System Study of a 60 GHz Wireless-Powered Monolithic Sensor System

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Outline

• Motivation
  • Wireless-Powered
  • Monolithic
  • 60 GHz
• System Overview
• System-Level Energy Budget Calculation
  • Comparison with a 2.4 GHz RFID system
• Conclusions
Sensors are Going Wireless

Battery-Operated Wireless Sensors

Advantage:
- Easy deployment
- Lifetime of many years

Disadvantage:
- Limited life time
- Battery replacement
- Big Size
- Relative higher cost

Temperature Sensor
Smoke Sensor
Motion Sensor
Water Sensor
Gas Sensor
Wind Sensor

Balkony

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Wireless-Powered Wireless Sensors

• Self-Powered sensors using energy harvesting
  • Vibration/Motion
  • Temperature difference
  • Light
  • Pressure
  • RF
  • ...
Wireless-Powered Wireless Sensors

- Self-Powered sensors using energy harvesting
  - Vibration/Motion
  - Temperature difference
  - Light
  - Pressure
  - RF
  - ...  

Energy Harvesting using RF (i.e. Wireless-Powered) is a natural choice for Wireless Sensors.
Monolithic

- Current energy scavenging sensors implement sensing and energy scavenging in two separate modules:
  - Larger size and higher price;
  - Not robust in harsh environments or on moving objects.
Monolithic

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- Monolithic sensor nodes:
  - On-chip energy harvesting, sensing and transceiving
  - Ultra low power TxRx
  - Small size (mm$^2$)
60 GHz

- Small wavelength (5mm), possible to
  - Integrate antenna on-chip,
  - Create large 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.
60 GHz Wireless-Powered Monolithic Sensor System

- Fully integrated sensor nodes with on-chip sensing, antenna, transceiver and energy scavenging.
- Central controller wirelessly transmits data and energy to sensor nodes.

A typical sensing cycle
1. Downlink: central controller sends energy and data to a sensor;
2. Uplink: the sensor sends required info. back to central controller.

Work in ongoing in the STW project “PREMISS” (Power REduced Monolithic Sensor System).
Possible Applications

• Temperature measurement
• Proximity sensing (used for e.g. lighting control)
• Presence detection and tracking
• Activity monitoring
System Architecture

emitted power $P_c$

ant. gain $G_c$

downlink

High Power Central Controller

propagation loss $L_p$

uplink

Matching Network

rectifier efficiency $\eta_{\text{rec}}$

Energy Scavenging Circuit

Electronic Switch (efficiency $\eta_{\text{sw}}$)

Transmitter

transmit efficiency $\eta_T$

Sensor Node

Energy Storage
Central Controller Antenna gain and Path Loss

- At the central controller, the antenna gain

\[ G_c = 10 \times \log_{10}(N_a) \]

- Free space propagation loss

\[ L_p = \left(\frac{4\pi d}{\lambda}\right)^2 = \left(\frac{4\pi df}{c}\right)^2 \]
Sensor antenna related considerations

- At 60 GHz, integration of antenna on chip is possible.
- Due to lossy substrate, the antenna efficiency is lower.

Due to small chip size (e.g. 1mm\(^2\) for the PREMISS project), the antenna impedance becomes more capacitive and results in more loss on the matching network.
The rectifier efficiency is heavily dependent on the frequency.

- At 2.4 GHz, 31% was achievable using 65 nm CMOS technology at an input power level of -19 dBm.
- For 60 GHz applications, the efficiency drops to 2% using state-of-the-art design.
- We project an improvement to about 10% for 60 GHz systems.
Loss on Electronic Switch and Capacitor Leakage.

- An electronic switch is required to switch the energy storage capacitor between charging and discharging mode.
- The efficiency of this switch can be assumed 90%.
- For the application considered in PREMISS, the energy stored is immediately used for transmission. Hence energy leakage is negligible.
Downlink Energy Budget

• The available power at the capacitor

\[ P_s = \frac{P_e G_c G_s}{L_p} \eta_a \eta_m \eta_{sw} \eta_{rec} \]

• We compare the PREMISS system with a typical 2.4 GHz RFID system

<table>
<thead>
<tr>
<th>Parameters</th>
<th>PREMISS</th>
<th>2.4 GHz RFID</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \lambda ) (mm)</td>
<td>5</td>
<td>125</td>
</tr>
<tr>
<td>( P_e ) (dBm)</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>( G_T ) (dB)</td>
<td>20</td>
<td>11</td>
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<tr>
<td>( G_s ) (dB)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>( \eta_a )</td>
<td>0.6</td>
<td>0.9</td>
</tr>
<tr>
<td>( \eta_m )</td>
<td>0.7</td>
<td>0.75 \times 0.95</td>
</tr>
<tr>
<td>( \eta_{sw} )</td>
<td>0.9</td>
<td>0.9</td>
</tr>
</tbody>
</table>
Downlink Energy Budget

Power available at Rectifier Input

Energy harvested in 10 ms

Key-challenge: achieve a decent rectifier efficiency with low input power.

Uplink transmission has to be very efficient.
The received signal power in the central controller is given by:

\[ P_c = \frac{E_s}{t_d} \frac{G_s G_c}{L_p} \eta_T, \]

where \( G_s \) and \( G_c \) are the gains of the transmitter and receiver, respectively, \( L_p \) is the propagation loss, \( E_s \) is the energy of the transmitted signal, \( t_d \) is the duration of the transmission, and \( \eta_T \) is the transmission efficiency.

For an RFID system using reflective transmission, the power is given by:

\[ P_c = \left( \frac{1}{4} | \Gamma_1 - \Gamma_2 |^2 \right) \left( \frac{P_e G_c^2 G_s^2}{L_p^2} \right) \left( \eta_a \eta_m \eta_{\text{rec}} \eta_{\text{sw}} \eta_T \right). \]
An SNR of 17 dB can be achieved at a distance of 5m for the PREMISS system.
Remarks

• More detailed modeling is being considered for various building blocks of the system (on-chip antenna, rectifier, uplink transmission... )
• Many activities in millimeter RFID systems. However, the range is below $1m$.
• We consider implicit sensing schemes for energy saving in the sensor node
  • e.g. temperature dependency of oscillator frequency
Conclusions

- The PREMISS system:
  - 60 GHz
  - Wireless-powered
  - Fully monolithic

- Preliminary system study shows an SNR of 17 dB can be achieved at the central controller at 5 m.

- Rectifier design is challenging.
Thank you