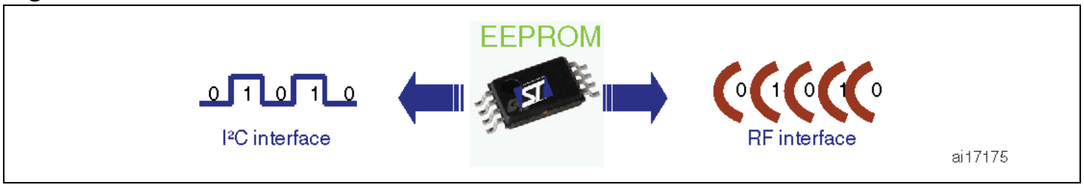
AN2972
Application note

Designing an antenna for the M24LRxx-R and M24LRxxE-R dual interface I²C/RFID devices

Introduction

The M24LRxx-R or M24LRxxE-R device is an EEPROM designed for access via two different interfaces: a wired I^2C interface and a standard contactless ISO 15693 RFID interface.

Figure 1. Dual interface EEPROM



Both interfaces are widely used industry standards. The M24LRxx-R or M24LRxxE-R can be integrated into almost any electronic application, provided that the processor offers an I^2C interface. It may also be accessed by any RFID reader that supports the ISO 15693 interface.

The purpose of this application note is also to:

- explain the basic principle of passive RFID
- describe the basics of a 13.56 MHz inductive antenna design
- provide some 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
Dual interface EEPROMs	M24LRxx-R, M24LRxxE-R
Evaluation boards	ANTx-M24LRxxx, M24LR-Discovery, ROBOT-M24LR16E-A STEVAL-IHP004V1, STEVAL-IPR002V1, STEVAL-IPE020V1

Note: The standard M24LRxx-R and energy-harvesting M24LRxxE-R devices will be referred to as M24LRxx devices throughout the document.

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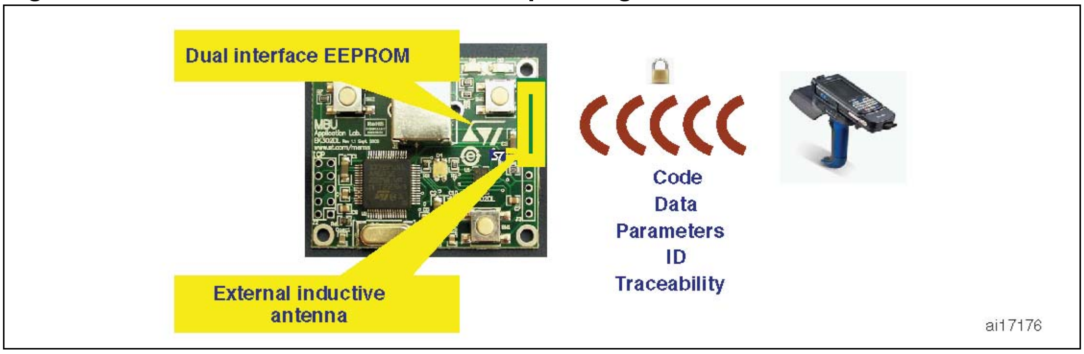
Integrating the M24LRxx-R or M24LRxxE-R in an application is simple: on the I^2C side, there is no specific design requirement as the device interfaces exactly as any serial I^2C EEPROM device. On the RF side, the M24LRxx-R or M24LRxxE-R needs to be connected to an external antenna to operate.

Figure 2. M24LRxx-R or M24LRxxE-R operating modes



The design principle of the M24LRxx-R or M24LRxxE-R antenna is very simple: the external antenna inductance ($L_{antenna}$) that needs to be designed on board the PCB should match the M24LRxx-R or M24LRxxE-R internal tuning capacitance (C_{tuning}) in order to create a circuit resonating at 13.56 MHz. The basic equation of the tuning frequency is:

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

1 Basic principles and equations

Definition

RFID reader: an electronic device used for communication between RFID tags (like the M24LRxx) and a host computer system. A reader generally consists of an RF transmitter and receiver and an antenna for communicating with tags. A digital interface enables the reader to communicate with the host computer system. RFID readers are capable of both reading and writing the tags.

1.1 Passive RFID technology

The ISO 15693 protocol is based on a passive RFID technology, operating in the high-frequency (HF) band, at 13.56 MHz.

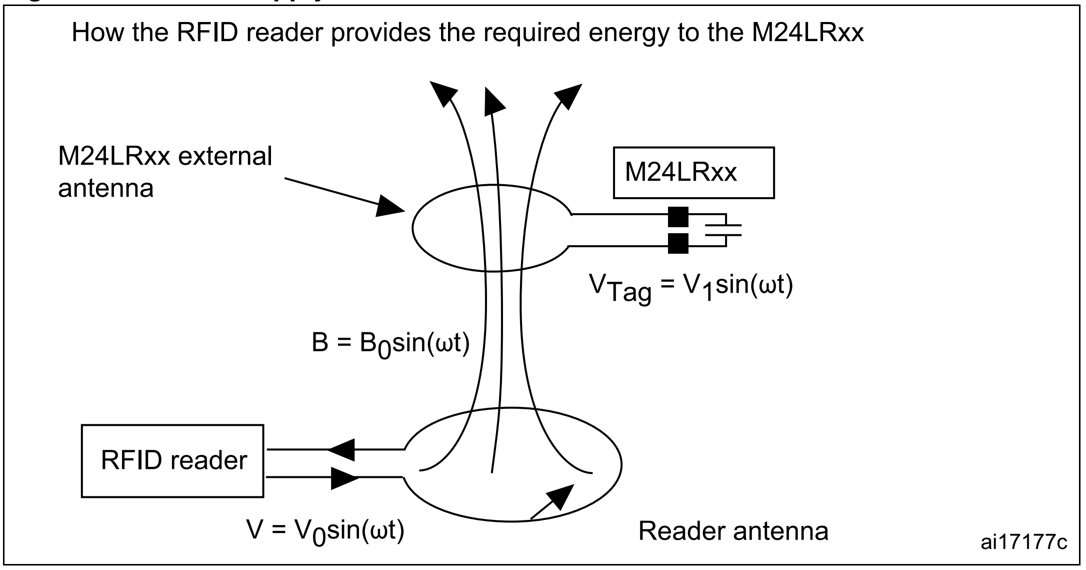
Power transfer

When the M24LRxx operates in the RF mode, it is powered by the RFID reader. No battery is then required to access it whether in write or read mode. With its external inductive antenna, the M24LRxx draws all of its operating power from the reader's electromagnetic field.

The RFID reader plays the same role as the primary of a voltage transformer that powers the secondary (in this case, the M24LRxx and its inductive antenna). The energy transfer ratio from the reader to the M24LRxx is similar to the coupling factor of a voltage transformer. It is a function of:

- how well the M24LRxx and its antenna are tuned to the reader's carrier frequency (around 13.56 MHz)
- the distance between the reader and the M24LRxx board
- the dimensions of the reader antenna and the M24LRxx board
- the reader power
- the M24LRxx antenna orientation with regards to the reader antenna

Figure 3. Power supply in RF mode

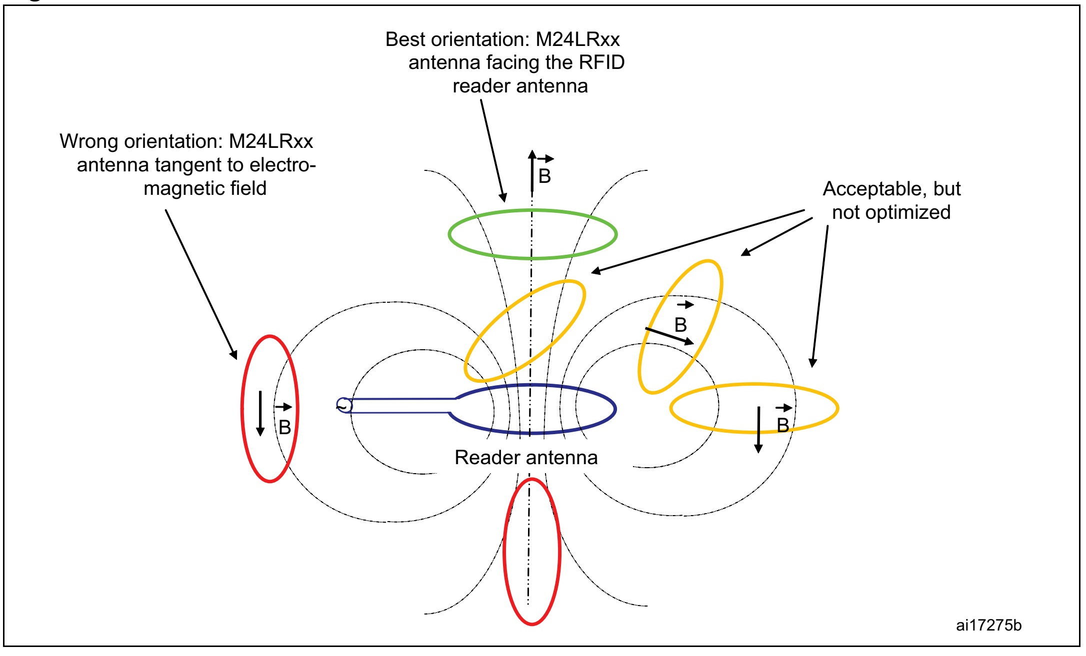


When the M24LRxx is placed in the RFID reader's electromagnetic field, the amount of energy powering the device is directly related to the orientation of the M24LRxx antenna with regards to the RFID reader antenna. Indeed, this energy depends on how the electromagnetic field lines generated by the reader flow through the M24LRxx antenna. This directly impacts the M24LRxx/reader read range:

- The best configuration is obtained when both antennas are parallel and face each other.
- The read range can drop to zero when both antennas are perpendicular to each other.
- Any other orientation is possible and will result in different read ranges.

Figure 5 shows different power transfer configurations.

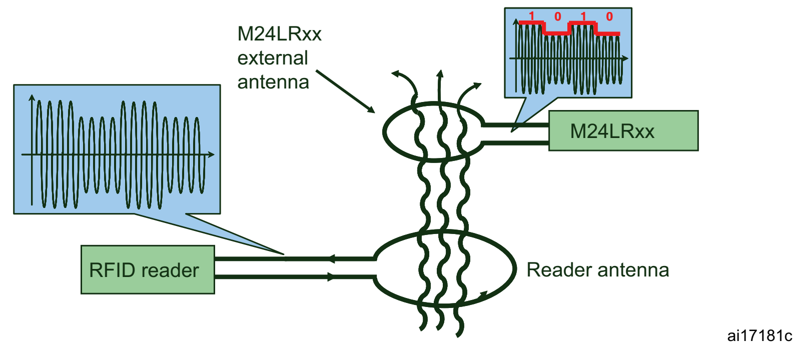
Figure 4. Power transfer versus reader/M24LRxx orientation



Data transfer

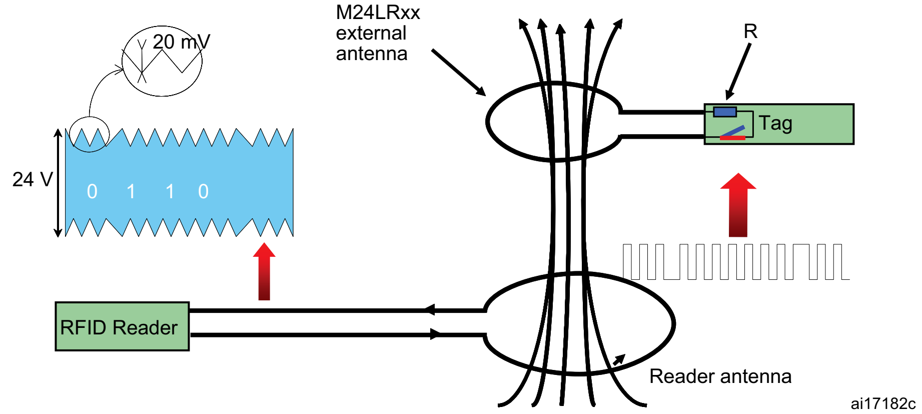
Placed in the RFID reader's electromagnetic field, the M24LRxx built-in circuitry demodulates the information coming from the reader.

Figure 5. From the RFID reader to the M24LRxx



In order to send its response back to the reader, the M24LRxx backscatters the data to the reader by internally changing its output impedance back and forth, which is detected by the reader.

Figure 6. From the M24LRxx to the RFID reader



All this is part of the standard protocol and taken care of by the M24LRxx embedded circuitry and the RFID reader's electronics.

The main thing designers need to concentrate on is designing the M24LRxx antenna that meets the application requirements in terms of read range and antenna size.

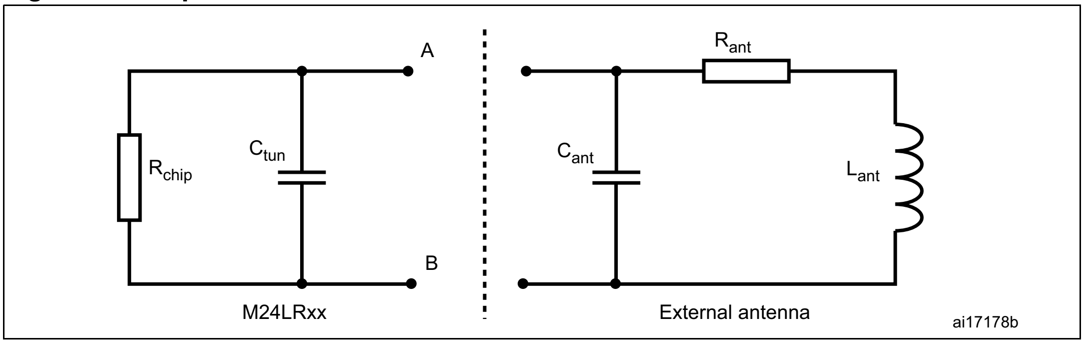
1.2 Simplified equivalent inlay circuit

The chip and its antenna can be symbolized using their equivalent electrical circuit.

Figure 7 shows the equivalent electrical circuit of the M24LRxx (parallel association of a resistance which emulates the current consumption of the chip and a capacitance added to the chip to ease tuning).

The antenna is a wire, so its equivalent electrical circuit is a wire with a resistance symbolized by R_{ant}. The antenna also has an inductance denoted by L_{ant}. The capacitance C_{ant} is the representation of parasitic elements (produced by the bridge).

Figure 7. Equivalent circuit of the M24LRxx and its antenna



In first-order equations, R_{chip}, C_{ant} and R_{ant} are negligible. This is why the basic equations that follow will only take L_{ant} and C_{tun} into consideration.

1.3 Basic equations

Resonant frequency

The resonant frequency of the LC circuit is defined by the equation:

$$LC\omega^2 = 1$$

where:

- L is the inductance in Henry
- C is the capacitance in Farad
- ω is the angular frequency in radians per second ($\omega = 2 \times \pi \times f$, with f = frequency in Hz)

1.4 Optimum antenna tuning

The total impedance of an LC loop is given by the sum of the inductive and capacitive impedances:

$$Z = Z_L + Z_C$$

By writing the inductive impedance as $Z_L = j\omega L$ and the capacitive impedance as $Z_C = 1/j\omega C$, and then substituting in the previous equation, you have:

$$Z = j\omega L + 1/j\omega C$$

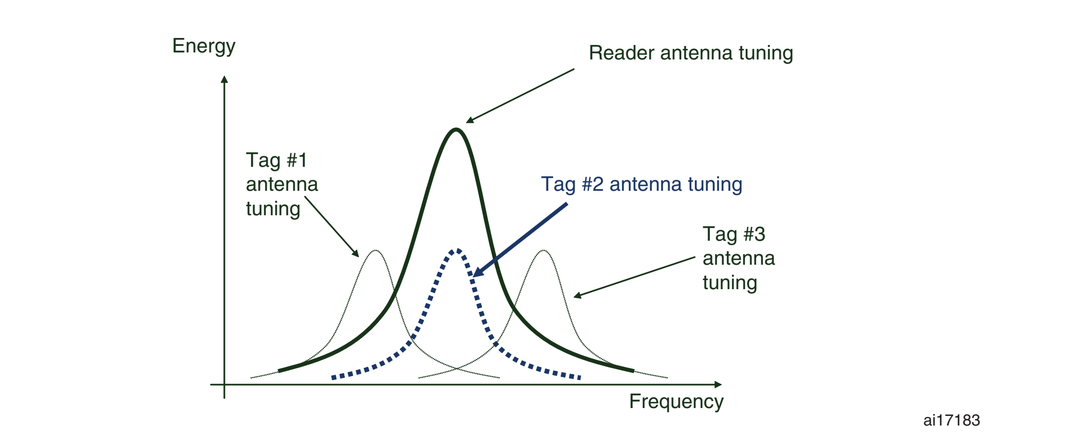
Now, extracting a common denominator yields:

$$Z = (1 - LC\omega^2) / j\omega C$$

Note: The total impedance Z is zero at the resonant frequency of the LC circuit (the numerator is zero when $LC\omega^2 = 1$). The resonant frequency corresponds to the maximum current received by the [L,C] loop; in this case, the M24LRxx (capacitor C) and the antenna (inductor L).
Consequently, the dual interface device's antenna must be tuned so that its resonating frequency matches the RFID reader antenna's tuning frequency as much as possible. At this

point, the coupling factor between the RFID reader and the dual interface EEPROM antenna is the best, meaning the best possible read range from the application standpoint.

Figure 8. Tuning the M24LRxx antenna



In *Figure 8*, Tag #2 is best tuned for this application configuration.

2 How to design an antenna on a PCB

Designing an inductive antenna is about impedance matching. The antenna impedance must match the conjugated impedance of the M24LRxx in order to obtain the needed tuning frequency.

A 13.56 MHz antenna can be designed with different shapes, depending on the application requirements. As explained previously, the major parameter is the inductance L of the antenna. The following paragraphs offer a way of computing the antenna dimensions for a determined value of inductance L.

2.1 Inductance of a circular antenna

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

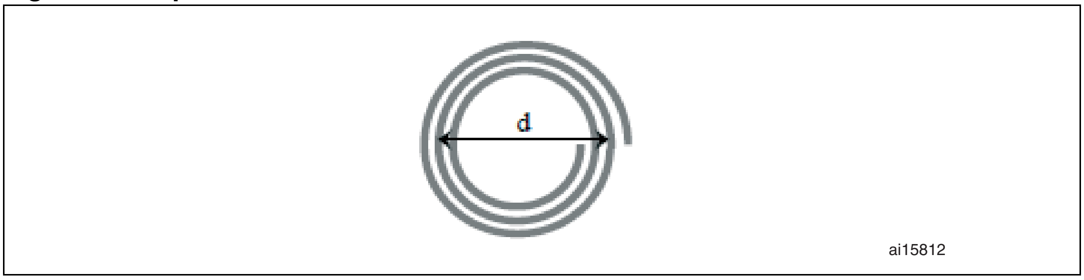
- r is the radius in millimeters
- r_0 is the wire diameter in millimeters
- N is the number of turns
- $\mu_0 = 4\pi \cdot 10^{-7}$ H/m
- L is measured in Henry

2.2 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 antenna 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 9. Spiral antenna



2.3 Inductance of a square antenna

$L_{ant} = K1 \times \mu_0 \times N^2 \times \frac{d}{1 + K2 \cdot p}$, 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 10. Square antennas

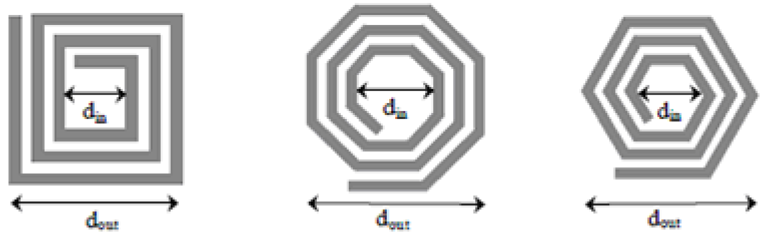


Table 2. K1 and K2 values according to layout

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

2.4 ST antenna calculation tool

ST provides a simplified software tool (**antenne.exe**) to compute inductances of rectangular planar antennas. The purpose of this tool is to give good approximations: the obtained results should be verified.

This tool uses the Grover method (see *Equation 1*). *Figure 11* shows the user interface.

Equation 1: Grover method

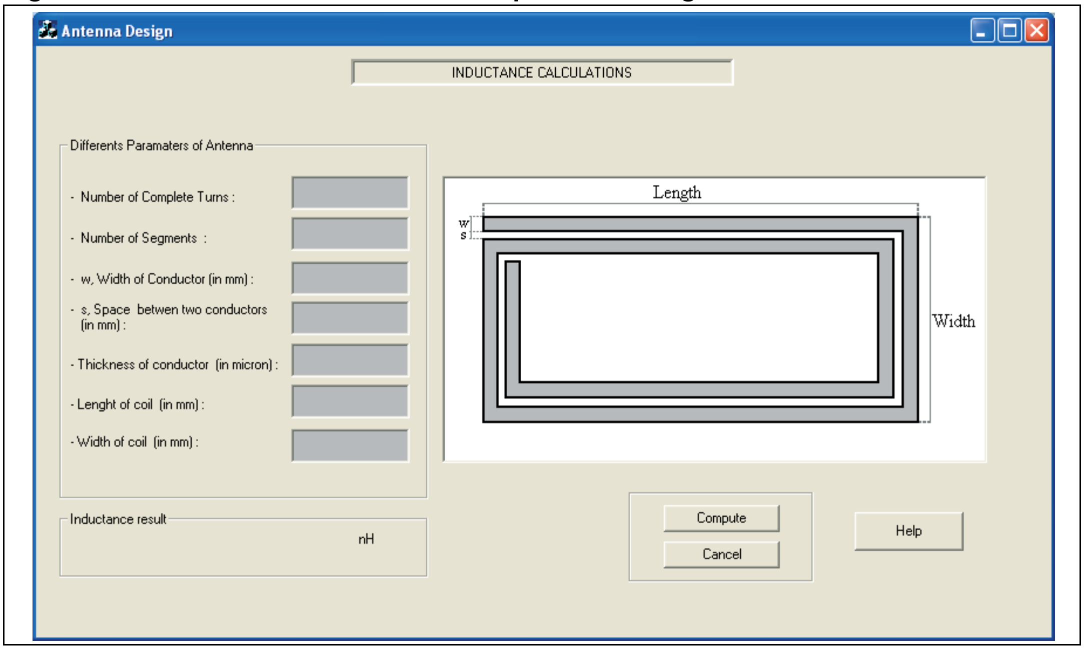
$L_{ant} = L_0 + \sum M$, where:

- M is the mutual inductance between each of the antenna segments
- L_0 is as defined in *Equation 2*

Equation 2: $L_0 = \sum_{j=1}^{s} L_j$, where:

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

Figure 11. User interface screen of the planar rectangular coil inductance calculator



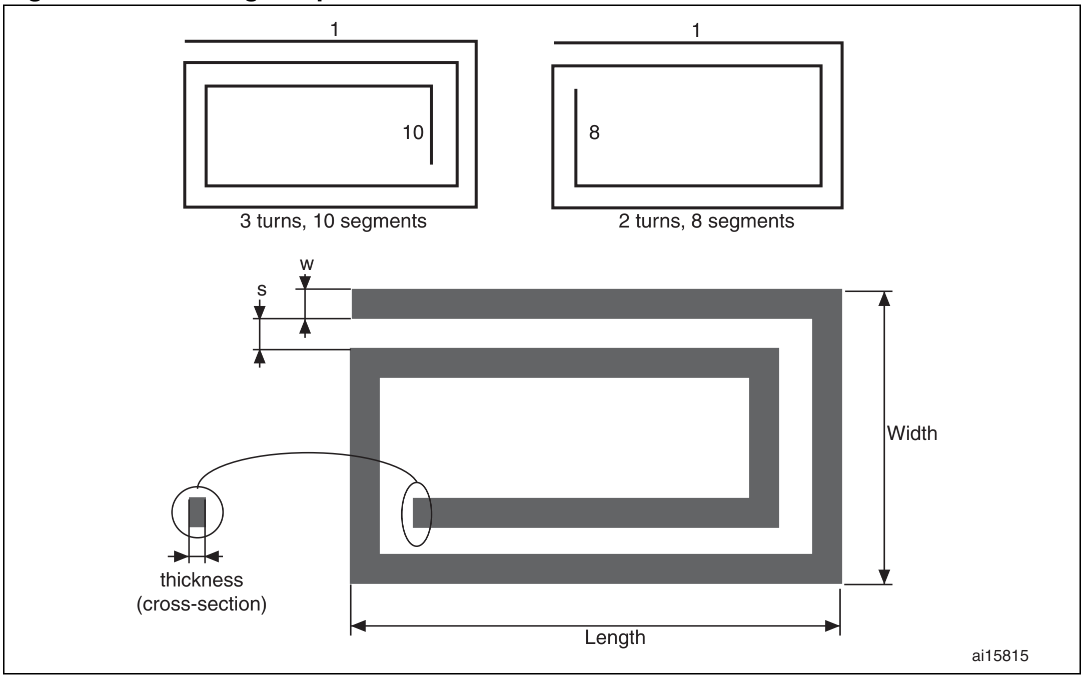
Examples:

The following antenna parameters have to be fed to the software to compute the antenna coil inductance:

- the number of turns
- the number of segments
- w: the conductor width in millimeters
- s: the conductor spacing in millimeters
- the conductor thickness in micrometers
- Length in millimeters
- Width in millimeters

The number of turns is incremented each time a segment is added to a complete turn.

Figure 12. Rectangular planar antennas



Once the antenna coil inductance has been calculated, a prototype coil is realized. The value of the so-obtained prototype must then be validated by measurement. This can be done using either a contactless or a non-contactless method.

2.5 PCB layout

2.5.1 M24LRxx-antenna distance

The M24LRxx must be laid out as close as possible to the antenna (a few millimeters). Any additional wire/trace would change the antenna characteristics and tuning.

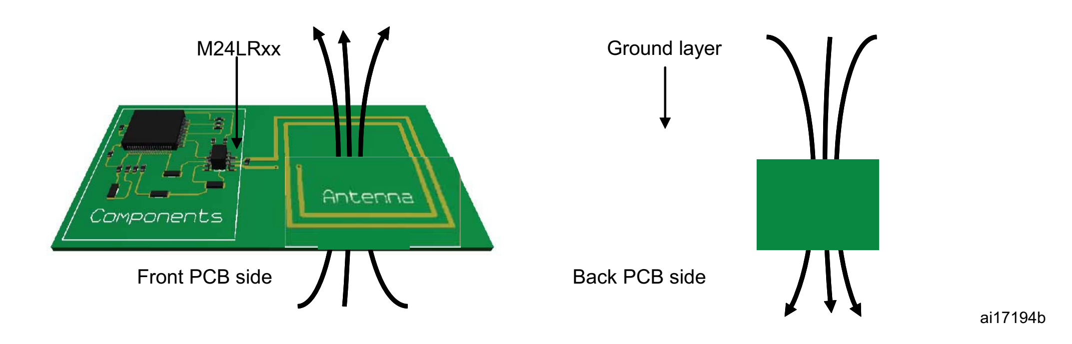
2.5.2 Ground layer considerations

Designing an inductive antenna on a PCB means that special attention must be paid to ground plane design:

- no ground plane above or below the antenna
- no ground plane surrounding the antenna

Figure 13 shows a correct layout.

Figure 13. M24LRxx close to antenna but ground plane distant from antenna



The signal and energy transfers between the reader and the M24LRxx board are good as long as the antenna and the ground layer do not overlap.

Examples of bad implementations

Figure 14 and *Figure 15* show two examples of bad implementation. In both cases, the electromagnetic flux cannot flow through the antenna, there is no energy transfer between the reader and the M24LRxx antenna.

Figure 14. Bad implementation No.1

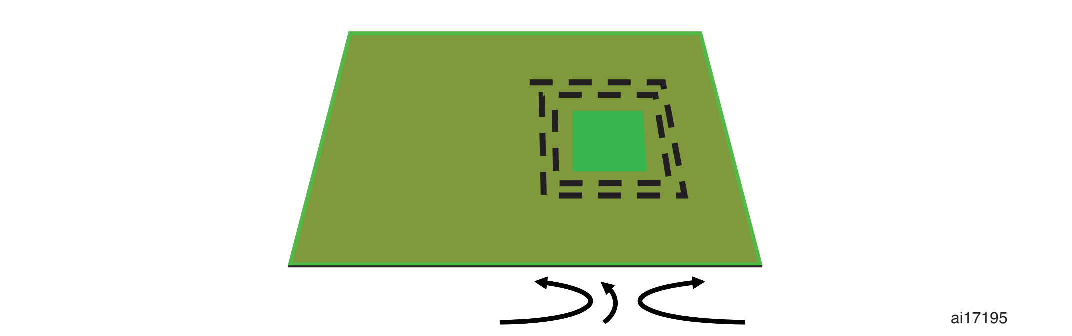


Figure 15. Bad implementation No.2

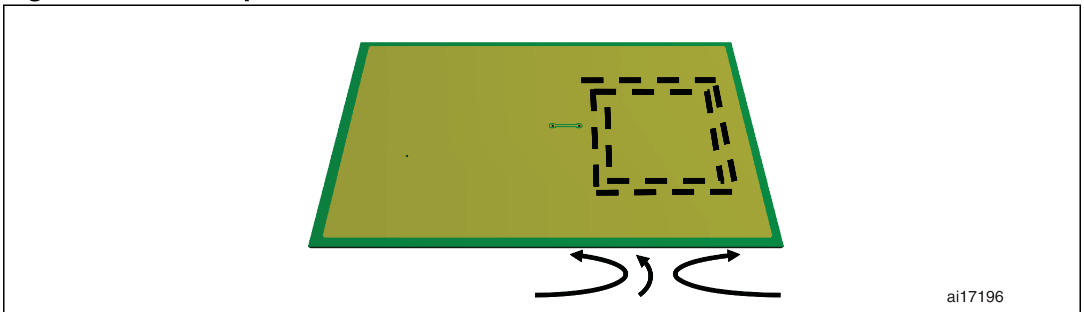


Figure 16 shows an example of a not recommended implementation. The electromagnetic flux is greatly attenuated by the short-circuited loop surrounding the M24LRxx antenna.

Figure 16. Not recommended implementation

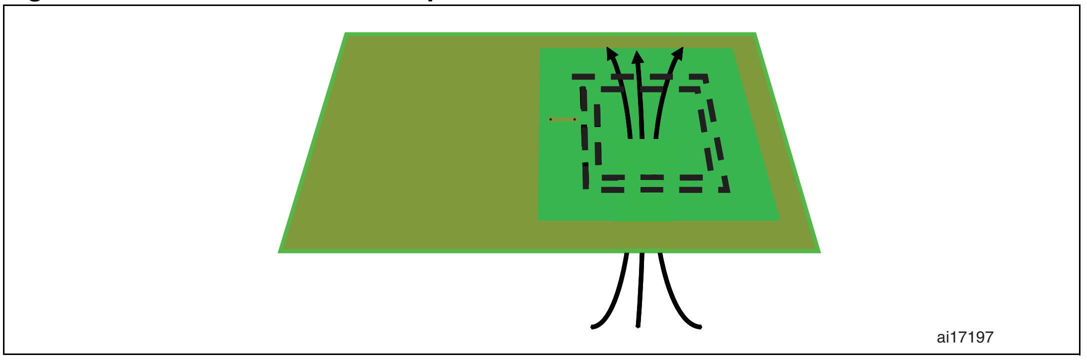


Figure 17 shows an acceptable implementation, if the antenna and the ground plane do not overlap.

Figure 17. Acceptable implementation

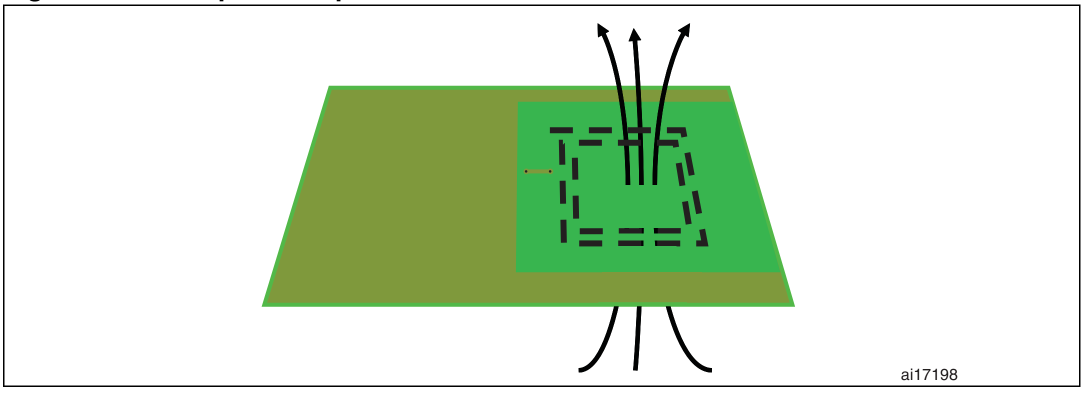


Figure 13 remains the best solution.

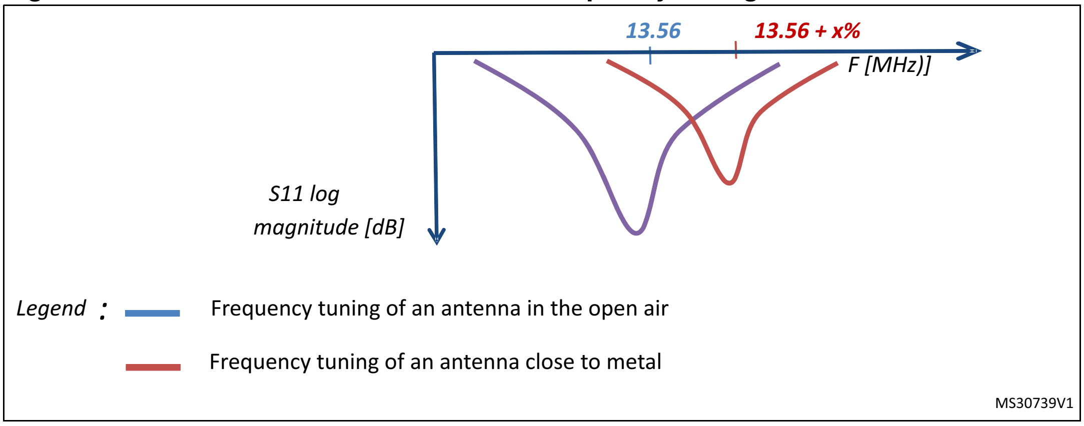
STMicroelectronics recommends designers to allocate a dedicated area of the PCB layout to the antenna only, with no surrounding ground layer.

2.5.3 Metal considerations

What does it happen when there is metal near the antenna?

When the antenna of the M24LRxx is close to metal, it changes its own resonance frequency, as shown in *Figure 18*.

Figure 18. Effect of metal on the antenna frequency tuning



Due to the modification of the tuning frequency, when an antenna is close to metal, the frequency tuning of a tag should be modified: tuned at 13.56 MHz in the metal environment.

In other words, when a tag is placed in a metal environment, the tuning frequency of the tag in the open air must be set to compensate for future shift. The metal environment induces eddy current, quality factor downgrading, frequency detuning and a modification of the field-strength distribution.

As a conclusion, when an antenna, which has been tuned in order to operate in the open air, is to operate near metal, it is necessary to redesign a new antenna which will be precisely tuned with the global application.

Table 3. Antenna features

Features	Antenna 1: ANT1-M24LR16E	Antenna 2: ANT1-M24LR16E with 74 pF in parallel of 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 stuck on the metal (1)	25 MHz	14 MHz
Read range in the open air (1)	7.5 cm	0.5 cm
Read range close to metal (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 DEMO-CR95HF-A.
2. The measurement has been done as per an antenna stuck on the full metal table.

3 How to check the M24LRxx antenna tuning

The methods of antenna design described in the previous section may lead to an inductance slightly different from the value that would offer optimum performance in the end application. This is because the overall inductance of the antenna might slightly drift in the application (with magnetic and ferromagnetic materials in the proximity of the antenna). It is therefore necessary to run actual measurements of the resonant frequency of the antenna.

3.1 Antenna tuning measurements with a network analyzer

The tuning frequency of the M24LRxx antenna can be measured using a network analyzer with a loop probe.

The RF electromagnetic field is generated by connecting a loop probe (like the 7405-901 Eaton/Alitech 6 cm loop) to the output of the network analyzer set in reflection mode (S11 measurement).

Figure 19. Measurement equipment

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

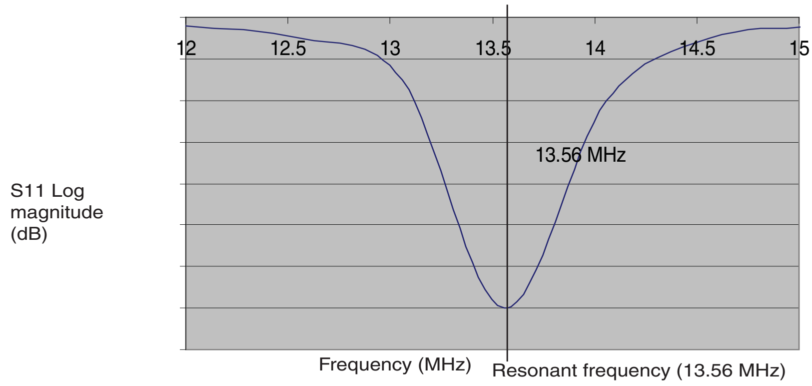
Experiments

As the objective is to find an [$L_{antenna}$ + M24LRxx C_{tuning}] tuned at 13.56 MHz, the frequency sweep range has to be set around this value, that is:

- 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 by the network analyzer + loop probe. The resonant frequency corresponds to the minimum observed on the S11 measurement curve.

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



3.2 Antenna measurements with standard laboratory tools

The antenna resonant frequency can also be measured with standard laboratory equipment like:

- a signal generator
- an oscilloscope
- two standard loop antennas

Experiment setup

Connect the first ISO 10373-7 standard loop antenna (see *Figure 21*) to the signal generator to provide the 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 (1M or 10M input impedance) or a 50 Ω BNC cable (oscilloscope input set to 50 Ω in this case).

Place the [antenna+M24LRxx] inside the RF electromagnetic field.

Figure 21. ISO standard loop antenna

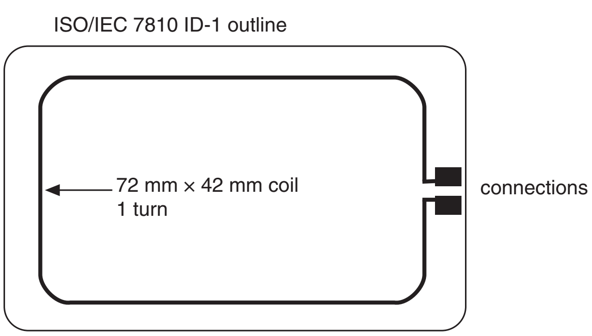
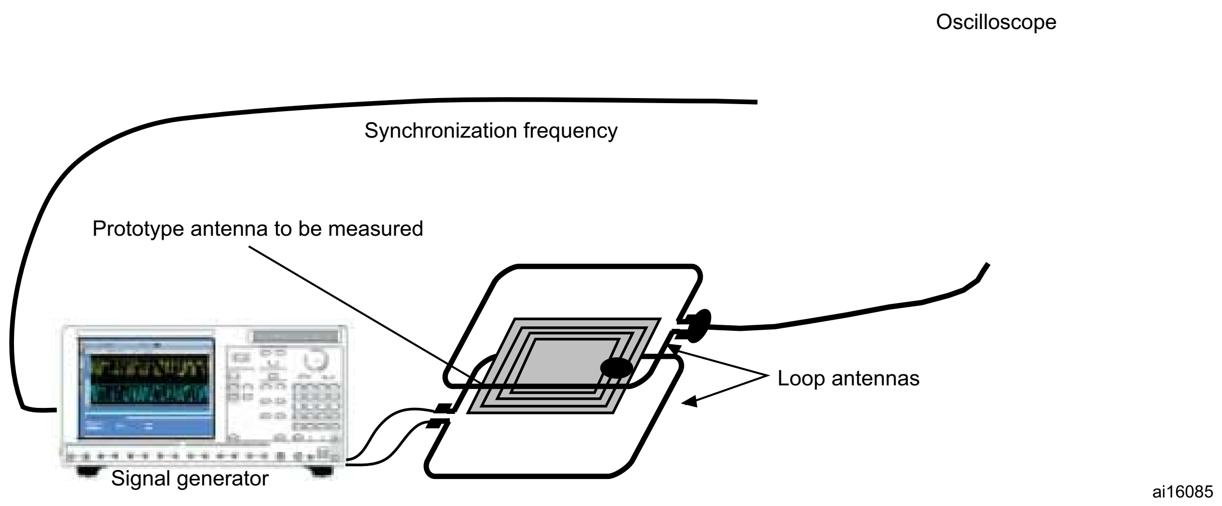


Figure 22. Setting up the standard laboratory equipment

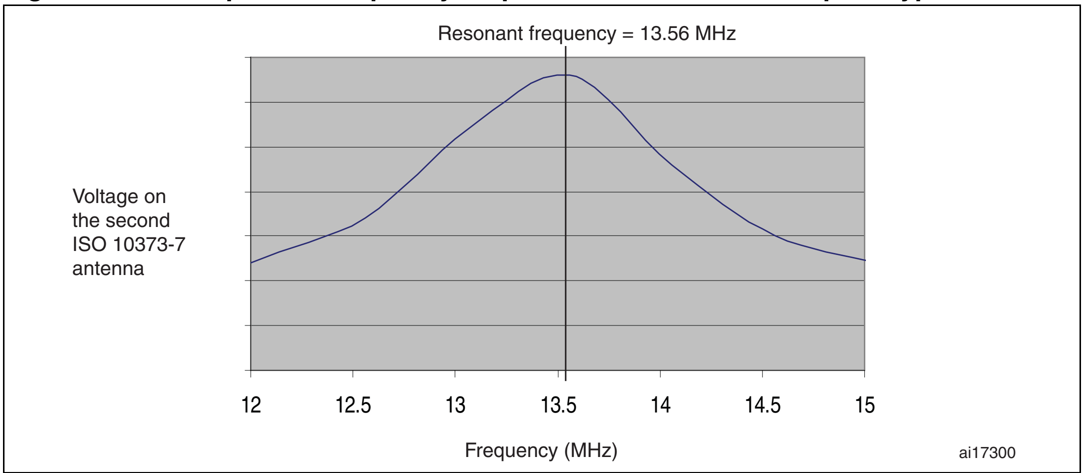


Experiments

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. The signal generator frequency then corresponds to the resonant frequency of the [antenna+M24LRxx] pair.

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

Figure 23. Example of a frequency response measurement of a prototype antenna



4 From design to production

Designers should expect some difference between the theoretical and the real performance of the antenna on the PCB in the end application.

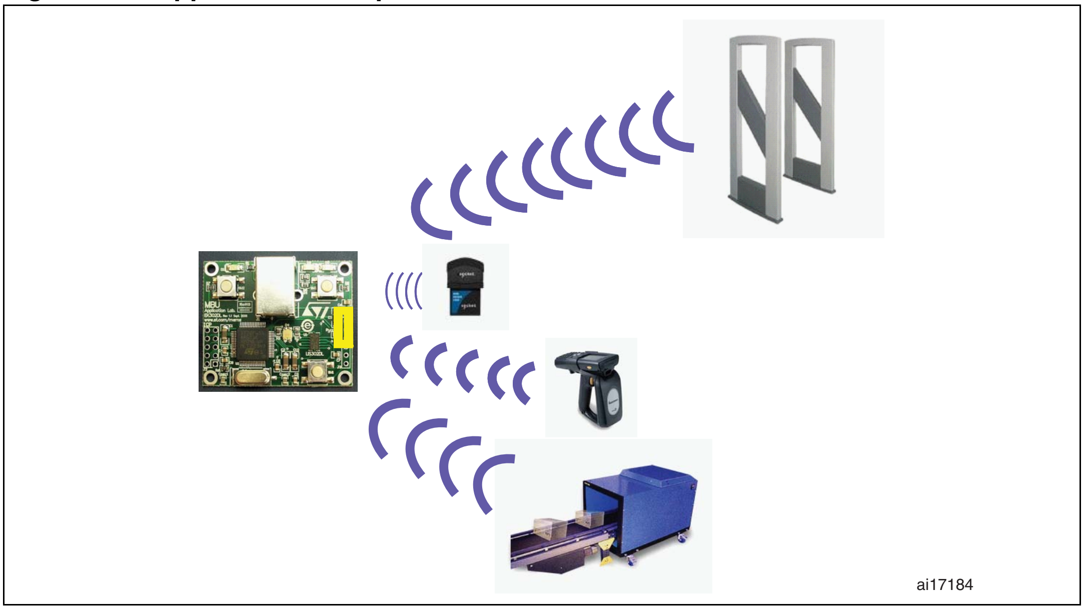
Here are a few considerations:

System level validation

It is paramount to take great care when validating the antenna tuning for the various application use cases, whether it be programming traceability information on the manufacturing line, performing inventory of several end-products in the warehouse or reading data (end user).

Different reader profiles would result in distinct performance levels on a given M24LRxx board.

Figure 24. Application examples



Considerations on the actual system tuning frequency

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

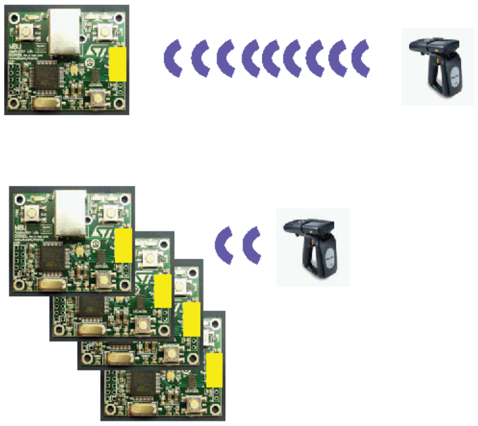
Some mutual mechanisms such as detuning/coupling between the reader antenna and the tag antenna may lead to an M24LRxx antenna with an optimum tuning frequency different from 13.56 MHz.

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 MR101 reader.

a. Using the method described in *Section 2.5.3: Metal considerations*.

The read range varies depending on whether the M24LRxx board is read alone or stacked with others (detuning effect). *Figure 25* illustrates the detuning effect.

Figure 25. Detuning effect



The vicinity of another M24LRxx 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.

Departments such as quality, operations and manufacturing should therefore be made aware of this.

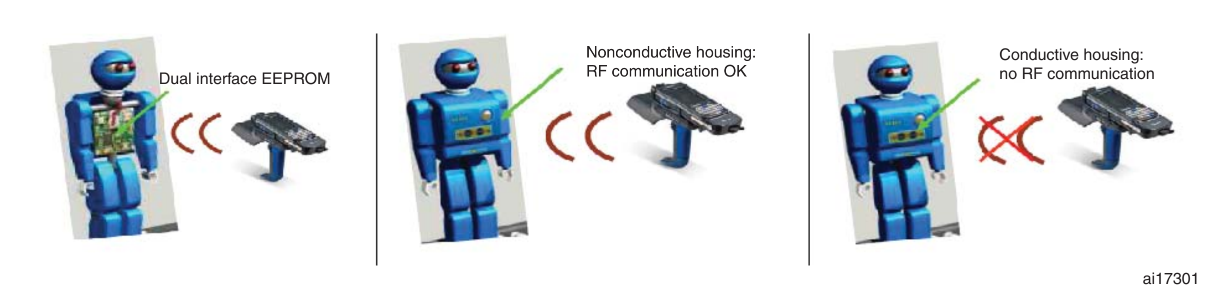
Product packaging/housing considerations

The read range of the dual interface M24LRxx 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 might also influence the PCB antenna's tuning frequency, which is why 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 M24LRxx mounting.

  For each prototype:
  – Measure the antenna's 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

5 Revision history

Table 4. Document revision history

Date	Revision	Changes
26-May-2009	1	Initial release.
06-Aug-2009	2	Modified: – *Introduction* – *Section 1.1: Passive RFID technology* – *Section 1.2: Simplified equivalent inlay circuit* – *Section 1.4: Optimum antenna tuning* – *Section 2.3: Inductance of a square antenna* Added: *Section 4: 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: Power supply in RF mode*, *Figure 5: From the RFID reader to the M24LRxx* and *Figure 6: From the M24LRxx to the RFID reader* modified. *Section 2.5: PCB layout* added. *Section 3.1: Antenna tuning measurements with a network analyzer* and *Section 3.2: 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 1.1: Passive RFID technology*. *Section 1.4* 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 3rd and 4th paragraphs on the cover page to an *Operating mode* section. Added *Table 1: Applicable products*. Added *Section 2.5.3: Metal considerations*.