The Mote Revolution:
Low Power Wireless Sensor Network Devices

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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

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
## Open Experimental Platform

- **TinyOS**
- **Networking**
- **Services**

### WeC 99
- "Smart Rock"
- Microcontroller:
  - 8 kB code
  - 512 B data
- Simple sensors
- Designed for experimentation
  - sensor boards
  - power boards

### Rene 11/00
- Microcontroller:
  - 10 kbps ASK
  - EEPROM (32 KB)
- Simple, low-power radio
  - 10 kbps ASK
  - EEPROM (32 KB)

### Dot 9/01
- Microcontroller:
  - 512 kB Flash
- Designed for experimentation
  - sensor boards
  - power boards

### Mica 1/02
- Microcontroller:
  - 128 kB code
  - 4 kB data
- Simple, low-power radio
  - 40 kbps OOK/ASK radio
  - 512 kB Flash

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

### Mica2 12/02
- 38.4 kbps radio
- FSK

### Spec 6/03
- "Mote on a chip"

### Commercial Off The Shelf Components (COTS)

## Mote Evolution

<table>
<thead>
<tr>
<th>Mote Type</th>
<th>Year</th>
<th>WeC 99</th>
<th>Rene 11/00</th>
<th>Dot 9/01</th>
<th>Mica 1/02</th>
<th>Mica2Dot 2002</th>
<th>Mica 2 2002</th>
<th>Telos 4/04</th>
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<tr>
<td>Microcontroller</td>
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<tr>
<td>Type</td>
<td>AT90LS8535</td>
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<td>Wakeup Time (ms)</td>
<td>1000</td>
<td>1000</td>
<td>36</td>
<td>180</td>
<td>1000</td>
<td>180</td>
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<td>Nonvolatile storage</td>
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<td>Chip</td>
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<td>ST M25MH1S</td>
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<td>Size (kB)</td>
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<td>Radio</td>
<td>TR1000</td>
<td>TR1000</td>
<td>CC1000</td>
<td>CC2420</td>
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<td>Data rate (kbps)</td>
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<td>38.4</td>
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<td>Minimum Operation (V)</td>
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<td>2.7</td>
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<td>Total Active Power (mW)</td>
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<td>27</td>
<td>44</td>
<td>89</td>
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<td>Programming and Sensor Interface</td>
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</tbody>
</table>

*Telos 4/04: Robust, low power, 250 kbps, easy to use*
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

*The Mote Revolution: Low Power Wireless Sensor Network Devices*
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
  - Fast processing, low active power
  - Avoid external oscillators
- Radio (FSK)
  - 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

Active

- Microcontroller
- 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
**Telos Platform**

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

Long lifetime, low power, low cost

Built from application experiences and low duty cycle design principles

Robustness
  - Integrated antenna
  - Integrated sensors
  - Soldered connections

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

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**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
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)
Power Calculation Comparison
Design for low power

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

- **MicaZ (AVR)**
  - 0.2 ms wakeup
  - 30 µW sleep
  - 6 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
  - 0.5 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

Integrated Antenna
Inverted-F Microstrip Antenna and SMA Connector

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

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

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