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
    - ~ 5%/year

The Future

Single-chip Wireless Sensor Node
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
• Which hardware/software component takes most energy?
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.
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 $\div$ Energy/op large even for short ranges!

### Mote-class Node

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

### WINS-class Node

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Energy breakdown for acoustic

**Encode** | **Decode** | **Transmit** | **Receive**

Energy breakdown for image

**Encode** | **Decode** | **Transmit** | **Receive**
Radio Power Consumption

Tx: Sender

Incoming information

Rx: Receiver

Outgoing information

$E_{\text{elec}}^{\text{Tx}}$
Transmit electronics

$E_{\text{RF}}$
Power amplifier

$E_{\text{elec}}^{\text{Rx}}$
Receive electronics

$nJ/\text{bit}$

$E_{\text{RF}}$ $E_{\text{elec}}^{\text{Tx}}$ $E_{\text{elec}}^{\text{Rx}}$

~ 1 km (GSM)

~ 50 m (WLAN)

~ 10 m (Mote)

$E_{\text{RF}}$ $E_{\text{elec}}^{\text{Tx}}$ $E_{\text{elec}}^{\text{Rx}}$
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</td>
<td>14 $\mu$J</td>
<td>3.1 $\mu$J</td>
</tr>
<tr>
<td>(RFM TR1000 @ 916 MHz)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>115.2 KHz ASK</td>
<td>372 nJ</td>
<td>65 nJ</td>
</tr>
<tr>
<td>(RFM TR1000 @ 916 MHz)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 Mbps Custom</td>
<td>570 nJ</td>
<td>740 nJ</td>
</tr>
<tr>
<td>(MIT $\mu$AMPS-1 @ 2.4 GHz)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11 Mbps 802.11b</td>
<td>236 nJ</td>
<td>91 nJ</td>
</tr>
<tr>
<td>(Cisco Aironet 350 @ 2.4 GHz)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>54 Mbps 802.11a</td>
<td>14.8 nJ</td>
<td>11 nJ</td>
</tr>
<tr>
<td>(Atheros, ISSCC2002)</td>
<td></td>
<td></td>
</tr>
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$E_{\text{bit}} = \alpha + \beta d^n$

Sender Side Power Consumption

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

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

- Modulation scaling: fewer bits per symbol
- Code scaling: more heavily coded
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
    - $P_{tr} = 2*P_{syn}$
    - $T_{ON}$ 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>
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<tr>
<th>Radio mode</th>
<th>Power (mW)</th>
</tr>
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<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

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

![Graph showing SNR vs angle offset](image_url)

The graph shows the relationship between SNR (in dB) and angle (in degrees). The equation for the curve is:

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

20 dB

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 Microreceptor 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?

Prototypes from IASL, UWE, Bristol.
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
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