Ultra-Low Energy Wireless Sensor and Monitor Networks

Jan M. Rabaey
http://www.eecs.berkeley.edu/~jan

In cooperation with Profs B. Brodersen, A. Sangiovanni-Vincentelli, K. Ramchandran, P. Wright, and the PicoRadio group.

PicoRadio Charter

Develop meso-scale low-cost radio’s for ubiquitous wireless data acquisition that minimize power/energy dissipation

– Minimize energy (<5 nJ/(correct) bit) for energy-limited source
– Minimize power (< 100 µW) for power-limited source (enabling energy scavenging)
– Target date 2004

By using the following strategies

– self-configuring networks
– fluid trade-off between communication and computation
– aggressive low-energy architectures and circuits
The Applications and Specs

The Obvious Choice - The Smart Home and Network Appliances

- Security
- Environment monitoring and control
- Object tagging
- Identification

Dense network of sensor and monitor nodes

Wireless in the Home

Source: IEEE Spectrum, December 99
Industrial Building Environment Management

- Task/ambient conditioning systems allow thermal condition in small, localized zones (e.g. work-stations) to be individually controlled by building occupants
- Requires dense network of sensor/monitor nodes
- Wireless infrastructure provides flexibility in composition and topology
- Joint research proposal CBE/BSAC/BWRC

The Interactive Museum

Other applications: toys, manufacturing, …
**System Requirements and Constraints**  
*(from Exploratorium scenario)*

- Large numbers of nodes — between 0.05 and 1 nodes/m²
- Cheap (<0.5$) and small ( < 1 cm³)
- Limited operation range of network — maximum 50-100 m
- Low data rates per node — 1-10 bits/sec average  
  - up to 10 kbit/sec in rare local connections to potentially support non-latency critical voice channel
- **Crucial Design Parameter:**  
  Spatial capacity (or density) — 100-200 bits/sec/m²

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**How to get there?**

- Network level
  - Functional & Performance Requirements
  - Network Architecture
  - Performance analysis

- Node level
  - Functional & Performance Requirements
  - Node Architecture
  - Performance analysis

**Think Energy!**
Opportunities

• **Exploit the application properties**
  – Sensor data is correlated in time and space
  – Sensing without precise localization seldom makes sense
  – Sensor networks rarely do need precise addressing
  – Duty cycle of sensor nodes is very small
• **And use node architectures that excel in the “common case”**
  – Stream-based data flow processing for baseband
  – Concurrent Finite State Machines for protocol stack

Some interesting numbers

• **Energy cost of digital computation**
  – 1999 (0.25μm): 1pJ/op (custom) … 1nJ/op (μproc)
  – 2004 (0.1μm): 0.1pJ/op (custom) … 100pJ/op (μproc)
    • Factor 1.6 per year; Factor 10 over 5 years
    • Assuming reconfigurable implementation: 1 pJ/op
• **Energy cost of communication**
  – 1999 Bluetooth (2.4 GHz band, 10m distance)
    • 1 nJ/bit transmission energy (thermal limit 30 pJ/bit)
    • Overall energy: 170 nJ/bit reception / 150 nJ/bit transmission (!)
    • Standby power: 300 μW
  – 2004 Radio (10 m)
    • Only minor reduction in transmission energy
    • Reduce transceiver energy with at least a factor 10-50
• **Trade-off**
  – @10m: 5000 operations / transmitted bit
  – @ 1m: 0.5 operations / transmitted bit
Power & energy dissipation in ad-hoc wireless networks

\[ P_{\text{link}} = (\alpha + \beta \times \text{dist}^\gamma) \times \frac{\text{bits}}{\text{sec}} + P_{\text{standby}} \]
\[ = \epsilon \left( \alpha + \beta \times \text{dist}^\gamma \right) \times \frac{\text{actual \_bits}}{\text{sec}} + P_{\text{standby}} \]
\[ E_{\text{actual \_bit}} = \epsilon \times \left( \alpha + \beta \times \text{dist}^\gamma \right) + \frac{P_{\text{standby}}}{\text{actual \_bits/\text{sec}}} \]

\( \alpha \): computation energy for transceiving a single bit
\( \beta \): transmission cost factor for a single bit
\( \gamma \): path-loss exponent (2..4)
\( \epsilon \): overhead (in extra bits needed for transmission of a single bit)

- \( P_{\text{standby}} \): standby power (eg., due to need to keep receiver on)

* These equations assume perfect power control

Saving Power at the Application Layer

\[ P_{\text{link}} = (\alpha + \beta \times \text{dist}^\gamma) \times \frac{\text{bits}}{\text{sec}} + P_{\text{standby}} \]
\[ = \epsilon \left( \alpha + \beta \times \text{dist}^\gamma \right) \times \frac{\text{actual \_bits}}{\text{sec}} + P_{\text{standby}} \]

- \( \alpha \): computation energy for transceiving a single bit
- \( \beta \): transmission cost factor for a single bit
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- \( P_{\text{standby}} \): standby power (eg., due to need to keep receiver on)

- \text{actual\_bits/sec}: source coding
  Opportunity: sensor data is correlated in time and space
  Trading off communication for computation
Distributed Source Coding (Ramchandran)

- Sensor networks present major spatial data correlation, but exploitation requires major intra-node communication

Good theoretical question:
How much performance loss if such communication unavailable?

- Answer: no performance loss! (under certain conditions) based on non-constructive information-theoretic argument (Slepian-Wolf).

Engineering question:
How do we develop a practical and constructive framework to optimize global network usage?

Distributed Source Coding using Spatial Correlation

- “Source Code”: Designed to get the desired distortion performance.
- Joint quantization and estimation:

  X  →  Quantizer  →  W  →  Estimation  →  Y↑  →  Ÿ

  Quantizer:
  • Quantize X to a finite set of codewords (W).
    (Mapping from X to W)
  • The codewords in the set W => “Source Codes”

  Estimation:
  • Estimate X from the index of W and the side information Y.
    (Mapping from W and Y to the reconstruction space Ÿ.)
Saving Power at the Network Layer

\[ P_{\text{link}} = (\alpha + \beta \times \text{dist}^\gamma) \times \frac{\text{bits}}{\text{sec}} + P_{\text{standby}} \]

- \( \alpha \): computation energy for transmission of a single bit
- \( \beta \): transmission cost factor for a single bit
- \( \gamma \): path-loss exponent (2..4)
- \( \epsilon \): overhead (in extra bits needed for transmission of a single bit)
- \( P_{\text{standby}} \): standby power (e.g., due to need to keep receiver on)

- \( \text{dist} \): network partitioning using multi-hop
- \( \epsilon \): cost of network discovery and maintenance

Opportunities:
- exploit application (i.e. sensing) properties
- merge with localization

Communicating over Long Distances

Multi-hop Networks

Example:
- 1 hop over 50 m
  - 1.25 nJ/bit
- 5 hops of 10 m each
  - \( 5 \times 2 \text{ pJ/bit} = 10 \text{ pJ/bit} \)
- Multi-hop reduces transmission energy by 125! (assuming path loss exponent of 4)

But … network discovery and maintenance overhead
**Proactive Routing**

- **Example: DSDV (Destination-sequenced Distance Vector)**
  - Nodes continuously evaluate routes
  - Routes are (almost) always optimal
  - Efficient if many routes are popular
  - Two main types of update packets
    - Periodic Broadcast - scheduled update
      - Periodicity depends on how accurate a picture is needed about the network topology. The rate has to be faster than the rate at which the network is changing.
    - Triggered Broadcast - scheduled as needed.

**Reactive Routing**

- **Examples: AODV (Ad-hoc On-Demand Distance Vector), DSR (Dynamic Source Routing)**
  - Nodes evaluate routes only on a “as-needed” basis.
  - Efficient if routes are used infrequently. Routes can become suboptimal over time.
    - New routes are acquired only if the old one expired or broke!
  - Two main types of routing packets
    - Request/Discover Packet
      - Uses controlled flooding
    - Reply Packet
      - Unicast back
  - Alternative versions directed towards sensor networks
    - Directed diffusion (Estrin) uses data-classes for addressing
    - Swarm intelligence (Sc. American March 00) uses reinforcement and evaporation
Comparing the approaches from an energy perspective

- Energy = Eb * Packet Size
- Reactive Routing good for rarely used routes
- Proactive Routing good for frequently used routes
- Need solution that is more adequate for problem at hand: class-based and location-based addressing.

Routing Overhead (bytes) (discovering one route)

Routing Overhead (bytes) Normalized (discovering n routes)

Joined Networking-Positioning

- Ubiquitous radio networks offer reasonable localization with minimal overhead
- Use network state to prune and filter updates
- Use positioning information to direct and dampen data traffic (geographic routing - Jain)
**Saving Power at the Media Access Layer (⃣)***

\[ P_{\text{link}} = (\alpha + \beta \times \text{dist}^\gamma) \times \frac{\text{bits}}{\text{sec}} + P_{\text{standby}} = (\alpha + \beta \times \text{dist}^\gamma) \times \frac{\text{actual bits}}{\text{sec}} + P_{\text{standby}} \]

- \( \alpha \): computation energy for transceiving a single bit
- \( \beta \): transmission cost factor for a single bit
- \( \gamma \): path-loss exponent (2..4)
- \( \epsilon \): overhead (in extra bits needed for transmission of a single bit)
- \( P_{\text{standby}} \): standby power (eg., due to need to keep receiver on)

- **\( P_{\text{standby}} \):** Power-management of inactive nodes
- **\( \epsilon \):** Cost of collisions and retransmissions (interference)
  - Opportunities: distribution of communication in time and frequency
    - rendez-vous scheduling in local neighborhood
    - usage of multiple virtual channels reduces interference

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**Mostly-Sleepy MAC Layer Protocols**

- **Computational** energy for receiving a bit is larger than the **computational** energy to transmit a bit (receiver has to discriminate and synchronize)
- Most MAC protocols assume that the receiver is always on and listening!
- Activity in sensor networks is low and random
- Careful scheduling of activity pays off big time, but ... has to be performed in distributed fashion
- **Options:**
  - Reactive MAC protocol, assumes that radio can be woken up - tough
  - Simulated reactive – each nodes occasionally wakes up and announces its presence - inefficient
  - Proactive or scheduled wake-up – challenge in ad-hoc networks, has to be addressed in distributed fashion
**Energy-Efficient Media Access**

Example: Collision-sense multiple access (CSMA) with overlayed locally-synchronized TDMA framing (rendez-vous)

Adding multi-channel diversity (CDMA or FDMA) reduces collisions and retransmissions (channels allocated in distributed fashion)

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**Saving Power at the Physical Layer**

\[
P_{\text{link}} = (\alpha + \beta \times \text{dist}^\gamma) \times \frac{\text{bits}}{\text{sec}} + P_{\text{standby}}
\]

- \(\alpha\): computation energy for transceiving a single bit
- \(\beta\): transmission cost factor for a single bit
- \(\gamma\): path-loss exponent (2..4)
- \(\varepsilon\): overhead (in extra bits needed for transmission of a single bit)

- \(P_{\text{standby}}\): standby power (e.g., due to need to keep receiver on)

- **\(\alpha\)**: Choice of data rate, modulation, physical channel access
- **\(\varepsilon\)**: Cost of framing, channel coding, synchronization, CRC

Opportunities: radio’s with fast acquisition (and probably less perfect channel)
**PicoRadio Implementation Issues**

- Dynamic nature of PicoRadio networks requires adaptive, flexible solution
- Traditional programmable platforms cannot meet the stringent low-power requirements
  - 3 orders of magnitude in energy efficiency between custom and programmable solutions
- Configurable (parameterizable) architectures combine energy efficiency with limited flexibility
- System-on-a-chip approach enables integration of heterogeneous and mixed mode modules on same die
- Predicted improvements: factor 10 each year!

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**The Mostly Digital Radio**

![Digital Baseband Receiver Diagram]

- RF input ($f_c = 2$GHz)
- RF filter
- LNA
- cos$[2\pi(2$GHz$)t]$ and sin$[2\pi(2$GHz$)t]$ signals
- A/D conversion
- Digital Baseband Receiver

- I (50MS/s)
- Q (50MS/s)
The Energy-Flexibility Gap

<table>
<thead>
<tr>
<th>Energy Efficiency (MOPS/mW)</th>
<th>Flexibility (Coverage)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td></td>
</tr>
<tr>
<td>100</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td></td>
</tr>
<tr>
<td>0.1</td>
<td></td>
</tr>
</tbody>
</table>

- **Embedded Processors**
  - SA110: 0.4 MIPS/mW
- **Reconfigurable Processor/Logic**
  - Pleiades: 10-80 MOPS/mW
- **ASIPs DSPs**
  - 2 V DSP: 3 MOPS/mW
- **Dedicated HW**

(Re)configurable Computing: Merging Efficiency and Versatility

Spatially programmed connection of processing elements.

"Hardware" customized to specifics of problem.

Direct map of problem specific dataflow, control.

Circuits “adapted” as problem requirements change.
Architecture Comparison

LMS Correlator at 1.67 MSymbols Data Rate
Complexity: 300 Mmult/sec and 357 Macc/sec

<table>
<thead>
<tr>
<th>Type</th>
<th>Power</th>
<th>Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>TMS320C54x</td>
<td>460 mW</td>
<td>1089 mm²</td>
</tr>
<tr>
<td>Pleiades</td>
<td>18.09 mW</td>
<td>5.448 mm²</td>
</tr>
<tr>
<td>ASIC [Zhang]</td>
<td>3 mW</td>
<td>1.5 mm²</td>
</tr>
</tbody>
</table>

Note: TMS implementation requires 36 parallel processors to meet data rate - validity questionable

16 Mmacs/mW!

Intercom TDMA MAC
Implementation alternatives

<table>
<thead>
<tr>
<th></th>
<th>ASIC</th>
<th>FPGA</th>
<th>ARM8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power</td>
<td>0.26mW</td>
<td>2.1mW</td>
<td>114mW</td>
</tr>
</tbody>
</table>

- ASIC: 1V, 0.25 μm CMOS process
- FPGA: 1.5 V 0.25 μm CMOS low-energy FPGA
- ARM8: 1 V 25 MHz processor; n = 13,000
- Ratio: 1 - 8 - >> 400

Idea: Exploit model of computation: concurrent finite state machines, communicating through message passing
The Integrated PicoNode

- Configurable DataPaths
- Configurable FSMs
- Embedded uP
- Dedicated DSP
- Configurable DataPaths

Data Acquisition And Monitoring
Baseband Communications Processing

Protocol Stack

A Testbed for PicoRadio

- Flexible platform for experimentation on networking and protocol strategies
- Size: 3”x4”x2”
- Power dissipation < 1 W (peak)
- Multiple radio modules: Bluetooth, Proxim, ...
- Collection of sensor and monitor cards
- Fully operational by late spring (including software support system)!
**TCI — An Exercise in Integrated Wireless Node Design**

- Known and tested specification of limited complexity allows focus on architectural implementation methodology
- Two-chip implementation leverages separates between analog (RF) and digital design concerns
- Duration of exercise: 1 year (summer ’00)

Up to 20 users per cell @ 64 kbit/sec per link
TDMA selected as MAC protocol

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**Two-Chip Intercom (TCI)**

- Custom analog circuitry
- Mixed analog/digital
- Fixed logic
- Programmable logic
- Software running on processor
- Protocol
- Digital Baseband processing

Direct down-conversion front-end
(Yee et al)
TCI Implementation Platform

Tensilica Embedded Proc.  Memory Sub-system

Sonics Backplane

Baseband Processing  Configurable Logic (Physical Layer)  Programmable Protocol Stack

Benefit: Build library of computational and networking modules (and models)

The Holy Grail: Energy Scavenging

<table>
<thead>
<tr>
<th>Energy Sources</th>
<th>Power (Energy) Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Batteries (Zinc-Air)</td>
<td>1050 - 1560 mWh/cm³</td>
</tr>
<tr>
<td>Batteries (rechargeable Lithium)</td>
<td>300 mWh/cm³ (3 - 4 V)</td>
</tr>
<tr>
<td>Solar</td>
<td>15 mW/cm² - direct sun</td>
</tr>
<tr>
<td></td>
<td>1 mW/cm² - ave. over 24 hrs.</td>
</tr>
<tr>
<td>Vibrations</td>
<td>0.05 - 0.5 mW/cm³</td>
</tr>
<tr>
<td>Inertial Human Power</td>
<td>3E-6 mW/cm² at 75 Db</td>
</tr>
<tr>
<td></td>
<td>9.6E-4 mW/cm² at 100 Db</td>
</tr>
<tr>
<td>Acoustic Noise</td>
<td>9.6E-4 mW/cm²</td>
</tr>
<tr>
<td>Non-Inertial Human Power</td>
<td>1.8 mW (Shoe inserts)</td>
</tr>
<tr>
<td></td>
<td>80 mW/cm³</td>
</tr>
<tr>
<td>Nuclear Reaction</td>
<td>1E6 mWh/cm³</td>
</tr>
<tr>
<td>One Time Chemical Reaction</td>
<td>800 mW/cm³</td>
</tr>
<tr>
<td>Fluid Flow</td>
<td>300 - 500 mW/cm²</td>
</tr>
<tr>
<td>Fuel Cells</td>
<td>4000 mWh/cm³</td>
</tr>
</tbody>
</table>

SOURCE:
P. Wright & S. Randy
UC ME Dept.
**Example: MEMS Variable Capacitor**

Out of the plane, variable gap capacitor

Up to 10 µW of power demonstrated

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**PicoRadio Design Challenges**

PicoNode Architecture Design

- Positioning
- Network Architecture
- Energy Constraints
- Use Cases
- Performance Analysis
- Analytical Analysis