The Mote Revolution:
Low Power Wireless Sensor Network Devices

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Hot Chips 2004 : Aug 22-24, 2004
Outline

- Trends and Applications
- Mote History and Evolution
- Design Principles
- Telos
Faster, Smaller, Numerous

- Moore’s Law
  - “Stuff” (transistors, etc) doubling every 1-2 years

- Bell’s Law
  - New computing class every 10 years

Streaming Data to/from the Physical World

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Applications

- Environmental Monitoring
  - Habitat Monitoring
  - Integrated Biology
  - Structural Monitoring

- Interactive and Control
  - Pursuer-Evader
  - Intrusion Detection
  - Automation

Density & Scale
Sample Rate & Precision
Disconnection & Lifetime
Mobility
Low Latency

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Open Experimental Platform

TinyOS

Services

Networking

WeC 99
“Smart Rock”

Rene 11/00

Dot 9/01

Mica 1/02

Small microcontroller
- 8 kB code
- 512 B data

Simple, low-power radio
- 10 kbps ASK

EEPROM (32 KB)

Simple sensors

Designed for experimentation

-sensor boards

-power boards

Demonstrate scale

NEST open exp. Platform
- 128 kB code, 4 kB data
- 40kbps OOK/ASK radio
- 512 kB Flash

Mica2 12/02
- 38.4kbps radio
- FSK

Spec 6/03
- “Mote on a chip”

Telos 4/04
- Robust
- Low Power
- 250kbps
- Easy to use

Commercial Off The Shelf Components (COTS)
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# Mote Evolution

## Microcontroller

<table>
<thead>
<tr>
<th></th>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Microcontroller</td>
<td>AT90LS8535</td>
<td>ATmega163</td>
<td>ATmega128</td>
<td>TI MSP430</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Type</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Program memory (KB)</td>
<td>8</td>
<td>16</td>
<td>128</td>
<td>60</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RAM (KB)</td>
<td>0.5</td>
<td>1</td>
<td>4</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Active Power (mW)</td>
<td>15</td>
<td>15</td>
<td>8</td>
<td>33</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sleep Power (μW)</td>
<td>45</td>
<td>45</td>
<td>75</td>
<td>75</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wakeup Time (μs)</td>
<td>1000</td>
<td>36</td>
<td>180</td>
<td>180</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

## Nonvolatile storage

<table>
<thead>
<tr>
<th>Chip</th>
<th>24LC256</th>
<th>AT45DB041B</th>
<th>ST M24M01S</th>
</tr>
</thead>
<tbody>
<tr>
<td>Connection type</td>
<td>I²C</td>
<td>SPI</td>
<td>I²C</td>
</tr>
<tr>
<td>Size (KB)</td>
<td>32</td>
<td>512</td>
<td>128</td>
</tr>
</tbody>
</table>

## Communication

<table>
<thead>
<tr>
<th>Radio</th>
<th>TR1000</th>
<th>TR1000</th>
<th>CC1000</th>
<th>CC2420</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radio</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Data rate (kbps)</td>
<td>10</td>
<td>40</td>
<td>38.4</td>
<td>250</td>
</tr>
<tr>
<td>Modulation type</td>
<td>OOK</td>
<td>ASK</td>
<td>FSK</td>
<td>O-QPSK</td>
</tr>
<tr>
<td>Receive Power (mW)</td>
<td>9</td>
<td>12</td>
<td>29</td>
<td>38</td>
</tr>
<tr>
<td>Transmit Power at 0dBm (mW)</td>
<td>36</td>
<td>36</td>
<td>42</td>
<td>35</td>
</tr>
</tbody>
</table>

## Power Consumption

<table>
<thead>
<tr>
<th>Minimum Operation (V)</th>
<th>2.7</th>
<th>2.7</th>
<th>2.7</th>
<th>1.8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Active Power (mW)</td>
<td>24</td>
<td>27</td>
<td>44</td>
<td>89</td>
</tr>
</tbody>
</table>

## Expansion and Sensor Interface

<table>
<thead>
<tr>
<th>Expansion</th>
<th>none</th>
<th>51-pin</th>
<th>51-pin</th>
<th>none</th>
<th>51-pin</th>
<th>19-pin</th>
<th>51-pin</th>
<th>10-pin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Communication</td>
<td>IEEE 1284 (programming) and RS232 (requires additional hardware)</td>
<td>USB</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Integrated Sensors</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
</tbody>
</table>
Mote

- A very low cost low power computer
- Monitors one or more sensors
- A Radio Link to the outside world
- Are the building blocks of Wireless Sensor Networks (WSN)
Low Power Operation

- Efficient Hardware
  - Integration and Isolation
    - Complementary functionality (DMA, USART, etc)
  - Selectable Power States (Off, Sleep, Standby)
  - Operate at low voltages and low current
    - Run to cut-off voltage of power source

- Efficient Software
  - Fine grained control of hardware
  - Utilize wireless broadcast medium
  - Aggregate

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Typical WSN Application

- **Periodic**
  - Data Collection
  - Network Maintenance
  - *Majority of operation*

- **Triggered Events**
  - Detection/Notification
  - *Infrequently occurs*
    - *But… must be reported quickly and reliably*

- **Long Lifetime**
  - Months to Years without changing batteries
  - Power management is the key to WSN success

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“*The Mote Revolution: Low Power Wireless Sensor Network Devices*”
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Design Principles

- Key to Low **Duty Cycle** Operation:
  - Sleep – majority of the time
  - Wakeup – quickly start processing
  - Active – minimize work & return to sleep
Sleep

- Majority of time, node is asleep
  - >99%
- Minimize sleep current through
  - Isolating and shutting down individual circuits
  - Using low power hardware
    - Need RAM retention
- Run auxiliary hardware components from low speed oscillators (typically 32kHz)
  - Perform ADC conversions, DMA transfers, and bus operations while microcontroller core is stopped

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Telos Platform

- A new platform for low power research
  - Monitoring applications:
    - Environmental
    - Building
    - Tracking

- Long lifetime, low power, low cost

- Built from application experiences and low duty cycle design principles

- Robustness
  - Integrated antenna
  - Integrated sensors
  - Soldered connections

- Standards Based
  - IEEE 802.15.4
  - USB

- IEEE 802.15.4 ZigBee
  - CC2420 radio
  - Frame-based
  - 250kbps
  - 2.4GHz ISM band

- TI MSP430
  - Ultra low power
    - 1.6µA sleep
    - 460µA active
    - 1.8V operation

Open embedded platform with open source tools, operating system (TinyOS), and designs.

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Minimize Power Consumption

- Compare to MicaZ: a Mica2 mote with AVR mcu and 802.15.4 radio

- Sleep
  - Majority of the time
  - Telos: 2.4\( \mu \)A
  - MicaZ: 30\( \mu \)A

- Wakeup
  - As quickly as possible to process and return to sleep
  - Telos: 290ns typical, 6\( \mu \)s max
  - MicaZ: 60\( \mu \)s max internal oscillator, 4ms external

- Active
  - Get your work done and get back to sleep
  - Telos: 4-8MHz 16-bit
  - MicaZ: 8MHz 8-bit
CC2420 Radio
IEEE 802.15.4 Compliant

- CC2420
  - Fast data rate, robust signal
    - 250kbps : 2Mchip/s : DSSS
    - 2.4GHz : Offset QPSK : 5MHz
    - 16 channels in 802.15.4
    - -94dBm sensitivity
  - Low Voltage Operation
    - 1.8V minimum supply
  - Software Assistance for Low Power Microcontrollers
    - 128byte TX/RX buffers for full packet support
    - Automatic address decoding and automatic acknowledgements
    - Hardware encryption/authentication
    - Link quality indicator (assist software link estimation)
      - samples error rate of first 8 chips of packet (8 chips/bit)

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## Power Calculation Comparison

### Design for low power

<table>
<thead>
<tr>
<th>Device</th>
<th>Power Consumption</th>
<th>Data Rate</th>
<th>Voltage</th>
<th>Battery Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mica2 (AVR)</strong></td>
<td>0.2 ms wakeup 30 µW sleep 33 mW active 21 mW radio 19 kbps 2.5V min</td>
<td>250 kbps</td>
<td>2.5V</td>
<td>2/3 of AA capacity</td>
</tr>
<tr>
<td><strong>MicaZ (AVR)</strong></td>
<td>0.2 ms wakeup 30 µW sleep 33 mW active 45 mW radio 250 kbps 2.5V min</td>
<td>250 kbps</td>
<td>2.5V</td>
<td>2/3 of AA capacity</td>
</tr>
<tr>
<td><strong>Telos (TI MSP)</strong></td>
<td>0.006 ms wakeup 2 µW sleep 3 mW active 45 mW radio 250 kbps 1.8V min</td>
<td>250 kbps</td>
<td>1.8V</td>
<td>8/8 of AA capacity</td>
</tr>
</tbody>
</table>

Supporting mesh networking with a pair of AA batteries reporting data once every 3 minutes using synchronization (<1% duty cycle)

- Mica2 (AVR): 453 days
- MicaZ (AVR): 328 days
- Telos (TI MSP): 945 days

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Sensors

- Integrated Sensors
  - Sensirion SHT11
    - Humidity (3.5%)
    - Temperature (0.5°C)
    - Digital sensor
  - Hamamatsu S1087
    - Photosynthetically active light
    - Silicon diode
  - Hamamatsu S1337-BQ
    - Total solar light
    - Silicon diode

- Expansion
  - 6 ADC channels
  - 4 digital I/O
  - Existing sensor boards
    - Magnetometer
    - Ultrasound
    - Accelerometer
    - 4 PIR sensors
    - Microphone
    - Buzzer