In the basic RFID system (as shown in Figure 1):
1. The Reader generates an electromagnetic field. This field is rectified to generate the supply voltage inside the Tag.
2. The Reader transmits information to the Tag by modulating the carrier wave.
3. The Tag back-scatters the carrier wave, by modifying its own impedance thereby perturbing the field, in order to transmit back information to the Reader.

Figure 1. Basic RFID System
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1 CRX14 Contactless Coupler Chip from ST

ST has designed the CRX14, a short range contactless coupler chip, compliant with the ISO14443 type B proximity standard. The CRX14 generates a 13.56MHz signal. Designed to deliver an RF power of 100mW, it operates in the Short Range on contactless memory tags (provided that they, too, are compliant with ISO14443 type B).

The CRX14 features the ST anti-collision mechanism, which allows the reader to detect and identify all the tags that are present in the operating range, and to access them individually. Because the CRX14 implements the France Telecom-proprietary anti-clone function, the reader can also perform authentication of tags that are equipped with the France Telecom anti-clone capability.

The CRX14 coupler interfaces between:

- the memory tags, on one side, through input/output buffers and the ISO14443 type B radio frequency protocol, and
- the system master processor, on the other side, through a 400kHz I²C bus.

Operating from a 5V power supply, and delivered in a SO16N package, the CRX14 coupler chip is an excellent solution for building contactless readers, embedded in the final equipment, and offering a good compromise between operating range and cost.
2 Short Range Contactless Memories from ST

All devices from the ST Short Range Contactless series are compliant with the ISO14443 type B standard. They are accessible via a 13.56MHz carrier frequency, and support a data transfer rate between tag and reader of 106kbit/s in both directions. All of them are totally compatible with each other, in terms of tag protocol access. The series is sub-divided into two families:

- Low-end SR Family
- Secure SRIX Family (equipped with anti-clone and anti-collision capabilities).

2.1 Low-end SR Family

SR176 is the first member of ST low-end short range family. It contains:

- 176 bits of EEPROM, organized as eleven 16-bit blocks, that can be write-protected
- a 64-bit UID, and
- a fixed 8-bit chip identifier.

2.2 Secure SRIX Family

SRIX is a family of highly secure devices that support the anti-clone capability, allowing tag authentication. The system master processor sends an authentication request to each of the tags present in the CRX14’s field. Each tag runs its anti-clone algorithm to compute a signature, and sends it back to the reader for an authentication check. The anti-clone function helps fight against fraud, since any tag that does not belong to the system will answer with a wrong signature.

The first member of the SRIX family is the SRIX4K, featuring 4096 bits of EEPROM organized as 128 words of 32 bits. These are, in turn, organized in five main areas:

- One 5-word OTP zone, accessible in user mode, whose bits can only be switched from 1 to 0
- Two 32-bit binary counters that can only be decremented
- 121 words of user EEPROM, of which 9 can be individually write protected
- One 8-bit chip identifier that allows a reader to identify uniquely each tag present in its field during the anti-collision operation
- One 64-bit read-only unique identifier (UID), programmed on the manufacturing line.

The family will be later extended to include a lower density, 512-bit, device.
3 Basic concepts and fundamental equations

To calculate the characteristics of a RFID system, we need some definitions and assumptions:
- The reader generates a tension
- This tension supplies the inductive antenna \( L_R \) by the tuning circuit.
- A current \( I_R \) flows through the antenna and creates a magnetic field defined at distance \( x \).
- This field is transformed into a supply voltage in the tag.
- When the tag is near the reader antenna, it modifies the antenna tuning.
- To calculate the real current, we need to calculate the mutual inductance \( M \) and the coupling factor between the reader antenna \( L_R \) and the tag antenna \( L_T \).
- We can also calculate the range within which the tag receives enough magnetic flux to work well.

3.1 Electromagnetic Field

To generate an electromagnetic field, we can assume a circular loop antenna (Figure 2).

**Figure 2. Circular Loop Antenna**

The Electromagnetic field is given by **Equation 1**.

**Equation 1**

\[
H_r(x) = \frac{I_R \times N_R \times r_R^2}{2 \times (r_R^2 + x^2)^{3/2}}
\]

Where:
- \( I_R \) is the current in the loop antenna
- \( N_R \) is the number of turns of the loop antenna
- \( r_R \) is the coil radius
- \( H_r(x) \) is measured in A/m
An inductive coupling is possible in the near field, the limit between a near field and a far field is given by \textit{Equation 2}.

\textbf{Equation 2}

\[ x \leq \frac{\lambda}{2 \times \pi} \]

Where:

- \( \lambda = \frac{c}{f} \)

In this application note, we use only Tags with a working frequency of 13.56MHz. So, the limit between a near field and a far field is:

- \( x \leq 3.52 \text{m} \)

\textit{Figure 3} illustrates the magnetic field as a function of the distance of the tag from the reader, for given values of the number of turns, \( N \), the current, \( I \), and the antenna radius, \( r \).

\textbf{Figure 3. Magnetic Field as a Function of the Distance of the Tag from the Reader}

\textit{Figure 4} illustrates the magnetic field as a function of the antenna radius, \( r \), for given values of the number of turns, \( N \), the current, \( I \), of reader antenna, and the distance between tag and antenna reader, \( x \).

\[ H(x) \]

\[ 0 0.02 0.04 0.06 0.08 0.1 0.12 0.14 0.16 \]

\[ 0 1 2 3 4 5 6 7 8 \]

Distance [m]
In this example we can see that the field decreases when the radius goes beyond an optimal value.

3.2 Inductance, $L$, and the Antenna

To tune the reader antenna, we need to be able to calculate its inductance.

**Equation 3: Inductance of a Circular Loop**

$$L = \mu_0 \times N^{1.9} \times r \times \ln\left(\frac{r}{r_0}\right)$$

Where:

- $r$ is the mean coil radius
- $r_0$ is the wire diameter
- $N$ is the number of turns
- $\mu_0 = 4\pi \times 10^{-7}$ H/m
- $L$ is measured in H
Figure 5. Round Planar Spiral Coils

Equation 4: Inductance of Round Planar Spirals

\[ L = 31.33 \times \mu_0 \times N^2 \times \frac{d}{8 \cdot \left( \frac{d}{d+11} \right) \cdot c} \]

Where:
- \( d \) is the mean coil diameter
- \( c \) is the thickness of the winding
- \( N \) is the number of turns
- \( \mu_0 = 4\pi \times 10^{-7} \text{H/m} \)
- \( L \) is measured in \( \text{H} \)

Figure 6. Planar Square, Hexagonal and Octagonal Spiral Coils

Equation 5: Inductance of Planar Square, Hexagonal and Octagonal Coil

\[ L = K_1 \times \mu_0 \times N^2 \times \frac{d}{1 + K_2 \cdot \rho} \]

Where:
- \( d \) is the mean coil diameter: \((d_{\text{out}} + d_{\text{in}})/2\)
  - \( d_{\text{out}} \) is the outer diameter
  - \( d_{\text{in}} \) is the inner diameter
- \( \rho = (d_{\text{out}} - d_{\text{in}})/(d_{\text{out}} + d_{\text{in}}) \)
- \( K_1 \) and \( K_2 \) depend on the layout (as summarized in Table 1.)
3.3 Inductance of a Planar Rectangular Coil

We have developed a convenient software tool, using the Grover method (Equation 6) for calculating the inductance of rectangular planar antenna. The user interface is shown in Figure 7.

We have found that the software gives a good approximation of the inductance $L$, in comparison to measurements of the inductance of a real antenna on an impedance meter.

**Equation 6: Grover Method**

$$L = L_0 + \sum M$$

Where:

- $M$ is the mutual inductance between each of the segments of the antenna
- $L_0$ is as defined in Equation 7

**Equation 7**

$$L_0 = \sum_{j=1}^{s} L_j$$

Where:

- $s$ is the number of segments
- $L_j$ is the self inductance of each segment

<table>
<thead>
<tr>
<th>Layout</th>
<th>$K_1$</th>
<th>$K_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Square</td>
<td>2.34</td>
<td>2.75</td>
</tr>
<tr>
<td>Hexagonal</td>
<td>2.33</td>
<td>3.82</td>
</tr>
<tr>
<td>Octagonal</td>
<td>2.25</td>
<td>3.55</td>
</tr>
</tbody>
</table>
3.4 Magnetic Coupling Factor

To have a good model of the system, we need to calculate the mutual inductance and coupling factor of the system.

**Equation 8: Magnetic Flux**

\[ \Phi = \oint_B B d\vec{S} \]

Where:
- \( B \) is the magnetic induction
- \( d\vec{S} \) is the surface cross by the magnetic induction

**Equation 9**

\[ \Phi = B \times S \times \cos \alpha \]

If \( \alpha = 0 \):
- \( \Phi = B \times S \)

Figure 7. User Interface Screen of the Planar Rectangular Coil Inductance Calculator
Equation 10: Mutual Inductance between Reader and Tag Antenna

\[ M = \frac{N_T \times \phi_R}{I_R} \]

Equation 11

\[ M(x) = \frac{\mu_0 \times r_R^2}{2 \times (r_R^2 + x^2)^{3/2}} \times \frac{2 \times S_T \times N_R \times N_T}{x^2} \]

Where:
- \( N_R \) is the number of turns on the reader antenna
- \( N_T \) is the number of turns on the tag antenna
- \( S_T \) is the area of the tag antenna
- \( r_R \) is the coil radius of the reader antenna
- \( x \) is the distance between the reader antenna and the tag antenna

Equation 12: Magnetic Coupling Factor between Reader and Tag Antenna

\[ k(x) = \frac{M(x)}{\sqrt{L_T \times L_R}} \]

Where:
- \( L_R \) is the inductance of reader antenna
- \( L_T \) is the inductance of tag antenna

Therefore:

Equation 13

\[ k(x) = \frac{\mu_0 \times r_R^2}{2 \times (r_R^2 + x^2)^{3/2}} \times \frac{S_T \times N_R \times N_T}{\sqrt{L_T \times L_R}} \]
4 Antenna

The quality factor is a characteristic of the antenna performance. This parameter is used when tuning the reader antenna.

Equation 14: Quality Factor

\[ Q_R = \frac{2 \times \pi \times f_0 \times L_R}{r_{LR}} \]

Where:
- \( L_R \) is the inductance of reader antenna
- \( r_{LR} \) is the resistance of reader antenna
- \( R_{LR} \) is the natural resistance of the reader antenna
- \( f_0 \) is the resonance frequency

4.1 Matching Circuit

To tune an antenna at the specific frequency, we performed the following analysis. First, we started with the equivalent circuit for the antenna system on the board.

Figure 8. Real Circuit for the Antenna System on the Board

Where:
- \( C_1 \) and \( C_2 \) are calculated later
- \( R_L \) is the natural resistance of the loop antenna
- \( L \) is the inductance value of the loop antenna
- \( R_a \) is an additional resistor to have the good value of antenna parameters.

Then we made use of the following series-to-parallel circuit equivalence.
Figure 9. Series-to-Parallel Circuit Equivalence

Where:

$$R_P = \frac{X_S^2}{R_S}$$

and:

$$X_P = X_S$$

If we assume that:

$$R_S \ll X_S^2$$

This gives a new equivalent circuit, as shown in Figure 10.

Figure 10. Parallel Equivalent Circuit

Where:

$$R_P = \frac{(L \times \omega_b)^2}{R_a + R_L}$$
1. See resonance frequency in Table 2.

### Table 2. Main Results

<table>
<thead>
<tr>
<th>Resonance frequency</th>
<th>Equivalent impedance of the circuit</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \omega_0 ) = ( \frac{1}{\sqrt{L(C_1 + C_2)}} )</td>
<td>( \Re[Z] = \frac{R_p L(C_1 + C_2)}{C_1^2 R_p^2 + L(C_1 + C_2)} )</td>
</tr>
<tr>
<td>( \omega_1 ) = ( \frac{1}{\sqrt{L C_2}} )</td>
<td>( \Re[Z] = R_p )</td>
</tr>
</tbody>
</table>

### Table 3. Values of Capacitors

<table>
<thead>
<tr>
<th>( C_1 )</th>
<th>( C_2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( C_1 = \frac{1}{\sqrt{Z \cdot R_p \times \omega_0}} )</td>
<td>( C_2 = \frac{1}{L \omega_0^2} - C_1 )</td>
</tr>
</tbody>
</table>
4.2 Current Calculation

To calculate the current, we use the complete system with tuning circuit and the influence of the tag when it is near the reader antenna. For this, we need to know the mutual inductance between the reader antenna and the Tag.

Figure 12. Coupling between One Tag and One Reader Antenna

Equation 15

\[
\begin{align*}
Z_R &= R + jL_R\omega \\
Z_T &= R_T + jL_T\omega + \frac{1}{jL_T\omega} = R_T + j\left(L_T\omega - \frac{1}{C_T\omega}\right)
\end{align*}
\]

Equation 16

\[
\begin{align*}
V_R &= Z_R \cdot I_R + jM\omega R \\
0 &= Z_T + jM\omega R
\end{align*}
\]

Equation 17

\[
V_R = \left(Z_R + \frac{M^2\omega^2}{Z_T}\right) \cdot I_R
\]
Equation 18
\[
I_R = \frac{V_R \cdot Z_T}{Z_T \cdot Z_R + M^2 \omega^2}
\]
This equation allows the current \( I_R \) in reader antenna to be calculated.

### 4.3 \( V_R \) Calculation

#### Figure 13. Equivalent Circuits

![Equivalent Circuits Diagram]

Equation 19
\[
R = R_a + R_L
\]

Equation 20
\[
V_R = \frac{V_e \times Z_2}{Z_1 + Z_2}
\]

Equation 21
\[
V_R = \frac{(R + jL\omega) \cdot jC_1 \omega}{(R + jL\omega) \cdot jC_1 \omega + jRC_2 \omega - LC_2 \omega^2 + 1} \times V_e
\]

### 4.4 Current Calculation

Combining Equation 18 and Equation 21 we get Equation 22.
Equation 22

\[ I_R = \frac{jR C_1 \omega - L C_1 \omega^2}{jR(C_1 + C_2)\omega - L(C_1 + C_2)\omega + 1} \times \left( \frac{R_T + \frac{1 - L_T C_T \omega^2}{jC_T \omega}}{R_T + \frac{1 - L_T C_T \omega^2}{jC_T \omega}} \right) \times (R + jL R \omega) + M^2 \omega^2 \times V_e \]
5 Designing an RFID application

It is not easy to calculate directly the optimal antenna to have specific reading distance. Here is a suggested method:

- Choose a Tag
- Start with an approximate antenna size
- Calculate the real reading range with these parameters
- Adjust the antenna size appropriately, to get the desired reading range.

Table 4 summarizes the different steps to calculate the additional components and reading range.

Table 4. Calculation steps

<table>
<thead>
<tr>
<th>Step</th>
<th>Action</th>
<th>Input Parameters</th>
<th>Output parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Choose Tag package</td>
<td>A3,A4,A5</td>
<td>$H_{\text{min}}$ [A/m]</td>
</tr>
<tr>
<td>2</td>
<td>Choose reading range and select first reader antenna size</td>
<td>$X_{\text{Tag}}$, $d_{\text{out}}$, $N_r$, $W_c$, $S_c$, $T_c$</td>
<td>$L_{\text{r}}$ [H], $R_L$ [Ω]</td>
</tr>
<tr>
<td>3</td>
<td>Calculate $C_1$, $C_2$ Current in Antenna reader</td>
<td>$f_{\text{tune}}$</td>
<td>$r_a$ [Ω], $C_1$ [F], $C_2$ [F], $I_r$ [A]</td>
</tr>
<tr>
<td>4</td>
<td>Calculate Reading distance min/max Coupling coefficient</td>
<td></td>
<td>$X_{\text{max}}$ [m], $X_{\text{min}}$ [m], $k_{\text{min}}$</td>
</tr>
</tbody>
</table>

- $N_r$: Number of turns for the reader antenna
- $W_c$: Conductor width of reader antenna
- $L_{\text{r}}$: Inductance of reader antenna
- $R_L$: Resistance of reader antenna
- $f_{\text{tune}}$: Tuning frequency of reader antenna
- $C_1$, $C_2$: Tuning capacitance
- $R_a$: Additional resistance of reader antenna
- $I_r$: Current in reader antenna
5.1 Using the Excel Spreadsheet

Before using the Excel spreadsheet, you must to configure it:

- In **Tools** menu, click on sub menu **Add-Ins**
- Select the **Analysis ToolPak** check box, then click **OK**

![Figure 14. Excel Configuration](image)

5.2 Step 1

Choose the Tag package according to your application:

- A3: size 38mm x 38mm
- A4: size 15mm x 15mm
- A5: size 65mm x 42mm

If you have no constrains on the size tag, select the maximum size (A5) to start.
5.3 Step 2

Choose reading distance and select first size antenna reader.

Select the diameter $d_{\text{out}}$ equal to the reading distance you wish. Start with:

- $d_{\text{out}} = X_{\text{Tag}}$
- $N_r = 2$
- $W_c = 0.002$ [m]
- $S_c = 0.0005$ [m]
- $T_c$ function of board specifications (Standard $35 \times 10^{-6}$ [m])
- $L$ and $R_L$ are the electrical characteristics of your antenna.

Table 5. Parameter values

<table>
<thead>
<tr>
<th>$d_{\text{out}}$ [m]</th>
<th>$N_r$</th>
<th>$W_c$ [m] (width of conductor)</th>
<th>$S_c$ [m] (space between conductor)</th>
<th>$L$ [H]</th>
<th>$T_c$ [m] Thickness of conductor</th>
<th>$R_L$ [ohm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.055</td>
<td>2</td>
<td>0.002</td>
<td>0.0005</td>
<td>4.77079E-07</td>
<td>0.000035</td>
<td>0.19853714</td>
</tr>
</tbody>
</table>

5.4 Step 3

- Keep the default parameter for the $f_{\text{tune}}$ (tuning frequency of reader antenna)
- $R_a$, $C_1$ and $C_2$ are the additional components to tune the reader antenna.

Table 6. Parameter values for tuning

<table>
<thead>
<tr>
<th>$f_{\text{tune}}$ Tuning Frequency [Hz]</th>
<th>$R_a$ [ohm]</th>
<th>$C_{1s}$ [pF]</th>
<th>$C_{2p}$ [pF]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.42E+07</td>
<td>0.33353276</td>
<td>1.1089E-10</td>
<td>1.5242E-10</td>
</tr>
</tbody>
</table>
5.5 Step 4

The last table gives three pieces of information (the green background, not shown in Table 7, indicates those values that are OK, and the red background, shown shaded in Table 7, indicates those that are not OK):

- The self supply distance available
- The coupling coefficient between reader and Tag available for each reading distance.
- The magnetic field value for each reading distance.

Table 7. Computed read range as a function of K and the H field

<table>
<thead>
<tr>
<th>Distance Between Tag and Reader [m]</th>
<th>K</th>
<th>H(x) [A/m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.29747676</td>
<td>4.09952789</td>
</tr>
<tr>
<td>0.005</td>
<td>0.28079988</td>
<td>4.07239802</td>
</tr>
<tr>
<td>0.01</td>
<td>0.23907764</td>
<td>3.92851237</td>
</tr>
<tr>
<td>0.015</td>
<td>0.18903897</td>
<td>3.57250903</td>
</tr>
<tr>
<td>0.02</td>
<td>0.14328997</td>
<td>3.02781035</td>
</tr>
<tr>
<td>0.025</td>
<td>0.10674754</td>
<td>2.42659743</td>
</tr>
<tr>
<td>0.03</td>
<td>0.07943063</td>
<td>1.88468486</td>
</tr>
<tr>
<td>0.035</td>
<td>0.05957594</td>
<td>1.44786262</td>
</tr>
<tr>
<td>0.04</td>
<td>0.0452454</td>
<td>1.11426535</td>
</tr>
<tr>
<td>0.045</td>
<td>0.0348568</td>
<td>0.86480968</td>
</tr>
<tr>
<td>0.05</td>
<td>0.02724888</td>
<td>0.67892022</td>
</tr>
<tr>
<td>0.055</td>
<td>0.02160527</td>
<td>0.53964094</td>
</tr>
<tr>
<td>0.06</td>
<td>0.01736053</td>
<td>0.43426455</td>
</tr>
<tr>
<td>0.065</td>
<td>0.0141234</td>
<td>0.35361388</td>
</tr>
<tr>
<td>0.07</td>
<td>0.01162142</td>
<td>0.29113953</td>
</tr>
<tr>
<td>0.075</td>
<td>0.00966294</td>
<td>0.24216658</td>
</tr>
<tr>
<td>0.08</td>
<td>0.00811155</td>
<td>0.20333723</td>
</tr>
<tr>
<td>0.085</td>
<td>0.00686896</td>
<td>0.1722174</td>
</tr>
<tr>
<td>0.09</td>
<td>0.00586343</td>
<td>0.14702389</td>
</tr>
<tr>
<td>0.095</td>
<td>0.00504195</td>
<td>0.12643577</td>
</tr>
</tbody>
</table>

In this example the maximum reading distance is 4.5cm.
Figure 15. Basic Schematic
Appendix A  Calculation details of serial-to-Parallel Conversion

The two circuits in Figure 9 are equivalent, where:

\[ R_S + jX_S = \frac{jR_P \times X_P}{R_P + jX_P} \]

Multiplying by the complex conjugate we find:

\[ R_P = \frac{R_S^2 + X_S^2}{R_S} = R_S + \frac{X_S^2}{R_S} \]

and:

\[ X_P = \frac{R_P \times R_S}{X_S} \]

If:

\[ R_S \ll X_S^2 \]

this simplifies to:

\[ R_P = \frac{X_S^2}{R_S} \]

and:

\[ X_P = X_S \]

This gives the equivalent circuit shown in Figure 10, whose impedance (Z) versus frequency (f) is plotted in Figure 11, where:

\[ R_P = \frac{(L_0b)^2}{R_a + R_L} \]

We start to calculate the equivalent impedance \( Z_{eq} \) from \( C_2 \), \( L \) and \( R_P \) in parallel:

\[ \frac{1}{Z_{eq}} = \frac{1}{R_P} + \frac{1}{jL\omega} + jC_2^2 \omega \]

and so:

\[ Z_{eq} = \frac{R_P \times jL\omega}{jL\omega + R_P + jC_2^2 \omega R_P \times jL\omega} \]
We can also calculate the equivalent impedance $Z$:

$$Z = \frac{1}{jC_1 \omega} + Z_{eq}$$

$$Z = \frac{1}{jC_1 \omega} + \frac{R_P^* jL \omega}{jL \omega + R_P + jC_2 \omega R_P^* jL \omega}$$

$$Z = \frac{jL \omega + R_P^* \left((1 - L(C_1 + C_2)^2) \omega^2\right)}{jC_1 \omega^2 \left(R_P - L C_2 R_P \omega^2\right) - C_1 \omega^2}$$

The first resonant frequency occurs when:

$$1 - L(C_1 + C_2)^2 \omega^2 = 0$$

We define $\omega = \omega_b$ to be at this point, and hence that:

$$\omega_b = \frac{1}{\sqrt{L(C_1 + C_2)}}$$

We find the equivalent impedance, $Z$, at this frequency, $\omega_b$:

$$Z = \frac{jL \omega_b}{jC_1 \omega_b^2 \left(R_P - L C_2 R_P \omega_b^2\right) - C_1 \omega_b^2}$$

$$Z = \frac{jL}{j^2 \left(C_1 R_P - L C_2 R_P \omega_b^2\right) - C_1 \omega_b^2}$$

We can separate the real and imaginary parts:

$$Z = \frac{C_1 R_P L - L^2 C_1 C_2 R_P \omega_b^2}{C_1 R_P - L C_1 C_2 R_P \omega_b^2 + (C_1 L \omega_b)^2} - j \cdot \frac{C_1 L^2 \omega_b}{(C_1 R_P - L C_1 C_2 R_P \omega_b^2)^2 + (C_1 L \omega_b)^2}$$

Taking the real part, and substituting for $\omega_b$ we obtain:

$$\Re \{Z\} = \frac{R_P L (C_1 + C_2)}{C_1^2 R_P^2 + L (C_1 + C_2)}$$
5.6 Calculation of the Impedance of Equivalent Circuit at the Second Resonance Frequency

We start with the expression of the equivalent impedance $Z$, calculated earlier:

$$Z = \frac{jL\omega + R_P \sigma (1 - L(C_1 + C_2)^2) \omega^2}{jC_1 \omega (R_P - LC_2 R_P \omega^2) - C_1 L \omega^2}$$

The second resonant frequency occurs when:

$$R_P - LC_2 R_P \omega^2 = 0$$

We define $\omega = \omega_1$ to be at this point, and hence that:

$$\omega_1 = \frac{1}{\sqrt{LC_2}}$$

We find the equivalent impedance, $Z$, at this frequency, $\omega_1$:

$$Z = \frac{jL\omega_1 + R_P \sigma (1 - L(C_1 + C_2)^2) \omega_1^2}{C_1 L \omega_1^2}$$

We can separate the real and imaginary parts, and take the real part:

$$\Re \{Z\} = -\frac{R_P \sigma (1 - L(C_1 + C_2)^2) \omega_1^2}{C_1 L \omega_1^2}$$

Substituting for $\omega_1$ we obtain:

$$\Re \{Z\} = R_P$$

<table>
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<tr>
<th>Table 8. Summary of the Main Results</th>
</tr>
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<tr>
<td><strong>Resonance frequency</strong></td>
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<td>$\omega_0 = \frac{1}{\sqrt{L(C_1 + C_2)}}$</td>
</tr>
<tr>
<td>$\omega_1 = \frac{1}{\sqrt{LC_2}}$</td>
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</tbody>
</table>
Now we can easily calculate the value of the C1 and C2 capacitors, in terms of Z, R_p, L, \( \omega_0 \):

\[
\omega_0 = \frac{1}{\sqrt{L/C_1 + C_2}} \Rightarrow C_1 \omega_0^2 + L C_2 \omega_0^2 = 1 \Rightarrow C_2 = \frac{1}{L \omega_0^2} - C_1
\]

We can substitute for \( \omega_0 \):

\[
C_1 = \frac{R_p - Z}{\sqrt{2 R_p Z}} \left( \frac{2 R_p Z}{L \omega_0^2} \right)
\]

and:

\[
C_2 = \frac{\sqrt{\frac{2 R_p Z}{L \omega_0^2}} - \sqrt{R_p - Z}}{L \omega_0^2 \sqrt{2 R_p Z}}
\]

Table 9. Values of the Capacitors

<table>
<thead>
<tr>
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<th>C1</th>
<th>C2</th>
</tr>
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<tbody>
<tr>
<td>C1</td>
<td>( \frac{1}{\sqrt{Z \cdot R_p \times \omega_0}} )</td>
<td>( \frac{1}{L \omega_0^2} - C_1 )</td>
</tr>
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Appendix B  Calculation Details of Current Calculation

To calculate the current, we use the complete system with tuning circuit and the influence of the tag when it is near the reader antenna.

For this, we need to know the mutual inductance between the reader antenna and the Tag.

Figure 16. Coupling factor model

\[ Z_R = R + jL_R \omega \]
\[ Z_T = R_T + jL_T \omega + \frac{1}{jL_T \omega} = R_T + j \left( \frac{1}{L_T \omega} - \frac{1}{C_T \omega} \right) \]

Equation 24

\[ \begin{align*}
V_R &= Z_R \cdot I_R + j M \omega I_R \\
0 &= Z_T + j M \omega I_R
\end{align*} \]

Equation 25

\[ V_R = \left( Z_R + \frac{M^2 \omega^2}{Z_T} \right) \cdot I_R \]

Equation 26: To calculate the Current, \( I_R \) in Reader Antenna

\[ I_R = \frac{V_R \cdot Z_T}{Z_T \cdot Z_R + M^2 \omega^2} \]
5.7 $V_R$ Calculation

Figure 17. Equivalent circuits

Note:

$$R = R_a + R_L$$

$$V_R = \frac{V_e \times Z_2}{Z_1 + Z_2}$$

$$V_R = \frac{(R + jL\omega) \cdot jC_1\omega}{(R + jL\omega) \cdot jC_1\omega + jRC_2\omega - LC_2\omega^2 + 1} \times V_e$$

$$Z_1 = \frac{1}{jC_1\omega}$$

$$Z_2 = \frac{R + jL\omega}{jRC_2\omega - LC_2\omega^2 + 1}$$

$$V_R = \frac{R + jL\omega}{jRC_2\omega - LC_2\omega^2 + 1} \times \frac{1}{jC_1\omega} \times V_e$$
5.8 Current Calculation

\[
V_R = \frac{R + jL_\omega}{\omega} \times \frac{(jR_2C_2 - LC_2\omega^2 + 1) \cdot jC_1\omega}{(R + jL_\omega) \cdot jC_1\omega + jR_2C_2 - LC_2\omega^2 + 1} \times V_e
\]

\[
V_R = \frac{(R + jL_\omega) \cdot jC_1\omega}{(R + jL_\omega) \cdot jC_1\omega + jR_2C_2 - LC_2\omega^2 + 1} \times V_e
\]

\[
I_R = \frac{jR_1C_1\omega - LC_1\omega^2}{jR(C_1 + C_2)\omega - L(C_1 + C_2)\omega + 1} \times \frac{R_T + \frac{1 - L_T C_T\omega^2}{jC_T\omega}}{R_T + \frac{1 - L_T C_T\omega^2}{jC_T\omega}} \times (R + jL_{R_1\omega}) \cdot M^2 \omega^2 \times V_e
\]
Appendix C  Demo kit board

Figure 18. Layout of Demo-kit Board
Figure 19. Component Implementation

Table 10. Bill of Materials

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Table 10.  Bill of Materials

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### 6 Revision history

Table 11. Document Revision History

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<th>Revision Details</th>
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<td>1.0</td>
<td>First Issue.</td>
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<tr>
<td>06-Dec-2005</td>
<td>2.0</td>
<td>Document moved to new template. Equations 4 and 5 corrected. Titles added to Appendix C, Figure 17, Table 1, Table 4, Table 5, Table 6 and Table 7. Title of Figure 16: Coupling factor model modified. ( \omega_1 ) and ( \omega_2 ) and note added to Figure 12: Coupling between One Tag and One Reader Antenna.</td>
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<tr>
<td>13-Feb-2006</td>
<td>3.0</td>
<td>CRX14 pinout modified in Figure 15: Basic Schematic.</td>
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