NFC Reader Design: Antenna design considerations

Public

MobileKnowledge
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Agenda

- Introduction to RFID and NFC
- Contactless reader design:
  - Initial considerations and architecture
- Illustrative contactless reader schematics:
  - RFID Elektor schematic
  - CLRC663 Point of Sales schematic
- NXP portfolio
  - NFC Reader IC overview
  - LPC microcontrollers overview

Previous session

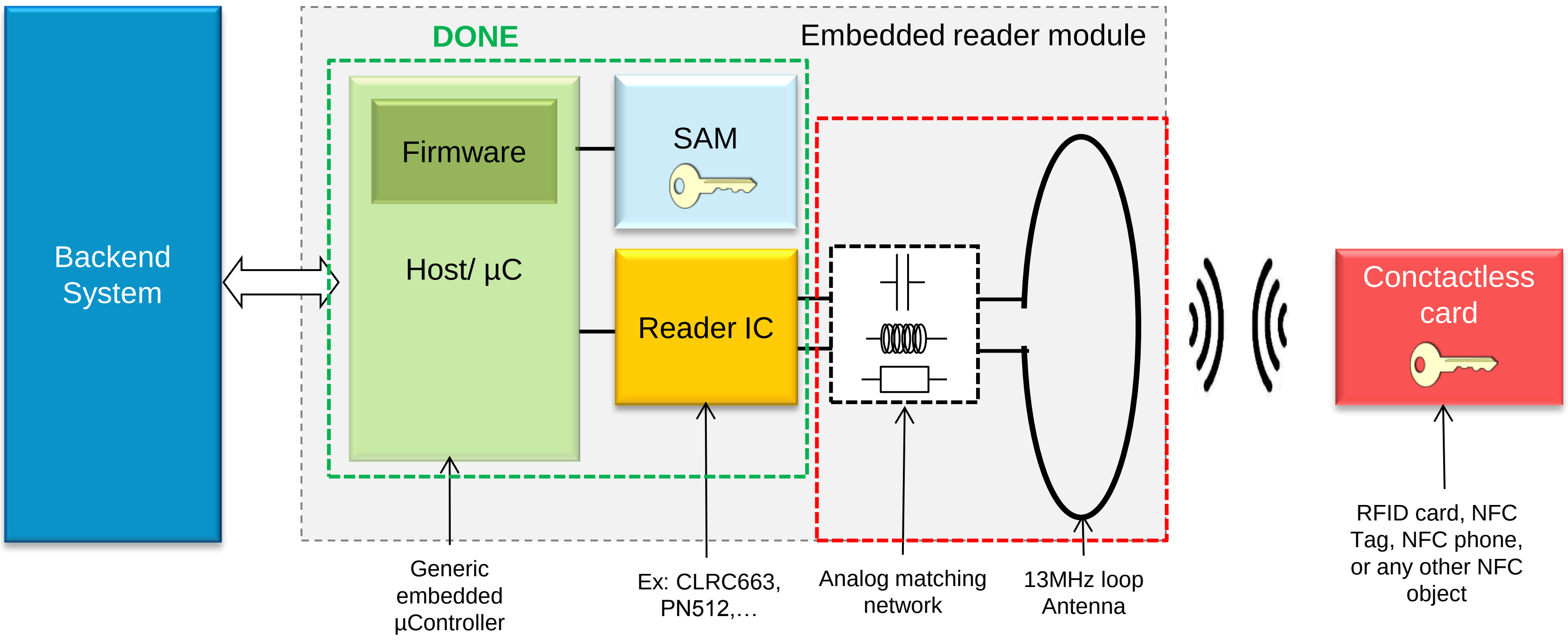
- NFC Reader Antenna design
  - Antenna principles
  - Antenna matching steps
  - Environmental influences
  - Testing & antenna qualification

For an in depth-training,
please refer to the webinar series on
antenna design of Renke Bienert
www.nxp.com/products/related/customer-training.html

Recap of the previous session

Steps to design a contactless reader

Typical contactless reader architecture



Steps to design a contactless reader

1

Selection of **contactless reader IC**
Which transponder do we need to interact with?

- Support of various RF standards
  - Dedicated use case & application may support only ISO/IEC 14443-A
  - Open application needs to support various RF standards such as ISO/IEC14443 A&B, ISO/IEC 15693
- Application specific requirements
  - EMVCo -> payments
  - NFC Forum -> Full NFC support on P2P and R&W
- Power consumption
  - Handheld contactless reader will require low energy consumption
- Selection of the host interface
  - SPI, I^2C, RS232, UART ..
- Specific features
  - Specific data rates, timing and reading distance

Steps to design a contactless reader

1. Selection of **contactless reader IC**
   Which transponder do we need to interact with?

2. Selection of **Host**
   The brain and heart of our contactless reader

- External interfaces
  - Serial, USB, Ethernet
  - RF connectivity (BL, Wifi, Zigbee,…)
- SW architecture
  - How heavy or light are the processing power requirements? (MCU clock)
- Host architecture
  - Impact on development environment and source code libraries
- Memory requirements
  - Flash, RAM, ROM
- Power requirements
- Specific requirements
  - Secure EEPROM to store keys?
  - Crypto accelerators?
- Manufacturer support

Steps to design a contactless reader

1 Selection of **contactless reader IC**
Which transponder do we need to interact with?

2 Selection of **Host**
The brain and heart of our contactless reader

3 Selection of **security** architecture
SAM or Host for key storage

- Host / MCU
  - Microcontrollers are not designed and developed to securely store and maintain cryptographic keys since they don't offer reliable protection and security mechanisms
  - They do not widely implement HW-based crypto-processors, so the execution of these crypto algorithms is not efficient
- SAM
  - It is a tamper-resistant chip that provides secure execution and secure key storage functions to the reader side
  - It carries HW based cryptography that allows one to perform complex cryptographic operations efficiently
  - ***SAM X-interface***: It supports the X-mode, which allows a fast and convenient contactless terminal development by connecting the SAM to the microcontroller and reader IC simultaneously.

Steps to design a contactless reader

1 Selection of **contactless reader IC**
Which transponder do we need to interact with?

2 Selection of **Host**
The brain and heart of our contactless reader

3 Selection of **security** architecture
SAM or Host for key storage

4 **Antenna** design

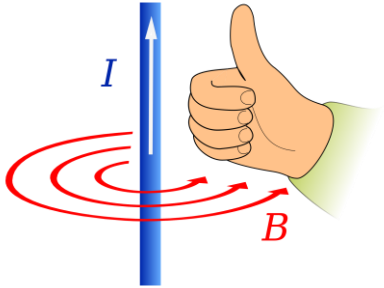
Today's session

5 **GO!**

Antenna principles

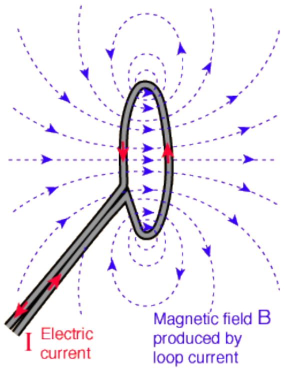
Magnetic field

- Magnetism is a phenomenon associated with the motion of electric charges. This motion can take many forms:
  - Charged particles moving through space
  - An electric current in a conductor
- The direction of such a magnetic field can be determined by using the “right hand grip rule”
  - Magnetic field lines form in concentric circles around a cylindrical current-carrying conductor such as a wire.

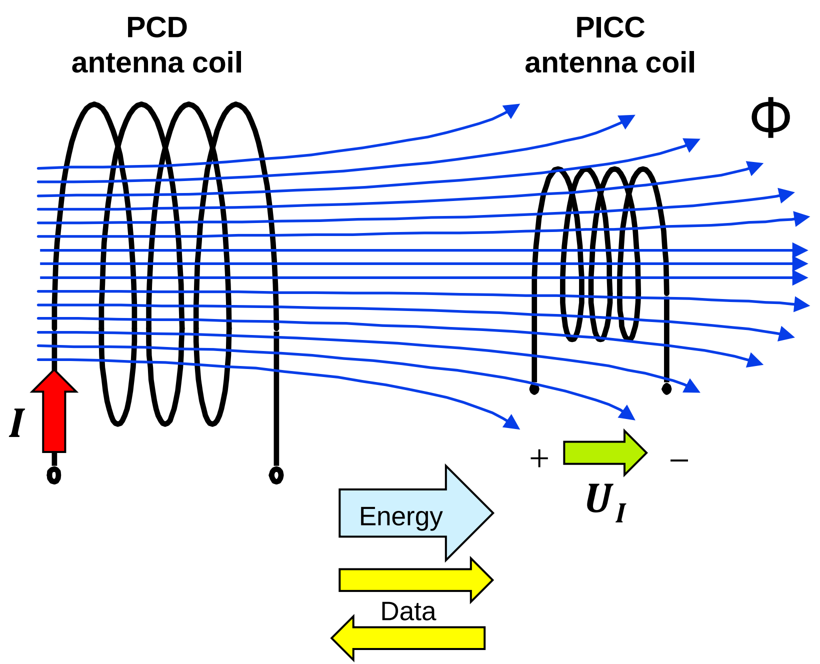


- Conductor loops are used as magnetic antennas to generate a magnetic alternating field in reader devices

- The strength of the magnetic field decreases with the distance from the wire.



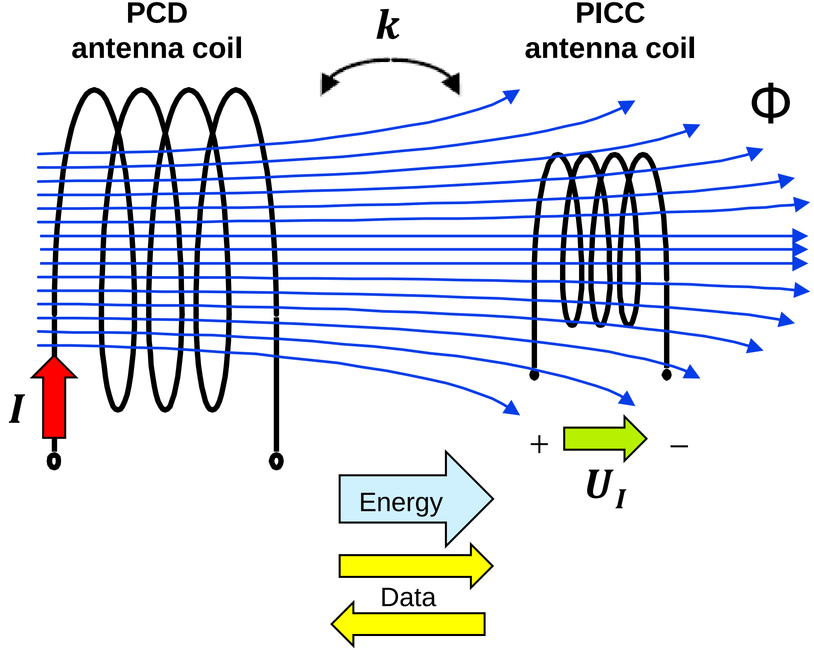
NFC antenna: Transformer principle



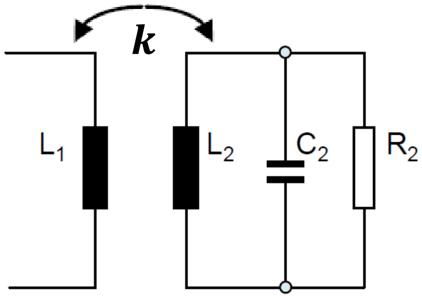
- The vast majority of RFID systems operate according to the principle of ***inductive coupling***.
  - Typical contactless smartcards contain no internal power supply. They need to get all their required energy from the magnetic field in which they operate
- The PCD transmitter coil generates an electromagnetic field with a frequency of 13,56Mhz.
- A small part of the emitted field penetrates the antenna coil of the transponder, which is some distance away from the reader coil.
- A voltage U_I is generated in the transponder's antenna by inductance. This voltage is rectified and serves as the power supply
  - A transformers-type coupling is created between the reader coil and the transponder coil.
- The PCD energy must be available to the PICC during the entire transaction.

NFC antenna: Transformer principle

Coupling coefficient



- The coupling coefficient depends on:
  - The geometric dimensions of both conductor loops.
  - The position of the conductor loops in relation to each other
  - The magnetic properties of the medium (μ_0)



$$0 < k < 1$$

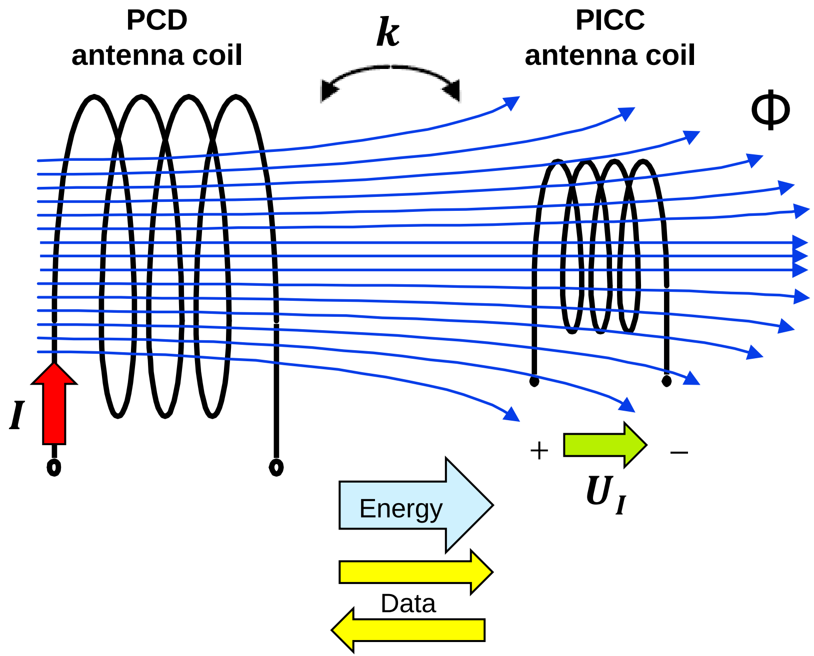
k =1 → total coupling

k =0 → full decoupling

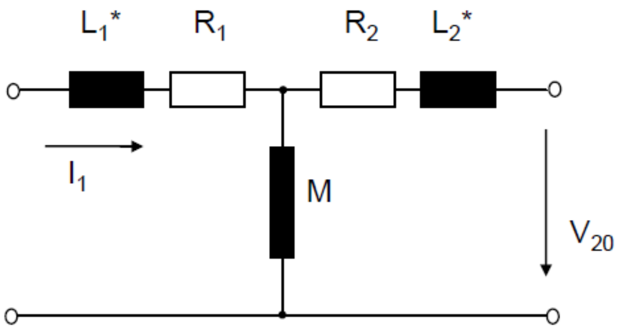
$$k = \mu_0 \cdot \frac{r^2}{2\sqrt{(r^2+x^2)^3}} \cdot \frac{A_2}{\sqrt{L_{01} \cdot L_{02}}}$$

Permeability constant — *Geometrical quantity* — *"Fixed"*

NFC antenna: Transformer principle
Mutual inductance



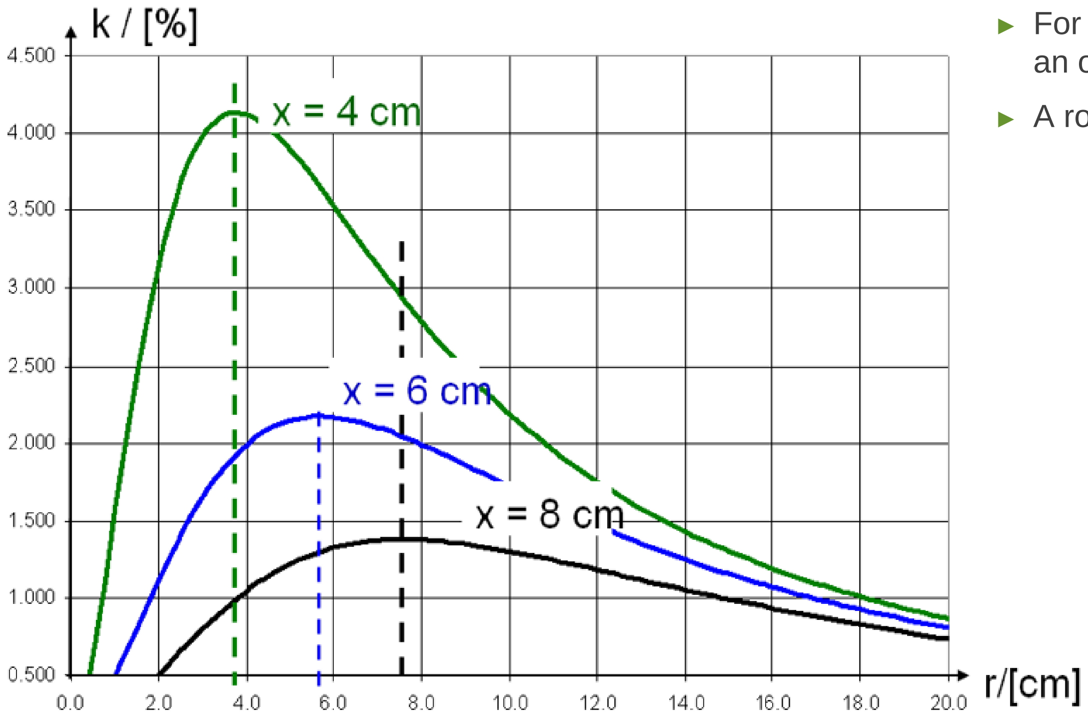
- The mutual inductance allows us to determine the voltage induced in the PICC antenna.
- This is a function of the coupling coefficient and the current provided in the reader antenna.



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

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

Optimum antenna size

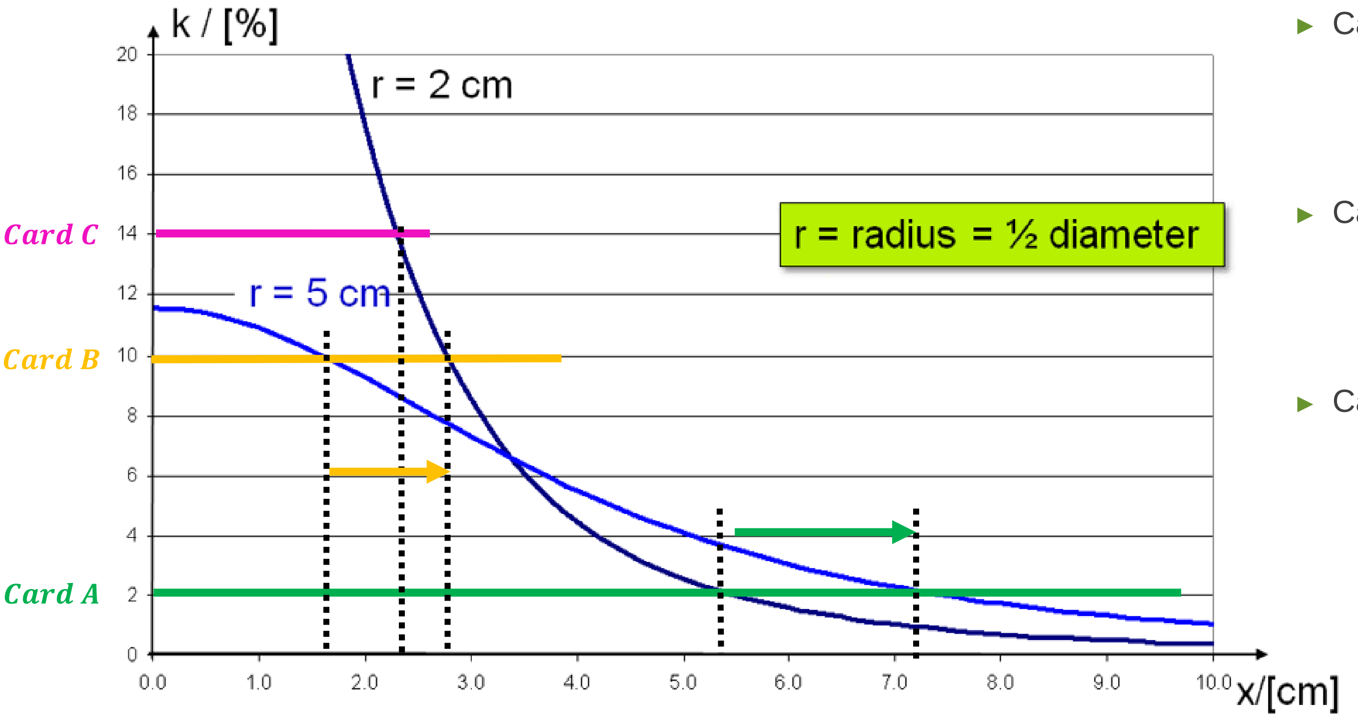


- For every read range x of an NFC system, there is an optimal antenna radius R.
- A rough approximation is that :

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

$$\boxed{r = x}$$

Optimum antenna size



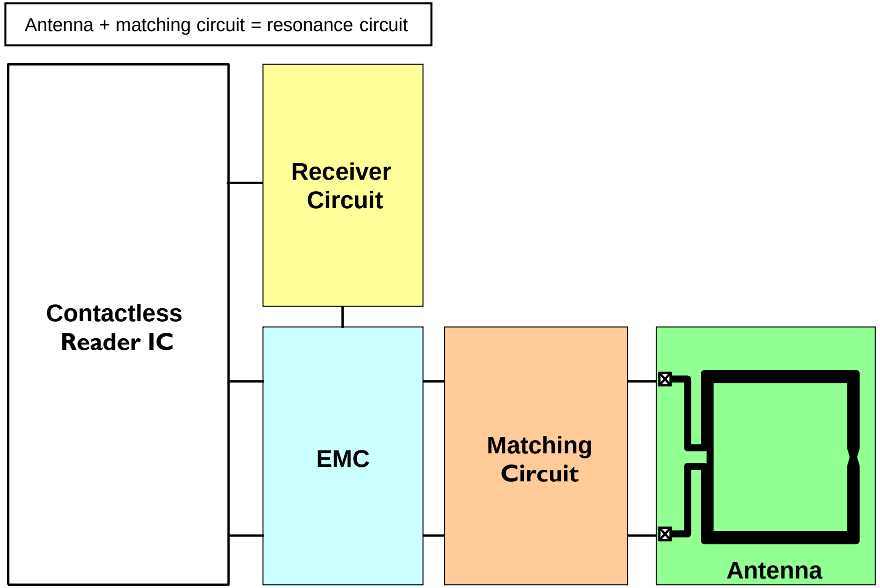
- Card A:
  - PCD r=2 cm → x ≈ 5.5 cm
  - ***PCD r=5 cm → x ≈ 7.2 cm***
- Card B:
  - ***PCD r=2 cm → x ≈ 2.8 cm***
  - PCD r=5 cm → x ≈ 1.8 cm
- Card C:
  - ***PCD r=2 cm → x ≈ 2.2 cm***
  - PCD r=5 cm → x ≈ - cm

Training Mobile Knowledge

Antenna matching steps

NFC antenna matching steps

1. Define target impedance
   To optimize RF output power or battery life
2. EMC filter design
   Filtering of unwanted harmonics
3. Measure antenna coil
   Determine LCR values of the antenna coil
4. Adjust Q-factor
   With damping resistor if needed
5. Calculate matching components
   Using provided excel sheet
6. Fine tuning
   Simulation and field measurement
7. Adjust receiver circuit
   Tuning reader sensitivity



- AN11019: CLRC663, MFRC630, MFRC631, SLRC610 Antenna design
- AN1445: Antenna design guide for MFRC52x, PN51x, PN53x

NFC antenna matching

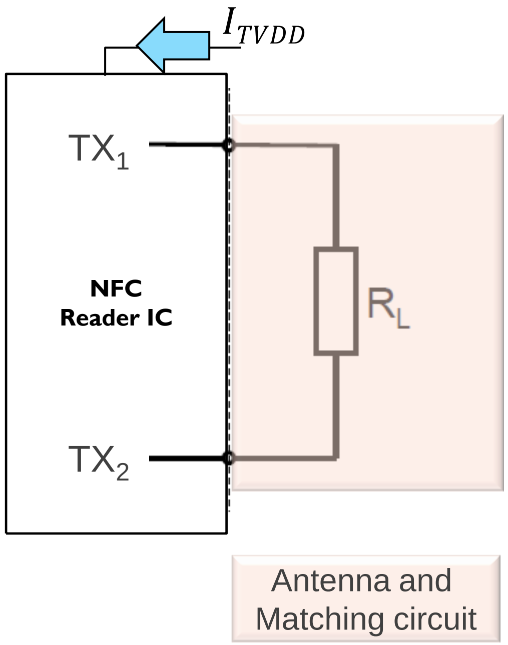
Step 1: Define target impedance

- We need to adjust the target impedance the NFC reader IC "sees" according to the performance we want to achieve.
  - Maximum output power
  - Minimum current consumption (battery life)
- The target impedance is chosen so that the highest possible output power does not exceed the maximum driver current (datasheet).

R_L = 20 ……… 80 Ω for CLRC663
R_L = 35 ……… 80 Ω for PN512

Maximum output power (Operating distance)

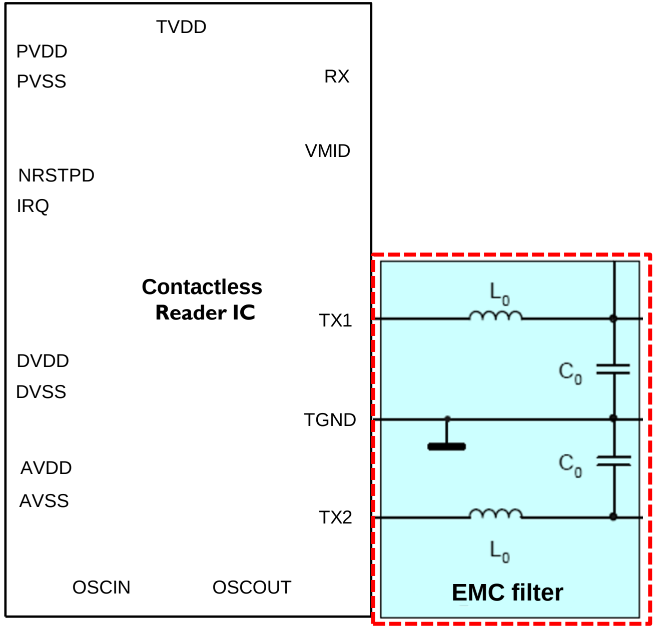
Minimum current Consumption (Battery life)



NFC antenna matching

Step 2: EMC filter design

- The EMC is a low pass filter reducing 2nd and higher harmonics and performs impedance transformation



- A convenient cutoff frequency (f_c) is between:

$$f_c = 14.5\,MHz\ \ldots\ 22\,MHz$$

- We begin specifying L_0 , this range of values have proven to be very useful in practice:

$$L_0 = 330\,nH\ \ldots\ 560\,nH$$

- With f_c and L_0, we can easily calculate C_0:

$$w_c = \frac{1}{\sqrt{C_0 \cdot L_0}} \Rightarrow C_0 = \frac{1}{(2 \cdot \pi \cdot f_c)^2 \cdot L_0}$$

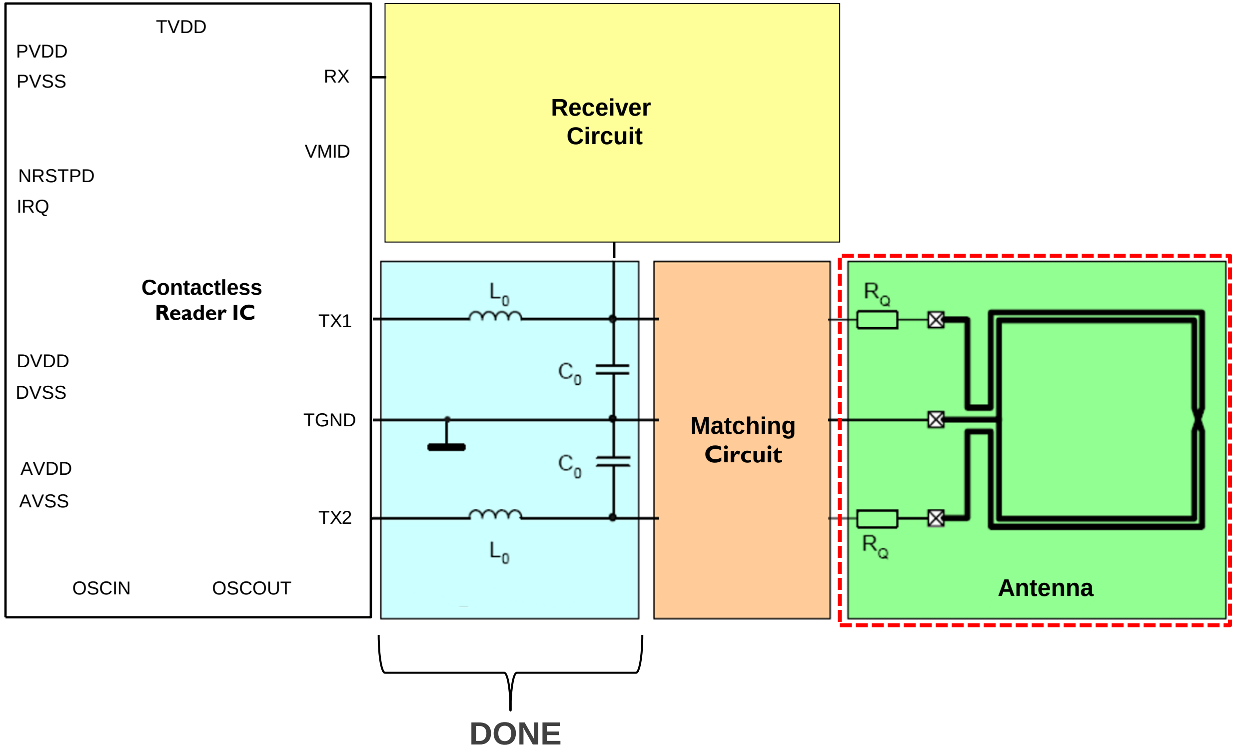
- **Example**: f_c = 21 MHz and L_0 = 470 nH:

$$C_0 = 122.2\,pF \Rightarrow \begin{array}{l} C_{01} = 68\,pF \\ C_{02} = 56\,pF \end{array}$$

Training Mobile Knowledge

NFC antenna matching

Step 3: Measure antenna coil



NFC antenna matching

Step 3: Measure antenna coil

- The antenna loop has to be connected to an impedance or network analyzer at 13.56 MHz to measure the series equivalent components

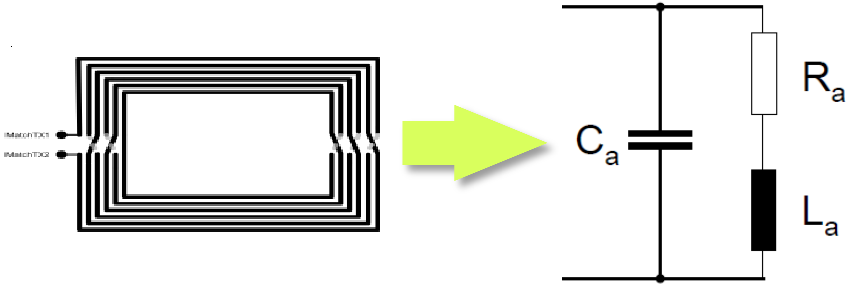


Fig. Antenna series equivalent circuit

Inductance (L): mainly defined by the number of turns of the antenna

Resistance (R): mainly defined by the diameter and length of the antenna wires

Capacitance (C): mainly defined by the distance of antenna wires from each other and number of turns

High-end network analyzer (i.e. Rohde & Schwarz ZVL)

- Powerful, accurate and easy to use

Low-end network analyzer (i.e. miniVNA PRO)

- Cheap, accurate enough and easy to use

NFC antenna matching

Step 3: Measure antenna coil

Practical approach:

- Measure L_a, R_a and estimate C_a.
- And imprecise measurement suffices for us, as the measured values are needed only as starting points and the tuning will be done later.

$$L_a \approx 1.5\ \mu H$$

$$R_a \approx 2.8\ \Omega$$

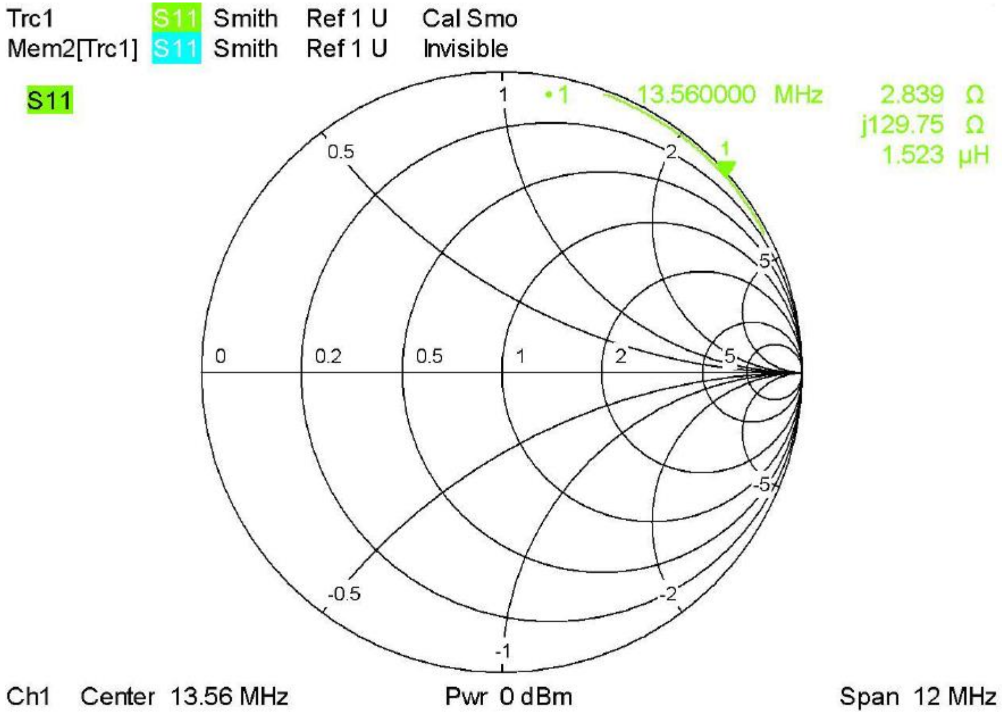
$$C_a \approx ? \Rightarrow C_a \approx 1\ pF$$

- Typical values:

$$L_a = 0.3\ \mu H\ \ldots 4 \mu H$$

$$R_a = 0.3\ \Omega\ \ldots 8\ \Omega$$

$$C_a = 1\ pF\ \ldots 30\ pF$$

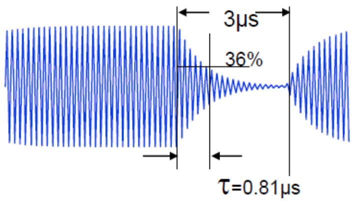


NFC antenna matching
Step 4: Adjust Q-factor

- A high Q factor leads to high current in the antenna coil and thus improves the power transmission to the transponder

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

- In contrast, the transmission bandwidth of the antenna is inversely proportional to the Q factor.
  - A low bandwidth, caused by an excessively high Q factor, can therefore significantly reduce the modulation sideband received from the transponder.



e.g.: ISO/IEC 14443-A @ 106Kbps

$$Q < f \cdot T$$

$$Q < 13.56MHz \cdot 3\mu s$$

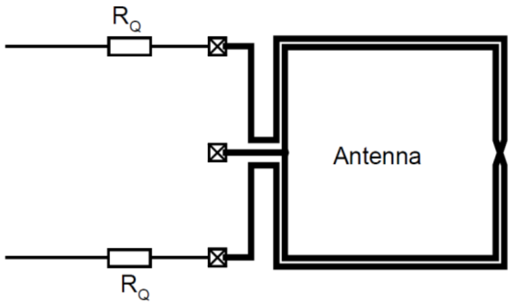
$$Q < 40$$

- The quality factor of the antenna is calculated with:

$$Q_a = \frac{\omega \cdot La}{R_a}$$

- If the calculated Q_a is higher than the target value, an external damping resistor (R_q) has to be added.
- The value of (each side of the antenna) is calculated by:

$$R_Q = 0.5\left(\frac{\omega \cdot La}{Q}\right)$$



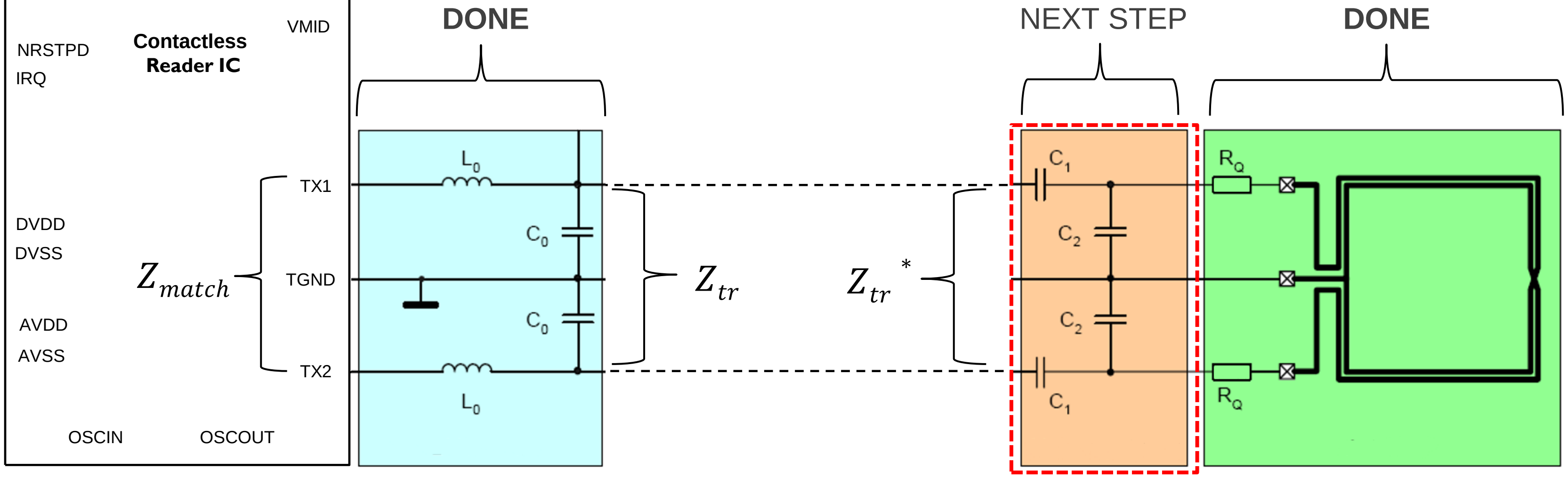
NFC antenna matching

Step 5: Calculate matching components

Matching condition

$$Z_{tr} = R_{tr} + jX_{tr}$$

$$Z_{tr}^{*} = R_{tr} - jX_{tr}$$



NFC antenna matching

Step 5: Calculate matching components (II)

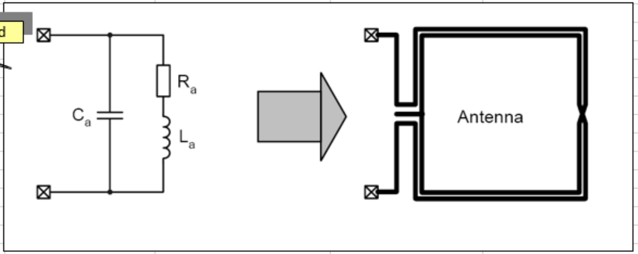
- We input the following values into the excel sheet:
  - Antenna coil measured / estimated values (L_a, C_a, R_a)
  - Q-factor
  - Target impedance (Rmatch).
- The excel sheet calculates the values for the matching circuit and damping resistor.
  - R_Q, C_1 and C_2

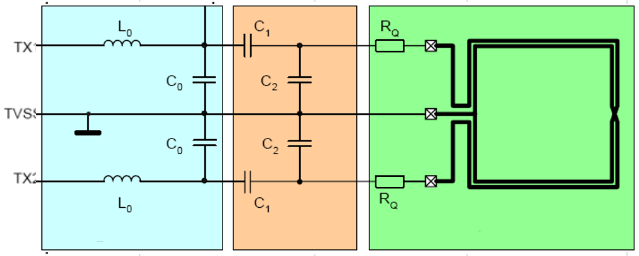
given					
	f	13,56	MHz		
	omega	85199992,77	1/s		
measured					
	La	2700	nH		
	Ca	0,1	pF		
	Ra	2,2	Ohm		
required					
	Q	20			
	Rmatch (Tx1-Tx2)	30	Ohm		
	fres filter	21,000	MHz	real:	20,848 MHz
calulated					
	Qa	105			
	Rq	4,65	Ohm		
	Rpa	4601	Ohm		
Hilfswert		4601			
chosen	L0	470	nH		
	C0 calculated	122,2	pF		
chosen	C01	68	pF		
	C02	56	pF		
	Rtr	84	Ohm		
	Xtr	116	Ohm		
	C1	31,9	pF		
	C2	64,0	pF		

provisional results:

$(1-\omega^2 \cdot L_0 \cdot C_0)$	$(1-\omega^2 \cdot L_0 \cdot C_0)^2$	$\left(\omega \cdot \frac{R_{match}}{2} \cdot C_0\right)$	$\left(\omega \cdot \frac{R_{match}}{2} \cdot C_0\right)^2$
0,576943221	0,33286348	0,158471987	0,025113371

measured



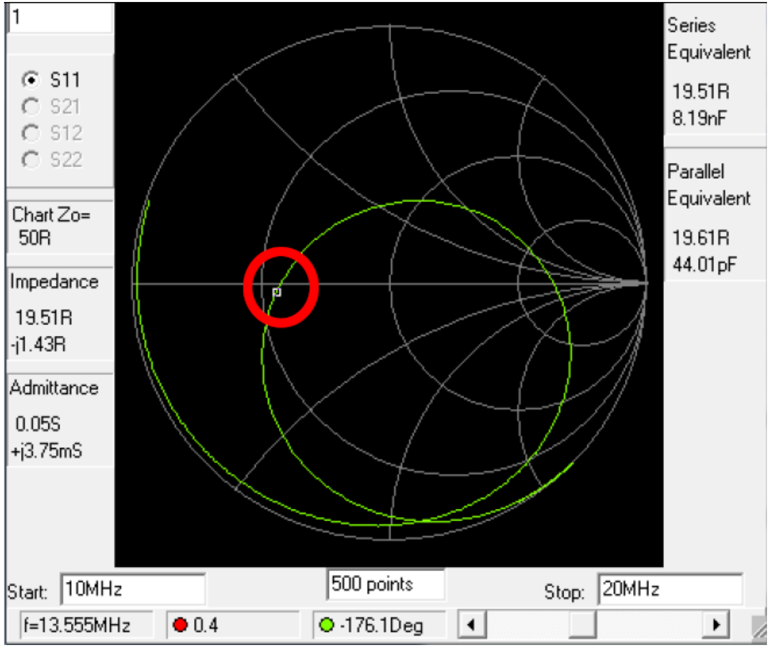


http://www.nxp.com/documents/other/AN11246_239810.zip

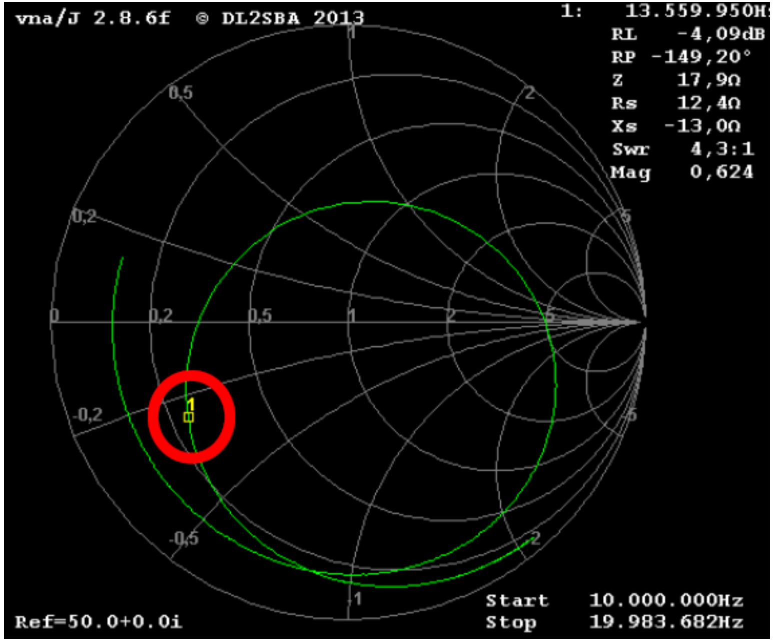
NFC antenna matching

Step 6: Fine tuning. Why is it required?

Simulation: RFSim99 software tool
http://www.electroschematics.com/835/rfsim99-download/



Reality: matching circuit assembled and measured with miniVNA

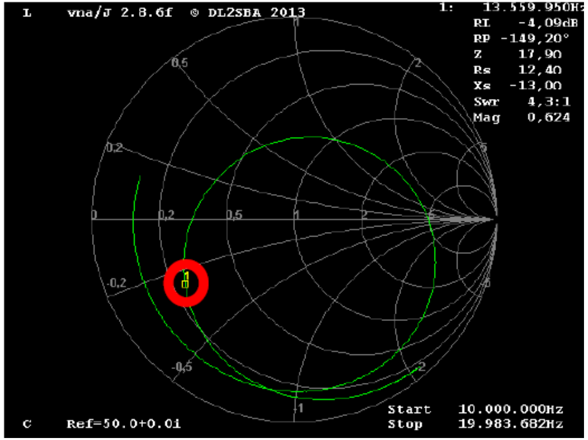


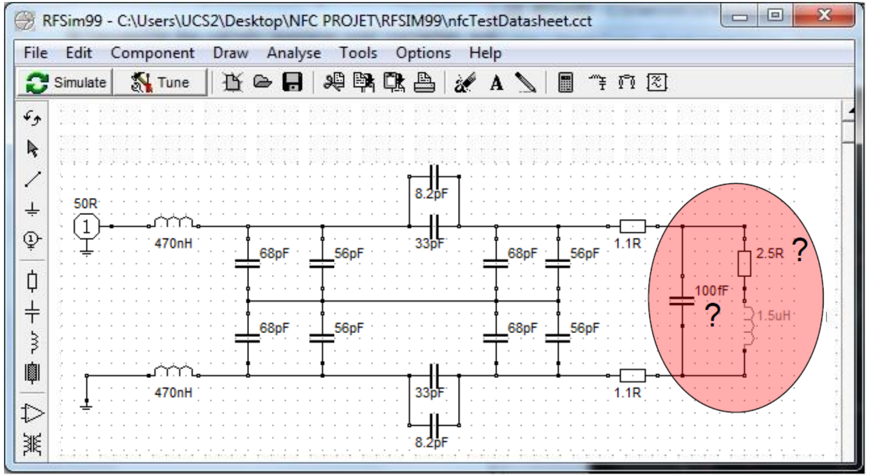
NFC antenna matching

Step 6: Fine tuning. Adapt simulation

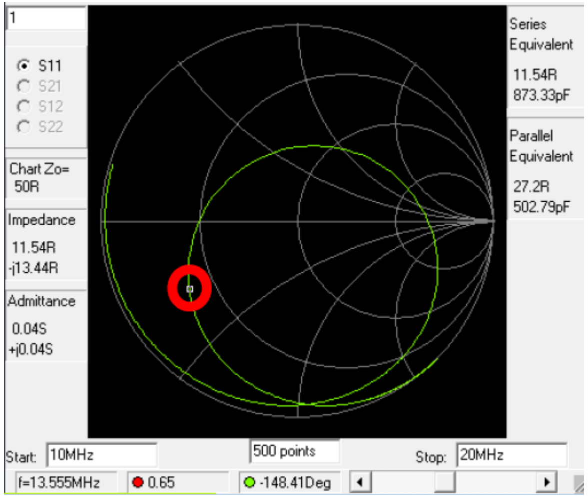
- Measured / estimated L_a, R_a and C_a antenna parameters are imprecise
- Tune R_a , C_a and L_a parameters until the simulation looks like the reality.

Reality (miniVNA)



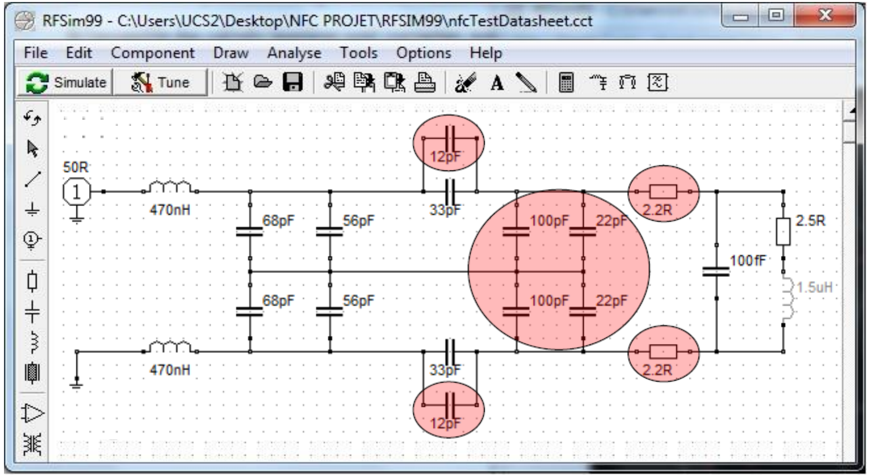


Simulation (RFSim99)

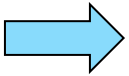


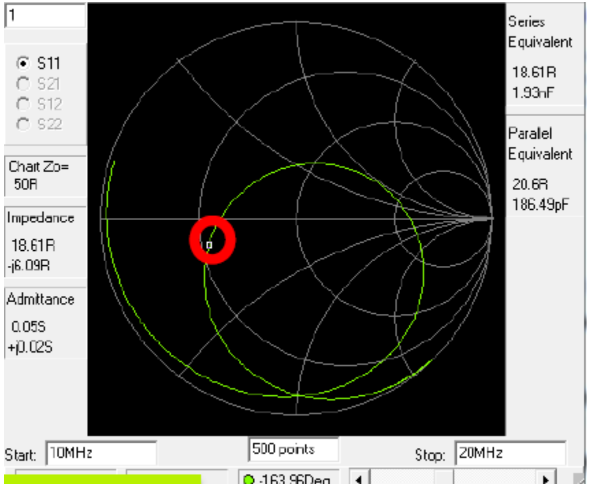
NFC antenna matching

Step 6: Fine tuning. Correct simulation

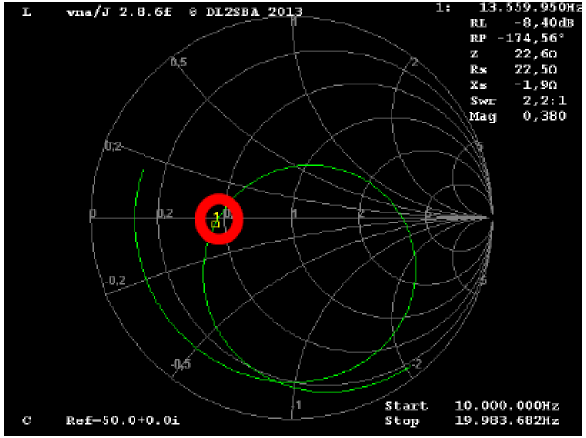


Simulation (RFSim99)





Reality (miniVNA)

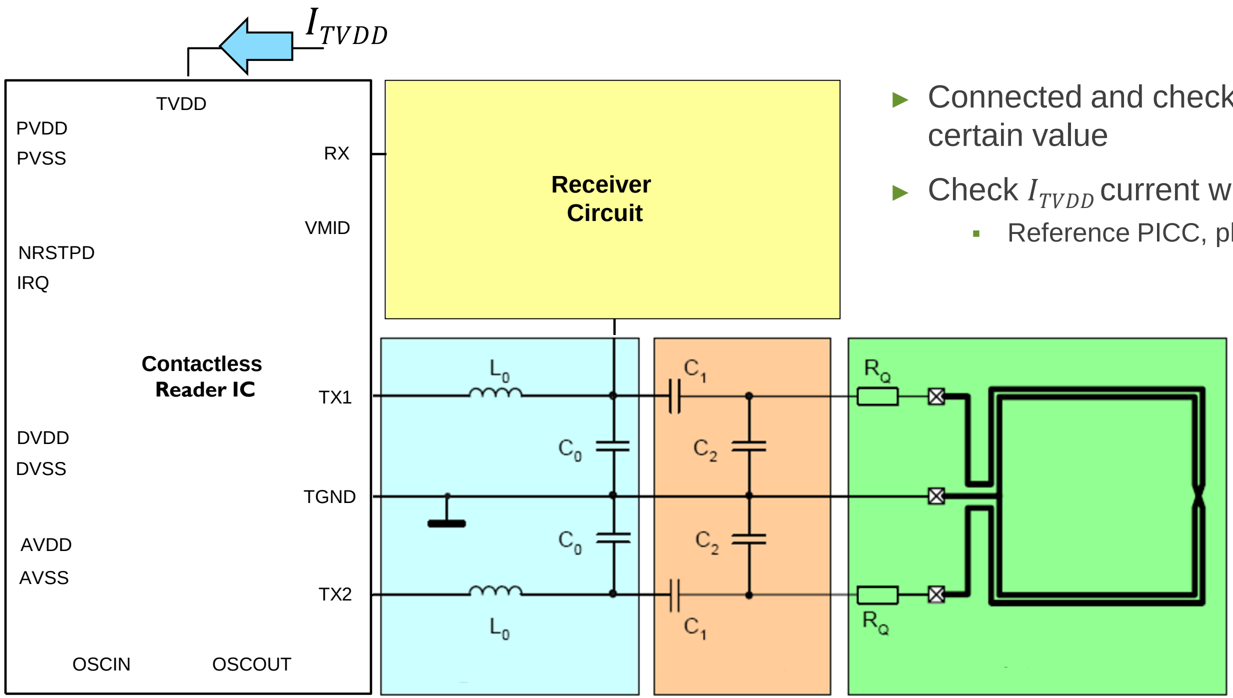


- Tune damping resistor (R_Q) and matching circuit capacitors (C_1, C_2) until the simulated circuit is matched.
- Then, assemble the components again and measure reality.
- The actual adjustment may be reached through a process of iteration.

Training Mobile Knowledge

NFC antenna matching

Step 6: Fine tuning (II): Measurements on the Tx pulse



- Connected and check I_{TVDD} current does not exceed a certain value
- Check I_{TVDD} current without card and all loading conditions
  - Reference PICC, phone, different cards , etc

- For CLRC663 reader IC:

$$I_{TVDD} < 200\ mA$$

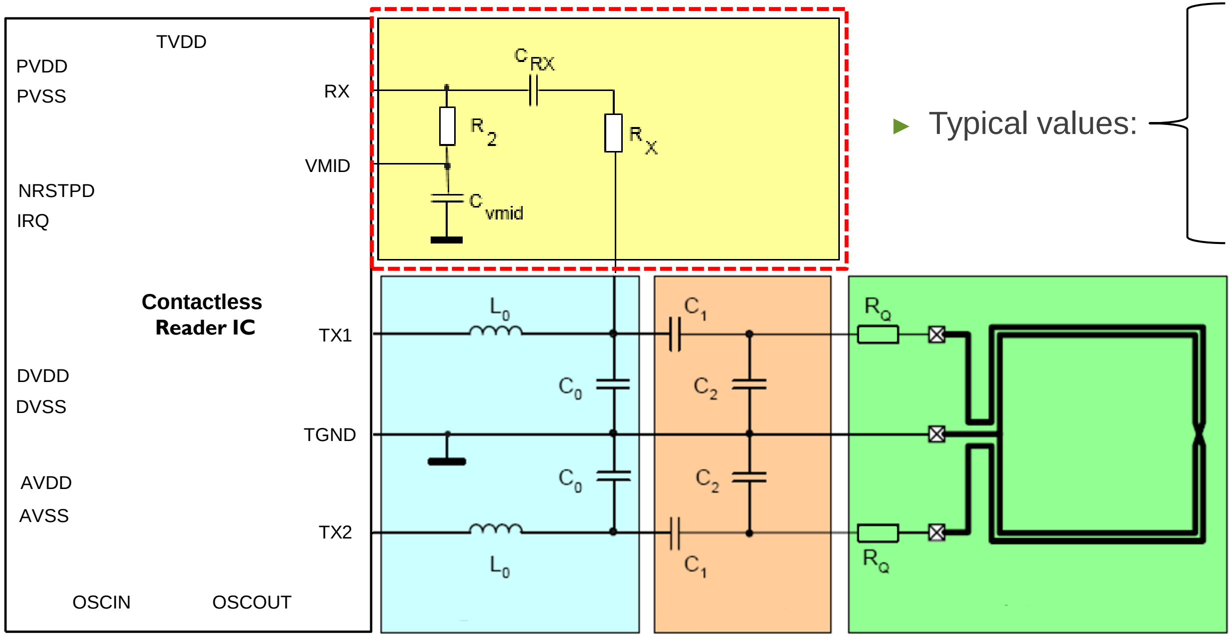
- For PN512 reader IC:

$$I_{TVDD} < 100\ mA$$

Training Mobile Knowledge

NFC antenna matching

Step 7: Receiver circuit

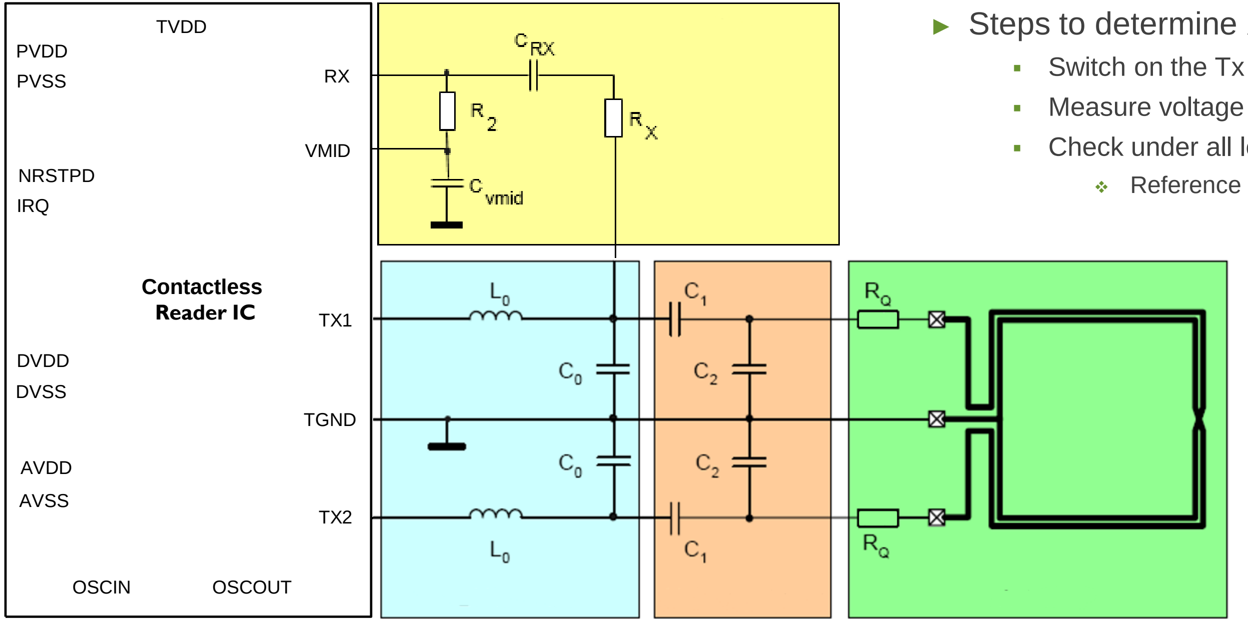


- Typical values:

$$C_{vmind} = 100\ nF$$
$$C_{rx} = 1\ nF$$
$$R_2 = 1\ k\Omega$$
$$R_x = ?\ k\Omega$$

NFC antenna matching

Step 7: Receiver circuit. Adjust Rx level



- Steps to determine R_x :
  - Switch on the Tx (continuous carrier)
  - Measure voltage at R_x pin with a low capacitance probe (<2pF)
  - Check under all loading conditions
    - Reference PICC, phone, different cards , etc

- For CLRC663 reader IC:

$$U_{Rx} < 1.7\,Vpp$$

$$\Downarrow$$

$$R_x = 12\,k\Omega\ \ldots 18\,k\Omega$$

- If U_{Rx} > 1,7 Vpp → increase R_x
- If U_{Rx} < 1 Vpp → decrease R_x

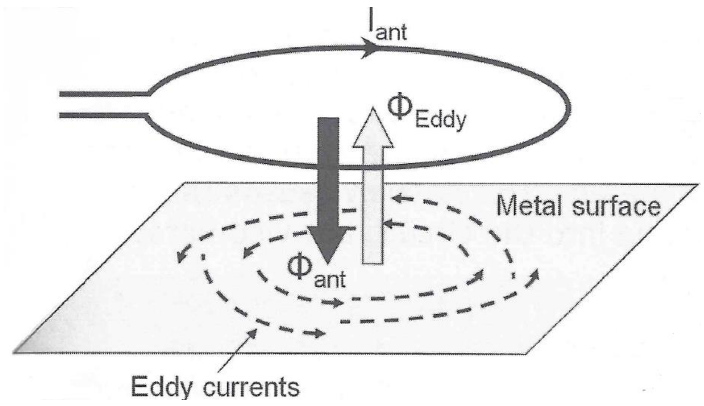
Environment effects

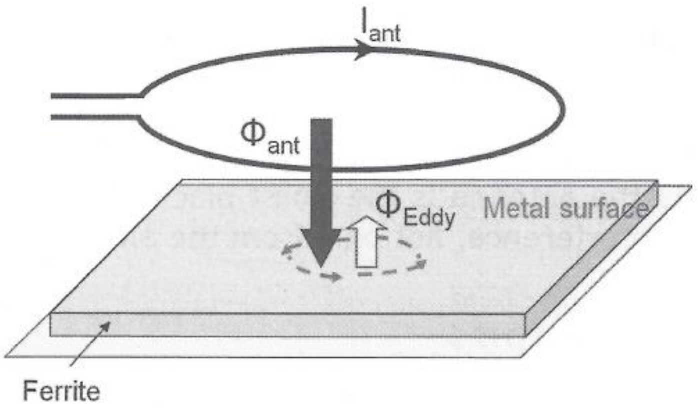
Metal environment influences

Eddy currents

- Metal surfaces in the immediate vicinity of the reader antenna have several negative effects.
- Our reader antenna's magnetic field generates eddy currents in metallic surfaces.
- These eddy currents produce a magnetic flow opposite to that of the reader device

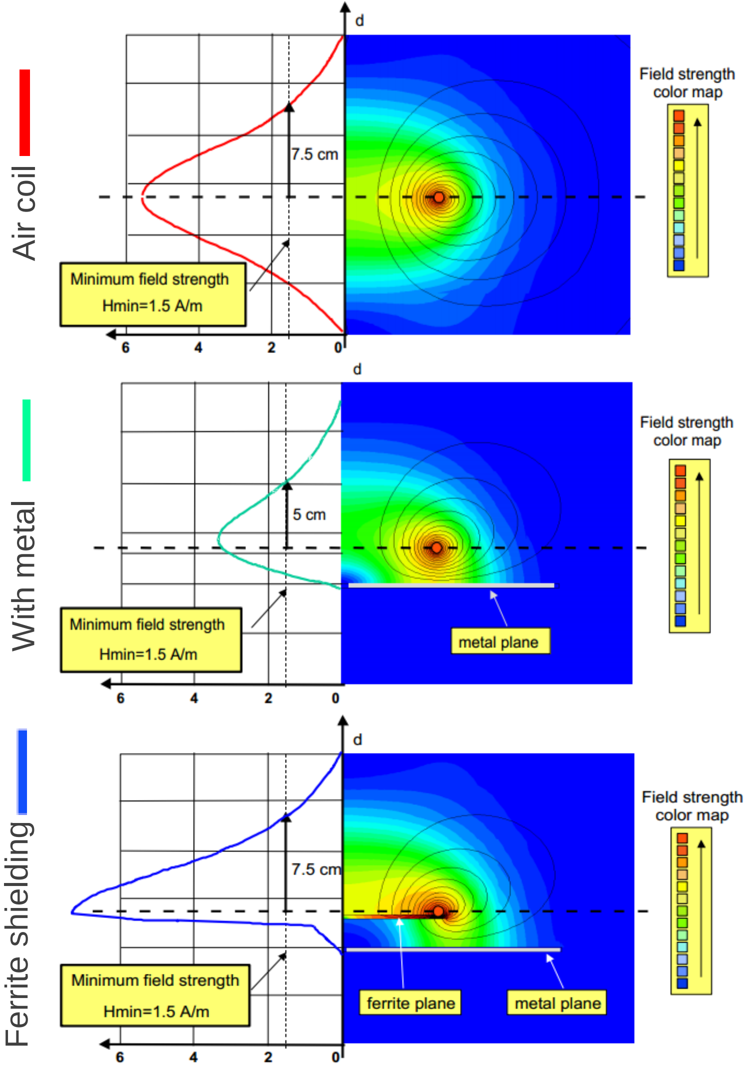
- Ferrites are basically poor electrical conductors but are very good at propagating magnetic flux (mostly of iron oxide Fe2O3)
- The ferrite material "shields" the metal behind it.
- It significantly reduces the generated eddy currents





Shielding and environment impact

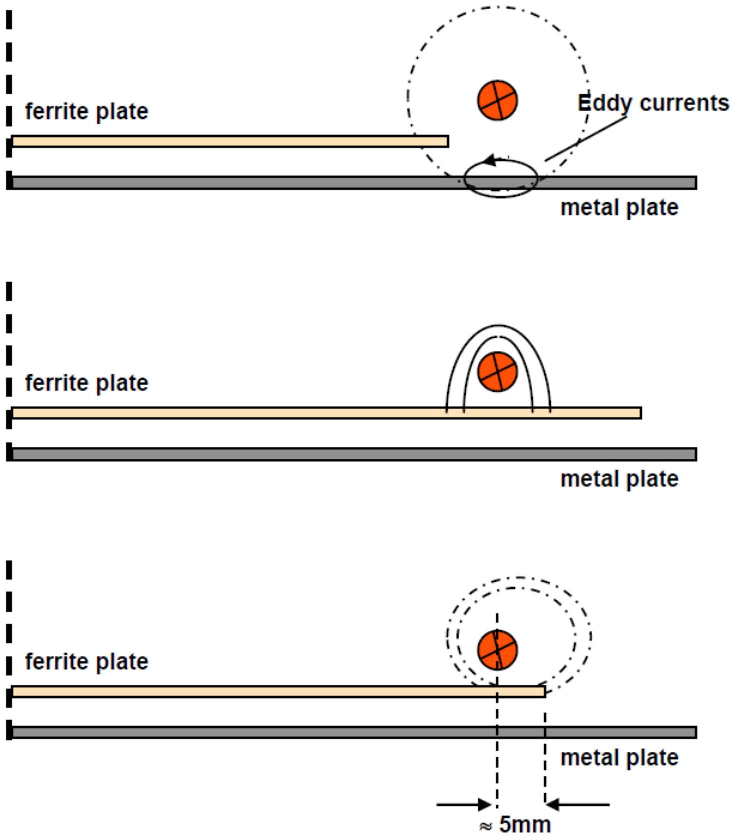
- The figures show three different field strength characteristics over reading distance x, for the same antenna coil:
  - Free air coil (7.5 cm)
  - Coil surrounded by a metal plate (5 cm)
  - Coil surrounded by a metal plate shielded by a ferrite plate (7.5 cm)
- We can achieve almost original operating distance using ferrite shielding. However, the ferrite detunes the antenna and produces:
  - Increase inductance
  - Increase Q-factor
  - Changed magnetic field distribution
- **Conclusion:** The antenna must be suited to its environment.



Training Mobile Knowledge

Ferrite shielding recommendation

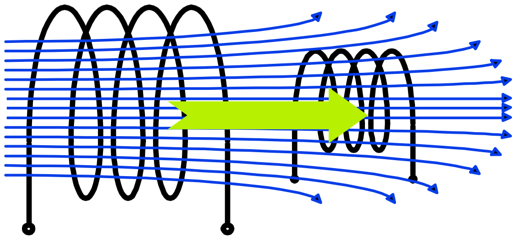
- If the surface of the ferrite material is too small, the shielding effect will be too weak
- If it is too large, the field lines will become highly concentrated in the plane of the antenna and the ferrite.
- In practice, favorable dimensions have emerged for medium-sized antennas.
  - Where an overlap is created by having the ferrite material around 5mm larger than the antenna coil.
- Different ferrite foils have different effects, some foils:
  - Have a better Q.
  - Provide a better field distribution (reader mode).
  - Provide a better LMA (card mode)



Test and Qualification

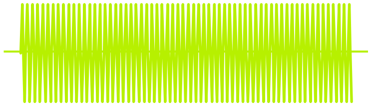
What must be tested?

FIELD STRENGTH

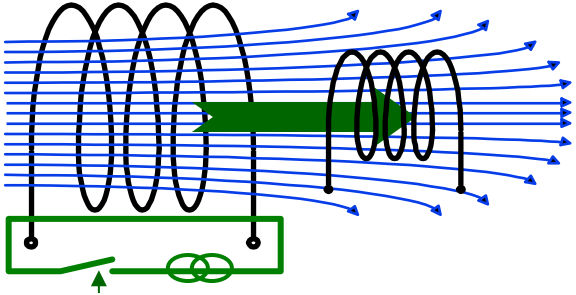


PCD → PICC

13.56 MHz Carrier



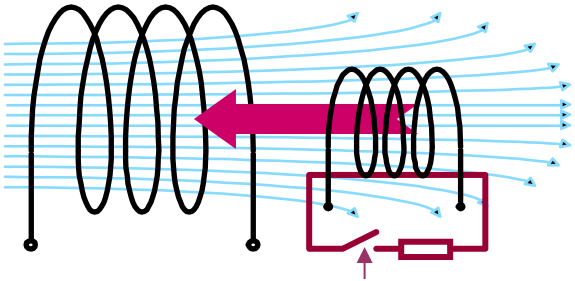
WAVE SHAPES



PCD → PICC

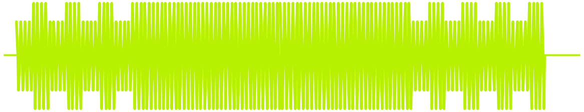
MILLER coded DATA

LOAD MODULATION



PCD ← PICC

LOAD modulated DATA



PCD: Proximity Coupling Device (“reader“)
PICC: Proximity Integrated Circuit Card (“card“)

Tests for NFC antenna performance

ISO/IEC 14443 tests:

- Test standard: ***ISO/IEC 10373-6 Proximity cards***
- Tests for PICC and PCD
- Type A and Type B
- Bit rates: 106, 212, 424, 848 Kbps
- No certification available
- Applicable for public transport, access control, ePassport & eID etc

NFC Forum tests:

- Test standard: ***NFC Analog Technical Specification***
- Mandatory for NFC Forum devices
- NFC-A, NFC-B & NFC-F
- Defines analog tests for NFC devices (P2P, Reader and Card modes)
- Bit rates: 106, 212, 424 Kbps
- Certification process available for NFC compliance
- Applicable for mobile phones

EMVCo tests:

- Test standard: ***EMV Contactless Specifications for Payment Systems (Book D***).
- Test for PICC and PCD
- Type A and Type B
- Only for 106 Kbps

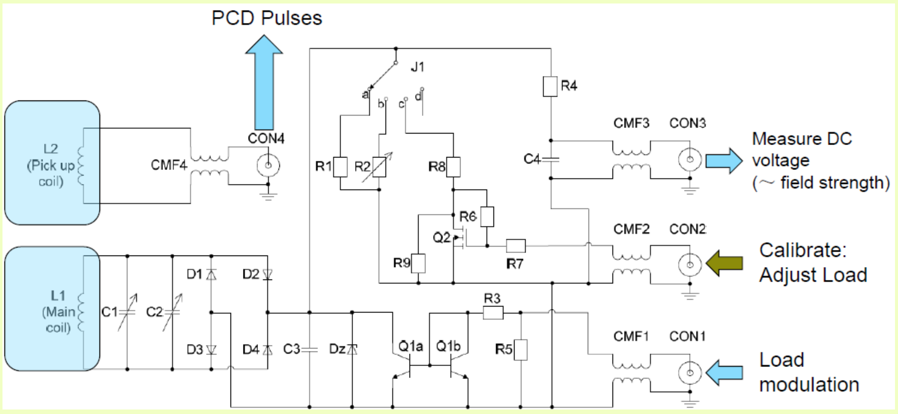
ISO/IEC 14443 Field strength test

Field strength test condition:

- Measure reader maximum reading distance.
  - Minimum field strength defined by ISO/IEC 14443 is 1.5 A/m

Tools: Reference PICC

- Reference PICC are designed specifically to allow complete conformance testing of contactless readers according to ISO/IEC 10373
- Pick up coil:
  - Allows to measure the PCD pulse shapes.
  - Low coupling between the two coils.
- Main coil:
  - Represents the “real smartcard”.
  - Loads the field like a read card and allows to measure field strength and test load modulation
- ISO/IEC 10373-6 defines 6 reference PICCs :

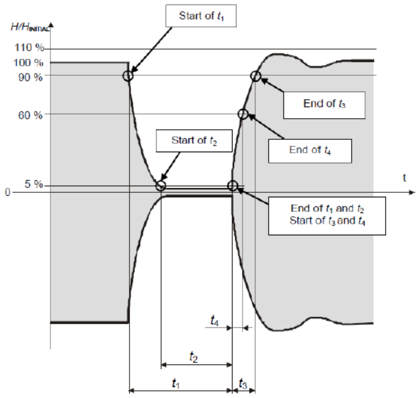


Reference PICC

ISO/IEC 14443 Wave shapes test
Type A @106kbps

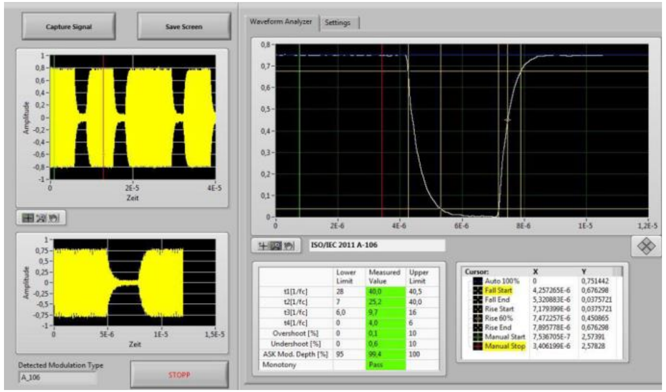
Wave shape test condition:

- Measure pulse shape in maximum reading distance
  - This is of course the worse possible case
- Requirements for the wave shapes are fixed in the ISO/IEC14443 standard for the different data rates
  - Pulse length, rise and fall times, overshoots etc



Tools: Wave checker tool

- PC tool that takes shoot from the scope, reads the data, checks the pulse shapes and compares it within the ISO/IEC limits.
- E.g.: Wavechecker from CETECOM
  - Flexible tool supporting measurements for ISO/IEC, NFC Forum or EMVCo.



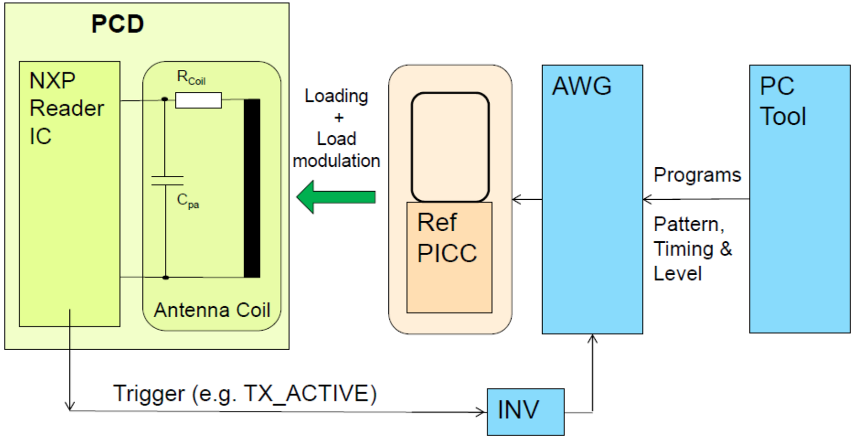
ISO/IEC 14443 Load modulation test

Load modulation test condition:

- Check if our reader can decode card responses properly in the maximum reading distance
- Inject a certain level of load modulation using a sub carrier pattern

Tools: Arbitrary Wave Generator (AWG) & PC Tools

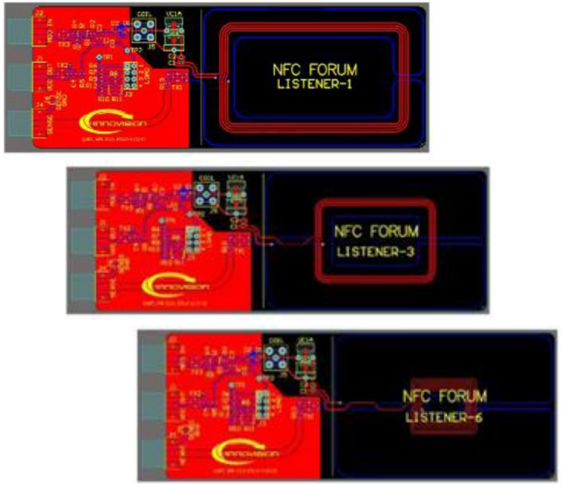
- Creates or generates pattern subcarriers together with a PC tool that allow us to define patterns and timing levels.
- E.g: Waveplayer from CETECOM as AWG
  - Includes many predefined patterns and flexible tests (ISO/IEC 14443-A & B, EMVCo)
  - Control level and timing of the load modulation index – amplitude signal.



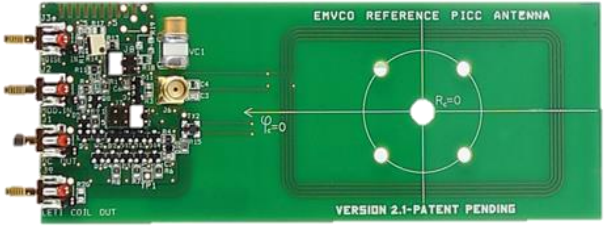
NFC Forum and EMVCo tests

“Reference PICCs”

- NFC Forum major analog NFC reader parameters:
  - Polling Device Power Transfer (“Field strength“)
  - Polling Device Modulation (“Wave shapes“)
  - Polling Device Load Modulation (“Load Modulation“)
  - Many more Listening Device parameters: not part of this webinar.



- EMVCo major analog PCD parameters:
  - Power Transfer PCD to PICC (“Field strength”)
  - Requirements for Modulation PCD to PICC (“Wave shapes”)
  - Requirements for Modulation PICC to PCD (“Load modulation”)



NFC antenna design

Wrap up

- NFC antennas are “transformers in resonance“
- The size (geometry) of an RFID/NFC antenna defines the operating distance (“performance“) in principle:
  - Small size = small operating distance
  - Large size = large operating distance
- Metal around or behind the NFC antenna “kills“ the magnetic field. Can be shielded with ferrite.
- The final design of an RFID/NFC antenna is quite straight forward with the right tools.
- Different requirements depending on ISO/IEC1443, NFC Forum and EMVCo
  - Use the correct reference tools (ref PICCs, Oscilloscope, PC tools
  - Or use test house services

Further information

NFC Reader Design: Antenna design considerations

- NFC Everywhere community
  http://www.nxp.com/techzones/nfc-zone/community.html
- NFC controller and frontend solutions
  http://www.nxp.com/products/identification_and_security/nfc_and_reader_ics/
- RFID: MIFARE and Contactless Cards in Application (**Co-author: Renke Bienert**)
  www.amazon.com/RFID-MIFARE-Contactless-Cards-Application/dp/1907920145
- In-depth NFC antenna design recorded webinars (**Renke Bienert**):
  - **Antenna design webinar 1**: Which antenna for what purpose?
  - **Antenna design webinar 2**: Antenna matching
  - **Antenna design webinar 3**: Metal environment
  - **Antenna design webinar 4**: Optimization and debugging
  - **Antenna design webinar 5**: Test & Qualification
  - **Antenna design webinar 6**: EMC related design

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