Power harvesting towards autonomous RFIDs and wireless sensors

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Outline

• Introduction
• Power scavenging / harvesting solutions
• Flexible Materials
• Integration of harvesting modules and sensors
• Electromagnetic / solar energy harvesting
• Summary
Introduction

• Ubiquitous sensor networks
  • Monitoring (environment, wild-life), security, health…
  • Conformal circuits
  • Low manufacturing / material / maintenance cost
• Independent - autonomous sensors
  • Optimize efficiency – minimize dissipated power / maximize harvested power
• Green networks
  • Environmental friendly
Power Harvesting

- Choice of harvesting module(s) is application dependent (in-door vs. out-door, static vs. mobile, highly populated vs. rural), defined by intensity of available energy sources.

- Hybrid harvesting modules required to guarantee sensor autonomy.

- Efficiency depends on power density.
## Power Harvesting

- **Energy sources:**

<table>
<thead>
<tr>
<th>Energy Sources</th>
<th>Harvested power</th>
<th>Conditions, Available power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar</td>
<td>10 mW/cm²</td>
<td>Sunlight (100 mW/cm²)</td>
</tr>
<tr>
<td></td>
<td>&lt; 0.1 mW/cm²</td>
<td>Indoor light (&lt; 1 mW/cm²)</td>
</tr>
<tr>
<td>Kinetic (vibration)</td>
<td>1.3 mW (toes) / 8.4 mW (heel)</td>
<td>Piezoelectric Shoe mounted, standard walk (N.S. Shenck IEEE Micro 2005)</td>
</tr>
<tr>
<td>Thermal (Thermoelectric generators (TEG))</td>
<td>25 uW/cm²</td>
<td>Wrist watch type TEG (IMEC 2007)</td>
</tr>
<tr>
<td>Acoustic</td>
<td>0.003-0.96 uW / cm³</td>
<td>75-100 dB of noise</td>
</tr>
<tr>
<td>Electromagnetic</td>
<td>0.1-0.5 uW/cm²</td>
<td>Harvesting, contrast to wireless power transmission</td>
</tr>
</tbody>
</table>
# Power Harvesting

- Energy Sources

<table>
<thead>
<tr>
<th>Human Body Sources</th>
<th>Total available power from body</th>
<th>Available power for harvesting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Body heat</td>
<td>2.8W - 4.8 W</td>
<td>0.2-0.32 W (neck brace)</td>
</tr>
<tr>
<td>Breathing band</td>
<td>0.83 W</td>
<td>0.42 W</td>
</tr>
<tr>
<td>Walking</td>
<td>67 W</td>
<td>5.0-8.3 W</td>
</tr>
</tbody>
</table>

*Thad Starner, 'Human powered wearable computing', IBM systems journal, vol. 35, no. 3-4, 1996*
Components / Materials

- Flexible substrates
  - Paper
  - Liquid crystalline polymer (LCP)
  - Textile
  - Metal coated PET (polyethylene terephthalate)
Components / Materials

Paper

- Dielectric constant (*): 3.3 (@ 2 GHz)
- Loss tangent (*): 0.08 (@ 2 GHz)
- Can be made hydrophobic
- Inkjet printing
- Cost: very low
- Multilayer capability

Components / Materials

Liquid crystalline polymer (LCP)
- Dielectric constant: 2.9 (@ 10 GHz)
- Loss tangent: 0.0025 (@ 10 GHz)
- Water absorption < 0.04%
- Lamination < 282° C
- Multilayer capability
- Laser drilling (YAG, CO2)
- Low cost
Components / Materials

Textile materials
- Substrates: natural or man-made fibers [1]
- Synthetic fibers:

<table>
<thead>
<tr>
<th>Textile</th>
<th>Aramid</th>
<th>Fleece</th>
<th>Upholstery fabric</th>
<th>Vellux</th>
<th>Cordura</th>
</tr>
</thead>
<tbody>
<tr>
<td>Properties</td>
<td>Strong Heat resistant</td>
<td>Dries rapidly</td>
<td>Mixture of polyester and polyacryl</td>
<td>Synthetic fibre covered by thin layers of foam</td>
<td>Polyamide fiber</td>
</tr>
<tr>
<td>Dielectric constant</td>
<td>1,85</td>
<td>1,25</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Loss tangent</td>
<td>0,015</td>
<td>0,019</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Components / Materials

Conductive Textiles

• FlecTron, Zelt, ShiedIt, Global EMC

• ShiedIt has adhesive backing (can be glued, stitched, sewn, ironed to substrate)

• Surface Resistivity (0.02-0.05 Ohm/sq)
Components / Materials

PET (Polyethylene Terephthalate)

- Dielectric constant: 3.3 (@ 0.9 GHz)
- Loss tangent: 0.003 (@ 0.9 GHz)
- Thickness: 50 um – 100 um
Integration

Possibilities

- Smart textiles
- MEMS
- Hybrid harvesting modules (Solar antennas)
- Organic electronics

Features

- Washability, Stretchability, User comfort, Conformal shape
Integration

Paper substrates, ink-jet printing.

• Passive circuits (antennas, interconnects)
• Active components (temperature sensor, battery, microcontroller, crystal oscillator) mounted using silver conducting epoxy
• 9.5 x 5 cm
• Multilayer capability by laminating paper sheets


Integration

- Textile passive and active circuit and sensor integration.
- Wearable smart fabric with sensing and communication (transmission) capabilities.

Integration

- **MEMS Piezoelectric energy harvester**
- IMEC developed piezoelectric energy harvesters capable of generating up to 85μW of power (unpackaged)
- CMOS compatible MEMS processes on 6’ silicon and SOI wafers.
- Piezoelectric material: Aluminium Nitride (AlN)
- Size: 1cm³
- Resonance: 150-1200Hz
- Vacuum package
- 220 uF capacitor for energy storage

Integration

Solar / Electromagnetic harvester

• 1.9GHz/-1.5 dBm Transmitter
  2.4x3.9 cm²


Electromagnetic Energy Harvesting

- Rectenna elements and arrays have been optimized achieving good RF-to-DC efficiency in directive, wireless power transmission applications.

- Recent interest for low profile, energy efficient, self-sustainable sensor networks, focuses on optimizing RF-to-DC efficiency for low power densities corresponding to ambient EM fields.
Electromagnetic Energy Harvesting

Design poses several challenges:

- Compact antenna elements, Arbitrary polarization, broadband, multi-band designs
- EM simulation to model radiating element.
- Nonlinear optimization to model rectenna circuit and optimize rectifier taking into account the antenna properties.
- Antenna in receiving mode (Norton, Thevenin equivalent)
Electromagnetic Energy Harvesting

Rectenna design example

- 2.40GHz - 2.48GHz ISM band
- Aperture coupled patch topology:
- Circuit and radiator layers are made of Arlon A25N 20mil thick
- Separated by a Rohacell51 layer of 6mm in order to achieve the desired bandwidth.
Electromagnetic Energy Harvesting

- Joint antenna and rectifier optimization using Thevenin equivalent of antenna in receive mode.
Electromagnetic Energy Harvesting

- Open circuit voltage maybe calculated using reciprocity theory

$$\eta = \frac{P_{DC}}{P_{RF,av}} = \frac{V_{DC}^2}{P_{RF,av}R_L}$$

$$V_{V,H}^{oc}(\theta_o, \phi_o, S) = \frac{4\pi}{jk\eta_o} F_{V,H}(\theta_o, \phi_o)E_o$$

$$P_{av} = \frac{1}{4} V^{oc*}[Z_A + Z_A^*]^{-1}V^{oc}$$

$$E_o = \sqrt{2\eta_o S} \quad \eta_o = 120\pi$$

- One may optimize in harmonic balance the input power density at the desired direction of arrival.
Electromagnetic Energy Harvesting

- Circularly polarized rectenna
Electromagnetic Energy Harvesting

- Ultra-wideband rectenna / solar harvester
Power Harvesting

- Harvesting and Storage modules must be considered
Flexible Storage Modules

Flexible Storage devices / modules

• Flexible super-capacitors
• Stores an energy density of 1.29 Watt-hour/kilogram with a specific capacitance of 64 Farad/gram
• Conventional capacitors: energy density < 0.1 Wh/kg and storage capacitance of several tenth millifarads.

Summary

- Hybrid harvesting systems
- Low cost materials and fabrication techniques
- Embedding electronics on flexible substrates
- Stretchability, Washability, Interconnects
- Storage modules
- Autonomous Sensors
Related Events / Contacts

- http://www.cost-ic0803.org/
- Upcoming meeting, Lausanne Nov. 8-9, 2010
Related Events / Contacts

- [http://ewtw.cttc.es/](http://ewtw.cttc.es/)
- September 15-16, 2011, Sitges - Barcelona
Thank you for your attention!

• Questions?

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