CS649
Sensor Networks
Lecture 2: Applications

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Outline

- Study WSN applications
  - Environmental Monitoring
  - Wildlife Monitoring
  - Sniper Detection
  - Structural Monitoring
- Derive application requirements for WSNs
Environmental Monitoring

- Two examples
  - Great Duck Island
  - Zebranet
Scientific motivation: Leach’s Storm Petrel

• Questions
  • What environmental factors make for a good nest? How much can they vary?
  • What are the occupancy patterns during incubation?
  • What environmental changes occur in the burrows and their vicinity during the breeding season?

• Methodology
  • Characterize the climate inside and outside the burrow
  • Collect detailed occupancy data from a number of occupied and empty nest
  • Spatial sampling of habitat – sampling rate driven by biologically interesting phenomena, non-uniform patches
  • Validate a sample of sensor data with a different sensing modality
  • Augmented the sensor data with deployment notes (e.g. burrow depth, soil consistency, vegetation data)
  • Try to answer the questions based on analysis of the entire data set
Computer science research

- Focus on problems that matter to users of the system!
  - Network architecture
    - Can this application be easily recast in other scenarios
  - Long-distance management
- Node design tradeoffs
  - Mechanical – expose sensors, while protecting the electronics
  - Low power hardware vs. high quality sensing
  - Size matters!
- Real world testbed
  - How do the simulation and lab results translate into the deployed application
  - What are common failure modes?
  - What factors impact the functionality and performance of the sensor network?
  - How do they vary across different deployments?
Sensor Node GDI ’02

- Mica platform
  - Atmel AVR w/ 512kB Flash
  - 916MHz 40kbps RFM Radio
    - Range: max 100 ft
    - Affected by obstacles, RF propagation
  - 2 AA Batteries, boost converter
- Mica weather board – “one size fits all”
  - Digital Sensor Interface to Mica
    - Onboard ADC sampling analog photo, humidity and passive IR sensors
    - Digital temperature and pressure sensors
- Designed for Low Power Operation
  - Individual digital switch for each sensor
- Designed to Coexist with Other Sensor Boards
  - Hardware “enable” protocol to obtain exclusive access to connector resources
- Packaging
  - Conformal sealant + acrylic tube
Application architecture

Sensor Node → Patch Network → Gateway → Transit Network → Basestation → Base-Remote Link → Internet

Client Data Browsing and Processing → Data Service
GDI 2002 deployment
GDI 2002 results: sensor data

Mote 18 – outside

Mote 53 – Burrow 115b
GDI ‘02 population

- 43 distinct nodes reporting data between July 13 and November 18
- Heavy daily losses
  - Between 3 and 5%
Redesign directions

- Node-level issues that need resolving
  - Size – motes were too large to fit in many burrows
  - Packaging – did not provide adequate protection for electronics or proper conditions for sensors
  - Node reliability
  - Power consumption
- Data interpretation challenges
  - Sensor calibration
  - Occupancy data interpretation – need more sophisticated processing of sensor data and/or ground truth data
  - Better metadata – sensor location & conditions
Miniature weather station

- Sensor suite
  - Sensirion humidity + temperature sensor
  - Intersema pressure + temperature sensor
  - TAOS total solar radiation sensor
  - Hamamatsu PAR sensor
  - Radiation sensors measure both direct and diffuse radiation
- Power supply
  - SAFT LiSO2 battery, ~1 Ah @ 2.8V
- Packaging
  - HDPE tube with coated sensor boards on both ends of the tube
  - Additional PVC skirt to provide extra shade and protection against the rain
Burrow occupancy detector

- Sensor suite
  - Sensirion humidity + temperature sensor
  - Melexis passive IR sensor + conditioning circuitry
- Power supply
  - GreatBatch lithium thionyl chloride 1 Ah battery
  - Maxim 5V boost converter for Melexis circuitry
- Packaging
  - Sealed HDPE tube, emphasis on small size
GDI ’03 patch network

- Single hop network deployed mid-June
  - Rationale: Build a simple, reliable network that allows
    - HW platform evaluation
    - Low power system evaluation
    - Comparisons with the GDI ’02 deployment
  - A set of readings from every mote every 5 minutes
  - 23 weather station motes, 26 burrow motes
  - Placement for connectivity
  - Network diameter 70 meters
  - Asymmetric, bi-directional communication with low power listening – send data packets with short preambles, receive packets with long preambles
  - Expected life time – 4+ months
    - Weather stations perform considerably better than burrow motes – their battery rated for a higher discharge current
GDI ’03 Multihop network

- Motivation
  - Greater spatial reach
  - Better connectivity into burrows
- Implementation
  - Alec Woo’s generic multihop subsystem
  - Low power listening: tradeoff channel capacity for average power consumption
- The network nodes
  - 44 weather motes deployed July 17
  - 48 burrow motes deployed August 6
  - Network diameter – 1/5 mile
  - Duty cycle – 2% to minimize the active time (compromise between receive time and send time)
  - Reading sent to base station every 20 minutes, route updates every 20 minutes. Expected lifetime: 2.5 months
  - 2/3 of nodes join within 10 minutes of deployment, remainder within 6 hours. Paths stabilize within 24 hours
Multihop network over time

Time-series characteristics of the multihop network

- Active nodes
- Parent changes
- Parent change-network size ratio
- PC uptime fraction
GDI 2003: mote lifetimes

Distribution of lifetimes in the single hop network

Distribution of lifetimes in the multi hop network

Days of activity

F

Days of activity

Spring 2006
Power management evaluation

![Graph showing power management evaluation results for Weather motes and Burrow motes. The graph displays lifetime (days) on the y-axis and number of single hop and multi-hop motes on the x-axis. The graph illustrates the impact of clustering caused by base-station shutdown and the duration of experiment.]

- **Weather motes**:
  - 4 single hop, 13 multihop motes
  - 17 single hop, 32 multihop motes

- **Burrow motes**:
  - 8 single hop, 11 multihop motes
  - 11 single hop, 33 multihop motes
  - 15 single hop motes still operate at the end of the experiment at the end of Oct.

Clustering caused by base-station shutdown in Sep.
Performance over time

Packet delivery CDF

- SH Weather, Mean: 182.34, Std Dev: 82.69, Median: 219
- SH Burrow, Mean: 169.08, Std Dev: 90.24, Median: 206
- MH Weather, Mean: 41.20, Std Dev: 37.59, Median: 38
- MH Burrow, Mean: 25.49, Std Dev: 20.46, Median: 20
Packet delivery in the multihop network

Packet delivery vs. network depth

Weather: $0.57 \times 0.9^{\text{depth}}$

Burrow: $0.46 \times 0.88^{\text{depth}}$
Multihop tree structure

Properties of the routing tree

N=101
Median # children=2
Mean # children= 4.64
Multihop links characteristics

CDF of links and packets delivered through those links

Link Longevity (packets received)

CDF of links and packets delivered through those links

Links

Packets

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Biological analysis
Conclusions

• Habitat monitoring networks
  • Smaller, longer lasting, more robust nodes
  • Integration with more general purpose software services – multihop routing, power management
  • So far, only mild challenges: low data rate, not really extreme environment
    • But considerably different and harder than the lab

• Lessons learned
  • Experimental discipline in the deployment
    • Calibration, sensor characterization
    • What is collected? All relevant information must be recorded as soon as possible
    • Ground truth and building of trust in the experimental method
  • Importance of packaging
  • Importance of infrastructure
    • Redundancy
    • Remote access
    • Data verification

• Starting to produce biological results!
  • Characterization of different habitats
  • Occupancy data
ZebraNet
How does ZebraNet work?

- Long-term, long-range wildlife tracking
- Individual nodes log GPS position data every 8 minutes, store in non-volatile flash memory
- Every two hours, nodes look for nearby peers
  - If found, swap data
  - Intentionally sparse network: often no collars in range
Hardware Introduction

**Microcontroller**
- TI MSP430F149
- 16-bit RISC
- 2KB RAM, 60KB ROM
- 8MHz/32KHz dual clock

**FLASH**
- ATMEL AT45DB041B
- 4Mbit
- 78 days data capacity

**Radio**
- MaxStream 902-928MHz
- 19.2Kbps
- 0.5-1mile transmit range

**GPS**
- µ-blox GPS-MS1E
- 10-20s position fix time

**Power supplies, solar modules, charging circuits**
Hardware Challenges

- **GPS Energy vs. Accuracy tradeoffs**
  - Cannot keep GPS “warm” at all times, yet want good data
- **Radio Support for Sparse networks**
  - Need radio range ~5 miles
- **Designing for bursts of communication**
  - Infrequent peer-to-peer encounters means relatively high data rate (19.2 kbps) when communicating
- **Power Management and Power Variability**
  - Large variations between peak and minimal current complicates power supply design in most sensor hardware platforms
- **Energy Scavenging**
  - Energy must be generated to allow for the use of high energy peripherals during long periods of autonomous operation
### GPS Accuracy vs. Energy

GPS modules vary in:
- Power dissipation while on
- Time to first-fix
- Time to acceptable fix

\[
\text{Energy} = \text{Power} \times \text{On-Time}
\]

<table>
<thead>
<tr>
<th>From datasheet</th>
<th>μ-blox</th>
<th>Xemics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power while on</td>
<td>462 mW</td>
<td>63 mW</td>
</tr>
<tr>
<td>Time to first-fix</td>
<td>2 s</td>
<td>12 s</td>
</tr>
<tr>
<td>Energy to first-fix</td>
<td>924 mJ</td>
<td>752 mJ</td>
</tr>
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</table>
GPS Experiences

- First-fix data is not very reliable...

Module takes the first lock

Standard Deviation: 32.57 m

Module is always on

Standard Deviation: 5.29 m
GPS Accuracy Improvements

- Use satellite info to filter out untrustworthy fixes...
- Approaches accuracy of Always-on method
- On-time average ~25 seconds

Module filters locks

Module is always on

Standard Deviation: 5.33 m

Standard Deviation: 5.29 m
Power Consumption

- Sensor hardware typified by highly variable power dissipation and current draw
- Natural stressors for power supply design

The GPS and radio are characterized by short bursts of high energy consumption.

The microcontroller consumes a negligible amount of power compared to the other components.
Energy Scavenging: Why Solar Cells?

- Solar cells are the most feasible option...
  - A string of 14 weighs just 100 grams and can generate .4 W in full sun
  - We have a lot of surface area on the collars
- ... as opposed to vibration or piezoelectric techniques
  - It would take a 1 kg weight to generate .1 W using vibration techniques
  - The wiring requirements of piezoelectric techniques such as converting pressure from the animal’s weight into electricity make it unfeasible
Experiences with Radio Range

![Graph showing received power (dBm) against range (km) for different versions and free space.]

- Version 2
- Version 3
- Free Space
Experiences with Radio Range

![Graph showing radio range reception percentage vs. range in kilometers. The graph includes three different symbols for different versions: v1, v2, and v3. The x-axis represents range in kilometers from 0 to 1, while the y-axis represents received percentage from 0% to 100%. The graph shows varying reception rates at different ranges.](image-url)
Deployment Results: Biology

- First night-time zebra movement data
- Preliminary data reflects that zebras explore more wooded areas and gullies at night
- Zebra Experiences:
  - More head shaking during first day with collar
  - Seemingly little effect after that

Movements of one zebra at the Sweetwaters game reserve in Central Kenya
Deployment Results: Engineering

- **Radio range:** Average radio range once deployed was much lower than it was in local NJ tests
  - Perhaps packaging of antenna and radio?
  - Significant absorption by both zebra and ground?
- **Microprocessor:**
  - Separate microcontroller from GPS processor eased software development/debug
  - 16-bit addressing was crucial for us
- **Communications Protocols:**
  - While in Africa: adding duplicated packets improved reliability of data transmission
  - 2 hours is a long time: future protocols more opportunistic
Conclusions

- The GPS module is not a black box
  - Smart filtering gives 6X accuracy improvement

- Sensor networks are the poster child for power supply difficulties
  - Inherently large current swings
  - Radio interference
  - Combining linear and switching techniques improved efficiency
  - Isolating power supplies and adding post filters reduced noise

- We hope that sharing our experiences is of use to other sensor network hardware designers
# ZebraNet System Structure Overview

<table>
<thead>
<tr>
<th>Application: Data Logging, Application Protocol</th>
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<tr>
<td>Impala Middleware: Operating System, Network Services</td>
</tr>
<tr>
<td>System Firmware: Peripheral, Clock, and Low-Level Energy Management</td>
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<tr>
<td>Hardware: Physical Chips, Power Supplies, Battery Charger, and Solar Array</td>
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Sniper Detection

- Detailed, Accurate Position Logs
  - Take a reading every 8 minutes
  - Readings should be as accurate as possible
- High Data Recovery Rate
  - Nodes form a sparse network, but latency is not an issue
- Autonomous Operation
  - The energy budget is limited to what we can generate
Based on the consistency function-based sensor fusion approach illustrated above.

Algorithm checks all detection data in a window (few tenths of seconds) and finds highest peak in consistency fn using a multiresolution search.

Afterwards, all detection data corresponding to found peak are removed, and search is restarted, etc.

Performance is remarkable: separates simultaneous shots, differentiates between shooters in close proximity, can handle 10 shots per second or more (bottleneck is network bandwidth!)
Demonstration at Ft Benning
Results

Based on 40 blank and SRTA shots from surveyed points
Average 2D error: 0.57m
Average 3D error: 0.98m
Structural Monitoring: Wisden

- Task: A wireless structural data acquisition system
- Existing system
  - Sensors connected to data loggers by cables
  - Data logger transmits data to PC
- Features:
  - Reliable multi-hop data transfer
  - Compression
  - Time stamping
Experience

- Performance
  - Need to work on scaling
- Deployability
  - Mostly wireless is important
- Use
  - Rapid, cheap, reasonably accurate instrumentation

QuickTime™ and a TIFF (LZW) decompressor are needed to see this picture.
Applications Requirements

- **Common Requirements**
  - Long lifetime
  - Ability to diagnose the system post-deployment
  - Physical constraints
- **Different Requirements**
  - Reliable vs. Best-effort delivery
  - Ad-hoc vs. Engineered deployments
  - Mobile vs. Fixed deployments
  - Time synchronization