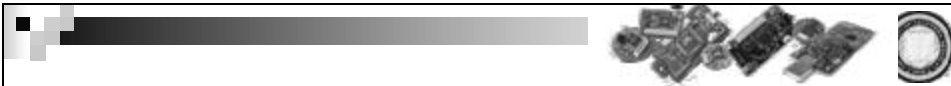


The Mote Revolution:

Low Power Wireless Sensor Network Devices

University of California, Berkeley

Joseph Polastre
Robert Szewczyk
Cory Sharp
David Culler



Outline

- Trends and Applications
- Mote History and Evolution
- Design Principles
- Telos

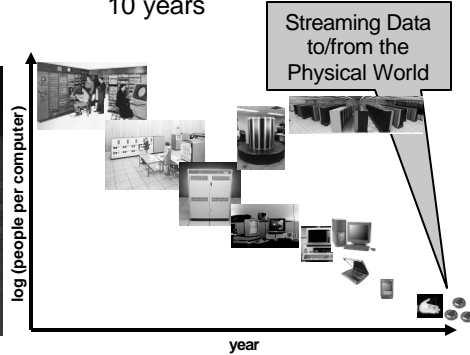
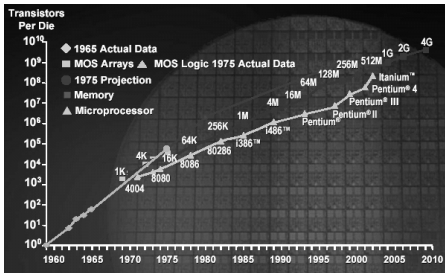
Faster, Smaller, Numerous

■ Moore's Law

- "Stuff" (transistors, etc) doubling every 1-2 years

■ Bell's Law

- New computing class every 10 years



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Applications

■ Environmental Monitoring

- Habitat Monitoring
- Integrated Biology
- Structural Monitoring

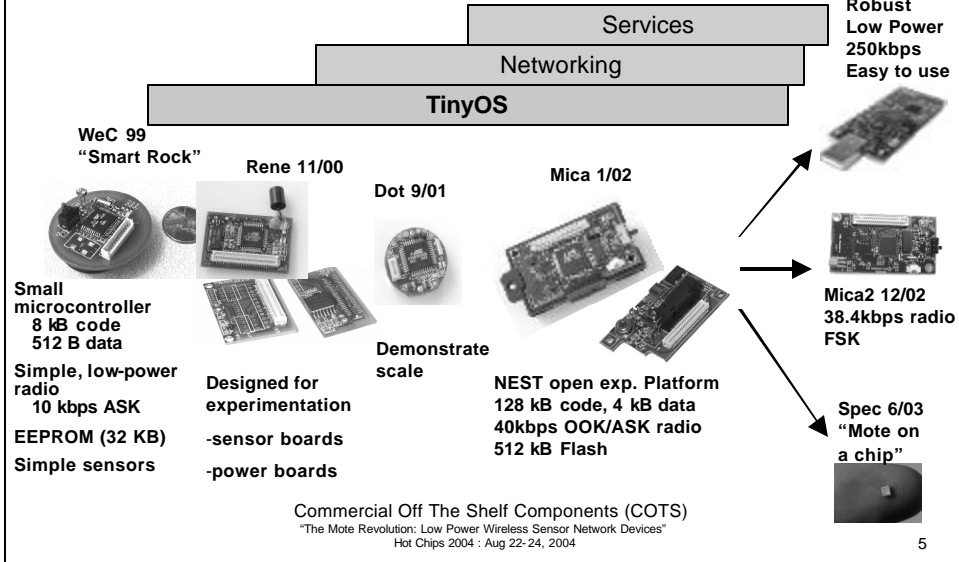
■ Interactive and Control

- Pursuer-Evader
- Intrusion Detection
- Automation



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Open Experimental Platform



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Mote Evolution

| Mote Type Year | WeC 1998 | René 1999 | René 2 2000 | Dot 2000 | Mica 2001 | Mica2Dot 2002 | Mica 2 2002 | Telos 2004 |
|----------------------------------|--|--------------|----------------|-------------|--------------|------------------|------------------|---------------|
| Microcontroller | | | | | | | | |
| Type | AT90LS8535 | | ATmega163 | | ATmega128 | | TI MSP430 | |
| Program memory (KB) | 8 | | 16 | | 128 | | 60 | |
| RAM (KB) | 0.5 | | 1 | | 4 | | 2 | |
| Active Power (mW) | 15 | | 15 | | 15 | | 60 | |
| Sleep Power (μ W) | 45 | | 45 | | 75 | | 75 | |
| Wakeup Time (μ s) | 1000 | | 36 | | 180 | | 180 | |
| Nonvolatile storage | | | | | | | | |
| Chip | 24LC256 | | | | AT45DB041B | | ST M24M01S | |
| Connection type | I ² C | | | | SPI | | I ² C | |
| Size (KB) | 32 | | | | 512 | | 128 | |
| Communication | | | | | | | | |
| Radio | TR1000 | | | | TR1000 | CC1000 | | CC2420 |
| Data rate (kbps) | 10 | | | | 40 | 38.4 | | 250 |
| Modulation type | OOK | | | | ASK | FSK | | O-QPSK |
| Receive Power (mW) | 9 | | | | 12 | 29 | | 38 |
| Transmit Power at 0dBm (mW) | 36 | | | | 36 | 42 | | 35 |
| Power Consumption | | | | | | | | |
| Minimum Operation (V) | 2.7 | | 2.7 | | 2.7 | | 1.8 | |
| Total Active Power (mW) | 24 | | | | 27 | 44 | 89 | 41 |
| Programming and Sensor Interface | | | | | | | | |
| Expansion | none | 51-pin | 51-pin | none | 51-pin | 19-pin | 51-pin | 10-pin |
| Communication | IEEE 1284 (programming) and RS232 (requires additional hardware) | | | | | | | USB |
| Integrated Sensors | no | no | no | yes | no | no | no | yes |

Low Power Operation

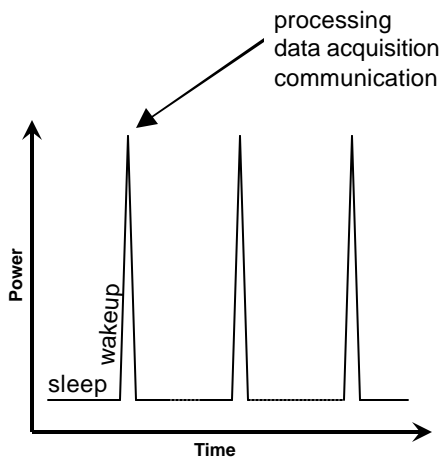
- Efficient Hardware
 - Integration and Isolation
 - Complementary functionality (DMA, USART, etc)
 - Selectable Power States (Off, Sleep, Standby)
 - Operate at low voltages and low current
 - Run to cut-off voltage of power source
- Efficient Software
 - Fine grained control of hardware
 - Utilize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

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

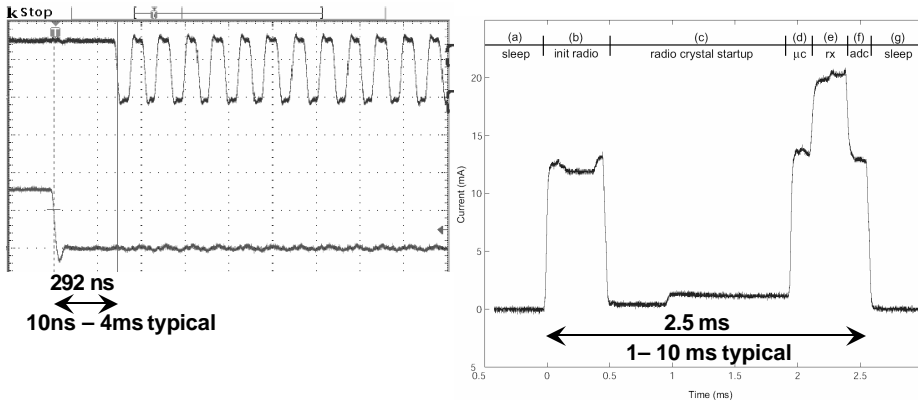


Sleep

- 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

Wakeup

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



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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

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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
 - 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.

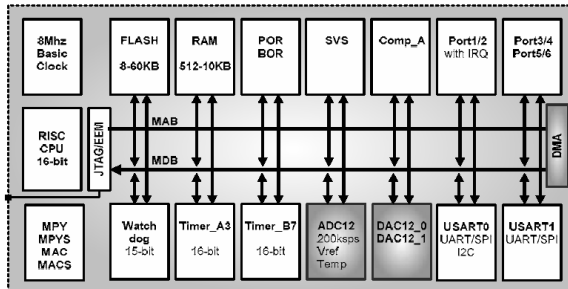
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Low Power Operation

- 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



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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 μ A
 - MicaZ: 30 μ A
- Wakeup
 - As quickly as possible to process and return to sleep
 - Telos: 290ns typical, 6 μ s max
 - MicaZ: 60 μ 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

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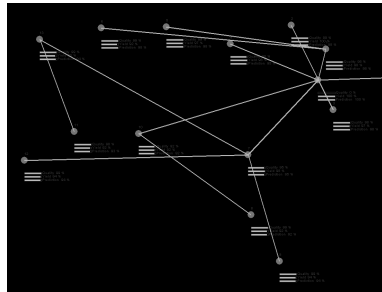
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CC2420 Radio

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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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



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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

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