Reducing the Energy Footprint for Wireless and Mobile Communication Systems

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Envisioning Energy Efficient Sensing and Computing Systems: In the Home
Envisioning Energy Efficient Sensing and Computing Systems: In the Field

http://www.fujitsu.com/global/Images/back-ground-03_tcm100-915575.jpg
Energy Concerns

- Large-scale energy reduction
  - Reduce use of fossil fuels
  - Help the environment
- Small-scale energy reduction
  - Reduce size of batteries
  - Ensure longer lifetimes for mobile devices
- Energy harvesting
  - Renewable energy
  - Potentially infinite lifetime
Goal: Reduce Energy Footprint for…

- **Sensing**: utilize sensor networks to connect physical world to virtual world
  - Requires energy efficient protocols and algorithms that meet application QoS

- **Computing**: exploit processing power provided by abundant energy efficient smart phones
  - Requires minimal disruption to devices

- **Communication**: efficiently communicate in energy harvesting networks
  - Requires protocols and algorithms that adapt to varying energy availability throughout the network
Wireless Communications and Networking Group @ UR

- Wireless Sensor Networks
  - Sleep management
  - Protocols and architectures
  - Wake-up radios
- Mobile-Cloud Computing
- Self-Powered Field Systems
- RFID Networks
  - MAC protocols
  - RFID-Sensor networks
- Mobile Ad Hoc Networks
  - Cross-layer architectures
  - Quality of Service (QoS)
- Emotion Classification from Speech
- Protein Structure Prediction
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Wireless Sensor Networks

- Tens to thousands of nodes scattered throughout an environment
- Data routed via other sensors to
  - One or more sinks or base stations
  - Other sensors
- Unique characteristics
  - Ad hoc network
  - No end-to-end communication
  - Co-operative operation
  - Redundancy in information

Networks of distributed data sources that provide information about environmental phenomena to an end user or multiple end users
Roles of Nodes in WSNs

- **Sources**
  - Measure data, report “somewhere”
  - Equip nodes with different kinds of actual sensors

- **Sinks**
  - Interested in receiving data from WSN
  - May be part of the WSN or external entity

- **Actuators**
  - Control some device based on data

- **Routers**
  - Forward data for other nodes
Popular Sensor Platforms

- Crossbow MICAz
  - http://www.xbow.com

- Sentilla Tmote Sky
  - http://www.sentilla.com

- Crossbow/Intel Imote2
  - http://www.xbow.com

- Ember EM250
  - http://www.ember.com

- Arduino UNO
  - http://www.adafruit.com/
Sample Applications

Health monitoring

Environment Monitoring

Structural Integrity

Security
Environmental Monitoring

- Raw sensor data or high level descriptions about environmental phenomena
- Example projects
  - Ecology of rare plants in Hawaii
  - ZebraNet
Health Monitoring

- Sensors monitor vital signs
  - Blood pressure, heart rate, EKG, blood O2
- Sense, process, understand, control
- Requires protocols that are
  - Reliable, flexible, scalable, secure
Precision Agriculture

- Deliver fertilizer/pesticides/irrigation only where needed
- Grape Networks
  - California-based company: WSN covers 50 acres, > 200 sensors
  - WSN broadcasts
    - Location of the sensors
    - Temperature, humidity, light
    - Powdery mildew
    - Degree days
  - Sensors buried next to grapes
  - Can view data over web
  - Can set thresholds for automatic alerts
- Many similar projects on monitoring vineyards

Source: http://blog.xbow.com/photos/uncategorized/2007/10/18/nodedeployment_2.jpg
Other Applications

- Disaster relief operations
  - Deploy sensors in area hit by disaster (fire, earthquake, etc.)
  - Derive a “map” of safe/dangerous areas within building, grounds, etc.

- Intelligent buildings (or bridges)
  - Reduce energy waste by proper HVAC control
  - Predict structure failures

Source: [http://www.disasterlogistics.org/assets/images/Turkey_Earthquake_103.jpg](http://www.disasterlogistics.org/assets/images/Turkey_Earthquake_103.jpg)

Source: [http://ds.informatik.rwth-aachen.de/teaching/ws0607/labsn](http://ds.informatik.rwth-aachen.de/teaching/ws0607/labsn)
Other Applications

- Logistics
  - Equip goods (parcels, containers) with sensors
  - Track whereabouts – total asset management
  - Note: passive readout might suffice – RFIDs

- Vehicular sensor networks
  - Provide better traffic control by obtaining finer-grained information about traffic conditions
  - Intelligent roadside
  - Cars as sensor nodes

Source:
Wireless Sensor Networks

Goals

- Provide rich understanding of environment
- Long lifetime
- Reliable

Challenges

- Resource-limited
- Maintaining application’s required quality of service

Applications

- Health Monitoring
- Environmental Monitoring
- Security
- Structural Monitoring
Energy Saving Techniques

- Ways to save energy in WSNs
  - Energy-efficient devices
  - Energy-efficient protocols
- Sleeping techniques → how to maintain QoS?

Current draw of node subsystems for Tmote Sky
Waking Up

- Two general solutions:

<table>
<thead>
<tr>
<th>Wake up approach</th>
<th>Potential Benefits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duty cycling</td>
<td>Less hardware cost</td>
</tr>
<tr>
<td>Nodes wake up periodically</td>
<td></td>
</tr>
<tr>
<td>Wake-up Radio</td>
<td>More energy efficient</td>
</tr>
<tr>
<td>Nodes are awakened by remote trigger</td>
<td>No added latency</td>
</tr>
</tbody>
</table>
Wake-up Radios

- Active wake-up radios
  - Consume battery energy at the receiver side
  - Better wake-up range than passive
  - Ex. Austria Microsystems’ wake-up receiver, 8.1 μW with a sensitivity of -37 dBm

- Passive wake-up radios
  - Do not battery consume energy at the receiver side
  - Shorter wake-up range than active
  - Ex. Intel Research’s passive RFID tag – WISP, works at 900 MHz, No battery energy consumption with a sensitivity of -10 dBm
WISP-Mote – a Sensor Node with Passive Wake-up Radio

- Intel WISP external wake-up radio for TmoteSky mote

<table>
<thead>
<tr>
<th>Operation</th>
<th>Average current consumption</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wake-up</td>
<td>10.4 mA</td>
<td>5 ms</td>
</tr>
<tr>
<td>Transmit 12 bytes packet</td>
<td>18.2 mA</td>
<td>30 ms</td>
</tr>
<tr>
<td>Receive and idle listening</td>
<td>20.2 mA</td>
<td></td>
</tr>
<tr>
<td>Sleep</td>
<td>0.2 mA</td>
<td></td>
</tr>
</tbody>
</table>
Field Test: Wake-up Probability
Broadcast-based Wake-up

Outdoor

Indoor
Simulation in a Data MULE Scenario

Simulation Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area</td>
<td>200m x 200m</td>
</tr>
<tr>
<td>Node deployment</td>
<td>Uniformly random</td>
</tr>
<tr>
<td>MULE’s mobility</td>
<td>Random direction, speed randomly chosen from [5m/s, 15m/s]</td>
</tr>
<tr>
<td>Range</td>
<td>From our field experiment, 40m for mote communication</td>
</tr>
<tr>
<td>Performance metrics</td>
<td>Delay, pdr, collision, energy consumption</td>
</tr>
</tbody>
</table>
Effect of Packet Rate

WISP-Mote vs. Duty-cycling with increasing packet rate
(0.002 nodes/m², 1 data MULE, unlimited buffer size)
Effect of Node Density

- Average packet delay (s)
- Undelivered packets ratio (UPR/\%)
- Average collisions per pkt
- Energy consumption per pkt (\mu J)

WISP-Mote vs. Duty-cycling with increasing node densities (1 pkt/min, 1 data MULE, unlimited buffer size)
Wildlife Monitoring Scenario

- Data collector placed at animal congregating points, e.g., ponds and rivers
- 1km² area with pond at the center
- Animals move follows random direction model with mean speed of 5m/s
- Move $t_r$ then stay at pond for $t_s$. $R = t_s/t_r$ varies in the simulation

Animal monitoring scenario
D1= 1% Duty-cycling with R = 1, W1=WISP-Mote with R = 1
D2=1% Duty-cycling with R = 2, W2=WISP-Mote with R = 2
(0.2 pkt=min, buffer size unlimited)
REACH-Mote: Improved Wake-up

Ultra Low Power Wake-up Pulse Generator

Fig. 4. REACH-Mote system components.
Field Test Results - Broadcast Wakeup

- **WuRx: WISP-Mote**
  - Range of the EH-WISP-Mote increases by 20% compared to WISP-Mote
  - Benefit of adding the energy harvesting circuit

- **WuRx: EH-WISP-Mote**
  - REACH-Mote best performance
  - Achieves 37ft wake-up range
  - Covers an area almost 3x that of the WISP-Mote and 2x that of the EH-WISP-Mote
Computing

- Wake-up radios enable energy-efficient sensing and transmission of data
- What about computation of data?
- Cloud computing increasingly popular for large amounts of computation, but is it energy efficient?
Mobile devices are increasingly popular

Mobile devices are becoming the most popular devices of all
Mobile devices are increasingly powerful

The gap of computing power between mobile devices and desktop PCs is narrowing
Mobile devices are **energy efficient**

**CPU Thermal Designed Power**

- Thermal Designed Power (Watt)
  - Tegra 2 (Smartphone): 2 Watt
  - Intel i7 (PC): 95 Watt

Mobile devices are expected to have higher energy efficiency than PCs
Mobile devices are often *idle*
Can we make better use of *idle* mobile CPU time?

Huge pool of untapped energy-efficient computing resource

The gap of computing power between mobile devices and PCs is narrowing

Mobile devices are often *idle*
GEMCloud: Green Energy Mobile Cloud

- What is GEMCloud?
  - Distributed computing using crowd-sourced mobile devices
  - A new way to satisfy increasing demand for computing resources
GEMCloud
## Test Environment

<table>
<thead>
<tr>
<th>Tested Device</th>
<th>CPU</th>
<th># of Cores</th>
<th>Memory</th>
<th>Release Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xiaomi Mi-One (MO)</td>
<td>Qualcomm Snapdragon S3 Dual Core 1.5GHz</td>
<td>2</td>
<td>1GB</td>
<td>2011</td>
</tr>
<tr>
<td>Samsung Galaxy S3 (GS3)</td>
<td>Qualcomm Snapdragon S4 Dual Core 1.5GHz</td>
<td>2</td>
<td>2GB</td>
<td>2012</td>
</tr>
<tr>
<td>Asus Nexus 7 (N7)</td>
<td>Nvidia Tegra 3 Quad Core 1.2GHz</td>
<td>4</td>
<td>1GB</td>
<td>2012</td>
</tr>
<tr>
<td>Workstation1 (WS1)</td>
<td>Intel Xeon E7505 * 2 Single Core 3.06GHz * 2</td>
<td>2</td>
<td>8GB</td>
<td>2003</td>
</tr>
<tr>
<td>Workstation2 (WS2)</td>
<td>Intel Xeon X5355 * 2 Quad Core 2.66GHz * 2</td>
<td>8</td>
<td>24GB</td>
<td>2006</td>
</tr>
<tr>
<td>Workstation3 (WS3)</td>
<td>AMD Opteron 6276 * 4 16-Core 2.33GHz * 4</td>
<td>64</td>
<td>192GB</td>
<td>2011</td>
</tr>
</tbody>
</table>
Computing Performance

Single thread → Full capacity

Time to complete (s)

Number of tasks

MO GS3 N7 WS1 WS2 WS3

35%

5x 102x 139x

Energy Consumption

Single thread → Full capacity

- 57~93x
- 18x
- 2x
- 59x

Bar chart showing energy consumption (J) vs. number of tasks to complete. Legends: MO, GS3, N7, WS1, WS2, WS3.
Energy Consumption when Idle

Mobile devices (screen off)
- MO 0.6W
- GS3 0.001W
- N7 0.5W

Workstations (monitor off)
- WS1 118W
- WS2 350W
- WS3 350W

The difference is at least 200 fold!
Save energy while being competitive on speed

- Single task, GS3 vs. WS3
  - Computing time: 5 : 1
  - Energy consumption: 1 : 57

- Full capacity, GS3 vs. WS3
  - Computing time: 139 : 1
  - Energy consumption: 1 : 2

- Full capacity, 32 GS3 vs. WS3
  - Computing time: 5 : 1 (1.5:1 for WS1; 3:1 for WS2)
  - Energy consumption: 1 : 2 (1:59 for WS1; 1:18 for WS2)

Using large number of mobile devices saves >50% of energy at any utilization level while providing competitive speed!
Challenges for Real-world Applications

- Cannot interfere with intended use of mobile devices
- Data security
- User motivation
Features to Ensure User Experience

- Installation is the *only* required user action
- Does NOT interfere with normal use of mobile devices
  - App automatically *throttles down* computing when device
    - is busy
    - is low on power or not being charged
    - is picked up
    - receives phone call
    - has higher-than-normal battery temperature
- Does NOT incur data costs
  - Only uses Wi-Fi, unless user explicitly allows data usage

Easy to use. No hassle.
Features for Data Security

- Multiple encryption levels
  - Balance encryption strength against time & energy use
  - Strong encryption only for important pieces of data

- Breaking data into thousands of pieces
  - Each mobile device gets a small piece of puzzle to solve
  - Hard to intercept all pieces of data
  - Pieces of data are encrypted by different encryption methods with different keys

Strong data security with minimum time & energy cost.
The Mobile Crowd: Motivation

I want to help medical research!

Let's save energy and reduce landfill!

It's a cool technology! I want to try it!

I want to be #1 on the scoreboard!

My friends are using this app!
GEMCloud: Save Energy, Reduce Landfill

Huge pool of untapped energy-efficient computing resource

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Let's save energy and reduce landfill!

I want to help epilepsy research!

Patients
Relatives
Friends
Advocacy groups
Doctors
Researchers

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Mobile Devices

Server
Communication

- Energy-harvesting becoming increasingly viable for long-lasting systems (e.g., solar)
- Field systems for sensing environmental data
- Varying energy for nodes in the network due to
  - Location
  - Load
  - Phenomena in the environment being sensed
- How to optimize communication for this scenario?
Multiple Input Multiple Output (MIMO) System

- Use multiple antenna at the Tx and/or Rx
- Spread transmission power among different antennas to increase performance
- Less transmission energy but higher circuit energy than SISO
- Dynamic antenna selection: choose MIMO, MISO, SIMO, SISO interchangeably during communication
Motivation

Dynamic antenna selection using MIMO
System Model

- Receiver power consumption
  
  \[ P_{rx} = M_{rx} (P_{RX-Circuit}) \]

- Transmitter power consumption
  
  \[ P_{rx} = M_{tx} \times (P_{TX-Circuit}) + P_{Transmission}(M_{tx}, M_{rx}) \]

- Energy consumption per bit for the transmitter and the receiver
  
  \[ E_{Cons}^X(M_{tx}, M_{rx}) = \frac{P^X}{R_b}, X = \{tx, rx\} \]
System Model (cont.)

- Transmitter and receiver lifetimes:

\[ L_X = \frac{E^X_{\text{init}}}{E^X_{\text{Cons}}(M_{tx}, M_{rx}) \times BER} \quad X = \{tx, rx\} \]

- System lifetime = number of successful packets:

\[ L = \min\{L_{tx}, L_{rx}\} \]
Dynamic Antenna Selection Policies

1. **TX Policy**: choose a MIMO scheme ($M_{tx}$ and $M_{rx}$) to maximize TX lifetime ($L_{tx}$).

2. **RX Policy**: choose a MIMO scheme ($M_{tx}$ and $M_{rx}$) to maximize RX lifetime ($L_{rx}$).

3. **Online Policy**: At each time slot $t$, choose MIMO scheme that maximizes the system’s lifetime $L$.

4. **Optimal Policy**:

   $\begin{align*}
   \max \text{ lifetime } L \\
   \text{s.t.} \quad & TX-E_{cons} < TX-E_{init} \\
   & RX-E_{cons} < RX-E_{init}
   \end{align*}$
Simulation Results

- Compare Optimal, Online, TX, and RX policies in terms of system lifetime
Conclusions

- Energy efficiency an important characteristic of wireless and mobile sensing and computing systems
- Must consider how to reduce energy footprint for sensing, computation and communication
- Ensures future systems will be “green” and provide longer network lifetimes
Questions?

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