Predicting the influence of permittive materials on passive inductive coupled RFID-transponders

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1. Modelling a planar RFID-Antenna Coil

- impedance of the antenna coil (measured)

- derived compact model

- condition: quasi stationary state
  - size of the antenna coil is small in comparison to the wavelength
  - example: $x_{\text{coil}} = 0.1 \text{ m}$ vs. $\lambda = 22.1 \text{ m}$ ($f = 13.56 \text{ MHz}$)
1. Modelling a planar RFID-Antenna Coil

- capacitance calculation of the cross-section (2D) by FEM-simulation

- calculation of the inductance by the method of partial inductances
  - development of the idea by A. Rühli in the 1970th
  - solving piecewise the integral:

\[
L_{12} = \frac{\mu}{4\pi \cdot A_{L1} \cdot A_{L2}} \int \int \int \int \frac{1}{r} \, dA_{L2} \cdot ds_{L2} \cdot dA_{L1} \cdot ds_{L1}
\]

- resistance

\[
R_{DC} = \rho \frac{L}{A}
\]
  - if necessary skin- and proximity-effect can be considered ($\delta_{\text{Cu,skin}} = 18 \, \mu\text{m} @ 13.56 \, \text{MHz}$)

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- model with one node per turn for calculation of all parameters:

\[
\begin{align*}
N & \quad \text{Inductances} \\
N & \quad \text{Ohmic Resistors} \\
(N^2 - N)/2 & \quad \text{Coupling Factors} \\
(N^2 + N)/2 & \quad \text{Capacitances}
\end{align*}
\]

- extraction of the parameter of the RLC-compact-model:
  - inductance and resistance

\[
L = \sum_{i=j} L_{ij} + \sum_{i\neq j} M_{ij} \quad R = \sum_{i=j} R_{ij}
\]
  - extraction of the 1st resonant frequency from the PSpice-simulation of the network
  - calculation of the parasitic capacitance $C_p$ by

\[
C_p = \frac{1}{(2\pi f_{\text{res}})^2 L + \frac{R^2}{L}}
\]

- method is verified by hundreds of simulations and measurements
- model generation and parameter extraction is implemented in a software tool

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2. Set-up of the Test Scenario

- two different technologies are considered to examine the permittive environment:

  - wounded wire
    \[(N = 6, A_{\text{cond.}} = 90 \times 90 \, \mu\text{m}^2, s = 300 \, \mu\text{m})\]

  - etched structure
    \[(N = 7, A_{\text{cond.}} = 500 \times 18 \, \mu\text{m}^2, s = 300 \, \mu\text{m})\]

- parameter for both antenna coils:
  - conducting material: aluminium
  - substrate: PVC, 200 µm thick
  - coil area: \(A = 48 \times 79 \, \text{mm}^2\)
  - inductance: \(L = 7.1 \, \mu\text{H}\)
  - resistance: \(R = 4.8 \, \Omega\)

  *) approximated by a square shaped cross section

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2. Set-up of the Test Scenario

- environmental conditions:
  1. coil mounted on the PVC substrate, air in the surrounding
  2. lamination in PVC (overall thickness 0.76 mm)
  3. mounting on a water filled container (PVC, thickness of the wall 1 mm)

- material stack:
3. Influence of permittive Material on Antenna and Transponder

- Inductance and resistance are not affected by the permittive material.
- Parasitic capacitance:
  1. Antenna mounted on the substrate: capacitance approx. 2 pF.
  2. Antenna laminated: capacitance rises 67% (wounded wire) and 44% (etched structure).
  3. Laminated antenna mounted on the water container: capacitance is up to nearly three times higher (etched structure).

### Graph: Parasitic Capacitance

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<tr>
<td>Wounded Wire</td>
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<tr>
<td>Etched Structure</td>
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- Question: What are the consequences?
- Answer: Detuned resonant circuit and in the result a reduced reading range.

- Needed resonance capacitance ($L = 7.1 \mu H$): $C_{total} = C_{IC} + C_p = 19.4 \text{ pF}$
  - $\Delta C_{p,\text{max}} = 3.7 \text{ pF}$ (due to permittive environment).

- Example: Voltage at the transponder-IC for a fixed field strength (etched antenna)
  - $U_{IC,\text{min}} / U_{IC,\text{max}} \sim 0.2$
  - $\Delta f_{\text{res, max}} = -1.1 MHz = -8.4 %$
4. Effects on the Reading Performance

- approach: calculation of the reading range via the coupling inductance \( M \):

\[
I_0 \quad L_r \quad M \quad L_s \quad M \quad R \quad U_{IC} \\
\text{Reading Device} \quad \text{Transponder}
\]

- calculation of \( U_{IC} \) (minimum operating voltage of the transponder-IC)

\[
U_{IC} = \frac{\omega M \cdot I_1}{\sqrt{\left(\frac{\omega L_2}{R_L} + \omega RC\right)^2 + \left(1 - \omega^2 L_2 C + \frac{R}{R_L}\right)^2}}
\]

- coupling inductance \( M \) is depending from the distance between the antennas
- assumptions for the following calculations:
  - reading antenna: \( A = 200 \times 200 \text{ mm}^2, I = 1 \text{ A} \)
  - transponder-IC: \( R_l = 20 \text{ k}\Omega, U_{IC,\text{min}} = 2 \text{ V} \)
  - transponder resonant frequency: \( f_{\text{res}} = 13.56 \text{ MHz} \) (for comparable results)
  - because no specific reading device is given, the powering range is calculated

results:

1. antenna mounted on the substrate: nearly 550 mm powering range for both technologies
2. antenna laminated: max. reduction of 21 % (wounded wire)
3. laminated antenna mounted on the water container: max. reduction of 43 % (etched structure)
4. laminated antenna mounted on the water container (tuned to 13.56 MHz after lamination):
   -19 % (wounded wire) vs. -37 % (etched structure)
Conclusion

• the presented modelling approach:
  – uses the compact model consisting of the elements:
    • resistance,
    • inductance,
    • parasitic capacitance,
  – allows to predict the electrical properties of the antenna coil up to the first self resonance,
  – is implemented in a software tool.

• permittive material in the surrounding of a planar antenna coil
  – results to a higher parasitic capacitance (nearly three times for the test set-up).
  – reading range is reduced due to detuning of the resonant frequency of the transponder.

• the compared manufacturing technologies show differences:
  – the wounded wire technology provides less sensitivity to permittive material

• antenna optimisation is required for applications in different environmental conditions

• careful set-up is necessary when performing measurements of the reading field:
  – the transponder may not mounted directly on plastic nor touched by hand

• further information: cichos@web.de

Thank you for your attention.