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

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Remote Monitoring Applications

Example Applications

Blood Pressure Monitoring System

ECG Monitoring System

Intraocular Pressure & Temperature Monitor

Cochlear Implants

Cardiac Pacemaker


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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

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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.
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: \[ d < \frac{\lambda}{2\pi} \]
  - 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 \( d < 10 \text{ cm} \)

- **Electro-magnetic Coupling (Far-Field)**
  - Far field region: \[ d > \frac{\lambda}{2\pi} \]
  - 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

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

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

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

Swiss SNF NanoTera Simos Project

O. Atasoy, PhD thesis n0 5992, EPFL, November 2013

C. Dehollain, EPFL, Lausanne
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.


C. Dehollain, EPFL, Lausanne
Wireless Remote Powering Through Ultrasound

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

Why ultrasound?

- To overcome electromagnetic attenuation limit in water:

<table>
<thead>
<tr>
<th>Type</th>
<th>Attenuation @ 10-20 cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultrasound</td>
<td>8-16 dB (@ 1 MHz)[2]</td>
</tr>
<tr>
<td>Electro-Magnetic</td>
<td>60-90 dB (@ 2.45 GHz)[3]</td>
</tr>
<tr>
<td>Magnetic</td>
<td>50 dB (@ 1 MHz)[3]</td>
</tr>
</tbody>
</table>

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

- Robustness towards hacking.

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Ultrasonic Remote Powering and Communication

European FP7 project: www.ultrasponder.org

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

C. Dehollain, EPFL, Lausanne
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 cm³
- 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

Targets
• Detection of different drugs
• Measurement of pH and temperature
• Detection of different endogenous compounds

Problems
• Size and weight to be implantable
• Low coupling factor due to distance & tissue

Swiss SNF Sinergia Project

Multi-Sensor
Electronics & Magnet
Implanted Coil

12 mm
12 mm

Conceptual design of battery-less implantable multiple sensor system

E. G. Kilinc, F. Maloberti, C. Dehollain:
E.G. Kilinc, PhD thesis n0. 6105, EPFL, Feb. 2014

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Metabolism Study

Sensor in Brown Adipose Tissue

Metabolism study

Inflammation and mobility

Wireless powered temperature sensor

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Thermistor Response Curve

- 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’

C. Dehollain, EPFL, Lausanne
Time-Domain Sensor Readout

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

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

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.

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

C. Dehollain, EPFL, Lausanne
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

C. Dehollain, EPFL, Lausanne
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»


C. Dehollain, EPFL, Lausanne
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

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 1 cm
- At least 1 month of successful in-vitro operation


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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

- **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

*Transmitter at 433 MHz 0.18um CMOS*
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

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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

PhD Thesis n0 6540, Author: Kerem Kapucu, EPFL, April 2015.

EPFL, Lausanne
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