AN2866
Application note

How to design a 13.56 MHz customized antenna for ST25 NFC / RFID Tags

Introduction

The ST25 NFC (near field communication) and RFID (radio frequency identification) tags extract their power from the reader field. The tag and reader antennas are inductances mutually coupled by the magnetic field similarly to a voltage transformer (see *Figure 1*).

The efficient transfer of energy from the reader to the tag depends on the loop antenna tuned to the carrier frequency (usually 13.56 MHz).

The purpose of this application note is to give a step-by-step procedure to easily design and optimize a customized tag antenna.

Table 1 lists the products concerned by this application note.

Table 1. Applicable products

Type	Applicable products
ST25 NFC / RFID Tags	LR and SR series ST25TA, ST25TB and ST25TV series NFC tags

Figure 1. RFID tag coupled to a reader's magnetic field

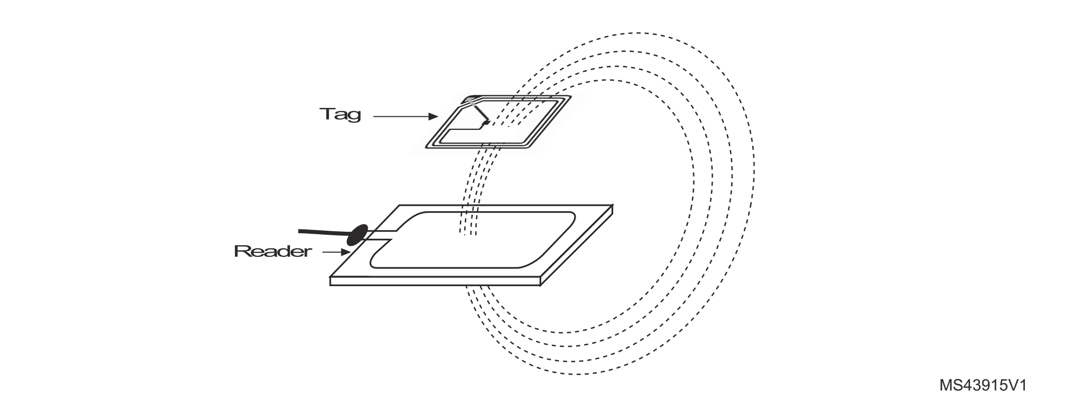
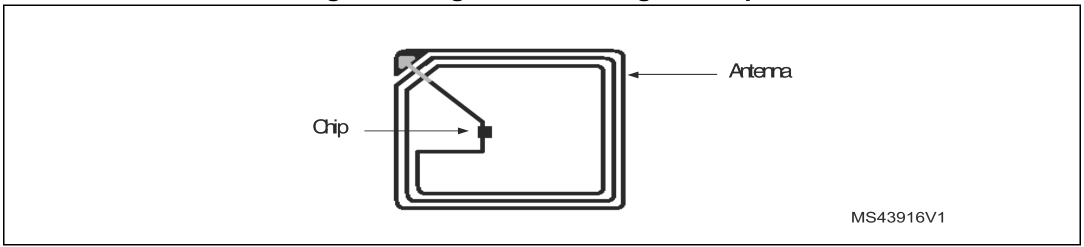


Figure 2. Tag antenna design example



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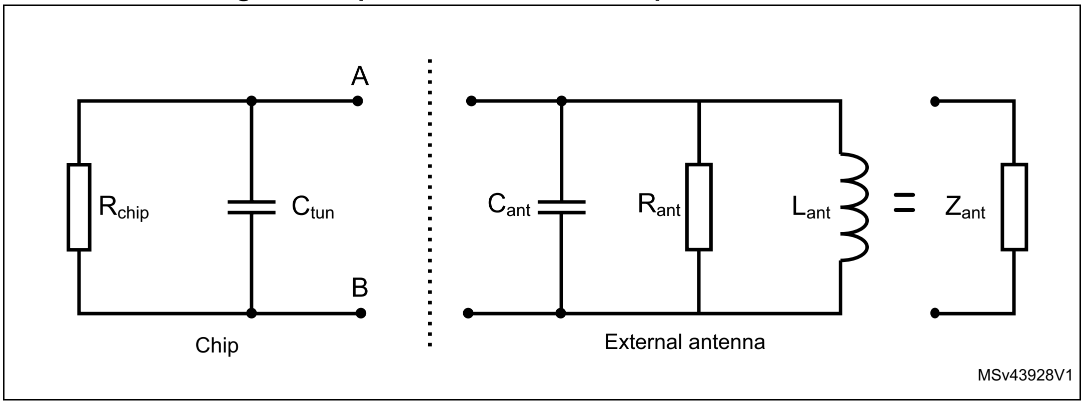
1 NFC / RFID tag and antenna equivalent circuit

Figure 3 shows the equivalent electrical circuit of an NFC / RFID tag chip and its antenna.

The NFC / RFID chip is symbolized by a resistor R_{chip} representing its current consumption, in parallel with a capacitor C_{tun} representing its internal tuning capacitance and internal parasitics.

Figure 3. Equivalent circuit of a chip and its antenna



The equivalent model of the antenna involves three components in parallel:

- **C_{ant}**: overall stray capacitance of the loop antenna
- **R_{ant}**: resistive loss of the loop antenna
- **L_{ant}**: self inductance of the loop antenna

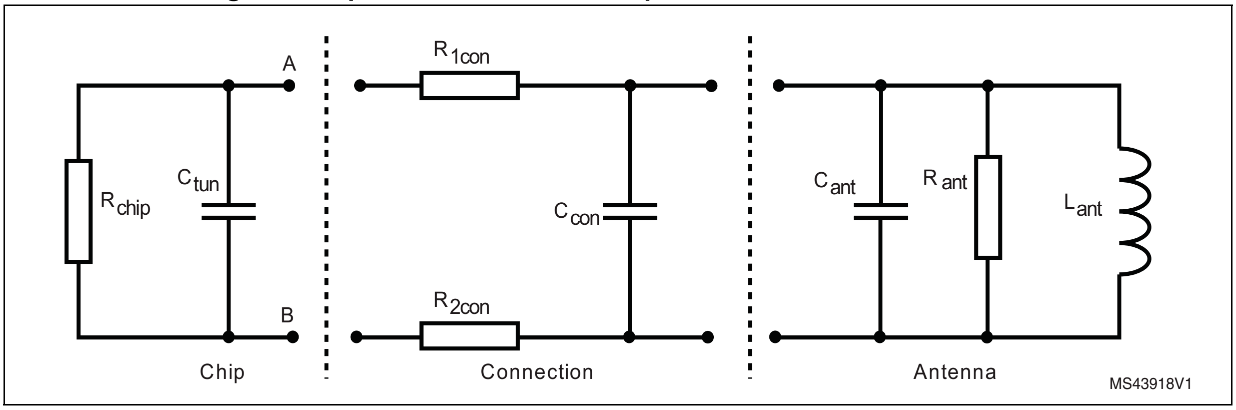
The resulting antenna impedance is given by $Z_{ant}=C_{ant} // R_{ant} // L_{ant}$.

2 Inlay equivalent circuit

For the products delivered in package, the schematic described in *Figure 3* is applicable.

For parts delivered in die and assembled on inlays, the equivalent schematic is in *Figure 4*,

Figure 4. Equivalent circuit of a chip, its antenna and connections



This schematic takes into account parasitics generated by the connections between the chip and the antenna:

- $\mathbf{R_{1con}}$ and $\mathbf{R_{2con}}$: equivalent parasitic resistances
- $\mathbf{C_{con}}$: equivalent parasitic capacitance

The parasitics due to assembly depends on the assembly process and the antenna material (copper, aluminum, conductive ink).

3 Antenna design procedure

The design procedure starts with the simplified model shown in *Figure 3*.

For a given antenna, R_{ant},C_{ant} and L_{ant} are constants but the resulting impedance Zant (R_{ant} // C_{ant} // L_{ant}) is frequency dependent. At self-resonance frequency (fself_res), the imaginary part of the antenna impedance is null and the antenna is purely resistive.Below the self-resonance frequency, the imaginary part of the antenna impedance is positive and the antenna behavior is inductive.

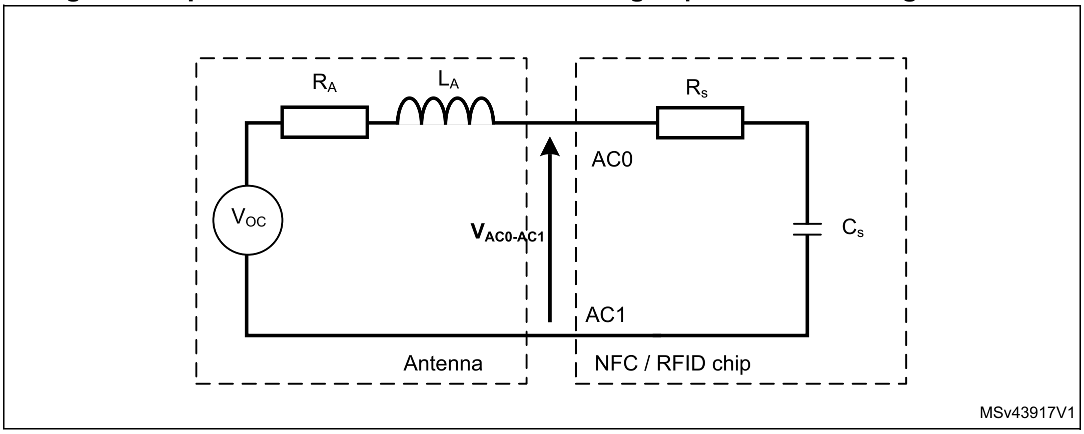
Figure 5 shows the equivalent model of an NFC / RFID tag in presence of a magnetic field. The loop antenna model includes:

- $\mathbf{V_{oc}}$: open circuit voltage delivered by the antenna which depends on the magnetic field strength, the antenna size and the number of turns
- $\mathbf{L_A}$: equivalent inductance defined by $L_A = X_A/\omega$ where X_A is the antenna reactance

The NFC / RFID chip model includes:

- $\mathbf{R_S}$: representing the equivalent power consumption
- $\mathbf{C_S}$: serial equivalent tuning capacitance

Figure 5. Equivalent model of an NFC / RFID tag in presence of a magnetic field



Basic equations

At very low frequencies (f < fself_res / 10), the stray capacitance C_{ant} is negligible. $L_A = L_{ant}$ and the antenna reactance is given by $X_A = jL_{ant}\omega$.

At 13.56 MHz, C_{ant} becomes in a range of some pF and $L_A > L_{ant}$.

The antenna impedance is $Z_{ant} = R_A + jL_A\omega$.

The NFC / RFID chip impedance is $Z_S = R_s + j \times 1 / C_S\omega$.

For the equivalent RLC circuit, the total impedance is $Z_{tot} = Z_{ant} + Z_s$ and the resonant frequency is given by the condition $L_A C_S \omega^2 = 1$.

Optimum antenna tuning

At resonant frequency, the total impedance is minimal, reduced to $Z_{tot} = R_A + R_S$. The current inside the antenna and the voltage delivered to the NFC / RFID chip are maximum. The maximum energy is provided to the device.

If the resonant frequency is close to the reader carrier frequency 13.56 MHz, the power transfer between the reader and the tag as well as the communication distance are maximum.

Table 2 gives examples of different NFC / RFID chips and antenna inductance calculation.

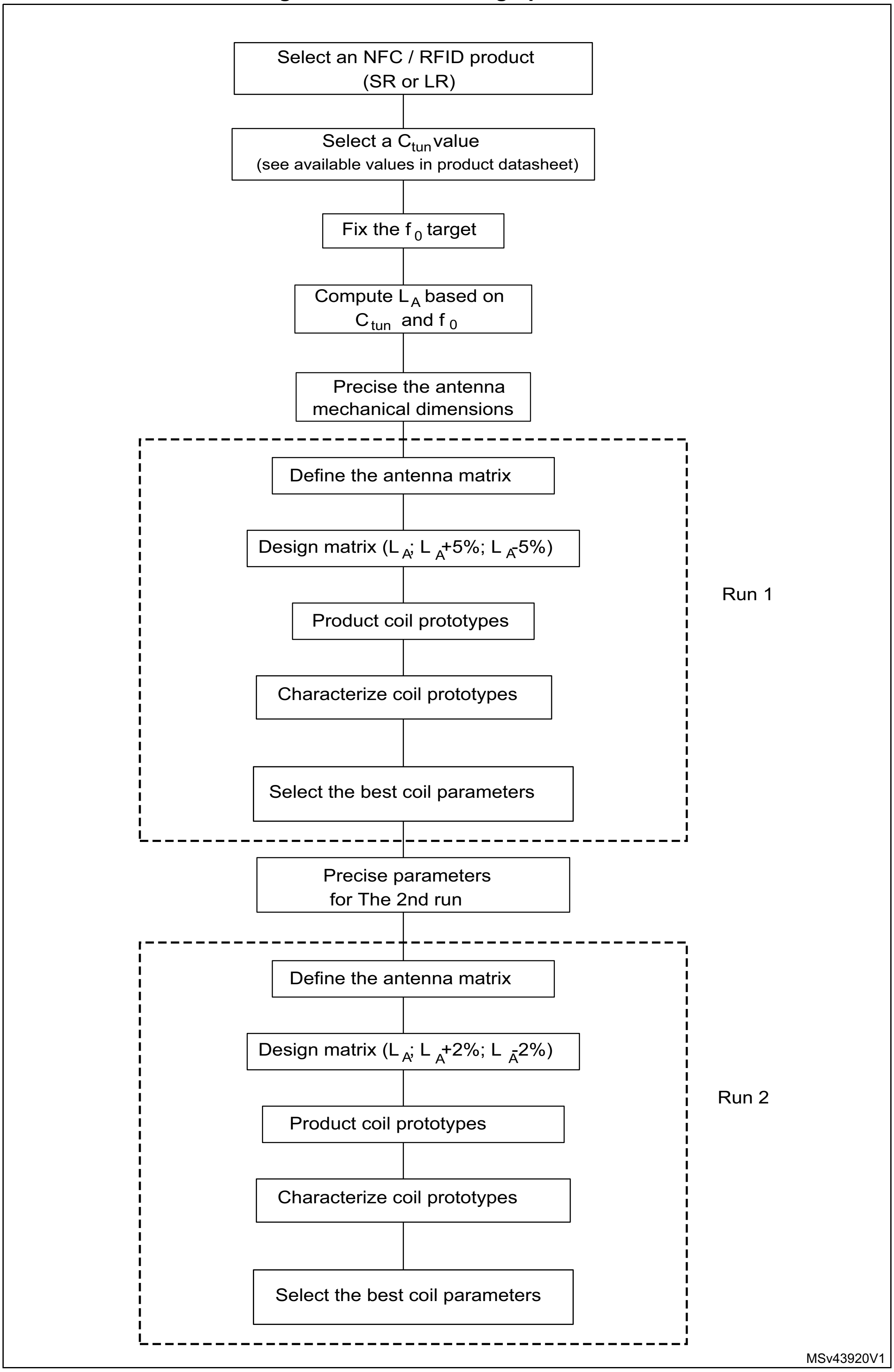
Table 2. Antenna coil inductances for different C_{tun} values at a given tuning frequency

Product	C_{tun} (pF)	Tuning frequency (MHz)	Antenna coil inductance (µH)
LR (long range) and ST25TV series	28.5	13.56	4.83
	23.5	13.56	5.86
	97	13.56	1.42
SR (short range) and ST25TB series	68	13.56	2.00
	68	14.40	1.80
ST25TA series	50	14	2.58
	27.5	14	4.70

Figure 6 describes an easy and reliable method to design and fine tune a customer's antenna in a minimum steps summarized below:

- manufacture a matrix of three antennas centered on the theoretical equivalent inductance L_A
- characterize and validate the performance of these antennas
- launch a second run with three fine-tuned L_A values to get the optimized antenna

Figure 6. Antenna design procedure



4 Designing the antenna coil

A 13.56 MHz antenna can be designed with different shapes, depending on the application requirements. As explained previously, the major parameter is the equivalent inductance L_A of the antenna around 13.56 MHz.

The stray capacitance is generally in a range of few pF for typical NFC / RFID products.

For some antenna shapes, *Section 4.1*, *Section 4.2* and *Section 4.3* give some useful formulas to calculate the self inductance L_{ant}.

Section 4.4 presents a calculation tool called antenna design to calculate the equivalent inductance of rectangular antennas, taking into account an approximation of the stray capacitance.

4.1 Inductance of a circular antenna

$L_{ant} = \mu_0 \times N^{1.9} \times r \times \ln\left(\frac{r}{r_0}\right)$, where:

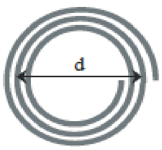
- r is the mean coil radius in millimeters
- r_0 is the wire diameter in millimeters
- N is the number of turns
- $\mu_0 = 4\pi \cdot 10^{-7}$ H/m
- L is measured in Henry

4.2 Inductance of a spiral antenna

$L_{ant} = 31.33 \times \mu_0 \times N^2 \times \frac{d}{8d + 11c}$, where:

- d is the mean coil diameter in millimeters
- c is the thickness of the winding in microns
- N is the number of turns
- $\mu_0 = 4\pi \cdot 10^{-7}$ H/m
- L is measured in Henry

Figure 7. Spiral coil



4.3 Inductance of a square antenna

$$L_{ant} = K1 \times \mu_0 \times N^2 \times \frac{d}{1 + K2 \cdot p}$$, where:

- d is the mean coil diameter
  $d = (d_{out} + d_{in})/2$ in millimeters, where d_{out} = outer diameter, d_{in} = inner diameter
- $p = (d_{out} - d_{in})/(d_{out} + d_{in})$ in millimeters
- K1 and K2 depend on the layout (refer to *Table 3* for values)

Figure 8. Square coils

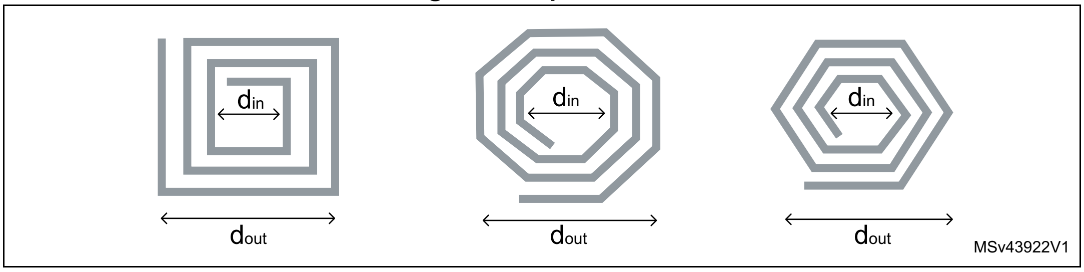


Table 3. K1 and K2 values according to layout

Layout	K1	K2
Square	2.34	2.75
Hexagonal	2.33	3.82
Octagonal	2.25	3.55

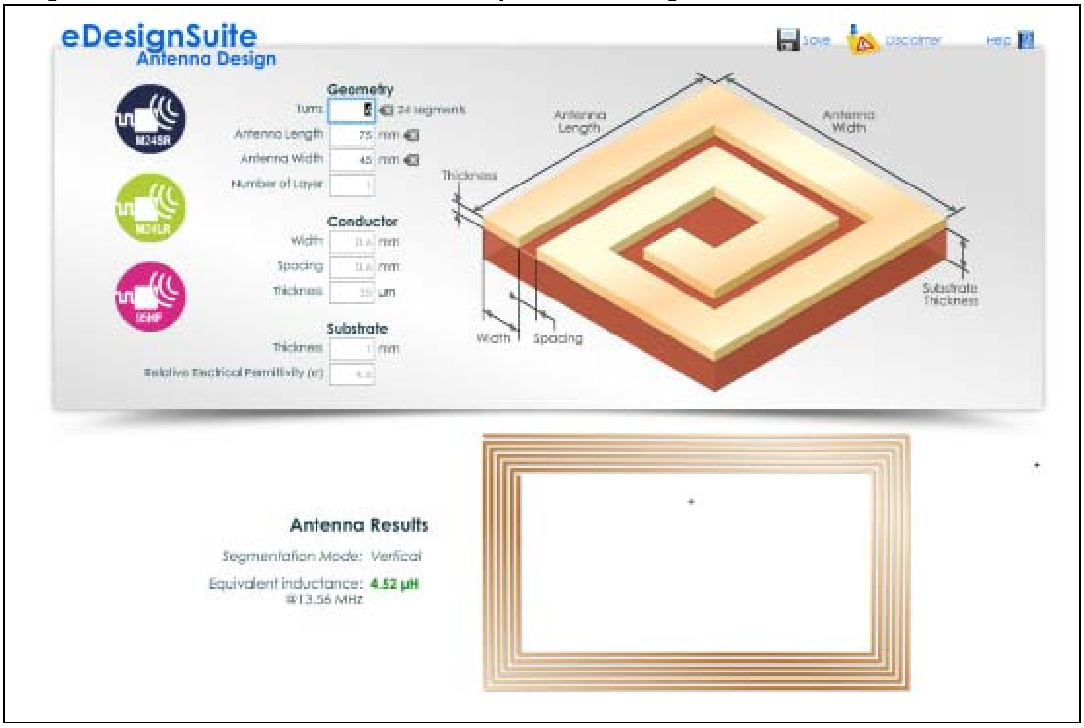
4.4 eDesignSuite antenna design tool

Please refer to the antenna design tool, part of the eDesignSuite tool available from *www.st.com* to compute rectangular antennas at 13.56 MHz.

This antenna design tool uses some parameters related to the PCB material and antenna dimensions and estimates the antenna equivalent inductance.

Figure 9 shows an example of antenna computation.

Figure 9. User interface screen of the planar rectangular coil inductance calculator



The user provides the following parameters:

Antenna geometry parameters:

- Turns: number of complete turns (4 segments per turn)
- Antenna length in mm
- Antenna width in mm
- Number of layer (1 by default)

Conductor parameters (copper is used by default)

- Width of tracks in mm
- Spacing between turns in mm
- Thickness of the conductor in µm

Substrate parameters

- Thickness in mm
- Dielectric permitivity

Once the antenna equivalent inductance is calculated, a prototype is produced. The antenna design is validated by measuring the antenna impedance (using an impedance analyzer, a network analyzer or an LCR meter) or by measuring the tuning frequency of the tag using a contactless method (see *Section 5*).

5 Antenna tuning contactless measurement method

The following parameters impact the tuning frequency of the NFC / RFID tag:

- the precision of the antenna equivalent inductance computation
- the length of the connexion between the chip and its antenna in the application
- the antenna environment (metal surface, ferromagnetic material)

It is important to check the resonant frequency in the final application conditions, using one of the methods described in *Section 5.1* and *Section 5.2*.

5.1 Antenna measurement with a network analyzer

The network analyzer with a loop probe allows to measure the tuning frequency of the prototypes.

The loop probe generates the RF electromagnetic field to the output of the network analyzer, which is set in reflection mode (S11 measurement).

The loop probe either comes from the market or is a self made single turn loop (using a coaxial connector and a copper wire twisted at the end). Building the loop probe like this allows to adjust the size of the loop to the size of the tag antenna for a better coupling during the measurement.

Figure 10. Measurement with a network analyzer

This equipment setup directly displays the resonant frequency of the system.

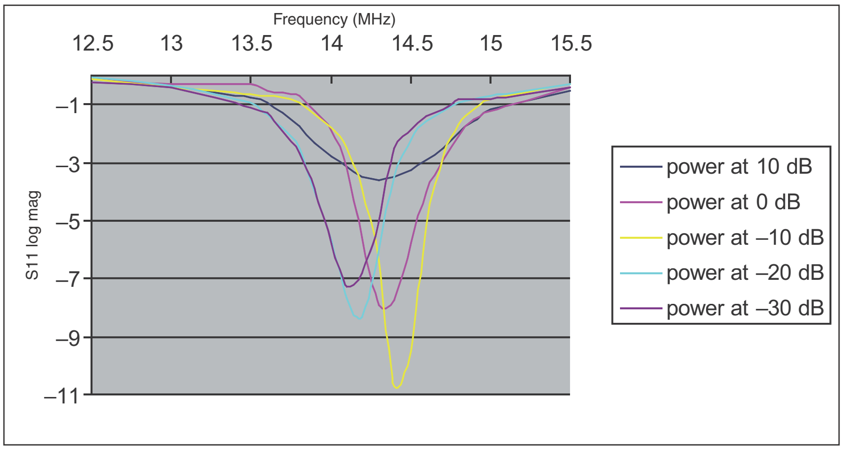
Instructions

Here is an example of instrument setup:

- start frequency: 10 MHz
- stop frequency: 20 MHz
- S11 or reflection mode
- display format: log magnitude
- output power: -10 dBm

The frequency sweep can be adjusted upon needed.

Figure 11. Resonance traces of the prototype at different powers



5.2 Antenna measurement with standard laboratory tools

Another method of measuring the tuning frequency is to use standard laboratory equipment like:

- a signal generator
- an oscilloscope
- two loop antennas

Experiment setup

- Connect an ISO 10373-7 standard loop antenna (see *Figure 12*) to the signal generator.
- Connect the second ISO 10373-7 standard loop antenna to the oscilloscope (see *Figure 13*)
  - using a standard oscilloscope probe (1 M or 10 M input impedance)
  - or a 50 Ω BNC cable (oscilloscope input set to 50 Ω in this case).

Note: The ISO 10373-7 standard antennas can be replaced by self-made antennas.

Figure 12. ISO standard loop antenna

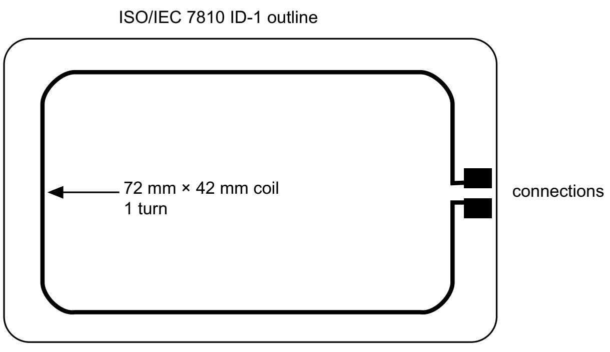
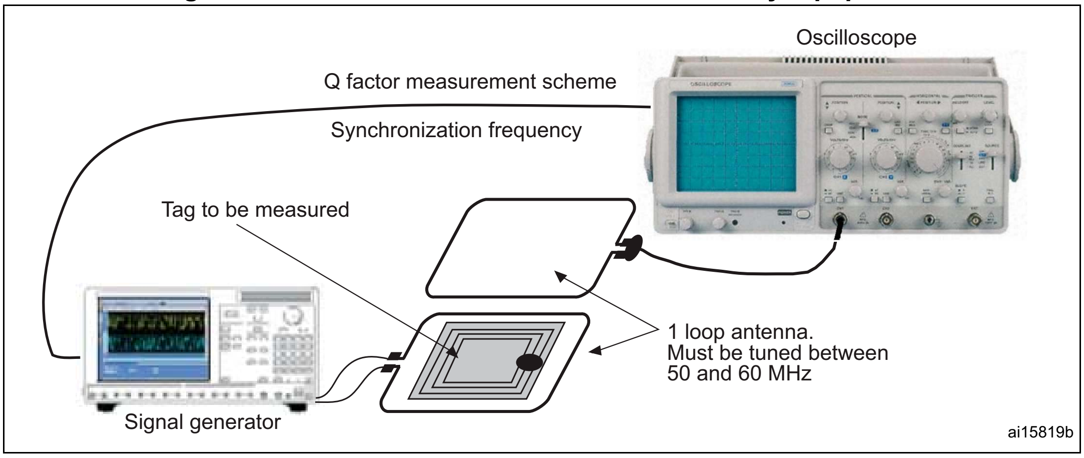


Figure 13. Measurement with standard laboratory equipment



Experiments

- Place the tag in front of the loop antenna connected to the signal generator. In presence of a magnetic field, a current flows into the tag antenna. This current generates a magnetic field which is captured by the second loop antenna connected to the oscilloscope. At tag resonant frequency, the current flowing into the tag antenna is maximum. The magnetic field generated by the tag antenna and the voltage amplitude displayed by the oscilloscope are maximum
- Place the prototype coil right in the transmission loop probe (with the reception loop probe at about 0.5 cm from the prototype coil).
- Generate a signal (sine 13.56 MHz) at a voltage of 0.25 V.
- Vary the transmission frequency in order to obtain a signal level as high as possible on the reception side.
- Use the oscilloscope to determine the signal level and the resonant frequency.

Figure 14 shows two signal waveforms at different transmission frequencies.

Figure 14. Oscilloscope views

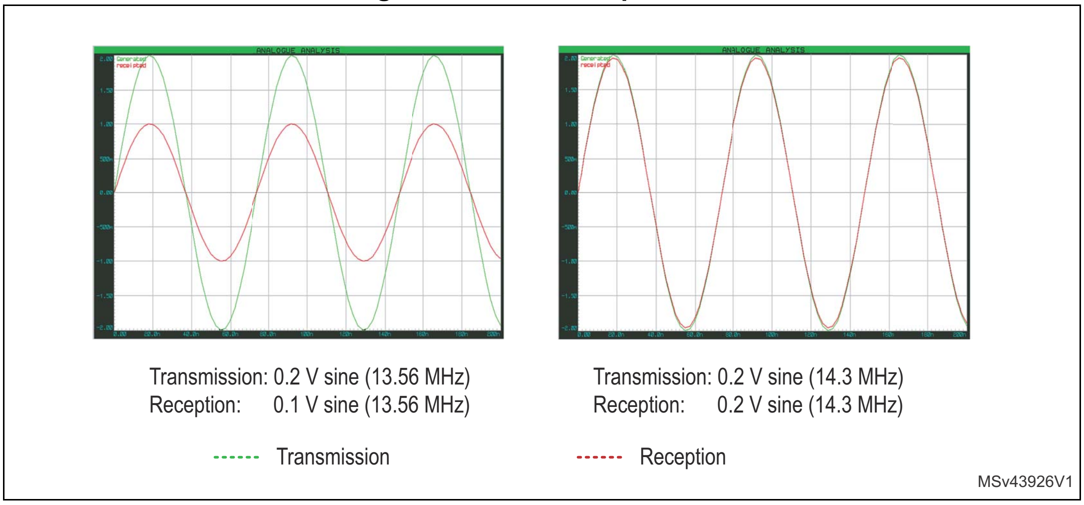
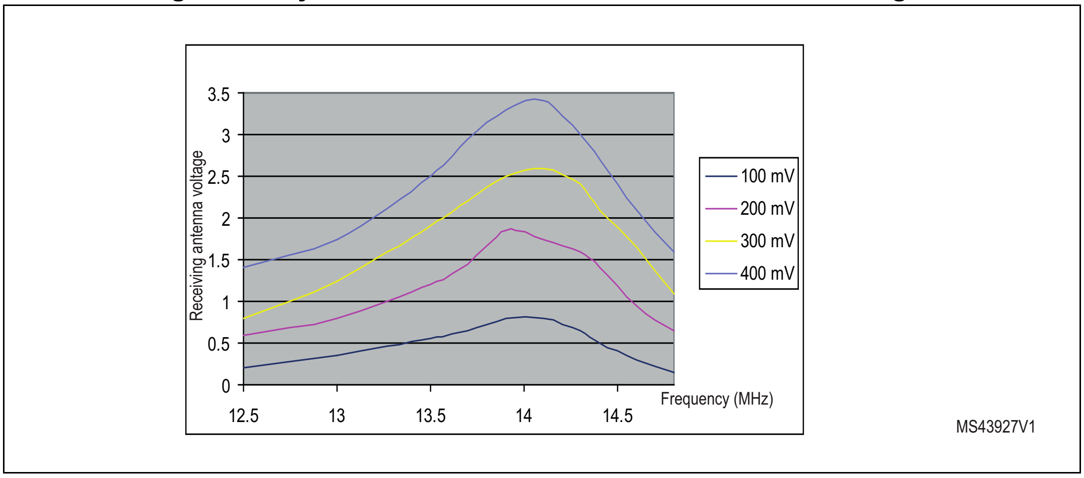


Figure 15 provides a synthesis of the measurements obtained by plotting characteristic points for different frequencies at a given voltage. Each resonance trace represents a synthesis for a defined voltage transmission.

Figure 15. Synthesis of resonance traces for different voltages



Note: Without any tag, the scope trace must be as flat as possible. It is the reason why the antenna connected to the generator must not be tuned at 13.56 MHz.

6 Frequency versus application: recommendations

When designing a tag antenna, it is important to know the frequency of the application:

- Long-range (LR) products are tuned between 13.6 MHz and 13.7 MHz (for distance optimization).
- Standard short-range (SR) products are tuned between 13.6 MHz and 13.9 MHz (for distance optimization).
- Short-range products used as transport tickets are tuned between 14.5 MHz and 15 MHz (for stack optimization).

The frequency shift due to the final label material and environment has to be considered also. In the example of a sticker tag with a paper label, the paper and adhesive decrease the inlay antenna frequency by about 300 kHz. It is therefore necessary to tune the initial inlay at about 13.9 MHz instead of the specified 13.6 MHz.

7 Revision history

Table 4. Document revision history

Date	Revision	Changes
15-Jan-2008	1	Initial release.
15-Dec-2016	2	Updated: – *Introduction* – *Section 1: NFC / RFID tag and antenna equivalent circuit* – *Section 2: Inlay equivalent circuit* – *Section 3: Antenna design procedure* – *Section 4: Designing the antenna coil* – *Section 5: Antenna tuning contactless measurement method* – *Section 6: Frequency versus application: recommendations* – *Figure 3: Equivalent circuit of a chip and its antenna* – *Figure 4: Equivalent circuit of a chip, its antenna and connections* – *Figure 5: Equivalent model of an NFC / RFID tag in presence of a magnetic field* – *Figure 6: Antenna design procedure* – *Figure 9: User interface screen of the planar rectangular coil inductance calculator* – *Figure 13: Measurement with standard laboratory equipment* – *Table 1: Applicable products* – *Table 2: Antenna coil inductances for different Ctun values at a given tuning frequency*

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