

Antenna Circuit Design

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INTRODUCTION

Passive RFID tags utilize an induced antenna coil voltage for operation. This induced AC voltage is rectified to provide a voltage source for the device. As the DC voltage reaches a certain level, the device starts operating. By providing an energizing RF signal, a reader can communicate with a remotely located device that has no external power source such as a battery. Since the energizing and communication between the reader and tag is accomplished through antenna coils, it is important that the device must be equipped with a proper antenna circuit for successful RFID applications.

An RF signal can be radiated effectively if the linear dimension of the antenna is comparable with the wavelength of the operating frequency. However, the wavelength at 13.56 MHz is 22.12 meters. Therefore, it is difficult to form a true antenna for most RFID applications. Alternatively, a small loop antenna circuit that is resonating at the frequency is used. A current flowing into the coil radiates a near-field magnetic field that falls off with r^{-3} . This type of antenna is called a *magnetic dipole antenna*.

For 13.56 MHz passive tag applications, a few microhenries of inductance and a few hundred pF of resonant capacitor are typically used. The voltage transfer between the reader and tag coils is accomplished through inductive coupling between the two coils. As in a typical transformer, where a voltage in the primary coil transfers to the secondary coil, the voltage in the reader antenna coil is transferred to the tag antenna coil and vice versa. The efficiency of the voltage transfer can be increased significantly with high Q circuits.

This section is written for RF coil designers and RFID system engineers. It reviews basic electromagnetic theories on antenna coils, a procedure for coil design, calculation and measurement of inductance, an antenna tuning method, and read range in RFID applications.

REVIEW OF A BASIC THEORY FOR RFID ANTENNA DESIGN

Current and Magnetic Fields

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

EQUATION 1:

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

where:

- I = current
- r = distance from the center of wire
- μ_0 = permeability of free space and given as $4\pi \times 10^{-7}$ (Henry/meter)

In a special case with an infinitely long wire where:

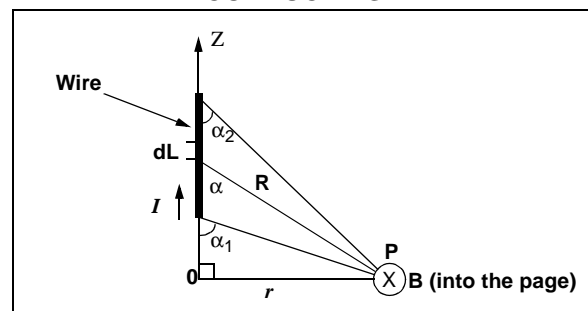
- $\alpha_1 = -180^\circ$
- $\alpha_2 = 0^\circ$

Equation 1 can be rewritten as:

EQUATION 2:

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

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 is given by:

EQUATION 3:

$$B_z = \frac{\mu_0 I N a^2}{2(a^2 + r^2)^{3/2}}$$

$$= \frac{\mu_0 I N a^2}{2} \left(\frac{1}{r^3}\right) \text{ for } r^2 \gg a^2$$

where

- I = current
- a = radius of loop
- r = distance from the center of wire
- μ_0 = permeability of free space and given as $\mu_0 = 4 \pi \times 10^{-7}$ (Henry/meter)

The above equation indicates that the magnetic field strength decays with $1/r^3$. A graphical demonstration is shown in Figure 3. It has maximum amplitude in the plane of the loop and directly proportional to both the current and the number of turns, N .

Equation 3 is often 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

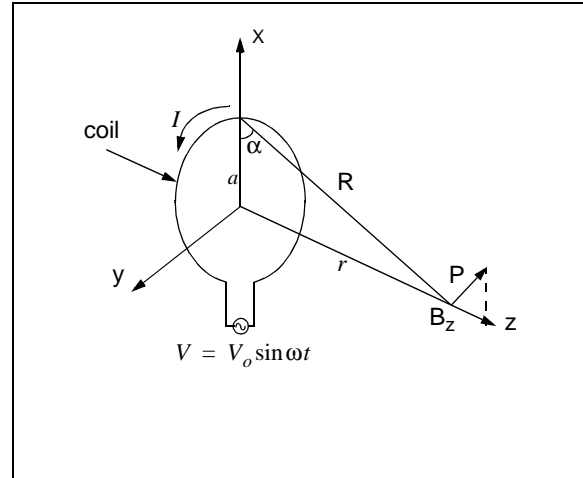
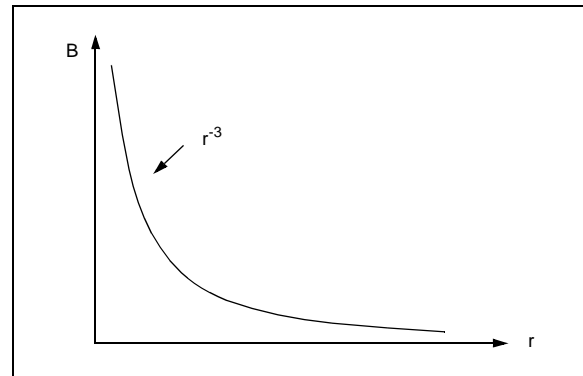


FIGURE 3: DECAYING OF THE MAGNETIC FIELD B VS. DISTANCE r



INDUCED VOLTAGE IN AN ANTENNA COIL

Faraday's law states that a time-varying magnetic field through a surface bounded by a closed path induces a voltage around the loop.

Figure 4 shows a simple geometry of an RFID application. When the tag and reader antennas are in close proximity, 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 closed tag antenna coil. The induced voltage in the coil causes a flow of current on 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:

$$\Psi = \int B \cdot dS$$

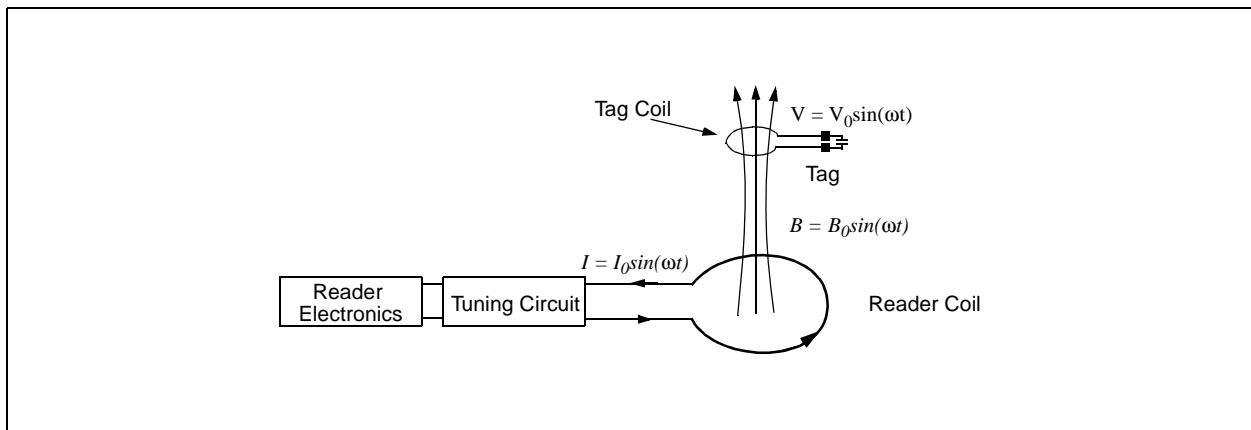
where:

- B = magnetic field given in Equation 2
- S = surface area of the coil
- \cdot = inner product (*cosine angle between two vectors*) of vectors B and surface area S

Note: Both magnetic field B and surface S are vector quantities.

The presentation of inner product 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 cosine angle between the two are 90 degree, or the two (B field and the surface of coil) are perpendicular to each other. The maximum magnetic flux that is passing through the tag coil is obtained when the two coils (reader coil and tag coil) are placed in parallel with respect to each other. This condition results in maximum induced voltage in the tag coil and also maximum read range. The inner product expression in Equation 5 also can be expressed in terms of a mutual coupling between the reader and tag coils. The mutual coupling between the two coils is maximized in the above condition.

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



Using Equations 3 and 5, Equation 4 can be rewritten as:

EQUATION 6:

$$\begin{aligned}
 V &= - N_2 \frac{d\Psi_{21}}{dt} = - N_2 \frac{d}{dt} \left(\int B \cdot dS \right) \\
 &= - N_2 \frac{d}{dt} \left[\int \frac{\mu_o i_1 N_1 a^2}{2(a^2 + r^2)^{3/2}} \cdot dS \right] \\
 &= - \left[\frac{\mu_o N_1 N_2 a^2 (\pi b^2)}{2(a^2 + r^2)^{3/2}} \right] \frac{di_1}{dt} \\
 &= - M \frac{di_1}{dt}
 \end{aligned}$$

where:

- V = voltage in the tag coil
- i_1 = current on the reader coil
- a = radius of the reader coil
- b = radius of tag coil
- r = distance between the two coils
- M = mutual inductance between the tag and reader coils, and given by:

EQUATION 7:

$$M = \left[\frac{\mu_o \pi N_1 N_2 (ab)^2}{2(a^2 + r^2)^{3/2}} \right]$$

The above equation is equivalent to a voltage transformation in typical transformer applications. The current flow in the primary coil produces a magnetic flux that causes a voltage induction at the secondary coil.

As shown in Equation 6, the tag coil voltage is largely dependent on the mutual inductance between the two coils. The mutual inductance is a function of coil geometry and the spacing between them. The induced voltage in the tag coil decreases with r^{-3} . Therefore, the read range also decreases in the same way.

From Equations 4 and 5, a generalized expression for induced voltage V_o in a tuned loop coil is given by:

EQUATION 8:

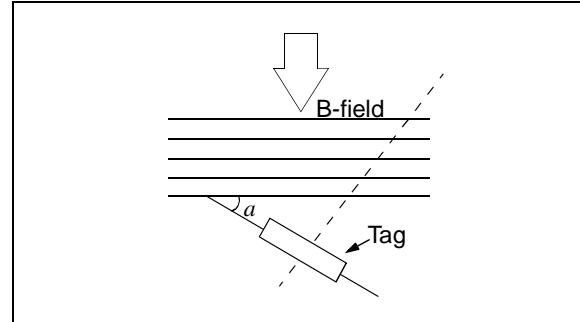
$$V_o = 2\pi f N S Q B_o \cos \alpha$$

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)
- Q = quality factor of circuit
- B_o = strength of the arrival signal
- α = angle of arrival of the signal

In the above equation, the quality factor Q is a measure of the selectivity of the frequency of the interest. The Q will be defined in Equations 31 through 47.

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 in parallel with the incoming signal where $\alpha = 0$.

EXAMPLE 1: CALCULATION OF B-FIELD IN A TAG COIL

The MCRF355 device turns on when the antenna coil develops 4 VPP across it. This voltage is rectified and the device starts to operate when it reaches 2.4 VDC. The B-field to induce a 4 VPP coil voltage with an ISO standard 7810 card size (85.6 x 54 x 0.76 mm) is calculated from the coil voltage equation using Equation 8.

EQUATION 9:

$$V_o = 2\pi f N S Q B_o \cos \alpha = 4$$

and

$$B_o = \frac{4/(\sqrt{2})}{2\pi f N S Q \cos \alpha} = 0.0449 \quad (\mu w b m^{-2})$$

where the following parameters are used in the above calculation:

- Tag coil size = (85.6 x 54) mm^2 (ISO card size) = 0.0046224 m^2
- Frequency = 13.56 MHz
- Number of turns = 4
- Q of tag antenna coil = 40
- AC coil voltage to turn on the tag = 4 VPP
- $\cos \alpha =$ = 1 (normal direction, $\alpha = 0$).

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

Assuming that the reader should provide a read range of 15 inches (38.1 cm) for the tag given in the previous example, the current and number of turns of a reader antenna coil is calculated from Equation 3:

EQUATION 10:

$$(NI)_{rms} = \frac{2B_z(a^2 + r^2)^{3/2}}{\mu_0 a^2}$$

$$= \frac{2(0.0449 \times 10^{-6})(0.1^2 + (0.38)^2)^{3/2}}{(4\pi \times 10^{-7})(0.1^2)}$$

$$= 0.43(\text{ampere} - \text{turns})$$

The above result indicates that it needs a 430 mA for 1 turn coil, and 215 mA for 2-turn coil.

EXAMPLE 3: OPTIMUM COIL DIAMETER OF THE READER COIL

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

EQUATION 11:

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

where: $K = \frac{2B_z}{\mu_0}$

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. optimum coil diameter. The optimum coil diameter is found as:

EQUATION 12:

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

where:

a = radius of coil
 r = read range.

The result indicates that the optimum loop radius, a , is 1.414 times the demanded 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 a higher DC resistance. The DC resistance for a conductor with a uniform cross-sectional area is found by:

EQUATION 13:

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

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 14:

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

where:

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

EXAMPLE 4:

The skin depth for a copper wire at 13.56 MHz can be calculated as:

EQUATION 15:

$$\begin{aligned} \delta &= \frac{1}{\sqrt{\pi f (4\pi \times 10^{-7}) (5.8 \times 10^{-7})}} \\ &= \frac{0.0179}{\sqrt{f}} \quad (m) \\ &= 0.187 \quad (mm) \end{aligned}$$

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 16:

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

where:

- a = coil radius

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

Note: 1 mil = 2.54×10^{-3} cm

Wire Size (AWG)	Dia. in Mils (bare)	Dia. in Mils (coated)	Ohms/1000 ft.	Cross Section (mils)
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 = 2.54×10^{-3} cm

INDUCTANCE OF VARIOUS ANTENNA COILS

An electric current element that flows 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:

EQUATION 17:

$$L = \frac{N\Psi}{I} \quad (\text{Henry})$$

where:

- N = number of turns
- I = current
- Ψ = the magnetic flux

For a coil with multiple turns, the inductance is greater as the spacing between turns becomes smaller. Therefore, the tag antenna coil that has to be formed in a limited space often needs a multilayer winding to reduce the number of turns.

Calculation of Inductance

Inductance of the coil can be calculated in many different ways. Some are readily available from references^[1-4]. It must be remembered that for RF coils the actual resulting inductance may differ from the calculated true result because of distributed capacitance. For that reason, inductance calculations are generally used only for a starting point in the final design.

Inductance of a Straight Wound Wire

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

EQUATION 18:

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

where:

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

EXAMPLE 5: INDUCTANCE CALCULATION FOR A STRAIGHT WIRE:

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

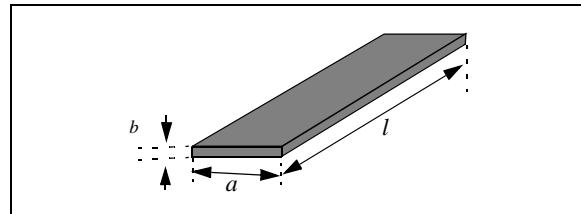
EQUATION 19:

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

Inductance of Thin Film Inductor with a Rectangular Cross Section

Inductance of a conductor with rectangular cross section as shown in Figure 6 is calculated as:

FIGURE 6: A STRAIGHT THIN FILM INDUCTOR



EQUATION 20:

$$L = 0.002l \left\{ \ln \left(\frac{2l}{a+b} \right) + 0.50049 + \frac{a+b}{3l} \right\} \quad (\mu H)$$

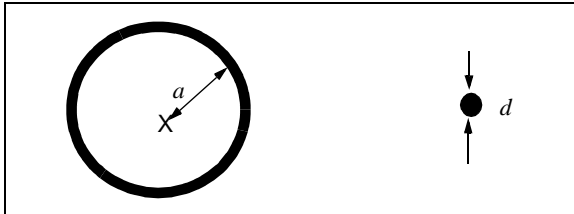
where:

- a = width in cm
- b = thickness in cm
- l = length of conductor in cm

Inductance of a Circular Coil with Single Turn

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

FIGURE 7: A CIRCULAR COIL WITH SINGLE TURN



EQUATION 21:

$$L = 0.01257(a) \left[2.303 \log_{10} \left(\frac{16a}{d} - 2 \right) \right] \quad (\mu H)$$

where:

- a = mean radius of loop in (cm)
- d = diameter of wire in (cm)

Inductance of an N-turn Circular Coil with Single Layer

The inductance of a circular coil with single layer is calculated as:

EQUATION 22:

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

where:

- N = number of turns
- l = length
- a = the radius of coil in cm

Inductance of N-turn Circular Coil with Multilayer

FIGURE 8: N-TURN CIRCULAR COIL WITH SINGLE LAYER

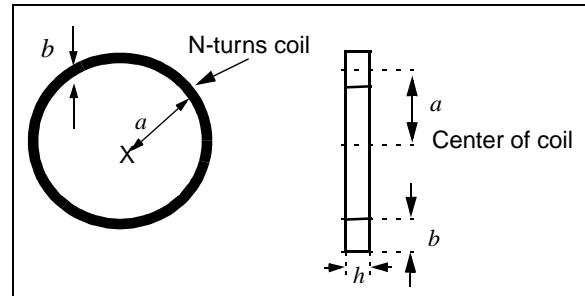


Figure 8 shows an N-turn inductor of circular coil with multilayer. Its inductance is calculated by:

EQUATION 23:

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

where:

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

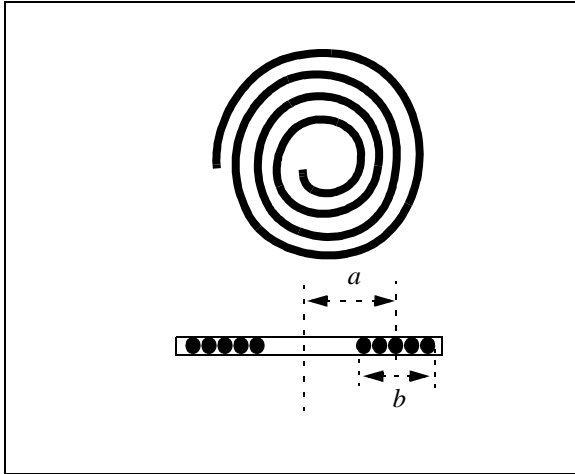
Inductance of Spiral Wound Coil with Single Layer

The inductance of a spiral inductor is calculated by:

EQUATION 24:

$$L = \frac{(aN)^2}{8a + 11b} \quad (\mu H)$$

FIGURE 9: A SPIRAL COIL



Inductance of N-turn Square Loop Coil with Multilayer

Inductance of a multilayer square loop coil is calculated by:

EQUATION 25:

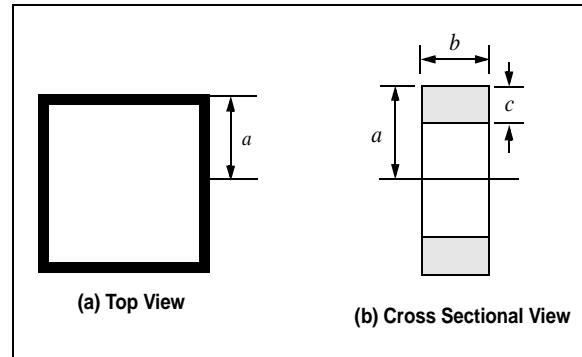
$$L = 0.008aN^2 \left\{ 2.303 \log_{10} \left(\frac{a}{b+c} \right) + 0.2235 \frac{b+c}{a} + 0.726 \right\} (\mu H)$$

where:

- N = number of turns
- a = side of square measured to the center of the rectangular cross section of winding
- b = winding length
- c = winding depth as shown in Figure 10.

Note: All dimensions are in cm.

FIGURE 10: N-TURN SQUARE LOOP COIL WITH MULTILAYER



Inductance of a Flat Square Coil

Inductance of a flat square coil of rectangular cross section with N turns is calculated by^[4]:

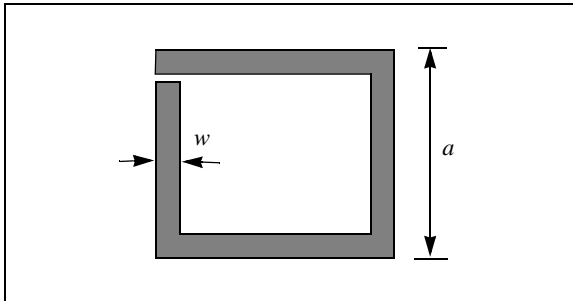
EQUATION 26:

$$L = 0.0467aN^2 \left\{ \log_{10} \left(\frac{2a^2}{t+w} \right) - \log_{10}(2.414a) \right\} + 0.02032aN^2 \left\{ 0.914 + \left[\frac{0.2235}{a}(t+w) \right] \right\}$$

where:

- L = in μH
- a = side length in inches
- t = thickness in inches
- w = width in inches

FIGURE 11: SQUARE LOOP INDUCTOR WITH A RECTANGULAR CROSS SECTION



The formulas for inductance are widely published and provide a reasonable approximation for the relationship between inductance and the 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 a right value. For production coils, it is best to specify an inductance and tolerance rather than a specific number of turns.

CONFIGURATION OF ANTENNA CIRCUITS

Reader Antenna Circuits

The inductance for the reader antenna coil for 13.56 MHz is typically in the range of a few microhenries (μH). The antenna can be formed by aircore or ferrite core inductors. The antenna can also be formed by a metallic or conductive trace on PCB board or on flexible substrate.

The reader antenna can be made of either a single coil, that is typically forming a series or a parallel resonant circuit, or a double loop (transformer) antenna coil. Figure 12 shows various configurations of reader antenna circuit. The coil circuit must be tuned to the operating frequency to maximize power efficiency. The tuned LC resonant circuit is the same as the bandpass filter that passes only a selected frequency. The Q of the tuned circuit is related to both read range and bandwidth of the circuit. More on this subject will be discussed in the following section.

Choosing the size and type of antenna circuit depends on the system design topology. The series resonant circuit results in minimum impedance at the resonance frequency. Therefore, it draws a maximum current at

the resonance frequency. Because of its simple circuit topology and relatively low cost, this type of antenna circuit is suitable for proximity reader antenna.

On the other hand, a parallel resonant circuit results in maximum impedance at the resonance frequency. Therefore, maximum voltage is available at the resonance frequency. Although it has a minimum resonant current, it still has a strong circulating current that is proportional to Q of the circuit. The double loop antenna coil that is formed by two parallel antenna circuits can also be used.

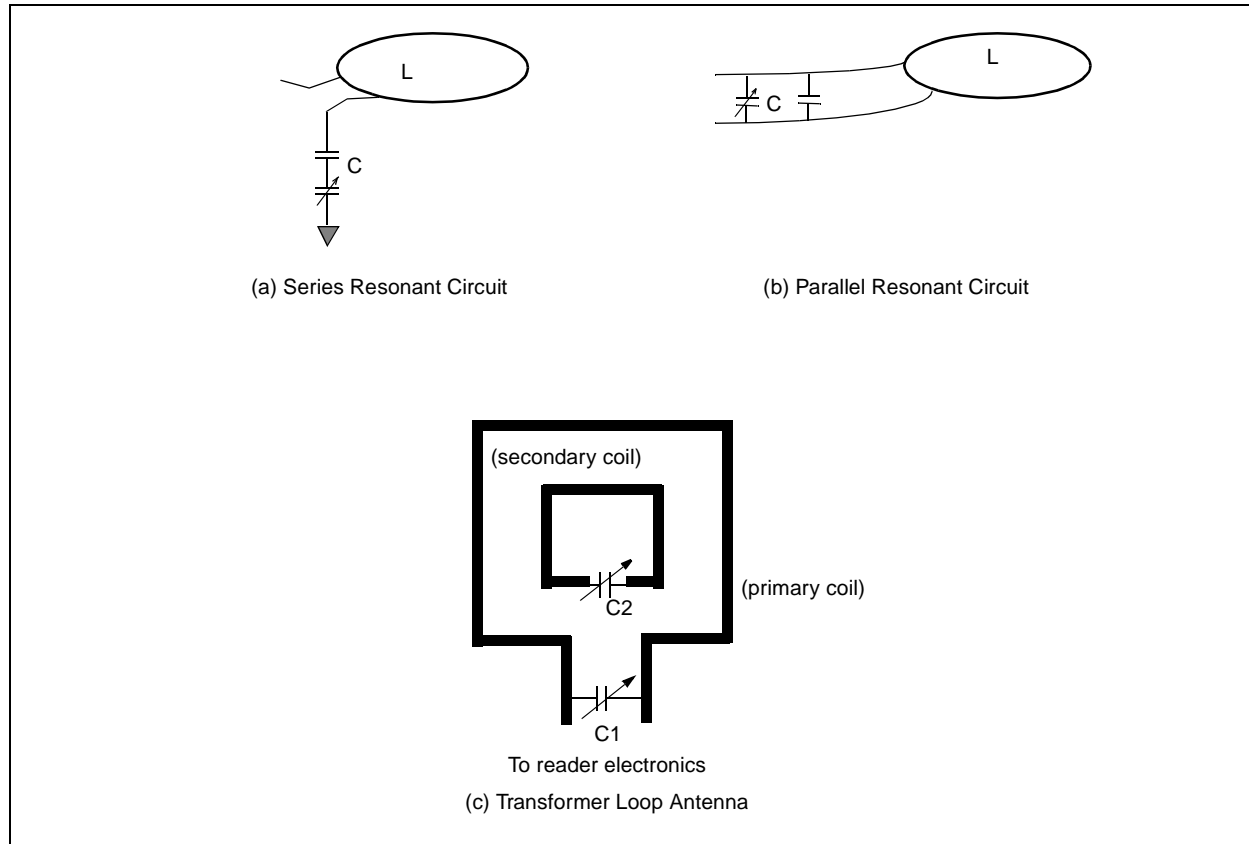
The frequency tolerance of the carrier frequency and output power level from the read antenna is regulated by government regulations (e.g., FCC in the USA).

FCC limits for 13.56 MHz frequency band are as follows:

1. Tolerance of the carrier frequency: 13.56 MHz $\pm 0.01\%$ = ± 1.356 kHz.
2. Frequency bandwidth: ± 7 kHz.
3. Power level of fundamental frequency: 10 mv/m at 30 meters from the transmitter.
4. Power level for harmonics: -50.45 dB down from the fundamental signal.

The transmission circuit including the antenna coil must be designed to meet the FCC limits.

FIGURE 12: VARIOUS READER ANTENNA CIRCUITS



Tag Antenna Circuits

The MCRF355 device communicates data by tuning and detuning the antenna circuit (see AN707). Figure 13 shows examples of the external circuit arrangement.

The external circuit must be tuned to the resonant frequency of the reader antenna. In a detuned condition, a circuit element between the antenna B and VSS pads is shorted. The frequency difference (delta frequency) between tuned and detuned frequencies must be adjusted properly for optimum operation. It has been found that maximum modulation index and maximum read range occur when the tuned and detuned frequencies are separated by 3 to 6 MHz.

The tuned frequency is formed from the circuit elements between the antenna A and VSS pads without shorting the antenna B pad. The detuned frequency is found when the antenna B pad is shorted. This detuned frequency is calculated from the circuit between antenna A and VSS pads excluding the circuit element between antenna B and VSS pads.

In Figure 13 (a), the tuned resonant frequency is

EQUATION 27:

$$f_o = \frac{1}{2\pi\sqrt{L_T C}}$$

where:

- L_T = $L_1 + L_2 + 2L_M$ = Total inductance between antenna A and VSS pads
- L_1 = inductance between antenna A and antenna B pads
- L_2 = inductance between ant. B and VSS pads
- M = mutual inductance between coil 1 and coil 2
- = $k\sqrt{L_1 L_2}$
- k = coupling coefficient between the two coils
- C = tuning capacitance

and detuned frequency is

EQUATION 28:

$$f_{detuned} = \frac{1}{2\pi\sqrt{L_1 C}}$$

In this case, $f_{detuned}$ is higher than f_{tuned} .

Figure 13(b) shows another example of the external circuit arrangement. This configuration controls C_2 for tuned and detuned frequencies. The tuned and untuned frequencies are

EQUATION 29:

$$f_{tuned} = \frac{1}{2\pi\sqrt{\left(\frac{C_1 C_2}{C_1 + C_2}\right)L}}$$

and

EQUATION 30:

$$f_{detuned} = \frac{1}{2\pi\sqrt{L C_1}}$$

A typical inductance of the coil is about a few microhenry with a few turns. Once the inductance is determined, the resonant capacitance is calculated from the above equations. For example, if a coil has an inductance of 1.3 μ H, then it needs a 106 pF of capacitance to resonate at 13.56 MHz.

CONSIDERATION ON QUALITY FACTOR Q AND BANDWIDTH OF TUNING CIRCUIT

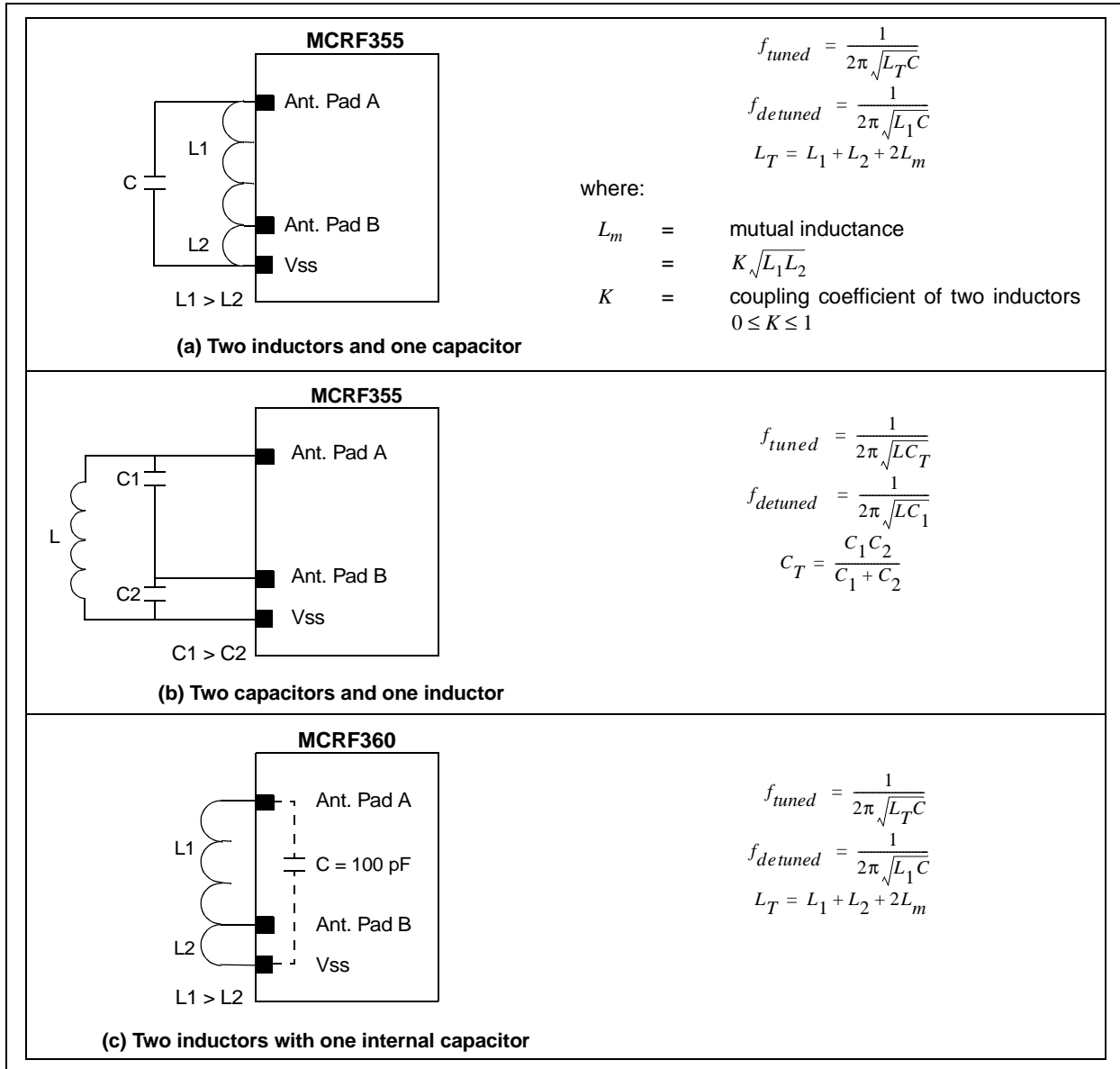
The voltage across the coil is a product of quality factor Q of the circuit and input voltage. Therefore, for a given input voltage signal, the coil voltage is directly proportional to the Q of the circuit. In general, a higher Q

results in longer read range. However, the Q is also related to the bandwidth of the circuit as shown in the following equation.

EQUATION 31:

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

FIGURE 13: VARIOUS EXTERNAL CIRCUIT CONFIGURATIONS



Bandwidth requirement and limit on circuit Q for MCRF355

Since the MCRF355 operates with a data rate of 70 kHz, the reader antenna circuit needs a bandwidth of at least twice of the data rate. Therefore, it needs:

EQUATION 32:

$$B_{\text{minimum}} = 140 \text{ kHz}$$

Assuming the circuit is turned at 13.56 MHz, the maximum attainable Q is obtained from Equations 31 and 32:

EQUATION 33:

$$Q_{\text{max}} = \frac{f_o}{B} = 96.8$$

In a practical LC resonant circuit, the range of Q for 13.56 MHz band is about 40. However, the Q can be significantly increased with a ferrite core inductor. The system designer must consider the above limits for optimum operation.

RESONANT CIRCUITS

Once the frequency and the inductance of the coil are determined, the resonant capacitance can be calculated from:

EQUATION 34:

$$C = \frac{1}{L(2\pi f_o)^2}$$

In practical applications, parasitic (distributed) capacitance is present between turns. The parasitic capacitance in a typical tag antenna coil is a few (pF). This parasitic capacitance increases with operating frequency of the device.

There are two different resonant circuits: parallel and series. The parallel resonant circuit has maximum impedance at the resonance frequency. It has a minimum current and maximum voltage at the resonance frequency. Although the current in the circuit is minimum at the resonant frequency, there are a circulation current that is proportional to Q of the circuit. The parallel resonant circuit is used in both the tag and the high-power reader antenna circuit.

On the other hand, the series resonant circuit has a minimum impedance at the resonance frequency. As a result, maximum current is available in the circuit. Because of its simplicity and the availability of the high current into the antenna element, the series resonant circuit is often used for a simple proximity reader.

Parallel Resonant Circuit

Figure 14 shows a simple parallel resonant circuit. The total impedance of the circuit is given by:

EQUATION 35:

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

where ω is an angular frequency given as $\omega = 2\pi f$.

The maximum impedance occurs when the denominator in the above equation is minimized. This condition occurs when:

EQUATION 36:

$$\omega^2 LC = 1$$

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

EQUATION 37:

$$f_0 = \frac{1}{2\pi\sqrt{LC}}$$

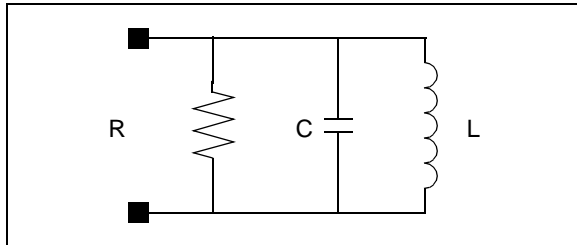
By applying Equation 36 into Equation 35, the impedance at the resonance frequency becomes:

EQUATION 38:

$$Z = R$$

where R is the load resistance.

FIGURE 14: PARALLEL RESONANT CIRCUIT



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

EQUATION 39:

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

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

EQUATION 40:

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

$$= \frac{\text{reactance}}{\text{resistance}}$$

$$= \frac{\omega L}{r} \quad \text{For inductance}$$

$$= \frac{1}{\omega cr} \quad \text{For capacitance}$$

$$= \frac{f_0}{B}$$

where:

- ω = $2\pi f$ = angular frequency
- f_0 = resonant frequency
- B = bandwidth
- r = ohmic losses

By applying Equation 37 and Equation 39 into Equation 40, the Q in the parallel resonant circuit is:

EQUATION 41:

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

The Q in a parallel resonant circuit is proportional to the load resistance R and also to 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 8 and 41:

EQUATION 42:

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

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

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.

Series Resonant Circuit

A simple series resonant circuit is shown in Figure 15. The expression for the impedance of the circuit is:

EQUATION 43:

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

where:

- r = a dc ohmic resistance of coil and capacitor
- X_L and X_C = the reactance of the coil and capacitor, respectively, such that:

EQUATION 44:

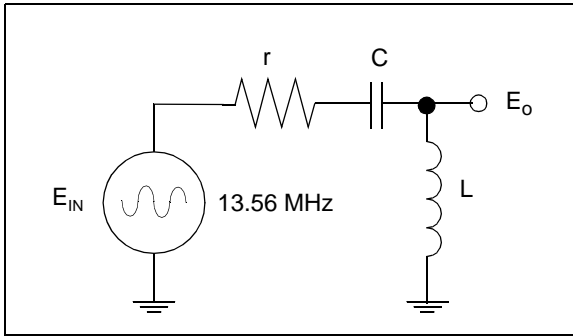
$$X_L = 2\pi f_o L \quad (\Omega)$$

EQUATION 45:

$$X_C = \frac{1}{2\pi f_o C} \quad (\Omega)$$

The impedance in Equation 43 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 37.

FIGURE 15: SERIES RESONANCE CIRCUIT



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

EQUATION 46:

$$B = \frac{r}{2\pi L} \quad (\text{Hz})$$

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

$$Q = \frac{f_0}{B} = \frac{\omega L}{r} = \frac{1}{r\omega C}$$

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

EQUATION 47:

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

When the circuit is tuned to a resonant frequency such as $X_L = X_C$, the voltage across the coil becomes:

EQUATION 48:

$$\begin{aligned} V_o &= \frac{jX_L}{r} V_{in} \\ &= jQV_{in} \end{aligned}$$

The above equation indicates that the coil voltage is a product of input voltage and Q of the circuit. For example, a circuit with Q of 40 can have a coil voltage that is 40 times higher than input signal. This is because all energy in the input signal spectrum becomes squeezed into a single frequency band.

EXAMPLE 6: CIRCUIT PARAMETERS

If the DC ohmic resistance r is 5Ω , then the L and C values for 13.56 MHz resonant circuit with $Q = 40$ are:

EQUATION 49:

$$X_L = Qr_s = 200\Omega$$

$$L = \frac{X_L}{2\pi f} = \frac{200}{2\pi(13.56\text{MHz})} = 2.347 \quad (\mu\text{H})$$

$$C = \frac{1}{2\pi f X_L} = \frac{1}{2\pi(13.56\text{MHz})(200)} = 58.7 \quad (\text{pF})$$

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:**

- Set up a voltage signal source at the resonance frequency.
- Connect a voltage signal source across the resonant circuit.
- Connect an Oscilloscope across the resonant circuit.
- Tune the capacitor or the coil while observing the signal amplitude on the Oscilloscope.
- Stop the tuning at the maximum voltage.

- **S-parameter or Impedance Measurement Method using Network Analyzer:**

- Set up an S-Parameter Test Set (Network Analyzer) for S11 measurement, and do a calibration.
- Measure the S11 for the resonant circuit.
- Reflection impedance or reflection admittance can be measured instead of the S11.
- 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 16: VOLTAGE VS. FREQUENCY FOR RESONANT CIRCUIT

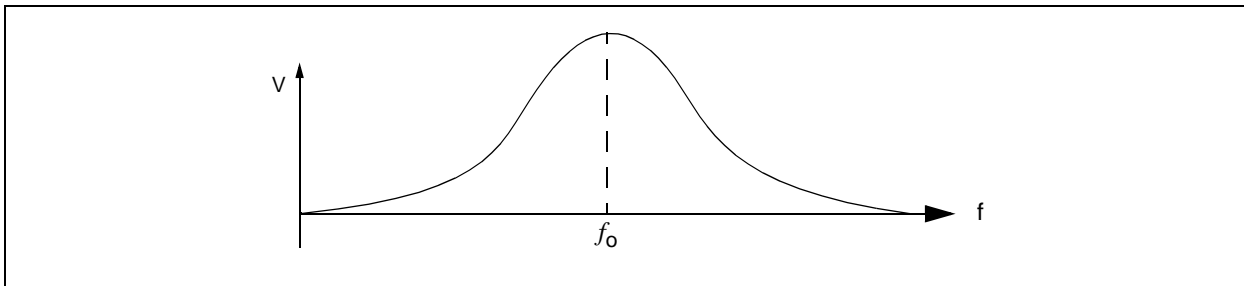
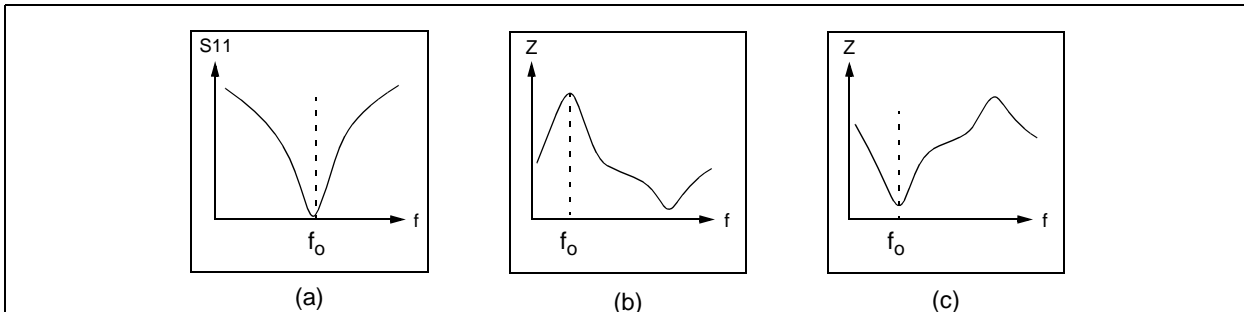


FIGURE 17: FREQUENCY RESPONSES FOR RESONANT CIRCUIT



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. In general, the read range of passive RFID products varies, depending on system configuration and is affected by the following parameters:

- Operating frequency and performance of antenna coils
- Q of antenna and tuning circuit
- Antenna orientation
- Excitation current
- Sensitivity of receiver
- Coding (or modulation) and decoding (or demodulation) algorithm
- Number of data bits and detection (interpretation) algorithm
- Condition of operating environment (electrical noise), etc.

The read range of 13.56 MHz is relatively longer than that of 125 kHz device. This is because the antenna efficiency increases as the frequency increases. With a given operating frequency, the conditions (a – c) are related to the antenna configuration and tuning circuit. The conditions (d – e) are determined by a circuit topology of reader. The condition (f) is a communication protocol of the device, and (g) is related to a firmware software program for data detection.

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 with a proper antenna design. Figures 18 and 19 show typical examples of the read range of various passive RFID devices.

FIGURE 18: READ RANGE VS. TAG SIZE FOR TYPICAL PROXIMITY APPLICATIONS*

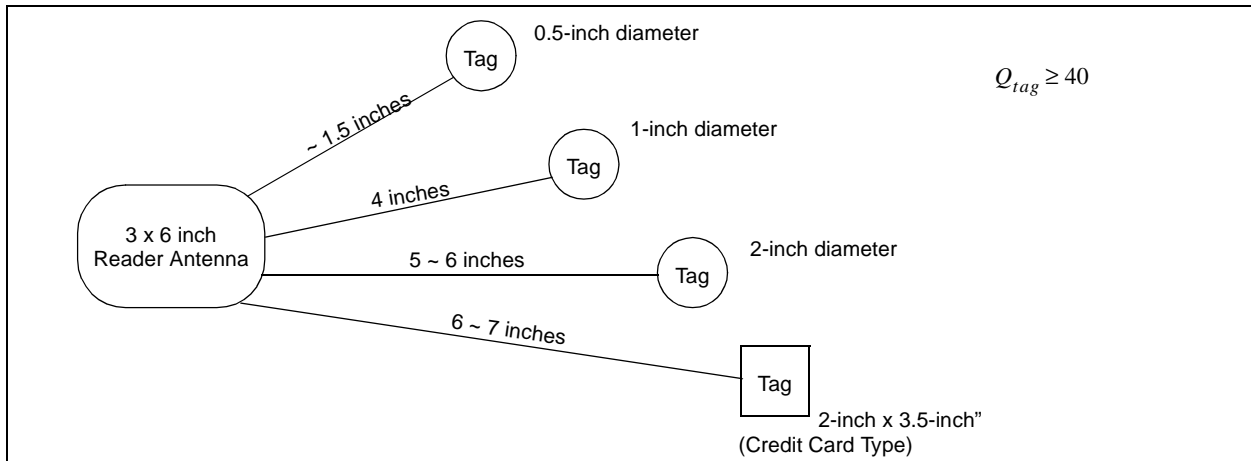
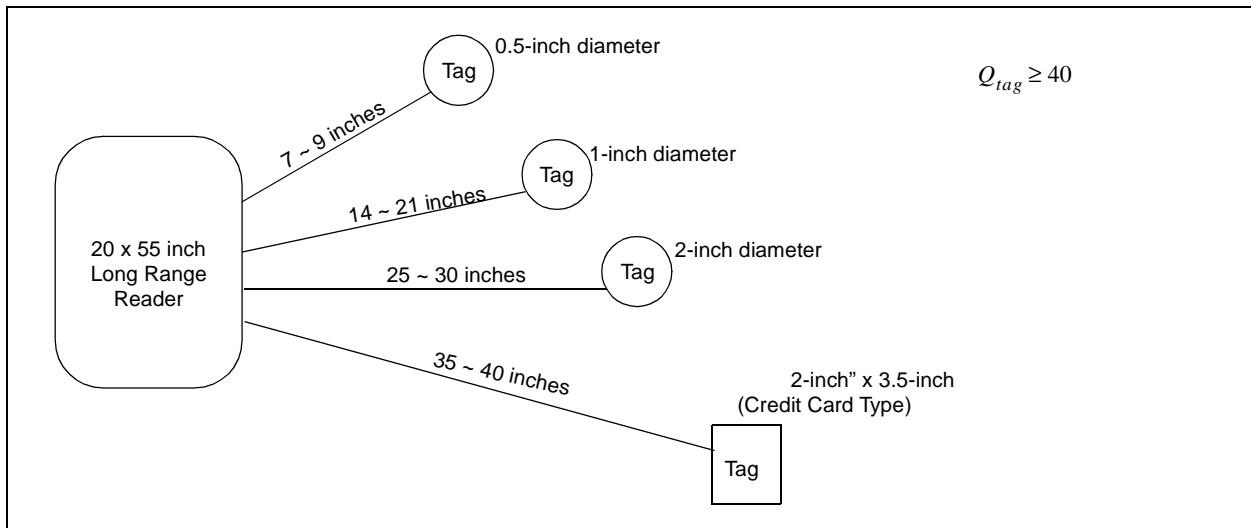


FIGURE 19: READ RANGE VS. TAG SIZE FOR TYPICAL LONG RANGE APPLICATIONS*



Note: Actual results may be shorter or longer than the range shown, depending upon factors discussed above.

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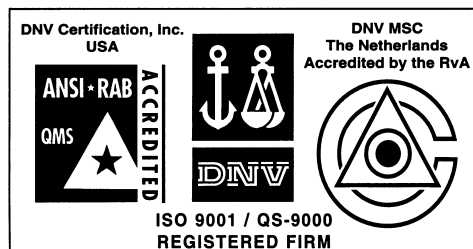
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