Design and Optimization of Remotely powered RFID Systems and Sensor Nodes

Dr. Catherine Dehollain

Ecole Polytechnique Fédérale de Lausanne (EPFL)
RFIC Group
CH-1015 Lausanne, Switzerland
http://rfic.epfl.ch

OUTLINE

Introduction

Wireless Power Transmission

Communication Issues

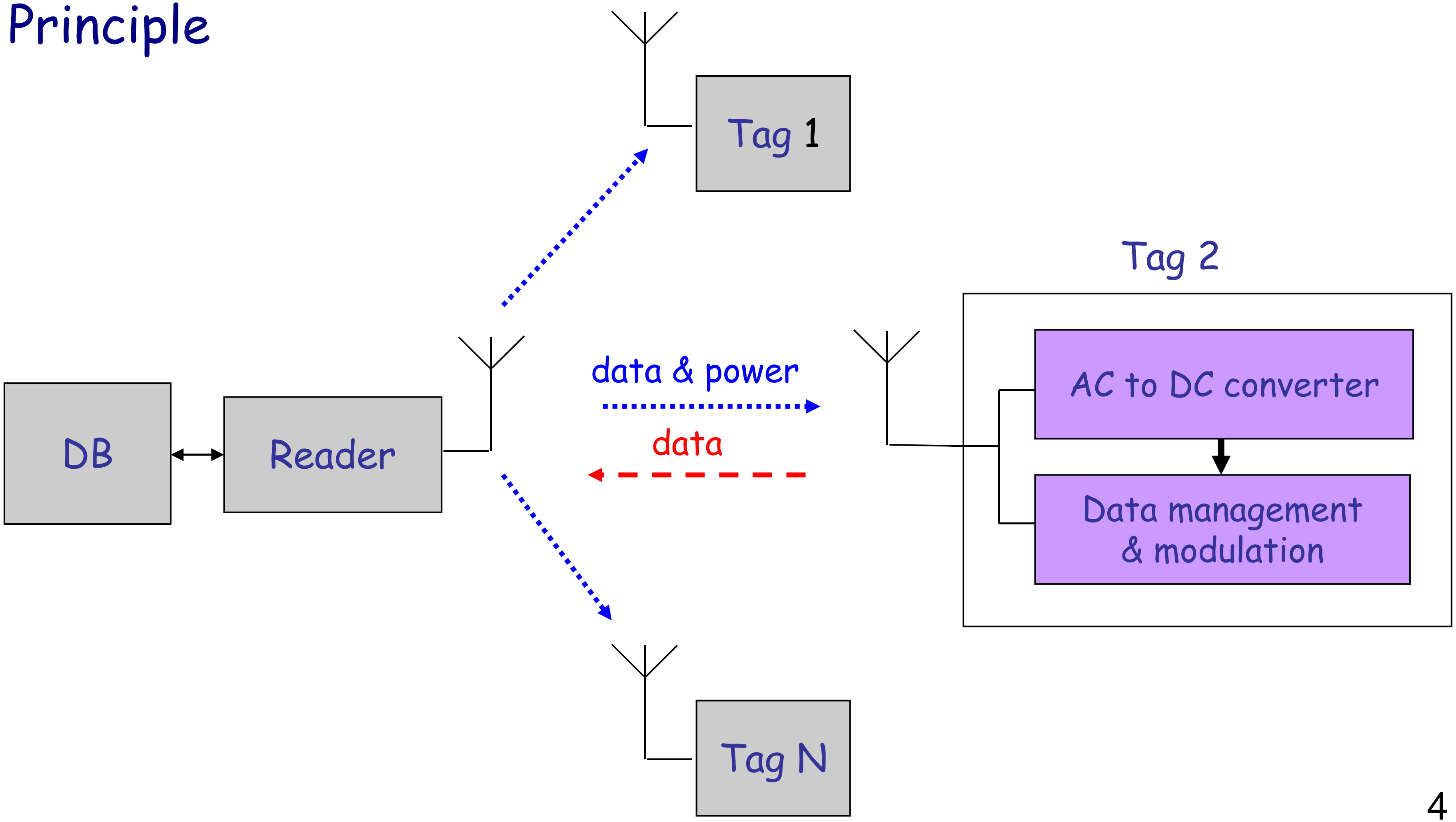
Transponder (tag) and Reader Design

Summary on RFID at long distance

Prospects

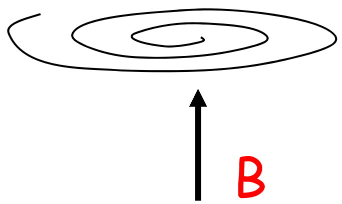
1. INTRODUCTION

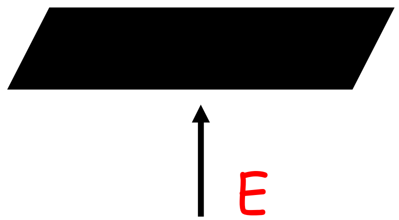
Principle


Tag 1
Tag 2
AC to DC converter
Data management & modulation
data & power
data
DB
Reader
Tag N

Near-field (low frequency applications, up to 100 MHz)

- Starts in the direct neighborhood of any antenna up to d = $\dfrac{\lambda}{2\pi}$
- 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 λ^{6}.





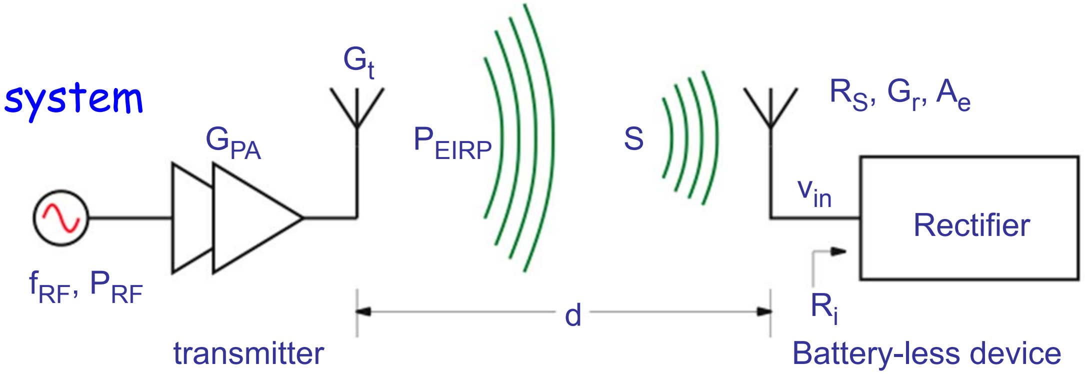
Far-field (high frequency applications, from 100 MHz)

- 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 λ^2.
- Link budget is a function of d^{-4} and λ^4.

Wireless Power Transmission (WPT) in UHF passive systems

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

Typical WPT system



- 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: $P_{AV} = A_E . S$

With Antenna Aperture $A_E = \frac{\lambda^2}{4\pi} . G_R$

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

For

λ = 0,1224 m (2,45 GHz)

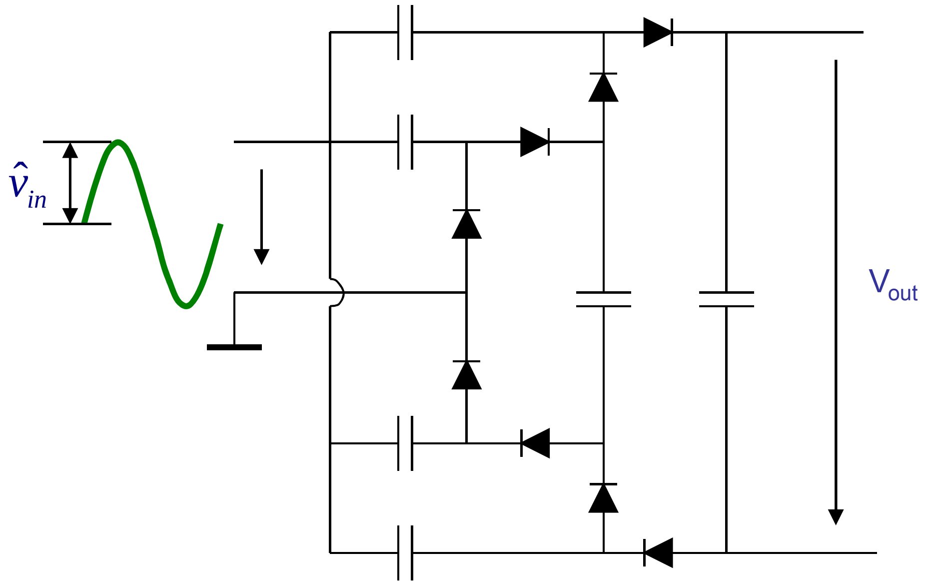
P_{EIRP} = 4 W

G_R = 1 (0 dB): Antenna gain

d(m)	P_{AV}(W)
1 m	379 µW
5 m	15.17 µW
10 m	3.79 µW
12 m	2.6 µW

2. Wireless Power Transmission

Rectifier Circuit (2 stage Greinacher)



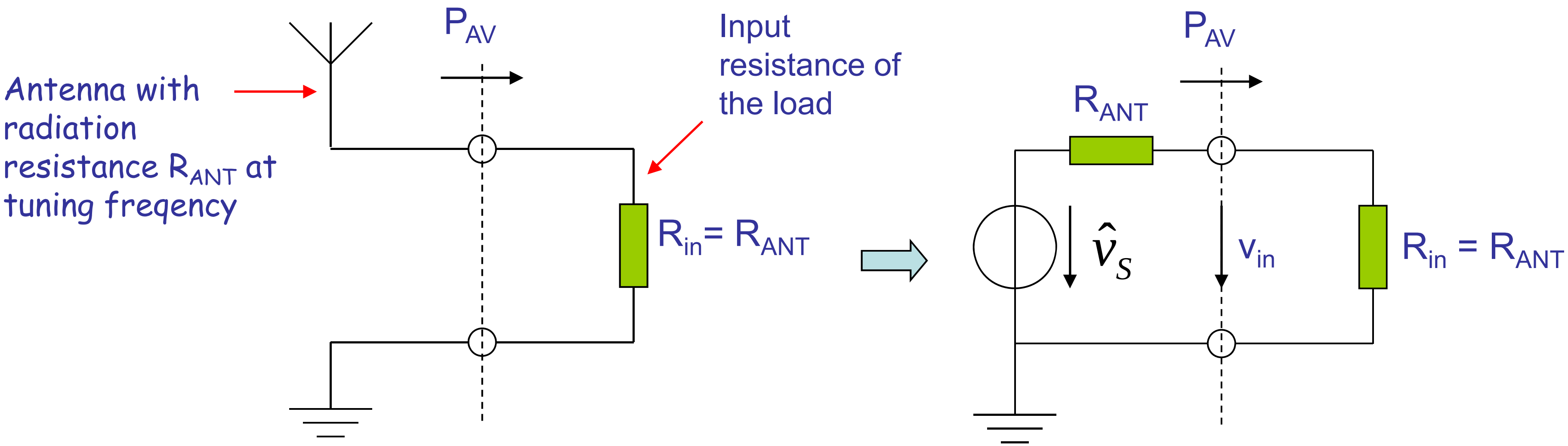
$$V_{out} = 4N\hat{v}_{in}$$

Where N is the number of stages

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

Antenna Model



$$P_{AV} = \frac{\hat{v}_{in}^2}{2R_{in}} \rightarrow$$ At load matching conditions ($R_{ANT} = R_{IN}$)

$$\hat{v}_S = 2\hat{v}_{in} = 2\sqrt{2.P_{AV}.R_{ANT}}$$

catherine.dehollain@epfl.ch

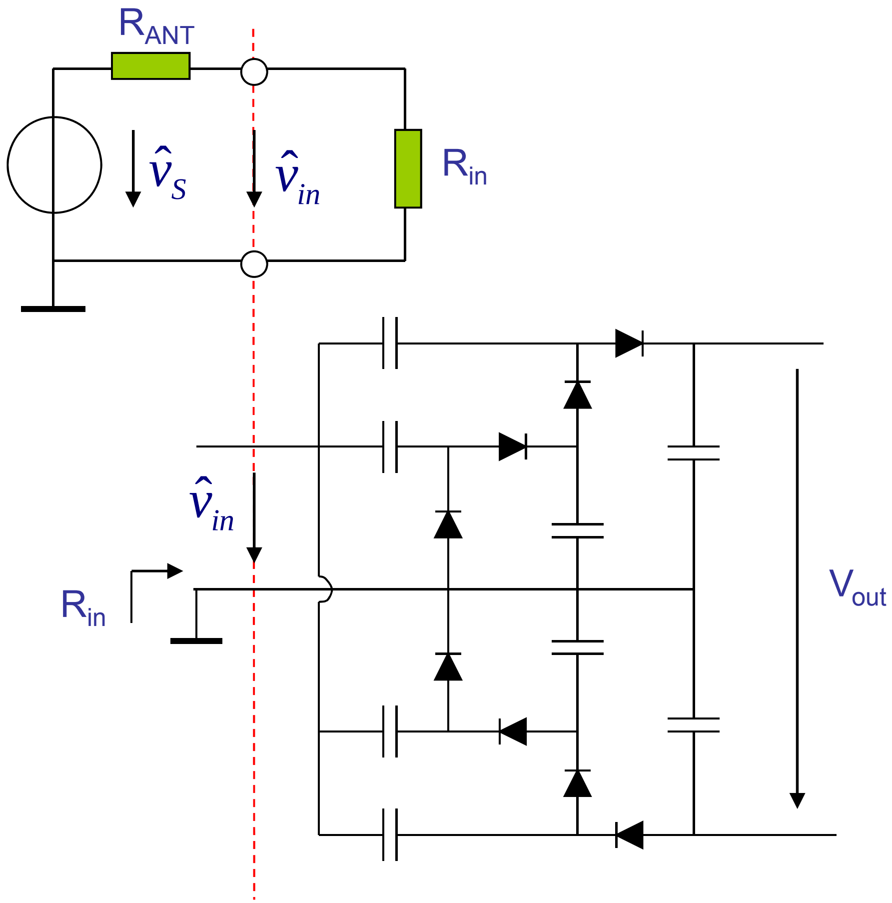
Rectifier input voltage: influence of R_{in}

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

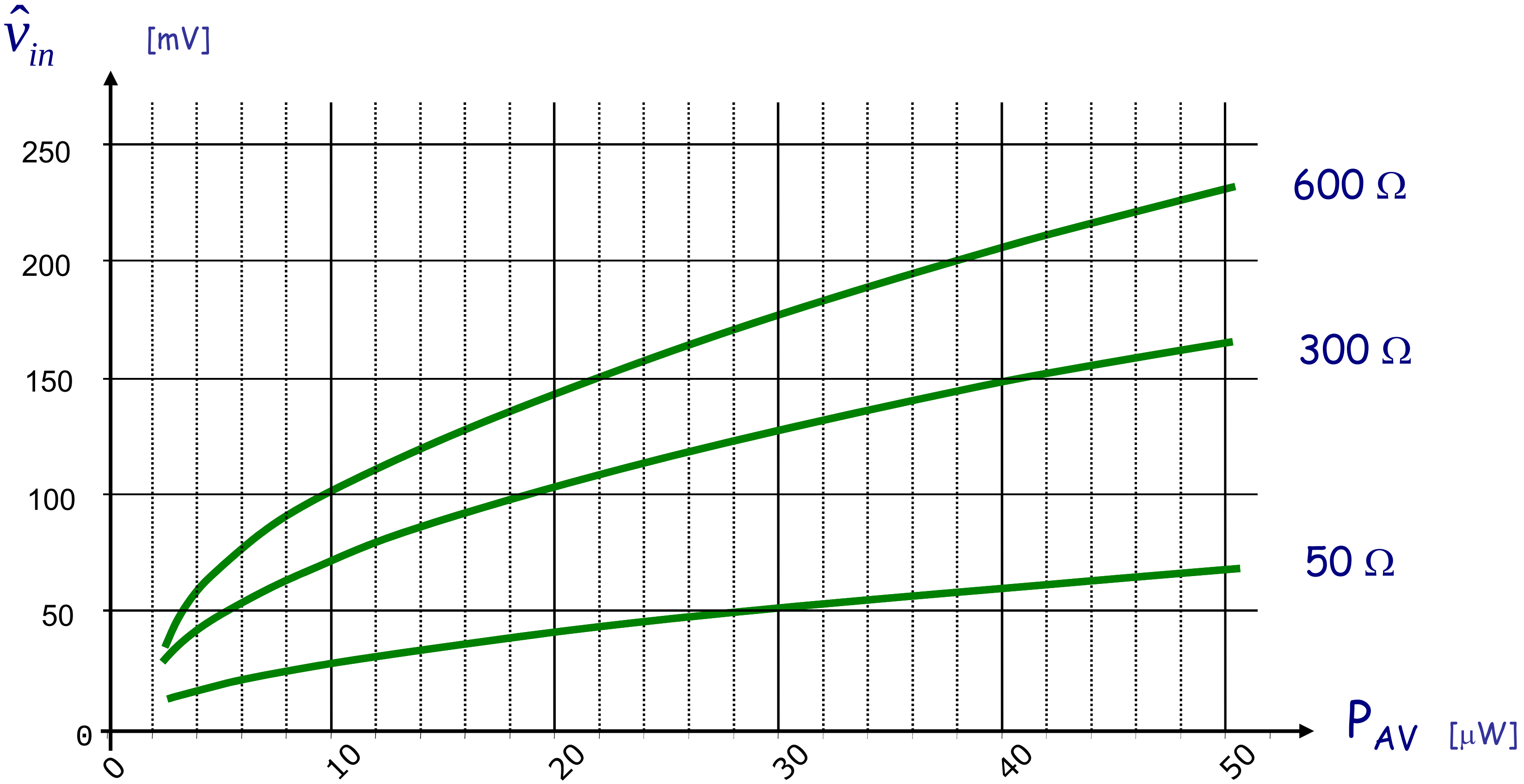
$$\hat{v}_{in} = 2\sqrt{2P_{AV}R_{ant}}\,\frac{R_{in}}{R_{in}+R_{ant}}$$

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

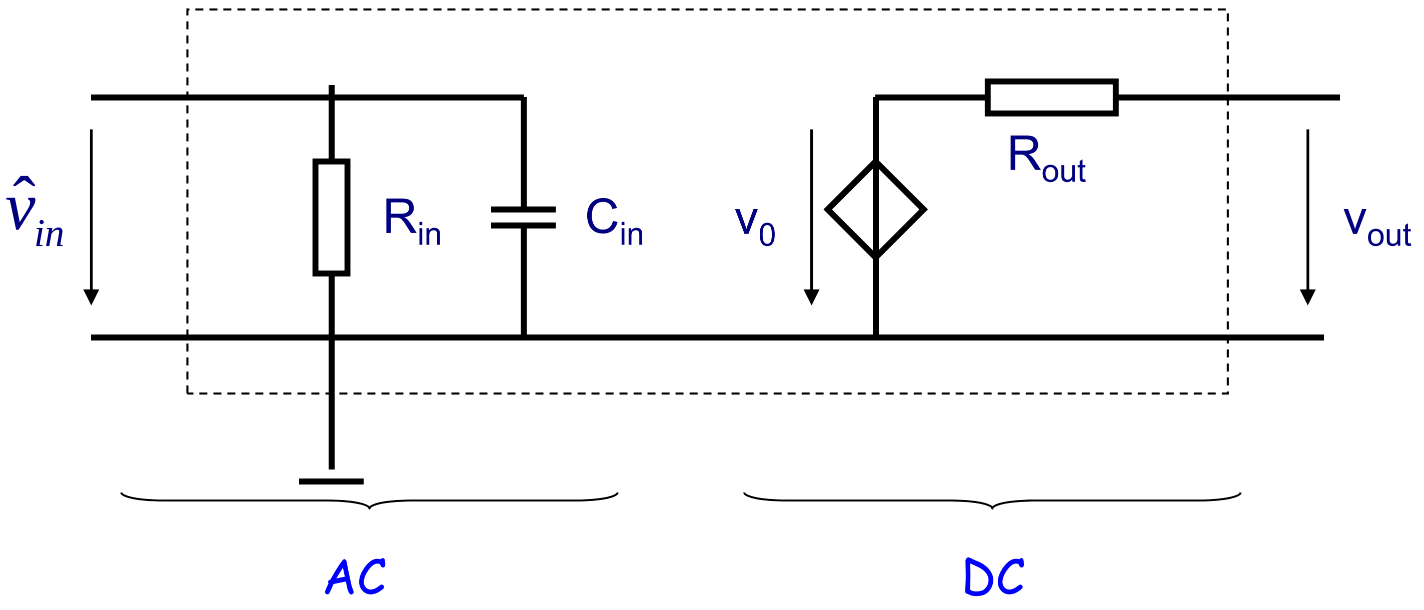
- Maximize R_{ant}
- Keep R_{in} equal to R_{ant}



Rectifier input voltage for $R_{ANT} = R_{in}$



Rectifier Equivalent Circuit Model



catherine.dehollain@epfl.ch

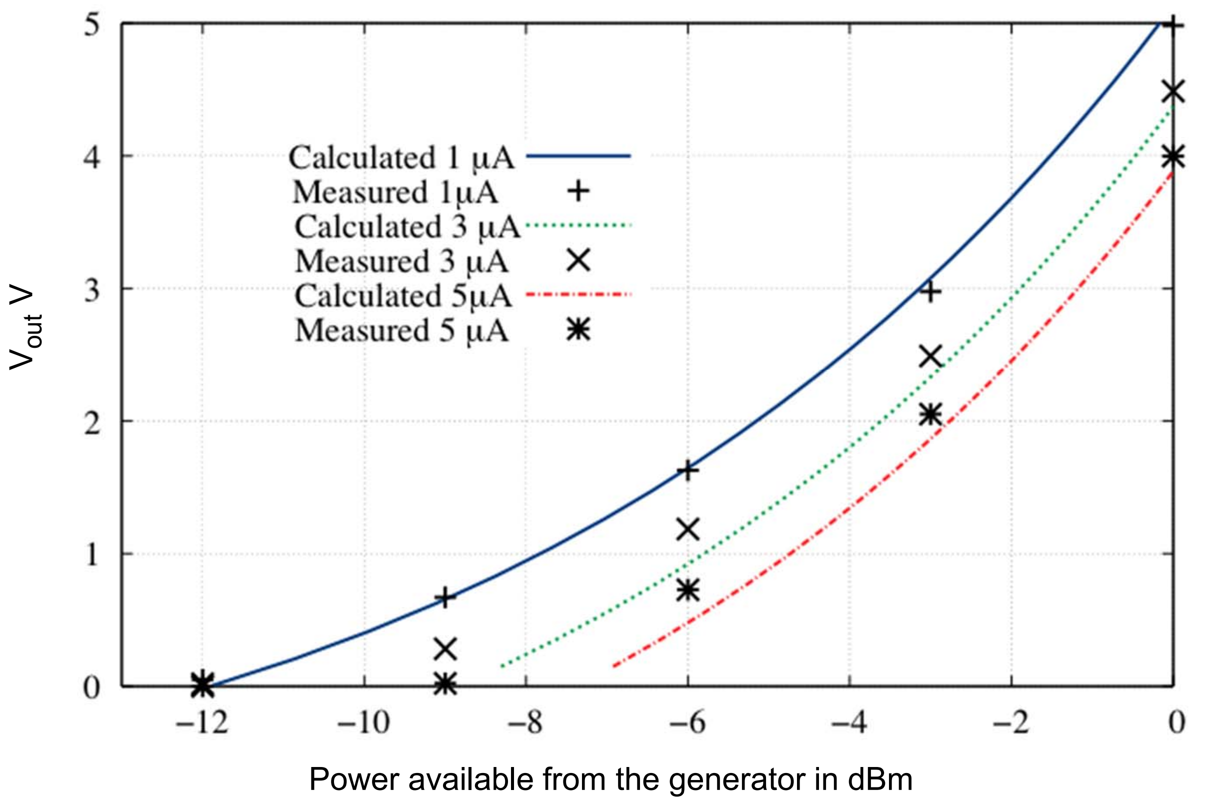
Assumptions

- 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

J.P. Curty, N. Joehl, F. Krummenacher, C. Dehollain and M. Declercq,
"A model for micro-power rectifier analysis and design",
IEEE Transactions on Circuits and Systems I, Vol. 52, no 12, Dec. 2005, pp. 2771-2779.

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

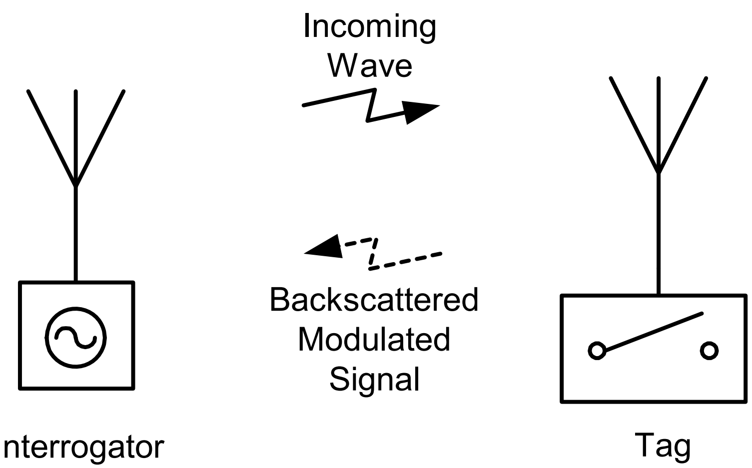
as a function of:

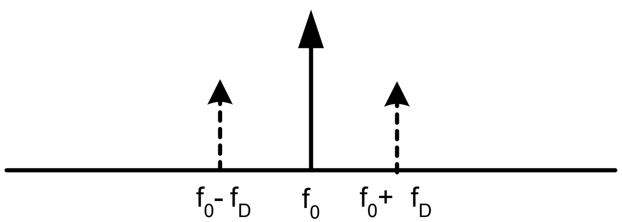
- The DC output Power / Current
- The antenna radiation resistance (R_{ant})
- The available power P_{AV} at the antenna
- The characteristics of the MOS diodes

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.





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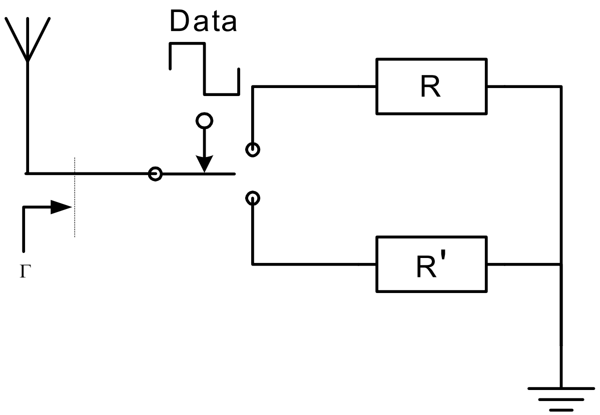
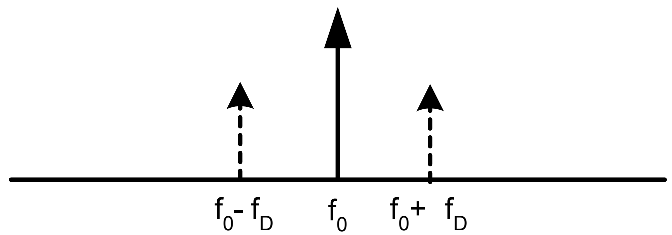
- If Data = Bit “1” :
  - Zin = R’ is mismatched to the tag antenna.
  - All the power of the RF incoming signal is reflected to the interrogator.
- If Data = Bit “0” :
  - Zin = R is matched to the tag antenna.
  - All the power of the RF incoming signal is absorbed by the tag.

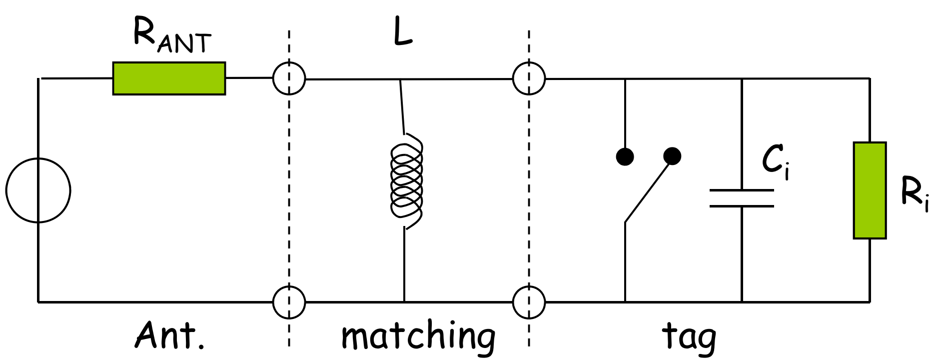


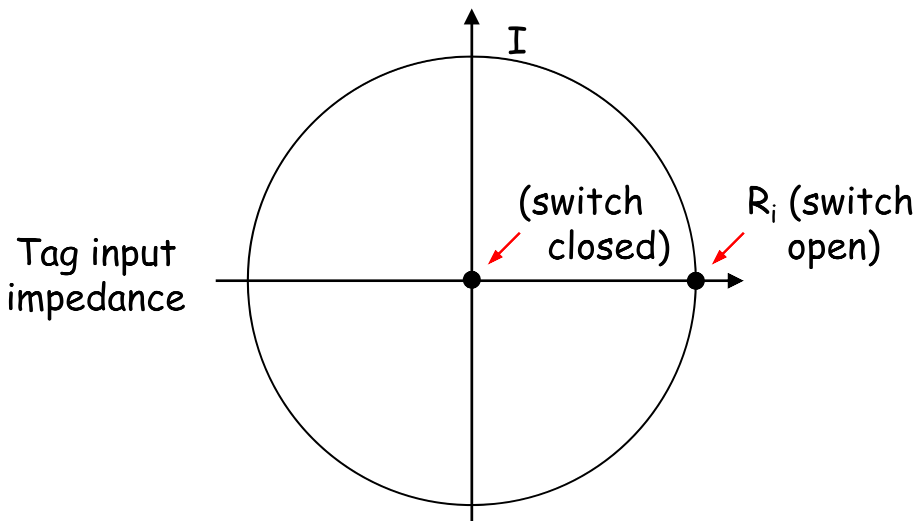


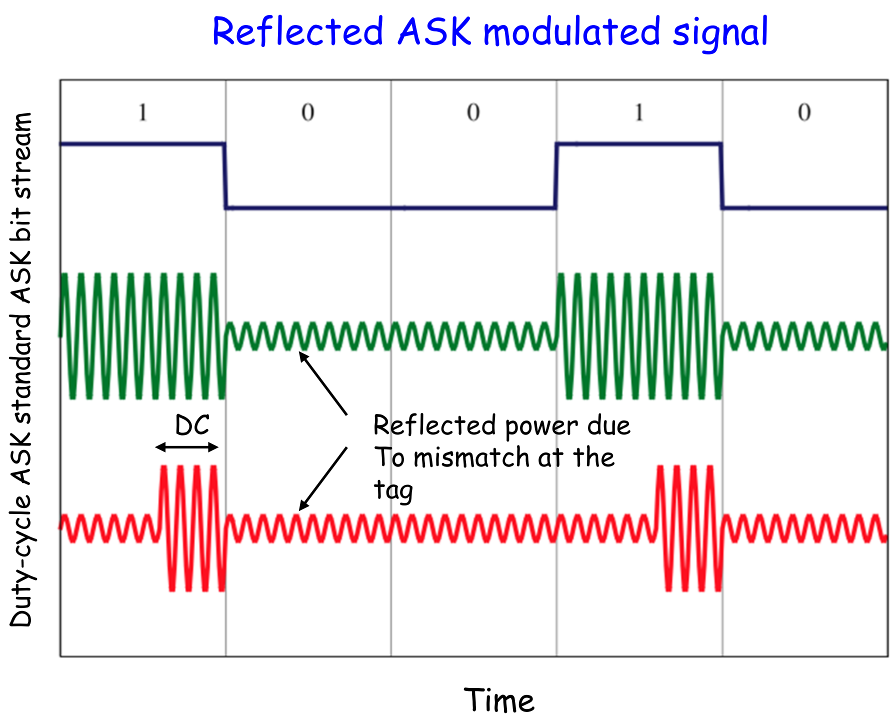
Backscattering communication

IEEE CAS Conference, C. Dehollain et al, 2001

ASK modulation

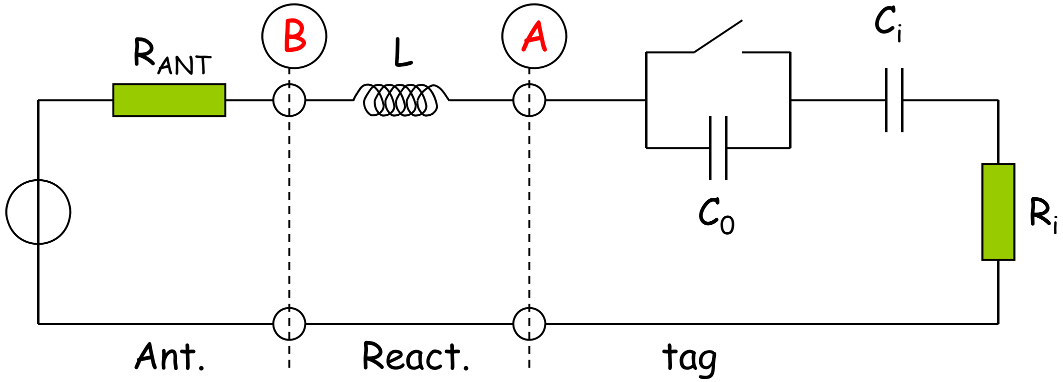






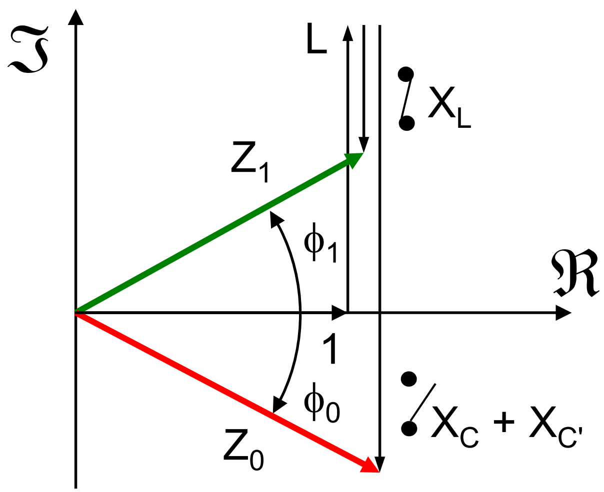
Bit « 1 »: switch closed
Bit « 0 »: switch open

PSK modulation



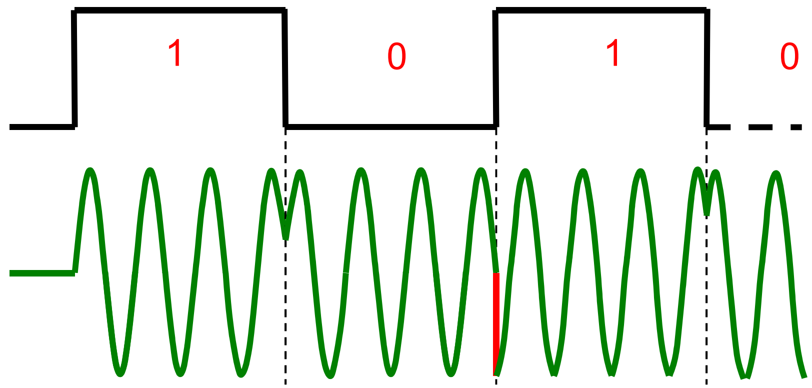
In B: Absorbed power and reflected power are constant

In A: Voltage at tag input is however not constant



State 1
Switch closed

State 0
Switch open



Tag input impedance at B

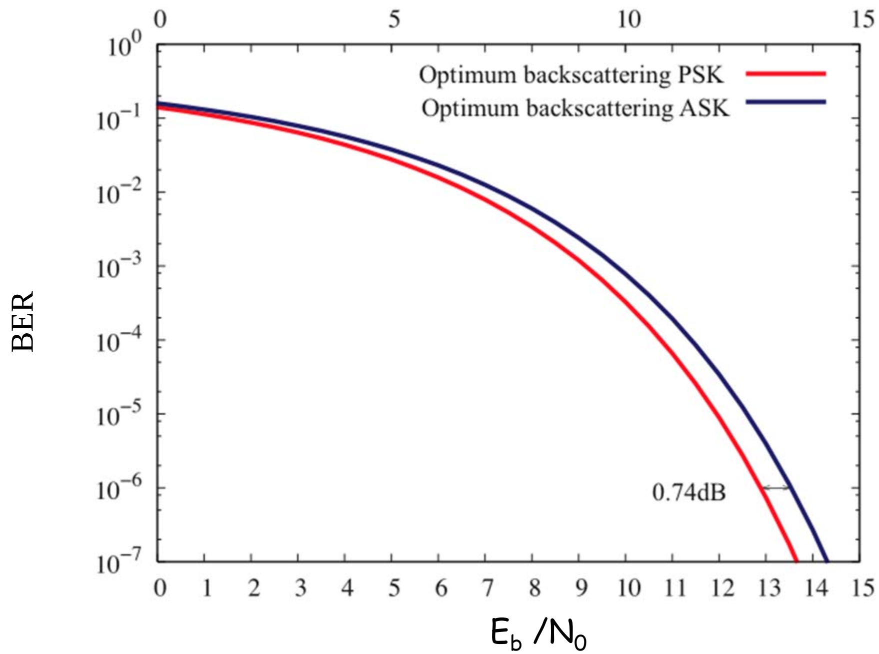
ASK / PSK Comparison through the BER

E_b = Average Energy per bit
N_0 = Noise level at receiver input
α = R_i / R_{ANT}
Q = tag input series Quality factor $1/\omega.R_i.C_i$
DC = Modulation Duty Cycle

J.P. Curty, M. Declercq, C. Dehollain, N. Joehl
Book: « Design and Optimization of Passive UHF RFID Systems »
Editor Springer, year 2007, ISBN: 0-387-35274-0.

ASK / PSK Comparison

BER for ASK and PSK in similar conditions



Optimal ASK and PSK BER comparison
(ASK: DC = 100%, α = 1 and PSK: α = 1, Qin = 5.6)

Tag input impedance for long-distance RFID

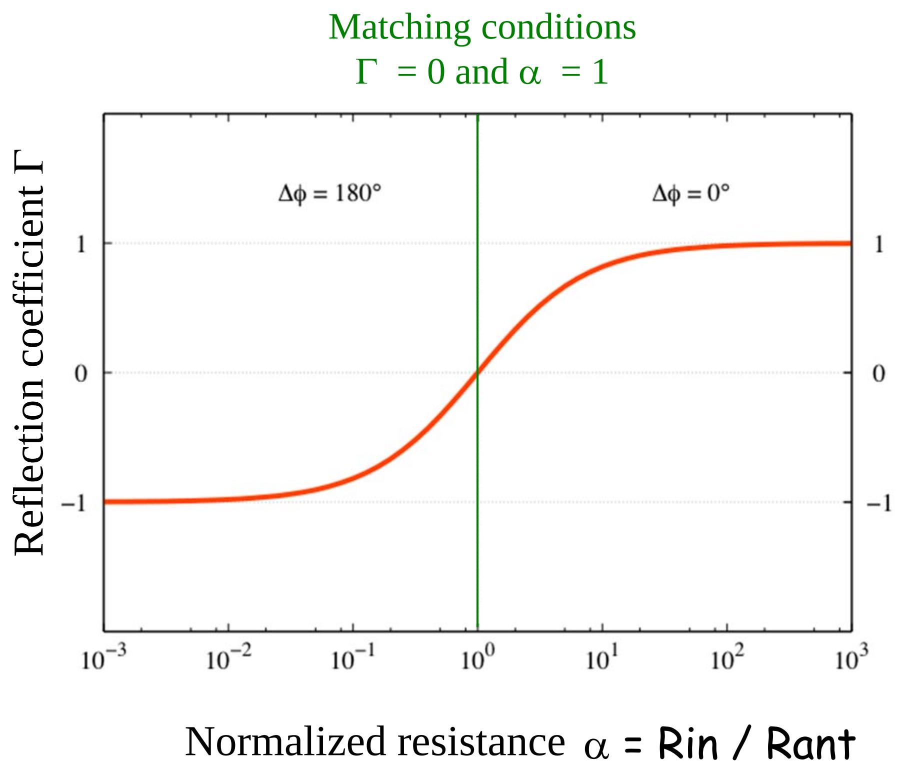
Priority is given to communication distance vs. data rate

The real part of R_{in} is very high (»1kΩ) and much higher than R_{ant}

Reflection coefficient is close to ±1

The input capacitance is equal to a few hundreds fF

Reflection coefficient amplitude

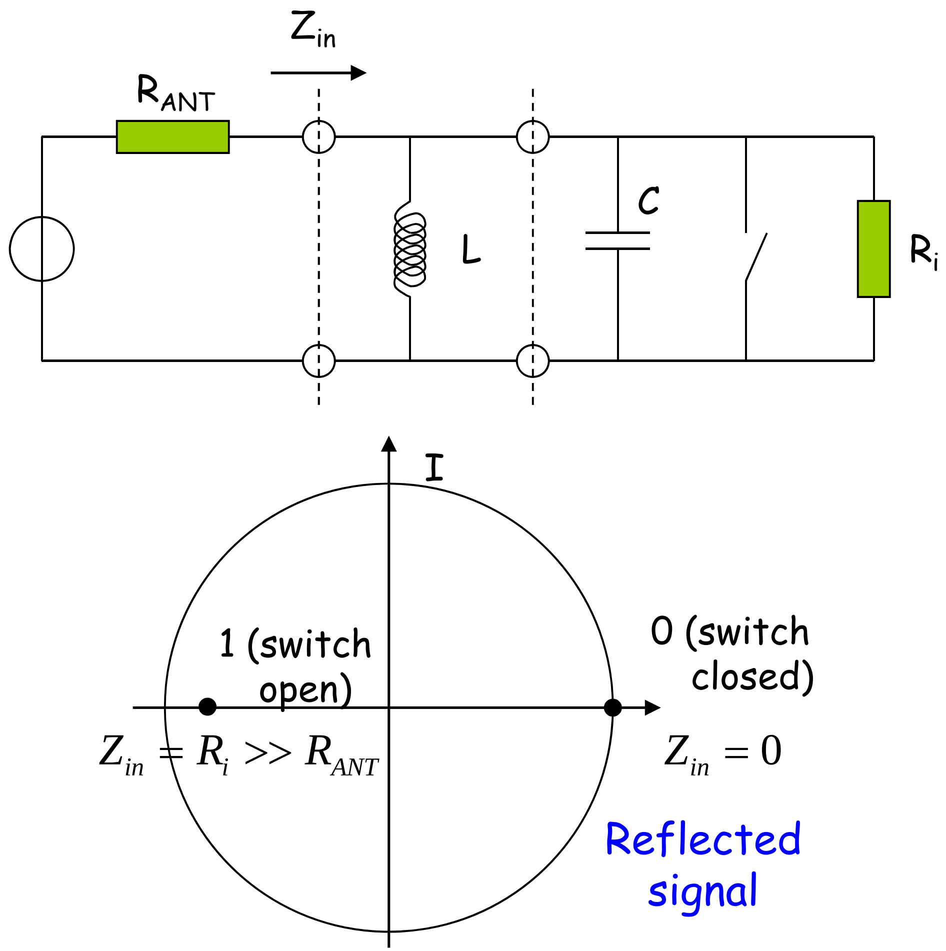


catherine.dehollain@epfl.ch

Pseudo - PSK

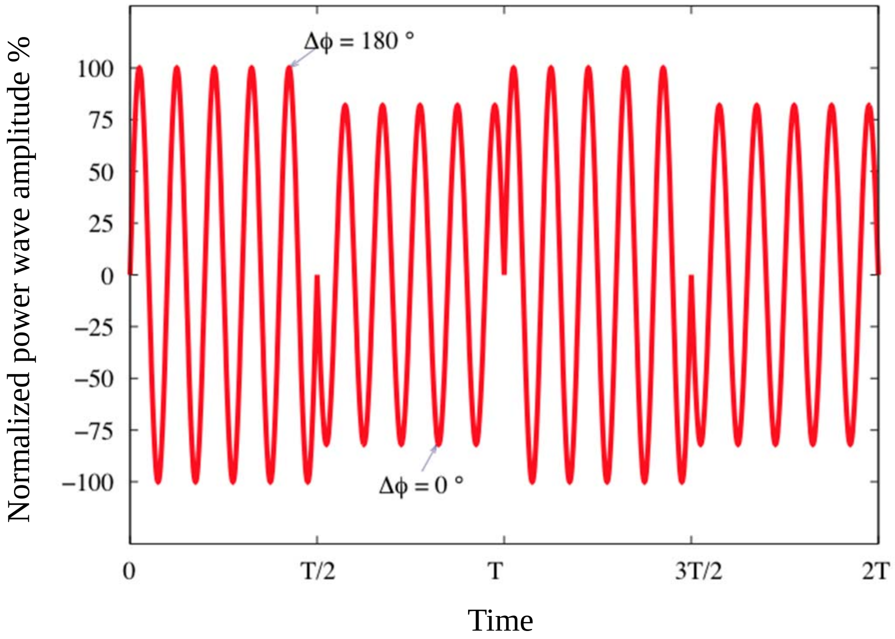
In practice $R_i > R_{ANT}$
(~1 order of magnitude)

- 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



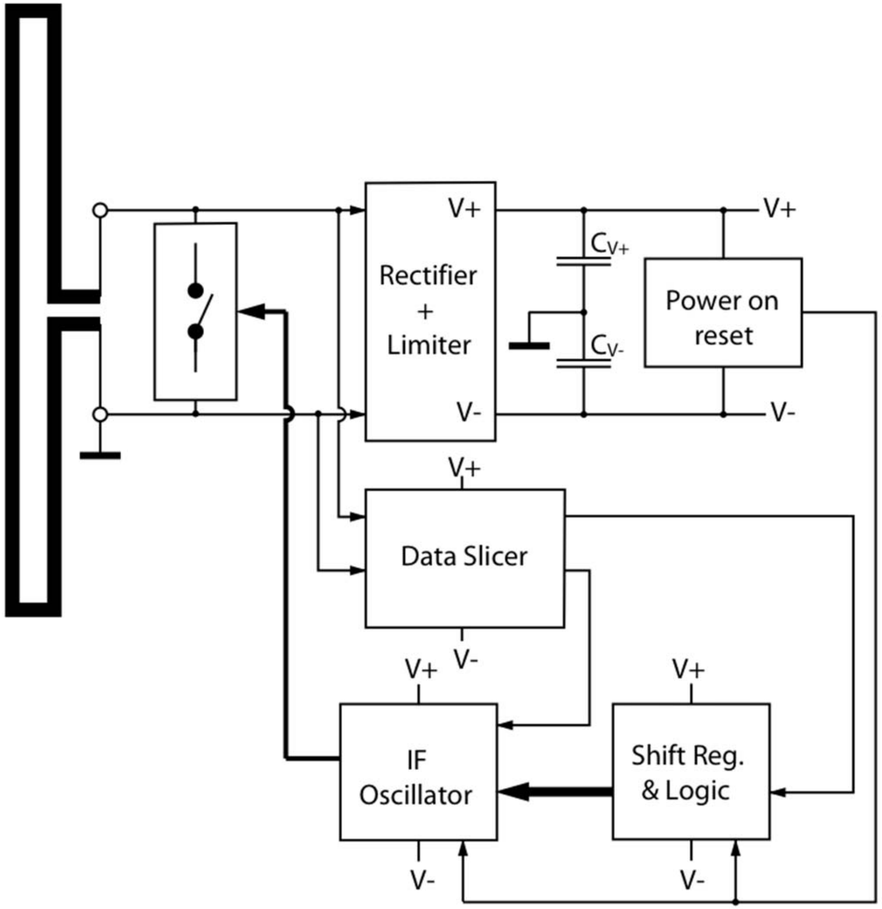
J.P. Curty, M. Declercq, C. Dehollain, N. Joehl
Book: « Design and Optimization of Passive UHF RFID Systems »
Editor Springer, year 2007, ISBN: 0-387-35274-0.

4. TAG AND READER DESIGN

Initial Specifications for the tag IC

Parameter	Value
Frequency range	2.40 - 2.48 Ghz
Reader P_{EIRP}	4 W
Tag power	≈ 1 μW
Operating distance	> 5 m
Reader to tag	AM (OOK) modulation
Tag to reader	p-PSK modulation
Data rate	≥ 10 kbps

Building Blocks



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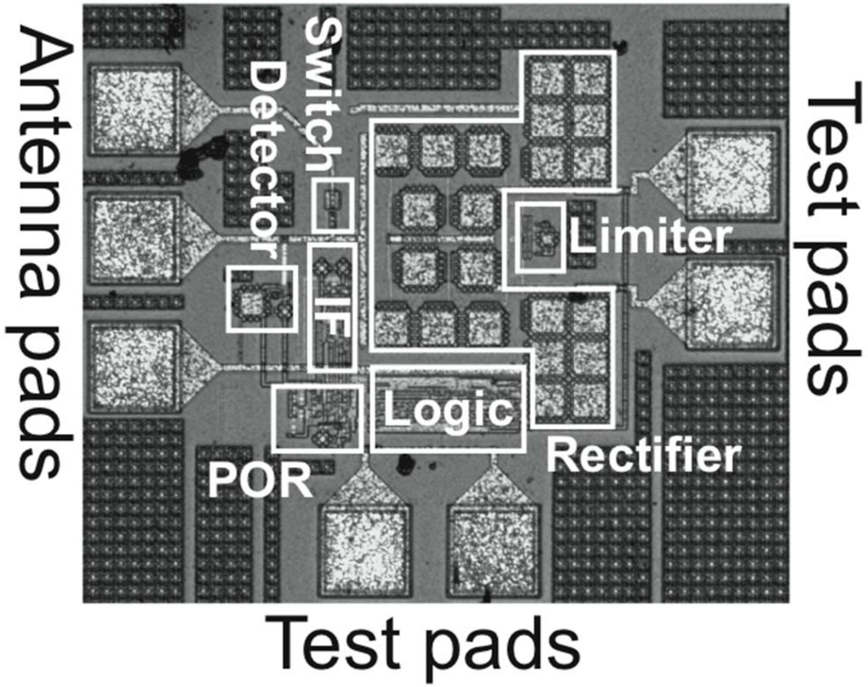
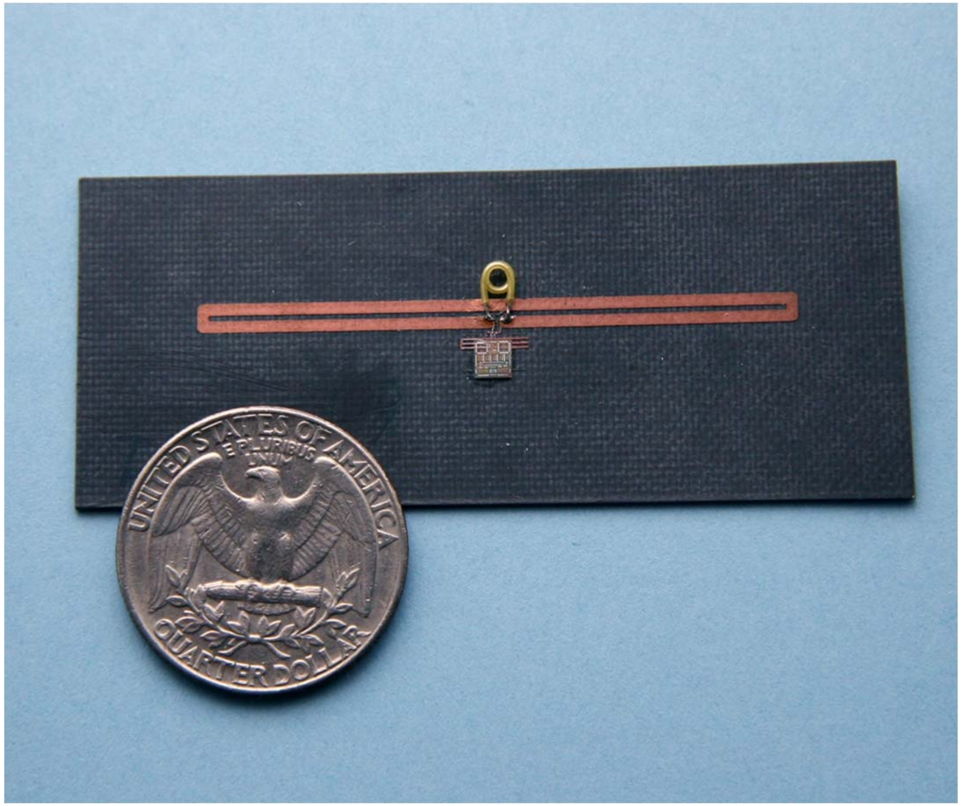
Tag Die



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

Frequency MHz	Antenna	Range m
2450	λ/2-dipole	6
2450	λ/2-dipole with inductive matching	9
2450	folded dipole	7
2450	folded dipole with inductive matching	12

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

J.P. Curty, N. Joehl, C. Dehollain and M. Declercq,
"Remotely Powered Addressable UHF RFID Integrated System ",
IEEE Journal of Solid-State Circuits, Vol. 40, No 11, November 2005, pp. 2193- 2202.

Summary on RFID at long distance

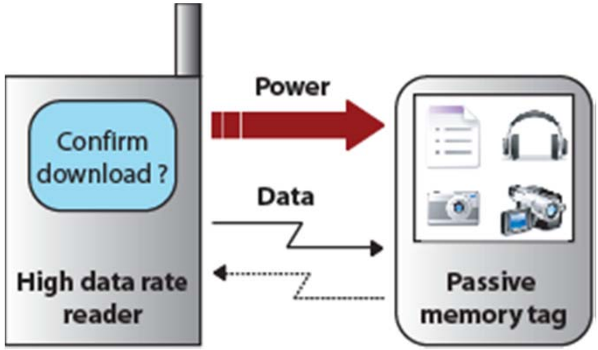
- Wireless power transmission & rectifier models have been developed for optimizing the power supply available for the tag
- Different backscattering modulation types were compared and pseudo-PSK was identified as an excellent candidate given the naturally high input impedance of the tag;
- Readers's 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

Other prospect

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 I_{DC} < 3mA

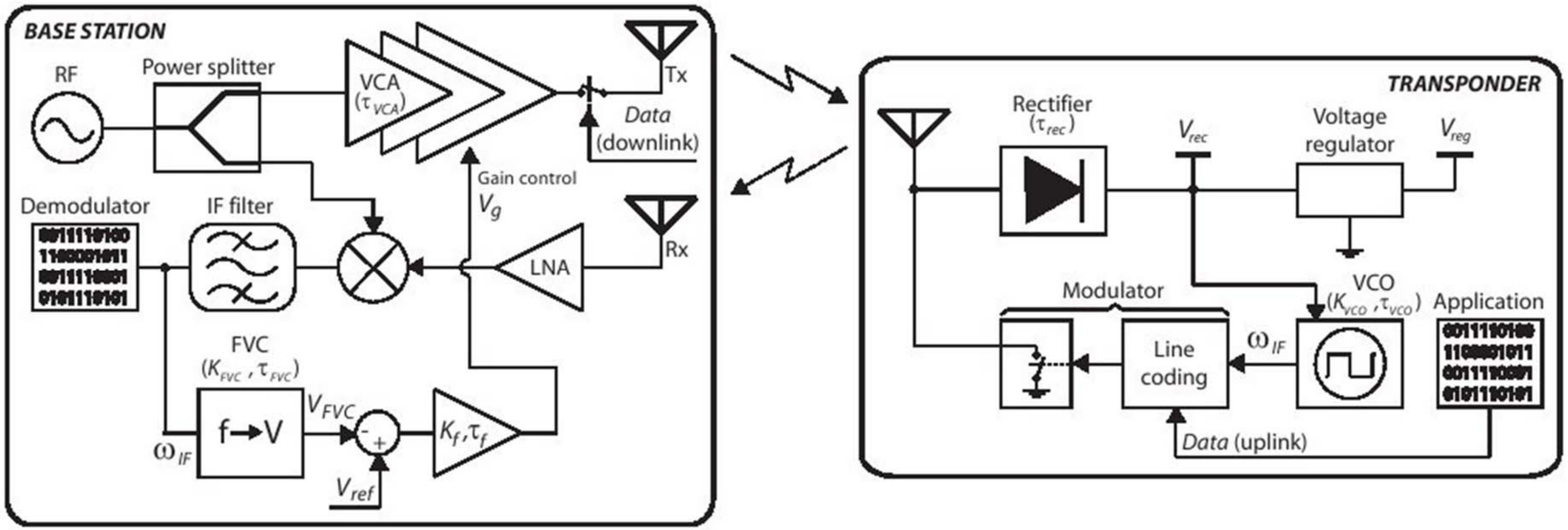
Communication link: 2.4GHz (ISM)

Remote powering: 0.9GHz (ISM)

catherine.dehollain@epfl.ch

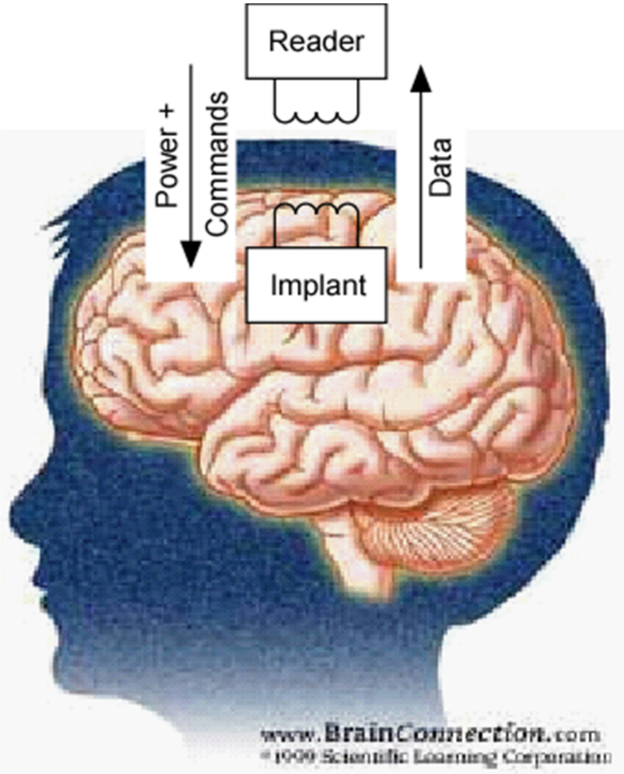
Other prospect

- The rectifier's output voltage Vrec controls the frequency of the IF signal.
- The reader measures this frequency and adapts the emitted power to stabilize Vrec to the desired voltage.



IEEE TCAS-I Journal, N. Pillin, N. Joehl, C. Dehollain, M. Declercq, March 2010

Other prospect



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

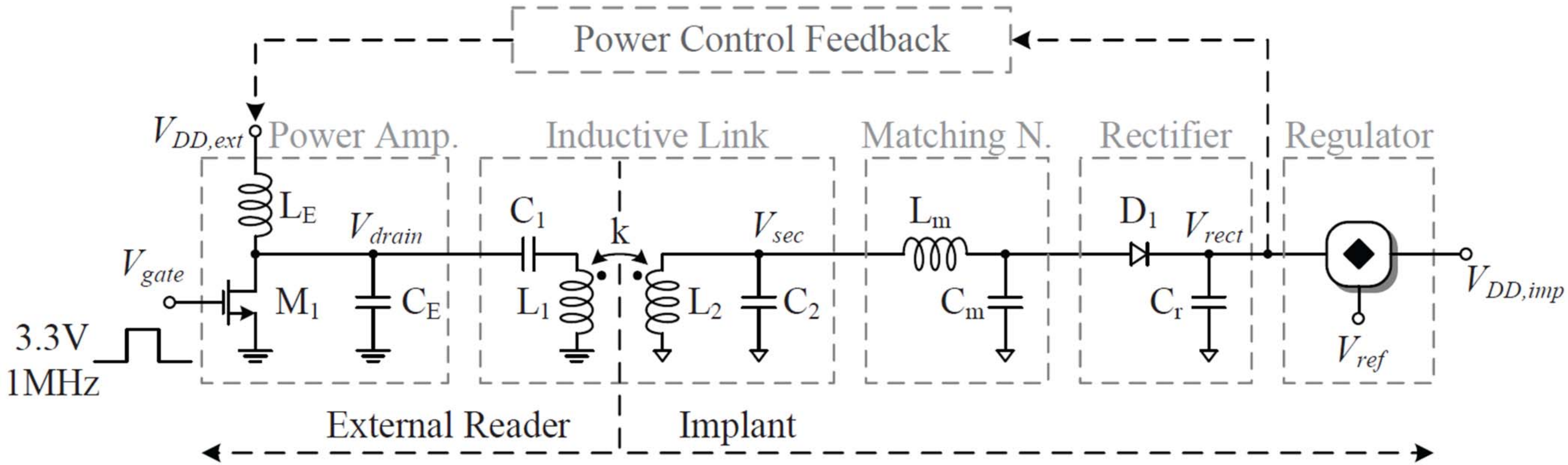
Description:
- two parts (inside & outside)
- power transmission &regulation
- signals acquisition, sampling and A-D conversion
- bidirectional data transmission
- signal processing

Constraints:
- thermal dissipation
- biological compatibility
- data rate

Swiss National Funding
NEURO-IC

catherine.dehollain@epfl.ch

Other prospect



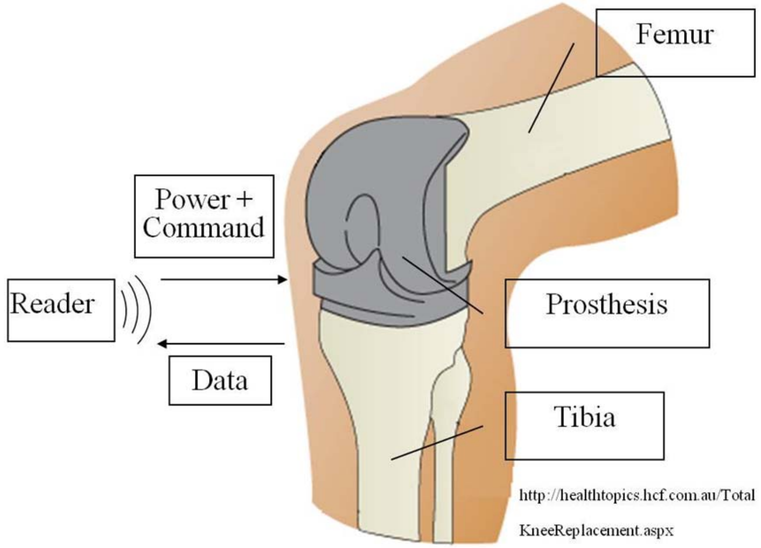
- Inductive power link:
  - Geometry optimized for power efficiency
  - Operation frequency at 1MHz
  - Distance between coils 10mm

K.M. Silay, C. Dehollain, M. Declercq, Sensors 2010 Conference

Knee prosthesis monitoring by inductive coupling

6

Other prospect



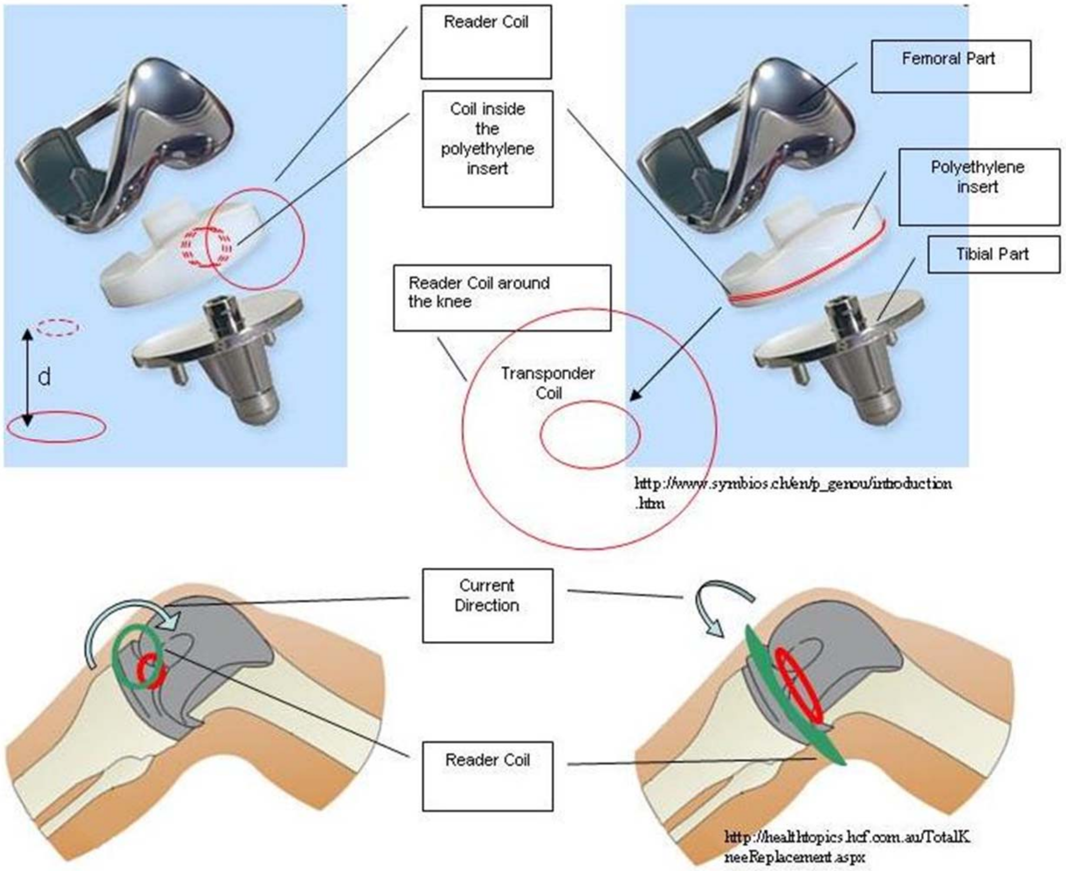
Swiss SNF NanoTera Simos Project

Project
- Increase of the life expectancy of the prostheses
- Monitoring of the force, movement of the knee and temperature

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

Our Objectives
- Transcutaneous powering by inductive link
- Communication between the prosthesis and outside reader

Other prospect



- 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 $k^2 Q_{Ls1} Q_{Ls2}$

O. Atasoy and C. Dehollain, PRIME 2010 Conference

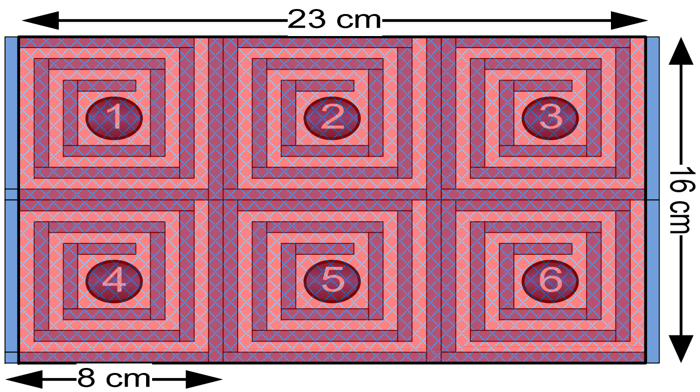
Mouse monitoring by magnetic coupling

Other prospect

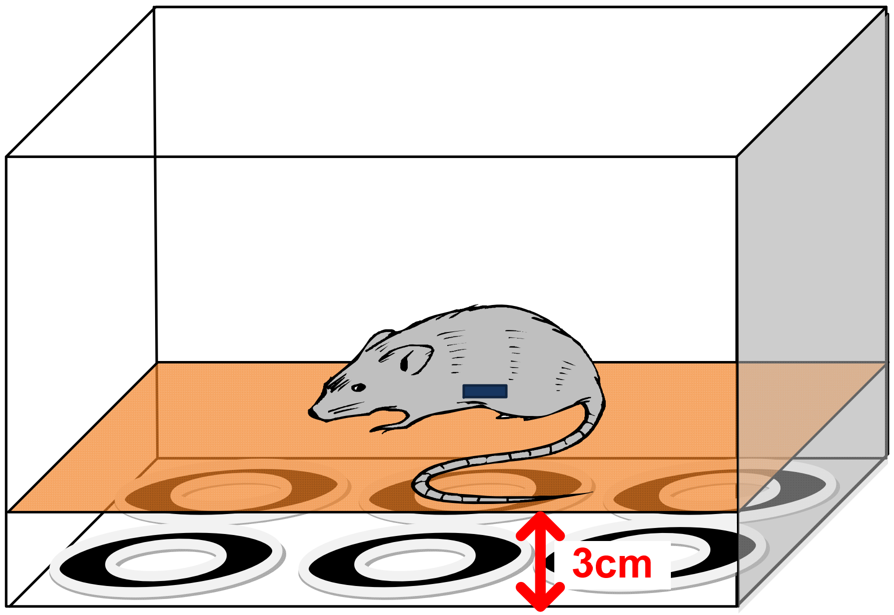
Challenges

- 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

Other prospect

Design Parameters Limited by Application

Parameter	Value
Link operation frequency (f)	13.56MHz
Distance between coils (d_{12})	30mm
Tag coil outer diameter (d_{o2})	20mm
Minimum spacing between line (s)	150µm
Minimum width of conductor (w)	150µm

Optimal Inductive Coil Designs

Parameter	Reader	Tag Coil
Outer diameter (d_o)	80mm	20mm
Inner diameter (d_i)	10mm	11mm
Number of turns (n)	5	6
Width of conductor (w)	1mm	250µm
Spacing of lines (s)	7.5mm	600µm

Comparison Between Analysis and HFSS Simulation Results

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

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.