Powering Systems from Ambient Energy Sources

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Internet of Things

- **Definition:** network of uniquely identifiable objects communicating using an Internet-like structure
  - Wireless connectivity for embedded processors running TCP/IP to enable machine-to-machine (M2M) communication
  - Physical channel and protocol choice is orthogonal
- **Potential market volume on the order of billions of devices**
  - 25 billion devices by 2015, 50 billion by 2020 (CISCO)
  - 15 billion devices by 2015 (Intel / IDC)
  - 3 billion subscribers with 5-10 devices each + 1.5 billion vehicles + 3 billion utility meters (Ericsson)
- **Trillions of dollars at stake**
IoT and Winemaking

- Instrumented networked fermentation tanks
  - Monitor temperature, brix, organic compound evolution, yeast growth
  - Control temperature, pump-over

- Precision irrigation
  - Sense single-vine water status and adjust delivered water volume
  - Improve grape quality
  - Decrease water use
Networked Smart Fermentation Tank
Leverage commercially-available M2M cloud solution
Long-range battery-powered small form-factor wireless
Centralized microcontroller-based valve control
Energy Scavenging Wireless Sensing IoT Node

- Extend sensor node lifetime beyond battery limitation
  Scavenging energy from light, heat, and vibrations
  Efficient power management

- Cope with the variability of the harvested power
  Energy scalable data conversion & approximate signal processing
# System Requirements

<table>
<thead>
<tr>
<th>Functional Block</th>
<th>Power</th>
<th>( V_{DD} )</th>
<th>( R_{EQ} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensor</td>
<td>( 185 \ \mu W )</td>
<td>1.2 V</td>
<td>7.78 k( \Omega )</td>
</tr>
<tr>
<td>ADC</td>
<td>( 3.1 \ \mu W )</td>
<td>1 V</td>
<td>322 k( \Omega )</td>
</tr>
<tr>
<td></td>
<td>[M. Scott et al, <em>JSSC</em>, 2003]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DSP</td>
<td>( 6 \ \mu W )</td>
<td>&lt;1 V</td>
<td>166 k( \Omega )</td>
</tr>
<tr>
<td>RF</td>
<td>( 1 \ mW )</td>
<td>1.2 V</td>
<td>1.44 k( \Omega )</td>
</tr>
<tr>
<td></td>
<td>[B. Otis et al, <em>ISSCC</em>, 2005]</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- System works with low duty-cycle, total average power = \( 5 \ \mu W \)
- ADC - requires low power and clean \( V_{DD} \)
- DSP - requires low power, noisy \( V_{DD} \) ok
- RF - requires high peak power
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
Review: CMOS Power Dissipation

Total Power:

\[ P_{TOT} = P_{dyn} + P_{sc} + P_{stat} + P_{leak} \]

\[ = \alpha C_L V_{dd}^2 f + V_{dd} I_{peak} \left( \frac{t_r + t_f}{2} \right) f \]

\[ + V_{dd} I_{static} + V_{dd} I_{leak} \]

- Neglect short circuit power, focus on reducing dynamic power, static power and leakage current

- Each subsystem will have different voltage/power/energy requirements
Outline

• Introduction
• **System Power Consumption**
• Energy Harvesting and Power Management
• Conclusions
Device Power Consumption

0.33 mW

0.51 mW

3.75 mW

2 mW – 4 mW

0.31-0.74 mW

0.45 mW – 9 mW
Mobile Phone Peak Power Consumption

- Li Ion battery capacity 800-3300 mAh at 3.7V (3-12 Wh)
# XBee RF Module Power Consumption

<table>
<thead>
<tr>
<th>Range</th>
<th>Active Power</th>
<th>Sleep Power</th>
<th>Frequency</th>
<th>Protocol</th>
<th>Tx Power</th>
<th>Data Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 m</td>
<td>1 W</td>
<td>20 $\mu$W</td>
<td>2.4 GHz</td>
<td>802.11b/g/n</td>
<td>40 mW</td>
<td>1-72 Mbps</td>
</tr>
<tr>
<td>30 - 90 m / 90 m – 1.6 km</td>
<td>100 – 710 mW</td>
<td>33 $\mu$W</td>
<td>2.4 GHz</td>
<td>802.15.4</td>
<td>1 – 63 mW</td>
<td>115.2 Kbps</td>
</tr>
<tr>
<td>40 – 90 m / 120 m – 3.2 km</td>
<td>120 – 700 mW</td>
<td>3.3 – 13.2 $\mu$W</td>
<td>2.4 GHz</td>
<td>ZigBee</td>
<td>1.25 – 63 mW</td>
<td>1200 bps – 1 Mbps</td>
</tr>
<tr>
<td>305 – 610 m / 6.5 – 14 km</td>
<td>750 mW</td>
<td>10 $\mu$W</td>
<td>900 MHz</td>
<td>Proprietary</td>
<td>250 mW</td>
<td>10 – 200 Kbps</td>
</tr>
</tbody>
</table>
Commercial Wireless Sensor Mote

Moteiv Sky mote, 2006

Jiang, IPSN/SPOTS 2005

• 2000’s sensor node: 70 mW all active, 17 µW idle
• 2012 mote-on-chip: 100 mW all active, 3 µW deep sleep
• 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
UC Davis Wireless Display Node

- **3” QVGA Display**
  - Requires 5 V, +/- 20 V, etc.
  - Update requires 27.6 mW for 6.61 s (155 mJ)

- **Wi-Fi Communication**
  - Receives & transmits data
  - Requires 190 mW for 4.10 s (778 mJ)

- **Temperature Sensing**
  - Thermistor on PCB
  - Requires 11.8 mW for 6.87 ms (81.1 uJ)

- **EFM32GG990 MCU**
  - 3.3 V
  - 28 nA (92.4 nW) in deep sleep
Display Node Power Transient

- **Wi-Fi Transmission**
  - Radio Boot Up
  - Average Wi-Fi Power
  - Broadcast, Associate and Network Connect
  - Sever Upload / Download

- **Display Update**
  - Average WDSN Update Cycle Power
  - Average E-Ink Display Power
  - Black Screen, White Screen, Black Screen, ASCII Text Update

Time [s]

Power [W]
The Cardiac Tissue Stimulator is powered by indoor PV with a stimulation power of 13.2 mW. The system includes a Delta-Sigma Modulator, a control circuit, a Force Transducer, and a Stimulator. The formula for $V_{sense}$ is $0.011F_{tissue} + 0.194 V$. The tissue electrode load requires a voltage of at least 5 V and has a resistance of approximately 100-200 Ω. The current stimulation $I_{stim}$ is calculated as $I_{stim} = \frac{V_{IN}}{R_s}$. The diagram also shows a digital input and a 400 μm area with 500 μm features.
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
- Reconfigurability enables power vs. performance tradeoff

Bridge Sensor
- SWNT or SiNW

Microcontroller to RF
- Ctrl
- Data

A/D Converter
- SWNT or SiNW

DSP Coprocessor
Extending Sensor Node Lifetime

- Controller chooses appropriate configuration based on input, available energy, desired output quality
- Power awareness leads to 60-200% battery lifetime improvement (Bhardwaj TVLSI01)
Energy Scalable DA Array Architecture

• DA tile functional unit performs energy scalable computation for a set of linear/nonlinear functions
• Low power island-style reconfigurable interconnect permits the direct realization of DSP flowgraphs
• Switch boxes and connection boxes implemented with full transmission gates
• Simulated power and projected recognition performance for biomedical event detection application
Outline

• Introduction
• System Power Consumption
• Energy Harvesting and Power Management
• Conclusions
Battery energy density increased 3% per year from 1950-2010 (Zu and Li, *Energy Environ. Sci.*, 2011)
### Power and Energy Density

<table>
<thead>
<tr>
<th>Technology</th>
<th>Conditions</th>
<th>Power Density</th>
<th>Energy Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar</td>
<td>Outdoors</td>
<td>20mW/cm²</td>
<td>73Wh/cm²</td>
</tr>
<tr>
<td></td>
<td>Indoors</td>
<td>20µW/cm²</td>
<td>73mWh/cm²</td>
</tr>
<tr>
<td>Thermoelectric</td>
<td>Mounted on Skin</td>
<td>60µW/cm²</td>
<td>219mWh/cm²</td>
</tr>
<tr>
<td>Vibration (Human)</td>
<td>Piezoelectric</td>
<td>67µW/cm³</td>
<td>245mWh/cm³</td>
</tr>
<tr>
<td></td>
<td>Electrostatic</td>
<td>6µW/cm³</td>
<td>22mWh/cm³</td>
</tr>
<tr>
<td></td>
<td>Electromagnetic</td>
<td>75µW/cm³</td>
<td>274mWh/cm³</td>
</tr>
<tr>
<td>Ambient RF</td>
<td>Within 3km of TV Antenna</td>
<td>0.8-2.6µW/cm²</td>
<td>3-9.5mWh/cm²</td>
</tr>
<tr>
<td></td>
<td>General Urban Environment</td>
<td>3nW/cm²</td>
<td>11µWh/cm²</td>
</tr>
<tr>
<td>Broadcast Power</td>
<td>From 3W at 10m</td>
<td>&lt; 0.294mW</td>
<td>&lt; 1Wh</td>
</tr>
<tr>
<td>AAA Battery</td>
<td>Lithium-Ion (not rechargeable)</td>
<td>-</td>
<td>493mWh/cm³</td>
</tr>
<tr>
<td>AAA Battery</td>
<td>NiMH (rechargeable)</td>
<td>-</td>
<td>268mWh/cm³</td>
</tr>
</tbody>
</table>

- Energy density calculated by assuming two hours of harvesting every day for five years.
Linear Regulator Fundamentals

\[ V_{\text{out}} \approx \eta \frac{V_{\text{out}}}{V_{\text{in}}} \]

- Efficiency \( \eta \approx \frac{V_{\text{out}}}{V_{\text{in}}} \)
Dynamically Biased LDO Linear Regulator

- Output capacitor-less flipped voltage follower architecture
- Dynamic biasing to speed up load response
- Adaptive biasing to improve light load efficiency
- 180 nm CMOS implementation
Integrated Photovoltaics

- On-die PV array using CMOS passive pixels
- Characterized across multiple process nodes
- Metal “gratings” can concentrate light
  - Improve indoor harvesting efficiency
  - Expand range of incident angles
## Integrated PV Performance Across Process

<table>
<thead>
<tr>
<th>Technology</th>
<th>0.35 µm P+/NW</th>
<th>90 nm P+/NW</th>
<th>180 nm P+/NW</th>
<th>180 nm PW/DNW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Illumination</td>
<td>20 kLux</td>
<td>20 kLux</td>
<td>17 kLux</td>
<td>17 kLux</td>
</tr>
<tr>
<td>Voc</td>
<td>533 mV</td>
<td>486 mV</td>
<td>523 mV</td>
<td>508 mV</td>
</tr>
<tr>
<td>Isc density</td>
<td>680 µA/mm²</td>
<td>824 µA/mm²</td>
<td>134 µA/mm²</td>
<td>52 µA/mm²</td>
</tr>
<tr>
<td>Power Density</td>
<td>225 µW/mm²</td>
<td>325 µW/mm²</td>
<td>56 µW/mm²</td>
<td>21 µW/mm²</td>
</tr>
<tr>
<td>Figure of Merit (FF)</td>
<td>0.66</td>
<td>0.8</td>
<td>0.8</td>
<td>0.81</td>
</tr>
</tbody>
</table>

- Area for 5 µW = 164 µm x 164 µm (0.35 µm), 124 µm x 124 µm (90 nm)
Switched-Capacitor Boost Converter

- Phase 2 – Charge capacitors to VIN
- Phase 1 – Boost output to 4x VIN
Swiched-Capacitor Boost Converter

- Phase 2 – Charge capacitors to VIN
- Phase 1 – Boost output to 4x VIN
• Phase 2 – Charge capacitors to VIN
• Phase 1 – Boost output to 4x VIN
• Switched capacitor boost converters for integrated PV with 1.2 $\mu$W output power
  – Fully integrated MIM flying caps
  – 180 nm CMOS
  – Accurate parasitic models developed
Electromagnetic Harvester Characterization

Walking Experiment
Test Fixture

Results

- $38 \mu W$ output power (neglecting conversion losses)
Multi-Electrode Piezoelectric Generator

- PZT (lead zirconate titanate) disk diameter = 1.5”, top plate divided into quarter-circle sections, bottom plate not divided, yielding 5 electrodes in total
- Multiple mechanical resonances means more efficient harvesting from random or time-varying vibrations
- 78\(\mu W\) output power at 615Hz after AC/DC conversion
**Full Wave CMOS Controlled Rectifier**

- Constructed in 0.35 µm CMOS
- PMOS power FET width = 500 µm
- Up to 98% power efficiency
Frequency Variation With AC Supply

- Self-timed datapath must be initialized at power-on
- Must maintain state across power supply cycles
Measured Frequency Variation with AC Supply

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

- **Technology**: 180 nm CMOS
- **Dimensions**: 2.6 mm x 2.6 mm
- **Transistors**: 135K
- **I/O \( V_{DD} \)**: 1.8 V
- **AC Supply (\( V_{PP} = 1.8 \) V)**: 60 Hz – 1 kHz
- **Core Freq. (max)**: 75.6 MHz
- **Power (Core)**: 127 – 113 µW

- Published Symposium on VLSI Circuits, 2007
AC/DC combines a rectified $V_{\text{vibe}}$ with $V_{\text{solar}}$

DC/DC further smoothes harvested energy to form $V_{\text{out}}$
Multiple-Input Power Management Unit

- DC/DC output controller switches between functional blocks
- DSP tolerates high ripple, so the controller trades efficiency for ripple
- 0.25 µm CMOS
- Low quiescent current version in 180 nm CMOS under development
Outline

• Introduction
• Energy Scalable Computation
• Energy Harvesting and Power Management
• Conclusions
Conclusions

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

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

• Managing peak (10 mW – 3 W) and average (1 µW – 1 mW) power essential

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

• Integrated DC/DC conversion can reduce power and cost
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