Microwatt Design for Energy Harvesting Wireless Sensors

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Emerging Microsensor Applications

Industrial Plants and Power Line Monitoring (courtesy ABB)

Operating Room of the Future (courtesy John Guttag)

Target Tracking & Detection (Courtesy of ARL)

Location Awareness (Courtesy of Mark Smith, HP)

Websign

NASA/JPL sensorwebs
Commercial Wireless Sensor Mote

Moteiv Sky mote, 2006

Jiang, IPSN/SPOTS 2005

• Current sensor node: 70 mW all active, 17 μW idle
• Power sources contribute significant volume and cost
• Smaller system (1 cm³) desirable (less obtrusive military sensor, implantable biomedical device)
• Reduce power consumption, get energy from environment
Energy Scavenging Wireless Sensor

- Extend sensor node lifetime beyond battery limitation
  Scavenging energy from light, heat, and vibrations
- Cope with the variability of the harvested power
  Energy scalable approximate signal processing
System Requirements

<table>
<thead>
<tr>
<th>Functional Block</th>
<th>Power Consumption</th>
<th>Voltage</th>
<th>Resistance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensor</td>
<td>185 μW</td>
<td>1.2 V</td>
<td>7.78 kΩ</td>
</tr>
<tr>
<td>[R. Amirtharajah et al, SPIE, 2005]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ADC</td>
<td>3.1 μW</td>
<td>1 V</td>
<td>322 kΩ</td>
</tr>
<tr>
<td>[M. Scott et al, JSSC, 2003]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DSP</td>
<td>6 μW</td>
<td>1 V</td>
<td>166 kΩ</td>
</tr>
<tr>
<td>[B. Warneke et al, ISSCC, 2004]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RF</td>
<td>1 mW</td>
<td>1.2 V</td>
<td>1.44 kΩ</td>
</tr>
<tr>
<td>[B. Otis et al, ISSCC, 2005]</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- System works with low duty-cycle, total average power = 5 μW
- ADC - requires low power and clean $V_{DD}$
- DSP - requires low power, noisy $V_{DD}$ ok
- RF - requires high peak power
# Common Vibration Sources

<table>
<thead>
<tr>
<th>Vibration Source</th>
<th>Frequency of Peak (Hz)</th>
<th>Peak Acceleration (m/s²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kitchen Blender Casing</td>
<td>121</td>
<td>6.4</td>
</tr>
<tr>
<td>Clothes Dryer</td>
<td>121</td>
<td>3.5</td>
</tr>
<tr>
<td>Door Frame (just after door closes)</td>
<td>125</td>
<td>3</td>
</tr>
<tr>
<td>Small Microwave Oven</td>
<td>121</td>
<td>2.25</td>
</tr>
<tr>
<td>HVAC Vents in Office Building</td>
<td>60</td>
<td>0.2-1.5</td>
</tr>
<tr>
<td>Wooden Deck with People Walking</td>
<td>385</td>
<td>1.3</td>
</tr>
<tr>
<td>Bread Maker</td>
<td>121</td>
<td>1.03</td>
</tr>
<tr>
<td>External Windows (size 2ftx3ft) next to a Busy Street</td>
<td>100</td>
<td>0.7</td>
</tr>
<tr>
<td>Notebook Computer while CD is Being Read</td>
<td>75</td>
<td>0.6</td>
</tr>
<tr>
<td>Washing Machine</td>
<td>109</td>
<td>0.5</td>
</tr>
<tr>
<td>Second Story of Wood Frame Office Building</td>
<td>100</td>
<td>0.2</td>
</tr>
<tr>
<td>Refrigerator</td>
<td>240</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Courtesy P. Wright, UC Berkeley
Vibration Generator Mechanical Model

- Second order mechanical system: spring + mass + dashpot
- Driven by amplitude forcing function at resonance

Output Electrical Power

\[ P = \frac{m \zeta_e A^2}{4 \omega \zeta_T^2} \]
Vibration to Electric Energy Converters

**Mesoscale Moving Coil**
- Estimated output power: 400 $\mu$W

**MESM Variable Capacitor**
- Estimated output power: 8.7 $\mu$W

**Mesoscale Piezo Bender**
- Output power: 375 $\mu$W

Courtesy P. Wright, UC Berkeley
Multi-Electrode Piezoelectric Generator

- Top plate divided into quarter-circle sections
- Bottom plate not divided, total of 5 electrodes
- PZT (lead zirconate titanate) disk diameter = 1.5"
Multiple Resonances with Cuts

• Without cuts only mode near 1 kHz is usable
• Simulated results from lumped model derived using rigid body analysis
• Traveling wave excites neighboring top plate signals with 90° relative phase shift
Rectifier Alternatives

- Conventional (inductively loaded) rectifier
  [M. Ghovanloo, et al., *JSSC* Nov. 2004]
• Dashed outline: one CMOS controlled rectifier (CCR)
• Snubbing diode used on each input for negative swings
• Input frequency = 10 kHz
Die Photograph

- Constructed in 0.35 μm CMOS
- PMOS power FET width = 500 μm
Multiple-Input Power Supply

- AC/DC combines a rectified $V_{vibe}$ with $V_{solar}$
- DC/DC further smoothes harvested energy to form $V_{out}$
Multiple-Input Power Supply Measured Output

- DC/DC output controller switches between functional blocks
- DSP tolerates high ripple, so the controller trades efficiency for ripple
Multiple-Input Power Supply Chip Photo

- 0.25\(\mu\)m CMOS, total active area
- To appear ISSCC 2009
Sensor Data Processing Subsystem

**Microcontroller**
- Sensor calibration
- DSP configuration
- High active power
- Low duty cycle

**DSP Coprocessor**
- Continuous sensor data processing (e.g., event detection)
- High duty cycle
- Ultra low active power

Bridge Sensor
- SWNT or SiNW
- SWNT or SiNW
- SWNT or SiNW
- SWNT or SiNW

Microcontroller

A/D Converter

DSP Coprocessor
Extend sensor node lifetime beyond battery limitation
Scavenging energy from light, heat, and vibrations

Improve total efficiency by co-design
Self-timed digital circuits enable simple power electronics
Self-Powered System Overview

- Vibration harvester output ($V_{IN}$) can vary rapidly
- Regulator exploits DSP delay/frequency feedback
  - Compensates for temperature, process, and computational workload variations
  - Allows simple all digital control (Amirtharajah JSSC 98, Dancy TVLSI 00)
- Regulator efficiency still limited to between 30% - 70%
Simplifying Voltage Regulation

- Eliminate AC/DC conversion from power electronics
- Use passive full-wave rectifier with minimum filter cap to reduce complexity and volume
- Self-timed DSP using critical path replica ring oscillator satisfies timing constraints while using rectifier output
- Self-timed datapath must be initialized at power-on
- Must maintain state across power supply cycles
AC Supply Test Chip Block Details
3T DRAM Cell Layout

- 46 µm² gate size chosen for 1.2ms retention
  - Vdd = 400 mV
  - 0°C < T < 50°C
- Hold time for 60 Hz supply
Rectified Waveform and POR Output

- POR Output

- On Chip Rectifier Output
  - From 60 Hz Sine Input
Measured Frequency Variation with AC Supply

- Ring Oscillator Frequency Varies
- Arbitrary Wave Form Generator Output Used For AC Input
AC Supply Test Chip Photo and Summary

<table>
<thead>
<tr>
<th>Technology</th>
<th>180 nm CMOS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions</td>
<td>2.6 mm x 2.6 mm</td>
</tr>
<tr>
<td>Transistors</td>
<td>135K</td>
</tr>
<tr>
<td>I/O V_{DD}</td>
<td>1.8 V</td>
</tr>
<tr>
<td>AC Supply (V_{pp} = 1.8 V)</td>
<td>60 Hz – 1 kHz</td>
</tr>
<tr>
<td>Core Freq. (max)</td>
<td>75.6 MHz</td>
</tr>
<tr>
<td>Power (Core)</td>
<td>127 – 113 µW</td>
</tr>
</tbody>
</table>

- Published Symposium on VLSI Circuits, 2007
Energy Scalable Array

Test Chip Features

- Sixteen tiles connected by island-style x and y routing
- Implemented in 0.25 μm CMOS from TSMC
- Includes test structures for low switching activity interconnect
- Includes multiple-input energy harvesting power supply (to appear ISSCC09)

- Several operations confirmed, working out configuration issues
- Currently testing array
• Simulated power and projected recognition performance for biomedical event detection application
Energy and Voltage Scalable Sensor Interfaces

- Passive modulator Sigma Delta ADC
- Chip verified over range of OSRs: about 10 bits, 450 nW power consumption for 1 kHz input BW
- Useful ENOB from $V_{DD} = 1$V down to 200 mV
- Submitted to VLSI 2009
Incorporate in (mostly) standard CMOS flow, between metals

- Poor device properties may be okay for sensor applications
Conclusions

• Energy harvesting for wireless sensors is made practical by leveraging low performance demands

• Mesoscale vibration transducers possible, but challenging to scale below 1 cm$^3$

• Exploiting the AC nature of mechanical vibration energy harvesting using self-timed circuits can improve total system efficiency

• Energy and voltage scalable digital and mixed-signal circuits and architectures crucial for energy harvesting systems

• Nanowire devices offer new opportunities for microwatt sensors, interfaces, and processing circuits
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