Energy-Efficient Computing for Wildlife Tracking: Design Tradeoffs and Early Experiences with ZebraNet

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ZebraNet as Biology Research

Biologists want to track animals
– Long-term
– Over long distances

Questions:
– Interactions within a species?
– Interactions between species?
– Impact of human development?
Current Tracking Technology

- Most common: VHF transmitter collar with triangulation
- GPS trackers: often must retrieve collar to retrieve data
- Satellite tracking: high-energy, low bitrate
- Overall, energy and reliability are key limiters
- Peer-to-peer offers opportunity to improve

Biologist’s Wishlist ➔ ZebraNet Design

- Lightweight
  ➔ Energy-efficient
- Detailed 24/7 archival position logs
  ➔ GPS-enabled
- Mobile
  ➔ Wireless
- No fixed base station (no cellular service)
  ➔ Peer-to-peer routing and data storage
- Restricted human access to systems
  ➔ Plan 1 year of autonomous operation

ZebraNet: Mobile sensor net with mobile (intermittent) base station.
Stringent energy limits relative to needed communication range
Basic System Operation

Potentially much later and far from node A…

Daily/weekly; Car or Plane
ZebraNet vs. Many Other Sensor Networks…

1. All nodes mobile: Even “base station” is mobile; intermittent drive-bys upload data
2. Large spatial extent: 100s-1000s of sq. kilometers
3. “Coarse-Grained” nodes: Storage and processing capability >> many other sensor systems
4. GPS on-board: Interesting protocol, system tricks
5. Long-running and autonomous: Reliability and energy-efficiency are key

This Paper

Hardware:
- Prototypes for early experiments
- Guide energy, weight, range estimates

Software:
- Protocols for data aggregation
- Peer-to-peer for range & reliability
- Detailed look at mobility/protocol match
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GPS/CPU/Flash core

- Detailed position info => GPS a must
- µBlox GPS/CPU/Flash:
  Integrated GPS
  + 20MHz Hitachi CPU
  + 1MB non-volatile Flash memory
  (~640K free to use)
- GPS allows:
  Precise global dist’d system clock
  Geographic routing

Evaluation card (unintegrated)
## ZebraNet: Energy Measurements

<table>
<thead>
<tr>
<th>Activity</th>
<th>Amperage (mA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Idle</td>
<td>&lt;1</td>
</tr>
<tr>
<td>GPS Position Sampling &amp; CPU / Storage</td>
<td>177</td>
</tr>
<tr>
<td>Base Discovery only</td>
<td>432</td>
</tr>
<tr>
<td>Transmit data to base</td>
<td>1622</td>
</tr>
</tbody>
</table>

(table shows amperage at 3.6V)

CPU: Order of magnitude less energy than data transmissions...

## ZebraNet: Weight & Battery...

<table>
<thead>
<tr>
<th>Component</th>
<th>Weight (grams)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GPS chip + CPU</td>
<td>8</td>
</tr>
<tr>
<td>Short-range radio</td>
<td>20</td>
</tr>
<tr>
<td>Long-range radio and packet modem</td>
<td>296</td>
</tr>
<tr>
<td>Rechargeable batteries</td>
<td>287</td>
</tr>
<tr>
<td>Solar cell array</td>
<td>540</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1151 grams (2.5lbs)</strong></td>
</tr>
</tbody>
</table>

Total Weight Goal ~3-5lbs. Energy Goal: 5 days if no recharge

Compute weight doesn’t matter much…
What data to track?

Current:
- GPS Position sample every 3 minutes
- Sun/Shade indication
- Detailed information for 3 minutes every hour:
  - Detailed position sampling: standing still or moving? Speed?
    “Step rate”
  - ~256 bytes per hour.
  - 1 “collar-day of info” ~ 6KB

Future:
- Head up or down: “bite rate”, Ambient temperature, Body temperature, Heart rate, Low res digital images, …
- Bit rate & storage needs could increase further...

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Weight ->
Energy ->
Communication Matters!
• Mobility?
• Range?
• Protocols…
• Energy?
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

Zebra Lifestyles II

- 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

GRASSING GRAZE-WALKING FAST MOVING

speed\textsubscript{g} speed\textsubscript{gw} speed\textsubscript{fm}
Zebra Movement Speeds

From field data:
- Grazing: 0.017 m/s
- Graze-walking: 0.072 m/s
- Fast: 0.155 m/s
- Turns ~ < 60°

ZebraNet Protocol Evaluations: ZNetSim

- Evaluated communications issues using ZNetSim
  - coarse-grained mobile communication simulator using field observations for mobility model
- For results here:
  - 50 collars
  - Tracked across a 20km by 20km area
  - For one month
  - Discovery/Transfer for 30 minutes every 2 hours
  - Base station: daily drive-bys
- Focus here on a single radio: vary range to understand trends
Two peer-to-peer protocols evaluated here
- Flooding: Send to everyone found in peer discovery.
- History-Based: After peer discovery, choose at most one peer to send to per discovery period: the one with best past history of delivering data to base.

Compared to “direct”: no peer-to-peer, just to base

Success rate metric: Of all data produced in a month, what fraction was delivered to the base station?

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
Mobility & Protocol Summary

- Radio range key to data homing success: ~3-4km for 50 collars in 20kmx20km 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

Status & Future Plans

Hardware:
- Nov '02: waterproof prototype for local animal tests
- Spring '03: build final rugged version

Software:
- Impala middleware: Allow for wireless software updates & adaptivity

Beyond wildlife tracking:
- Resource recovery, traffic management, security, surveillance
Deployment plans

- Generation 0: Fall '02
  Domesticated horses in NJ
- Generation 1: Wild horses on
  Atlantic barrier islands
- Generation 2: Full ecosystems
  (lions, zebras, hyenas…) at Mpala
  Research Centre, Kenya

Conclusions

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

ZebraNet People
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- Undergrads: Julie Buechner, Karen Tang, Kinari Patel, Jeremy Wall, Chido Enyinna

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www.ee.princeton.edu/~mrm/zebranet.html