Modelling of HF and UHF RFID Technology for System and Circuit Level Simulations

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Outline

1. Background and Methodology
2. Scattering Matrices and S-Parameters
3. Integration into Cadence Spectre
4. Channel Modelling
   - HF-Channel
   - UHF-Channel
5. HF-Systems
   - Maximise Power at Tag
   - A Simplified Model
6. Complete System
   - HF System
   - UHF System
7. Summary
Background and Methodology

- Simulation of RFID-tags within complete system
  - Analysis of system behaviour
  - Stepwise model refinement down to transistor level
- S-parameter models for circuit simulators
- Implementation with Verilog-A
  - Verilog-like syntax
  - Enables modelling of analog quantities
  - Verilog + Verilog-A = Verilog-AMS
- Extension of Verilog-A to wave domain
  - Incident wave $a$
  - Reflected/transmitted wave $b$
- Switch from $a/b$- to $V/I$-plane everywhere in model possible
- Modelling is performed in the appropriate domain
- Wave domain
  - UHF-channel Wave guide circulators, directional coupler, . . .
- $V/I$-domain
  - HF-channel, LC-matching networks, circuits, . . .
Mathematical: Linear transform from voltage and current to incident and reflected wave:

\[ V = V_i + V_r \]
\[ IZ_0 = V_i - V_r \]

Can be seen as: A wave \( V_i \) propagates along a transmission line with a characteristic impedance of \( Z_0 \) towards the port, and a wave \( V_r \) travels away from the port.

The classical two port equations relate the voltages and currents at the ports to each other (\( Z-, Y-, H- \) or \( G- \) Matrix). The scattering matrix relates the incident and reflected waves at the ports to each other:

\[
\begin{pmatrix}
  b_1 \\
  b_2
\end{pmatrix} =
\begin{pmatrix}
  S_{11} & S_{12} \\
  S_{21} & S_{22}
\end{pmatrix}
\begin{pmatrix}
  a_1 \\
  a_2
\end{pmatrix}
\]

mit \( a = \frac{V_i}{\sqrt{Z_0}} \), \( b = \frac{V_r}{\sqrt{Z_0}} \)
Verilog-A enables **multidisziplinary simulations**

**Example:** Mechanically loaded electrical engine and corresponding control electronics

- There are **Nodes** which are related to **Disciplines**
- For each **Discipline** a certain quantity is modelled as flow and a related quantity is modelled as potential

**Examples:**

<table>
<thead>
<tr>
<th>Discipline</th>
<th>Flow</th>
<th>Potential</th>
</tr>
</thead>
<tbody>
<tr>
<td>elektrical</td>
<td>Current</td>
<td>Voltage</td>
</tr>
<tr>
<td>Kinematics</td>
<td>Force</td>
<td>Position</td>
</tr>
<tr>
<td>rotational</td>
<td>Torque</td>
<td>Angle</td>
</tr>
<tr>
<td><strong>Waves</strong></td>
<td><strong>incident</strong></td>
<td><strong>reflected</strong></td>
</tr>
</tbody>
</table>

- The discipline “**Waves**” has been added
Definition of wave quantities

- Flow: Incident wave
- Potential: Reflected wave

Converter from $V/I$ to $a/b$

Potential or flow can be assigned to a branch:

$$b = \frac{V + Z_0 \cdot I}{2\sqrt{Z_0}}$$

$$V = 2\sqrt{Z_0} \cdot a + Z_0 \cdot I$$

Two controlled potential sources
Reflected/transmitted wave of module A represents incident wave of module B und vice versa.

This cannot be accomplished by simple connections.

A special "connection module" is required.

→ Flow-Potential-Converter

Maps reflected/transmitted wave of module A to incident wave of module B.

Consists of two controlled flow sources.

Connection with the controlled potential sources of the "normal" modules does not cause any problems.
The model itself is described the following way (in case of a two port):

\[ b_1 = S_{11}a_1 + S_{12}a_2 \]
\[ b_2 = S_{21}a_1 + S_{22}a_2 \]

This can directly be implemented in Verilog-A:

```
Scattering Matrix Implementation

...  
B(W1Port) <+ laplace_nd(A(W1Port), Num11, Denom11);
B(W1Port) <+ laplace_nd(A(W2Port), Num12, Denom12);
B(W2Port) <+ laplace_nd(A(W1Port), Num21, Denom21);
B(W2Port) <+ laplace_nd(A(W2Port), Num22, Denom22);
```

Can be easily extended to \( N \)-ports
module MutInd (P1, P2, S1, S2);
electrical P1, P2, S1, S2;
branch (P1, P2) Primary;
branch (S1, S2) Secondary;

analog begin
  V(Primary) <+ Lp*ddt(I(Primary)); // Self inductance
  V(Primary) <+ M*ddt(I(Secondary)); // Mutual inductance
  V(Primary) <+ Rp*I(Primary); // Wire resistance
  V(Secondary) <+ Ls*ddt(I(Secondary)); // Self inductance
  V(Secondary) <+ M*ddt(I(Primary)); // Mutual inductance
  V(Secondary) <+ Rs*I(Secondary); // Wire resistance
end
endmodule
module channel(w1,w2,w3);
wave w1,w2,w3;
...

analog begin
  aF = -147.6 + 20*log(distance) + 20*log(freq) - 10*log(GT) - 10*log(GR);
  s = pow(10,(-aF/20));
  B(wreader) <+ s*A(wtransponder) + A(wnoise);
  B(wtransponder) <+ s*A(wreader) + A(wnoise);
end
endmodule

module Wavedelay(win,wout);
wave win,wout;
...

analog begin

  B(win) <+ absdelay(A(win),td);
  B(wout) <+ absdelay(A(wout),td);
end
endmodule
Available Power at Tag

\[ P_t = \frac{|V_t|^2}{4 \cdot \Re\{Z_t\}} = P_s \cdot \frac{R_s \omega^2 k^2 L_1 L_2}{R_2 \left( (R_s + R_1)^2 + (X_s + \omega L_1)^2 \right) + \omega^2 k^2 L_1 L_2 (R_s + R_1)} \]

\( P_s \): Maximum available power from interrogator

How to design the matching network of the reader antenne in order to maximise \( P_t \)?

\[ \frac{\partial P_t}{\partial R_s} = \frac{\partial P_t}{\partial X_s} = 0 \quad \Rightarrow \]

Ideal source impedance for given \( P_s \)

\[ R_{s,\text{opt}} = \sqrt{R_1^2 + \omega^2 k^2 L_1 L_2} \frac{R_1}{R_2} \]

\[ X_{s,\text{opt}} = -\omega L_1 \]
With **optimally matched** Interrogator:

\[
Z_t^* = R_2 + \frac{\omega^2 k^2 L_1 L_2}{R_1 + \sqrt{R_1^2 + \omega^2 k^2 L_1 L_2 R_1 R_2}} - j\omega L_2
\]

This is the impedance which the tag has to exhibit in order to transfer maximal power to it.

Generally, the coupling \( k \) is not known **a priori**. Nevertheless, for weak coupling

\[
Z_t^* \approx R_2 - j\omega L_2
\]

can be assumed.

Correspondingly, the **ideal source impedansce** can be approximated by

\[
Z_{s,\text{opt}} \approx R_1 - j\omega L_1.
\]
## Comparison: Opt. Solution vs. Other Cases

Driver 5 V, 3 Ω, 13.56 MHz; $Q = 20$; $R_2 = 4 \Omega$; $L_1 = L_2 = 2 \mu\text{H}$; Voltage at $R_L$ (V):

### $R_L = 1 \text{kΩ}$

<table>
<thead>
<tr>
<th></th>
<th>$k = 10.0%$</th>
<th>$k = 5.0%$</th>
<th>$k = 1.0%$</th>
<th>$k = 0.5%$</th>
<th>$k = 0.1%$</th>
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<tbody>
<tr>
<td>1)</td>
<td>32.61</td>
<td>24.06</td>
<td>6.53</td>
<td>3.31</td>
<td>0.67</td>
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<tr>
<td>2)</td>
<td>29.05</td>
<td>23.18</td>
<td>6.52</td>
<td>3.31</td>
<td>0.67</td>
</tr>
<tr>
<td>3)</td>
<td>29.05</td>
<td>23.18</td>
<td>6.52</td>
<td>3.31</td>
<td>0.67</td>
</tr>
<tr>
<td>4)</td>
<td>21.28</td>
<td>21.73</td>
<td>6.52</td>
<td>3.31</td>
<td>0.67</td>
</tr>
<tr>
<td>5)</td>
<td>30.46</td>
<td>19.37</td>
<td>4.32</td>
<td>2.17</td>
<td>0.43</td>
</tr>
<tr>
<td>6)</td>
<td>28.69</td>
<td>19.24</td>
<td>4.32</td>
<td>2.17</td>
<td>0.43</td>
</tr>
</tbody>
</table>

### $R_L = 10 \text{kΩ}$

<table>
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<tr>
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<th>$k = 10.0%$</th>
<th>$k = 5.0%$</th>
<th>$k = 1.0%$</th>
<th>$k = 0.5%$</th>
<th>$k = 0.1%$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1)</td>
<td>103.12</td>
<td>76.07</td>
<td>20.63</td>
<td>10.48</td>
<td>2.11</td>
</tr>
<tr>
<td>2)</td>
<td>91.85</td>
<td>73.30</td>
<td>20.63</td>
<td>10.48</td>
<td>2.11</td>
</tr>
<tr>
<td>3)</td>
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</tr>
<tr>
<td>5)</td>
<td>85.35</td>
<td>69.57</td>
<td>20.30</td>
<td>10.33</td>
<td>2.08</td>
</tr>
<tr>
<td>6)</td>
<td>59.96</td>
<td>64.30</td>
<td>20.30</td>
<td>10.33</td>
<td>2.08</td>
</tr>
</tbody>
</table>

1) Opt. Solution
2) Tag matched to $R_2 + j\omega L_2$, Interrogator perfectly matched
3) Interrogator matched to $R_1 + j\omega L_1$, Tag perfectly matched
4) Interrogator matched to $R_1 + j\omega L_1$, Tag matched to $R_2 + j\omega L_2$
5) Tag: Capacitor $C_r = 1/(\omega^2 L_2)$, Interrogator perfectly matched
6) Interrogator matched to $R_1 + j\omega L_1$, Tag: Capacitor $C_r = 1/(\omega^2 L_2)$
Neglecting the effect on the interrogator antenna yields the following equivalent circuit for the tag antenna:

\[ V_{t0} = j\omega k \sqrt{L_1 L_2} I_1 \]

Comparison of this model with the previous results (given in parantheses):

\[
\begin{array}{cccccc}
\text{RL} &=& 1 \text{k}\Omega \\
\hline
k &=& 10.0 \% & 5.0 \% & 1.0 \% & 0.5 \% & 0.1 \% \\
4) &=& 66.62 (21.28) & 33.31 (21.73) & 6.66 (6.52) & 3.33 (3.31) & 0.67 (0.67) \\
6) &=& 43.45 (28.6) & 21.73 (19.24) & 4.35 (4.32) & 2.17 (2.17) & 0.43 (0.43) \\
\hline
\text{RL} &=& 10 \text{k}\Omega \\
\hline
k &=& 10.0 \% & 5.0 \% & 1.0 \% & 0.5 \% & 0.1 \% \\
4) &=& 210.65 (67.3) & 105.33 (68.73) & 21.1 (20.63) & 10.53 (10.48) & 2.11 (2.11) \\
6) &=& 207.97 (59.96) & 103.99 (64.3) & 20.8 (20.3) & 10.4 (10.33) & 2.08 (2.08)
\end{array}
\]
Channel $u_{tp}(t)$

Demodulated Subcarrier $u_{sc}(t)$

Mixed Model: System and Circuit Level
Voltage Supply, Modulator and Clock Recovery

Supply Voltage $V_{DD}$

Modulation Signal

Clock Recovery

Clock: $CLK, \overline{CLK}$
Simulation of Clock Recovery (within Complete System)

![Simulation Diagram]

- **CLK (V) vs Time (µs)**: A periodic signal indicating clock recovery.
- **CLK (V) vs Time (µs)**: An inverted clock signal for comparison.
- **Antenna Voltage (V) vs Time (µs)**: A waveform showing the antenna voltage response.
- **Antenna Voltage (V) vs Time (µs)**: Another waveform illustrating antenna voltage during modulation.

Modulation starts at 46.6 µs.
Code Generation for Simple Read-Only Tag

Manchester Coding

Generated Code

<p>| | | | | |</p>
<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>0010</td>
<td>1001</td>
<td>0001</td>
<td>0000</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>9</td>
<td>1</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>
Simulation of the Model ($k = 0.5\%$)

Data (V)

Supply (V)

Antenna Vtg. (V)

$\propto u_{sc}(t)$

Time ($\mu$s)
Tag currently realised as behavioural model

Modelling performed almost completely in wave domain

Enables automatic extraction of system features

- e.g. Bit Error Rate BER
- Analysis performed within “real” environment
Simulation of the Model: Modulation

- **Data**: Transition "0" to "1"
- **Reflected Wave from Tag**
- **Circulator: Transmitted Wave @ Port 3**
- **Voltage @ LNA**
Simulation of the Model: Demodulation

Data from Tag

After Demodulation @ Interrogator
Summary

- Background: Simulation of RFID-Tags within complete system
- Theoretical analysis of HF-channel
  - Maximum transferrable power
  - Comparison of different designs
  - Neglecting the effect on the interrogator antenna yields a simplified model
- Mixed modelling enables stepwise model refinement
- Verilog-A is a good opportunity to use these models within conventional circuit simulators
- Mixed system and circuit model of an HF system
- Extension of Verilog-A by wave domain
- System model of an UHF system
Thank You