DESIGN TRADE-OFF BETWEEN REMOTE POWER AND DATA COMMUNICATION FOR REMOTELY POWERED SENSOR NETWORKS

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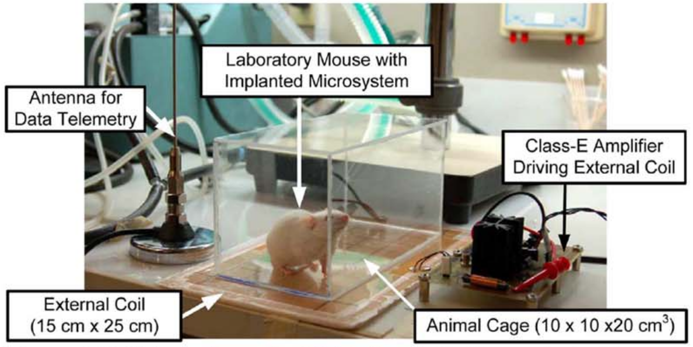
31ST MARCH 2017

Remote Monitoring Applications

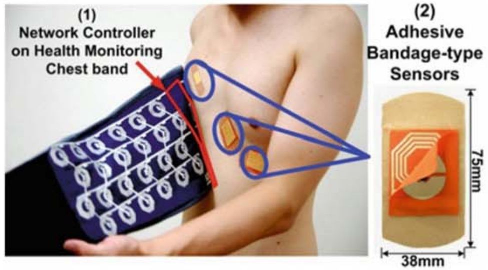
Example Applications

Blood Pressure Monitoring System



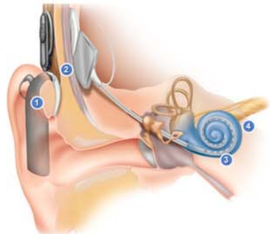
P. Cong et al., "A Wireless and Battery less 10-Bit Implantable Blood Pressure Sensing Microsystem With Adaptive RF Powering for Real-Time Laboratory Mice Monitoring," IEEE Journal of Solid State Circuits, Dec. 2009.

ECG Monitoring System



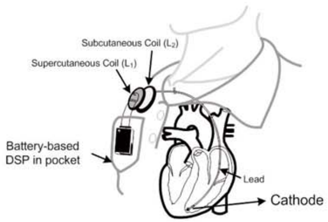
J. Yoo, et al., "A 5.2 mW Self-Configured Wearable Body Sensor Network Controller and a 12 µW Wirelessly Powered Sensor for a Continuous Health Monitoring System," IEEE Journal of Solid-State Circuits, Jan 2010.

Cochlear Implants



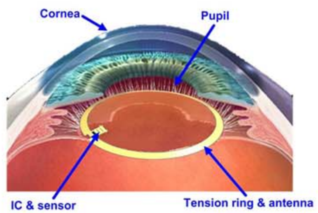
cochlearamericas.com

Cardiac Pacemaker



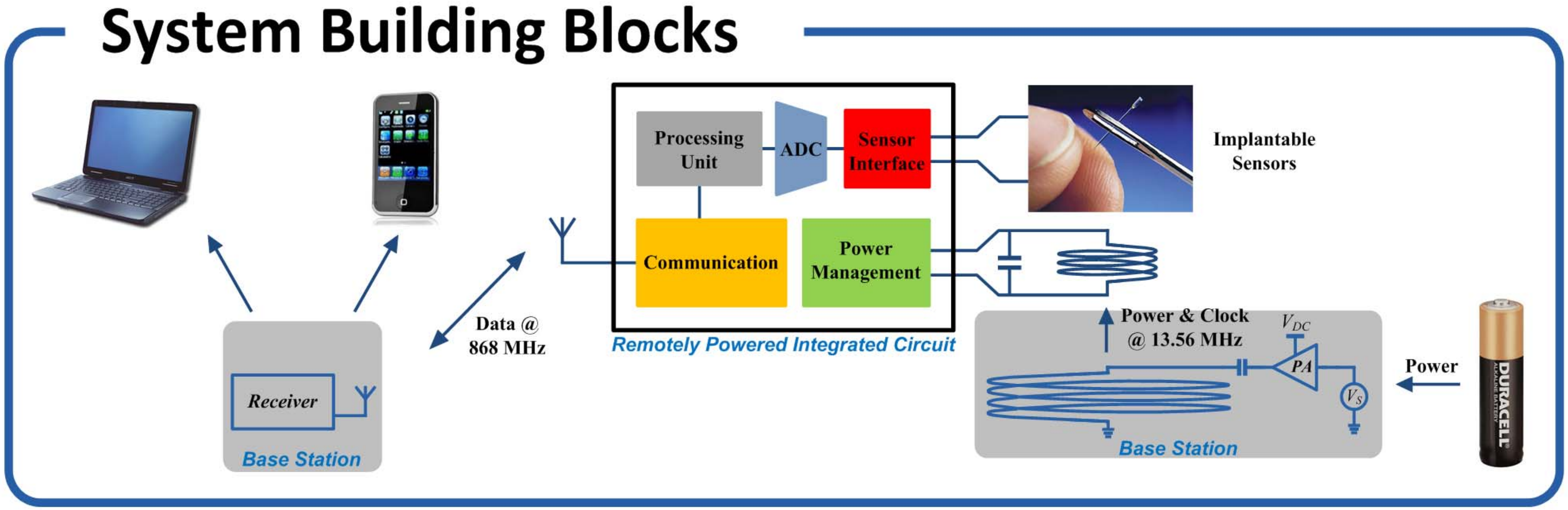
S.Lee, et al., "A Programmable Implantable Micro-Stimulator SoC with Wireless Telemetry: Application in Closed-Loop Endocardial Stimulation for Cardiac Pacemaker," in ISSCC Digest of Technical Papers, Feb. 2011, pp 44-45.

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.

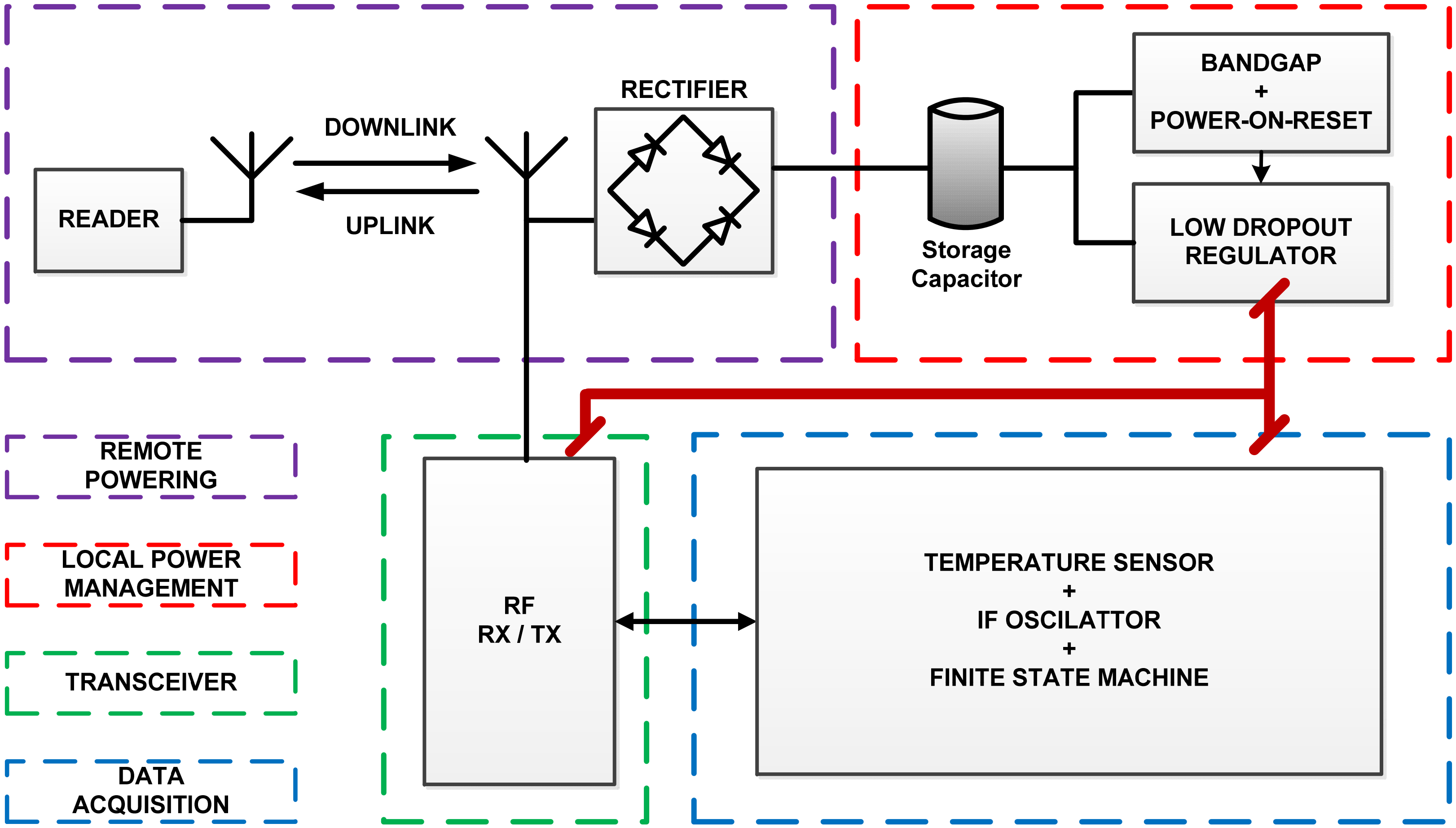
Overview of Wireless Sensor Systems



→ Three fundamental units

1. Implantable sensor system
2. External base station for remote powering and data communication
3. Long distance data communication for database and reporting

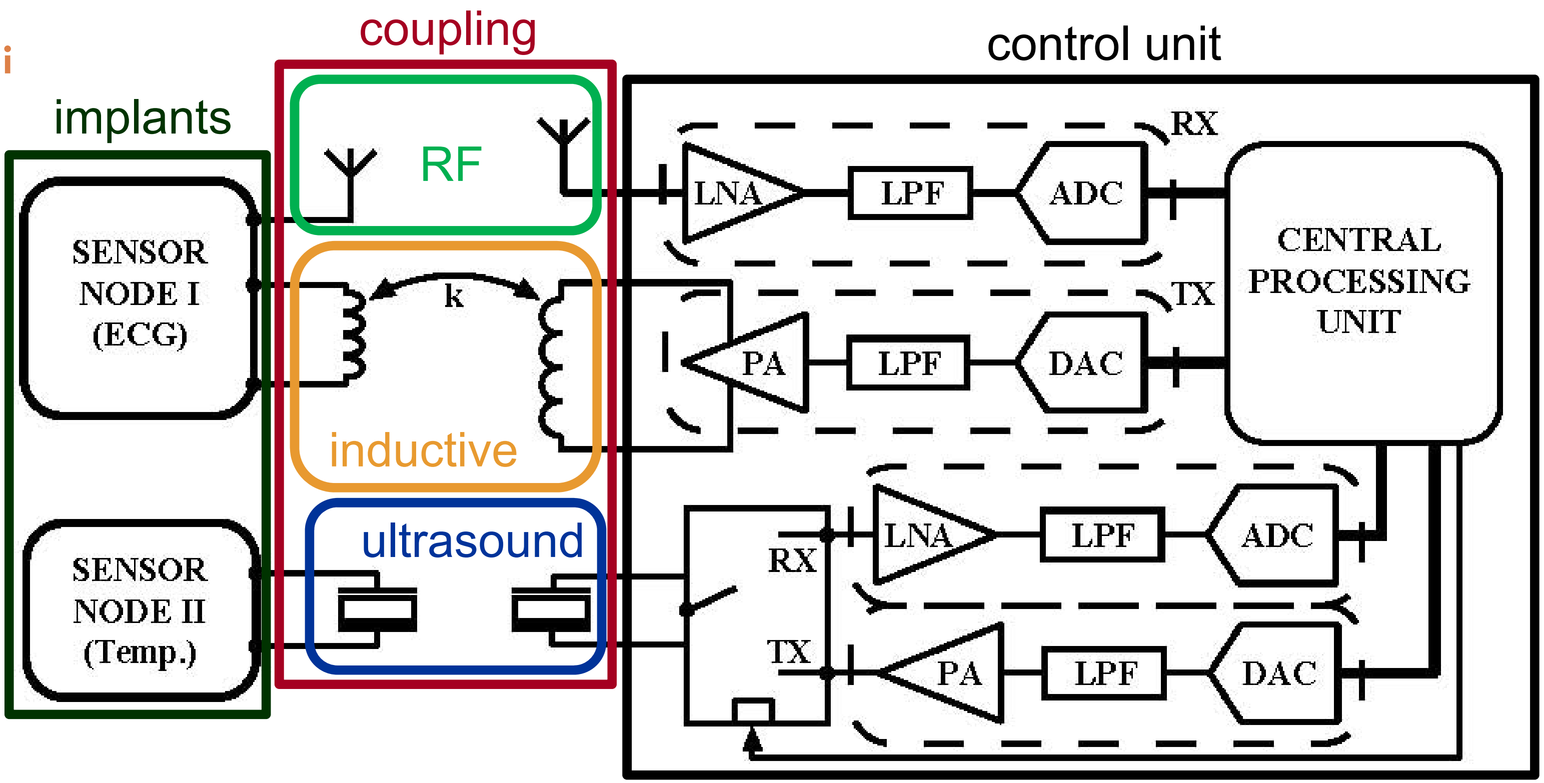
Overview of Wireless Sensor Systems



System overview

1) Implant: up to ten sensor nodes.
2) Control unit: base station to allow energy and data transfer.
3) Coupling: electro-magnetic, magnetic or ultrasound.

F. Mazzilli

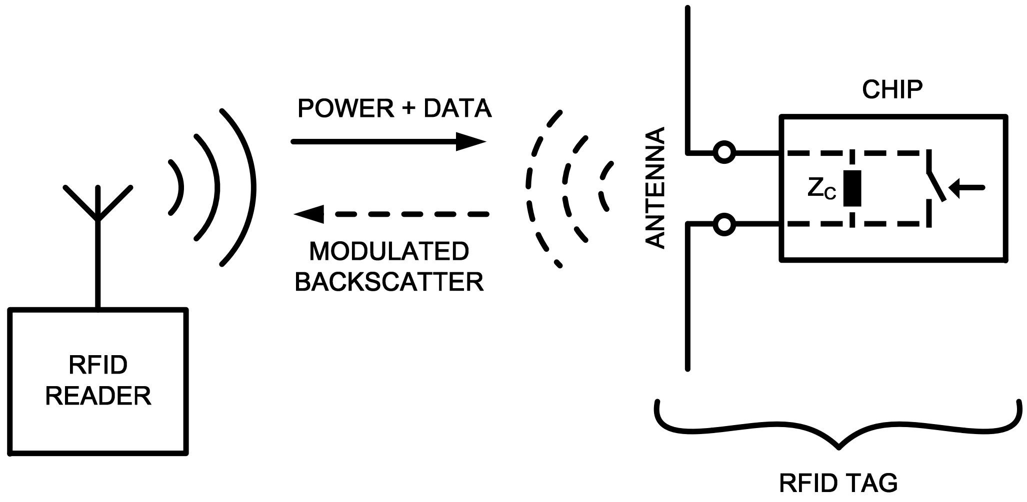


Different Research Topics

- **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 (e.g. RFID, passive memory tag)
- **Remotely powered wireless circuits**
  - Through RF wave by magnetic coupling , electro-magnetic coupling, electro-acoustic coupling (ultrasound).
  - Rechargeable micro-batteries.
- **Low-power wireless communications**
  - Low supply voltage imposed by advanced technologies, low current operation
- **Frequency range**
  - 0.1 MHz to 10 GHz.
- **Low power innovative sensor interfaces**
- **Fully integrated solutions**
  - RF and Mixed-mode circuits.
  - Circuits in advanced CMOS technologies.

Wireless Backscattering Data Communication

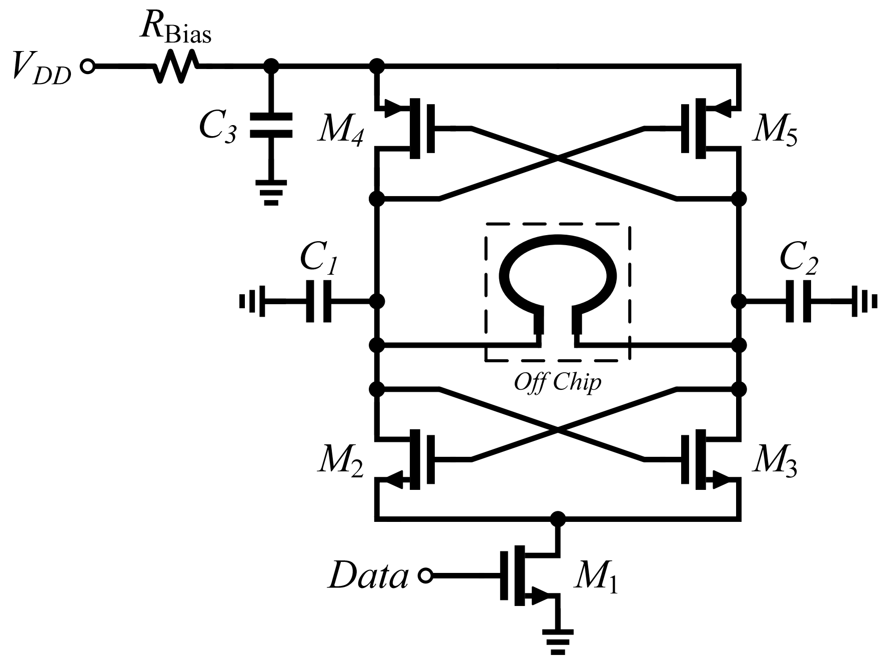
- The tagged object is tracked if the main station (reader or interrogator) is in **range**
- **The tags** (transponders) can contain **sensors** that transmit valuable data
- Minimization of the **power consumption** of the tag → Generating the **carrier** at base station and **backscattering** the incident wave
- **Wireless** and **batteryless** operation



Harry Stockman, "Communication by Means of Reflected Power", **1948**

Wireless Active Transmitter for Data Communication

- The carrier is generated in the tag.
- LC OOK Transmitter.
- The frequency of the carrier is determined by the LC tank.

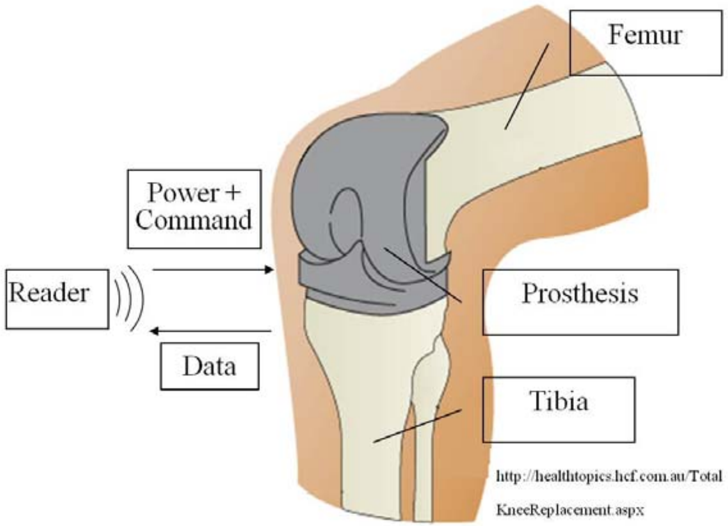


Wireless Remote Powering

- Inductive Coupling (Near-Field)
  - Near field region → $d < \lambda/2\pi$
  - Typical frequency bands: 125 kHz, 6.78 MHz, 13.56 MHz
  - Effective operation distance of 10 cm in air
  - Highly sensitive to misalignment between the primary coil and the secondary coil of the transformer
  - Higher energy efficiency in short distance at d<10 cm

- Electro-magnetic Coupling (Far-Field)
  - Far field region: → $d > \lambda/2\pi$
  - Typical frequency bands: 868 MHz, 915 MHz, 2.45 GHz, 5.8 GHz.
  - Effective operation distance up to 15 m in air
  - Higher data rate than the near-field systems

Knee prosthesis monitoring by inductive coupling



Swiss SNF NanoTera

Simos Project

Goals

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

Objectives

- Transcutaneous powering by inductive link
- Communication between the prosthesis and external reader

Challenges

- Low coupling factor of inductive link due to distance between the two coils and limited antenna size
- High power requirement (10 to 20 mW)

O. Atasoy and C, Dehollain, IEEE NEWCAS Conf. 2012, PRIME Conf. 2010, PRIME Conf. 2013
O. Atasoy, PhD thesis n0 5992, EPFL, November 2013

Digestive Track Diagnostic by Inductive Coupling

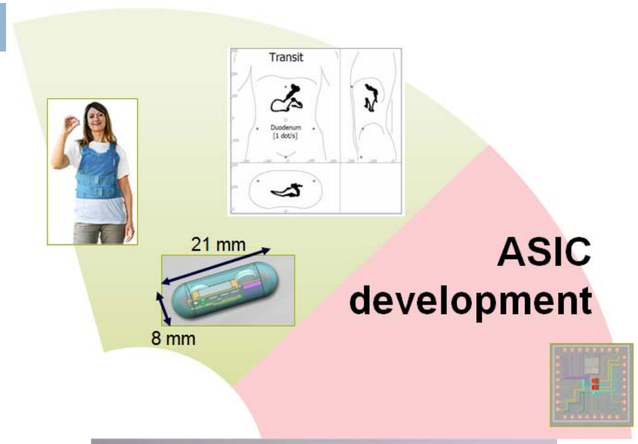
→ Diagnosis of digestive system for:

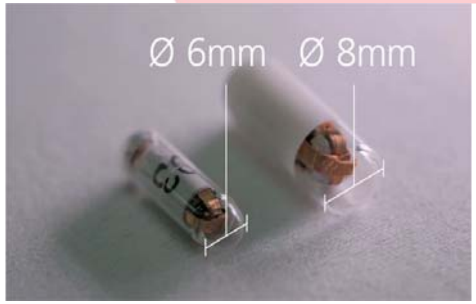
- Constipation
- Irritable Bowel Syndrome (IBS)
- Gastroparesis

→ 3D trajectory information of the pill through the gastrointestinal track.

→ The pill provides three axis magnetic field for location information.

→ Fully integrated ASIC development enables miniaturization of the pill.

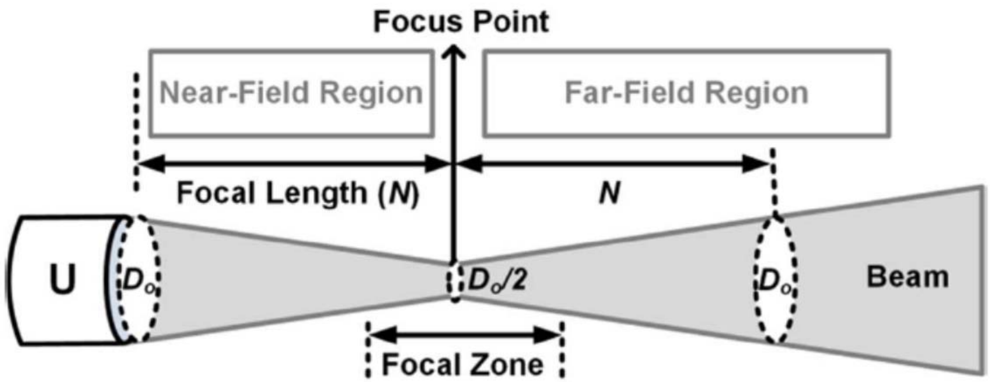




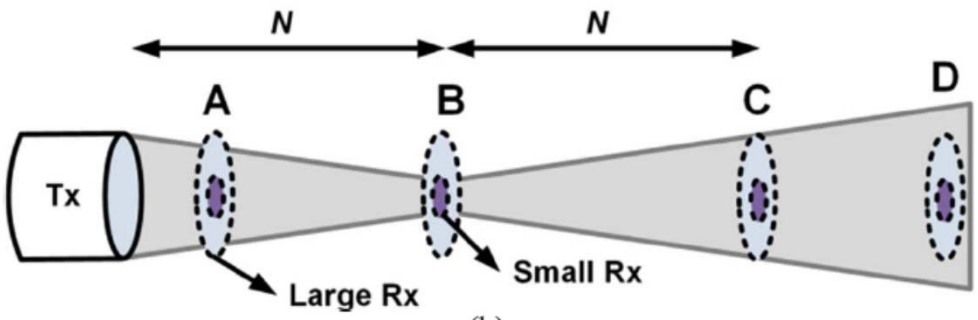
CTI Swiss Project

J.L. Merino, C. Dehollain: ICECS 2012, ISMICT 2013, ISCAS 2015

Wireless Remote Powering Through Ultrasound



(a)



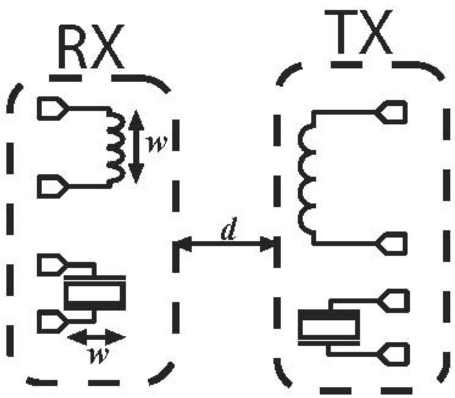
(b)

M. Meng, M. Kiani, IEEE Journal TBioCas, Feb. 2017

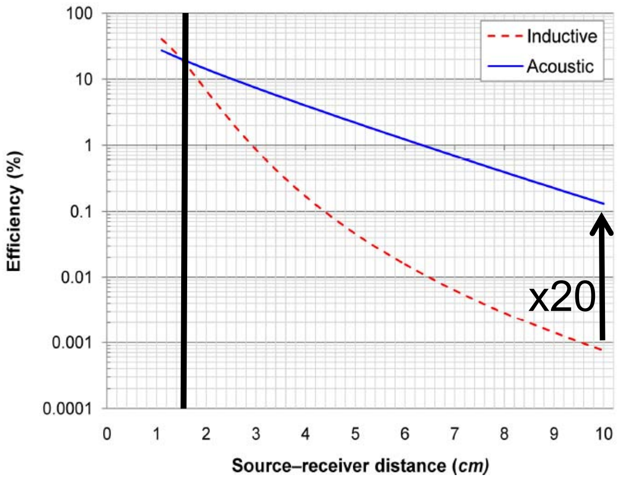
Inductive vs. Ultrasound: Energy Transmission

Acoustic f_0 = 1 MHz

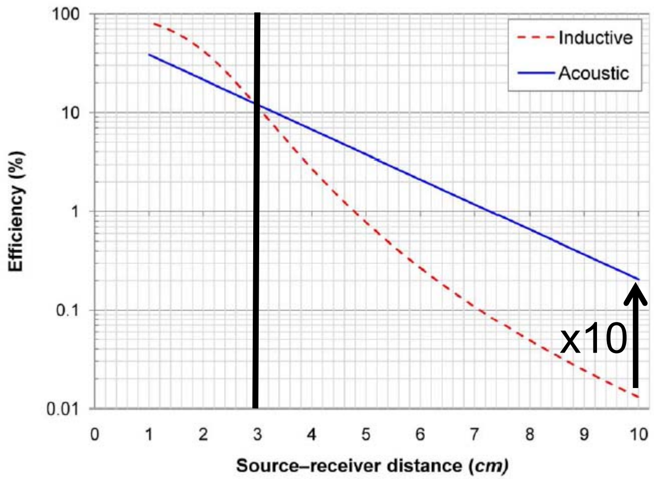
Inductive f_0 = 13.56 MHz



Receiver diameter = 5 mm



Receiver diameter = 10 mm



[1] A. Denisov, International Conference on Body Sensor Networks, 2010.

Why ultrasound?

- To overcome electromagnetic attenuation limit in water:

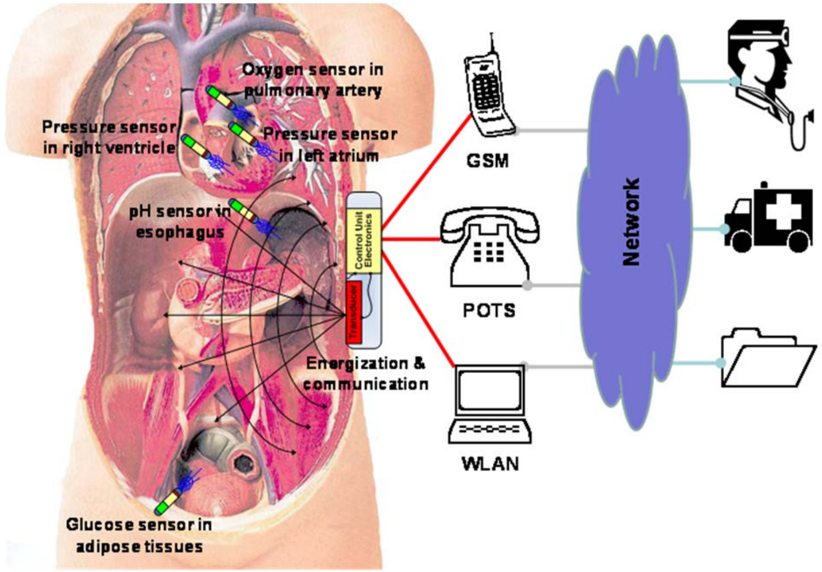
	Attenuation @ 10-20 cm
Ultrasound	**8-16 dB (@ 1 MHz)[2]**
Electro-Magnetic	**60-90 dB (@ 2.45 GHz)[3]**
Magnetic	**50 dB (@ 1 MHz)[3]**

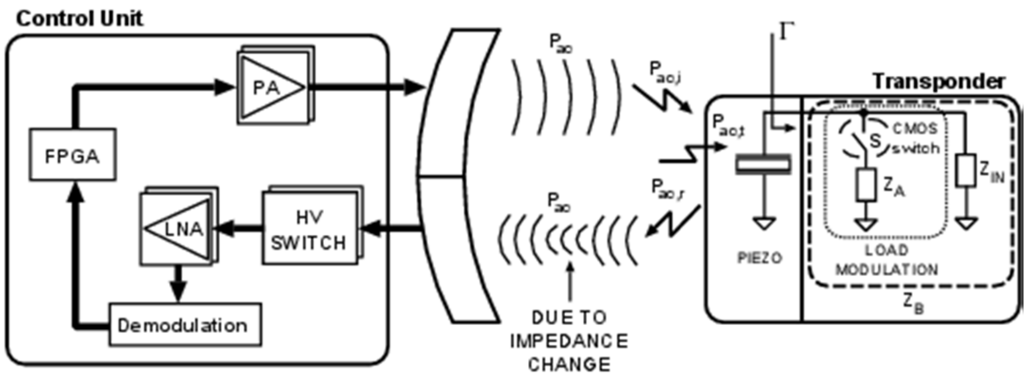
- Inherently avoid interference with other medical systems (magnetic resonance imaging, pacemaker, …).
- Robustness towards hacking.

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

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

Ultrasonic Remote Powering and Communication





European FP7 project: www.ultrasponder.org

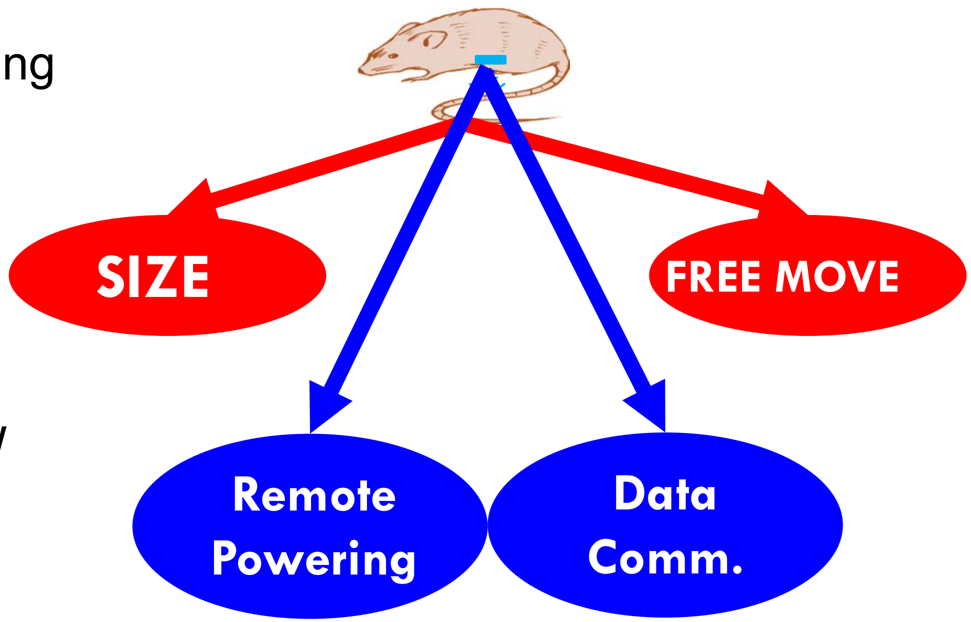
F. Mazzilli, C. Dehollain: IEEE TBioCas Journal in 2014, Conf. BioCAS in 2014, Electronic Letters in 2016

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

Magnetically-Coupled Remote Powering System for Freely Moving Animals

Freely Moving Laboratory Rodents

- Application: Multi-bio sensor monitoring
- Condition of animal: mobile/awake
- Fully implantable sensor node
- Weight: Less than 2 g
- Volume: Less than 1.5 cm^3
- Maximum power consumption: 2 mW
- Wireless Power Transfer
- Remote powering distance: 3 cm
- Data communication data rate: 100 kbit/s
- Data communication distance: 40 cm



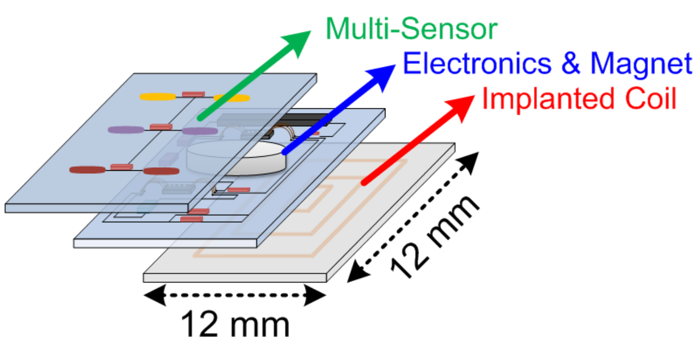
Implantable Bio-Monitoring System

Continuous and Long-term monitoring

Swiss SNF Sinergia Project

Targets

- **Detection of different drugs**
- **Measurement of pH and temperature**
- **Detection of different endogenous compounds**



Conceptual design of battery-less implantable multiple sensor system

Problems

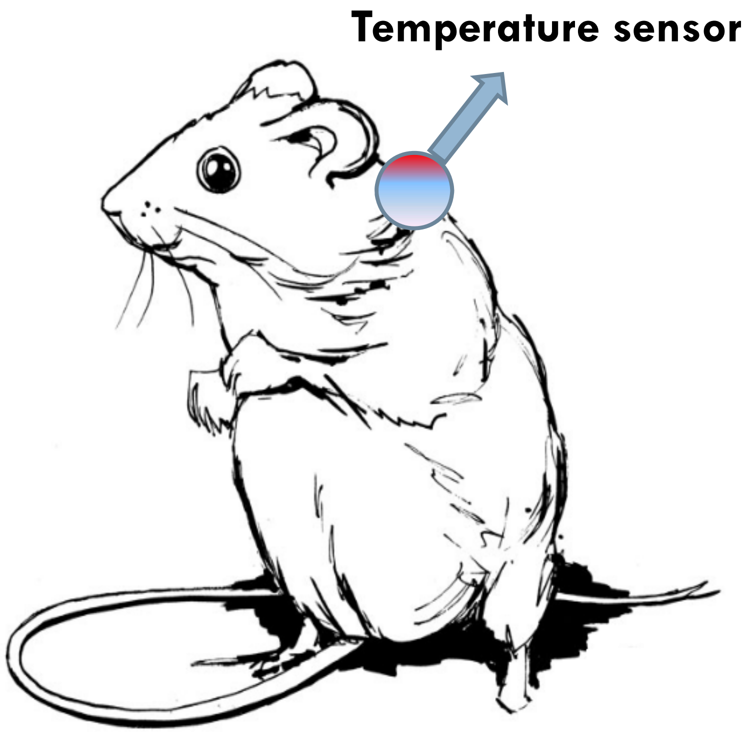
- **Size and weight to be implantable**
- **Low coupling factor due to distance & tissue**

E. G. Kilinc, F. Maloberti, C. Dehollain:

IEEE SM2ACD 2010, ISCAS 2012, BIOCAS 2012, NEWCAS 2013, Sensors Journal 2015, TBioCas 2016

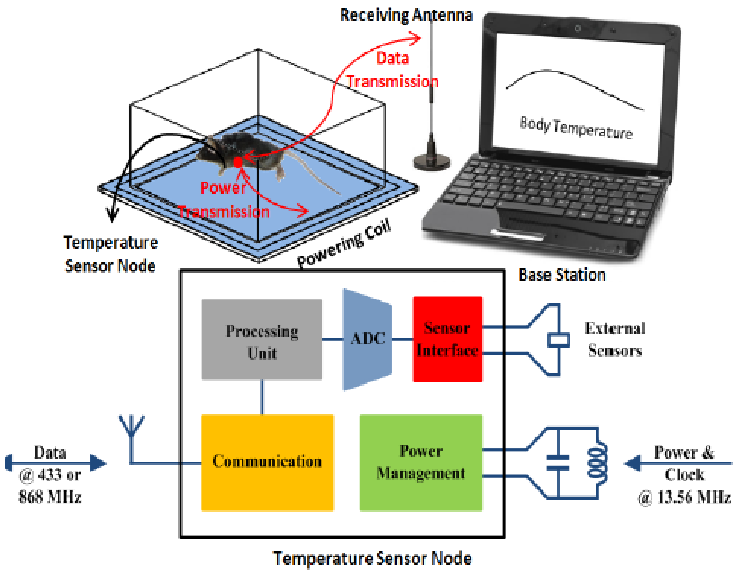
E.G. Kilinc, PhD thesis n0. 6105, EPFL, Feb. 2014

Metabolism Study

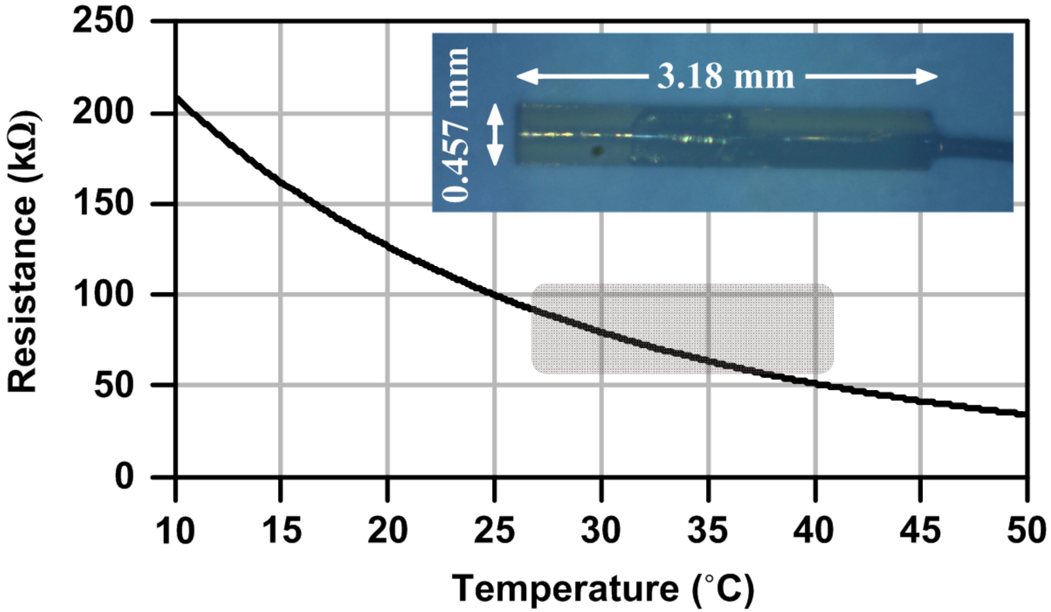


Sensor in Brown Adipose Tissue

- Metabolism study
- Inflammation and mobility
- Wireless powered temperature sensor



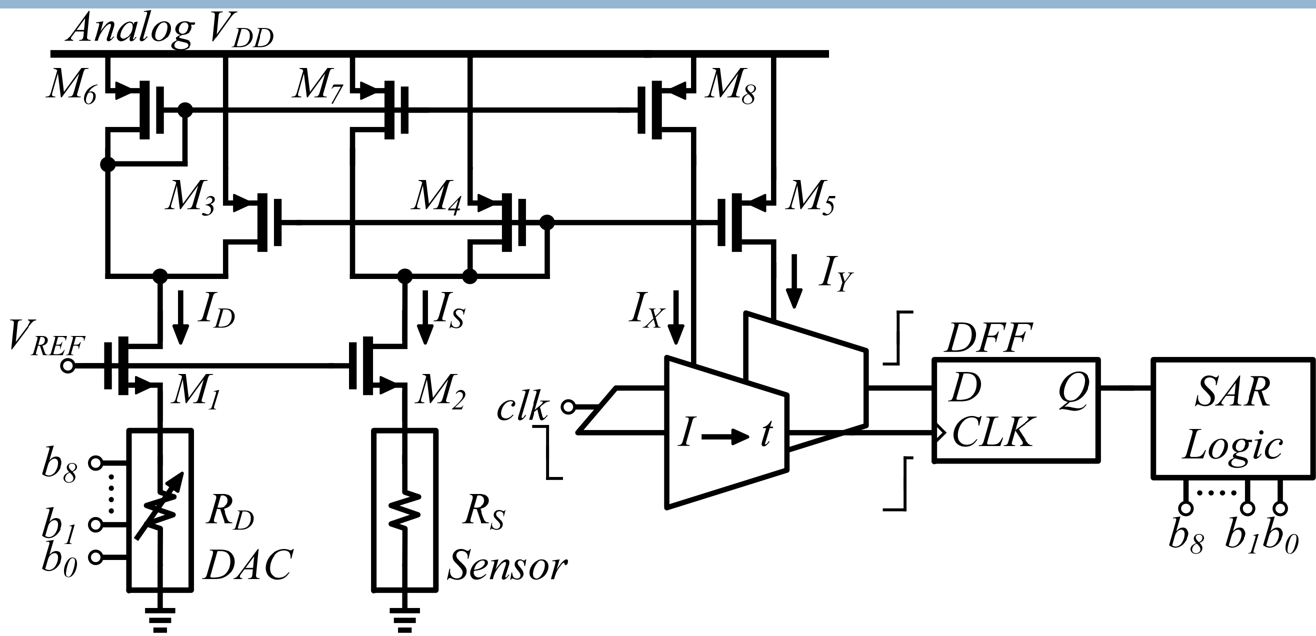
Thermistor Response Curve



100K6MCD1, BetaTHERMSensors

- Target temperature range: 27 °C to 42 °C
- Target resolution: 0.05 °C to 0.1 °C

Time-Domain Sensor Readout



- SAR algorithm tries to minimize the R_S-R_D
- Power dissipation: 17 uW @ 21 kS/s
- 9-bits (samples LSB twice)

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 (Asian Solid-State Circuits Con

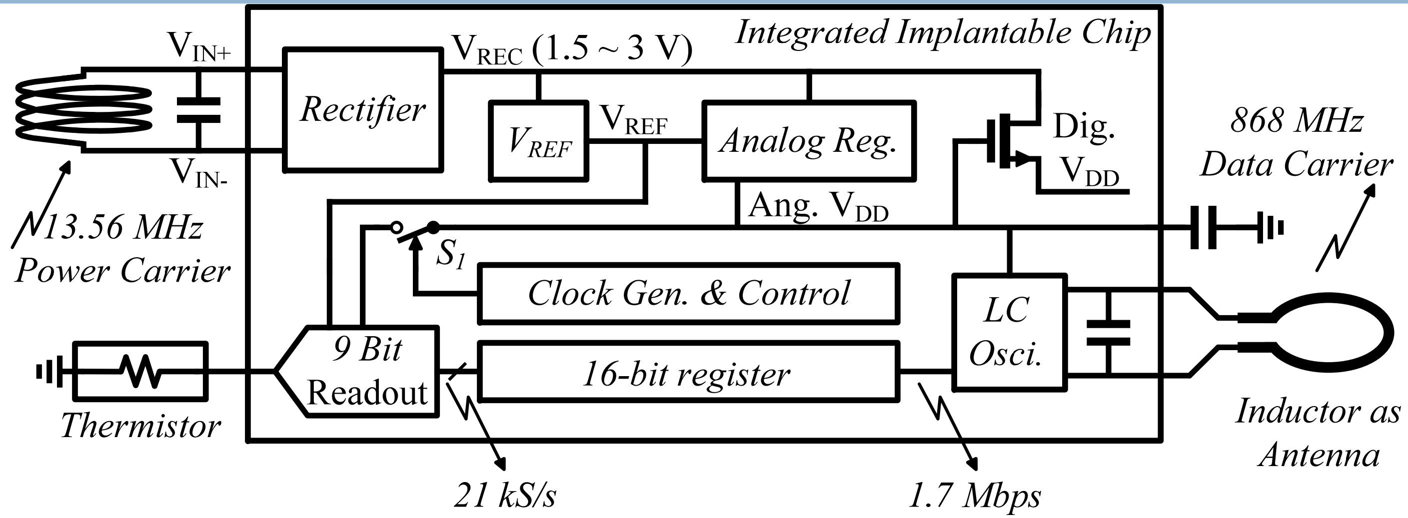
Time-Domain Sensor Readout

The sensor response is directly digitized by a time-domain comparator to achieve ultra-low-power operation.

Sensor Readout	Measurement
Technology	0.18 um
Sensor Type	Thermistor
ADC Type	SAR
Supply Voltage	1.5 V
Power	15 (uW)
Sampling Rate	5.5 (kS/s)
ENOB	7.6
FoM	14 (pJ/c-s)

M. A. Ghanad, M. M. Green, and C. Dehollain, "A 15 uW 5.5 kS/s Resistive Sensor Readout Circuit with 7.6 ENOB," 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.
M. A. Ghanad, M. M. Green, and C. Dehollain, IEEE TBioCas Journal, year 2017.

Low-power Implantable Chip

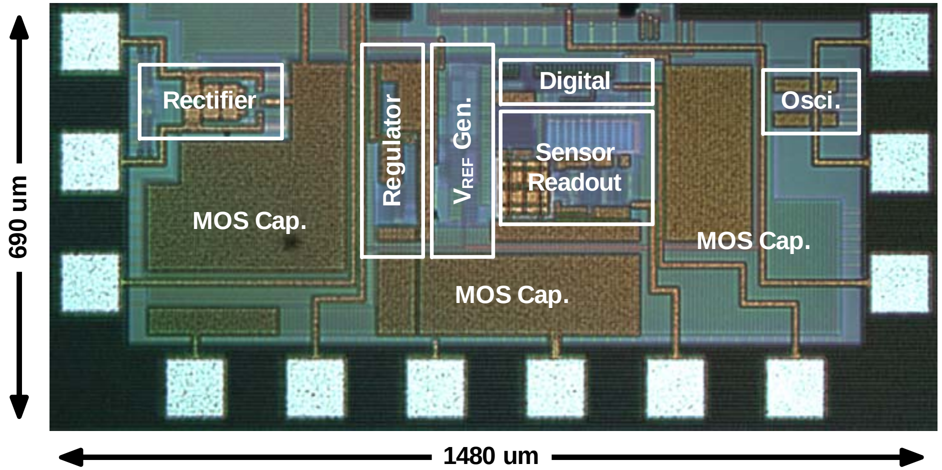


- High efficiency semi-active rectifier
- Time-domain resistance to digital converter
- Time interleaved sensor readout and data transmission

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 (Asian Solid-State Circuits Conf).

Local Temperature Sensing Implantable Chip

- Semi active rectifier with leakage current control.
- Time-domain sensor readout.
- Duty cycled free-running oscillator for data communication.
- Power Consumption is 6X smaller than similar reported works.

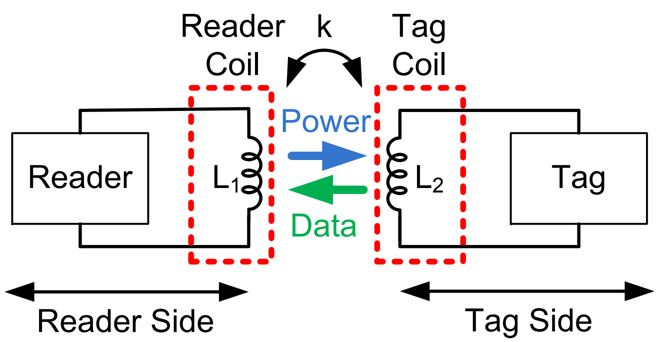


Implantable Chip Measurement	
Technology	0.18 um
Sensor type	Thermistor
Power	53 (uW)
V_{REC} Min.	1.5 (V)
Tran. Data Rate	1.7 (Mbps)
Sampling Rate	21 (kS/s)
Accuracy	$\pm 0.09\ C^{\circ}$

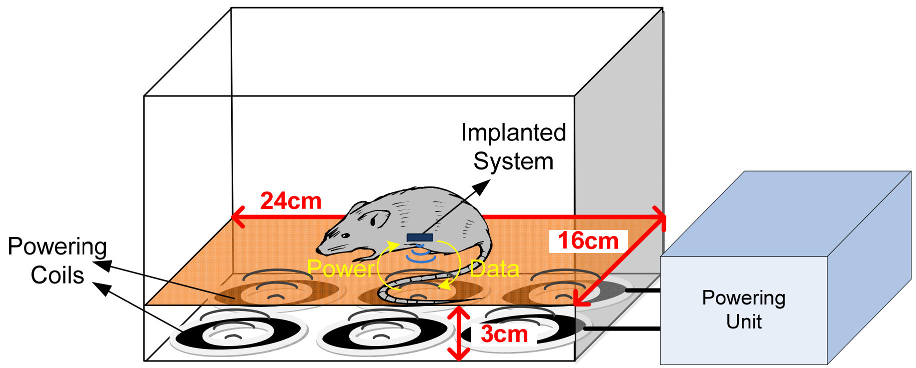
M. A. Ghanad, M. M. Green, and C. Dehollain, "A Remotely Powered Implantable IC for Recording Mouse Local Temperature with ±0.09 °C Accuracy," IEEE A-SSCC 2013 (Asian Solid-State Circuits Conference).

Magnetically-Coupled Remote Powering System for Freely Moving Animals

- Real-time long-term monitoring → Continuous remote powering
- Condition of subject is important in order to obtain reliable measurement results
  - Conscious → Awake (without anesthetized)
  - Non-stress environment → Freely moving



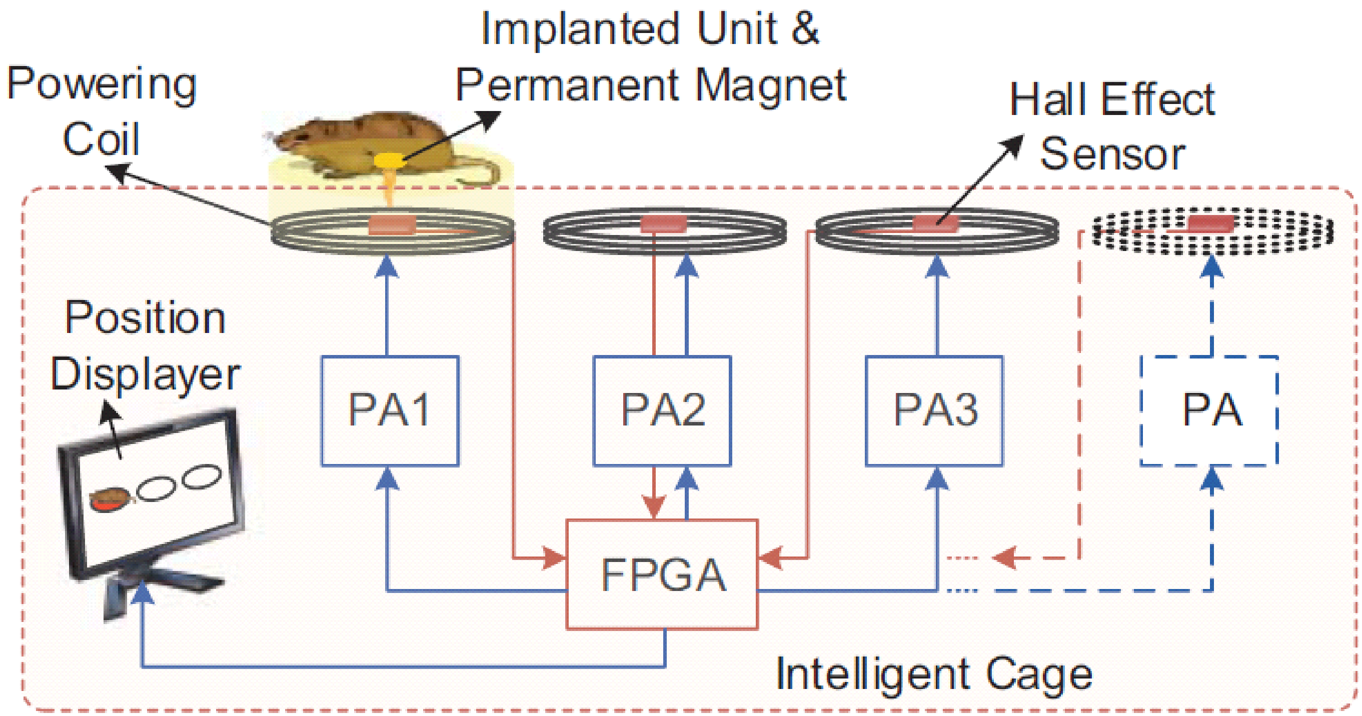
General RFID concept



Scenario for remotely powered systems

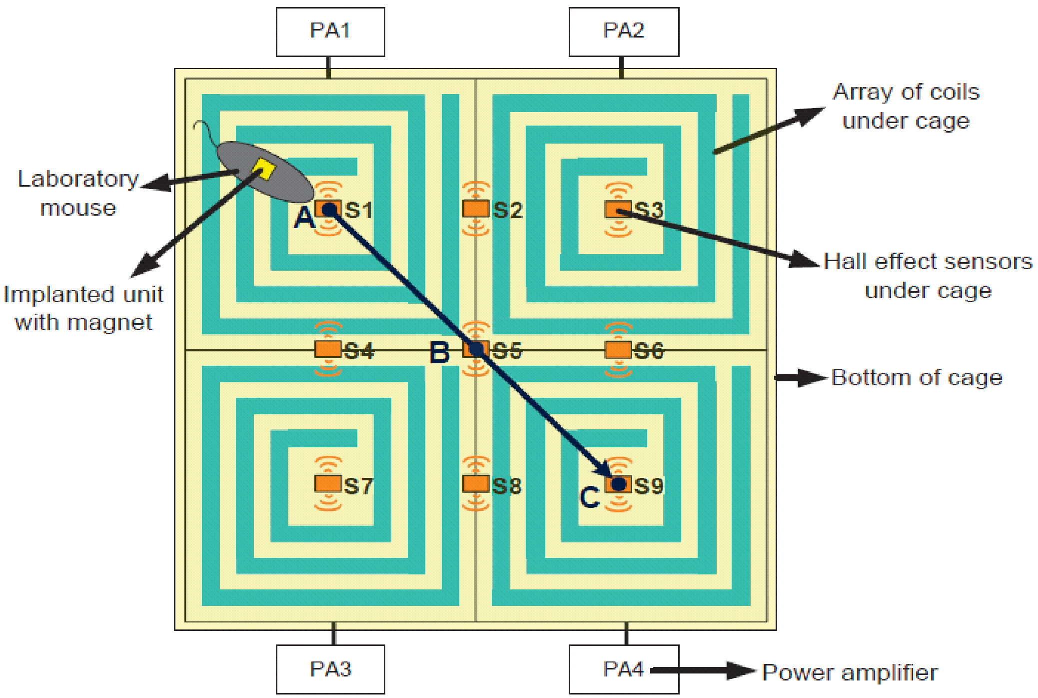
Intelligent Cage

- Cage with array of powering coils and magnetic field sensors



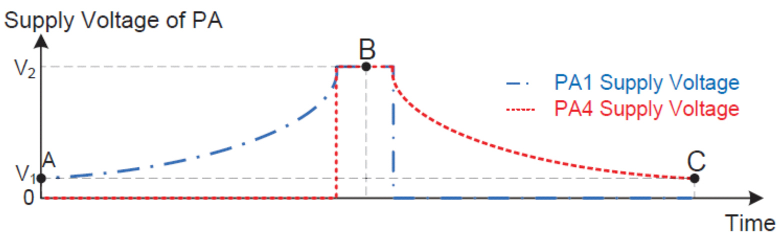
E.G. Kilinc, B. Canovas, F. Maloberti and C. Dehollain, IEEE ISCAS 2012 Conference

Scenario



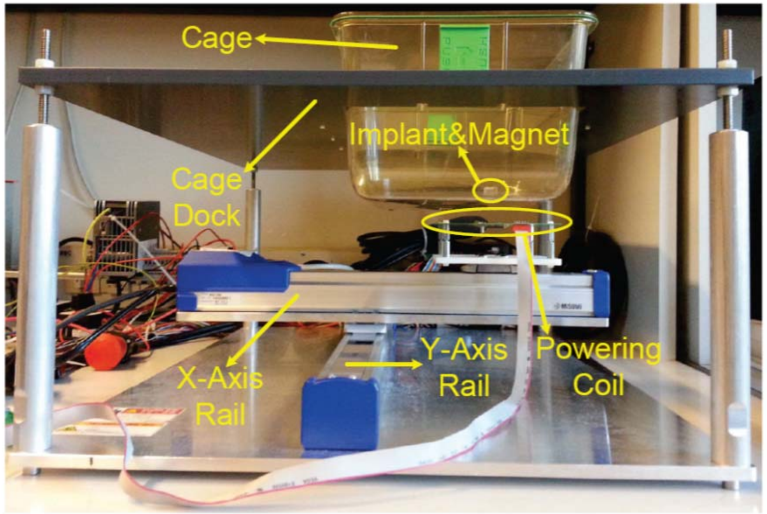
- Assume animal moves from A to B, then C

- Animal tracking
- Smart powering



IRPower System

- Test setup of IRPower system
- Rails move at the maximum speed of 30 cm/s
- Faster than animal inside cage (~7 cm/s)



E.G. Kilinc, C. Dehollain, ”Intelligent Remote Powering»
EPO Patent 12180919.8, August 17, 2012. PCT/EP2013/056611 Patent, August 13, 2013. US Patent Application 14/421,374, Nov 2015

E.G. Kilinc, G. Conus, C. Weber, B. Kawkabani, F. Maloberti, C. Dehollain, IEEE Sensors Journal, Feb. 1014

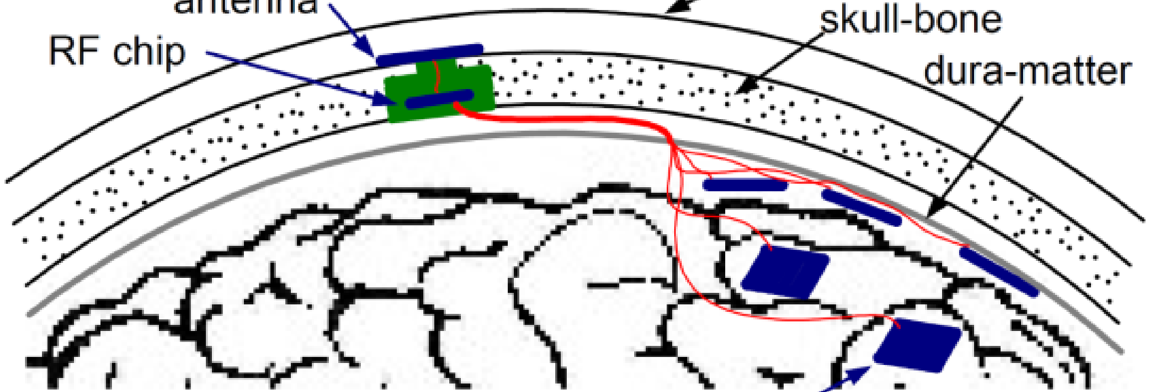
Wireless Power and Data Transfer for Intracranial Epilepsy Monitoring

Intracranial Neural Implants

- Macro iEEG electrodes
  - 10 mm diameter
  - 10 mm separation
- Data extraction
  - Cable bundles
  - Amplified and processed outside

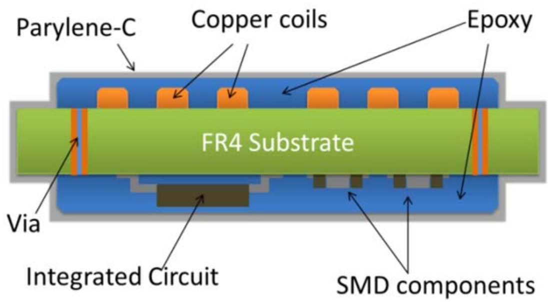
J. Van Gompel et al., Neurosurgical Focus, vol. 25, no. 3, p. E23, Aug. 2008.

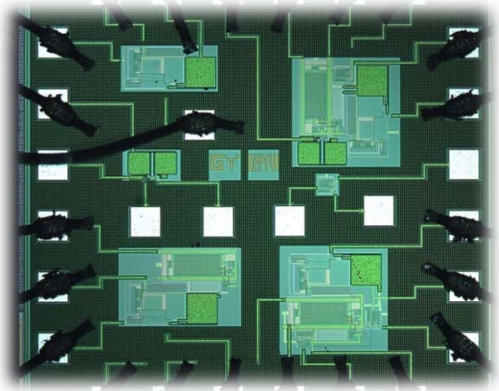
Scenario proposed by EPFL



Wireless Power and Data Transfer for Intracranial Epilepsy Monitoring

- Wireless Power Transfer by Magnetic Coupling at 10 MHz
- Implanted coil size < 15 x 15 mm2
- Polymer based packaging and modeling of the packaging
- 10 mW delivered power with 35% power efficiency from 1cm
- At least 1 month of successful in-vitro operation

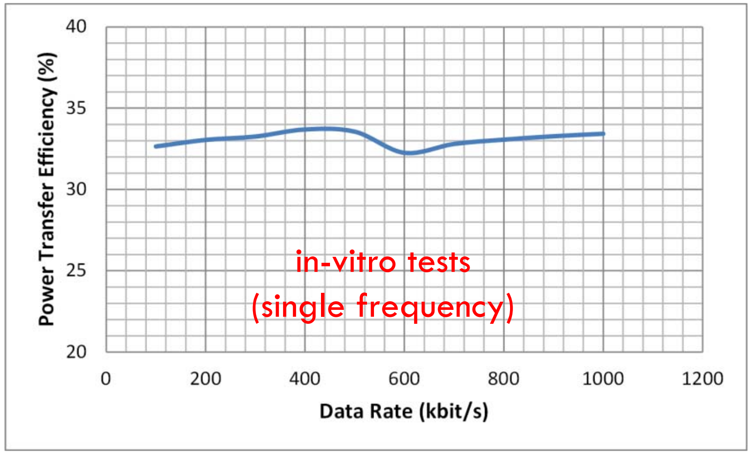


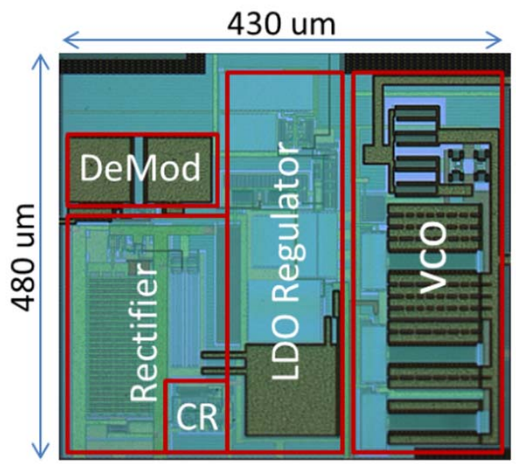


- EPFL news on 9th Feb 2015: http://actu.epfl.ch/news/monitoring-epilepsy-in-the-brain-with-a-wireless-s/
- PhD Thesis n0 6447, Author: Gurkan Yilmaz, EPFL, December 2014.
- G. Yilmaz, O. Atasoy, C. Dehollain, «Wireless energy and data transfer for in-vivo epileptic focus localization», IEEE Sensors Journal, Nov. 2013.
- G. Yilmaz and C. Dehollain, Springer book, year 2017

Wireless Power and Data Transfer for Intracranial Epilepsy Monitoring

- **Wireless Data Communication (single frequency approach)**
  - Load modulation on the power transfer frequency
  - 1Mbps on 8.4 MHz carrier has been realized (BER < 10^{-5})
  - 33% power efficiency in *in-vitro* experiments





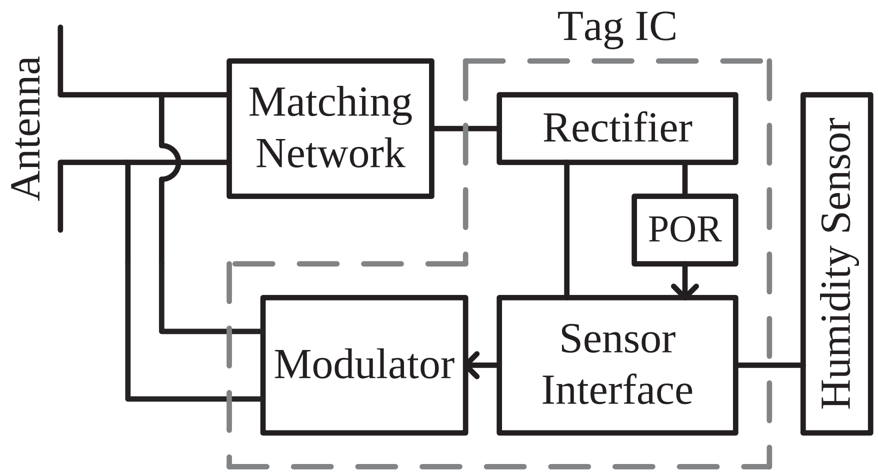
Transmitter
at 433 MHz
0.18um CMOS

- **Wireless Data Communication (independent frequency approach)**
  - A 433 MHz active transmitter has been designed
  - 1.8 Mbps has been realized (BER < 10^{-5})
  - Base station in discrete components

Far-Field Remotely Powered Wireless Sensor System at 868 MHz

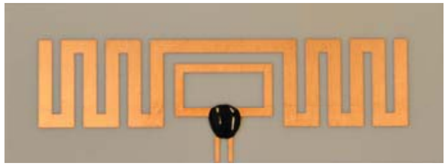
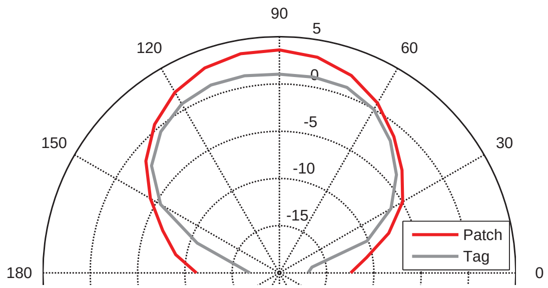
Passive UHF RFID Tags

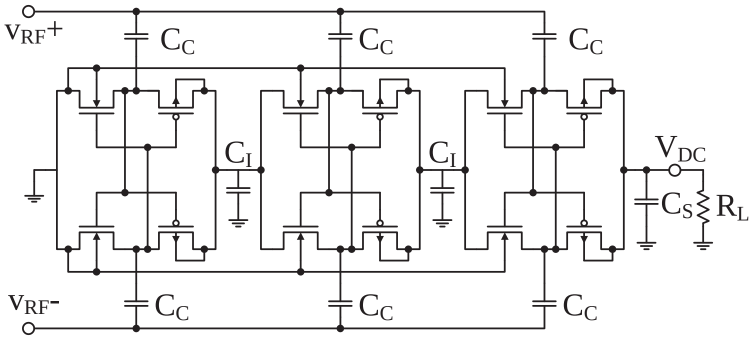
- Capacitive Humidity Sensor
- Oscillator Based Sensor Readout
- Back-Scattering Wireless Com.
- Remote Powering Link
  - Base Station
  - Base Station Antenna
  - Tag Antenna
  - Rectifier
- Low Power Analog Circuitry
  - Supply Generation
    - Low Drop-Out Voltage Regulator
    - Bandgap Reference
  - Current Reference

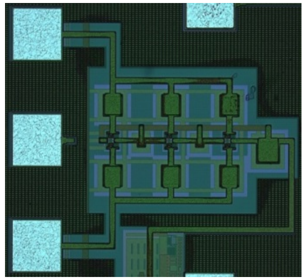


Electro-Magnetic Remote Powering

- Base Station Antenna
  - Patch
  - Gain = 3.6 dB
  - S11 = -24 dB @ 866 MHz
- Tag Antenna
  - Inductively Coupled Meandered Dipole
  - Gain = 1.2 dB
  - Matched to chip impedance
- Rectifier
  - Differential
  - Threshold voltage cancellation
  - PCE = 65% measured

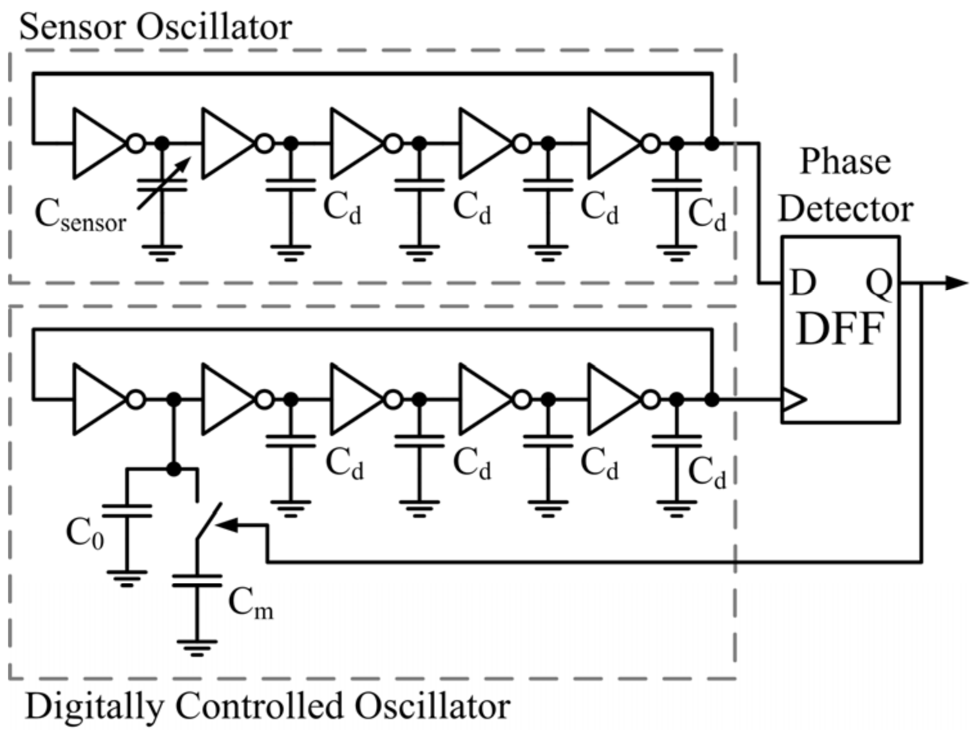




K. Kapucu, C. Dehollain, IEEE ICECS Conference, Dec. 2013
K. Kapucu, C. Dehollain, IEEE RFID-TA Conference, Sept. 2014

Low Power Sensor Interface

- Capacitive sensor
  - Printed humidity sensor
- Sensor readout
  - Supply voltage
    - Down to 0.8 V
  - Low power
    - 12 µW @ 0.8 V
    - UMC 0.18 µm CMOS
- Distance range: 4 m
  - 3.3 W EIRP from the base station



K. Kapucu, J.L. Merino, C. Dehollain, PRIME Conference in June 2013 and ICECS Conference in Dec. 2013
K. Kapucu , C. Dehollain: 4 conference papers at PRIME 2014, RFID-TA 2014, RFID 2015, RFID 2016
PhD Thesis n0 6540, Author: Kerem Kapucu, EPFL, April 2015.

Summary

- Research spans
  - Circuit development for low power consumption
  - New architectures for wireless systems
  - Use of wireless energy sources for remote powering, e.g. magnetic, electro-magnetic, ultrasound, etc.

  Aiming scientific innovation through various applications
- Research in
  - Radio Frequency Integrated Circuits
  - RFIDs
  - Implantable Wireless Sensor Systems