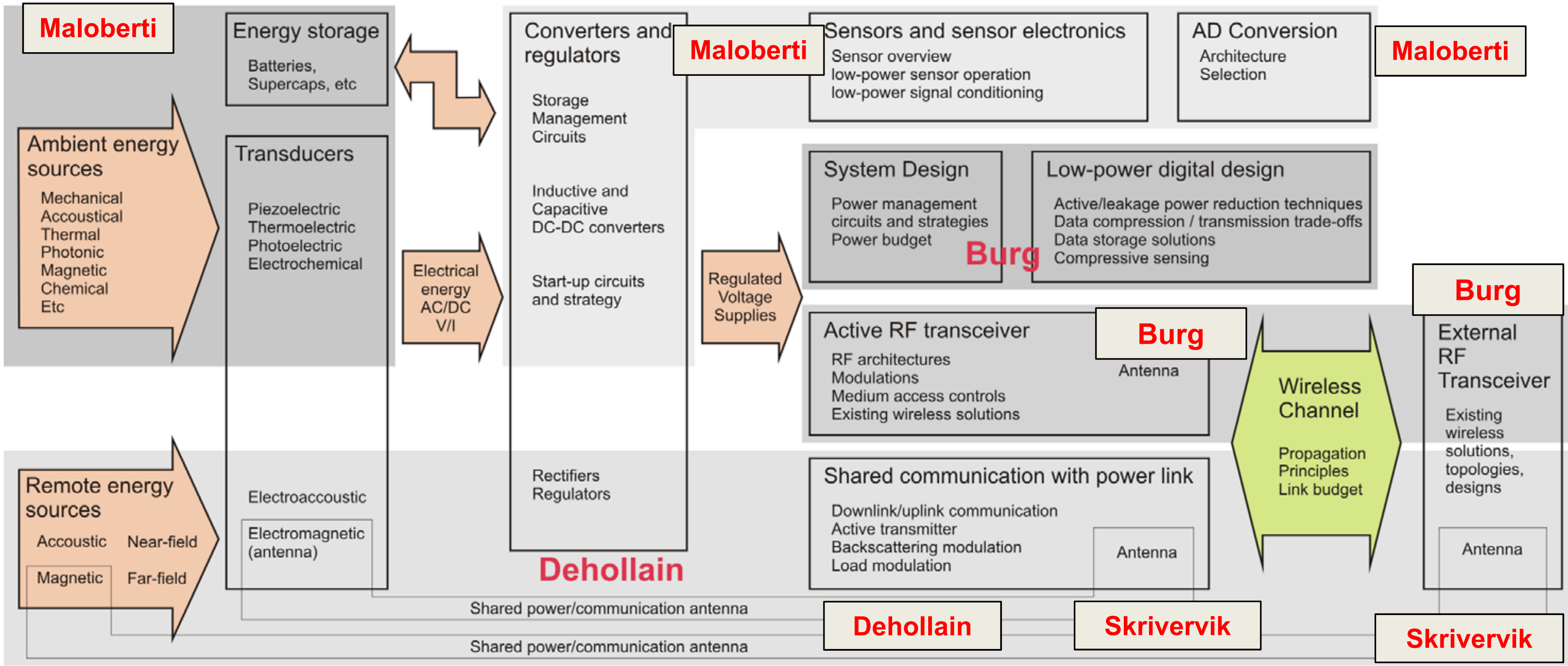
PART 1 –
Introduction to the EAWS Course

Prof. Catherine Dehollain
Group Leader of the RFIC group at EPFL

Practical aspects

Energy Autonomous Wireless Systems - topics in graphics representation



Time Schedule of the Day

- **9h to 10h30: Introduction and Wireless Power Transmission (slide 1 to 37)**
- **10h30 to 11h: Coffee Break**
- **11h to 12h: Backscattering Data Communication, CMOS Tag at 2.4 GHz (slides 38 to 67)**
- **12h to 13h30: Lunch Break**
- **13h30 to 14h: Exercise on Remote Power**
- **14h to 15h: Dual Frequency System, Wireless Power Control Loop (slide 68 to 90)**
- **15h to 15h45: Exercise on LC Oscillator**
- **15h45 to 16h15: Coffee Break**
- **16h15 to 17h15: Remote Power, Data Communication by Ultrasound (slides 91 to 111)**

Catherine Dehollain

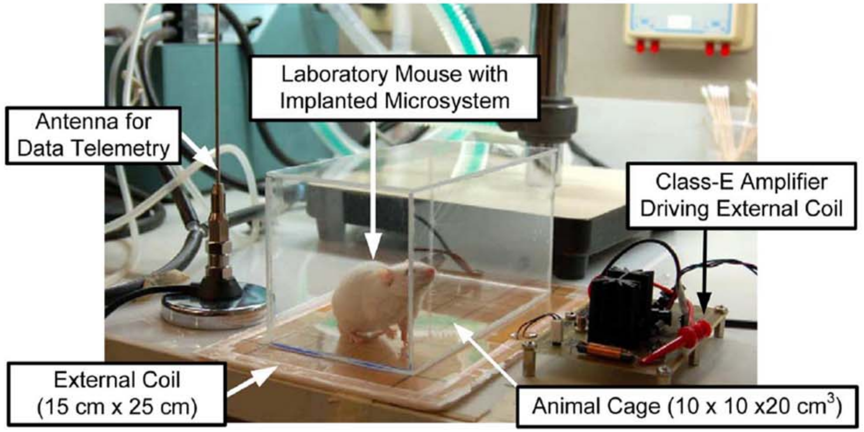
- 1978-1982 – Bachelor / Master in Electrical Engineering at EPFL
- 1982-1984 – Research Assistant at EPFL
  - Modeling of the charge injection in MOS transistors
  - Design of low power switched-capacitor filters
- 1984-1990 – Design Engineer in Telecoms at Motorola, Geneva
  - Design of integrated circuits for the fixed phone subscriber line
- 1990-1995 – Senior Research Assistant at EPFL
  - PhD thesis on impedance broadband matching
  - Lecturer on electrical filters design
- 1995 up to now – Group Leader of the RFIC Research Group at EPFL
  - Lecturer since 1998: HF and VHF circuits, PSPICE, electrical filters, analog integrated circuits
  - MER since 2006 and Professor since 2014
  - Radio Frequency Wireless Communication Systems
  - Radio Frequency Identification Systems (RFID)
  - Remotely Powered Electronic Circuits / Power Management Circuits
  - Electronic Circuits dedicated to Biomedical Applications
  - Micro Power Analog Integrated Circuits
  - Electrical Analog Filters / Broadband Impedance Matching Circuits

Main Research Activities of the RF IC Group

- New architectures of sensor nodes for wireless communications at short distance
  - Back-scattering/ Load modulation (e.g. RFIDs)
  - Impulse Radio Ultra Wideband (IR UWB)
  - Super-regenerative transceivers
- Biomedical field (implants), consumer electronics field (passive memory tag)
- Remotely powered wireless circuits
  - Magnetic coupling , electro-magnetic coupling, electro-acoustic coupling
- Ultra low-power wireless communications
- 0.1 MHz to 10 GHz-range Integrated Circuits
- RF and mixed-mode CMOS circuits

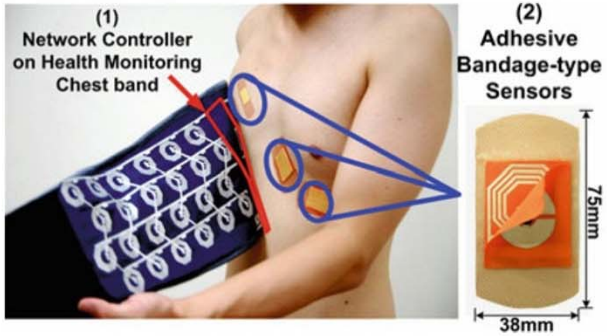
Example Applications

Blood Pressure Monitoring System



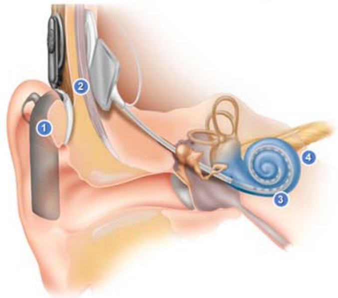
P. Cong et al., "A Wireless and Battery less 10-Bit Implantable Blood Pressure Sensing Microsystem With Adaptive RF Powering for Real-Time Laboratory Mice Monitoring," IEEE Journal of Solid State Circuits, Dec. 2009.

ECG Monitoring System



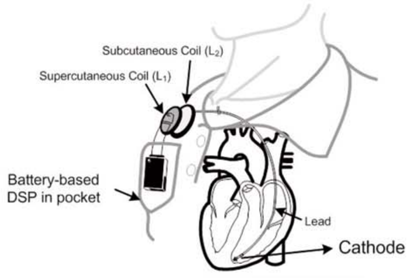
J. Yoo, et al., "A 5.2 mW Self-Configured Wearable Body Sensor Network Controller and a 12 µW Wirelessly Powered Sensor for a Continuous Health Monitoring System," IEEE Journal of Solid-State Circuits, Jan 2010.

Cochlear Implants



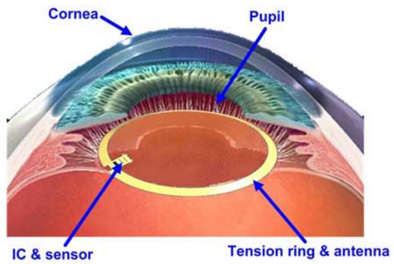
cochlearamericas.com

Cardiac Pacemaker



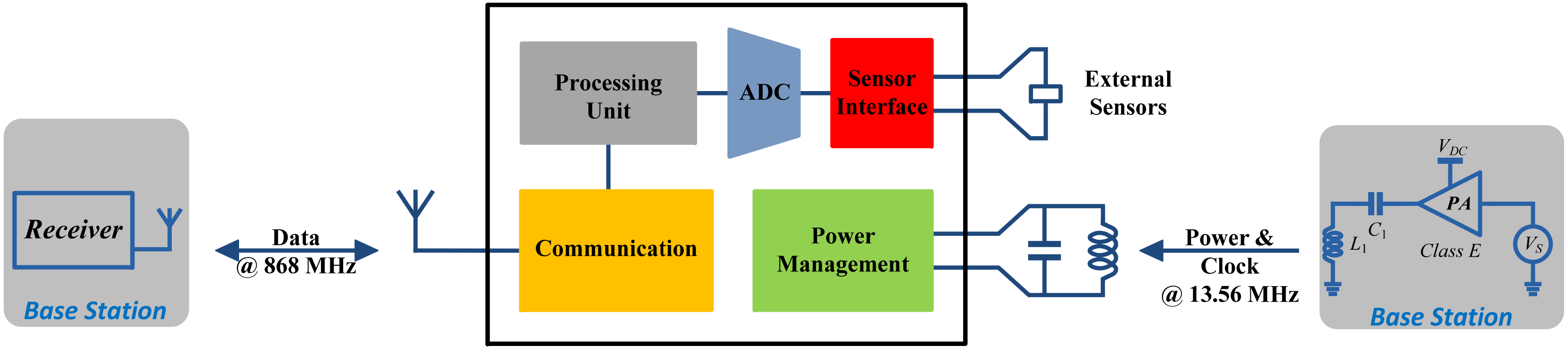
S.Lee, et al., "A Programmable Implantable Micro-Stimulator SoC with Wireless Telemetry: Application in Closed-Loop Endocardial Stimulation for Cardiac Pacemaker," in ISSCC Digest of Technical Papers, Feb. 2011, pp 44-45.

Intraocular Pressure & Temperature Monitor



Y. C. Shih, T. Shen, and B. P. Otis, "A 2.3 uW wireless Intraocular pressure/temperature monitor," IEEE Journal of Solid State Circuits, vol. 46, no. 11, pp. 2592-2601, Nov. 2011.

Remotely Powered Sensor Node



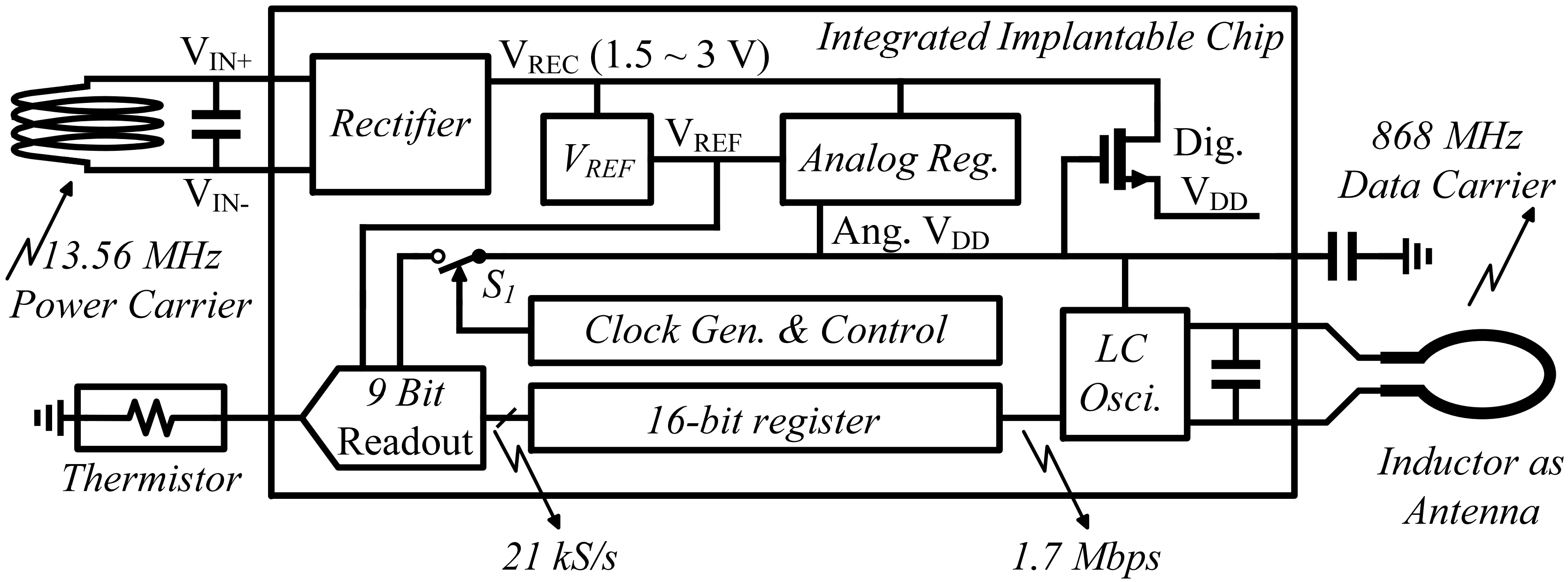
Main challenges

- To design a very low power CMOS integrated circuit dedicated to the sensor node
- To maximize the transfer of power from the base station to the sensor node

Possible application

- Metabolism: to measure the local temperature of the brown adipose tissue (on the back of the animal) of a living mouse

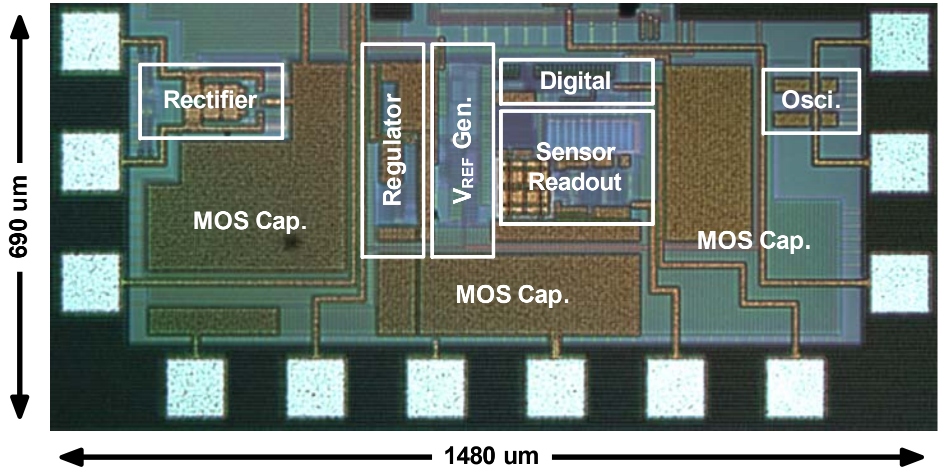
Implanted Electronic Circuit



- **High efficiency semi-active rectifier**
- **Time-domain resistance to digital converter**
- **Time interleaved sensor readout and data transmission**

M. A. Ghanad, M. M. Green, and C. Dehollain, "A Remotely Powered Implantable IC for Recording Mouse Local Temperature with ±0.09 °C Accuracy," IEEE A-SSCC 2013 Conference (Asian Solid-State Circuits)

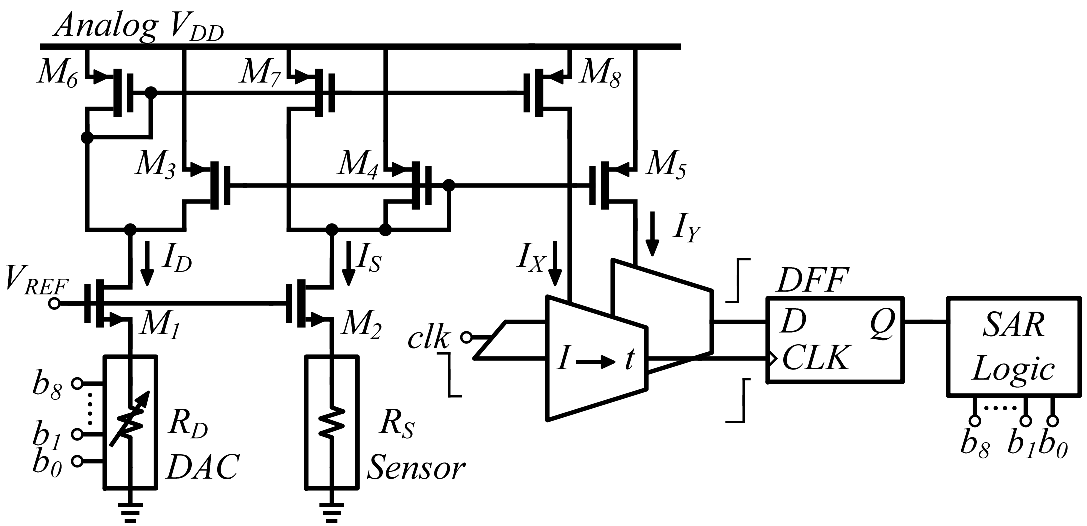
Implanted Electronic Circuit



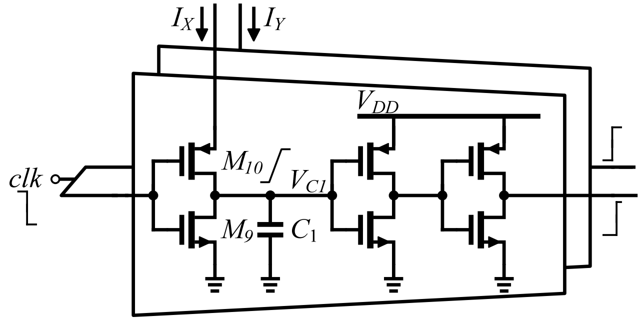
Implantable Chip Measurement	
Technology	0.18 um
Sensor type	Thermistor
Power	53 (uW)
V_{REC} Min.	1.5 (V)
Tran. Data Rate	1.7 (Mbps)
Sampling Rate	21 (kS/s)
Accuracy	± 0.09 C°

- M. A. Ghanad, M. M. Green, and C. Dehollain, "A Remotely Powered Implantable IC for Recording Mouse Local Temperature with ±0.09 °C Accuracy," IEEE A-SSCC 2013 Conference (Asian Solid-State Circuits)
- M. A. Ghanad, M. M. Green, and C. Dehollain, "A 15 uW 5.5 kS/s Resistive Sensor Readout Circuit with 7.6 ENOB," accepted for publication in IEEE Transactions on Circuits and Systems I: Regular Papers, year 2014.
- M. A. Ghanad, M. M. Green, and C. Dehollain, "Improving Signal-to-Noise of Current Mode Circuits by a cross-coupled Current Mirror Topology», IEE Electronics Letters, year 2014.

CMOS Time-Domain Read-out Circuit



Current to Time Converter



- Power consumption: 8.7 uW @ 21 kS/s
- 9-bits (512 levels)
- The sensor response is directly digitized by a time-domain comparator (DFF) to achieve ultra-low-power operation
- SAR algorithm tries to minimize the value (R_S-R_D)

M. A. Ghanad, M. M. Green, and C. Dehollain, "A Remotely Powered Implantable IC for Recording Mouse Local Temperature with ±0.09 °C Accuracy," IEEE A-SSCC 2013 Conference (Asian Solid-State Circuits)

References (Books)

- J.P. Curty, M. Delercq, C. Dehollain, N. Joehl, Design and Optimization of Passive UHF RFID Systems, Springer, 2007, 148 pages.
- E.G. Kilinc, C. Dehollain, F. Maloberti, Remote Powering and Data Communication for Implanted Biomedical Systems, Springer, 2016, 145 pages.
- G. Yilmaz, C. Dehollain, Wireless Power Transfer and Data Communication for Neural Implants, Springer, 2017, 110 pages.
- K. Türe, C. Dehollain, F. Maloberti, Wireless Power Transfer and Data Communication for Intracranial Neural Recording, Springer, to be published in 2020.
- F. Mazzilli, C. Dehollain, Ultrasound Energy and Data Transfer for Medical Implants, Springer, to be published in 2020 or 2021.
- K. Finkenzeller, RFID Handbook, 3rd Edition, Wiley, 2010, 478 pages.
- S. Shepard, Radio Frequency Identification, McGraw-Hill, 2005, 256 pages.

Access to Springer Books for free from EPFL network

you can have access for free to the pdf files of Springer scientific books on: http://rd.springer.com/

References (Journals and Proceedings of Conference)

Scientific journals

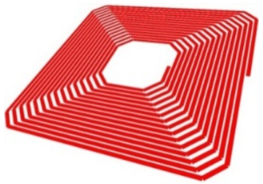
- IEEE Sensors Journal
- IEEE Journal on Solid State Circuits
- IEEE Transactions on Circuits and Systems
- IEEE Transactions on Wireless Communications
- IEEE Transactions on Biomedical Applications

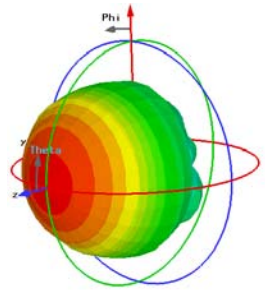
Conferences

- IEEE Sensors Conference
- IEEE Solid State Circuits Conference
- IEEE International Symposium on Circuits and Systems (ISCAS)
- IEEE BioCAS Conference

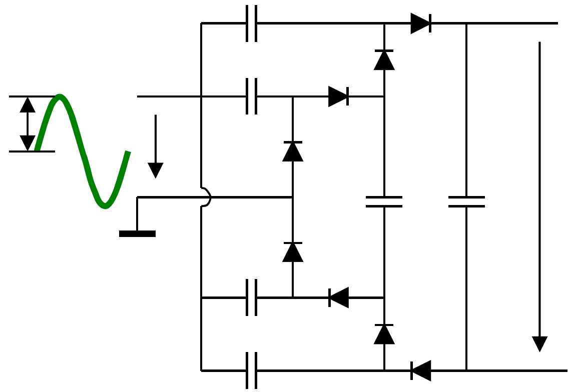
Remote powering for EAWS

- **Wireless Power Transmission**
  - Far field / Electro-magnetic coupling
  - Near field / Magnetic coupling
  - Ultrasonic Coupling



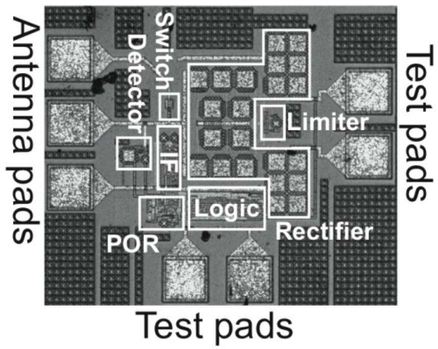


- **AC to DC conversion**
  - Greinacher topology
  - Equivalent model of the antenna
  - Equivalent electrical model of the rectifier



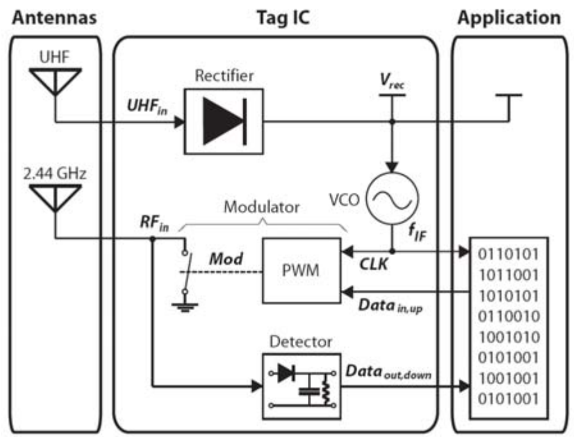
- **Back-scattering Data Communication**
  - Principle
  - Amplitude modulation
  - Phase modulation
  - Pseudo PSK modulation

- **Remotely powered tag at 2.45 GHz**

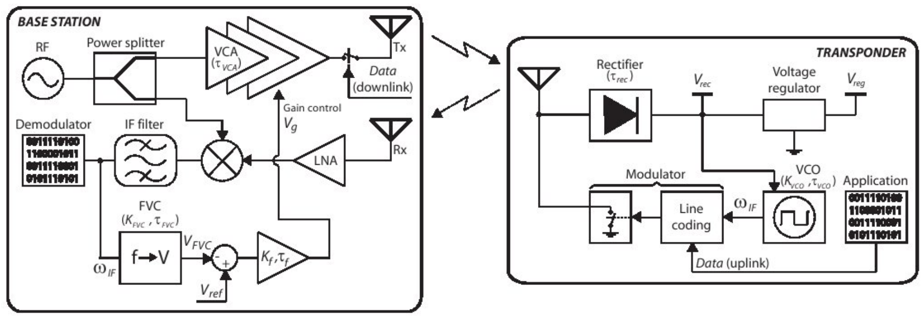


Remote powering for EAWS

- **Dual frequency system**
  - Principle at system level
  - Determination of the frequency for remote power
  - Determination of the frequency for data communication
  - Case study at 868 MHz / 2.4 GHz



- **Optimisation of the transfer of power**
  - Principle at system level
  - Sub-carrier oscillator
  - Improvement of the power efficiency
  - Case study at 868 MHz

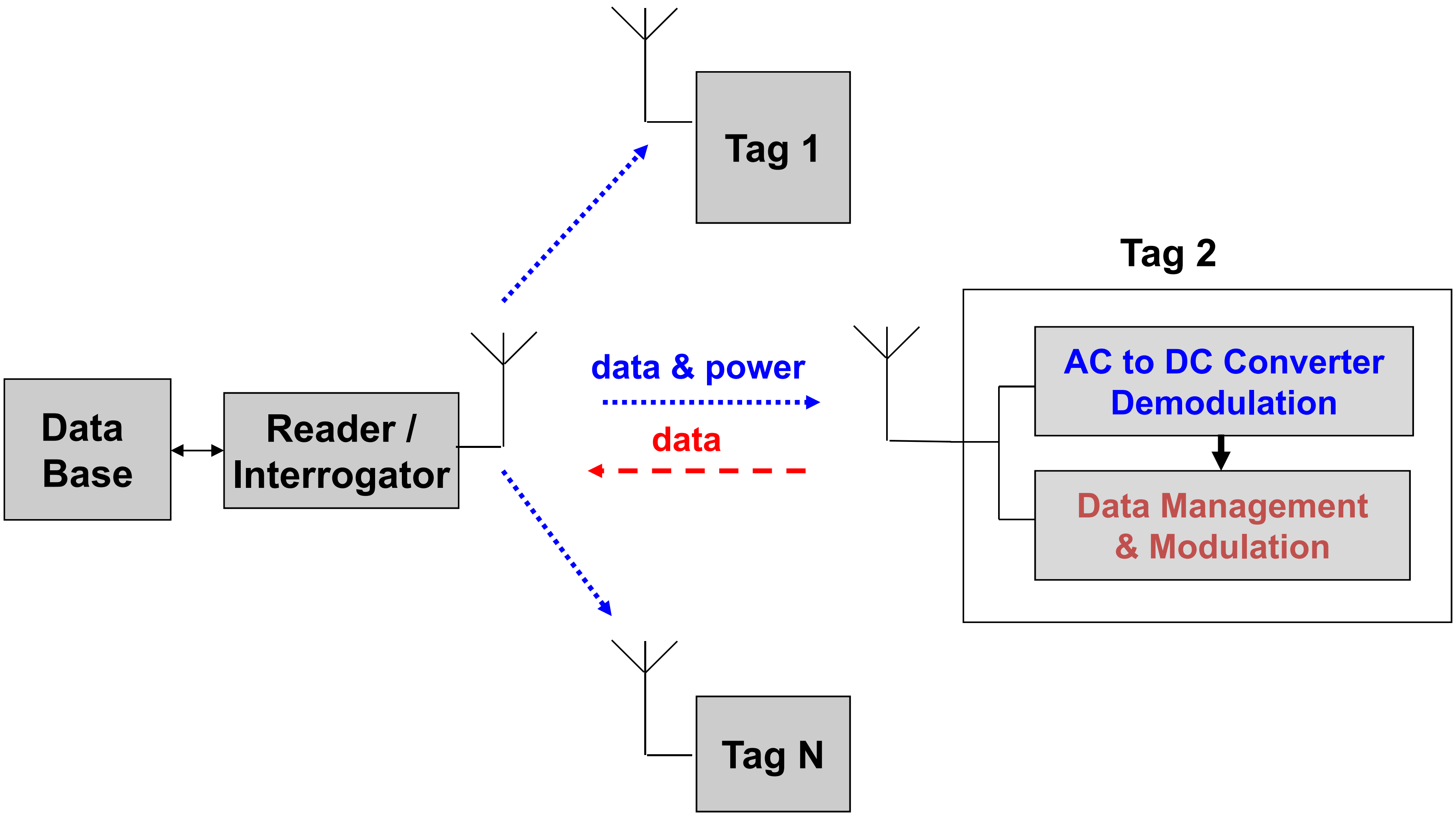


- **Remote power and data communication through ultrasonic wave**
  - Principle at system level
  - Determination of the frequency for remote power and data communication
  - Case study at 1 MHz

PART 2 –
Wireless Power Transmission

Prof. Catherine Dehollain
Group Leader of the RFIC group at EPFL

Wireless Power Transmission System (WPT)

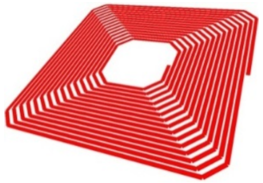


Passive Tag / Active Tag

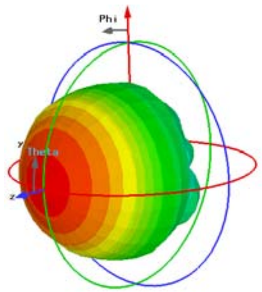
- **Passive tag**
  - **No internal power supply.**
  - **Energy to power the tag comes from the RF field produced by the reader also called interrogator.**

- **Active tag**
  - **Internal power supply by batteries.**

- **Inductive Coupling (Near-Field)**
  - **Near field region → d < λ/2π**
  - **Typical frequency bands: 125 kHz, 6.78 MHz, 13.56 MHz**
  - **Effective operation distance of 10 cm**
  - **Higher energy efficiency than far-field at short distance (d<10 cm)**
  - **Load modulation operation for data communication**



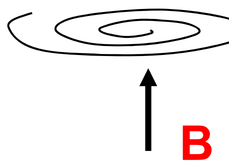
- **Electro-magnetic Coupling (Far-field)**
  - **Far field region: → d > λ/2π**
  - **2.45 GHz: distance larger than 2 cm**
  - **Typical frequency bands: 868 MHz, 915 MHz, 2.45 GHz**
  - **Maximum distance up to 15 meters**
  - **Higher data rate than in near-field due to the larger frequency bandwidth available**
  - **Back-scattering operation for data communication**

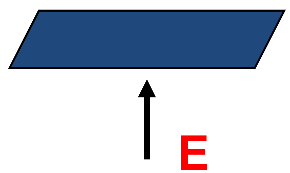


Far field / Near field

- **Far-field**
  - **Antennas are typically of N-poles types (monopole, dipoles, folded dipole etc)**
  - **Available Power at the input is a function of d^{-2} and λ^2**

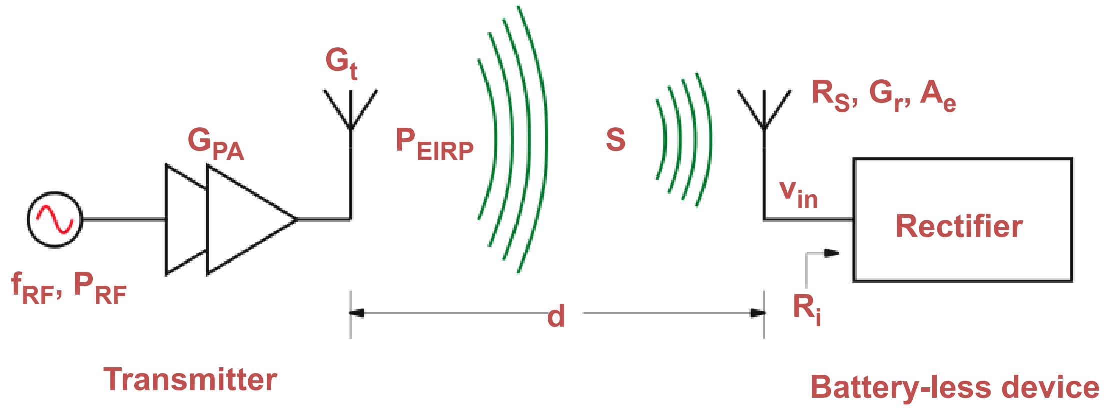
- **Near-field**
  - **Usually inductive coupling (magnetic field)**
  - **But can be also capacitive coupling (electric field)**
  - **Antennas have to be either coils for inductive coupling, or metallic surfaces for capacitive coupling**
  - **Available Power at the input is a function of d^{-6} and λ^6**





Estimation of the input power available in far field

WPT: Wireless Power Transmission 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 $$A_E = \frac{\lambda^2}{4\pi} . G_R$$

Estimation of input available power in far field

Friis Transmission Relation

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

Application at 2.45 GHz

λ = **0.1224 m**

P_{EIRP} = 4 W

Antenna gain: G_R = 1 (0 dB):

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

Electro-Magnetic Coupling

- **Friis transmission equation**

$$P_r = P_t \; G_t \; G_r \left(\frac{\lambda}{4\pi d} \right)^2$$

- **The maximum available power Pr depends on**
  - **the transmitted power Pt**
  - **the antenna gain Gt of the transmitter, the antenna gain Gr of the tag**
  - **the wavelength of the RF signal**
  - **the distance**
- **In practical case: for Pr = 2 mW → Pt > 1 W for 12 cm at 2.45 GHz (see ref.)**

O. Kazanc, F. Maloberti and C. Dehollain, "Simulation oriented rectenna design methodology for remote powering of wireless sensor systems," in *Proc. IEEE ISCAS 2012*, pp. 2877-2880.

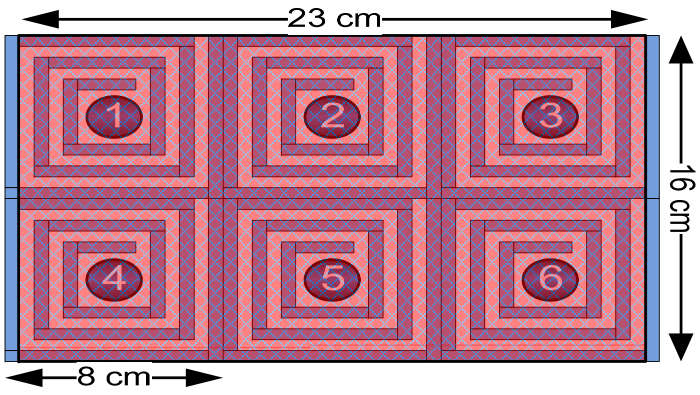
Magnetic Coupling

$$P_r = P_t \ \frac{\mu_0^2 \pi^2 N_t^2 N_r^2 r_t^4 r_r^4 \ \omega^2}{16 R_t R_r (r_t^2 + d^2)^3}$$

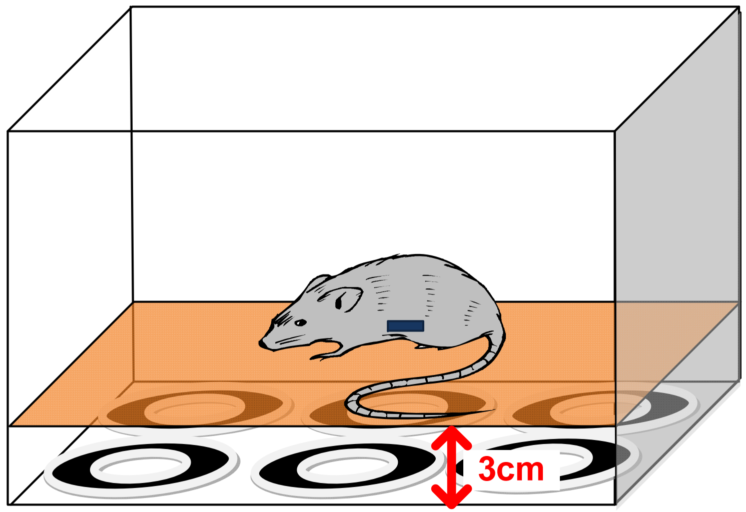
- **The maximum available power P_r depends on**
  - **the transmitted power P_t**
  - **the permeability of air**
  - **the number of turns N_t (transmit) and N_r (receive) of the two coils**
  - **The radius of the two coils r_t (transmit) and r_r (receive)**
  - **the frequency**
  - **the resistances of the two coils R_t (transmit) and R_r (receive)**
  - **the distance d between the two coils**
- **Optimal option for short-range remote powering in air (d < 10 cm)**
- **In practical case: for P_r = 2 mW → P_t = 20 mW at 10 cm (see ref.)**

D.C. Yates, A.S. Holmes, A.J. Burdett, "Optimal transmission frequency for ultralow-power short-range radio links," in *IEEE Trans. Circuits Syst. I*, 2004, vol. 51, no. 7, pp. 1405-1413.

- **Low coupling factor of the inductive link due to the distance between the two coils and the limited dimensions of the implanted coil**
- **The coupling factor k depends on the position of the mouse**



Array of coils under basement of the cage



3D model of array of coils under basement

E. G. Kilinc, C. Dehollain, F. Maloberti, SM2ACD Conference, Oct. 2010

Geometry of the coils

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
Mini spacing between line (s)	150μm
Minimum width of conductor (w)	150μm

Optimal Inductive Coil Designs

Parameter	Reader Coil	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

E. G. Kilinc, C. Dehollain, F. Maloberti, SM2ACD Conference, Oct. 2010

Assumption to compare Electro-Magnetic to Magnetic Coupling

- **Electro-magnetic coupling: Friis equation is used with path loss exponent of 2**

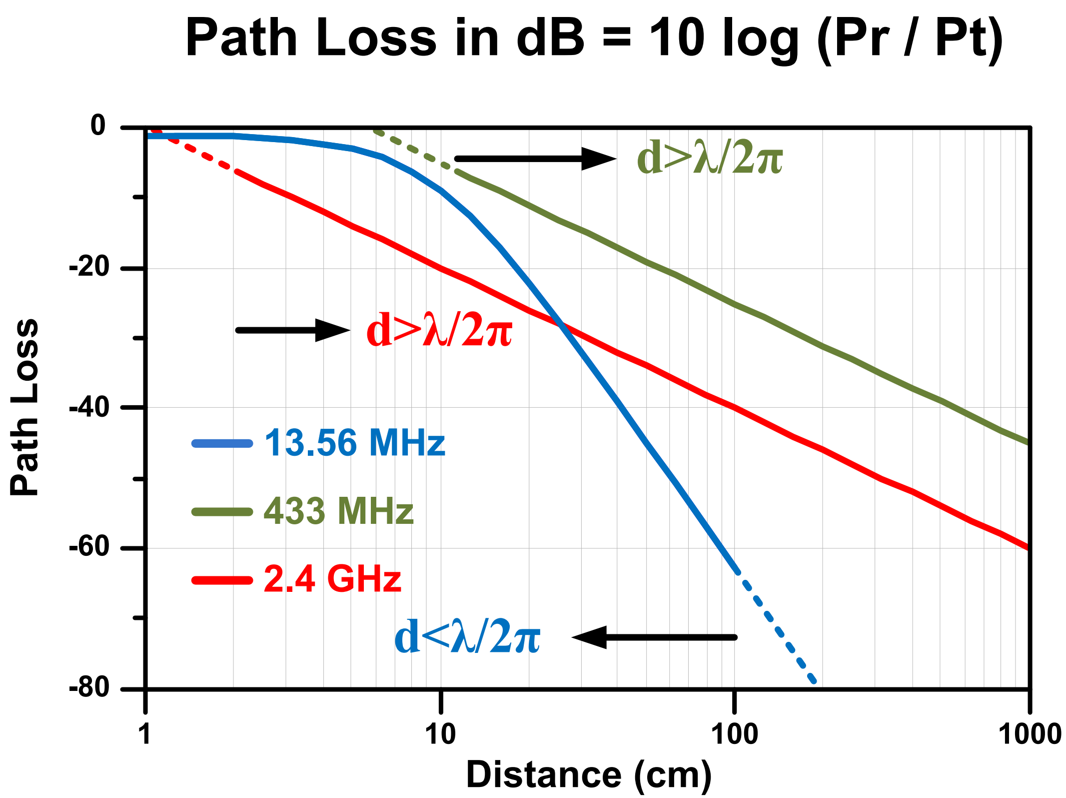
$$\frac{P_r}{P_t} = \left(\frac{\lambda}{4\pi}\right)^2 \left(\frac{1}{d}\right)^2$$

  - **λ is the wavelength of the RF signal**
  - **d is the distance between the two antennas**
  - **The gain of the two antennas are equal to 1**

- **Magnetic coupling: the inductor parameters of the following article are used for calculation at 13.56 MHz**
  - **E. G. Kilinc, C. Dehollain, F. Maloberti, SM2ACD Conference, Oct. 2010.**

- **The matching and antenna losses of the sensor node are not included (this loss can be as high as 30 dB for the implant).**

Comparison of Magnetic and Electro-Magnetic Coupling



Path Loss at 10 cm
-10 dB at 13.56 MHz
-20 dB at 2.4 GHz
Difficult to estimate at 433 MHz because at the boundary between far field and near field

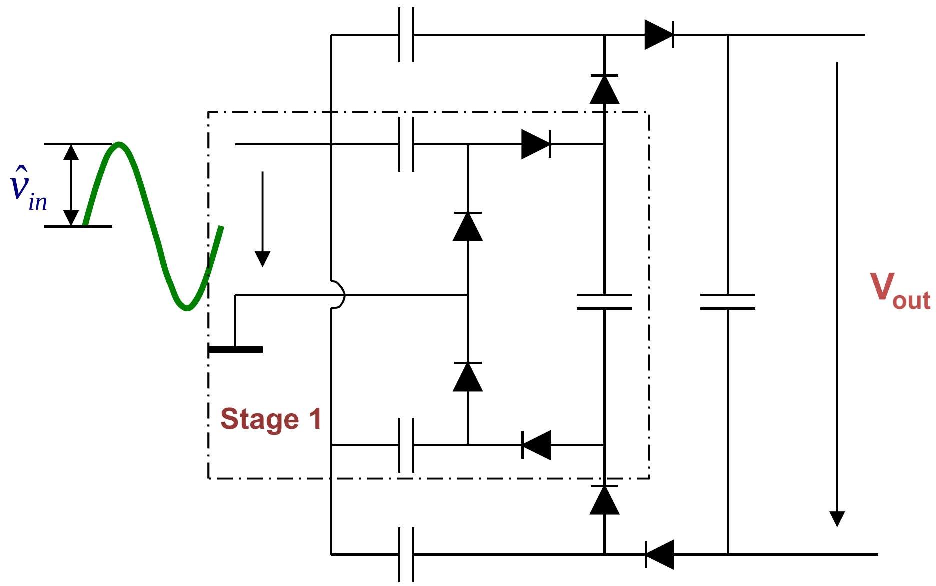
The matching and antenna losses of the sensor node are not included (this loss can be as high as 30 dB).

- **Received power** $$P_r = \eta_{AE} \; I_{AC} \; S_A$$
  - **Received power depends on**
    - **the acousto-electric efficiency ηAE**
    - **the acoustic intensity**
    - **the surface of the transducer**
  - **ηAE is high in water but is very low in air**
  - **Good approach for deeply implanted device (d larger than 5 cm)**
  - **In practical case: for Pr = 2 mW → Pt = 20 mW at 11 cm (see ref)**

F. Mazzilli, et. al., ”Ultrasound energy harvesting system for deep implanted-medical-devices (IMDs)”, in Proc. IEEE ISCAS 2012, 2012, pp. 2865-2868.

AC to DC Conversion

2 stages Differential Greinacher Topology



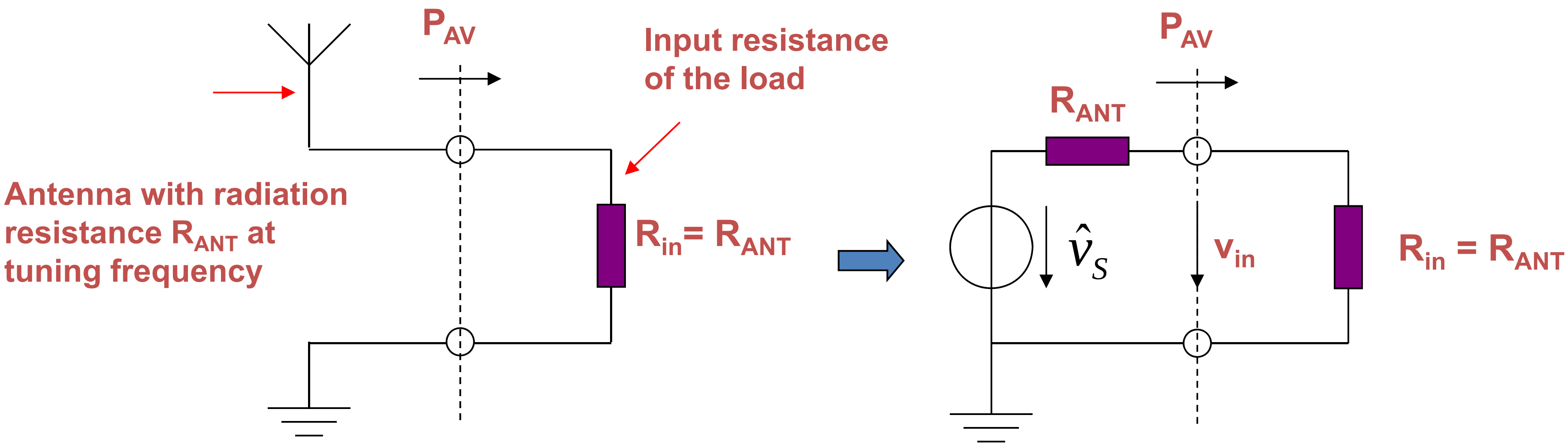
$$V_{out} = 4N\hat{v}_{in}$$

Number of stages: N
Differential: factor 4
Single-ended: factor 2

There is a need for a model taking into account

- **The current delivered to the load**
- **The diodes non-idealities**

Voltage Source (Thevenin) Equivalent Model



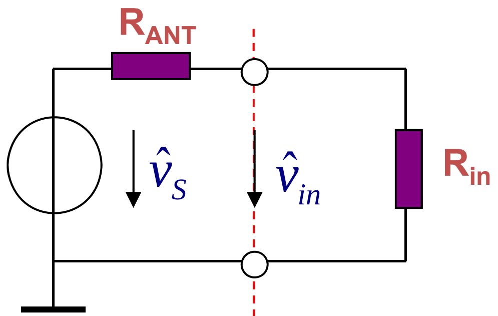
At Impedance Matching

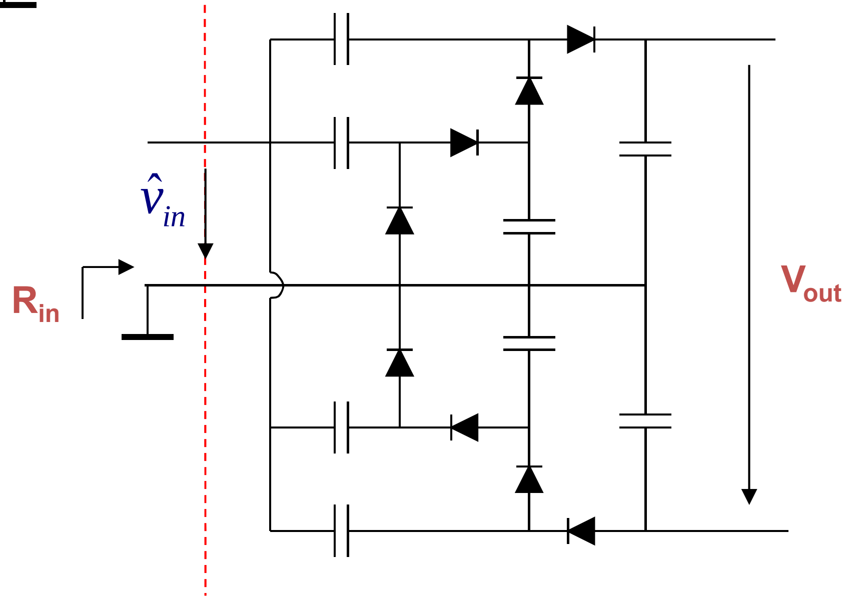
$$R_{ANT} = R_{IN} \quad \rightarrow \quad P_{AV} = \frac{\hat{v}_{in}^2}{2R_{in}}$$

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

Effect of Rin on the Rectifier input voltage

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

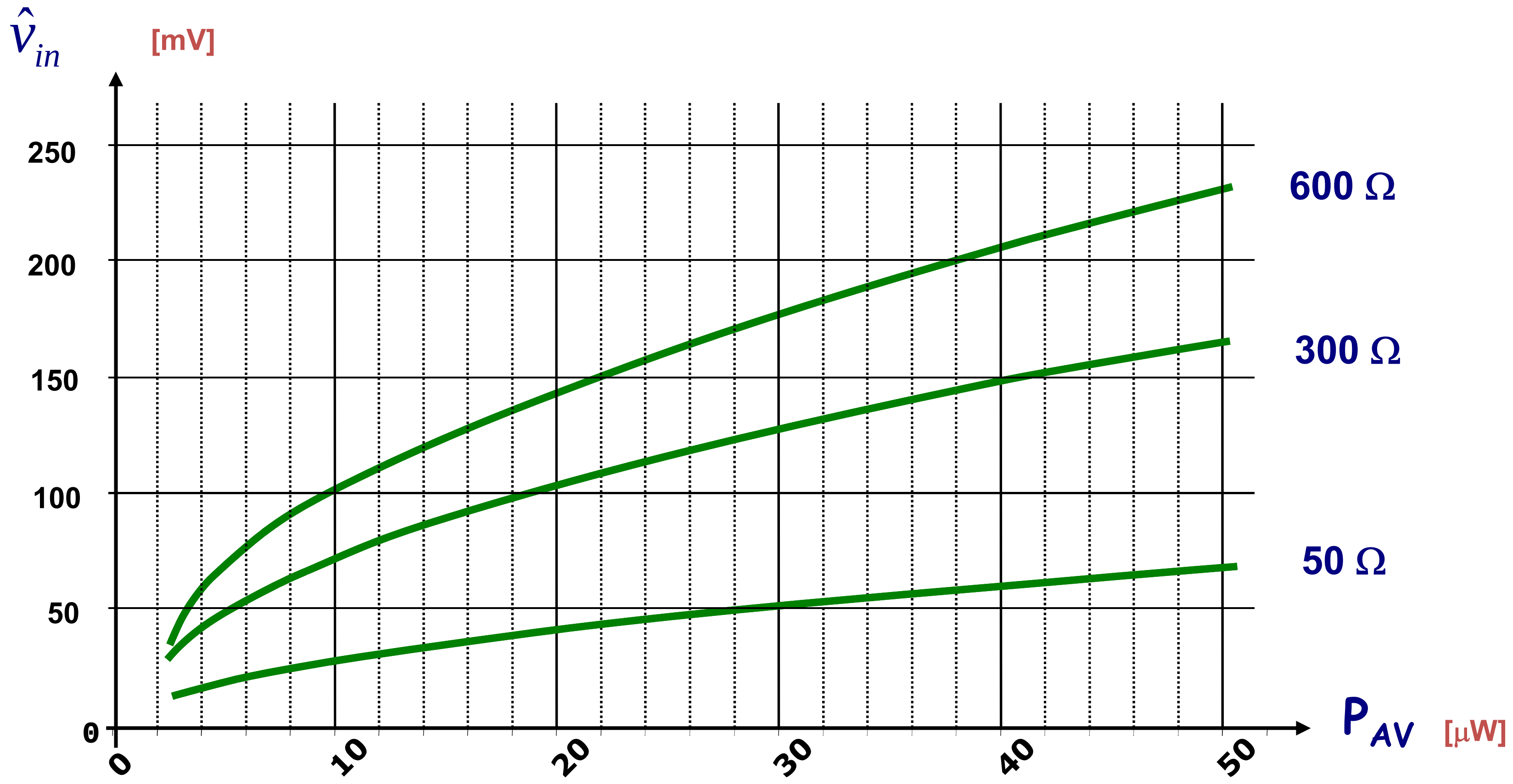




To maximize input Power and $\hat{v}_{in}$

- **Keep Rin equal to Rant**
- **Maximize Rant**

Rectifier Input Voltage in Impedance Matching Condition



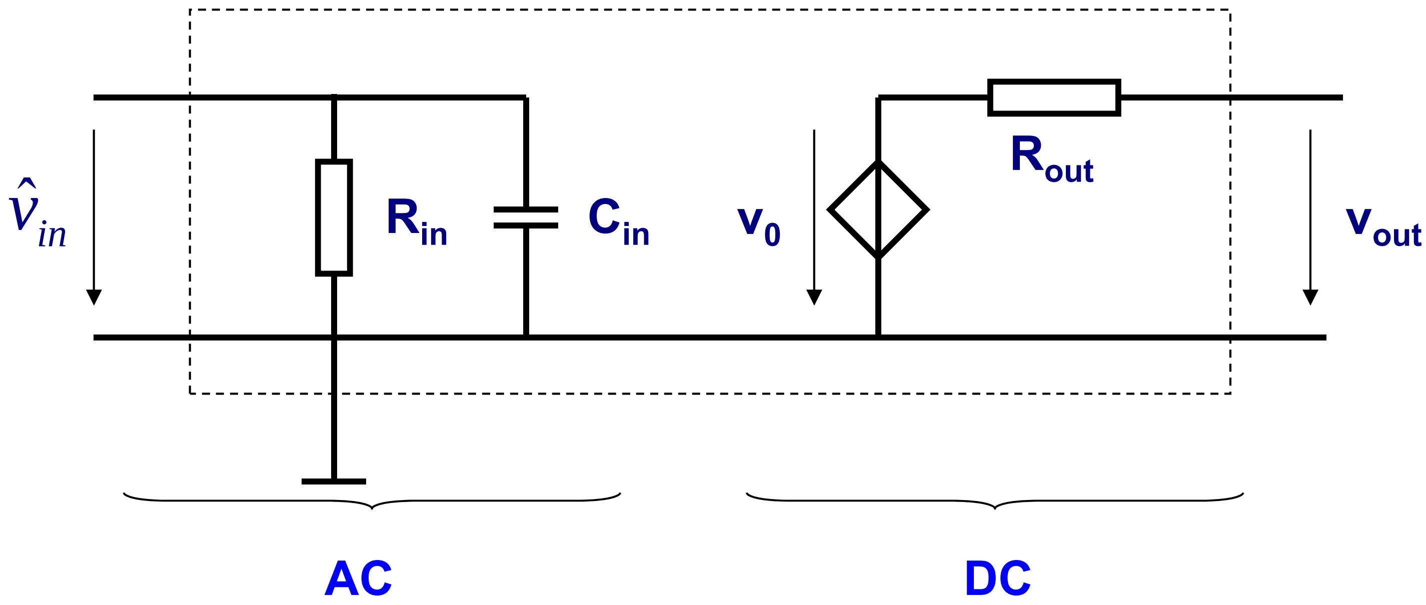
Rin = Rant

Assumptions to determine the rectifier equivalent model

- **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, n° 12, Dec. 2005, pp. 2771-2779**

Rectifier Equivalent Circuit Model



- **The antenna radiation resistance (R_{ant})**
- **The input power P_{in}**
- **The characteristics of the diodes which correspond to MOS diodes**

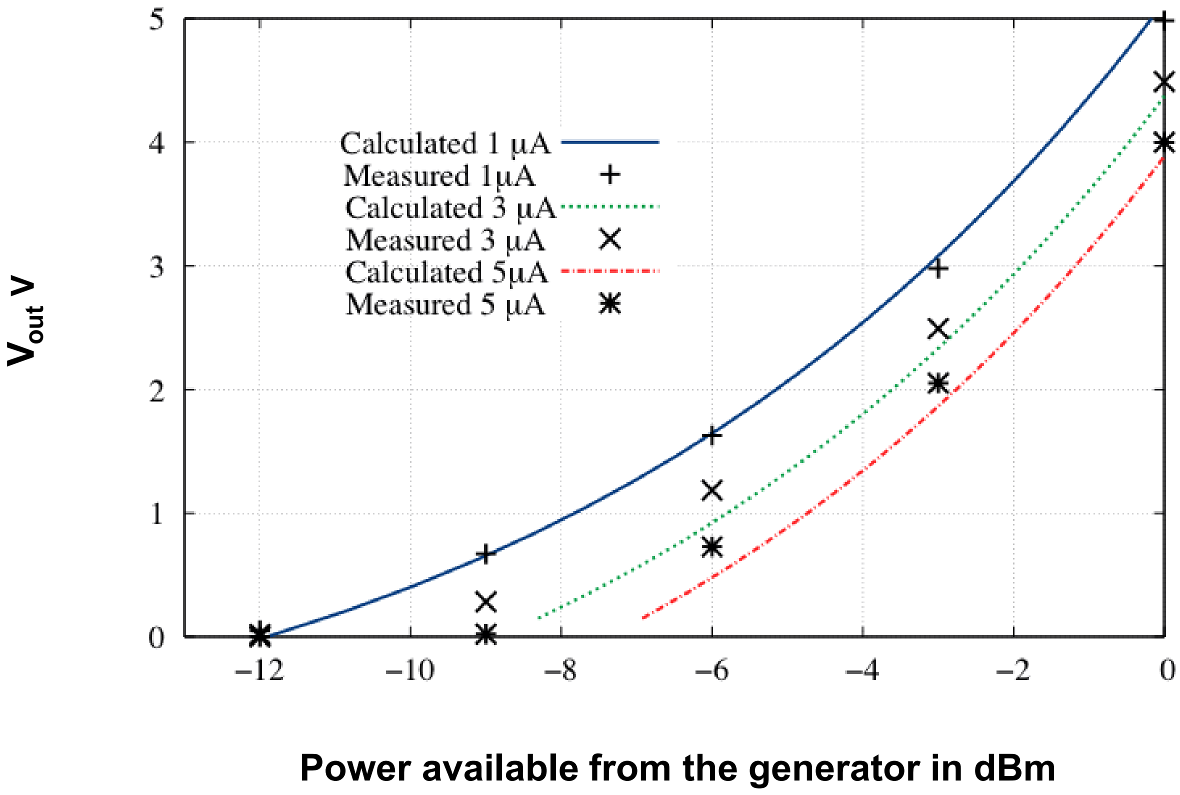
INPUTS

↓

- **The input impedance (R_{in}, C_{in})**
- **The output voltage V_{out}**
- **The output resistance R_{out}**
- **The DC output power P_{out} and the DC output current I_{out}**
- **The conversion power efficiency P_{out} / P_{in}**

OUTPUTS

Output voltage vs Input Power (Rant= 50Ω, freq= 900 MHz)
Technology: 0.5um CMOS Silicon On Saphire (SOS) Technology



0 dBm =
10 log (1 mW/ 1 mW)

- 10 dBm =
10 (log 0.1 mW/ 1 mW)

PART 3 –

Wireless Backscattering Data Transmission CMOS Tag at 2.4 GHz

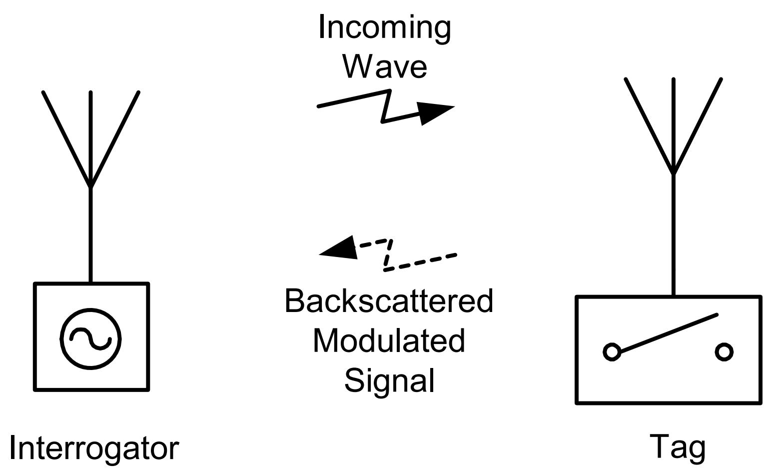
Prof. Catherine Dehollain

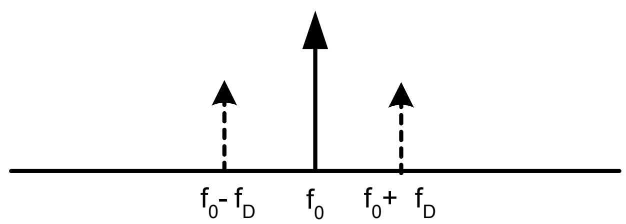
Group Leader of the RFIC group at EPFL

Principle of the Backscattering Data 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



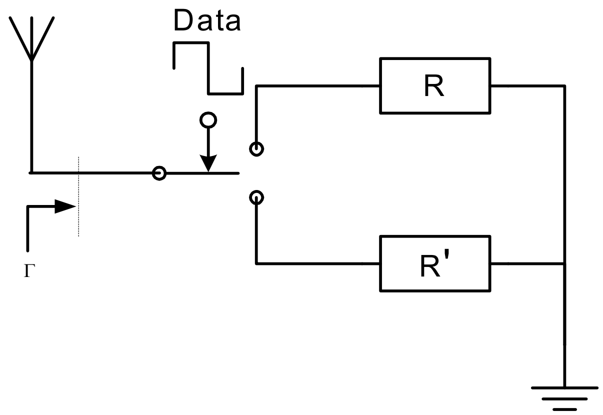


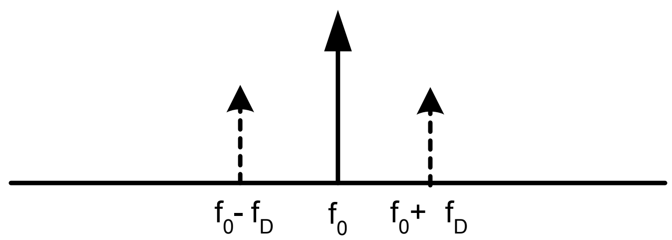
If Data = Bit "1"

- **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"

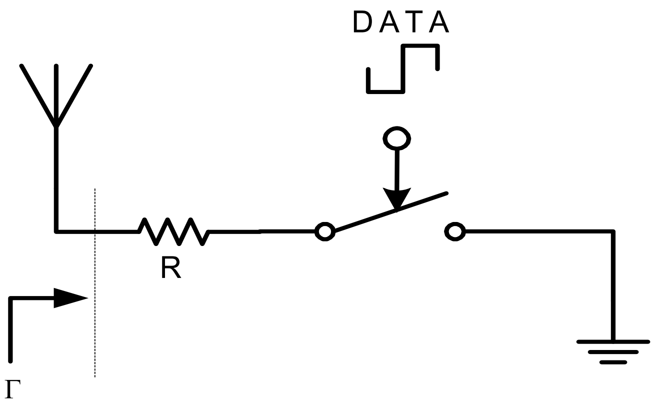
- **Zin = R is matched to the tag antenna**
- **All the power of the RF incoming signal is absorbed by the tag**



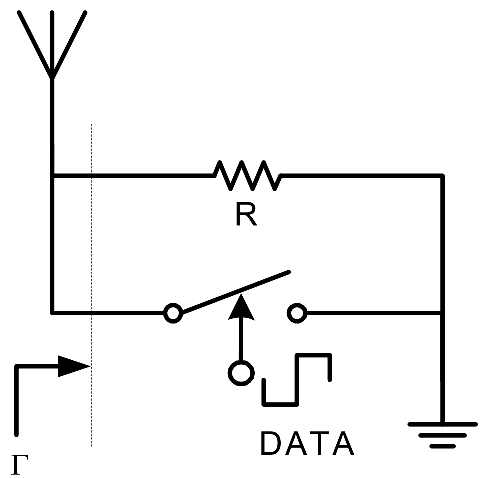


IEEE CAS Conference, C. Dehollain et al, 2001

Examples of Input Impedance Switcher



Series impedance switcher



Parallel impedance switcher

Motivation of the Back-Scattering Data Communication

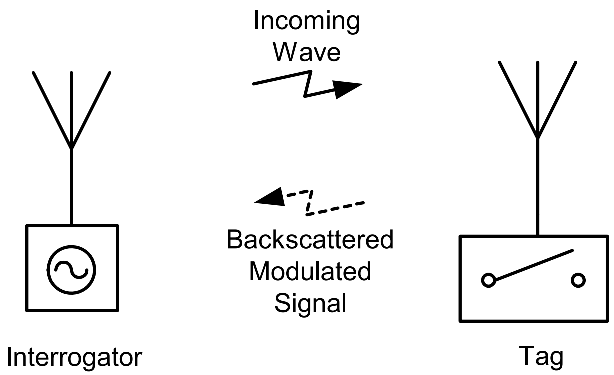
Motivation

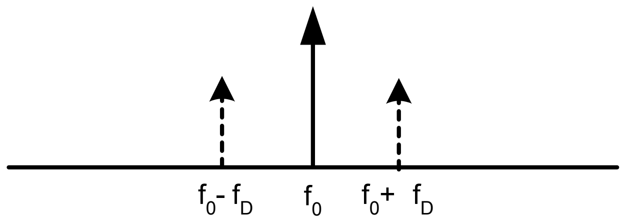
- Particularly suited when the power constraints are not the same on both sides of the radio link

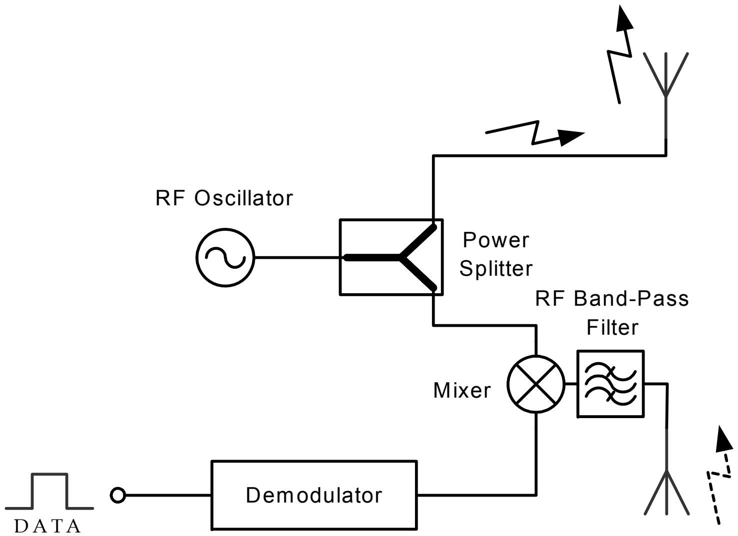
Examples

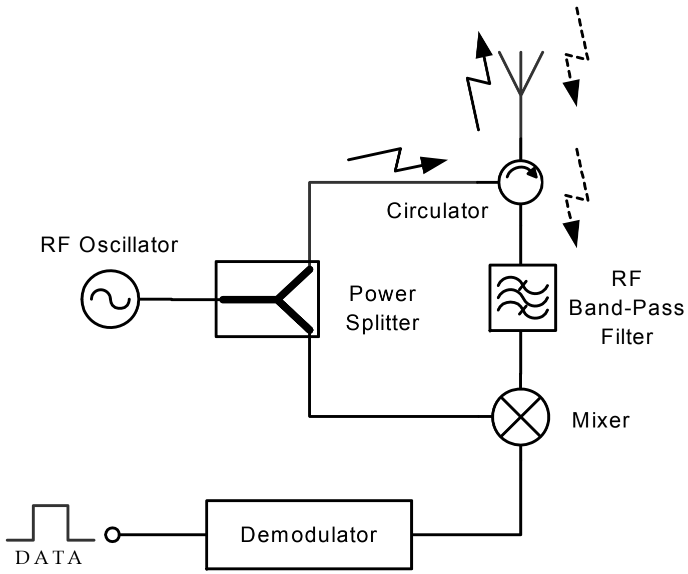
- House door-openers: one side of the wireless system is plugged into the mains supply
- Wireless computer peripherals (e.g. mice)
- Wireless memory tags
- Biomedical applications

Architecture of the Reader (Interrogator)

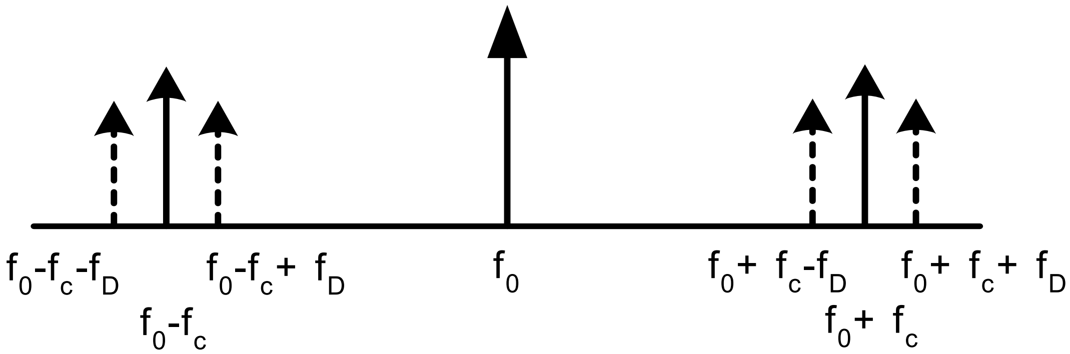


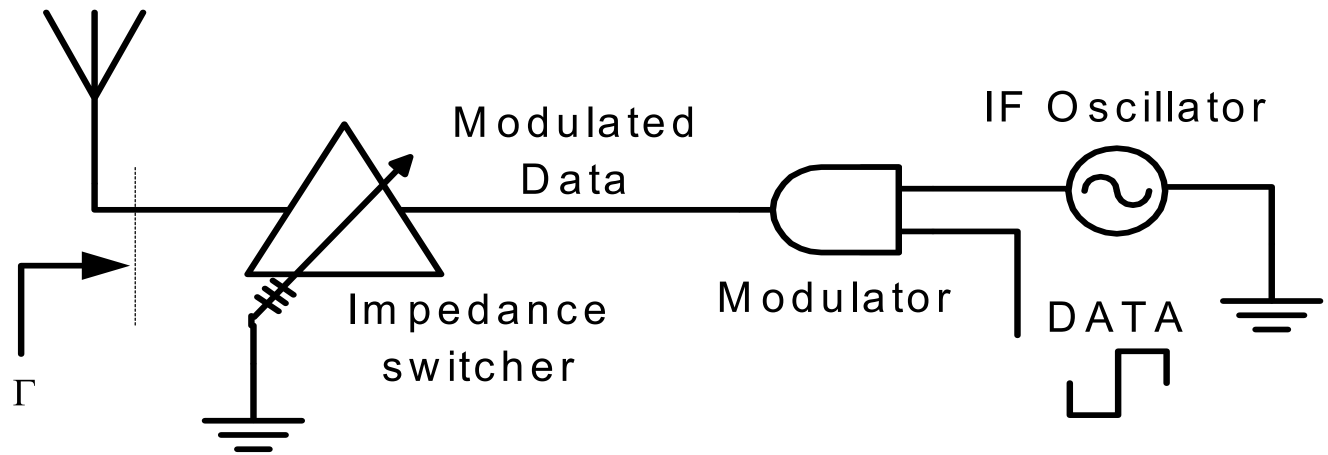






Intermediate Frequency (IF) Backscattering Data Communication





The reflection coefficient at the tag-antenna interface can vary in

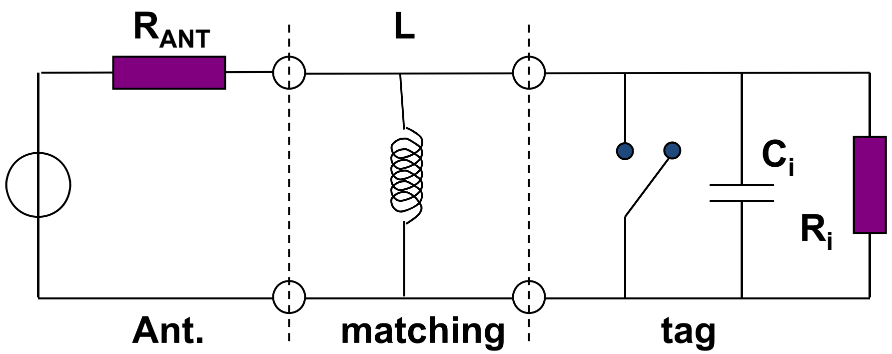
- **Amplitude**
- **Phase**

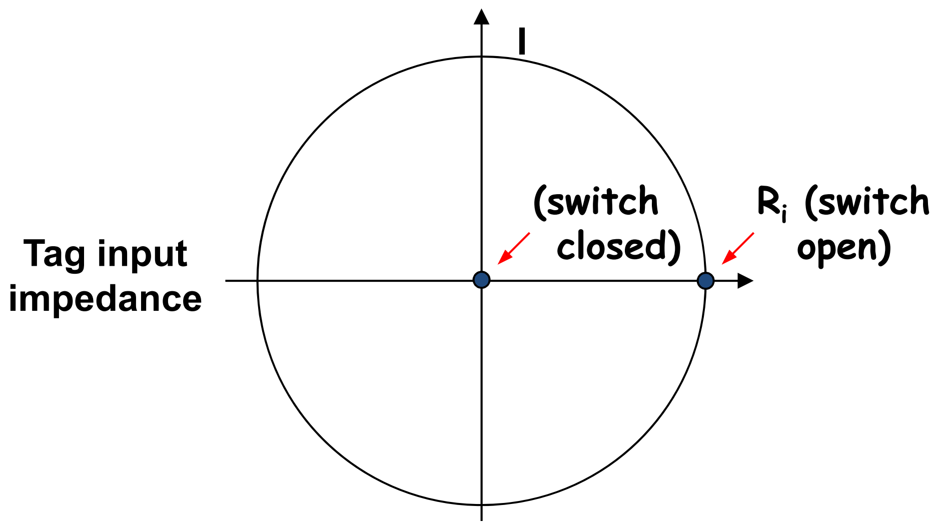
Two basic binary modulation types are possible: ASK & PSK

They must be compared in terms of

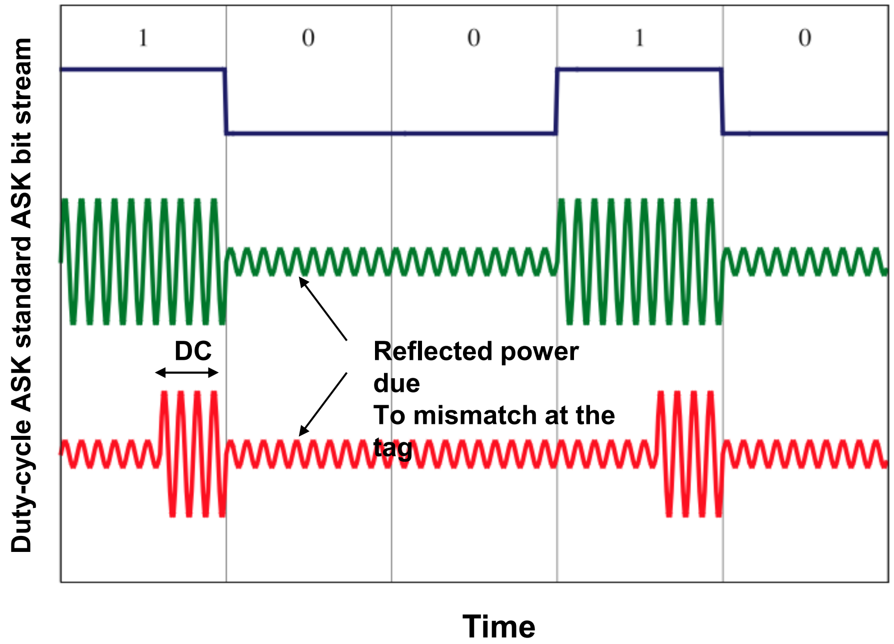
- **Power available for both tag supply & for communication**
- **Communication quality (Bit Error Rate BER)**

ASK Modulation



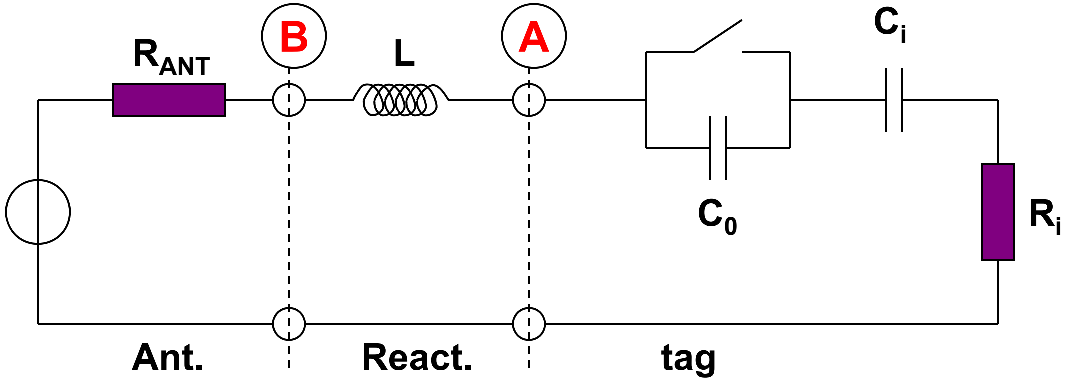


Reflected ASK modulated signal



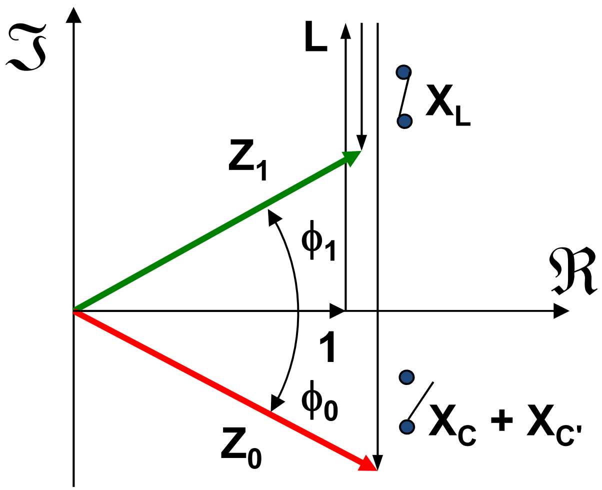
Bit « 1 »: switch closed

Bit « 0 »: switch open



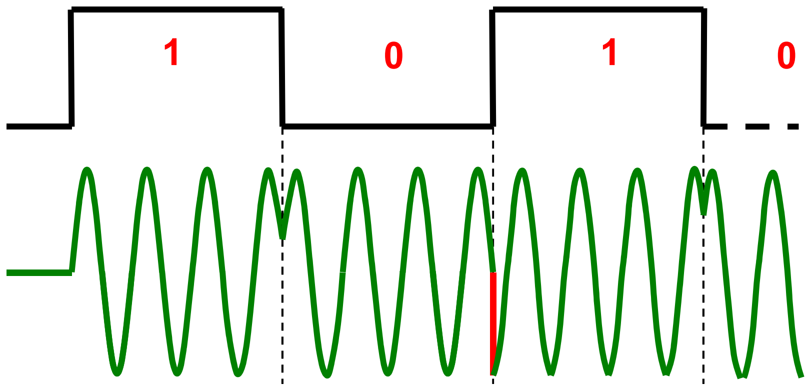
In **B**: Absorbed power and reflected power are constant

In **A**: Voltage at tag input is however **not** constant



State 1
Switch closed

State 0
Switch open



Tag input impedance at B

Definition of the Bit Error Rate

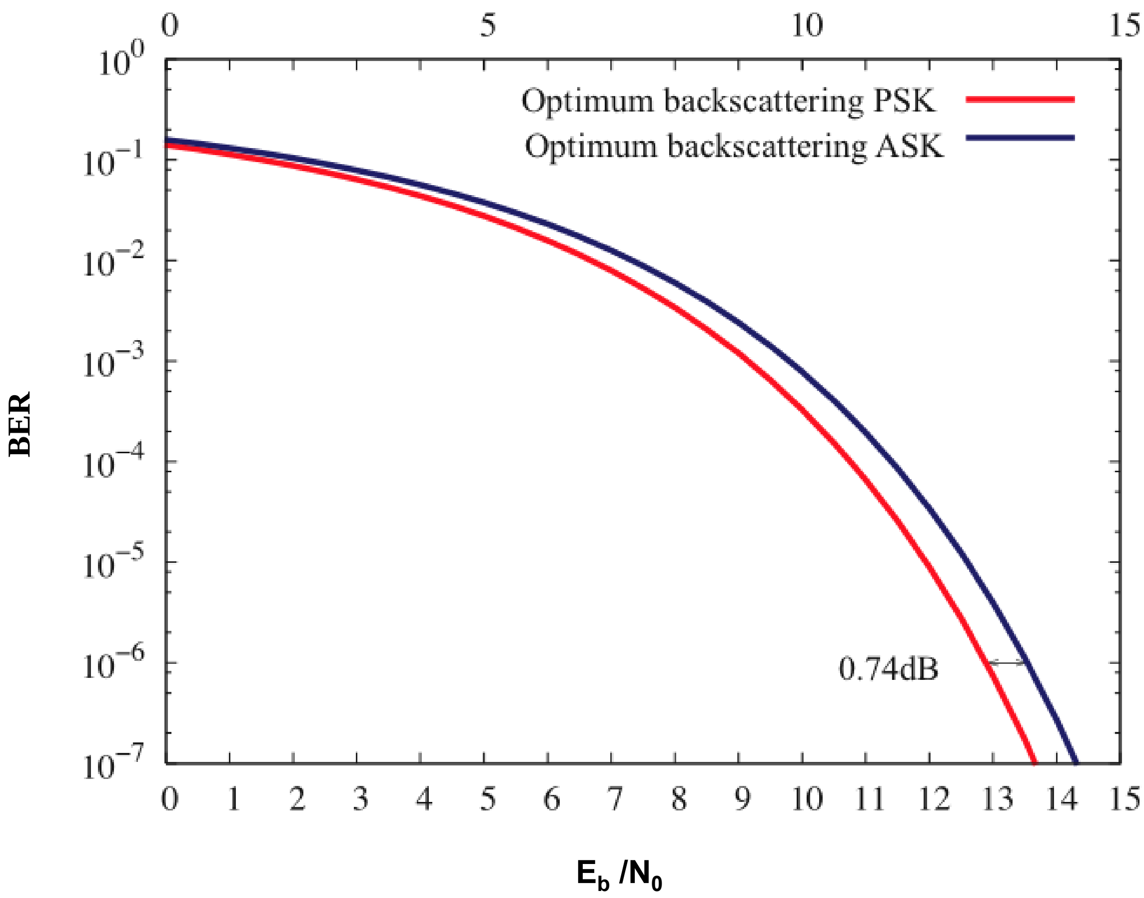
BER = 10^{-4} → 1 bit is fault over 10'000

Comparison through the Bit Error Rate (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
« Design and Optimization of Passive UHF RFID Systems »
Editor Springer, year 2007, ISBN: 0-387-35274-0.

Performance of ASK / PSK Modulations

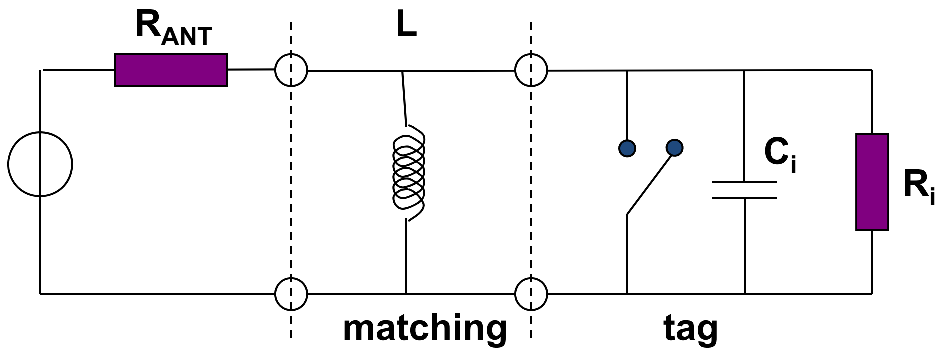


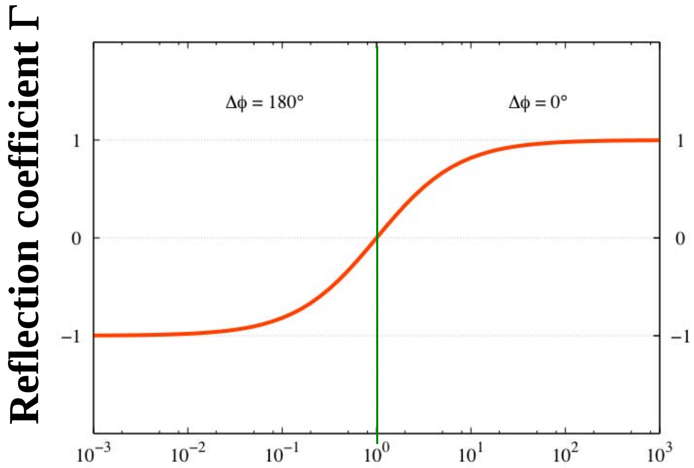
Optimal ASK and PSK BER comparison
(ASK: DC = 100%, α = 1 and PSK: α = 1, Qin = 5.6)

L and Ci resonate at the operating frequency

Reflection coef. = (Ri – Rant) / (Ri + Rant) = (α – 1) / (α + 1)

Impedance Matching conditions
$\Gamma = 0$ and $\alpha = 1$





Normalized resistance α = Rin / Rant

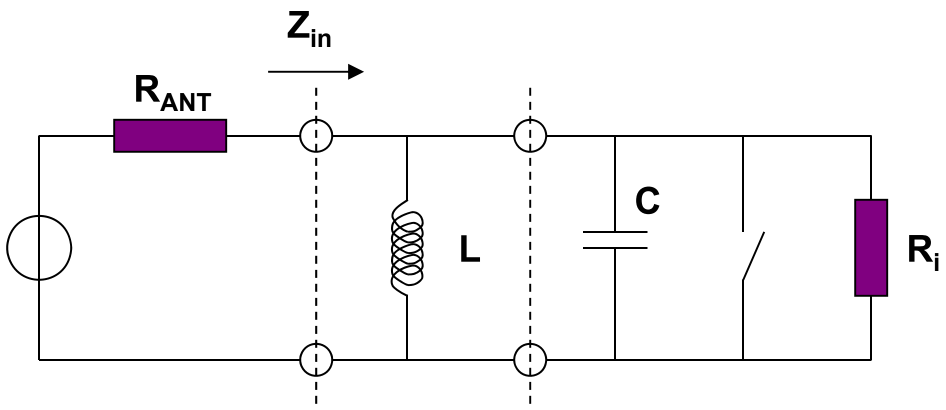
Priority to communication distance

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

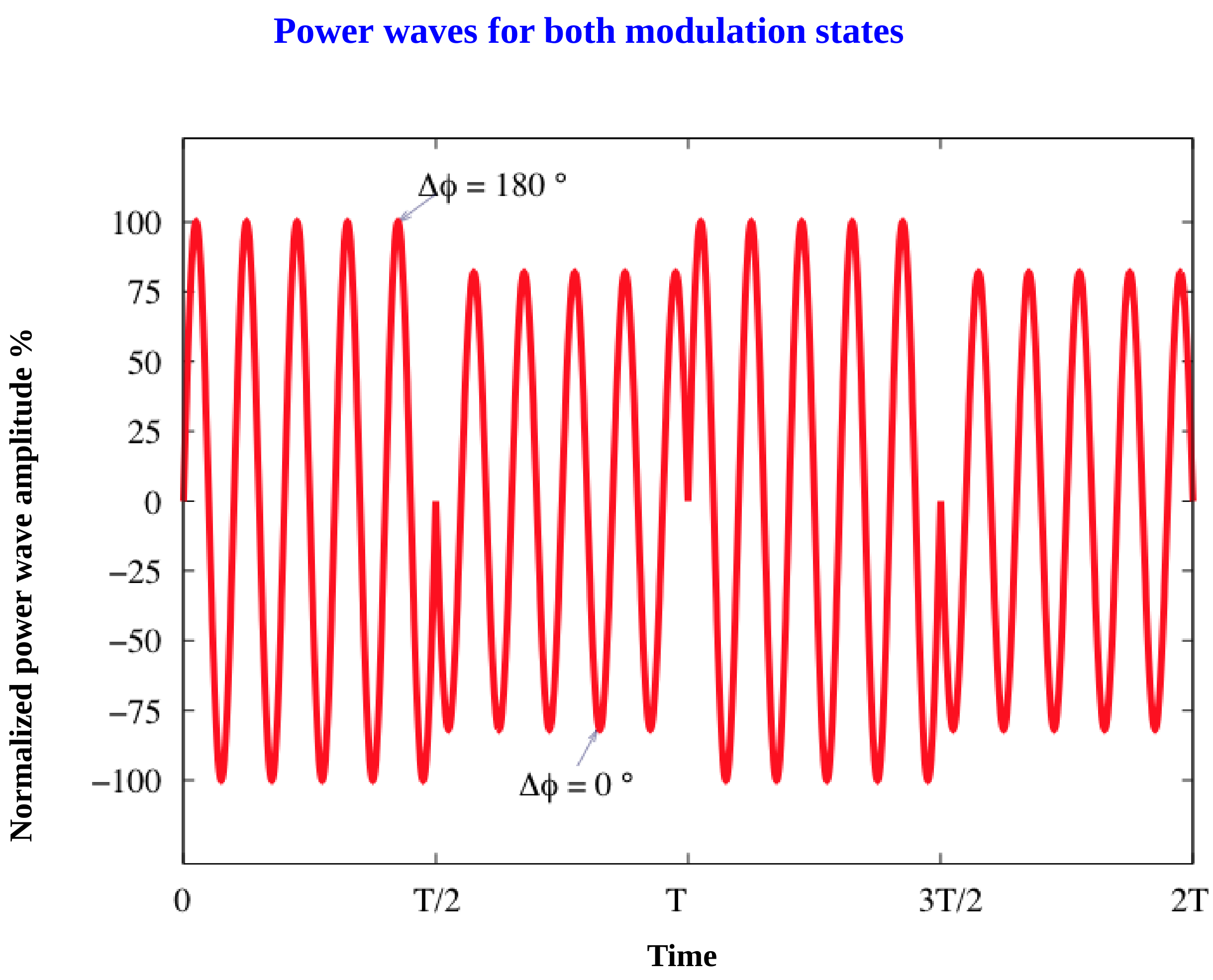
Pseudo PSK Modulation



In practice R_{in} is much larger than R_{ANT}

- **Voltage at rectifier input is higher than in impedance matching condition so that the rectifier has enough input voltage to operate**
- **Absorbed power is lower than in impedance matching condition**
- **Modulation is efficient with a 180° phase shift of the reflection coefficient**

Power waves for both modulation states



Tag and Reader

Initial Specifications for the tag IC

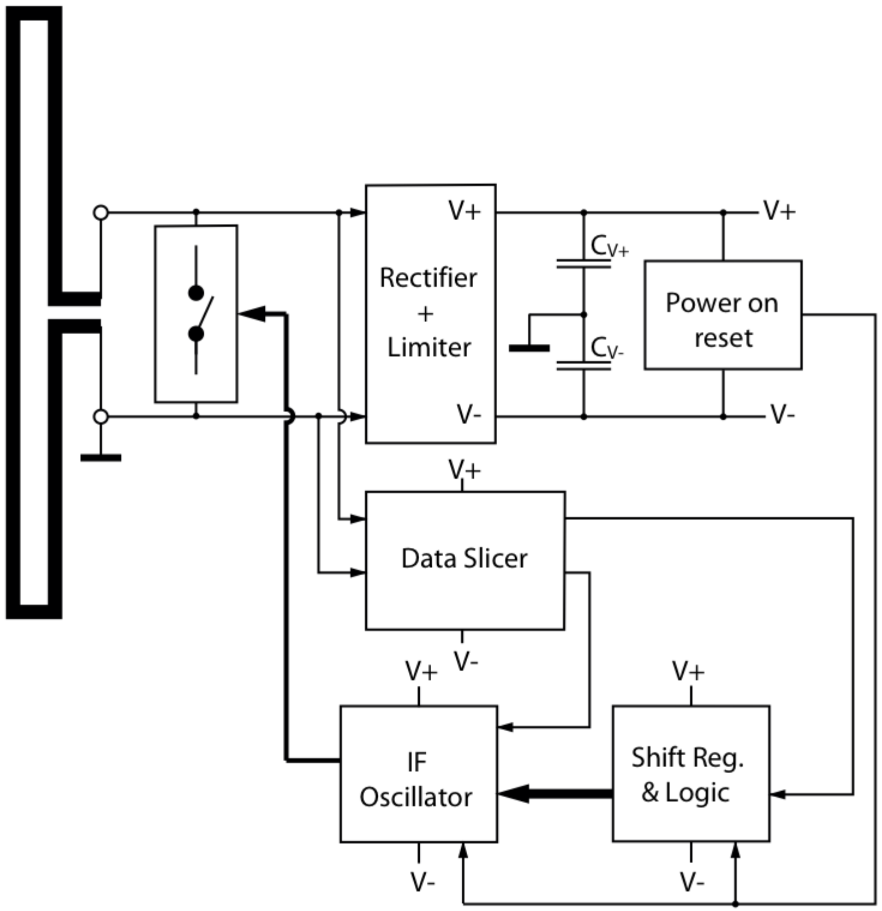
Parameter	Value
Frequency range	2.40 – 2.48 GHz
Reader P_{EIRP}	4 W
Tag power	≈ 1 μW
Operating distance	> 5 m
Reader to tag	AM (OOK) modulation
Tag to reader	p-PSK modulation
Data rate	≥ 10 kbps

- Desired features
  - Low-V_T rectifying devices ➔ start-up voltage
  - Steep subthreshold slope ➔ efficiency
  - Overall excellent RF behaviour ➔ μwave operation

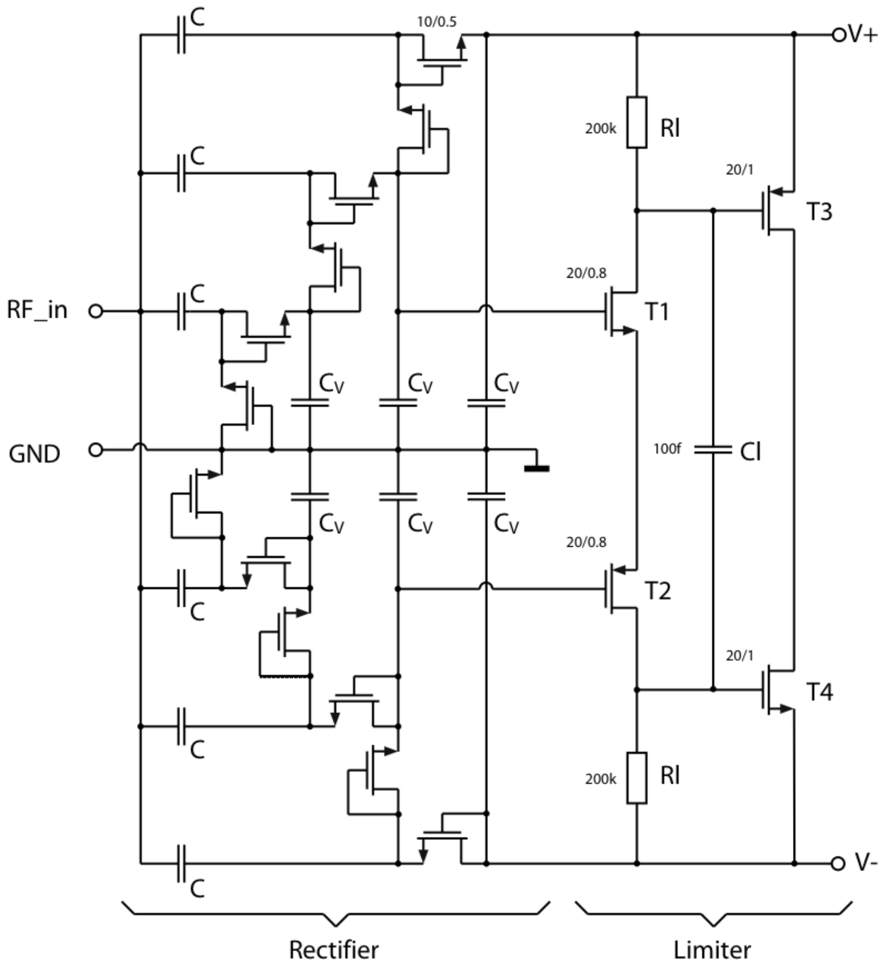
- Selected technology

  PEREGRINE 0.5μm FD SOS Technology
  Gate oxide thickness : 10 nm
  Silicon layer thickness : 100 nm
  3 V_T's available for both N-channel & P-channel transistors
  F_T,typ = 14 Ghz, F_{MAX},typ = 55 Ghz @ V_{DS}=1.5V & I_D=5mA (n-chan.)

Building Blocks

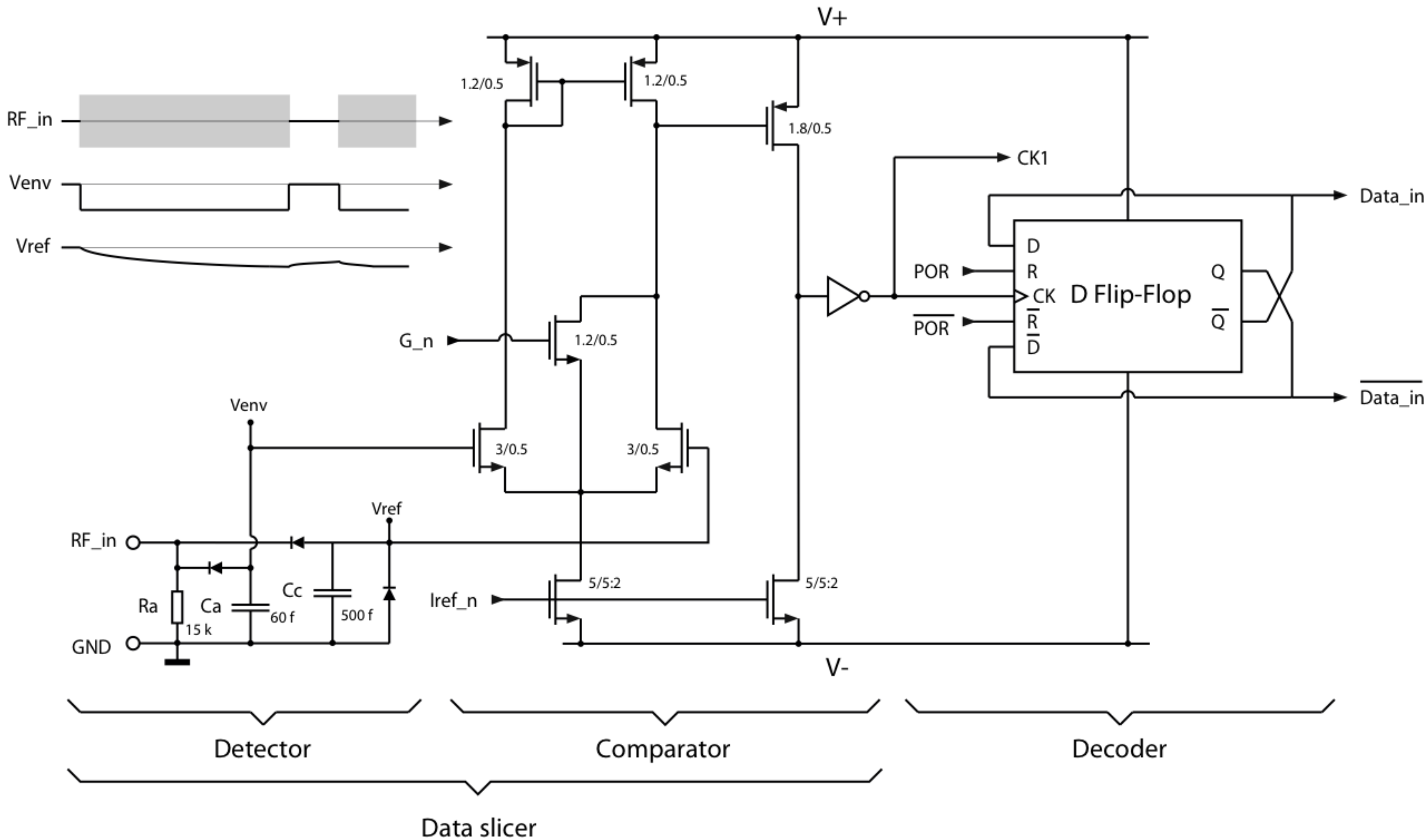


Rectifier and Limiter

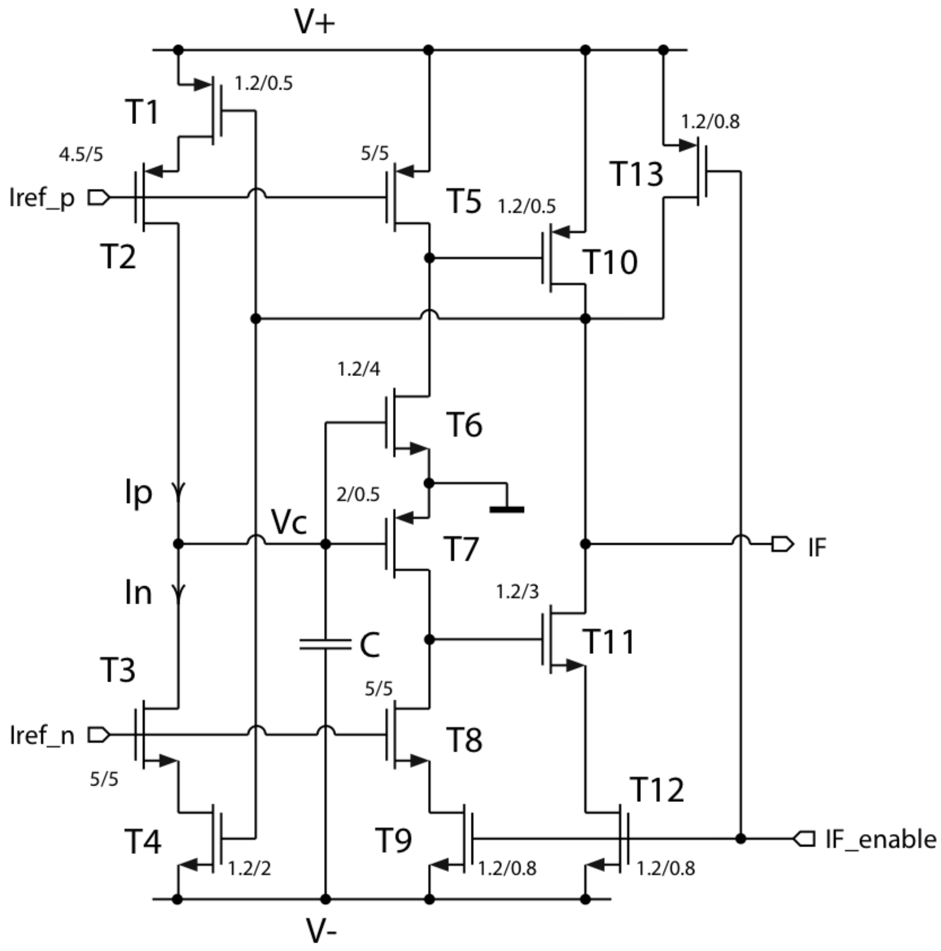


3 Stages Greinacher Rectifier

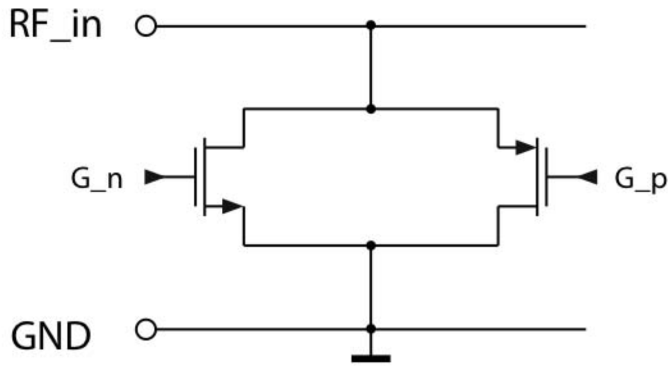
Detector + signal conditioning



IF Oscillator and Modulator

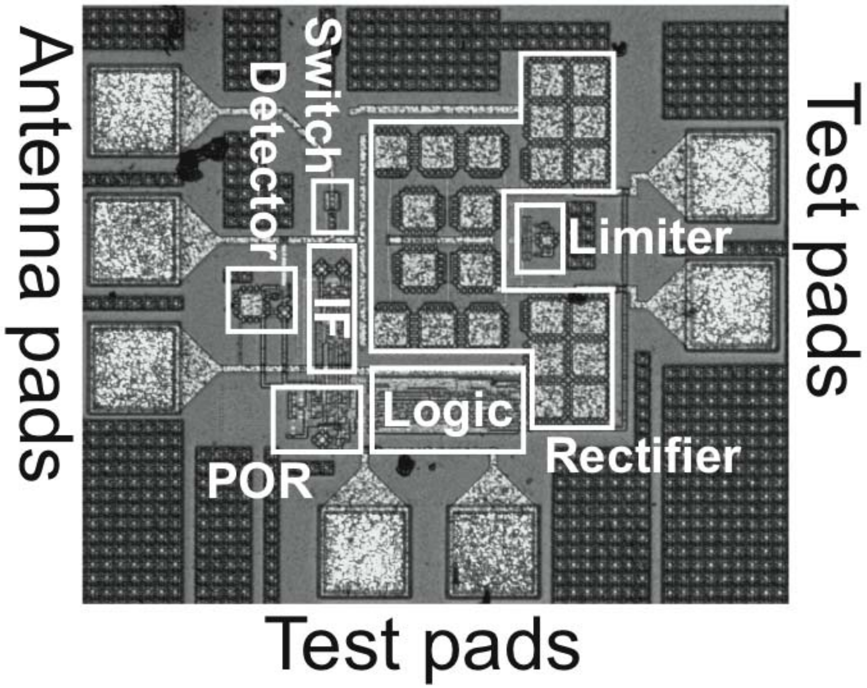


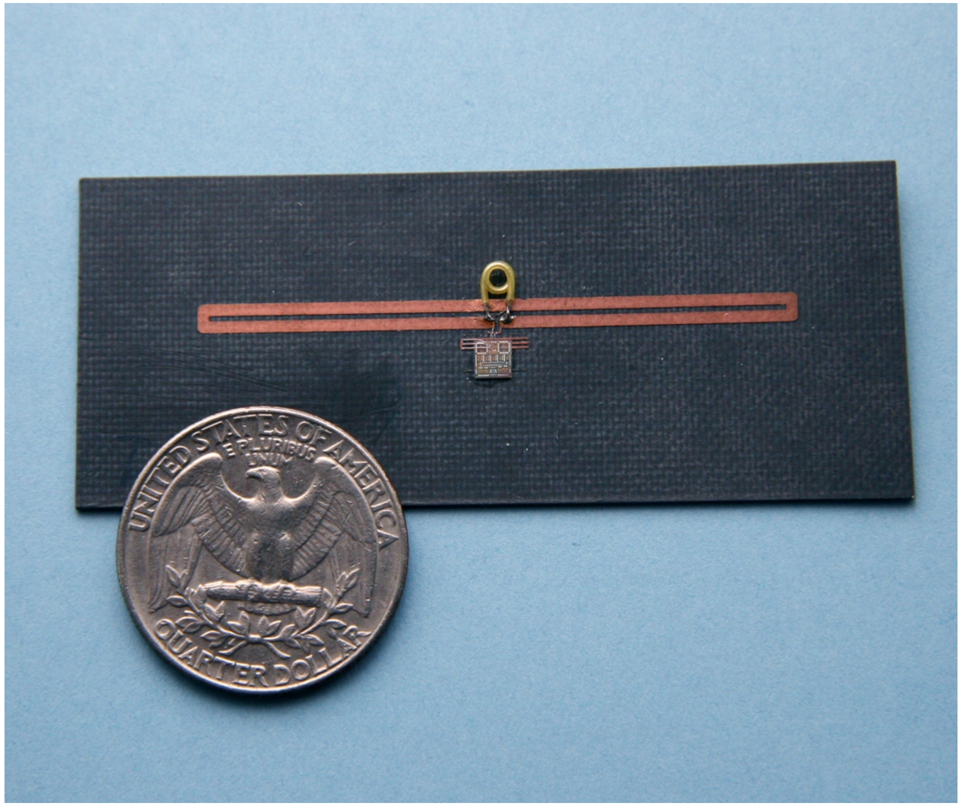
IF Oscillator



Modulator

Complete Tag with antenna





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

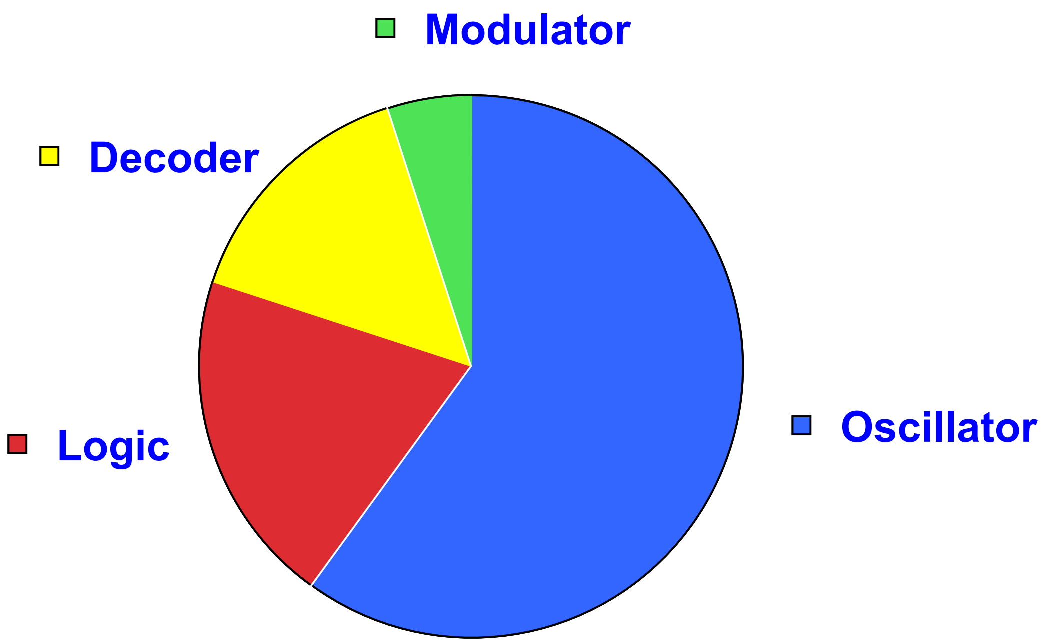
Frequency MHz	Antenna	Range m
2450	λ/2-dipole	6
2450	λ/2-dipole with inductive matching	9
2450	folded dipole	7
2450	folded dipole with inductive matching	12

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

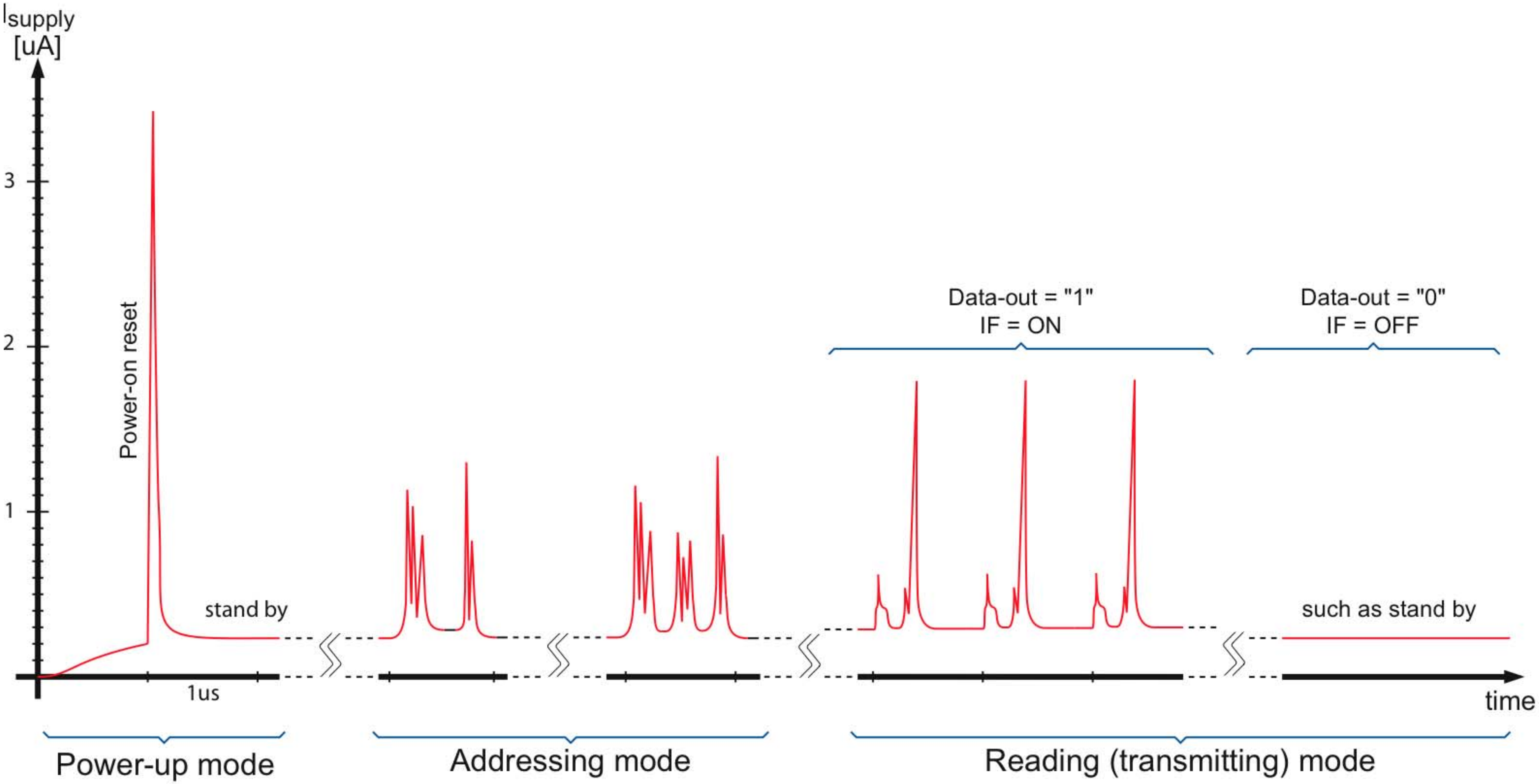
J.P. Curty, N. Joehl, C. Dehollain and M. Declercq,
"Remotely Powered Addressable UHF RFID Integrated System ",
IEEE Journal of Solid-State Circuits, Vol. 40, No 11, November 2005, pp. 2193- 2202.

Power distribution between tag components

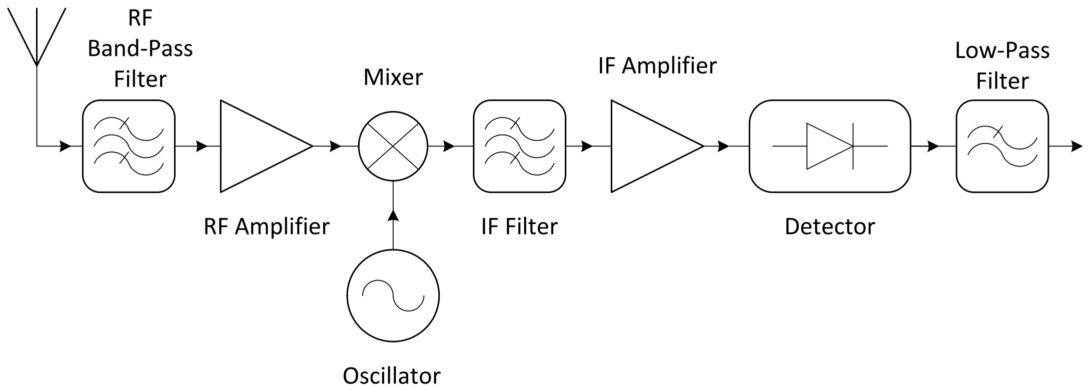
Power management is a key issue



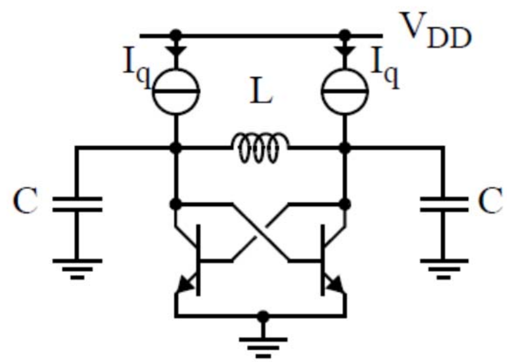
Tag current consumption



Basic Architecture of the Receiver of the Reader

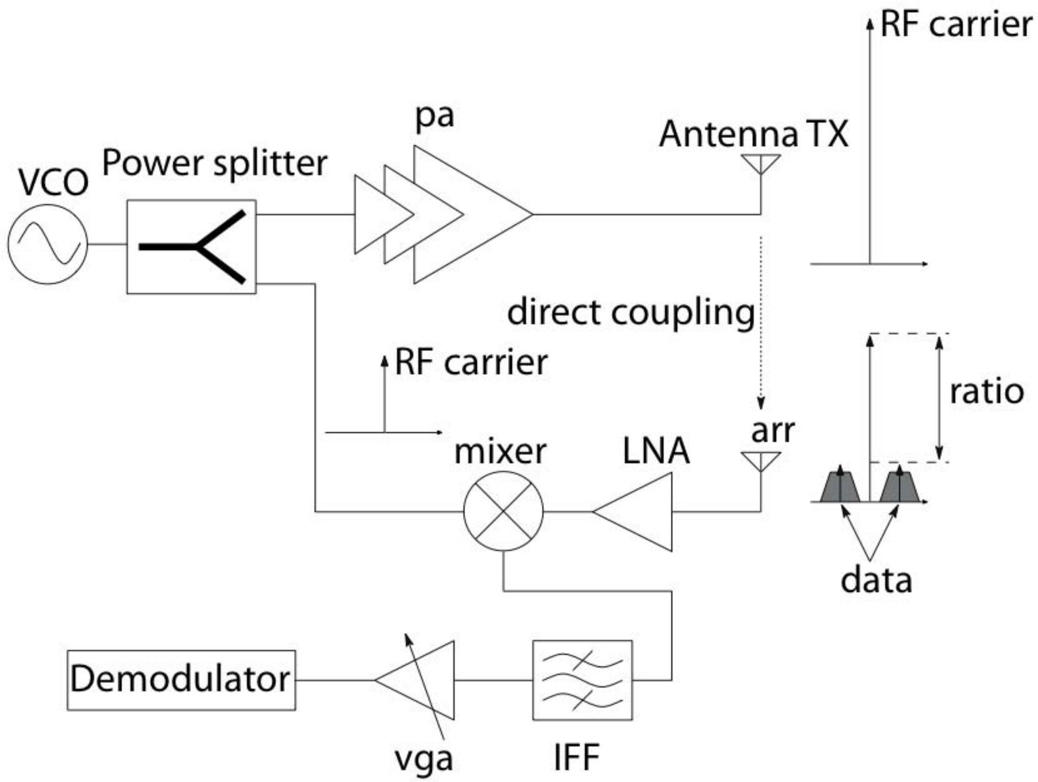


Super-heterodyne receiver
for AM demodulation



LC cross-coupled pair oscillator

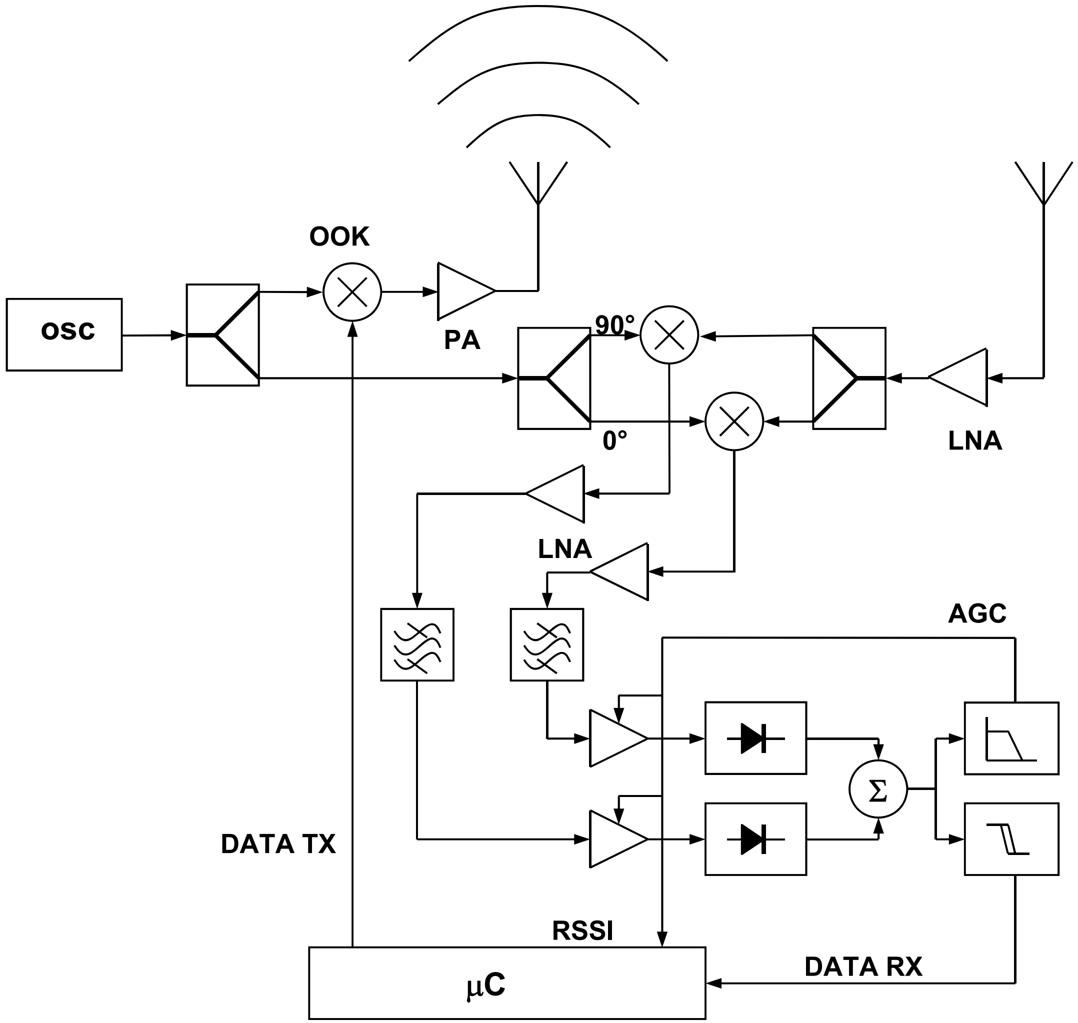
Basic Architecture of the Reader (Receiver and Transmitter)



- **RF Front-end desensitization can occur due to direct-coupling effect: IP3 issue**

Advanced Architecture of the Reader (Receiver and Transmitter)

Receiver sensitivity: -105 dBm



Summary

- Wireless power transmission & rectifier models have been developed for optimizing the power supply available for the tag
- Different backscattering modulation types were compared and pPSK was identified as an excellent candidate given the naturally high input impedance of the tag
- Readers's main issues were studied and optimized
- 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 matched led to a measured reading distance of 12 m.

PART 4 –
Dual Frequency System
Wireless Power Control Loop

Prof. Catherine Dehollain
Group Leader of the RFIC group at EPFL

Dual frequency system

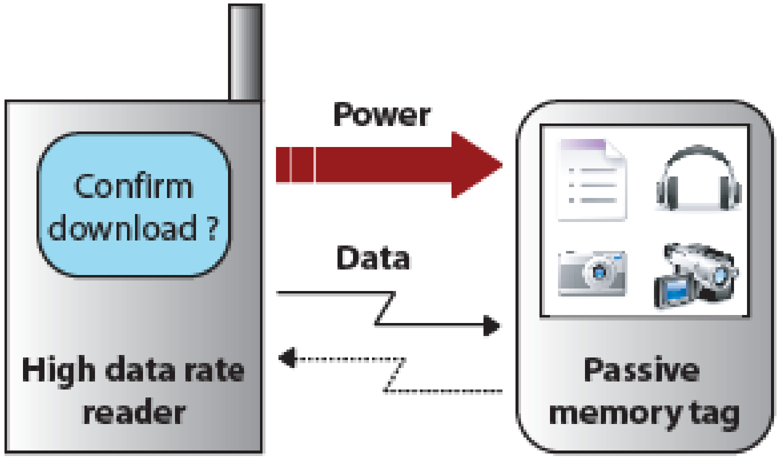
- **Some regulations are fine for WPT (high Tx power)**
- **Others for communication (large bandwidth)**

Frequency band	Max. power	Bandwidth	Suitable for
2400.0-2483.5 MHz	10 mW ERP	83.5 MHz	Communication
865.6-867.6 MHz	2 W ERP[1]	2 MHz	Remote powering
2446-2454 MHz	4 W EIRP[2]	8 MHz	Both[2]

([1]~3.3 W EIRP, [2]for indoor use)

Scenario 1: Single frequency system
Scenario 2: Dual frequency system

Passive Memory Tag



European IP

Project MINAMI

- Contain high capacity non volatile memory
- Can store multimedia content
- New distribution method for
  - Videos
  - Music
  - Images

Passive Memory Tag

Read/write data rate: 10 Mbit/s

Distance range: 15 cm to 30 cm

$V_{DC} < 3V$ $I_{DC} < 3$ mA

Compatible with state-of-the-art Non Volatile Memory (NVM)

FRAM (reference): 7 mW @ 10Mbps

Total consumption (IC + memory): 10 mW

Tag IC realized in a standard CMOS process

Rectifier efficiency: 40%

Dual Frequency System

SPECIFICATIONS
Distance Range: 0.15 m
Data Rate: 10 Mbit/s
Power Consumption: 10 mW

Medium operating range
High data rate

Data Rate: 10 Mbit/s → Minimum Frequency Bandwidth = 10 MHz
RF Frequency for data transmission: 2.4 GHz to 2.485 GHz

Power Consumption: 10 mW → Mini Pav = 25 mW for rectifier power efficiency = 0.4

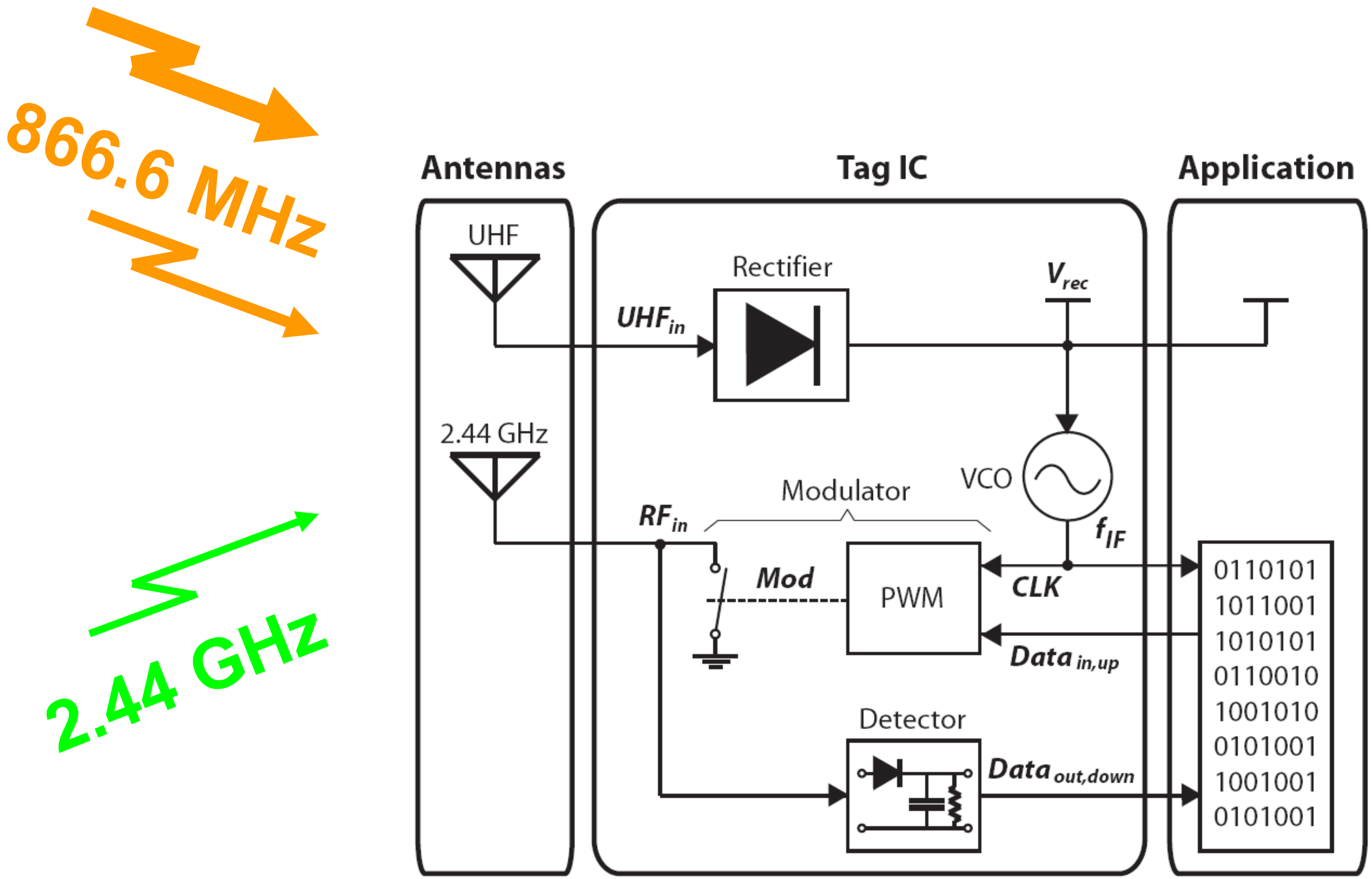
Peirp = 3.3 W, Gr = 1, d = 0.15 m, f = 868 MHz → Pav max = 102 mW: OK
Peirp = 4 W, Gr = 1, d = 0.15 m, f = 2.4 GHz → Pav max = 16.2 mW: Not OK

→IT IS NECESSARY TO HAVE A DUAL FREQUENCY SYSTEM: 0.87 GHz, 2.4 GHz

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

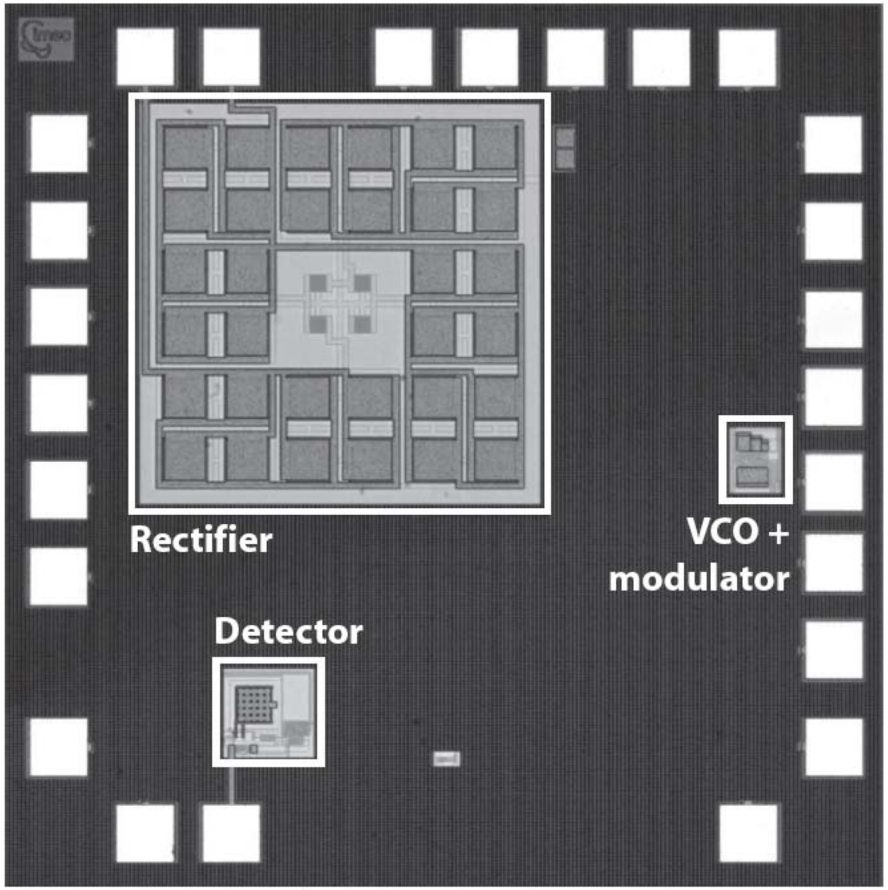
Issues in write mode

Insufficient selectivity of the 2.4 GHz antenna due to Large UHF interfering signal



Chapter 7 of PhD thesis, No 4616, N. Pillin, year 2010, EPFL

Photo of the dual frequency passive RFID Backscattering tag



- **Process: UMC CMOS 0.18μm**
- **Area: 1.5 mm x 1.5 mm (with I/O pads)**

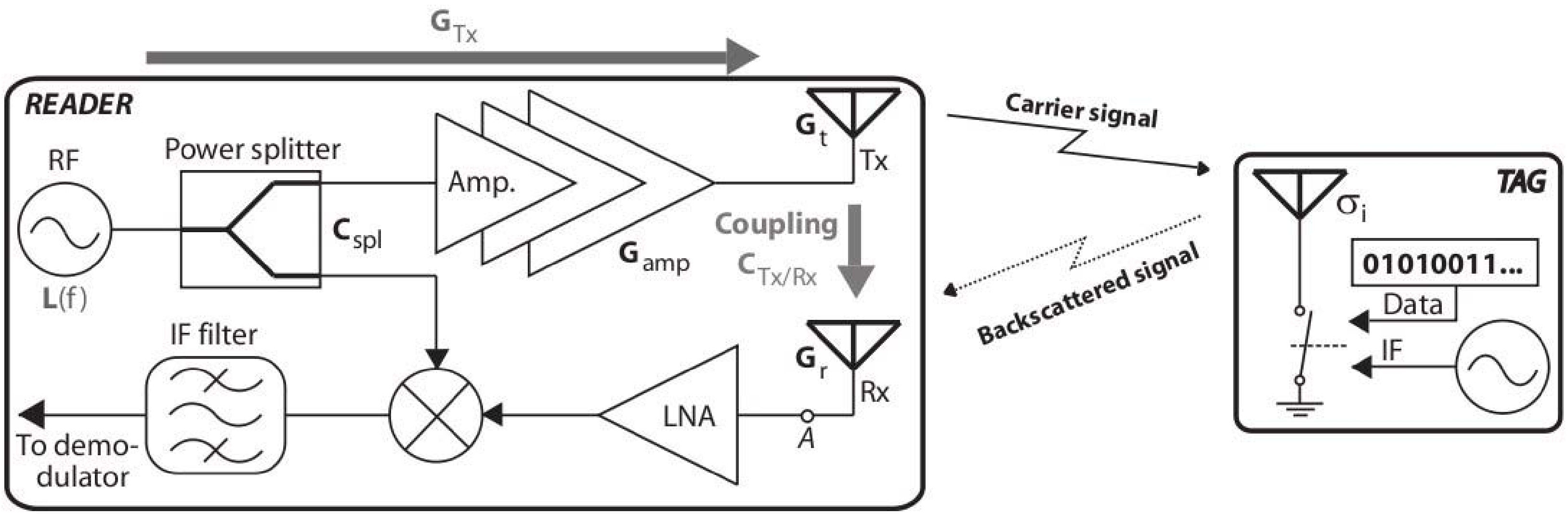
Summary on the RFID dual frequency passive tag

- Dual frequency, passive RFID tag that can be read at 10 Mbps at 33 cm
- Outperforms commercial products and published works
- IC realized in 0.18um CMOS process
- Rectifier's power efficiency: 36%
- Tag detector's able to operate at 10 Mbps in read mode

Read Range of passive, far field RFID systems

A model is derived to estimate the read range of passive, far-field RFID systems

The phase noise of the local oscillator in the reader, which is transmitted to the Rx antenna through Tx/Rx coupling, has an important impact

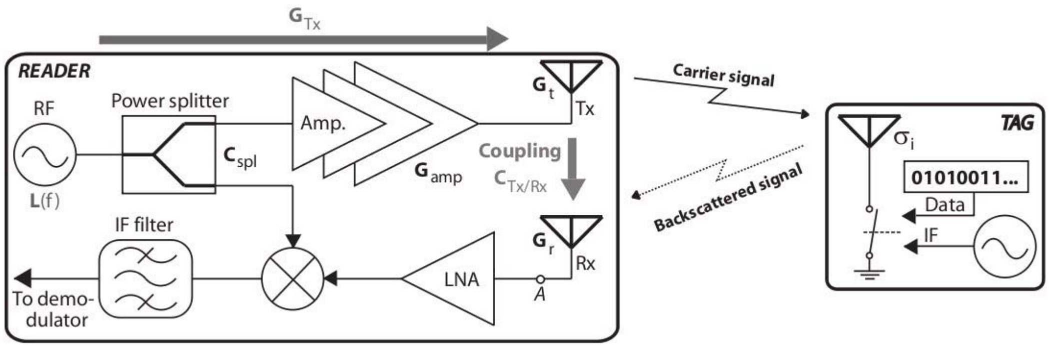


PRIME Conference, N. Pillin, C. Dehollain, M. Declercq, Cork, July 2009

Tag antenna switches between two different Radar Cross Section called RCS: $\boldsymbol{\sigma_1}$ and $\boldsymbol{\sigma_2}$

Effective tag antenna RCS is expressed by:

$$\sigma_i = \left(\frac{\sqrt{\sigma_1} - \sqrt{\sigma_2}}{2}\right)^2$$

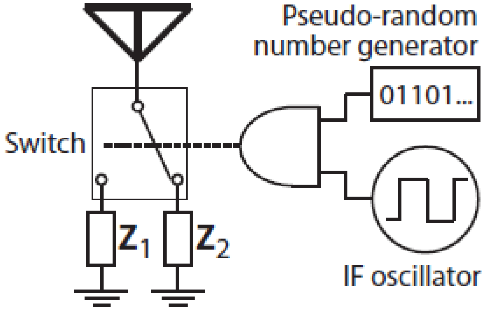


Model

$$d_{max} = \sqrt[4]{\frac{G_t G_r \alpha \sigma_i}{C_{Tx/Rx} N(f_{SB}, B) SNR_{min}} \frac{\lambda^2}{(4\pi)^3}}$$

N (fsb, B): integral of the phase noise on B
Gt: gain of the antenna of the tag
Gr: gain of the antenna of the reader
CTx/Rx: coupling factor
SNRmin: mini SNR at the input of the reader

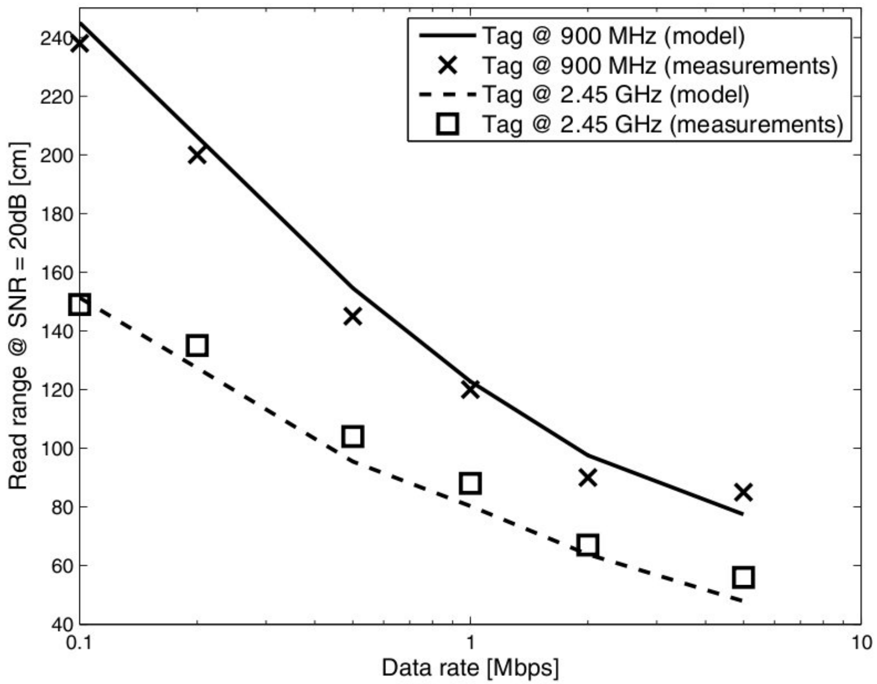
PRIME Conference, N. Pillin, C. Dehollain, M. Declercq, Cork, July 2009



Name	Tag @ 900 MHz	Tag @ 2.45 GHz	Unit
f_{RF}	900	2450	MHz
λ	33.3	12.2	cm
f_{IF}	10	10	MHz
G_t	2	7	dBi
G_r	2	7	dBi
$C_{Tx/Rx}$	-23	-27	dB
Z_1	50	50	Ω
Z_2	0	∞	Ω
σ_i	64.4	17.4	cm^2
α	-7	-7	dB

Measurements compared to Model

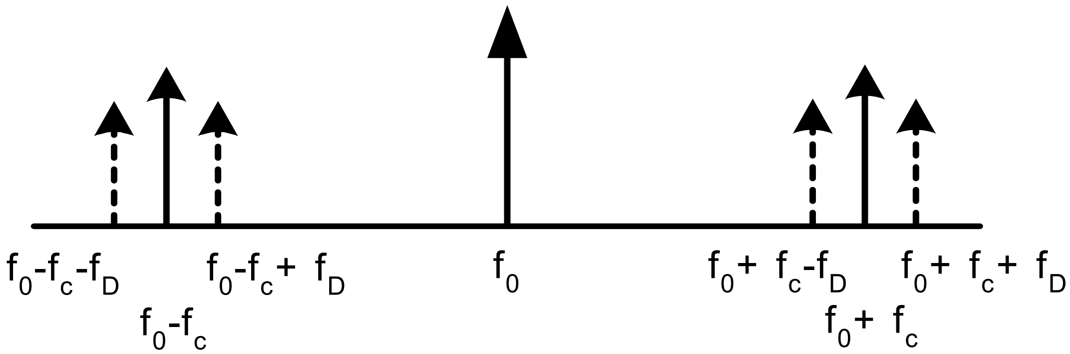
Measurements were achieved on a laboratory reader/tag system at 900 MHz and 2.45 GHz to verify the model.

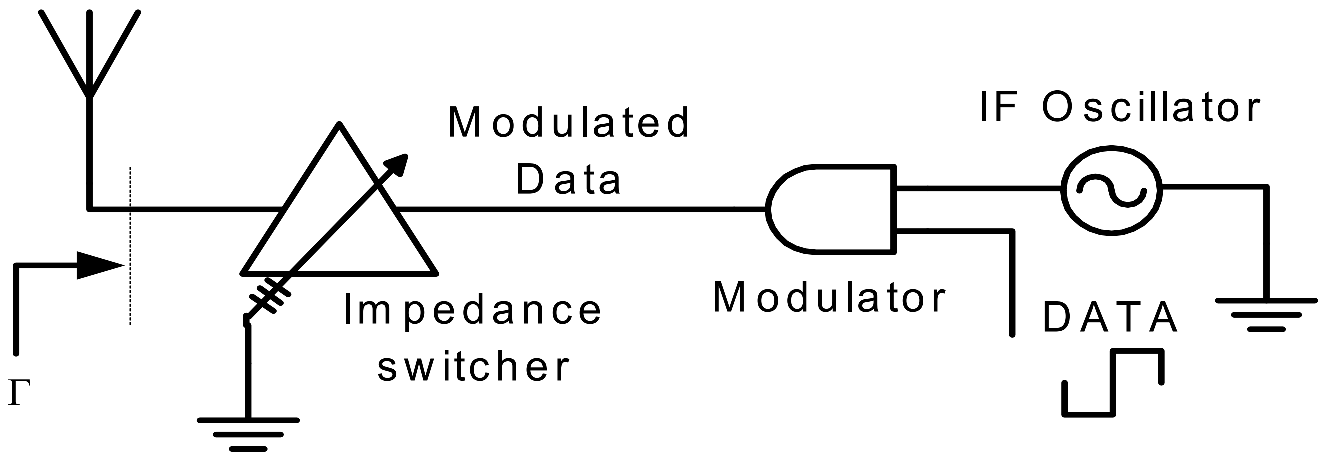


PRIME Conference, N. Pillin, C. Dehollain, M. Declercq, Cork, July 2009

Optimisation of the transfer of power

Sub-Carrier (IF) Oscillator





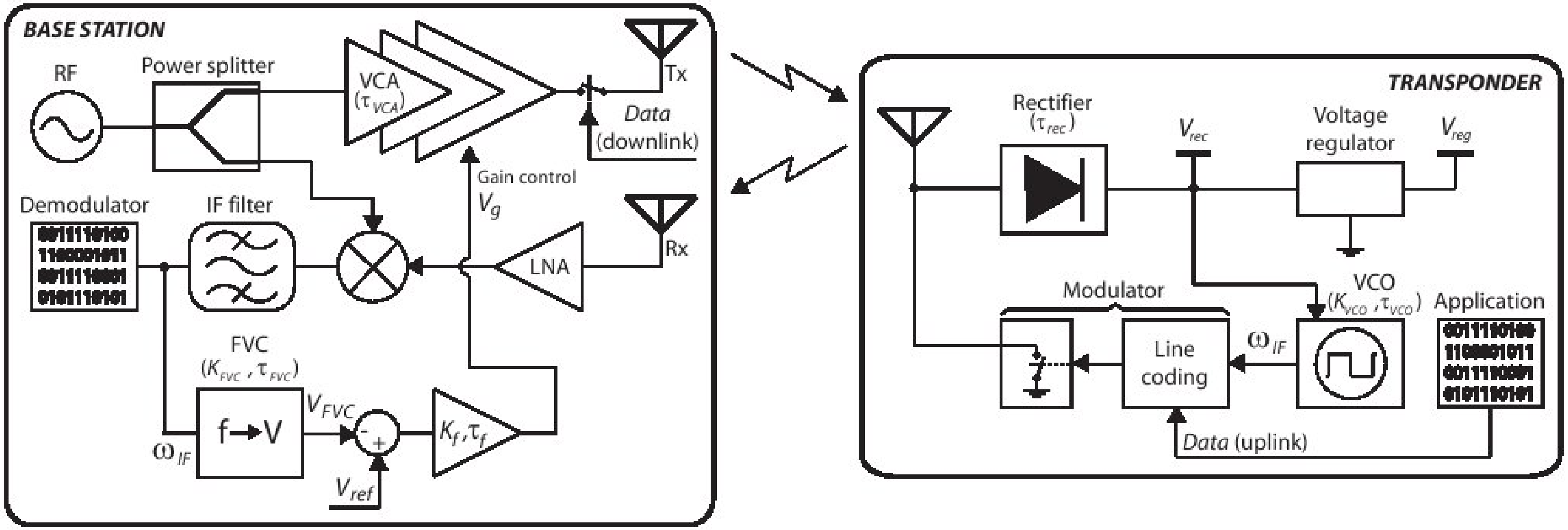
Wireless Voltage Regulation (WVR)

The rectifier output voltage V_{rec} controls the frequency of the IF oscillator

The reader measures this freq. and adapts the emitted power to stabilize V_{rec} to the desired voltage

WVR is combined with a voltage regulator:

a very stable supply voltage is obtained while the losses are minimized.



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

Wireless Voltage Regulation (WVR)

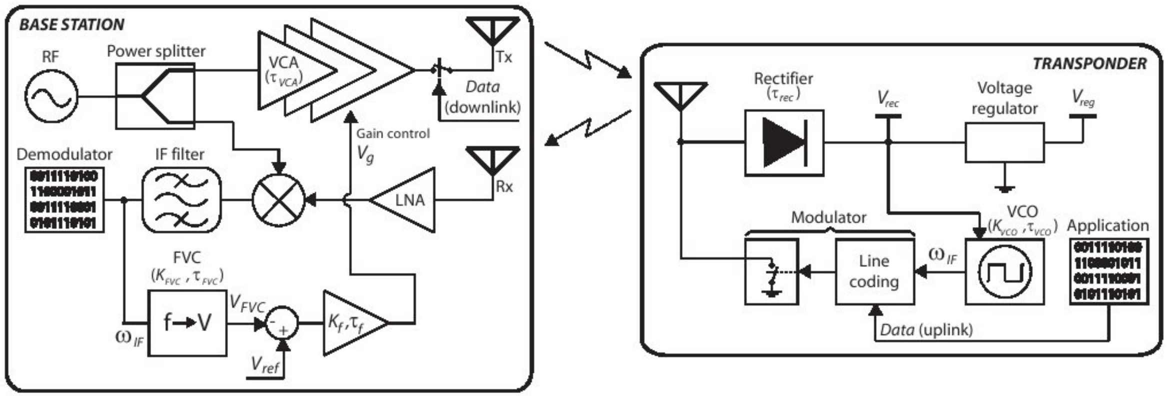
A strict mathematical description of the loop is very difficult because

- **some components (like the rectifier) are non-linear**
- **some loop parameters vary over time**

However, a first-order small-signal model is sufficient to study the loop dynamics with required accuracy

Open-loop transfer function of the WVR loop from a small change of the reference voltage to the corresponding small change at the output of the FVC :

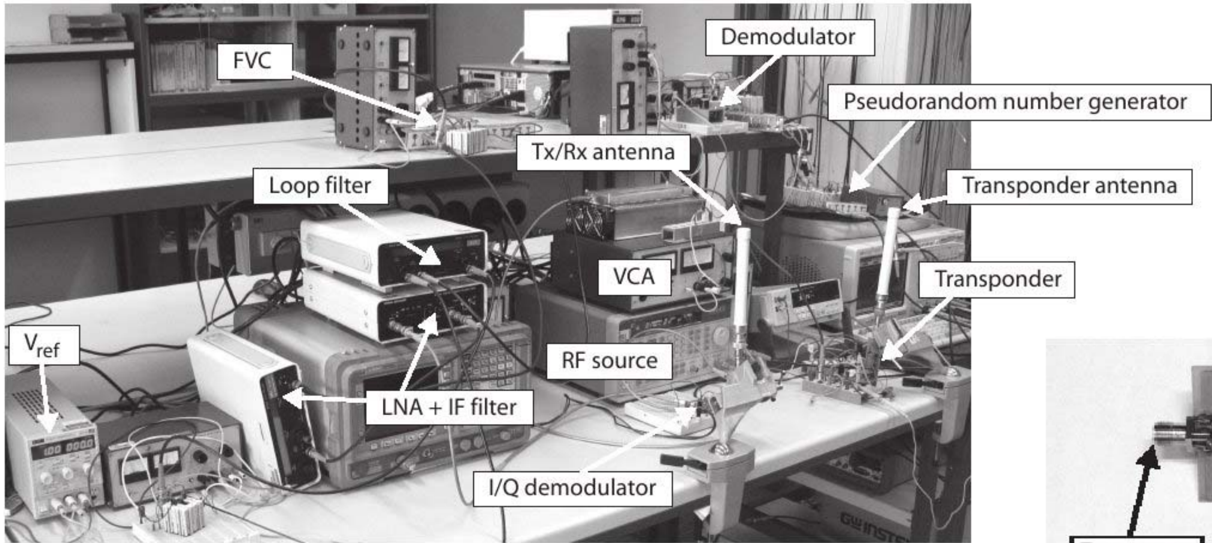
$$H_{WVR}(j\omega) = K_{WVR}\{(1 + j\omega\tau_f)(1 + j\omega\tau_{VCA})\ldots$$
$$\ldots(1 + j\omega\tau_{rec})(1 + j\omega\tau_{VCO})(1 + j\omega\tau_{FVC})\}^{-1}$$



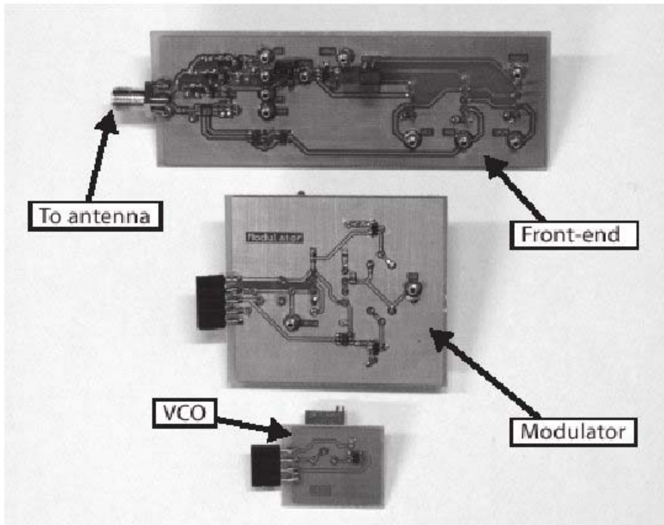
Implementation of the Wireless Voltage Regulation

A reader/tag system at 900 MHz is realized to validate the mathematical model

Reader



Tag

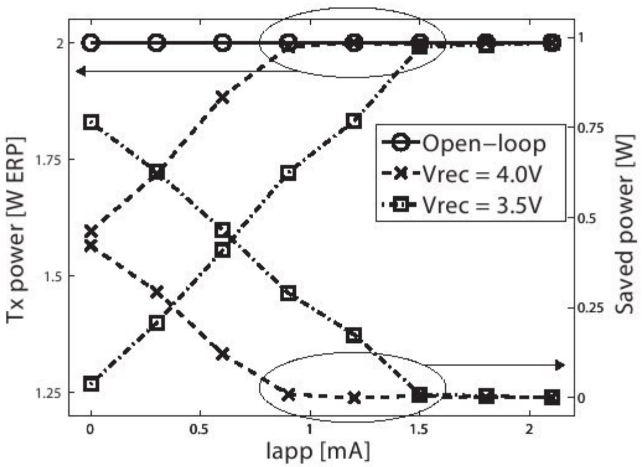


IEEE TCAS-I Journal, March 2010

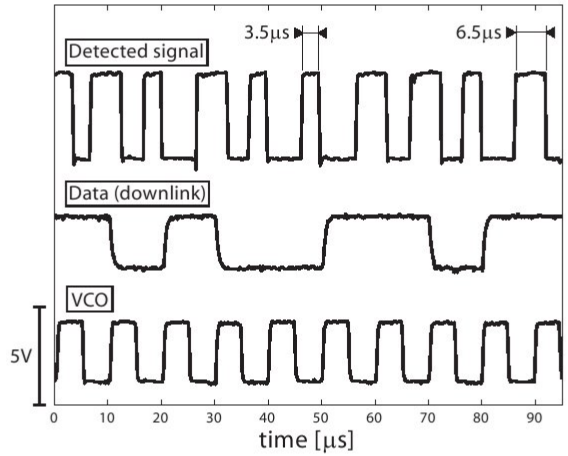
Measurements of the Wireless Voltage Regulation

- The static behaviour shows that power can be saved thanks to WVR
- The tag can communicate with the reader when WVR is ON

Measurements with respect to emitted power by the reader



Communication from Tag to Reader, 100 kbit/s

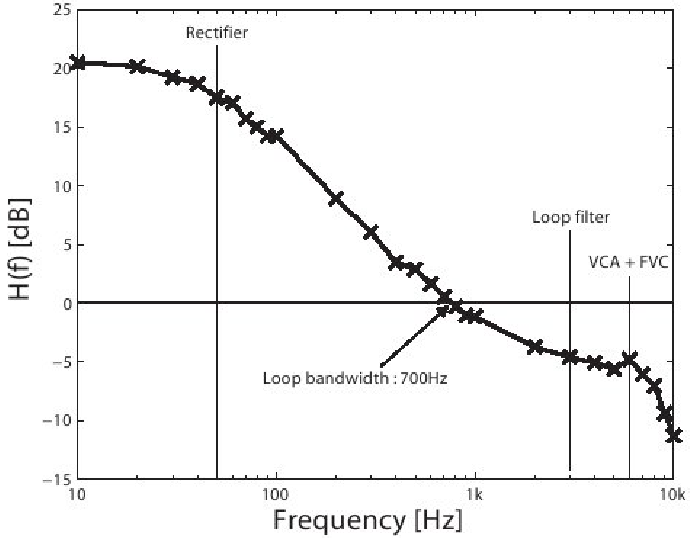


IEEE TCAS-I Journal, March 2010

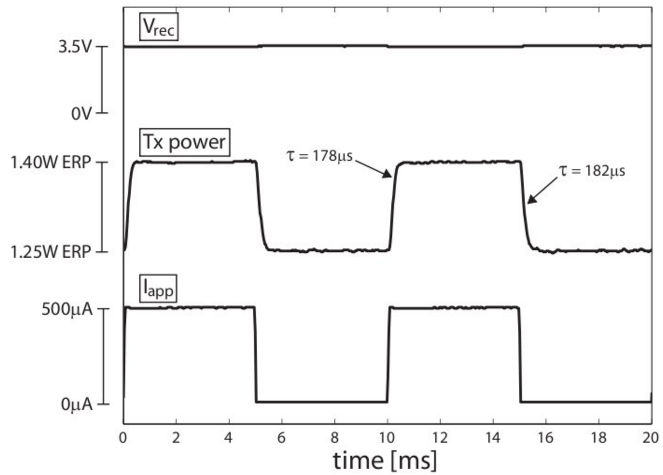
Measurements of the Wireless Voltage Regulation

The dynamical measurements confirm that the small-signal approach is valid

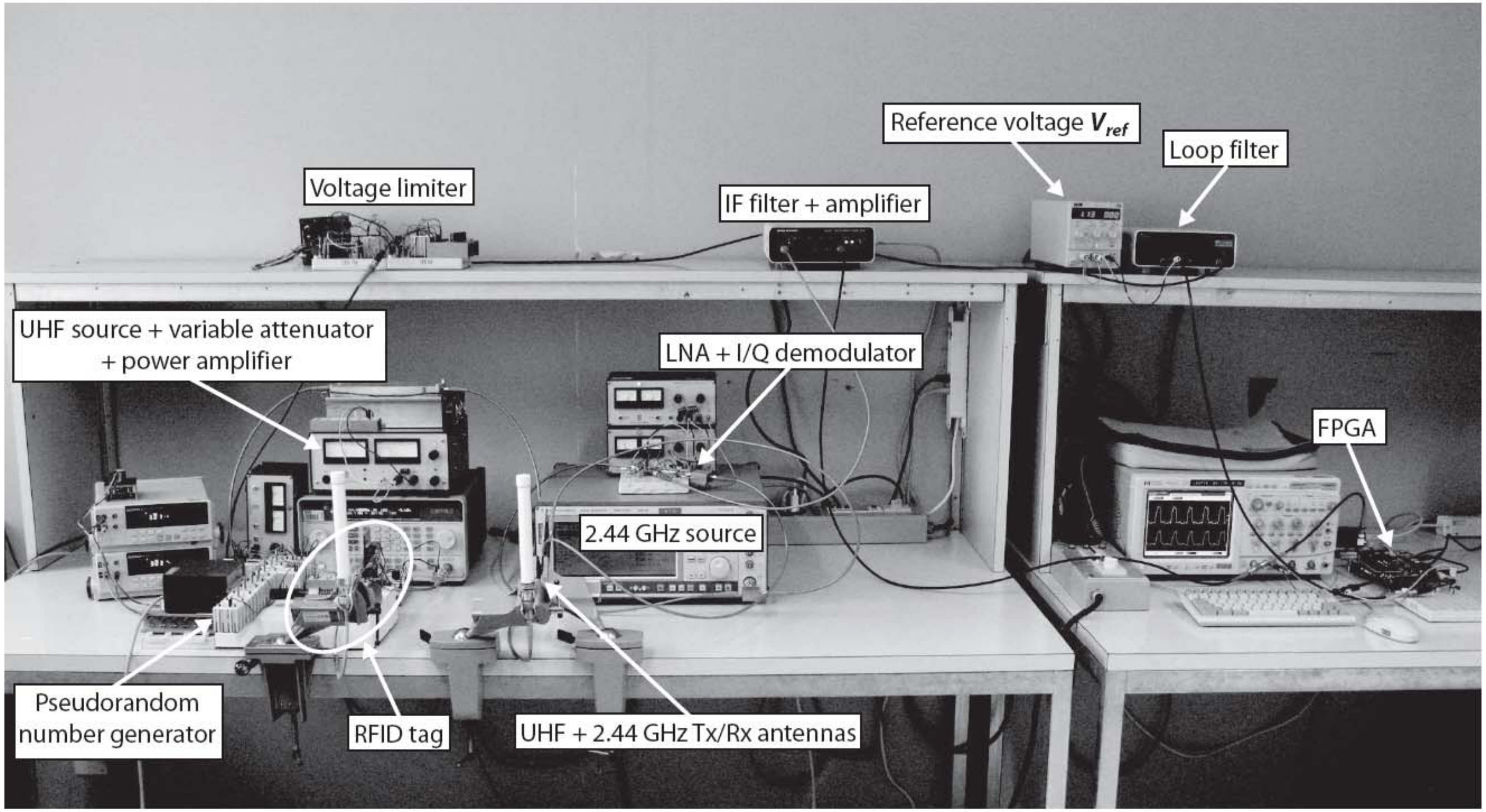
Open-loop transfer function



Transient response



Photograph of the system to test the dual frequency RFID tag



Summary

- **Design of the CMOS dual frequency RFID remotely powered tag**
  - **Measurements of the CMOS dual frequency RFID remotely powered tag**
  - Chapter 7 of the PhD thesis of Nicolas Pillin, EPFL, year 2010, No 4616

- **Analysis of the read range limitation of passive, far-field RFID systems**
  - **Model developed and validated to estimate the read range of passive, far-field RFID systems**
  - PRIME International Conference, year 2009

- **Study of the "wireless voltage regulation" (WVR)**
  - **Model developed and validated to study the WVR.**
  - March 2010, IEEE TCAS-I Journal.

PART 5 –
Remote Power
Data Communication
through Ultrasonic waves

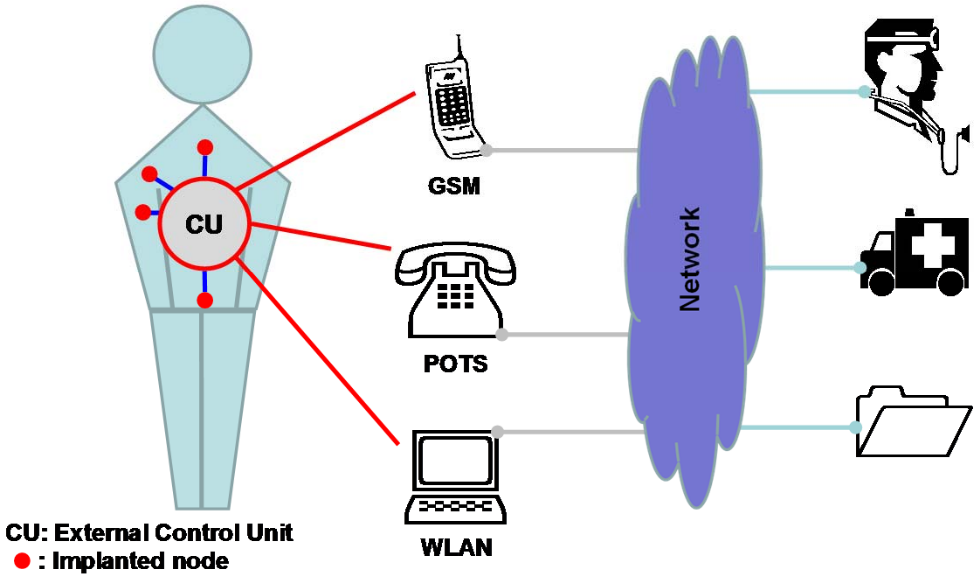
Prof. Catherine Dehollain
Group Leader of the RFIC group at EPFL

- **Health care solution.**
- **Partially/totally introduced, surgically/medically, into the human body.**
- **Remain in the body after the procedure for many years.**
- **Treat/monitor physiological condition, such as temperature, pressure, or fluid flow.**
- **Different kinds of IMDs: pacemakers, implantable cardiac defibrillator (ICD), drug delivery systems and neuro-stimulators.**

Implanted Medical Devices (IMD)

Continuous monitoring system to help patients to have a normal life.

Wireless communication would help monitor patients during normal activity.

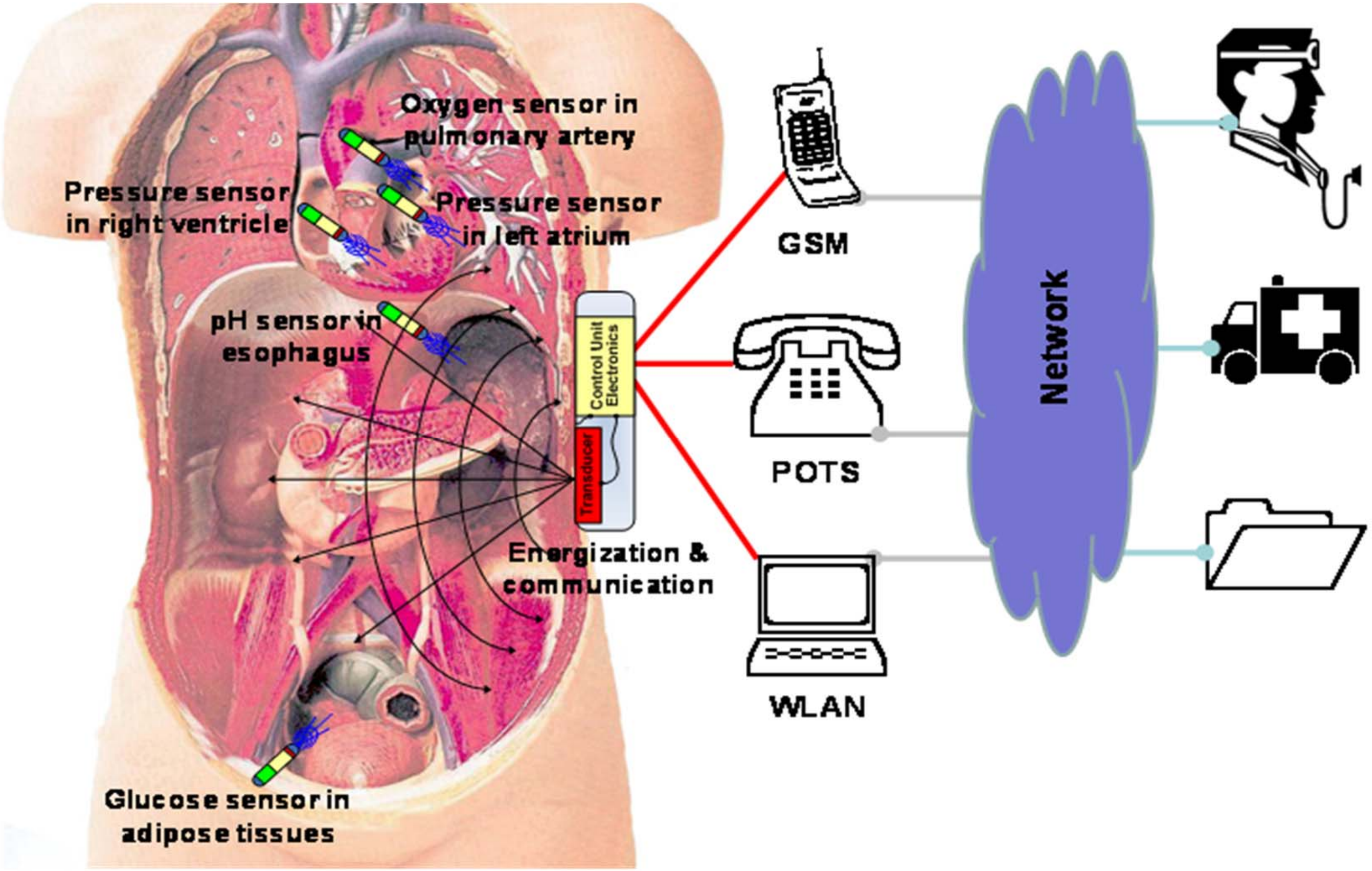


***source: www.ultrasponder.org**

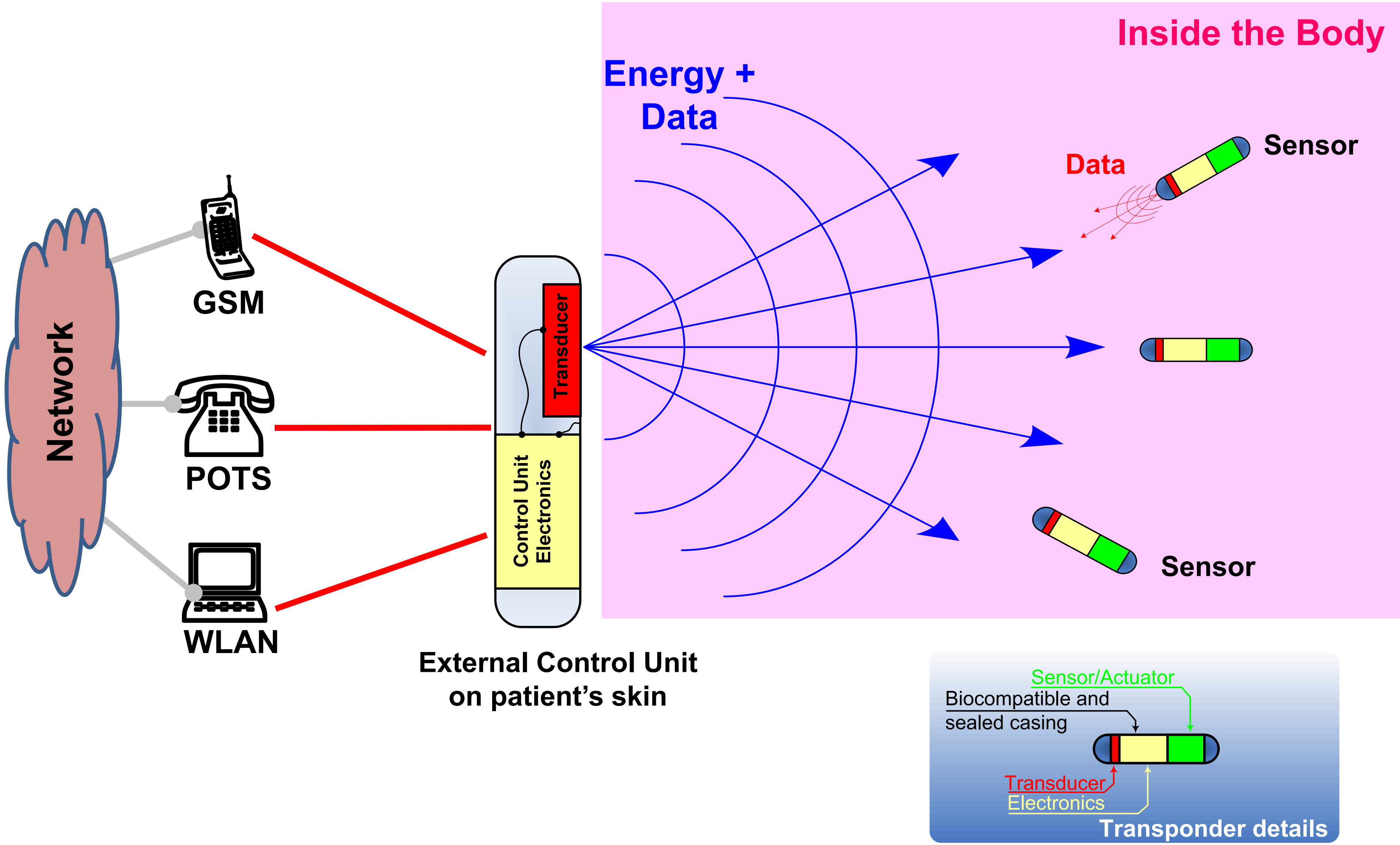
IMD deeply introduced into the human body

- Type of AC Source
- Implant Size
- Long Term Implant
- Long Autonomy
- Low-Power Circuitry (Modulator)

Implanted Medical Devices (IMD)



Implanted Medical Devices (IMD)



- **Continuous monitoring in the diagnosis and the treatment of cardiac congestive heart failure (CHF)**
  - **To follow the day and night heart activity**
  - **To see how the heart reacts to stress, to physical activities and to medications**
  - **To make a direct comparison of the actual patient condition with a past condition**

Comparison of Ultrasound with Magnetic and Electro-Magnetic

	Attenuation @ 10-20 cm
Ultrasound	8-16 dB (@ 1 MHz)[1]
Electro-Magnetic	60-90 dB (@ 2.45 GHz)[2]
Magnetic	50 dB (@ 1 MHz)[2]

Ultrasound is a good solution to overcome electromagnetic/ magnetic attenuation limit in the body

Ultrasound inherently avoid interference with other medical systems (magnetic resonance imaging, pacemaker, etc)

[1] Francis A. Duck., Physical Properties of Tissue, 1990.

[2] Tomohiro Yamada et al., JJAP, 44(7A), 2005.

Ultrasound Backscattering Technique

Backscattering modulation also known as load or impedance modulation

- Low power
- Concept is well-known in RF

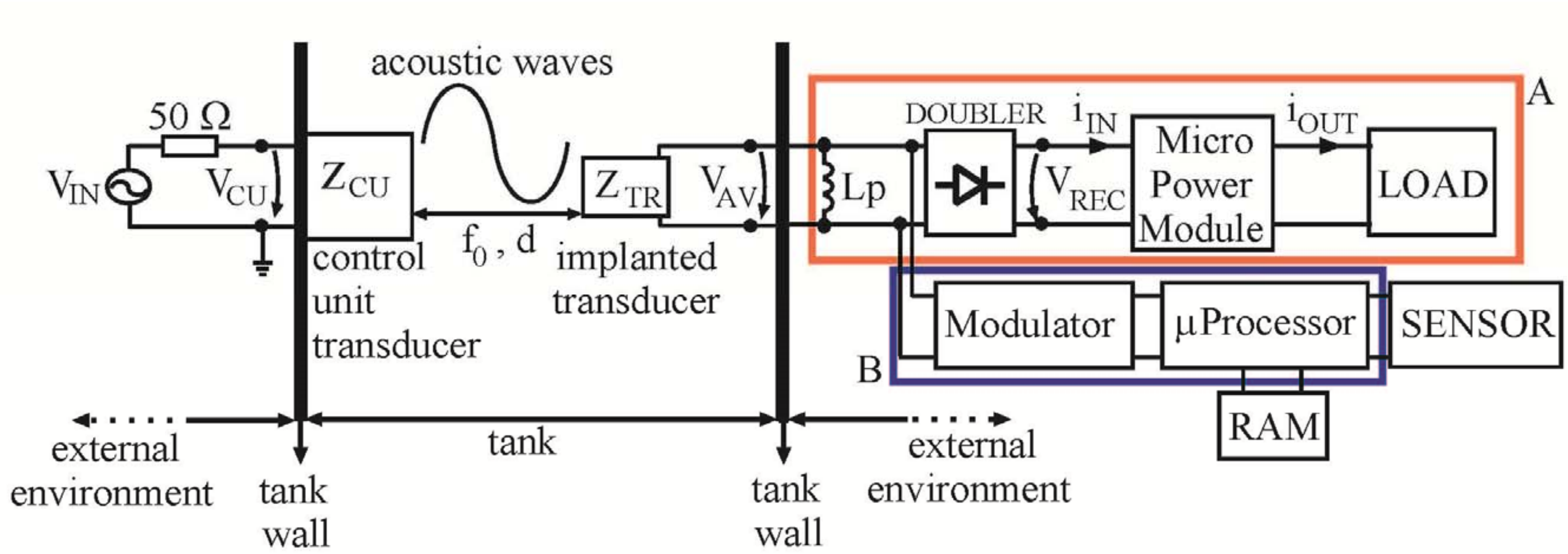
A continuous or pulsed wave is transmitted from the reader towards the tag

The tag reflects the wave back according to the data by changing its load impedance

The received echo is demodulated by the reader

Ultrasound energy harvesting (module A)

Ultrasound data wireless communication (module B)



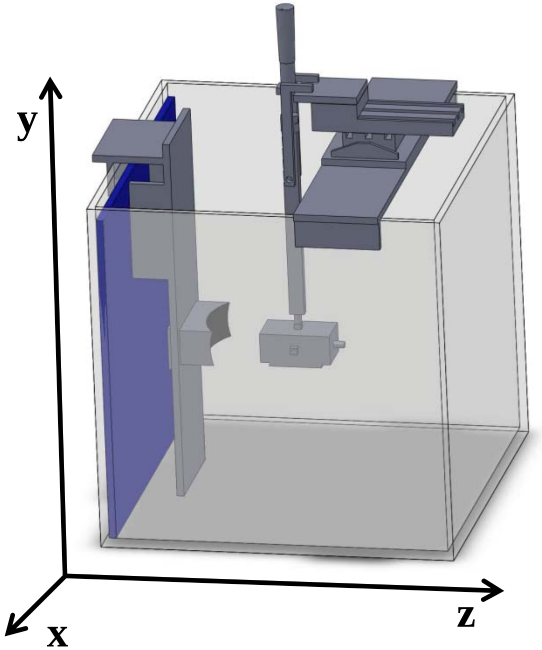
F. Mazzilli et al.: EMBC Conf. 2010, IEEE Transactions TBioCas 2014, BioCAS Conf. 2014, Electronic Letters 2016

F. Mazzilli, PhD thesis no. 5631, March 2013, EPFL

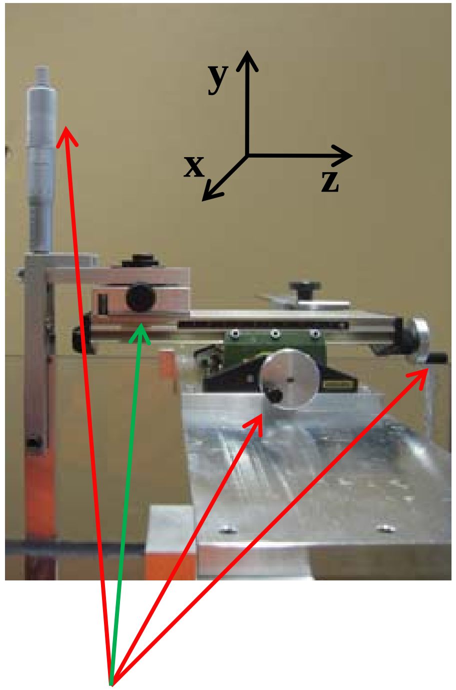
Anechoicity

APTFLEX 28[1]

Dimension (125 liter)



Flexibility of motion



- *x*, *y* and *z* displacement
- *x* rotation

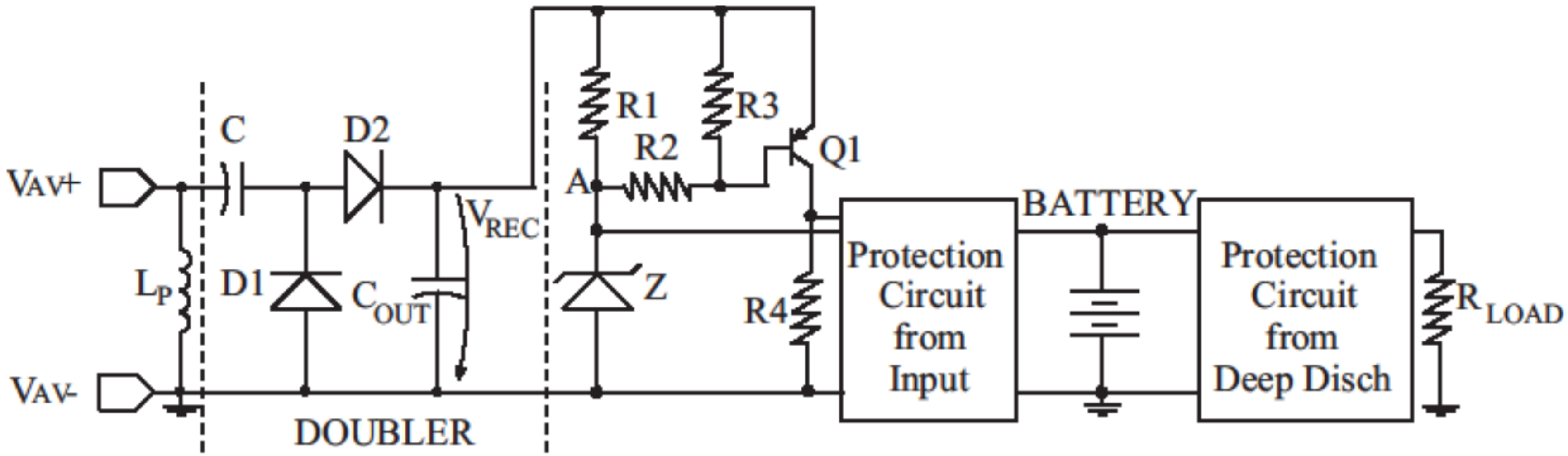
[1] http://www.acoustics.co.uk/products/aptflex-28

V_{AV} is the output signal yielded by the piston transducer (Pz26)

V_{REC} is the output of the voltage doubler

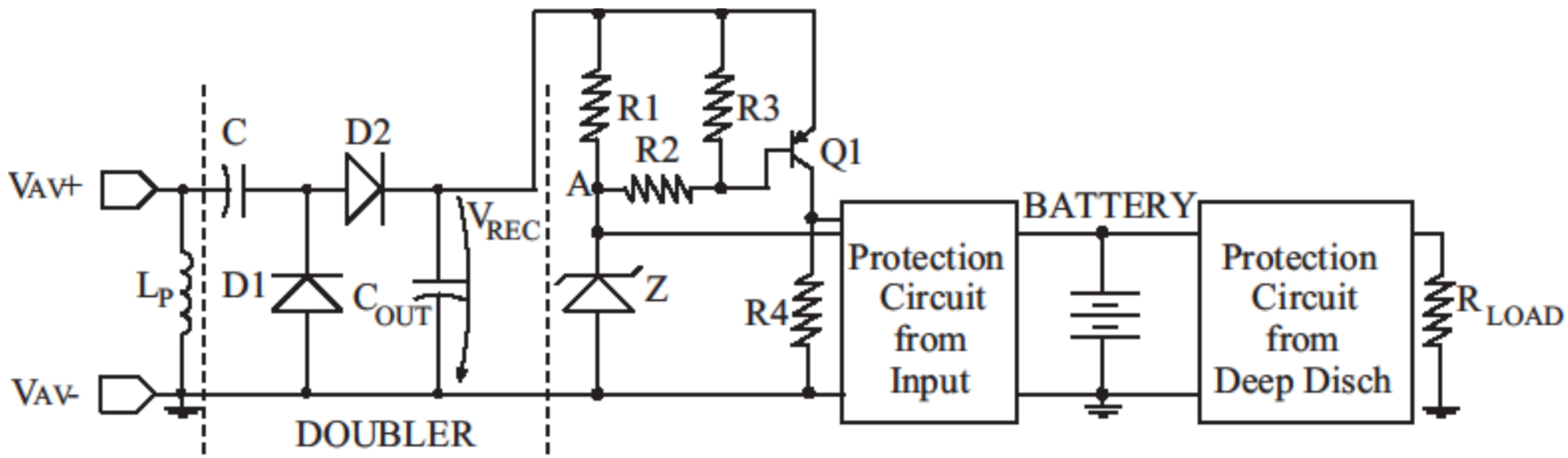
Voltage at node A is set to 4.1 V by the Zener diode

Two circuits to protect the battery against too low input voltage and to avoid excessive discharge



L_p (ferrite coil) is used to tune out imaginary parts both transducer and input recharging circuits at 1 MHz

Lithium Polymer Ion (LIPON) Battery → Capacity 300 µAh



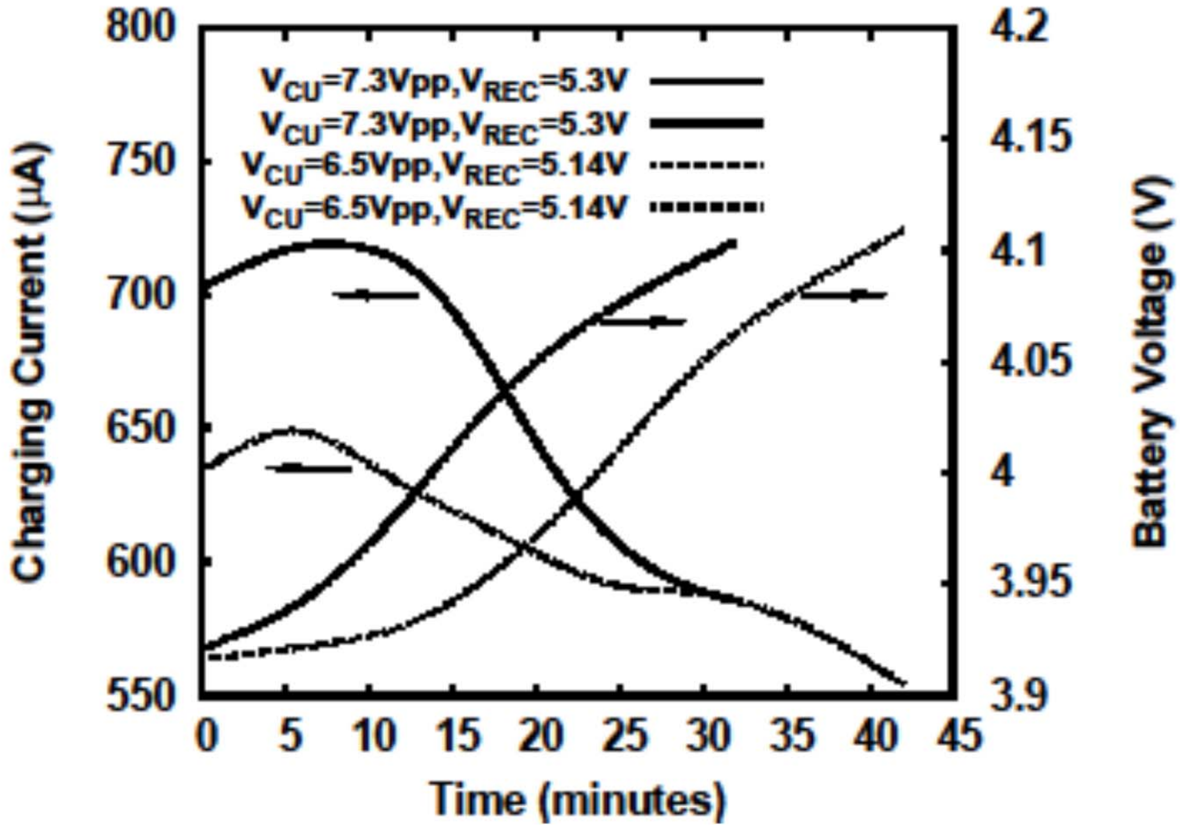
Electro-acoustic transducer

<u>Reader: Single element focused transducer</u>
Central frequency = 1.1 MHz
Diameter = 50 mm
Focal distance = 50 mm
Thickness = 2 mm
Piezo material = Ferroperm Pz28

<u>Tag: Single element piston transducer</u>
Central frequency 1.05 MHz
Diameter = 6.35 mm
Thickness = 2 mm
Piezo material = Ferroperm Pz26

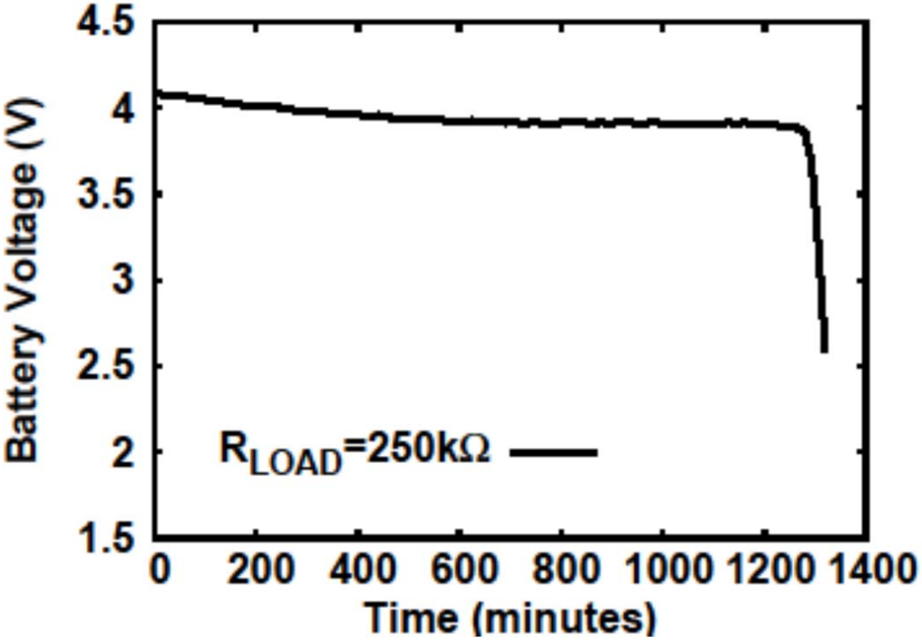
Ferroperm Piezoceramics A/S

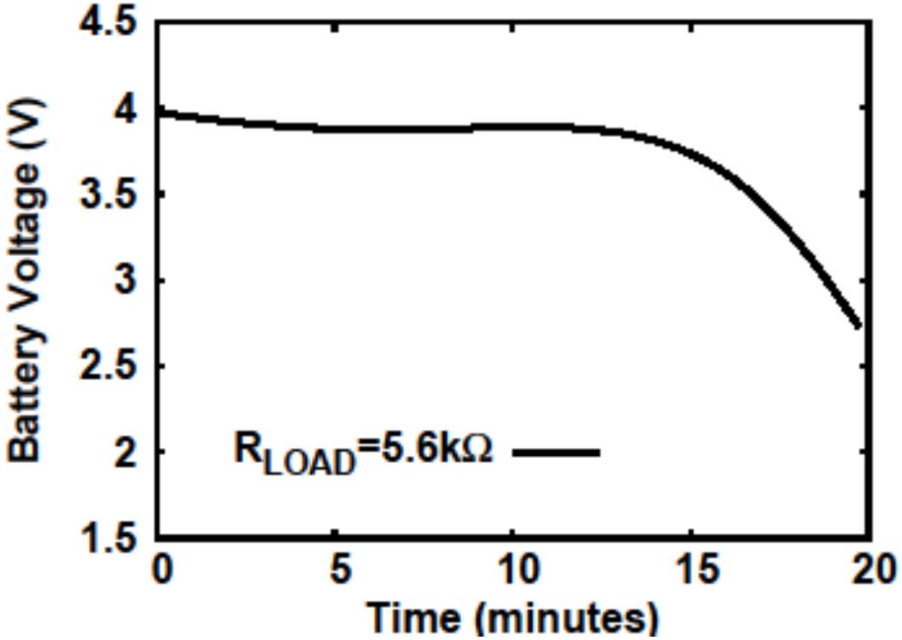
End of charge detected at 4.1 V battery voltage



Discharging under constant load

Cut-off battery voltage at 2.5 V





Discharge time ~ 22 hours

Discharge current ~ 16 μA

Discharge time ~ 20 minutes

Discharge current ~ 730 μA

An array of elements is used for the reader

- **one element is used as transmitter and a second element is used as receiver.**

The tag modulates the incident wave (back-scattering modulation).

On-Off Keying (OOK) modulation.

Data rate 20 Kbps.

The demodulator is present on the reader side, two amplifiers are used (gain of 20 dB per amplifier) to raise the amplitude of the received wave.

Reader: linear phase array – 64 elements

Central frequency = 1 MHz

Manufacturer IMASONIC

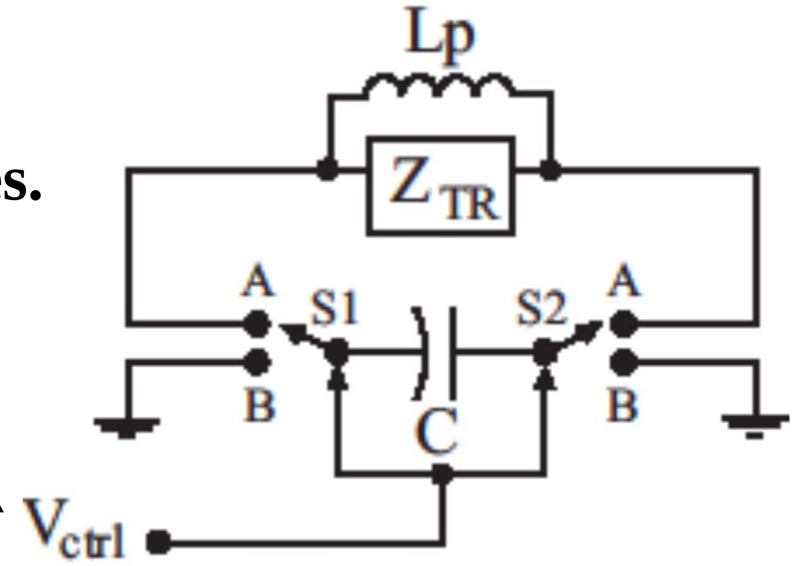
Tag: single element piston transducer

Central frequency = 1 MHz

Diameter = 13 mm

Manufacturer IMASONIC

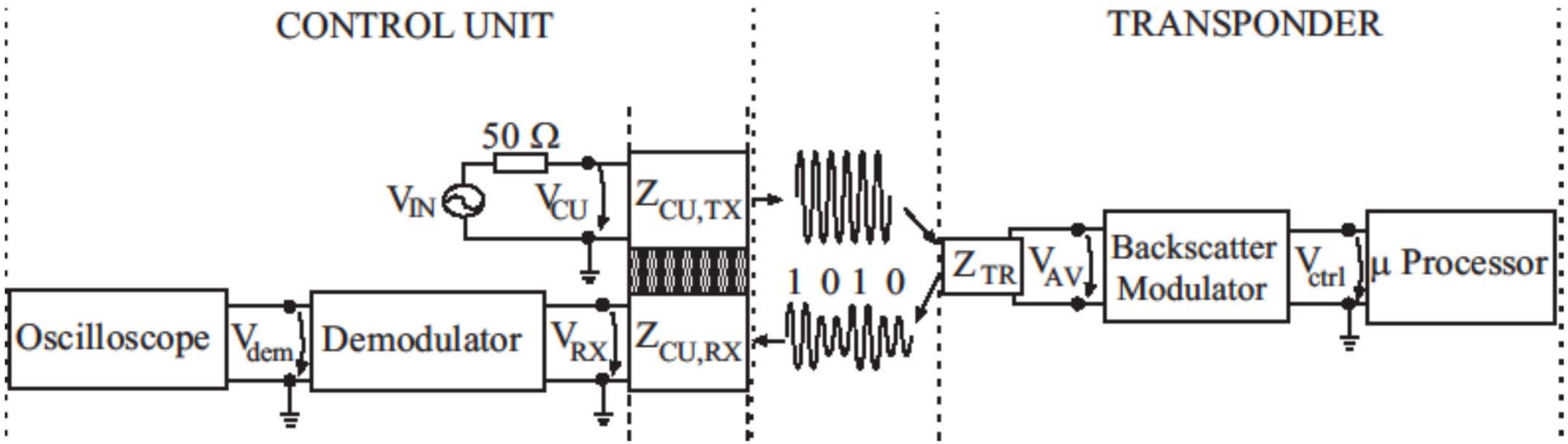
Data signal controls the switches.

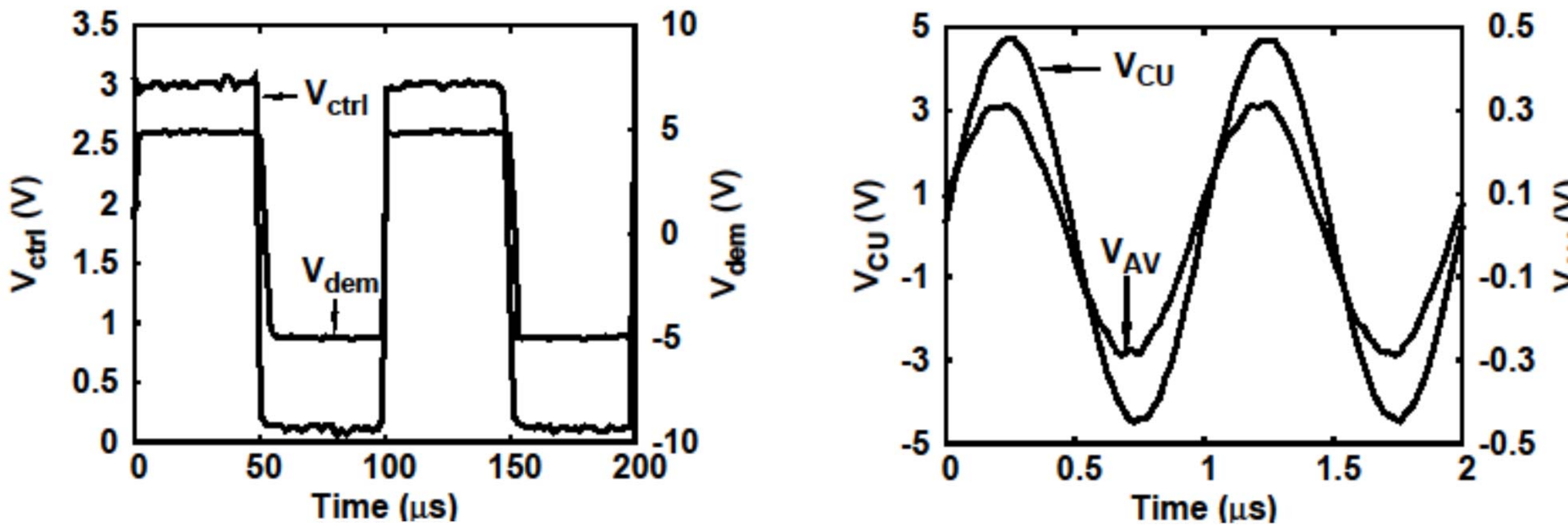


Vctrl = 1, switch S1 & S2 in position A: The transducer is made stiffer and reflects back the incoming signal so a high state is transmitted to the CU receiver.

Vctrl = 0, switch S1 & S2 in position B: The transducer is allowed to vibrate so that the incoming signal is absorbed, thus a low state is transmitted to the CU receiver.

Measurements of the Wireless Data Communication





Summary on Ultrasonic waves

Ultrasound is a very good solution for deeply implanted devices inside the body

1 MHz is an appropriate trade-off for data communication and remote power

Backscattering method is used for data communication