APPLICATION NOTE

mifare® (14443A)

13.56 MHz RFID Proximity Antennas

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Philips
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13.56 MHz RFID Proximity Antennas

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CONTENTS

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13.56 MHz RFID Proximity Antennas

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1 INTRODUCTION

1.1 Purpose and Scope

This application note is intended to support RF-related design–in of Micore reader ICs. 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 used antenna designs.

1.2 Abbreviations

ASK   Amplitude Shift Keying

OOK   On-Off Keying

UID   **U**nique **ID**entifier

RF   **r**adio **f**requency

Micore   contactless reader IC family including :
             MF RC500
             MF RC530
             MF RC 531
             SL RC400
             CL RC632

PCD   13.56MHz Proximity **Reader** (Proximity Coupling Device according to the ISO14443)

PICC   MIFARE® Proximity **Card**

1.3 Reference Documents

1) "MIFARE® and I Code, Micore Directly Matched Antenna Design"

2) "Data Sheet; SL RC400 I Code Reader IC"

3) "MIFARE® MF RC500; Highly Integrated ISO 14443A Reader IC"

4) "MIFARE® MF RC 530 ISO14443A reader IC"

5) "MIFARE® MF RC531; ISO 14443 Reader IC"

6) "MIFARE® and I Code CL RC632 Multiple protocol contactless reader IC"

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2 HOW TO USE THIS DOCUMENT

The chapter 3 of this document shows the basic principles of the RF interface as it used with MIFARE®. The general understanding of this principle helps to do a fast and reliable antenna design based on Micore reader ICs, but none of the given formulas (especially those in the annex) are necessary to design such an antenna.

The chapter 4 describes some basic facts about the PCD antenna, its optimum size, and how to minimize environmental influences. The given rules and design recommendations should generally be considered for a PCD antenna design. This is true for a Micore based antenna design, too.

The chapter 5 gives an overview and comparison of the two antenna design principles for Micore antennas. A help is given to find the best solution based on certain application requirements.

This application note cannot and does not replace any of the relevant datasheets.

"Card" in this document means a contactless smart card according to the ISO14443A (or MIFARE®) or a contactless tag / label according to the ISO15693 (or I-Code®).

"Micore" includes all contactless reader ICs as the MF RC500, MF RC530, MF RC531, SL RC400 and the CL RC632. For all of these ICs the antenna matching is the same.

Remarks and Comments are given in italic letters (blue marked).

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3 THE MIFARE® RF INTERFACE

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

Table 1 gives a short overview on the MIFARE® RF interface. Essentially the MIFARE® RF interface follows the transformer principle, although both the PCD and PICC antenna of course are resonance circuitries as antennas usually are. The PICC is passive with no onboard battery. Thus, an energy transmission from the PCD to the PICC is required in addition to the communication (data transmission) in both directions between the PCD and the PICC (see Figure 1).

Table 1: Overview MIFARE® RF interface

Energy transmission	Transformer principle; MIFARE® card is passive
Operating frequency	13.56 MHz
Communication structure	Half duplex, reader talks first
Data rate	105.9 kHz
Data transmission	
RWD → Card	100 % ASK, Modified Miller Code
Card → RWD	Load Modulation, Subcarrier 847.5 kHz,
	OOK, Manchester Code

In the following the fundamentals of the MIFARE® RF interface are described starting with the basic energy transmission. Finally, the data transmission and the used data coding in both directions will be shown.
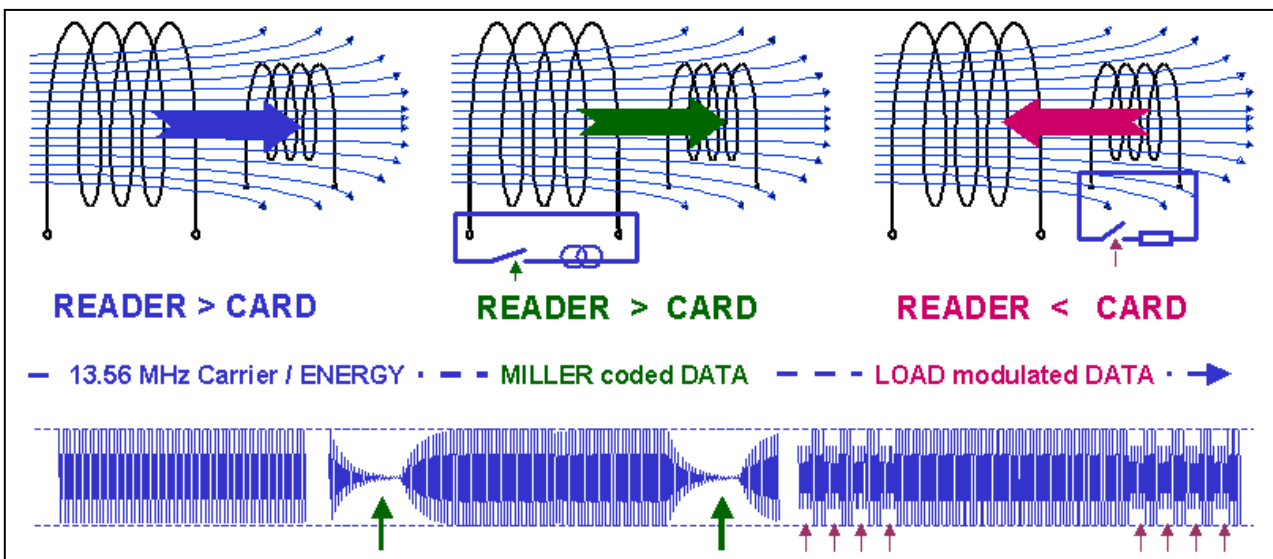

Figure 1: Mifare Interface Principle

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3.1 Energy Transmission

The energy transmission from the PCD to the passive PICC is based on the transformer principle. At PCD side an antenna coil is required as well as a card coil implemented in the MIFARE® card (PICC). Figure 2 shows the basic principle and the equivalent electronic circuitry.
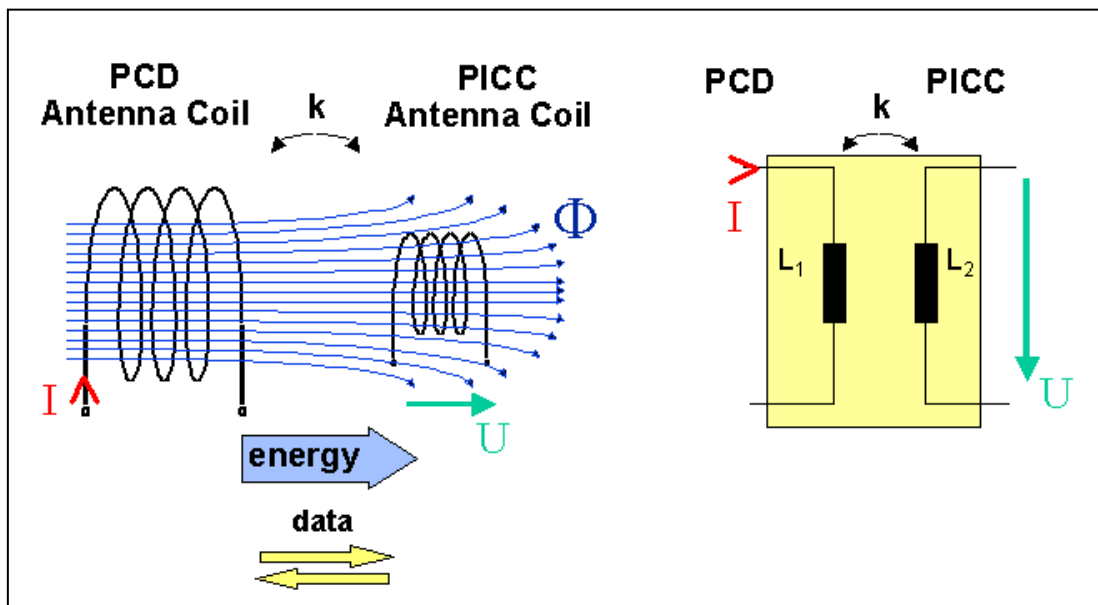

Figure 2: Transformer Model

The figure's left part describes the antennas and the energy transmission. The current I in the PCD antenna coil generates a magnetic flux Φ. Parts of this flux Φ flow through the card coil and induce a voltage U in the card coil itself. This voltage U is rectified and the card IC is activated when the operating voltage is reached. The induced voltage will vary within the distance between PCD antenna and the PICC. 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.

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3.2 Data Transmission PCD → PICC

To transfer data between the PCD and the PICC a half-duplex communication structure is used. The PCD always starts the communication ("reader talks first"). The data transmission from the PCD to the PICC uses a 100% ASK modulation according to the ISO14443 Type A. Figure 3 shows a typical signal shape.
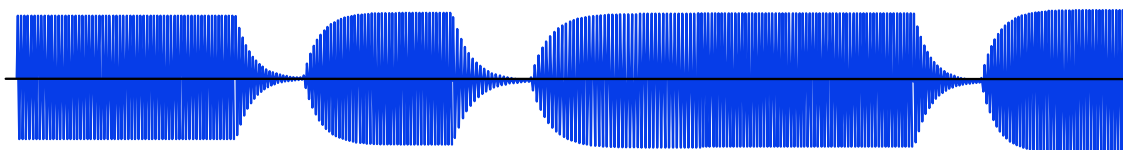

Figure 3: Data Transmission PCD → PICC, typical signal shape

Due to the quality factor Q of the antenna the transmitted signal is deformed to the shape shown in Figure 3. This shape can be used to measure the tuning of the antenna. For details refer to the "MIFARE® and I Code, Micore Directly Matched Antenna Design".

As the PICC is passive, the energy for the PICC has to be provided during the communication between PCD and PICC. Therefore, MIFARE® (ISO14443A) uses an optimised coding to provide a constant level of energy independently from the data transmitted to the PICC. This is the modified Miller code, which is shown is shown in Figure 4 in detail.

13.56 MHz RFID Proximity Antennas   mifare® (14443A)
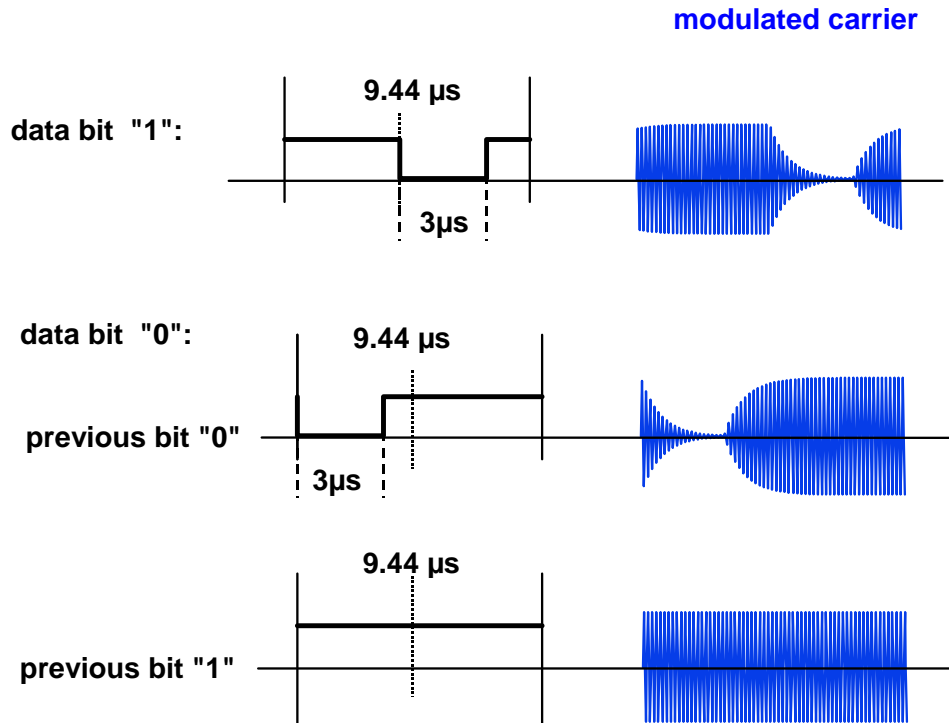
Figure 4: Data Transmission PCD → PICC, Miller Coding

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

A logical '1' is expressed with a pulse in the centre 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 3µs 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.

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3.3 Data Transmission PICC → PCD

3.3.1 SUBCARRIER LOAD MODULATION PRINCIPLE

The data transmission from the PICC back to the PCD uses the principle of load modulation shown in Figure 5. The PICC is designed as a resonance circuitry and consumes energy generated by the PCD. This energy consumption has a feedback effect as a voltage drop on PCD side. This effect is used to transfer data from the PICC back to the PCD by changing the load in the card IC.
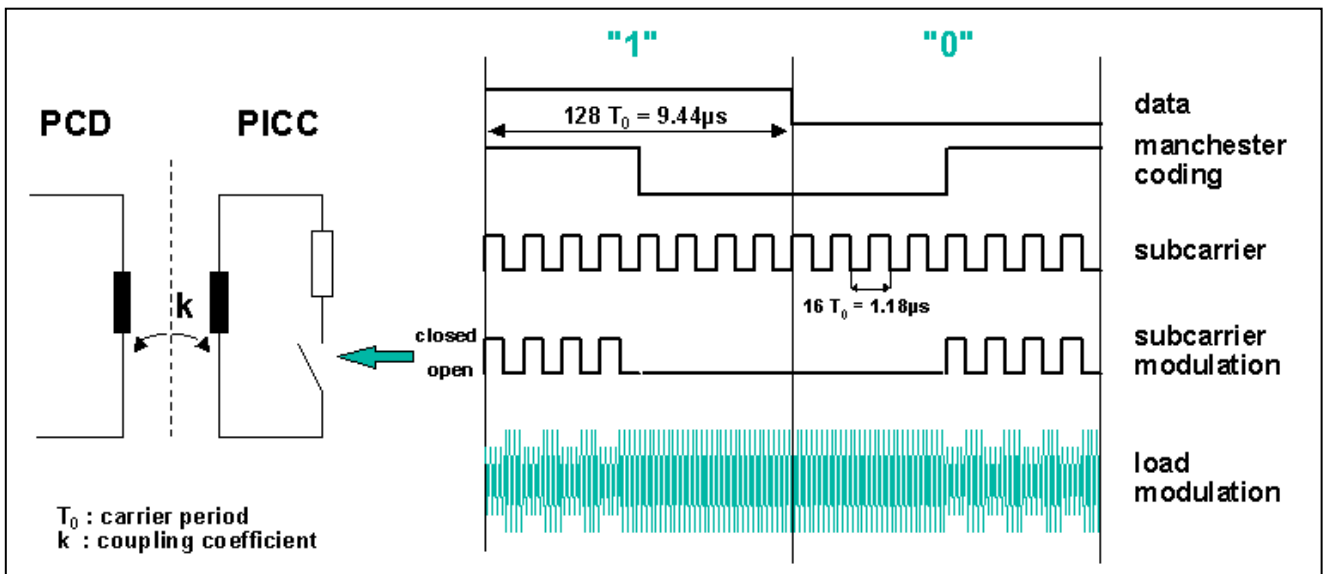

Figure 5: Subcarrier Load Modulation Principle

The PCD antenna is tuned to a resonance frequency f_R = 13.56 MHz. The time T_O expresses the pulse length of the operating frequency $T_0 = \frac{1}{f_R} \approx 74ns$. In fact, this resonance circuit generates voltages at the PCD antenna several times higher than the supply voltage. Due to the small coupling factor between the PCD and PICC antenna the PICC's response is up to 60dB below the voltage generated by the reader. To detect such a signal, it requires a well designed receiving circuit.

The PICC data transfer back to the PCD uses a data rate of 105.9kbit/s with Manchester coding. At Manchester Coding each bit is represented by either a raising or a falling edge in the centre of a bit frame. For the MIFARE® principle this is shown on the right side of Figure 5:

A logical '1' is expressed with a falling edge in the centre of the bit frame.

A logical '0' is expressed with a rising edge in the centre of the bit frame.

This Manchester coded data modulates a sub carrier $f_{SUB} = \frac{f_R}{16} = 847.5kHz$.

Finally, this modulated sub carrier switches the load of the PICC, which results in the load modulation as shown in the last line of Figure 5, and which is received and decoded again by the PCD.

13.56 MHz RFID Proximity Antennas

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Figure 6 shows the relation between the time and the frequency domain of the load modulation. Due to the data rate of $v \approx 106kBd \approx \dfrac{1}{9.44\mu s}$ the Manchester code generates sidebands at both sides of the sub carrier frequency:

$$f_{mSUB} = 847.5kHz\big|_{Subcarrier} \pm 106kHz\big|_{Data}$$

The modulated sub carrier then generates sidebands at both sides of the carrier frequency:

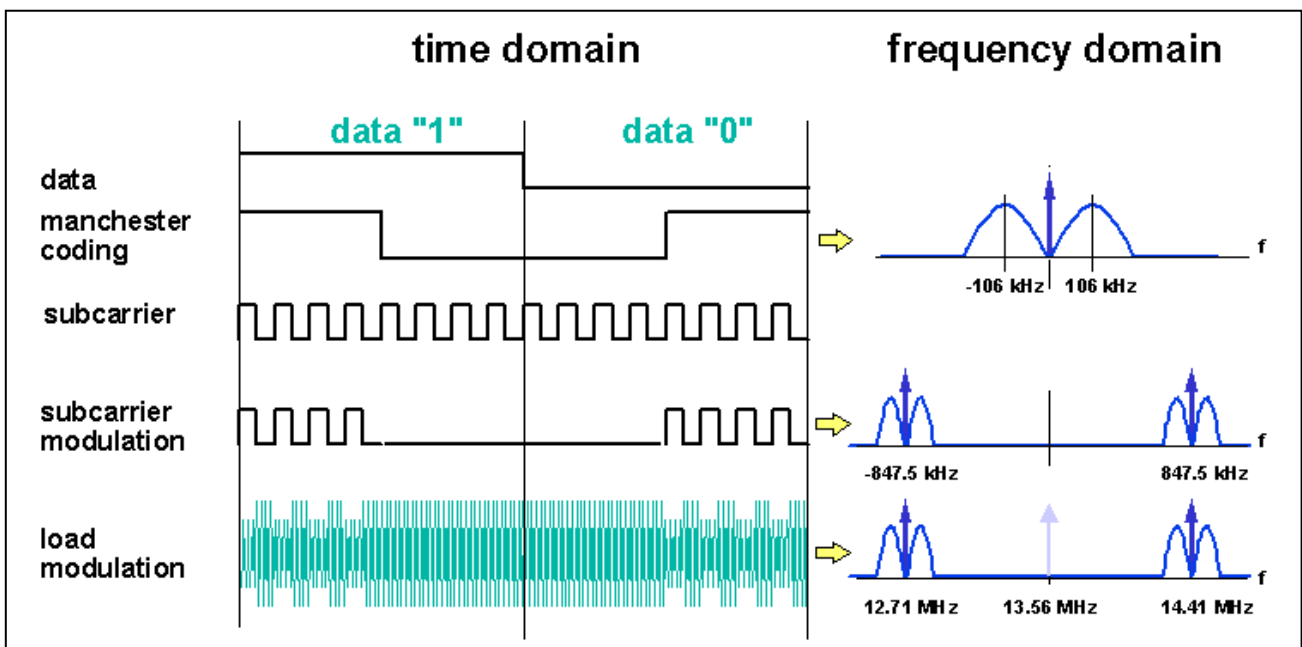$$f_{mR} = 13.56MHz\big|_{Carrier} \pm 847.5kHz\big|_{Subcarrier} \pm 106kHz\big|_{Data}$$

Figure 6: Principle of Data Coding PICC → PCD, Time and Frequency Domain

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4 THE PCD ANTENNA

The achievable operating distance for a Proximity RFID system depends on:

- PCD (and PICC) Antenna size

- Matching of the antenna

- Quality factor of the antenna and matching circuit

- Power of the PCD

- Environmental influences

Assuming that the matching of the antenna is optimised, the Q-Factor, the PICC antenna, and the delivered power of the PCD are given and fix, only the PCD antenna size and the environmental influences have to be considered for the antenna design principle. For the details of the Micore antenna design refer to "MIFARE® and I Code, Micore Directly Matched Antenna Design".

In the first step the environmental influences are neglected. This can even be done in many practical cases. The environmental influence and the way, how to avoid it, is shown in chapter 4.2.

4.1 The PCD Antenna size

Based on the transformer principle (as shown in Figure 2) and with the help of the law of the electromagnetic induction, the law of Biot and Savart the mean flux density in dependence on the operating distance and the PCD antenna radius can be calculated. Based on the limit of the minimum required field strength as specified in the ISO14443-2:

$$H_{min} = 1.5\ ^A\!/\!_m$$

the coupling factor can be calculated in dependence on the operating distance and the PCD antenna radius.[1]

As a rule of thumb the following can be shown (see Figure 7):

$$x = R = \frac{D}{2}$$

x: maximum operating distance

R: PCD antenna radius

D: PCD antenna diameter

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[1] as shown in the Annex, chapter 6.1

13.56 MHz RFID Proximity Antennas

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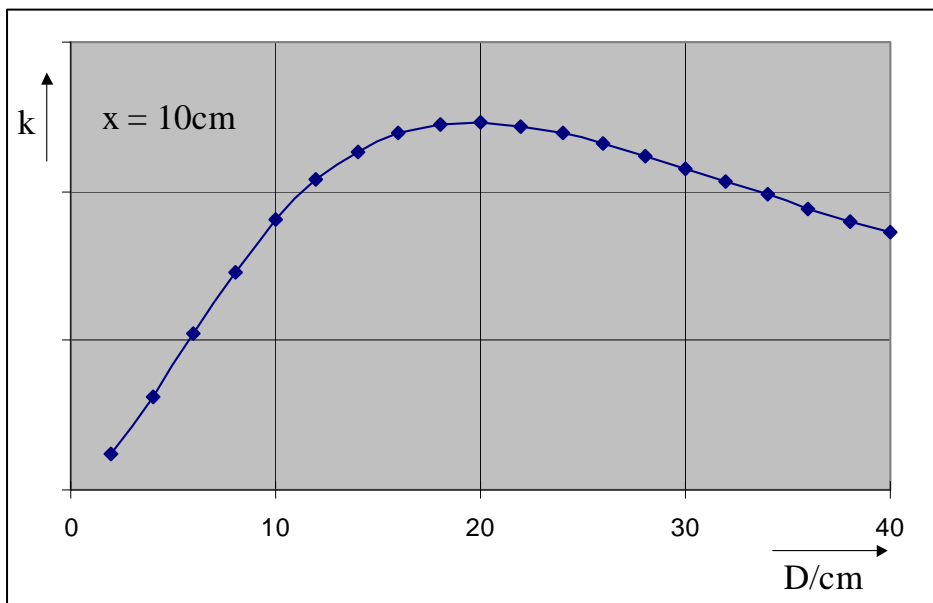
Figure 7: Coupling factor vs. Antenna diameter

Figure 7 shows the coupling factor k versus antenna diameter D based on the required operating distance of x = 10cm. The optimum antenna diameter is D = 20cm, which means bigger antennas give no better (but even less) performance. Although the curve is very flat on its top, it can be seen that an antenna diameter less than 16cm shows a significant decrease of the coupling factor (and performance). The coupling factor and performance goes dramatically down at antenna diameter below 12 cm.

Remark:

The above shown relation between antenna size and operating distance is independent on the number of turns (and the inductance) of the PCD antenna.

The above shown relation 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 considered.

The coupling coefficient is a limiting factor not only for the energy that is transported to the PICC, but also for the PICC's answer that has to be received by the PCD.

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4.2 Environmental Influences

4.2.1 METAL 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 (on both sides of the PCD antenna).

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 strictly recommended.

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

4.2.2 MULTIPLE PCD 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 Proximity PCD 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!

4.2.3 TEMPERATURE

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

Experiments can show 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.

4.3 Antenna Shielding and Compensation

Three topics 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.

4.3.1 ELECTRICAL SHIELDING

4.3.1.1 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 improve the 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.

top view   side view
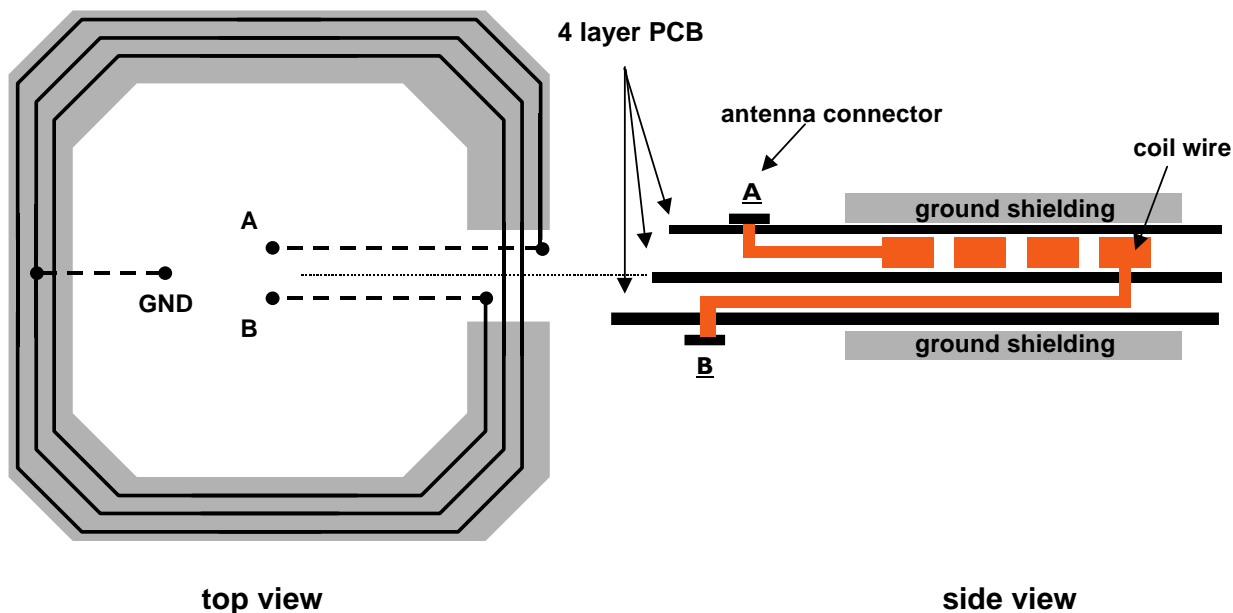
Figure 8: Electrical shielding for a directly matched antenna

13.56 MHz RFID Proximity Antennas   **mifare® (14443A)**

4.3.1.2   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 improve the EMC behaviour. The shielding has to be connected **in one point** to system ground.

Tx
TGND
Shield   Triax-cable

Antenna   (4-Layer-PCB)

Figure 9: Electrical shielding for a 50 Ω matched antenna using a triax cable.

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.

13.56 MHz RFID Proximity Antennas   mifare® (14443A)

4.3.2 COMPENSATION

Figure 10: 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 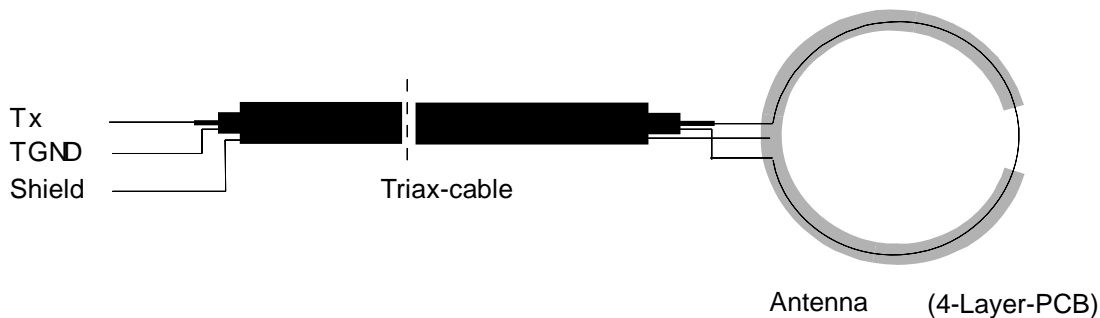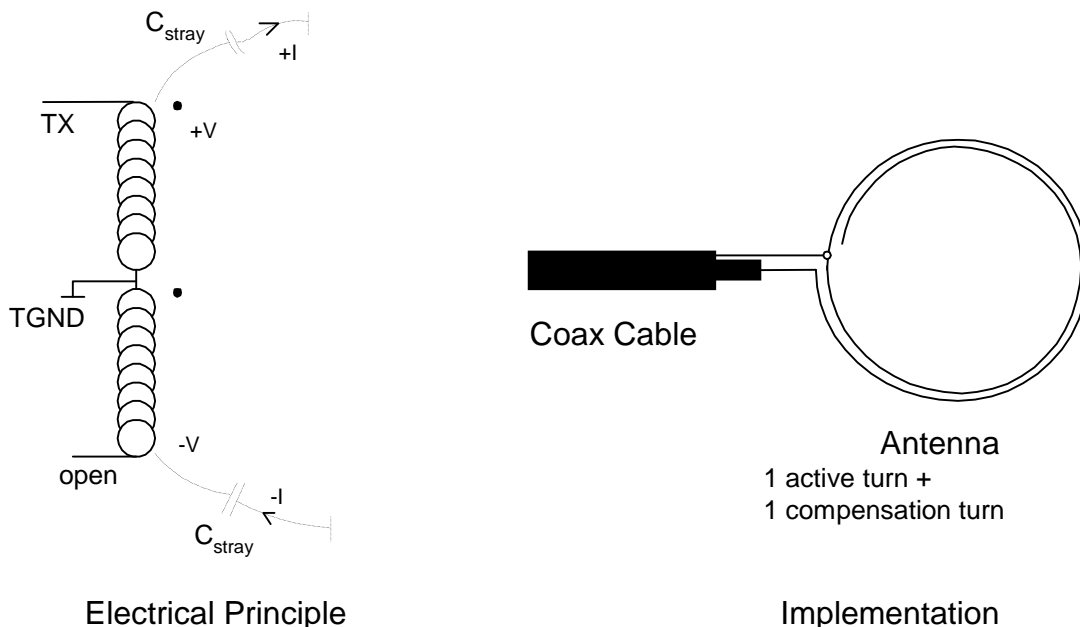is inverted. The stray capacitance of the active and the compensation loop have nearly the same value. The effect will be, that the current across these capacitance has nearly the same magnitude but opposite direction. By that a compensation of these currents is done. These currents can reach values in a range of several mA at 13.56 MHz, so compensation is necessary to avoid problems with ground currents.

4.3.3 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.

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Figure 11 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. The line of a minimal field strength of $H_{MIN} = 1.5$ A/m according to ISO 14443 is marked.
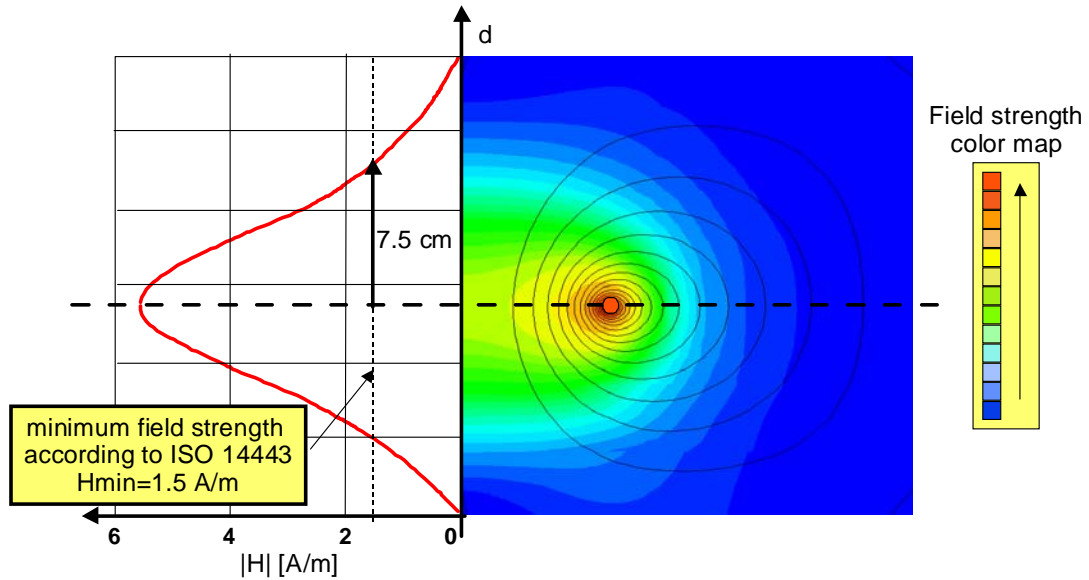
Figure 11: Non disturbed field distribution of a circular antenna

Figure 12 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.
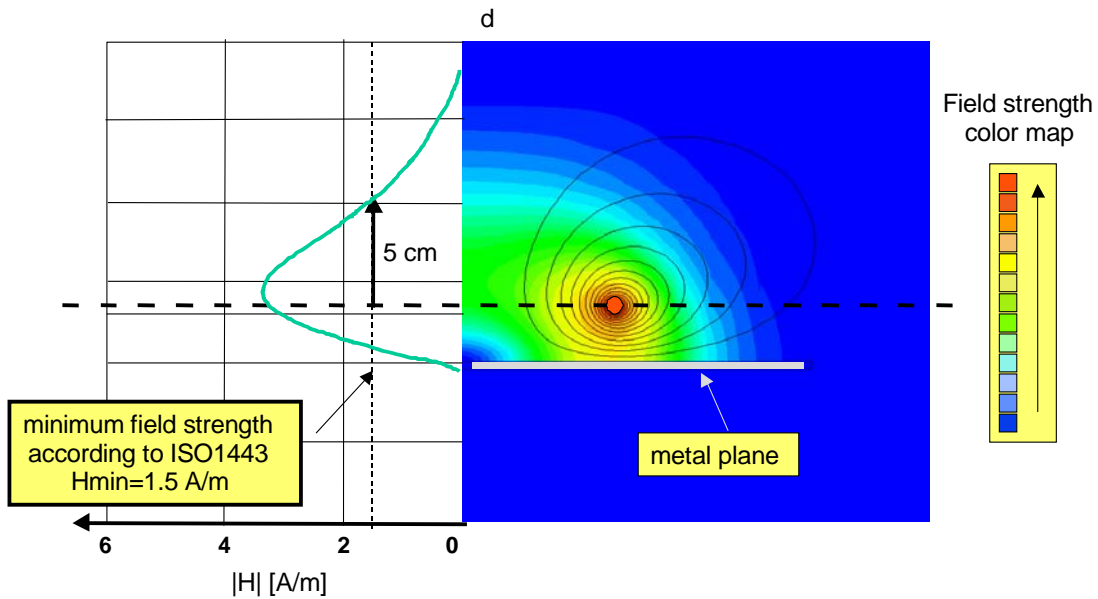
Figure 12: Field distribution of a circular antenna with a metal plane

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Now, as shown in Figure 13 a ferrite plane (μ_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_{MIN} value according to ISO 14443.
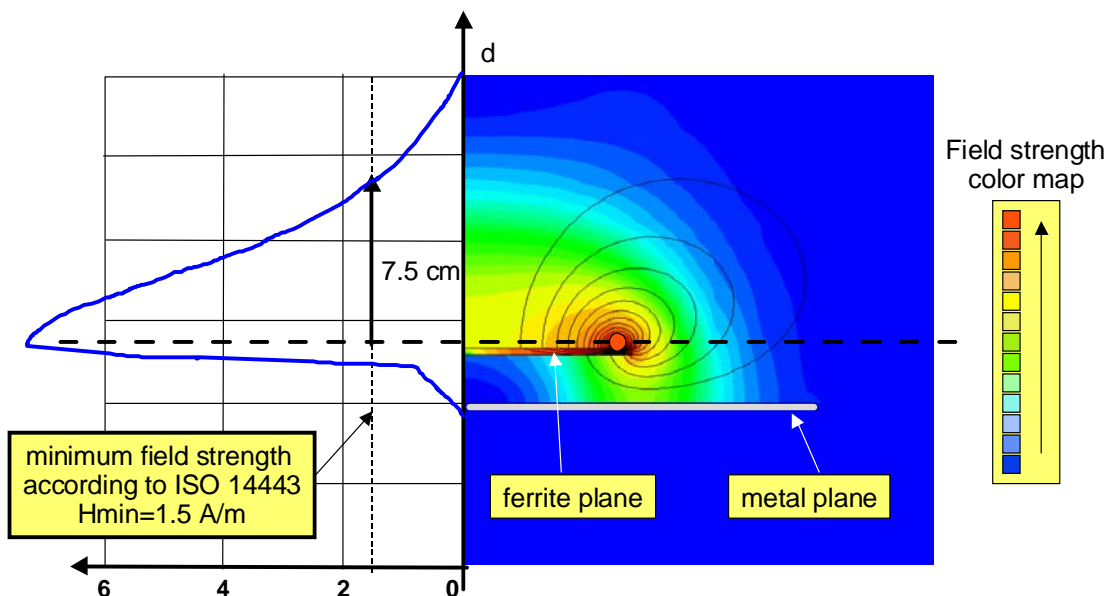
Figure 13: Ferrite shielded field distribution of a circular antenne

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 14 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.
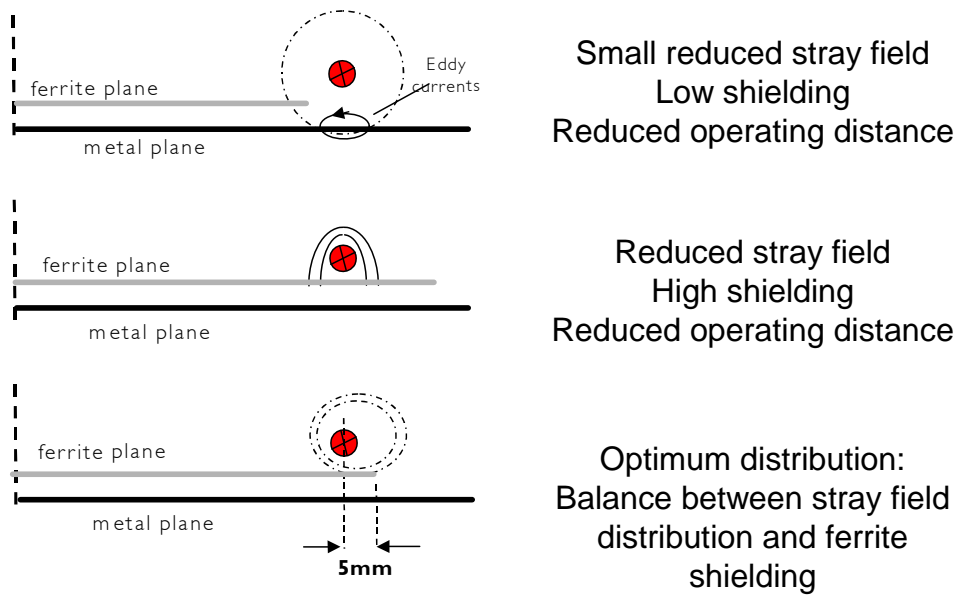
Figure 14: Estimation of the optimum ferrite dimensions

Tests 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.

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5 ANTENNA DECISION GUIDE

Micore is a single reader IC family, which is designed to achieve operating distances up to 100mm without external amplifiers. The design of the remaining passive RF part is straightforward.

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. 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.

At first it has to be decided, which of the possible basic concepts meets the application requirements best. The design help shown in Figure 15 and the comparison shown in Table 2 shall give a support for this decision.

Table 2: Comparison of antenna concepts

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

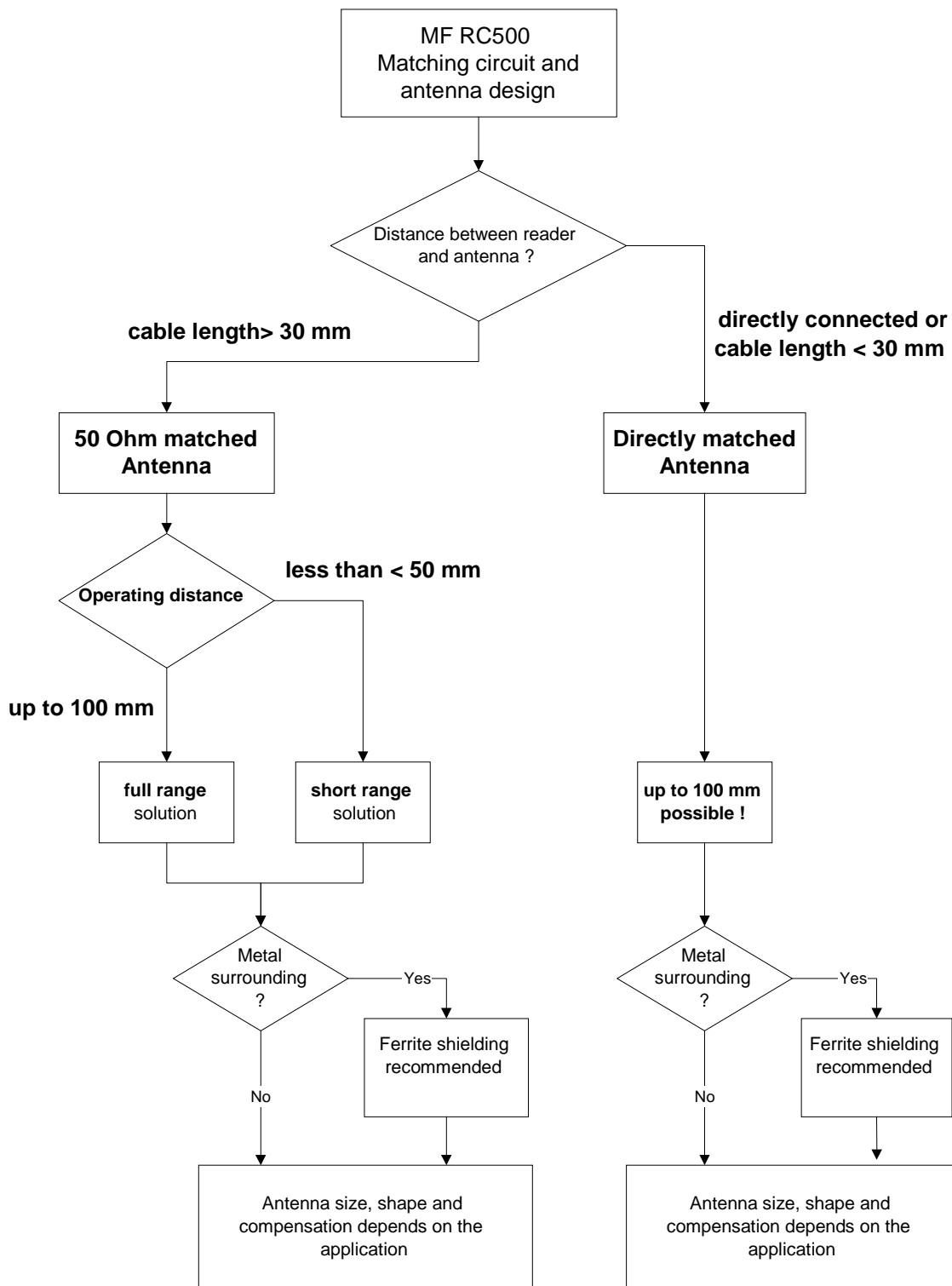## 13.56 MHz RFID Proximity Antennas   mifare® (14443A)

```
                          ┌─────────────────────┐
                          │      MF RC500       │
                          │ Matching circuit and│
                          │   antenna design    │
                          └──────────┬──────────┘
                                     │
                                     ▼
                              ╱──────────────╲
                             ╱ Distance between╲
                             ╲ reader and      ╱
                              ╲  antenna ?    ╱
                               ╲────────────╱
```

cable length> 30 mm   **directly connected or cable length < 30 mm**

```
┌──────────────────┐                    ┌──────────────────┐
│  50 Ohm matched  │                    │ Directly matched │
│     Antenna      │                    │     Antenna      │
└────────┬─────────┘                    └────────┬─────────┘
         │                                       │
         ▼                                       │
```

less than < 50 mm

```
    ╱──────────────╲
   ╱  Operating     ╲
   ╲  distance      ╱
    ╲──────────────╱
```

up to 100 mm

```
┌────────────┐   ┌────────────┐       ┌────────────┐
│ full range │   │ short range│       │ up to 100 mm│
│  solution  │   │  solution  │       │  possible ! │
└─────┬──────┘   └─────┬──────┘       └──────┬──────┘
      │                │                     │
      ▼                                      ▼
   ╱──────╲                               ╱──────╲
  ╱ Metal  ╲──── Yes                     ╱ Metal  ╲──── Yes
  ╲surround.╱                            ╲surround.╱
   ╲  ?   ╱                               ╲  ?   ╱
      │ No                                   │ No
```

```
      │            ┌──────────────┐         │            ┌──────────────┐
      │            │Ferrite shield│         │            │Ferrite shield│
      │            │ recommended  │         │            │ recommended  │
      │            └──────┬───────┘         │            └──────┬───────┘
      ▼                   ▼                 ▼                   ▼
┌────────────────────────────┐     ┌────────────────────────────┐
│  Antenna size, shape and   │     │  Antenna size, shape and   │
│ compensation depends on the│     │ compensation depends on the│
│        application         │     │        application         │
└────────────────────────────┘     └────────────────────────────┘
```

Figure 15: Design Help

13.56 MHz RFID Proximity Antennas

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6 ANNEX

6.1 Theory for estimating the optimum PCD antenna radius

It's not necessary to know and use the below given formulas for the design of a Micore PCD antenna. The principle is described above and details for that design can be found in "MIFARE® and I Code, Micore Directly Matched Antenna Design".
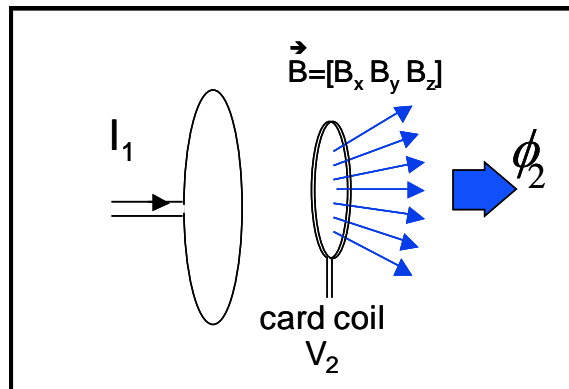
Electromagnetic Induction:

$$V_{ind} = -N_2 \cdot \frac{d\phi}{dt} = -N_2 \cdot \frac{d}{dt} \int_A B_x \cdot dA$$

Induced open loop voltage:

$$v_{20}(t) = N_2 \frac{d\,\hat{\phi}_2 \cdot \sin \omega t}{dt}$$
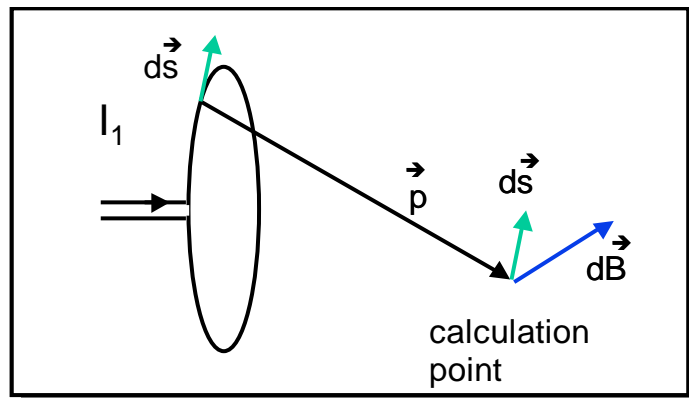$$= N_2 \cdot \omega \cdot \hat{\phi}_2 \cdot \cos \omega t$$

$$V_{20} = N_2 \cdot \omega \cdot \hat{\phi}_2$$
$$= N_2 \cdot \omega \cdot \hat{B} \cdot A_2$$

card coil parameters:
A_2 : area
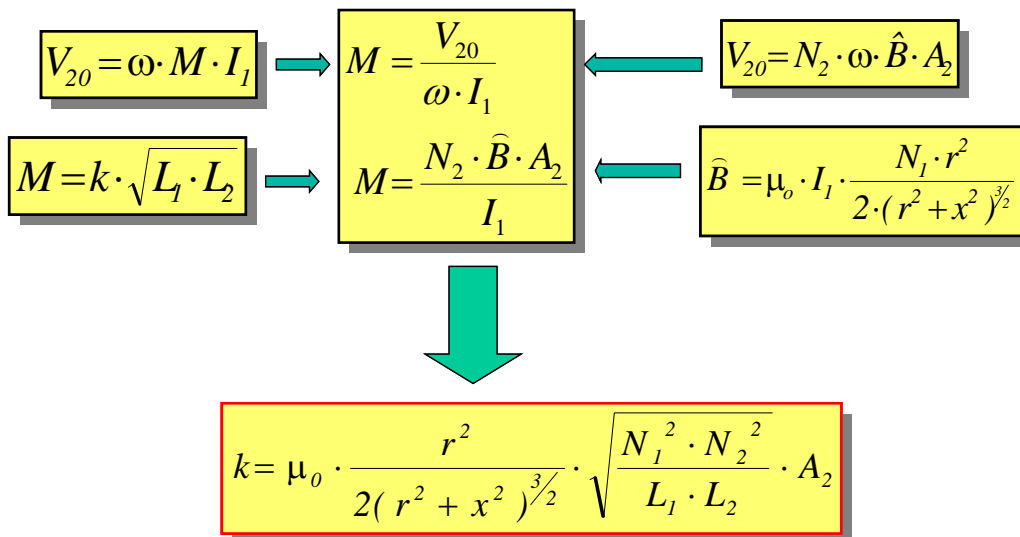N_2 : number of turns

Law of Biot and Savart:

$$\vec{B} = \frac{\mu_0 \cdot I_1}{4\pi} \cdot \oint \frac{\left[d\vec{s} \times \vec{p} \right]}{p^3}$$

13.56 MHz RFID Proximity Antennas

mifare® (14443A)

Optimisation of the coupling coefficient:

$$V_{20} = \omega \cdot M \cdot I_1$$

$$M = \frac{V_{20}}{\omega \cdot I_1}$$

$$V_{20} = N_2 \cdot \omega \cdot \hat{B} \cdot A_2$$

$$M = k \cdot \sqrt{L_1 \cdot L_2}$$

$$M = \frac{N_2 \cdot \hat{B} \cdot A_2}{I_1}$$

$$\hat{B} = \mu_o \cdot I_1 \cdot \frac{N_1 \cdot r^2}{2 \cdot (r^2 + x^2)^{3/2}}$$

$$k = \mu_0 \cdot \frac{r^2}{2(r^2 + x^2)^{3/2}} \cdot \sqrt{\frac{N_1^2 \cdot N_2^2}{L_1 \cdot L_2}} \cdot A_2$$

$$L_1 = L_{01} \cdot N_1^2 \qquad L_2 = L_{02} \cdot N_2^2$$

L_{01}, L_{02} : single turn inductance

$$L_{01} \approx \frac{2 \cdot 10^{-7}}{[m]} \cdot 2\pi \cdot r \cdot \ln(\frac{2\pi \cdot r}{d})$$

Coupling coefficient k = f(r, x):

$$k = \mu_0 \cdot \frac{r^2}{2(r^2 + x^2)^{3/2}} \cdot \frac{A_2}{\sqrt{L_{01} \cdot L_{02}}}$$

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6.2 Parameters and Units

V_{ind}:   Induced voltage

N: Number of turns

Φ: Magnetical Flux

t: time

B: Magnetical Flux densitiy

A: (Coil) Area

V_{20}:   Induced open loop voltage (card antenna coil)

I_1:   PCD antenna coil current

M: Mutual inductance (transformer model)

L: Inductance

r: PCD antenna radius

x: PCD-PICC operating distance

k: coupling coefficient

L_{01}, L_{02}: Single turn inductance

Index 1 is used for the PCD antenna.

Index 2 is used for the PICC antenna. Parameter with index 2 are fixed (according to the ISO14443-1).