How to design an antenna for dynamic NFC tags

Introduction

The dynamic NFC (near field communication) tag devices manufactured by ST feature an EEPROM that can be accessed either through a low-power I^2C interface or an RF contactless interface operating at 13.56 MHz. Both short-range (ISO/IEC 14443 Type A) and long-range (ISO/IEC 15693) standards are supported.

Figure 1. Dynamic NFC tags

Dynamic NFC tag can be used in many applications, with the requirement that the processor features an I^2C interface.

This application note intends to:

* explain the basic principle of passive RFID
* describe the basics of a 13.56 MHz inductive antenna design
* provide guidelines for a successful integration, from design to production.

Table 1 lists the products concerned by this application note.

Table 1. Applicable products

Type	Applicable products
Dynamic NFC tags	ST25DV-I2C, ST25DV-PWM, M24LR and M24SR series Dynamics NFC Tags

Contents

List of tables

List of figures

1 Operating mode

The integration of dynamic NFC tag in an application is a straightforward task: on the I^2C side, the device must be connected to a master I^2C interface (like any serial I^2C EEPROM device), on the RF side, the dynamic NFC tag chip needs to be connected to an external antenna to operate.

Figure 2. Dynamic NFC tag operating mode
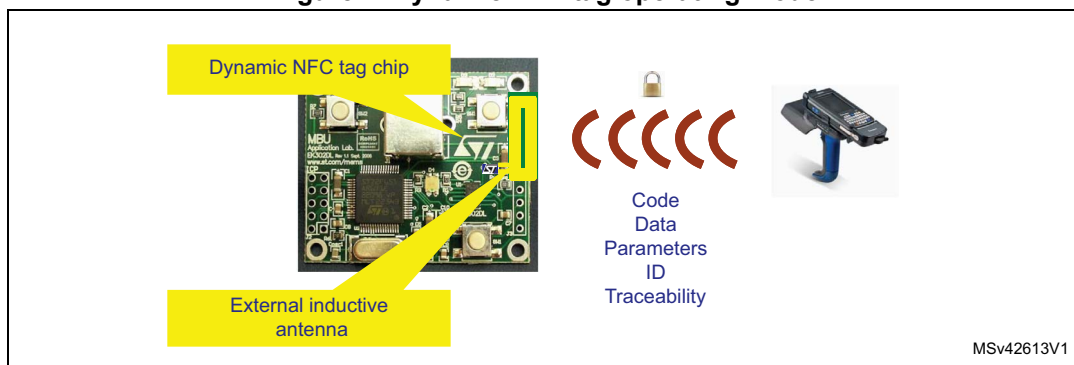
The design of an antenna for dynamic NFC tag is based on the placement of a loop on the application PCB. Its impedance matches the device internal tuning capacitance value (C_{tuning}) to create a circuit resonating at 13.56 MHz. The basic equation of the tuning frequency is:

$$f_{tuning} = \frac{1}{2\Pi \times \sqrt{L_{antenna} \times C_{tuning}}}$$

2 Basic principles and equations

Definitions

Tag   : the dynamic NFC tag chip mounted on the PCB and connected to its antenna.

Reader : an electronic device able to communicate with tags in RF mode.

2.1 Passive RFID technology

The ISO 15693 and ISO 14443 RF protocols used by dynamic NFC tag devices manufactured by ST are based on passive RFID technology, operating in the high frequency (HF) range, at 13.56 MHz.

Power transfer

When the dynamic NFC tag chip operates in RF mode, it is powered by the reader. No battery is required to access it in RF mode, neither in read nor in write mode. The dynamic NFC tag chip draws all the power it needs to operate from the magnetic field generated by the reader through its loop antenna.

The reader - tag system is similar to a voltage transformer, where the reader acts as the primary winding, and the tag as the secondary winding.

Reader and tag are magnetically and mutually coupled to each other.

The energy transfer from the reader to the dynamic NFC tag chip depends on:

- how well the tag antenna is tuned, close to the reader's carrier frequency (13.56 MHz)
- the distance between the reader and the tag antenna board
- the dimensions of the reader antenna and of the tag antenna board
- the reader power
- the tag antenna orientation related to the reader antenna.

Figure 3. Dynamic NFC tag chip power mechanism in RF mode
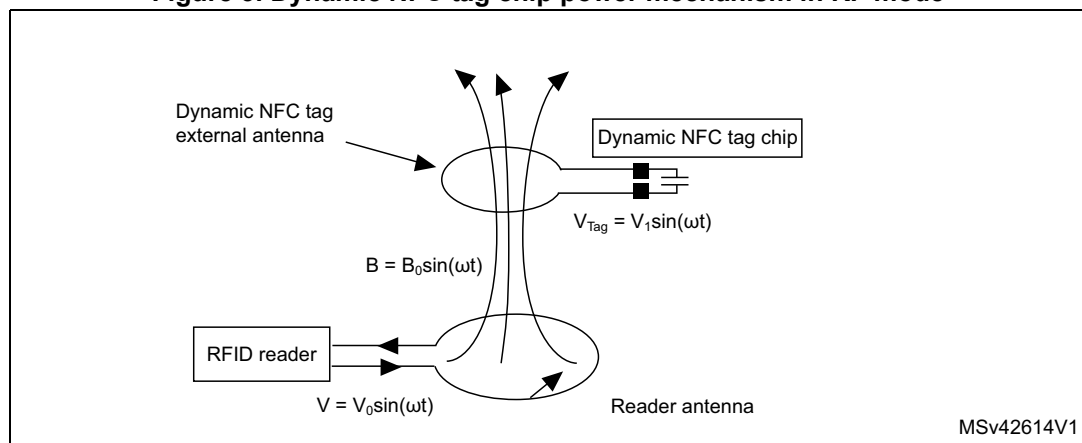
When the dynamic NFC tag is placed in the RFID reader's electromagnetic field, the amount of energy powering the device is directly related to the orientation of the dynamic NFC tag antenna and to the RFID reader antenna. Indeed, this energy depends on how the electromagnetic field lines generated by the reader flow through the dynamic NFC tag antenna (see *Figure 4*).

This directly impacts the read range, more in detail:

*   the best configuration is obtained when the antennas are parallel and face each other
*   the read range drops to zero when the antennas are perpendicular to each other
*   any other orientation is possible and will result in different read ranges.

Figure 4. Power transfer versus reader/dynamic NFC tag orientation
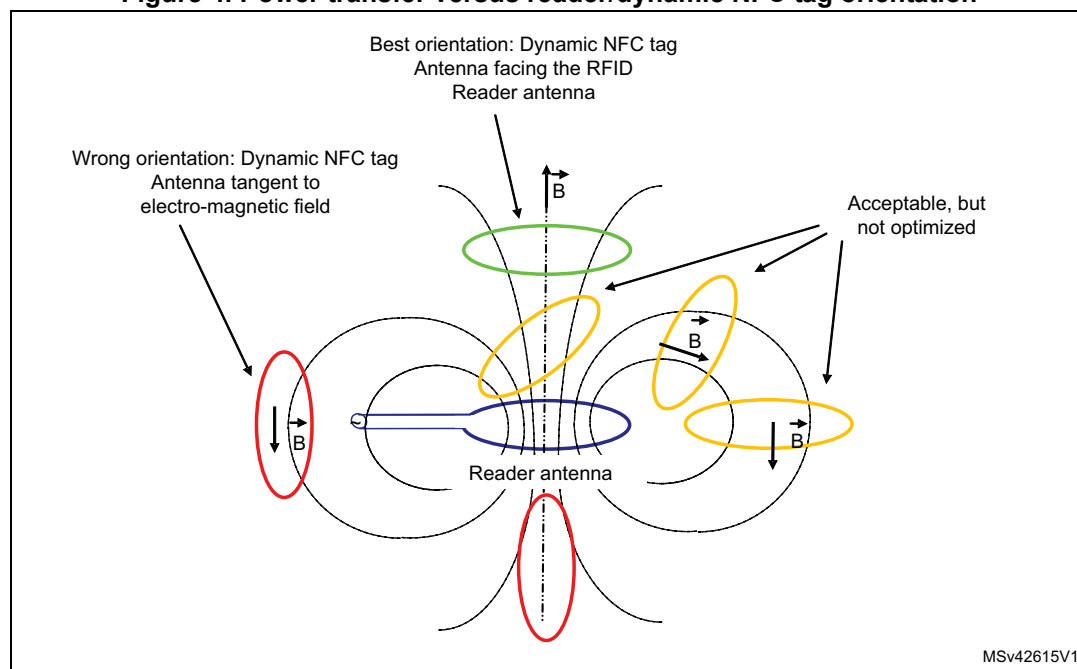
Data transfer

When placed in a reader's magnetic field able to power it, the dynamic NFC tag chip built-in circuitry demodulates the information coming from the reader (see *Figure 5*).

Figure 5. Communication from the reader to the tag

At the end of the request, the reader keeps the magnetic field non modulated to power the tag, and allows it to generate an answer. To send its response back to the reader, the dynamic NFC tag chip backscatters the data to the reader by internally modulating its input impedance. Tag chip input impedance variation modulates the signal across the reader antenna due to the mutual coupling between reader and tag antennas. The reader demodulates this signal and decodes the tag answer.
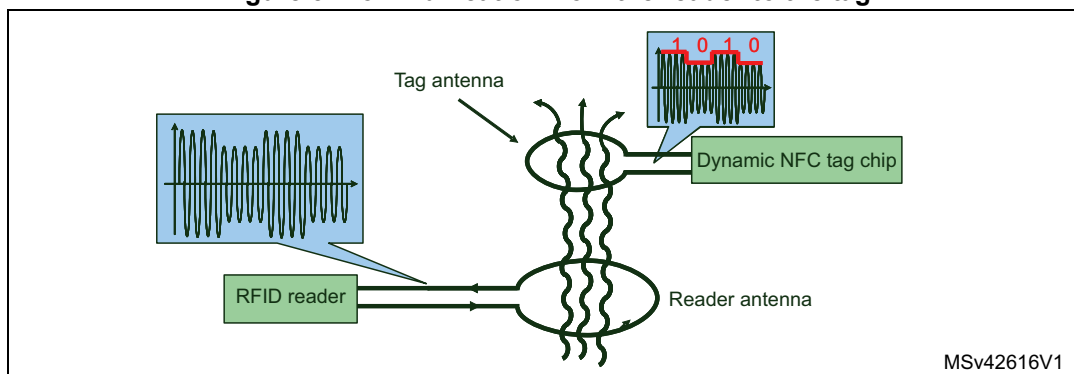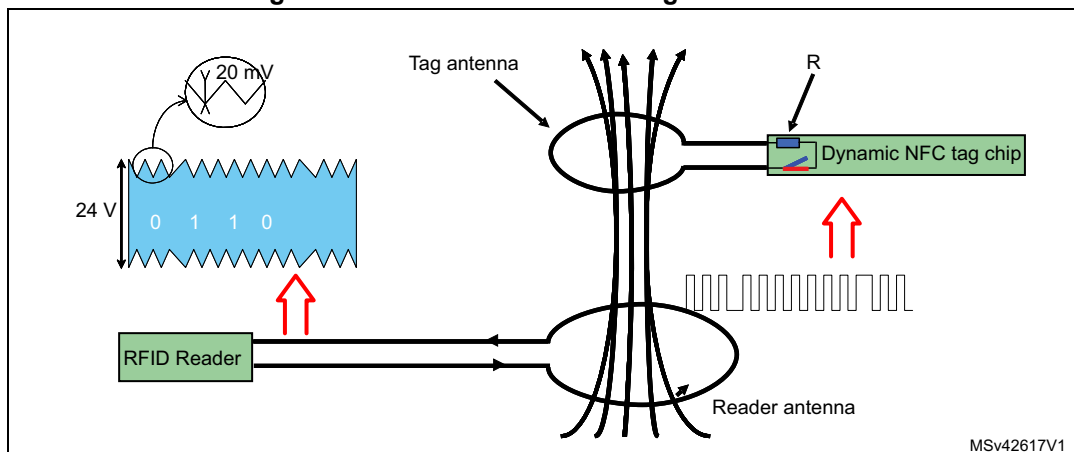
Figure 6. Communication from tag to the reader

All this is part of the standard protocol and is taken into account by the dynamic NFC tag chip embedded circuitry and by the RFID reader's electronics.

2.2 Simplified equivalent inlay circuit

Figure 7 shows the equivalent electrical circuits of the dynamic NFC tag and its antenna.

- Dynamic NFC tag 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.
- Measuring a loop antenna impedance evidences a self-resonant frequency. The corresponding equivalent model involves an inductance in parallel to a capacitance. C_{ant} represents the overall stray capacitance of the loop antenna (including the

assembly), R_{ant} the resistive loss of the antenna and L_{ant} the self-inductance of the loop antenna.

Figure 7. Equivalent circuit of the dynamic NFC tag chip and its antenna
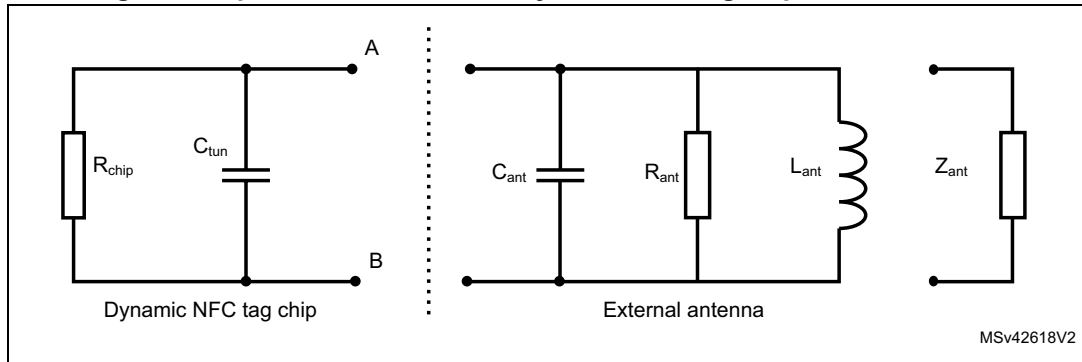
C_{ant}, R_{ant} and L_{ant} are constants but the resulting impedance (their parallel combination) is frequency dependent. At self-resonance frequency, the imaginary part of the antenna impedance Z_{ant} is null and Z_{ant} is purely resistive. Below the self-resonance frequency, the imaginary part of the antenna impedance is positive and the antenna behavior is inductive. The equivalent inductance of the antenna is defined L_A as $L_A = X_A / \omega$ for frequencies below the self resonant frequencies ($Z_{ant} = R_A + jX_A$).

At low frequencies, where the impact of stray capacitance C_{ant} is negligible, $L_A = L_{ant}$ (self-inductance). However, at 13.56 MHz the impact of stray capacitance cannot be neglected and $L_A > L_{ant}$.

2.3 Basic equations

Resonant frequency

Figure 8. Equivalent circuit of the dynamic NFC tag chip mounted on a loop antenna
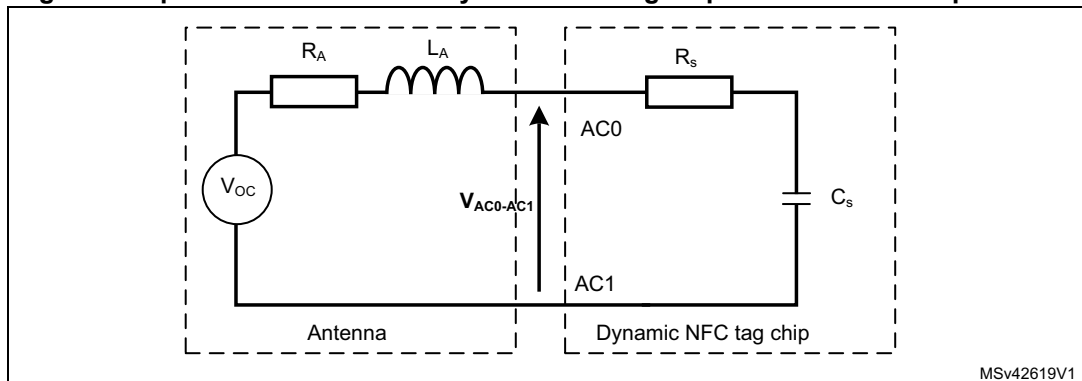

Figure 8 shows the equivalent circuit of an dynamic NFC tag chip mounted on a loop antenna in the presence of a sinusoidal magnetic field. V_{OC} represents the open circuit voltage delivered by the antenna, which depends on the magnetic field strength, the antenna size and the number of turns.

The tag antenna impedance is $Z_{ant} = R_A + jL_A\omega$, where L_A is the antenna inductance.

The dynamic NFC tag chip impedance is given by $Z_S = R_S + j \times 1 / C_S\omega$, where R_S represents the power consumption of the chip, and C_S represents the ==serial equivalent tuning capacitance,== both converted in serial model.

The resonant frequency of the equivalent RLC circuit is given by the condition $L_A C_S \omega^2 = 1$, where ($\omega = 2 \pi f$, f in Hz).

2.4 Optimum antenna tuning

The total impedance of the RLC circuit is $Z_{tot} = Z_{ant} + Z_S$.

At resonant frequency $L_A C_S \omega^2 = 1$, the total impedance is reduced to $Z_{tot} = R_A + R_S$ (the total impedance of the antenna is minimal, the current inside the antenna and the voltage delivered to the dynamic NFC tag chip are maximum), and the maximum energy is provided to the device.

Figure 9 shows three examples of dynamic NFC tag antenna tuning.

Tag #2 is the best tuned for this application configuration.

Figure 9. Tuning the dynamic NFC tag antenna
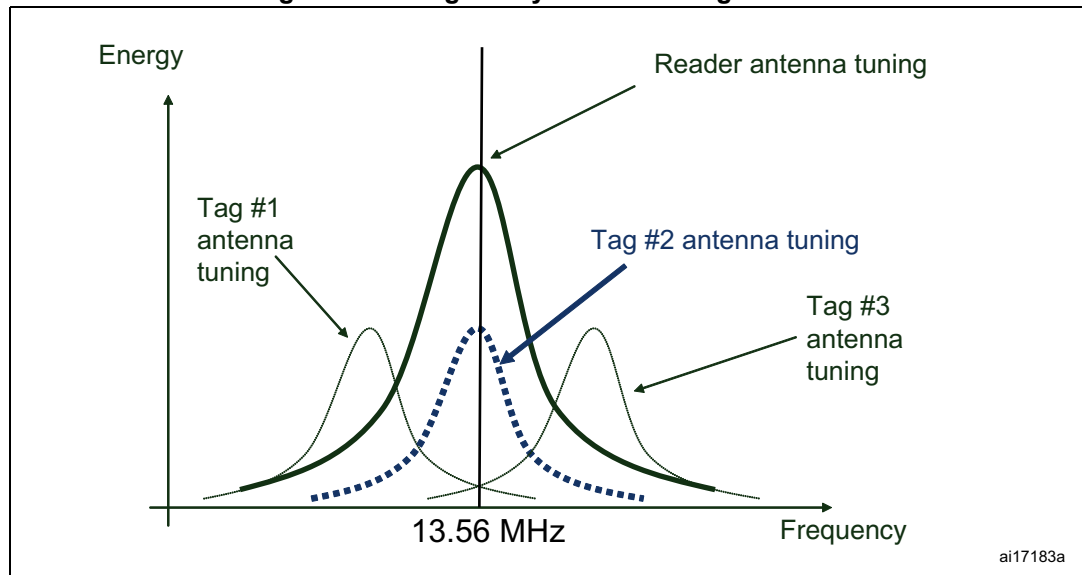
3   How to design the antenna on a PCB

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 at 13.56 MHz.

The stray capacitance is difficult to approximate, but for typical NFC/RFID products is in the range of few pF.

For some antenna shapes, *Section 3.1*, *Section 3.2*, and *Section 3.3* give useful formulas to calculate the self-inductance L_{ant}, even if the stray capacitance of the antenna is not estimated.

Section 3.4 presents a calculation tool called Antenna Design, which is a part of the eDesignsuite, to calculate equivalent inductance of rectangular antennas taking into account an approximation of the stray capacitance.

3.1   Inductance of a circular antenna

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

- r is the 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

3.2   Inductance of a spiral antenna

$$L_{ant} = 31.33 \times \mu_0 \times N^2 \times \frac{a^2}{8a + 11c}, \text{ where (see } Figure\ 10):$$

- a = (r_{in} + r_{out}) / 2 (the average radius, in meters)
- c = r_{out} - r_{in} is the thickness of the winding, in meters
- $\mu_0 = 4\pi \cdot 10^{-7}$ H / m
- L is measured in Henry
- N is the number of turns

Figure 10. Spiral antenna

MS51744V1
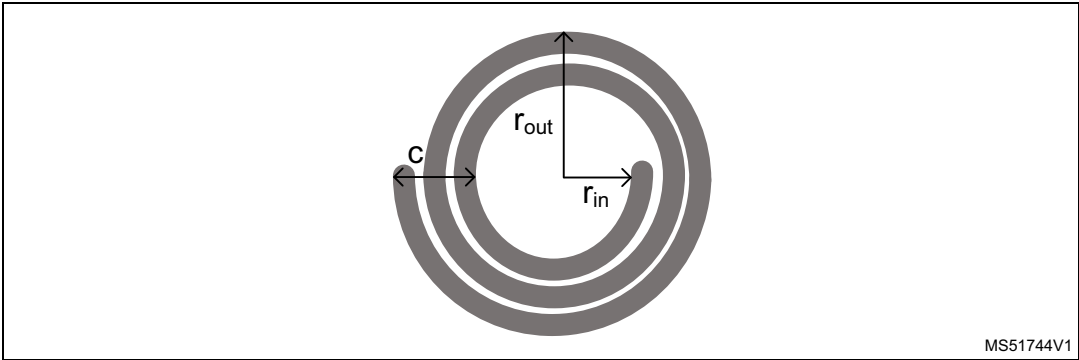
3.3 Inductance of a square antenna

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

- $d = (d_{out} + d_{in}) / 2$ 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 2* for values)

Figure 11. Square antennas
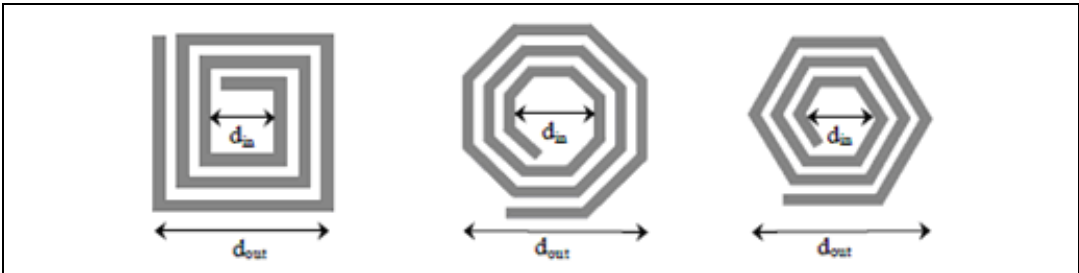
Table 2. K1 and K2 values according to layout

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

3.4 eDesignSuite antenna design tool

To easily develop the customer antenna, ST provides an antenna design tool, part of eDesignsuite, available from the NFC product web page on *www.st.com,* to compute rectangular antennas at 13.56 MHz.

After entering some parameters related to the PCB material and antenna dimensions, the tool estimates the antenna equivalent inductance by calculating the self-inductance and estimating the stray capacitance of the antenna.

Figure 12. Antenna user interface screen design module of eDesignsuite
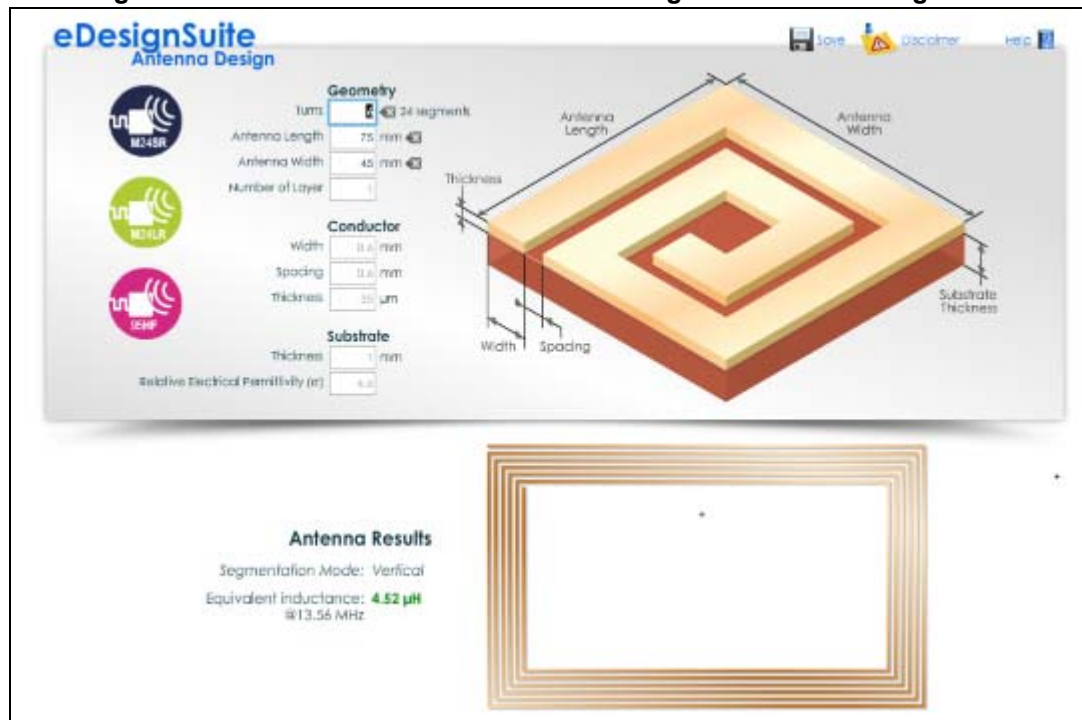
Figure 11 shows an example of antenna computation, the following parameters have to be defined:

- Antenna geometry parameters
  - Turns: number of complete turns (four segments per turn)
  - Antenna length, in mm
  - Antenna width, in mm
  - Number of layers (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 permittivity

Once the antenna equivalent inductance has been calculated, a prototype can be produced.

The antenna design is validated measuring the antenna impedance (using an impedance analyzer, a network analyzer or an LCR meter) or measuring the tuning frequency of the tag using a contactless method (see *Section 4*).

3.5 PCB layout

3.5.1 Length of the connections between dynamic NFC tag chip and antenna

The dynamic NFC tag chip must be laid out as close as possible to the antenna (a few millimeters). Any additional wire/trace changes the antenna characteristics and tuning.
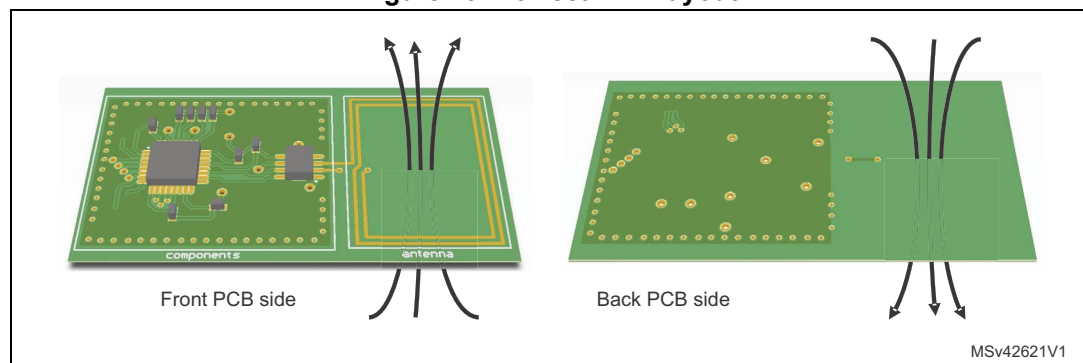
3.5.2 Ground, power, and signal layers

The layout of an inductive antenna on a PCB requires special attention:
- no copper planes above or below the antenna
- no copper planes surrounding the antenna.

Figure 13 shows what can be considered the optimal layout: the dynamic NFC tag chip is close to antenna, the ground plane is far from it.

Figure 13. Correct PCB layout

The energy transfer and the communication between the reader and the dynamic NFC tag are suitable because no copper planes overlap the antenna.

Bad design examples

Figure 14 and *Figure 15* show examples of incorrect design. In both cases, the electromagnetic flux cannot flow through the antenna, consequently there is no energy transfer between the reader and the dynamic NFC tag antenna.

Figure 14. Bad implementation - Example 1

Figure 15. Bad implementation - Example 2
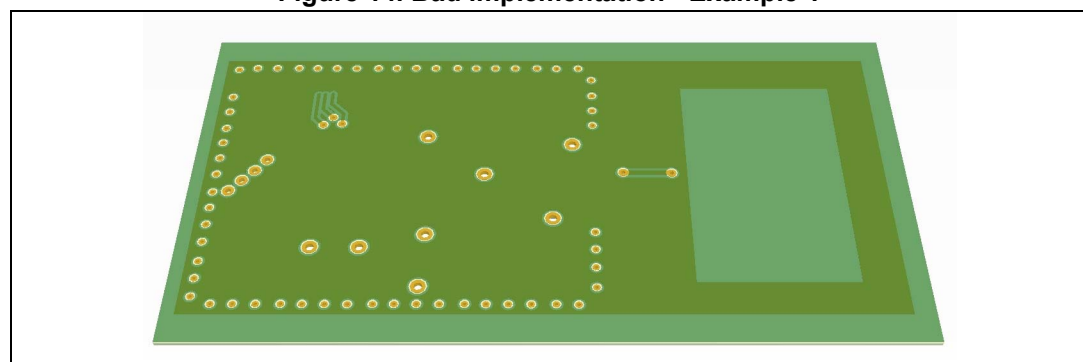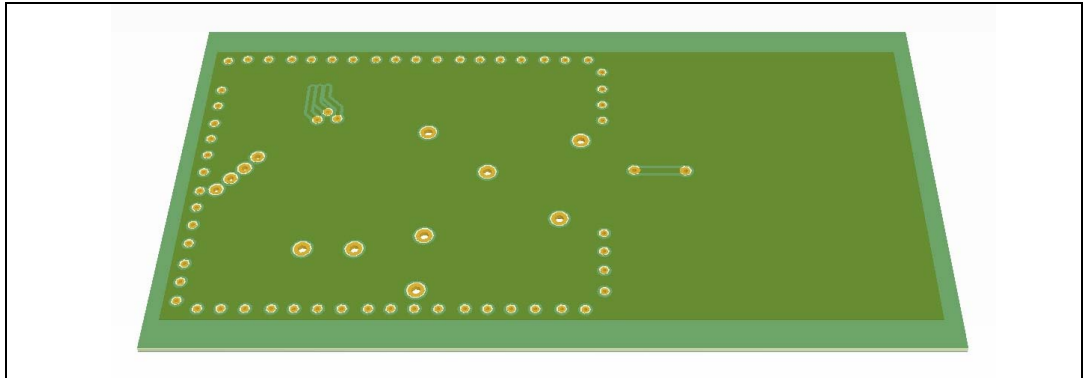

Figure 16 shows an example of a not recommended implementation. The electromagnetic flux is greatly attenuated by the short-circuited loop surrounding the dynamic NFC tag antenna.
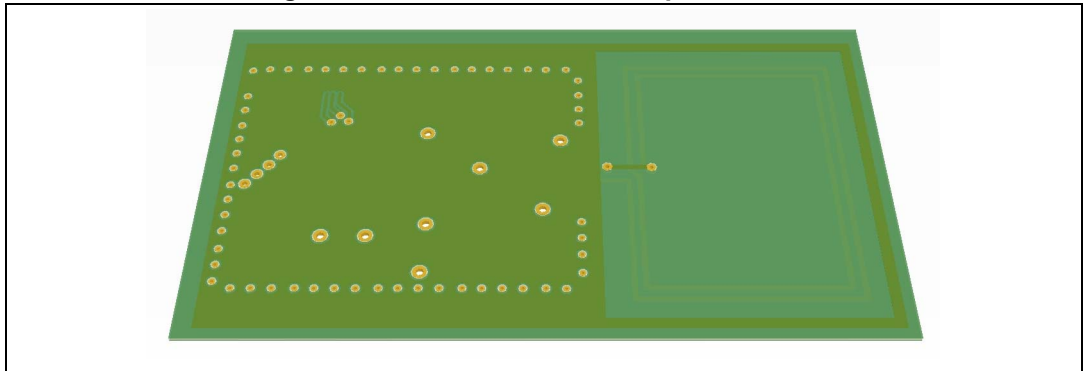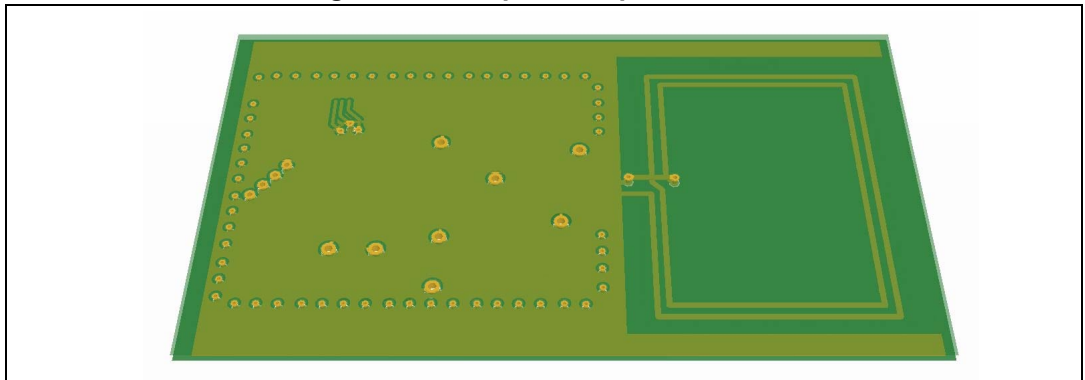
Figure 16. Not recommended implementation

*Figure 17* shows an acceptable implementation, here the antenna and the ground plane do not overlap.

Figure 17. Acceptable implementation

It is recommended to allocate a dedicated area of the PCB layout to the antenna only, with no surrounding ground layer, as shown in *Figure 13*.

3.5.3 Metal surfaces

When the antenna is placed close to a conductive surface, its self-inductance decreases. As a consequence, the tuning frequency of the NFC/RFID tag increases, as shown in *Figure 18*.

Figure 18. Effect of metal surfaces on the antenna frequency tuning
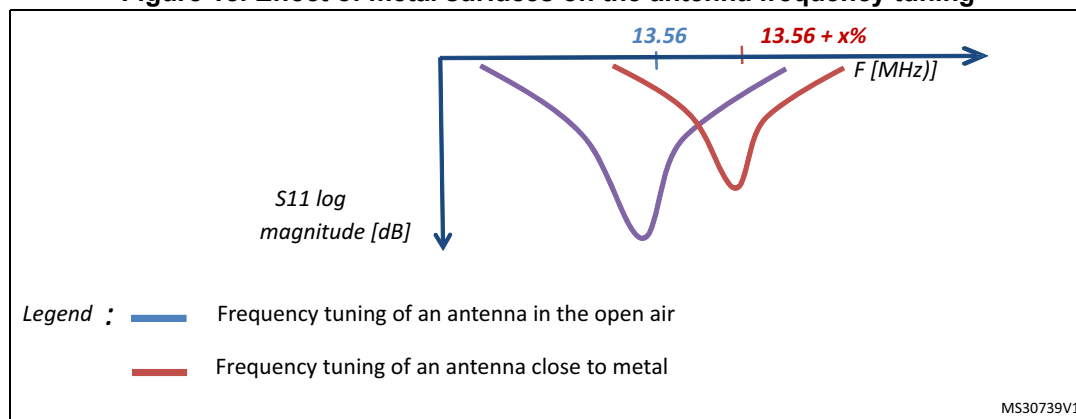
In addition to the tuning frequency drift, the tag quality factor decreases.

When an antenna designed to work in free space has to operate close to a metal surface, the frequency tuning drift must be compensated to get 13.56 MHz tuning frequency in the environment.

This can be achieved designing a new antenna with a larger equivalent inductance or adding an external tuning capacitance to the existing antenna.

Table 3 shows an example of tuning frequency drift compensation using an external cap.

Table 3. Frequency compensation examples

Features	ANT1-M24LR16E	ANT1-M24LR16E with 74 pF in parallel to the antenna
Antenna size	45 mm x 75 mm	45 mm x 75 mm
Frequency tuning in the air	13.7 MHz	7.5 MHz
Frequency tuning close to the metal surface [1]	25 MHz	14 MHz
Read range in the open air [1]	7.5 cm	0.5 cm
Read range close to the metal surface[1][2]	No detection	2.5 cm
Status	This antenna is tuned to operate in the open air	This antenna is tuned to operate close to metal

1. The measurement has been done with the CR95HF RF transceiver board from M24LR-Discovery kit.

2. The measurement has been done on an antenna stuck on the full metal table.

Antenna redesign results in an increased number of turns: this is possible only when sufficient space is available on PCB, and requires time for the new development steps.

When antenna redesign is not possible, an external capacitance has to be used.

4 How to check the NFC/RFID dynamic NFC tag antenna tuning

Different parameters can impact the tuning frequency of the NFC/RFID tag:

- antenna equivalent inductance computation precision
- length of the connexion between the device and its antenna in application
- antenna environment (metal surface, ferromagnetic materials close to the antenna).

It is then needed to check the resonant frequency of the NFC/RFID tag by measurement in the final application conditions.

4.1 Antenna tuning measurements with a network analyzer

The tuning frequency of the dynamic NFC tag antenna can be measured using a network analyzer with a loop probe.

The RF electromagnetic field is generated by connecting a loop probe to the output of the network analyzer set in reflection mode (S11 measurement).

Loop probe can come from the market, or be a self-made single turn loop made with a coaxial connector and a copper wire twisted at the end. Building the loop probe like this makes it possible to adjust the size of the loop to the size of the tag antenna for a better coupling during the measurement.

Figure 19. Measurement equipment

Network analyser   Loop probe   Antenna prototype with the M24LRxx
(represented as a capacitor)

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This equipment setup will directly display the system's resonant frequency.
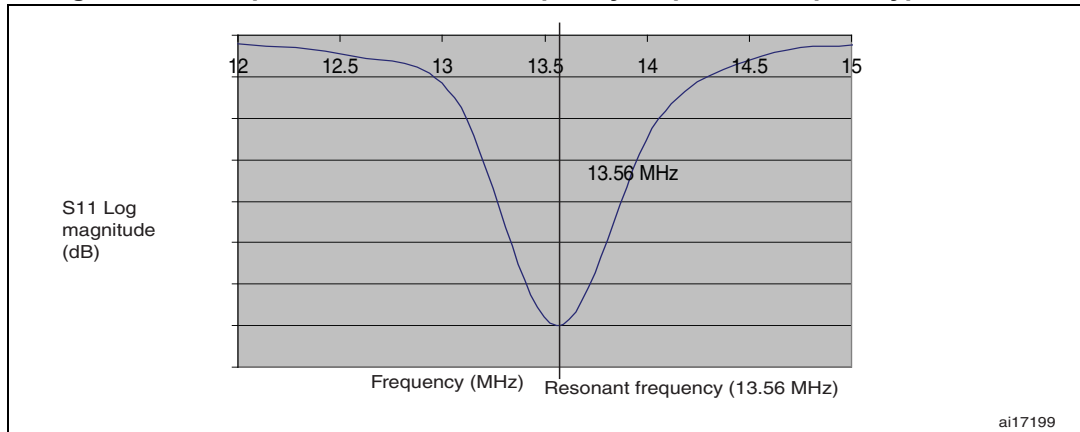
Experiments

The following list of parameters shows an example of instrument setup for measurement:

- start frequency: 5 MHz
- end frequency: 20 MHz
- output power: - 10 dBm
- measurement: reflection or S11
- format: log magnitude.

Place the antenna within the field generated the loop probe connected to the network analyzer. During the measurement, loop probe and tag antenna are magnetically and mutually coupled. In presence of the tag, the mutual coupling causes a change in the loop probe impedance.

At resonant frequency of the tag, loop probe impedance resistance reaches the maximum while the reactance returns to the self-resonance value; the loop probe impedance is nearly 50 Ω, evidenced by a minimum on the S11 curve.

Figure 20. Example of the resonant frequency response of a prototype antenna

4.2　Antenna measurements with standard laboratory tools

The antenna resonant frequency can also be measured with standard laboratory equipment like a signal generator, an oscilloscope and two standard loop antennas.

Experiment setup

Connect the first ISO 10373-7 standard loop antenna (see *Figure 21*) to the signal generator, to generate an RF electromagnetic field.

Connect the second ISO 10373-7 standard loop antenna to the oscilloscope (see *Figure 22*) by using either a standard oscilloscope probe (1 MΩ or 10 MΩ 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 single turn loop antennas, whose size can be matched to the tested tag.

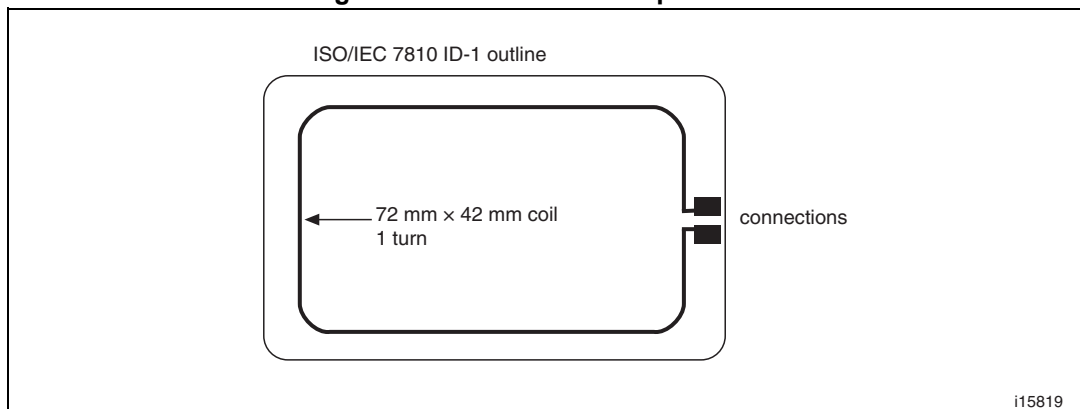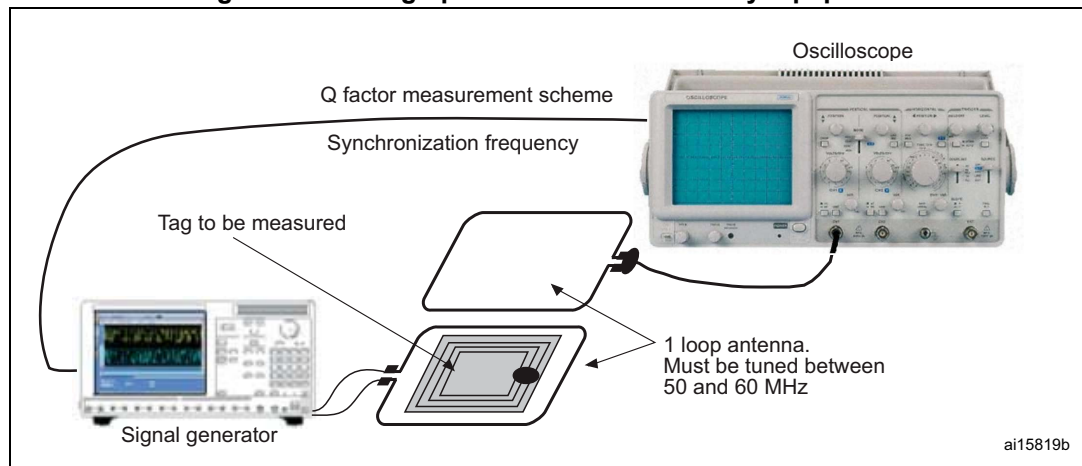**Figure 21. ISO standard loop antenna**

**Figure 22. Setting up the standard laboratory equipment**

Experiments

Place the tag in front of the loop antenna connected to the signal generator.

When a magnetic field is present, 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 the tag resonant frequency, the current flowing into the tag antenna, the magnetic field generated by the tag antenna and the voltage amplitude displayed by the oscilloscope are at their maximums.

Set the signal generator to output a sine wave with a peak-to-peak amplitude in the range of 200 mV. Starting from 5 MHz, increase the signal generator frequency until you reach the maximum amplitude of the signal measured with the oscilloscope, then the signal generator frequency corresponds to the resonant frequency of the tag.

Figure 23 provides the frequency response curve of the prototype antenna, which is based on measurement of the received signal amplitude at different frequencies.

Figure 23. Example of a frequency response measurement of a prototype antenna
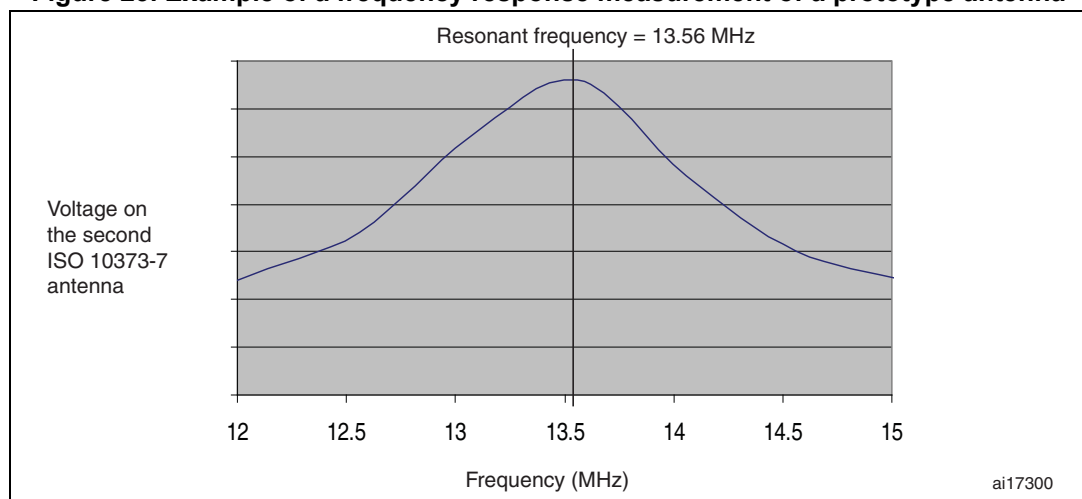
5 From design to production

Designers must expect some differences between the theoretical and the real performance of the antenna on the PCB in the end application. Here are a few considerations.

System level validation

Take great care when validating the antenna tuning for the various application use cases, programming traceability information on the manufacturing line, performing inventory of several end-products in the warehouse and reading data (end user).

Different reader profiles result in distinct performance levels on a given dynamic NFC tag board.

Figure 24. Application examples

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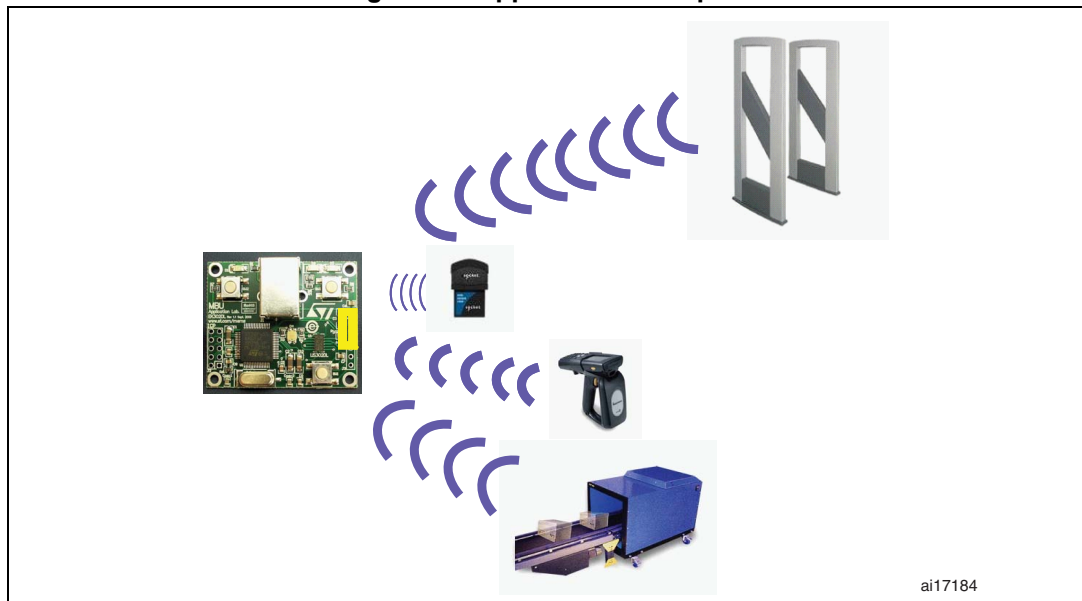
Considerations on the actual system tuning frequency

Even though all readers transmit at 13.56 MHz, the optimal tuning frequency of the M24LRxx or ST25DVxx antenna is not necessarily 13.56 MHz.

Some mutual mechanisms such as detuning/coupling between the reader antenna and the tag antenna may lead to an dynamic NFC tag chip antenna with an optimum tuning frequency different from 13.56 MHz.

A good example is ST's reference antenna (Gerber files available from *www.st.com*), whose tuning frequency is 13.74 MHz[a] to provide the best performance with the FEIG ELECTRONIC MR101 reader.

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a. Using the method described in *Section 3.5.3: Metal surfaces*.

The read range varies, depending on whether the dynamic NFC tag board is read alone or stacked with others (detuning effect). *Figure 25* illustrates the detuning effect.

Figure 25. Detuning effect
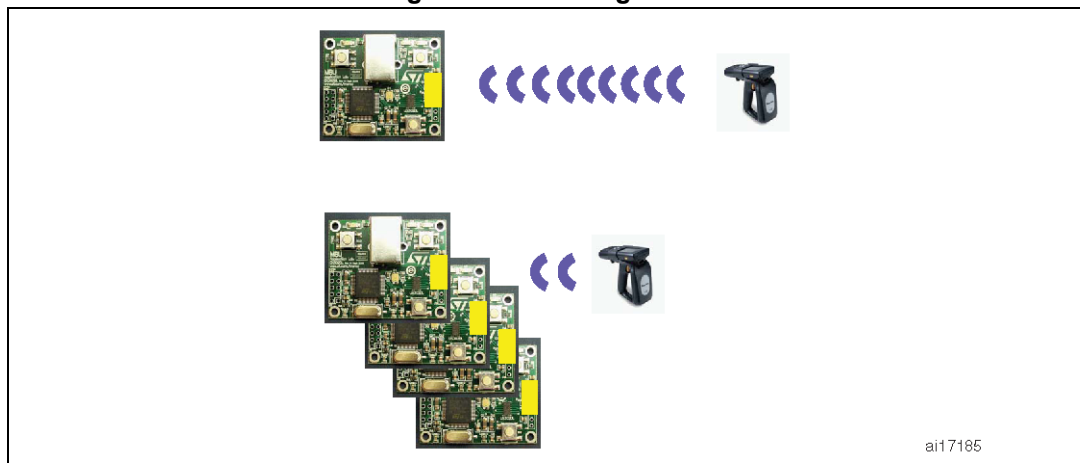
The vicinity of another dynamic NFC tag board may change the inductance dynamics. The boards may couple with each other, leading to a resultant antenna resonant frequency different from the individual one.

These are just examples of what may induce a difference between theory and real use cases. They are meant to emphasize the need for real life validation of antenna designs.

PCB manufacturing process validation

The PCB fabrication parameters (such as the copper or epoxy layer thickness) have an impact on the antenna inductance. Variations happen if the parameters of the PCB fabrication process change or in case of a change of PCB supplier.

Product packaging/housing considerations

The read range of the dual interface dynamic NFC tag board can be greatly affected by the housing of the final product.

The most obvious case is when a metallic housing is used. The product packaging then behaves as a Faraday cage, preventing the reader energy and signal from attaining the dual interface EEPROM device.

The housing also influences the PCB antenna's tuning frequency, for this reason, it is always recommended to measure the RF performance of the application in the final product configuration.

Figure 26. Impact of housing/packaging material on RF communication
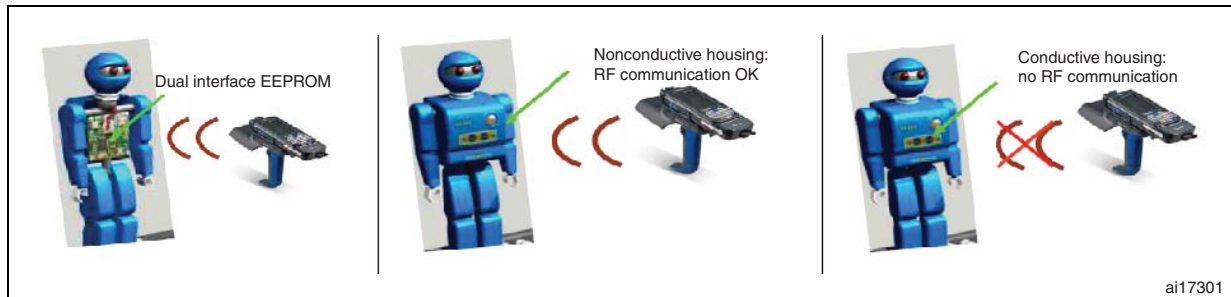
Process flow

- Design:
  - Start from the dual interface EEPROM's internal tuning frequency (C_{tuning}).
    Hint: check the device datasheet.
  - Calculate the theoretical $L_{antenna}$ value based on C_{tuning} and f_{tuning}.
    Hint: use the simplified models in this application note or other more sophisticated models developed in the RF literature.
  - Define the antenna dimensions.
  - Compute the theoretical antenna design and layout.
- Prototyping
  - Define an antenna matrix with different values centered around the targeted $L_{antenna}$ value.
    Hint: select 6 to 10 antennas with inductances that vary around $L_{antenna}$ by steps of 5 %.
  - Fabrication of the antennas and dynamic NFC tag chip mounting.

  For each prototype:
  - Measure the antenna tuning frequency.
  - Measure the read range with all types of selected RFID readers.
  - Measure the read range in configurations close to the actual product usage.
- Industrialization
  - Characterize the tuning frequency dispersion on a significant number of samples.
  - Measure the read range of the lowest and highest tuning frequency boards with various readers and in the various configurations.
  - Validate that the selected target $L_{antenna}$ value is appropriate versus the process variation.
- Production
  - Process monitoring

6 Revision history

Table 4. Document revision history

Date	Revision	Changes
26-May-2009	1	Initial release.
06-Aug-2009	2	Modified: – *Introduction* – *Section 2.1: Passive RFID technology* – *Section 2.2: Simplified equivalent inlay circuit* – *Section 2.4: Optimum antenna tuning* – *Section 3.3: Inductance of a square antenna* Added: *Section 5: From design to production*
18-Aug-2009	3	Corrected equation allowing to compute the tuning frequency on cover page.
04-Sep-2009	4	*Figure 3: Dynamic NFC tag chip power mechanism in RF mode*, *Figure 5: Communication from the reader to the tag* and *Figure 6: Communication from tag to the reader* modified. *Section 3.5: PCB layout* added. *Section 4.1: Antenna tuning measurements with a network analyzer* and *Section 4.2: Antenna measurements with standard laboratory tools* modified. *Considerations on the actual system tuning frequency* added. *PCB manufacturing process validation* modified. *Product packaging/housing considerations* and *Process flow* added. Small text changes.
11-Feb-2010	5	Document classification level changed to public. Power transfer updated in *Section 2.1: Passive RFID technology*. *Section 2.4* title modified.
21-Dec-2012	6	M24LR64-R replaced by M24LRxx-R and M24LRxxE-R on the cover page, then by M24LRxx (see *Note:*). Moved former third and fourth paragraphs on the cover page to *Section 1: Operating mode*. Added *Table 1: Applicable products*. Added *Section 3.5.3: Metal surfaces*.

Table 4. Document revision history (continued)

Date	Revision	Changes
17-Jan-2017	7	Updated: – *Introduction* – *Section 1: Operating mode* – *Section 2: Basic principles and equations* – *Section 3: How to design the antenna on a PCB* – *Section 4: How to check the NFC/RFID dynamic NFC tag antenna tuning* – *Figure 1: Dynamic NFC tags* – *Figure 3: Dynamic NFC tag chip power mechanism in RF mode* – *Figure 4: Power transfer versus reader/dynamic NFC tag orientation* – *Figure 5: Communication from the reader to the tag* – *Figure 6: Communication from tag to the reader* – *Figure 7: Equivalent circuit of the dynamic NFC tag chip and its antenna* – *Figure 8: Equivalent circuit of the dynamic NFC tag chip mounted on a loop antenna* – *Figure 11: Square antennas* – *Figure 13: Correct PCB layout* – *Figure 14: Bad implementation - Example 1* – *Figure 15: Bad implementation - Example 2* – *Figure 16: Not recommended implementation* – *Figure 17: Acceptable implementation* – *Figure 22: Setting up the standard laboratory equipment* – *Table 1: Applicable products* – *Table 3: Frequency compensation examples*
24-Jul-2018	8	Updated *Table 1: Applicable products*.
04-Mar-2019	9	Updated *Section 3.2: Inductance of a spiral antenna*. Updated *Figure 10: Spiral antenna*. Minor text edits across the whole document.

IMPORTANT NOTICE – PLEASE READ CAREFULLY