Wireless Energy for Battery-less Sensors

Hao Gao

Mixed-Signal Microelectronics
Outline

- System of Wireless Power Transfer (WPT)
- 2.4 GHz RF Wireless Power Transfer
- 60 GHz RF Wireless Power Transfer
- 60 GHz Ultra Low Power Radio
- Conclusions
Wireless Power Transfer (WPT) Application

- **Medical and Health monitoring**
- **Structure Health monitoring**
- **Body Area Network**
- **Wireless Sensor Networks**
- **Smart building**

**Low data rate / low duty cycle / ultra-low power**

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Wireless Sensor Network

Battery Supply

**Advantage:**
- Easy to build
- Easy to assembly
- Long communication distance

**Disadvantage:**
- Limited life time
- Battery replacement
- Big Size
- High Cost
### Applications and Objectives

#### 2.4 GHz
- **RF WPT**

#### 60 GHz
- **RF WPT**

#### 60 GHz ULP Radio

### Background
- **Video, audio data transferring**
- **Relay node**
- **Security monitor**
- **Universal remote control**
- **Access point for positioning and wireless charging**
- **Invisible actuator, e.g. for lighting purpose**

### Conclusion

![Diagram](image-url)

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<td>RF WPT</td>
<td>RF WPT</td>
<td>Radio</td>
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RF Power Transfer System

Energy Harvesting:
- Chemical
- Mechanical
- Electrical

Sensor Network Composed of:
- Central controller as gateway
- Power wireless transfer to nodes
- ULP Wake Up radio

RF Power Transfer
- Wire-free
- Reliable
- Easy to integrated

STW Project: “PREMISS” (Power Reduced Monolithic Sensor System)
Architecture of Sensor Node


RF Rectifier → \( C_{\text{storage}} \) → Energy Storage → \( V_{\text{dd}} \) → Mode Selector

Wake Up Radio → Bias Network

Sensor Node Powered by WPT instead of Battery

WPT System Background

2.4 GHz RF WPT
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University of Technology
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2.4 GHz Dickson Structure multi-stage Rectifier

Basic Element: RF-DC Convertor
(Voltage Doubler)

Dickson vs. Villard Cascaded:
- Symmetric in AC and DC path
- Stronger current drive ability
- Capacitor with full DC voltage

WPT System Background | 2.4 GHz RF WPT | 60 GHz RF WPT | 60 GHz ULP Radio | Conclusion
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Diodes for CMOS Technology

- Diode Connected Transistor

Future: Schottky Diodes
Cut-off Frequency of Schottky Diodes in 65nm CMOS beyond 220 GHz

But: Non-standard in CMOS Technology
Efficiency with Input Voltage Swing

Bigger input voltage/power, the better efficiency, but limited by antenna and matching
Efficiency with Threshold Voltage

$V_{in}=0.4V$, $I_{load}=2\mu A$

An optimized equivalent threshold voltage value for given technology
**Efficiency with Pre-Bias Technology**

**Principle:** shift the original threshold to fit the given process

![Graph showing the efficiency of rectifier with pre-bias voltage](image)

- **WPT System:**
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- **Technische Universiteit Eindhoven**
  - University of Technology
Another way to treat diode connected:

Pre-Biasing High Efficiency Rectifier: Original: 21.5%, Improved: 31%
Outline

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Motivation: 60 GHz

Problems:
- Antenna Integration
- Assembly Components
- Battery Size
- Cost

(2.4 GHz)

Problems:
- PCB Based
- Harvesting Method
- Not easy to integrate

(1.8 GHz)

Solution:
- mm-Wave
- On-chip antenna

(60 GHz)

WPT System Background 2.4 GHz RF WPT 60 GHz RF WPT 60 GHz ULP Radio Conclusion
Motivation: 60 GHz

- Small wavelength enables:
  - Integrate antenna on-chip
  - Create antenna arrays to
    - Provide high antenna gain
    - Create highly directional pencil beams

- Wide bandwidth available at 60 GHz enables
  - High data rate in the order of Gbits/s
  - Short transmission burst
Proposed System of 60 GHz Monolithic Wireless Sensor Nodes

**On-Chip Antenna:**
Small size

**Rectifier:**
Used as the supply voltage generator

**End-of-Burst:**
Used as the input power monitor

**Advantage:**
- Monolithic, fully integration
- Small size, 2mm × 1mm
60 GHz Rectenna:

- Co-design of on-chip antenna + Rectifier
- Self-threshold voltage modulation
60 GHz Rectenna: On-Chip Antenna

- Metal plate
- Feed-line
- Silicon substrate
- Dipole

Graphs showing:
- S11 (dB) vs. Frequency (GHz)
- Antenna Gain (dBi) vs. Angle (°)
- Antenna Impedance (Ω) vs. Frequency (GHz)

Ulf Johannsen (Electromagnetics Group)

WPT System Background 2.4 GHz RF WPT 60 GHz RF WPT 60 GHz ULP Radio Conclusion
With 1.5kΩ load, it reaches 4.4% efficiency in simulation with 7dBm input power, and output voltage 0.7V. Corresponding output current is 0.46mA.
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System-Level Research

- Average power consumption optimization

**Power consumption of The mmW front-end**

**Reasons**
- High stand-by power
- Circuitry complexity
- Modulation complexity
- System architecture

**Solutions!**
- Duty-cycled wake-up receiver (WuRx)
- Injection-locked oscillator (IJLO)
- Minimum Linearity
- Eliminate the square-law

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Radio-Triggered Monolithic Wireless Sensor Node

**Receiving Module**

- Matching Network
- LNA
- Injection-locked Oscillator (IJLO)
- Self-mixer

**Rx Biasing and Supply Circuit**

**Wireless Power Receiver + Wake Up Module**

<table>
<thead>
<tr>
<th>Gain (dB)</th>
<th>NF (dB)</th>
<th>IIP3 (dBm)</th>
<th>Pdc (mW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LNA</td>
<td>16.2</td>
<td>-18</td>
<td>5</td>
</tr>
<tr>
<td>Mixer</td>
<td>-15</td>
<td>-22.4</td>
<td></td>
</tr>
</tbody>
</table>

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<tr>
<th>f&lt;sub&gt;rf&lt;/sub&gt; (GHz)</th>
<th>P&lt;sub&gt;out&lt;/sub&gt; (dBm)</th>
<th>Sensitivity (dBm)</th>
<th>Pdc (mW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IJLO</td>
<td>-22.5</td>
<td>-60</td>
<td>3</td>
</tr>
</tbody>
</table>

60 GHz RF Front-End Parameters
System Evaluation

Future: mm-wave Direction

Future work:
- Improve mm-wave rectifier efficiency
- ULP radio
- Directional on-chip antenna array

### System parameters

<table>
<thead>
<tr>
<th>TX Power</th>
<th>Ant Gain TX</th>
<th>Ant Gain Rx</th>
<th>Modulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 dBm</td>
<td>20 dBi</td>
<td>0 dBi</td>
<td>OOK</td>
</tr>
<tr>
<td>BW</td>
<td>$T_{\text{scav}}$</td>
<td>Pac. Len</td>
<td>Rx %</td>
</tr>
<tr>
<td>2 GHz</td>
<td>1ms</td>
<td>20 bits</td>
<td>50</td>
</tr>
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Battery-less sensor nodes enable many applications

Mm-wave wireless power transfer with integrated on-chip antenna is an elegant way for low cost solution

- **Key Circuit Blocks:** High efficiency rectifier
- **System Level:** 60 GHz Ultra Low Power Radio
Acknowledgement

- STW
- Philips
- Holst Centre