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RFID Coil Design

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INTRODUCTION

In a Radio Frequency Identification (RFID) application, an antenna coil is needed for two main reasons:

- To transmit the RF carrier signal to power up the tag
- To receive data signals from the tag

An RF signal can be radiated effectively if the linear dimension of the antenna is comparable with the wavelength of the operating frequency. In an RFID application utilizing the VLF (100 kHz – 500 kHz) band, the wavelength of the operating frequency is a few kilometers (λ = 2.4 Km for 125 kHz signal). Because of its long wavelength, a true antenna can never be formed in a limited space of the device. Alternatively, a small loop antenna coil that is resonating at the frequency of the interest (i.e., 125 kHz) is used. This type of antenna utilizes near field magnetic induction coupling between transmitting and receiving antenna coils.

The field produced by the small dipole loop antenna is not a propagating wave, but rather an attenuating wave. The field strength falls off with r^{-3} (where r = distance from the antenna). This near field behavior (r^{-3}) is a main limiting factor of the read range in RFID applications.

When the time-varying magnetic field is passing through a coil (antenna), it induces a voltage across the coil terminal. This voltage is utilized to activate the passive tag device. The antenna coil must be designed to maximize this induced voltage.

This application note is written as a reference guide for antenna coil designers and application engineers in the RFID industry. It reviews basic electromagnetics theories to understand the antenna coils, a procedure for coil design, calculation and measurement of inductance, an antenna-tuning method, and the relationship between read range vs. size of antenna coil.

REVIEW OF A BASIC THEORY FOR ANTENNA COIL DESIGN

Current and Magnetic Fields

Ampere's law states that current flowing on a conductor produces a magnetic field around the conductor. Figure 1 shows the magnetic field produced by a current element. The magnetic field produced by the current on a round conductor (wire) with a finite length is given by:

EQUATION 1:

$$B_\phi = \frac{\mu_o I}{4\pi r}(\cos\alpha_2 - \cos\alpha_1) \qquad (\text{Weber}/m^2)$$

where:

I = current

r = distance from the center of wire

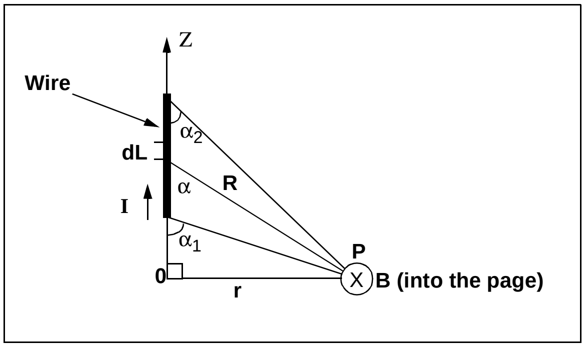
μ_o = permeability of free space and given as $\mu_o = 4\,\pi \times 10^{-7}$ (Henry/meter)

In a special case with an infinitely long wire where α_1 = -180° and α_2 = 0°, Equation 1 can be rewritten as:

EQUATION 2:

$$B_\phi = \frac{\mu_o I}{2\pi r} \qquad (\text{Weber}/m^2)$$

FIGURE 1: CALCULATION OF MAGNETIC FIELD B AT LOCATION P DUE TO CURRENT I ON A STRAIGHT CONDUCTING WIRE



The magnetic field produced by a circular loop antenna coil with N-turns as shown in Figure 2 is found by:

EQUATION 3:

$$B_z = \frac{\mu_o I N a^2}{2(a^2 + r^2)^{3/2}}$$

$$= \frac{\mu_o I N a^2}{2}\left(\frac{1}{r^3}\right) \qquad \text{for} \quad r^2 >> a^2$$

where:

a = radius of loop

Equation 3 indicates that the magnetic field produced by a loop antenna decays with $1/r^3$ as shown in Figure 3. This near-field decaying behavior of the magnetic field is the main limiting factor in the read range of the RFID device. The field strength is maximum in the plane of the loop and directly proportional to the current (I), the number of turns (N), and the surface area of the loop.

Equation 3 is frequently used to calculate the ampere-turn requirement for read range. A few examples that calculate the ampere-turns and the field intensity necessary to power the tag will be given in the following sections.

FIGURE 2: CALCULATION OF MAGNETIC FIELD B AT LOCATION P DUE TO CURRENT I ON THE LOOP

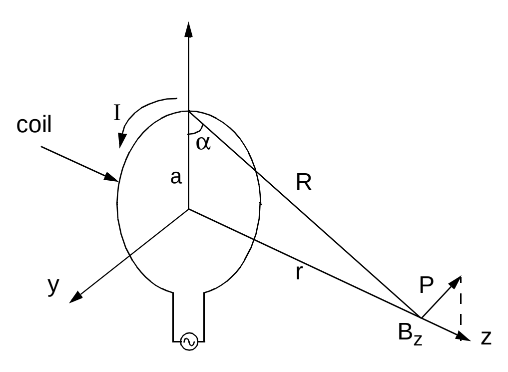
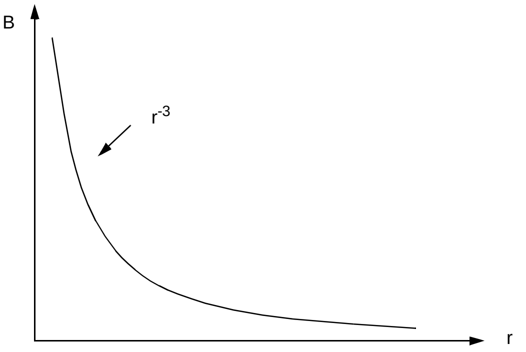


FIGURE 3: DECAYING OF THE MAGNETIC FIELD B VS. DISTANCE *r*



Note: The magnetic field produced by a loop antenna drops off with r^{-3}.

INDUCED VOLTAGE IN ANTENNA COIL

Faraday's law states a time-varying magnetic field through a surface bounded by a closed path induces a voltage around the loop. This fundamental principle has important consequences for operation of passive RFID devices.

Figure 4 shows a simple geometry of an RFID application. When the tag and reader antennas are within a proximity distance, the time-varying magnetic field B that is produced by a reader antenna coil induces a voltage (called electromotive force or simply EMF) in the tag antenna coil. The induced voltage in the coil causes a flow of current in the coil. This is called Faraday's law.

The induced voltage on the tag antenna coil is equal to the time rate of change of the magnetic flux Ψ.

EQUATION 4:

$$V = -N\frac{d\Psi}{dt}$$

where:

N = number of turns in the antenna coil
Ψ = magnetic flux through each turn

The negative sign shows that the induced voltage acts in such a way as to oppose the magnetic flux producing it. This is known as Lenz's Law and it emphasizes the fact that the direction of current flow in the circuit is such that the induced magnetic field produced by the induced current will oppose the original magnetic field.

The magnetic flux Ψ in Equation 4 is the total magnetic field B that is passing through the entire surface of the antenna coil, and found by:

EQUATION 5:

$$\psi = \int B \cdot dS$$

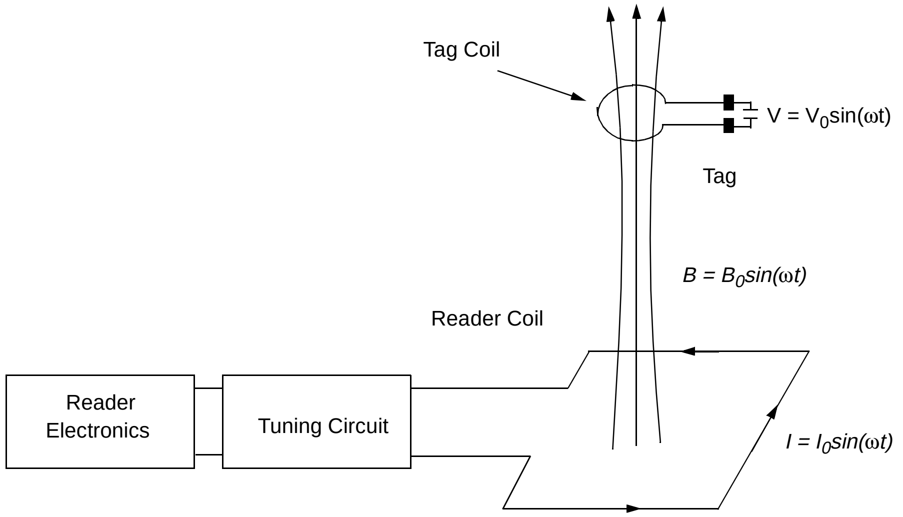
where:

B = magnetic field given in Equation 3
S = surface area of the coil
$\bullet$ = inner product (*cosine angle between two vectors*) of vectors B and surface area S

Note: Both magnetic field $\boldsymbol{B}$ and surface $\boldsymbol{S}$ are vector quantities.

The inner product presentation of two vectors in Equation 5 suggests that the total magnetic flux ψ that is passing through the antenna coil is affected by an orientation of the antenna coils. The inner product of two vectors becomes maximized when the two vectors are in the same direction. Therefore, the magnetic flux that is passing through the tag coil will become maximized when the two coils (reader coil and tag coil) are placed in parallel with respect to each other.

FIGURE 4: A BASIC CONFIGURATION OF READER AND TAG ANTENNAS IN AN RFID APPLICATION



From Equations 3, 4, and 5, the induced voltage V_0 for an untuned loop antenna is given by:

EQUATION 6:

$$V_o = 2\pi f N S B_o \cos\alpha$$

where:

f = frequency of the arrival signal
N = number of turns of coil in the loop
S = area of the loop in square meters (m^2)
B_o = strength of the arrival signal
α = angle of arrival of the signal

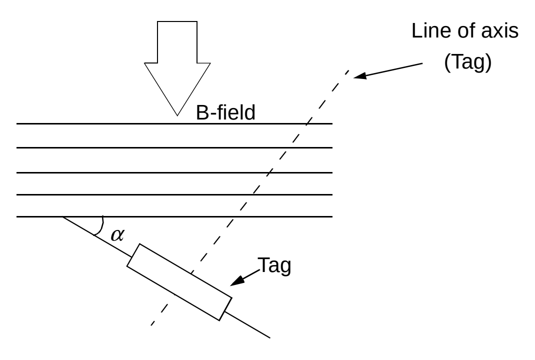
If the coil is tuned (with capacitor C) to the frequency of the arrival signal (125 kHz), the output voltage V_0 will rise substantially. The output voltage found in Equation 6 is multiplied by the loaded Q (Quality Factor) of the tuned circuit, which can be varied from 5 to 50 in typical low-frequency RFID applications:

EQUATION 7:

$$V_o = 2\pi f_o N Q S B_o \cos\alpha$$

where the loaded Q is a measure of the selectivity of the frequency of the interest. The Q will be defined in Equations 30, 31, and 37 for general, parallel, and serial resonant circuit, respectively.

FIGURE 5: ORIENTATION DEPENDENCY OF THE TAG ANTENNA.



The induced voltage developed across the loop antenna coil is a function of the angle of the arrival signal. The induced voltage is maximized when the antenna coil is placed perpendicular to the direction of the incoming signal where α = 0.

EXAMPLE 1: B-FIELD REQUIREMENT

The strength of the B-field that is needed to turn on the tag can be calculated from Equation 7:

EQUATION 8:

$$B_o = \frac{Vo}{2\pi f_o N Q S \cos\alpha}$$

$$= \frac{7(2.4)}{(2\pi)(125\text{ kHz})(100)(15)(38.71\text{cm}^2)}$$

$$\approx 1.5 \qquad \mu\text{Wb/m}^2$$

where the following parameters are used in the above calculation:

tag coil size = 2 x 3 inches = 38.71 cm^2: (credit card size)
frequency = 125 kHz
number of turns = 100
Q of antenna coil = 15
AC coil voltage to turn on the tag = 7 V
cos α = 1 (normal direction, α = 0).

EXAMPLE 2: NUMBER OF TURNS AND CURRENT (AMPERE-TURNS) OF READER COIL

Assuming that the reader should provide a read range of 10 inches (25.4 cm) with a tag given in Example 1, the requirement for the current and number of turns (Ampere-turns) of a reader coil that has an 8 cm radius can be calculated from Equation 3:

EQUATION 9:

$$(NI) = \frac{2B_z(a^2 + r^2)^{3/2}}{\mu a^2}$$

$$= \frac{2(1.5\times10^{-6})(0.08^2 + 0.254^2)^{3/2}}{(4\pi\times10^{-7})(0.08)}$$

$$= 7.04 \text{ (ampere - turns)}$$

This is an attainable number. If, however, we wish to have a read range of 20 inches (50.8 cm), it can be found that NI increases to 48.5 ampere-turns. At 25.2 inches (64 cm), it exceeds 100 ampere-turns.

For a longer read range, it is instructive to consider increasing the radius of the coil. For example, by doubling the radius (16 cm) of the loop, the ampere-turns requirement for the same read range (10 inches: 25.4 cm) becomes:

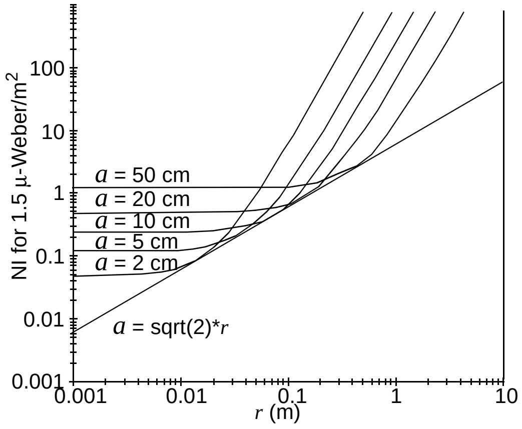
EQUATION 10:

$$NI = \frac{2(1.5\times 10^{-6})(0.16^2+0.25^2)^{3/2}}{(4\pi\times 10^{-7})(0.16^2)}$$

$$= 2.44 \text{ (ampere-turns)}$$

At a read range of 20 inches (50.8 cm), the ampere-turns becomes 13.5 and at 25.2 inches (64 cm), 26.8. Therefore, for a longer read range, increasing the tag size is often more effective than increasing the coil current. Figure 6 shows the relationship between the read range and the ampere-turns (*IN*).

FIGURE 6: AMPERE-TURNS VS. READ RANGE FOR AN ACCESS CONTROL CARD (CREDIT CARD SIZE)



Note: B_O = 1.5 µWb/m^2 is used.

The optimum radius of loop that requires the minimum number of ampere-turns for a particular read range can be found from Equation 3 such as:

EQUATION 11:

$$NI = K\frac{(a^2+r^2)^{\frac{3}{2}}}{a^2}$$

where:

$$K = \frac{2B_z}{\mu_o}$$

By taking derivative with respect to the radius a,

$$\frac{d(NI)}{da} = K\frac{3/2(a^2+r^2)^{1/2}(2a^3)-2a(a^2+r^2)^{3/2}}{a^4}$$

$$= K\frac{(a^2-2r^2)(a^2+r^2)^{1/2}}{a^3}$$

The above equation becomes minimized when:

$$a^2-2r^2 = 0$$

The above result shows a relationship between the read range vs. tag size. The optimum radius is found as:

$$a = \sqrt{2}r$$

where:

a = radius of coil
r = read range

The above result indicates that the optimum radius of loop for a reader antenna is 1.414 times the read range r.

WIRE TYPES AND OHMIC LOSSES

Wire Size and DC Resistance

The diameter of electrical wire is expressed as the American Wire Gauge (AWG) number. The gauge number is inversely proportional to diameter and the diameter is roughly doubled every six wire gauges. The wire with a smaller diameter has higher DC resistance. The DC resistance for a conductor with a uniform cross-sectional area is found by:

EQUATION 12:

$$R_{DC} = \frac{l}{\sigma S} \qquad (\Omega)$$

where:

l = total length of the wire
σ = conductivity
S = cross-sectional area

Table 1 shows the diameter for bare and enamel-coated wires, and DC resistance.

AC Resistance of Wire

At DC, charge carriers are evenly distributed through the entire cross section of a wire. As the frequency increases, the reactance near the center of the wire increases. This results in higher impedance to the current density in the region. Therefore, the charge moves away from the center of the wire and towards the edge of the wire. As a result, the current density decreases in the center of the wire and increases near the edge of the wire. This is called a *skin effect*. The depth into the conductor at which the current density falls to 1/e, or 37% of its value along the surface, is known as the *skin depth* and is a function of the frequency and the permeability and conductivity of the medium. The skin depth is given by:

EQUATION 13:

$$\delta = \frac{1}{\sqrt{\pi f \mu \sigma}}$$

where:

f = frequency
μ = permeability of material
σ = conductivity of the material

EXAMPLE 3:

The skin depth for a copper wire at 125 kHz can be calculated as:

EQUATION 14:

$$\delta = \frac{1}{\sqrt{\pi f (4\pi \times 10^{-7})(5.8 \times 10^{-7})}}$$

$$= \frac{0.06608}{\sqrt{f}} \qquad (m)$$

$$= 0.187 \qquad (mm)$$

The wire resistance increases with frequency, and the resistance due to the skin depth is called an AC resistance. An approximated formula for the ac resistance is given by:

EQUATION 15:

$$R_{ac} \approx \frac{1}{2\sigma\pi\delta} = (R_{DC})\frac{a}{2\delta} \qquad (\Omega)$$

where:

a = coil radius

For copper wire, the loss is approximated by the DC resistance of the coil, if the wire radius is greater than $0.066 / \sqrt{f}$ cm. At 125 kHz, the critical radius is 0.019 cm. This is equivalent to #26 gauge wire. Therefore, for minimal loss, wire gauge numbers of greater than #26 should be avoided if coil Q is to be maximized.

TABLE 1: AWG WIRE CHART

Wire Size (AWG)	Dia. in Mils (bare)	Dia. in Mils (coated)	Ohms/ 1000 ft.	Cross Section (mils)
1	289.3	—	0.126	83690
2	287.6	—	0.156	66360
3	229.4	—	0.197	52620
4	204.3	—	0.249	41740
5	181.9	—	0.313	33090
6	162.0	—	0.395	26240
7	166.3	—	0.498	20820
8	128.5	131.6	0.628	16510
9	114.4	116.3	0.793	13090
10	101.9	106.2	0.999	10380
11	90.7	93.5	1.26	8230
12	80.8	83.3	1.59	6530
13	72.0	74.1	2.00	5180
14	64.1	66.7	2.52	4110
15	57.1	59.5	3.18	3260
16	50.8	52.9	4.02	2580
17	45.3	47.2	5.05	2060
18	40.3	42.4	6.39	1620
19	35.9	37.9	8.05	1290
20	32.0	34.0	10.1	1020
21	28.5	30.2	12.8	812
22	25.3	28.0	16.2	640
23	22.6	24.2	20.3	511
24	20.1	21.6	25.7	404
25	17.9	19.3	32.4	320
26	15.9	17.2	41.0	253
27	14.2	15.4	51.4	202
28	12.6	13.8	65.3	159
29	11.3	12.3	81.2	123
30	10.0	11.0	106.0	100
31	8.9	9.9	131	79.2
32	8.0	8.8	162	64.0
33	7.1	7.9	206	50.4
34	6.3	7.0	261	39.7
35	5.6	6.3	331	31.4
36	5.0	5.7	415	25.0
37	4.5	5.1	512	20.2
38	4.0	4.5	648	16.0
39	3.5	4.0	847	12.2
40	3.1	3.5	1080	9.61
41	2.8	3.1	1320	7.84
42	2.5	2.8	1660	6.25
43	2.2	2.5	2140	4.84
44	2.0	2.3	2590	4.00
45	1.76	1.9	3350	3.10
46	1.57	1.7	4210	2.46
47	1.40	1.6	5290	1.96
48	1.24	1.4	6750	1.54
49	1.11	1.3	8420	1.23
50	0.99	1.1	10600	0.98

Note: 1 mil = 2.54 x 10^{-3} cm

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INDUCTANCE OF VARIOUS ANTENNA COILS

The electrical current flowing through a conductor produces a magnetic field. This time-varying magnetic field is capable of producing a flow of current through another conductor. This is called inductance. The inductance L depends on the physical characteristics of the conductor. A coil has more inductance than a straight wire of the same material, and a coil with more turns has more inductance than a coil with fewer turns. The inductance L of inductor is defined as the ratio of the total magnetic flux linkage to the current I through the inductor: i.e.,

EQUATION 16:

$$L = \frac{N\psi}{I} \qquad \text{(Henry)}$$

where:

N = number of turns

I = current

Ψ = magnetic flux

In a typical RFID antenna coil for 125 kHz, the inductance is often chosen as a few (mH) for a tag and from a few hundred to a few thousand (µH) for a reader. For a coil antenna with multiple turns, greater inductance results with closer turns. Therefore, the tag antenna coil that has to be formed in a limited space often needs a multi-layer winding to reduce the number of turns.

The design of the inductor would seem to be a relatively simple matter. However, it is almost impossible to construct an ideal inductor because:

a) The coil has a finite conductivity that results in losses, and

b) The distributed capacitance exists between turns of a coil and between the conductor and surrounding objects.

The actual inductance is always a combination of resistance, inductance, and capacitance. The apparent inductance is the effective inductance at any frequency, i.e., inductive minus the capacitive effect. Various formulas are available in literatures for the calculation of inductance for wires and coils[1, 2].

The parameters in the inductor can be measured. For example, an HP 4285 Precision LCR Meter can measure the inductance, resistance, and Q of the coil.

Inductance of a Straight Wire

The inductance of a straight wound wire shown in Figure 1 is given by:

EQUATION 17:

$$L = 0.002l\left[\log_e\frac{2l}{a} - \frac{3}{4}\right] \qquad (\mu H)$$

where:

l and a = length and radius of wire in cm, respectively.

EXAMPLE 4: CALCULATION OF INDUCTANCE FOR A STRAIGHT WIRE

The inductance of a wire with 10 feet (304.8 cm) long and 2 mm diameter is calculated as follows:

EQUATION 18:

$$\begin{aligned} L &= 0.002(304.8)\left[\ln\left(\frac{2(304.8)}{0.1}\right) - \frac{3}{4}\right] \\ &= 0.60967(7.965) \\ &= 4.855(\mu H) \end{aligned}$$

Inductance of a Single Layer Coil

The inductance of a single layer coil shown in Figure 7 can be calculated by:

EQUATION 19:

$$L = \frac{(aN)^2}{22.9l + 25.4a} \qquad (\mu H)$$

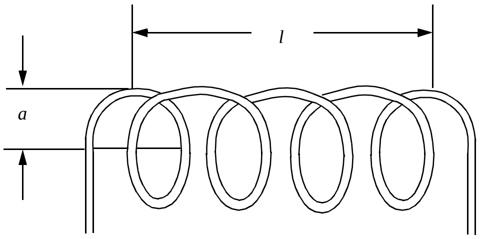
where:

a = coil radius (cm)

l = coil length (cm)

N = number of turns

FIGURE 7: A SINGLE LAYER COIL



Note: For best Q of the coil, the length should be roughly the same as the diameter of the coil.

Inductance of a Circular Loop Antenna Coil with Multilayer

To form a big inductance coil in a limited space, it is more efficient to use multilayer coils. For this reason, a typical RFID antenna coil is formed in a planar multi-turn structure. Figure 8 shows a cross section of the coil. The inductance of a circular ring antenna coil is calculated by an empirical formula[2]:

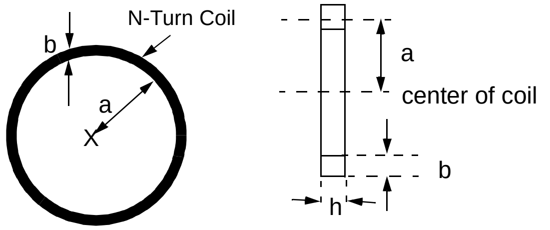
EQUATION 20:

$$L = \frac{0.31(aN)^2}{6a + 9h + 10b} \qquad (\mu H)$$

where:

a = average radius of the coil in cm
N = number of turns
b = winding thickness in cm
h = winding height in cm

FIGURE 8: A CIRCULAR LOOP AIR CORE ANTENNA COIL WITH N-TURNS



The number of turns needed for a certain inductance value is simply obtained from Equation 20 such that:

EQUATION 21:

$$N = \sqrt{\frac{L_{\mu H}(6a + 9h + 10b)}{(0.31)a^2}}$$

EXAMPLE 5: EXAMPLE ON NUMBER OF TURNS

Equation 21 results in N = 200 turns for L = 3.87 mH with the following coil geometry:

a = 1 inch (2.54 cm)
h = 0.05 cm
b = 0.5 cm

To form a resonant circuit for 125 kHz, it needs a capacitor across the inductor. The resonant capacitor can be calculated as:

EQUATION 22:

$$C = \frac{1}{(2\pi f)^2 L} = \frac{1}{(4\pi^2)(125 \times 10^3)(3.87 \times 10^{-3})}$$

$$= 419 \qquad (pF)$$

Inductance of a Square Loop Coil with Multilayer

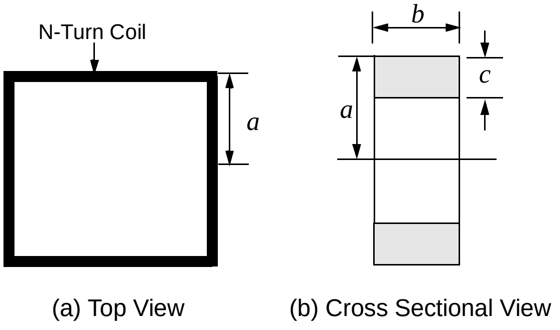
If N is the number of turns and a is the side of the square measured to the center of the rectangular cross section that has length b and depth c as shown in Figure 9, then[2]:

EQUATION 23:

$$L = 0.008aN^2\left(2.303\log_{10}\left(\frac{a}{b + c}\right) + 0.2235\frac{b + c}{a} + 0.726\right) \quad (\mu H)$$

The formulas for inductance are widely published and provide a reasonable approximation for the relationship between inductance and number of turns for a given physical size[1]-[4]. When building prototype coils, it is wise to exceed the number of calculated turns by about 10%, and then remove turns to achieve resonance. For production coils, it is best to specify an inductance and tolerance rather than a specific number of turns.

FIGURE 9: A SQUARE LOOP ANTENNA COIL WITH MULTILAYER



(a) Top View (b) Cross Sectional View

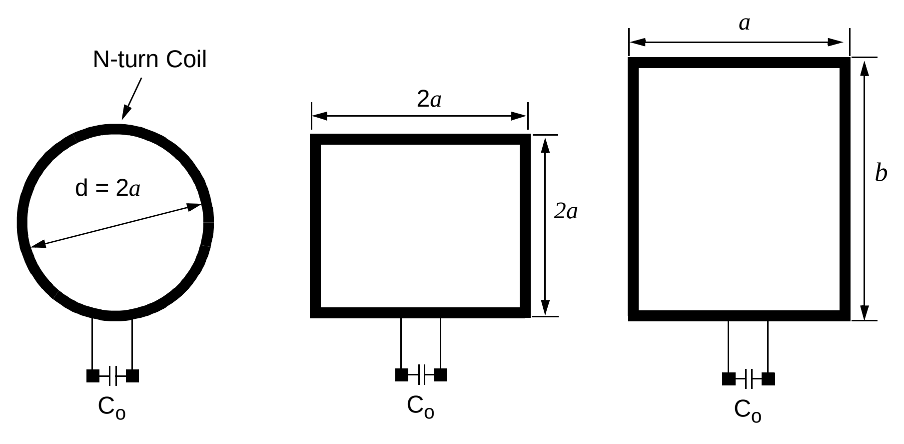
CONFIGURATION OF ANTENNA COILS

Tag Antenna Coil

An antenna coil for an RFID tag can be configured in many different ways, depending on the purpose of the application and the dimensional constraints. A typical inductance L for the tag coil is a few (mH) for 125 kHz devices. Figure 10 shows various configurations of tag antenna coils. The coil is typically made of a thin wire. The inductance and the number of turns of the coil can be calculated by the formulas given in the previous section. An Inductance Meter is often used to measure the inductance of the coil. A typical number of turns of the coil is in the range of 100 turns for 125 kHz and 3~5 turns for 13.56 MHz devices.

For a longer read range, the antenna coil must be tuned properly to the frequency of interest (i.e., 125 kHz). Voltage drop across the coil is maximized by forming a parallel resonant circuit. The tuning is accomplished with a resonant capacitor that is connected in parallel to the coil as shown in Figure 10. The formula for the resonant capacitor value is given in Equation 22.

FIGURE 10: VARIOUS CONFIGURATIONS OF TAG ANTENNA COIL



Reader Antenna Coil

The inductance for the reader antenna coil is typically in the range of a few hundred to a few thousand micro-Henries (µH) for low frequency applications. The reader antenna can be made of either a single coil that is typically forming a series resonant circuit or a double loop (transformer) antenna coil that forms a parallel resonant circuit.

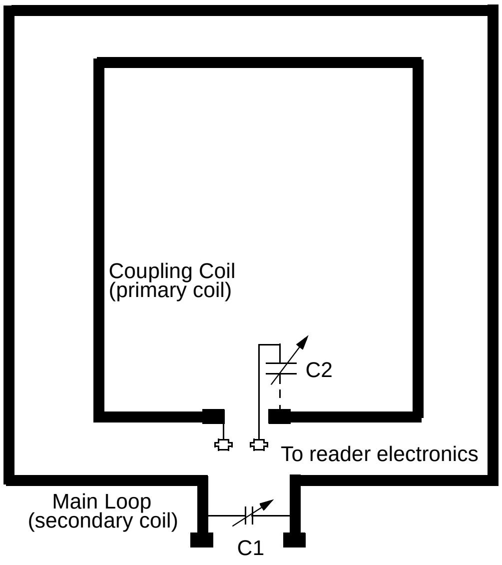
The series resonant circuit results in minimum impedance at the resonance frequency. Therefore, it draws a maximum current at the resonance frequency. On the other hand, the parallel resonant circuit results in maximum impedance at the resonance frequency. Therefore, the current becomes minimized at the resonance frequency. Since the voltage can be stepped up by forming a double loop (parallel) coil, the parallel resonant circuit is often used for a system where a higher voltage signal is required.

Figure 11 shows an example of the transformer loop antenna. The main loop (secondary) is formed with several turns of wire on a large frame, with a tuning capacitor to resonate it to the resonance frequency (125 kHz). The other loop is called a coupling loop (primary), and it is formed with less than two or three turns of coil. This loop is placed in a very close proximity to the main loop, usually (but not necessarily) on the inside edge and not more than a couple of centimeters away from the main loop. The purpose of this loop is to couple signals induced from the main loop to the reader (or vise versa) at a more reasonable matching impedance.

The coupling (primary) loop provides an impedance match to the input/output impedance of the reader. The coil is connected to the input/output signal driver in the reader electronics. The main loop (secondary) must be tuned to resonate at the resonance frequency and is not physically connected to the reader electronics.

The coupling loop is usually untuned, but in some designs, a tuning capacitor C2 is placed in series with the coupling loop. Because there are far fewer turns on the coupling loop than the main loop, its inductance is considerably smaller. As a result, the capacitance to resonate is usually much larger.

FIGURE 11: A TRANSFORMER LOOP ANTENNA FOR READER



RESONANCE CIRCUITS, QUALITY FACTOR *Q*, AND BANDWIDTH

In RFID applications, the antenna coil is an element of resonant circuit and the read range of the device is greatly affected by the performance of the resonant circuit.

Figures 12 and 13 show typical examples of resonant circuits formed by an antenna coil and a tuning capacitor. The resonance frequency (f_o) of the circuit is determined by:

EQUATION 24:

$$f_o = \frac{1}{2\pi\sqrt{LC}}$$

where:

L = inductance of antenna coil

C = tuning capacitance

The resonant circuit can be formed either series or parallel.

The series resonant circuit has a minimum impedance at the resonance frequency. As a result, maximum current is available in the circuit. This series resonant circuit is typically used for the reader antenna.

On the other hand, the parallel resonant circuit has maximum impedance at the resonance frequency. It offers minimum current and maximum voltage at the resonance frequency. This parallel resonant circuit is used for the tag antenna.

Parallel Resonant Circuit

Figure 12 shows a simple parallel resonant circuit. The total impedance of the circuit is given by:

EQUATION 25:

$$Z(j\omega) = \frac{j\omega L}{(1-\omega^2 LC) + j\frac{\omega L}{R}} \qquad (\Omega)$$

where:

ω = angular frequency = $2\pi f$

R = load resistor

The ohmic resistance r of the coil is ignored. The maximum impedance occurs when the denominator in the above equation minimized such as:

EQUATION 26:

$$\omega^2 LC = 1$$

This is called a resonance condition and the resonance frequency is given by:

EQUATION 27:

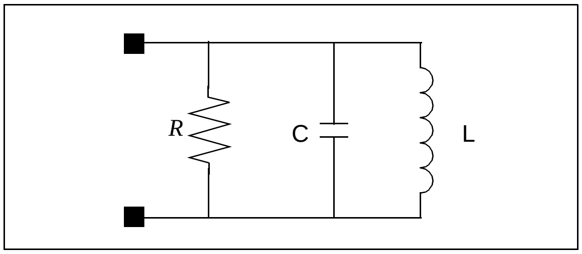
$$f_o = \frac{1}{2\pi\sqrt{LC}}$$

By applying Equation 26 into Equation 25, the impedance at the resonance frequency becomes:

EQUATION 28:

$$Z = R$$

FIGURE 12: PARALLEL RESONANT CIRCUIT



The R and C in the parallel resonant circuit determine the bandwidth, B, of the circuit.

EQUATION 29:

$$B = \frac{1}{2\pi RC} \qquad (Hz)$$

The quality factor, Q, is defined by various ways such as:

EQUATION 30:

$$Q = \frac{\text{Energy Stored in the System per One Cycle}}{\text{Energy Dissipated in the System per One Cycle}}$$

$$= \frac{f_o}{B}$$

where:

f_o = resonant frequency
B = bandwidth

By applying Equation 27 and Equation 29 into Equation 30, the loaded Q in the parallel resonant circuit is:

EQUATION 31:

$$Q = R\sqrt{\frac{C}{L}}$$

The Q in parallel resonant circuit is directly proportional to the load resistor R and also to the square root of the ratio of capacitance and inductance in the circuit.

When this parallel resonant circuit is used for the tag antenna circuit, the voltage drop across the circuit can be obtained by combining Equations 7 and 31,

EQUATION 32:

$$V_o = 2\pi f_o NQSB_o \cos\alpha$$

$$= 2\pi f_o N\left(R\sqrt{\frac{C}{L}}\right)SB_o \cos\alpha$$

The above equation indicates that the induced voltage in the tag coil is inversely proportional to the square root of the coil inductance, but proportional to the number of turns and surface area of the coil.

The parallel resonant circuit can be used in the transformer loop antenna for a long-range reader as discussed in "Reader Antenna Coil" (Figure 11). The voltage in the secondary loop is proportional to the turn ratio (n_2/n_1) of the transformer loop. However, this high voltage signal can corrupt the receiving signals. For this reason, a separate antenna is needed for receiving the signal. This receiving antenna circuit should be tuned to the modulating signal of the tag and detunned to the carrier signal frequency for maximum read range.

Series Resonant Circuit

A simple series resonant circuit is shown in Figure 13. The expression for the impedance of the circuit is:

EQUATION 33:

$$Z(j\omega) = r + j(X_L - X_C) \qquad (\Omega)$$

where:

r = ohmic resistance of the circuit

EQUATION 34:

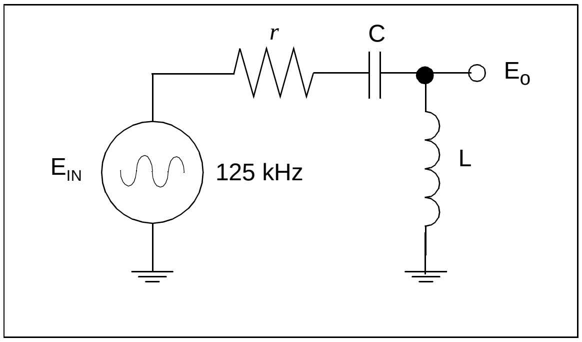
$$X_L = 2\pi f_o L \qquad (\Omega)$$

EQUATION 35:

$$X_c = \frac{1}{2\pi f_o C} \qquad (\Omega)$$

The impedance in Equation 33 becomes minimized when the reactance component cancelled out each other such that $X_L = X_C$. This is called a resonance condition. The resonance frequency is same as the parallel resonant frequency given in Equation 27.

FIGURE 13: SERIES RESONANCE CIRCUIT



The half power frequency bandwidth is determined by r and L, and given by:

EQUATION 36:

$$\boldsymbol{B} = \frac{r}{2\pi L} \qquad (Hz)$$

The quality factor, Q, in the series resonant circuit is given by:

EQUATION 37:

$$Q = \frac{f_o}{B} = \begin{cases} \frac{\omega L}{r} = \frac{1}{\omega C r} & \text{; for unloaded circuit} \\ \frac{1}{r}\sqrt{\frac{L}{C}} & \text{; for loaded circuit} \end{cases}$$

The series circuit forms a voltage divider; the voltage drops in the coil is given by:

EQUATION 38:

$$V_o = \frac{jX_L}{r + jX_L - jX_c} V_{in}$$

or

EQUATION 39:

$$\left|\frac{V_o}{V_{in}}\right| = \frac{X_L}{\sqrt{r^2 + (X_L - X_c)^2}} = \frac{X_L}{r\sqrt{1 + \left(\frac{X_L - X_c}{r}\right)^2}} = \frac{Q}{\sqrt{1 + \left(\frac{X_L - X_c}{r}\right)^2}}$$

EXAMPLE 6: CIRCUIT PARAMETERS.

If the series resistance of the circuit is 15 Ω, then the L and C values form a 125 kHz resonant circuit with Q = 8 are:

EQUATION 40:

$$X_L = Qr_s = 120\Omega$$

$$L = \frac{X_L}{2\pi f} = \frac{120}{2\pi(125 \text{ kHz})} = 153 \qquad (\mu H)$$

$$C = \frac{1}{2\pi f X_L} = \frac{1}{2\pi(125 \text{ kHz})(120)} = 10.6 \qquad (nF)$$

EXAMPLE 7: CALCULATION OF READ RANGE

Let us consider designing a reader antenna coil with L = 153 µH, diameter = 10 cm, and winding thickness and height are small compared to the diameter.

The number of turns for the inductance can be calculated from Equation 21, resulting in 24 turns.

If the current flow through the coil is 0.5 amperes, the ampere-turns becomes 12. Therefore, the read range for this coil will be about 20 cm with a credit card size tag.

Q and Bandwidth

Figure 14 shows the approximate frequency bands for common forms of Amplitude Shift Keying (ASK), Frequency Shift Keying (FSK), and Phase Shift Keying (PSK) modulation. For a full recovery of data signal from the tag, the reader circuit needs a bandwidth that is at least twice the data rate. Therefore, if the data rate is 8 kHz for an ASK signal, the bandwidth must be at least 16 kHz for a full recovery of the information that is coming from the tag.

The data rate for FSK (÷ 10) signal is 12.5 kHz. Therefore, a bandwidth of 25 kHz is needed for a full data recovery.

The Q for this FSK (÷ 10) signal can be obtained from Equation 30.

EQUATION 41:

$$Q = \frac{f_o}{B} = \frac{125 \text{ kHz}}{25 \text{ kHz}}$$

$$= 5$$

For a PSK (÷ 2) signal, the data rate is 62.5 kHz (if the carrier frequency is 125 kHz) therefore, the reader circuit needs 125 kHz of bandwidth. The Q in this case is 1, and consequently the circuit becomes Q-independent.

This problem may be solved by separating the transmitting and receiving coils. The transmitting coil can be designed with higher Q and the receiving coil with lower Q.

Limitation on Q

When designing a reader antenna circuit, the temptation is to design a coil with very high Q. There are three important limitations to this approach.

a) Very high voltages can cause insulation breakdown in either the coil or resonant capacitor.

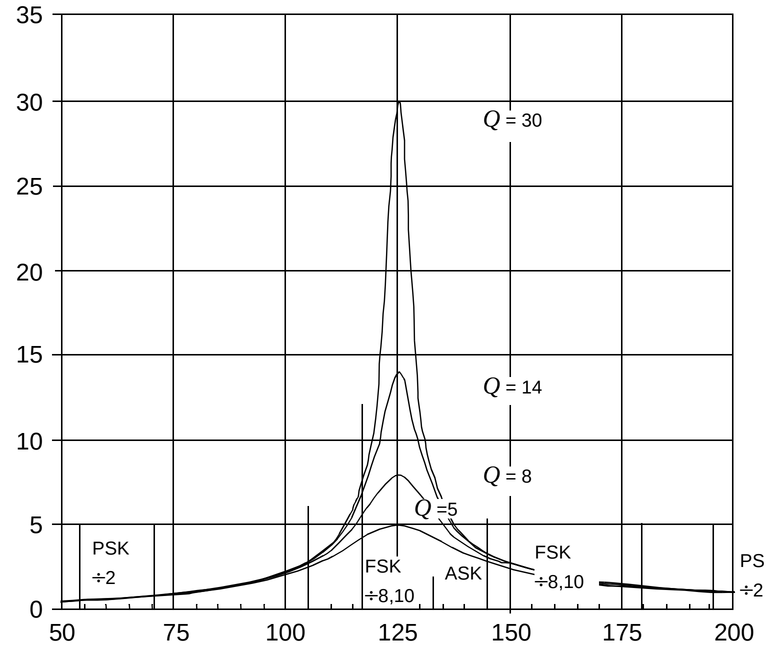
For example, a 1 ampere of current flow in a 2 mH coil will produce a voltage drop of 1500 V_{PP}. Such voltages are easy to obtain but difficult to isolate. In addition, in the case of single coil reader designs, recovery of the return signal from the tag must be accomplished in the presence of these high voltages.

b) Tuning becomes critical.

To implement a high Q antenna circuit, high voltage components with a close tolerance and high stability would have to be used. Such parts are generally expensive and difficult to obtain.

c) As the Q of the circuit gets higher, the amplitude of the return signal relative to the power of the carrier gets proportionally smaller complicating its recovery by the reader circuit.

FIGURE 14: Q FACTOR VS. MODULATION SIGNALS



Tuning Method

The circuit must be tuned to the resonance frequency for a maximum performance (read range) of the device. Two examples of tuning the circuit are as follows:

- **Voltage Measurement Method:**
  a) Set up a voltage signal source at the resonance frequency (125 kHz)
  b) Connect a voltage signal source across the resonant circuit.
  c) Connect an Oscilloscope across the resonant circuit.
  d) Tune the capacitor or the coil while observing the signal amplitude on the Oscilloscope.
  e) Stop the tuning at the maximum voltage.
- **S-parameter or Impedance Measurement Method using Network Analyzer:**
  a) Set up an S-Parameter Test Set (Network Analyzer) for S11 measurement, and do a calibration.
  b) Measure the S11 for the resonant circuit.
  c) Reflection impedance or reflection admittance can be measured instead of the S11.
  d) Tune the capacitor or the coil until a maximum null (S11) occurs at the resonance frequency, f_o. For the impedance measurement, the maximum peak will occur for the parallel resonant circuit, and minimum peak for the series resonant circuit.

FIGURE 15: VOLTAGE VS. FREQUENCY FOR RESONANT CIRCUIT

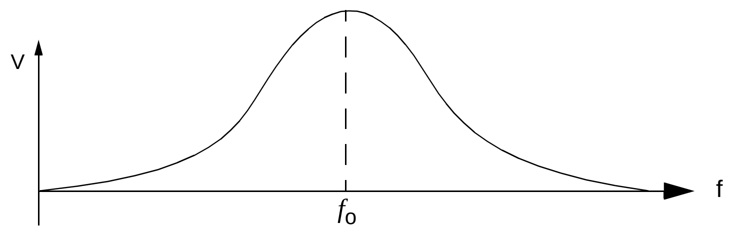
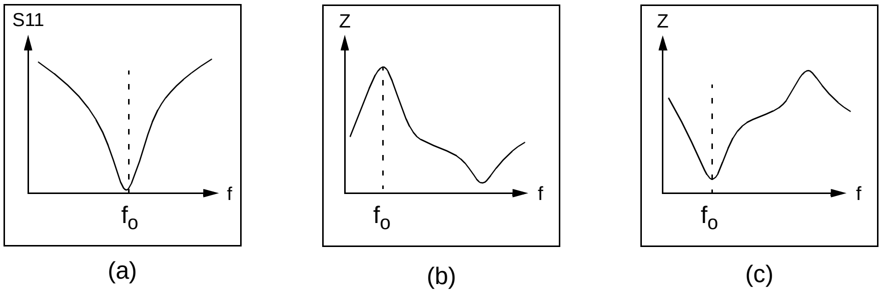


FIGURE 16: FREQUENCY RESPONSES FOR RESONANT CIRCUIT



Note 1: (a) S11 Response, (b) Impedance Response for a Parallel Resonant Circuit, and (c) Impedance Response for a Series Resonant Circuit.

2: In (a), the null at the resonance frequency represents a minimum input reflection at the resonance frequency. This means the circuit absorbs the signal at the frequency while other frequencies are reflected back. In (b), the impedance curve has a peak at the resonance frequency. This is because the parallel resonant circuit has a maximum impedance at the resonance frequency. (c) shows a response for the series resonant circuit. Since the series resonant circuit has a minimum impedance at the resonance frequency, a minimum peak occurs at the resonance frequency.

READ RANGE OF RFID DEVICES

Read range is defined as a maximum communication distance between the reader and tag. The read range of typical passive RFID products varies from about 1 inch to 1 meter, depending on system configuration. The read range of an RFID device is, in general, affected by the following parameters:

a) Operating frequency and performance of antenna coils
b) *Q* of antenna and tuning circuit
c) Antenna orientation
d) Excitation current and voltage
e) Sensitivity of receiver
f) Coding (or modulation) and decoding (or demodulation) algorithm
g) Number of data bits and detection (interpretation) algorithm
h) Condition of operating environment (metallic, electrical noise), etc.

With a given operating frequency, the above conditions (a – c) are related to the antenna configuration and tuning circuit. The conditions (d – e) are determined by a circuit topology of the reader. The condition (f) is called the communication protocol of the device, and (g) is related to a firmware program for data interpretation.

Assuming the device is operating under a given condition, the read range of the device is largely affected by the performance of the antenna coil. It is always true that a longer read range is expected with the larger size of the antenna. Figures 17 and 18 show typical examples of the read range of various passive RFID devices.

FIGURE 17: READ RANGE VS. TAG SIZE FOR PROXIMITY APPLICATIONS

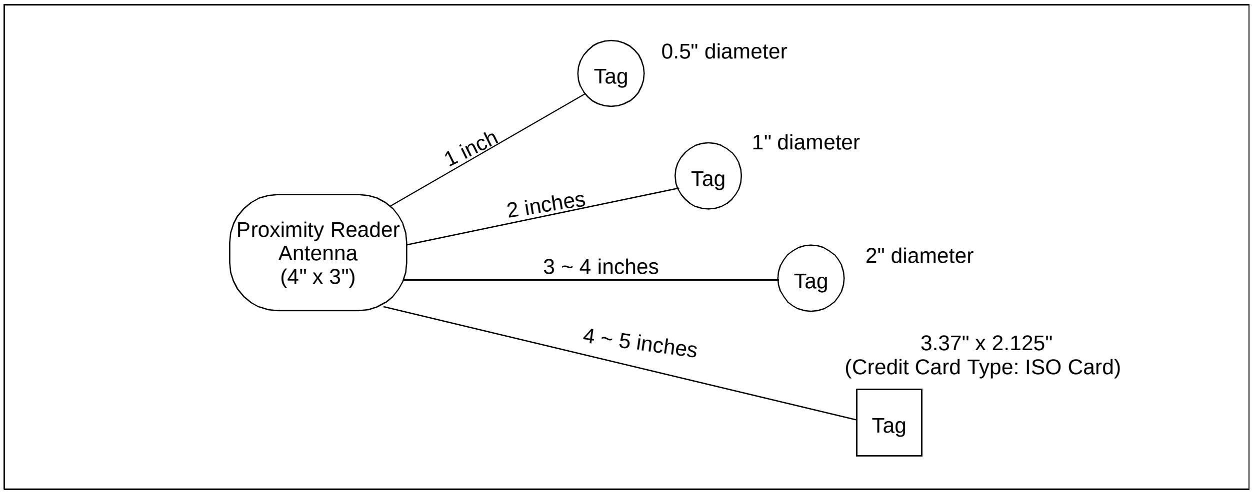
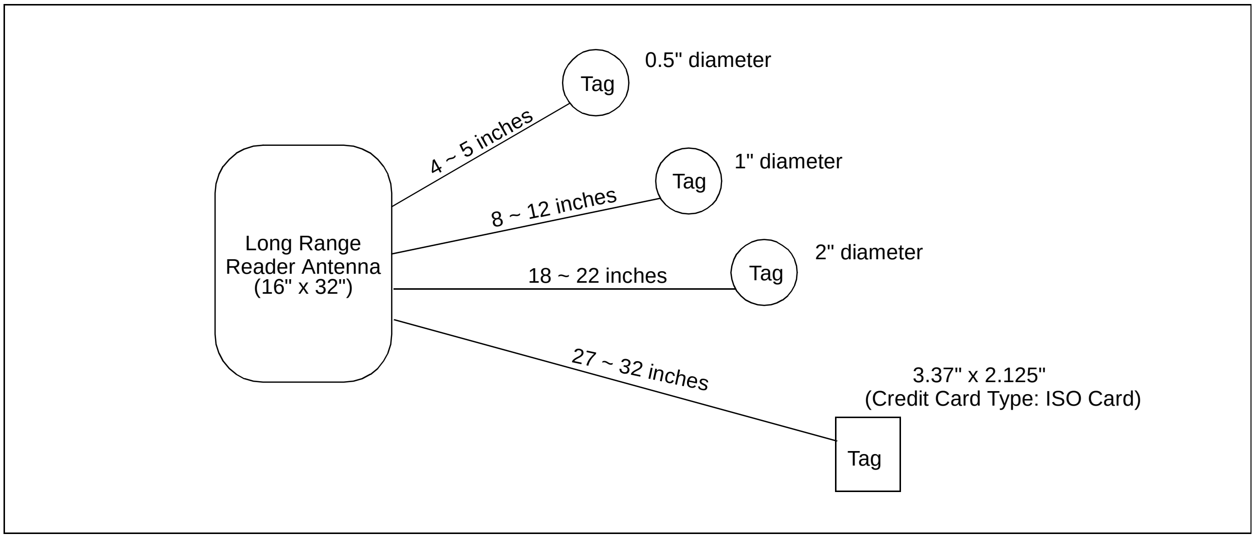


FIGURE 18: READ RANGE VS. TAG SIZE FOR LONG RANGE APPLICATIONS



REFERENCES

1. Frederick W. Grover, Inductance Calculations: Working Formulas and Tables, Dover Publications, Inc., New York, NY., 1946.
2. Keith Henry, Editor, Radio Engineering Handbook, McGraw-Hill Book Company, New York, NY., 1963.
3. V. G. Welsby, The Theory and Design of Inductance Coils, John Wiley and Sons, Inc., 1960.
4. James K. Hardy, High Frequency Circuit Design, Reston Publishing Company, Inc., Reston, Virginia, 1975.

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