Energy of Wireless Devices
The Showstopper: Energy

- Need long lifetime with battery operation
  - No infrastructure, high deployment & replenishment costs
- Continual improvement in functionality, size, weight, and power
  - 1.6x/year in DSP power
  - sensing and RF components based on MEMs
- But
  - energy to wirelessly transport bits is \(~constant\)
    - Shannon, Maxwell
  - fundamental limit on ADC speed*resolution/power
  - no Moore’s law for battery technology
    - \(\sim 5\%/\text{year}\)

The Future
Approaches to reduce energy consumption

- OS turns off parts of the computer when are not in use (mostly IO devices such as display)
- Application program uses less energy, possibly degrading quality of the user experience
Hardware Issues

• Battery
  – Handheld devices: disposable batteries,
  – Laptops: rechargeable batteries

• Multiple power states for CPU, memory and I/O devices
  – Sleeping
  – Hibernating
  – Off

• Transition between power states:
  – Idle for a certain period of time, transition into lower power state
  – Activated when it is accessed
OS Issues

• Keep track of the states of different devices
• Which device to transition into low-power state?
• Window's ACPI - Advanced Configuration and Power Interface
• OS sends commands asking the device driver to report on device's states (power information)
  – if it shuts down a device and that device is needed again quickly, then there is overhead delay to restart the device;
  – if the device is long on, and it is not needed, then energy is wasted.
Which hardware/software component takes most energy?
Display Energy Management

• The biggest energy consumption
• Reason
  – Require backlit to get a bright sharp image
• What solutions would reduce display energy?
  – shut down the display if there is no activity for some number of minutes.
  – divide the screen into zones and turn on only zones where the active window resides (work by Flinn and Satyanarayanan)
  – Change color mapping scheme
Hard Disk

• Disk takes substantial energy
  – spinning at high speed, even if there are no accesses.
• What would be the solution to decrease energy?
  – spin the disk down after a certain idle time of activities.
  – When it is needed, it is spun up again
  – Disk cache in RAM can save energy
    • If a needed block is in the cache, the idle disk does not have to be restarted
  – Another possibility is to keep application programs informed when disk is down.
Memory

• Two options to save energy with memory:
  – cache is flushed and then switched off (hibernation)
  – write content of memory to disk and switch off the memory
• When memory is shut off
  – CPU has to shut off or has to execute out of ROM;
  – If CPU is off and interrupt wakes it up, it has to read from ROM
to load the memory.
• What are the tradeoff?
  – Switching off memory has high overhead
  – but it might be worth while if the idle times are long.
• Multiple power-mode
  – Active
  – Nap
  – Standby
  – Power-down
Wireless Communications is a Major Energy Hog

- 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><strong>Transmit</strong></td>
<td>720 nJ/bit</td>
<td>6600 nJ/bit</td>
</tr>
<tr>
<td><strong>Receive</strong></td>
<td>110 nJ/bit</td>
<td>3300 nJ/bit</td>
</tr>
<tr>
<td><strong>Processor</strong></td>
<td>4 nJ/op</td>
<td>1.6 nJ/op</td>
</tr>
<tr>
<td>~ 200 ops/bit</td>
<td></td>
<td>~ 6000 ops/bit</td>
</tr>
</tbody>
</table>

Energy breakdown for acoustic

- Transmit
- Receive
- Decode
- Encode

Energy breakdown for image

- Transmit
- Receive
- Decode
- Encode
Radio Power Consumption

Tx: Sender

Incoming information

Rx: Receiver

Outgoing information

\[ E_{\text{elec}}^{\text{Tx}} \quad E_{\text{RF}} \quad E_{\text{elec}}^{\text{Rx}} \]

Transmit electronics

Power amplifier

Receive electronics

\[ nJ/\text{bit} \]

\[ E_{RF} \quad E_{\text{elec}}^{\text{Tx}} \quad E_{\text{elec}}^{\text{Rx}} \]

\sim 1 \text{ km (GSM)}

\sim 50 \text{ m (WLAN)}

\sim 10 \text{ m (Mote)}^{11}
Domination of Electronics at Short Range

Sender Side Power Consumption

<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 @ 916 MHz)</td>
<td>14 $\mu$J</td>
<td>3.1 $\mu$J</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 $\mu$AMPS-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>
<tr>
<td>54 Mbps 802.11a (Atheros, ISSCC2002)</td>
<td>14.8 nJ</td>
<td>11 nJ</td>
</tr>
</tbody>
</table>

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

Static Power, Digital Processing

Power amp, Receiver Sensitivity

Re: Min et. al., Mobicom 2002 (Poster)
Radio Electronics Trends

Radiated power
63 mW (18 dBm)

Intersil PRISM II
(Nokia C021 wireless LAN)

Power amplifier
600 mW
(~11% efficiency)

Analog electronics
240 mW

Digital electronics
170 mW

Trends:
- Move functionality from the analog to the digital electronics
- Digital electronics benefit most from technology improvements
- Analog is bottleneck
- Digital complexity still increasing (robustness)
What can be done?

- Reduce energy/bit
- Increase energy availability
1. Radio Energy Management

• Parameter of interest:
  - energy consumption per bit

\[ E_{bit} = \frac{P}{T_{bit}} \]

\[ P^{Tx}_{elec} \]
\[ P_{RF} \]
\[ P_{Total} \]

Modulation scaling
fewer bits per symbol

Code scaling
more heavily coded

RF Dominates
Electronics Dominates
MAC: Scaling for Energy

- Radios with scalable modulation and coding
- MAC protocol that decides
  - Which node transmits
  - What packet
  - At what time
  - On what channel
  - With what RF power
  - What modulation and coding setting

Example: radio with Dynamic Modulation Scaling & scaling-aware scheduler
Shutdown

- Radio modes: active, idle, shutdown, transient

- Transient period
  - Active/idle to sleep is short and can be ignored
  - Sleep to active/idle period, $T_{ON}$, is not
    - PLL in the frequency synthesizer takes time to settle
    - $P_{tr} = 2P_{syn}$
    - $T_{ON}$ is $O(10)$-$O(100)$ uS
    - mixer & power amp startup can be ignored

- Problem: $T_{ON}$ is significant fraction of packet duration
  - Packet sizes small in sensor nets (reporting events)

- Leads to high energy per bit!

- Radios with fast start-up and acquisition
On-demand Data-driven Wakeup

- Sensor-triggered node wakeup

  Path nodes need to be woken up

  - How to wakeup?
  - Duty cycle the radio
    - trade-off between energy and latency
  - Wake-up circuit & protocols exploiting them
    - instantly wake up remote receiver radio when needed
    - minimize spurious wake ups & interference, and their impact
      - match destination address in addition to preamble
      - cheap directional antennas

<table>
<thead>
<tr>
<th>Radio mode</th>
<th>Power (mW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmit</td>
<td>14.88</td>
</tr>
<tr>
<td>Receive</td>
<td>12.50</td>
</tr>
<tr>
<td>Idle</td>
<td>12.36</td>
</tr>
<tr>
<td>Sleep</td>
<td>0.016</td>
</tr>
</tbody>
</table>
2. Reduced Path Loss via Directional Antenna

![SNR vs angle offset graph]

\[ y = 0.0017x^2 - 0.3827x + 28.444 \]

- **Smart antenna**
  - Signal processing (beamforming)
  - Low transient cost, high quiescent cost
- **Reconfigurable antennas**
  - Mechanical articulation, electrical reconfiguration
  - High transient cost, low quiescent cost

Microceptor QD2402
[Pon & Wu, UCLA, 2003]
Energy: Communication vs. Articulation

- 51 degrees/second latency
- Breakeven point: # of bits vs. gain in SNR
- Spend upfront energy and save on subsequent per-packet energy

[Articulated Microceptor QD2402
[ Pon & Wu, UCLA, 2003]
3. Exploiting Articulation & Mobility for Energy

• Rich source of system lifetime improvement
  – Nodes with articulated appendages
  – Nodes that move
    • Controlled, predictable, unpredictable
    • Restricted, unrestricted

• Opportunities
  – Better communication & sensing channel
  – Diversity gain due mobility
  – Mechanical transport of bits & energy
  – Better energy harvesting

• Challenges
  – Platforms with articulation & mobility
  – Protocols and collaboration algorithms to exploit mobility
  – Understanding the fundamental impact of mobility on lifetime
4. Beyond Reduction: Energy Harvesting

- Sensor nodes that extract energy from the environment and store in a capacitor or battery
  - Wind
  - Solar
  - Vibration/Motion
  - Chemical

- Challenge: how to manage energy harvesting?
  - Variation in harvesting opportunities
    - E.g. light level is a function of node location
  - How to extract maximum performance?
Harvesting-aware Network-level Tasking

- Tasking aware of battery status & harvesting opportunities
  - Richer nodes take more load
  - Looking at the battery status is not enough
- Learn the energy environment

Learn Local Energy Characteristics

Learn Consumption Statistics

Predict Future Energy Opportunity

Distributed Decision for Scheduling

Topology Control
Routing
Clustering
Example: Solar Harvesting Aware Routing

Simulation using light traces from James Reserve

HelioMote Platform
Summary

• Energy-efficient radios
  – Efficient shutdown and wake-up for short range
  – Energy-performance scalability for long range

• Directional antennas
  – Electrical or mechanical reconfiguration of directional elements

• Platforms and algorithms to exploit mobility and articulation
  – Better communication & sensing channel
  – Diversity gain due mobility
  – Mechanical transport of bits and energy
  – Better energy harvesting

• Energy harvesting
  – Network operation that is aware of spatio-temporal characteristics of environmental energy availability
Challenges

- Technologies
  - Energy-efficient and energy-scalable components
    • Radios, reconfigurable antenna, sensor processing (image, biochem)
  - Energy harvesting
    • Wind, solar, motion, vibration, chemical
  - Ad hoc infrastructure elements / hierarchy
    • Energy & data mule, Mobile Microservers
    • EM and wired energy delivery

- Techniques
  - Energy-latency-accuracy-coverage trade-offs
  - Algorithms: energy-efficient, battery-aware, harvesting-aware
  - Distributed in-network processing

- Metrics, Benchmarks, Tools, and Testbeds
  - Energy-metrics for sensing, signal processing, event detection, and communication protocols
  - Benchmark suite of representative functions
  - Simulators with models of energy producers and consumers
  - Instrumented testbeds
Beyond Saving Energy

• Ambient Backscatter
  – http://abc.cs.washington.edu/

• Wireless charging
  – https://www.youtube.com/watch?v=qr63Kl0SuFo