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

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# Outline

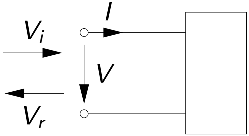
# Background and Methodology

- 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, ...

# Brief Review: Scattering Matrix/S-Parameters

Mathematical: Linear transform from voltage and current to incident and reflected wave:

$$\begin{aligned} V &= V_i + V_r \\ IZ_0 &= V_i - V_r \end{aligned}$$



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:

$$\begin{pmatrix} b_1 \\ b_2 \end{pmatrix} = \begin{pmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{pmatrix} \begin{pmatrix} a_1 \\ a_2 \end{pmatrix} \quad \text{mit} \quad a = \frac{V_i}{\sqrt{Z_0}}, \quad b = \frac{V_r}{\sqrt{Z_0}}$$

# Scattering Matrices and S-Parameters in Verilog-A (I)

- 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:

| Discipline | Flow | Potential |
|---|---|---|
| elektrical | Current | Voltage |
| Kinematics | Force | Position |
| rotational | Torque | Angle |
| **Waves** | **incident** | **reflected** |

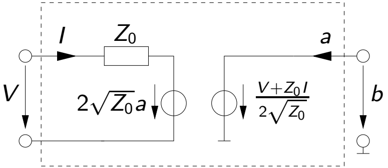
- The discipline "Waves" has been added

# Scattering Matrices and S-Parameters in Verilog-A (II)

- Definition of wave quantities
    - Flow: Incident wave
    - Potential: Reflected wave

**mydisciplines.vams**

```
nature IncidentWave
units = “V/sqrt(Ohm)”;
access = A;
endnature

nature ReflectedWave
units = “V/sqrt(Ohm)”;
access = B;
endnature

discipline waves
potential ReflectedWave;
flow IncidentWave;
enddiscipline
```



- 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

# Flow-Potential-Converter

- 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

**Flow-Potential-Converter**

```
module FPX (W1, W2);
waves W1, W2;
branch (W1) W1port;
branch (W2) W2port;

analog begin
A(W1port) <+ −B(W2port);
A(W2port) <+ −B(W1port);
end
endmodule
```

# The Model itself

- The model itself is described the following way (in case of a two port):

$$\begin{aligned} b_1 &= S_{11}a_1 + S_{12}a_2 \\ b_2 &= S_{21}a_1 + S_{22}a_2 \end{aligned}$$

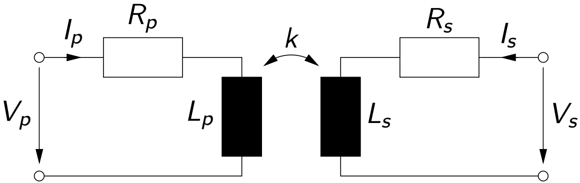
- This can directly be implemented in Verilog-A:

### 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

# HF-Channel



## HF-Channel

```
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
```

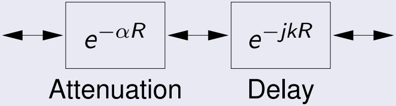
# UHF-Channel

## UHF-Channel

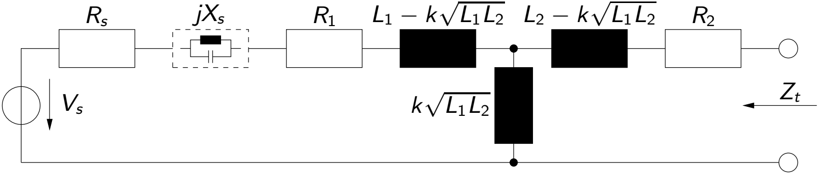
```
module channel(w1,w2,w3);

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(wout) <+ absdelay(A(win),td);
    B(win) <+ absdelay(A(wout),td);
end

endmodule
```



# HF-Systems: Maximise Power at Tag (I)



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 $P_t$?

$$\frac{\partial P_t}{\partial R_s} = \frac{\partial P_t}{\partial X_s} = 0 \qquad \Rightarrow$$

**Ideal source impedance for given $P_s$**

$$\begin{aligned} R_{s,opt} &= \sqrt{R_1^2 + \omega^2 k^2 L_1 L_2 \frac{R_1}{R_2}} \\ X_{s,opt} &= -\omega L_1 \end{aligned}$$

# HF-Systems: Maximise Power at Tag (II)

With optimally matched Interrogator:

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

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

$$Z_{s,opt} \approx R_1 - j\omega L_1.$$

# Comparison: Opt. Solution vs. Other Cases

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

$R_L = 1\,\mathrm{k}\Omega$

|  | $k = 10.0\,\%$ | $k = 5.0\,\%$ | $k = 1.0\,\%$ | $k = 0.5\,\%$ | $k = 0.1\,\%$ |
|---|---|---|---|---|---|
| 1) | 32.61 | 24.06 | 6.53 | 3.31 | 0.67 |
| 2) | 29.05 | 23.18 | 6.52 | 3.31 | 0.67 |
| 3) | 29.05 | 23.18 | 6.52 | 3.31 | 0.67 |
| 4) | 21.28 | 21.73 | 6.52 | 3.31 | 0.67 |
| 5) | 30.46 | 19.37 | 4.32 | 2.17 | 0.43 |
| 6) | 28.6 | 19.24 | 4.32 | 2.17 | 0.43 |

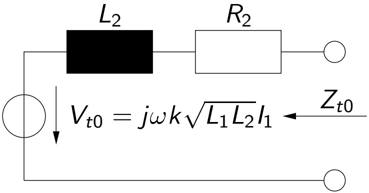
$R_L = 10\,\mathrm{k}\Omega$

|  | $k = 10.0\,\%$ | $k = 5.0\,\%$ | $k = 1.0\,\%$ | $k = 0.5\,\%$ | $k = 0.1\,\%$ |
|---|---|---|---|---|---|
| 1) | 103.12 | 76.07 | 20.63 | 10.48 | 2.11 |
| 2) | 91.85 | 73.3 | 20.63 | 10.48 | 2.11 |
| 3) | 91.85 | 73.3 | 20.63 | 10.48 | 2.11 |
| 4) | 67.3 | 68.73 | 20.63 | 10.48 | 2.11 |
| 5) | 85.35 | 69.57 | 20.3 | 10.33 | 2.08 |
| 6) | 59.96 | 64.3 | 20.3 | 10.33 | 2.08 |

1) Opt. Solution
2) Tag matched to $R_2 + j\omega L_2$, Interrogatorï¿$\frac{1}{2}$ 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 $C_r = 1/(\omega^2 L_2)$

# Simplified Model

Negelcting the effect on the interrogator antenna yields the following equivalent circuit for the tag antenna



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

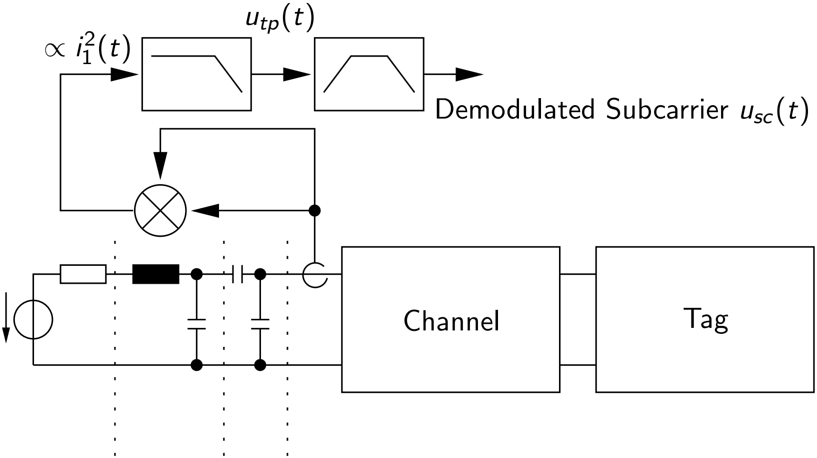
$R_L = 1\,\mathrm{k\Omega}$

| | $k = 10.0\,\%$ | $k = 5.0\,\%$ | $k = 1.0\,\%$ | $k = 0.5\,\%$ | $k = 0.1\,\%$ |
|---|---|---|---|---|---|
| 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) |

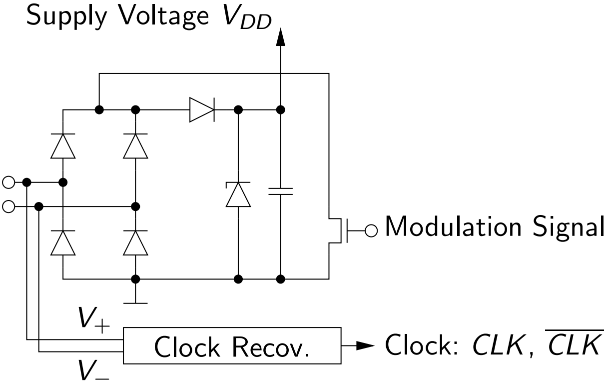
$R_L = 10\,\mathrm{k\Omega}$

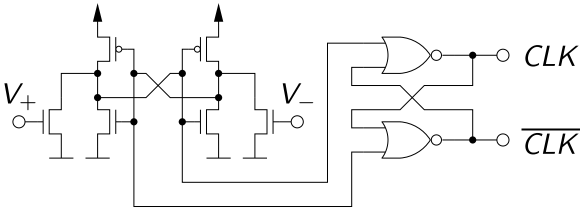
| | $k = 10.0\,\%$ | $k = 5.0\,\%$ | $k = 1.0\,\%$ | $k = 0.5\,\%$ | $k = 0.1\,\%$ |
|---|---|---|---|---|---|
| 4) | 210.65 (67.3) | 105.33 (68.73) | 21.1 (20.63) | 10.53 (10.48) | 2.11 (2.11) |
| 6) | 207.97 (59.96) | 103.99 (64.3) | 20.8 (20.3) | 10.4 (10.33) | 2.08 (2.08) |

# Mixed Model: System and Circuit Level

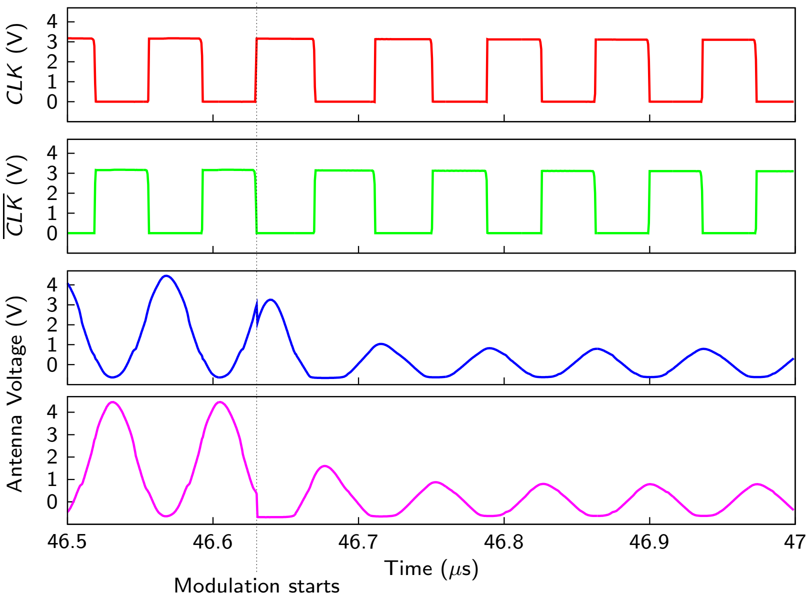


# Voltage Suppy, Modulator and Clock Recovery

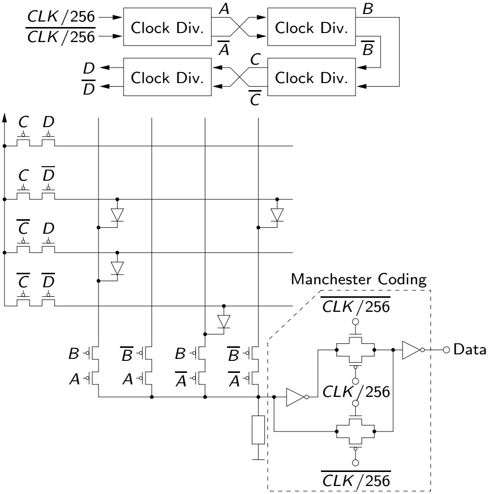


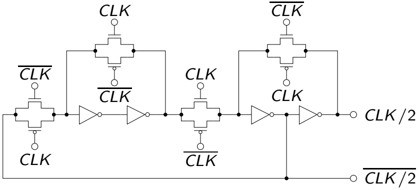


# Simulation of Clock Recovery (within Complete System)



# Code Generation for Simple Read-Only Tag

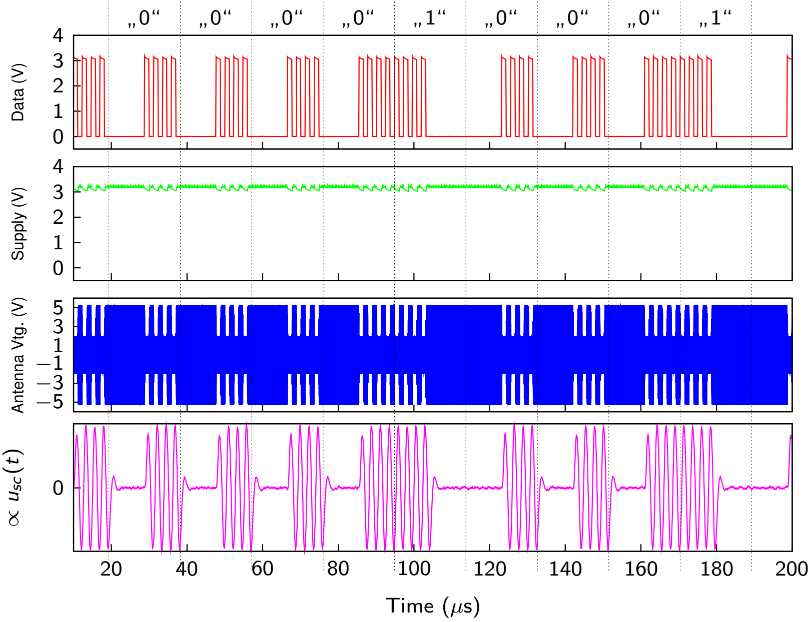




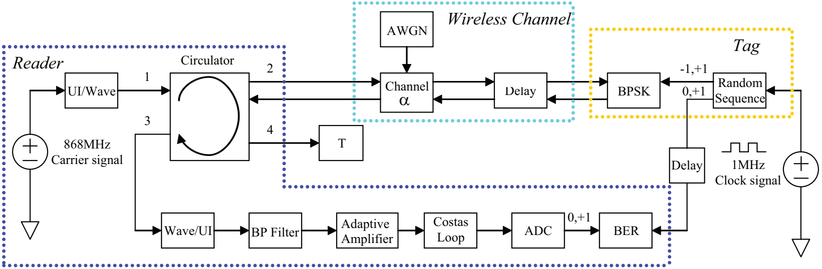
## Generated Code

| | | | |
|---|---|---|---|
| 0010 | 1001 | 0001 | 0000 |
| 2 | 9 | 1 | 0 |

# Simulation of the Model ($k = 0.5\,\%$)

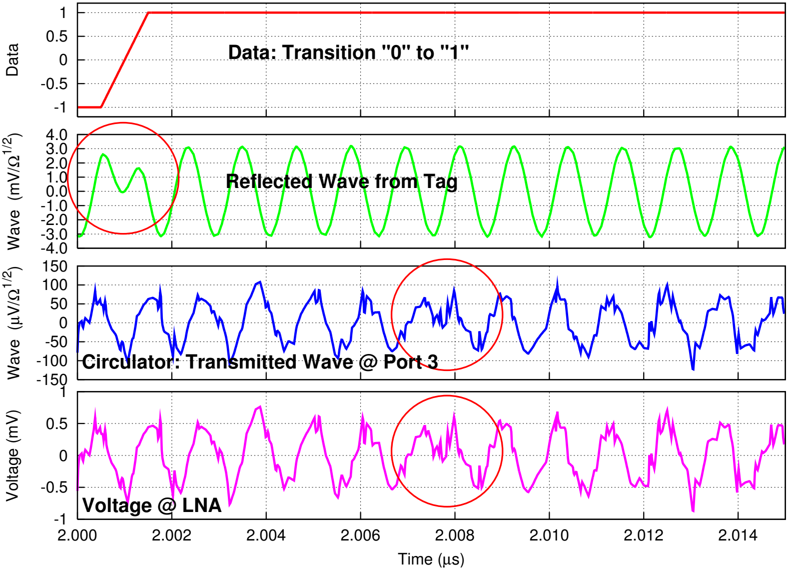


# System Model of UHF-Tag

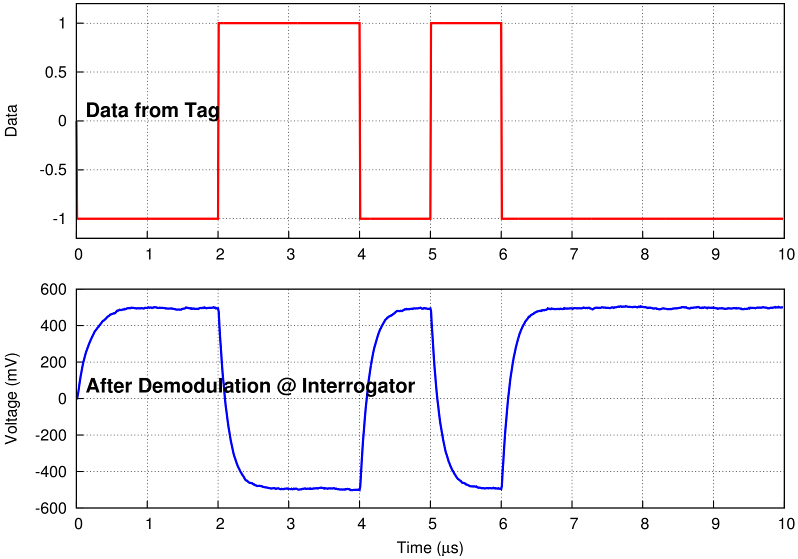


- Tag currently realised as behavioural model
- Modelling performed almost completely in wave domain
- Enables automatic extraction of system features
  - e.g. Bit Error Rate BER
  - Analysis performed within “real” environment

# Simulation of the Model: Modulation



# Simulation of the Model: Demodulation



# Summary

- Background: Simulation of RFID-Tags within complete system
- Theoretical analysis of HF-channel
  - Maximum transferrable power
  - Comparison of differnt 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

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? Thank You !

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