The Mote Revolution:
Low Power Wireless Sensor Network Devices

University of California, Berkeley

Joseph Polastre
Robert Szewczyk
Cory Sharp
David Culler

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**

Hot Chips 2004 : Aug 22-24, 2004
Applications

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

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

Hot Chips 2004 : Aug 22-24, 2004
Open Experimental Platform

Networking

TinyOS

Services

WeC 99
“Smart Rock”

Rene 11/00

Dot 9/01

Mica 1/02

Simple, low-power
radio
10 kbps ASK

EEPROM (32 KB)

Small microcontroller
8 kB code
512 B data

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

Simple sensors

Commercial Off The Shelf Components (COTS)
Hot Chips 2004 : Aug 22-24, 2004
## Mote Evolution

<table>
<thead>
<tr>
<th>Mote Type</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>WeC</td>
<td>1998</td>
</tr>
<tr>
<td>René</td>
<td>1999</td>
</tr>
<tr>
<td>René 2</td>
<td>2000</td>
</tr>
<tr>
<td>Dot</td>
<td>2000</td>
</tr>
<tr>
<td>Mica</td>
<td>2001</td>
</tr>
<tr>
<td>Mica2Dot</td>
<td>2002</td>
</tr>
<tr>
<td>Mica 2</td>
<td>2002</td>
</tr>
<tr>
<td>Telos</td>
<td>2004</td>
</tr>
</tbody>
</table>

### Microcontroller

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

| Minimum Operation (V)        | 2.7        | 2.7        | 2.7        | 1.8       |
| Total Active Power (mW)      | 24         | 27         | 44         | 89        |

### Expansion and Sensor Interface

<table>
<thead>
<tr>
<th>Expansion</th>
<th>none</th>
<th>51-pin</th>
<th>51-pin</th>
<th>51-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>
</tr>
<tr>
<td>Integrated Sensors</td>
<td>yes</td>
<td>no</td>
<td>yes</td>
<td>no</td>
</tr>
</tbody>
</table>
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
**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

---

Hot Chips 2004 : Aug 22-24, 2004
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
Wake up

- Overhead of switching from Sleep to Active Mode
- Microcontroller
- Radio (FSK)

292 ns
10ns – 4ms typical

2.5 ms
1 – 10 ms typical

Hot Chips 2004 : Aug 22-24, 2004
Active

- Microcontroller
  - Fast processing, low active power
  - Avoid external oscillators

- Radio
  - High data rate, low power tradeoffs
  - Narrowband radios
    - Low power, lower data rate, simple channel encoding, faster startup
  - Wideband radios
    - More robust to noise, higher power, high data rates

- External Flash (stable storage)
  - Data logging, network code reprogramming, aggregation
  - High power consumption
  - Long writes

- Radio vs. Flash
  - 250kbps radio sending 1 byte
    - Energy : 1.5μJ
    - Duration : 32μs
  - Atmel flash writing 1 byte
    - Energy : 3μJ
    - Duration : 78μs

Hot Chips 2004 : Aug 22-24, 2004
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
  - CC2420 radio
  - 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.
Low Power Operation

- TI MSP430 -- Advantages over previous motes
  - 16-bit core
  - 12-bit ADC
    - 16 conversion store registers
    - Sequence and repeat sequence programmable
  - < 50nA port leakage (vs. 1μA for Atmels)
  - Double buffered data buses
  - Interrupt priorities
  - Calibrated DCO

- Buffers and Transistors
  - Switch on/off each sensor and component subsystem

Hot Chips 2004 : Aug 22-24, 2004
Minimize Power Consumption

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

- Sleep
  - Majority of the time
  - Telos: 2.4μA
  - MicaZ: 30μA

- Wakeup
  - As quickly as possible to process and return to sleep
  - Telos: 290ns typical, 6μs max
  - MicaZ: 60μs 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)

Hot Chips 2004 : Aug 22-24, 2004
Power Calculation Comparison
Design for low power

- **Mica2 (AVR)**
  - 0.2 ms wakeup
  - 30 μW sleep
  - 33 mW active
  - 21 mW radio
  - 19 kbps
  - 2.5V min
    - 2/3 of AA capacity

- **MicaZ (AVR)**
  - 0.2 ms wakeup
  - 30 μW sleep
  - 33 mW active
  - 45 mW radio
  - 250 kbps
  - 2.5V min
    - 2/3 of AA capacity

- **Telos (TI MSP)**
  - 0.006 ms wakeup
  - 2 μW sleep
  - 3 mW active
  - 45 mW radio
  - 250 kbps
  - 1.8V min
    - 8/8 of AA capacity

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

453 days
328 days
945 days

Hot Chips 2004 : Aug 22-24, 2004
Integrated Antenna
Inverted-F Microstrip Antenna and SMA Connector

- **Inverted-F**
  - Psuedo Omnidirectional
  - 50m range indoors
  - 125m range outdoors
  - Optimum at 2400-2460MHz

- **SMA Connector**
  - Enabled by moving a capacitor
  - > 125m range
  - Optimum at 2430-2483MHz

Hot Chips 2004 : Aug 22-24, 2004
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

---

Hot Chips 2004 : Aug 22-24, 2004
Conclusions

- New design approach derived from our experience with resource constrained wireless sensor networks
  - Active mode needs to run quickly to completion
  - Wakeup time is crucial for low power operation
    - Wakeup time and sleep current set the minimal energy consumption for an application
  - Sleep most of the time
- Tradeoffs between complexity/robustness and low power radios
- Careful integration of hardware and peripherals