space. In many modular and discrete transmitter designs the transmitter's output power is purposefully set higher than the legal limit. This allows a designer to utilize an inefficient antenna to achieve size, cost, or cosmetic objectives and still radiate the maximum allowed output power. Since gain is easily realized at the transmitter, its antenna can generally be less efficient than the antenna used on the receiver.

The receiver antenna

The receiving antenna intercepts the electromagnetic waves radiated from the transmitting antenna. When these waves impinge upon the receiving antenna, they induce a small voltage in it. This voltage causes a weak current to flow, which contains the same frequency as the original current in the transmitting antenna.

A receiving antenna should capture as much of the intended signal as possible and as little as possible of other off-frequency signals. It should give its maximum performance at the frequency or in the band for which a receiver was designed. The efficiency of the receiver's antenna is critical to maximizing range performance. Unlike the transmitter antenna, where legal operation may mandate a reduction in antenna efficiency, the receiver's antenna should be optimized as much as is practical.

Understanding transmission lines

A transmission line is any medium whereby contained RF energy is transferred from one place to another. Many times a transmission line is referred to as "a length of shielded wire" or a "piece of coax". While technically correct, such casual references often indicate a lack of understanding and respect for the complex interaction of resistance, capacitance, and inductance that is present in a transmission line.

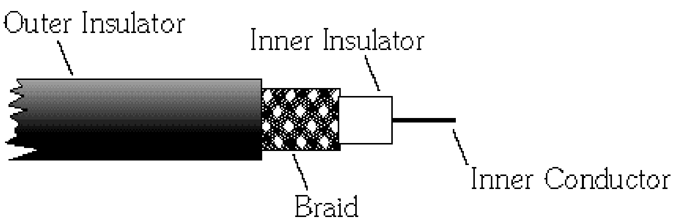


Figure 1 Typical Transmission Line

The diameter and spacing of the conductors as well as the dielectric constant of the materials surrounding and separating the conductors plays a critical role in determining the transmission line's properties. One of the most important of these properties is called *characteristic impedance*. Characteristic impedance is the ohmatic value at which the voltage-to-current ratio is constant along the transmission line. All Linx modules are intended to be utilized with transmission lines having a characteristic impedance of 50 ohms.

In order to achieve the maximum transfer of RF energy from the transmission line into the antenna, the characteristic impedance of the line and the antenna at frequency should be as close as possible. When this is the case the transmission line and antenna are said to be *matched*. When a transmission line is terminated into an antenna that differs from its characteristic impedance, a mismatch will exist. This means that all the RF energy is not transferred from the transmission line into the antenna. The energy which cannot be transferred into the antenna is reflected back on the transmission line. Since this energy is not reflected into space, it represents a loss. The ratio between

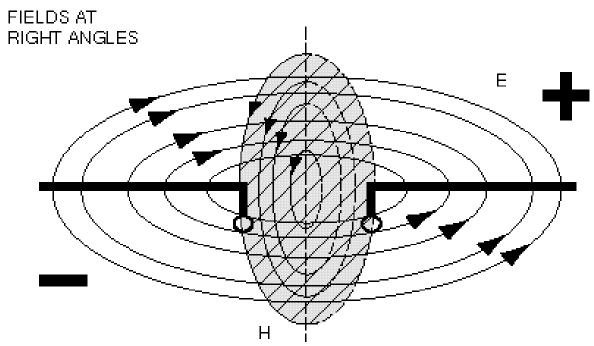


Figure 2 E&H fields surrounding an antenna

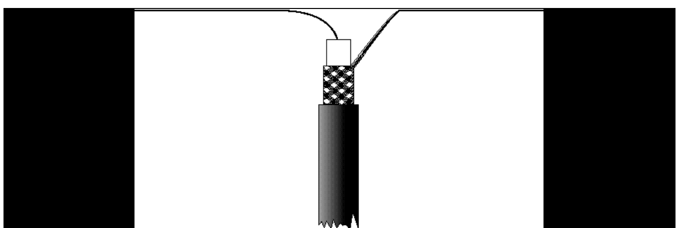
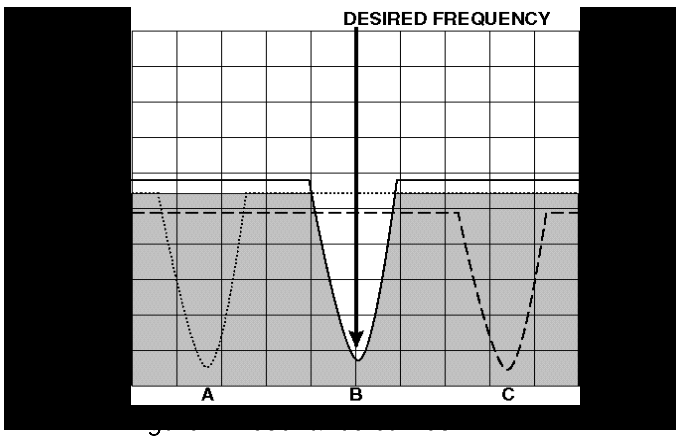


Figure 3 basic antenna



length determined?

Every frequency has a certain physical length that it occupies in space. That length is aptly referred to as the *wavelength* and is determined by two factors: 1) the frequency itself and 2) the speed of propagation. In free space, a frequency's wavelength can be found using the following formula:

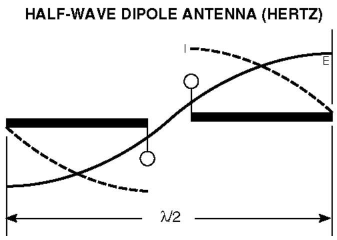
$$L = \frac{984}{F_{MHz}} \text{ Feet}$$

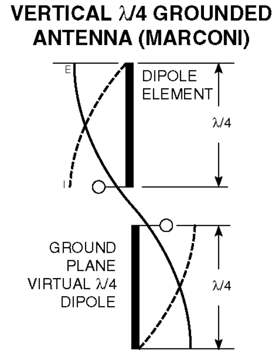
However, since an antenna has a dielectric constant greater than that of free space, the velocity of a wave on the antenna is slower. This fact, along with several other factors, has led antenna designers to accept the following formula as accurate for all practical purposes in determining the physical length of a full-wave antenna:

$$L = \frac{936}{F_{MHz}} \text{ Feet}$$

While this formula is excellent for getting the antenna's length in the ballpark, always bear in mind that the true issue is antenna resonance. Depending on physical factors such as antenna diameter, nearby conductors, etc., it may be necessary to add or cut the antenna slightly to reach resonance.

An antenna does not have to be the physical length of a full wave in order to operate. Indeed, most of the time for size and impedance considerations, the antenna will be some fraction of a full wavelength. A half-wave antenna is the shortest resonant length of an antenna. However, shorter wavelengths can be resonant on harmonics. Because of its compact length, one of the most popular antennas for Part 15 applications is the 1/4 wave whip. In this configuration, the antenna element is 1/4 of a full wavelength. In order to operate effectively the 1/4 wave must radiate against a ground-plane. The ground-plane can be a metal case or ground area on a PCB of at least equivalent area to the antenna's surface. The ground-plane acts as a counterpoise that forms the other quarter-wave element, in essence forming an effective half-wave

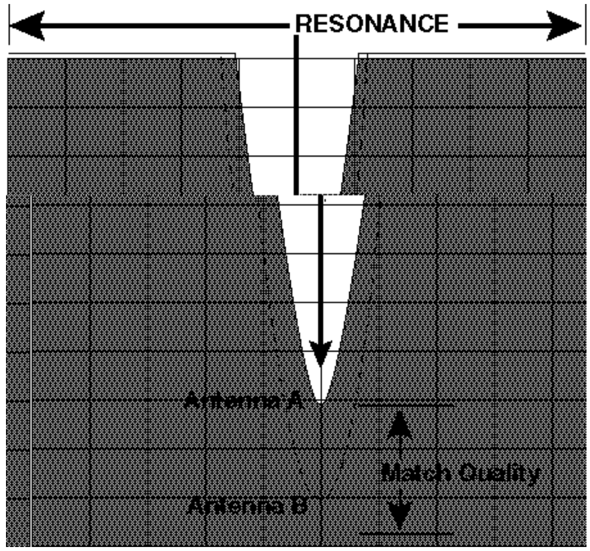




dipole as illustrated.

Antenna matching

Antenna resonance should not be confused with antenna impedance. The difference between resonance and impedance is most easily understood by considering the value of VSWR at its



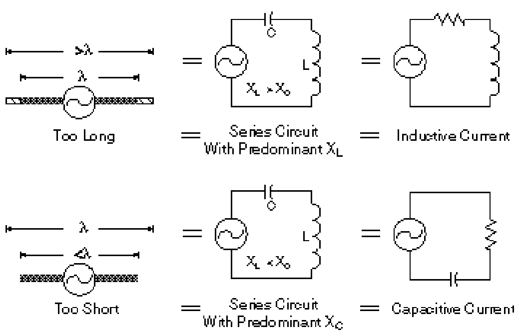
lowest point. The lowest point of VSWR indicates the antenna is resonant, but the value of that low point is determined by the quality of the match between the antenna and the transmission line it is attached to. This point of attachment is called the *feedpoint*. In the diagram below you will notice both antenna (A) and antenna (B) are resonant; however, antenna (B) exhibits a much lower VSWR. This is because the feedpoint impedance of (B) is more closely matched to the impedance of the transmission line. Clearly an antenna must be both resonant and matched for maximum RF energy to be propagated into free space.

We have learned that the point of resonance is largely determined by antenna length, but how is antenna impedance determined? When an antenna is at resonance it presents a purely resistive load. This resistance is made up of three factors. First, when the antenna is considered only as a conductor, there is loss through the real physical resistance of the antenna element. This is called *ohmic resistance loss*. The second and most important area of loss is through *radiation resistance (Rr)*. Radiation resistance is the ohmic value of a theoretical resistor that, if substituted for the antenna, would dissipate the same amount of RF energy that the antenna radiates into space. The last source of resistive loss is though the leakage resistance of dielectric elements such as insulators.

Since the real and leakage resistances are usually negligible, we will focus on radiation resistance. As mentioned previously, radiation resistance is a hypothetical concept that describes a fictional resistance which, if substituted in place of the antenna, would dissipate the same power that the antenna radiates into free space. The radiation resistance of an antenna varies along the length of the antenna element but our concern is with the resistance at the feedpoint. The radiation resistance increases as a conductor lengthens. In general, the radiation resistance for a 1/4 wave vertical is about 37 ohms, for a half-wave about 73 ohms.

Antenna tuning

This is the process whereby the resonant point of an antenna is adjusted. If an antenna is too short, its input impedance will be both resistive and capacitive. This capacitance can be offset and the antenna electrically lengthened to resonance by adding an inductor in series. If an antenna is too long, its input impedance will be both resistive and inductive. The antenna can be electrically shortened by adding a capacitor to cancel the inductance, thus leaving the antenna resonant and purely resistive at the desired frequency.

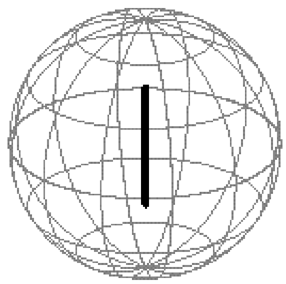


10/97 NOTE: *Due to the overwhelming request for this application note, we are releasing it prior to the completion of this section. You will want to obtain a final copy after 11/1 via our website or fax if you are interested in learning more about the matching process.*

Antenna performance

In addition to broad concepts of antenna function outlined in the preceding section, there are specific issues of antenna performance that are equally important to consider. The most important of these issues are covered in the following section.

Radiation Pattern



The term *radiation pattern* is used to define the way in which the radio frequency energy is distributed or directed into free space. The term *isotopic* antenna is commonly used to describe an antenna with a theoretically perfect radiation pattern. That is one which radiates electromagnetic energy equally well in all directions. Such an antenna is, of course, only theoretical and has never actually been built, but the isotopic model serves as a conceptual standard against which “real world” antennas can be compared.

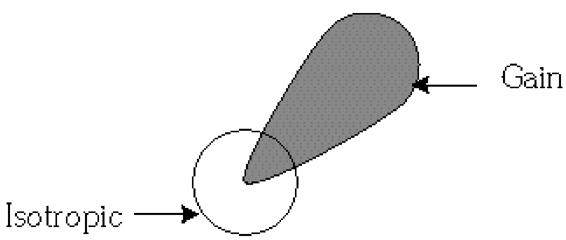
In the real world an antenna will efficiently radiate RF energy in certain directions and poorly in others. The point(s) of greatest efficiency are called peaks while the areas of no field strength are called nulls. The overall distribution characteristics of the antenna make up the radiation pattern. In many applications it is advantageous to have the antenna perform equally well in all directions. In these instances a designer would choose an antenna style with an omni-directional radiation pattern as such characteristics would be desirable. In instances where highly directional antenna characteristics are needed an antenna style such as a yagi would be chosen

Antenna Gain

The term *gain* refers to the antenna’s effective radiated power as compared to the effective radiated power of some reference antenna. When the isotopic model is used, the gain will be stated in dBi (meaning gain in dB over isotopic). In instances where the gain is being compared to a standard dipole, the rating will be stated in dBd (meaning gain over dipole). The generally accepted variation between an isotopic point source and a standard dipole is 2.2 dB. Thus, an antenna rated as having 15 dBi would indicate that the antenna had 15dB of gain over an isotopic source or 12.8dB of gain as compared to a standard single-element dipole.

The term *"gain"* is commonly misunderstood. Many engineers construe gain to mean an increase in output power above unity. Of course, this is impossible as the effective radiated power would be in excess of the power originally introduced into the antenna.

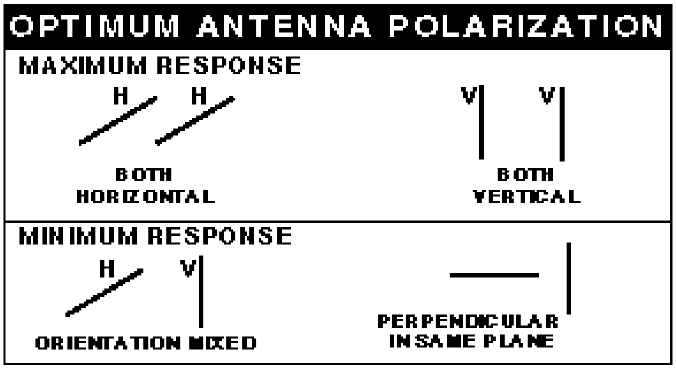
The simplest way to understand gain is to think of a focusable light source. Assume that the light output is constant at all times and focused so the light covers a wide area. If the light were refocused to a spot setting, it would appear substantially brighter because all of the light energy is concentrated into a small area. Even though the overall light output has remained constant, the light will have a gain in lux at the focus point over the original pattern.



In the same way, an antenna which focuses RF energy into a narrow beam can be said to have gain (at the point of focus), over an antenna which radiates equally well in all directions. In other words, the higher an antenna's gain the narrower the antenna's radiation pattern. If all other characteristics are equal, an antenna with high gain will be more effective at distance than an antenna which radiates in all directions.

Antenna Polarization

The effective polarization of an antenna is an important characteristic. *Polarization* refers to the orientation of the lines of flux in an electromagnetic field. When an antenna is oriented horizontally with respect to ground it is said to be horizontally polarized. Likewise, when it is perpendicular to ground it is said to be vertically polarized.



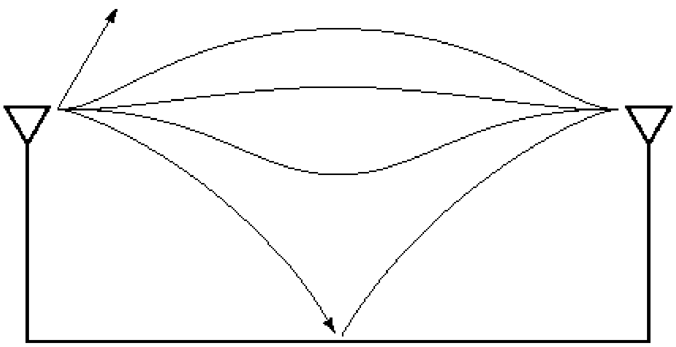
The polarization of an antenna normally parallels the active antenna of an element; thus, a horizontal antenna radiates and best receives fields having horizontal polarization while a vertical antenna best radiates and receives fields having a vertical polarization. If the transmitter and receiver's antennas are not oriented in the same polarization, a certain amount of effective radiated power cannot be captured by the receiving antenna. In many applications involving portable devices there is little control over the antenna orientation; however, to achieve maximum range the antennas should be oriented with like polarization whenever possible. In the VHF and UHF spectrums horizontal polarization will generally provide better noise immunity and less fading than a vertically polarized element.

Antenna efficiency

Not all of the power delivered into the antenna element is radiated into space. Some power is dissipated by the antenna and some is immediately absorbed by surrounding materials.
Forward power- the power originally applied to the antenna input.

Reflected power- a portion of the forward power reflected back toward the amplifier due to a mismatch at the antenna port.

Net power- the power applied to the antenna that actually transitions into free space is called the net power or effective radiated power. Net power is usually calculated by finding the difference between the actual forward and reflected power values.



Multiple paths for a signal to take between transmitter and receiver.

Multipath Effect

Multipath fading is a form of fading caused by signals arriving at the receiving antenna in differing phases. This effect is due to the fact that a signal may travel many different paths before arriving at the antenna. Some portions of the original signal may travel to the receiver's antenna via a direct free space path. Others which have been reflected travel longer paths before arrival. The longer path taken by the reflected waves will slightly delay their arrival time from that of the free space wave. This creates an out-of-phase relationship between the two signals. The resulting voltage imposed on the receiving antenna will vary based on the phase relationship of all signals arriving at the antenna. While this effect is environmental and not related directly to the antenna, it is still important to understand the role multipath may play in theoretical vs. realized antenna performance.

Antenna design for Part 15-compliant low-cost, low-power designs

A designer who is specifying an antenna for a Part 15-compliant product faces a number of challenges not normally encountered in antenna design. Since many products engineered for Part 15 compliance are compact and portable, a designer may have to balance the issue of antenna performance with issues such as packaging and cosmetic considerations. In addition, Part 15 places some unusual restrictions on the actual antenna design. Most notable is the requirement that an antenna be either permanently attached or utilize a unique and proprietary connector. This is intended to prevent the end user from changing the performance characteristics of the products from those present when it was originally manufactured.

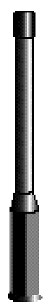
If you have waded through to this point in the hope of discovering a magic formula for easily designing low-cost, high-performance antennas without experience or test equipment, I am sorry to have waited so long to disappoint you. It is simply not possible in the context of this brief note to give the reader a full understanding of antenna design and testing procedures. In addition, an antenna's performance is closely dependent on individual application variables such as the dielectric constants, proximity to other components, and material properties. In order to design and evaluate the performance of an antenna correctly, several tools are required. Among the most important are a network analyzer, spectrum analyzer, and frequency source. A network analyzer is particularly valuable as it allows the antenna's resonate points, characteristic impedance, and SWR to be accurately measured. Without access to these resources, antenna design is a blind hit-and-miss proposition.

If your application does not call for maximum range performance and you are able to utilize a antenna style such a whip which can be easily calculated, you may achieve satisfactory performance through trial and error methods. For more sophisticated antenna designs, however, it is always best to use a professionally manufactured antenna, such as those made by Linx, or to rent some basic level of test equipment for the design phase.

For those with adequate equipment and measurement expertise, a brief design outline of design considerations for the three most popular antenna styles follows.

Popular antenna styles for low-cost wireless

Whip



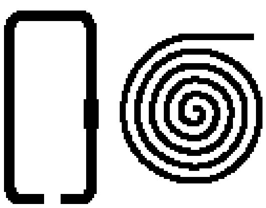
A whip-style antenna provides exceptional performance and is easily designed and integrated. Many off-the-shelf whip designs are available for purchase. These are generally made of rubber-encapsulated wire or cable. A whip can also easily be made by cutting a piece of wire or rod to the appropriate length. Since a full-wave whip is generally quite long and its feedpoint impedance high, most whips are either a 1/4 or 1/2 wave. The correct length for either is easily determined as follows:

For example, suppose we wanted to find the approximate length of a 1/2 wave antenna resonant at 418 Mhz. Using the formula above, 468 divided by 418 = 1.1196 ft., we can determine that the antenna element should be cut to about 13.4”. By dividing this result in half we can also easily find that a 1/4 wave antenna should be about 6.7” in length.

While an antenna can be matched more precisely, the characteristic impedance of both a 1/2 and 1/4 whip is close enough to 50 ohms to provide a generally acceptable value of SWR.

Helical

A helical is a wire coil usually wound from steel, copper, or brass. The helical is an excellent choice for products requiring good range performance and a concealed antenna element. Care must be exercised in placement, however, as a helical detunes badly when located in proximity to other conductive objects. Because a helical has a high Q factor, its bandwidth is very narrow and the spacing of the coils has a pronounced effect on antenna performance. It is possible to calculate the length of a helical once the diameter, material type and coil spacing are known. In most cases, however, it is just as easy to arrive at a design empirically by taking a excessively long coil and tuning it by clipping until it is resonant at the desired frequency. The length may then be calculated by the turns and radius values or simply by straightening the coil and measuring it.



Loop Trace

The last style of antenna we will discuss is the loop trace. This style is extremely popular in low-cost applications. Since a loop trace is generally etched as part of the PCB it can be easily concealed and adds little cost to the overall product cost. A loop can be very difficult to tune and match. It is also subject to detuning based on the dielectric constant of the board material and board production variances. For these reasons the use of loops are generally confined to low-cost transmitter devices such as garage door openers, car alarms, etc. If great care is paid to the design of the loop and it is optimized for impedance and then resonated with a capacitor or inductor, excellent performance can be obtained. In many cases, however, it is much easier to achieve maximum performance from a helical or whip style.

Attenuating output power

In order to meet Part 15 requirements many designers attempt to attenuate their fundamental output power by shortening or lengthening the antenna to shift its point of resonant efficiency away from the fundamental. This is not usually a good idea for two reasons. First, by raising the SWR and reducing an antenna’s efficiency at your intended fundamental frequency you have potentially increased the output efficiency at a harmonic as shown in figure ????. Second, by creating such a mismatch the transmitter’s output or oscillator stage may become unstable. To properly attenuate output power an attenuation pad should be used as described in Linx application note 00150.

Putting It All Together

In the design process the antenna should be viewed as a critical component in system performance. After reviewing this application note we hope you have a better understanding of the basic considerations necessary to achieve optimum antenna function. At Linx the science of RF is our business. We attempt to make its application as straightforward as possible so you can concentrate on profitably bringing your product to market. In keeping with this objective Linx offers a growing line of optimized antenna products. If you require additional assistance in your antenna selection process, please feel free to contact a Linx application engineer at (800) 736-6677.