Design and Optimization of Remotely powered RFID Systems and Sensor Nodes

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OUTLINE

Introduction
Wireless Power Transmission
Communication Issues
Transponder (tag) and Reader Design
Summary Other prospects
Summary on RFID at long distance
Prospects
1. INTRODUCTION
Principle

Introduction to RFID & Main issues

Near & Far-field
Ultra-High Frequency (UHF) Issues

Principle

Reader

Tag 1

Tag 2

AC to DC converter

Data management & modulation

DB

data & power

data

Tag N

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Design and Optimization of Passive RFID Systems
Near-field (low frequency applications, up to 100 MHz)

- Starts in the direct neighborhood of any antenna up to \( d = \frac{\lambda}{2\pi} \)
- Usually inductive coupling (magnetic field)
- But can be capacitive coupling (electric field)
- Antennas have to be either coils for inductive coupling, or metallic surfaces for capacitive coupling
- Link budget in both cases is proportional to \( d^{-6} \) and \( \lambda^6 \).
Far-field (high frequency applications, from 100 MHz)

- Far-field occurs at a distance larger than $\frac{\lambda}{2\pi}$ from the antenna
- Electromagnetic coupling
- Antennas are typically of N-poles types (monopole, dipoles, etc.)
- Available Power varies with $d^{-2}$ and $\lambda^2$.
- Link budget is a function of $d^{-4}$ and $\lambda^4$. 
Wireless Power Transmission (WPT) in UHF passive systems

A first estimation of power levels at tag (1/2):

- **Power density at tag antenna:** \( S = P_{EIRP} \cdot \frac{1}{4\pi d^2} \)
- **Power collected by tag antenna and available to the load:** \( P_{AV} = A_E \cdot S \)

With **Antenna Aperture**

\[
A_E = \frac{\lambda^2}{4\pi} \cdot G_R
\]
Wireless Power Transmission (WPT) in UHF passive systems

A first estimation of power levels at tag (2/2):

\[ P_{AV} = S \frac{\lambda^2}{4\pi} G_R = P_{EIRP} G_R \frac{\lambda^2}{(4\pi d)^2} \]

Friis Relation

\[ \lambda = 0.1224 \text{ m (2.45 GHz)} \]

For \[ P_{EIRP} = 4 \text{ W} \]

\[ G_R = 1 \text{ (0 dB): Antenna gain} \]

<table>
<thead>
<tr>
<th>d(m)</th>
<th>( P_{AV}(W) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 m</td>
<td>379 ( \mu \text{W} )</td>
</tr>
<tr>
<td>5 m</td>
<td>15.17 ( \mu \text{W} )</td>
</tr>
<tr>
<td>10 m</td>
<td>3.79 ( \mu \text{W} )</td>
</tr>
<tr>
<td>12 m</td>
<td>2.6 ( \mu \text{W} )</td>
</tr>
</tbody>
</table>
2. Wireless Power Transmission
There is a need for a model taking into account:

- The AC source $v_{in}$ (antenna)
- The current delivered to the load
- Diodes non-idealities

![Rectifier Circuit (2 stage Greinacher)](image)

$$V_{out} = 4N\hat{v}_{in}$$

Where $N$ is the number of stages
Antenna Model

At load matching conditions ($R_{\text{ANT}} = R_{\text{IN}}$)

$$\hat{v}_S = 2\hat{v}_{in} = 2\sqrt{2P_{AV}.R_{\text{ANT}}}$$
Rectifier input voltage: influence of $R_{in}$

The voltage amplitude $\hat{v}_{in}$ at the rectifier input is given by:

$$\hat{v}_{in} = 2\sqrt{2P_{AV}R_{ant}} \frac{R_{in}}{R_{in} + R_{ant}}$$

To maximize $\hat{v}_{in}$ and Power:

- Maximize $R_{ant}$
- Keep $R_{in}$ equal to $R_{ant}$
Rectifier input voltage for $R_{\text{ANT}} = R_{\text{in}}$

\[ \hat{V}_{\text{in}} \quad [\text{mV}] \]

\[ P_{\text{AV}} \quad [\mu\text{W}] \]

- $600 \ \Omega$
- $300 \ \Omega$
- $50 \ \Omega$
Rectifier Equivalent Circuit Model

\[ \hat{V}_{\text{in}} \]

\[ R_{\text{in}} \quad C_{\text{in}} \quad v_0 \]

\[ R_{\text{out}} \]

\[ V_{\text{out}} \]

\[ \text{AC} \]

\[ \text{DC} \]
Assumptions

- The rectifier operates in steady-state mode;
- The output current is constant;
- All diodes are identical;
- The coupling capacitors are considered as short-circuits at the RF frequency

Measurements & Comparisons

Output voltage vs Input Power (50Ω, 900 MHz), 0.5μm CMOS SOS Technology
Model possibilities

The model allows a reasonably accurate prediction of:

- The output voltage ($V_{out}$)
- The input impedance ($R_{in}$, $C_{in}$)
- The output resistance $R_{out}$
- The conversion power efficiency

as a function of:

- The DC output Power / Current
- The antenna radiation resistance ($R_{ant}$)
- The available power $P_{AV}$ at the antenna
- The characteristics of the MOS diodes
3. COMMUNICATION ISSUES
Backscattering communication

- The tag (transponder) modulates and reradiates the RF signal that is coming from the interrogator (reader).
- The power consumption on the tag side is minimised because there is no RF section.
- If Data = Bit “1” :
  - $Z_{in} = R'$ is mismatched to the tag antenna.
  - All the power of the RF incoming signal is reflected to the interrogator.
- If Data = Bit “0” :
  - $Z_{in} = R$ is matched to the tag antenna.
  - All the power of the RF incoming signal is absorbed by the tag.

IEEE CAS Conference, C. Dehollain et al, 2001
ASK modulation

- **Basic principle**
- **Analysis**
- Pseudo-PSK (pPSK)

**Reflected ASK modulated signal**

Duty-cycle ASK standard ASK bit stream

- Bit « 1 »: switch closed
- Bit « 0 »: switch open

Reflected power due to mismatch at the tag

Tag input impedance

<table>
<thead>
<tr>
<th>Time</th>
<th>DC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

R_i (switch closed) R_i (switch open)

R_{ANT} L C_i
PSK modulation

\[ R_{\text{ANT}} - B - L - A - C_i - R_i \]

Ant.  React.  tag

\[ Z_1, X_L, Z_0, X_C + X_C' \]

1 0 1 0

State 1  Switch closed
State 0  Switch open

In B: Absorbed power and reflected power are constant

In A: Voltage at tag input is however not constant

Tag input impedance at B
ASK / PSK Comparison through the BER

\[
E_b = \text{Average Energy per bit} \\
N_0 = \text{Noise level at receiver input} \\
\alpha = \frac{R_i}{R_{\text{ANT}}} \\
Q = \text{tag input series Quality factor } \frac{1}{\omega R_i C_i} \\
DC = \text{Modulation Duty Cycle}
\]

J.P. Curty, M. Declercq, C. Dehollain, N. Joehl  
Book: « Design and Optimization of Passive UHF RFID Systems »  
ASK / PSK Comparison

Optimal ASK and PSK BER comparison
(ASK: DC = 100%, \( \alpha = 1 \) and PSK: \( \alpha = 1 \), Qin = 5.6)
Communication Issue

Tag input impedance for long-distance RFID

Priority is given to communication distance vs. data rate

The real part of $R_{\text{in}}$ is very high ($\gg 1\text{k}\Omega$) and much higher than $R_{\text{ant}}$

Reflection coefficient is close to ±1

The input capacitance is equal to a few hundreds fF

Reflection coefficient amplitude

Matching conditions
\[ \Gamma = 0 \text{ and } \alpha = 1 \]

Normalized resistance $\alpha = \frac{R_{\text{in}}}{R_{\text{ant}}}$

\[ \Delta \phi = 180^\circ \]
\[ \Delta \phi = 0^\circ \]
Pseudo - PSK

In practice $R_i > R_{ANT}$ (~1 order of magnitude)

- Absorbed power is lower than ideal
- Voltage available at rectifier input is higher
- Modulation is very efficient with a 180° phase shift
Power waves

Power waves for both modulation states

\[ \Delta \phi = 180^\circ \]
\[ \Delta \phi = 0^\circ \]

Time

Normalized power wave amplitude %

J.P. Curty, M. Declercq, C. Dehollain, N. Joehl
Book: « Design and Optimization of Passive UHF RFID Systems »
4. TAG AND READER DESIGN
Initial Specifications for the tag IC

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency range</td>
<td>2.40 - 2.48 Ghz</td>
</tr>
<tr>
<td>Reader $P_{EIRP}$</td>
<td>4 W</td>
</tr>
<tr>
<td>Tag power</td>
<td>$\approx 1 \mu W$</td>
</tr>
<tr>
<td>Operating distance</td>
<td>&gt; 5 m</td>
</tr>
<tr>
<td>Reader to tag</td>
<td>AM (OOK) modulation</td>
</tr>
<tr>
<td>Tag to reader</td>
<td>p-PSK modulation</td>
</tr>
<tr>
<td>Data rate</td>
<td>$\geq 10$ kbps</td>
</tr>
</tbody>
</table>
Building Blocks
Tag Die

- Antenna pads
- POR
- Logic
- Rectifier
- Switch

Complete Tag with antenna

Maxi data rate: 10kbit/s
Maxi distance: 12m @ 2.45GHz
Technology: 0.5um SOS CMOS
Area: 0.4mm * 0.55mm
### Reading Range

<table>
<thead>
<tr>
<th>Frequency MHz</th>
<th>Antenna</th>
<th>Range m</th>
</tr>
</thead>
<tbody>
<tr>
<td>2450</td>
<td>$\lambda/2$-dipole</td>
<td>6</td>
</tr>
<tr>
<td>2450</td>
<td>$\lambda/2$-dipole with inductive matching</td>
<td>9</td>
</tr>
<tr>
<td>2450</td>
<td>folded dipole</td>
<td>7</td>
</tr>
<tr>
<td>2450</td>
<td>folded dipole with inductive matching</td>
<td>12</td>
</tr>
</tbody>
</table>

At 12 m, the available power at the tag input is about 4.2 uW for a folded dipole antenna (2dB gain).

Summary on RFID at long distance

- Wireless power transmission & rectifier models have been developed for optimizing the power supply available for the tag.
- Different backscattering modulation types were compared and pseudo-PSK was identified as an excellent candidate given the naturally high input impedance of the tag.
- Reader's architecture was studied and optimized to achieve a sensitivity of -105 dBm @ BER = 10^{-5} & BW = 200 kHz.
- Power management of tag circuits and signal encoding has been carefully studied and proved to be a major issue in the overall performance.
- A 2.45 GHz tag IC, connected to a folded dipole antenna and inductively loaded, led to a measured reading distance of 12 m.
6. Other prospects
Goal:
To obtain a medium operating range between the interrogator and the passive memory tag for a given RF output power of the interrogator and a high data rate.

European IP
Project MINAMI

Read/write data rate: 10Mbit/s
Distance range: 15cm to 30cm
\[ V_{DC} < 3V \quad I_{DC} < 3mA \]
Communication link: 2.4GHz (ISM)
Remote powering: 0.9GHz (ISM)
- The rectifier’s output voltage $V_{rec}$ controls the frequency of the IF signal.
- The reader measures this frequency and adapts the emitted power to stabilize $V_{rec}$ to the desired voltage.

Goals:  - wireless transmission of cortical signals to record neural activity of the brain

Description:  - two parts (inside & outside)
  - power transmission & regulation
  - signals acquisition, sampling and A-D conversion
  - bidirectional data transmission
  - signal processing

Constraints:  - thermal dissipation
  - biological compatibility
  - data rate
• Inductive power link:
  – Geometry optimized for power efficiency
  – Operation frequency at 1MHz
  – Distance between coils 10mm

K.M. Silay, C. Dehollain, M. Declercq, Sensors 2010 Conference
Our Objectives
• Transcutaneous powering by inductive link
• Communication between the prosthesis and outside reader

Challenges
• Low coupling factor of inductive link due to distance between the two coils and limited antenna size
• Relatively high power requirement

Swiss SNF NanoTera Simos Project

Project
• Increase of the life expectancy of the prostheses
• Monitoring of the force, movement of the knee and temperature
Knee prosthesis monitoring by inductive coupling

- **Vertical**
  - There is a distance, which decreases the coupling factor \( k \) between the two coils

- **Horizontal**
  - The implanted coil is larger than the vertical one
  - Better coupling factor
  - Larger reader coil

- **Remote powering**
  depends on \( k^2Q_{Ls1}Q_{Ls2} \)

O. Atasoy and C. Dehollain, PRIME 2010 Conference
Challenges
• Low coupling factor of inductive link due to distance between the two coils and limited antenna size
• Changing coupling factor due to moving mouse

Swiss SNF Sinergia Project

Array of coils under basement of the cage

3D model of array of coils under basement

E. Kilinc, C. Dehollain, F. Maloberti, Conference SM2ACD
Mouse monitoring by magnetic coupling

**Design Parameters Limited by Application**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Link operation frequency (f)</td>
<td>13.56MHz</td>
</tr>
<tr>
<td>Distance between coils (d_{12})</td>
<td>30mm</td>
</tr>
<tr>
<td>Tag coil outer diameter (d_{o2})</td>
<td>20mm</td>
</tr>
<tr>
<td>Minimum spacing between line (s)</td>
<td>150μm</td>
</tr>
<tr>
<td>Minimum width of conductor (w)</td>
<td>150μm</td>
</tr>
</tbody>
</table>

**Optimal Inductive Coil Designs**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Reader</th>
<th>Tag Coil</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer diameter (d_o)</td>
<td>80mm</td>
<td>20mm</td>
</tr>
<tr>
<td>Inner diameter (d_i)</td>
<td>10mm</td>
<td>11mm</td>
</tr>
<tr>
<td>Number of turns (n)</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>Width of conductor (w)</td>
<td>1mm</td>
<td>250μm</td>
</tr>
<tr>
<td>Spacing of lines (s)</td>
<td>7.5mm</td>
<td>600μm</td>
</tr>
</tbody>
</table>

**Comparison Between Analysis and HFSS Simulation Results**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Analysis</th>
<th>Simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reader coil inductance (L_1)</td>
<td>1.075μH</td>
<td>1.002μH</td>
</tr>
<tr>
<td>Tag coil inductance (L_2)</td>
<td>0.90μH</td>
<td>0.75μH</td>
</tr>
<tr>
<td>Reader coil resistance (R_1)</td>
<td>0.597Ω</td>
<td>0.560Ω</td>
</tr>
<tr>
<td>Tag coil resistance (R_2)</td>
<td>0.715Ω</td>
<td>0.740Ω</td>
</tr>
<tr>
<td>Reader coil quality factor (Q_1)</td>
<td>152</td>
<td>156</td>
</tr>
<tr>
<td>Tag coil quality factor (Q_2)</td>
<td>81</td>
<td>85</td>
</tr>
<tr>
<td>Mutual inductance (M_{12})</td>
<td>36.04nH</td>
<td>37.12nH</td>
</tr>
<tr>
<td>Power efficiency (η_{12})</td>
<td>65.5%</td>
<td>66.7%</td>
</tr>
</tbody>
</table>

Other prospect
Back-scattering technique dedicated to wireless communications for communication between the sensor node and the main station. For identification: RFIDs.

Choice of the carrier frequency for communication
- Distance range.
- Data rate.
- Dimensions of the antenna.

Remote powering
- Remotely powered sensor node /RFIDs through the RF wave.
- Rechargeable micro-battery.
- Comparison of advanced technologies.

System level
- Bi-frequency systems.
- Comparison of different types of modulation (e.g. PSK, Pseudo-PSK, ASK).
- Design of the master station called interrogator or reader.

Distance measurement between the sensor node and the main station by backscattering tracking, localization.