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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:

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

where:

I = current

r = distance from the center of wire

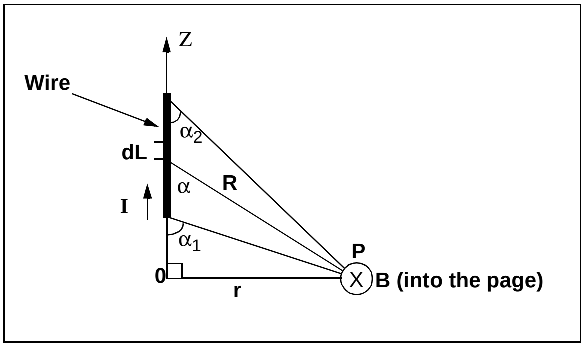
μ_o = permeability of free space and given as $\mu_o = 4\pi \times 10^{-7}$ (Henry/meter)

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:

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

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

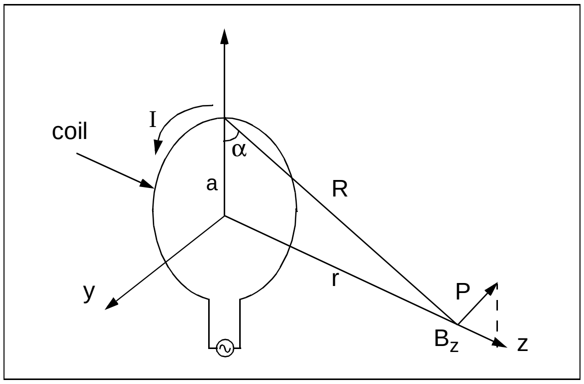
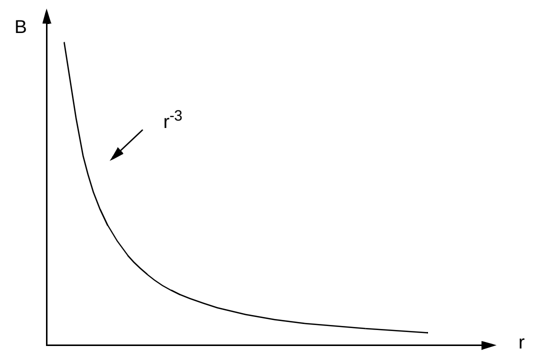


FIGURE 3: DECAYING OF THE MAGNETIC FIELD B VS. DISTANCE *r*



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:

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

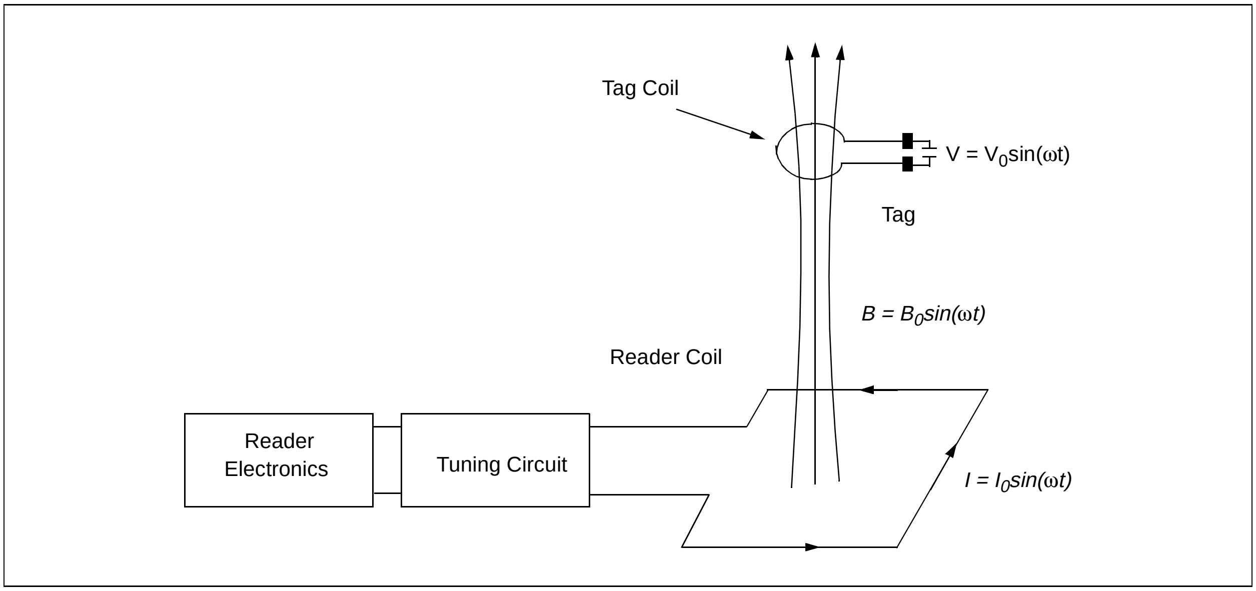
where:

B	=	magnetic field given in Equation 3
S	=	surface area of the coil
•	=	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

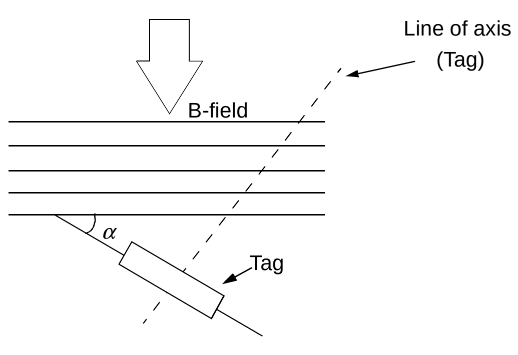
If the coil is tuned (with capacitor C) to the frequency of the arrival signal (125 kHz), the output voltage V_o will rise substantially. The output voltage found in Equation 6 is multiplied by the loaded Q (Quality Factor) of the tuned circuit, which can be varied from 5 to 50 in typical low-frequency 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 $\alpha = 0$.

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, $\alpha = 0$).

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:

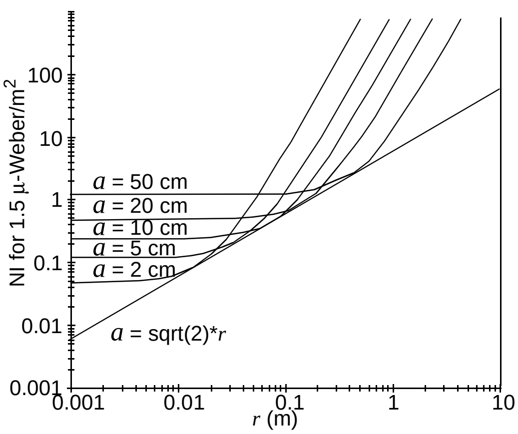
EQUATION 10:

$$NI = \frac{2(1.5\times10^{-6})(0.16^2+0.25^2)^{3/2}}{(4\pi\times10^{-7})(0.16^2)}$$

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

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: $B_O = 1.5\ \mu Wb/m^2$ 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 = 2.54×10^{-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:

$$L = 0.002(304.8)\left[\ln\left(\frac{2(304.8)}{0.1}\right) - \frac{3}{4}\right]$$

$$= 0.60967(7.965)$$

$$= 4.855(\mu H)$$

Inductance of a Single Layer Coil

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

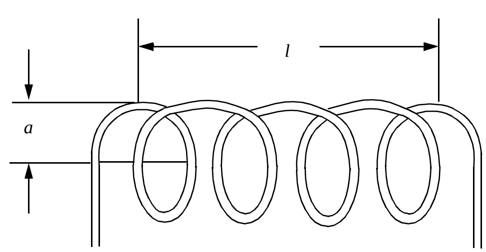
EQUATION 19:

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

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]:

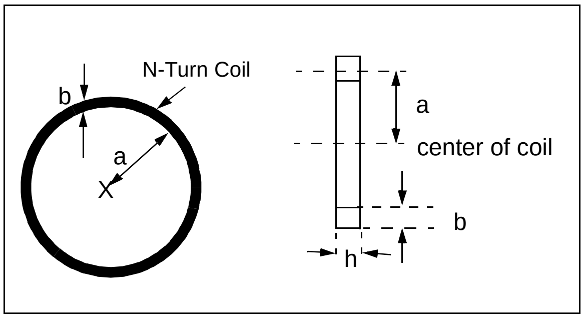
EQUATION 20:

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

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

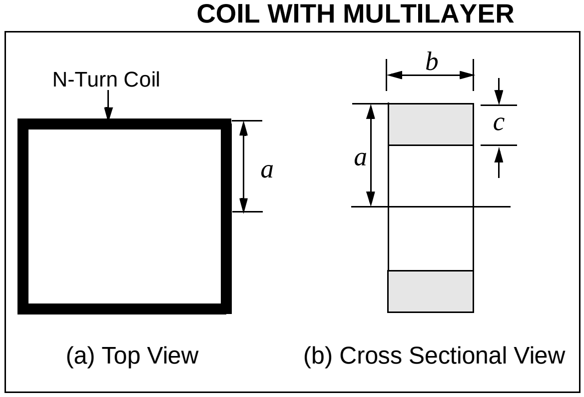
If N is the number of turns and a is the side of the square measured to the center of the rectangular cross section that has length b and depth c as shown in Figure 9, then[2]:

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



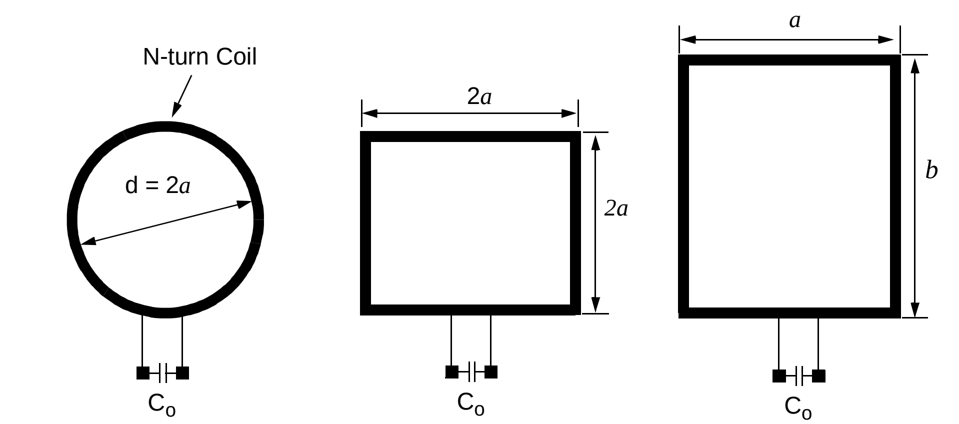
CONFIGURATION OF ANTENNA COILS

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.

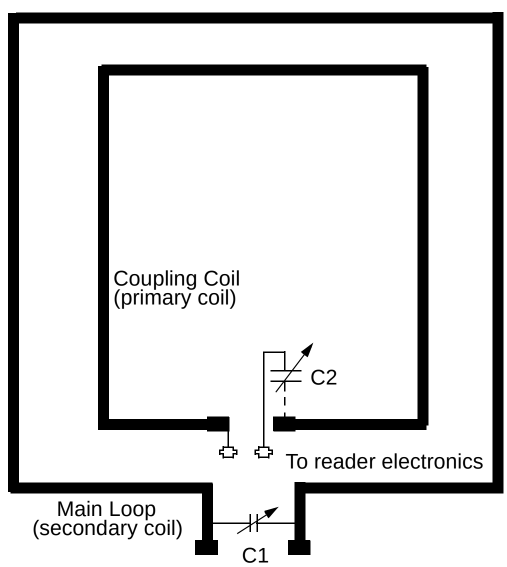
The series resonant circuit results in minimum impedance at the resonance frequency. Therefore, it draws a maximum current at the resonance frequency. On the other hand, the parallel resonant circuit results in maximum impedance at the resonance frequency. Therefore, the current becomes minimized at 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:

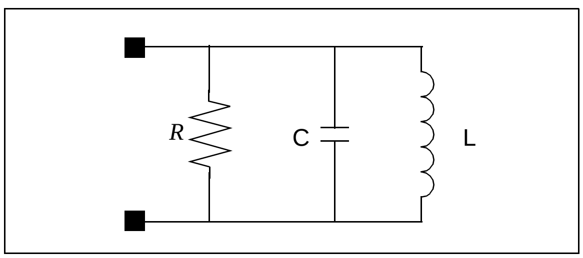
$$f_o = \frac{1}{2\pi\sqrt{LC}}$$

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:

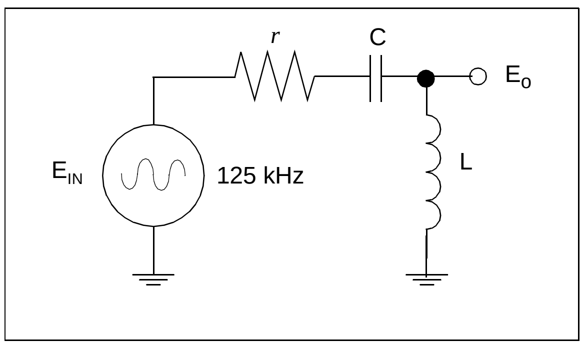
$$X_L = 2\pi f_o L \qquad (\Omega)$$

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:

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

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.

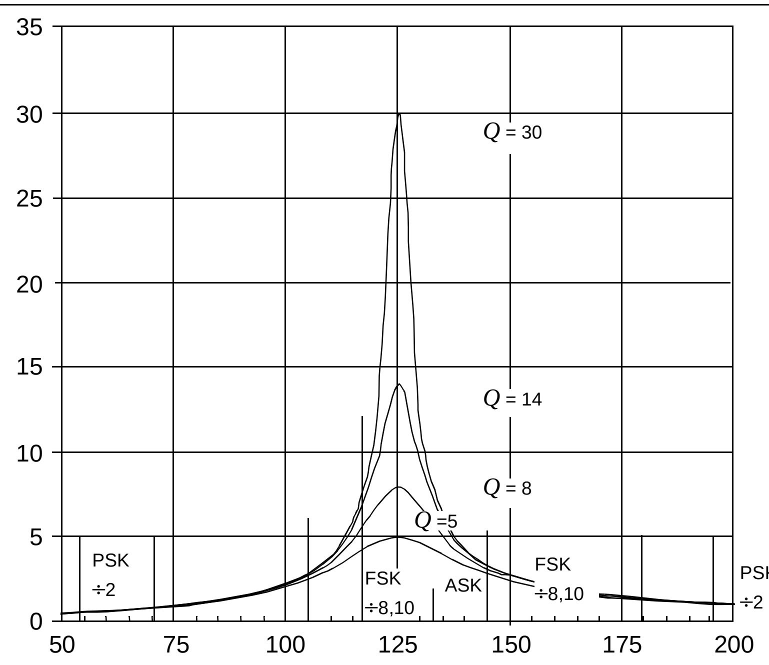
   For example, a 1 ampere of current flow in a 2 mH coil will produce a voltage drop of 1500 V_{PP}. Such voltages are easy to obtain but difficult to isolate. In addition, in the case of single coil reader designs, recovery of the return signal from the tag must be accomplished in the presence of these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

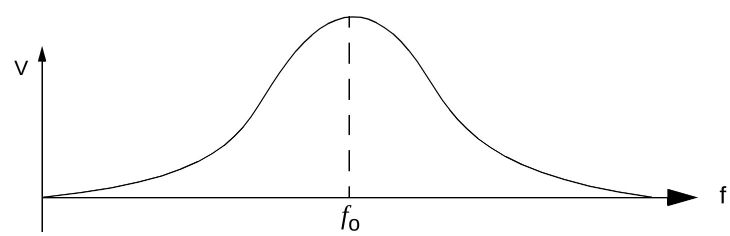
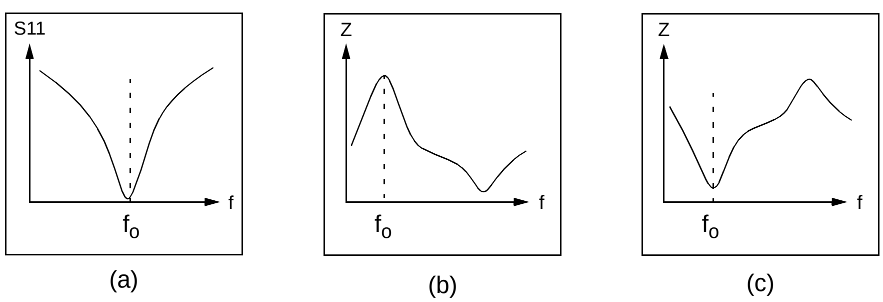


FIGURE 16: FREQUENCY RESPONSES FOR RESONANT CIRCUIT



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

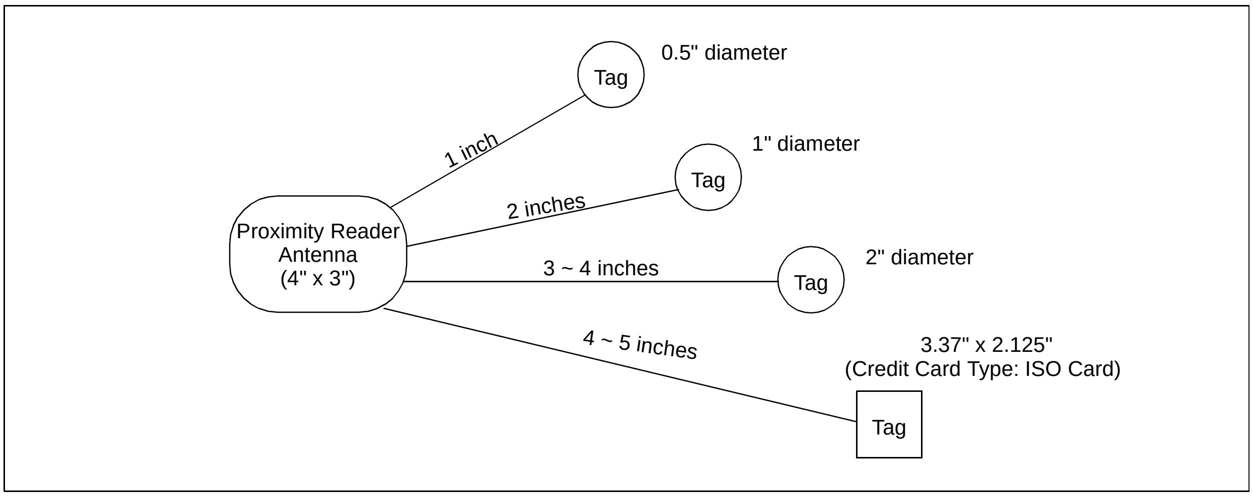
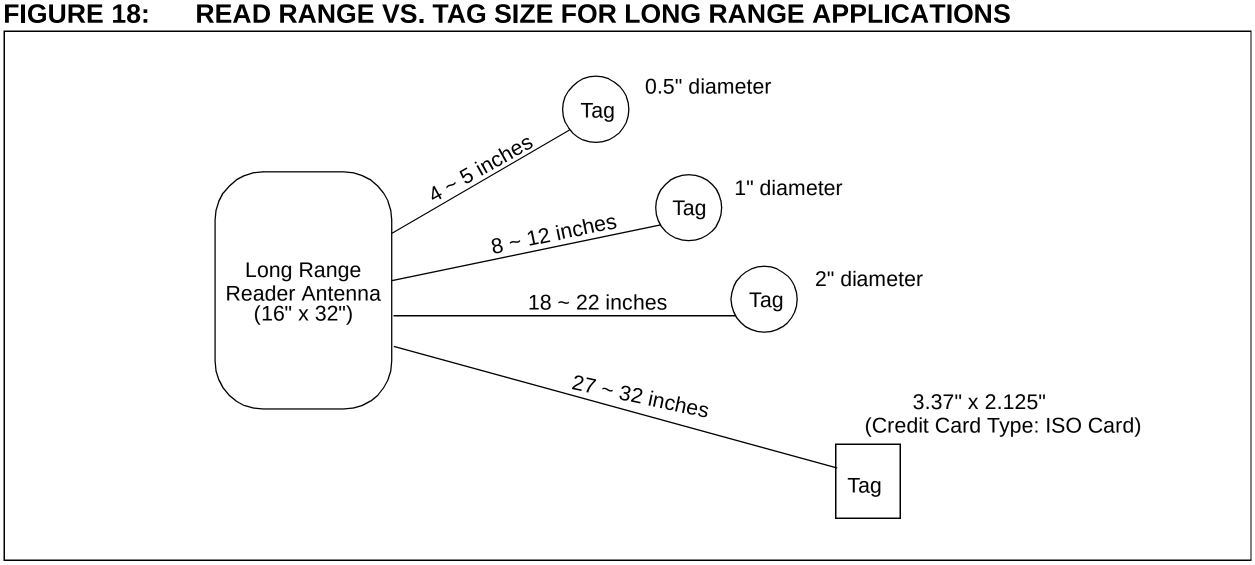


FIGURE 18: READ RANGE VS. TAG SIZE FOR LONG RANGE APPLICATIONS



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AN680

Passive RFID Basics

Author: Pete Sorrells
Microchip Technology Inc.

INTRODUCTION

Radio Frequency Identification (RFID) systems use radio frequency to identify, locate and track people, assets, and animals. Passive RFID systems are composed of three components – an interrogator (reader), a passive tag, and a host computer. The tag is composed of an antenna coil and a silicon chip that includes basic modulation circuitry and non-volatile memory. The tag is energized by a time-varying electromagnetic radio frequency (RF) wave that is transmitted by the reader. This RF signal is called a *carrier signal*. When the RF field passes through an antenna coil, there is an AC voltage generated across the coil. This voltage is rectified to supply power to the tag. The information stored in the tag is transmitted back to the reader. This is often called backscattering. By detecting the backscattering signal, the information stored in the tag can be fully identified.

DEFINITIONS

Reader

Usually a microcontroller-based unit with a wound output coil, peak detector hardware, comparators, and firmware designed to transmit energy to a tag and read information back from it by detecting the backscatter modulation.

Tag

An RFID device incorporating a silicon memory chip (usually with on-board rectification bridge and other RF front-end devices), a wound or printed input/output coil, and (at lower frequencies) a tuning capacitor.

Carrier

A Radio Frequency (RF) sine wave generated by the reader to transmit energy to the tag and retrieve data from the tag. In these examples the ISO frequencies of 125 kHz and 13.56 MHz are assumed; higher frequencies are used for RFID tagging, but the communication methods are somewhat different. 2.45 GHz, for example, uses a true RF link. 125 kHz and 13.56 MHz, utilize transformer-type electromagnetic coupling.

Modulation

Periodic fluctuations in the amplitude of the carrier used to transmit data back from the tag to the reader.

Systems incorporating passive RFID tags operate in ways that may seem unusual to anyone who already understands RF or microwave systems. There is only one transmitter – the passive tag is not a transmitter or transponder in the purest definition of the term, yet bidirectional communication is taking place. The RF field generated by a tag reader (the energy transmitter) has three purposes:

1. **Induce enough power into the tag coil to energize the tag.** Passive tags have no battery or other power source; they must derive all power for operation from the reader field. 125 kHz and 13.56 MHz tag designs must operate over a vast dynamic range of carrier input, from the very near field (in the range of 200 V_{PP}) to the maximum read distance (in the range of 5 V_{PP}).
2. **Provide a synchronized clock source to the tag.** Many RFID tags divide the carrier frequency down to generate an on-board clock for state machines, counters, etc., and to derive the data transmission bit rate for data returned to the reader. Some tags, however, employ on-board oscillators for clock generation.
3. **Act as a carrier for return data from the tag.** Backscatter modulation requires the reader to peak-detect the tag's modulation of the reader's own carrier. See page 2 for additional information on backscatter modulation.

SYSTEM HANDSHAKE

Typical handshake of a tag and reader is as follows:

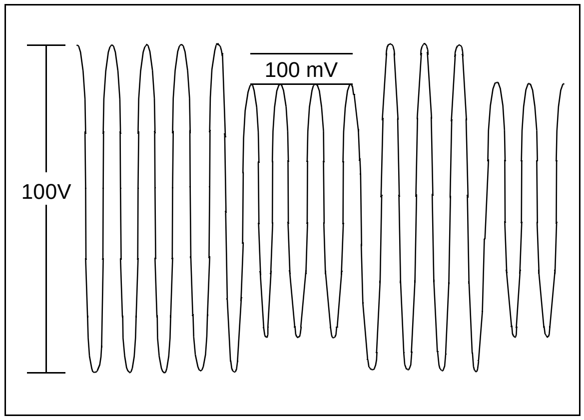
1. The reader continuously generates an RF carrier sine wave, watching always for modulation to occur. Detected modulation of the field would indicate the presence of a tag.
2. A tag enters the RF field generated by the reader. Once the tag has received sufficient energy to operate correctly, it divides down the carrier and begins clocking its data to an output transistor, which is normally connected across the coil inputs.
3. The tag's output transistor shunts the coil, sequentially corresponding to the data which is being clocked out of the memory array.
4. Shunting the coil causes a momentary fluctuation (dampening) of the carrier wave, which is seen as a slight change in amplitude of the carrier.
5. The reader peak-detects the amplitude-modulated data and processes the resulting bitstream according to the encoding and data modulation methods used.

BACKSCATTER MODULATION

This terminology refers to the communication method used by a passive RFID tag to send data back to the reader. By repeatedly shunting the tag coil through a transistor, the tag can cause slight fluctuations in the reader's RF carrier amplitude. The RF link behaves essentially as a transformer; as the secondary winding (tag coil) is momentarily shunted, the primary winding (reader coil) experiences a momentary voltage drop. The reader must peak-detect this data at about 60 dB down (about 100 mV riding on a 100V sine wave) as shown in Figure 1.

This amplitude-modulation loading of the reader's transmitted field provides a communication path back to the reader. The data bits can then be encoded or further modulated in a number of ways.

FIGURE 1: AMPLITUDE – MODULATED BACKSCATTERING SIGNAL

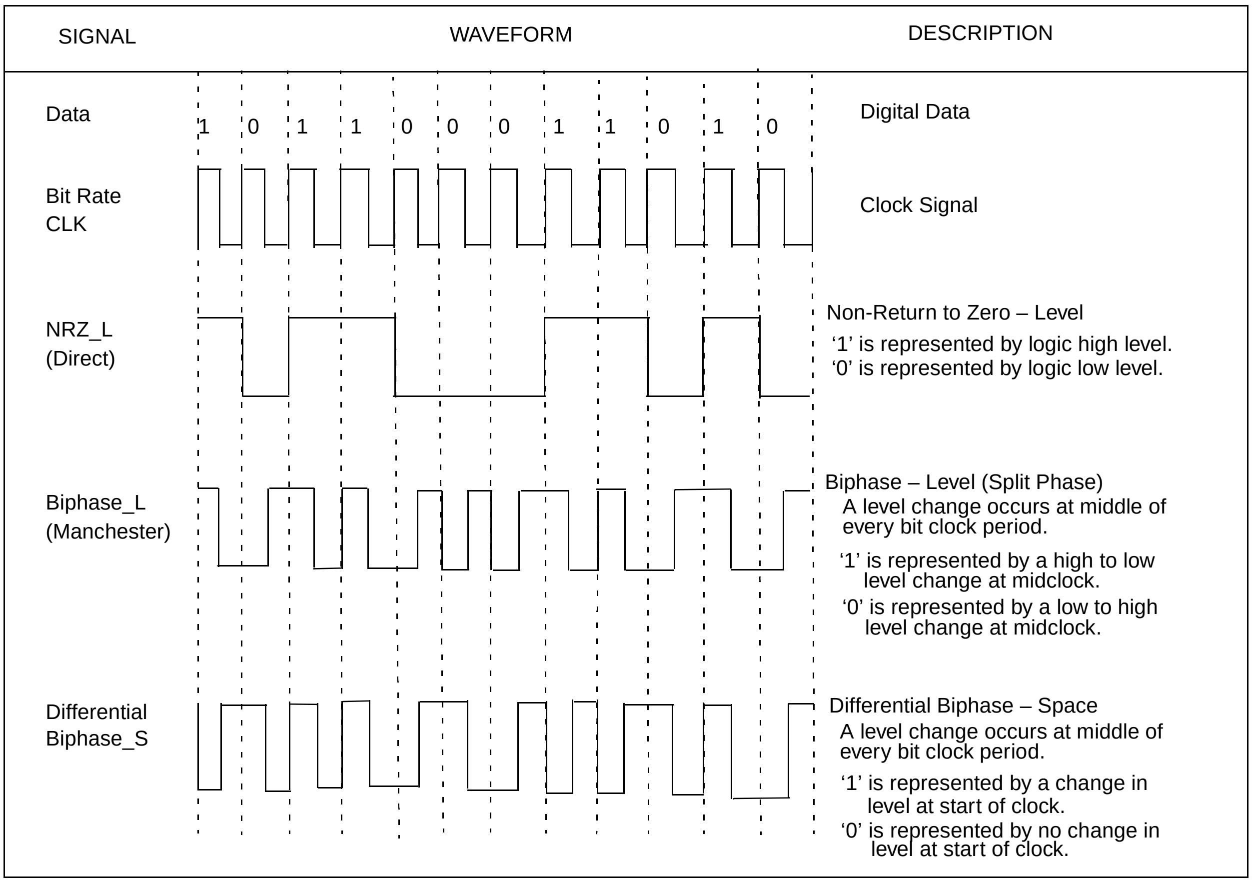


DATA ENCODING

Data encoding refers to processing or altering the data bitstream in-between the time it is retrieved from the RFID chip's data array and its transmission back to the reader. The various encoding algorithms affect error recovery, cost of implementation, bandwidth, synchronization capability, and other aspects of the system design. Entire textbooks are written on the subject, but there are several popular methods used in RFID tagging today:

1. **NRZ (Non-Return to Zero) Direct.** In this method no data encoding is done at all; the 1's and 0's are clocked from the data array directly to the output transistor. A low in the peak-detected modulation is a '0' and a high is a '1'.
2. **Differential Biphase.** Several different forms of differential biphase are used, but in general the bitstream being clocked out of the data array is modified so that a transition always occurs on every clock edge, and 1's and 0's are distinguished by the transitions within the middle of the clock period. This method is used to embed clocking information to help synchronize the reader to the bitstream; and because it always has a transition at a clock edge, it inherently provides some error correction capability. Any clock edge that does not contain a transition in the data stream is in error and can be used to reconstruct the data.
3. **Biphase_L (Manchester).** This is a variation of biphase encoding in which there is not always a transition at the clock edge.

FIGURE 2: VARIOUS DATA CODING WAVEFORMS



DATA MODULATION

Although all the data is transferred to the host by amplitude-modulating the carrier (backscatter modulation), the actual modulation of 1’s and 0’s is accomplished with three additional modulation methods:

1. **Direct.** In direct modulation, the Amplitude Modulation of the backscatter approach is the only modulation used. A high in the envelope is a ‘1’ and a low is a ‘0’. Direct modulation can provide a high data rate but low noise immunity.
2. **FSK (Frequency Shift Keying).** This form of modulation uses two different frequencies for data transfer; the most common FSK mode is Fc/8/10. In other words, a ‘0’ is transmitted as an amplitude-modulated clock cycle with period corresponding to the carrier frequency divided by 8, and a ‘1’ is transmitted as an amplitude-modulated clock cycle period corresponding to the carrier frequency divided by 10. The amplitude modulation of the carrier thus switches from Fc/8 to Fc/10 corresponding to 0's and 1's in the bitstream, and the reader has only to count cycles between the peak-detected clock edges to decode the data. FSK allows for a simple reader design, provides very strong noise immunity, but suffers from a lower data rate than some other forms of data modulation. In Figure 3, FSK data modulation is used with NRZ encoding.
3. **PSK (Phase Shift Keying).** This method of data modulation is similar to FSK, except only one frequency is used, and the shift between 1’s and 0’s is accomplished by shifting the phase of the backscatter clock by 180 degrees. Two common types of PSK are:
   - Change phase at any ‘0’, or
   - Change phase at any data change (0 to 1 or 1 to 0).

   PSK provides fairly good noise immunity, a moderately simple reader design, and a faster data rate than FSK. Typical applications utilize a backscatter clock of Fc/2, as shown in Figure 4.

FIGURE 3: FSK MODULATED SIGNAL, FC/8 = 0, FC/10 = 1

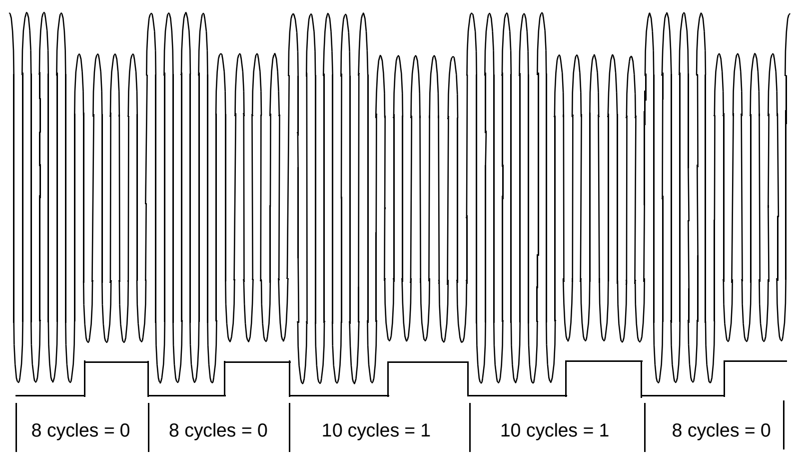
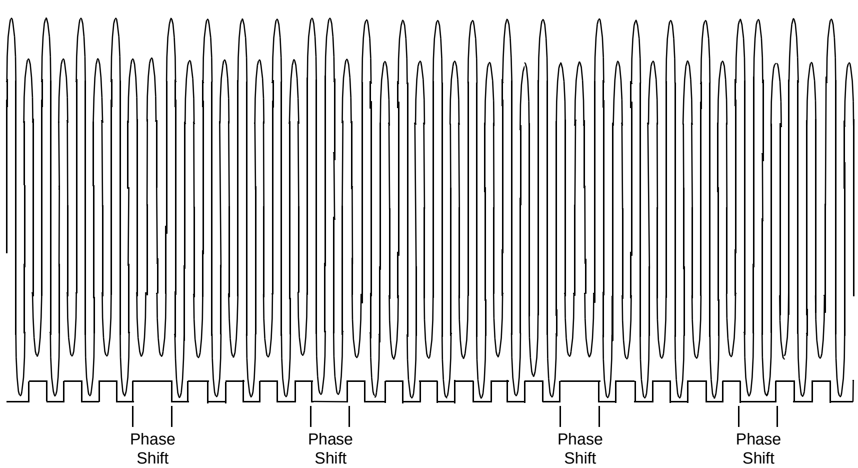


FIGURE 4: PSK MODULATED SIGNAL



ANTICOLLISION

In many existing applications, a single-read RFID tag is sufficient and even necessary: animal tagging and access control are examples. However, in a growing number of new applications, the simultaneous reading of several tags in the same RF field is absolutely critical: library books, airline baggage, garment, and retail applications are a few.

In order to read multiple tags simultaneously, the tag and reader must be designed to detect the condition that more than one tag is active. Otherwise, the tags will all backscatter the carrier at the same time, and the amplitude-modulated waveforms shown in Figures 3 and 4 would be garbled. This is referred to as a *collision*. No data would be transferred to the reader. The tag/reader interface is similar to a serial bus, even though the “bus” travels through the air. In a wired serial bus application, arbitration is necessary to prevent bus contention. The RFID interface also requires arbitration so that only one tag transmits data over the “bus” at one time.

A number of different methods are in use and in development today for preventing collisions; most are patented or patent pending, but all are related to making sure that only one tag “talks” (backscatters) at any one time. See the *MCRF355/360 Data Sheet* (page 7) and the *13.56 MHz Reader Reference Design* (page 47) chapters for more information regarding the MCRF355/360 anticollision protocol.

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AN707

MCRF 355/360 Applications

Author: *Dr. Youbok Lee, Ph.D.*
Microchip Technology Inc.

INTRODUCTION

The MCRF355 passive RFID device is designed for low cost, multiple reading, and various high volume tagging applications using a frequency band of 13.56 MHz. The device has a total of 154 memory bits that can be reprogrammed by a contact programmer. The device operates with a 70 kHz data rate, and asynchronously with respect to the reader's carrier. The device turns on when the coil voltage reaches 4 V_{PP} and outputs data with a Manchester format (see Figure 2-3 in the data sheet). With the given data rate (70 kHz), it takes about 2.2 ms to transmit all 154 bits of the data. After transmitting all data, the device goes into a sleep mode for 100 ms +/- 50%.

The MCRF355 needs only an external parallel LC resonant circuit that consists of an antenna coil and a capacitor for operation. The external LC components must be connected between antenna A, B, and ground pads. The circuit formed between Antenna Pad A and the ground pad must be tuned to the operating frequency of the reader antenna.

MODE OF OPERATION

The device transmits data by tuning and detuning the resonant frequency of the external circuit. This process is accomplished by using an internal modulation gate (CMOS), that has a very low turn-on resistance (2 ~ 4 ohms) between Drain and Source. This gate turns on during a logic "High" period of the modulation signal and off otherwise. When the gate turns on, its low turn-on resistance shorts the external circuit between Antenna Pad B and the ground pad. Therefore, the resonant frequency of the circuit changes. This is called *detuned* or *cloaking.* Since the detuned tag is out of the frequency band of the reader, the reader can't see it.

The modulation gate turns off as the modulation signal goes to a logic "Low." This turn-off condition again tunes the resonant circuit to the frequency of the reader antenna. Therefore the reader sees the tag again. This is called *tuned* or *uncloaking.*

The tag coil induces maximum voltage during "uncloaking (tuned)" and minimum voltage during cloaking (detuned). Therefore, the cloaking and uncloaking events develop an amplitude modulation signal in the tag coil.

This amplitude modulated signal in the tag coil perturbs the voltage envelope in the reader coil. The reader coil has maximum voltage during cloaking (detuned) and minimum voltage during uncloaking (tuned). By detecting the voltage envelope, the data signal from the tag can be readily reconstructed.

Once the device transmits all 154 bits of data, it goes into "sleep mode" for about 100 ms. The tag wakes up from sleep time (100 ms) and transmits the data package for 2.2 ms and goes into sleep mode again. The device repeats the transmitting and sleep cycles as long as it is energized.

FIGURE 1: VOLTAGE ENVELOPE IN READER COIL

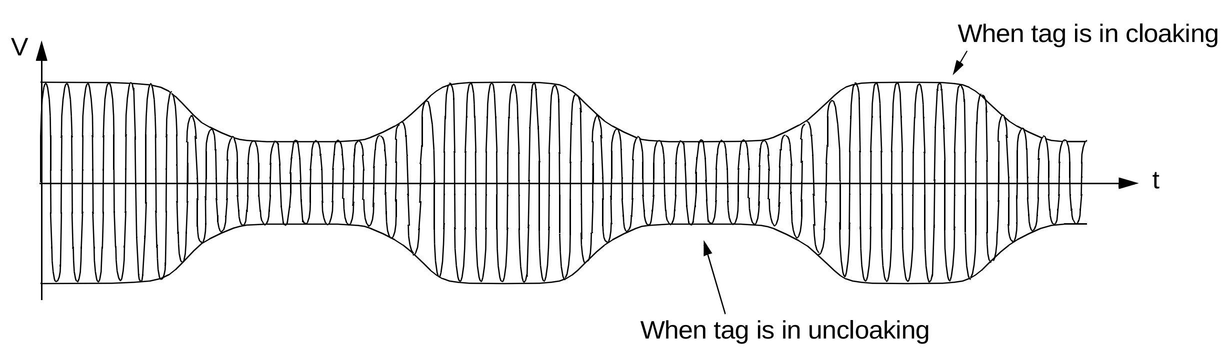
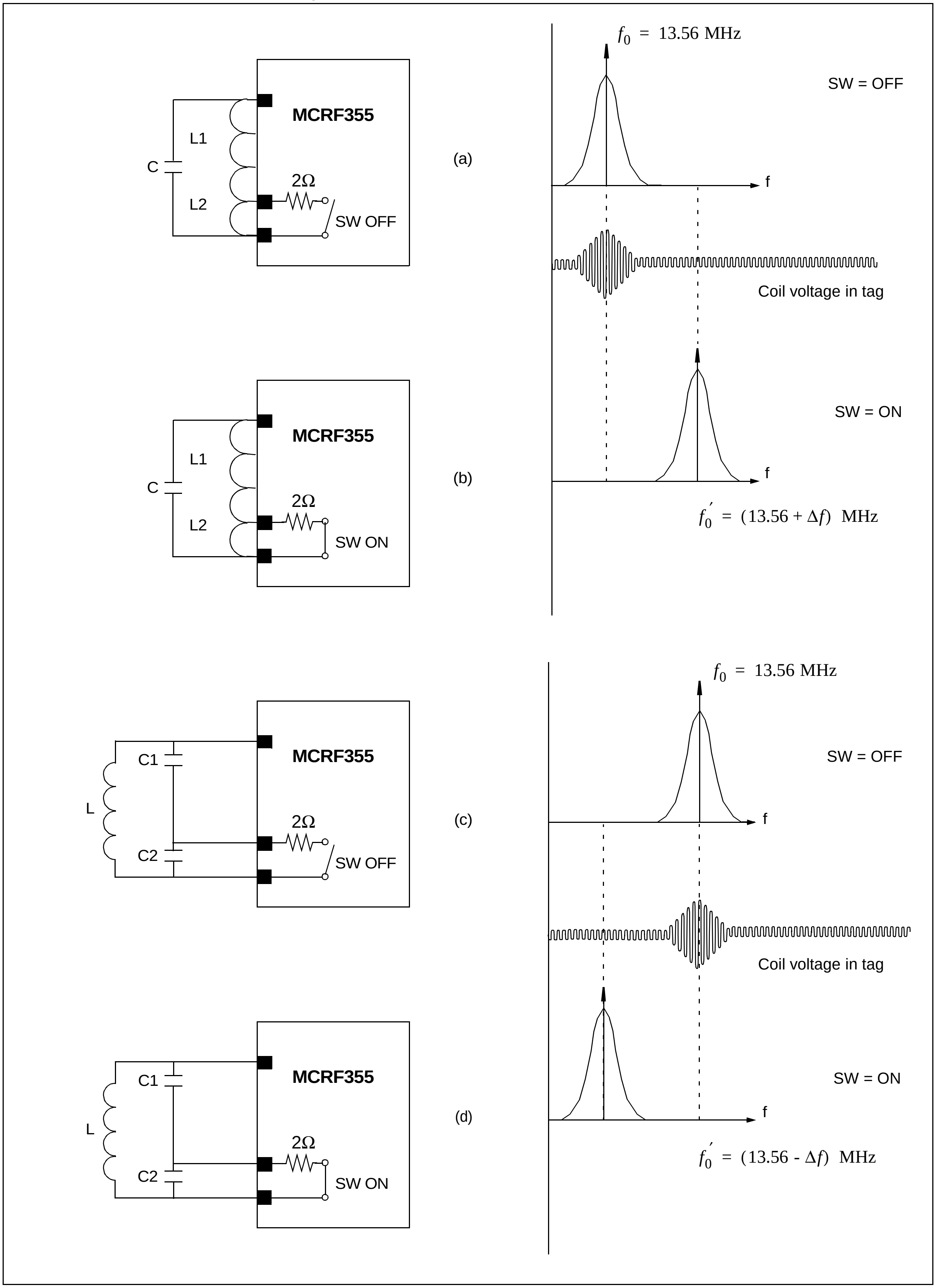


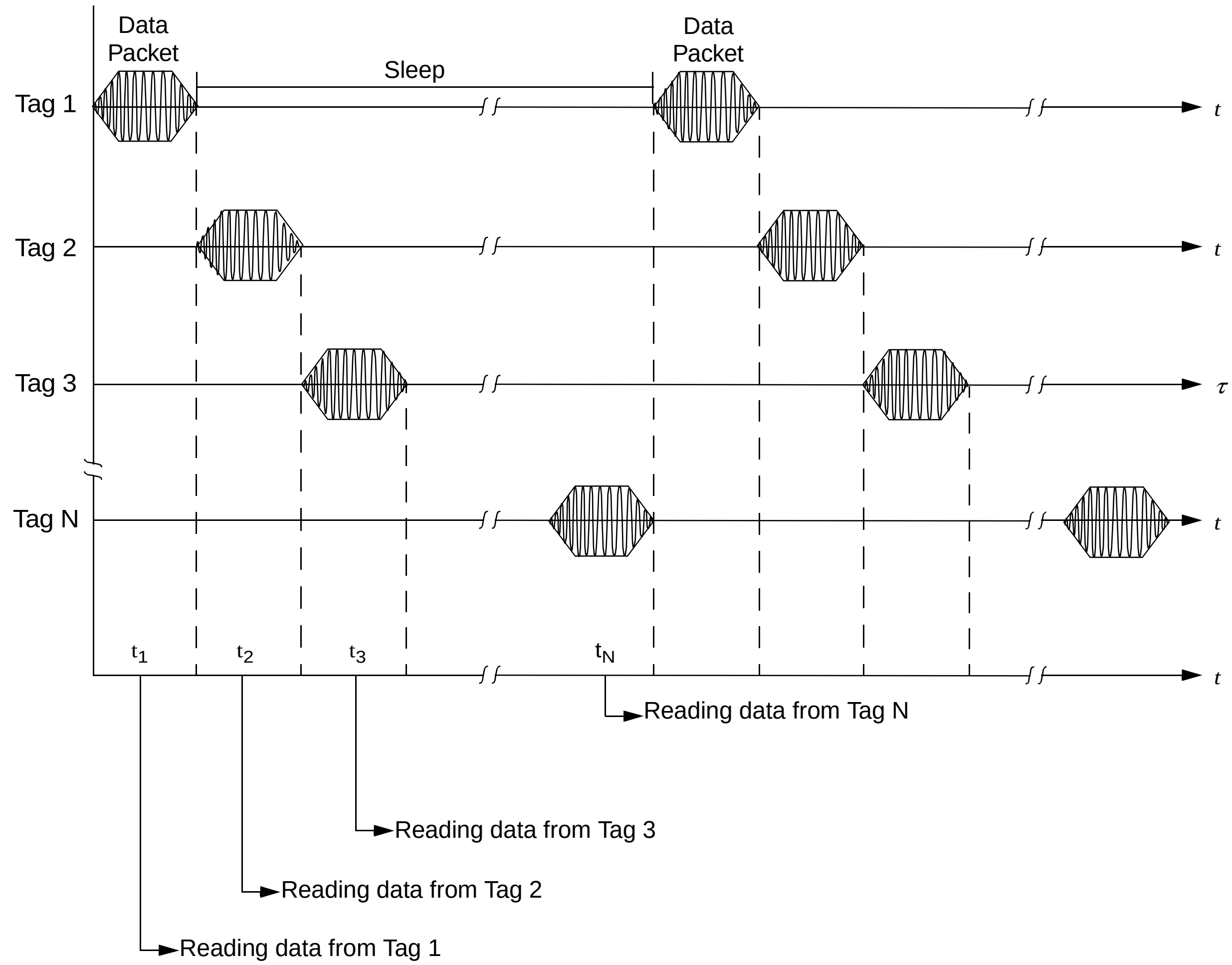
FIGURE 2: (A) UNCLOAKING (TUNED) AND (B) CLOAKING (DETUNED) MODES AND THEIR RESONANT FREQUENCIES



ANTICOLLISION FEATURES

During sleep mode, the device remains in a cloaked state where the circuit is detuned. Therefore, the reader can't see the tag during sleep time. While one tag is in sleep mode, the reader can receive data from other tags. This enables the reader to receive clean data from many tags without any data collision. This ability to read multiple tags in the same RF field is called a*nticollision.* Theoretically, more than 50 tags can be read in the same RF field. However, it is affected by distance from the tag to the reader, angular orientation, movement of the tags, and spacial distribution of the tags.

FIGURE 3: EXAMPLE OF READING MULTIPLE TAGS



EXTERNAL CIRCUIT CONFIGURATION

Since the device transmits data by tuning and detuning the antenna circuit, caution must be given in the external circuit configuration. For a better modulation index, the differences between the tuned and detuned frequencies must be wide enough (about 3 ~ 6 MHz).

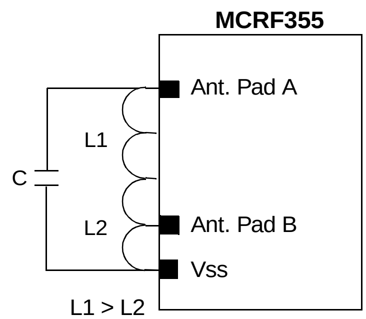
Figure 4 shows various configurations of the external circuit. The choice of the configuration must be chosen depending on the form-factor of the tag. For example, (a) is a better choice for printed circuit tags while, (b) is a better candidate for coil-wound tags. Both (a) and (b) relate to the MCRF355.

In configuration (a), the tuned resonance frequency is determined by a total capacitance and inductance from Antenna Pad A to VSS. During cloaking, the internal switch (modulation gate) shorts Antenna Pad B and VSS. Therefore, the inductance L2 is shorted out. As a result, the detuned frequency is determined by the total capacitance and inductance L1. When shorting the inductance between Antenna Pad B and VSS, the detuned (cloak) frequency is higher than the tuned (uncloak) frequency

In configuration (b), the tuned frequency (uncloak) is determined by the inductance L and the total capacitance between Antenna Pad A and VSS. The circuit detunes (cloak) when C_2 is shorted. This detuned frequency (cloak) is lower than the tuned (uncloak) frequency

The MCRF360 includes a 100 pF internal capacitor. This device needs only an external inductor for operation. The explanation on tuning and detuning is the same as for configuration (a).

FIGURE 4: VARIOUS EXTERNAL CIRCUIT CONFIGURATIONS



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

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

$$L_T = L_1 + L_2 + 2L_m$$

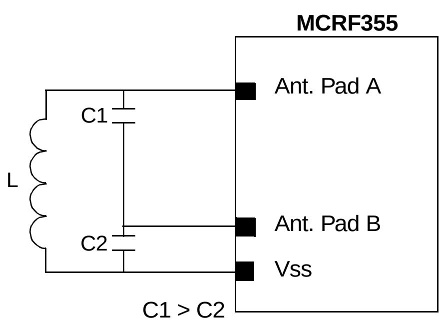
where:

L_m = mutual inductance

= $K\sqrt{L_1 L_2}$

K = coupling coefficient of two inductors $0 \le K \le 1$

(a) Two inductors and one capacitor

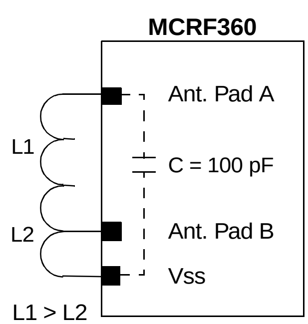


$$f_{tuned} = \frac{1}{2\pi\sqrt{LC_T}}$$

$$f_{detuned} = \frac{1}{2\pi\sqrt{LC_1}}$$

$$C_T = \frac{C_1 C_2}{C_1 + C_2}$$

(b) Two capacitors and one inductor



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

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

$$L_T = L_1 + L_2 + 2L_m$$

(c) Two inductors with one internal capacitor

PROGRAMMING OF DEVICE

All of the memory bits in the MCRF355/360 are reprogrammable by a contact programmer or by factory programming prior to shipment, known as Serialized Quick Turn Programming℠ (SQTP℠). For more information about contact programming, see page 69 of the *microID™ 13.56 MHz System Design Guide* (DS21299). For information about SQTP programming, please see TB032 (DS91032), page 19 of the design guide.

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AN710

Antenna Circuit Design

Author: Dr. Youbok Lee, Ph.D.
Microchip Technology Inc.

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:

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

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:

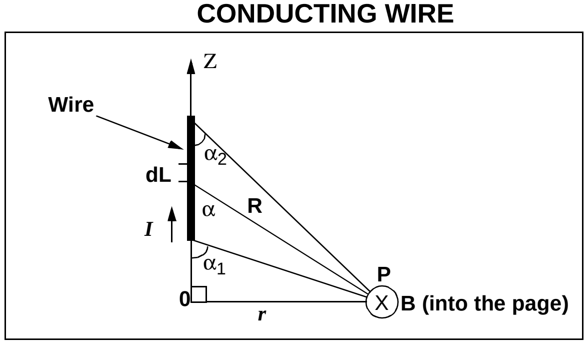
α_1	=	-180°
α_2	=	0°

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 is given by:

EQUATION 3:

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

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

where

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

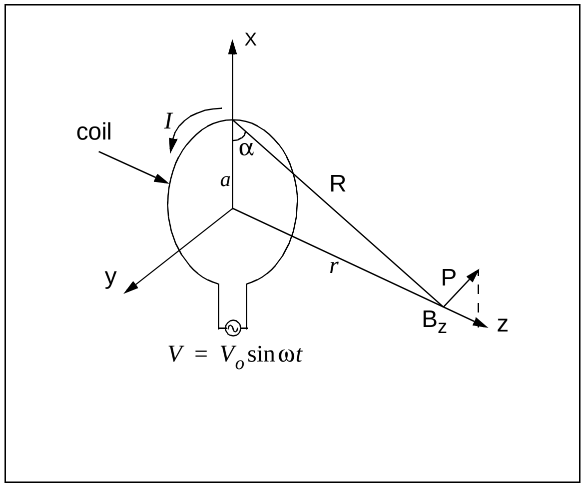
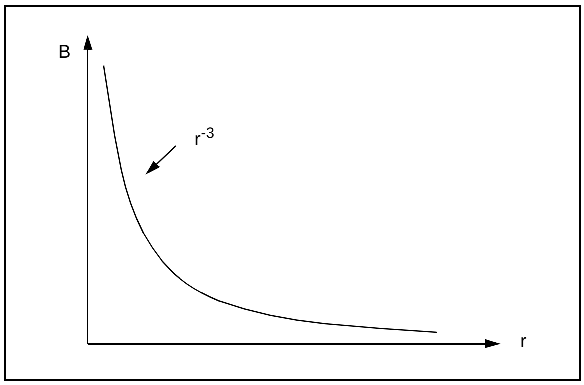


FIGURE 3: DECAYING OF THE MAGNETIC FIELD B VS. DISTANCE *r*



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:

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

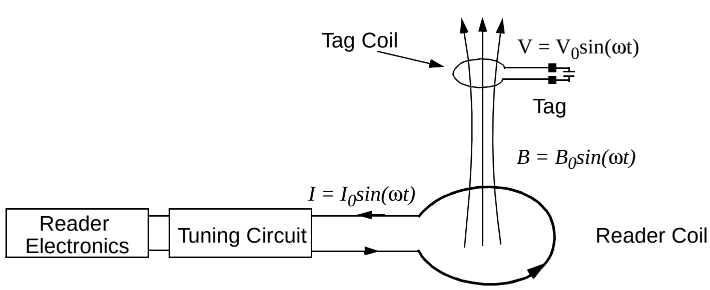
where:

B	=	magnetic field given in Equation 2
S	=	surface area of the coil
•	=	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:

$$V = -N_2\frac{d\Psi_{21}}{dt} = -N_2\frac{d}{dt}\left(\int B \cdot dS\right)$$

$$= -N_2\frac{d}{dt}\left[\int\frac{\mu_o i_1 N_1 a^2}{2(a^2+r^2)^{3/2}} \cdot dS\right]$$

$$= -\left[\frac{\mu_o N_1 N_2 a^2(\pi b^2)}{2(a^2+r^2)^{3/2}}\right]\frac{di_1}{dt}$$

$$= -M\frac{di_1}{dt}$$

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:

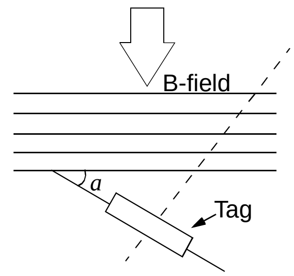
$$V_0 = 2\pi f N S Q B_o \cos\alpha$$

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

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

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
cosα =	=	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:

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

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

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

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:

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

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. 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:

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

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 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:

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

$$= \frac{0.0179}{\sqrt{f}} \qquad (m)$$

$$= 0.187 \qquad (mm)$$

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 16:

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

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 x 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 x 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:

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

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:

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

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:

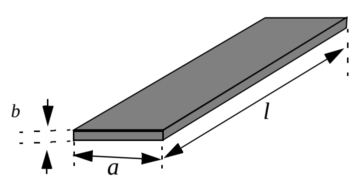
EQUATION 19:

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

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:

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

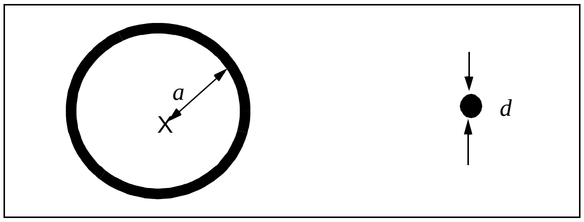
where:

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:

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

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:

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

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

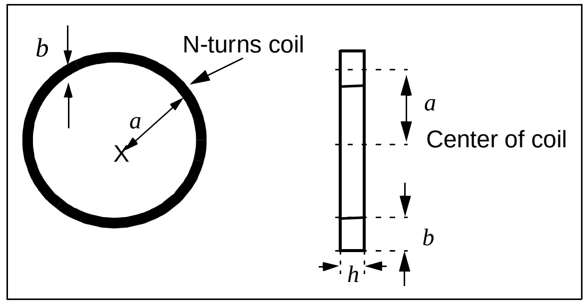


Figure 8 shows an N-turn inductor of circular coil with multilayer. Its inductance is calculated by:

EQUATION 23:

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

where:

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

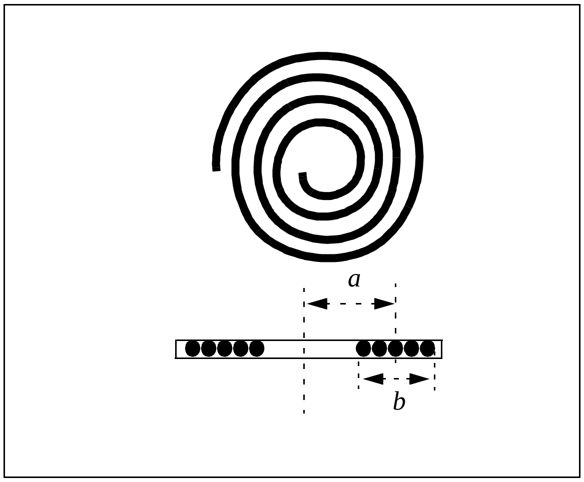
Inductance of Spiral Wound Coil with Single Layer

The inductance of a spiral inductor is calculated by:

EQUATION 24:

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

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:

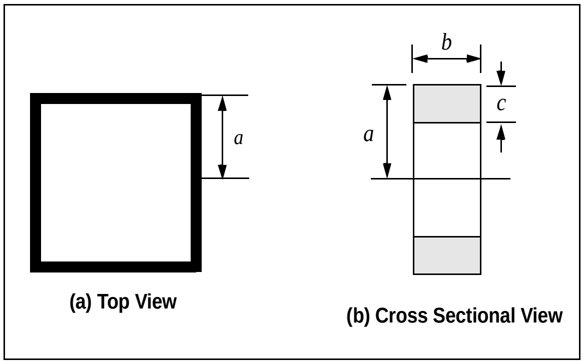
$$L = 0.008aN^2\left\{2.303\log_{10}\left(\frac{a}{b+c}\right) + 0.2235\frac{b+c}{a} + 0.726\right\}(\mu H)$$

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]:

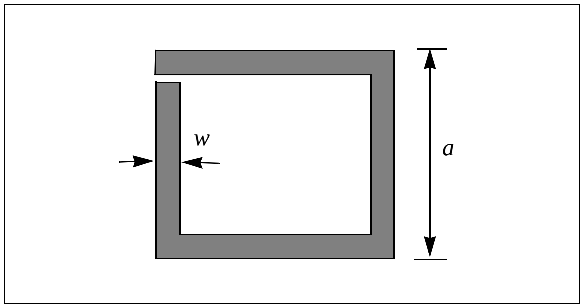
EQUATION 26:

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

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.

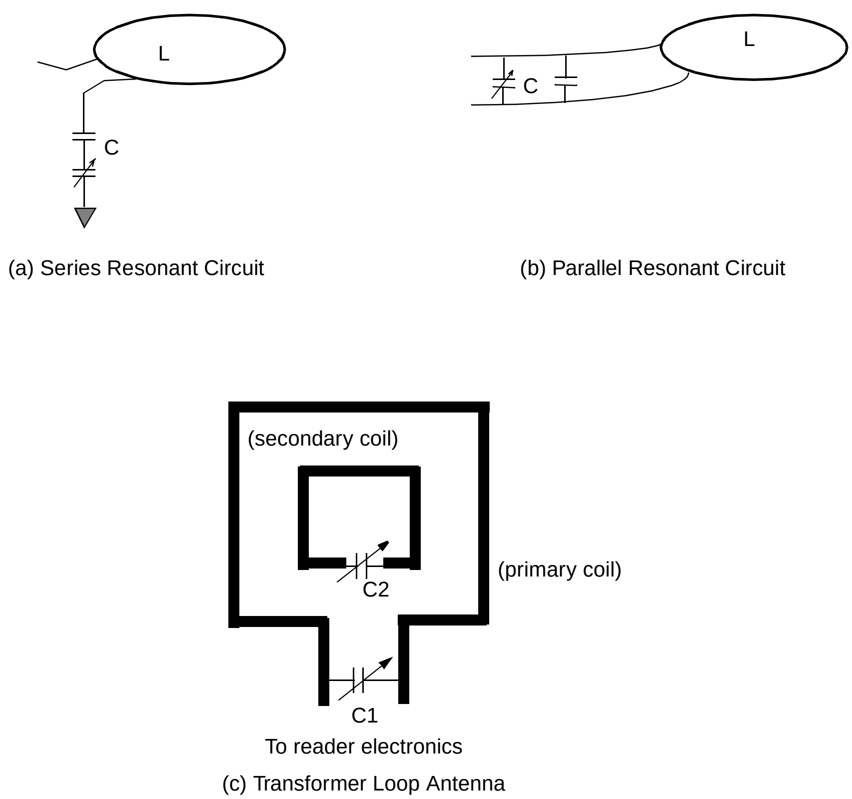
The frequency tolerance of the carrier frequency and output power level from the read antenna is regulated by government regulations (e.g., FCC in the USA).

FCC limits for 13.56 MHz frequency band are as follows:

1. Tolerance of the carrier frequency: 13.56 MHz +/- 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:

$$f_{detuned} = \frac{1}{2\pi\sqrt{LC_1}}$$

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 µH, then it needs a 106 pF of capacitance to resonate at 13.56 MHz.

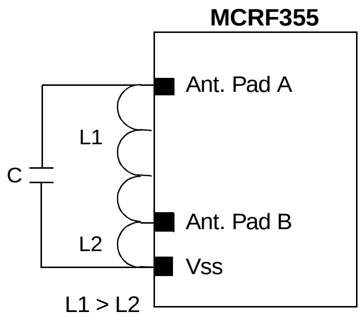
CONSIDERATION ON QUALITY FACTOR Q AND BANDWIDTH OF TUNING CIRCUIT

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



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

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

$$L_T = L_1 + L_2 + 2L_m$$

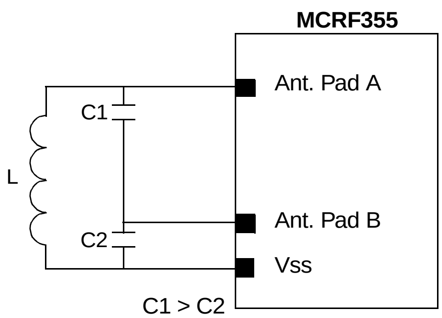
where:

L_m = mutual inductance

= $K\sqrt{L_1 L_2}$

K = coupling coefficient of two inductors $0 \le K \le 1$

(a) Two inductors and one capacitor

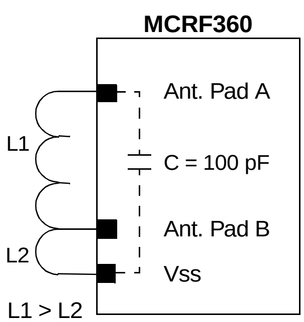


$$f_{tuned} = \frac{1}{2\pi\sqrt{LC_T}}$$

$$f_{detuned} = \frac{1}{2\pi\sqrt{LC_1}}$$

$$C_T = \frac{C_1 C_2}{C_1 + C_2}$$

(b) Two capacitors and one inductor



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

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

$$L_T = L_1 + L_2 + 2L_m$$

(c) Two inductors with one internal capacitor

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:

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

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

EQUATION 33:

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

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:

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

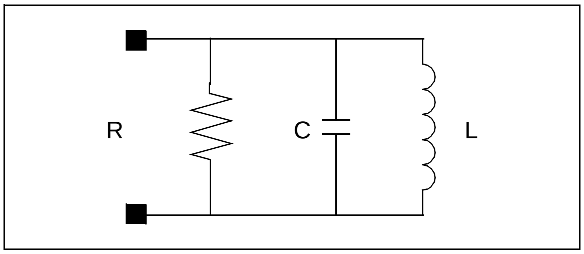
By applying Equation 36 into Equation 35, the impedance at the resonance frequency becomes:

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:

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

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

EQUATION 40:

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

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

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

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

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

where:

ω = $2\pi f$ = angular frequency

f_o = 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: .

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

$$= 2\pi f_0 N\left(R\sqrt{\frac{C}{L}}\right)SB_0 \cos\alpha$$

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:

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

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:

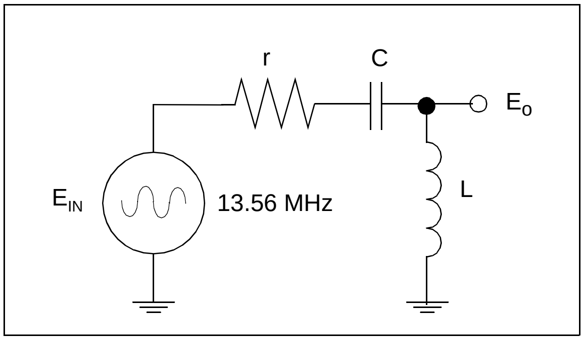
$$X_L = 2\pi f_o L \qquad (\Omega)$$

EQUATION 45:

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

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:

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

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:

$$V_o = \frac{jX_L}{r}V_{in}$$

$$= jQV_{in}$$

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 5 Ω, then the L and C values for 13.56 MHz resonant circuit with Q = 40 are:

EQUATION 49:

$$X_L = Qr_s = 200\Omega$$

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

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

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:**
  - a) Set up a voltage signal source at the resonance frequency.
  - 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 16: VOLTAGE VS. FREQUENCY FOR RESONANT CIRCUIT

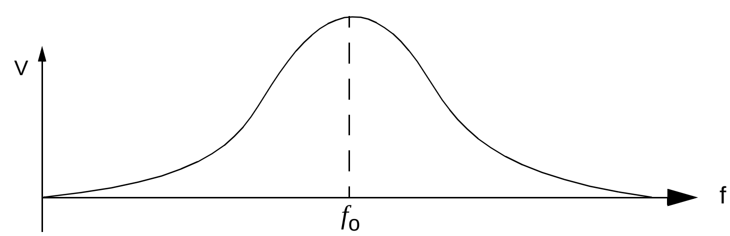
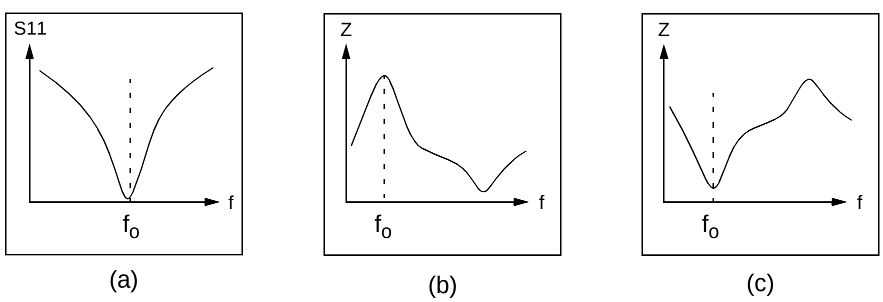


FIGURE 17: FREQUENCY RESPONSES FOR RESONANT CIRCUIT



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:

a) Operating frequency and performance of antenna coils
b) Q of antenna and tuning circuit
c) Antenna orientation
d) Excitation current
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 (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*

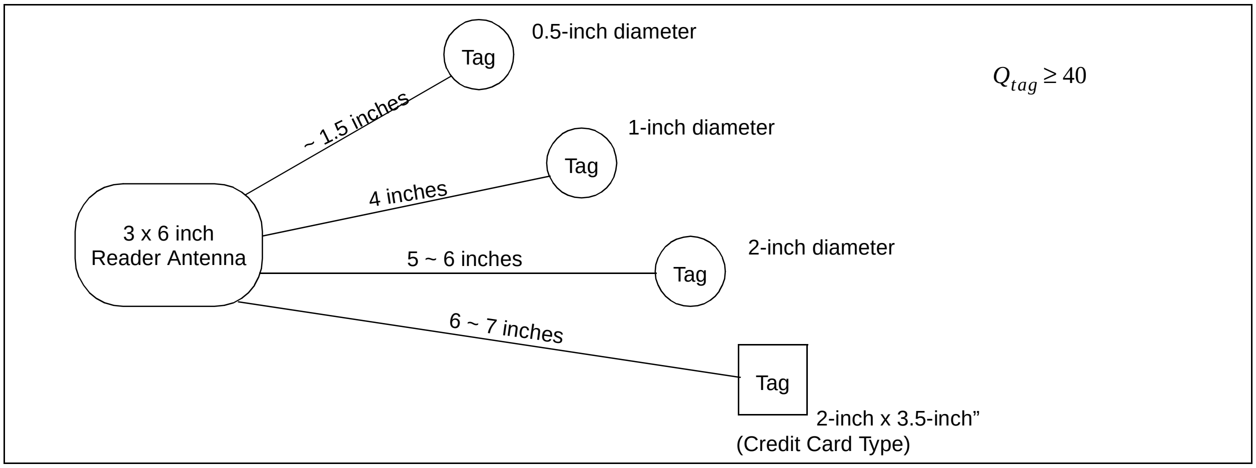
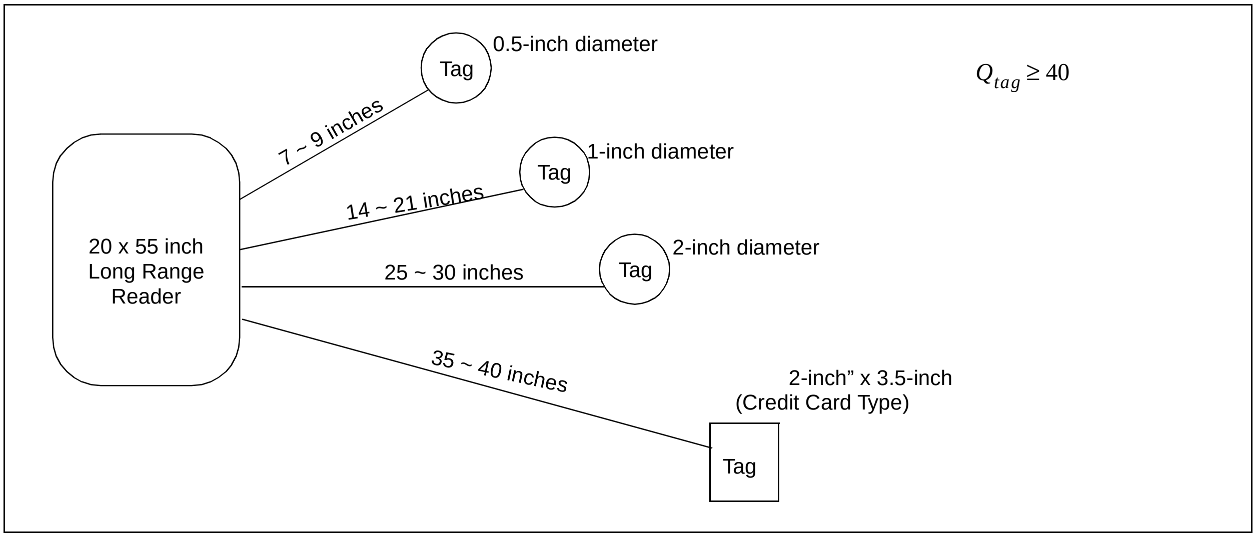


FIGURE 19: READ RANGE VS. TAG SIZE FOR TYPICAL LONG RANGE APPLICATIONS*



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

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AN725

Optimizing Read-Range of the 13.56 MHz Demonstration Reader

Author: *Youbok Lee, Ph.D*
Microchip Technology Inc.

INTRODUCTION

The 13.56 MHz Anticollision Reader in the DV103003 microID™ Developer's Kit is designed to demonstrate basic operation of the MCRF355, but not to show the limits of its performance. The MCRF355 is a very advanced, carrier-independent tagging IC with the lowest power consumption and highest speed in the industry as of this writing. Designing a reader that takes advantage of the inherent performance of the MCRF355 involves two primary optimizations:

a) Increasing the speed of the digital processing by using a high-end PICmicro® microcontroller (MCU) to sample the data and calculate the checksums. This will help take advantage of the 2.2 msec data burst time and high-speed anticollision capabilities of the MCRF355.

b) Increasing the reader's carrier field volume and/or power output in order to provide power to the tag at longer distance from the reader. This application note describes one method of accomplishing this improvement.

Following are the steps to achieve a read-range of 12 inches to 18 inches using a 2-inch x 2-inch sample tag based on MCRF355, properly tuned to the carrier frequency.

1. Disconnect the power cable and RS-232 cable from the reader, and remove the six screws from the back of the case.

2. Make an antenna with the following parameters:
   a) Use AWG #18 ~ #20 wire.
   b) Make one turn: a rectangular loop with 7.85-inches x 7.75-inches as shown in Figure 1. This antenna will fit in PAC TEC's CF-125 enclosure. The enclosure is available from PAC TEC or its distributors. This will result in about 800 nH ~ 1 µH of inductance.
   c) This inductance requires 172 pF ~ 138 pF of capacitance to tune the antenna circuit to 13.56 MHz.

3. Connect the new inductor (antenna) and capacitor to the demo reader board by following these steps:
   a) Disconnect the C31, C9, and C10 from the circuit board.
   b) Disconnect L3 (printed antenna) from the circuit. This can be accomplished by cutting off the metallic trace on the board.
   c) Connect the new resonant capacitance (172 pF ~ 138 pF) at C31, C9, C10.
   d) Connect the new antenna at L3. Connect one side of the antenna to the resonant capacitor and the other side to ground.

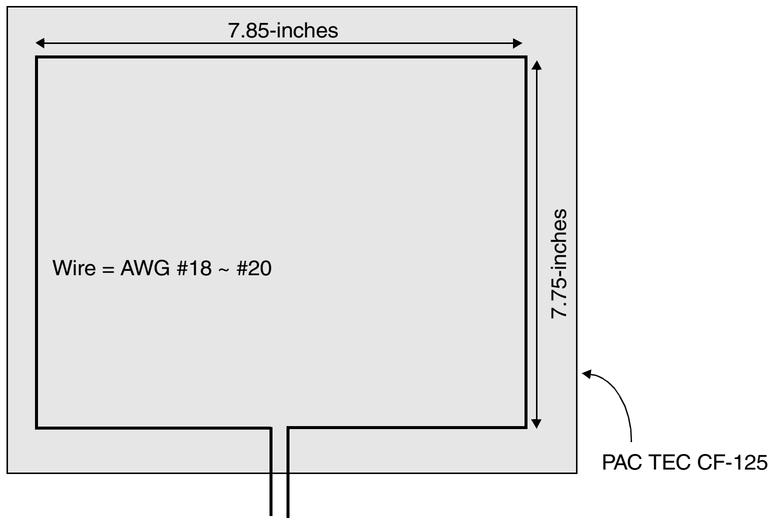
4. Tuning the antenna circuit:

   The benefit of this modification will be realized only if the antenna circuit is tuned precisely to the 13.56 MHz carrier. Here is one method for tuning the circuit:
   a) Connect an oscilloscope across the new antenna (L3).
   b) Observe the voltage while adjusting the capacitance (C31, C9, C10).
   c) Adjust the cap to **+** and **-** direction and stop at the maximum voltage.
   d) Bring the voltage to above 200 V_{PP}.

5. Read-Range Measurement:

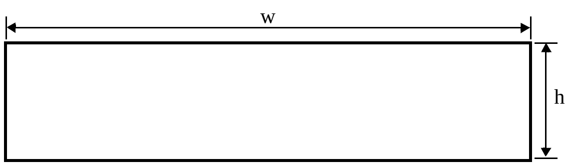
   Reconnect the power and RS-232 cables to the reader. The reader should now provide between 12 ~ 18 inches of read range. If it does not exhibit this performance, check the following:
   a) Check the antenna voltage again, bringing it to above 200 V_{PP}.
   b) Adjust VR1 in the reader circuit; VR1 is very sensitive to voltage. Connect a 1 MΩ resistor across C17 permanently. Then, connect a Digital Volt Meter across the resistor, and adjust the VR1 between 4.7-volts to 4.87-volts while measuring the read range. Set the VR1 for maximum range.

FIGURE 1: ANTENNA GEOMETRY



1.1 Formula for Inductance Calculation

EQUATION 1: RECTANGULAR LOOP

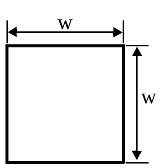


$$L_{rect}[nH] = (N^2)(10.16)\left[-2(w+h)+2\sqrt{h^2+w^2}-h\ln\left(\frac{h+\sqrt{h^2+w^2}}{w}\right)-w\ln\left(\frac{w+\sqrt{h^2+w^2}}{h}\right)+h\ln\left(\frac{2w}{a}\right)+w\ln\left(\frac{2h}{a}\right)\right]$$

where:

N = number of turns
w = width of the rectangle (inches)
h = height of the rectangle (inches)
a = wire radius (inches)

EQUATION 2: SQUARE LOOP



$$L_{square}[nH] = (N^2)(20.32)w\left[\ln\left(\frac{w}{a}\right)-0.774\right]$$

where:

N = number of turns
w = length of one side (inches)
a = wire radius (inches)

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