INTEGRATED CIRCUITS

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APPLICATION NOTE

mifare®

(Card) Coil Design Guide

Product Specification

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Contents

1 INTRODUCTION

1.1 Scope

This document gives guidelines and definitions how to built coils for Philips MIFARE® ICs or Philips MIFARE® chip modules, which are compatible with MIFARE® reader / write devices built according to specifications.

Generally we recommend to carry out careful tests with the cards and all different read / write devices which will be used with the cards.

1.2 Structure of the Document

This Document is subdivided into four parts.

As a first part we introduce sample designs based on MIFARE® cards at ISO size.

The second part handles the theory that is used for the coil design and includes the general electrical behaviour of the MIFARE® IC family.

The third part handles the suggested measurement methods that are used while the design process.

The fourth part is a suggested design flow that can be used to design specific inlet/label/card coils. This part includes the practical used formulas and matrix suggestions and the decision parameters to determine the correct and best suitable design.

1.3 The MIFARE® Interface

The MIFARE® system is designed to offer a technology platform for contactless smart cards with different components on the reader as well as on the card side. PHILIPS Semiconductors open scenario strategy for the MIFARE® technology platform allows various suppliers to provide different components for this system. Nevertheless maximum compatibility of all components that claim to be part of the MIFARE® world is an essential goal that needs to be kept. For the physical design of a MIFARE® card this goal of maximum compatibility leads to a coil design procedure which is an content of this paper.

NOTE: The compatibility of MIFARE® Cards and Readers is designed to serve the requirements of ISO1 sized Cards. Therefore the reader infrastructure based on MCI (MIFARE® Certification Institute) is compatible with MIFARE® cards certified by MCI.

If different inlet shapes and sizes are used, the interoperability of inlets with MCI certified readers is not necessarily given.

1.4 How to use this Document:

If you want to produce ISO sized cards is sufficient to take chapter 2 as a reference.

For more detailed information about the theory behind it please refer to chapter 3 to 5.

1.5 Abbreviations

A_c	Average coil area
A_{Active}	Active Coil Area
A_i	Area of coil winding i
a_{avg}, b_{avg}	Average dimensions of the coil
a_{max}, b_{max}	Maximum dimensions of the coil
a_o, b_o	Overall dimensions of the coil
C_c	Coil capacitance
C_{br}	Bridge capacitance
C_{Con}	Capacitance due to the connection MIFARE® IC – coil
C_{IC}	MIFARE® IC input capacitance
C_{ICT}	MIFARE® IC input capacitance for threshold condition
C_{in}	Designed inlet capacitance
C_{it}	Inter turn capacitance of the coil
C_{pl}	Parallel equivalent capacitance of the inlet
C_{plT}	Parallel equivalent capacitance of the inlet for threshold condition
d	Coil wire diameter
f	Frequency
f_{op}	Operating frequency of PCD
f_R	Resonance frequency of the inlet
f_{RT}	Threshold resonance frequency of the inlet
g	Gap between tracks
H_T	Threshold field strength
H_{Tmin}	Minimal threshold field strength
H_{Top}	Threshold field strength at operating frequency
I_1	Reader antenna current
L_{calc}	Inductance calculated out of geometrical coil parameters
L_o	Objective inductance of the coil
L_{pc}	Parallel equivalent inductance of the coil
L_{sc}	Series equivalent inductance of the coil
M	Mutual inductance between inlet antenna and reader antenna
N_c	Number of turns of the coil
p	Turn exponent
Q	Quality factor of the inlet
Q_{pc}	Quality factor of the coil for parallel equivalent circuit
Q_{sc}	Quality factor of the coil for series equivalent circuit
Q_T	Threshold quality factor of the inlet
R_{Con}	Resistance of the connection MIFARE® IC – coil
R_{IC}	MIFARE® IC input resistance
R_{ICT}	MIFARE® IC input resistance for threshold condition
R_{pc}	Parallel equivalent resistance of the coil
R_{pl}	Parallel equivalent resistance of the inlet
R_{plT}	Parallel equivalent resistance of the inlet for threshold condition
R_{sc}	Series equivalent resistance of the coil
t	Track thickness
V_{LA-LB}	MIFARE® IC input voltage
$V_{LA-LB\ min}$	Minimal voltage level for MIFARE® IC operation
w	Track width

2 THE MIFARE® CARD

This part of the document is valid for ISO sized Cards based on MIFARE® interface family with 16.5 pF input capacitance C_{IC}.

If more detailed information regarding the theory are needed, or if using the 50 pF MIFARE® interface family, please refer to chapter 3.

The design of the MIFARE® card ICs allows a very cost efficient card production. Only a coil has to be added to the chip and no more additional trimming is necessary. The figure below shows a typical construction of a MIFARE® card.

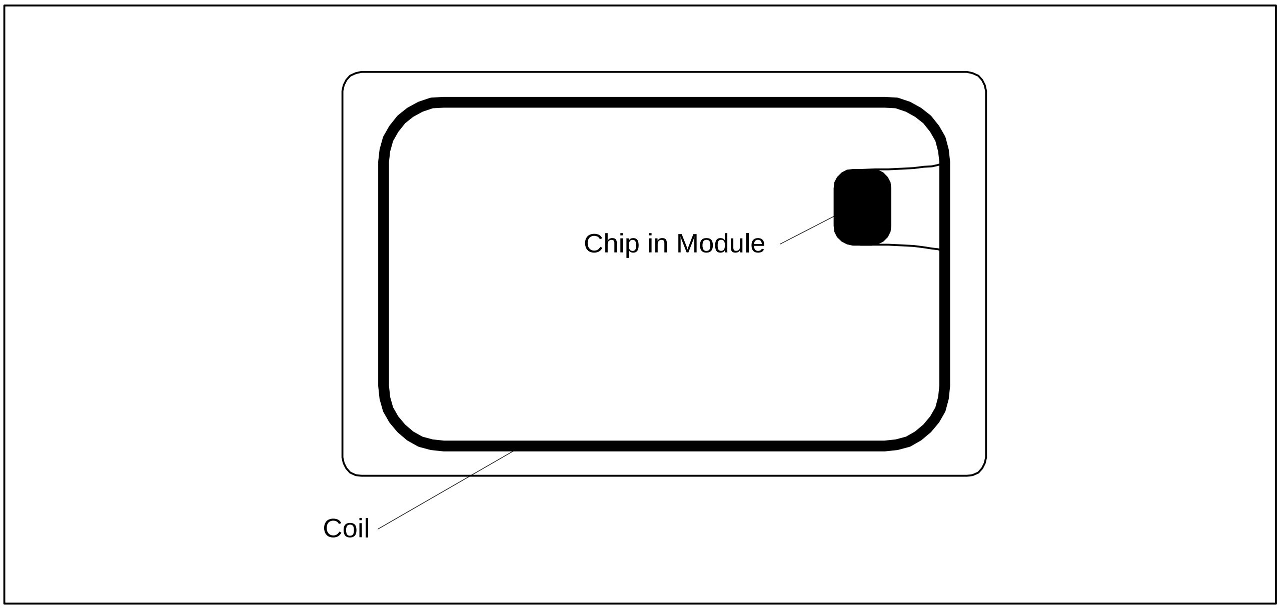


figure 1

The design of the coil together with the card package material has to consider marginal conditions to fulfil all compatibility requirements and to be suitable for different types of MIFARE® ICs.

2.1 The Components

A MIFARE® card typically comprises mainly four components, which influence the performance of the card.

- the MIFARE® IC
- the module
- the card package material
- the coil

How these components contribute to the performance of a MIFARE® card is discussed below

2.1.1 THE MIFARE® IC

The MIFARE® IC is the heart of a MIFARE® card. It mainly determines the function of a card and the application relevant performance. Different existing MIFARE® ICs vary e.g. in their input capacitance and the required operating voltage. These values determine application relevant features like maximum operating distance and the ability to operate several cards simultaneously.

The correct measurement of the chip capacitance versus the operating voltage is difficult and shall not be part of this paper. Consequently this paper, if applicable (see scope) gives a design procedure for the coil, which needs no detailed knowledge of the chip parameters.

2.1.2 THE MODULE

The module is the housing for the MIFARE® IC. It allows easy handling of the IC and protects it against physical stress like extensive bending or UV rays. It provides easy to use large contact areas La and Lb for different coil connecting methods.

For the card assembly process the module is more likely the component that is used than the bare MIFARE® IC.

From the electrical point of view the mounting of the IC into the module adds the capacitance C_{mount} to the resonance circuit of the MIFARE® card. Still the main portion of the module capacitance is given by the ICs input capacitance.

2.1.3 THE CARD PACKAGE MATERIAL

Due to its dielectric property the card package material adds the capacitance C_{pack} to the resonance circuit of the MIFARE® card.

Note: Keep this dependence in mind, when changing from one package material to an other and verify the new card material with the given limits.

Important: This value is clearly influenced by the card manufacturing process and must therefore be considered in the verification of a coil design.

2.1.4 THE COIL

The coil is the electrical component which supplies the power for the card IC and enables additionally the communication between the card IC and the reader. A well designed helps the MIFARE® IC to maximum performance. A bad designed coil will drastically weaken the possible performance of the MIFARE® card. To understand the importance of a correct coil design the main issues are given below.

2.1.4.1 Requirements for a MIFARE® Card Coil

In the following the necessary properties of a suitable MIFARE® card coil are listed and discussed.

- Maximum operating distance.
  The coil in context with the card material shall be designed to achieve maximum operating distance without any impact on the functionality of the card.
- Multiple cards in the field.
  The coil shall be designed in a way to achieve operation of multiple MIFARE® cards in the field even if they are on top of each other.
- Defined position of the coil in the card.
  The position of the coil in the card has to be within certain limits to ensure that this card works properly with readers with small antennas (e.g. slot readers). These readers require the card’s antenna at a defined position within the card for defined magnetic coupling of both antennas.
- Compatibility of cards based on different coil technology.
  Even MIFARE® cards with different coil technology inside have to be compatible.
- One coil should work with various ICs.
  It is of advantage to have a coil design together with a card package material which is suitable for modules housing different MIFARE® ICs.
- No requirement for additional components.
  The coil shall be designed providing that no additional components (e.g. capacitor, etc.) are necessary to fulfil compatibility with the MIFARE® system performance requirements.

2.2 Design Procedure for the Coil

2.2.1.1 Mean Coil Area

Readers designed for low power consumption require maximum magnetic coupling of reader antenna and card antenna. Cards that shall be handled reliably with these readers need the position of the coil and therefore the mean coil area within well defined limits.

For MIFARE® cards an area within the card which shall not be violated by the mean coil area is defined. With this definition the necessary positioning accuracy of the coil and the minimum mean coil area are defined simultaneously.

The larger the coil's size the less are the requirements for precise positioning.

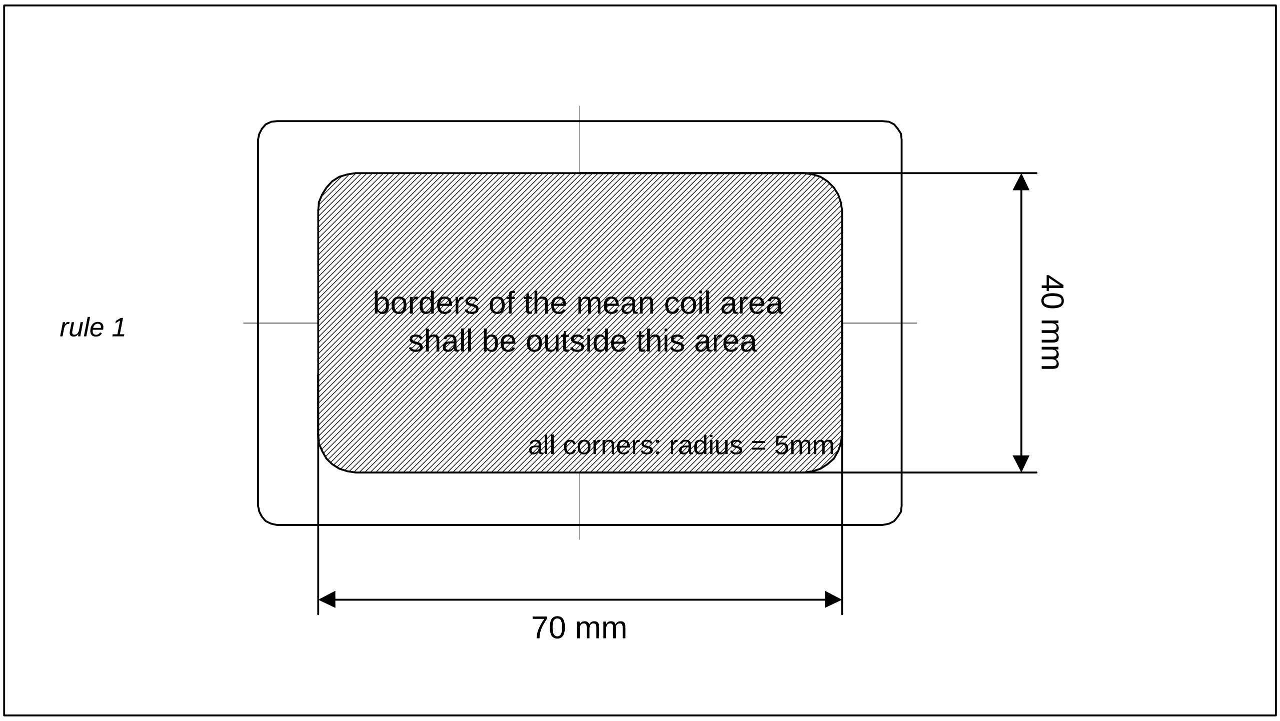


figure 2

From the upper drawing the minimum allowed mean coil area can be derived at the assumption of ideal positioning:

$$\mathbf{A_c \geq 2778.5\ mm^2}$$

PHILIPS Semiconductors recommends a typical coil area of 3330 mm².

The barycentre of the mean coil area shall be centric on the card with a maximum deviation of +/- 6mm from geometric card centre.

Note: In case a coil of more than 4 turns is used, only the 4 largest windings are considered for the calculation of the mean coil area.

For cards using an external visible module (e.g. Dual Interface Cards, ISO 14443A + ISO 7816) the following minimum area for the mean coil area is defined. In this case an unsymmetrical coil area is tolerable.

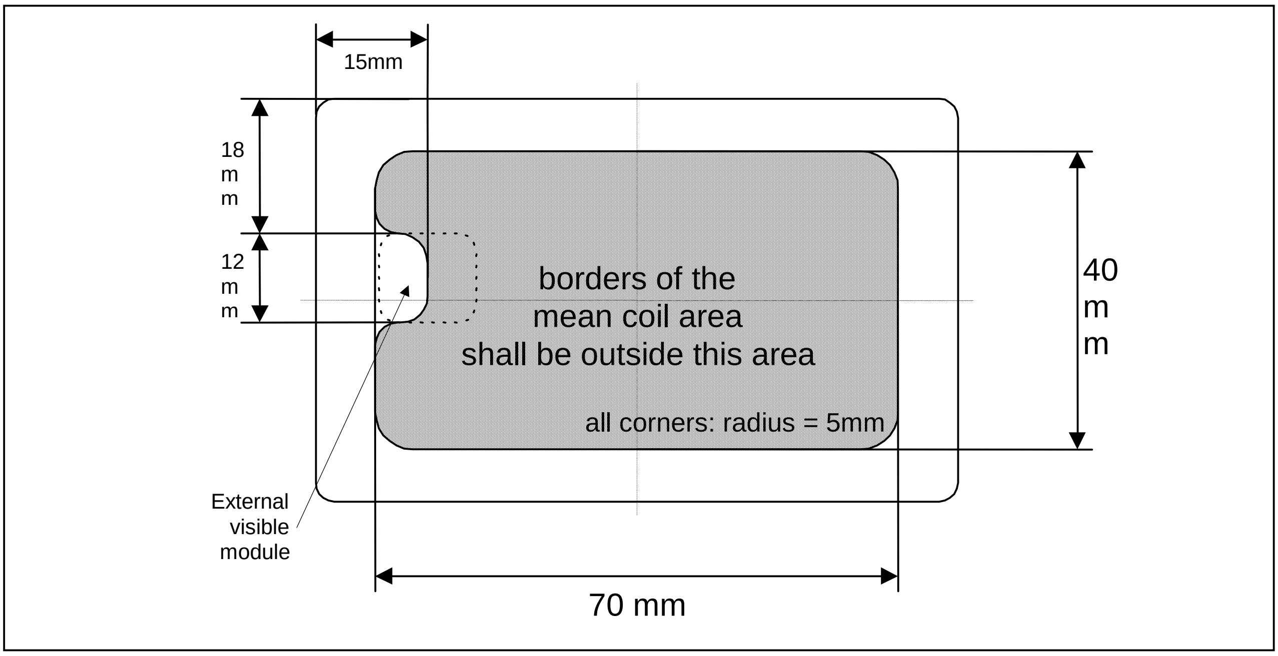


figure 3

2.2.1.2 *Resistance of the Coil / Quality Factor*

Best results for performance can be reached by using coils that lead to Quality factors of

$$\mathbf{30 < Q_{SC} < 60}$$

2.2.1.3 *Threshold Resonance frequency*

To be granted the MIFARE® Certification the threshold resonance frequency of the card need to be between 14.5 MHz and 18.5 MHz. (please also refer to chapter 3.3). To cover manufacturing tolerances Philips recommends a resonance frequency of

$$\mathbf{15\ MHz < f_{RT} < 17.5\ MHz}$$

2.2.1.4 *Active Coil Area*

The active coil A_{active} area is the sum of the area of the individual turns of the coil A_i.

$$A_{active} = \sum_{i=1}^{n} A_i \qquad \mathbf{A_{active} \geq 11200\ mm^2}$$

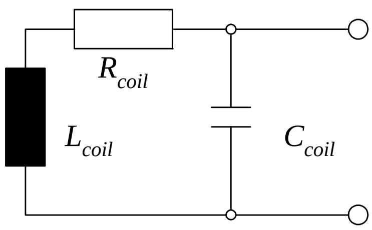
2.3 Examples of Coils

2.3.1 EXAMPLE OF A WIRED COIL

Let's use the design procedure discussed in the chapter before and verify whether all requirements are met with the following wired coil.

2.3.1.1 Electrical Data.

Description	Unit	Value	Tolerance
turns	n	4	
Inductance	L_{sc} [µH]	3.6	+/- 3%
Parallel capacitance	C_{sc} [pF]	4.7	+/- 3%
Series resistance	R_{sc} [Ohm]	6.07	+/- 4%
Operating frequency	f_{op} [MHz]	13.56	



equivalent electrical circuit

2.3.1.2 Physical Data.

Description	Unit	Value	Remark
Length	a_{max} [mm]	74	
Height	b_{max} [mm]	45	
Minimum enclosed area	A_c [mm²]	3330	
Coil wire	d [mm]	0.15	Elektrofeindraht(Backlack), Code S155, Grad 1B, Electrisola
Card Package Material	C_P [pF]	5.25	± 5%

2.3.1.3 Verification

Description	Unit	Value	Minimum requirement	Verification
Minimum enclosed area	A_c [mm²]	3330	2778,5	✓
Active area	A_{active} [mm²]	13320	11200	✓
Threshold Resonance Frequency [1)]	f_{RT} [MHz]	16,3 [2)]	15 – 17.5	✓

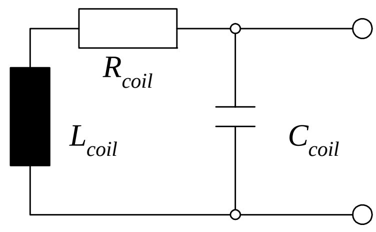
[1)]Based on a MF1ICS5001
[2)]With an approximate overall tolerance of +/- 7% the limits can be kept.

2.3.2 SAMPLE FOR AN ETCHED COIL

Let's use the design procedure discussed in the chapter before and verify whether all requirements are met with the following etched coil.

2.3.2.1 Electrical Data.

Description	Unit	Value	Tolerance
Turns	n	4	
Inductance	L_{sc} [µH]	3.65	+/- 1%
Parallel capacitance	C_{sc} [pF]	4.1	+/- 10%
Series resistance	R_{sc} [Ohm]	6.3	+/- 10%
Operating frequency	f_{sc} [MHz]	13.56	



equivalent electrical circuit

2.3.2.2 Physical Data.

Description	Unit	Value	Remark
Length	a_{max} [mm]	76	
Height	b_{max} [mm]	46	
Minimum enclosed area	A_c [mm²]	3496	
Track width	w [µm]	150	
Track thickness	t [µm]	35	
Card Package Material	C_P [pF]	5.25	± 5%

2.3.2.3 Verification

Description	Unit	Value	Minimum requirement	Verification
Minimum enclosed area	A_c [mm²]	3496	2778,5	✓
Active area	A_{active} [mm²]	13984	11200	✓
Threshold Resonance Frequency [1]	f_{RT} [MHz]	16.38 [2]	15 – 17.5	✓

[1] Based on a MF1ICS5001
[2] With an approximate overall tolerance of +/- 6% the limits can be kept.

3 THEORY

3.1 The MIFARE® IC

The MIFARE® IC has to be connected to the coil with the pads L_A and L_B:

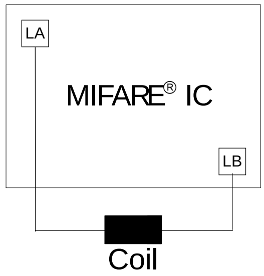


Fig. 1: MIFARE® IC

3.1.1 EQUIVALENT CIRCUIT OF THE MIFARE® IC

The following simple equivalent circuit describes the properties of the MIFARE® IC which are relevant for the coil design.

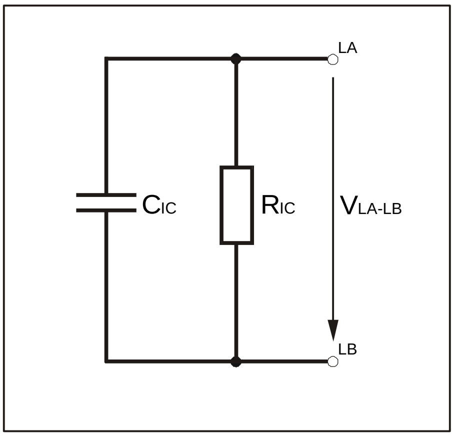


Fig. 2: Equivalent circuit of the MIFARE® IC

R_{IC}	MIFARE® IC input resistance
C_{IC}	MIFARE® IC input capacitance

3.1.2 MIFARE® IC INPUT RESISTANCE R_{IC}

The MIFARE® IC shows an Input Resistance of typical 15 kOhm.

3.1.3 MIFARE® IC INPUT CAPACITANCE C_{IC}

This electrical parameter of the MIFARE® IC is the most important factor for the coil design.

The input capacitance depends on the applied chip voltage.

The following value of this capacitance for the given type of MIFARE® IC is specified (for packages see according delivery type specification):

Type	C_{IC}	Measurement Conditions[1]
MF1 ICS50	16.1 pF	V_{LA-LB} = 2 V_{rms}, f = 13.56 MHz
MF1 ICS70	16.1 pF	V_{LA-LB} = 2 V_{rms}, f = 13.56 MHz
MF0 ICU10	16.9 pF	V_{LA-LB} = 2 V_{rms}, f = 13.56 MHz
MF0 ICU11	50 pF	V_{LA-LB} = 2 V_{rms}, f = 13.56 MHz
MF2 ICD8x	15.1 pF	V_{LA-LB} = 2 V_{rms}, f = 13.56 MHz
P8RF5016	16.9 pF	V_{LA-LB} = 2 V_{rms}, f = 13.56 MHz

[1] Measured with HP 4285A LCR Meter

3.2 Equivalent Circuits

3.2.1 SERIES EQUIVALENT CIRCUIT OF THE COIL

The coil can be described by an inductance L_{sc} in series to a loss resistance R_{sc}. The coil capacitance C_c is in parallel to this series circuit. This capacitance consists of the inter-turn capacitance and a possibly designed inlet capacitance. The design of such an inlet capacitance is not considered in this application note.

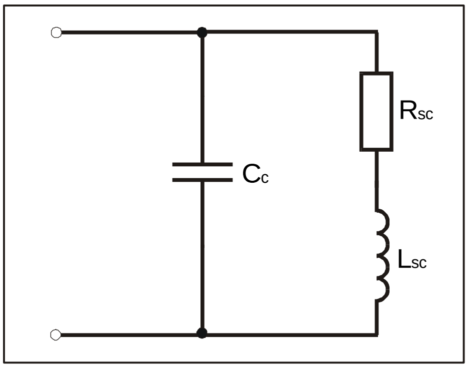


Fig. 3: Series equivalent circuit of the coil

R_{sc}	Series equivalent resistance of the coil
L_{sc}	Series equivalent inductance of the coil
C_c	Coil capacitance

The coil quality factor is calculated by

$$Q_{sc} = \frac{2 \cdot \pi \cdot f_{op} \cdot L_{sc}}{R_{sc}}$$

with operating frequency f_{op} = 13.56 MHz.

3.2.2 PARALLEL EQUIVALENT CIRCUIT OF THE COIL

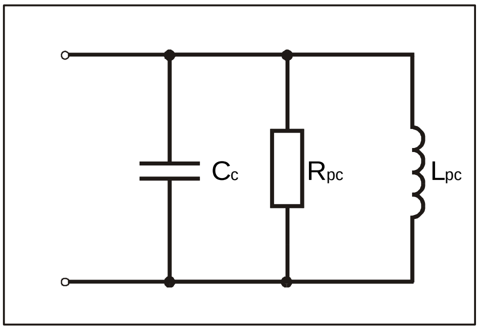


Fig. 4: Parallel equivalent circuit of the coil

R_{pc} Parallel equivalent resistance of the coil

L_{pc} Parallel equivalent inductance of the coil

The following applies:

$$L_{pc} = \frac{R_{sc}^{\ 2} + (2 \cdot \pi \cdot f_{op} \cdot L_{sc})^2}{(2 \cdot \pi \cdot f_{op})^2 \cdot L_{sc}} = L_{sc} \cdot \frac{1 + Q_{sc}^{\ 2}}{Q_{sc}^{\ 2}}$$

$$R_{pc} = \frac{R_{sc}^{\ 2} + (2 \cdot \pi \cdot f_{op} \cdot L_{sc})^2}{R_{sc}} = R_{sc} \cdot (1 + Q_{sc}^{\ 2})$$

$$Q_{pc} = \frac{R_{pc}}{2 \cdot \pi \cdot f_{op} \cdot L_{pc}} = Q_{sc}$$

For the further calculations the parallel equivalent circuit was chosen to simplify the resonance circuit. This makes calculation easier.

3.2.3 EQUIVALENT CIRCUIT OF THE INLET

The following figure shows the equivalent circuit of the whole inlet.

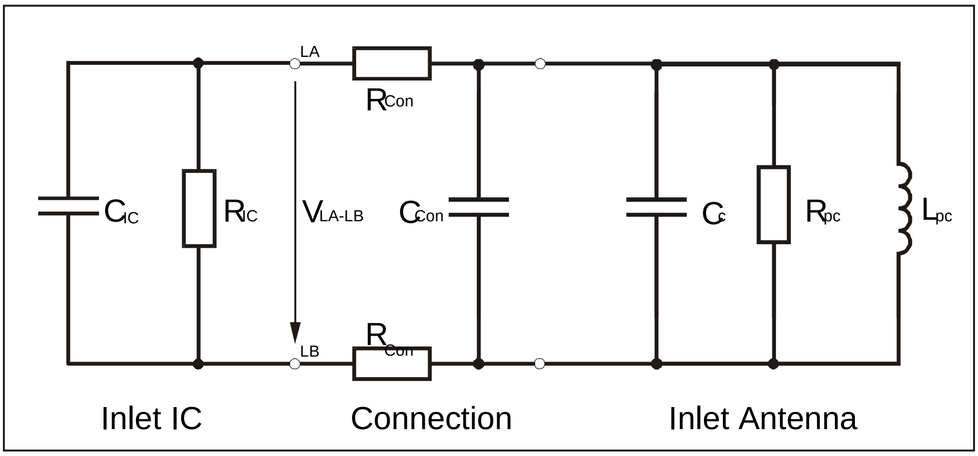


Fig. 5: Equivalent circuit of the inlet

R_{Con}	Resistance of the connection MIFARE® IC – coil
C_{Con}	Connection capacitance

The MIFARE® IC capacitance C_{IC} together with the coil capacitance and the parasitic connection capacitance forms a resonance circuit with the inductance of the coil.

The MIFARE® IC input resistance R_{IC} together with the loss resistance of the coil and the connection resistance defines the quality factor of the inlet. This quality factor has an effect on the threshold field strength of the inlet and will be explained in the following sections.

R_{Con} should be kept as low as possible in order not to influence the total parallel equivalent resistance of the inlet R_{pl}. A relatively high connection resistance will decrease the total quality factor of the inlet and therefore decrease the transmission range.

C_{Con} describes the increase of the total inlet capacitance due to dielectric changes (under filler, adhesive, ..) in the connection area when the chip is applied to the coil.

For $R_{Con} << 1\ \Omega$ the following simplified equivalent circuit can be used for the inlet:

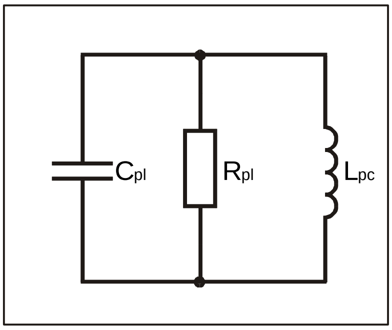


Fig. 6: Simplified equivalent circuit of the inlet

With:

$$C_{pl} = C_{IC} + C_{Con} + C_c$$ Parallel equivalent capacitance of the inlet

$$R_{pl} = \frac{R_{IC} \cdot R_{pc}}{R_{IC} + R_{pc}}$$ Parallel equivalent resistance of the inlet

3.3 Resonance Frequency and Quality Factor of the Inlet

Based on the simplified equivalent circuit the resonance frequency f_R of the inlet can be calculated with:

$$f_R = \frac{1}{2 \cdot \pi \cdot \sqrt{L_{pc} \cdot C_{pl}}}$$

f_R Resonance frequency of the inlet

The value of the MIFARE® IC input capacitance C_{IC} depends on the chip input voltage $V_{LA-LB.}$ Therefore the resonance frequency of the inlet changes with the IC input voltage.

Based on the simplified equivalent circuit (Fig. 6) the quality factor Q of the inlet at the operating frequency can be calculated with:

$$Q = \frac{R_{pl}}{2 \cdot \pi \cdot f_{op} \cdot L_{pc}}$$

Q Quality factor of the inlet

The value of the MIFARE® IC input resistance R_{IC} depends on the chip input voltage V_{LA-LB}. Therefore also the quality factor of the inlet changes with the IC input voltage.

3.3.1 THRESHOLD RESONANCE FREQUENCY F_{RT} AND THRESHOLD QUALITY FACTOR Q_T

The threshold resonance frequency f_{RT} is the resulting resonance frequency for the minimum operating input voltage of the IC.

$V_{LA-LB\ min}$ Minimal voltage level for MIFARE® IC operation

$$C_{plT} = C_{ICT} + C_{Con} + C_c$$

C_{ICT} MIFARE® IC input capacitance for threshold condition

C_{plT} Parallel equivalent capacitance of the inlet for threshold condition

C_{ICT} represents the MIFARE® IC input capacitance for minimal operating conditions and corresponds to the specified typical value.

$$f_{RT} = \frac{1}{2 \cdot \pi \cdot \sqrt{L_{pc} \cdot C_{plT}}}$$

f_{RT} Threshold resonance frequency

$$R_{plT} = \frac{R_{ICT} \cdot R_{pc}}{R_{ICT} + R_{pc}}$$

R_{ICT} MIFARE® IC input resistance for threshold condition

R_{plT} Parallel equivalent resistance of the inlet for threshold condition

R_{ICT} represents the MIFARE® IC input resistance for the minimal operating conditions and corresponds to the shown typical value.

$$Q_T = \frac{R_{plT}}{2 \cdot \pi \cdot f_{RT} \cdot L_{pc}}$$

Q_T Threshold quality factor

3.4 Threshold field strength H_T

This section gives formulas to calculate the threshold field strength H_T which is significant for the transmission range. The influence of the threshold resonance frequency f_{RT} and coil quality factor Q_{pc} on this field strength is figured out.

The voltage on the IC generated by the magnetic field of the reader with antenna current I_1 is given by:

$$V_{LA-LB} = \frac{2 \cdot \pi \cdot f \cdot M}{\left(\left(1 - \left(\frac{f}{f_R} \right)^2 \right)^2 + \left(\frac{2 \cdot \pi \cdot f \cdot L_{pc}}{R_{pl}} \right)^2 \right)^{1/2}} \cdot I_1$$

M	Mutual inductance between inlet antenna and reader antenna
I_1	Reader antenna current
f	Frequency

With the assumption that the turns of the inlet coil are concentrated on the average coil dimensions, the threshold field strength for MIFARE® IC operation can be calculated with:

$$H_T = \frac{\left(\left(1 - \left(\frac{f}{f_{RT}} \right)^2 \right)^2 + \left(\frac{2 \cdot \pi \cdot f \cdot L_{pc}}{R_{plT}} \right)^2 \right)^{1/2}}{2 \cdot \pi \cdot f \cdot \mu_0 \cdot N_c \cdot A_c} \cdot V_{LA-LB\,\min}$$

N_c	Number of turns of the inlet coil
A_c	Average coil area calculated with average coil dimensions
$V_{LA-LB\ min}$	Minimal voltage level for MIFARE® IC operation

The following figure shows the behaviour of the threshold field strength H_T versus the frequency f of the inducing magnetic field for a inlet with the threshold resonance frequency f_{RT}.

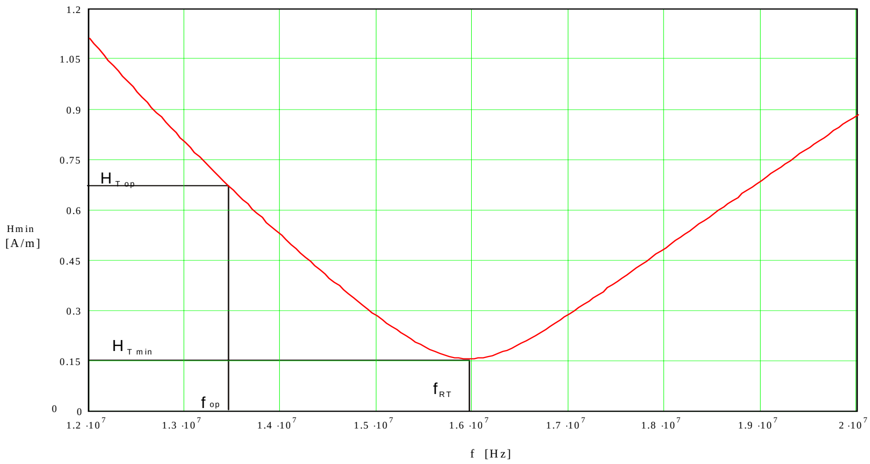


Fig. 7: Threshold field strength vs. frequency

The curve of the threshold field strength reaches its minimum at the threshold resonance frequency f_{RT} of the inlet. For f = f_{RT} the minimal threshold field strength $H_{T\ min}$ results in:

$$H_{T\ \min} = \frac{L_{pc}}{\mu_0 \cdot N_c \cdot A_c \cdot R_{plT}} \cdot V_{LA-LB\ \min}$$

At the operating frequency f_{op} the threshold field strength results in:

$$H_{T\ op} = \frac{\left(\left(1 - \left(\frac{f_{op}}{f_{RT}} \right)^2 \right)^2 + \left(\frac{2 \cdot \pi \cdot f_{op} \cdot L_{pc}}{R_{plT}} \right)^2 \right)^{1/2}}{2 \cdot \pi \cdot f_{op} \cdot \mu_0 \cdot N_c \cdot A_c} \cdot V_{LA-LB\ \min}$$

Lowest operating field strength is reached if f_{RT} = f_{op} = 13.56 MHz resulting in H_T = H_{Tmin}

<u>IMPORTANT NOTE:</u> For Cards it has to be considered, that stacked cards influence each other. Therefore the suggested threshold resonance frequency f_{RT} for multi-operated (stacked) and MCI (MIFARE® Certification Institute) cards is between 14.5 MHz and 18.5 MHz (Philips recommends 15 – 17.5 MHz). For other designs and applications use a frequency between 14 MHz and 17.5 MHz. based on requirements of the application. (Please also refer to chapter 5.2)

<u>NOTE:</u> The compatibility of MIFARE® cards and readers is designed to serve the requirements of ISO1 sized cards. Therefore the reader infrastructure based on MCI is compatible with MIFARE® cards certified by MCI. If different inlet shapes and sizes are used, the interoperability of inlets with MCI certified readers is not necessarily given.

4 MEASUREMENT METHODS

4.1 Coil Characterisation

The equivalent circuit of the coil (without IC) can be determined by using the following measuring instruments with associated measuring principals.

4.1.1 IMPEDANCE ANALYSER WITH EQUIVALENT CIRCUIT CALCULATION

The following instruments among others can determine the serial or parallel equivalent circuit by measuring the magnitude and the phase of the impedance of the connected coil.

Instruments: HP 4194A

HP 4294A

HP 4195A

HP 4295A

The coil must be connected to the analyser by using an appropriate test fixture which do not influence the coil parameters (no metal parts near the coil, ...).

The analyser must be calibrated (open, short and load compensation at the calibration plane) and the test fixture compensated (open, short compensation at the connection points) according to the instruments manual before each measurement.

Settings: $|Z|, \Theta$

Centre frequency: 16 MHz

Span: ± 4 MHz

Parallel Equivalent circuit is used for measurement. The values can then be used for the design procedure.

4.2 Inlet Characterisation

In this case there is already an IC connected to the coil.

4.2.1 METHOD ACCORDING TO MCI FOR ISO 1 SIZED CARD

For ISO 1 sized cards a measurement method is available which is also used by the MCI.

Measurement Principle:

A measurement coil has to be connected to the instrument. A short-compensation has to be performed with this measurement coil connected to the terminals of the instrument.

The measuring coil itself is described in ***ISO10373-6 6.1 (Calibration Coil)*** which meets the following requirements:

- Roughly the same dimensions as the card coil
- 1 turn
- Low parasitic capacitance
- High quality factor

The measurement of the bare short-compensated measuring coil (no inlet coil next to it) shows a very low impedance. For inlet characterisation it has to be positioned without any distance and covering the measuring coil completely. The measurement of R and X shows a well defined maximum of the resistance. The resonance frequency of the inlet is found at the maximum of R.

Resonance frequency: f_r @ / R = maximum

Measurement Preparations:

- The measuring coil has to be connected to the test fixture of the instrument
- A short correction of the measuring coil has to be performed and switched on
- Settings: R, X , frequency sweep (if using LCR meter this has do be done manually or by software)
- Output power has to be set to 15mA. **Note:** If the RLC meter is not able to provide this current use the smallest applicable distance between inlet and measuring coil for the measurement.

Advantage:

Fast and simple measurement.

Measurement is also used by MCI for ISO 1 sized card certification.

Disadvantage:

Comparable results only for ISO 1 sized cards.

4.2.2 IMPEDANCE ANALYSER OR LCR METER

Measurement Principle:

A measurement coil has to be connected to the instrument. A short-compensation has to be performed with this measurement coil connected to the terminals of the instrument.

The measuring coil has to meet the following requirements:

- About the same dimensions as the inlet coil
- 1 turn
- Low parasitic capacitance
- High quality factor

The measurement of the bare compensated measuring coil (no inlet coil next to it) shows a very low impedance. The inlet has to be positioned close to the measuring coil (appr. 1 cm distance). The measurement (R, X) of the measuring coil shows a well defined maximum of the resistance now The resonance frequency is found at this maximum of R.

Resonance frequency: f_r @ / R = maximum

Measurement Preparations:

- The measurement coil has to be connected to the test fixture of the instrument
- A short correction of the measurement coil has to be performed and switched on
- Settings: R, X , frequency sweep (for LCR meter this has do be done manually or by software)
- Use highest possible output power of the measurement equipment (2Vrms or 15dBm, depending on instrument)

Advantage:

Fast and simple measurement

Disadvantage:

The output power of common impedance analysers is not high enough to reach the appropriate field strength to measure exact measurement of f_{RT}. Therefore measurement deviations for f_{RT} of up to **+1 MHz** are possible.

4.2.3 REFERENCE MEASUREMENT USING CAPACITOR

This measurement generally just verifies the coil because there is no IC connected. Because you can use this measurement for verifying the tuning of a inlet it is mentioned in the inlet characterisation chapter (§4.2).

Measurement Principle:

Instead of an inlet consisting of Coil and MIFARE® IC, a dummy inlet consisting of coil and reference capacitor is used.

The reference capacitor should meet the following requirements:

- Value of reference capacitor optimal is the nominal capacitance of the used MIFARE® IC. This value can also be achieved by using more than one capacitor in parallel by adding the single capacitance values. It's also possible to use a trim capacitor and tune to the needed value.
- High quality capacitors have to be used.

A measuring coil has to be connected to the instrument. A short-compensation has to be performed with this measuring coil connected to the terminals of the instrument.

The measuring coil has to meet the following requirements:

- About the same dimensions as the inlet coil (for ISO1 sized cards refer to ISO10373)
- 1 turn
- Low parasitic capacitance
- High quality factor

The measurement of the bare compensated measuring coil (no inlet coil next to it) shows a very low impedance. The inlet has to be positioned close to the measuring coil (appr. 1 cm distance). The measurement (R, X) of the measuring coil shows a well defined maximum of the Resistance now. The resonance frequency is found at this maximum of R.

Resonance frequency: f_r @ R = maximum

Measurement Preparations:

- The measurement coil has to be connected to the test fixture of the instrument
- A short correction of the measurement coil has to be performed and switched on
- Settings: R, X, frequency sweep

Advantage:

Fast and simple measurement.

High reliability of the measurement.

Independent from instrument output power.

Disadvantage:

Interconnection capacitance is not considered. (between IC and antenna, C_{Con})

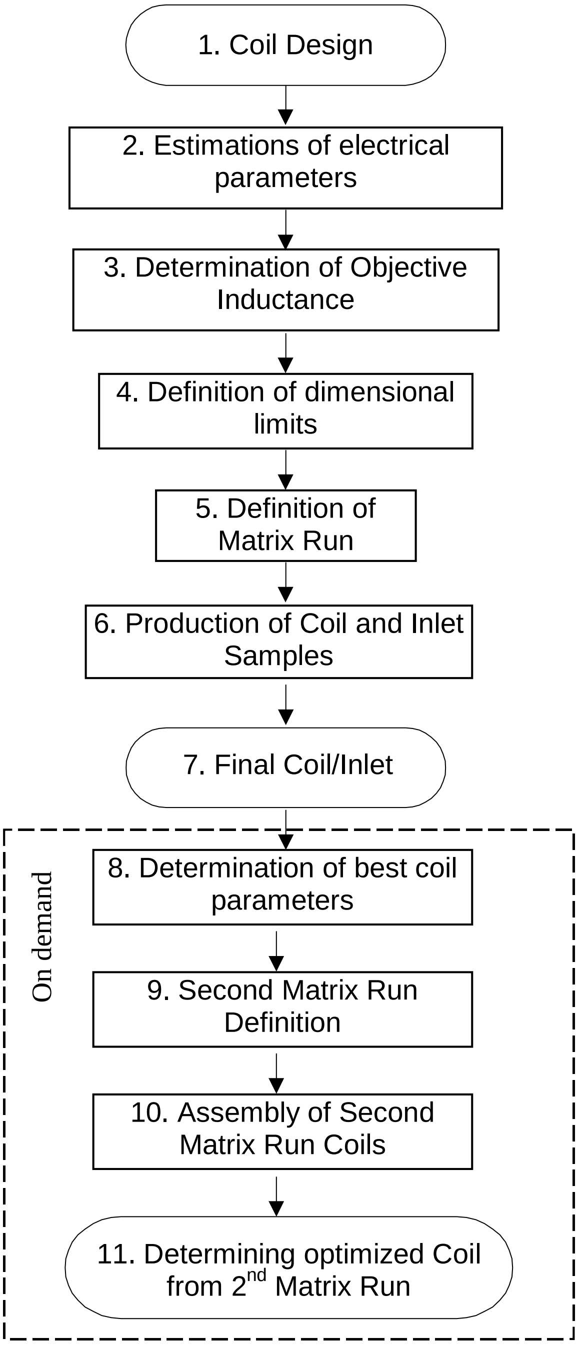
4.2.4 MINIMUM FIELDSTRENGHT MEASUREMENT

With this measurement the frequency is determined where the inlet can be operated with the lowest field strength. This frequency is called resonance frequency. (see chapter §3.4)

This measurement is performed with the measurement configuration as it is used in ISO 10373-6.

5 COIL DESIGN PROCEDURE

5.1 Design Flow



5.2 Estimation of electrical parameters

5.2.1 IDEAL THRESHOLD FREQUENCY F_{IDEAL} DETERMINATION

Based on the application it is necessary to determine what resonance frequency the inlet should be tuned to.

For cards a frequency between 15 MHz and 17.5 MHz should be used to guarantee multi card operation also for stacked cards.

For single inlet operation a tuning slightly above 13.56 MHz would lead to maximum read-/write distance. Due to manufacturing tolerances a nominal resonance frequency of 14,5 MHz for single inlet operation is recommented.

5.2.2 ESTIMATION OF THE COIL CAPACITANCE C_C

In order to be able to calculate roughly the objective inductance L_o of the coil, it is necessary to estimate the capacitance C_c of the coil. This capacitance can be split up into the always existent coil inter turn capacitance C_{it}, the additional capacitance due to a possibly realised bridge C_{br} and a possibly designed on inlet capacitance C_{in}.

The coil inter turn capacitance C_{it} is dependent upon the technology used for the coil manufacturing. The following table shows the estimated values for some often used technologies.

Coil manufacturing technology	C_{it} [pF]
Wired	5 - 7
Etched	2 - 4
Printed	2 - 4

The capacitance of a possibly realised bridge C_{br} depends on the bridge length and bridge width.

Estimated value: C_{br} = 1 – 5 pF

An additional capacitance realised on the inlet C_{in} depends on the capacitor area. This capacitance is difficult to estimate, so it is recommended to make a measurement of this on inlet capacitor.

$$C_c = C_{it} + C_{br} + C_{in}$$

5.2.3 ESTIMATION OF THE CONNECTION CAPACITANCE C_{CON}

The connection capacitance can be estimated by choosing a value out of the following range:

C_{Con} = 0.5 – 2 pF

5.2.4 CALCULATION OF OBJECTIVE COIL INDUCTANCE L_O BASED ON AN ESTIMATED INLET CAPACITANCE C_{PLT}

$$C_{plT} = C_{ICT} + C_{Con} + C_c$$ Estimated parallel equivalent capacitance of the inlet

With C_{ICT} = 16.5 pF

$$L_o = \frac{1}{(2 \cdot \pi \cdot f_{RT})^2 \cdot C_{plT}}$$

With $f_{RT} = f_{ideal}$

5.3 Determination of Objective Inductance L_O

5.3.1 RECTANGULAR (SQUARE) COILS

5.3.1.1 Calculation of Inductance

The inductance of the coil out of geometrical parameters estimates to:

$$L_{calc} = \frac{\mu_0}{\pi} \cdot [x_1 + x_2 - x_3 + x_4] \cdot N_c{}^p$$

With:

$$d = \frac{2 \cdot (t + w)}{\pi}$$

$$a_{avg} = a_o - N_c \cdot (g + w)$$

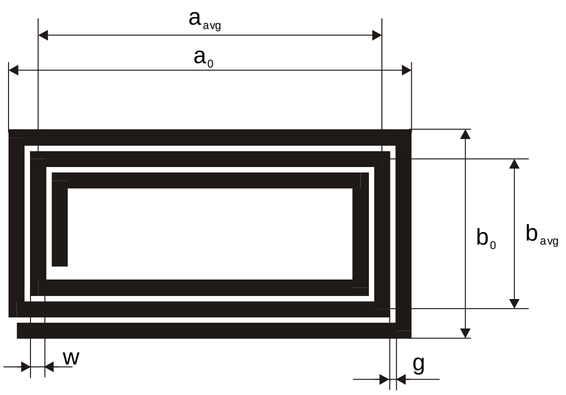
$$b_{avg} = b_o - N_c \cdot (g + w)$$

$$x_1 = a_{avg} \cdot \ln\left[\frac{2 \cdot a_{avg} \cdot b_{avg}}{d \cdot \left(a_{avg} + \sqrt{a_{avg}{}^2 + b_{avg}{}^2}\right)}\right]$$

$$x_2 = b_{avg} \cdot \ln\left[\frac{2 \cdot a_{avg} \cdot b_{avg}}{d \cdot \left(b_{avg} + \sqrt{a_{avg}{}^2 + b_{avg}{}^2}\right)}\right]$$

$$x_3 = 2 \cdot \left[a_{avg} + b_{avg} - \sqrt{a_{avg}{}^2 + b_{avg}{}^2}\right]$$

$$x_4 = \frac{a_{avg} + b_{avg}}{4}$$



Variables:

a_o, b_o	Overall dimensions of the coil
a_{avg}, b_{avg}	Average dimensions of the coil
t	Track thickness
w	Track width
g	Gap between tracks
N_c	Number of turns
d	Equivalent diameter of the track
p	Turn exponent

5.3.2 ROUND COILS

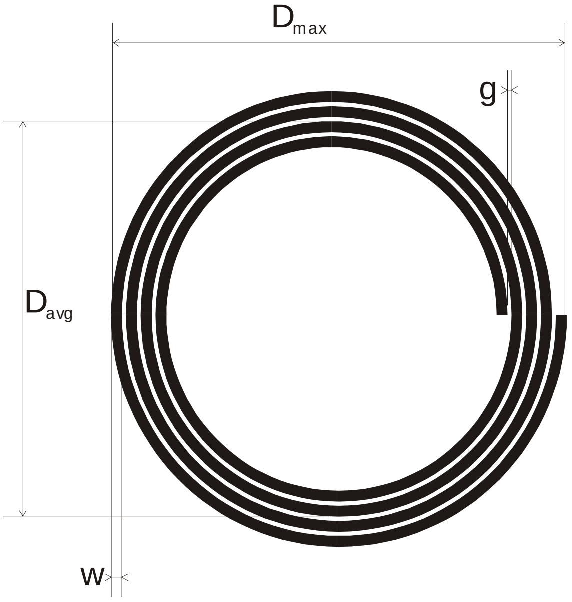
The inductance of the coil out of geometrical parameters estimates to:

$$L_{calc}[nH] = 2 \cdot l \cdot \left[\ln \frac{l}{d} - 1{,}07 \right] \cdot N^p$$

$$l = D_{avg} \cdot \pi$$

$$D_{avg} = D_o - N \cdot (g + w)$$

$$d = \frac{2 \cdot (w + t)}{\pi}$$



D_{max}	Coil diameter [cm]
D_o	Coil diameter [cm]
t	Track thickness
w	Track width
g	Gap between tracks
N_c	Number of turns
d	Equivalent diameter of the track
p	Turn exponent
D_{avg}	Average coil Diameter[cm]
l	average coil circumference [cm]

Variables:

5.4 Determination of Dimensional Limits

5.4.1 RECTANGULAR (SQUARE) COILS

5.4.1.1 Maximum coil dimensions a_{max}, b_{max}

The maximum dimensions of the coil a_{max} and b_{max} are determined by the application which the inlet is designed for.

Therefore the starting point for the calculations is always:

$$a_o = a_{max}$$

$$b_o = b_{max}$$

The actual overall dimensions of the coil a_o and b_o can also be smaller than a_{max} and b_{max} in some cases (big inlets) but the product $A_c \cdot N_c$ should be kept always as high as possible (see ”Minimal threshold field strength”)!

$$A_c = a_{avg} \cdot b_{avg}$$ Average coil area

The active coil A_{active} area is the product of average coil area A_c and the number of turns N_C.

$$A_{active} = A_C \cdot N_C$$ Active coil area

5.4.1.2 Gap between tracks g

The minimal gap between the tracks g_{min} is defined by the coil production process.

To get the highest possible average coil area:

$$g = g_{min}$$

5.4.1.3 Track thickness t and track width w

For Aluminium and Copper coils a track thickness of $t \geq 30$ µm should give a sufficient quality factor even for a small track width w.

For printed coils the track thickness should be chosen as high as possible to get highest possible quality factors.

The track width w remains as fit-parameter for the calculation of the inductance L_{calc}. It is recommended to choose the track width w not to small as it influences the quality factor Q_{pc} and a variation of the track width w is needed for the second matrix run as well.

5.4.1.4 Estimation of Turn Exponent p

Under the assumption that all turns are concentrated on the outline of the coil, so all magnetic flux passes the enclosed area of all turns (no stray field) and the magnetic coupling between the turns is 100 %, the inductance is proportional to N_c^2.

As this is not possible to realise the following table gives estimated values for the turn exponent p for different coil manufacturing technologies.

Coil manufacturing technology	p
Wired	1.8 – 1.9
Etched	1.75 – 1.85
Printed	1.7 – 1.8

5.4.2 ROUND COILS

5.4.2.1 Maximum coil dimensions D_{max}

The maximum dimension of the coil D_{max} is determined by the application the inlet is designed for.

Therefore the starting point for the calculations is always:

$$D_o = D_{max}$$

The actual overall dimension of the coil D_o can also be smaller than D_{max} in some cases (big inlets) but the product $A_c \cdot N_c$ should be kept always as high as possible (see ”Minimal threshold field strength”)!

$$A_c = D_{avg}{}^2 \cdot \frac{\pi}{4}$$ Average coil area

5.4.2.2 Gap between tracks g

The minimal gap between the tracks g_{min} is defined by the coil production process.

To get the highest possible average coil area:

$$g = g_{min}$$

5.4.2.3 Track thickness t and track width w

For Aluminium and Copper coils a track thickness of t ≥ 30 µm should give a sufficient quality factor even for a small track width w.

For printed coils the track thickness should be chosen as high as possible to get highest possible quality factors.

The track width w remains as fit-parameter for the calculation of the inductance L_{calc}. It is recommended to choose the track width w not to small as it influences the quality factor Q_{pc} and a variation of the track width w is needed for the second matrix run as well.

5.4.2.4 Estimation of Turn Exponent p

Under the assumption that all turns are concentrated on the outline of the coil, so all magnetic flux passes the enclosed area of all turns (no stray field) and the magnetic coupling between the turns is 100 %, the inductance is proportional to N_c^2.

As this is not possible to realise the following table gives estimated values for the turn exponent p for different coil manufacturing technologies.

Coil manufacturing technology	p
Wired	1.8 – 1.9
Etched	1.75 – 1.85
Printed	1.7 – 1.8

5.5 Definition of Matrix Run

5.5.1 RECTANGULAR (SQUARE) COILS

5.5.1.1 Matrix run definition

The following values have to be fixed before starting the matrix run calculations:

L_o

p

a_{max}, b_{max}

t

g

The calculation of the inductance L_o is based on estimated values and also the calculation of the coil parameters at this time can only be made approximately. Therefore the inductance of the matrix run coils should be varied within ± 20 % of the estimated objective inductance L_o.

i ... First matrix run coil number

i	1	2	3	4	5
$L_{calc, i}$	0.8 L_o	0.9 L_o	L_o	1.1 L_o	1.2 L_o
$a_{o, i}$					
$b_{o,i}$					
$N_{c, i}$					
w_i					

The coil parameters $a_{o, i}$, $b_{o, i}$, $N_{c, i}$ and w_i must be iterative varied until $L_{calc, i}$ is equal to the given percentage of the estimated objective inductance L_o. During this coil parameter determination it must be always attempted to keep the product $A_{c, i} \cdot N_{c ,i}$ as high as possible!

5.5.2 ROUND COILS

5.5.2.1 Matrix run definition

The following values have to be fixed before starting the matrix run calculations:

L_o

p

D_{max}

t

g

The calculation of the inductance L_o is based on estimated values and also the calculation of the coil parameters at this time can only be made approximately. Therefore the inductance of the matrix run coils should be varied within ± 20 % of the estimated objective inductance L_o.

i ... First matrix run coil number

i	1	2	3	4	5
$L_{calc,\,i}$	$0.8\ L_o$	$0.9\ L_o$	L_o	$1.1\ L_o$	$1.2\ L_o$
$D_{o,\,i}$					
$N_{c,\,i}$					
w_i					

The coil parameters $D_{o,i}$, $N_{c,i}$ and w_i must be iterative varied until $L_{calc,\,i}$ is equal to the given percentage of the estimated objective inductance L_o. During this coil parameter determination it must be always the target to keep the product $A_{c,\,i} \cdot N_{c\,,i}$ as high as possible!

5.6 Production of Coil and Inlet Samples

5.7 Final Coil/Inlet

To decide with coil fits the requirements of resonance frequency best, it is recommended to measure the Inlets resonance frequency and compare with the targets defined at the beginning (f_{Ideal}).

For this measurement the ISO setup or a measurement as described in §4.2.2 or §4.2.3. is recommended.

5.7.1 RESULTTABEL

k	1	2	3	4	5
f_R					

5.7.2 CHOOSING THE BEST COIL

Calculate the difference between the measured resonance frequency $f_{R,}$ and the ideal resonance frequency f_{Ideal}

$$\Delta f_{Ideal-R,\,j} = \left| f_{Ideal} - f_{R,\,j} \right|$$

j	1	2	3	4	5
$f_{Ideal\text{-}R,j}$					

The optimum coil is the coil that’s nearest to f_{Ideal}.

$$\Delta f_{Ideal-R,\,j} = Minimum$$

Summary Tabel of Parameters of Coil j (rectangular):

J	
$L_{pc,\,j}$	
$C_{c,\,j}$	
$a_{o,\,j}$	
$b_{o,j}$	
$N_{c,\,j}$	
w_j	

Summary Tabel of Parameters of Coil j (round):

J	
$L_{pc,\,j}$	
$C_{c,\,j}$	
$D_{o,\,j}$	
$N_{c,\,j}$	
w_j	

5.8 Determination of Best Coil Parameters

If there is no coil fitting to your requirements up to here, it is possible to do a second optimisation step. Based on the results of §5.8.1.3 respectively §5.8.2.3, a second matrix run can be performed.

5.8.1 RECTANGULAR (SQUARE) COILS

5.8.1.1 Equivalent Circuit Measurement and Evaluation of Coils

The parallel equivalent circuit of the matrix run coils must be determined (see also chapter ”Measurement Methods”).

i	1	2	3	4	5
$C_{c,\,i}$					
$L_{pc,\,i}$					
$R_{pc,i}$					
$Q_{pc,\,i}$					

5.8.1.2 Calculation of Objective Coil Inductance $L_{o,i}$

The value of the coil capacitance $C_{c,i}$ is determined for all coils now. These values are used to calculate the objective coil inductance $L_{o,i}$ for all coils again.

$C_{plT,i} = C_{ICT} + C_{Con} + C_{c,i}$ Parallel equivalent capacitance of the inlet with coil i

$$L_{o,i} = \frac{1}{(2 \cdot \pi \cdot f_{RT})^2 \cdot C_{plT,i}}$$

With $f_{RT} = f_{ideal}$

5.8.1.3 Minimal Difference between $L_{pc,i}$ and $L_{o,i}$

The optimum coil of the matrix run is the one where the difference of measured inductance $L_{pc,i}$ and objective inductance $L_{o,i}$ is a minimum.

$$\Delta L_i = \left| L_{pc,i} - L_{o,i} \right|$$

i	1	2	3	4	5
$L_{pc,i}$					
$L_{o,i}$					
ΔL_i					

The coil number i with minimum ΔL_i: j = i

j... C number with minimum ΔL_j

Parameter Summary:

j	
$L_{pc,j}$	
$C_{c,j}$	
$a_{o,j}$	
$b_{o,j}$	
$N_{c,j}$	
w_j	

Usually the coil chosen here is the final coil design for MIFARE® inlets. If more exact tuning is necessary for the application, this coil is the starting point for the second matrix run calculation.

5.8.1.4 Determination of Turn Exponent p

For the chosen coil j the precise turn exponent p can be calculated now.

$$a_o = a_{o,j}$$

$$b_o = b_{o,j}$$

$$L_{pc,j} = L_{calc} = \frac{\mu_0}{\pi} \cdot [x_1 + x_2 - x_3 + x_4] \cdot N_{c,j}{}^{p}$$

$$p = \frac{\ln\left(\frac{L_{pc,j} \cdot \pi}{\mu_0 \cdot [x_1 + x_2 - x_3 + x_4]}\right)}{\ln N_{c,j}}$$

5.8.2 ROUND COILS

5.8.2.1 Equivalent Circuit Measurement and Evaluation of Coils

The parallel equivalent circuit of the matrix run coils must be determined (see also chapter ”Measurement Methods”).

i	1	2	3	4	5
$C_{c,i}$					
$L_{pc,i}$					
$R_{pc,i}$					
$Q_{pc,i}$					

5.8.2.2 Calculation of Objective Coil Inductance $L_{o,i}$

The value of the coil capacitance $C_{c,i}$ is determined for all coils now. These values are used to calculate the objective coil inductance $L_{o,i}$ for all coils again.

$C_{plT,i} = C_{ICT} + C_{Con} + C_{c,i}$ Parallel equivalent capacitance of the inlet with coil i

$$L_{o,i} = \frac{1}{(2 \cdot \pi \cdot f_R)^2 \cdot C_{plT,i}}$$

With $f_R = f_{Ideal}$

5.8.2.3 *Minimal Difference between $L_{pc,i}$ and $L_{o,i}$*

The optimum coil of the martix run is the one where the difference of measured inductance $L_{pc,i}$ and objective inductance $L_{o,i}$ is a minimum.

$$\Delta L_i = \left| L_{pc,i} - L_{o,i} \right|$$

i	1	2	3	4	5
$L_{pc,i}$					
$L_{o,i}$					
ΔL_i					

The coil number i with minimum ΔL_i: j = i

j... Matrix run coil number with minimum ΔL_j

Parameter Summary:

j	
$L_{pc, j}$	
$C_{c, j}$	
$D_{o, j}$	
$N_{c, j}$	
w_j	

Usually the coil chosen here is the final coil design for MIFARE® inlets. If more exact tuning is necessary for the application, this coil is the starting point for the second matrix run calculation.

5.8.2.4 Determination of Turn Exponent p

For the chosen coil j the precise turn exponent p can be calculated now.

$$D_o = D_{o,j}$$

$$p = \frac{\ln\left(\dfrac{L_{pc,j}}{2 \cdot l_j \cdot \left\{ \ln \cdot \left({l_j}/{d_j} \right) \cdot 1{,}07 \right\}} \right)}{\ln N_{c,j}}$$

5.9 Second Matrix Run Definition

5.9.1 RECTANGULAR COILS

$$a_o = a_{o,j}$$

$$b_o = b_{o,j}$$

$$L_{calc} = \frac{\mu_0}{\pi} \cdot \left[x_1 + x_2 - x_3 + x_4 \right] \cdot N_{c,j}{}^{p}$$

5.9.2 CIRCULAR COILS

$$D_o = D_{o,j}$$

$$L_{calc}\left[nH\right] = 2 \cdot l \cdot \left[\ln \frac{l_j}{d_j} - 1{,}07 \right] \cdot N_{c,j}{}^{p}$$

5.9.3 TABEL FOR OPTIMIZED COILS

The calculation of the inductance $L_{o,j}$ is still based on an estimated connection capacitance C_{Con} and also the coil parameters have influence on each other giving a non linear system. Therefore the inductance of the second matrix run coils should be varied within ± 8 % of the objective inductance $L_{o,j}$.

k... Second matrix run coil number

k	1	2	3	4	5
$L_{calc,k}$	0.92 $L_{o,j}$	0.96 $L_{o,j}$	$L_{o,j}$	1.04 $L_{o,j}$	1.08 $L_{o,j}$
w_k					

Only the coil parameter track width w_k (a_{avg}, b_{avg} resp. D_{avg}) should be varied until $L_{calc,\ k}$ is equal the given percentage of the objective inductance $L_{o,j}$. In order to keep the accuracy of the calculation on a high level the overall dimensions a_o, b_o, D_o and the gap between the tracks g as well as the track thickness t should not be varied anymore.

5.10 Assembly of Second Matrix Run Coils

5.11 Determining Optimized Coil from Second Matrix Run

5.11.1 INLET/CARD (WITH IC)

The unloaded resonance frequency f_R of the second matrix run inlets should be characterised (see 4.2).

A inlet must be determined where the value of the measured threshold resonance frequency $f_{RT,k}$ is closest to the optimal value. The used track width w_k of this inlet defines the optimum track width for the coil.

5.11.2 RESULT TABEL

k	1	2	3	4	5
f_R					

5.11.3 CHOOSING THE BEST COIL

Calculate the difference between the measured resonance frequency $f_{RT,}$ and the ideal resonance frequency f_{Ideal}

$$\Delta f_{Ideal-R,k} = \left| f_{Ideal} - f_{R,k} \right|$$

k	1	2	3	4	5
$f_{Ideal-RTNom,k}$					

The optimum coil is the coil that's nearest to f_{Ideal}.

$$\Delta f_{Ideal-R,k} = Minimum$$

Summary Tabel of Parameters of Coil k:

k	
$L_{pc,\ k}$	
$C_{c,\ k}$	
$a_{o,\ k}$	
$b_{o,k}$	
$N_{c,\ k}$	
w_k	

6 REVISION HISTORY

REVISION	DATE	CPCN	PAGE	DESCRIPTION
1.2	July 1997	-		1st published version
3.0	September 2002	-		completely revised version, new editorial structure
3.1	March 2004	-		Add embossed cards at paragraph “2.2.1.1 Mean Coil Area” Add calculation value for minimal voltage level for MIFARE® IC operation $V_{LA\text{-}LB\ min}$ in chapter “3.4 Threshold field strength H_T”
3.2	June 2006	-		Chapter 2.2.1.1: Replace “embossed cards” by additional mean coil area calculation rule
		-		
		-		
		-		

Table 6-1: Document Revision History

7 DEFINITIONS

Data sheet status	
Objective specification	This data sheet contains target or goal specifications for product development.
Preliminary specification	This data sheet contains preliminary data; supplementary data may be published later.
Product specification	This data sheet contains final product specifications.
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.	

8 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.

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