VIBRATION POWERED
WIRELESS SENSOR NETWORKS

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Intro

- What are wireless sensor networks?
- The problem of the power supply: batteries are not a viable solution
- Our approach: use vibrations present in the environment

General scheme

- Vibration harvesting + energy storage + sensing + processing + communicating

In detail

- Vibration harvesting: a commercial approach
- Energy storage: the problem of impedance matching
- Sensing example
- Processing and communications
- Future perspectives
Wireless sensor network (WSN) is a particular type of network characterized by a distributed architecture and it's realized by autonomous electronic devices capable of collecting information about the physical environment (temperature, pressure, proximity, vibration, sound, electromagnetic, etc.) to provide monitoring, automation and control for many varied applications.

The uses of wireless sensor networks are almost unlimited with many industries and applications having specific technology requirements such as reliability, permanence, battery life, range, frequencies, topologies, network size, sampling rate, data throughput and sensor use.
What are wireless sensor networks?

Main wireless network topologies are categorized into the following basic types:

- **Peer to Peer Network**
- **Star Topology Network**
- **Mesh Network**
- **Cluster Network**

Reduced Function Device (Sensor, Controller, Actuator, etc.)

PAN Coordinator

Full Function Device (Performs network routing functions)
The problem of the power supply: batteries are not a viable solution

Wireless sensors that must operate for very long time without service must survive on large primary batteries or utilize alternate methods of obtaining the energy necessary for operation. An emerging area of alternate energy sources is Energy Harvesting.
The problem of the power supply: batteries are not a viable solution

Energy storage requirements: long cycle life, low self discharge, rechargeable and small form factor.

Today's solution

THIN FILM TECHNOLOGY BATTERIES

- All solid state construction
- Can be operated at high and low temperatures
- Can be made in any shape or size
- Cost does not increase with reduction in size (constant $/cm²)

<table>
<thead>
<tr>
<th>Device</th>
<th>Equivalent Charge (µAh)</th>
<th>Self-Discharge (%/day)</th>
<th>Supplemental Charge Required (µAh) per 10 years</th>
<th>CR2032 Capacity (mAh)</th>
<th>% of CR2032 Used in Compensating for Self-Discharge</th>
</tr>
</thead>
<tbody>
<tr>
<td>CBC012</td>
<td>12</td>
<td>0.1</td>
<td>43.2</td>
<td>225</td>
<td>0.0192</td>
</tr>
<tr>
<td>CBC050</td>
<td>50</td>
<td>0.1</td>
<td>180</td>
<td>225</td>
<td>0.08</td>
</tr>
<tr>
<td>0.047 F</td>
<td>20</td>
<td>30</td>
<td>21600</td>
<td>225</td>
<td>9.6</td>
</tr>
<tr>
<td>0.2 F</td>
<td>80</td>
<td>30</td>
<td>86400</td>
<td>225</td>
<td>38.4</td>
</tr>
</tbody>
</table>
Current requirements of the battery management, battery charger, charge pump and charge control circuits are significant.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Condition</th>
<th>Min</th>
<th>Typical</th>
<th>Max</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parasitic Load Current</td>
<td>Boost converter off</td>
<td>-</td>
<td>800</td>
<td>-</td>
<td>nA</td>
</tr>
<tr>
<td></td>
<td>Boost converter on</td>
<td>-</td>
<td>20</td>
<td>-</td>
<td>µA</td>
</tr>
<tr>
<td>$V_{out}$ - 2µA Load</td>
<td>Battery charged</td>
<td>3.5</td>
<td>3.55</td>
<td>3.6</td>
<td>V</td>
</tr>
<tr>
<td>$V_{in}$</td>
<td>Operating</td>
<td>0.25</td>
<td>-</td>
<td>4</td>
<td>V</td>
</tr>
<tr>
<td>$V_{ref}$ Charging Voltage</td>
<td>25°C</td>
<td>-</td>
<td>4.06</td>
<td>-</td>
<td>V</td>
</tr>
<tr>
<td>Battery Cutoff Voltage</td>
<td>4.7kΩ load</td>
<td>3.0</td>
<td>3.3</td>
<td>3.6</td>
<td>V</td>
</tr>
<tr>
<td>UVLO Trip Select Voltage</td>
<td>25°C</td>
<td>-</td>
<td>0.7</td>
<td>-</td>
<td>V</td>
</tr>
<tr>
<td>Pulse Discharge Current [1]</td>
<td>20 ms</td>
<td>600</td>
<td>-</td>
<td>-</td>
<td>µA</td>
</tr>
<tr>
<td>Self-Discharge (non-recoverable average)</td>
<td>25°C</td>
<td>2.5</td>
<td>-</td>
<td>70</td>
<td>% per year</td>
</tr>
<tr>
<td>Operating Temperature</td>
<td></td>
<td>0</td>
<td>25</td>
<td>70</td>
<td>°C</td>
</tr>
<tr>
<td>Recharge Cycles (to 80% of rated capacity, 4.1V charge voltage)</td>
<td>25°C</td>
<td>10% depth-of-discharge</td>
<td>5000</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>50% depth-of-discharge</td>
<td>1000</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>40°C</td>
<td>10% depth-of-discharge</td>
<td>2500</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>50% depth-of-discharge</td>
<td>500</td>
<td>-</td>
</tr>
<tr>
<td>Recharge Time (to 80% of rated capacity)</td>
<td>From 50% state-of-charge</td>
<td>-</td>
<td>10</td>
<td>-</td>
<td>minutes</td>
</tr>
<tr>
<td></td>
<td>From deep discharge</td>
<td>-</td>
<td>50</td>
<td>-</td>
<td>minutes</td>
</tr>
<tr>
<td>Capacity</td>
<td>16 µA discharge: 25°C</td>
<td>-</td>
<td>100</td>
<td>-</td>
<td>µAh</td>
</tr>
</tbody>
</table>
Vibration harvesting + energy storage + sensing + processing + communicating

A extreme low power Wireless Sensor consists of five basic elements:
1) The **sensor** itself, to detect and quantify any number of environmental parameters such as motion, proximity, temperature, pressure, pH, light, strain, vibration etc.
2) An **energy harvesting transducer** to convert some form of ambient energy to electricity.
3) A **power module** to collect, store and deliver electrical energy to the electronic devices.
4) A **microcontroller** to receive the signal from the sensor, convert it into a useful form for analysis, and communicate through the radio link.
5) A **radio link** to transmit the information from the processor on a continuous, periodic, or event-driven basis to a host receiver and data collection point.
Vibration harvesting

Midé PEH20w

The PEH20w consists of a piezoelectric cantilever specifically shaped in order to take advantage of vibrations available in the frequency range between 75 - 175 Hz.

http://www.mide.com/products/voltage/peh20w/peh20w.php
Energy storage: the problem of impedance matching

Test of the Midé PEH20w on our shaker with different resistor load.

*Sinusoidal Excitation*: $F_{exc} = F_{RES} = 94.5 \text{ Hz}$
Our approach: use vibrations present in the environment

Highly efficient integrated rectifier and voltage boosting circuits for energy harvesting applications
D. Maurath, C. Peters, T. Hehn, M. Ortmanns, and Y. Manoli
Chair of Microelectronics, Department of Microsystems Engineering (IMTEK), University of Freiburg, Georges-Koehler-Allee 102, 79110 Freiburg, Germany
Sensing example (Texas Instruments and Microchip Technology)

Texas Instruments eZ430-RF2500-SEH
Solar Energy Harvesting Development Tool

NiPS Laboratory
Noise in Physical Systems

Summer School on Energy Harvesting – Avigliano Umbro – Italy – Aug. 1/8, 2010
Sensing example (Texas Instruments)

Current profile of an End Device over four seconds based on MSP430F2274
Sensing example (Texas Instruments)
Processing and communications: requirements and technologies

**PIC24F16KA102**
- Sleep currents down to 20 nA
- Active Mode currents down to 100μA / MIPS
- Modified Harvard Architecture
  

**MSP430x2xx family**
- Sleep currents down to 100 nA
- Active Mode currents down to 250-μA / MIPS
- von-Neumann architecture
  
  http://focus.ti.com/lit/ug/slau144e/slau144e.pdf
Processing and communications: requirements and technologies

IEEE 802.15.4™ Standard Compliant RF Transceiver: ISM Band 2.405-2.48 GHz
Low-Current Consumption: RX mode: 19 mA, TX mode: 23 mA, Sleep: 2 μA
-95 dBm Typical Sensitivity, -36 dBm to +0 dBm Typical Output Power
“Small”, 40-Pin Leadless QFN 6x6 mm² Package
IEEE 802.15.4 in the 2400 MHz band uses Offset Quadrature-PSK, while in the lower bands use Binary-PSK.

In all cases, both forms of PSK are anywhere from 7 to 18 dB better, which directly translates to a range increase from 2 to 8 times the distance for the same energy per bit, or an exponential increase in reliability at any given range.

Friis Transmission equation

\[ P_R = G_T \cdot G_R \left( \frac{\lambda}{4\pi r} \right)^2 \cdot P_T \]

AWGN Power density (channel noise)

\[ P_N = k \cdot T \cdot B = -174 \text{ dBm/Hz @ 290 K} \]
Processing and communications: requirements and technologies

A programmer should always:
1. minimize the number of transmissions
2. fit as many bytes into the transmission packet as is feasible for the application.
Processing and communications: requirements and technologies

Last but not least: particular attention must be dedicated to the antenna. Dimensions are generally related to the operating frequency.
Future perspectives

• Vibration transducer have to be more efficient: increase energy density
• AC/DC converter: reduce losses in semiconductors
• Battery: increase the energy density
• Voltage regulator: reduce the dissipated power during the up/down conversion
• Microcontroller: reduce the power consumed during sleep mode, optimize the architecture and reduce the current in active mode - uA / MIPS
• Firmware / network: development of new algorithm
• Sensors: reduce the current requirements
• RTX: develop new modulation techniques, increase the sensitivity and reduce the transmission power
• Antenna: attention to the impedance matching, gain, pattern etc.