The Princeton ZebraNet Project:
Mobile Sensors for Wildlife Tracking and Beyond

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Sensor Networks: Emerging Research and Societal Impact

Photo credits: UCLA, Harvard, Princeton, Lehigh
Diverse Applications, But Common Characteristics

Sensor Network Characteristics:
- Many distributed sensing nodes
- Size-constrained, energy-constrained, Bandwidth-constrained,
- Usage: Data aggregation & distributed queries
- Long-running hw, software
- Often: Mobile systems, LARGE areas to cover

Applications:
- **Science**: environmental, habitat monitoring, ...
- **Commercial**: Traffic monitoring, social networks, manufacturing control, ...
- **Other**: Aging-in-place, telemedicine, hazardous waste detection, ...
- **Homeland Security**
Abstraction Layers and Research Questions

- Portability across apps?
- Impact of app constraints and needs on design?
  - energy, weight, lifetime, datarate
  - latencies, data rates, accuracy
- Info passing between interface layers?
ZebraNet: Application
Motivation & Overview

System design Issues:
  – Protocols
  – Impala Middleware/OS
  – Hardware

Deployment experiences and plans

Broader applications view

Conclusions

More photos (time permitting)
Goal: Biologists want to track animals long-term, over long distances
- Interactions within a species?
- Interactions between species?
- Impact of human development?

Current technology is limited:
- VHF Triangulation is difficult & error-prone
- GPS trackers limit data to coarse sampling and require collar retrieval

Overall, energy and info retrieval are key limiters
Peer-to-peer offers opportunity to improve
Research Questions
- Protocols and mobility?
- Energy-efficiency?
- Software layering design?

ZebraNet vs. Other SensorNets
- All sensing nodes are mobile
- Large area: 100’s-1000s sq. kilometers
- “Coarse-Grained” nodes
- GPS on-board
- Long-running and autonomous
Basic System Operation

Tracking Node A

Tracking Node B
Basic System Operation

Potentially much later and far from node A…

Daily/weekly; Car or Plane

Tracking Node B

Tracking Node C

Node A

Node B

Node C
What data to track?

Current:
- GPS Position sample every 8 minutes
- Sun/Shade indication
- ~256 bytes per hour
- 1 “collar-day of info” ~ 6KB
- ~78 collar-days in 8Mbit FLASH chip
- XYZ accelerometer data for head motions

Future:
- Ambient temperature, Body temperature, Heart rate, Low res digital images, …
- Bit rate & storage needs could increase arbitrarily…
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Modeling Mobility: Zebra Lifestyles…

- **Harem**: Long-term bond between 1 male and several females + offspring
- **Herd**: Looser coalition of several harems

➤ Track 30-50 samples from several harems + bachelors
Mostly: herbivores graze

Sometimes: graze-walk while looking for greener pastures.

Rare: run to/away from something

Water

“thirsty” ~ once a day

Model at random time

Walk to nearest water

After drink, resume ambient motion
Protocol Success Rate: Ideal

Radio range for 100% delivery:
- No peer-to-peer: ~12km
- With Peer-to-peer: ~6km
Protocol Success Rate: Constrained Bandwidth

Short-range: Flooding best
Long-range: History best.
(Flooded data swamps limited bandwidth)
Protocol Energy Dissipation

Energy normalized to “direct” protocol of same radio range. History tracks “direct”. Flooding energy explodes.
Radio range key to data homing success: \(~3-4\text{km}\) for 50 collars in 20\(\text{km}\times20\text{km}\) area

Success rate:
- Ideal: flooding best
- Constrained bandwidth: history best

Energy trends make selective protocols best

Mobility model key to protocol evaluations
- Fast random moves hurt history
- Chicken and Egg: mobility model is the biology research goal
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Impala: Middleware/OS Support for Application/Protocol Modularity

Monolithic Approach:
- Source code hardwired to particular situations
- App responsible for adapting situation/version choices
- Difficult to debug, maintain
- Difficult to update on the fly
- Difficult for other apps to reuse

Layered Approach:
- OS provides network and event-handling services
- Middleware adapts, updates apps, protocols dynamically
- New protocols can be plugged in at any time

Individual Protocols

A
B
C
D

Impala Layer

Aggregate Protocol

A
B
C
D
Impala Middleware/OS Layers

Application 1
Application 2
Application 3
Application 4

Asynchronous Network Transmission
Protected FLASH Access
Application Timer Control
System Clock Time Read

GPS Data Event Handler
Application Timer Event Handler
Network Packet Event Handler
Network Send Done Event Handler

Adapter
Updater
Operation Scheduler
Event Filter
Network Support

Access and Control to All Devices

GPS Data Event
Radio Packet Event
Timer Event

CPU
Radio
GPS
FLASH
Timer
WDT
Code and Data Size: Memory Footprint of Impala Layers

- **Code Size**
  - Firmware
  - Impala
  - Application
  - Unused

- **Data Size**
  - Firmware
  - Impala
  - Application
  - Unused
Impala Code Updates

- High Node Mobility
- Constrained Bandwidth
- Wide Range of Updates
- Incomplete Updates
- Updates vs. Execution
- Out of order Updates

ZebraNet Characteristics

- High Node Mobility
- Constrained Bandwidth
- Wide Range of Updates

On a single sensor node

Full network

Updater

Updater

Node

n

n

n

n

n
Impala Status and Summary

- Sensor networks need modular, adaptable, repairable software
- Impala OS:
  - Lightweight common support for sensor services & networking
  - Event handler & low-level services
- Impala middleware
  - Adaptive application management
  - Remote software update
- Prototype implementations and simulations demonstrate:
  - Low overhead
  - Efficient network reprogramming
  - Code updates
<table>
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<th>Motivation &amp; Overview</th>
<th>System design Issues:</th>
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ZebraNet Hardware Design

Microcontroller
TI MSP430
16-bit RISC
~2KB RAM, 60KB ROM
8MHz/32KHz dual clock

ATMEL FLASH
~80 days data capacity

Maxstream Radio
0.5-1mile transmit range

GPS
10-20s position fix time

Power supplies, solar modules, charging circuits

<table>
<thead>
<tr>
<th>Mode</th>
<th>Power</th>
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<tbody>
<tr>
<td>32Khz CPU</td>
<td>9.6 mW</td>
</tr>
<tr>
<td>8MHz CPU</td>
<td>19.32 mW</td>
</tr>
<tr>
<td>8MHz w/ GPS</td>
<td>568 mW</td>
</tr>
<tr>
<td>8MHz + radio xmit</td>
<td>780 mW</td>
</tr>
<tr>
<td>8MHz + radio rcv</td>
<td>312 mW</td>
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ZebraNet Hardware: Time-Lapse View...
January, 2004 ZebraNet Hardware
January, 2004:
Initial test deployment

- Ate/slept/worked at Mpala Research Centre near Nanyuki Kenya
- Deployed collars at Sweetwaters Preserve, also near Nanyuki Kenya
Deployment Results

Biology
- Zebras affected by collar first day (head shaking) but little thereafter.
- First night-time zebra movement data: animals appear to explore more wooded areas and gullies at night.

Engineering
- Radio range: <1 km in final collar packaging,
  - Disappointing vs. NJ tests
  - Even more attention needed on ground plane and noise effects
- Communication protocols: generally worked as plans, although duplicated ACK packets improved their performance.
15 months later...

Collar on Zebra for roughly 1.25 years:
- Hot sun, tough weather.
- Zebra attacked/killed by a lion (not unusual, probably not related to collar)

How did the collar do?
Next Steps

Second Deployment:  June/July, 2005

– Amorphous silicon solar cells with Tefzel coating
– Leather rather than butyl rubber collar
– New version of msp processor
– New radio
– New GPS
– New collar design
– Improved code (latencies, interrupt handling….)

[Images of solar cell, leather collar, and horse]
Talk Outline

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- Broader applications view
- Conclusions
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Applications...
Protocols & Data Collection
Middleware/OS
Hardware
Physical Design, Circuits, Antennas, …
More than just zebras…

CPU and Hardware Design

Software Systems Research

Networking, Analytic Modeling, Simulation

ZebraNet

Smart Buildings

Traffic Management
Model-based Mobility-Adaptive Protocols

Fixed mobility  Design  Fixed protocol

Mobility_1  Mobility_2  Mobility_3  ...  Mobility_n

Model

Protocol_a  Protocol_b  Protocol_c

Sense and update

With Yong Wang, LS Peh, Mobihoc 2004
Example:

Markov Model based on route cache lifetimes

<table>
<thead>
<tr>
<th>Traffic Rate</th>
<th>Original (DSR)</th>
<th>Markov approach</th>
<th>% latency improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 pkts/s</td>
<td>6.2</td>
<td>5.2</td>
<td>16%</td>
</tr>
<tr>
<td>4 pkts/s</td>
<td>4.1</td>
<td>3</td>
<td>27%</td>
</tr>
<tr>
<td>8 pkts/s</td>
<td>2.7</td>
<td>2.1</td>
<td>22%</td>
</tr>
</tbody>
</table>
Erasure-Coding Based Routing for Disruption-Tolerant Networks

- In sparse, disrupted networks like ZebraNet, inter-contact duration (link-off time) is heavy-tailed
  - Flooding to all nodes will work but with heavy energy/storage cost
  - Reducing flooding risks choosing “loner” or unreliable nodes.

- Erasure-coding approach
  - Replicate via erasure-coded packets, rather than strict redundancy.
  - Partial packet delivery can be used to reconstruct original message

- Results depend on mobility/connectivity model, but overall:
  - Erasure-coded replication tends to increase success rate
  - With slight degradation in “best-case” latency
Summary

- **ZebraNet as Biology Research:**
  - Enabling technology for long-range migration research
  - Good view of key inter-species interactions

- **ZebraNet as Engineering Research:**
  - Early detailed look at mobile sensor net with mobile base stations
  - Demonstrates promise of large-extent, long-life sensor networks with GPS
  - Detailed look at power/energy concerns
  - Novel protocol, middleware, and hardware designs to support research goals

- **Sensor Networks Overall**
  - Unique characteristics and challenges: Energy-constraints, Mobility, Long-lived hardware/software
The Princeton ZebraNet Project: Mobile Sensor Networks for Wildlife Tracking

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Funded by NSF ITR since 9/2002

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More questions?

For more info, see papers:
ASPLOS02, PPOPP03,
Mobisys04, SenSys04

... and my webpage
www.princeton.edu/~mrm