APPLICATION NOTE

mifare®

Design of MF RC500 Matching Circuits and Antennas

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Philips Semiconductors
# Application Note Design of MF RC500 Matching Circuits and Antennas

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1 INTRODUCTION

This application note is intended to support RF-related design-in of the MF RC500 MIFARE® reader IC. The aim is to provide the required understanding of the MIFARE® RF interface (ISO 14443A) to design application specific antennas and matching circuits to achieve the best performance for a communication with a contactless MIFARE® card. This paper shall give a background on the system's RF part and an overview on the procedure how to design and tune antennas for standard applications. Two different antenna and matching concepts are explained in detail as well as examples for the antenna design itself. Furthermore, the complete tuning procedure is described. As part of the Annex, the interested reader will find a detailed theoretical description of the RF interface.
2 SYSTEM FUNDAMENTALS

2.1 Block Diagram

The MF RC500 is a member of a new family of highly integrated reader ICs for contactless communication based on 13.56 MHz. The MF RC500 supports all layers of ISO 14443. Figure 2-1 shows a simplified block diagram.

![Figure 2-1. Simplified MF RC500 Block Diagram](image)

The MF RC500 fulfills the following functions:

- The parallel μ-Controller interface detects automatically the connected 8 bit parallel interface.
- The data processing part performs the parallel to serial conversion of the data. It supports the framing generation check, the CRC/Parity generation and check as well as the bit coding and processing. All layers of ISO 14443-A are supported, as the MF RC500 operates in full transparent mode.
- The status and control part allows for configuration of the device to environmental influences to achieve the best performance for each application.
- The Crypto1 stream cipher unit is implemented to support communication to MIFARE® CLASSIC products.
- A secure non-volatile key memory is included to store Crypto 1 key-sets.
- The analog part includes two internal bridge driver outputs to achieve an operating distance up to 100mm depending on the antenna coil and the environmental influences. Furthermore, the internal receiving part allows for the receiving and decoding of data without external filtering.
2.2 System Configurations

The system configuration for a MIFARE® reader based on the MF RC500 is shown in Figure 2-2. To connect an antenna to the reader IC, the user can choose between two different concepts. Depending on the application, either a

- 50Ω matched antenna or a
- directly matched antenna configuration can be used.

Generally, the system components for both concepts are comparable. Three parts are needed:

- A receiving circuit has to be designed to receive data sent by the card.
- A filtering and impedance transformation circuit suppresses higher harmonics and optimises the power transmission to the reader antenna.
- A matching circuit for the antenna coil to achieve the best performance and the antenna coil itself has to be designed. A connection either directly or using a cable between the antenna and the reader itself is needed too.

Both concepts have to fulfil different requirements to achieve an optimum in performance. Designing these components is subject of the next chapters.
2.3 The MIFARE® RF Interface

The MIFARE® technology describes an ISO 14443-Type A compliant RF interface for a communication between a reader and a contactless card.

Table 1 gives a short overview on the MIFARE® RF interface. Basically, the MIFARE® RF interface follows the transformer principle. The MIFARE® card is passive with no onboard battery. Thus, an energy transmission is required for a communication between a reader module and a card as well as a possibility to transmit data in both directions.

Table 1. Overview MIFARE® RF interface

<table>
<thead>
<tr>
<th>Energy transmission</th>
<th>Transformer principle; MIFARE® card is passive</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating frequency</td>
<td>13.56 MHz</td>
</tr>
<tr>
<td>Communication structure</td>
<td>Half duplex, reader talks first</td>
</tr>
<tr>
<td>Data rate</td>
<td>105.9 kHz</td>
</tr>
<tr>
<td>Data transmission</td>
<td>Both directions</td>
</tr>
<tr>
<td>RWD → Card</td>
<td>100 % ASK, Miller Coded</td>
</tr>
<tr>
<td>Card → RWD</td>
<td>subcarrier load modulation, subcarrier frequency 847.5 kHz, Manchester Coded</td>
</tr>
</tbody>
</table>

The following parts describe the fundamentals of the MIFARE® RF interface starting with the basic energy transmission. Finally, the data transmission and the used data coding in both directions will be shown.
2.3.1 ENERGY TRANSMISSION

The energy transmission between the reader antenna and the passive MIFARE® card is based on the transformer principle. At reader side an antenna coil is required as well as a card coil implemented in the MIFARE® card. Figure 2-3 shows the basic principle and the equivalent electronic circuitry. The figure's left part describes the antennas and the energy transmission basically.

The current I in the RWD antenna coil generates a magnetic flux. Parts of this flux flow through the card coil and induce a voltage in the card coil itself. This voltage is rectified and the card IC is activated when the operating voltage is reached. The induced voltage will vary within the distance between reader antenna and the MIFARE® card. Due to that voltage variation, the achievable operating distance is limited by the transferred power. The right part shows the equivalent electrical circuitry, the transformer model. In detail, the energy transmission is described in Annex A of this document.

2.3.2 DATA TRANSMISSION RWD \rightarrow CARD

To transfer data from the reader to the card, MIFARE® uses a half-duplex communication structure. The reader talks first and starts the communication. The data transmission from the reader to the card is done using a 100 % ASK pulse-pause modulation according to ISO14443 Type A. Figure 2-4 show a typical signal shape.
Due to the quality factor \( Q \) of the antenna the transmitted signal deforms to the shape shown in Figure 2-5. This shape can be used to measure the tuning of the antenna. The theoretical background to calculate the antenna quality factor \( Q \) and the procedure to calculate the components of the matching circuitry will be described in chapter 3.

As mentioned before, the MIFARE® card is passive. To communicate between reader and card, energy has to be transmitted to the card. Therefore, MIFARE® uses an optimised coding to provide a constant level of energy independently from the data transmitted to the card. This is the modified Miller code, which is used to transmit data from the reader to the card.

Figure 2-6 describes the Miller coding in detail.

The data rate of MIFARE® is 105.9 KHz, so the length of a bit frame is 9.44\( \mu \)s. A pulse in the Miller coding has a length of 3\( \mu \)s.

A logical ‘1’ is expressed with a pulse in the middle of the bit frame.

Two possibilities are given to code a logical ‘0’. This coding depends on the previous bit:

- If the previous bit was a ‘0’, the following ‘0’ is expressed with a pulse of 3\( \mu \)s at in the first half of the next bit frame.
- If the previous bit was a ‘1’, the following ‘0’ is expressed without a pulse in the next bit frame.

![Miller Coding Diagram](image-url)
2.3.3 DATA TRANSMISSION CARD → RWD

2.3.3.1 Subcarrier Load Modulation Principle

The data transmission from the card back to the RWD is done using the principle of load modulation shown in Figure 2-7. The card is designed as a resonance circuit and consumes energy generated by the reader. This energy consumption has a reactive effect as a voltage drop on RWD side. This effect can be used to transfer data from the card back to the reader by changing a load or a resistance in the card IC.

![Figure 2-7. Subcarrier Load Modulation Principle](image)

The MIFARE® reader antenna should be tuned to a resonance frequency $f_R$ of 13.56 MHz. In fact, the resonance circuit generates voltages at the reader antenna several times higher than the supply voltage. Due to the small coupling factor between the RWD and card antenna the card responds is about 60 dB weaker than the voltage generated by the reader. To detect such a signal, requires a well designed receiving circuit. Instead of using a direct load modulation, MIFARE® uses a sub-carrier frequency $f_{SUB}$ to modulate the data. The result of this sub-carrier modulation is the generation of side-bands at $\pm f_{SUB}$ around the carrier frequency of 13.56 MHz. The sub-carrier load modulation allows an easy and robust detection of the received signal.

The MIFARE® RF interface uses a Manchester coding for the data in the base-band before the sub-carrier modulation is done. Figure 2-8 shows the typical data coding and the sub-carrier load modulation in the time domain. Firstly, the data are internally coded to the Manchester coding. The data rate of MIFARE® for the communication from the card to the reader is 105.9 kHz and the same as for the communication between reader and card, so the length of a bit frame is 9.44µs. The Manchester code uses rising and falling edges to code the data.

A logical ‘1’ is expressed with a falling edge in the middle of the bit frame.

A logical ‘0’ is expressed with a rising edge in the middle of the bit frame.

The MIFARE® card IC generates the sub-carrier frequency $f_{SUB} = f_R/16 = 847.5$ kHz. The time $T_O$ expresses the pulse length of the operating frequency, $T_O=1/f_R=74$ns. The Manchester coded data is modulated to the sub-carrier frequency. Finally, the sub-carrier load modulation is done.
Figure 2-8. Principle of Data Coding Card, RWD, time domain

Thus, the sub-carrier load modulation generates two side-bands in the frequency domain; an upper at 14.41 MHz and a lower one at 12.71 MHz. Figure 2-9 shows the spectral domain of the signal. On the one hand the side-bands of the data coding are shown, on the other hand the side-bands of the carrier frequency to the operating frequency are shown.

Figure 2-9. Data Coding Card, RWD, Frequency Domain
3 DESIGN OF MF RC500 MATCHING CIRCUITS AND ANTENNAS

3.1 Basic Design Rules

The MF RC500 is a single reader IC. It is designed to achieve operating distances up to 100mm without external amplifiers. The design of the remaining passive RF part is straightforward. Firstly it has to be decided, which of the possible basic concepts meets the application requirements best. The design help shown in Figure 3-1 shall give a support for this decision. Two different concepts are possible to design an antenna and a matching circuit.

- **Directly matched antennas** can be used to build up small, complete terminals with a minimum distance between a reader and antenna. Possible applications could be an access control reader in a small housing or a handheld reader.

- **50Ω matched antennas** can be used for an easy solution to achieve long distances between the reader and the antenna using a coaxial cable. Using a coaxial cable between the reader matching circuit and the antenna itself, distances up to 10 m between these parts are possible.
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![Diagram](image-url)

**Figure 3-1. Design Help**

**Note:** This design help is a first step. To achieve the aspired operating distance the antenna design itself and the environmental influences have to be taken into consideration.
Table 2 compares the different concepts and shows the needed components in more detail. Basically, there is a 50Ω matched or a directly matched antenna concept. For the 50Ω matched concept, a high-end solution to achieve an operating distance up to 100mm as well as a low cost solution for operating distances lower than 50 mm is available.

Table 2. Comparison of antenna concepts

<table>
<thead>
<tr>
<th>Concept</th>
<th>50 Ω matched</th>
<th>Directly matched</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Full range</td>
<td>Short range</td>
</tr>
<tr>
<td>Reader</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MF RC 500</td>
<td></td>
<td></td>
</tr>
<tr>
<td>EMC-Circuit</td>
<td>same circuitry and values</td>
<td></td>
</tr>
<tr>
<td>Receiving circuit</td>
<td>same circuitry and values</td>
<td></td>
</tr>
<tr>
<td>Impedance Transformation</td>
<td>using $T_{X1}$ and $T_{X2}$</td>
<td>using only $T_{X1}$</td>
</tr>
<tr>
<td>Cable</td>
<td>50 Ω coaxial</td>
<td>Short wire or directly connected</td>
</tr>
<tr>
<td>Antenna matching circuitry</td>
<td>same circuit, but different values depending on the antenna size</td>
<td>same circuit, but different values depending on the antenna size</td>
</tr>
<tr>
<td>Antenna coil</td>
<td>operating distance depends on the antenna size and environmental influences</td>
<td>operating distance depends on the antenna size and environmental influences</td>
</tr>
<tr>
<td>Antenna shielding</td>
<td>Shielding depends on the application, e. g. the housing and environmental influences</td>
<td></td>
</tr>
</tbody>
</table>

It is recommended to use the shown concepts. The next part will start with an estimation of the achievable operating distance depending on the antenna shape followed by the design of the required circuit itself.

3.2 Estimation of the Optimum Antenna Size

The achievable operating distance for a MIFARE® system depends on several factors:

- Reader Antenna size
- Quality of the matching circuit for the given antenna
- Environmental influences

The next design step is to estimate the operating distance depending on the antenna size. The complete calculation can be found in Annex A.
The MIFARE® card is powered by a flux generated by the reader. The achievable energy for the card IC varies depending on the distance between reader antenna and card. As mentioned in chapter 2.3, the MIFARE® system is based on the transformer principle. One important parameter describing a transformer is the coupling coefficient k. It can be defined as a geometrical parameter depending on the distance between reader antenna and the card coil and both, the size of the reader antenna as well as the one of the card coil itself. Assuming that for a standard application the MIFARE® card has chip card dimensions, the card coil dimensions are fixed.

In Annex A it is shown that the maximum coupling coefficient k for a fixed distance between reader antenna and card coil is achieved, when the radius of the reader antenna is equal to the distance. The calculation is done for a circular antenna. If a rectangular or square antenna is practically in use a circular one with an equivalent area can be used for the estimation.

This result can be taken as a rule of thumb for the design of an optimum antenna for a given application.

Important Notes:

- The estimation, that the radius of the reader antenna should be equal to the achievable operating distance is only a first step for a successful antenna design. For a complete design, the environmental influences as well as antenna size limitations due to application related restrictions have to be taken into consideration.

- This estimation shows, that increasing the antenna radius will not automatically increase the operating distance. The energy transmission from the reader to the card is a limiting factor, which can be expressed with a minimum coupling coefficient of 0.3.

- The formula for the calculation of the coupling coefficient is not depended on the number of turns of the reader antenna.
Figure 3-2 gives an approximation of the R/W distance for different antenna sizes. It shows that the best R/W distances can be achieved with antennas of about 20cm diameter (R=10cm). Larger antennas provide no bigger operating distance!

![Graph showing Antenna Radius versus operating distance](image-url)
3.3 Directly Matched Antennas

One of the proposals in table 2 is a directly matched antennas. The recommended circuit can be used to reach operating distances up to 100 mm. The operating distance depends primarily on the size of the antenna as well as the correct values for antenna’s matching circuit. The needed components, the EMC filter, the receiving circuit and the antenna matching itself will be described as well as their necessity for a proper functionality of the MIFARE® system. Figure 3-3 shows the recommended circuitry for directly matched antennas.

3.3.1 EMC CIRCUIT

The MIFARE® system is based on an operating frequency of 13.56 MHz. This frequency has to be generated by a quartz oscillator which will also generate higher harmonics. To conform with the international EMC regulations the third, fifth and higher harmonics of the 13.56Mhz have to be suppressed adequately. Beside a multi-layer layout, it is strongly recommended to implement a low pass filter as shown in Figure 3-3. The low pass filter consists of the components L₀ and C₀. The values are given in Table 3.

3.3.2 RECEIVING CIRCUIT

The internal receiving part of the MF RC 500 uses a new receiving concept. It uses both side-bands generated by sub-carrier load modulation of the card’s response. It is recommended to use the internally generated V_MID potential as an input potential of the R_X pin. To reduce disturbances a capacitance to ground has to be connected to V_MID. The receiving part of the reader needs a voltage divider connected between the R_X and the V_MID pin. Additionally, it is recommended to use a serial capacitance between the antenna coil and the voltage divider. Figure 3-3 shows the recommended receiving circuit. The receiving circuit consists of the components R₁, R₂, C₃ and C₄. The values are given in Table 3.
The values for the filtering and receiving components $L_0$, $C_0$, $R_1$, $R_2$, $C_3$ and $C_4$ are fix.

Table 3. Values for the EMC-Filter and Receiving Circuit

<table>
<thead>
<tr>
<th>Components</th>
<th>Value</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_0$</td>
<td>2.2 µH ± 10%</td>
<td>Magnetic shielded e.g. TDK ACL3225S-T</td>
</tr>
<tr>
<td>$C_0$</td>
<td>47 pF ± 2%</td>
<td>NP0 material</td>
</tr>
<tr>
<td>$R_1$</td>
<td>820 Ω ± 5%</td>
<td></td>
</tr>
<tr>
<td>$R_2$</td>
<td>2.7 kΩ ± 5%</td>
<td></td>
</tr>
<tr>
<td>$C_3$</td>
<td>15 pF ± 2%</td>
<td>NP0 material</td>
</tr>
<tr>
<td>$C_4$</td>
<td>100 nF ± 2%</td>
<td>NP0 material</td>
</tr>
</tbody>
</table>

Note: To achieve the best functionality the used capacitors and inductors should have at least the performance and the tolerances of the recommended ones.
3.3.3 ANTENNA MATCHING CIRCUIT FOR DIRECTLY MATCHED ANTENNAS

It is recommended to do the design of a directly matched antenna step by step. Firstly, the antenna coil has to be designed. The antenna itself is a low ohm device. To connect this antenna coil to the MF RC500 a matching circuit is required. Starting with the estimation of the antennas equivalent circuit and the calculation of the quality factor, the recommended values for the capacitors of the matching circuit will result.

3.3.3.1 Determination of the Antenna's Equivalent Circuit:

The reader antenna coil can be described with the equivalent circuit shown in the left part of Figure 3-4. The recommended antenna design for directly matched antennas should have a grounded centre tap in the antenna coil. This centre tap is implemented to improve the EMC behaviour of the antenna. The coil itself can be described by the inductances $L_a$ and $L_b$, the resistances $R_a$ and $R_b$ to describe ohmic losses and capacitive losses described by the parallel capacitances $C_a$ and $C_b$. Anyhow it is not recommended to calculate the components of this equivalent circuit because of coupling effects between $L_a$ and $L_b$.

Instead of the complete model, it is recommended to use the model shown in the right part of Figure 3-4. The complete antenna coil between the connectors Tx11 and Tx12 can be described by $L_{ant}$, the complete ohmic losses by $R_{ant}$. The coil capacitance $C_{ant}$ describes losses between both windings and between the connectors.

![Figure 3-4. Equivalent circuit of an antenna coil for a directly matched antenna](image)

It is recommended to measure the antennas equivalent circuit with an impedance analyser. Connect the antenna loop (when using shielded antennas connect the shield to ground) and measure the shown equivalent circuit. The value for the coil’s capacitance $C_{ant}$ can be neglected for the calculation of the quality factor and the tuning of the antenna.

**Note:** If an impedance analyser is not available, use as starting value the calculated values for the inductance and resistance. To estimate these values formulas are given in Annex A. The operating frequency of MIFARE® is 13.56 MHz. At this frequency the ohmic skin effect losses can not be neglected, that is why it is not correct to use only the DC resistance of the coil.
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Please use the estimation in Annex A to find a start value for the impedance $R_{\text{ant}}$. It is recommended to check the complete design later by measuring the quality factor. If necessary, this starting value has to be changed and the complete tuning procedure has then to be done once again.

### 3.3.3.2 Quality factor

For the following part it is presumed that the values for the antenna’s inductance $L_{\text{ANT}}$ and resistance $R_{\text{ANT}}$ are known. It is recommended to measure $L_{\text{ANT}}$ and $R_{\text{ANT}}$ with an impedance analyser. If the estimation is done using the formula to calculate the values, keep in mind that these values are only starting values and might have to be changed after verification of the Q-factor.

The antenna’s quality factor is an important characteristic for the correct tuning of the antenna and the achievable performance. The quality factor of the antenna is defined as:

$$Q = \frac{\omega_R \cdot L_{\text{ANT}}}{R_{\text{ANT}}}, \quad \omega_R = 2\pi f_R$$

Depending on the geometrical conditions of the antenna $Q$ has usually a value in the range of 50...100. This value has to be reduced for a proper data transmission. As mentioned in chapter 2.3.2 the baudrate of MIFARE® is 105.9 kHz/sec and the data transmitted from the RWD to the card are Miller-coded with a pulse length of $T=3\mu s$.

Using the definitions for the bandwidth $B$

$$B = \frac{f_R}{Q}$$

And the definition for the time-bandwidth product

$$B \cdot T \geq 1$$

The required Q-factor can be calculated as

$$Q \geq \frac{f_R \cdot T}{13.56 MHz \cdot 3 \mu s} \approx 40.68$$

Due to tolerances and temperature dependencies of the components, it is recommended to use a value of 35 for the Q-factor.

To reduce the original Q-factor it is required to implement an additional external resistance $R_{\text{EXT}}$ as shown in Figure 3-5. The value of $R_{\text{EXT}}$ can be calculated by

$$R_{\text{EXT}} = \frac{\omega_R \cdot L_{\text{ANT}}}{Q} - R_{\text{ANT}} = \frac{\omega_R \cdot L_{\text{ANT}}}{35} - R_{\text{ANT}}$$

As mentioned above, it is recommended to use a centre tap to design an antenna coil for a directly matched antenna. Therefore, the result for the external resistances has to be split up into two equal parts. The complete circuit to reduce the antenna’s quality factor is shown in Figure 3-5.
3.3.3.3 Impedance Matching for directly matched antennas

To design a matching circuit for a directly matched antenna it is recommended to use the circuit shown in Figure 3-6. The values for the capacitors $C_s$ and $C_p$ depend on the antenna itself and the environmental influences.

It is recommended to use the values for the capacitors shown in Table 4 as starting values for the tuning procedure. To tune an antenna to an optimum the procedure described in chapter 7 for directly matched antennas has to be followed. The start values depend on the antenna’s inductance.
Table 4. Starting Values for the antenna matching circuit

<table>
<thead>
<tr>
<th>L_{ANT} [µH]</th>
<th>C_{S} [pF]</th>
<th>C_{P1} [pF]</th>
<th>C_{P2} [pF]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.8</td>
<td>27</td>
<td>270</td>
<td>330</td>
</tr>
<tr>
<td>0.9</td>
<td>27</td>
<td>270</td>
<td>270</td>
</tr>
<tr>
<td>1.0</td>
<td>27</td>
<td>220</td>
<td>270</td>
</tr>
<tr>
<td>1.1</td>
<td>27</td>
<td>180</td>
<td></td>
</tr>
<tr>
<td>1.2</td>
<td>27</td>
<td>180</td>
<td>180</td>
</tr>
<tr>
<td>1.3</td>
<td>27</td>
<td>180</td>
<td>180</td>
</tr>
<tr>
<td>1.4</td>
<td>27</td>
<td>150</td>
<td>180</td>
</tr>
<tr>
<td>1.5</td>
<td>27</td>
<td>150</td>
<td>150</td>
</tr>
<tr>
<td>1.6</td>
<td>27</td>
<td>120</td>
<td></td>
</tr>
<tr>
<td>1.7</td>
<td>27</td>
<td>120</td>
<td>150</td>
</tr>
<tr>
<td>1.8</td>
<td>27</td>
<td>120</td>
<td>120</td>
</tr>
</tbody>
</table>

This table assumes a stray capacitance of 15 pF of the antenna coil. The capacitors C_{S} and C_{P} should have a NP0 dielectric with a tolerance of ±2%. Actual values of the antenna inductance and capacitance depend on various parameters:

- antenna construction (Type of PCB)
- thickness of conductor
- distance between the turns
- shielding layer
- metal or ferrite in the near environment

Due to these influences, the values for C_{P} have to be optimised with the actual design. For an appropriate procedure see chapter 7.1.1.
3.4 50 Ω Matched Antennas

In table 2 two concepts are proposed to design a 50Ω antenna. In both concepts the EMC circuit and the receiving circuit are identical. Firstly, these parts will be described, followed by a description for the long- and the short-range impedance transformation circuits. The last part will show the recommended design for a matching circuit for 50Ω matched antennas.

3.4.1 EMC CIRCUIT

The MIFARE® system is based on an operating frequency of 13.56 MHz. This frequency has to be generated by a quartz oscillator which will also generate higher harmonics. To conform with the international EMC regulations the third, fifth and higher harmonics of the 13.56MHz have to be suppressed adequately. Beside a multi-layer layout, it is strongly recommended to implement a low pass filter as shown in Figure 3-7. The low pass filter consists of the components L₀ and C₀. The values are given in Table 5.

3.4.2 RECEIVING CIRCUIT

The internal receiving part of the MF RC500 uses a new receiving concept. It uses both side-bands generated by sub-carrier load modulation of the card’s response. It is recommended to use the internally generated V_{MID} potential as an input potential of the Rₓ pin. To reduce disturbances a capacitance to ground has to be connected to V_{MID}. The receiving part of the reader needs a voltage divider connected between the Rₓ and the V_{MID} pin. Additionally, it is recommended to use a serial capacitance between the antenna coil and the voltage divider. Figure 3-7 shows the recommended receiving circuit. The receiving circuit consists of the components R₁, R₂, C₃ and C₄. The values are given in Table 5.

<table>
<thead>
<tr>
<th>Components</th>
<th>Value</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>L₀</td>
<td>1.0 µH ±10%</td>
<td>Magnetic shielded e.g. TDK ACL3225S-T</td>
</tr>
<tr>
<td>C₀</td>
<td>47 pF ±2%</td>
<td>NP0 material</td>
</tr>
<tr>
<td>R₁</td>
<td>820Ω ±5%</td>
<td></td>
</tr>
<tr>
<td>R₂</td>
<td>2.7kΩ ±5%</td>
<td></td>
</tr>
<tr>
<td>C₃</td>
<td>15 pF ±2%</td>
<td>NP0 material</td>
</tr>
<tr>
<td>C₄</td>
<td>100 nF ±2%</td>
<td>NP0 material</td>
</tr>
</tbody>
</table>

**Note:** To achieve the best functionality, the used capacitors and inductors should have at least the performance and the tolerances of the recommended ones.
3.4.3 50 Ω FULL RANGE SOLUTION

To be able to connect a 50Ω coaxial cable to the MF RC500 an impedance transformation has to be done. This impedance transformation should fulfil three requirements:

- Implementation of an EMC- Filter
- Impedance transformation between the low output impedance of the MF RC500 and 50 Ω.
- The MF RC500 has symmetrical output drivers Tx1 and Tx2. To be able to connect a coaxial cable an unsymmetrical potential to Ground has to be generated.

A way to design a circuit fulfilling these requirements is to use a transformer or a Balun\(^1\) to generate a ground unsymmetrical potential. Figure 3-7 shows one typical realisation using a Balun. The EMC filter based on L0 and C0 has the same structure as mentioned in the design hints for directly matched antennas. The combination of the components L0, C0 and C1 have the structure of a T- filter. This filter transforms the output driver resistance to the 50Ω resistance of the coaxial cable. The balun B1 should have a 1:1 ratio and should match to 50Ω. The capacitance C\(_{2b}\) is just optional\(^2\). The small unsymmetrical behaviour of the balun can be reduced trimming that tuning capacitance to the maximum output voltage at the antenna.

**Important Note**: The bridge output drivers of the MF RC 500 are low ohmic devices. To achieve the best performance a matching of 30Ω between Tx1 and Tx2 should be used.

The easiest way to calculate the needed impedance transformation is to use a smith chart.

---

\(^1\) balun : Abbreviation for Balanced to Unbalanced. A Balun is a type of a transformer.

\(^2\) This tuning capacitance C\(_{2b}\) is recommended in the design–in phase to find an optimum performance.
Using a transformer or a balun is a way to generate a to ground unsymmetrical potential. The balun concept demonstrates how to reach with a few external components the full operating distance with a 50Ω match. The basic functions of the balun and the calculation for impedance networks can be found in standard literature. The result of that calculation will give starting values for a tuning procedure to find the best solution. To provide the functionality of the EMC filter a compromise between a matching to 50Ω and the filtering has to be found. Table 6 shows the results of the tuning procedure. The optional tuning capacitance should be used to find the best result for the actual design.

**Table 6. Type50-1 Values for the impedance transformation**

<table>
<thead>
<tr>
<th>Components</th>
<th>Value</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>82pF ± 2%</td>
<td>NP0 material</td>
</tr>
<tr>
<td>C2a</td>
<td>69 pF± 2%</td>
<td>NP0 material</td>
</tr>
<tr>
<td>C2b</td>
<td>0-30 pF</td>
<td></td>
</tr>
<tr>
<td>B1</td>
<td>1:1 Transformer</td>
<td>e.g. Coilcraft 1812WBT-3</td>
</tr>
</tbody>
</table>

**Note:** To achieve the best functionality the used capacitors and inductors should have at least the performance and the tolerances of the recommended ones.
3.4.4 50 Ω SHORT RANGE SOLUTION

The second proposal to build up a 50Ω antenna uses only one driver stage, \( T_{X1} \) or \( T_{X2} \). In Figure 3-8 the complete impedance transformation and the receiving part are shown. The EMC filter based on \( L_0 \) and \( C_0 \) has the same structure as mentioned in the design hints for directly matched antennas. The combination of the components \( L_0 \), \( C_0 \) and \( C_1 \) have the structure of a T- filter. This filter transforms the output driver resistance to the 50Ω resistance of the coaxial cable. The capacitance \( C_{1b} \) is optional. It is recommended to use this tuning possibility for the first tests to find the optimum value for \( C_1 \).

![Diagram of 50Ω Short Range solution: 50Ω impedance transformation using one driver stage](image)

To provide the functionality of the EMC filter a compromise between a matching to 50 Ω and the filtering has to be found. Table 7 shows the results of the tuning procedure.

<table>
<thead>
<tr>
<th>Components</th>
<th>Value</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>( C_{1a} )</td>
<td>69pF ± 2%</td>
<td>NP0 material</td>
</tr>
<tr>
<td>( C_{1b} )</td>
<td>0-30 pF</td>
<td>NP0 material</td>
</tr>
</tbody>
</table>

**Note:** To achieve the best functionality the used capacitors and inductors should have at least the performance and the tolerances of the recommended ones.
3.4.5 ANTENNA MATCHING CIRCUIT FOR 50 Ω ANTENNAS

The design of an antenna that matches the 50 Ω cable has to fulfil several requirements. Firstly The antenna coil itself has to be constructed and its inductance has to be measured or estimated using the formula to calculate the antenna’s inductance. This formula can be found in Annex A. Such an antenna is a low ohmic device. To connect this coil to an 50 Ω cable an impedance transformation has to be done. Additionally it needs a resonance circuitry to generate the highest voltage at the operating frequency of 13.56 MHz.

3.4.5.1 Determination of the Antenna’s Equivalent Circuit:

The reader antenna coil can be described with the equivalent circuit shown in Figure 3-9. The antenna exists of the winding itself. This winding has an inductance \( L_{\text{ANT}} \). Additionally, this winding has the serial impedance \( R_{\text{ANT}} \) to describe the ohmic losses and a parallel capacitance \( C_{\text{ANT}} \) to describe losses both between windings and between the connectors.

It is recommended to measure the antennas equivalent circuit with an impedance analyser. Connect the antenna loop (when using shielded antennas connect the shield to ground) and measure the shown equivalent circuit. The value for the coils capacitance \( C_{\text{ANT}} \) can be neglected for the calculation of the quality factor and the tuning of the antenna.

Note: If an impedance analyser is not available, use as starting value the calculated values for the inductance and resistance. To estimate these values formulas are given in Annex A. The operating frequency of MIFARE® is 13.56 MHz. At this frequency the ohmic skin effect losses can not be neglected, that is why it is not correct to use only the DC resistance of the coil. Please use the estimation in Annex A to find a start value for the impedance \( R_{\text{ANT}} \). It is recommended to check the complete design later by measuring the quality factor. If necessary the starting value will have to be changed and the complete tuning procedure has to be redone.

3.4.5.2 Quality Factor

For the following part it is presumed that the values for the antenna’s inductance \( L_{\text{ANT}} \) and resistance \( R_{\text{ANT}} \) are known. It is recommended to measure \( L_{\text{ANT}} \) and \( R_{\text{ANT}} \) with impedance analyser. If the estimation is made using the formula to calculate to values, please note that these values are only starting values to calculate the Q-factor.

The antenna’s quality factor is an important characteristic for the correct tuning of the antenna and the achievable performance. The quality factor of the antenna defined as:
Depending on the geometrical design of the antenna, $Q$ usually is in the range of 50...100, in the following it is shown that this value has to be reduced for a proper data transmission. As mentioned in chapter 2.3.2 the baudrate of MIFARE® is 105.9 kHz/sec and the data transmitted from the RWD to the card are Miller-coded with a pulse length of $T=3\mu s$.

Using the definition for the bandwidth $B$,

$$B = \frac{f_R}{Q},$$

And definition for the time – bandwidth product

$$B \cdot T \geq 1$$

The required $Q$-factor can be calculated as

$$Q \leq \frac{f_R \cdot T}{13.56 \text{MHz} \cdot 3 \mu s} \leq 40.68$$

Due to tolerances of the components it is recommended to use a value of 35 for the $Q$-factor. It is required to reduce the $Q$-factor using an additional external resistance $R_{EXT}$. Figure 3-10 shows how to connect the external resistance $R_{EXT}$.

![Figure 3-10. External resistance](image)

The value of $R_{EXT}$ can be calculated by

$$R_{EXT} = \frac{\omega \cdot L_{ANT} - R_{ANT}}{Q} = \frac{\omega \cdot L_{ANT}}{35} - R_{ANT}$$

### 3.4.5.3 Calculation of the Capacitors for the Matching Circuit

Figure 3-11 shows the recommended circuit to match the antenna coil to 50 Ω. The matching is done using a serial and parallel capacitance. The input resistance $Z$ should match to 50 Ω.
To calculate $C_S$ and $C_P$ the following equations have to be solved:

With

$$\frac{1}{w^2 L_{ant}} \sqrt{\frac{R_{ext} + R_{ant}}{Z}}$$

Follows

$$C_P = \frac{1}{w^2 L_{ant}} \left( \frac{R_{ext} + R_{ant}}{Z} \right)$$

$C_S$ and $C_P$ should be SMD types with NP0 dielectricum for best temperature stability. It is recommended to split up $C_P$ in a fixed value and a trimmer ($C'_P$) with a maximum value of 10... 20 pF.
4 ENVIRONMENTAL INFLUENCES

4.1 Metallic Antenna Environment

Any alternating magnetic field induces a voltage in metal components positioned nearby the reader antenna. This induced voltage generates eddy currents in the metal plane. These eddy currents cause loss combined with a detuning of the antenna and decreasing of the magnetic field. The result of these effects is a reduced operating distance as well as possible transmission errors.

It is recommended that the distance between antenna and massive metal components is at least as large as the operating distance.

To avoid negative influences of a metallic environment a ferrite shielding should be used.

The antenna distance from massive metal should be at least 10cm for full R/W distance, 3cm for reduced R/W distance and for close metal ferrite shielding is a must!

In all cases the tuning of the antenna has to be made with the metal placed in the finally intended position.

4.2 Multiple Antennas

Antennas are resonance circuits with a high quality factor and tuned to the operating frequency. According to the reciprocity law a good transmitting antenna is also a good receiving antenna and vice versa. This means that an antenna positioned close to the used reader antenna and tuned to the same frequency dissipates energy from the field. This causes a detuning of the antenna and a reduced operating distance. If two active antennas for an MIFARE® application are positioned in a close distance a communication to the card will be disturbed.

Multiple MIFARE® R/W antennas should be at least 30 cm away from each other if they are magnetically shielded and 10 times of the antenna radius if they are not shielded!

4.3 Temperature

The R/W antenna may be detuned as a consequence of temperature drifts of the electrical parameters of the antenna itself and the matching circuit. This will resulting reduction of the transmitting power available at the antenna. The consequence will be a reduced operating distance.

Measurements have shown that these influences can be neglected when appropriate components with low temperature coefficient for the matching circuit (SMD capacitors with NP0 dielectric medium) are used.
5 ANTENNA SHIELDING, COMPENSATION

Three different concepts shall be discussed.

- **Electrical Shielding**
  The electrical shielding absorbs the electrical field generated by the antenna coil as well as the electrical field of the reader PCB.

- **Compensation**
  Compensation should be used to reduce common mode earth currents.

- **Ferrite Shielding**
  Ferrite Shielding should be used if metal has to be placed very close to the antenna itself. This metal, e.g. metal housing of the terminal generates eddy currents. The effect of the eddy currents is a dramatically reduced operating distance. A ferrite shielding should be used to reduce the generated eddy currents.

  **Note:** Ferrite shielding will not increase the operating distance above values achievable in non metallic environment.

5.1.1 ELECTRICAL SHIELDING

5.1.1.1 Directly Matched Antennas

An electrical shielding should be used to reduce the electrical field generated by the antenna coil itself. To build a shielded antenna on a PCB at least one with 4 layers should be used, with the shielding loop on the top and the bottom layer. **These loops must not be closed.** The loops provide electrical shielding and improves EMC behaviour. The shielding has to be connected in one point to system ground. The coil is routed in the first inner layer. The centre tap of the coil is done with the marked Via to GND. The connection of the coil ends to the matching circuit shall be routed close together, to avoid additional inductance.

![Electrical shielding for a directly matched antenna](image)

*Figure 5-1. Electrical shielding for a directly matched antenna*
5.1.1.2 50 Ω Matched Antennas

An electrical shielding should be used to reduce the electrical field generated by the antenna coil itself. To build a shielded antenna on a PCB at least one with 4 layers should be used with the shielding loop on the top and the bottom layer. **These loops must not be closed.** The loops provide electrical shielding and improves EMC behaviour. The shielding has to be connected in one point to system ground.

![Electrical shielding for a 50 Ω matched antenna using a triax cable.](image)

On the top and bottom layers of the PCB a shielding plane is placed directly above the active antenna loop which is an inside layer of the PCB. These shielding planes must not be closed loops! The shielding should be connected with a triax cable.

5.1.2 COMPENSATION

![Electrical Principle](image)

**Figure 5-3. Compensated 50Ω antenna**
To compensate the stray capacitance of the antenna another turn with an open end is added. Due to the transformer's principle the induced voltage in the open loop is inverted. The stray capacitance of the active and the compensation loop have nearly the same value. The effect will be, that the current across these capacitance has nearly the same magnitude but opposite direction. By that a compensation of these currents is done. These currents can reach values in a range of mA at 13.56 MHz, so compensation is necessary to avoid problems with ground currents.

5.1.3 FERRITE SHIELDING

The benefit of a ferrite is to shield an antenna against the influence of metal. A metal plane could be part of the housing of the reader or a ground plane of the reader PCB itself, which has to be connected very near to the antenna. If metal is placed very near to the antenna the alternating magnetic field generates eddy currents in the metal. These eddy currents absorb power, and lead to detuning of the antenna due to a decreased inductance and quality factor. Therefore for operation of an antenna in metallic environment, it is necessary to shield the antenna with ferrite.

The following examples should give an impression on the influence of ferrite for the distribution of a magnetic field.

For easy simulation a circular antenna has been used in all case. A circular antenna is rotation symmetrical to the x-axis. Therefore the simulation can be reduced to a two dimensional mathematical problem. The simulations shows on the one hand the field distribution of a non disturbed antenna. Common for all examples: Radius of the RWD antenna 7.5 cm, 1 turn, wire width 1mm copper.

Figure 5-4 shows the two dimensional field of the circular antenna. The right part shows the field distribution. The highest field strength is generated in the area of the coil. The left part shows the magnitude of the field strength H over the distance d. Marked is the line of a minimal field strength of $H_{\text{MIN}} = 1.5 \text{ A/m}$ according to ISO 14443.

Figure 5-5 shows the field distribution of the same antenna with a metal plane near to the antenna. Compared to the disturbed field it is obvious that the magnitude of the field strength has decreased leading to a decreased operating distance.
Now, as shown in Figure 5-6 a ferrite plane ($\mu_R = 40$) is positioned in-between the metal plane and the antenna coil itself. The field strength very near to the ferrite increases, but this increasing of the magnitude is not combined with an increasing of the operating distance. This is marked once again with the $H_{\text{MIN}}$ value according to ISO 14443.

These simulations show how the use of ferrite reduces the generated eddy currents in a metal plane. The ferrite generates an additional field component and the effect for the design of the antenna is a fixed detuning of the antenna itself.

Figure 5-7 gives recommendations how to dimension the ferrite to find the optimum dimensions between ferrite plane and metal plane. To calculate the optimum dimensions of the ferrite plane and the optimum...
distance and overlapping is very hard and not recommended. Application specific tests have to be made to find the best ferrite dimensions.

Test have shown that the best performance is achieved when the overlapping of the antenna coil and the ferrite is in a range of 5 mm. That gives a balance between needed stray field to communicate to the card and the shielding of the ferrite.

Applying the distance estimation to specific applications, it is recommended to make test to find the best solution. Once again it has to be mentioned that ferrite does not increase the operating distance compared to a non-disturbed field.

Figure 5-7. Estimation of the optimum ferrite dimensions

Small reduced stray field
Low shielding
Reduced operating distance

Reduced stray field
High shielding
Reduced operating distance

Optimum distribution:
Balance between stray field distribution and ferrite shielding

5mm
6 EXAMPLE DESIGN OF MF RC 500 ANTENNAS

The following examples are PCB antennas without a ferrite shielding. If ferrite is used, the values for the capacitors will change due to the detuning effects of the ferrite. It is recommended to place a metal plate behind the ferrite, connect this metal plate to ground and tune the antenna with that metal plate in place and connected. In this case there will be no difference if the antenna is placed in metallic or non-metallic environment. This metal plate should be connected to the shield of the triax-cable or to the ground shield if a coax cable is used.

Tuning must be done after assembling the complete antenna or after mounting the antenna to its final position respectively!

6.1 General Layout Hints

6.1.1 EMC FILTER AND RECEIVING CIRCUIT

$L_0$ and $C_0$ are used for filtering of the output signal of the MF RC500 and must be placed very close to the $T_{X1}$ and $T_{X2}$ pin of the MF RC500. For satisfying EMC results the layout of these components is critical. The ground connection of $C_0$’s should be very short and should have very low impedance to the TGND pin of the MF RC500 (ground plane with multiple vias for connection). The narrow placement of these components is essential for suppression of higher harmonics of the carrier frequency.

The layout of the receiving circuitry is less critical and special requirements are not needed.

Figure 6-1 shows a part of an layout for the MF RC500 with the critical components.

6.2 Layout of the Antenna and the Matching Circuit

The antenna layout depends on the used shielding and the matching itself.

For direct matched antennas it is recommended to use a centre tap to achieve a better EMC performance.
6.3 Example for a Directly Matched Antenna

6.3.1 SHIELDED AND COMPENSATED RECTANGULAR ANTENNA

Size of turn = 115 x 115mm, Drawing not in scale
Component values: to be calculated

<table>
<thead>
<tr>
<th>Antenna</th>
<th>External Components</th>
</tr>
</thead>
<tbody>
<tr>
<td>( L_{\text{ANT}} ) = t.b.d.</td>
<td>( C_S = \text{t.b.d.} )</td>
</tr>
<tr>
<td>( C_{\text{ANT}} ) = t.b.d.</td>
<td>( C_P = \text{t.b.d.} )</td>
</tr>
<tr>
<td>( R_{\text{ANT}} ) = t.b.d.</td>
<td>( R_{\text{EXT}} = \text{t.b.d.} )</td>
</tr>
</tbody>
</table>

Figure 6-3. Example of rectangular antenna
6.3.2 RECTANGULAR ANTENNA

Size of turn = 78.5 x 67mm, Drawing not in scale

Component values: to be calculated

<table>
<thead>
<tr>
<th>Antenna</th>
<th>External Components</th>
</tr>
</thead>
<tbody>
<tr>
<td>L\text{ANT} = \text{t.b.d.}</td>
<td>C\text{S} = \text{t.b.d.}</td>
</tr>
<tr>
<td>C\text{ANT} = \text{t.b.d.}</td>
<td>C\text{P} = \text{t.b.d.}</td>
</tr>
<tr>
<td>R\text{ANT} = \text{t.b.d.}</td>
<td>R\text{EXT} = \text{t.b.d.}</td>
</tr>
</tbody>
</table>

Figure 6-4. Example for rectangular antenna
6.3.3 SHIELDED RECTANGULAR ANTENNA

A layout example is given in Figure 6-5.

Figure 6-5. Shielded rectangular antenna
6.4 Example for an 50 Ω Matched Antenna

6.4.1 COMPENSATED RECTANGULAR ANTENNA

Size of turn = 115 x 75mm. Drawing not in scale.

Component values:

<table>
<thead>
<tr>
<th>Antenna</th>
<th>External Components</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_{\text{ANT}} = 330 , \text{nH}$</td>
<td>$C_S = 47 , \text{pF} \parallel 3.3 , \text{pF}$</td>
</tr>
<tr>
<td>$C_{\text{ANT}} = 20.2 , \text{pF}$</td>
<td>$C_P = 270 , \text{pF} \parallel 68 , \text{pF}$</td>
</tr>
<tr>
<td>$R_{\text{ANT}} = 0.25 , \Omega$</td>
<td>$R_{\text{EXT}} = 0.5 , \Omega$</td>
</tr>
</tbody>
</table>

Figure 6-6. Example of compensated rectangular antenna
6.4.2 COMPENSATED CIRCULAR ANTENNA

Diameter = 15cm. Drawing not in scale

Component values:

<table>
<thead>
<tr>
<th>Antenna</th>
<th>Ext. Components</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_{\text{ANT}} = 545\text{nH}$</td>
<td>$C_S = 33 \parallel 4.7\text{pF}$</td>
</tr>
<tr>
<td>$C_{\text{ANT}} = 25.4\text{pF}$</td>
<td>$C_P = 220 \parallel 8.2\text{pF}$</td>
</tr>
<tr>
<td>$R_{\text{ANT}} = 0.32\Omega$</td>
<td>$R_{\text{EXT}} = 1.0\Omega$</td>
</tr>
</tbody>
</table>

Figure 6-7. Compensated circular antenna
6.4.3 SHIELDED CIRCULAR ANTENNA

Diameter = 15cm; 3-layer PCB. Drawing not in scale

Component values:

<table>
<thead>
<tr>
<th>Antenna</th>
<th>ext. Components</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_{\text{ANT}} = 460,\text{nH}$</td>
<td>$C_S = 39 \parallel 3.3,\text{pF}$</td>
</tr>
<tr>
<td>$C_{\text{ANT}} = 38.7,\text{pF}$</td>
<td>$C_P = 180 \parallel 15,\text{pF}$</td>
</tr>
<tr>
<td>$R_{\text{ANT}} = 0.53,\Omega$</td>
<td>$R_{\text{EXT}} = 0.5,\Omega$</td>
</tr>
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</table>

[Diagram of shielded circular antenna with component values]
Figure 6-8. Shielded circular antenna
7 ANTENNA TUNING

A correct tuning of the antenna is necessary to achieve an optimum performance. It is recommended to do the final antenna tuning in the complete terminal. This includes, that all parts of the terminal should be connected to the power supply as well as the adjustment of the antenna and the reader PCB to their final position.

The explanation of the tuning procedure is divided into two parts. The first part shows the tuning to achieve an optimum operating distance based on the energy transmission. The second part shows how to check the quality factor of the antenna to ensure proper data transmission.

The antenna tuning procedure is divided into a tuning method for first test during development and secondly during production test. It is recommended to do the first tuning as well as the measurements of the coils equivalent parameters with an impedance analyser. If this device is not available production tuning procedures may also be applied. However in this case a more complex iteration procedure will be necessary.

The most important thing for a successful tuning is the knowledge of the antenna's equivalent electrical parameters to find the best starting values for the tuning itself. The easiest way to measure the antenna's equivalent parameters is an impedance analyser.
7.1 Tuning Methods for an Optimum Operating Distance

7.1.1 TUNING OF DIRECTLY MATCHED ANTENNAS

The tuning of directly matched antennas should follow the iteration process shown in Figure 7-1. Starting values for the tuning capacitors depend on the coil’s inductance as shown in Table 4.

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**Figure 7-1. Tuning of direct matched antennas**
7.1.2 TUNING OF 50 Ω MATCHED ANTENNAS

50 Ω matched antennas can be tuned using several procedures and different measurement equipment.

- Tuning with an impedance analyser. This method is the most precise and easiest one. It requires an impedance analyser which is relatively expensive.

- Tuning with an oscilloscope

7.1.2.1 Tuning with Impedance Analyser

The most precise and easiest way to tune an antenna is using an impedance analyser e.g. a HP 4195 with a 50Ω-signal divider. Connect the antenna directly to the calibrated analyser and tune the antenna using the iteration process described in Figure 7-2.

**Note:** It is important that the analyser is warmed up, calibrated (range e.g. 1-30 MHz) and correctly compensated with the measurement cable for precise measurements!
Iteration Process:

Since the values for $C_s$ and $C_p$ can only be calculated with an error of 20% the final circuitry has to be determined by the following iteration process:

![Iteration Process Flowchart]

Tolerance for the input impedance of the antenna at 13.56 MHz:

$$|Z| = 50 \Omega \pm 5 \Omega$$
$$\phi = 0^\circ \pm 10^\circ$$

Figure 7-2. Tuning 50 \Omega antennas using an impedance analyser
7.1.2.2 Tuning procedure with oscilloscope

Remark: The complete tuning of a 50 Ω antenna using only an oscilloscope is not as precise as the tuning with an impedance analyser. It is recommended to do the first tuning of the antenna with an analyser and not with an oscilloscope. The tuning with a scope can be used for production tuning when only one parallel capacitance $C_p$ has to be tuned.

The most critical part in the antenna design and tuning procedure without an impedance analyser is to calculate the value for $L_{ANT}$ and $R_{ANT}$. Depending on this value the tuning has to be redone after checking the Q-factor. Based on these values for $L_{ANT}$ and $R_{ANT}$ the values for the serial and parallel capacitors have to be calculated as described in chapter 3.4.5.

To tune the antenna, reduce the calculated values for the capacitors by 40% and insert them as $C_s$ and $C_p$ in the impedance matching network. Add parallel variable capacitors $C_s'$ and $C_p'$ allowing to adjust ± 20% of the calculated value.

The necessary equipment for the final tuning is shown in Figure 7-4. A reference resistor of 50 Ω ± 2% (e.g. 50 Ω BNC terminating resistor) is inserted in the ground line between the function generator output and the antenna connector. The two probes of the oscilloscope are connected to the function generator output and in parallel to the reference resistor. The components $C_s$ probe and $C_p$ probe present the oscilloscope probe input capacitance. The oscilloscope will display a Lissajous figure, allowing to derive the absolute magnitude and the phase. The magnitude is given by the angle of the Lissajous figure and the area as depicted in the figure below gives the phase.

The tuning procedure has to be done in two steps:

**Step 1: Calibration**

For the calibration a calibration resistance of 50 Ω has to be inserted instead of the antenna.

The calibration procedure is depicted in the next figure. The function generator shall be set to:

- Wave form: Sinusoidal
- Frequency: 13.56 MHz
- Amplitude: 2V - 5V
The x-probe capacitance $C_{x\text{probe}}$ reduces only the amplitude at the function generator output. This has no influence on the tuning results.

The y-probe capacitance $C_{y\text{probe}}$ affects a phase shift, which changes the area of the Lissajous figure. To compensate this effect, the capacitor $C_{\text{cal}}$ is connected in parallel to the matching network. In the calibration phase the matching network is replaced with a second resistor of 50 Ω (e.g. 50 Ω BNC terminating resistor). The calibration capacitor has to be adjusted until the Lissajous figure is completely closed. Then the calibration capacitance $C_{\text{cal}}$ is equal to the capacitance $C_{y\text{probe}}$. The y-probe voltage is in phase and the amplitude is exactly half of the function generator voltage ($x$-probe).

**NOTE:** If the scale for the x-probe is chosen twice the scale for the y-probe (e.g. x-scale: 2V/DIV and y-scale: 1V/DIV) the Lissajous figure angle shall be 45 degree.

**NOTE:** A loop of the ground cable of the probe shall be avoided to minimise inductive coupling from the antenna.
Step 2: Tuning Procedure:

After the calibration, the calibration resistor has to be replaced by the antenna. The matching network shall be tuned by the variable capacitor $C_s$ and $C_P$ until the Lissajous figure is completely close. The Lissajous figure angle has to be compared to the Lissajous figure angle of the calibration resistor. If the angle is equal to the angle of the calibration resistor, the matching circuit impedance is $50 \, \Omega$.

Notes to interpret the Lissajous figures:

- If the figure is not closed, the phase between $x$ and $y$ is unequal to zero.
- If the angle $\phi = 0^\circ$, the Lissajous figure is closed completely.
- If the angle is greater than $45^\circ$, $Z$ is greater than $50 \, \Omega$.
- If the angle is smaller than $45^\circ$, $Z$ is greater than $50 \, \Omega$.

The resonance curve of an antenna has two zeros in the phase as shown in Figure 7-7. It is only possible to tune the lower frequency $f_{\text{LOW}}$ to $Z=50 \, \Omega$ and $\phi = 0^\circ$. The zero at the higher frequency cannot be tuned to $Z=50 \, \Omega$. 

Figure 7-6. Tuning of an $50 \, \Omega$ antenna
To be sure that the tuning is done to the lower frequency, it is recommended to reduce the calculated value for $C_S$ and $C_P$ by 40% and add tuning capacitors in that range. Start the tuning with the lowest values for the tuning capacitors.

The complete tuning procedure is described as a flow chart in Figure 7-8.
Tuning with an oscilloscope

Calculate Lant and Rant optional Rext

Calculate Cs-40% and Cp-40%

Change the frequency to the lower frequency $f_{Low}$ with $\phi = 0^\circ$

- Increase $C_p$ by 10 pF
- Decrease $C_p$ by 10 pF

- Decrease Cs by 10%
- Increase Cs by 10%

- Z > 50 Ω?
  - Yes: Q factor okay?
  - No: Increase Rext by 10%

- Z < 50 Ω?
  - Yes: Check the Q-factor
  - No: Decrease Cs by 40% and Cp-40%

Tuning okay

Figure 7-8. Tuning of 50 Ω antennas using an oscilloscope
7.2 Checking the Q-Factor

To check the calculated Q-factor for a tuned antenna a very simple measurement set-up can be used. An oscilloscope with a bandwidth of at least 50 MHz has to be used and two probes have to be connected as shown in Figure 7-9.

The probes have to be connected in the following way:

CH1: Form a loop with the ground line at the probe to enable inductive signal coupling. Hold the probe loop closely above the antenna.

CH2: Connect probe to the NPAUSE0 signal in your MIFARE® reader, (it is used for easy triggering) Trigger source = CH2.

To check the pulse shape it is recommended to compare the plot on the scope to Figure 7-10. The values can be found in Table 8. To check the correct tuning the time $t_2$ is of special interest. This time describes the time span, in which the signal falls under the 5% value of the 90% value of the amplitude of the signal. For a correct tuning of antenna especially for a correct value of the external resistance $R_{\text{EXT}}$ the following has to be fulfilled:

The signal has to fall under the 5% value.

The time $t_2$ should not exceed 1.4µs. If $t_2$ is greater than 1.4µs the Q-factor is greater than 35 and the correct data transmission can not be guaranteed. Increase $R_{\text{EXT}}$. 

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If the time $t_2$ is shorter than 0.7 µs the Q-factor is too high and the operating distance will be dissatisfying. Decrease $R_{\text{EXT}}$.

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<th>Pulses Length</th>
<th>$t_1$ [µs]</th>
<th>$t_2$ [µs]</th>
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<td>$T_1\text{ MIN}$</td>
<td>2.0</td>
<td>0.7</td>
<td>1.0</td>
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Figure 7-10. Pulse shape according to ISO 14443.

Table 8. Pulse duration according to ISO 14443.
8 REFERENCES

[1] Data Sheet MIFARE® MF RC500 Highly Integrated ISO 14443A Reader IC
[2] ISO 14443 Identification cards- Contactless integrated circuits cards- Proximity cards, part 1-4
9 ANNEX A

9.1 Abbreviations

The following abbreviations are used:

- **ASK**: Amplitude shift keying
- **EMC**: Electro-Magnetic Conformity
- **ISO 14443**: International Standard: Identification cards- Contactless integrated circuit(s) card- Proximity cards
- **MIFARE® Classic**: Family of MIFARE® Hardwired card ICs (MIFARE® STANDARD and MIFARE® LIGHT)
- **MIFARE® Pro**: MIFARE® Dual interface card IC
- **RWD**: Read / Write Device \( \rightarrow \) MIFARE® reader

9.2 Calculation of the Antenna’s Coil Inductance

The precise calculation of the antenna coils inductance is not practicable and for the practical use not recommended. We recommend designing an antenna either with a circular or rectangular shape. For these a formula for a first estimation of the inductance is as follows:

\[
L_{\text{[mH]}} = 2 \cdot l_{\text{[cm]}} \cdot \frac{\ln\left(\frac{D_1}{l_{\text{1}}}ight)}{N_1} - K \cdot N_1
\]

- \( l_{\text{1}} \) ............ Length of the conductor loop of one turn
- \( D_1 \) ............ Diameter of the wire or width of the PCB conductor respectively
- \( K \) ............. = 1.07 for circular antennas
- \( = 1.47 \) for square antennas
- \( N_1 \) ............ Number of turns
- \( \ln \) ............. Natural logarithm function

Actual values of the antenna inductance depend on various parameters.

- antenna construction (Type of PCB)
- thickness of conductor
- distance between the turns
- shielding layer
- metal or ferrite in the near environment
Additionally, the number of turns $N$, which is needed for a certain size and a given inductance can be calculated. Figure 9-1 shows the number of turns needed for the antenna versus the antenna radius for a circular antenna. At a radius of 5cm the number of turns changes.

![Figure 9-1: Antenna radius versus inductance and number of turns](image)

9.3 Estimation of the Coils’ Resistance

The operating frequency of MIFARE® is 13.56 MHz. In this frequency range it is not enough to describe the antenna coil with its DC resistance $R_{DC}$. The skin effect can not be neglected. The relevant depth can be calculated at 13.56 MHz and copper material to 18µm.

It is not practicable to calculate the complete AC resistance of the antenna coil $R_{ANT}$ in general. The antenna's resistance depend on several factor as material, dimensions of the wire, number of turns, shape and shielding concept.

As a first estimation to tune the antenna without an impedance analyser the following formula should be used.

$$R_{ANT} = 5 \times R_{DC}$$

**Note:** The formula is the result of tests made with designed antennas. It is recommended to use an impedance analyser for an exact determination of $R_{ANT}$. 
10 DEFINITIONS

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<td>Objective specification</td>
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</tr>
<tr>
<td>Preliminary specification</td>
<td>This data sheet contains preliminary data; supplementary data may be published later.</td>
</tr>
<tr>
<td>Product specification</td>
<td>This data sheet contains final product specifications.</td>
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Limiting values

Limiting values given are in accordance with the Absolute Maximum Rating System (IEC 134). Stress above one or more of the limiting values may cause permanent damage to the device. These are stress ratings only and operation of the device at these or at any other conditions above those given in the Characteristics section of the specification is not implied. Exposure to limiting values for extended periods may affect device reliability.

Application information

Where application information is given, it is advisory and does not form part of the specification.

11 LIFE SUPPORT APPLICATIONS

These products are not designed for use in life support appliances, devices, or systems where malfunction of these products can reasonably be expected to result in personal injury. Philips customers using or selling these products for use in such applications do so on their own risk and agree to fully indemnify Philips for any damages resulting from such improper use or sale.
12 REVISION HISTORY

Table 1 Revision History

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