Anatomy of an Antenna

By

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As a RFID implementer, you may find yourself responsible for the maintenance of reader systems that both radiate and receive electromagnetic energy. All RFID reader systems require an antenna to make use of this electromagnetic energy. In this paper, we will discuss antenna characteristics, types, construction, tuning and safety.

ANTENNA CHARACTERISTICS

An antenna may be defined as a conductor or group of conductors responsible for radiating electromagnetic energy into space and collecting it from space. The antenna converts electrical energy from the transmitter of the RFID system into electromagnetic energy and radiates it into space. Conversely, the antenna collects electromagnetic energy from space and converts it into electrical energy that is delivered back to the receiver of the RFID system. This space is known as the air interface.

The electromagnetic energy transmitted by the antenna consists of two components known as the electrical field and the magnetic field. The total energy radiated from an antenna is constant in space, except for factors such as absorption by the earth or nearby objects. As the wave advances, the energy spreads out over a greater area causing the amount of given energy in an area to decrease as the distance from the antenna source increases.

The actual design of the antenna for transmitting purposes is critical for efficient operation. The antenna must deliver maximum energy to the air interface so that the power from the transmitter is not wasted. An efficient antenna must be cut to exact dimensions as determined by the operating frequency. The dimensions for a receiving antenna are less important at fairly low frequencies but dimensional importance increases dramatically as the frequency increases.

Most practical transmitting antennas are based upon two fundamental characteristics. Half-wave (Hertz) antennas are generally installed above ground and are positioned to radiate either horizontally or vertically. Quarter-wave (Marconi) antennas operate with one end grounded and are mounted perpendicular to the earth or another surface acting as a ground. The half-wave (Hertz) antenna is also referred to as a dipole and forms the basis for more complex antennas generally operating at 2MHz or higher. Quarter-wave (Marconi) antennas are generally used at frequencies below 2MHz.

All antennas regardless of their configuration have four basic characteristics defined as directivity, gain, polarization and reciprocity.

DIRECTIVITY

Directivity is a measure of an antenna or array to focus the radiated energy in one or more specific directions. The directivity of an antenna can be determined by viewing the radiation pattern. A given amount of energy from a directional antenna can be propagated in one or more directions. The elements of a directional antenna can be arranged to radiate energy more evenly or conversely precisely focus radiation in one direction more than others. As shown in Figure 1.1, the patch (linear) and dipole antenna designs propagate radiated energy in specific directions when compared against the loop (omni-directional) antenna design.

The three antenna types deliver distinct geometrical coverage

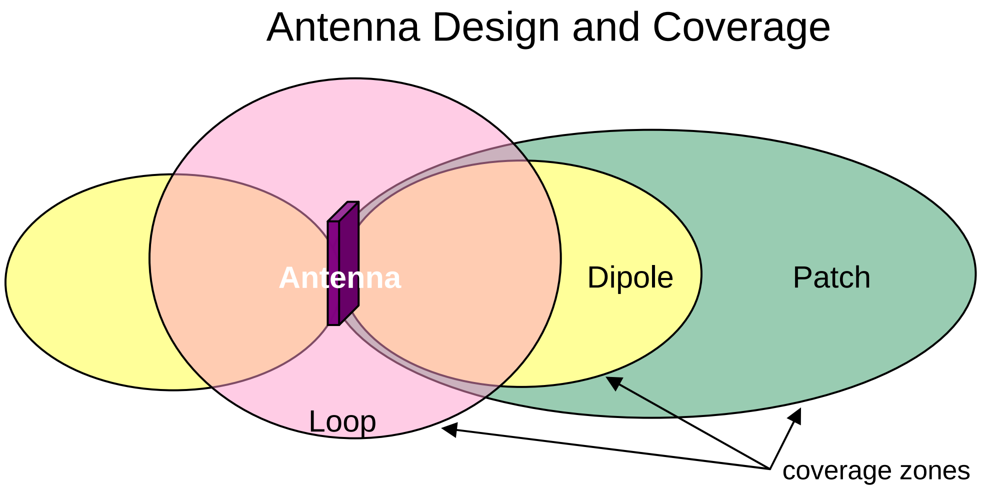

Figure 1.1

GAIN

The gain of a directional antenna propagating energy in one or more directions is a ratio between the energy focused in these directions and the energy that would have been propagated if the antenna were not directional. The gain of an antenna is constant for both transmitting and receiving.

POLARIZATION

The radiation field is made up of magnetic and electric lines of force that are always at right angles to each other. Most electromagnetic fields in space are said to be linearly polarized. The direction of polarization is the direction of the electric vector. That is, if the electric lines of force (E lines) are horizontal, the wave is said to be horizontally polarized (figure 1.2), and if the E lines are vertical, the wave is said to be vertically polarized. Since the electric field is parallel to the axis of the dipole, the antenna is in the plane of polarization.

A horizontally placed antenna produces a horizontally polarized wave, and a vertically placed antenna produces a vertically polarized wave. In general, the polarization of a wave does not change over short distances. Therefore, transmitting and receiving antennas are oriented alike, especially if they are separated by short distances. Where separate antennas are used for transmitting and receiving, the receiving antenna is generally polarized in the same direction as the transmitting antenna.

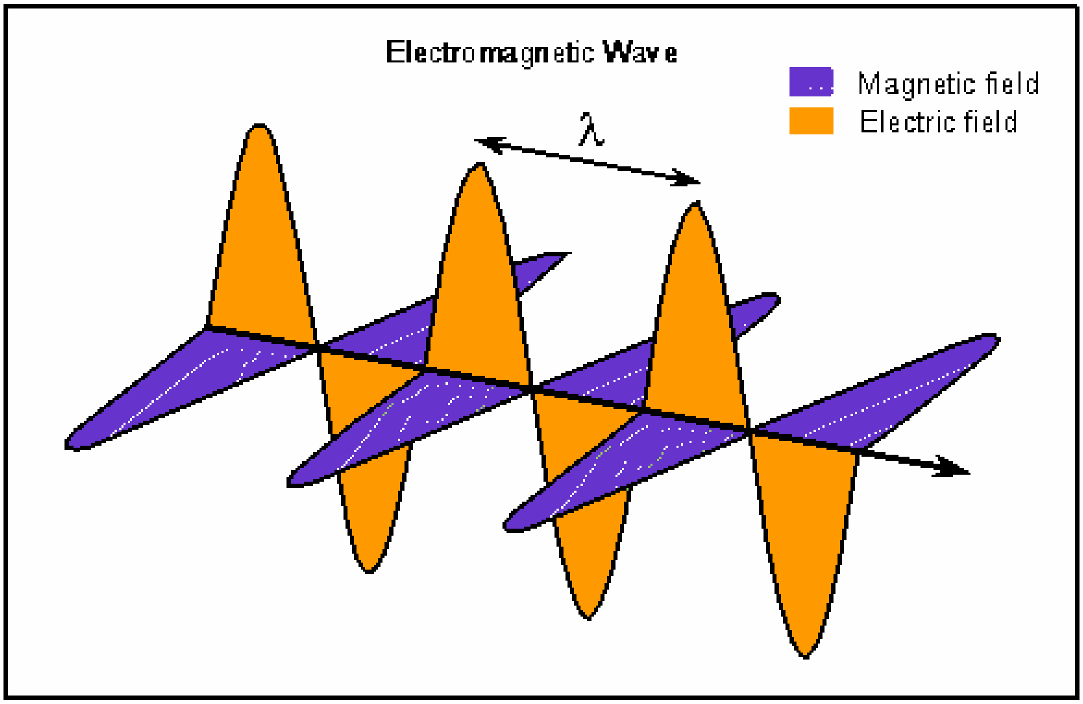

Figure 1.2 Electromagnetic Wave

RECIPROCITY

Reciprocity is the ability to use the same antenna for both transmitting and receiving. The electrical characteristics apply equally for both. The more efficient an antenna is for transmitting at a given frequency, the more efficient it will be for receiving signals at that same frequency. For example, when a dipole antenna is used for transmitting maximum energy occurs at right angles to its axis (Figure 1.3). When the same antenna is used for receiving the best reception is along the same path; that is, at right angles to its axis.

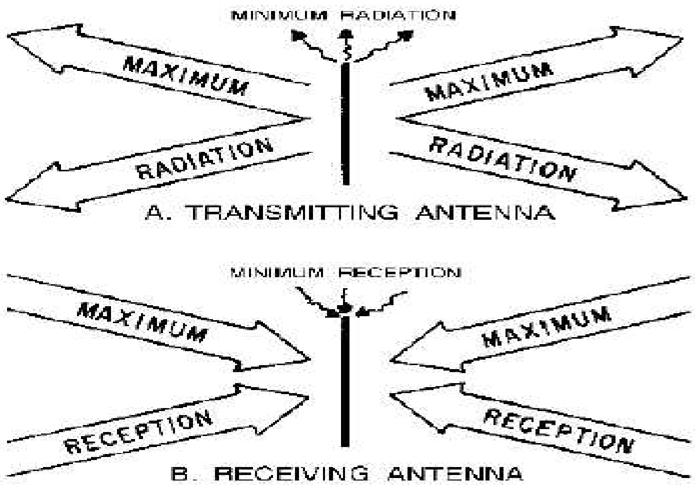

Figure 1.3 Antenna Reciprocity

RADIATION OF ELECTROMAGNETIC ENERGY

Various factors in the antenna circuit affect the radiation of electromagnetic energy. In figure 1-4, for example, if an alternating current is applied to the A end of wire antenna AB, the wave will travel along the wire until it reaches the B end. Since the B end is free, an open circuit exists and the wave cannot travel further. This is a point of high impedance. The wave bounces back (reflects) from this point of high impedance and travels toward the starting point, where it is again reflected. Theoretically, the resistance of the wire should gradually dissipate the energy of the wave during this back-and-forth motion (oscillation). However, each time the wave reaches the starting point; it is reinforced by an impulse of energy sufficient to replace the energy lost during its travel along the wire. This results in continuous oscillations of energy along the wire and a high voltage at the A ends of the wire. These oscillations move along the antenna at a rate equal to the frequency of the RF voltage and are sustained by properly timed impulses at point A.

The rate at which the wave travels along the wire is constant at approximately 300,000,000 meters per second. The length of the antenna must be such that a wave will travel from one end to the other and back again during the period of 1 cycle of the RF voltage. The distance the wave travels during the period of 1 cycle is known as the wavelength. It is found by dividing the rate of travel by the frequency. The maximum movement of electrons is in the center of the antenna at all times; therefore, the center of the antenna is at a low impedance.

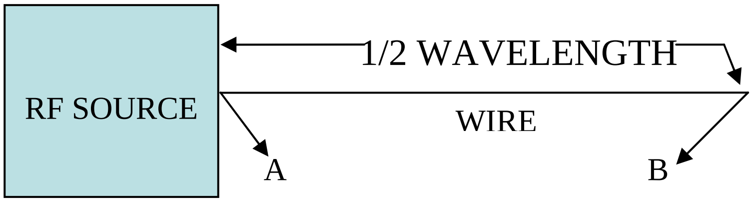

Figure 1.4 Impedance

IMPEDANCE

Impedance is the generalization of the concept of resistance from DC to AC. In other words, a way to represent how much current will flow with a specified (AC) voltage across the impedance. In its simplest form, if you have one volt AC across an impedance that lets one ampere of AC current flow, the impedance is defined by the AC version of Ohm's law and is one ohm.

Since AC has not only amplitude, like DC, but also frequency and phase, this introduces the possibility that an impedance will not only allow a current to flow, but will change the phase of the signal, and respond with different amplitudes and phases as frequency changes.

There are ways to calculate impedance that are analytically correct. For the purpose of this paper, the concept of impedance is illustrated by using two examples. Let us assume you have four (4) items on your lab bench. These items are:

a) Eight “AA” batteries wired in series to provide a 12-volt supply
b) A 12-volt fully charge automotive battery
c) A tiny 12-volt lamp or flashlight bulb
d) A heavy-duty automotive headlamp

Well if we connect the eight “AA” battery string to the small 12-volt lamp, everything would be fine, at least for a time until the batteries discharge. Similarly, if we connected the automotive high beam headlamp to the fully charged automotive things would be great.

Now picture the situation reversed with the headlamp connected to the “AA” batteries and the tiny 12-volt lamp connected to the fully charge automotive battery. One can quickly envision the headlamp would to a quick job of trashing the “AA” batteries. The tiny 12-volt lamp presents a different picture. This lamp will glow happily for a very long time and therein lays the explanation of impedance.

The heavy-duty automotive battery is capable of delivering very large amounts of power, but the series string of “AA” batteries is capable of delivering minimal or very low power. The automotive battery represents a source of low impedance, while the “AA” batteries represent a source of high impedance.

Imagine a tiny caterpillar chewing on a large blade of grass - no problem plenty to eat there. Now on the other hand imagine a poor cow stuck in a desert with only one similar blade of grass available to eat.

Matching the impedance of the transmitter, coaxial cable and antenna is critical to delivering the maximum energy to the air interface and will result in the most efficient tag reads in the RFID world.

STANDING WAVES OF VOLTAGE AND CURRENT ON AN ANTENNA

Standing waves on an antenna are of a current and/or voltage nature. All antenna designs, no matter how efficient, have some degree of standing waves. Standing wave ratio measures the standing waves. Standing-wave ratio (SWR) is a mathematical expression of the non-uniformity of an electromagnetic field (EM Field) on a transmission line such as coaxial cable. Usually, SWR is defined as the ratio of the maximum radio frequency (RF) voltage to the minimum RF voltage along the line. This is also known as the voltage standing-wave ratio (VSWR). The SWR can also be defined as the ratio of the maximum RF current to the minimum RF current on the line (current standing-wave ratio or ISWR). For most practical purposes, ISWR is the same as VSWR.

Under ideal conditions, the RF voltage on a signal transmission line is the same at all points on the line, neglecting power losses caused by electrical resistance in the line wires and imperfections in the dielectric material separating the line conductors. The ideal VSWR is therefore 1:1. (Often the SWR value is written simply in terms of the first number, or numerator, of the ratio because the second number, or denominator, is always 1). When the VSWR is 1, the ISWR is also 1. This optimum condition can exist only when the load (such as an antenna or a wireless receiver), into which RF power is delivered, has impedance identical to the impedance of the transmission line. This means that the load resistance must be the same as the characteristic impedance of the transmission line, and the load must contain no reactance (that is, the load must be free of inductance or capacitance). In any other situation, the voltage and current fluctuate at various points along the line, and the SWR is not 1.

When the line and load impedances are identical and the SWR is 1, all of the RF power that reaches a load from a transmission line is utilized by that load. When the load is an antenna, the utilization takes the form of EM-field radiation. If the load is a communications receiver or terminal, the signal power is converted into some other form, such as an audio-visual display. If the impedance of the load is not identical to the impedance of the transmission line, the load does not absorb all the RF power (called forward power) that reaches it. Instead, some of the RF power is sent back toward the signal source when the signal reaches the point where the line is connected to the load. This is known as reflected power or reverse power.

The presence of reflected power, along with the forward power, sets up a pattern of voltage maxima (loops) and minima (nodes) on the transmission line. The same thing happens with the distribution of current. The SWR is the ratio of the RF voltage at a loop to the RF voltage at a node, or the ratio of the RF current at a loop to the RF current at a node. In theory, there is no limit to how high this ratio can get. The worst cases (highest SWR values) occur when there is no load connected to the end of the line. This condition, known as an un-terminated transmission line, is manifested when the end of the line is either short-circuited or left open. In theory, the SWR is infinite in either of these cases; in practice, it is limited by line losses, but can exceed 100. This can give rise to extreme voltages and currents at certain points on the line.

The SWR on a transmission line is mathematically related to (but not the same as) the ratio of reflected power to forward power. In general, the higher the ratio of reflected power to forward power, the greater is the SWR. The converse is also true. When the SWR on a transmission line is high; the power loss in the line is greater than the loss that occurs when the SWR is 1. This exaggerated loss, known as SWR loss, can be significant, especially when the SWR exceeds 2 and the transmission line has significant loss to begin with. For this reason, RF engineers strive to minimize the SWR on communications transmission lines. A high SWR can have other undesirable effects, too, such as transmission-line overheating or breakdown of the dielectric material separating the line conductors.

RADIATION TYPES AND PATTERNS

Logically one may assume that radiation from an antenna emits in all directions. This is not the case for every antenna. The energy radiated from an antenna forms a field having a definite RADIATION PATTERN. The radiation pattern for any given antenna is determined by measuring the radiated energy at various angles at constant distances from the antenna and then plotting the energy values on a graph. The shape of this pattern depends on the type of antenna being used. Some antennas radiate energy equally in all directions. Radiation of this type is known as ISOTROPIC RADIATION. The sun is a good example of an isotropic radiator. If you were to measure the amount of radiated energy around the sun's circumference, the readings would all be fairly equal (Figure 1.5) Most antennas emit (radiate) energy more strongly in one direction than in another and are ANISOTROPIC. A flashlight is a good example of an anisotropic radiator. The beam of the flashlight lights only a portion of the space surrounding it. The area behind the flashlight remains unlit, while the area in front and to either side is illuminated. A linear antenna radiates energy similar to a flashlight and has a very directional wave front. An example is shown in Figure 1.6.

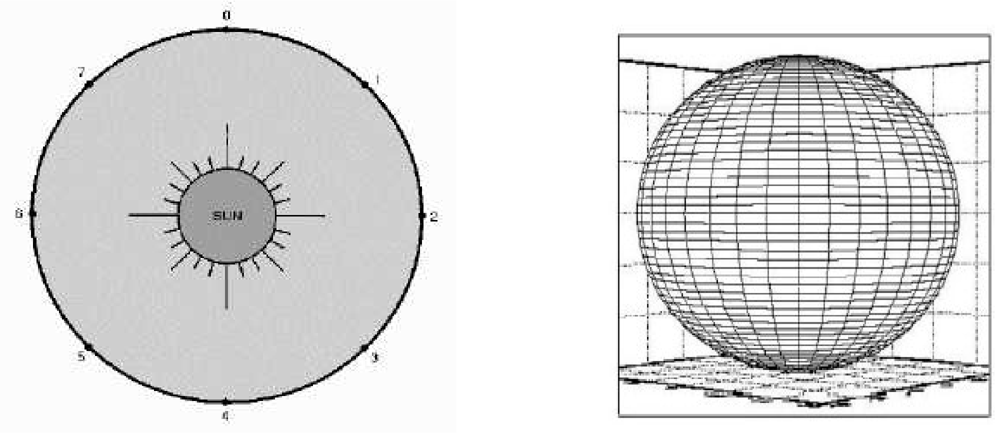

Figure 1.5 Isotropic Radiation

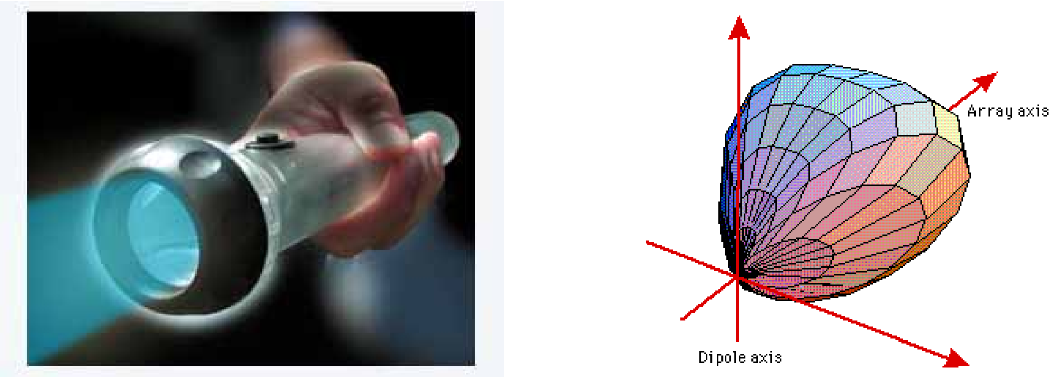

Figure 1.6 Anisotropic Radiation

ANTENNA TUNING

There is an idea antenna design for every frequency in the spectrum. By that, we mean that all of the power provided from the transmitter to the antenna is into space. Unfortunately, this ideal condition is more of a dream than reality. Usually some power is lost between the transmitter and antenna. This power loss, measured as VSWR, is the result of the antenna not having the perfect dimensions and size to radiate all of the power delivered to it from the transmitter. To overcome this problem, we use ANTENNA TUNING to lengthen and shorten antennas electrically to better match the frequency on which we want to transmit. The antenna tuning for the typical antenna used in the RFID world is customarily achieved using a RF tuning or matching circuit that is integral to the antenna design. The matching circuit is connected electrically to the antenna and is used to adjust the apparent physical length of the antenna by electrical means. This simply means that the antenna does not physically change length; instead, it is adapted electrically to the output frequency of the transmitter and “appears” to change its physical length.

Q-factor

Q determines the sharpness or selectivity of this resonant circuit. The "Q" of capacitors is generally so high that it can be ignored. However, the "Q" of an inductor or antenna is of significant concern.

An inductor like a coil exhibits a "resistance" equivalent to an energy loss to alternating current (AC) or radio frequency (RF) energy. The value of the reactance of an inductor at the resonant frequency of a series-resonant circuit divided by the series resistance in the circuit is called the Q or quality factor of the circuit. Q (sharpness or selectivity of this resonant circuit) is calculated using the formula:

$$\mathbf{Q = (2p\ f\ L) / R}$$

Where (2p f L) is, equal to the reactance of either coils or capacitors in ohms, and R the sum of AC or RF resistance plus the DC resistance of the windings. That means that for a wire showing a DC resistance of 1 ohm, for a conductor showing an inductive reactance of 50 ohms, the Q of this coil will be 50/1 = 50. In using a lower resistance value, you will increase the Q (For example 0.5 ohm gives 50/0.5 = 100). Thus, if one keeps the DC resistance of a coil as low as possible, the larger the coil, the higher the Q; that represents the number of times that current circulates before is dissipated.

The Q of a coil can be increased by adding a ferrite core inside the coil. This approach typically causes the system to saturate in strong RF fields and presents difficulty to stabilize the design in a transmission environment.

Another way of reducing the Q of an antenna is to limit the bandwidth. For example, for an antenna working on 13.56 MHz and showing an SWR 1.5:1, the bandwidth can typically be as large as 300 kHz. The Q of this antenna will be 14/.3 ~ 47. If your bandwidth is only 50 KHz, your Q becomes 14/.05 = 280. This means an antenna system displaying a high Q shows also a high SWR except in a very narrow bandwidth centered on the design frequency (50 KHz in this example). The higher is Q, sharper the resonance is of the circuit and the sharper or narrower the bandwidth. Narrowing the bandwidth also means higher SWR at frequencies above and below the antenna band pass or the center design frequency.

Resonance

Resonance occurs when the reactance of an inductor balances the reactance of a capacitor at some given frequency, when $X_L = X_C$. With both values consistent, the current will decrease quite slowly as the frequency is moved in either direction away from resonance, with the design target of covering the entire band of operation. In series resonance, the current will be at a maximum and will offer minimum impedance. The opposite is true in parallel resonant circuits. Using units consistent with RF circuits, the resonance formula is:

$$\mathbf{f = 10^6 / (2p \sqrt{LC})}$$

With f, being the calculated resonance frequency in kilohertz (kHz); L the inductance in mille-henries (mH); and C is the capacitance in pico-farads (pF).

Bandwidth

Several factors determine the bandwidth of an antenna. The main factor is the size of conductors used to build the antenna. An antenna made with electrical wire will display a larger bandwidth than an antenna made of large tubing or wide copper foil tape. Matching networks including Q reducing or dampening resistors increase the antenna bandwidth and tend to reduce the SWR especially at nearby frequencies. The outside area (diameter or width) of the antenna conductors affects the losses as the RF energy travels only on the outside of the wire or antenna elements. This phenomenon is known as the “skin effect”.

If you work with a high SWR over 1.5:1 on the transmission line, your antenna begins to loose some energy and is no longer performing efficiently. Keeping the SWR below 1.5:1 enables the antenna to couple more energy to the air interface. This more efficient antenna means that the maximum amount of energy will be transmitted enabling greater extended tag read distances.

All antenna manufacturers and designers center the lowest SWR reading on the center of the band. For example, a design for the 13.56 MHz ISM band is centered on that particular frequency. The edges of the 13.56 MHz ISM band are 13.110 and 14.010 MHz respectively. Most antennas designed for this particular frequency displays a SWR near 1:1. However, a few hundred kHz away from the center frequency, the SWR may often exceed 2:1. It is a design requirement for a 13.56 MHz antenna that its bandwidth accommodate the entire band while keeping the SWR near 1:1.

Care should be taken not confuse bandwidth with the gain of your antenna. Larger sized tubing, copper foil, or wire does not provide more gain; it does open your bandwidth, potentially lowers the SWR and handles more power.

SAFETY

The safety concerns for antennas operating in the typical RFID environment are far less stringent when compared to antennas being driven by high power transmitters. The reader antennas so they are at least 9 inches away from the nearest person who will be in range of the RF signal for prolonged periods. Reader antennas should be positioned so that personnel in the area for prolonged periods may safely remain at least 23 cm (9 in) in an uncontrolled environment from the antenna’s surface. See FCC OET Bulletin 56 “Hazards of radio frequency and electromagnetic fields” and Bulletin 65 “Human exposure to radio frequency electromagnetic fields”. NOTE: disconnect power to prevent unnecessary transmission of RF energy when reader is not desired.

LOOP ANTENNA CONSTRUCTION

For the purposes of this paper, a decision was made to construct a RFID Loop Antenna operating in the 13.56 MHz ISM band. The antenna can be constructed from any conductive material and is customarily made using copper printed circuit board tracks, copper tape or copper tube. The conductive material selected for this project is adhesive copper foil tape.

As a general rule of thumb, the larger the antenna the greater the RFID tag read distance. Since it was my desire to maximize the tag read range, the antenna will be approximately 40”x24”. As the antenna size increases, the width of the copper foil tape should increase to keep the antenna inductance to a minimum.

For example, when building an antenna measuring 6”x 6”, construction with ½ “ copper foil tape will suffice. Building an antenna 40” x 24” will require the use 3” copper foil tape. The copper foil tape selected for this prototype utilizes conductive adhesive. All joints were soldered and a precaution, with minimum overlap to avoid adding parasitic capacitance. The corners of the rectangular antenna are cut at a 45° angle. The adhesive copper foil tape needs to be placed on a backing suitable to prevent bending, distortion or rippling of the foil tape. Luan ¼” plywood was selected for this purpose. The plywood backing and stand are shown in Figure 1.7.

Figure 1.7 Antenna Backing

MATCHING NETWORK

The 13.56 MHz antenna will utilize a T-matching network as shown in Figure 1.8. The matching arms are constructed with ½” copper foil tape and connected to the center and shielded conductors of the RG58 coaxial cable. Optimum performance requires the coaxial cable be cut to ¼ wavelength or 3.63 meters. Even though we have a copper foil loop that will resonate at 50 ohms, the loop will not will not be 50 ohms impedance, which is the impedance of the coaxial cable. The T-matching arms accomplish this important task. The objective here is to match a 50-ohm impedance load represented by the coaxial cable.

Figure 1.8 T Matching

ANTENNA RESONANCE & Q

The resonance adjustments are accommodated using two variable capacitors for course and fine-tuning. The values of the variable capacitors are 10-80 pF and 0.8-10 pF respectively. Q dampening is accomplished by adding a 10 K ohm thick film resistor in parallel with the tuning capacitors, as shown in Figure 1.8. Proper Q dampening will enable the antenna to exhibit minimum VSWR across the 13.56 MHz ISM band. All three of these components are installed in the upper portion of the main antenna loop and soldered across a ½" gap cut in this portion of the loop as shown in Figure 1.9.

After cutting a gap in the antenna loop, the inductance now measured about 2.2µH. The addition of a capacitors and Q dampening resistor across the gap enables the antenna to resonate at 13.56MHz. The value of this capacitor can be calculated by satisfying the following equation:

$$f_{(\mathrm{res})} = \frac{1}{2\pi\sqrt{LC}}$$

Where L = Inductance and C = Capacitance

Rearranging this formula to solve for capacitance, we have:

$$C_{(\mathrm{RES})} = \frac{1}{(2\pi f)^2 \times L}$$

Solving the equation for the capacitor value for the antenna, we have:

$$C_{\mathrm{RES}} = \frac{1}{(2 \times 3.142 \times 13560000)^2 \times 0.0000022}$$

$$= 6.26 \times 10^{-11}$$

$$= 63 \text{ pF}$$

Using a variable capacitor covering the calculated value facilitates a course adjustment for tuning the antenna. For this purpose a 10-80 pF mica capacitor was selected. In addition, a 0.8 to 10--pF multi-turn air gap capacitor was added in parallel to serve as a fine-tuning adjustment.

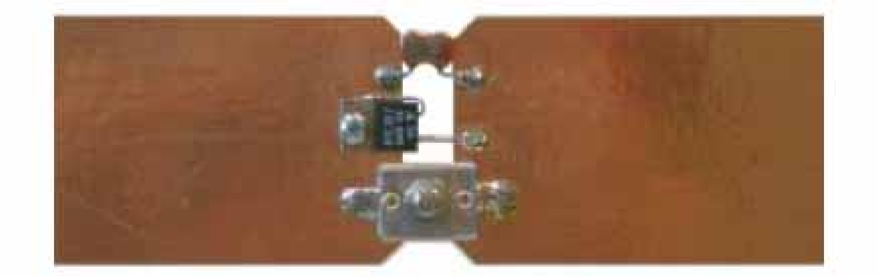

Figure 1.9 Resonance Adjustments and Q Dampening

An antenna analyzer is used to determine the characteristics of an antenna without connecting it to a reader. The antenna analyzer uses a variable frequency signal generator that can indicate the matching frequency, impedance, and VSWR of the antenna being tuned. The antenna analyzer in conjunction with an oscilloscope can calculate the Q (quality factor) of the antenna under test. Alternately, antenna tuning is accomplished by powering the antenna via a reader and adjusting the course and fine adjustments for minimum VSWR across the 13.110 and 14.010 MHz (13.56 MHz) ISM band. The VSWR meter is connected between the antenna cable and reader. With either approach, the course and fine tuning capacitors are adjusted for minimum VSWR. The antenna analyzer and completed antenna are shown in Figure 1.10.

Figure 1.10 Antenna Analyzer and Antenna

ELIMINATING READ HOLES

It is also recommended that a common mode choke be added to the coaxial cable to increase read reliability and eliminate "reading holes". The choke is constructed by passing the coax through a Ferroxcube (Phillips) 4C65 grade ferrite ring core and secured with cable ties. See Figure 1.11.

Figure 1.11 Common Mode Choke

CONCLUSION

Constructing a HF antenna can provide a cost effective method of efficiently utilizing the air interface to affect reliable reading of RFID tags. Several home-brew antennas may be combined to accommodate special or difficult real world situations. Combining antennas can customarily be accomplished by using coax splitters. Splitters are constructed to provide either in phase or out of phase operation when connected to a reader. Splitters introduce losses but the added antenna diversity is usually a big plus. However, careful attention is required as coupling can enhance or degrade the performance of individual antennas.

If one wishes to probe further, there are many interesting antenna concepts that can be discovered. For example, using a pair of antennas to introduce a rotating field (circular) by utilizing coaxial feeder cables of different lengths enables greater read accuracy when tags are presented with random orientation. In this case, the coaxial cable from one of the antennas should be ¼ wave longer than the other after the splitter. The included angle of the pair of antennas should be 90º when mounted in a crossed arrangement.

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HF Antenna Design Notes Technical Application Report (Texas Instruments)
Constructing a 1000 x 600 HF Antenna Technical Application Report (Texas Instruments)
The ARRL Antenna Book (American Radio Relay League)
The Radio Amateur's Handbook (American Radio Relay League)
FCC OET Bulletin 56 "Hazards of radio frequency and electromagnetic fields"
FCC Bulletin 65 "Human exposure to radio frequency electromagnetic fields".

GLOSSARY

Antenna	An antenna may be defined as a conductor or group of conductors responsible for radiating electromagnetic energy into space and collecting it from space.
Antenna Tuning	The process of lengthening and shortening antennas electrically to better match the frequency on which we want to transmit.
Bandwidth	The operating frequency range of antenna exhibiting acceptable SWR
Directivity	Directivity is a measure of an antenna or array to focus the radiated energy in one or more specific directions.
Gain	The gain of a directional antenna propagating energy in one or more directions is a ratio between the energy focused in these directions and the energy that would have been propagated if the antenna were not directional.
Impedance	Impedance is the generalization of the concept of resistance from DC to AC.
Loop Antenna	An antenna consisting of an inductive winding and matching capacitors.
Matching Network	Components that match the impedance of the antenna to the coaxial cable.
Polarization	The radiation field is made up of magnetic and electric lines of force that are always at right angles to each other.
Q Factor	Q determines the sharpness or selectivity of this resonant circuit.
Radiation	Electromagnetic energy moving between an antenna and the air interface.
Radiation Pattern	The radiation pattern for any given antenna is determined by measuring the radiated energy at various angles at constant distances from the antenna and then plotting the energy values on a graph.
Read Holes	Anomalies in the antenna radiation pattern that affects tag read redundancy.
Reciprocity	Reciprocity is the ability to use the same antenna for both transmitting and receiving. The electrical characteristics apply equally for both.
Resonance	Resonance occurs when the reactance of an inductor balances the reactance of a capacitor at some given frequency, when $X_L = X_C$.
Safety	The reader antennas so they are at least 9 inches away from the nearest person who will be in range of the RF signal for prolonged periods.
Standing Wave Ratio	Standing-wave ratio (SWR) is a mathematical expression of the non-uniformity of an electromagnetic field (EM Field) on a transmission line such as coaxial cable.