RF-HARVESTING AND WIRELESS POWER TRANSFER

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EnABLES Summer School – Perugia, September 2019

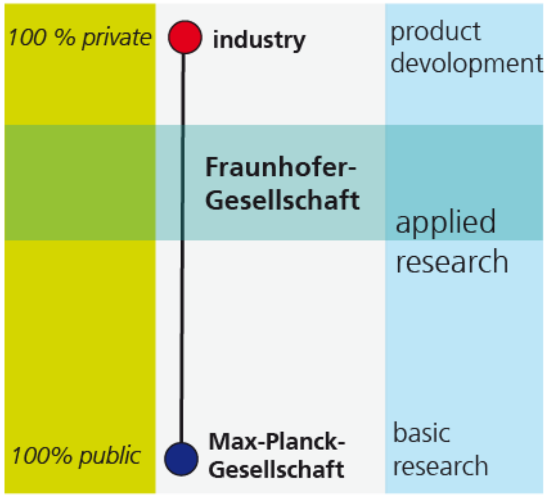
Figure: Fraunhofer IMS

CONTENT

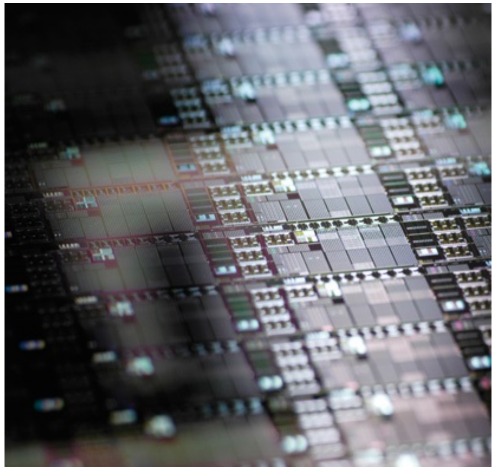
- Introduction to Fraunhofer IMS
- Motivation and Application Examples
  - Wireless sensors, battery charging, human implants
- Overview and general properties of different frequency bands
- Inductive principle (LF/HF)
  - Coil Parameters, Resonant Operation
- Electromagnetic principle (UHF/SHF)
  - Key components of a transmission line
  - Link budget - calculating a transmission line
- Standards and Limitations
- Conclusion and Outlook

Fraunhofer IMS - Facts

- Foundation: 1984/85
- Staff: > 250
- Mission:
  - Applied research and development of microelectronic systems and circuits
  - Technology development and transfer
- Budget: (> 30 Mio. Euro)
  - 25 % Basic Funding for Corporate Research and Administration
  - 25 % Publicly funded Projects
  - 50 % Projects funded by Industry



Infrastructure
CMOS Fab



Total area:	1,300 m^2
Wafer size:	200 mm
Staff:	4 shifts / 7 days a week
Capacity:	> 50,000 wafer p. a.

Capabilities — CMOS process line

- Mixed signal ASICs
- HT and HV based on SOI
- Imagers
- Smart pressure sensors

Mission — Customer specific CMOS products

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Motivation

Application

Demand of the customer

- Easy solution for monitoring of existing machinery and equipment
- Jump on the bandwagon of digitization and smart industry

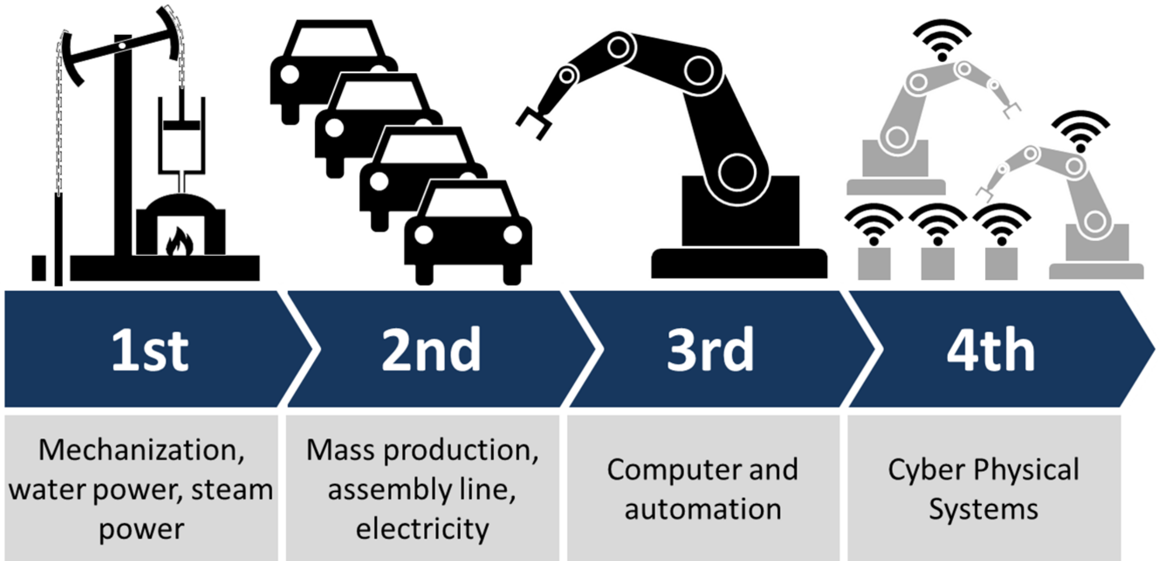


Figure: Christoph Roser at AllAboutLean.com

RF-Energy-Harvesting for Powering of IoT-Devices

Application

Idea

- Determination of process conditions from the supply current
- Wireless IoT devices , e.g. current sensor, as a clip
- Smart signal processing at the sensor side
- Energy-Self-Sufficient IoT devices

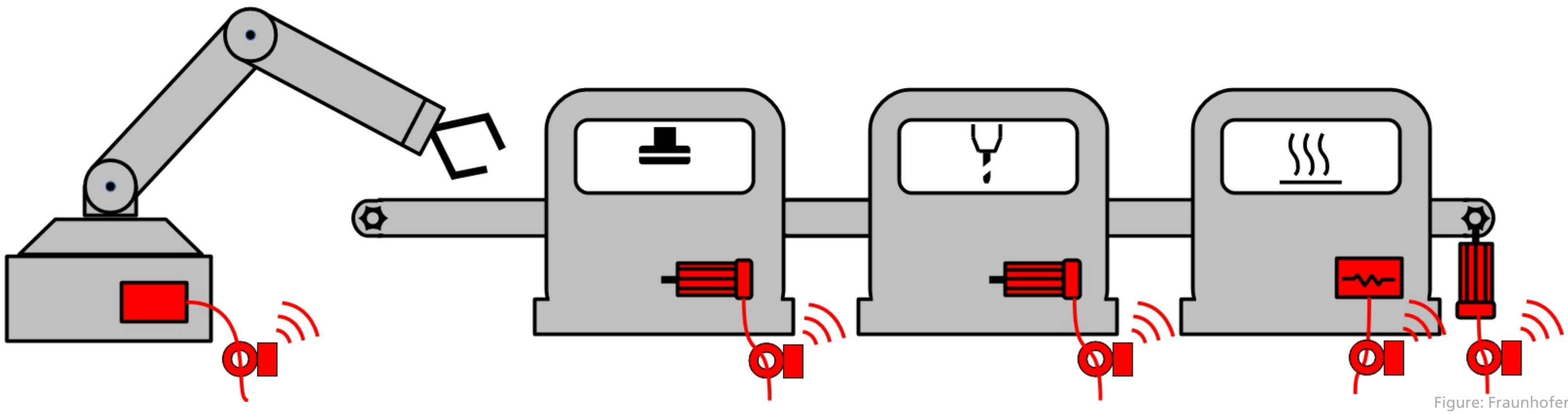
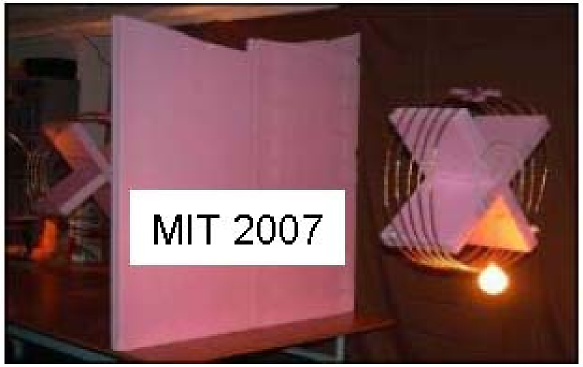


Figure: Fraunhofer IMS

Wireless Power Transfer - Impressions

Application



WPT – Wireless Power Transfer

Application

- WPT has recently evolved to:
  - a subject of rapid **technological** progress
  - a very active **research** topic
  - a domain of emerging **practical development** and commercial application
- **Specialized** journals, conferences and first books have appeared.
- **Wireless Power Consortium** - Cooperation of Asian, European, and American companies in diverse industries. Working towards the **global** ***standardization*** *charging technology* **(Qi standard)**.
- **Alliance for Wireless Power** - Independently operated organization composed of global wireless power and technology industry leaders **(Rezense standard)**.
- **Commercial products** utilizing wireless power transfer are already available in the market.

Definition of Wireless Power

Application

- The essential principles of WPT are
  - given a distances over which the power is transferred through air or other non-conductive medium
  - The coupling is almost always less than a quarter wavelength, so the fundamental operation of all of these systems can be described by simple coupled models
- Wireless power transfer (WPT)
- Contactless power system (CPS)
- Inductive power transfer (IPT)
- Capacitive wireless power transfer
- Strongly coupled magnetic resonance
- Wireless energy transfer

Ref: Grant Covic and John Boys, "Modern Trends in Inductive Power Transfer for Transportation Applications," IEEE journal of emerging and selected topics in power electronics, vol. 1, no. 1, march 2013

History of Wireless Power Transfer

Application

- 1830's: Faraday's law of induction
- 1890's: Tesla had a dream to send energy wirelessly
- 1990's: GM EV1 used an Inductive charger
- 2007: MIT demonstrated a system that can transfer 60W of power over 2 m distance at very low efficiency
- 2010: Wireless/inductive chargers are available: electronics, factories, medical
- 2012: Qualcomm, Delphi (Witricity), Plugless Power, KAIST, etc. have developed EV wireless charger prototypes
- 2014: in-motion charging demonstration: Daejoeng, Vienna, London

"Tesla Broadcast Tower 1904" by Unattributed(Life time: Unattributed) - Original publication: UnknownImmediate source: http://www.sftesla.org/images/Tesla_Broadcast_Tower.JPG. Licensed under Public domain via Wikimedia Commons - http://commons.wikimedia.org/wiki/File:Tesla_Broadcast_Tower_1904.jpeg#mediaviewer/File:Tesla_Broadcast_Tower_1904.jpeg

The Predicted Wireless Charging Market: $17 Billion by 2019, including applications in consumer electronics, home appliance, industrial robots, and EV charging

WPT – Wireless Power Transfer

Application

- A **WPT system** consists of:
  - **chargers** which transmit power **wirelessly**
  - **receivers** which **harvest** the energy from the chargers
- Envisioned by **Tesla,** now becoming a game-changing technology.[1]
- **More reliable and controllable** than ambient energy harvesting (solar, light, wind etc.)

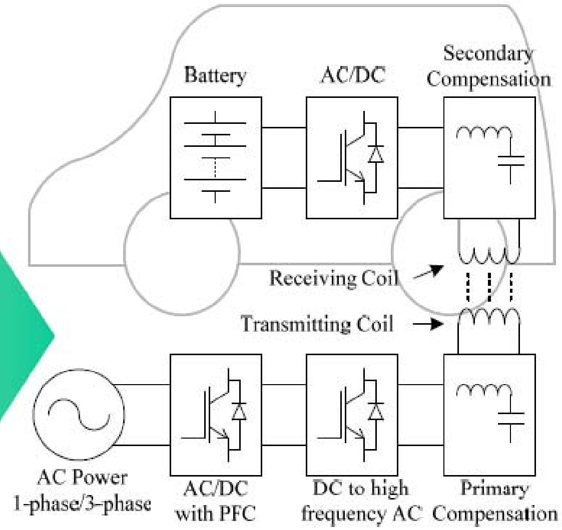
Application: Electrical Vehicles Charging

Application

Electric safety is of concern: electric shock due to rain, etc.

Charge station, plug and cable can be easily damaged, stolen

Charge/swap station takes a lot of space and affect the views



Possible Solution:

Wireless Charging

Application: Charging an Inspection Drone

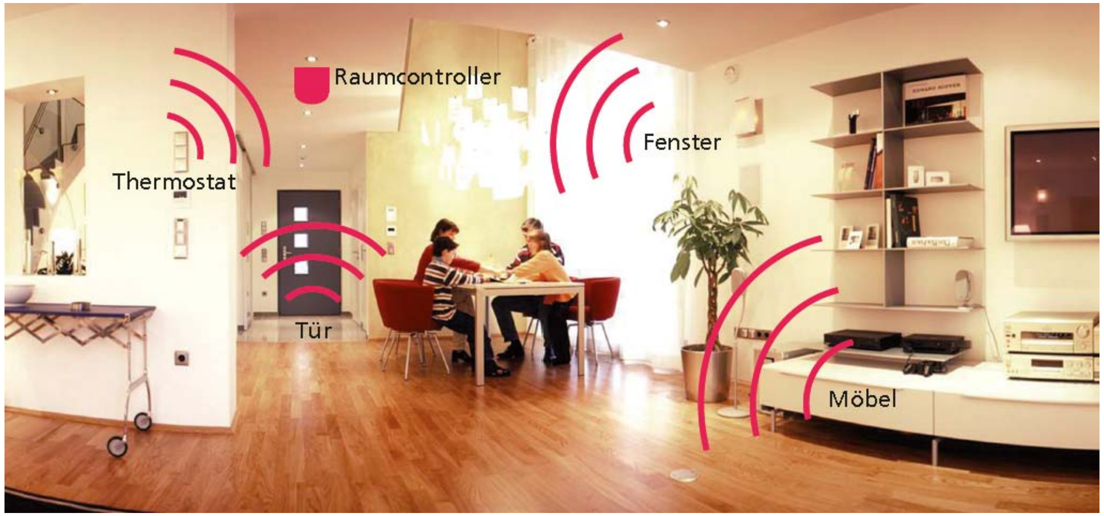
Application

Application: Charging electronic Devices using Qi

Application: Smart Home passive Sensors

Application

- Central controller with RF-transmitter
- Contact sensor for windows and any other contacts
- Temperature sensor
- Humidity sensor



Product Example: WLAN Harvester

Application

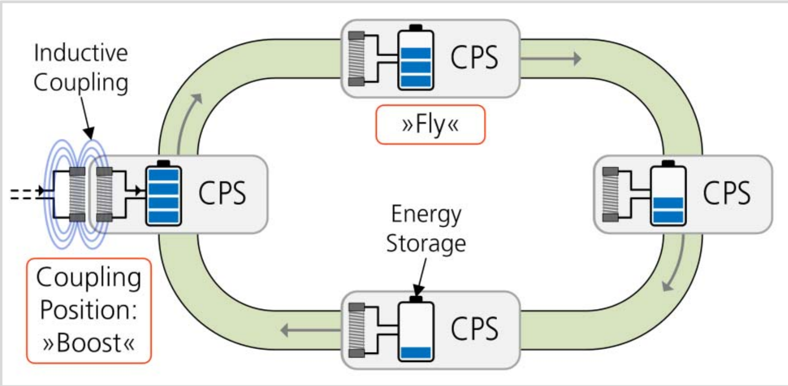
- Vendor: RCA
- Energy Source: WLAN-Signals
- Charging of mobile Phones
- Charging time for a Blackberry: 90 min from 30% to 100%
- Available: 2011 for ca. US$40

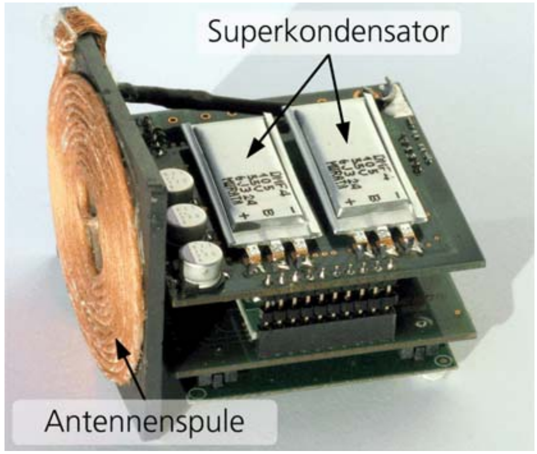
Fake Product

- http://www.energyharvestingjournal.com/articles/harvesting-power-from-wifi-signals-00001966.asp?sessionid=1

Application: Industrial Automation: Boost&Fly

Application





- Wireless energy supply solution for sensors in smart production processes
- Self-sufficient operation of cyber-physical systems
- High availability and robustness (industrial production environment)
- Contactless energy transfer by inductive transmission
- Operation time ("Fly") up to 7 minutes (@ 50 mW) with a charging time ("Boost") of 2 seconds

Applications in Industrial Automation: Energy-Self-Sufficient Current-Sensor

Application

Features

- Non-invasive installation - no power interruption
- Easy installation - clip around the conductor
- Wireless - no cabling needed
- Maintenance-free - thanks to energy harvesting
- Smart - near-sensor signal processing

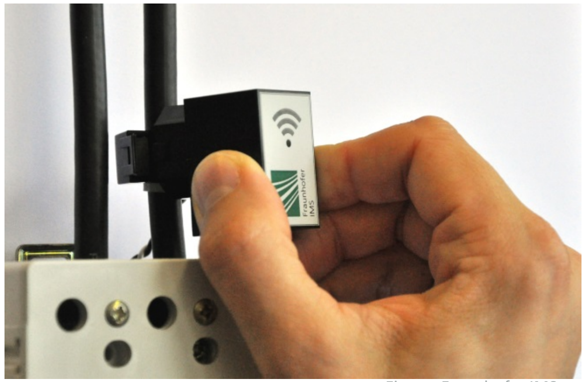


Figure: Fraunhofer IMS

Applications in Industrial Automation:

Application

- Possible application scenario

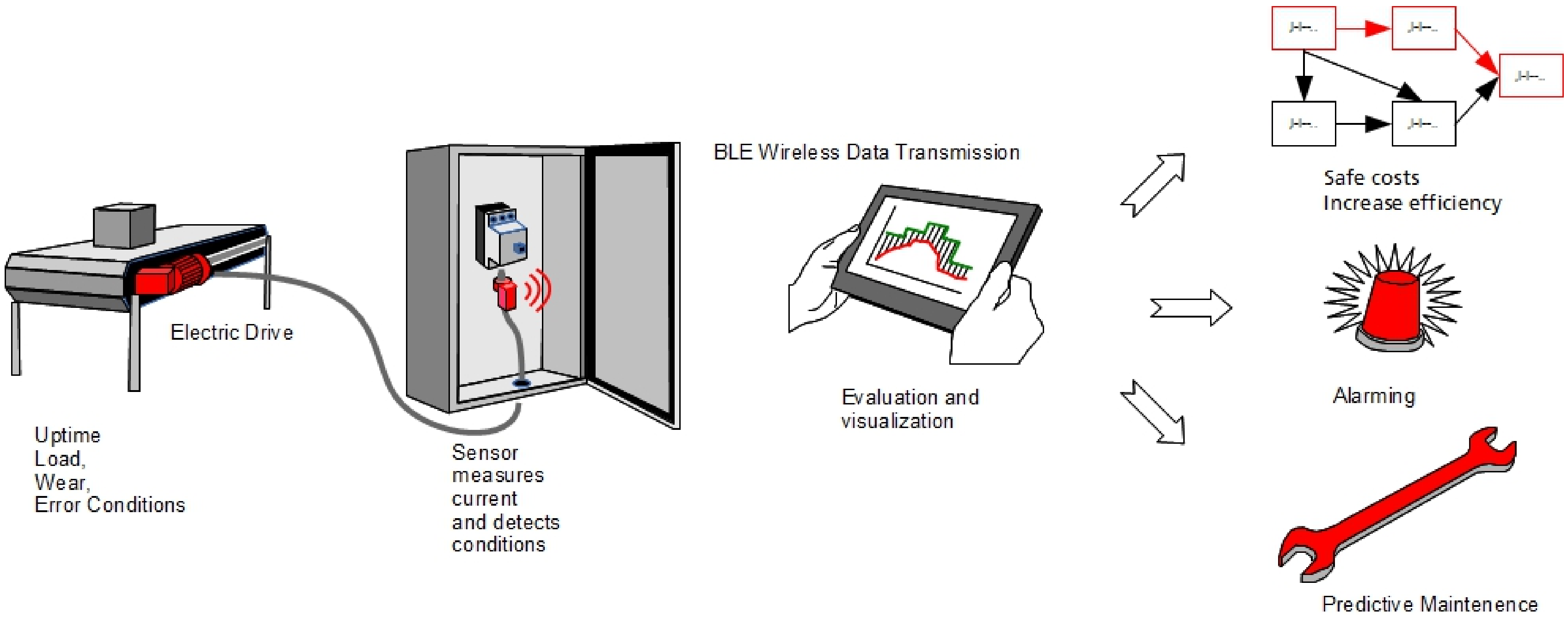
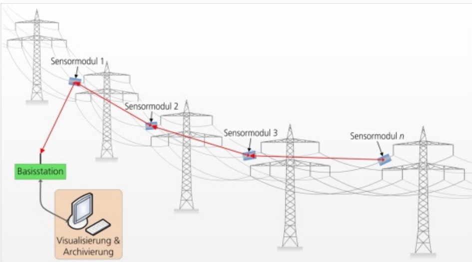


Figure: Fraunhofer IMS

Application:

Overhead Line Sensor System

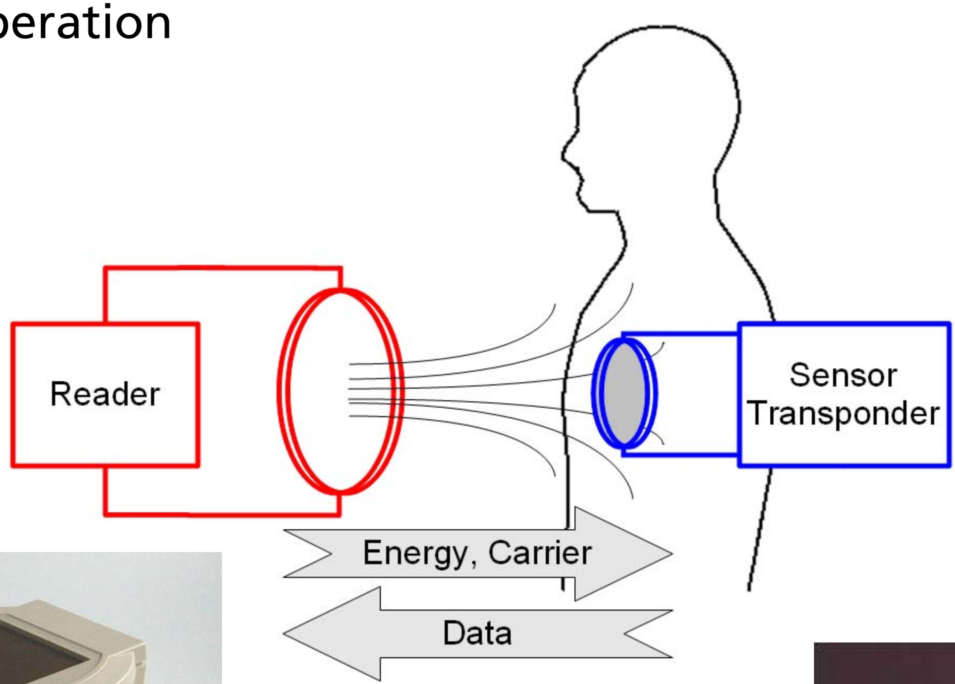


Sensor based monitoring of line parameters and wireless transmission to a control unit for fault localization and prediction

- IMS Development
  - System concept and specification
  - Modelling of communication mechanisms
  - Development of all components
  - Setup and evaluation of field trials
- Features
  - Complete wireless network
  - robust & fault tolerant transmission protocol
  - Energy harvesting for the sensor unit

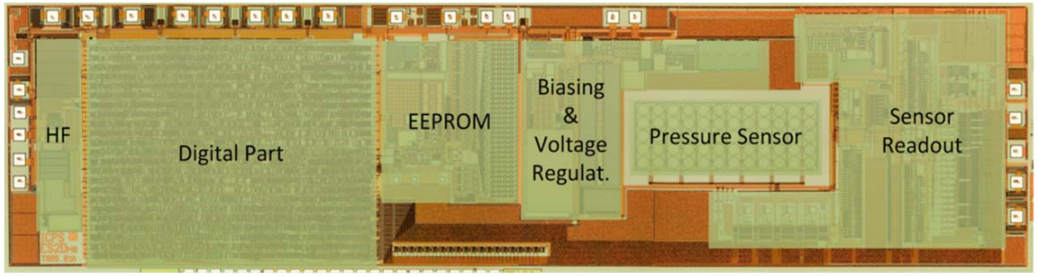
Application: Medical Implants

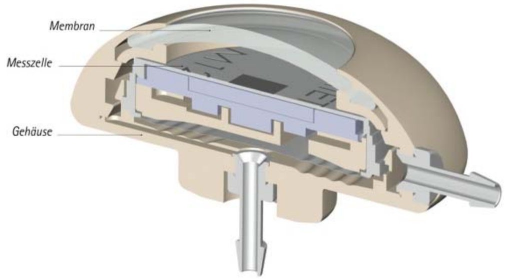
- Principle of Operation

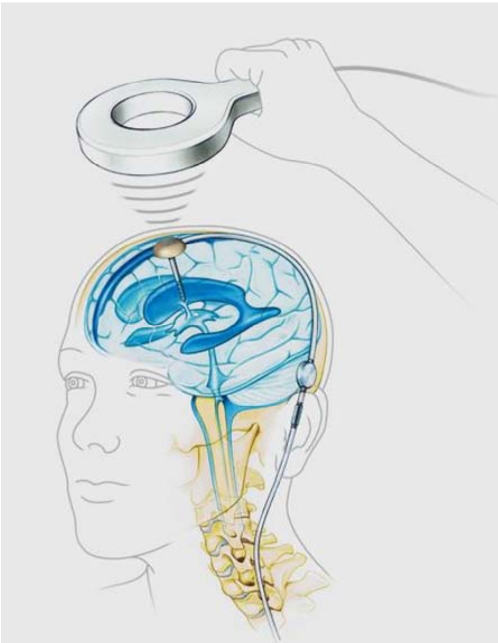


Medical Implants

Shunt Sensor







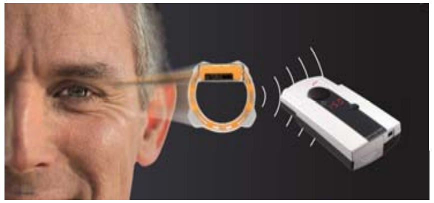
Wireless measurement of the intracranial pressure

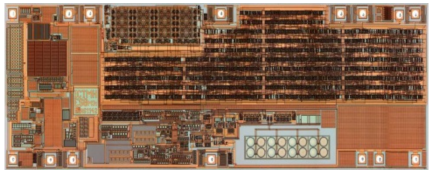
- IMS Development
    - ASIC design and test
    - Calibration of the pressure transponder
    - Development of the reader unit (hardware and software)
  - Manufacturing of ASIC and reader unit
- Features
  - Wireless readout in human bodies
  - ASIC and reader unit medical approved

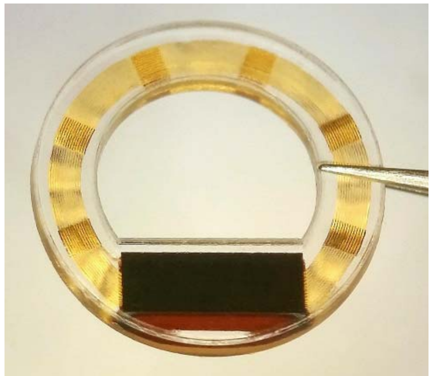
Medical Implants

Application

Monitoring of the Intra Ocular Pressure







Continuous monitoring of the intra ocular pressure for better glaucoma therapy

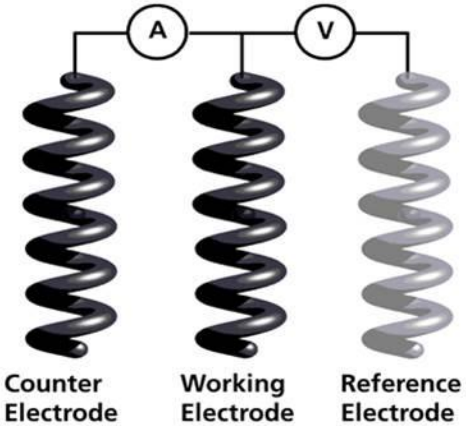
Goal: Measurement in normal daily routine without inconvenience

- IMS Development
  - Development of demonstrator and prototype
  - Series product with CE approval
- Features
  - Fully implantable sensor system
  - Low power consumption (< 200 µW)
  - Single chip solution

Biohybrid Systems (BS)

Glucose Sensor for measurements in tear fluid

Application



- Key Specifications
  - Wireless readout
  - Better control of therapy success
  - Amperometric Single-Chip Potentiostat
  - HF-frequency: 13.56 MHz
- Features
  - Miniaturization
  - Low power consumption
  - Transponder capability
  - Manufacturing of ASIC and reader unit

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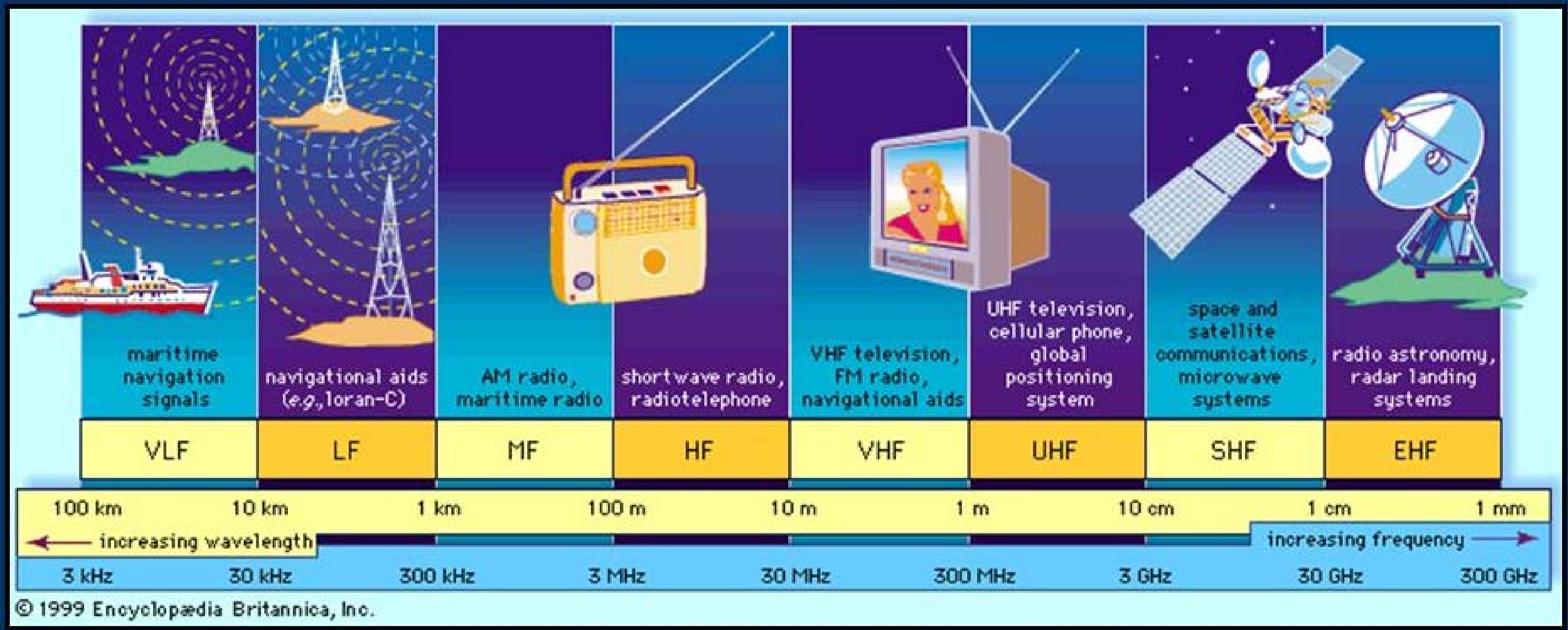
➢ Radiowaves

- lowest energy EM radiation

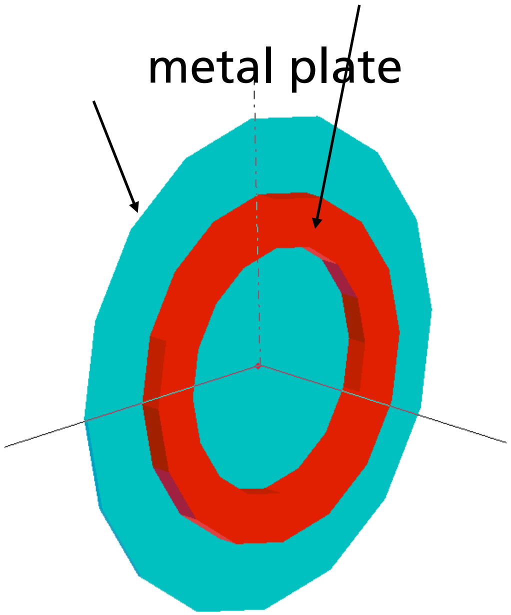


Field strength near metal

Overview

Coil and

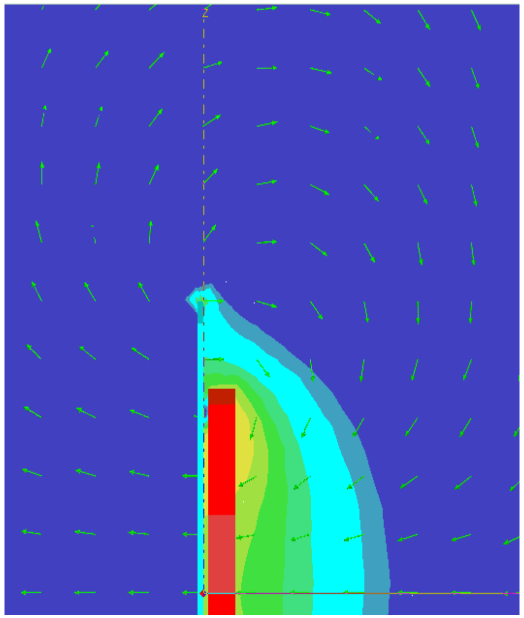
metal plate



Cross section of simulation

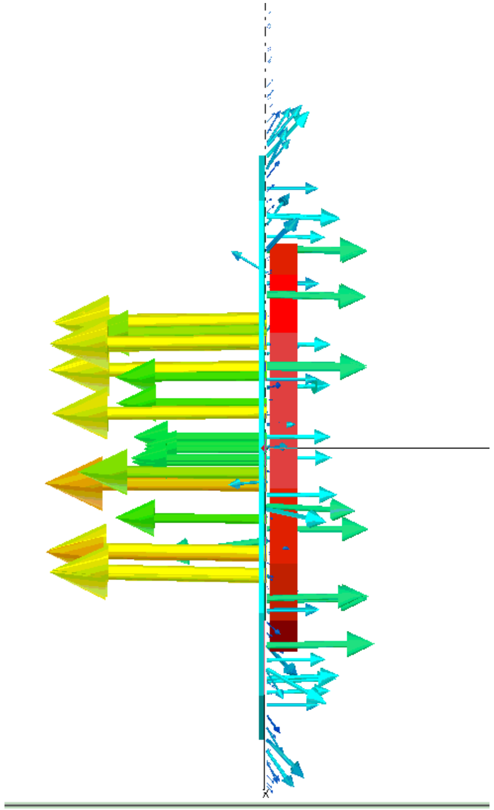
Field strength

and orientation



Orientation of field

at metal surface



Influence by Metal

Overview

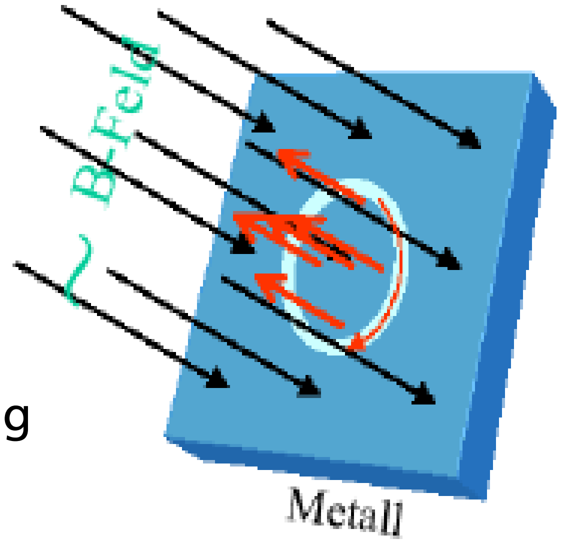
Metal has strong influence on the propagation of electromagnetic waves:

Magnetic field: eddy currents is induced in metal.

The magnetic field generated from the eddy currents is mutual to the generating field.

Depending on frequency and thickness of metal the goes through the metal.

Due to capacitive effects, metal in the surrounding of an antenna coil detunes the antenna.



Electric field: waves are reflected by the surface of the metal, this leads to interference

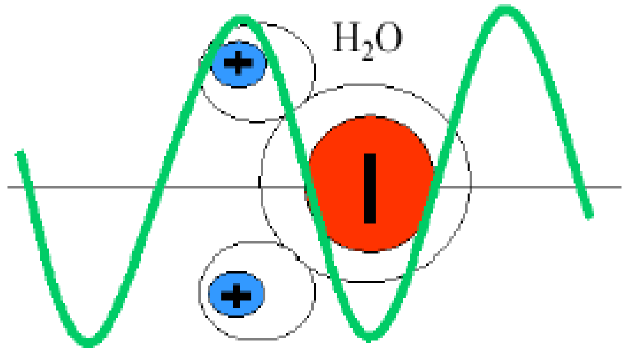
Influence by Water

Overview

Water also has an influence on the propagation of the fields.

Magnetic field: The influence on the magnetic field is low, in the LF range virtually without influence, in the HF range up to 10%.

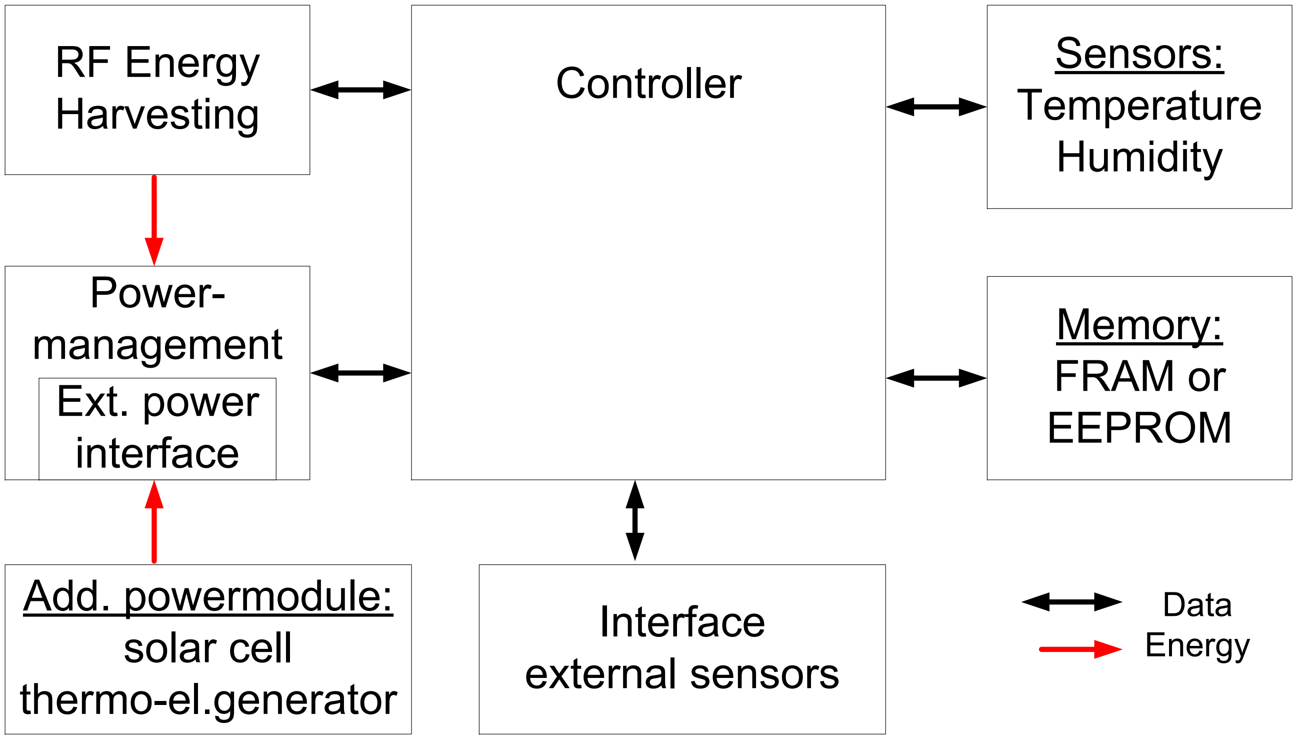
Electric field: At higher frequencies from approx. 1 GHz the influence increases strongly. Due to the dipole character of the water molecules, the field is increasingly strongly attenuated.



Fraunhofer
IMS

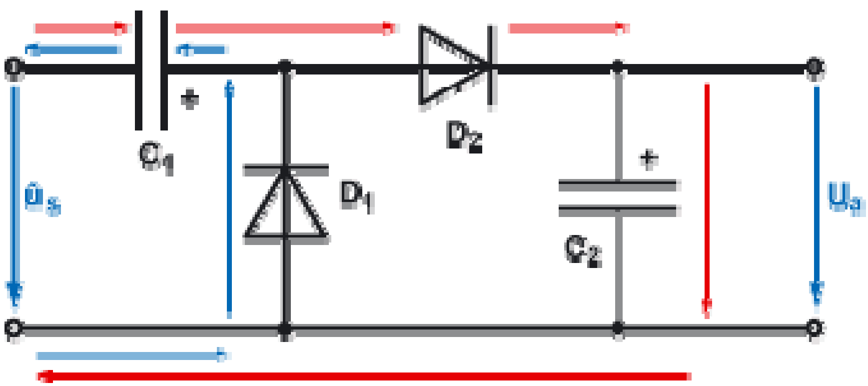
IoT Module (Block Diagram)

Overview

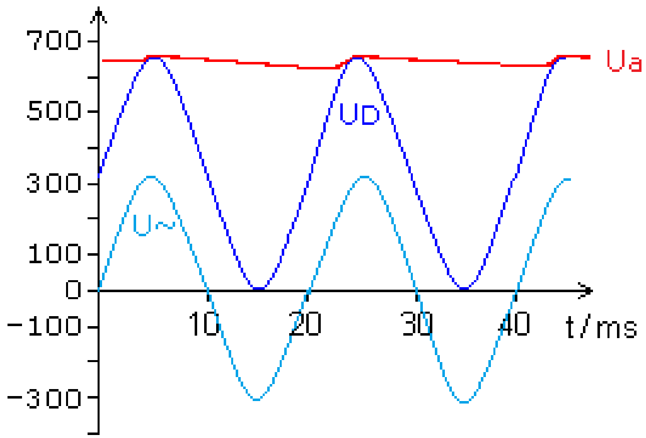


Voltage Conversion / Multiplication

Overview

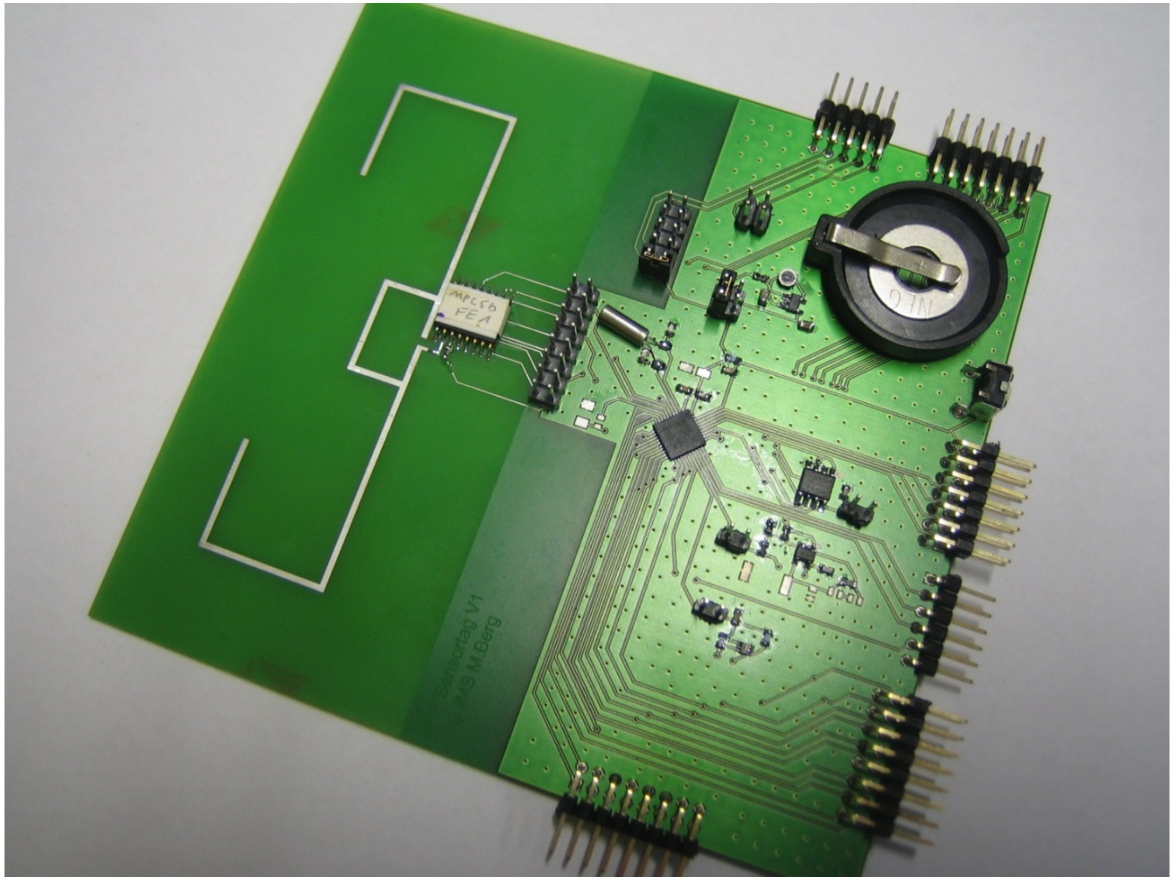


V / mV



IMS-Approach: Demonstrator (Harvester + µC)

Overview



Examples Energy Consumption of Sensor Modules

- **Temperature Sensor**:
  - Power Consumption for Conversion and State-Machine: 20 µW
  - Capacity in case of 1 measured Value per min : 0,2 µWs (per min)
  - Capacity with RF-Modul: 0,3 mWs (per min)
- **Pressure Sensor**:
  - Power Consumption for Conversion and State-Machine: 200 µW
  - Capacity in case of 40 measured Values per sec: 18 mWs (per min)
  - Capacity with RF-Modul: 100 mWs (per min)
- **RFID**:
  - Power Consumption for State-Machine: 1 µW

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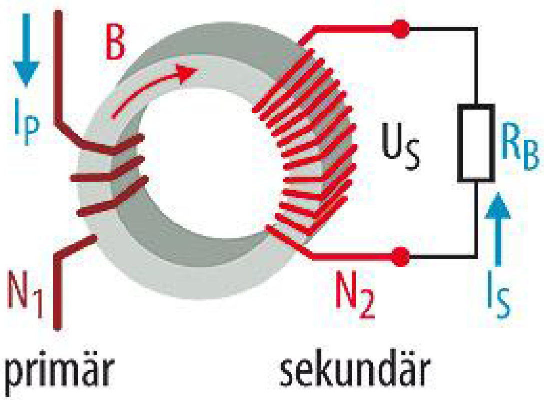
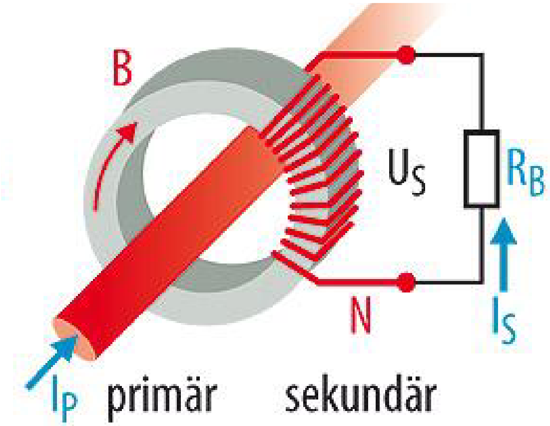
Inductive Principle



$$U_S = I_P R_B \frac{N_1}{N_2}$$



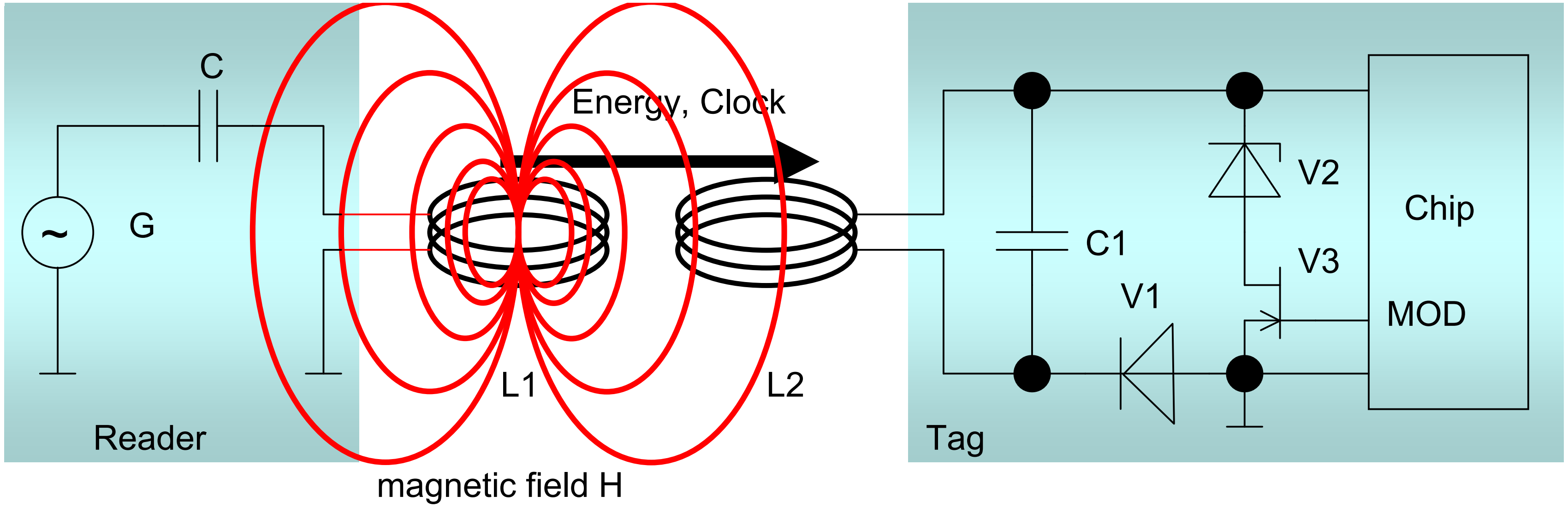
$$\cancel{U_S = I_P \frac{R_B}{N}}$$

Equations from transformer

are not valid!

Inductive Principle
a) aligned coils

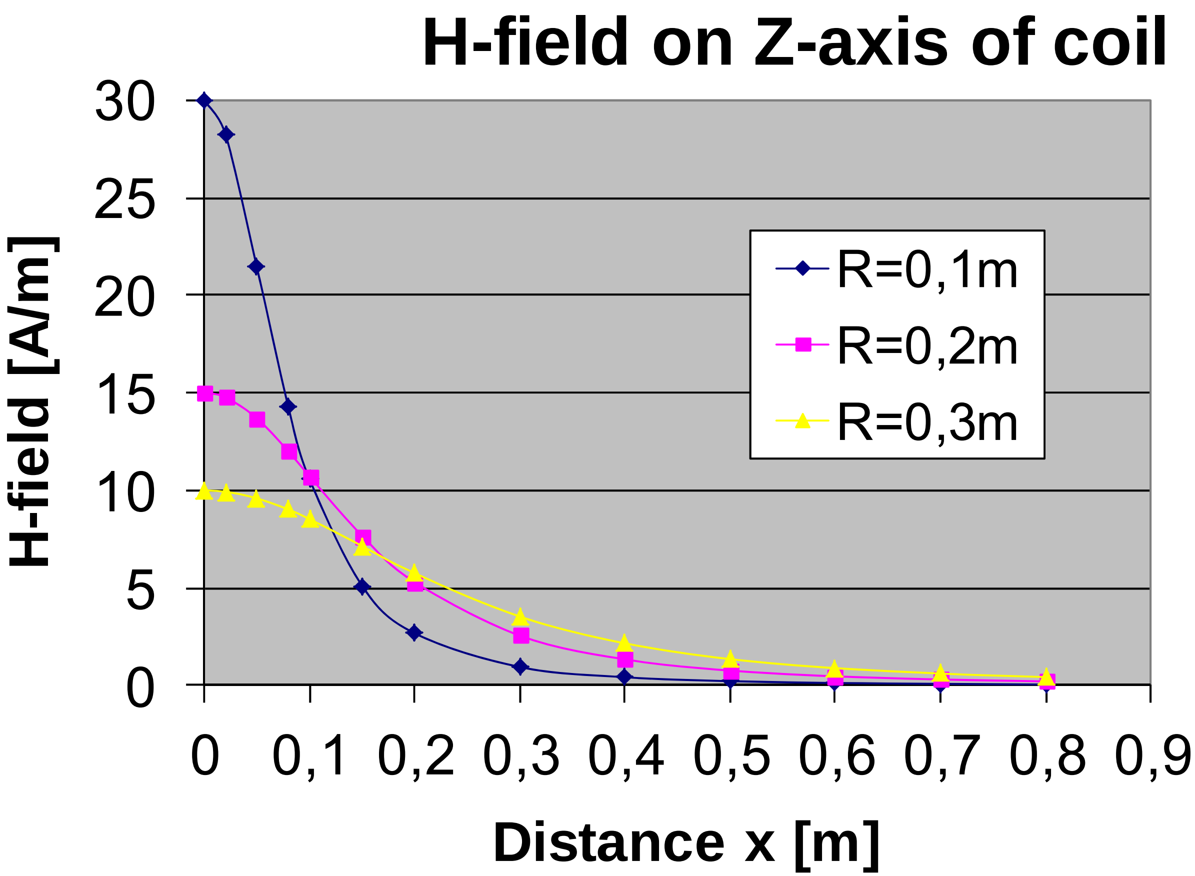
Inductive EH



Inductive Principle (aligned coils)
Magnetic field over distance

Inductive EH

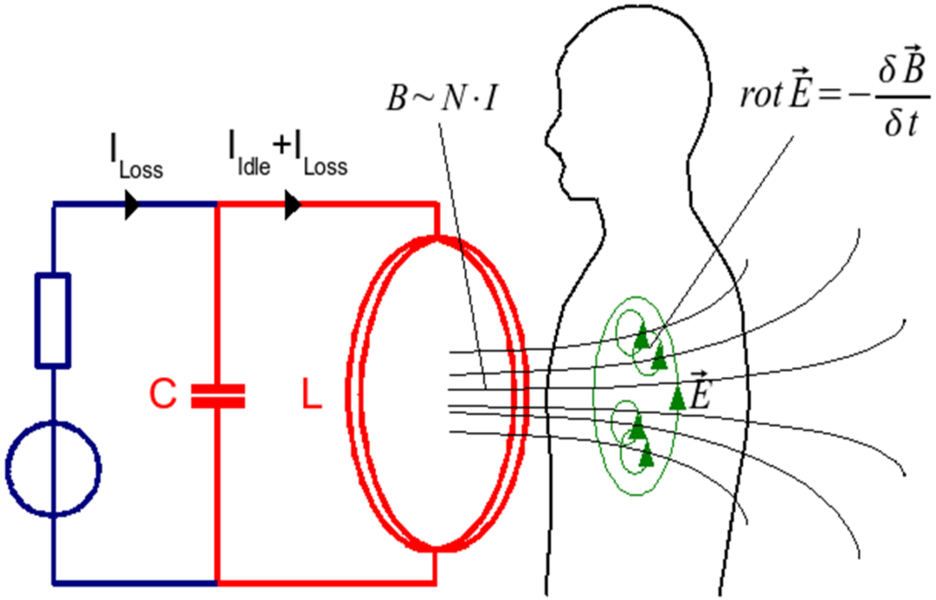
$$H = \frac{I_2 \cdot N_2 \cdot R_2^2}{2 \cdot \sqrt{(R_2^2 + x^2)^3}}$$



Influence of Human Body

Inductive EH

- Energy and data transmission through human body
- Absorption by human tissue



- Different frequency and tissues, different properties!

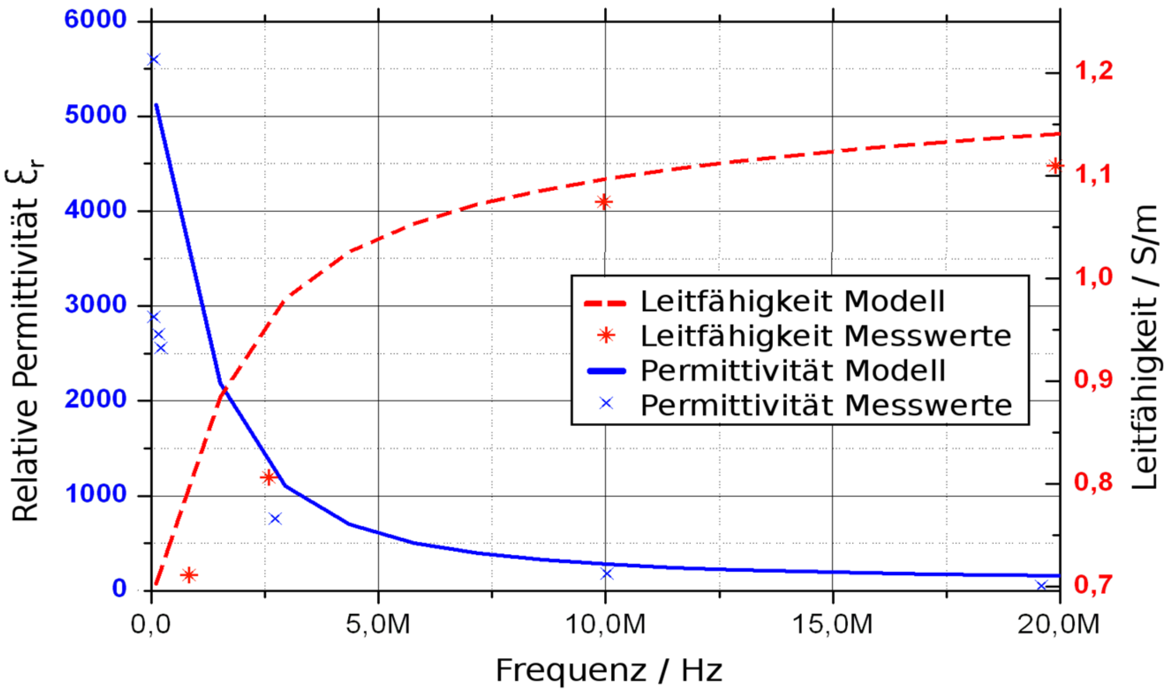
Voxel Man

Properties of Human Tissues

Inductive EH

- Energy is converted into heat: $P = \frac{1}{2}\int_V \frac{|J|^2}{\bar{\sigma}}\,dV$

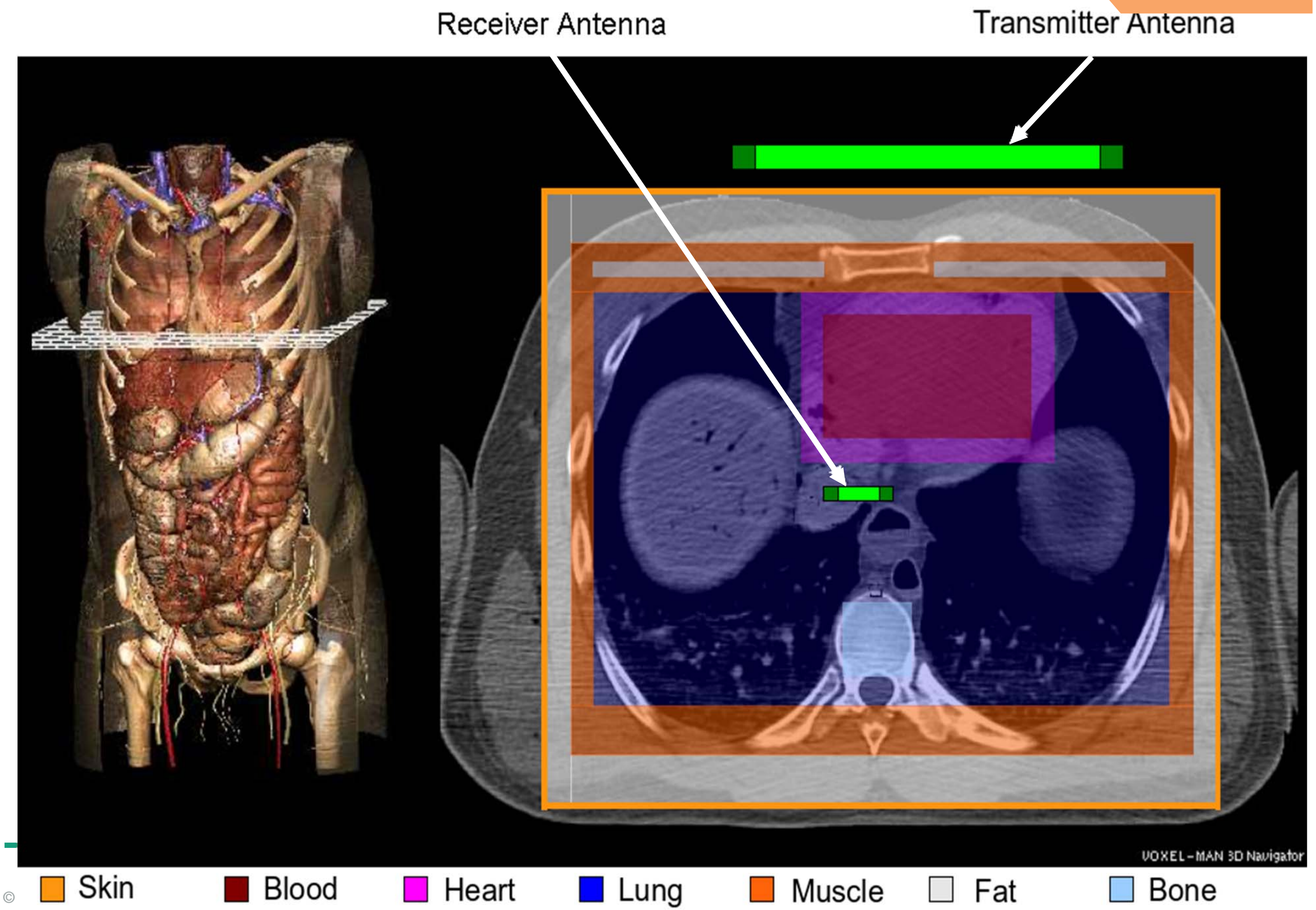
- Frequency depending losses modelled by complex permitivity:



Fraunhofer IMS

Numerical Approximation

Inductive EH

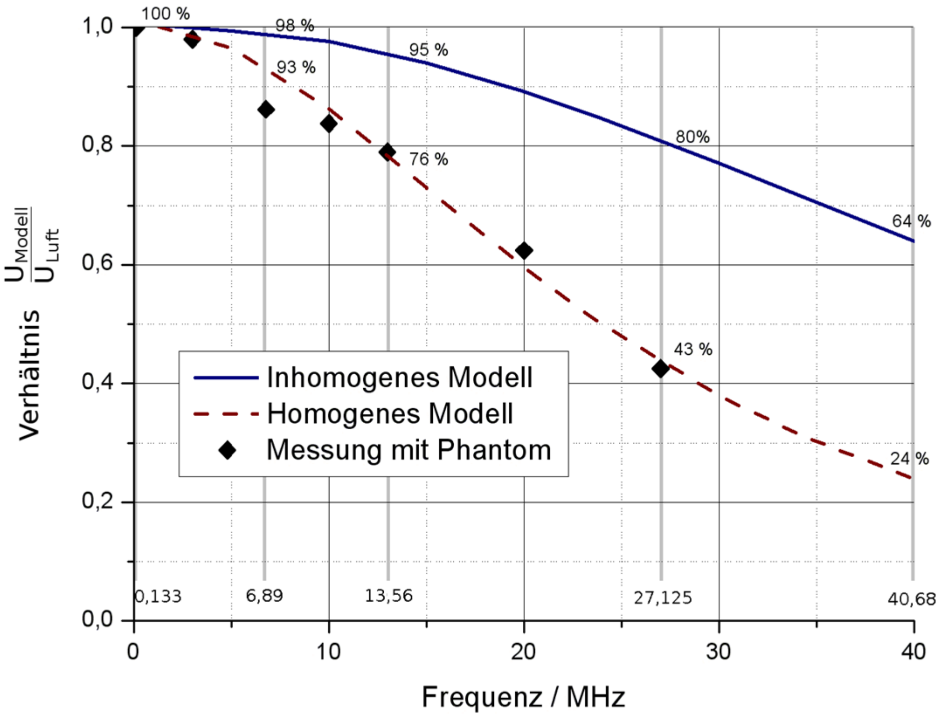


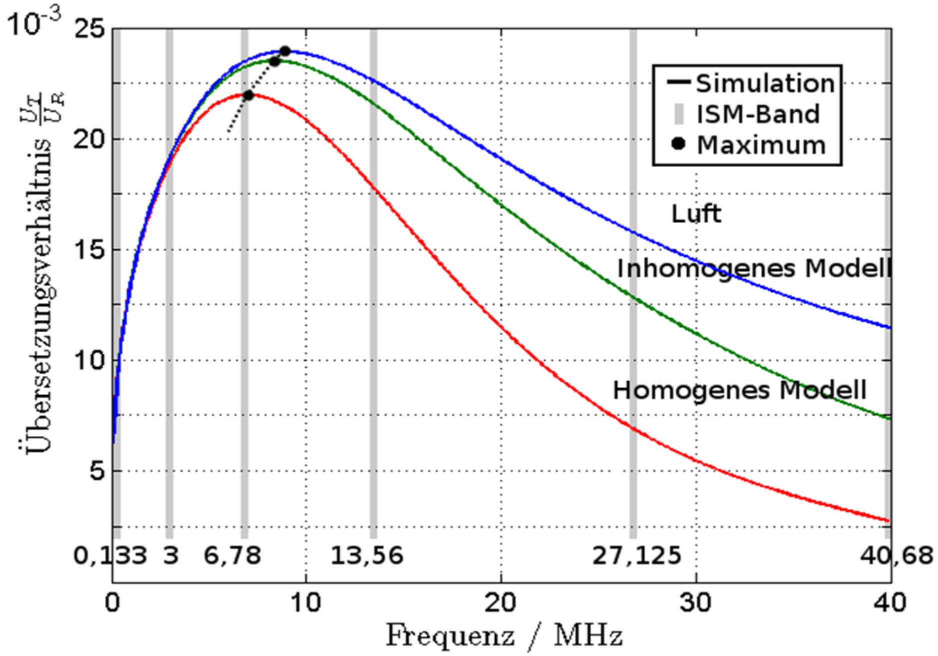
Picture: Deutsches Röntgen-Museum

Influence of Human Body

Inductive EH

- Frequency characteristic





- For deeply implanted transponders the hf band is adequate!

Fraunhofer IMS

Results of improved Technology

	State of the ASNR rt	Improved Technology
SNR @ 40 cm	-58,2 dB	+3 dB
Range	10 cm	45 cm

Inductive Principle
b) transformer

Inductive EH

How does it work?

- Sensor detects current in the enclosed conductor
- Local intelligence by means of neuronal network
- Determination of machine conditions and energy consumption
- Bluetooth LE compatible wireless data transmission
- Energy harvesting via magnetic stray field of the conductor

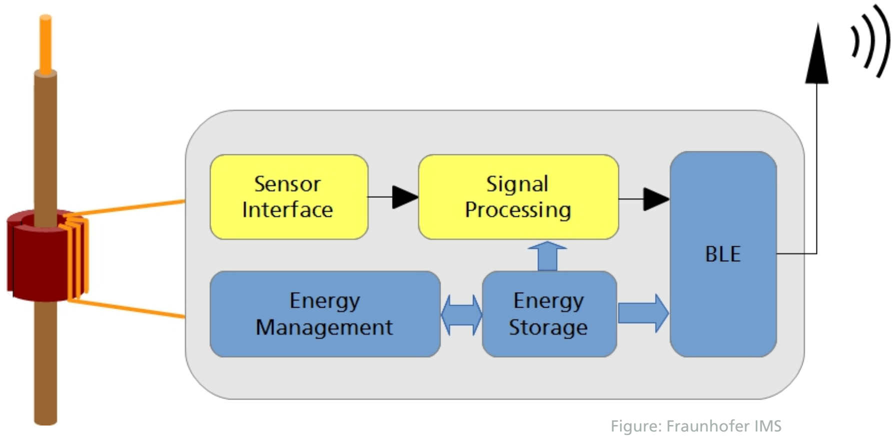
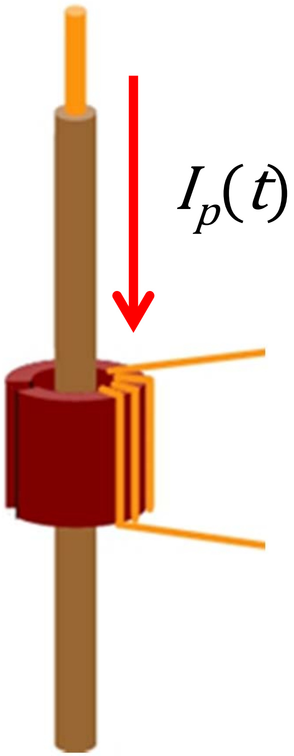
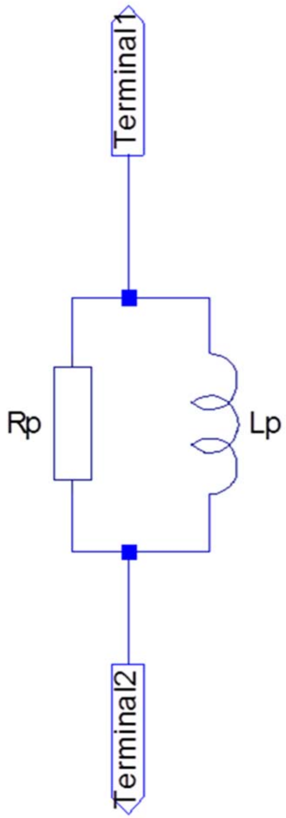


Figure: Fraunhofer IMS

Inductive Principle
b) transformer

Inductive EH





Equivalent
Circuit

A principal upper bound for the harvestable power exists :

$$P_{max}(t) = \frac{1}{2} \cdot \omega L_p \cdot I_p{}^2(t)$$

- With :

$P_{max}(t)$	=	Maximum harvestable power,
$I_p(t)$	=	Current through the wire,
L_p	=	Primary Inductivity,
ω	=	$2\pi \cdot 50$Hz

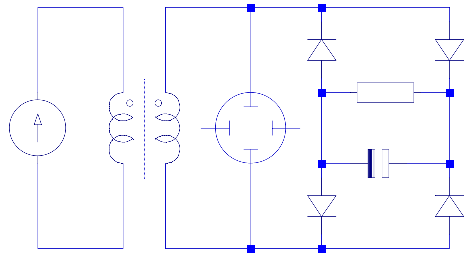
- Conclusion: The primary inductivity L_p has to be maximized!
- Example: For a typical L_p of 2mH the maximum harvestable power is 25mW @ $I_p = 2A_{eff}$.

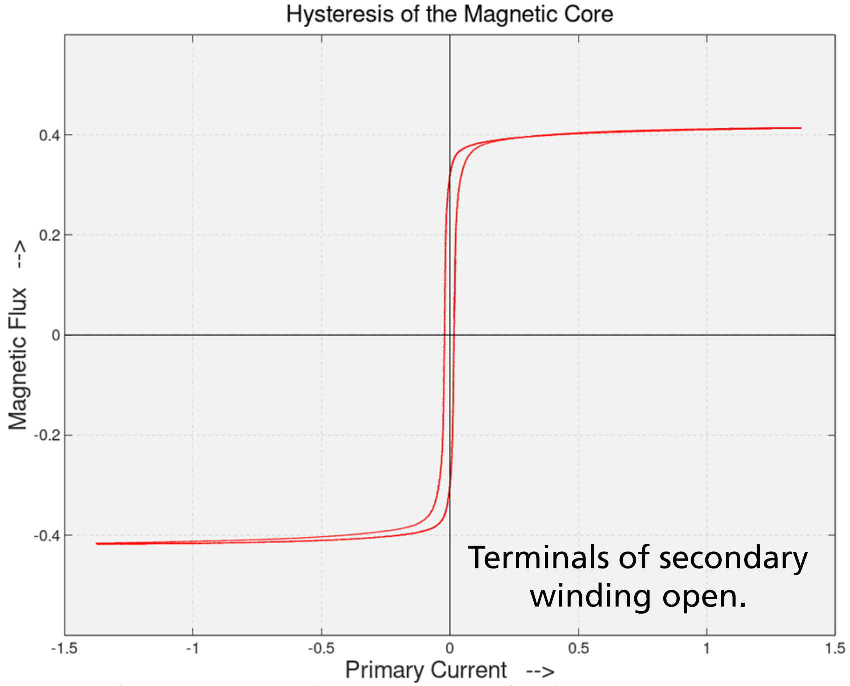
Inductive Principle b) transformer

Inductive EH

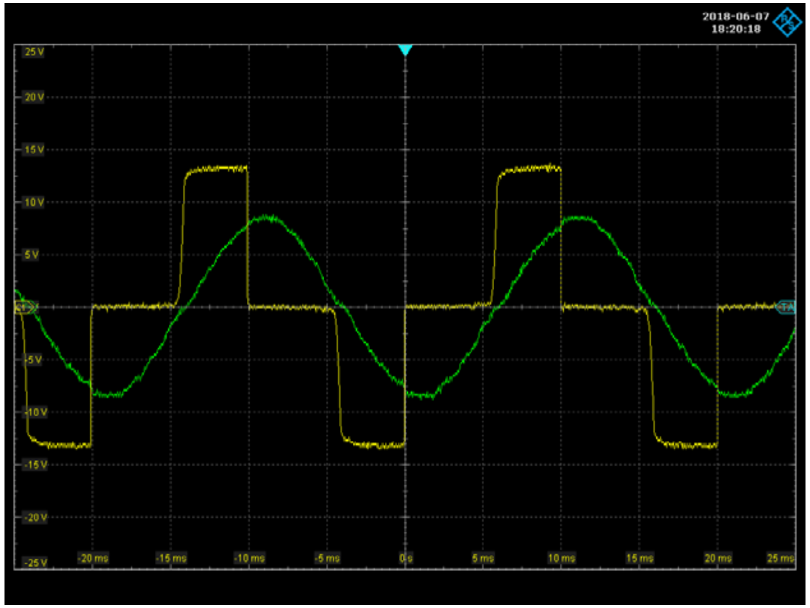
There are additional reductions of the maximum harvestable power by nonlinear effects:

- Saturation of magnetic flux in the core
- Losses by magnetic hysteresis





The enclosed area equals the energy losses per cycle.



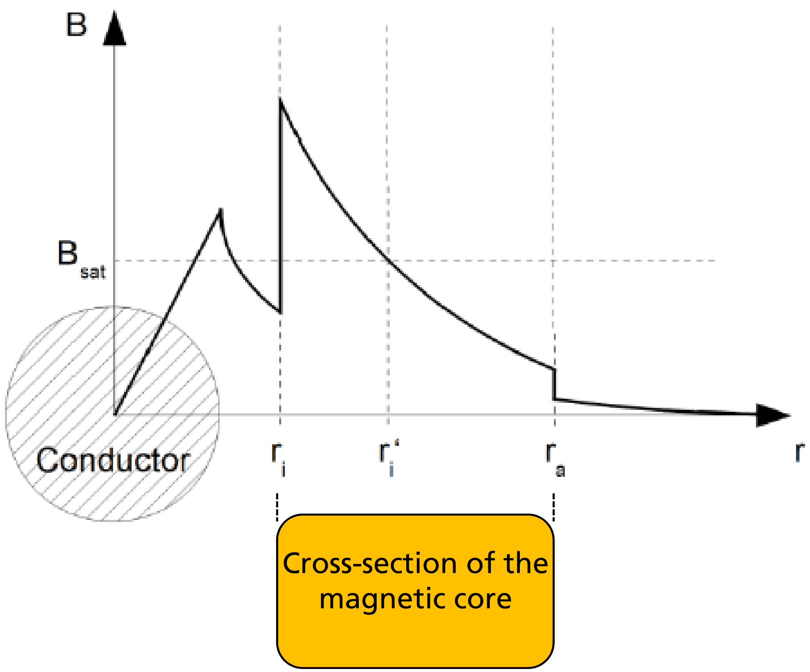
Screenshot from oscilloscope :
YELLOW: Voltage across secondary winding,
GREEN : Primary current through harvester.

Inductive Principle b) transformer

Inductive EH

Managing the dynamic range

- Assuming a minimum primary current of 1A and a maximum current of 32A results in a dynamic range of $1 : 32^2 = 1 : 1024$.
- Magnetic Saturation effects can be exploited to reduce this inkonvenient high dynamic range:



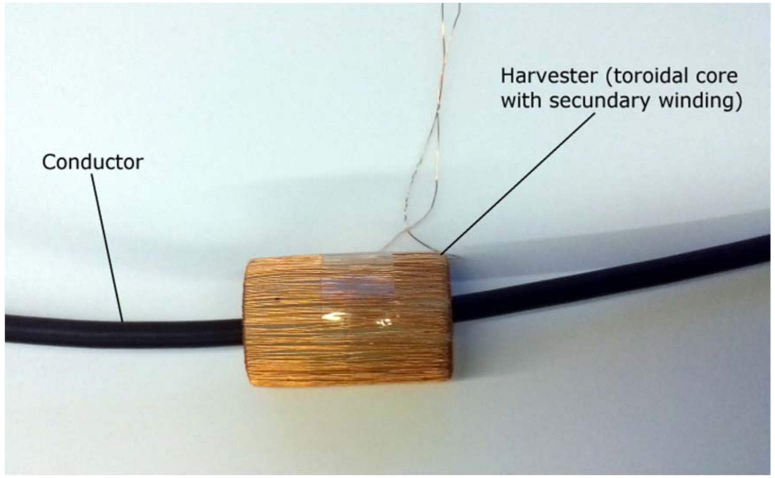
- The magnetic core is NOT magnetized uniformly.
- Regions at inner radii reach saturation first.
- This results in a time-dependent reduction of the primary inductivity.
- By this, the dynamic range of harvested power is compressed successfully.

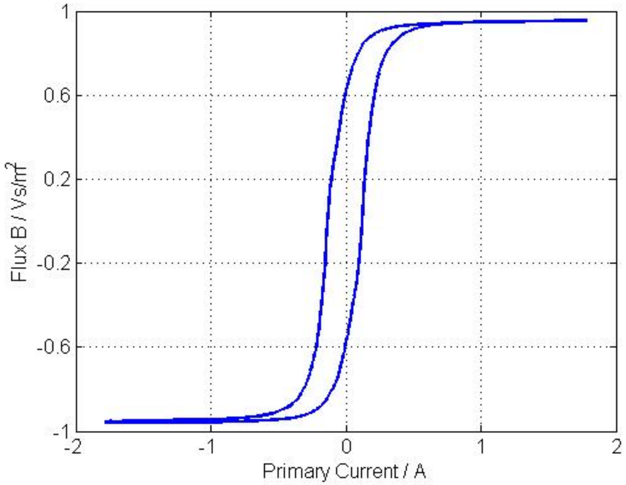
Inductive Principle
b) transformer

Inductive EH

Realization of harvester

- First lab version using off-the-shelf available material
- Toroidal core r_i=7 mm, r_a=12 mm, l=50mm
- Secondary winding with 250 turns
- Suitable saturation behavior



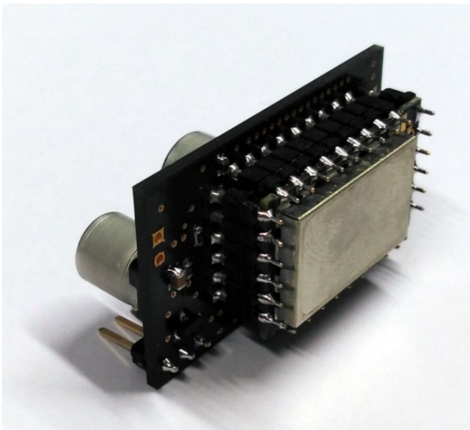


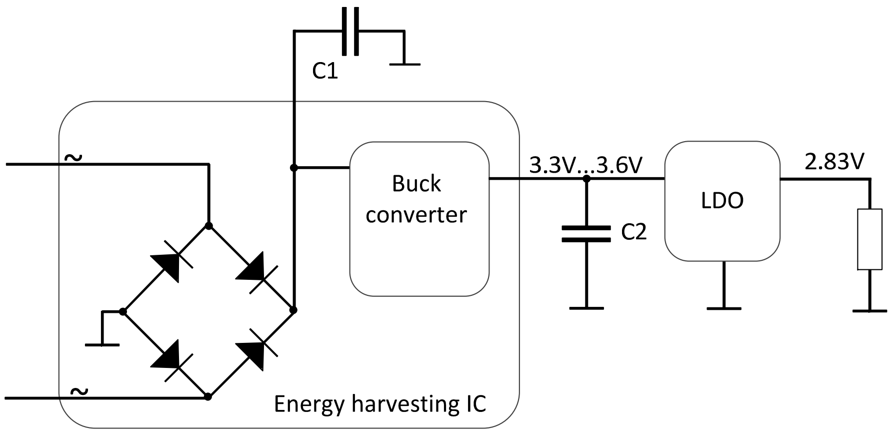
Inductive Principle
b) transformer

Inductive EH

Energy management module

- Rectification
- Buck converter for power point adjustment
- Using energy harvesting IC LTC3588
- Aluminum electrolyte capacitor for energy storage
- Linear voltage regulator for stable supply voltage (LDO)



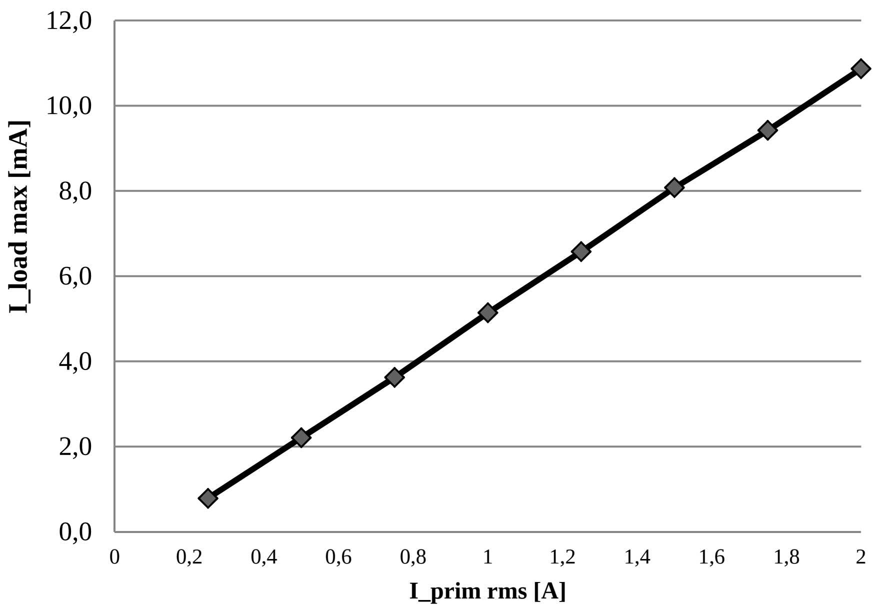


Inductive Principle
b) transformer

Inductive EH

Measurement results

- Measurement of maximum possible load current depending on the primary current of the enclosed conductor
- A primary current of 1 A is sufficient to power the current sensor



Primary current [A] rms	Maximum average current at 2.83 V regulator output [mA]	Harvested output Power [mW]
0.25	0.8	2.2
0.5	2.2	6.2
0.75	3.6	10.2
1	5.1	14.5
1.25	6.6	18.6
1.5	8.1	22.8
1.75	9.4	26.6
2	10.9	30.7

CONTENT

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- Motivation and Application Examples
  - Wireless sensors, battery charging, human implants
- Overview and general properties of different frequency bands
- Inductive principle (LF/HF)
  - Coil Parameters, Resonant Operation
- Electromagnetic principle (UHF/SHF)
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Electromagnetic coupling

EM EH

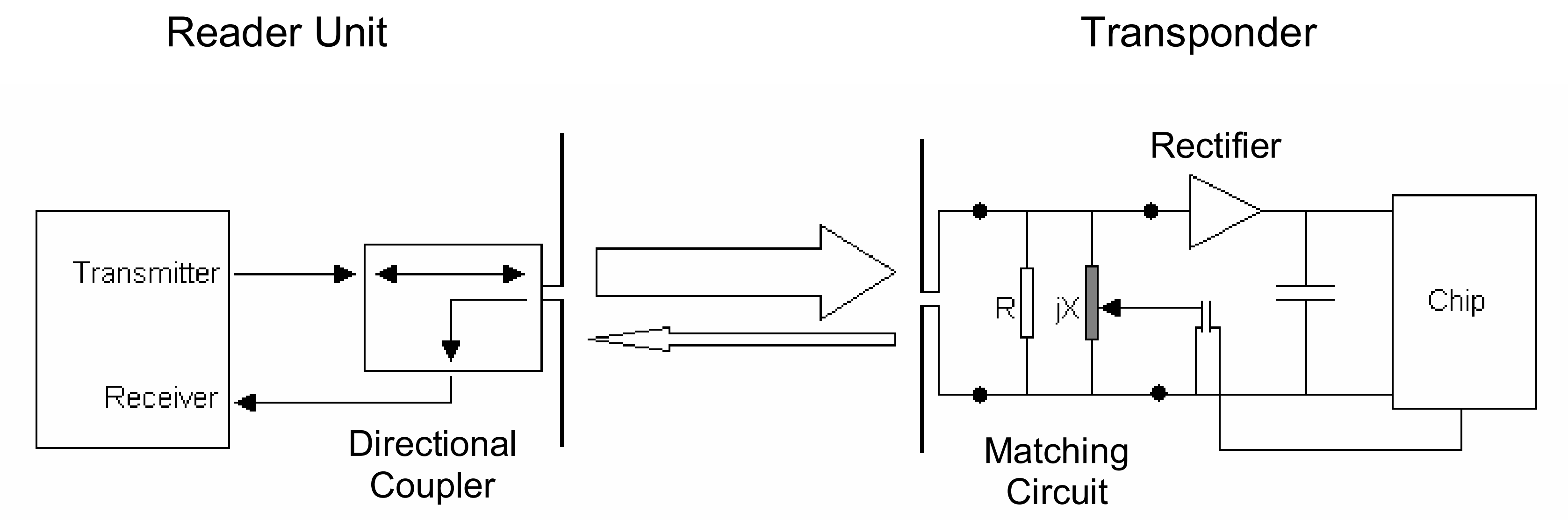
- **Friis Model** (widely used):

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

  where G_t, G_r antenna gains, λ the wavelength and R the distance.
- It is a **scalar (1-dimensional) model,** assuming received is **additive.**
- A gross model, **unable to explain detailed phenomena** in real applications with many nodes:
  - **power cancellation** effects
  - **super-additive** received power
- Still, in case of one charger or few remote chargers, it is valid. When **"micro management"** is needed in the presence of **several nearby chargers**, then it is not **sufficient.**

Energy Transmission in RFID-Systems (UHF)

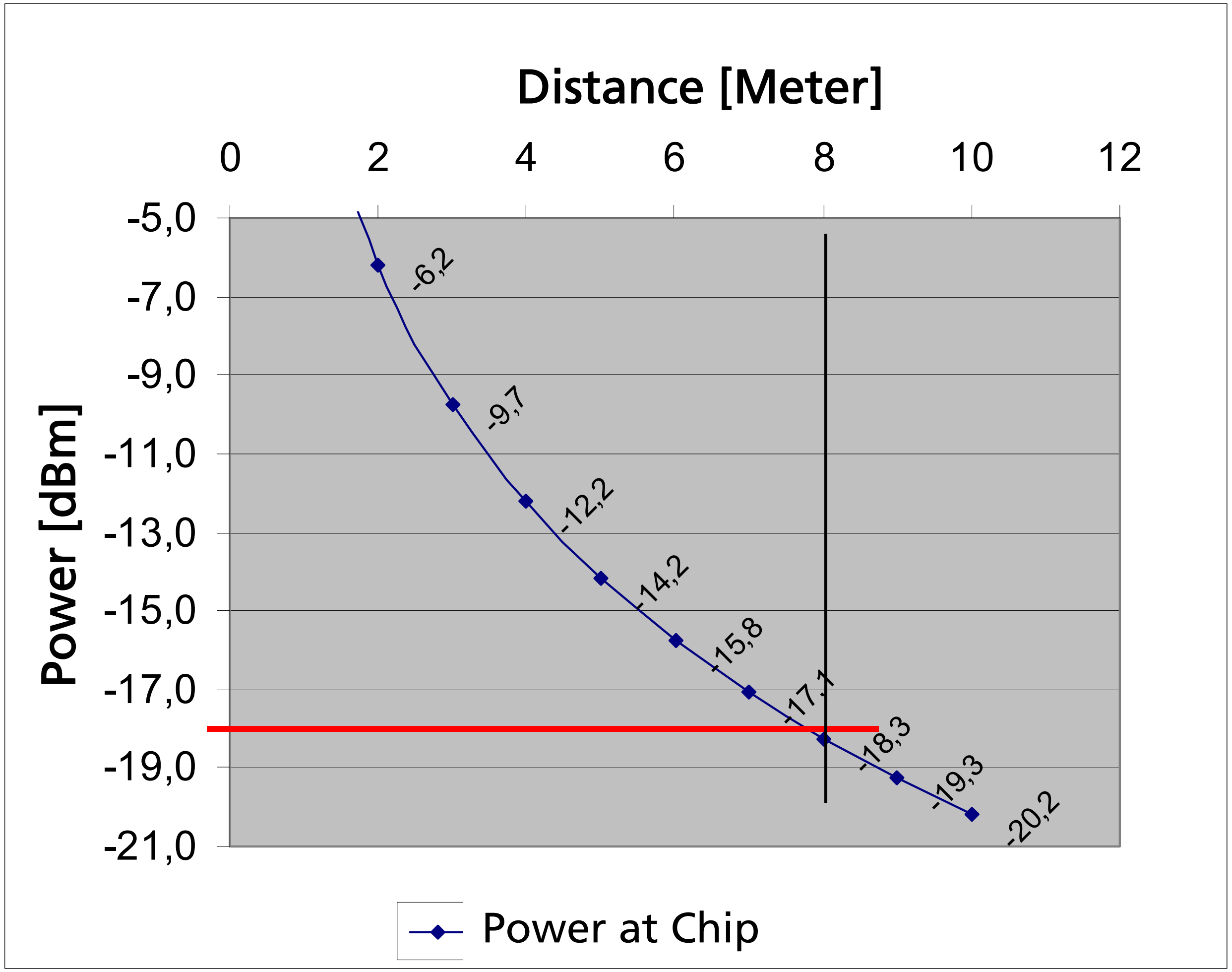
EM EH



30 dBm 1000 mW	4 dBi	-41 dB (3m)	0 dBi	-10 dB	⇒ -20 dBm ⇒ 10 µW

Energy Transmission in RFID-Systems (UHF)

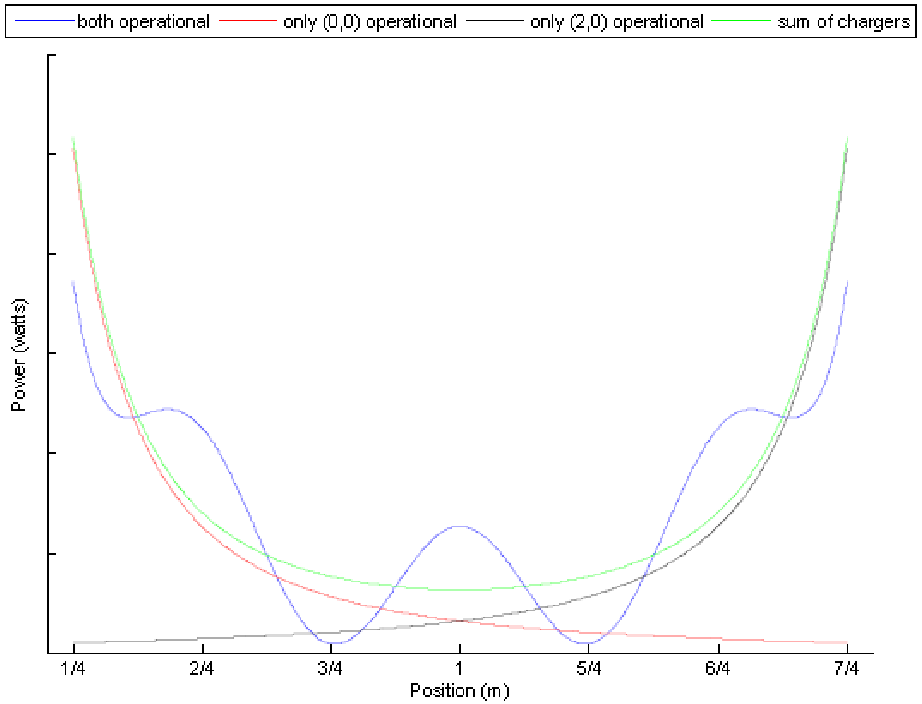
EM EH



Fraunhofer IMS

EM Couppling -Superposition

EM EH



- **Local maxima** indicate points of **superadditive** power.
- **Local minima** occur at points of **cancellation**.
- **Note**: It is highly **non-trivial to derive a closed formula** for the points of maximum/minimum power. So we have to examine **a whole space of system configurations** and evaluate power received.

Power Level from TV Broadcast Transmitters

EM EH

- TV:
  - Frequency: 500 to 750 MHz
  - Transmit Power: 100 kW (80 dBm)
  - Free Space Loss at 1.5 km Distance: 89 dB
  - Available Power at 1.5 km Distance: 250 µW (- 9 dBm)
  - Free Space Loss at 10 km Distance: 106 dB
  - Available Power at 10 km Distance: 2.5 µW (-26 dBm)
  - Size of Antenna (Dipole) ca. 40 cm

-> Use is very restricted

Power Level from Audio Broadcast Transmitters

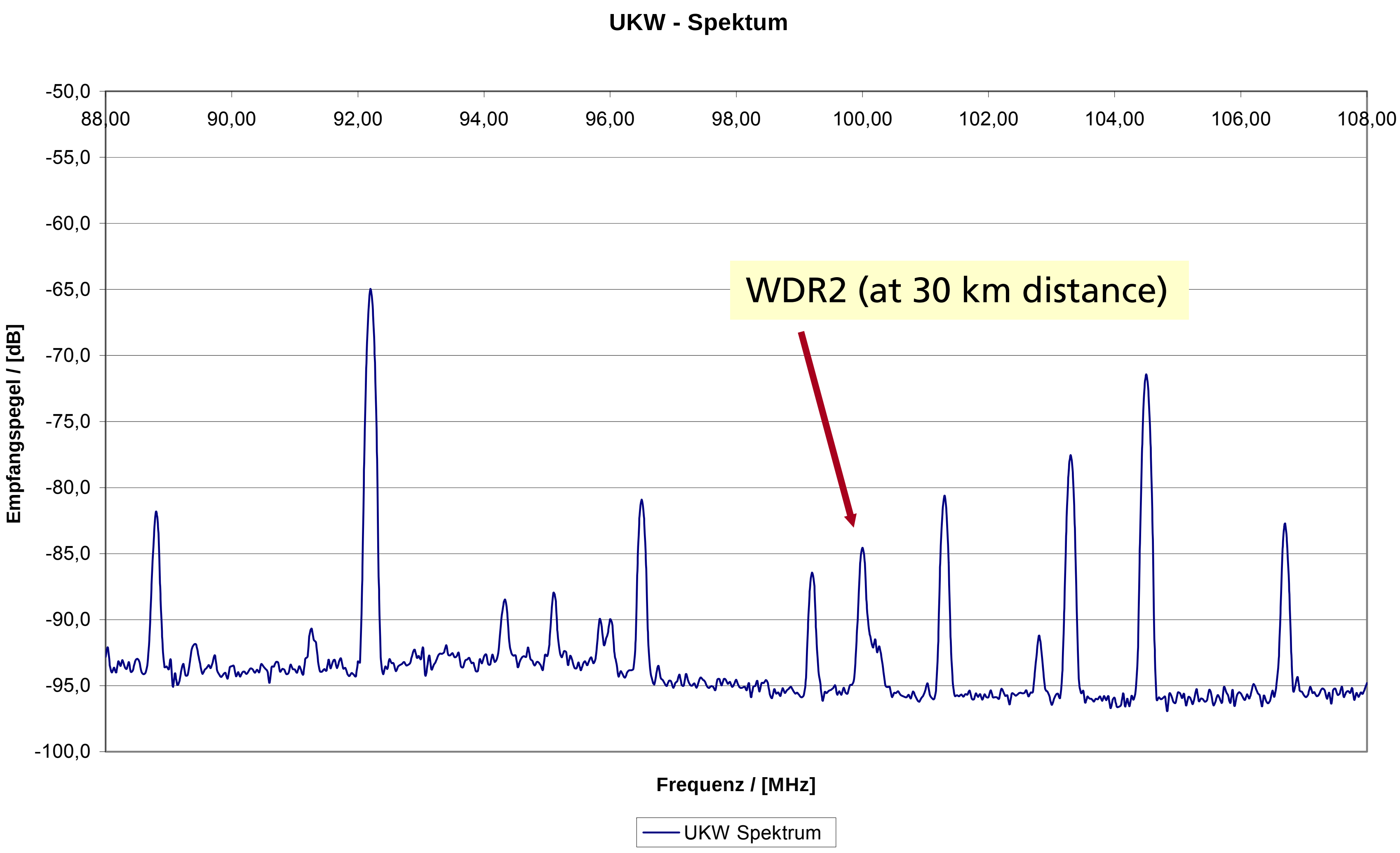
- Radio (analog):
  - Frequency: 88 to 108 MHz
  - Transmit Power: 100 kW (80 dBm)
  - Free Space Loss at 1.5 km Distance: 75 dB
  - Available Power at 1.5 km Distance: 3 mW (+ 5 dBm)
  - Free Space Loss at 10 km Distance: 91 dB
  - Available Power at 10 km Distance: 79 µW (-11 dBm)
  - Size of Antenna (Dipole) ca. 75 cm

-> Useable with limitations

Fraunhofer IMS

Frequency Spectrum UKW-Band (Indoor, Duisburg)

EM EH



Power Level from Mobile Phone Base Stations

EM EH

- Mobile Phone Base Station (GSM, D-Net):
  - Frequency: 880 to 920 MHz
  - Transmit Power: 25 W (44 dBm)
  - Free Space Loss at 100 m Distance: 71 dB
  - Available Power at 100 m Distance: 2 µW (- 27 dBm)
  - Size of Antenna: 17 cm (like UHF-RFID)

-> Practically not useable

Power Level from WLAN Access Points

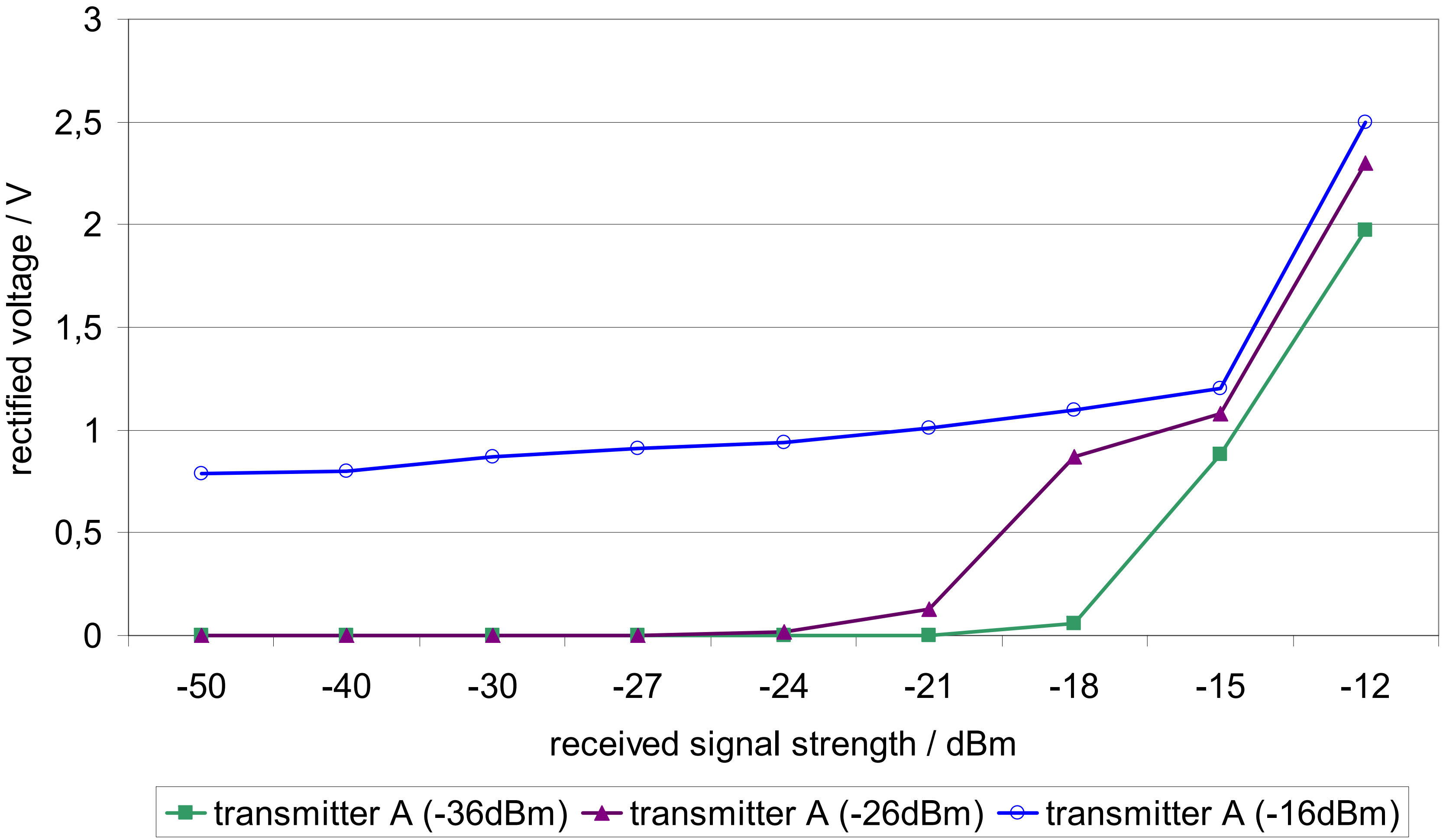
EM EH

- Frequency: 2.4 to 2.5 GHz
    - Transmit Power: 100 mW (20 dBm)
    - Free Space Loss at 5 m Distance: 54 dB
    - Available Power at 5 m Distance: 4 µW (- 24 dBm)
    - Size of Antenna (Dipole) ca. 6 cm

-> Use is very restricted

Overlap of multiple RF-Signals (Multi-Carrier)

EM EH



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Standards: Inductive coupling

- a) aligned coils
  - Qi-Standard
    - Frequency: 87 bis 205 kHz (long wave)
    - Up to 5 Watt (Baseline Power Profile) and up to 15 Watt (Extended Power Profile)
    - Data transmission sender to receiver 2 kbit / second
  - RFID
    - ISO 18000-2 and -3, ISO 330200
- b) Inductive coupling: transformer
  - No standard

Standards:
Electromagnetic coupling

- RFID UHF (Europe)
  - ISO 18000-6, ISO 330300
    - Frequency: 865 to 867 kHz (Europe)
    - Up to 2 Watt stationary and mobile reader

CONTENT

SUMMARY

- Use Cases in: Industry, Medical, Infrastructure Applications
- High Reliability in Operation
- Inexpensively Solutions
- More Standardization necessary
- Permanent Radiation not accepted in all Applications

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Thank you for your attention!

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High Efficiency Wireless Power Transfer for EV Charging and Other Applications

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