Power Supply for Wireless Sensor Systems

Chair for Electrical Instrumentation
Prof. Dr. Leonhard Reindl

"We enable autonomous devices to perceive the environment."

- Wireless sensor & actuator networks
- Indoor localization
- Environmental and structural health monitoring
- Energy harvesting
- RF passive sensors

Wireless node

Motivation for Wireless

On the long run we can increase prosperity only if all industrial processes run more and more efficiently at their optimum!

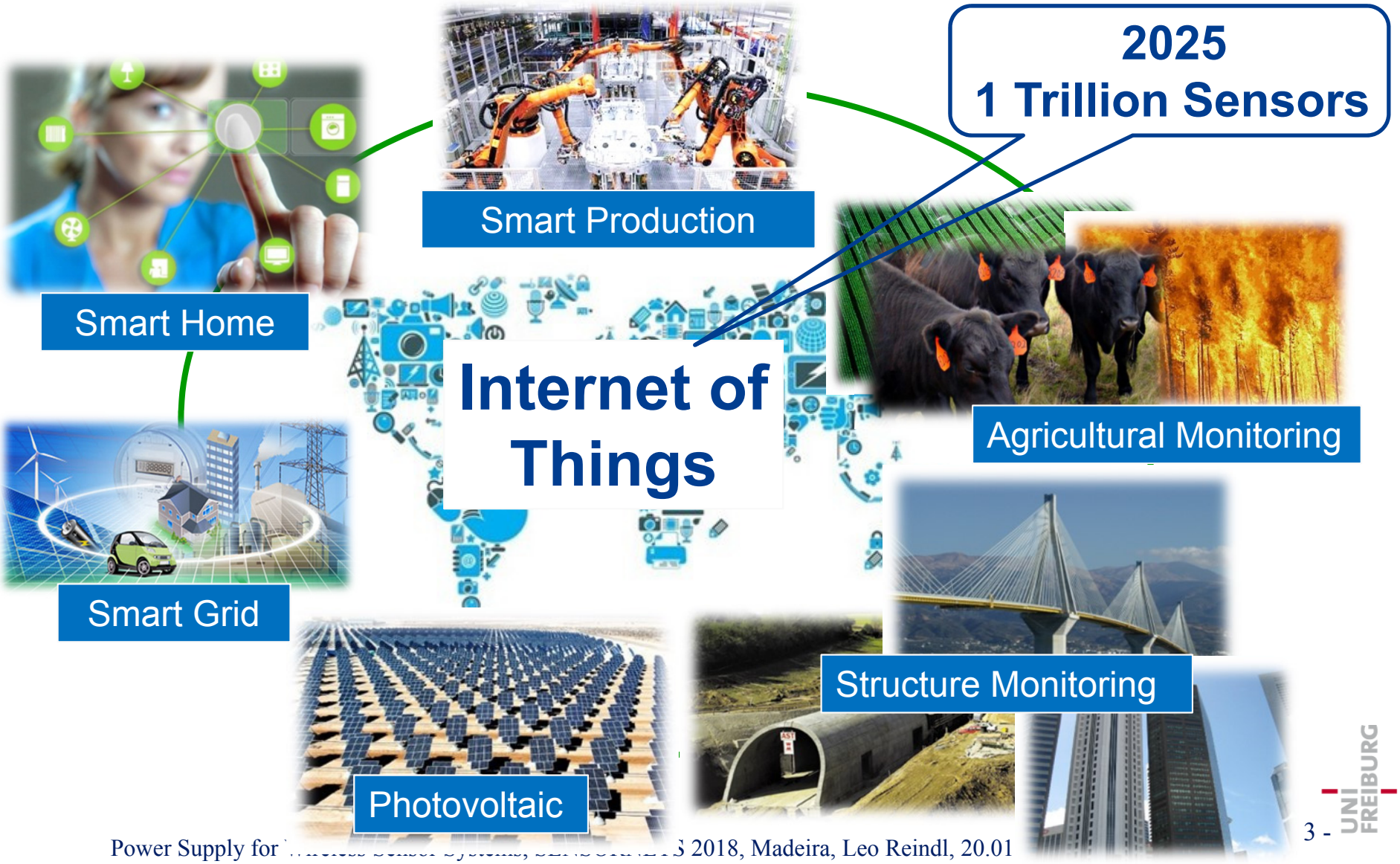
This can only be achieved by closed loop controls of the processes.

Sensors and actuators are fundamental parts in each control.

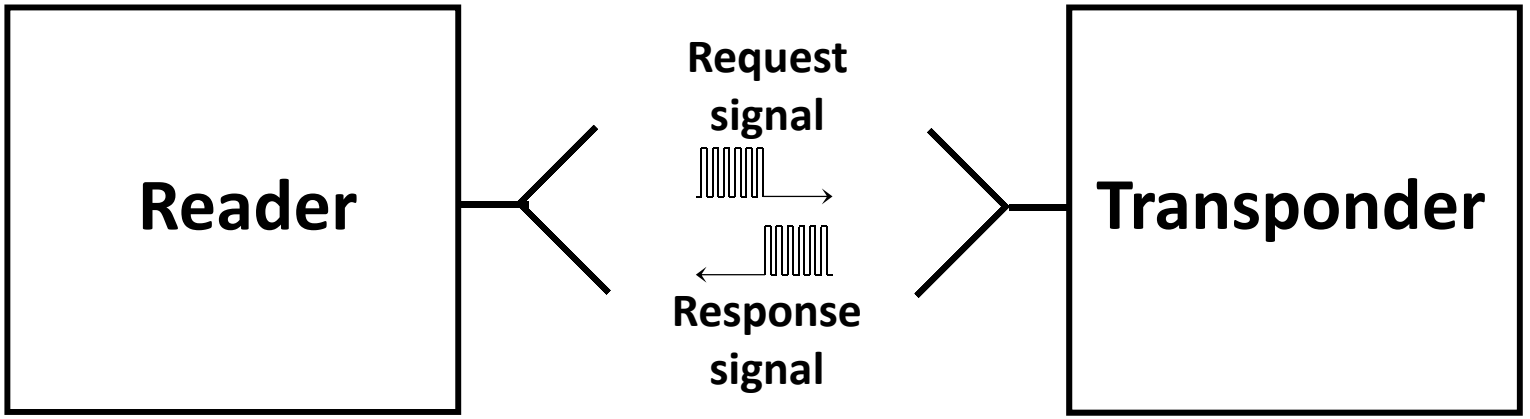
Wireless sensors are used

- on rotating or movable parts,
- on animals or human beings,
- or when a wireless connection saves installation costs.

Smart sensors everywhere!



Operating Principle of a Wireless Sensor Systems

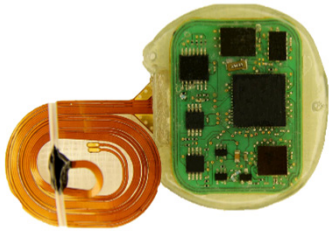


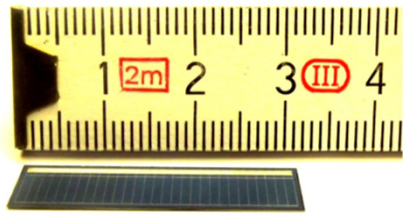
Outline

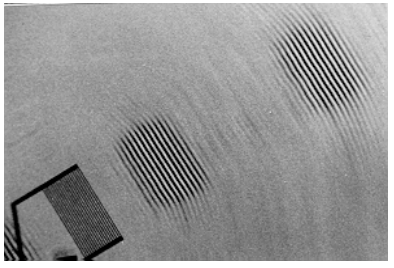
Wireless sensing

Wireless networking	Near field coupling	Energy harvesting	Chipless sensing

Low Power Communication	Monitoring	Localization	Inductive coupled	RFID	RF	Photovoltaic	Thermoelectric	Acoustic	Electromagnetic

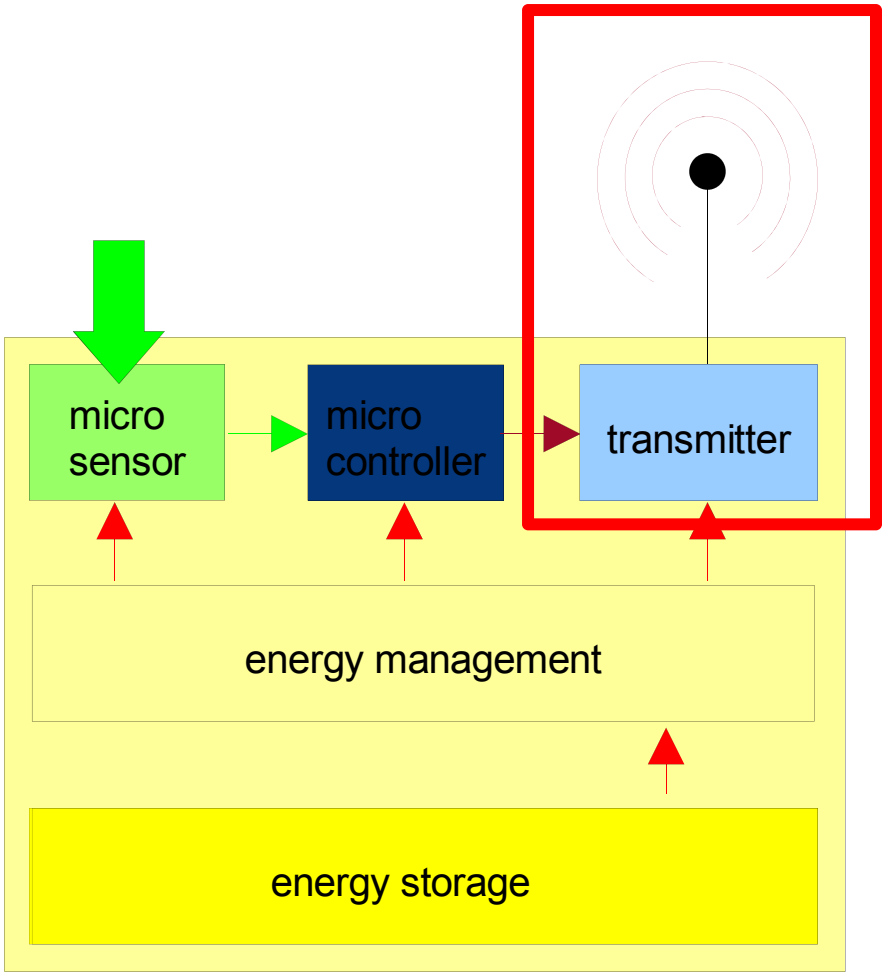




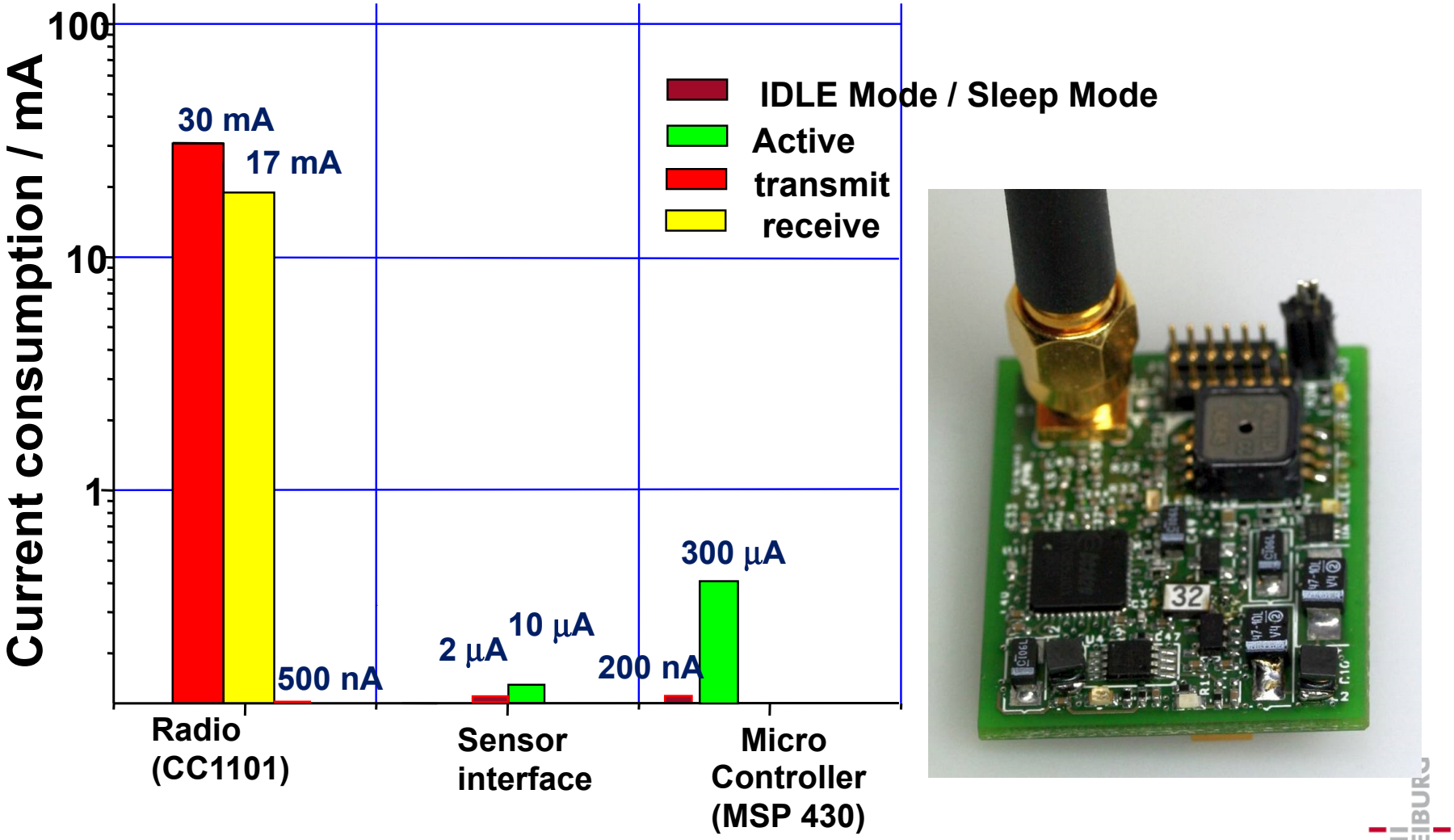


Wireless Sensors

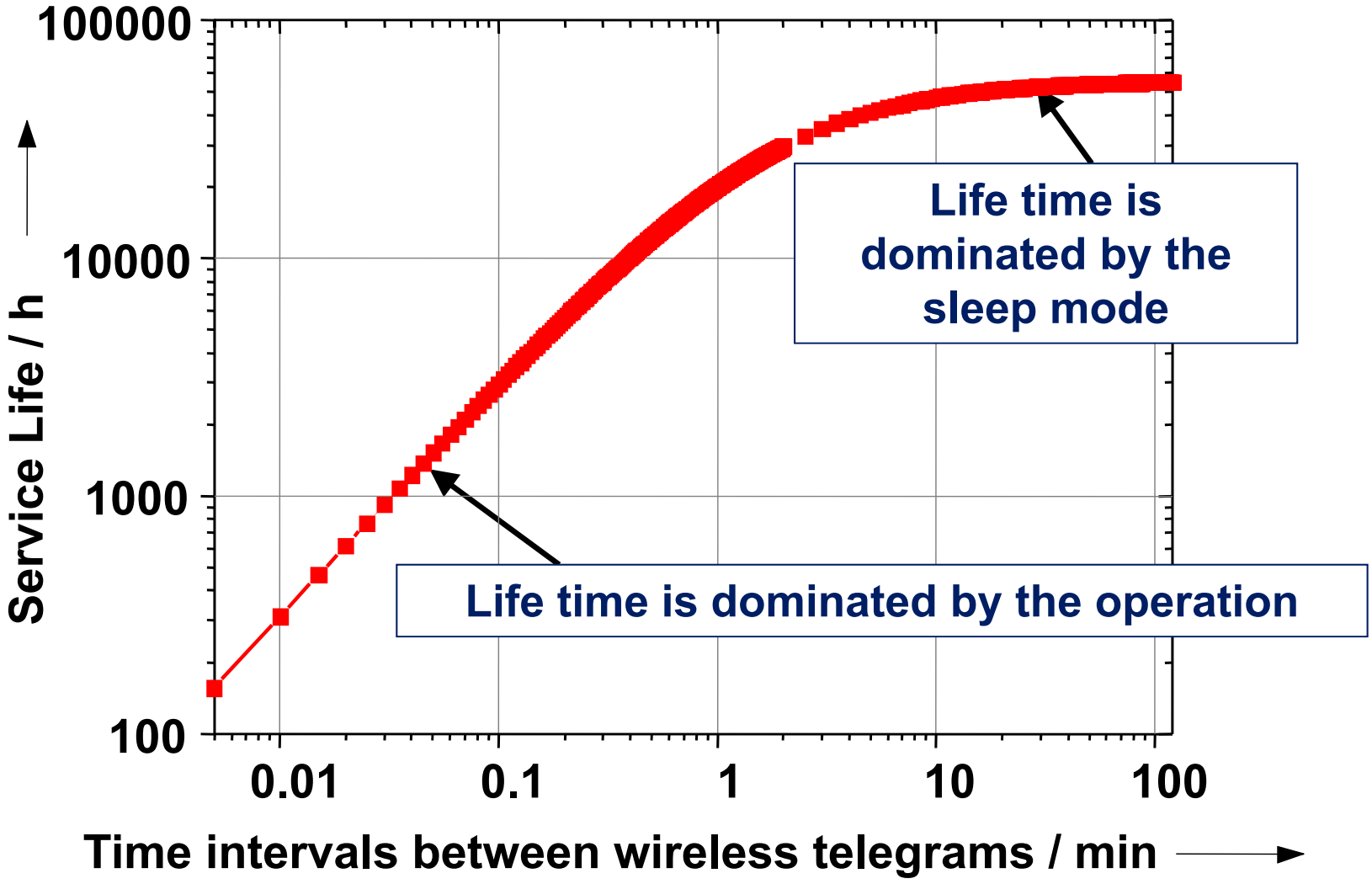
- fully autonomous
- limited operating time
- No maintenance
- easy to install
- …at remote sites
- Average power 10 µW



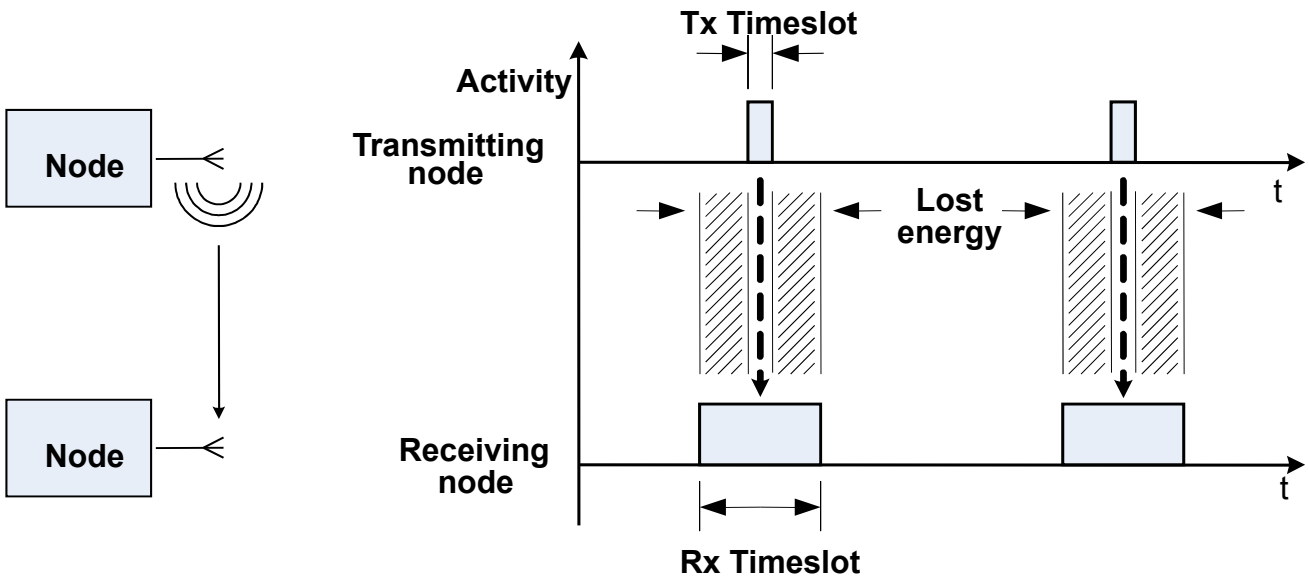
Energy consumption of a sensor node



Service Life of a Battery Based Wireless Sensor Node



Cyclic Wake-up to Save Power

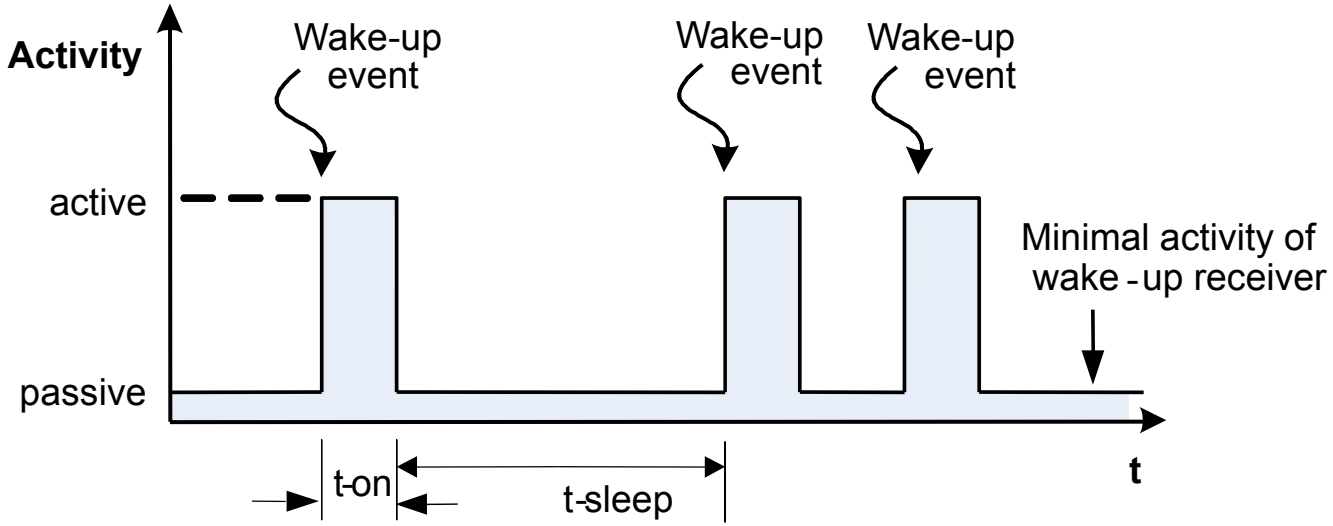


- Predefined wake-up time slots
- Unnecessary wake-up of all nodes
- Accurate clock and synchronization is required
- **No real time operation!**

Our Solution

- Communication on demand
- Ultra Low Power consumption (factor of 10,000)
- Simple
- Maintenance-free

For real time operation: Wake-up on Demand



Transceiver at 868 MHz

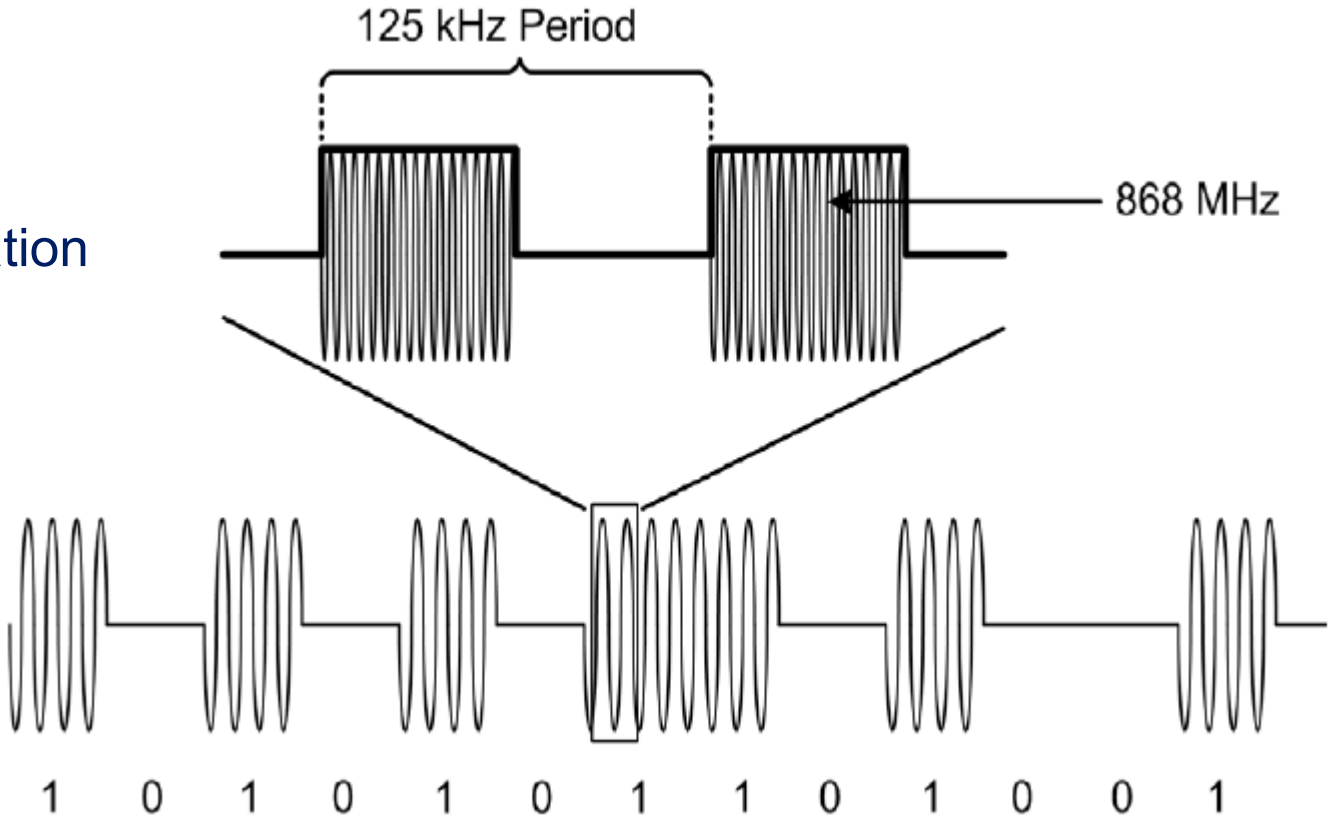
+ Multipath propagation
+ λ/2 antenna size of 17 cm (λ=34 cm)
+ Datarate ≥ 500 kBit/s
- Power consumption ≈ 50-100 mW (Rx/Tx)

Transceiver at 125 kHz

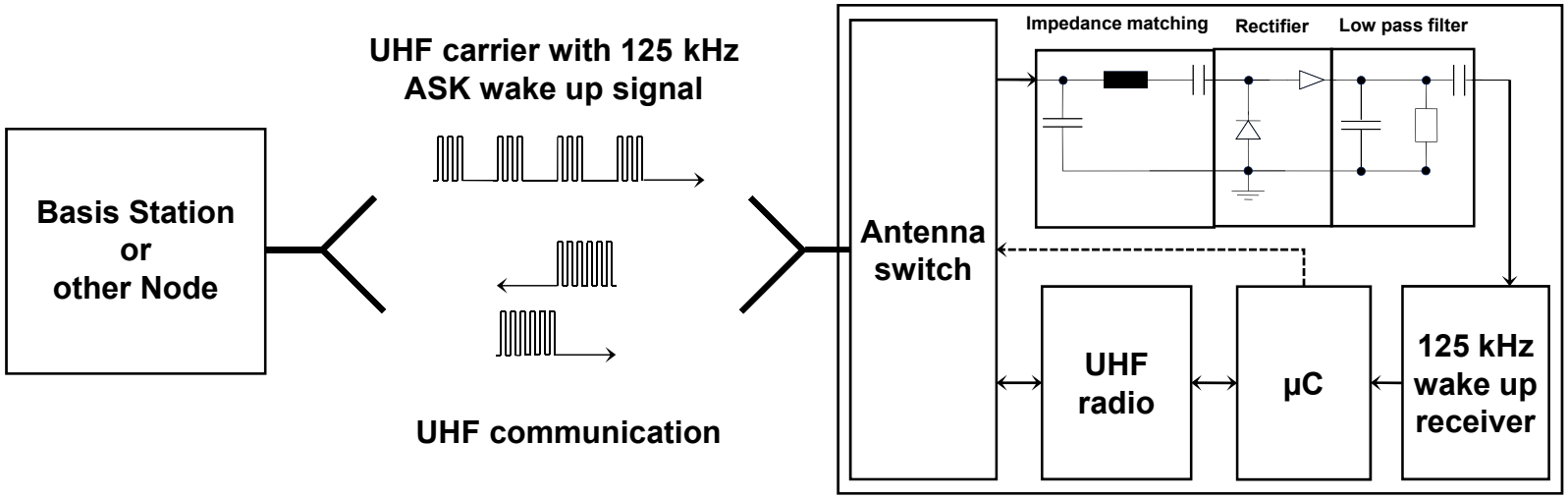
- Nearfield effects, inductive cuppling
- Coils instead of antennas (λ=2398m)
- Datarate < 1 kBit/s
+ Power consumption ≤ 6-20 µW

Wake Up Signals

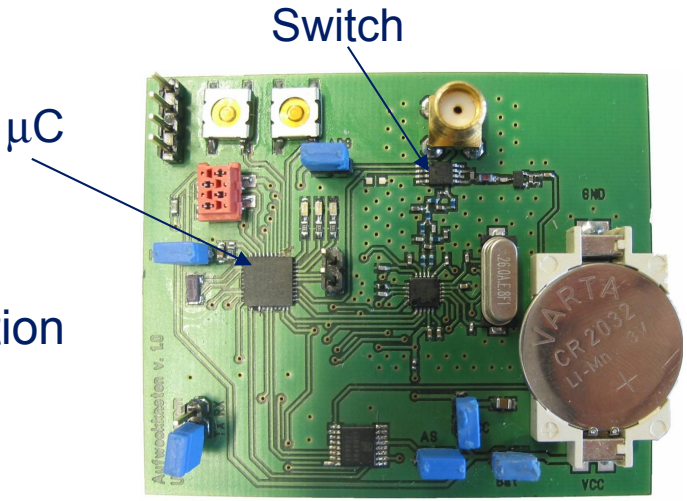
- Carrier modulation
- Address modulation



Wake up receiver

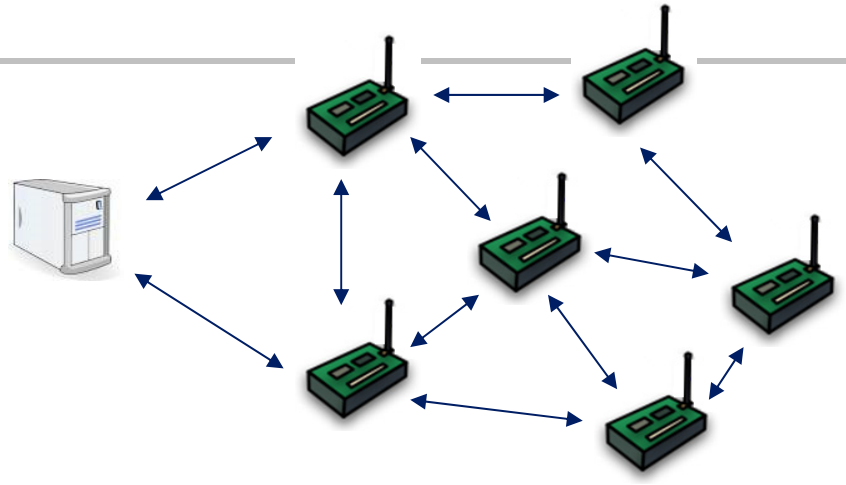


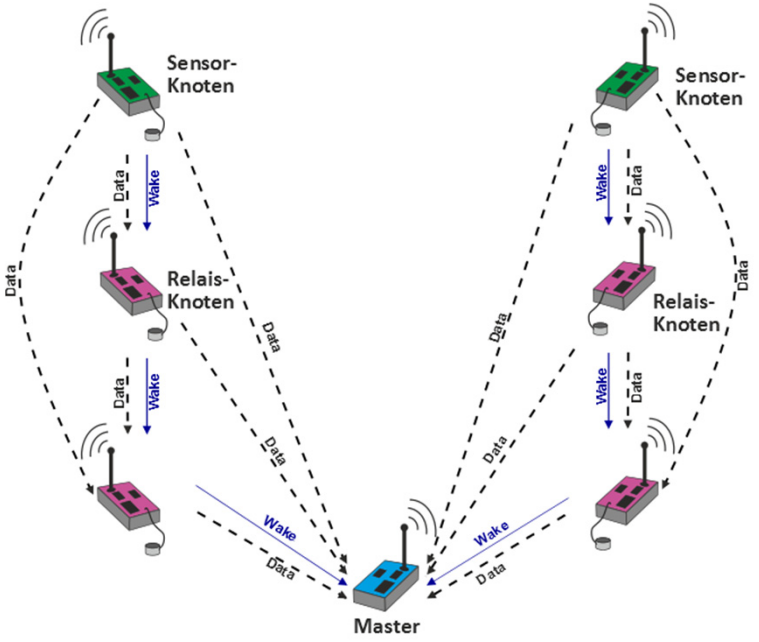
- 868 MHz or 2.4 GHz standard bands
- Addressable wake-up with 125 kHz
- Wake up distance 50 … 100 m
- Real-time wake-up @ 10 µW power consumption
- Network protocols for wake-up and multi-hop networks



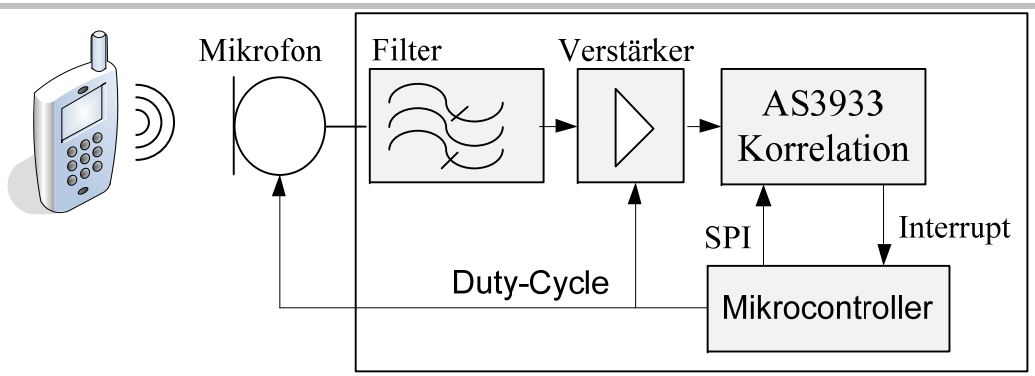
Routing Protokoll

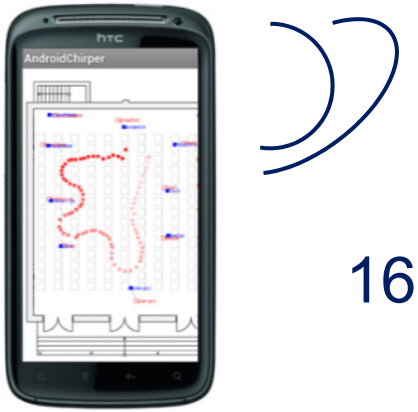
- Multi-Hop Wireless Sensor Network
- Wake-up distance
  - app. 30 m
- Communication distance
  - app. 200 m
- Communication via hopping over several nodes



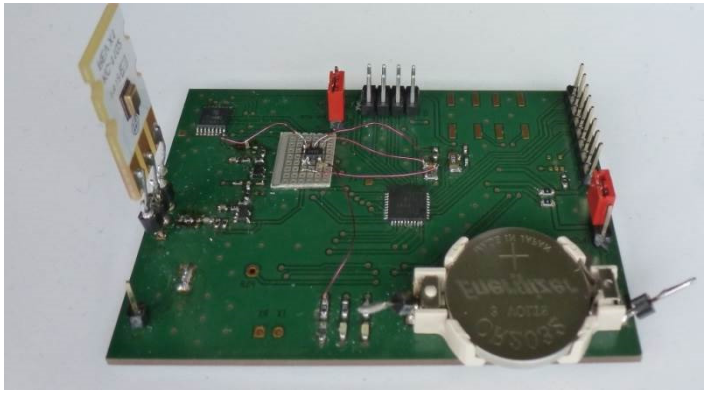


Ultrasonic Wake Up Receiver





16 bit address



- 45 µW in sleep mode
- Frequency >20 kHz
- Wake up distance using Smartphone Samsung S4 Mini ≈ 25 m

Outline

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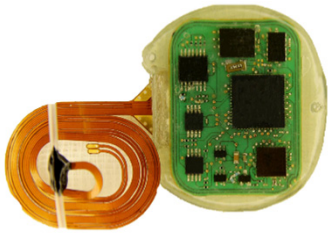
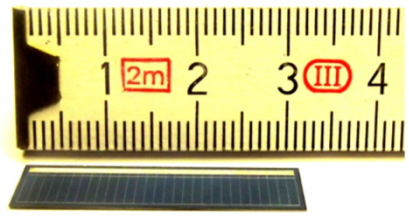
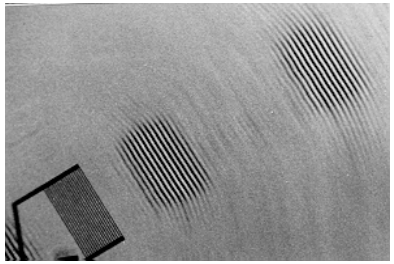
Wireless networking	Near field coupling	Energy harvesting	Chipless sensing

Low Power Commu-nication	Moni-toring	Locali-zation	Inductive coupled	RFID	RF	Photo-voltaic	Thermo-electric	Acoustic	Electro-magnetic







Structural monitoring

Bridge over river Mosel (Germany)
Height: approx. 135 m

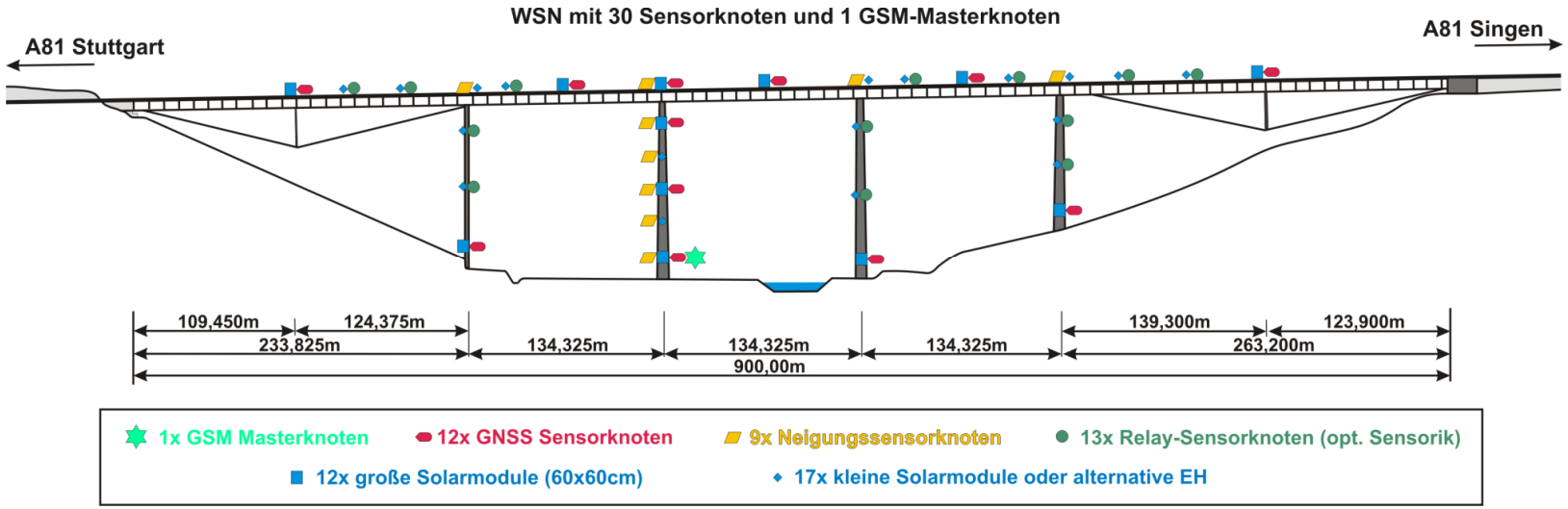
Installing a sensor

Detection of cracks

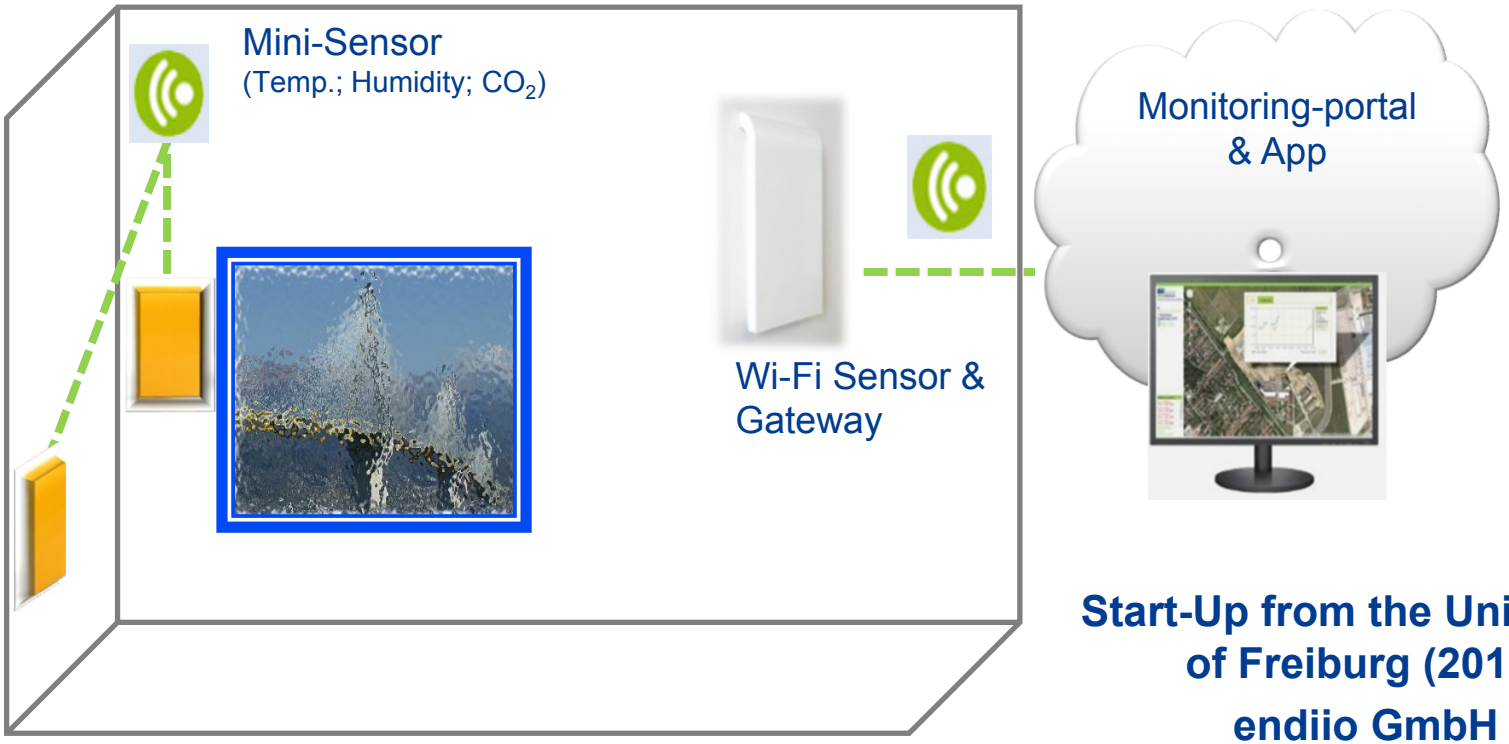
- Most bridges reaches their lifetime!
- Evaluation of structural stability needed
- Position for sensors is hard to reach

Neckar Valley Bridge Weitingen

- Installation of a multi-hop wireless sensor network with sensors, wireless repeater and one master node.



Smart Home System



Start-Up from the University of Freiburg (2013)

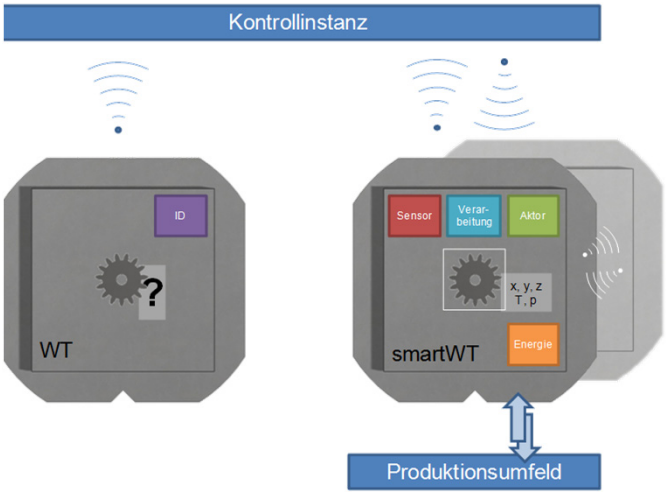
endiio GmbH

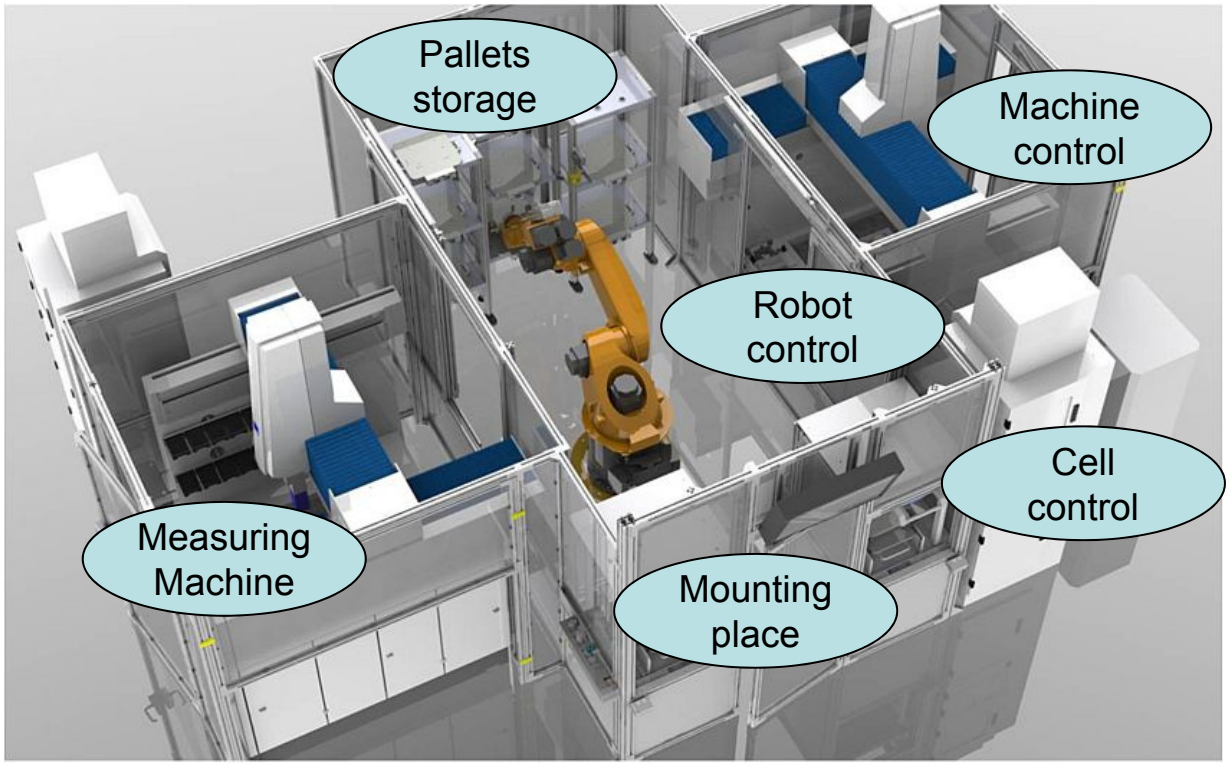
https://www.endiio.com/

- Self powered Gateway (Wi-Fi and GSM)
- Self powered and real-time Mini-Sensor mesh-network
- Molt and Oxygen monitoring and warning system

Industry 4.0: Smart production

Connection of moveable work piece carrier to the wired infrastructure





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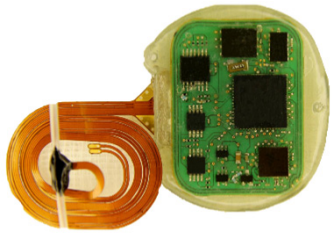
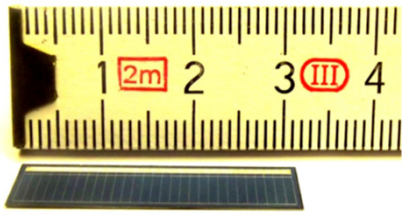
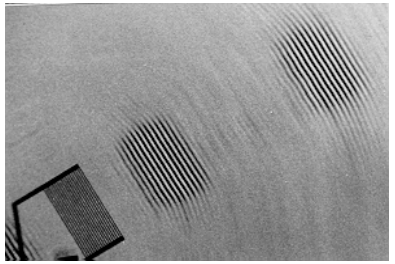




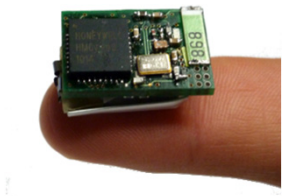


Localization

Radio (Nanotron)

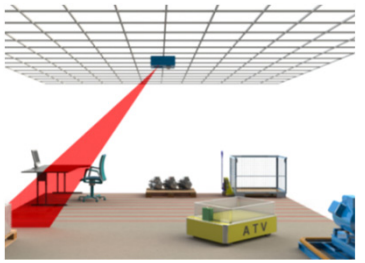
[Höflinger et al., IPIN2011]

Mikro-IMU



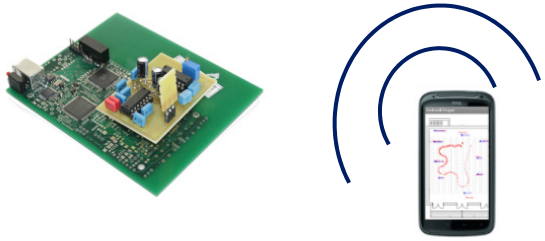
[Höflinger et al., Journal IEEE IM 2013]

Laser



[K., Höflinger et al., IPIN2013]

Acoustical < 21 kHz



[Höflinger et al., IPIN2012]

Acoustical 40 kHz

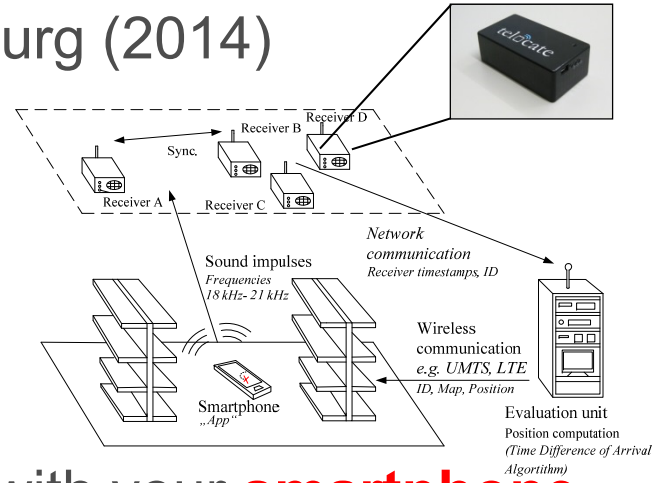
[W, Höflinger et al., Journal ILBS 2013]

Industry 4.0

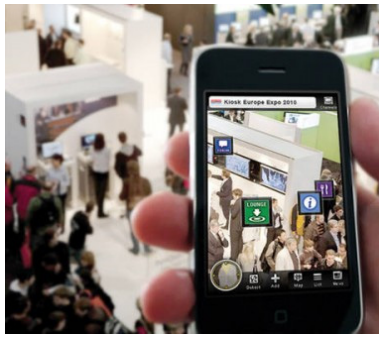
telocate
Precise indoor sensing and navigation

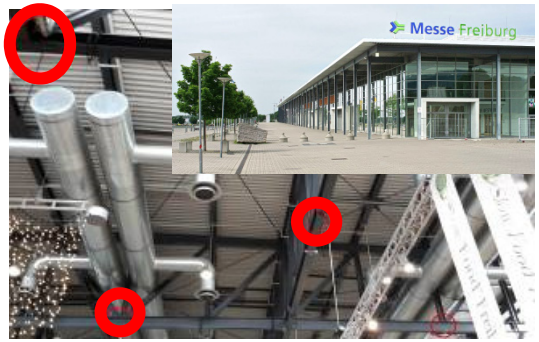
- Start-Up from the University of Freiburg (2014)
  - Team of 12 people
  - Precise Indoor-localization (< 30 cm)

  Telocate GmbH
  https://de.telocate.de/



- Find things and places interactively with your **smartphone**
  - Places in a shopping mall and public building (e.g. hospital)
  - Booth at an exhibition

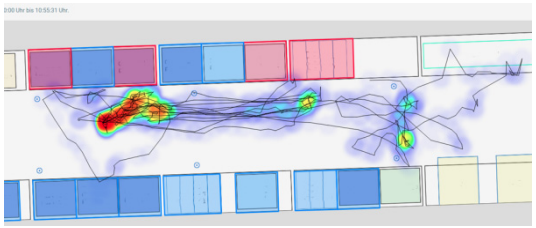




Industrial application

telocate
Precise indoor sensing and navigation

- Tracking more than just smartphones
  - Custom devices
  - E.g. Localisation of barcode scanner



- Customers wish to understand their logistics (production) processes
  - Analysis of movements (time, distance) for order picking
  - Process optimization

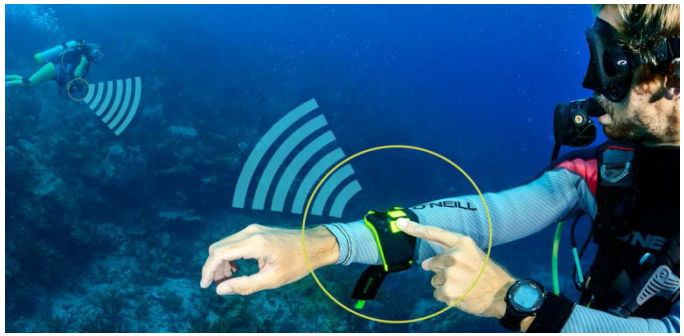
Restaurants

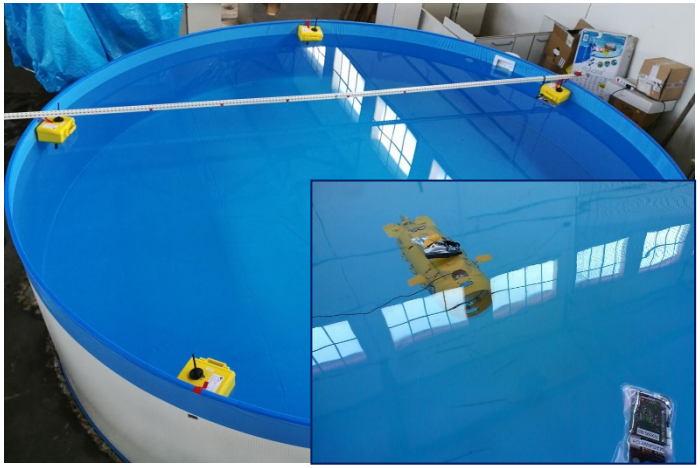
telocate
Precise indoor sensing and navigation

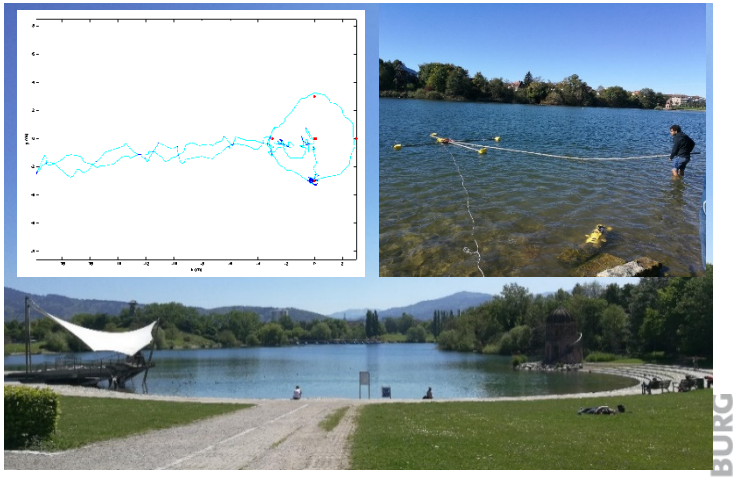
- Customer service for restaurants
  - Help to provide better service to the customer (delivery to table)

Diver localisation

- Contacted by another company
- Diver positioning
- Transfer of technology
  - Easy, since not linked to a fixed product







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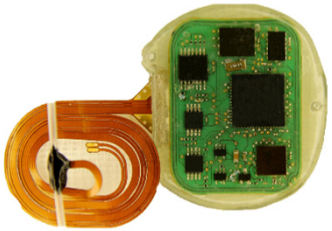
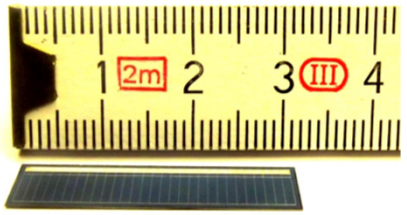
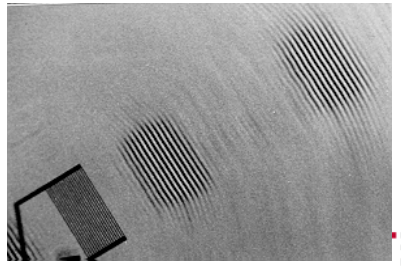
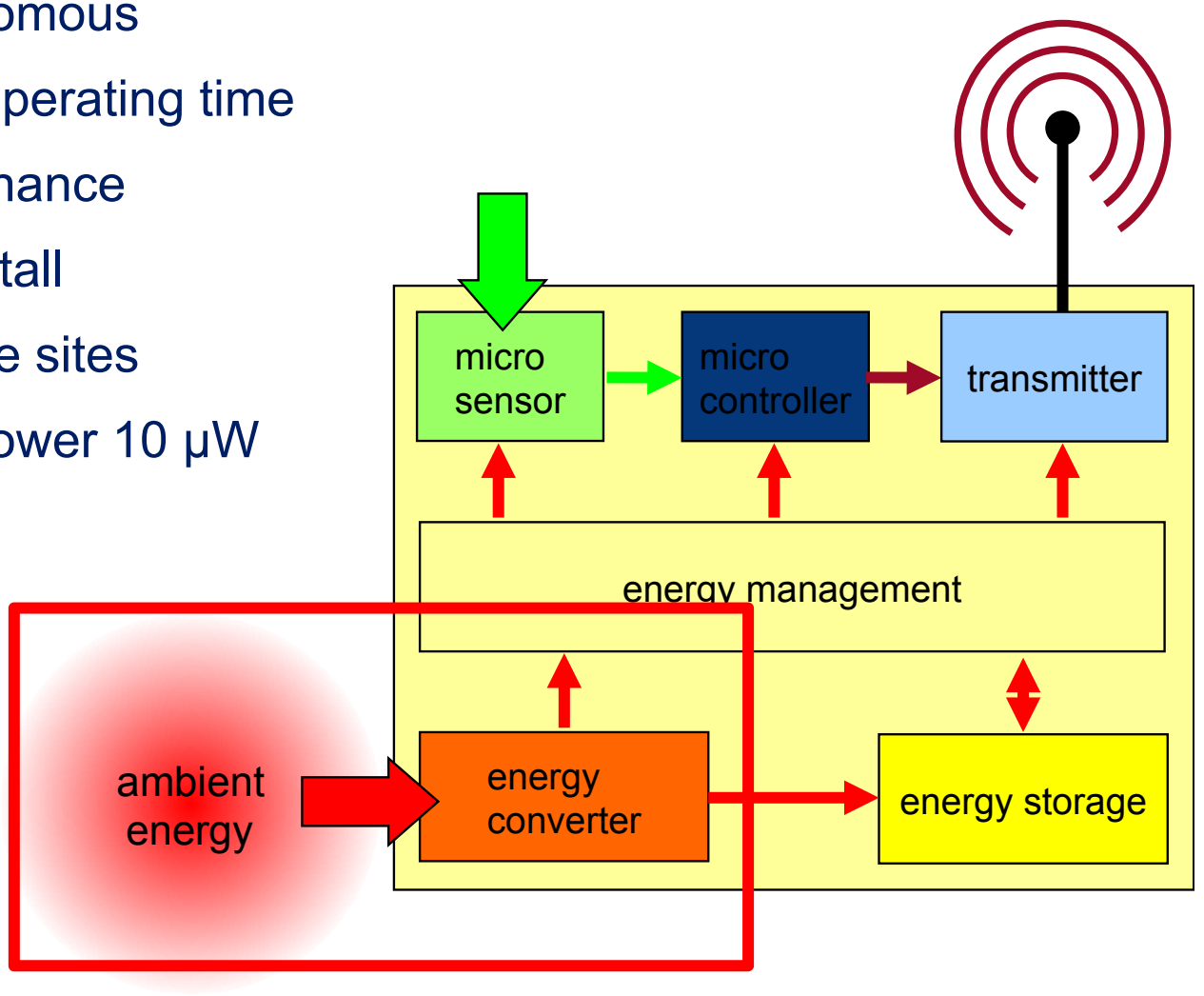




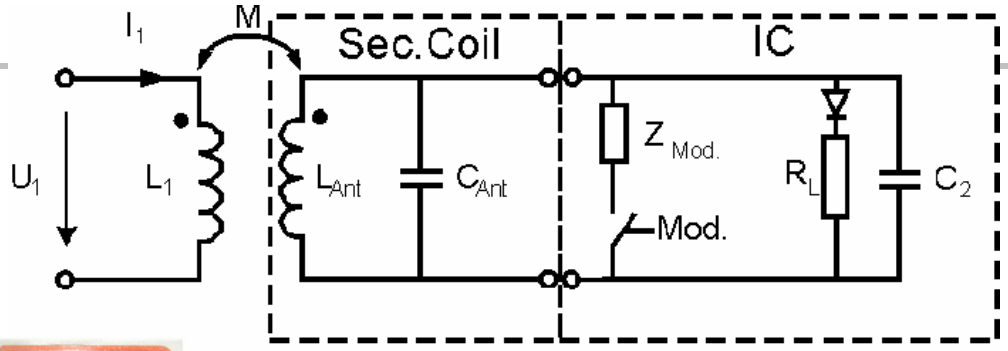


Wireless Sensors using Energy Harvesting

- fully autonomous
- unlimited operating time
- No maintenance
- easy to install
- …at remote sites
- Average power 10 µW



Inductive Coupled RFID Systems



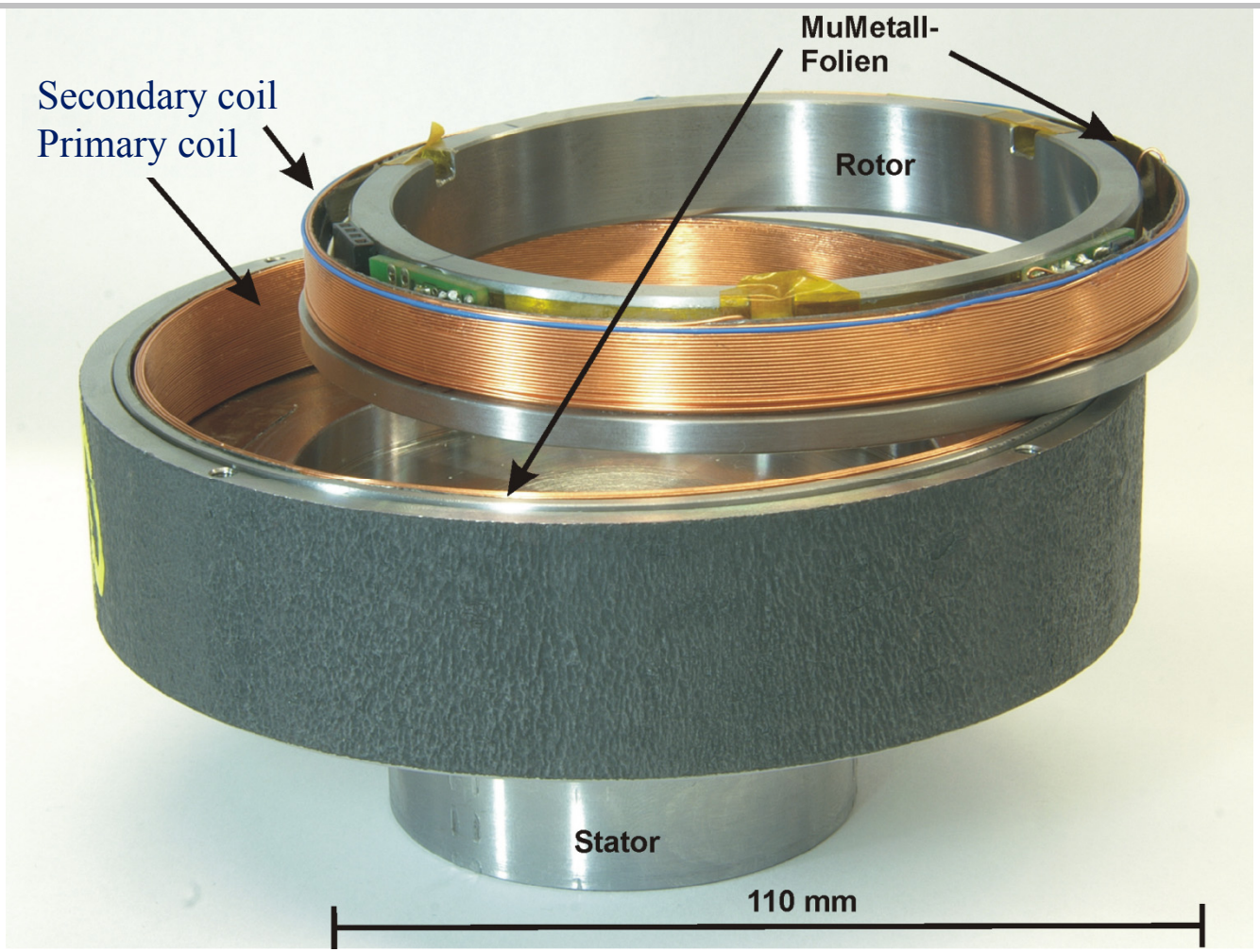
Inductive coupling
(125 kHz, 13.56 MHz):

- Weak coupled transformer

Feed-in distance:
U_{min}=2 V
f= 13.56 MHz.
reader coil:
I=1A;D=30cm; windings=1
[very loose coupling]
Label coil:
L=5mH; windings=4;
A=5·8 cm²

➡ **Feed-in distance ≈ diameter of reader coil**

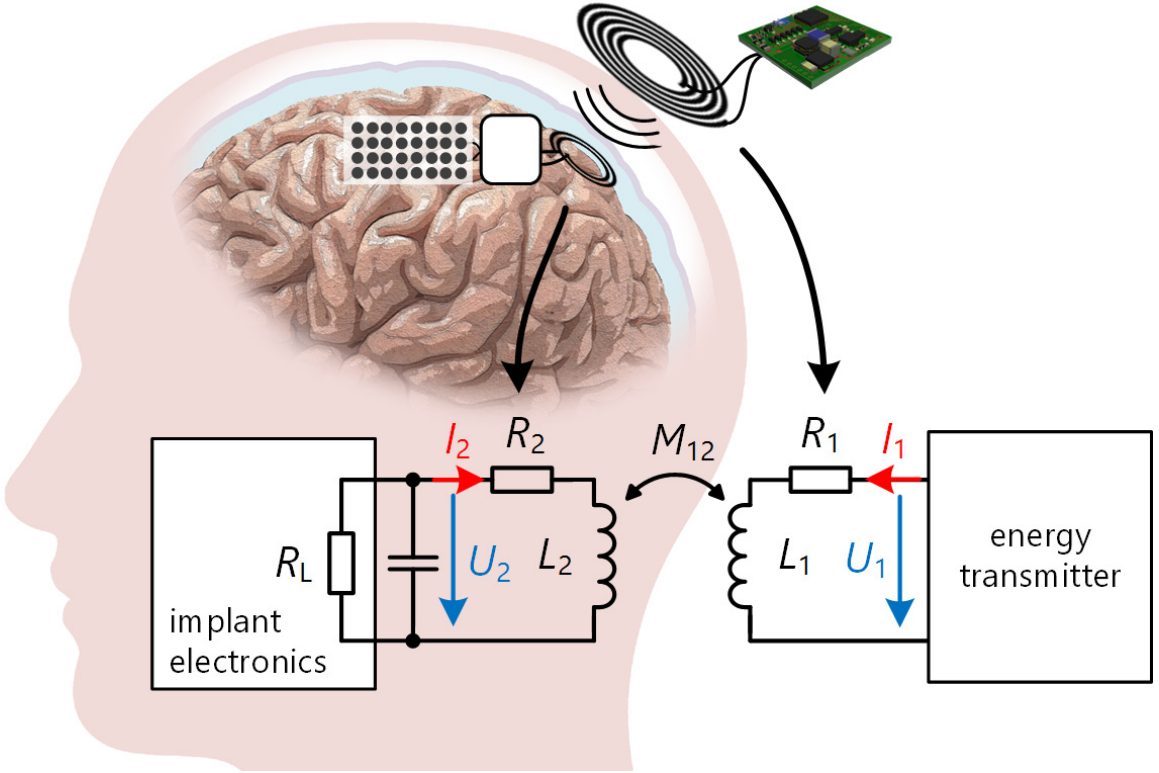
Inductive Coupled Sensor Systems



To the rotor of a high speed drill or a rotary cuter

For Biomedical Implants

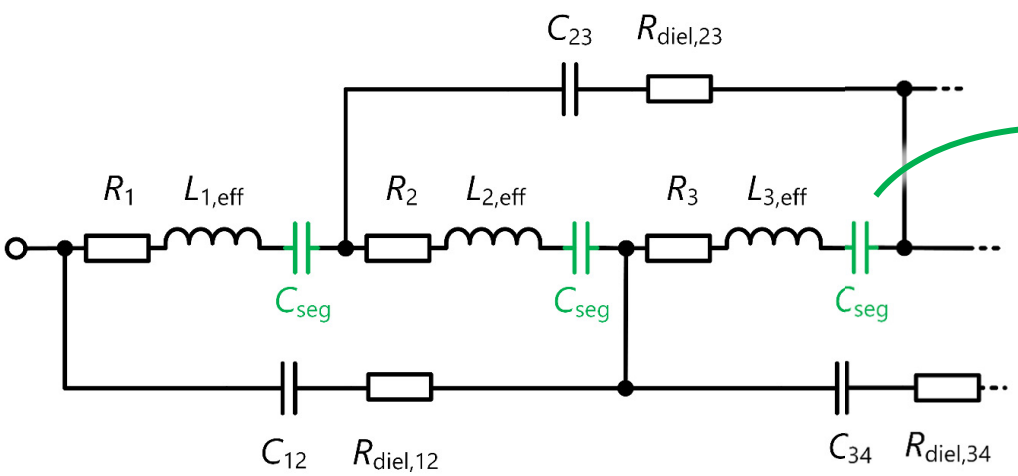
- Neural read-out for Epilepsy treatment and brain-computer-interfaces
  - small size
  - high efficiency
  - low tissue heating
  - variable operational conditions
  - large data streams

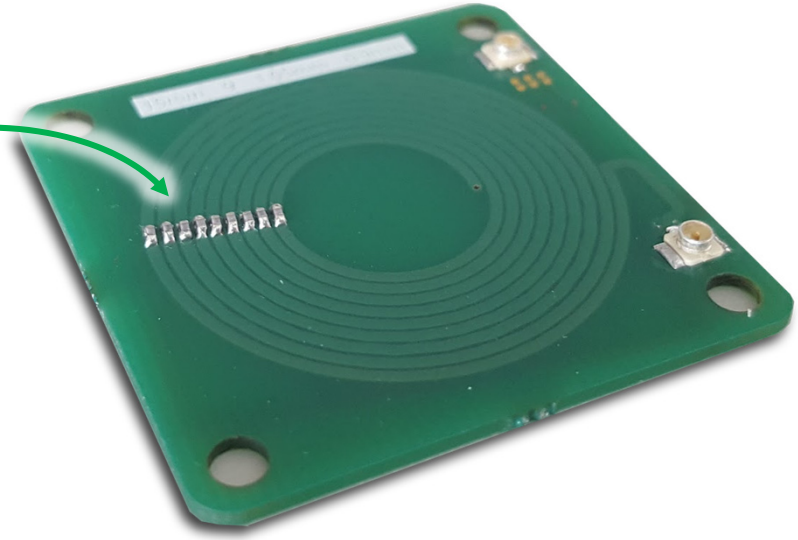


BrainLinks BrainTools

Segmented Coils

Concept: Cancelling $L_{i,eff}$ by C_{seg}



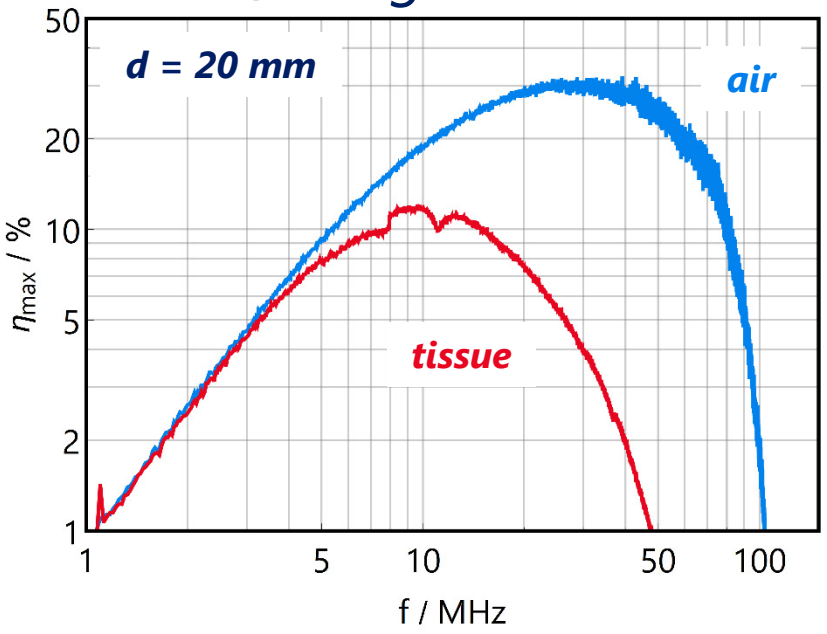


Segmented Coils

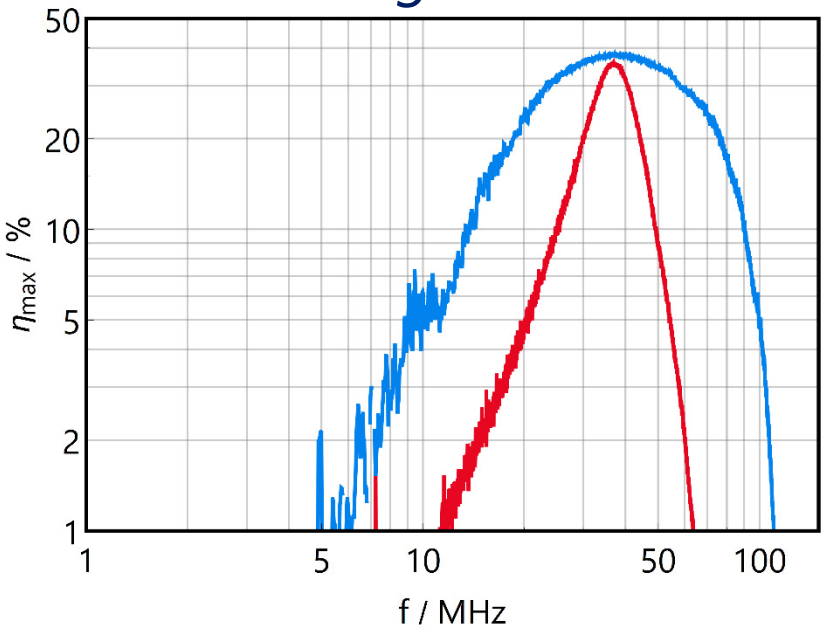
Results: Efficiency vs. Frequency

- minimization of dielectric losses
- improved uniformity of currents

w/o segmentation



with segmentation



Wireless Power Transfer Electronics

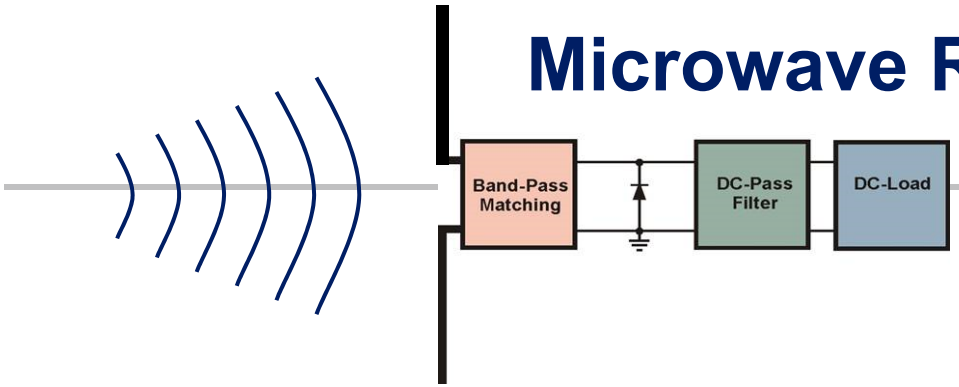
Power Transmitter

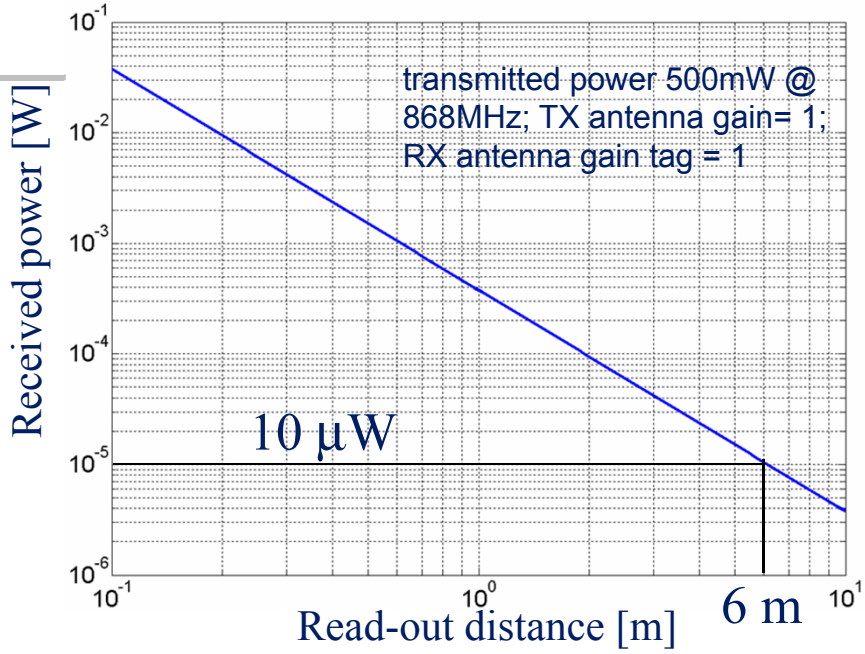
- *adaptive class E amplifier* to compensate for load changes
- 40.68 MHz RF transmitter & power controller

Power Receiver

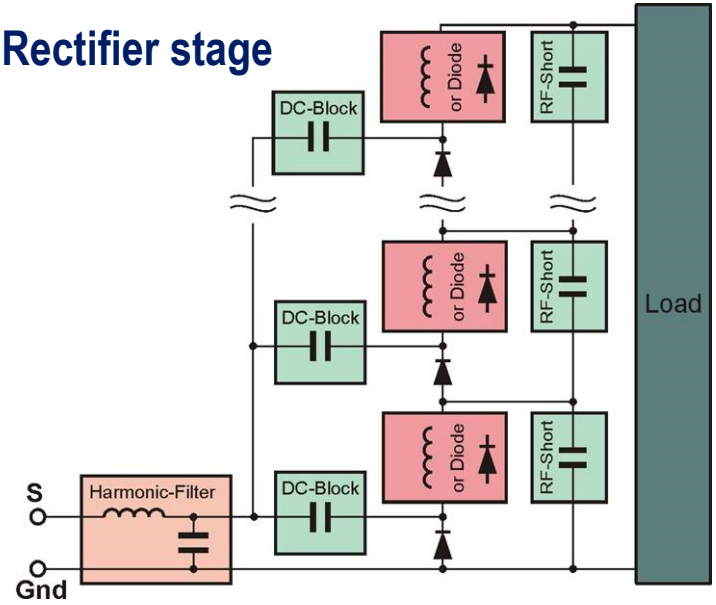
- *dynamic impedance matching* (MPPT with buck-boost converter)
- ARM processor, FPGA, 2.4 GHz radio & antenna on 12x18 mm^2 footprint

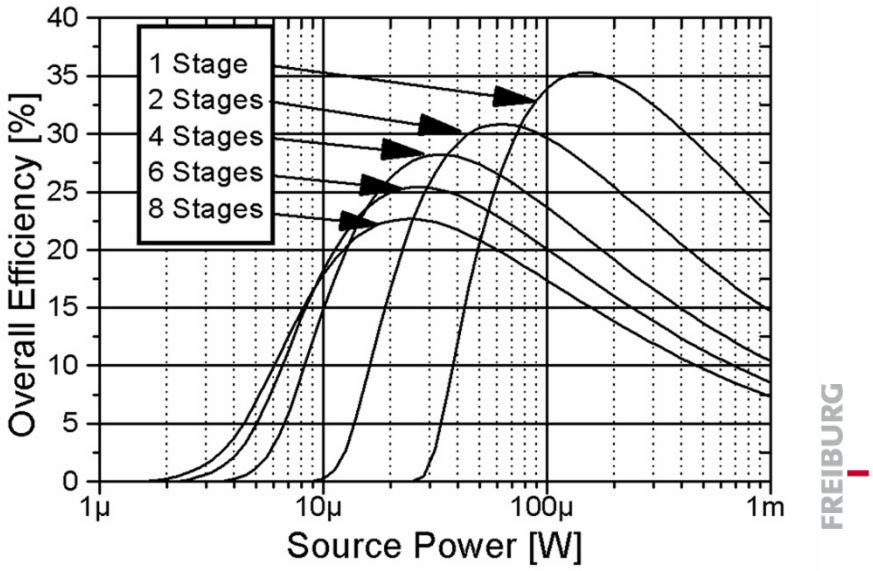
Microwave RFID Systems





Rectifier stage





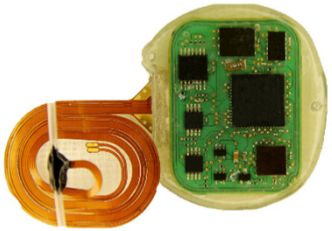
Realistic max. efficiency at CMOS rectifier
→ 5-10%!

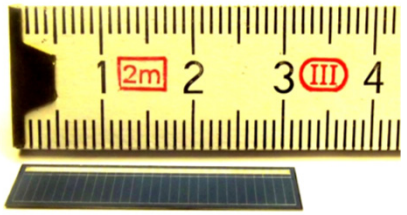
Outline

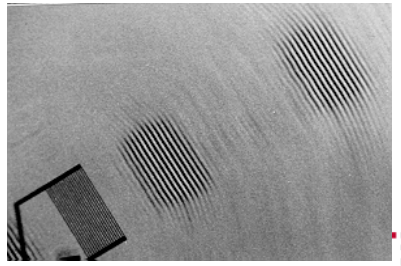
Wireless sensing

Wireless networking	Near field coupling	Energy harvesting	Chipless sensing

Low Power Commu-nication	Moni-toring	Locali-zation	Inductive coupled	RFID	RF	Photo-voltaic	Thermo-electric	Acoustic	Electro-magnetic



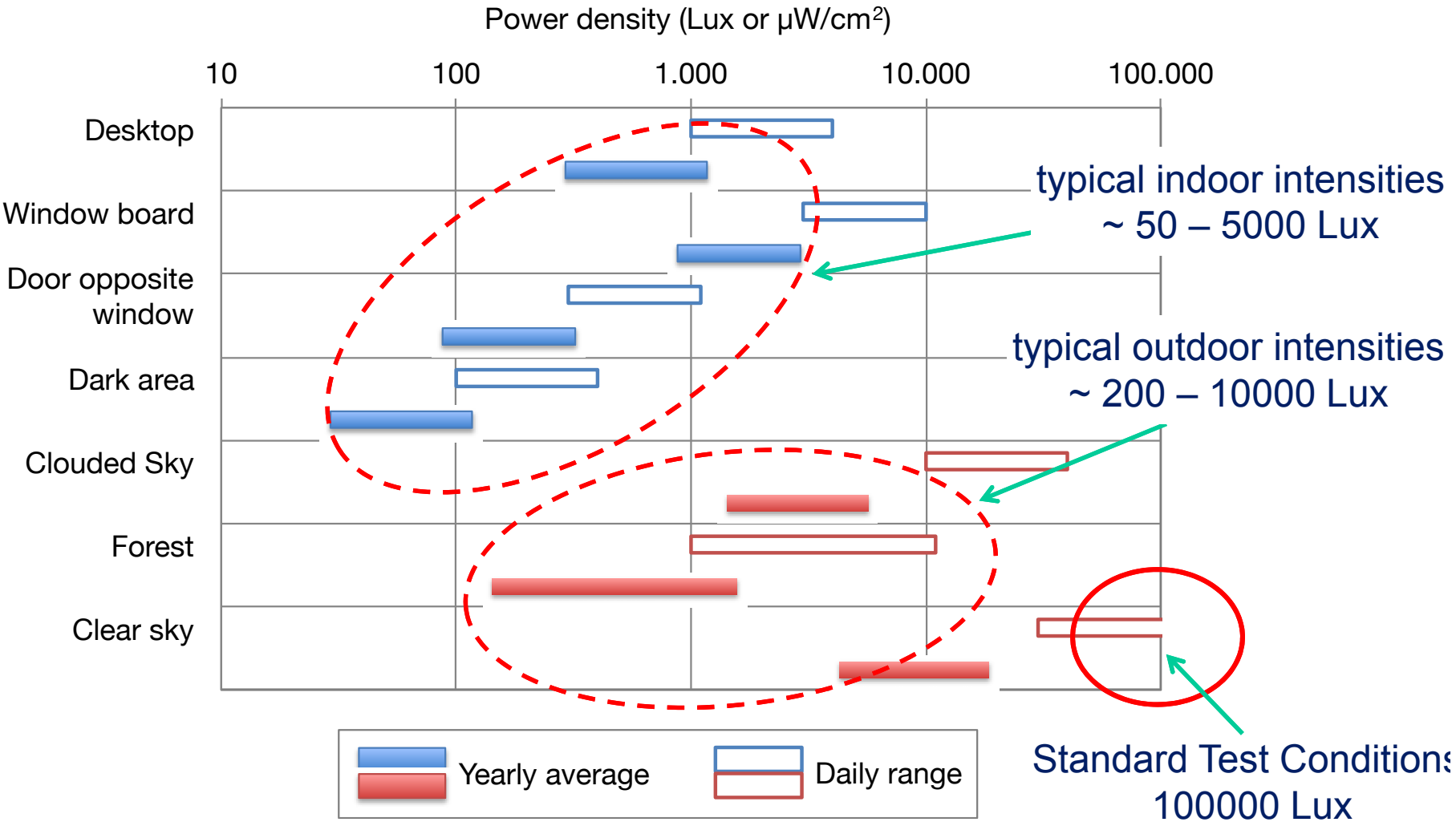




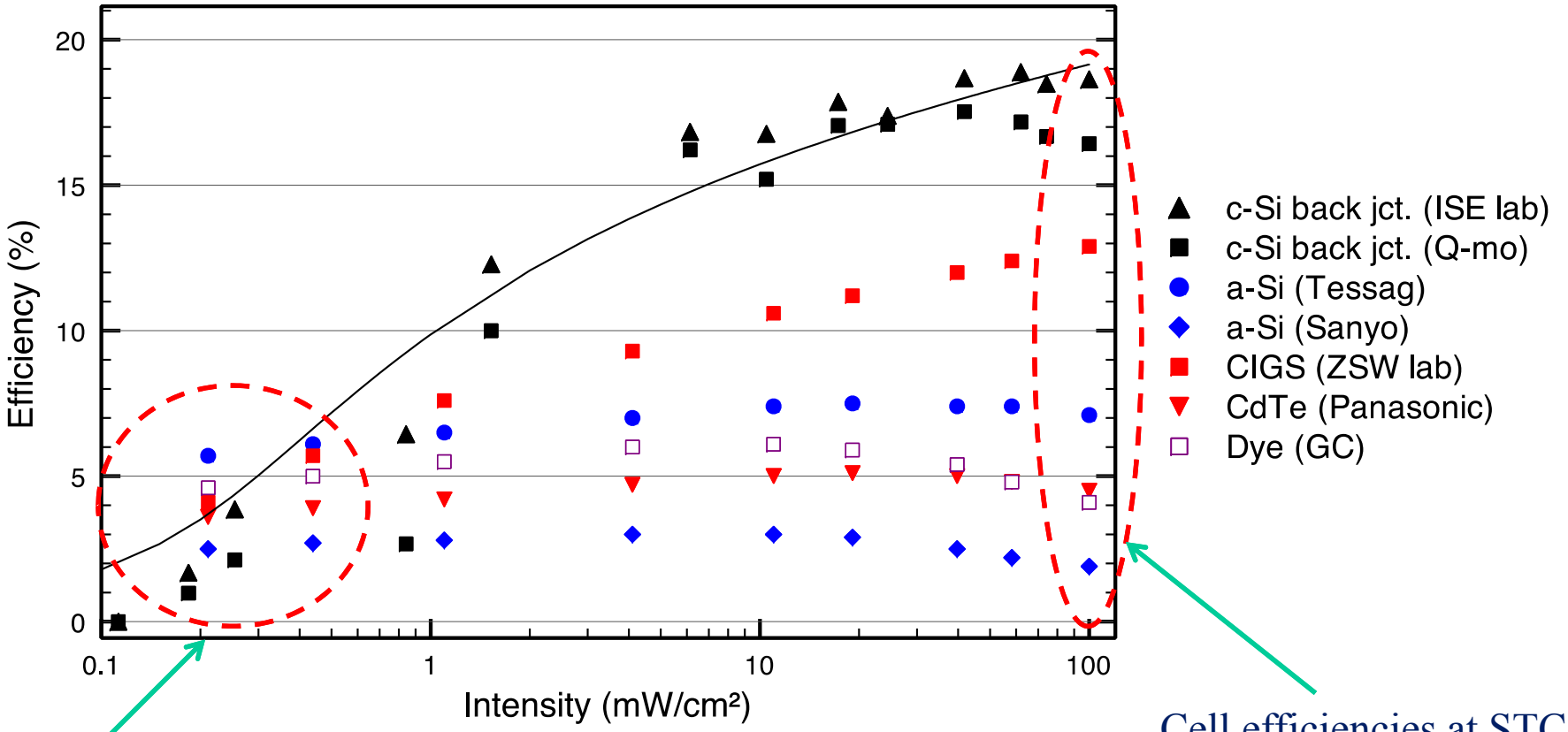
Solar cells

flexible silicon solar cell
© FhG-ISE, Freiburg

Solar Cells: Typical Irradiances



Varying light intensity –
Commercial Cells under different irradiance levels

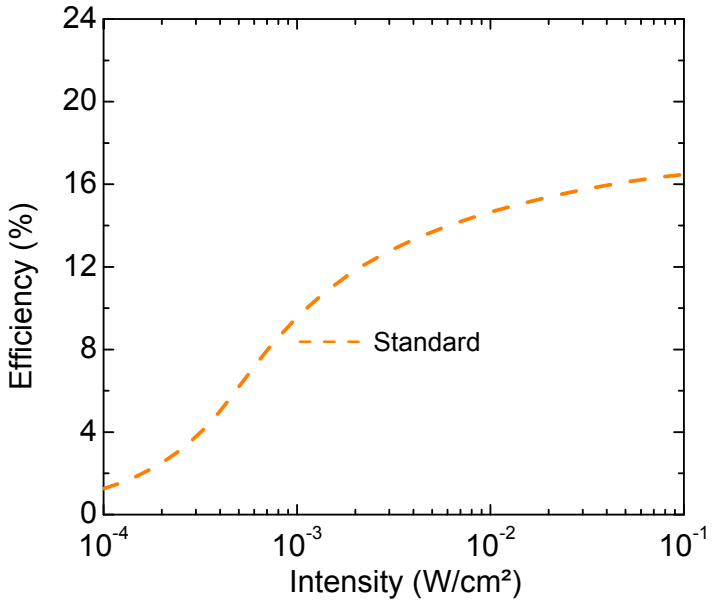


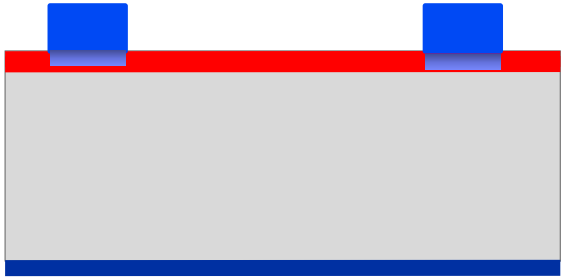
Cell efficiencies at typical indoor intensities

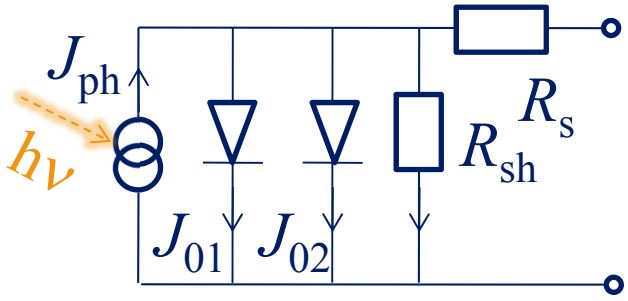
Cell efficiencies at STC (100 mW/cm^2)

Simualtion : Optimizing Photovoltaic Cells

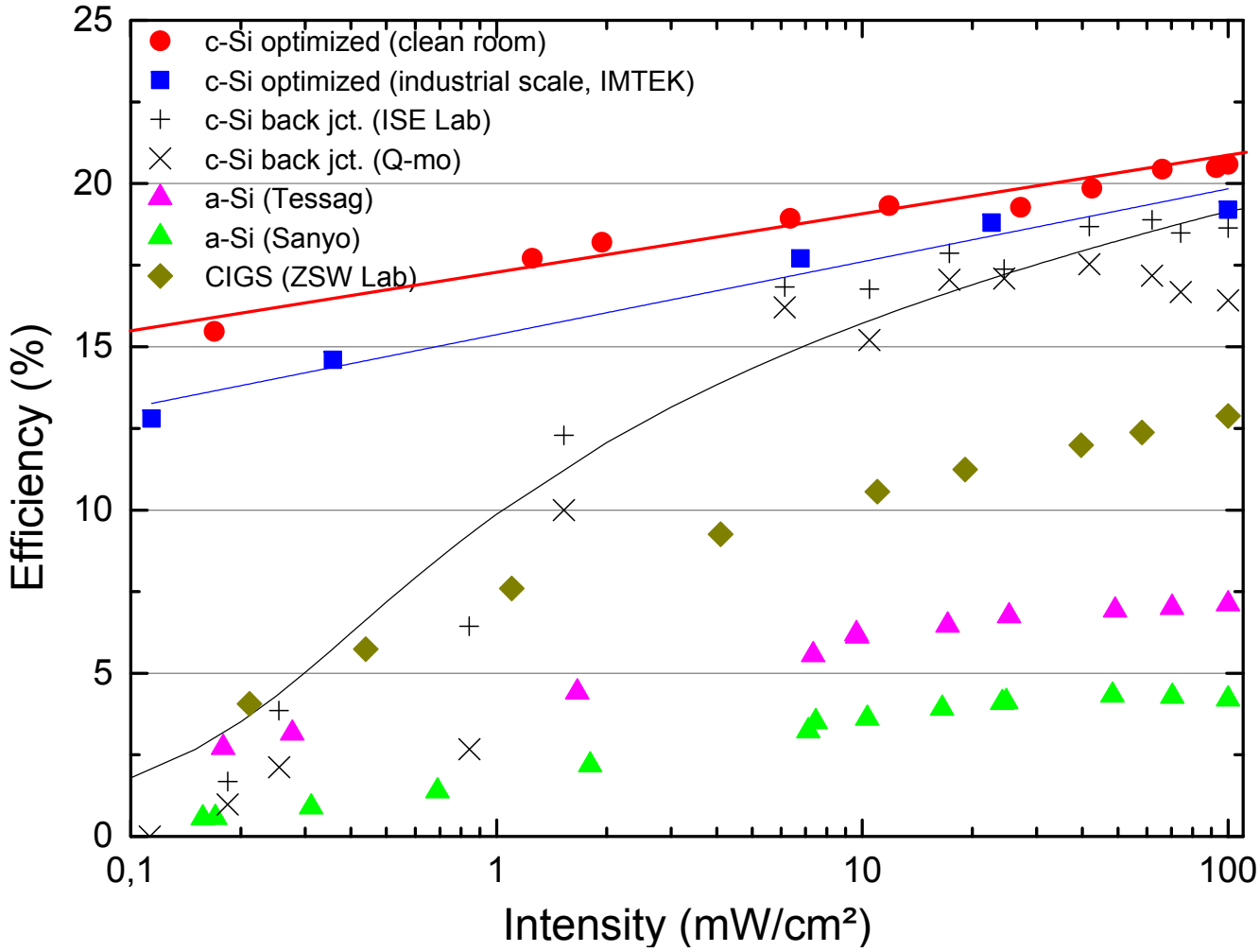
- Cell efficiency collapses indoor light intensities ~ 0,01 - 1 mW/cm2
  - ➢ Can a solar cell be optimized to improve cell efficiency at indoor lighting conditions?





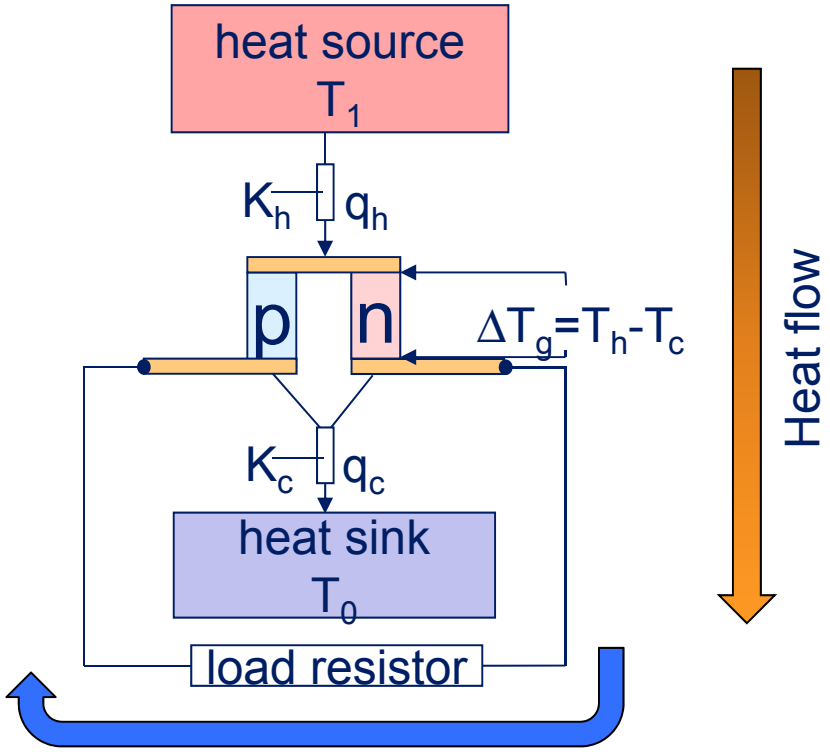


Efficiency of Optimized c-Si Indoor Solar Cell in Comparism to State of the Art

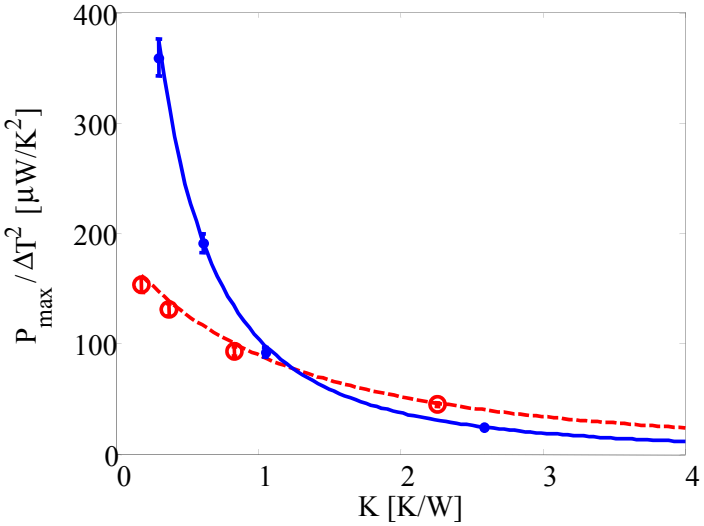


* Part of data taken from Randall and Jacot, Renewable Energy, 28, 2003, pp. 1851-1864

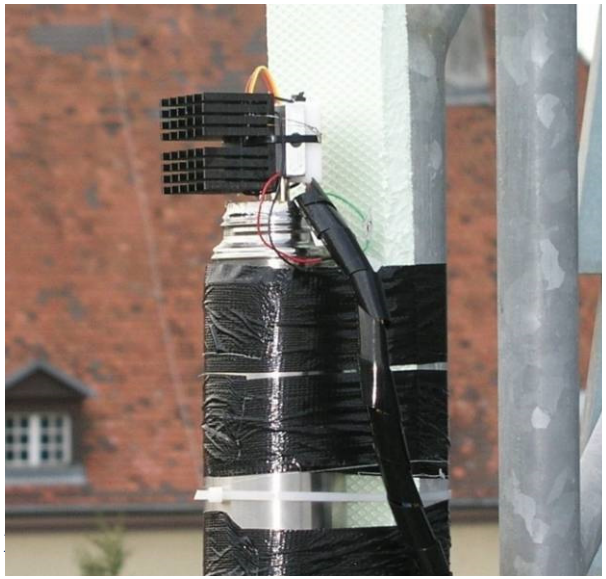
Thermoelectric Harvesting



Electrical Circuit



$$P_{opt} = 0.15 \frac{\Delta T^2}{4 T_0 K}$$



Thermo-electric harvesting of day – night cycle using a thermos flask

Piezoelectric transmitter module by EnOcean (PTM 100)

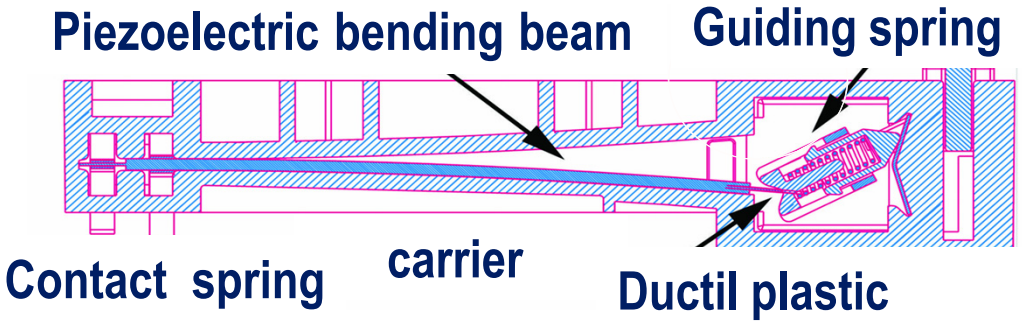
1st generation

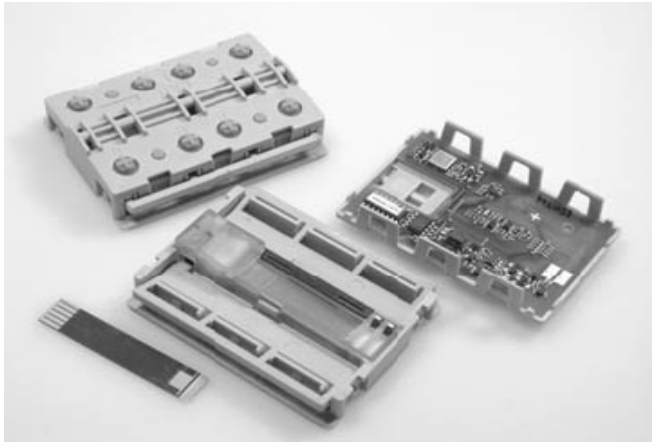
A pre-stressed biomorph Piezo cantilever bends over two circular surface from one opposite to the other .

C = 60 nF
E = 80 µWs

Operating range:

- 300m in free space
- up to 30m inside buildings



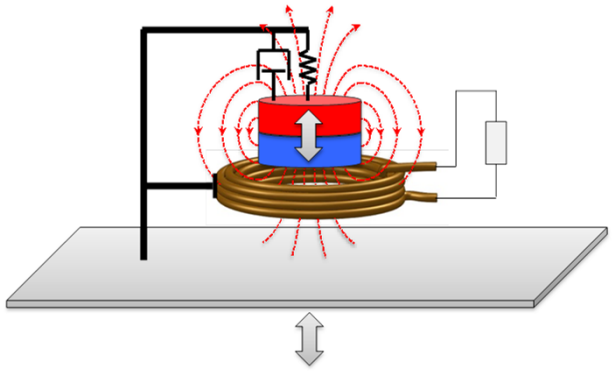


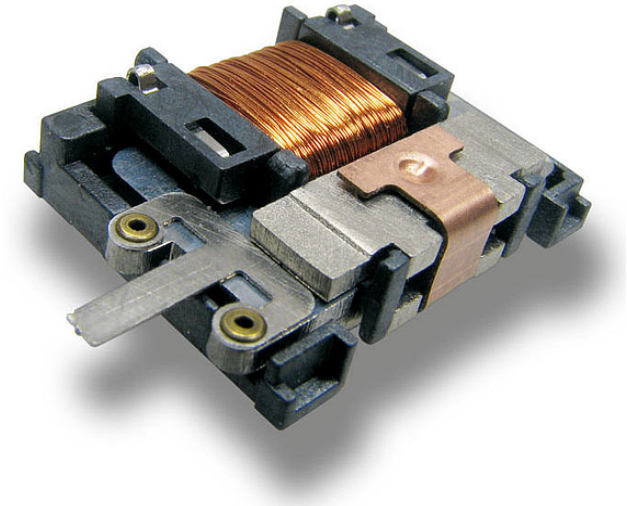
- Transmitter module
- Piezoelectric harvester
- Energy conversion mechanism

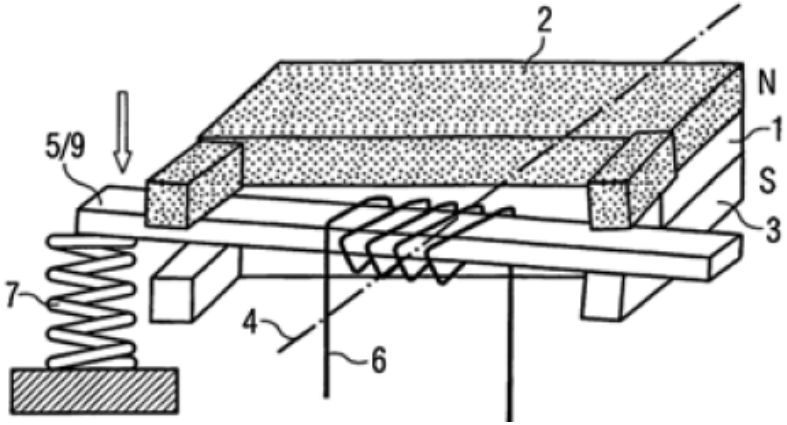
The Goal:

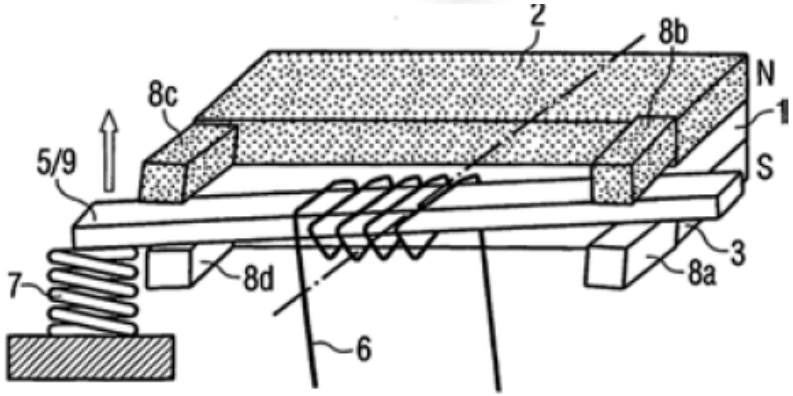
- Increase Life time
- Increase the efficiency
- Reduce the cost of the harvester

Electromagnetic Generators





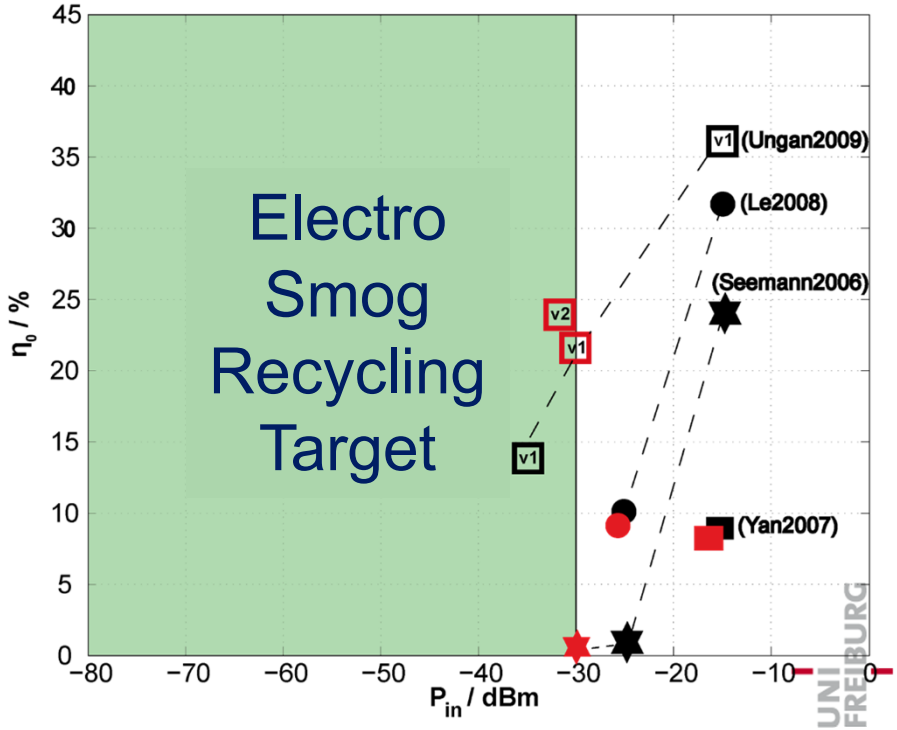




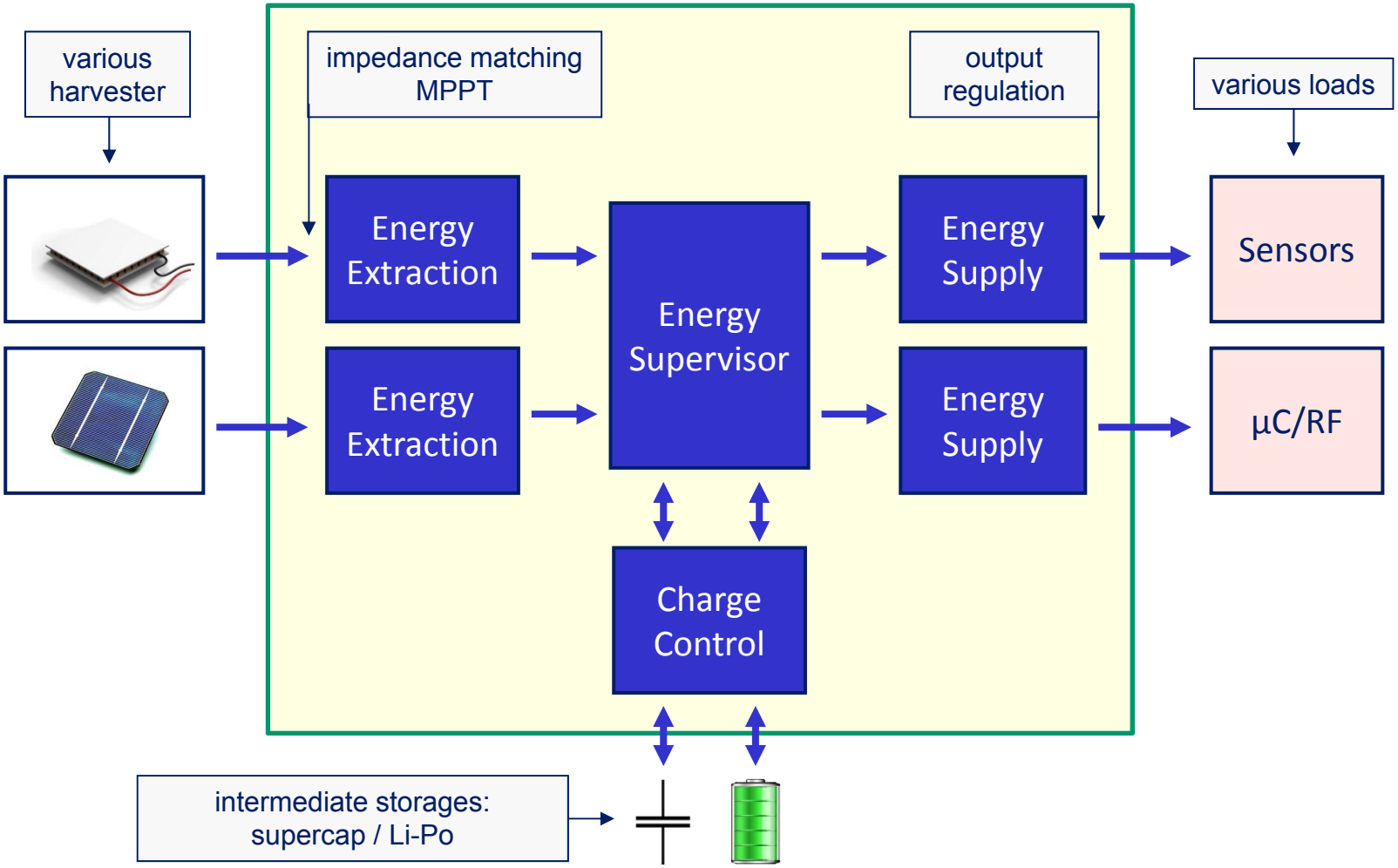
EnOcean, 2nd generation, Munich, 2006

Is even Electro Smog Recycling possible?

- Ambient UHF energies in urban areas:
  - Radio and TV transmitter
  - base stations
  - cell phones
  - various radio services
- Maximum power density in urban areas: 0,3 - 1 µW/cm^2
- Electro smog harvesting is not yet possible!
- But, we still work on it...

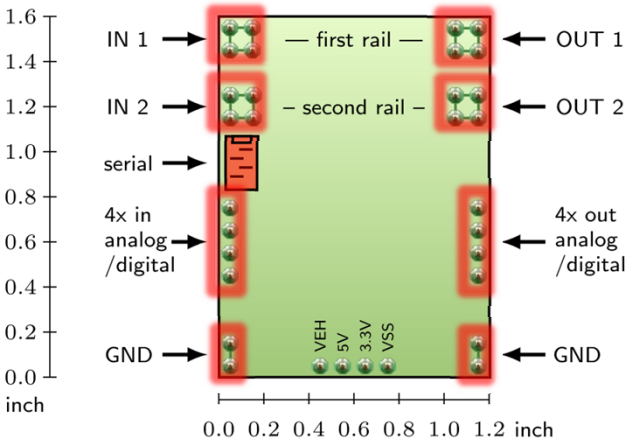


Micro Power Management Structure

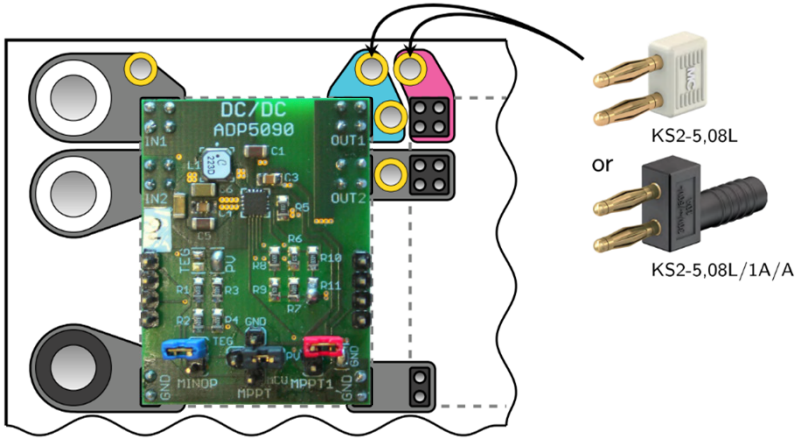


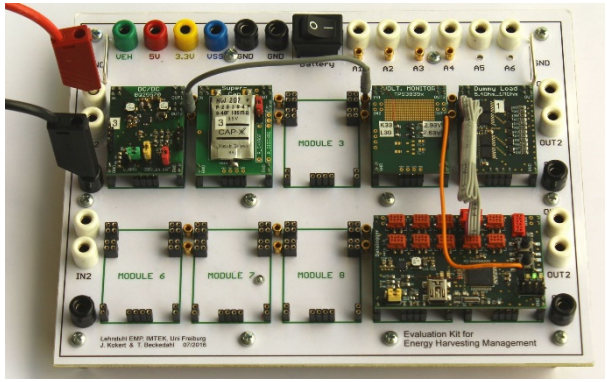
Modular Kit for Micro Power Management

- *building blocks* → uniform modules
  - Power ports: IN, OUT, GND
  - Analog & digital ports



- Base board (5x2):





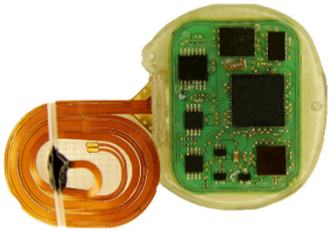
J. Kokert, T. Beckedahl, and L. M. Reindl, "Development and evaluation of a modular energy management construction kit," in 18. GMA/ITG-Fachtagung Sensoren und Messsysteme 2016, 2016, pp. 84–91.

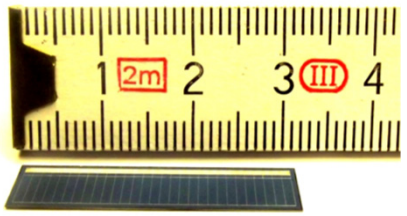
Outline

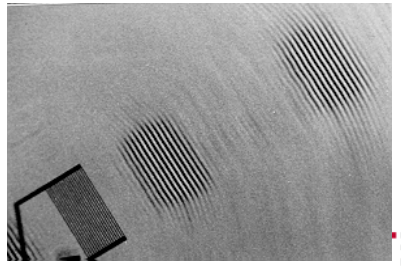
Wireless sensing

Wireless networking	Near field coupling	Energy harvesting	Chipless sensing

Low Power Commu-nication	Moni-toring	Locali-zation	Inductive coupled	RFID	RF	Photo-voltaic	Thermo-electric	Acoustic	Electro-magnetic

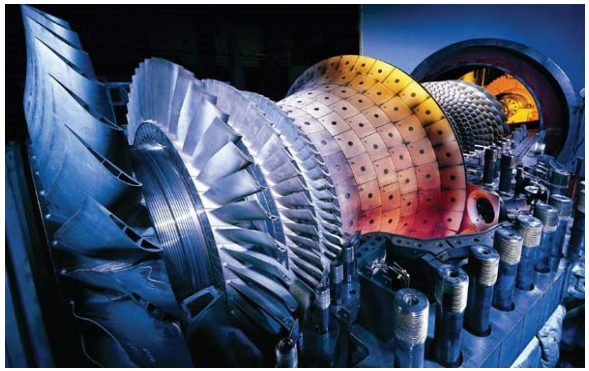






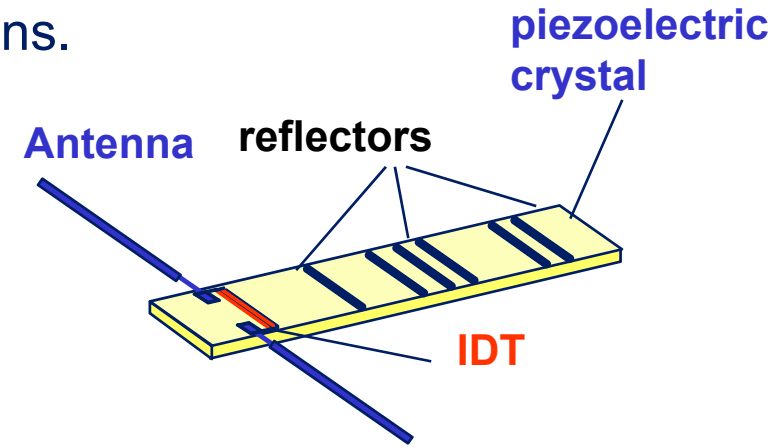
Why chipless sensing

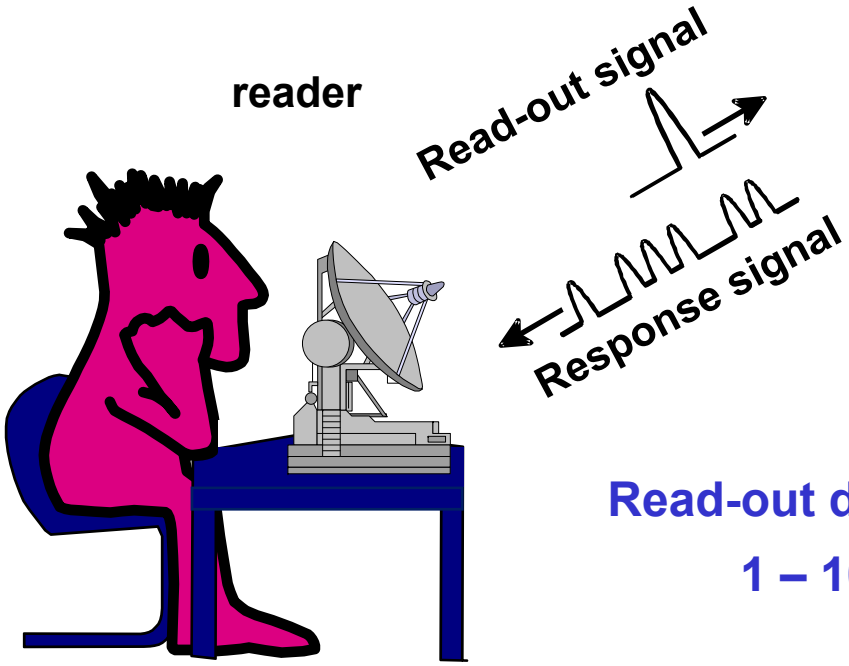
- Sensing in harsh environments.
  - Moving parts
  - High humidity
  - High temperature
- Condition based monitoring
  - Safety
  - Reliability.
- Reduced overall system cost.
- No batteries – low environmental impact.
- Large scale manufacturability.
- **Pervasive sensing!**



Wireless SAW Sensors

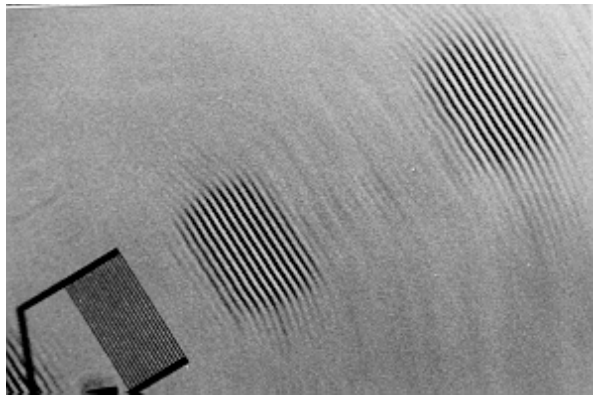
- Discovered in mid 1990's at Siemens.
- Surface acoustic delay lines
- Core team still active in WPS



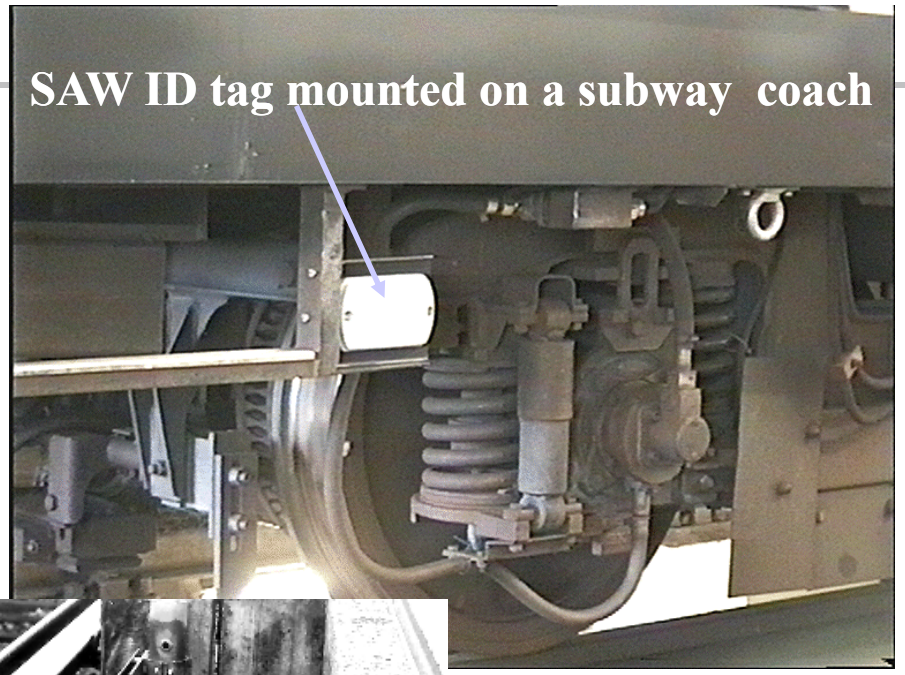


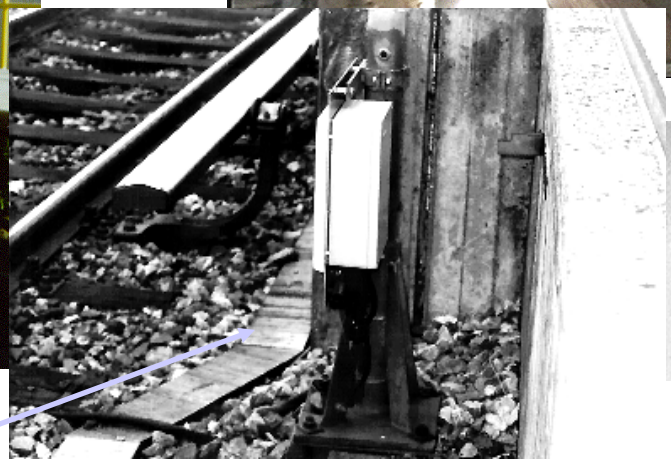
Read-out distance:

1 – 10 m



SAW ID System SOFIS installed on the SIEMENS Munich Subway System

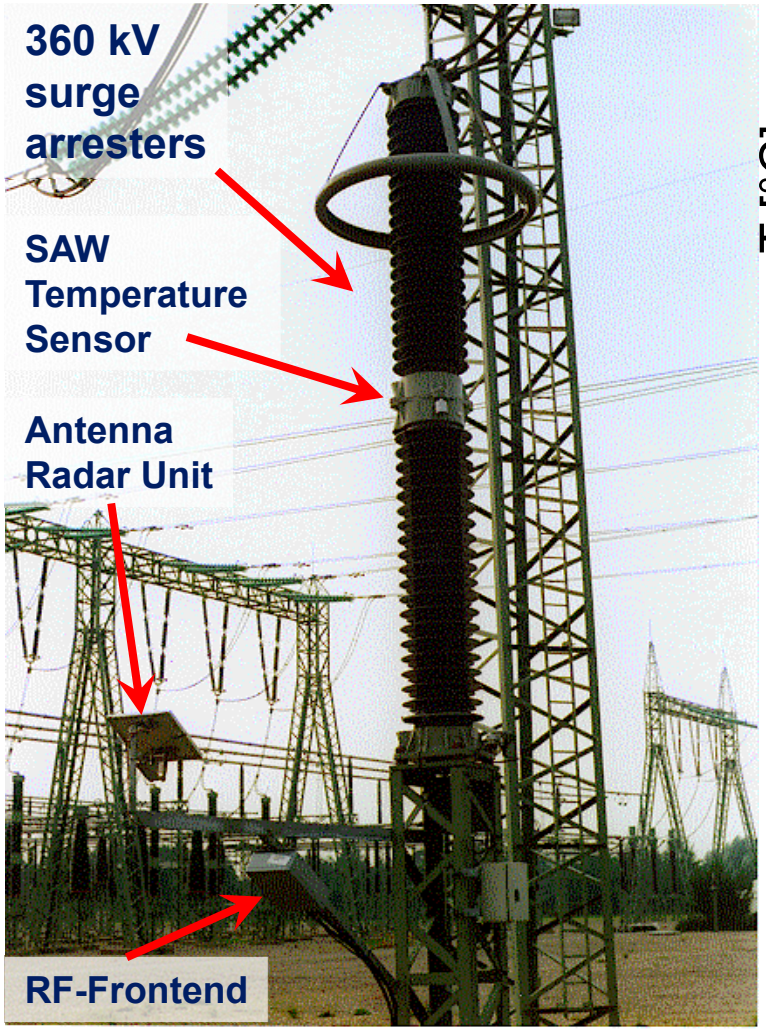


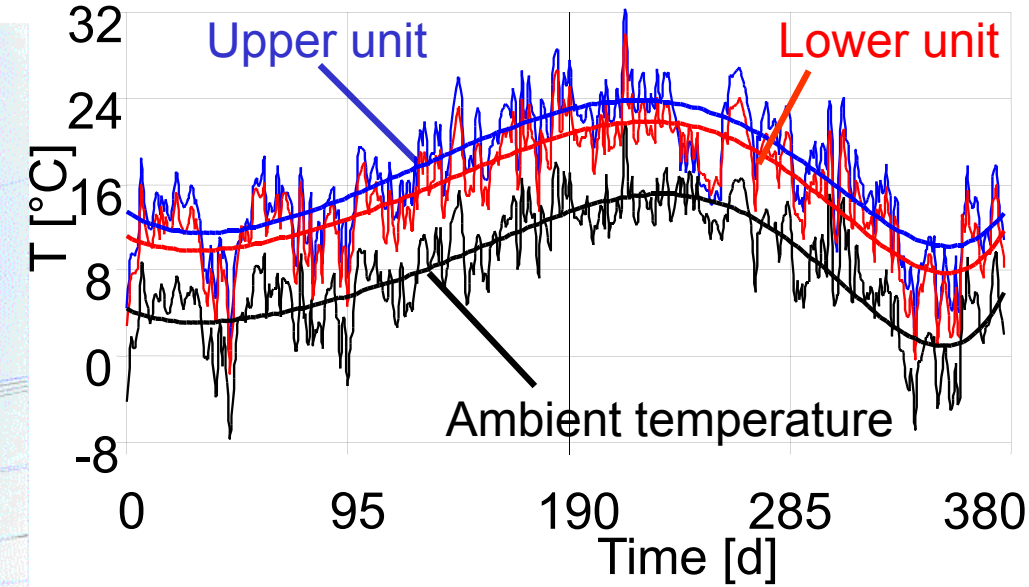


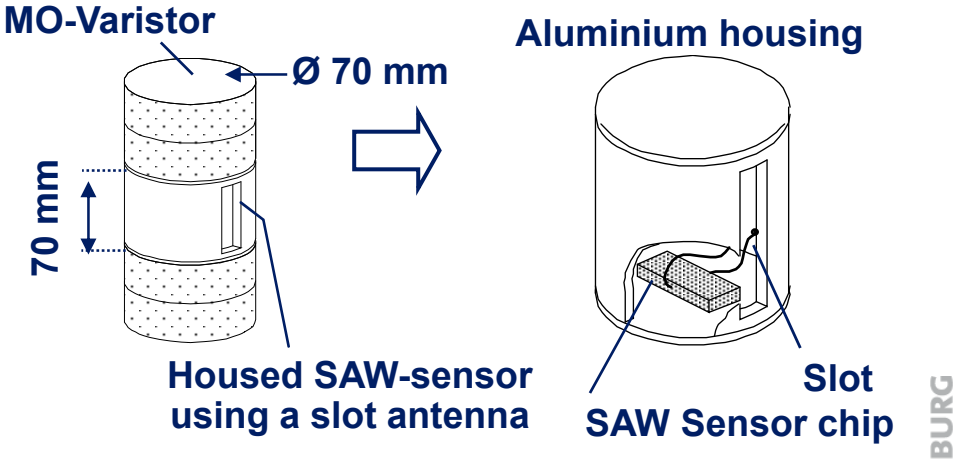
antenna of the 2.45 GHz interrogation unit

Tag housing

Temperature sensors: Online Monitoring for High-Voltage Surge Arresters

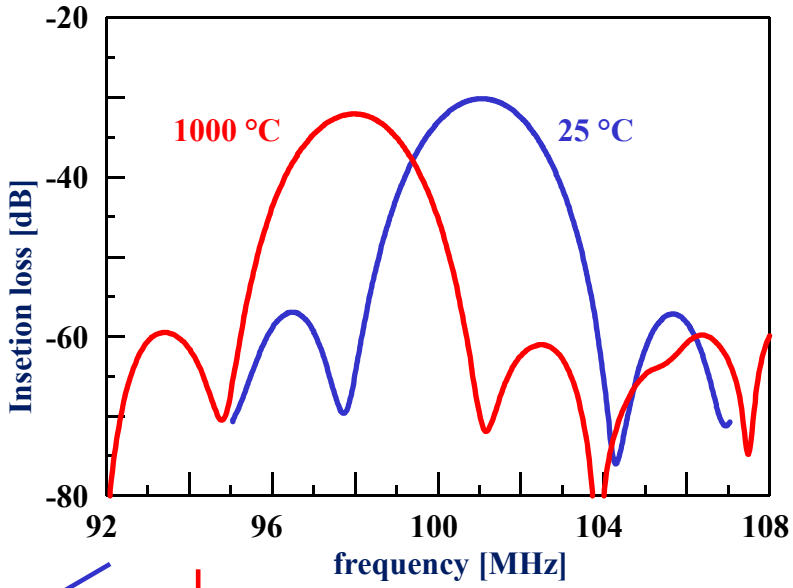




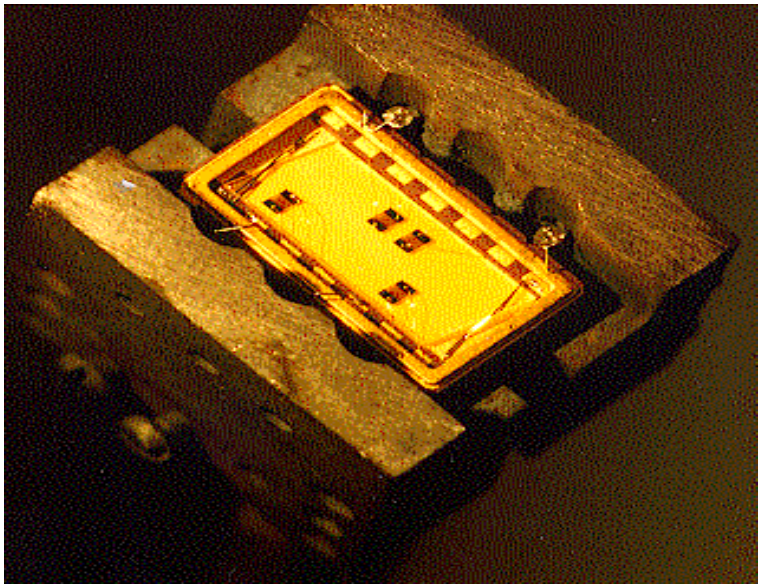


G. Scholl, C. Korden, E. Riha, C.C.W. Ruppel, U. Wolff, G. Riha, L. Reindl, R. Weigel, „SAW-Based Radio Sensor Systems for Short-Range Applications", *IEEE microwave magazine*, pp. 68-76 , December 2003

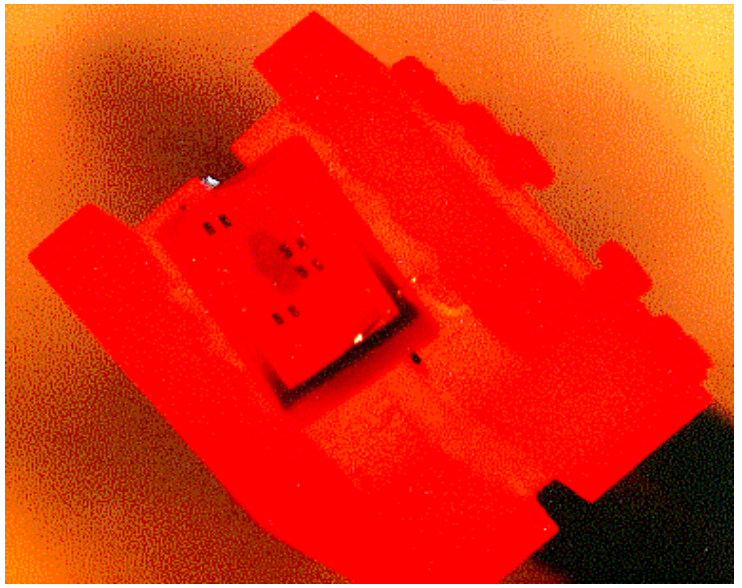
High Temperature SAW Sensors with Platinum Electrodes on Langasit ($La_3Ga_5SiO_{14}$)



Test chip at room temperature

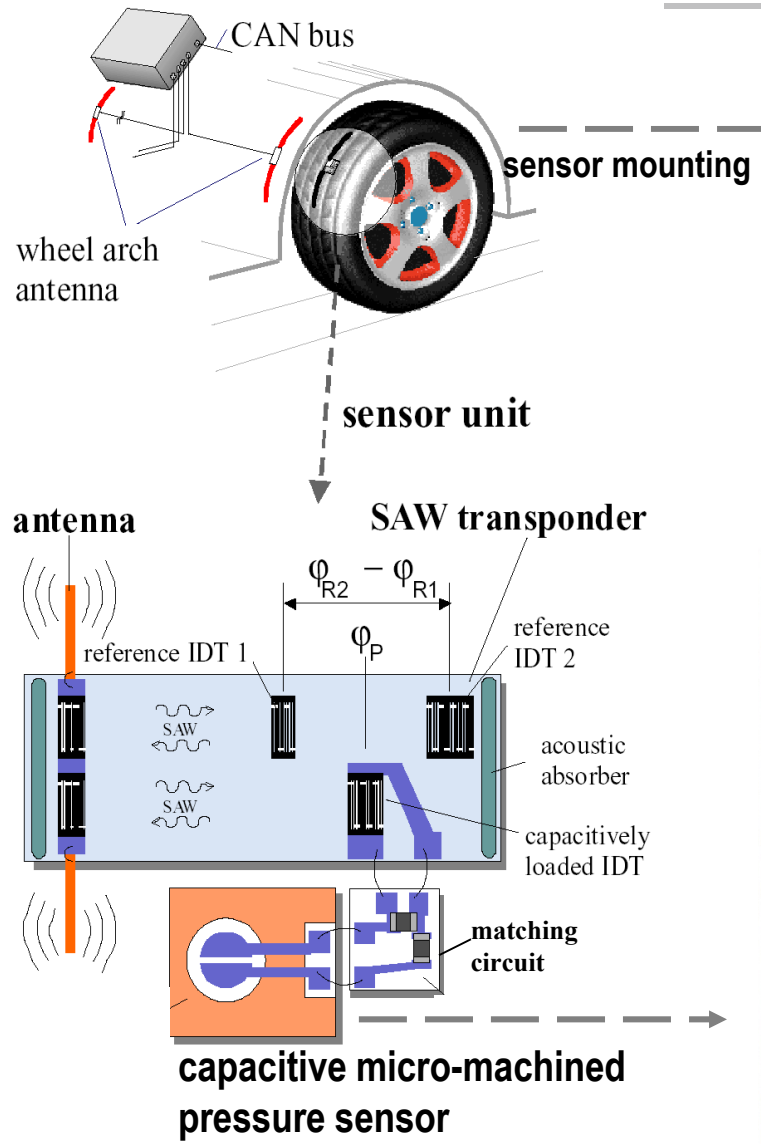


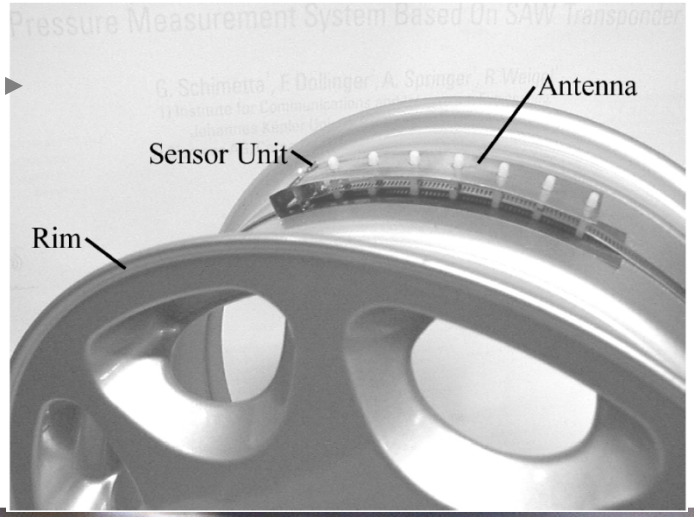
Test chip at 1000°C



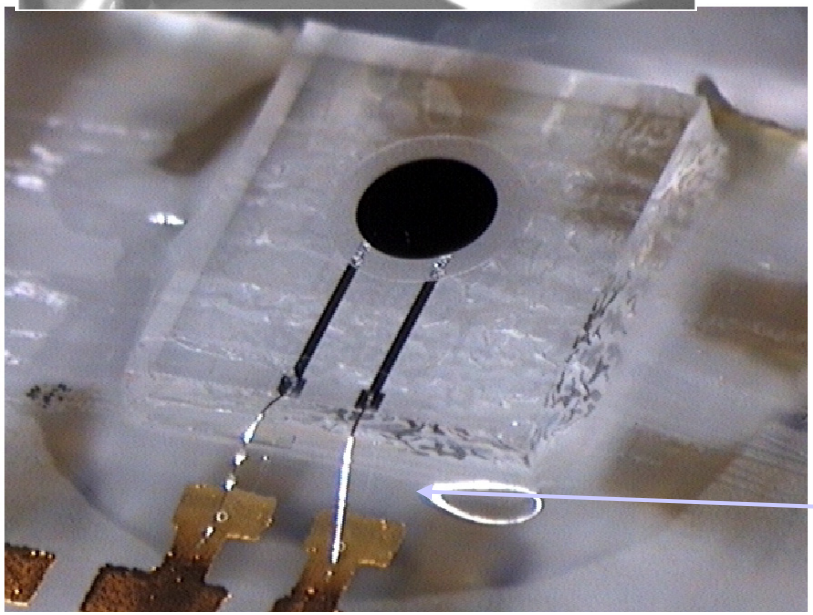
tire pressure sensor, presented by G. Schimetta

SIEMENS





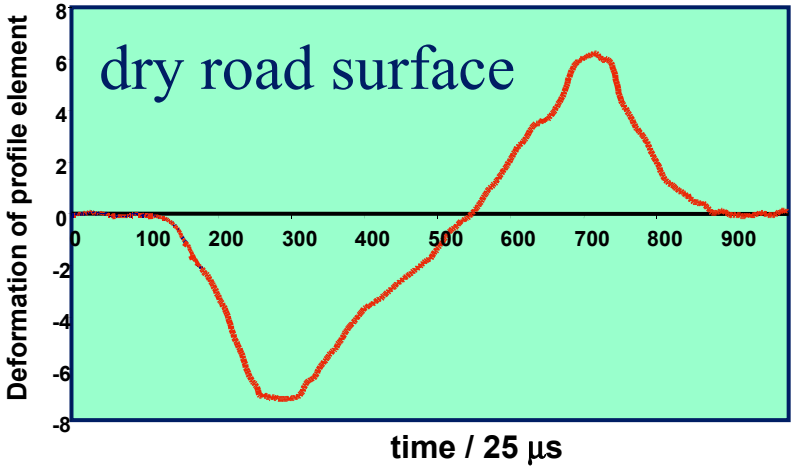
The patch antenna with the integrated sensor board is mounted on the rim with a stress ribbon.

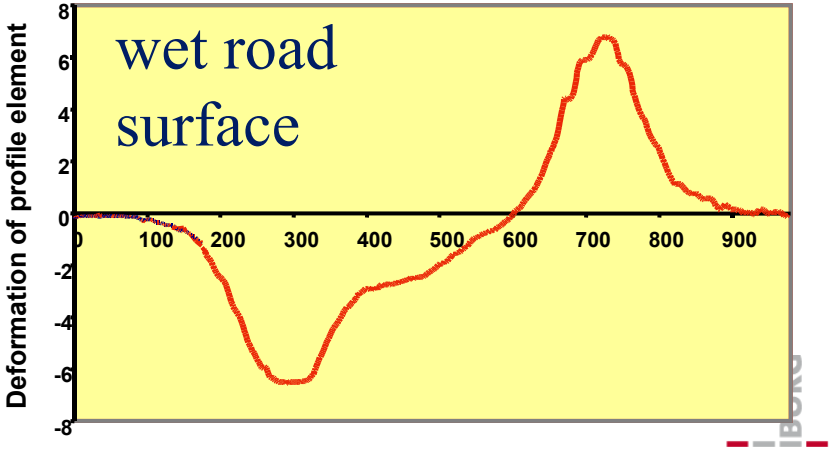


SAW Sensor for Tire Friction Control

The deformation of a profile element gives information of the friction coefficient between tire and road

SAW sensor integrated into a standard tire

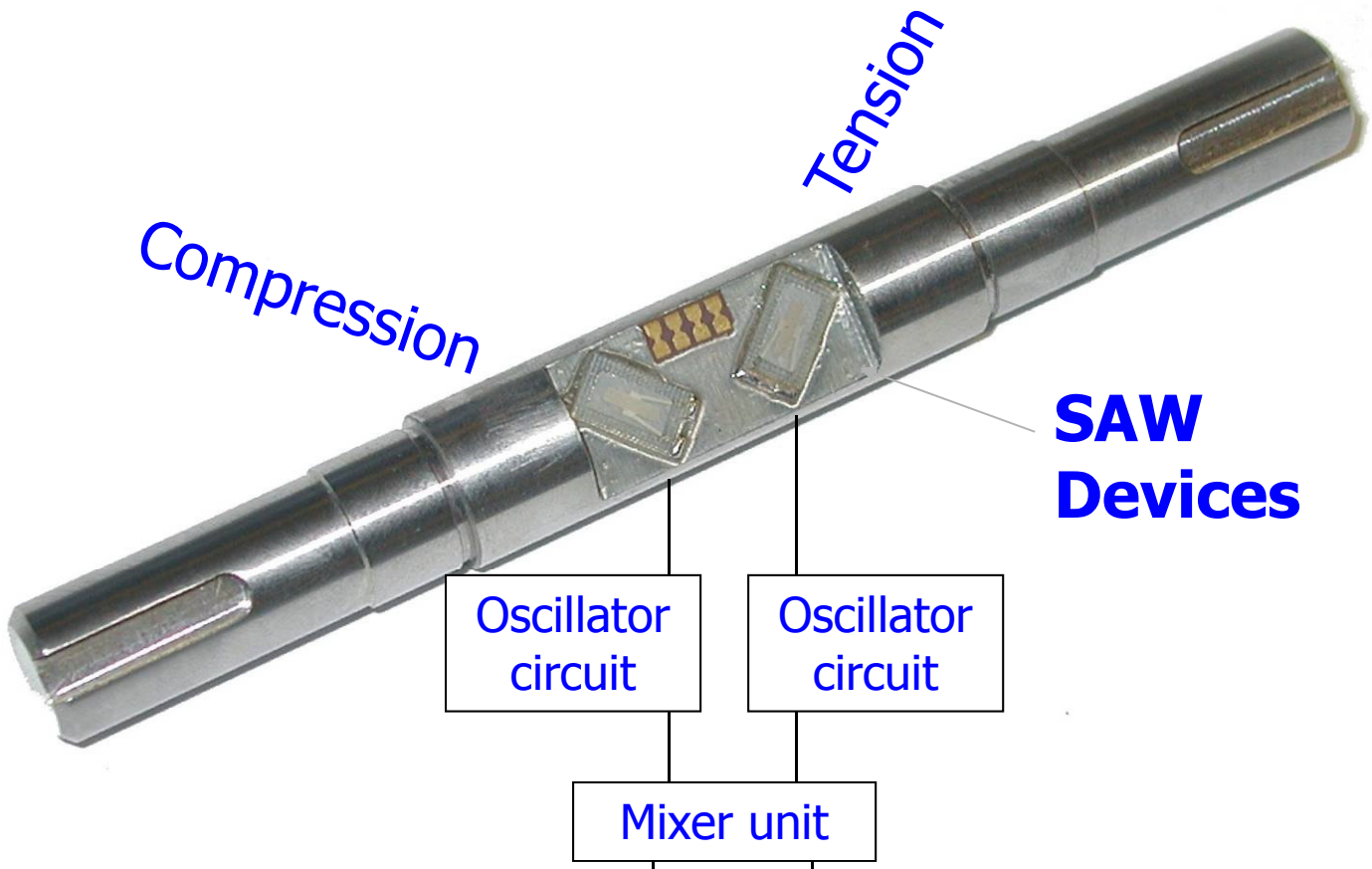




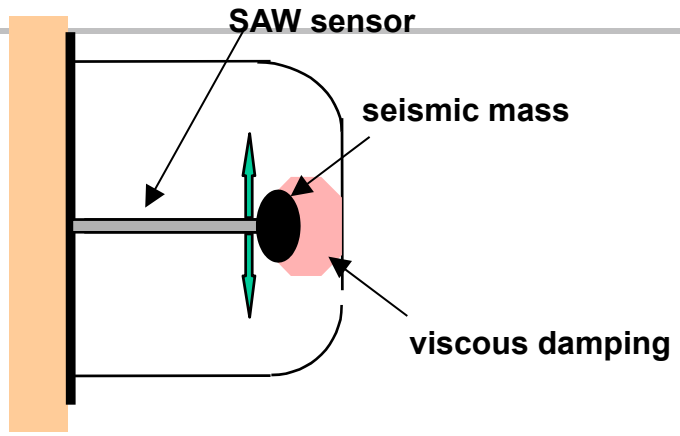
A. Pohl, R. Steindl, L. Reindl, „The 'intelligent tire' utilizing passive SAW sensors - measurement of tire friction“, *IEEE Trans.Instrumentation and Measurement*, 48 (6), pp. 1041-1046, 1999

torque sensors: Sensor Technology

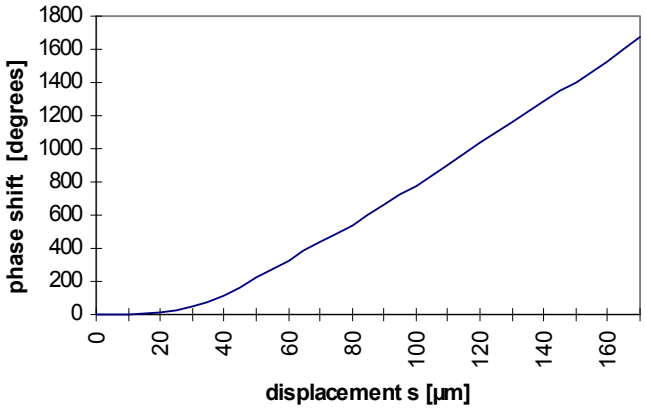
TORQSENSE™ E300 RWT 1 System



SAW accelerometer



SAW accelerometer using a seismic mass and a flexured SAW cantilever beam



Phase variation of a 5 µs SAW delay line on a Quartz substrate relative to the displacement of one edge of the substrate, the opposite edge remaining fixed

Passive SAW sensor fixed to a dart arrow, invading the target

A. Pohl, R. Steindl, L. Reindl, „The 'intelligent tire' utilizing passive SAW sensors - measurement of tire friction“, *IEEE Trans.Instrumentation and Measurement*, 48 (6), pp. 1041-1046, 1999

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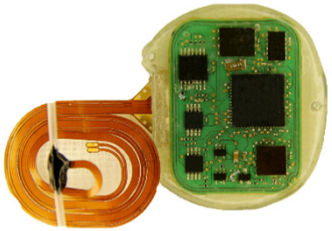
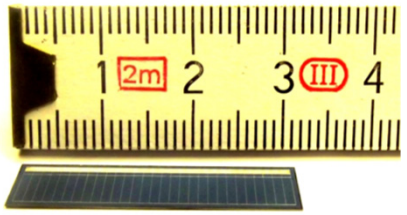
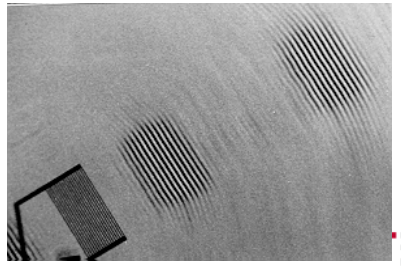
Low Power Commu-nication	Moni-toring	Locali-zation	Inductive coupled	RFID	RF	Photo-voltaic	Thermo-electric	Acoustic	Electro-magnetic

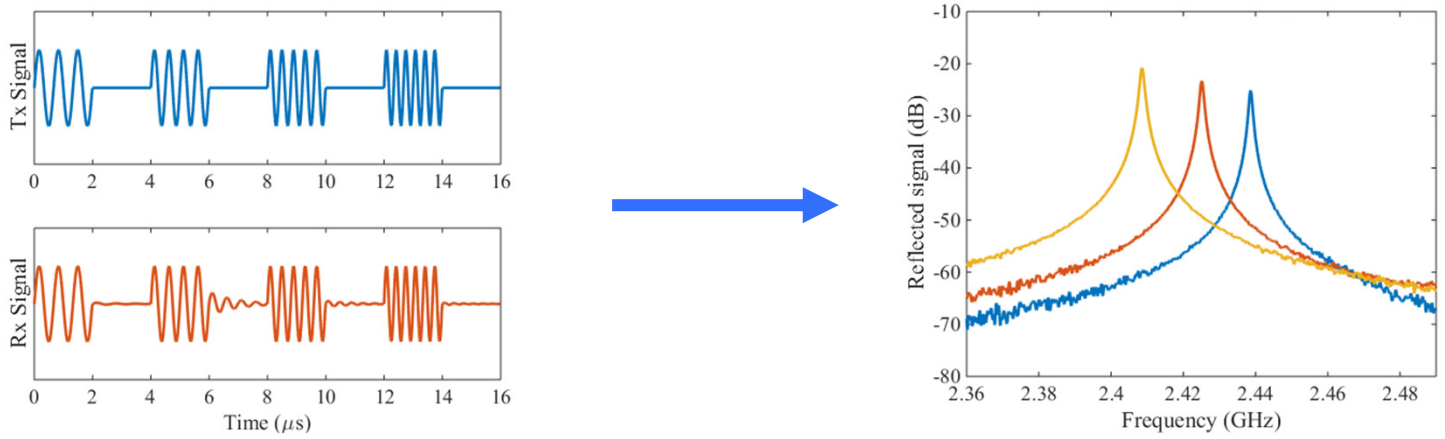






Wireless sensing principle

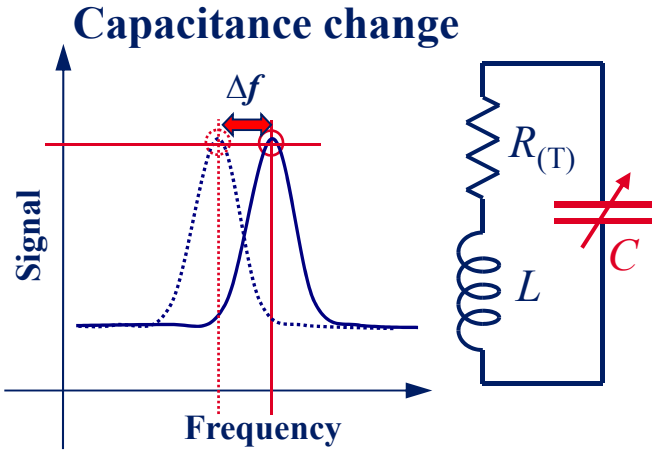
- Interrogation of high-Q resonators.



LC Based Wireless Passive Sensor Systems

- Resonance circuit: capacitive sensor and planar coil;
  f ~ quantity to be measured
- Wireless resonance detection
- Sensor Q factor allows for compensation of temperature cross-sensitivity

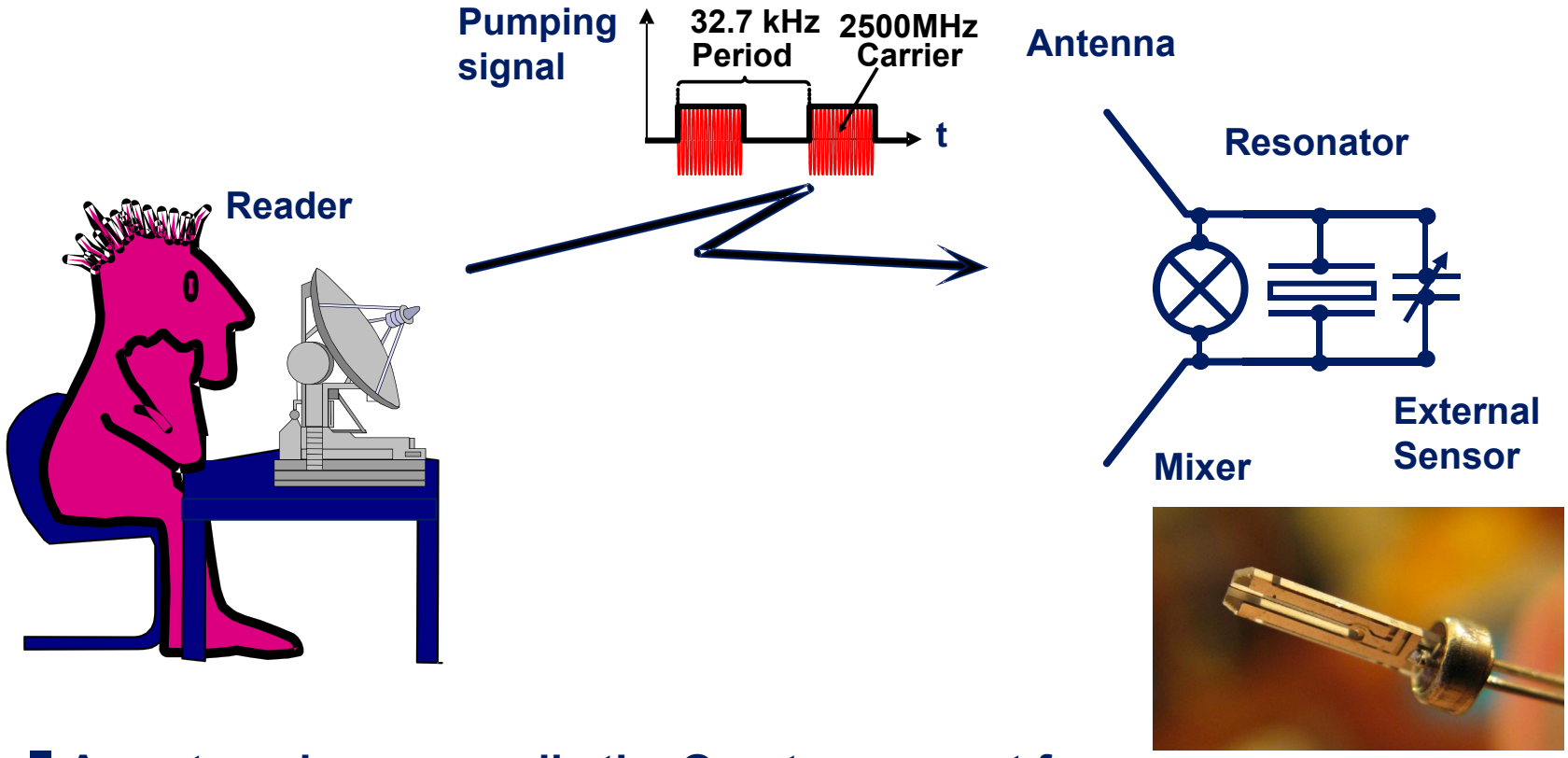
Silicon micromachined wireless pressure sensor prototype by Bosch



R. Nopper, R.Niekrawietz, L. Reindl, "Wireless Readout of Passive LC Sensors", IEEE Trans. on Instrumentation and Measurement, Vol 59 (9), pp. 2450-2457, Sep 10, 2010

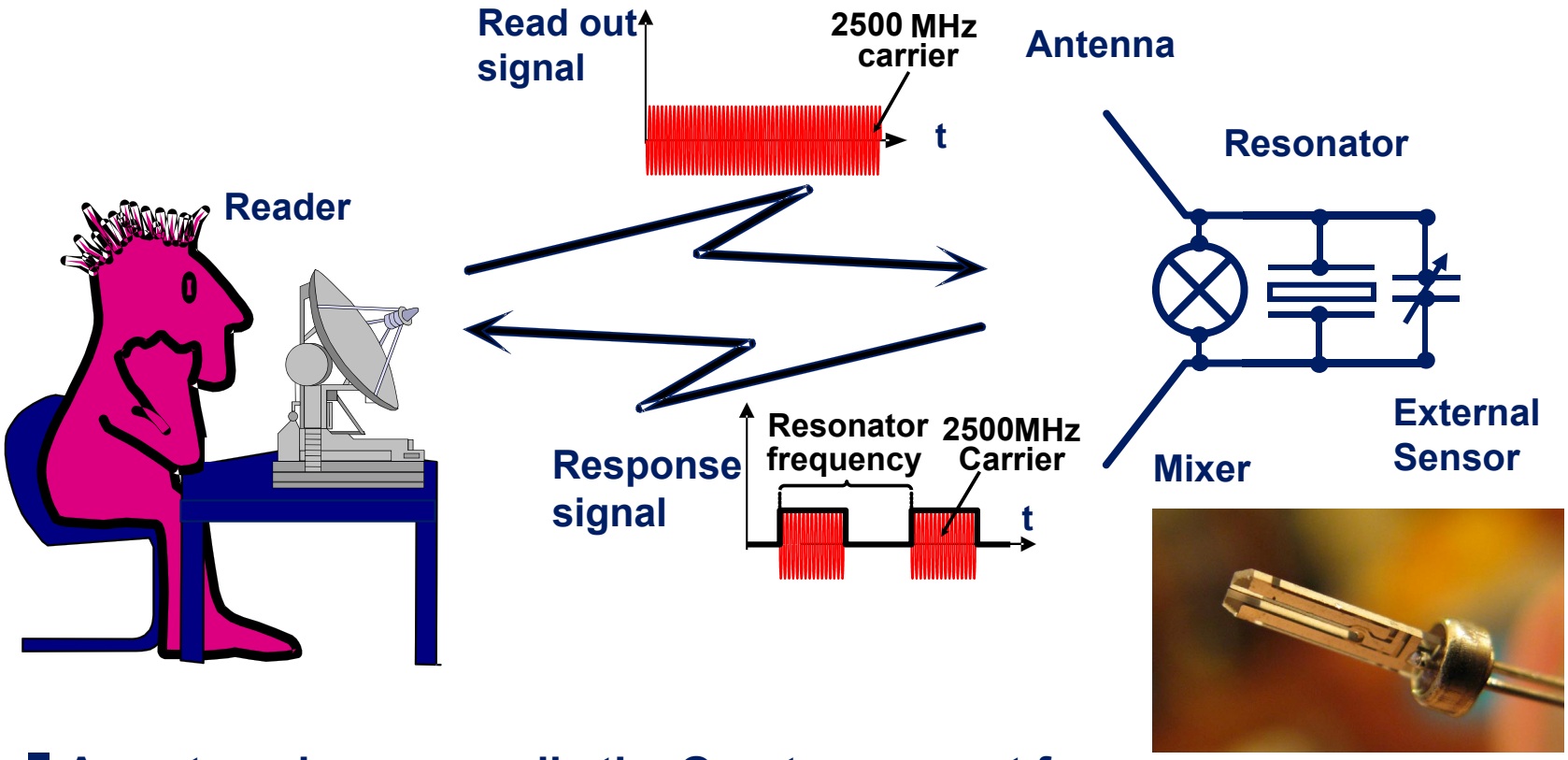
"Inductively Coupled Passive Sensors for Measurements in Difficultly Accessible Environments", Reinhard Nopper[1], Dr. Remigius Has[1], Prof. Dr. Leonhard Reindl[2], VDI/VDE congress "Sensoren und Messsysteme", Nurenburg, 19. Mai 2010,
[1]: Robert Bosch GmbH, Gerlingen-Schillerhöhe, Germany, 2: Laboratory for Electrical Instrumentation, IMTEK, Albert-Ludwigs-Universität Freiburg, Germany

Wireless Passive Sensor Systems Based on Quartz Crystal Resonators



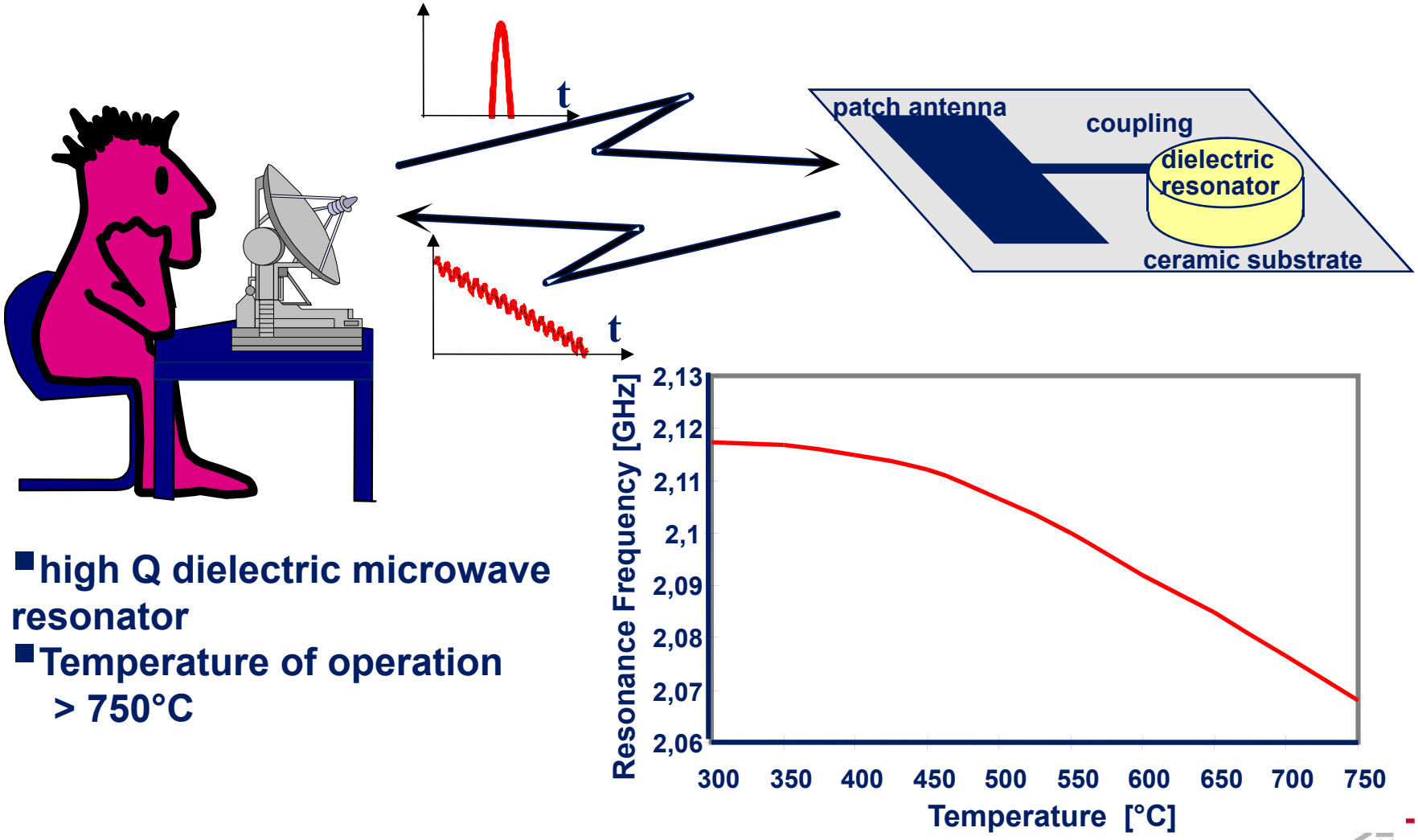
- An external sensor pulls the Quartz resonant frequency
- Might be combined with the mixing sensor

Wireless Passive Sensor Systems Based on Quartz Crystal Resonators



- An external sensor pulls the Quartz resonant frequency
- Might be combined with the mixing sensor

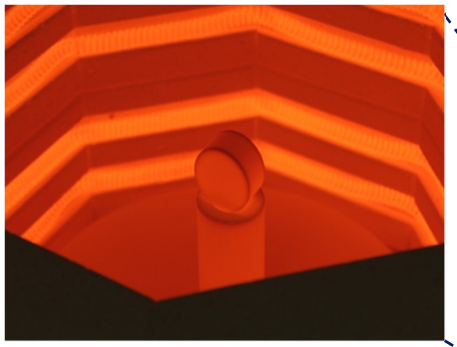
Wireless Passive Sensor Systems Based on High-Q Dielectric Resonators



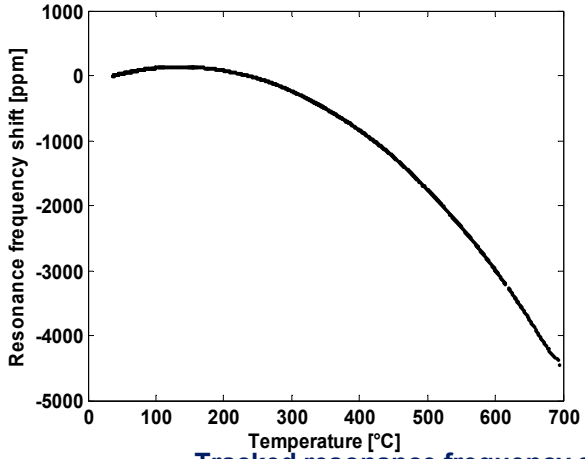
- high Q dielectric microwave resonator
- Temperature of operation > 750°C

Wireless Dielectric Temperature Sensor

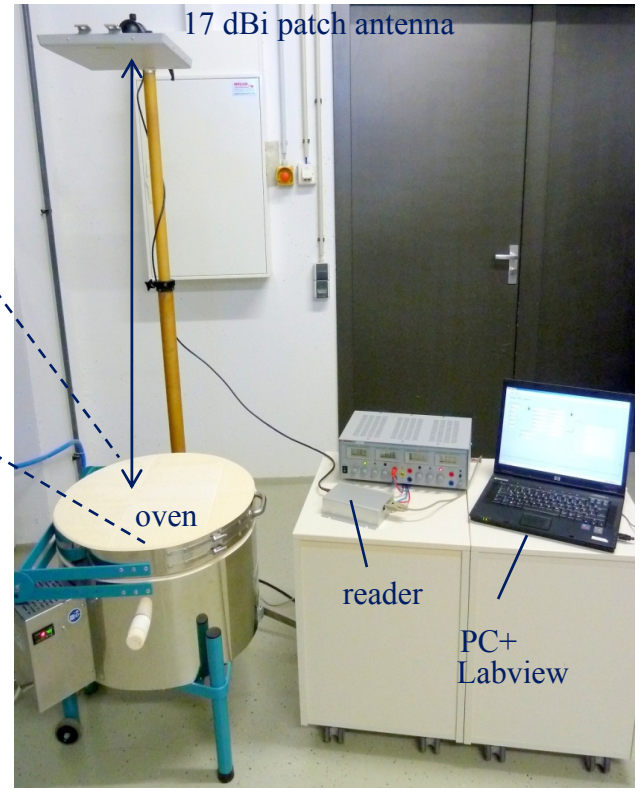
- **Metallization free dielectric resonator based high temperature sensing**



Inner view of the oven at 700 °C with a dielectric resonator placed inside



Tracked resonance frequency shift
Maximum frequency shift of -4500 ppm

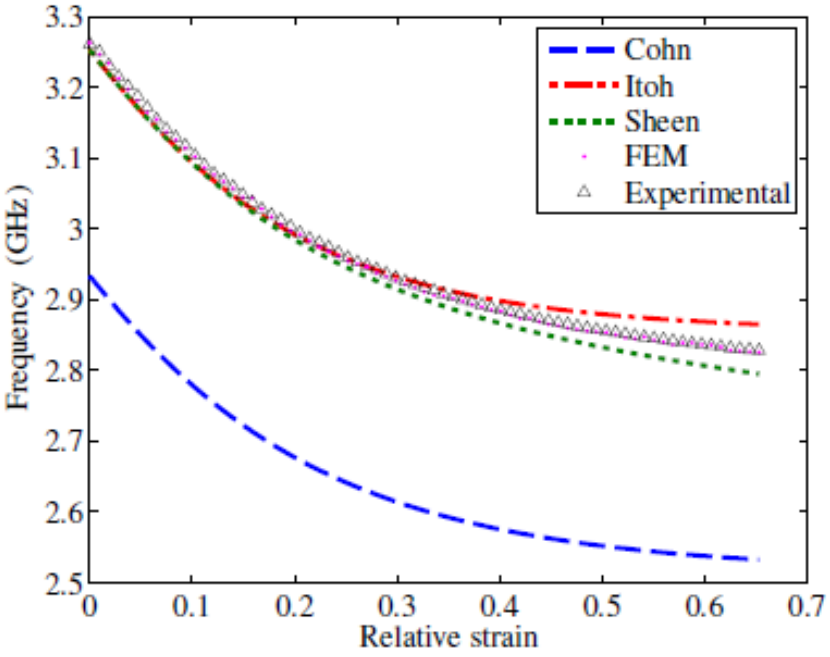


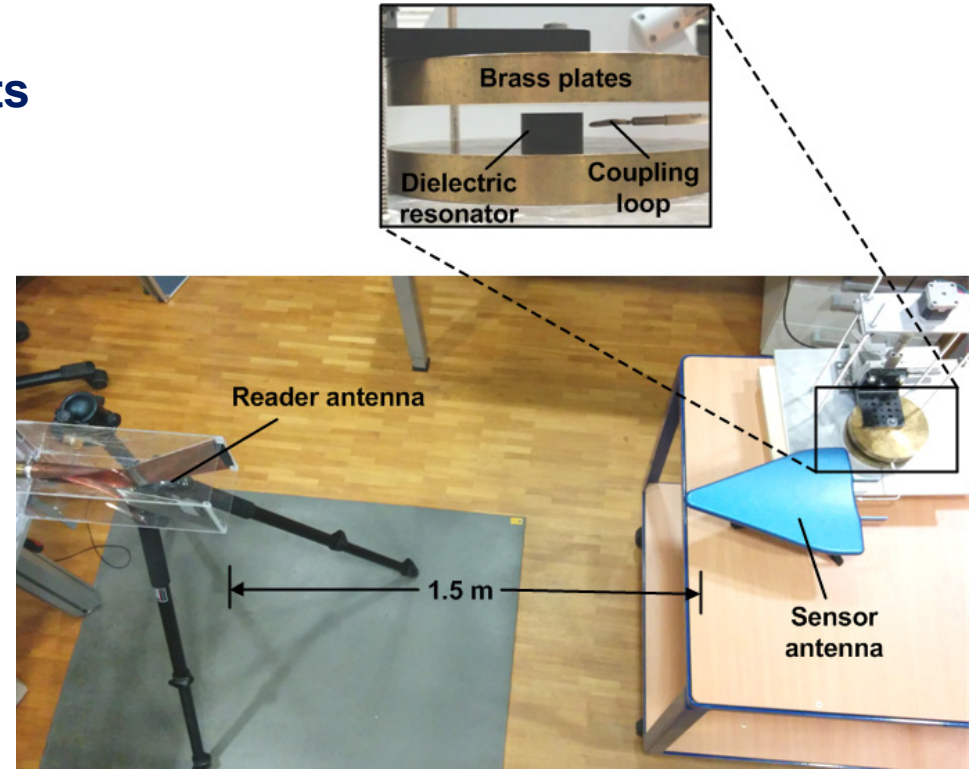
Complete measurement setup
Reading distance: 1.20 m

J.-M. Boccard, T. Aftab, J. Hoppe, A. Yousaf, R. Hütter, L. M. Reindl,Far- Field passive temperature sensing up to 700 °C using a dielectric resonator 2014 IEEE International Conference on Wireless for Space and Extreme Environments, Wisee, European Space Agency, ESTEC,

Wireless Passive Strain Sensor

- Parallel Plate Dielectric Resonator (PPDR) as Wireless Passive Sensor
- High Q factor
- High operational frequencies
- Suitable for extreme environments

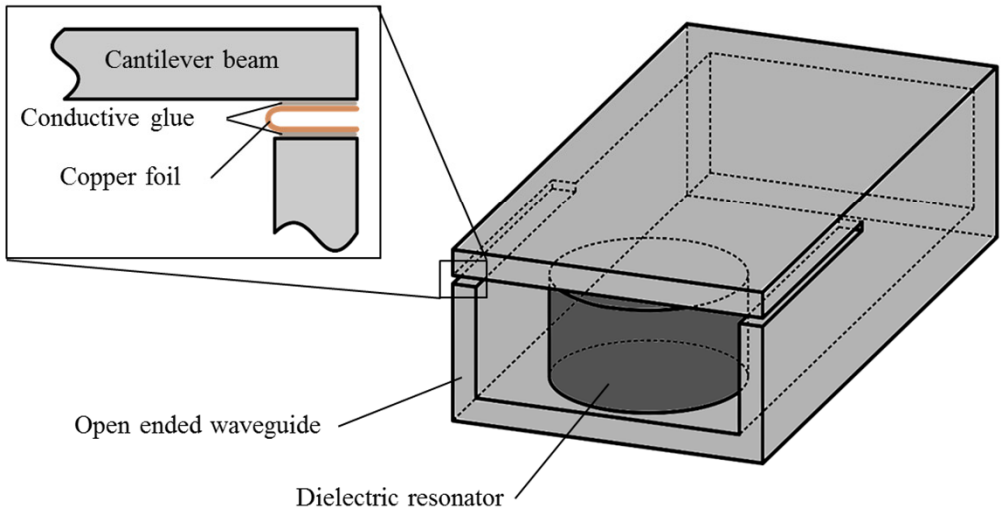


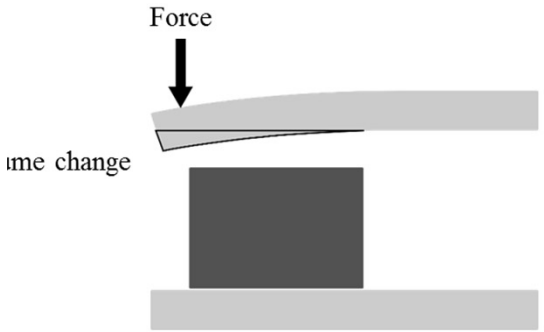


T. Aftab, A. Yousaf, J. Hoppe, S. Stöcklin, T.Ostertag and L.M Reindl (2015): A parallel plate dielectric resonator as a wireless passive strain sensor, IEEE Sensors Applications Symposium, April 13-15, Zadar Croatia

Force Sensor

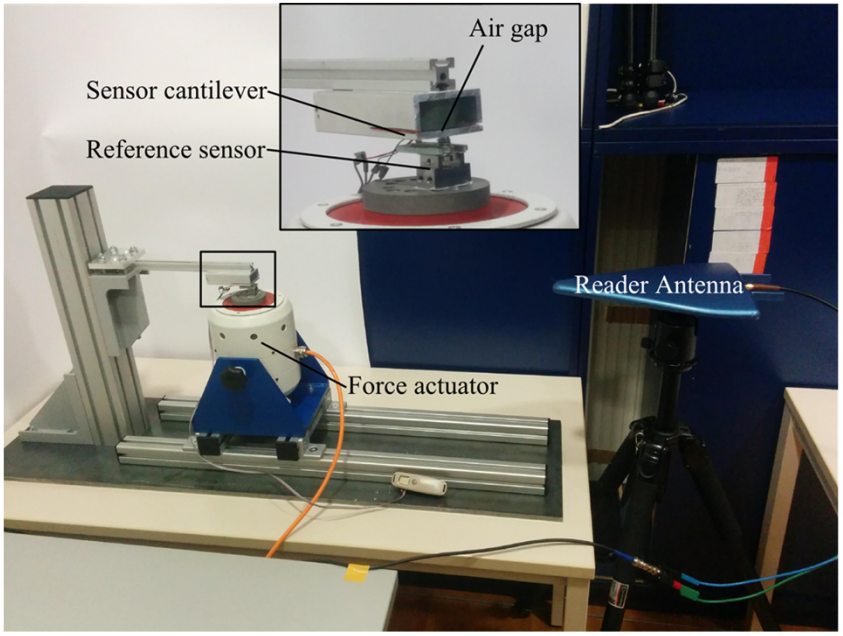
- Evanescent open ended waveguide antenna.
- Loaded with a dielectric resonator
- Cantilever beam spring.
- Force → Displacement → Frequency shift

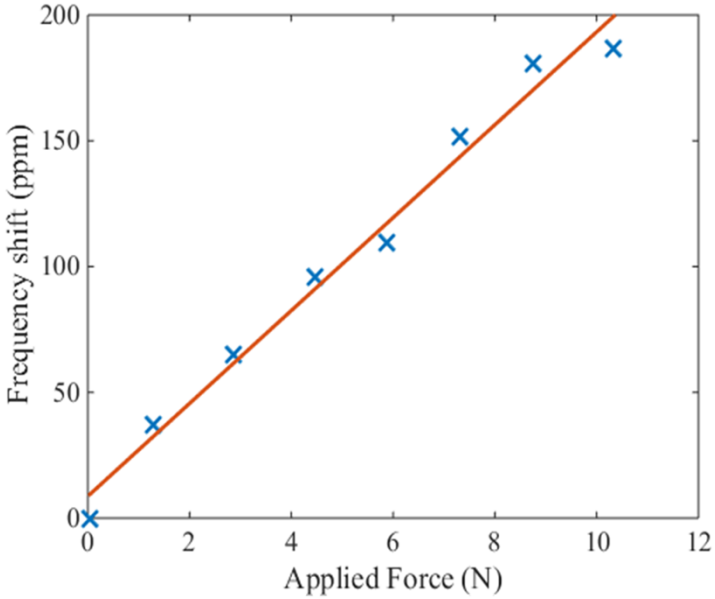




Implementation and results: Force sensor

- Electromagnetic force actuator
- Readings at 1-2 m.
- 3 MHz (1500x 1σ noise) shift with ‘normal thumb force’



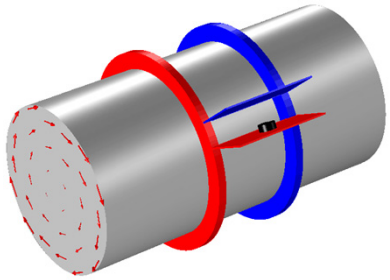


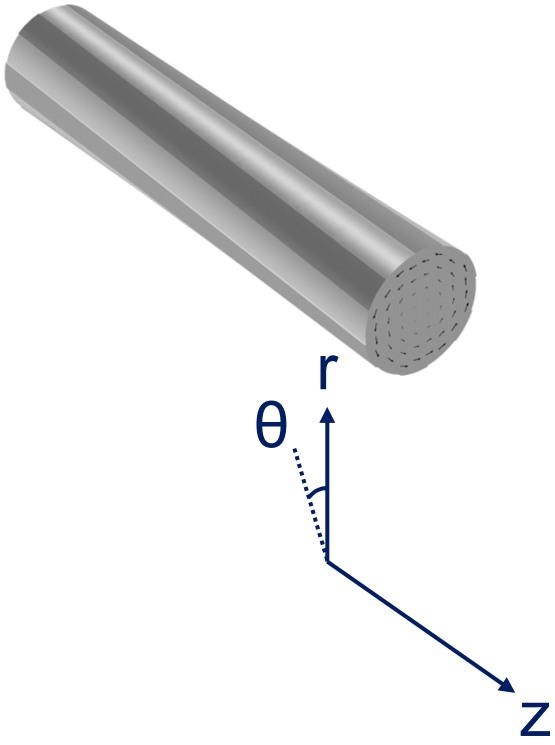
Wireless Passive Torque Sensor

- Dielectric resonator as a transducer.

  Shaft as a linear elastic torsional spring

  St. Venant's Torsion Theory

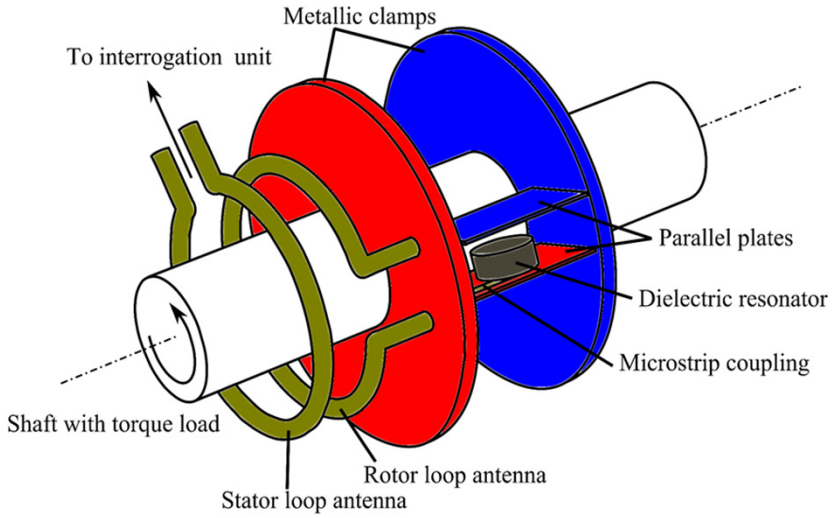




$$G = \frac{E}{2(1+\nu)}$$

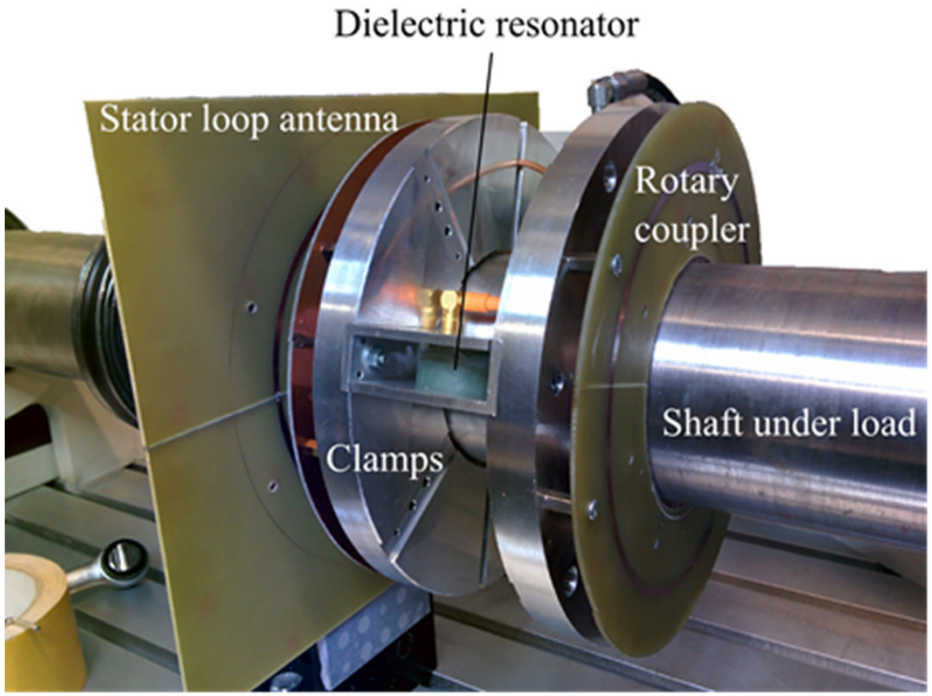
$$T = G\, I_T \frac{d\theta}{dz}$$

$$I_T = \frac{\pi d^4}{32}$$



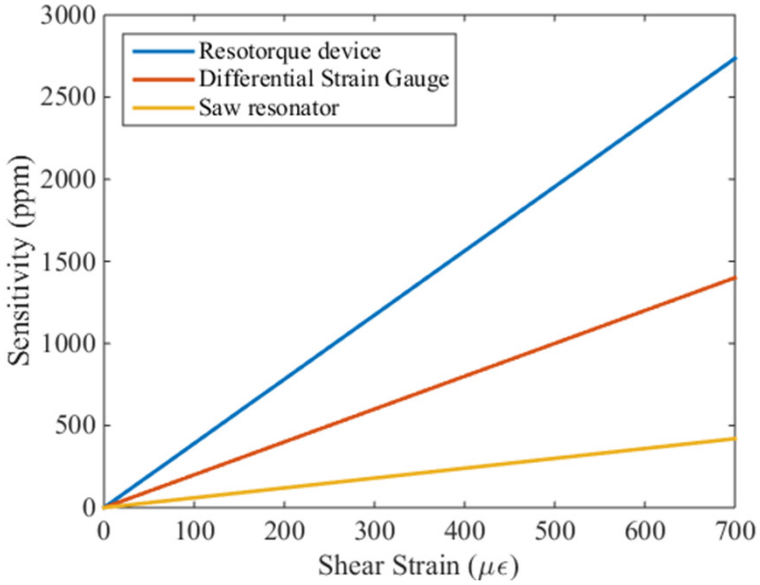
Implementation: Torque sensor

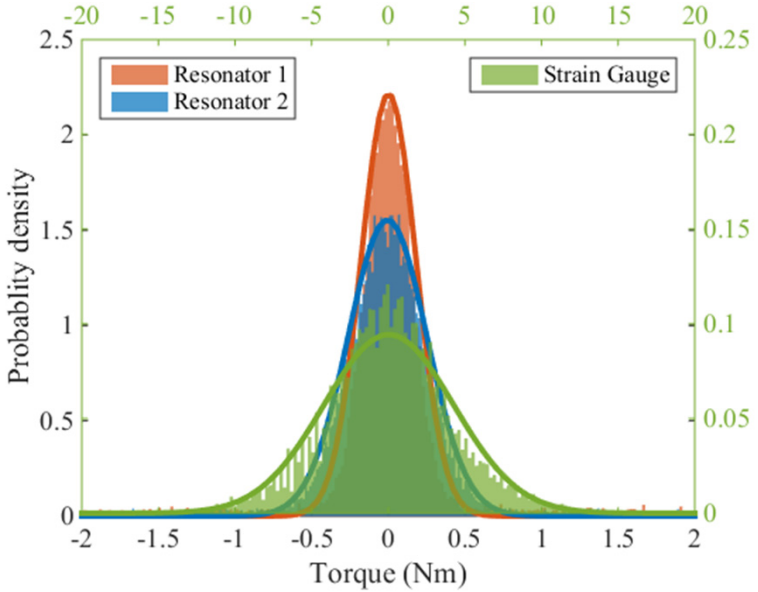
- Clamp on device.
- Low installation time.
- 2.4 GHz ISM band compatible
- Dual sensors on each side for offset compensation
- Offset due to
  - Temperature
  - Sideways force
  - Coupler imperfections



Results: Torque sensor

- Higher sensitivity when compared to strain gauge
- Sensitivity in frequency shift rather than small Wheatstone bridge perturbation.



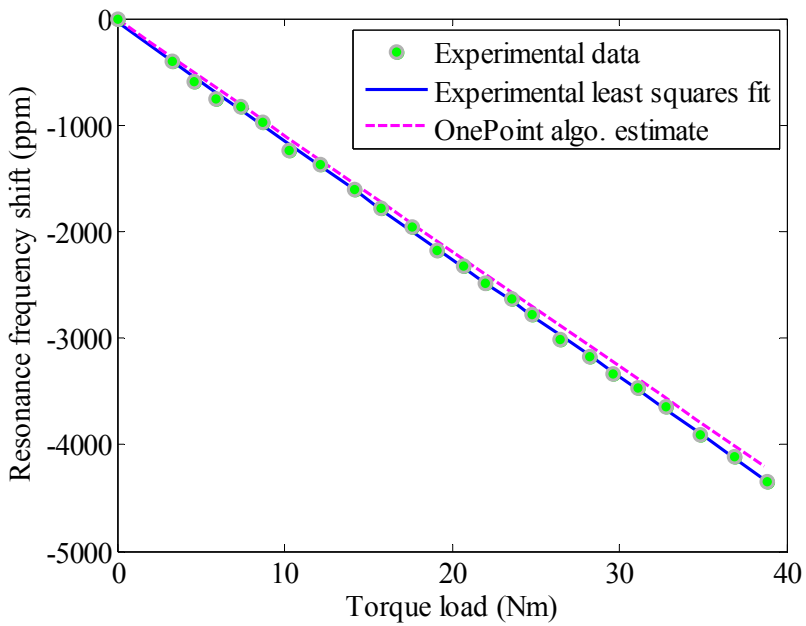


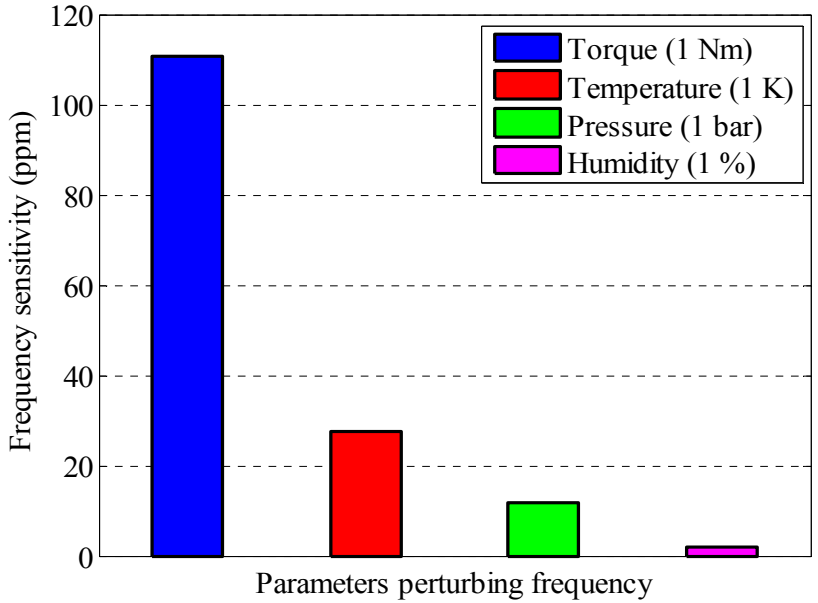
DUT: 3.9 (kHz/GHz)/με

DMS: 2 (μV/V)/με

SAWR: 0.6 (kHz/GHz)/με

Wireless Passive Torque Sensor



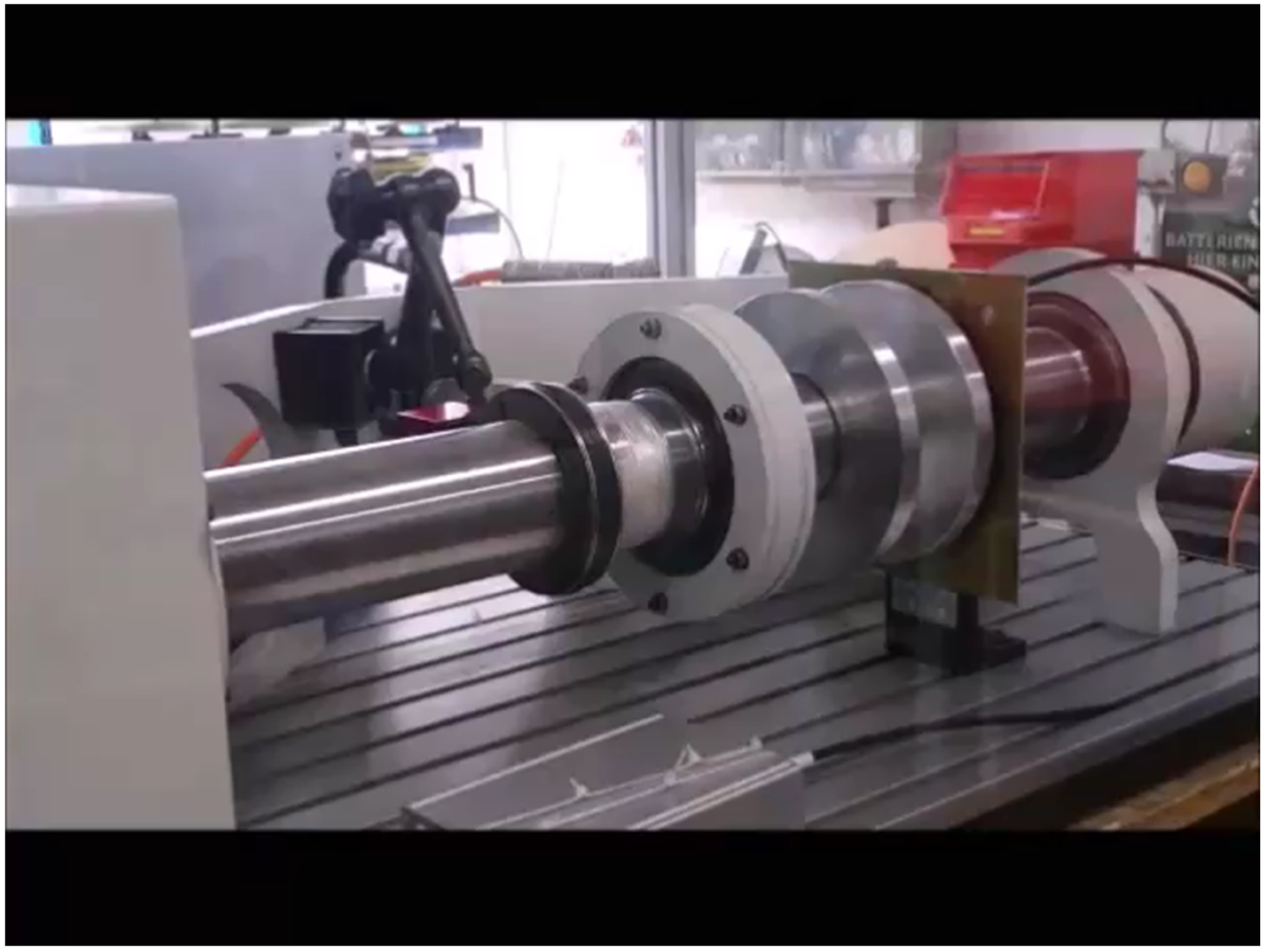


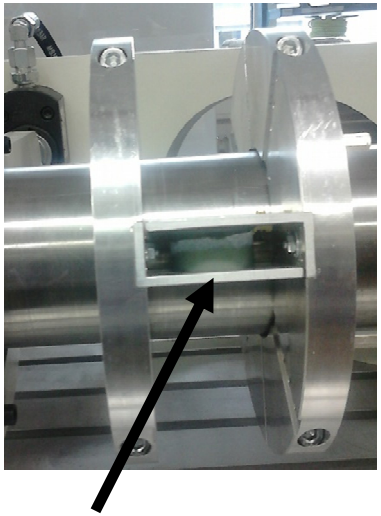
- **Easy to assemble clamp based measurement**
- **Low cost solution with high torque resolution**

J. Hoppe, J.-M. Boccard, T. Aftab, A. Yousaf, A. Ojha, T. Ostertag, L.M. Reindl Open parallel-plate dielectric resonator for passive torque sensing 2014 Proc. of Multi-Conference on Systems, Signals & Devices (SSD), Barcelona (Spain) , Band: 1,Number: 5, pp.: 11 - 14

Wireless Passive Torque Sensor

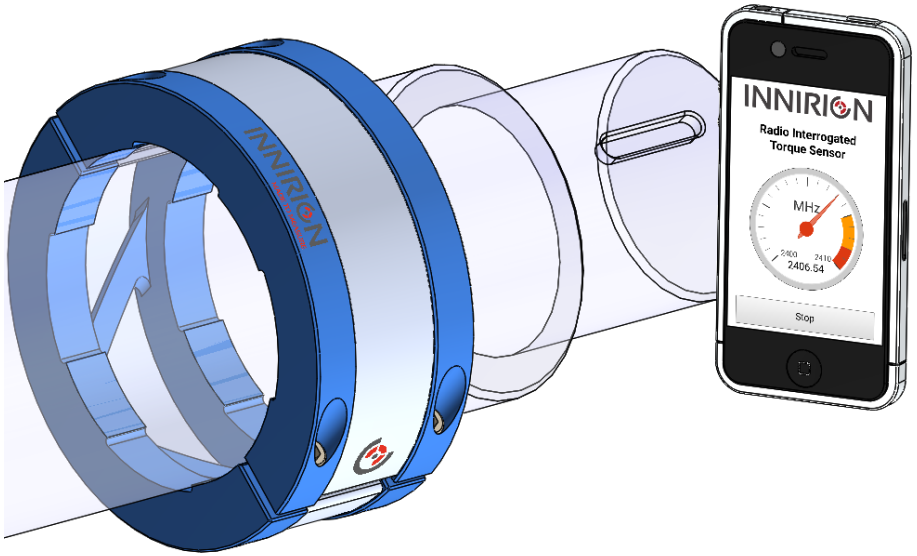
Field tests @ 2000 Nm





Dielectric resonators mounted on the rotating shaft

Torque Clamp

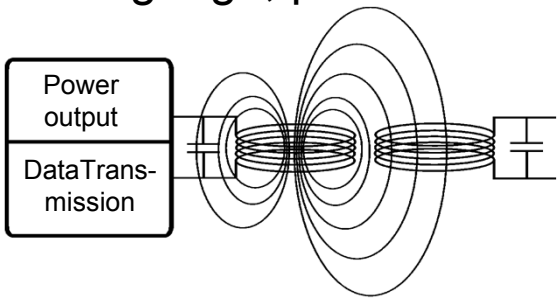


- Innovative clamp-on design

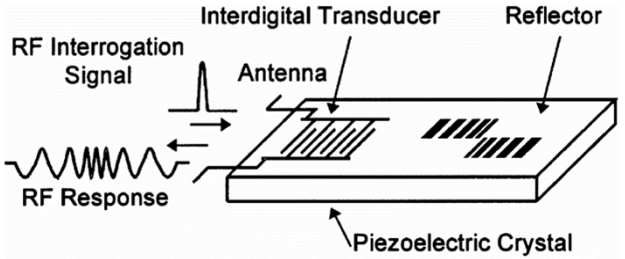
Start up company
by University Freiburg
INNIRION GmbH
https://www.innirion.com/

Strain gauge, µC / RF

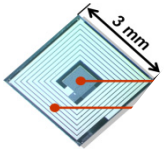
Strain gauge, µC / RF

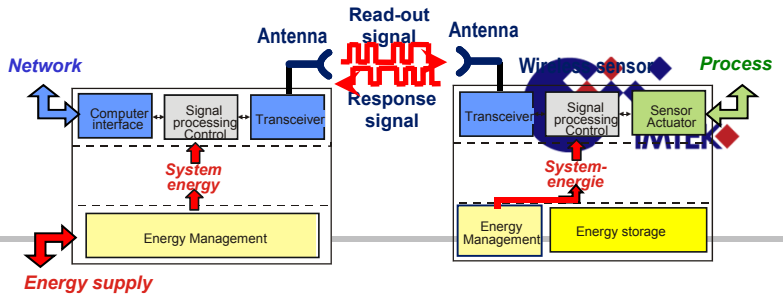


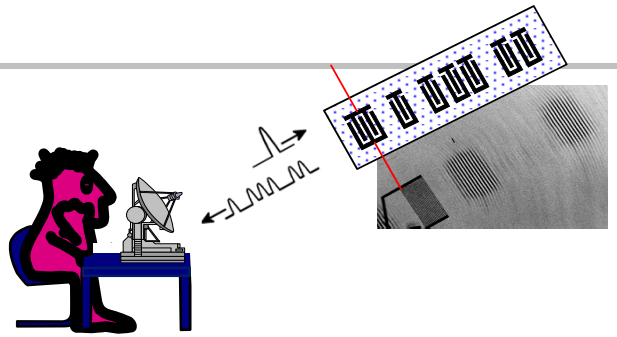
SAW / DRO, passiv

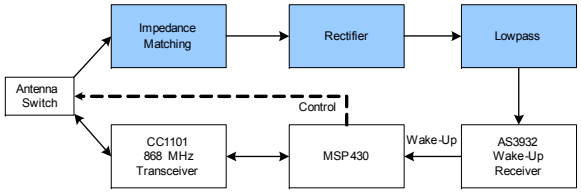


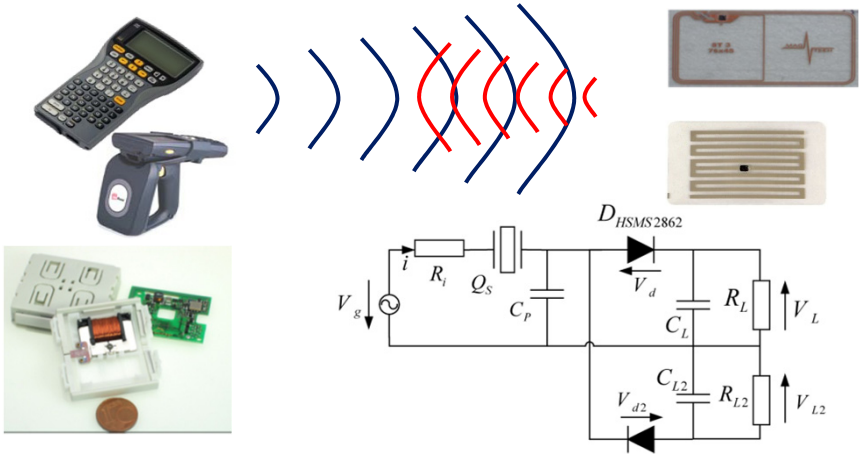
Conclusion











- All wireless sensor systems suffer on energy insufficiency!
- Battery bases systems: service life ~ (1/ measurement rate)
- Low power wake up system for real time applications developed
- Inductive RFID systems: read-out distance ~ diameter of reader coil
- Microwave RFID systems: read-out distance ~ 1-6 meters, or more
- Energy harvesting systems:
  New photocells needed, formulas for thermoelectric developed
- Mixer systems: read-out distance > IC based systems
- SAW/BAW systems: read-out distance ~ 5-10 meters, possible high temperature resistance

Thanks for your attention!

- Thanks to

- and

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Bundesministerium für Bildung und Forschung

SEVENTH FRAMEWORK PROGRAMME

ALLIANZ INDUSTRIE FORSCHUNG

FVA Forschungsvereinigung Antriebstechnik e.V.

Ministerium für Wissenschaft, Forschung und Kunst Baden-Württemberg

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Biosensors	Sensor technology
Sensor networks	Remote sensors
Sensing principles	Applications of sensors

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