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

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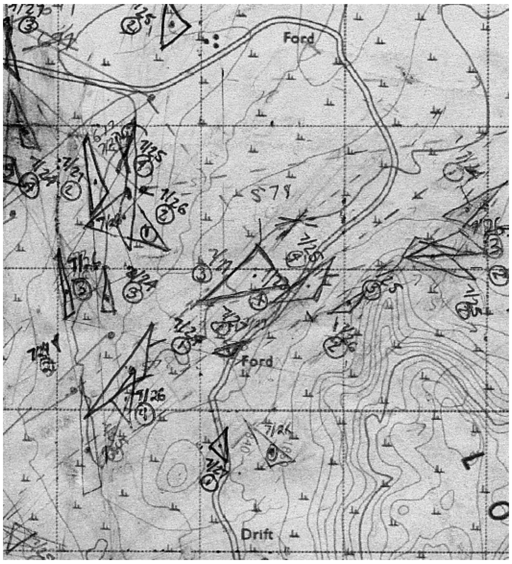
ZebraNet as Biology Research

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

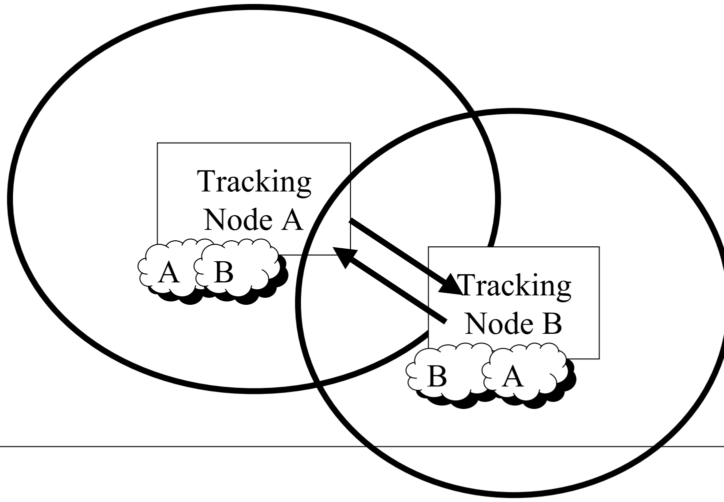
Biologist's Wishlist ➨ ZebraNet Design

- 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.

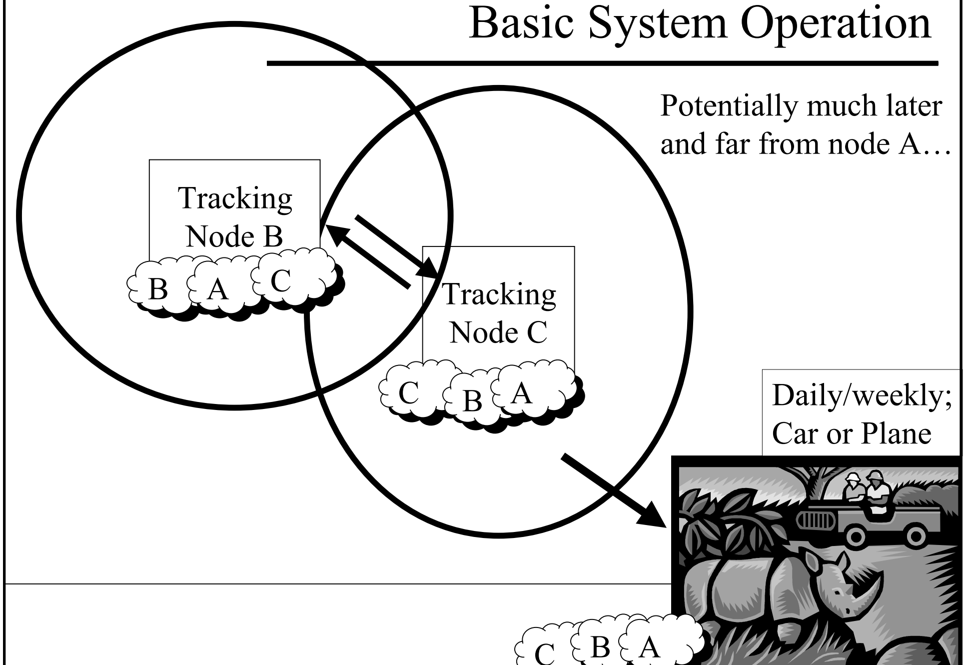
Stringent energy limits relative to needed communication range

Basic System Operation



Basic System Operation

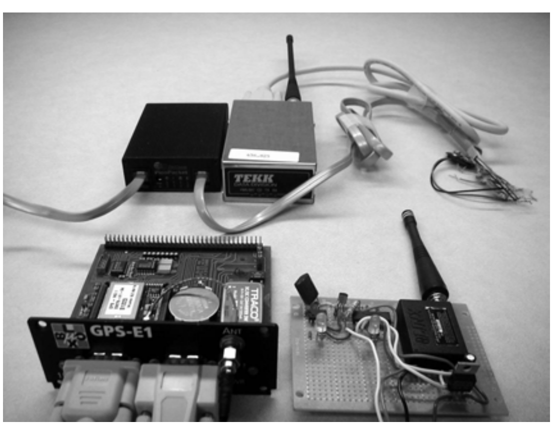
Potentially much later
and far from node A…



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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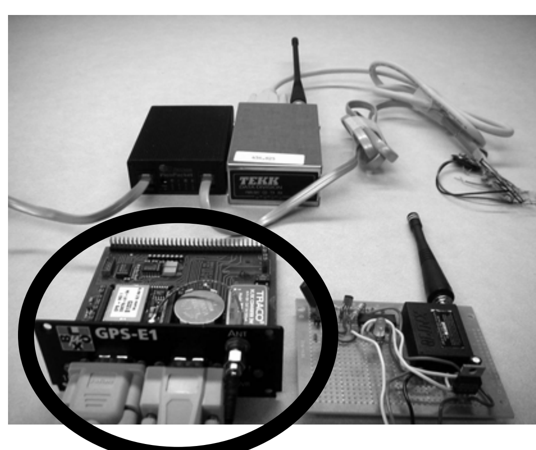
GPS/CPU/Flash core

- 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

Idle	<1 mA
GPS Position Sampling & CPU / Storage	177 mA
Base Discovery only	432 mA
Transmit data to base	1622 mA

CPU: Order of magnitude less energy than data transmissions…

(table shows amperage at 3.6V)

ZebraNet: Weight & Battery…

GPS chip + CPU	8 grams
Short-range radio	20 grams
Long-range radio and packet modem	296 grams
Rechargeable batteries	287 grams
Solar cell array	540 grams
Total	1151 grams (2.5lbs)

Compute weight doesn't matter much…

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

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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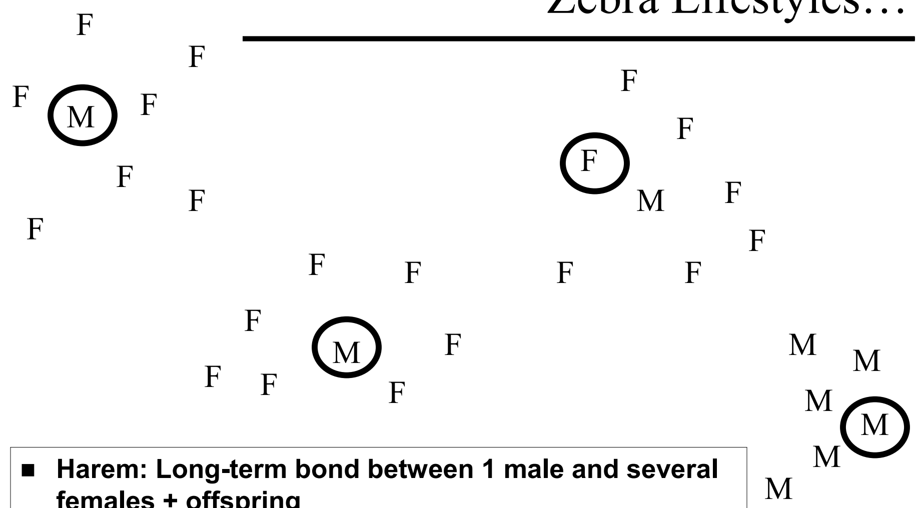
Weight -> Energy -> Communication Matters!

•Mobility?
•Range?
•Protocols…
•Energy?

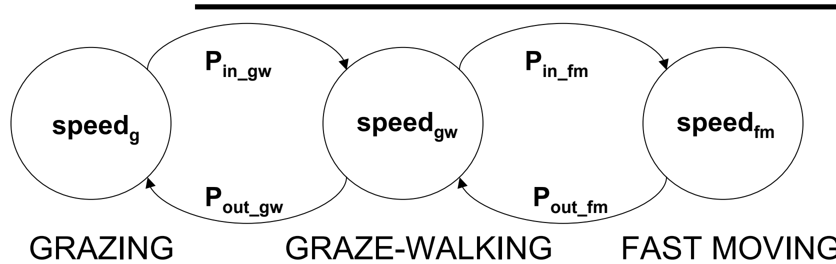
Zebra Lifestyles…



- **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**

Zebra Lifestyles II

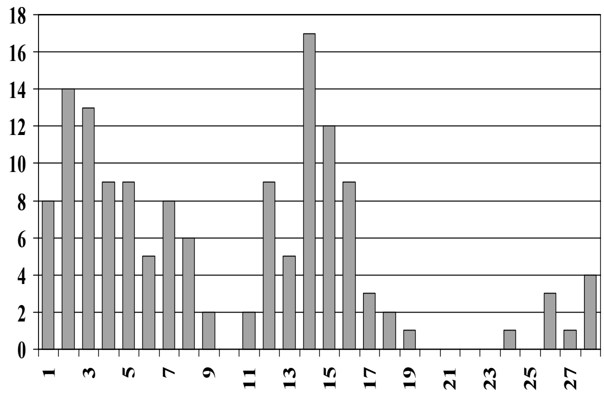


- Mostly: herbivores graze
- Sometimes: graze-walk while looking for greener pastures.
- Rare: run to/away from something

Water

- “thirsty” ~once a day
- Model at random time
- Walk to nearest water
- After drink, resume ambient motion

Zebra Movement Speeds



net meters traveled in 3 minutes

From field data:

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

ZebraNet Protocol Evaluations: ZNetSim

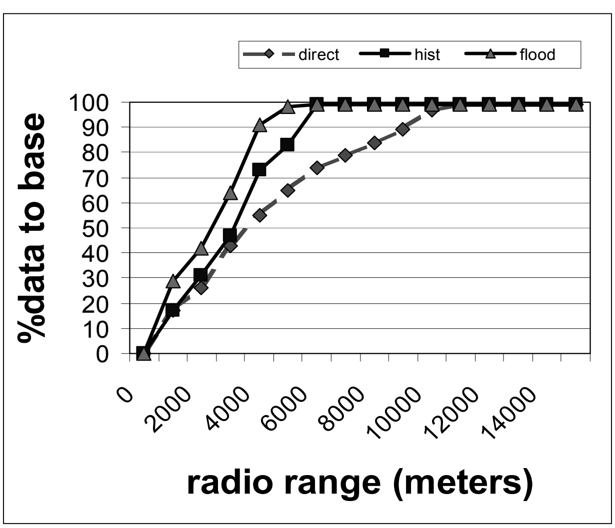
- Evaluated communications issues using ZNetSim
  - coarse-grained mobile communication simulator using field observations for mobility model
- For results here:
  - 50 collars
  - Tracked across a 20km by 20km area
  - For one month
  - Discovery/Transfer for 30 minutes every 2 hours
  - Base station: daily drive-bys
- Focus here on a single radio: vary range to understand trends

ZebraNet Protocols

- 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

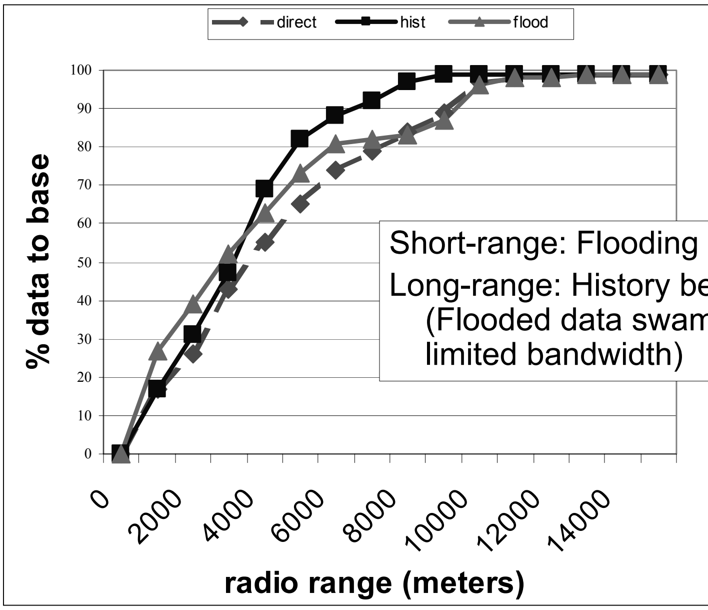
- Success rate metric: Of all data produced in a month, what fraction was delivered to the base station?

Protocol Success Rate: Ideal



- Radio range for 100% delivery:
  - No peer-to-peer: ~12km
  - With Peer-to-peer: ~6km

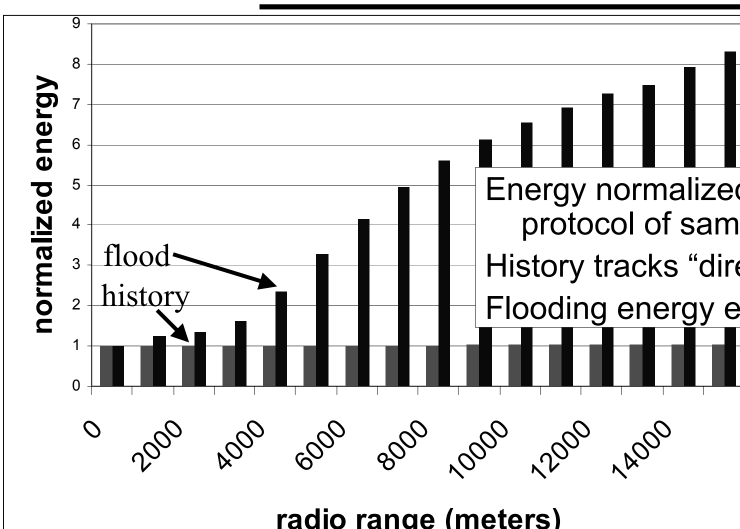
Protocol Success Rate: Constrained Bandwidth



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.

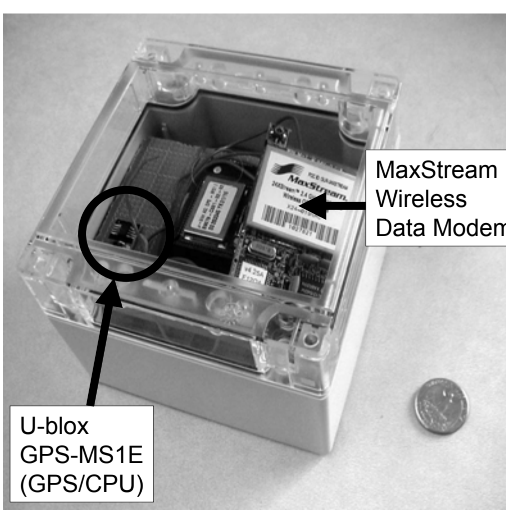
History tracks "direct"

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

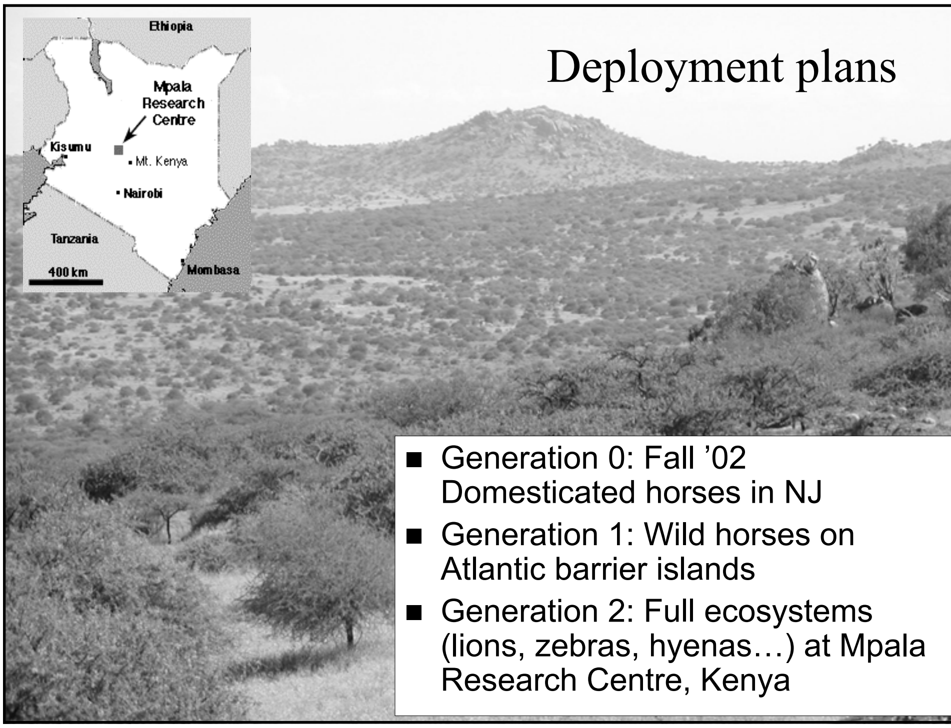
Software:

- 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

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

ZebraNet People

- Grads: Philo Juang, Hide Oki, Yong Wang, Ting Liu, Ilya Fischoff
- Profs: Margaret Martonosi, Li-Shiuan Peh, Vince Poor, Dan Rubenstein, Steve Lyon
- Undergrads: Julie Buechner, Karen Tang, Kinari Patel, Jeremy Wall, Chido Enyinna

Support

- National Science Foundation ITR program