CS649
Sensor Networks
Lecture 3: Hardware

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Outline

- Hardware characteristics of a WSN node
  - CPU and Memory
  - Radio
  - Power
- Examples architectures
  - Telos
  - Pushpin
  - XYZ
Wide Spectrum of Devices

- Sensors with implantable RFIDs
- Smart-dust size nodes
  - Typically they act as data-collectors or “trip-wires”
  - Cannot afford to have massive processing and communication
- Mote-size devices
- More powerful gateway nodes etc
- For some applications, form factor is also dictated by the size of individual sensors
- Many designs out there, each design has its own philosophy

A Generic Sensor Network Architecture

![Diagram of a generic sensor network architecture with sub-systems labeled: Sensing, Processing, Communication, Power Mgmt., Actuation]
Base Case: The Mica Mote
(The most popular sensing platform today)

AVR 128, 8-bit MCU

DS2401 Unique ID

Transmission Power Control

Hardware Accelerators

Radio Transceiver (CC1000 or CC2420)

Power Regulation MAX1678(3V)

51-PIN I/O Connector

Digital I/O Analog I/O Programming Lines

Another Example: Stargate

- A single board, wireless-equipped computing platform
- Developed at Intel Research

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**Stargate System architecture**

**MCU Basics: Many flavors of Microcontrollers**

- From embedded x86 processors 16 and 32-bit processors all the way down to tiny 4-bit processors
- Some of the popular 8-bit families
  - AVR, 8051, Z80, 6502, PIC, Motorola HC11
- 16-bit families
  - Hitachi, Dragon
- Many embedded Java controllers are also emerging
- Reading Sensors
  - A/D Controllers
  - Registers
Power Consumption

- Need long lifetime with battery operation
  - No infrastructure, high deployment & replenishment costs
- Challenges
  - Energy to wirelessly transport bits is \( \sim \)constant
    - Shannon, Maxwell
  - Fundamental limit on ADC speed*resolution/power
  - No Moore’s law for battery technology
    - \( \sim 5\% \)/year
- How is power consumed
  - CPU
  - Radio
  - Power Source
  - Mechanisms to conserve power

Energy Consumption in Wireless Sensor Nodes

- Processing
  - excluding low-level processing for radio, sensors, actuators
- Radio
- Sensors
- Actuators
- Power supply
Power Consumption in CMOS Digital logic

\[ P = A.C.V^2.f + A.I_{sw}.V.f + I_{leak}.V \]

where
- \( A \) = activity factor (probability of 0 \( \rightarrow \) 1 transition)
- \( C \) = total chip capacitance
- \( V \) = total voltage swing, usually near the power supply voltage
- \( f \) = clock frequency
- \( I_{sw} \) = short circuit current when logic level changes
- \( I_{leak} \) = leakage current in diodes and transistors

CPU: Approaches to Energy Efficiency

\[ P = \alpha C V^2 f \]

- “Continuous”
  - Only Throughput is Important
  - Reduce \( V \)
  - Increase h/w and algorithmic concurrency
- “Event-Driven”
  - Latency is Important (Burst throughput)
  - Make \( f \) low or 0
  - Shutdown when inactive

Reduce \( \alpha C \)
- Energy efficient s/w
- System partitioning
- Efficient Circuits & Layouts
Shutdown for Energy Saving

- Subsystems may have small duty factors
  - Wireless interface is often idle
- Huge difference between “on” & “off” power
  - Some Low-Power CPUs:
    - StrongARM: 400mW (active)/ 50 mW (idle) / 0.16 mW (sleep)
  - Matches WSN Applications

Energy in Radio

- Wireless communication subsystem consists of three components with substantially different characteristics
- Their relative importance depends on the transmission power of the radio
Examples

- The RF energy increases with transmission range
- The electronics energy for transmit and receive are typically comparable
- Note: For Telos $E_{tx} = 129 \text{nJ/bit}$, $E_{rx} = 144 \text{nJ/bit}$

Dominance of Electronics at Short Ranges

$E_{bit} = \alpha + \beta d^n$

Static Power, Digital Processing
Power amp, Receiver Sensitivity

<table>
<thead>
<tr>
<th>Radio</th>
<th>$\alpha$</th>
<th>Maximum $\beta d^n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.4 KHz OOK (RFM TR1000 @ 915 MHz)</td>
<td>14 nJ</td>
<td>3.1 nJ</td>
</tr>
<tr>
<td>115.2 KHz ASK (RFM TR1000 @ 916 MHz)</td>
<td>372 nJ</td>
<td>65 nJ</td>
</tr>
<tr>
<td>1 Mbps Custom (MIT µAMPS-1 @ 2.4 GHz)</td>
<td>570 nJ</td>
<td>740 nJ</td>
</tr>
<tr>
<td>11 Mbps 802.11b (Cisco Aironet 350 @ 2.4 GHz)</td>
<td>236 nJ</td>
<td>91 nJ</td>
</tr>
</tbody>
</table>

Re: Min et. al., Mobicom 2002 (Poster)
Energy Consumption of Transmitting a Bit

\[ \frac{E_{\text{packet}}}{L} = \left[ P_{\text{transmit}} + P_{\text{electronics}} \right] T_{\text{bit}} \left[ 1 + \frac{H}{L} \right] + \frac{E_{\text{overhead}}}{L} \]

- \( E_{\text{bit}} \): Optimize modulation
- Minimize header size
- Minimize overhead

\[ T_{\text{bit}} = \frac{1}{b \cdot R_S} \]

\[ E_{\text{bit}} = C_S \cdot G_S \cdot \left( 2^b - 1 \right) \cdot R_S + C_{E+R} \cdot \frac{1}{b} \]

Function of the target performance, only very weakly dependent on \( b \)

Operate at Max Symbol Rate

\[ R_S \uparrow \iff \begin{cases} E_{\text{bit}} \downarrow \\ T_{\text{bit}} \downarrow \end{cases} \]

It is preferable to operate at the maximum symbol rate that can be implemented efficiently (i.e. without severe penalty)

\[ E_{\text{bit}} = C_S \cdot G_S \cdot \left( \frac{2^b - 1}{b} \right) + C_{E+R} \cdot \frac{1}{b} \]

The energy is a function of the modulation level: there is an optimum value of \( b \), which depends on the parameters of the system.
Energy per Bit

Region of modulation scaling

Energy-Delay Trade-off

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### Computation & Communication

- Energy/bit + Energy/op large even for short ranges!

<table>
<thead>
<tr>
<th></th>
<th>Mote-class Node</th>
<th>WINS-class Node</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmit</td>
<td>720 nJ/bit</td>
<td>6600 nJ/bit</td>
</tr>
<tr>
<td>Receive</td>
<td>110 nJ/bit</td>
<td>3300 nJ/bit</td>
</tr>
<tr>
<td>Processor</td>
<td>4 nJ/op</td>
<td>1.6 nJ/op</td>
</tr>
<tr>
<td></td>
<td>~ 200 ops/bit</td>
<td>~ 6000 ops/bit</td>
</tr>
</tbody>
</table>

#### Energy breakdown for acoustic

- **Encode**
- **Decode**
- **Transmit**

#### Energy breakdown for image

- **Encode**
- **Decode**
- **Transmit**
- **Receive**

### Other power management features

- Wake on wireless: Bluetooth based remote wakeup
  - BT module awake, rest of the system is shutdown
  - Incoming BT packet causes wakeup
  - On-demand power management (event-driven apps)
  - BT module in “wake on wireless” mode draws ~ 3mA
- Motion detection for wake up
  - Passive small-bead mercury switch connected to GPIO
  - Movement causes switch to close and wakeup system
  - Can also be used to trigger wireless scanning for APs
**Source of Power: Batteries**

- Let’s go back to high school
  - When in operation the *electrochemical cell* essentially *discharges* its chemical energy in favor of electric energy. If the cell is connected via an external circuit from the cathode to the anode, electrons flow from the oxidized anode and are received by the cathode, which is subsequently reduced. The electric circuit is completed by cations and anions, within the electrolyte, which flow to the cathode and anode, respectively.

**Battery Characteristics**

- Important characteristics:
  - energy density (Wh/liter) and specific energy (Wh/kg)
  - power density (W/liter) and specific power (W/kg)
  - open-circuit voltage, operating voltage
  - cut-off voltage (at which considered discharged)
  - shelf life (leakage)
  - cycle life
- The above are decided by “system chemistry”
  - advances in materials and packaging have resulted in significant changes in older systems
    - carbon-zinc, alkaline manganese, NiCd, lead-acid
  - new systems
    - primary and secondary (rechargeable) Li
    - secondary zinc-air, Ni-metal hydride
Modeling the Battery Behavior

- Theoretical capacity of battery is decided by the amount of the active material in the cell
  - batteries often modeled as buckets of constant energy
    - e.g. halving the power by halving the clock frequency is assumed to double the computation time while maintaining constant computation per battery life
- In reality, delivered or nominal capacity depends on how the battery is discharged
  - discharge rate (load current)
  - discharge profile and duty cycle
  - operating voltage and power level drained

Battery Capacity

- Current in “C” rating: load current normalized to battery’s capacity
  - e.g. a discharge current of 1C for a capacity of 500 mA-hrs is 500 mA

from [Powers95]
Battery Capacity vs. Discharge Current: Peukert’s Formula

- Energy capacity: $C = \frac{k}{I^\alpha}$
  - $k$ = constant dependent on chemistry & design
  - $\alpha = 0$ for ideal battery (constant capacity), up to 0.7 for most loads in real batteries
    - also depends on chemistry and design
- Good first order approximation
  - does not capture effects of discharge profile
- Battery life at constant voltage and current:

$$L = \frac{C}{P} = \frac{C}{V \star I} = \frac{K}{I^\alpha} = \frac{K}{V \star I} = \frac{K}{V \star I^{-(1+\alpha)}}$$

Many ways to Optimize Power Consumption

- Power aware computing
  - Ultra-low power microcontrollers
  - Dynamic power management HW
    - Dynamic voltage scaling (e.g Intel’s PXA, Transmeta’s Crusoe)
    - Components that switch off after some idle time
- Energy aware software
  - Power aware OS: dim displays, sleep on idle times, power aware scheduling
  - Power management of radios
    - Sometimes listen overhead larger than transmit overhead
  - Energy aware packet forwarding
    - Radio automatically forwards packets at a lower level, while the rest of the node is asleep
  - Energy aware wireless communication
    - Exploit performance energy tradeoffs of the communication subsystem, better neighbor coordination, choice of modulation schemes
Outline

- Hardware characteristics of a WSN node
  - CPU and Memory
  - Radio
  - Power
- Examples architectures
  - Telos
  - Pushpin
  - XYZ

Mote Evolution

<table>
<thead>
<tr>
<th></th>
<th></th>
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<tbody>
<tr>
<td>Mote 1</td>
<td>1999</td>
<td>8</td>
<td>16</td>
<td>128</td>
<td>60</td>
<td></td>
<td></td>
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<tr>
<td>Mote 2</td>
<td>1999</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>2</td>
<td></td>
<td></td>
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<tr>
<td>Mote 3</td>
<td>2000</td>
<td>15</td>
<td>15</td>
<td>8</td>
<td>35</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Mote 4</td>
<td>2000</td>
<td>45</td>
<td>45</td>
<td>75</td>
<td>75</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>Mote 5</td>
<td>2004</td>
<td>1000</td>
<td>36</td>
<td>180</td>
<td>180</td>
<td>6</td>
<td></td>
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</table>

Nondurable storage

<table>
<thead>
<tr>
<th>Chip</th>
<th>AT89C2051</th>
<th>AT89S8251</th>
<th>ST M32RF151</th>
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<tbody>
<tr>
<td>Connection type</td>
<td>RS-232</td>
<td>RS-232</td>
<td>UART</td>
</tr>
<tr>
<td>Size (KB)</td>
<td>32</td>
<td>512</td>
<td>128</td>
</tr>
<tr>
<td>Communication</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rate</td>
<td>19.2 kbps</td>
<td>19.2 kbps</td>
<td>19.2 kbps</td>
</tr>
<tr>
<td>Modulation type</td>
<td>FSK</td>
<td>FSK</td>
<td>OQPSK</td>
</tr>
<tr>
<td>Receiver Power (mW)</td>
<td>9</td>
<td>12</td>
<td>38</td>
</tr>
<tr>
<td>Transmit Power at 4dBm (mW)</td>
<td>36</td>
<td>36</td>
<td>35</td>
</tr>
<tr>
<td>Minimum Operation (V)</td>
<td>2.7</td>
<td>2.3</td>
<td>2.7</td>
</tr>
<tr>
<td>Power Consumption (mA)</td>
<td>24</td>
<td>27</td>
<td>44</td>
</tr>
<tr>
<td>Integrated Sensors</td>
<td>no</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>Communication</td>
<td>IEEE 1294 (programming) and RS232 (requires additional hardware)</td>
<td>USB</td>
<td></td>
</tr>
</tbody>
</table>
Telos Platform

- Radio:
  - IEEE 802.15.4
  - CC2420 radio
  - 250kbps
  - 2.4GHz ISM band
- Processor:
  - TI MSP430 (16bit) @8MHz
  - 1.6µA sleep
  - 460µA active
  - 1.8V operation
- Robustness
  - Integrated antenna
  - Integrated sensors
  - Soldered connections

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. 1mA 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: 2.4mA
  - MicaZ: 30mA
- Wakeup
  - As quickly as possible to process and return to sleep
  - Telos: 290ns typical, 6ms max
  - MicaZ: 60ms 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)
Enclosures

Additional Architectures (Pushpin, MIT Media Lab)

- Stacked architecture
- Processor: Cygnal C8051F 22MHz (8 bit)
- Memory:
  - 2.25 KB RAM
  - 32 KB ROM
- Radio: Infrared
- Sensors: Microphone, light sensor
- Power: From special board
**Additional Architectures (XYZ, Yale)**

- Processor: OKI ML67Q5002 @ 56MHz
  - Scales down to 1MHz
  - Multiple operating modes
    - STANDBY, HALT, Sleep
- Memory:
  - 4KB Boot ROM
  - 32KB (+ 2 MB) RAM
  - 256 KB Flash
- Radio: Zigbee
- Sensors: Light Temperature, Accelerometer
- Motor
- Power Supply: 3 AA

**XYZ Power Consumption**

- CPU Cost:
  - CPU and total current is a function of frequency
- Memory Cost:
  - Read/Write 20mA
- Radio vs. Flash
  - 250kbps radio sending 1 byte
    - Energy: 1.5µJ
    - Duration: 32µs
  - Atmel flash writing 1 byte
    - Energy: 3µJ
    - Duration: 78µs
- Communication Cost:
  - Tx lower consumption than Listen(!)
- Mobility Cost:
  - 80mA (@6V)
- Compare with Telos
  - 460µA Active (3mW)
  - 1.8V operation