05 Contactless Transponders
5th unit in course 3, RF Basics and Components

Dipl.-Ing. Dr. Michael Gebhart, MSc

RFID Qualification Network, University of Applied Sciences, Campus 2
WS 2013/14, September 30th
Content

- What is a contactless transponder?
  - Relevant Standards for a Contactless Card
  - Functional blocks
  - Main circuitry (simplified)

- Transponder chip impedance measurement
  - Setup
  - Typical traces for equivalent $R_P$, $C_P$ over RF voltage
  - Relation to $H_{MIN}$ based on a linear equivalent circuit model

- Simulation of 3 operational states in communication

- Stationary “Card Loading” effect

- Transponder Load Modulation estimation

- Examples
What is a “Smart Label”?

- The contactless transponder is the electrically functional part.
- “Label” refers to object-oriented tagging (e.g. logistics).
What is a “SmartCard”?  

- **ISO/IEC14443** The **Contactless Proximity Air Interface** for **person-related cards / applications** was standardized 1 decade ago.

  - **Applications** in Government (e-Passports, driver license, health card...), Payment (Contactless Credit Cards), Public Transport (Ticketing), Secure Access Control, etc. are successfully deployed.

  - The same **battery-less**, proven secure chip technology now migrates into objects e.g. SD-Cards, watches, USB-Sticks, which requires small antennas. **Very High Data Rates ~ 10 Mbit/s** also allow new applications. **This requires more accurate chip characterization and tolerance consideration.**

- **Standards (ISO/IEC)**
  - 7810 Card geometry (e.g. ID-1 format) and physical properties
  - 7811-3/-3 Embossing (letters raised in relief)
  - 7811 magnetic stripe cards
  - 7812 optical character recognition cards
  - 7813 bank cards
  - 7816 contact cards with ICs
  - 10373 test methods

Card geometry specifications.
Introducing Contactless Proximity systems

- The Proximity coupling system operates in the 13.56 MHz world-wide license-free band in the Near Field (~10 cm range). Contactless supply power and communication interface.

- These systems "live" from intentional de-tuning and are not 50 Ohm impedance matched between antenna and chip!
Functional blocks in the transponder chip

- We can differentiate analog part and digital part.
- The analog part is relevant for the air interface and offers required operating conditions to the digital part.

Transponder Card, Smart Label

- Analog Part:
  - Over-voltage protection
  - Capacitance for resonant antenna circuit
  - Clock generation (from 13.56 MHz carrier)
  - Voltage regulator (limiter)
  - Demodulator for reader commands
  - Modulator for load modulation

- Digital Part:
  - Decoder (recognizes reader commands),
  - Encoder (for data transfer transponder → Reader),
  - Framing for data transmission (Buffer...),
  - Error detection / protection (depends on protocol, e.g. CRC),
  - Access control (also rights, encryption,...),
  - Program and / or data memory
Supply voltage control (for the digital part)
Clock generation / extraction (for dig. part)

- The reader carrier period is the time reference of communication.

- So the clock can be directly extracted from the RF carrier frequency (this is done in practice, it assures synchronicity of the transponder to the reader).

- For lower clock frequencies (< 13.6 MHz) only a comparator and divisor stages are required. For higher clock frequencies e.g. a PLL may be used.
Demodulator (for reader command)

- Demodulator may sense the antenna voltage, or the current (in this example).
- An analog comparator with different time constants may be used, or an ADC.
Modulator (for transponder load modulation)

- Modulator can be a shunt resistor (Q-shift) or a capacitor ($f_{RES}$ shift).
- Resistor can short antenna voltage (⇒ clock extraction difficult) or draw more current behind the rectifier (our example).
Transponder equivalent electrical circuit

- From a system perspective, the analogue RF performance of a battery-less transponder can be considered using a simplified equivalent circuit.

- **Chip**
  - $C_C$.....(equivalent) chip capacitance voltage (& state) dependent!
  - $R_C$.....(equivalent) chip resistance voltage (& state) dependent!

- **Assembly**
  - $C_{AS}$.....assembly capacitance
  - $R_{AS}$.....assembly serial resistance

- **Antenna**
  - $L_A$.....(equivalent) antenna inductance
  - $R_A$.....(equivalent) parallel antenna resistance (losses)
  - $C_A$.....(equivalent) parallel antenna capacitance

- **RF system requirements for a transponder are mainly**
  - Minimum $H$-field for Card operation, $H_{MIN}$
  - Load Modulation Side Band Amplitude, LMA
Chip input impedance characterization @ 13.56

The extended setup for network analysis is used to characterize impedance over frequency and voltage - also in the operating point and up to destruction levels.

The voltage on the DUT is calculated with a voltage divider (50 Ohm source and measured load impedance), from a previously measured output voltage to 50 Ohms.

\[ U_{DUT} = U_S \frac{R_P}{\sqrt{(R_P + R_S)^2 + (\omega R_P R_S C_P)^2}} \]

\[ Z_C = \frac{1 + \Gamma_C}{1 - \Gamma_C} Z_0 = \frac{1}{Y_C} \]

\[ R_P = \text{Re}\{Z_C\} = \text{Re}\left\{\frac{1}{Y_C}\right\} = \text{Re}\left\{\frac{1}{G_P + jB_P}\right\} = \frac{1}{G_P} \]

\[ C_P = \text{Im}\left\{\frac{1}{Y_C}\right\} = -\text{Im}\left\{\frac{1}{2\pi f_{MEAS} Z_C}\right\} = \frac{B}{\omega} \]
Eq. Chip admittance measurement

- Equivalent circuit values for a simple, linear model can be extracted.
- We measure the real part (parallel resistance, $R_C$) and imaginary part ($C_C$).

This allows to verify some main points (e.g. power-on reset, start of chip operation, dependency on chip settings like clock / current source setting...)

Note: It does not include any state transition or chip operation!
(to verify time-independence, obverse and reverse voltage sweep can be done)
Fabrication Technologies

**Antenna Technologies**

- Embedded Wire Antenna
- Etched Antenna
- Printed Antenna
- Galvano Antenna

**Assembly Technology**

- Crimping
- Welding
- Soldering
- Conductive Glueing

**Conductor materials:** Copper, aluminum, conductive paste (e.g. silver ink)

**Chip packages:** Module (8 x 5 mm), Flip-Chip, Strap, bumped wafer
Loop antenna equivalent circuit

The loop antenna is a **distributed component** with inductance (L) as main element and capacitance (C) and resistance (R) as parasitic network elements.

For simulation it must be represented by an **equivalent circuit** network of **lumped elements**. Over a wide frequency range this can be a loose coupled reactive ladder network of resonance circuits - it has several resonances in frequency domain.

At 13.56 MHz carrier frequency we use the **fundamental (lowest) resonance**. So we can simplify the equivalent circuit e.g. to a parallel resonance circuit (since losses are mainly determined by chip current consumption in Proximity Systems).

**Note:** This is a **narrow-band approximation** only!
RF System aspects of a contactless transponder

- This simplified linear analytical model can be used to consider some aspects of contactless Transponder behaviour at the RF Air Interface:
  - Energy perspective, $H_{\text{MIN}}$
  - Energy perspective, $H_{\text{MAX}}$
  - „Card Loading“ to the reader
  - Transponder Load Modulation (LMA) and ISO Sideband Amplitudes

- This can be used to relate contact-based chip & antenna properties to the RF system behaviour, which is required by the standard.

- Note: Considerations in this context relate to the Proximity base standard, ISO/IEC14443, and the Proximity Test Standard, ISO/IEC10373-6. Details on Standards will be discussed in another Training Course (Dec. 2, 3, 2013).
Transponder properties – Energy ($H_{MIN}$)

- The simple time-independent equ. circuit model allows to consider the $H$-field

![Circuit Diagram]

The transmission function is given by

$$U_C = U_I \cdot \frac{R_T}{sR_TR_T + 1} \cdot \frac{sL_A + \frac{R_T}{sR_TR_T} + 1}{1 + j\omega \frac{L_A}{R_T} - \omega^2 L_A C_T} = U_I \cdot \frac{1}{1 + j\omega \frac{L_A}{R_T} - \omega^2 L_A C_T}$$

Where the resonance frequency is given by...

$$\omega_R = \frac{1}{\sqrt{L_A C_T}}, \quad f_R = \frac{1}{2\pi \sqrt{L_A C_T}}$$

and the transponder quality factor is...

$$Q_T = \frac{R_T}{\omega_R L_A} = \omega_R C_T R_T$$

Finally, we substitute $U_I$ and re-arrange the function to express the required $H$-field by chip, antenna and system parameters:

$$H = \frac{\omega L_A}{\omega R} - \frac{(\omega L_A)^2}{R_T} \cdot U_C$$

$$\mu_0 N A$$

Transponder properties – Energy ($H_{MIN}$)
$H_{MIN}$ as function of chip and antenna properties

- Evaluating the analytical equation for $H_{MIN}$ allows to consider how chip and antenna properties influence contactless transponder RF performance.

- As there are production tolerances, performance over resonance frequency is important.

- As standard compliance requires all samples to achieve an Hmin, the allowable resonance frequency range can be determined.
**$H_{\text{MIN}}$ as function of chip and antenna properties**

- Evaluating the analytical equation for $H_{\text{MIN}}$ allows to consider how chip and antenna properties influence contactless transponder RF performance.

- As there are production tolerances, performance

\[
    f_{\text{LIM}} = \frac{f_c}{\sqrt{1 \pm \sqrt{\left(\frac{H_{\text{SMIN}}}{U_{\text{CMIN}}} \frac{2 \pi f_c \mu_0 N A}{U_{\text{CMIN}}} \right)^2 - \left(\frac{2 \pi f_c L_A}{R_T}\right)^2}}}
\]
\( H_{MIN} \) as function of chip and antenna properties

\[
Q_T = R_P \sqrt{\frac{C}{L}}
\]

\[
f_{RES} = \frac{1}{2 \pi \sqrt{LC}}
\]

\[
H_{MIN} \approx \sqrt{1 - \left( \frac{f_{CAR}}{f_{RES}} \right)^2} + \left( \frac{2 \pi f_{CAR} L_A}{R_p} \right)^2 \cdot U_{CHIP,MIN}
\]
Transponder analog front-end

- Analogue Design simulation environment (e.g. CADENCE) is used to simulate functional blocks of a Proximity transponder chip analogue front-end.

- Hierarchical simulation model, based on semiconductor process component models (includes parasitics & dependencies).

- As power supply and communication share one common interface, the resonant antenna circuit, 3 functional states are mainly investigated, for the power requirement ($H_{MIN}$) analysis:

  Command reception - Operation (e.g. r/w memory access) - Load modulation
3 functional states for the transponder
Thermal consideration and $H_{\text{MAX}}$

- To provide a constant supply to the digital part in the chip, a shunt regulator usually limits the chip voltage for an $H$-field > $H_{\text{MIN}}$.

- The antenna basically acts as a current source then, and it is possible to give a simple conversion ratio between $H$-field at transponder, and the (active) current provided to the chip.

- In the analytical formula, this is reflected by $R_T$, which is voltage dependent. So we can re-arrange our formula, to calculate $R_T$ out of the frame conditions.

$$R_T = \frac{\omega_c L_A}{\sqrt{\left(\frac{\omega_c \mu_0 N A H}{U_{\text{CLIM}}}\right)^2 - \left[1 - \left(\frac{\omega_c}{\omega_R}\right)^2\right]^2}}$$

$$I_A = \frac{U_{\text{CLIM}}}{R_T \left(\text{@ } \omega_{\text{RES}} \equiv \omega_{\text{CAR}}\right)}$$

- This is useful to estimate, how much current will be available for the chip, and it also allows to calculate the maximum thermal power dissipation for a card.

$$P_{TH} = U_{\text{CLIM}} \cdot I_A \left(\text{@ } H \equiv H_{\text{MAX}}\right)$$
Transponder properties – „Card Loading“

- The inductive coupling of the Transponder to the Reader resonant antenna circuit (both loop antennas carry currents) have an impact:
  - mutual inductance – reader antenna resonance is shifted
  - transponder draws current – reader antenna $Q$-factor is decreased
  - a 2$^{\text{nd}}$ resonance may be introduced in the transmission function...

- To consider effects, the contactless transformer model can be modified into a galvanically connected equivalent circuit, which includes the „transformed transponder impedance“ $Z_T'$. 

\[ \begin{align*}
U_{TX} & \quad U_{RX} \\
I_1 & \quad I_2 \\
U_{L1} & \quad U_{L2} \\
L_1 & \quad L_2 \\
C_1 & \quad C_2 \\
R_1 & \quad R_2 \\
R_L & \quad R_M \\
S_M & \quad k \\
U_{TX} & \quad U_{RX} \\
Z_T' & \quad R_1 \\
L_1 & \quad U_{RX} \
\end{align*} \]
Transponder properties – „Card Loading“

- The Proximity Standard defines „Card Loading“ just over the aspect of reduction of the reader $H$-field:

$$CLF = \frac{(H - \text{field with transponder}) - (H - \text{field without transponder})}{H - \text{field without transponder}}$$

- The transformed transponder impedance is given by...

$$Z'_T \approx \frac{1 + j \frac{f_{\text{CAR}}}{f_{\text{RES}}} Q_T}{\left(\frac{f_{\text{RES}}}{f_{\text{CAR}}} - \frac{f_{\text{CAR}}}{f_{\text{RES}}}\right) Q_T + j} k^2 2\pi f_{\text{CAR}} L_{\text{READER}}$$

  for $f_{\text{RES}} = f_{\text{CAR}}$ → $Z'_T \approx k^2 2\pi f_{\text{CAR}} L_{\text{READER}} (Q_T - 1)$

- So the „Card Loading factor“ is given by

$$CLF \approx \frac{1}{\text{abs}\left(1 + \frac{Z'_T}{Z_{\text{READER}}}\right)} - 1$$
Maximum allowable Card Loading

- Card Loading refers to a decrease of emitted $H$-field strength due to proximity coupling of the resonant reader antenna to a transponder card.

- The reader minimum $H$-field emission is tested under certain loaded conditions.

- So the test standard specifies a test case for cards, the maximum allowable card loading. It is specified relative to a so-called Reference PICC, for resonance at carrier frequency and a high $Q_T$-factor, specified as 6 VDC @ $H_{MIN}$, for antenna size class 1.

- This means, transponder cards will pass, if $Q_T$ is below the value for the Ref. PICC at $H_{SMIN}$, considering similar antenna size (this is general and allows to vary L/C).

### Reference PICC Measurement for Transponder Size Classes

<table>
<thead>
<tr>
<th>Class</th>
<th>PCD</th>
<th>$H_{SMIN}$</th>
<th>$L_A$</th>
<th>$U_{DC}$</th>
<th>$R_{2 typ}$</th>
<th>$\Delta H$</th>
<th>$Q_{TLIM}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>A/m(rms)</td>
<td>µH</td>
<td>V DC</td>
<td>Ω</td>
<td>%</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>1.5</td>
<td>2.29</td>
<td>6.0</td>
<td>975</td>
<td>6.9</td>
<td>3.0</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>1.5</td>
<td>2.38</td>
<td>4.5</td>
<td>1191</td>
<td>3.1</td>
<td>3.3</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>1.5</td>
<td>2.38</td>
<td>4.5</td>
<td>1308</td>
<td>3.2</td>
<td>3.6</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>2.0</td>
<td>2.36</td>
<td>4.5</td>
<td>1074</td>
<td>7.2</td>
<td>3.0</td>
</tr>
<tr>
<td>5</td>
<td>2</td>
<td>2.5</td>
<td>2.36</td>
<td>4.5</td>
<td>1092</td>
<td>4.7</td>
<td>3.1</td>
</tr>
<tr>
<td>6</td>
<td>2</td>
<td>4.5</td>
<td>2.25</td>
<td>4.5</td>
<td>839</td>
<td>2.1</td>
<td>2.5</td>
</tr>
</tbody>
</table>

* defined, ** measured, *** calculated from measurement

- for $f_{RES} = f_{CAR}$ we get
  \[
  R_T(\omega_R = \omega_c) = \frac{U_C L_A}{\mu_0 N A H}
  \]

- which means for $Q_T$
  \[
  Q_{TLIM} = \frac{U_{CR}}{2 \pi f_C \mu_0 N A H_{SMIN}}
  \]
Transponder properties – Load Modulation

- The Transponder transmits data via impedance change / load modulation
- This can be seen as dynamic switch of the „Loading“ ($f_{RES}$ or $Q_T$ can be varied)

Subcarrier $f_c / 16 = 847.5$ kHz

Data stream in line coding (e.g. manchester)

Modulated (on/off switched) Subcarrier

RF-carrier with $f_c = 13.56$ MHz (sine wave)

H-field carrier (13.56 MHz) with Card Loadmodulation

The Transponder transmits data via impedance change / load modulation. This can be seen as dynamic switch of the „Loading“ ($f_{RES}$ or $Q_T$ can be varied).
Transponder quality factor $Q_T$

- Extracting the quality factor:
  - Measurement of the time constant $\tau$ of the rising slope & calculate $Q_T$ using
    \[ Q_T = \frac{\omega_R}{2} \]
    $\rightarrow$ this $Q_T$ is named "$Q_{meas}$"
  - Calculation based on measuring the parallel resistance $R_{lc} \parallel R_{QLim}$

- $R_{lc} \parallel R_{QLim}$ is measured with Network Analyzer (Chip impedance Measurement) $\rightarrow$ this $Q_T$ is named "$Q_{NWA}$"

- **Alternative:** Calculate $R_{lc}$ of transponder chip measuring the time constant $\tau$ without $R_{QLim}$ and calculate $Q_T$ with component values of $R_{QLim}$ $\rightarrow$ "$Q_{calc}$"
Consistency Check: Determination of $Q_T$

- **$Q_{meas}$**
  
  \[ Q_T = \frac{D_R}{2} \]

- **$Q_{NWA}$**
  
  Measure $R_{ic} \parallel R_{QLim}$

- **$Q_{calc}$**

  (i) calculate $R_{ic}$ by measuring $\tau$ w/o $R_{QLim}$
  
  (ii) calculate $Q_T$ with component value of $R_{QLim}$

---

Class 1 Antenna

- Class 1 Qnwa
- Class 1 Qcalc
- Class 1 Qmeas

Transponder quality factor $Q_T$ vs Measurement number

- Measurement number: 1 to 12
- $Q_T$ values from 50 to 0
Consistency Check: Determination of $Q_T$

- **$Q_{meas}$**: Calculation of $Q_T$
  \[ Q_T = \frac{D_R}{2} \]

- **$Q_{NWA}$**: Measure $R_{ic} \parallel R_{QLim}$
  \[ Q_T = \frac{1}{R_s + \omega_{res}L_s + \omega_{res}L_i} \]

- **$Q_{calc}$**: Calculate $R_{ic}$ by measuring $\tau$ w/o $R_{QLim}$
  (i) calculate $R_{ic}$
  (ii) calculate $Q_T$ with component value of $R_{QLim}$

Class 2 Antenna

- **Class 2 Qnwa**
- **Class 2 Qcalc**
- **Class 2 Qmeas**
Consistency Check: Determination of $Q_T$

- **$Q_{\text{meas}}$**
  \[ Q_T = \frac{D_R}{2} \]

- **$Q_{\text{NWA}}$**
  Measure $R_{ic} \parallel R_{QLim}$

- **$Q_{\text{calc}}$**
  1. Calculate $R_{ic}$ by measuring $\tau$ w/o $R_{QLim}$
  2. Calculate $Q_T$ with component value of $R_{QLim}$

---

**Class 3 Antenna**

- Class 3 Qnwa
- Class 3 Qcalc
- Class 3 Qmeas

---

**Measurement number**

- Measurement numbers from 1 to 14 are plotted against $Q_T$ values.
Consistency Check: Determination of $Q_T$

- **$Q_{meas}$**
  
  $Q_T = \frac{D_R}{2}$

- **$Q_{NWA}$**
  
  measure $R_{ic} \parallel R_{Q\text{Lim}}$

- **$Q_{\text{calc}}$**
  
  (i) calculate $R_{ic}$ by measuring $\tau$ w/o $R_{Q\text{Lim}}$
  
  (ii) calculate $Q_T$ with component value of $R_{Q\text{Lim}}$

---

Class 4 Antenna

- **Class 4 Qnwa**
- **Class 4 Qcalc**
- **Class 4 Qmeas**

Transponder quality factor $Q_T$ vs. measurement number.
Consistency Check: Determination of $Q_T$

$Q_{meas}$

$$Q_T = \frac{Q_T}{2}$$

$Q_{NWA}$

measure $R_{ic} || R_{QLim}$

$$Q_T = \frac{1}{\frac{R_s}{\omega_{res} L_s} + \frac{\omega_{res} L_s}{\omega_{res} L_s}}$$

$Q_{calc}$

(i) calculate $R_{ic}$ by measuring $\tau$ w/o $R_{QLim}$

(ii) calculate $Q_T$ with component value of $R_{QLim}$
Consistency Check: Determination of $Q_T$

- **$Q_{meas}$**
  
  \[ Q_T = \frac{Q_R}{2} \]

- **$Q_{NWA}$**
  
  measure $R_{ic} \parallel R_{QLim}$

  \[ Q_T = \frac{1}{R_s + \frac{\omega_{res} L_s}{R_{QLim}}} \]

- **$Q_{calc}$**
  
  (i) calculate $R_{ic}$ by measuring $\tau$ w/o $R_{QLim}$
  
  (ii) calculate $Q_T$ with component value of $R_{QLim}$
Modulation “Strength”

- 2 effects reduce the ideally achievable load modulation:

\[ \text{Modulation strength} = \frac{\hat{U}_{ic,mod}}{\hat{U}_{ic,unmod}} \]

- Modulation Amplitude \( M_{pp} \rightarrow U_{ic,ima} \)
  - if antenna voltage \( \neq 0 \) for closed shunt
    \( \Rightarrow Q_T = Q_M \neq 0 \)
  - if signal time constant < resonance time constant.

![Graph showing modulation strength and envelope of chip input voltage](image)
Estimation of the load modulation

based on empirical measurement data analysis

- Empirical formula for ISO/ IEC 14443-2 SBA estimation (ideal case)

\[
SBA \approx \frac{2}{3} k^2 H \Delta Q_T \sqrt[4]{1 + Q_T^2 \left( \frac{\omega_{RES}}{\omega_{CAR}} - \frac{\omega_{RES}}{\omega_{CAR}} \right)}
\]

\( SBA_{\text{ISO}} \) ISO sideband amplitudes in V(peak)

\( k \) Coupling coefficient between sense coil A and transponder antenna

\( H \) Magnetic field strength in DUT position in A/m (rms)

\( Q_T \) Quality factor of the transponder (includes antenna and chip)

\( \Delta Q_T \) Difference between the modulated and the unmodulated \( Q_T \)

\( \omega_{RES} \) Angular resonance frequency of the transponder in \( \text{s}^{-1} \)

\( \omega_{CAR} \) Angular Frequency of the modulated sideband in \( \text{s}^{-1} \), e.g. \( 2\pi(13.56 \text{ MHz} \pm 847.5 \text{ kHz}) \)

Note: This empirical model is most accurate for \( Q_T < 25 \), and \( \Delta Q = Q_T \) if modulation is ideal (\( Q_M = 0 \))
ISO sideband amplitudes over transponder $Q_T$

Mean normalized ISO SBA per $k^2$ in mV(p) per A/m(rms)

Calculated transponder quality factor $Q_T$

$SBA \approx 500 \cdot k^2 H Q_T$ in $mV(p)$

$SBA$ reduction for $\frac{T}{2} \ll \frac{2 Q_T}{\omega_{RES}}$

$\hat{U}_{ic,848} \approx \hat{U}_{ic}$
ISO sideband amplitudes over transponder $Q_T$

$SBA \approx 500 \cdot k^2 H Q_T \text{ in } mV(p)$

$SBA$ reduction for $\frac{T}{2} \ll \frac{2 Q_T}{\omega_{RES}}$

$\hat{U}_{ic,1695} \approx \hat{U}_{ic}$
ISO SBA measurement for Class 1 antenna

Sideband Amplitude over Quality Factor

Calculated transponder quality factor $Q_T$

Normalized ISO Sideband Amplitudes over Quality Factor

Calculated transponder quality factor $Q_T$
ISO SBA measurement for Class 2 antenna

**Sideband Amplitude over Quality Factor**

- 848k LSB
- 848k USB
- 1695k LSB
- 1695k USB

**Normalized ISO Sideband Amplitudes over Quality Factor**

- 848k LSB
- 848k USB
- 1695k LSB
- 1695k USB
ISO SBA measurement for Class 3 antenna

**Sideband Amplitude over Quality Factor**

- 848k LSB
- 848k USB
- 1695k LSB
- 1695k USB

**Normalized ISO Sideband Amplitudes over Quality Factor**

- 848k LSB
- 848k USB
- 1695k LSB
- 1695k USB
ISO SBA measurement for Class 4 antenna

Sideband Amplitude over Quality Factor

Normalized ISO Sideband Amplitudes over Quality Factor
ISO SBA measurement for Class 5 antenna
ISO SBA measurement for Class 6 antenna

Sideband Amplitude over Quality Factor

Normalized ISO Sideband Amplitudes over Quality Factor
$Q_T$ and ISO SBA as function of $H$-field strength
Comparison model versus measurement
Min. antenna area limit for ISO SBA compliance

- Passive 14443 transponders
- Postulated lower border for antenna size
- Measured data

Constraints:
- $H = 1.5 \, \text{A/m (rms)}$
- only PCD 1 and class 1-3 SBA limits

$V_{LMA,mVP} > \frac{22}{\sqrt{H_{A/m}}}$
We can distinguish 3 phases during communication:

- Phase 1: Communication Reader to Card, 100 % AM modulation of carrier H-field
- Phase 2: Unmodulated Carrier
- Phase 3: Transponder Load Modulation.

In good contactless chip design, energy and not communication is the limiting factor. This allows to calculate $H_{MIN}$ as function of resonance frequency and other parameters.

$$H_{MIN} \approx \sqrt{\left[1 - \left(\frac{f_{CAR}}{f_{D1}}\right)^2\right]^2 + \left(\frac{2\pi f_{CAR} L_A''}{R_P}\right)^2} \cdot U_{MIN}$$

A remaining problem is the resonance frequency measurement.

- Mutual inductance, and
- chip voltage level

must be taken into account properly.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Meaning</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_{CAR}$</td>
<td>carrier frequency</td>
<td>MHz</td>
<td>13.56</td>
</tr>
<tr>
<td>$R_{C0}$</td>
<td>eq. parallel chip resistance (measured at 0.3 Vrms)</td>
<td>Ohm</td>
<td>14000</td>
</tr>
<tr>
<td>$R_{C1}$</td>
<td>eq. parallel chip resistance at start of operation (at 2.7 Vrms)</td>
<td>Ohm</td>
<td>1500</td>
</tr>
<tr>
<td>$U_{MIN}$</td>
<td>voltage for start of chip operation</td>
<td>V(rms)</td>
<td>2.7</td>
</tr>
<tr>
<td>$L_F$</td>
<td>inductance of fixture (Cal. Coil)</td>
<td>Henry</td>
<td>$2 \times 10^{-7}$</td>
</tr>
<tr>
<td>$L_S$</td>
<td>inductance of one Sense Coil</td>
<td>Henry</td>
<td>$4.2 \times 10^{-7}$</td>
</tr>
<tr>
<td>$L_A$</td>
<td>inductance of card antenna</td>
<td>Henry</td>
<td>$1.86 \times 10^{-6}$</td>
</tr>
<tr>
<td>$k_{AF}$</td>
<td>coupling factor antenna - fixture</td>
<td>---</td>
<td>0.115</td>
</tr>
<tr>
<td>$k_{AS}$</td>
<td>coupling factor Sense Coil - antenna</td>
<td>---</td>
<td>0.22</td>
</tr>
<tr>
<td>$R_{SA}$</td>
<td>eq. serial antenna resistance (measured at 13.56 MHz)</td>
<td>Ohm</td>
<td>1.7</td>
</tr>
<tr>
<td>$A$</td>
<td>antenna area</td>
<td>m²</td>
<td>0.0014</td>
</tr>
<tr>
<td>$N$</td>
<td>loop antenna turns</td>
<td>---</td>
<td>3.8</td>
</tr>
</tbody>
</table>
Resonance frequency (1)

As instruments usually do not allow sufficiently high output levels to measure the resonance frequency in the operating range (\(f_{res}\) and \(Q\) vary), one option is to measure at low \(H\)-fields (where the traces are flat and voltage-independent) and to re-calculate values for operating conditions, based on the known impedance trace.

2 aspects need to be taken into account:

1. The well-know Thomson equation (for parallel resonance circuits)...
\[
f_1 = \frac{1}{2\pi\sqrt{LC}}
\]
...needs to be adjusted to a more appropriate equivalent circuit of the transponder....

\[
f_{RES} = \frac{1}{2\pi} \sqrt{\frac{R_C + R_{SA}}{L_A(C_C + C_A)R_C}}
\]
2. The mutual inductance due to close coupling to other coils in the specified test setup needs to be taken into account.

One option is, to measure the resonance frequency at low H-field in the voltage-independent region. The natural frequency (without de-tuning by the measurement coil) can be calculated according to

\[ f_{T0} = \sqrt{L_A' \cdot \frac{R_{C0} + R_{SA}}{R_{C0} L_A}} \cdot f_{M0} \]

\[ L'_A = \frac{L_A + L_F}{2} + \sqrt{\left(\frac{L_A + L_F}{4}\right)^2 - \left(\frac{L_A L_F}{k_{AF}^2 L_A L_F}\right)} \]

Then we can calculate the resonance frequency in the operating point knowing the \( \Delta C \... \]

\[ f_{T1} = \frac{1}{2\pi} \sqrt{\frac{R_{C1} + R_{SA}}{R_{C1} L_A \left[ \frac{R_{C0} + R_{SA}}{R_{C0} L_A (2\pi f_{T0})^2} + \Delta C_C \right]}} \]

...and we can even calculate the de-tuned resonance frequency in the measurement setup

\[ f_{D1} = \frac{1}{2\pi} \sqrt{L''_A \cdot \frac{R_{C1} + R_{SA}}{R_{C1} L_A (2\pi f_{T1})^2}} \]

\[ L''_A = \frac{L_A + 2L_S}{2} + \sqrt{\left(\frac{L_A + 2L_S}{4}\right)^2 - \left(\frac{L_A 2L_S - k_{AS}^2 L_A 2L_S}{k_{AF}^2 L_A 2L_S}\right)} \]
Minimum $H$-field over resonance frequency

With these corrections, the trace of minimum $H$-field strength for transponder operation can be calculated accurately from chip impedance trace and loop antenna parameters.

It is also possible to calculate min. and max. allowable resonance to achieve certain $H_{\text{min}}$:

\[
f_{\text{MIN}} = \sqrt{\frac{f_{\text{CAR}}}{\sqrt{1 + \left(\frac{H_{\text{MIN}} 2\pi f_{\text{CAR}} \mu_0 N A}{U_{\text{MIN}}} \right)^2 - \left(\frac{2\pi f_{\text{CAR}} L_A}{R_p} \right)^2}}}
\]

\[
f_{\text{MAX}} = \sqrt{\frac{f_{\text{CAR}}}{\sqrt{1 - \left(\frac{H_{\text{MIN}} 2\pi f_{\text{CAR}} \mu_0 N A}{U_{\text{MIN}}} \right)^2 - \left(\frac{2\pi f_{\text{CAR}} L_A}{R_p} \right)^2}}}
\]

This allows to consider tolerances for chip and antenna parameters, or e.g. to optimize operating conditions for the chip, like clock frequency.
Chip current consideration

Finally this allows also to consider the available internal Chip current:

\[
I_{DC} = \frac{U_{CHIP} - U_{DROP}}{R_C} = \left(\frac{U_{CHIP} - U_{DROP}}{R_A}ight) \cdot \left(\frac{R_A - R_T}{R_T}\right)
\]

Here we get

\[IDC = 1.38 \text{ mA at the limits}\]
\[IDC = 2.24 \text{ mA for optimum}\]

for 0.9 A/m and Voltage Drop of 0.9 V.

Antenna power loss is 5.9 – 10.6 %.
Conclusions

- The way to relate chip input impedance to the SmartCard system behaviour was discussed in detail and applied for an ISO/IEC14443A compatible SmartCard Chip according to the measurement methods of ISO/IEC10373-6.

- As practical example, the $H$-field required for operation was measured as a function of the resonance frequency. These measurements show a good fit to the quasi-static calculation model based on $R_P - C_P$ for the point of start of operation, for the investigated chip. This closes the loop to applications and proofs the concept.
Example 2: SmartCard chip impedance

- The CPU clock can be configured by the user according to application requirements.
- This means, the (expected) required current for operation is set accordingly.
- To prevent chip reset, there is a voltage sensor which can stop the clock (and so the current consumption), if the digital supply voltage drops too much.
- This behaviour can be seen well in the traces for equivalent chip impedance, and allows identification of specific operating points.

To note: The chip must be measured in the correct configuration!!
Example 2: SmartCard chip impedance

– One Engineering Chip sample was measured 10 times (clock settings 4 ... 61 MHz).
– A part of the $R_P$ trace is shown for detailed interpretation.
– The LDR demodulator (on antenna voltage) is principally always functional.

After the power on reset and some switching of security logic (and non intended limiter behaviour) the voltage point for CPU start can be identified. The chip will operate at 106 kbit/s from this point on ($H_{MIN} @ 106$ is independent of the clock setting).

– The HDR demodulator gets active if the 1st limiter has sufficient current. So the voltage point for start of operation at HDR depends on clock setting.
– $R_P$ and voltage are dependent on clock setting!
– Out of the diagram, a practical assumption for chip current consumption is $1.6 + 0.08$ mA/MHz.
– An estimation for the voltage point at 18 MHz CPU is $3.2$ V(rms).

– $4$ MHz $\sim 1.9$ mA
– $61$ MHz $\sim 6.4$ mA

**Diagram:**

- CPU start, $\sim 106$ kbit/s OK
- HDR DEM active
- $4$ MHz $\sim 1.9$ mA
- $61$ MHz $\sim 6.4$ mA
- POR, LDR DEM OK
Example 2: SmartCard chip impedance

- To note: Also the equivalent parallel capacitance depends on the Chip current settings.
- Reason is the shift introduced by the relation of resistances in the real chip network (rectifier serial resistance, limiter parallel resistance), which influence the simplified equivalent network $C_P - R_P$.
- So it will need considerations, which is the most important operational point for a specific chip platform, and settings controlled by software take influence on this decision, if we consider it accurately!
Example 2: SmartCard chip impedance

The analytical model allows us to relate chip impedance to contactless transponder behaviour. One critical question is, how the chip power consumption changes during the modulation pause. This may require to take a duty cycle into account. In principle, $H_{MIN}$ can be calculated with chip and antenna parameters and fits to contactless measurement results on the ISO test bench.

$$H_{MIN} \approx \sqrt[2]{\left[1 - \left(\frac{f_{CAR}}{f_{RES}}\right)^2\right]^2 + \left(\frac{2\pi f_{CAR} L_A}{R_P}\right)^2} \cdot U_{CHIP,MIN} \cdot F_{DUTY}$$

Data used for calculation:

**Antenna (Class 1 testboard)**
- $L_A$........3.08 µH
- $N$...........4 turns
- outline 74 x 45 mm
- $A_{EFF}$.....0.0034 m²

**Chip (CD081)**
- (DEM100)
- $R_P$........1.5 kOhm
- $U_{MIN}$......2.3 V(rms)

**System (ISO/IEC14443)**
- $f_{CAR}$......13.56 MHz
- $\mu_0$........$4 \pi 10^{-7}$
- $f_{RES}$......15 - 18 MHz
- $F_{DUTY}$....1.05

$H_{MIN}$ is 0.42 A/m for 15 MHz and 0.77 A/m for 18 MHz – measured and calculated.
Example 2: SmartCard chip impedance

– In addition, we see the typical trace for $H_{MIN}$ over resonance frequency (here for a different chip), for LDR and HDR.

– Note that resonance frequency is measured under low $H$-field conditions in this case – the minimum is not centered at 13.56 MHz carrier frequency.

– More in detail, the minimum for 212 kbit/s is shifted against the minimum for 106 kbit/s!
Example 2: SmartCard chip impedance

- It is also instructive, to see the influence of limiter voltage and current consumption on the ISO Sideband Amplitudes over the $H$-field range (for a fixed $f_{RES}$).
- Higher $U_{\text{LIM}}$ increases SBA, but only if the required current is already available from $H$-field (means increase of $Q_T$).
- Less current consumption helps in the critical, low $H$-field region (e.g. clock)
Example: Contactless sticker antenna design matrix

- Example: A design matrix of 5 different embedded wire antennas was fabricated in normal Card production flow.

- Varied parameters were
  - wire pitch (distance between turns)
  - number of turns
  for equal outline (size).

- Antenna equivalent circuit parameters were measured for
  - Air coils, and
  - Coils on ferrite foil.

<table>
<thead>
<tr>
<th>ANTEENA GEOMETRY DATA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td>outline</td>
</tr>
<tr>
<td>wire diam.</td>
</tr>
<tr>
<td>pitch</td>
</tr>
<tr>
<td>turns</td>
</tr>
</tbody>
</table>

Equivalent circuit electrical data for air coils on PVC

| $L_A$ | µH   | 1.595 | 1.304 | 1.692 | 1.937 | 2.303 |
| $C_A$ | pF   | 2.09  | 1.80  | 1.55  | 1.72  | 2.08  |
| $R_A$ | kΩ   | 16.97 | 12.40 | 17.92 | 21.81 | 27.40 |

Equivalent circuit electrical data for coils on ferrite foils

| rel. perm. | $\mu_r$ | 45 |
| thickness  | µm      | 100 |
| $L_A$      | µH      | 2.008 | 1.649 | 2.162 | 2.433 | 2.901 |
| $C_A$      | pF      | 3.55  | 3.18  | 3.80  | 3.95  | 3.89  |
| $R_A$      | kΩ      | 12.85 | 10.18 | 11.91 | 13.80 | 17.20 |

Relative increase of inductance due to ferrite sheet

| $k_L$ | 1.259 | 1.268 | 1.278 | 1.256 | 1.259 |

Conclusions: Inductance increase due to ferrite. The relative increase is constant. So the inductance for coils on ferrite can be calculate by the inductance for the air coil times factor $k_L$.

In addition, there is a loss increase due to losses in ferrite foil.
Minimum required \( H \)-field for operation

- Typically an antenna is designed to allow optimum contactless transponder performance (energy requirements, load modulation) for a selected chip.

- Tolerances in fabrication process (e.g. transponder capacitance) require to consider traces over a resonance frequency tolerance range (to cover all parts out of production).

- The shift in (antenna) inductance due to ferrite causes a shift in the resonance frequency.

- For energy-optimum resonance at 13.56 MHz carrier frequency, a different capacitance is required.

- The resonance frequency tolerance range is similar, but...

- Due to additional losses in the ferrite, the \( H_{\text{min}} \) achievable with ferrite foil is higher / worse than for the air coil (depending on the ferrite properties).

**To note:**

- Metal objects below the ferrite can again decrease inductance, and shift resonance!
Load modulation at upper sideband \((f_c + f_{SC})\)

- Sufficient load modulation is the second main requirement for the transponder at the air interface.
- The level must be high enough to allow error-free communication of transponder to reader, as defined in the standard.
- We compare the phasor of the signal in the upper sideband for energy-optimum free air coil and coil on ferrite transponder (capacitance is adjusted properly).

\[\text{Load modulation decrease}\]

- We find an increase in the starting point for load modulation, which is caused by the increased \(H_{\text{min}}\) (due to ferrite losses).
- We find a decrease in the load modulation level.
- For this case, the decrease is about 15 - 20 %.
- The reason are, basically, losses of the ferrite foil.

\textbf{Basically, the ferrite foil means a transponder performance degradation compared to free air coils.}
Thank you for your Audience!

Please feel free to ask questions...