The Princeton ZebraNet Project: Sensor Networks for Wildlife Tracking

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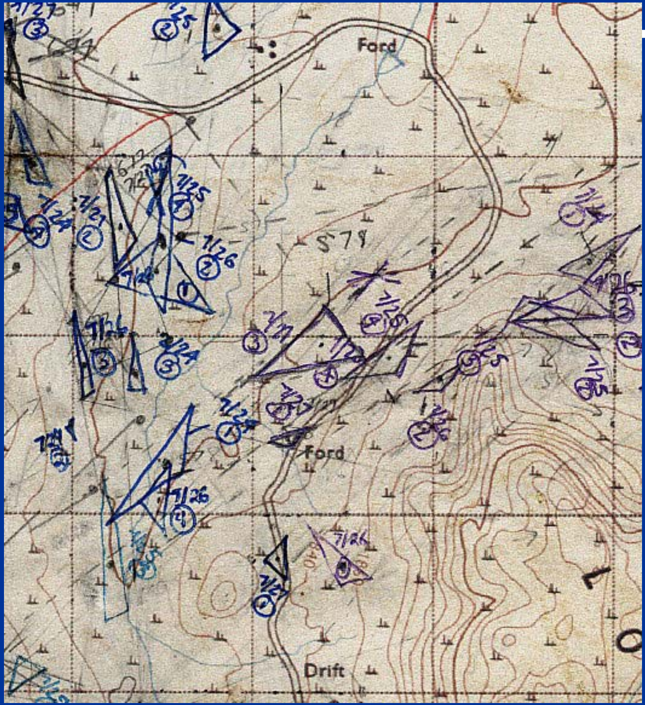
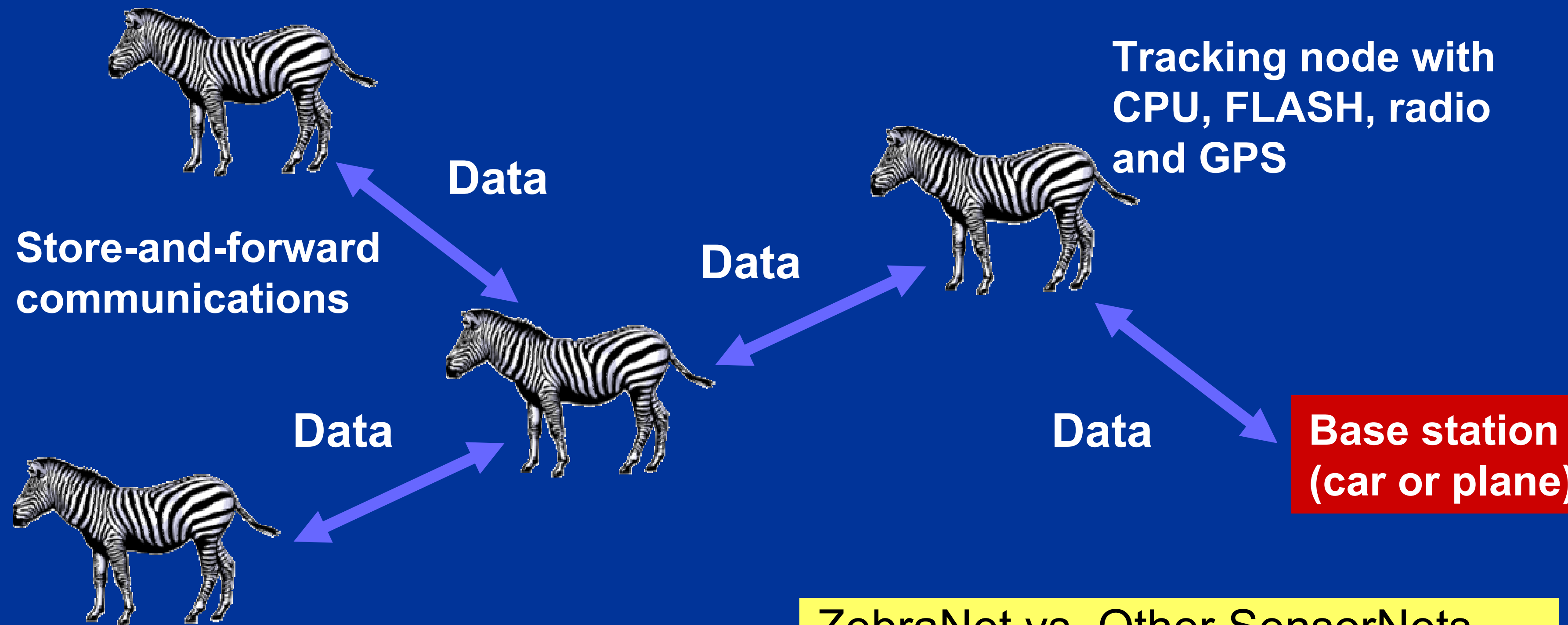
ZebraNet as Biology Research



- 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

ZebraNet as Computing Research



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

Research Questions

- Protocols and mobility?
- Energy-efficiency?
- Software layering design?

Biologist's Wishlist ➨ ZebraNet Design

Design Issues:

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

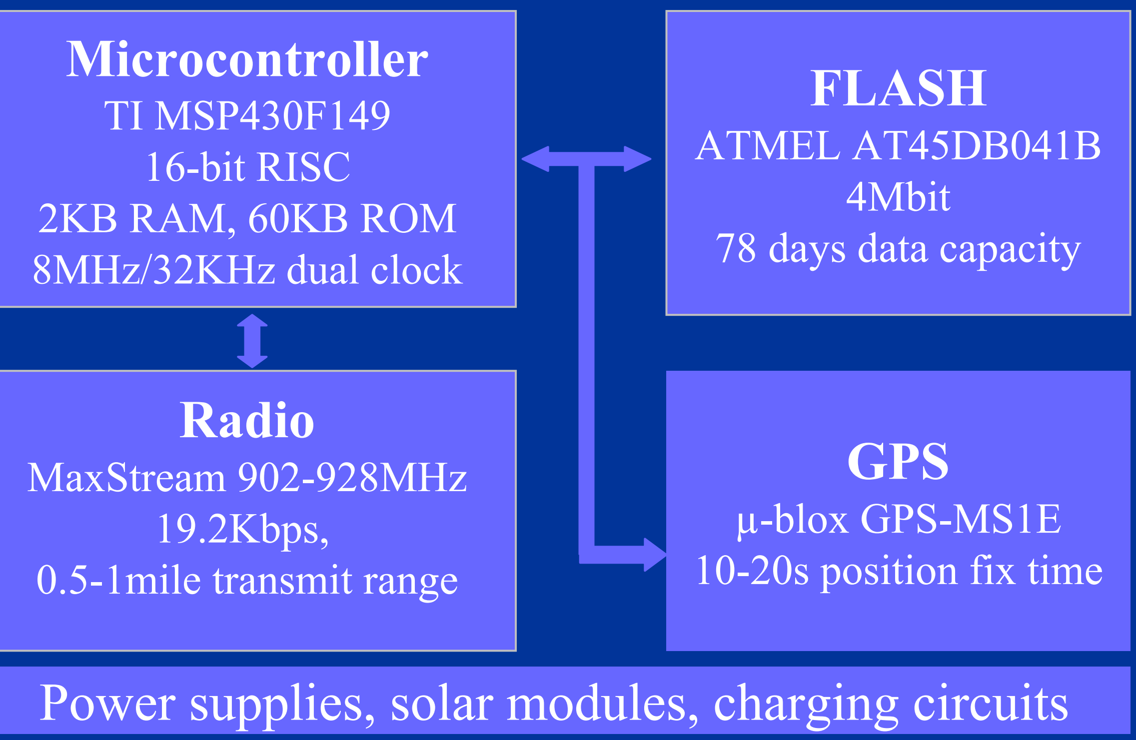
Research Questions

- What are suitable protocols for the expected mobility patterns?
- How to model mobility well enough to determine this?
- Can systems of sufficient radio range be designed to operate energy-efficiently enough?
- How can one design software layers that enable long-lived adaptable software and yet are also very energy-efficient?

Talk Outline

- Sensor Networks: Intro & Overview
- ZebraNet
  - Problem statement and system overview
  - Protocols and mobility models
  - Impala middleware
  - Hardware details and energy issues
- Broader view…

ZebraNet Hardware Design



Mode	Power
32Khz CPU	9.6 mW
8MHz CPU	19.32 mW
8MHz w/ GPS	568 mW
8MHz + radio xmit	780 mW
8MHz + radio rcv	312 mW

What data to track?

Current:

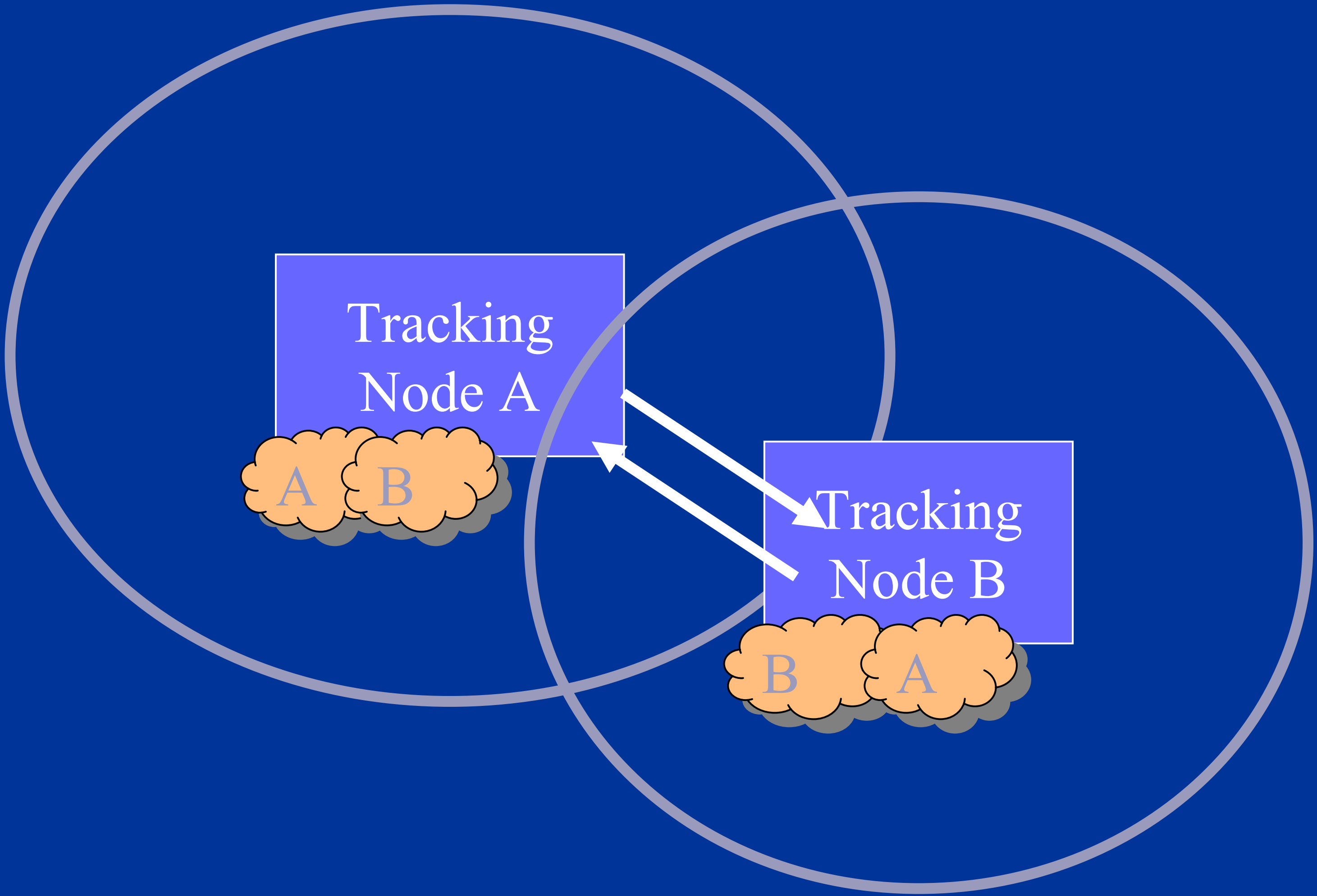
- GPS Position sample every 3 minutes
- Sun/Shade indication
- Detailed information for 3 minutes every hour:
  - Detailed position sampling: standing still or moving? Speed? “Step rate”

- ~256 bytes per hour
- 1 “collar-day of info” ~ 6KB
- ~170 collar-days in 8Mbit FLASH chip

Future:

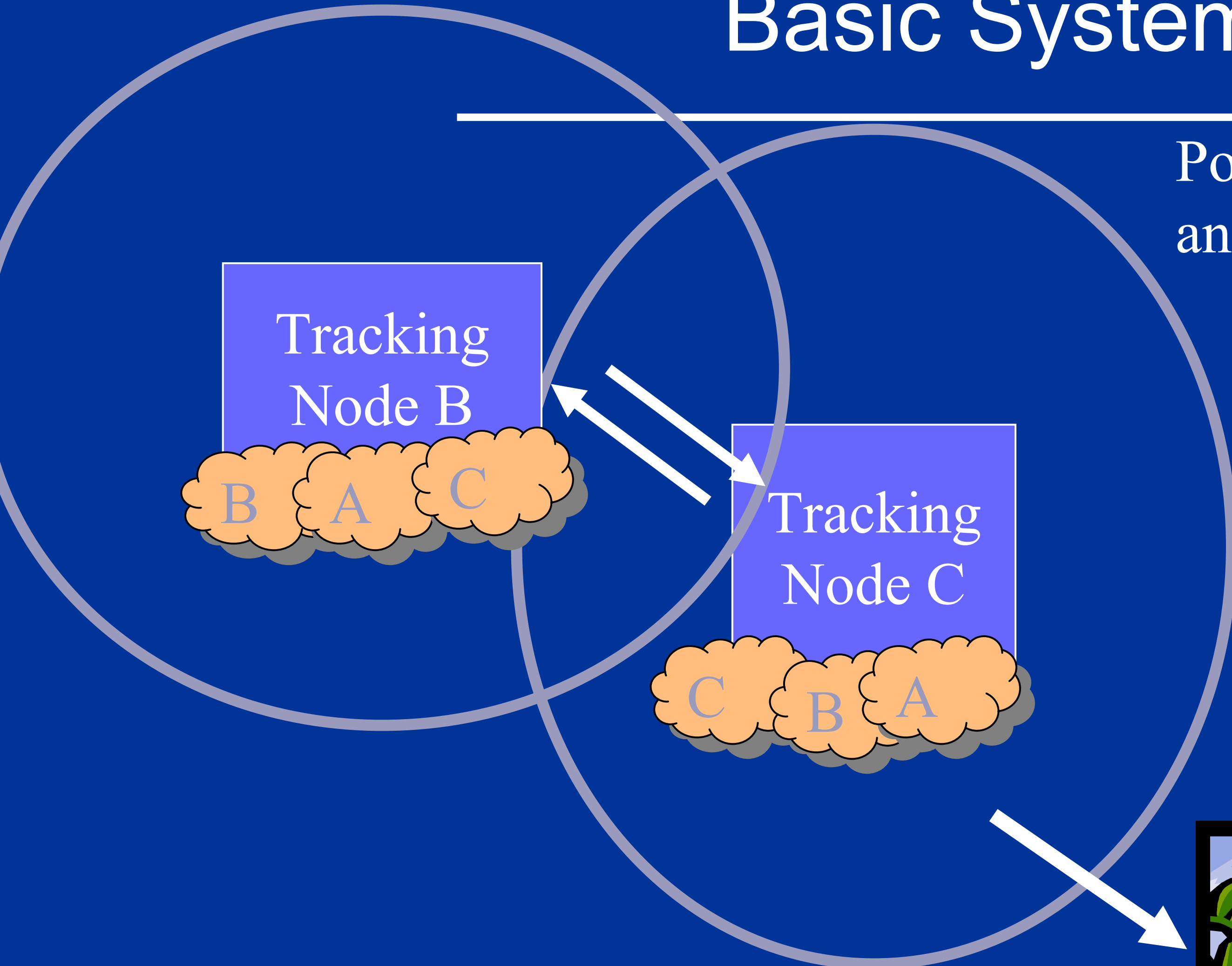
- Head up or down: “bite rate”, Ambient temperature, Body temperature, Heart rate, Low res digital images, …
- Bit rate & storage needs could increase further…

Basic System Operation

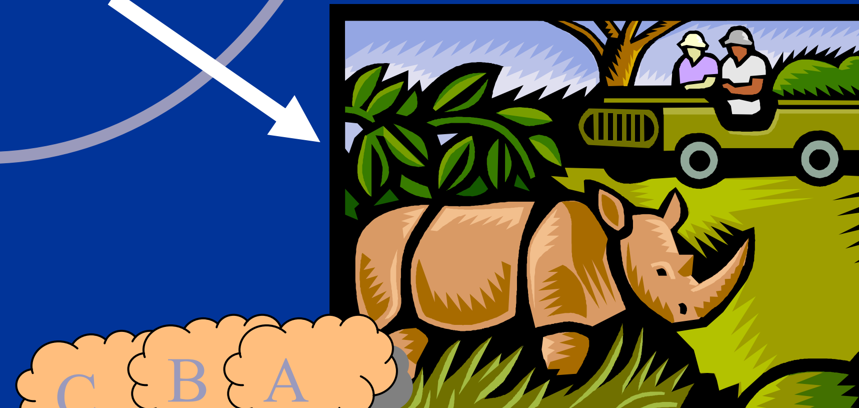


Basic System Operation

Potentially much later
and far from node A…



Daily/weekly
Car or Plane



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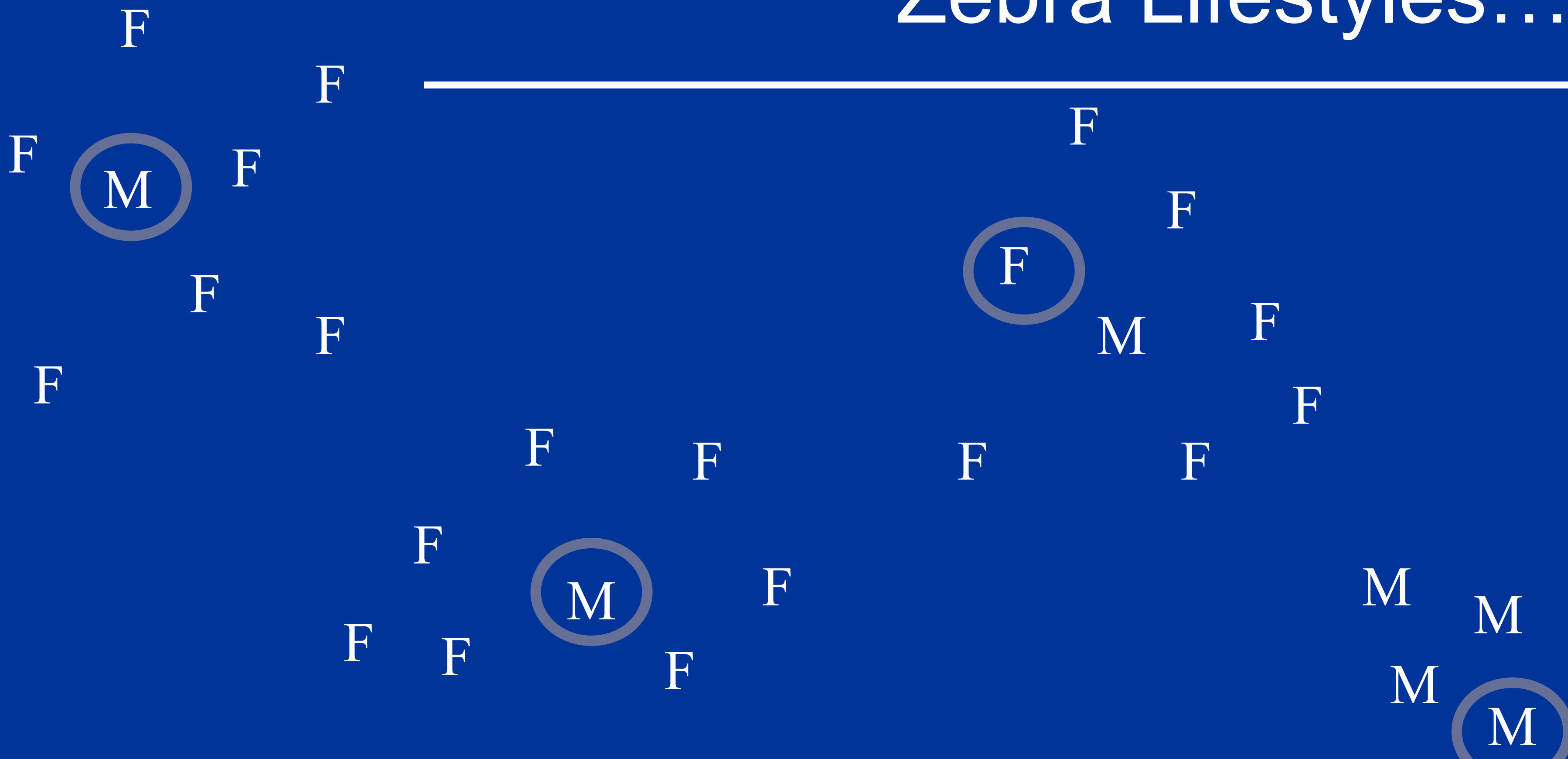
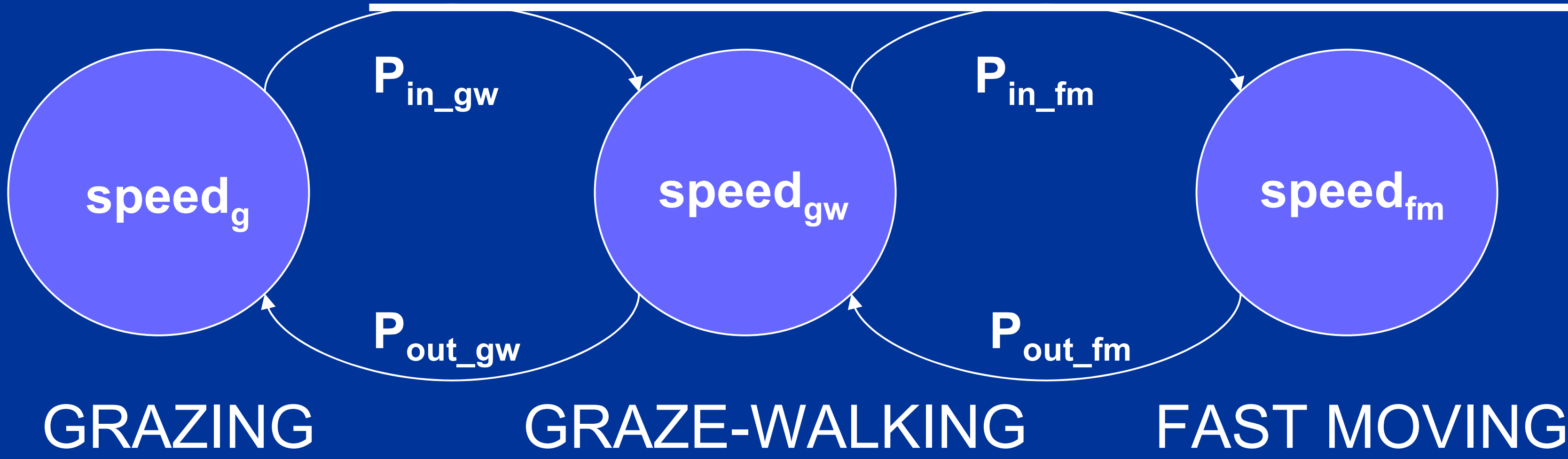
Zebra Lifestyles…



- **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

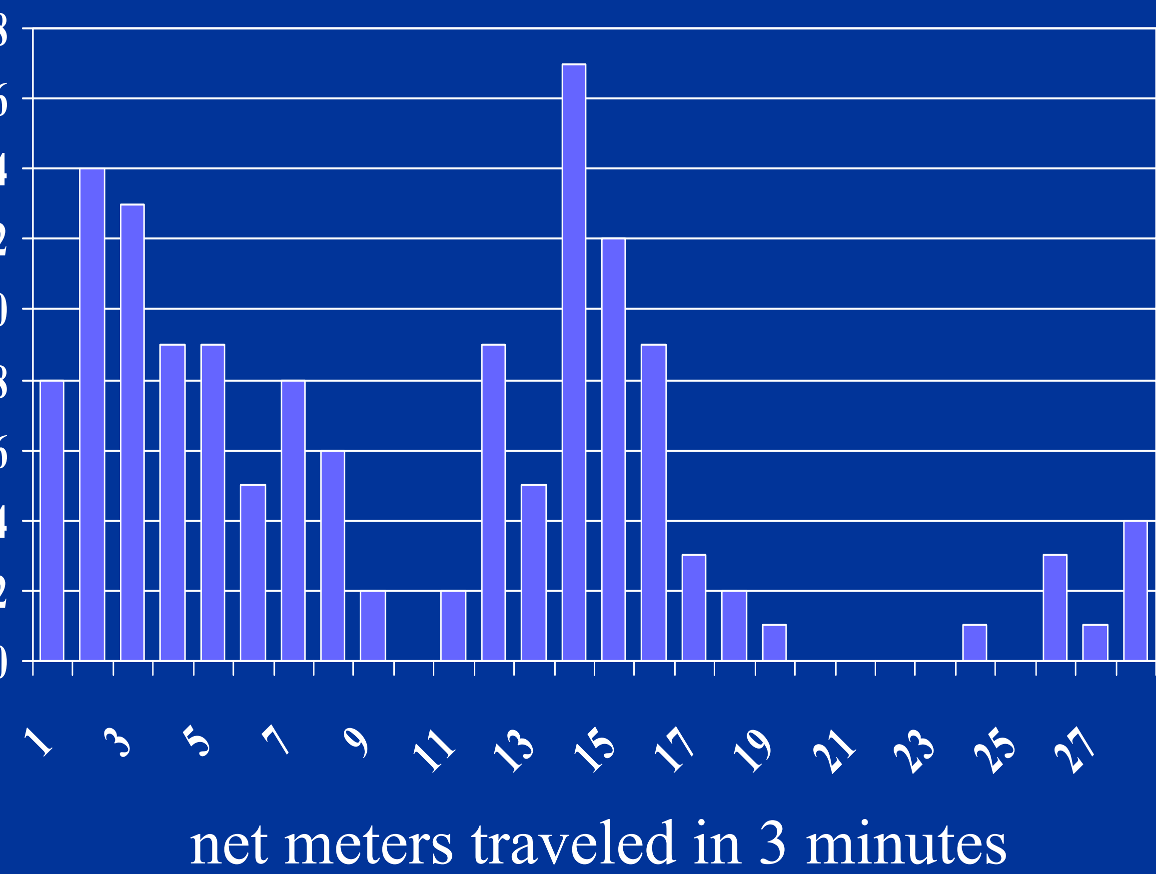
Sometimes: graze-walk while looking for greener pastures.

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



From field data:

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

ZebraNet Protocol Evaluations: ZNetSim

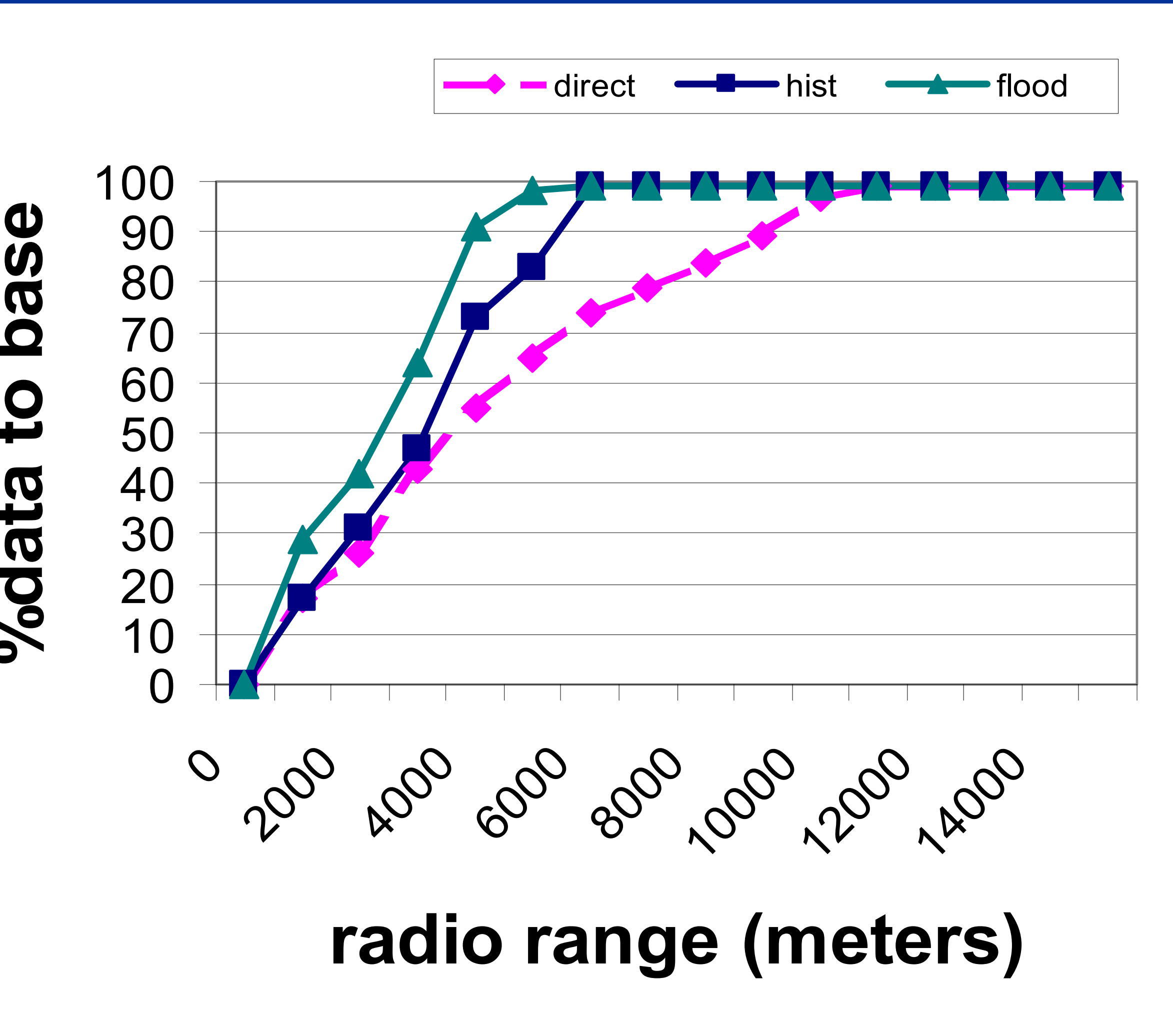
- Evaluated communications issues using ZNetSim
  – coarse-grained mobile communication simulator using field observations for mobility model
- For results here:
  – 50 collars
  – Tracked across a 20km by 20km area
  – For one month
  – Discovery/Transfer for 30 minutes every 2 hours
  – Base station: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

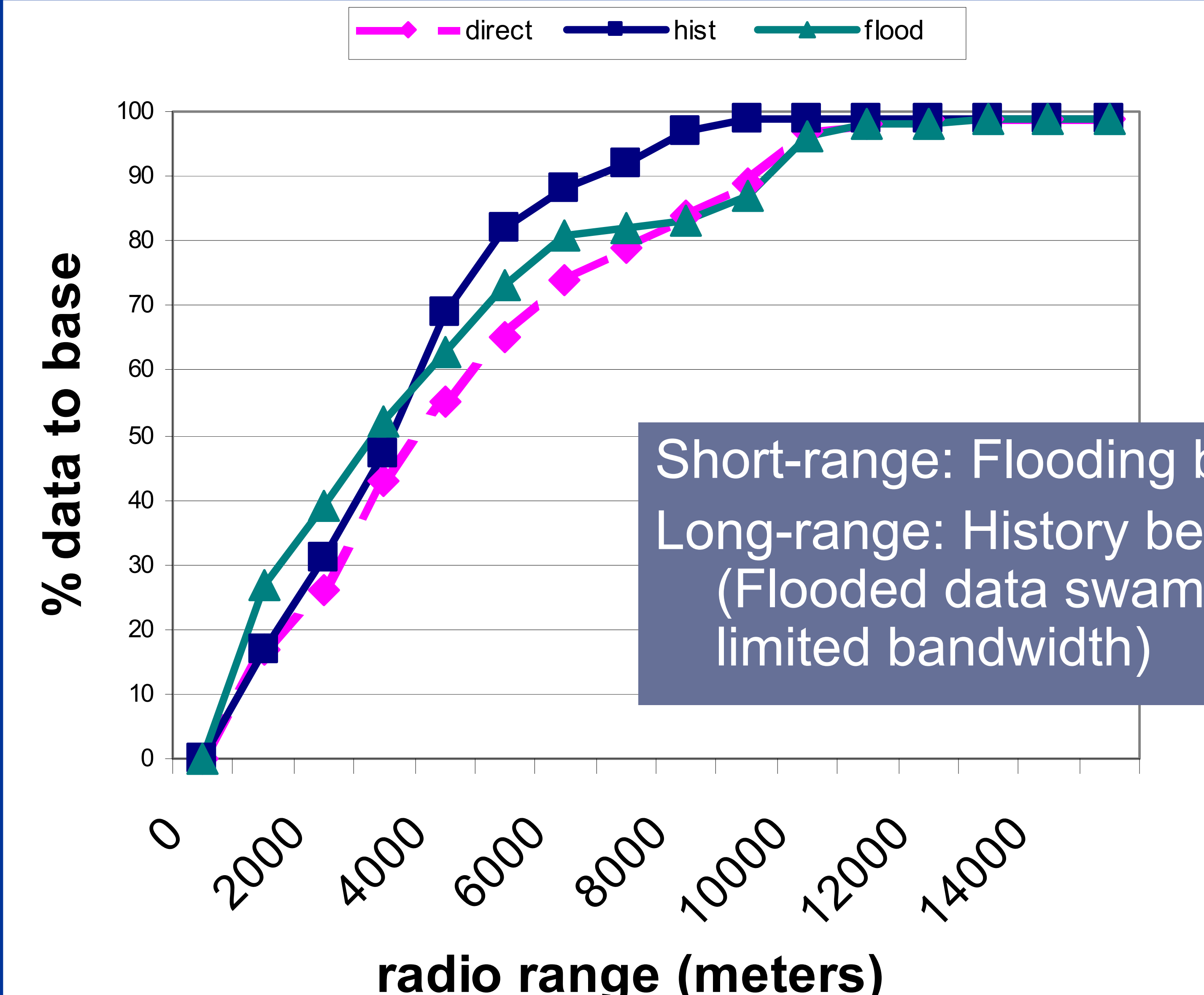
- Success rate metric: Of all data produced in a month, what fraction was delivered to the base station?

Protocol Success Rate: Ideal



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

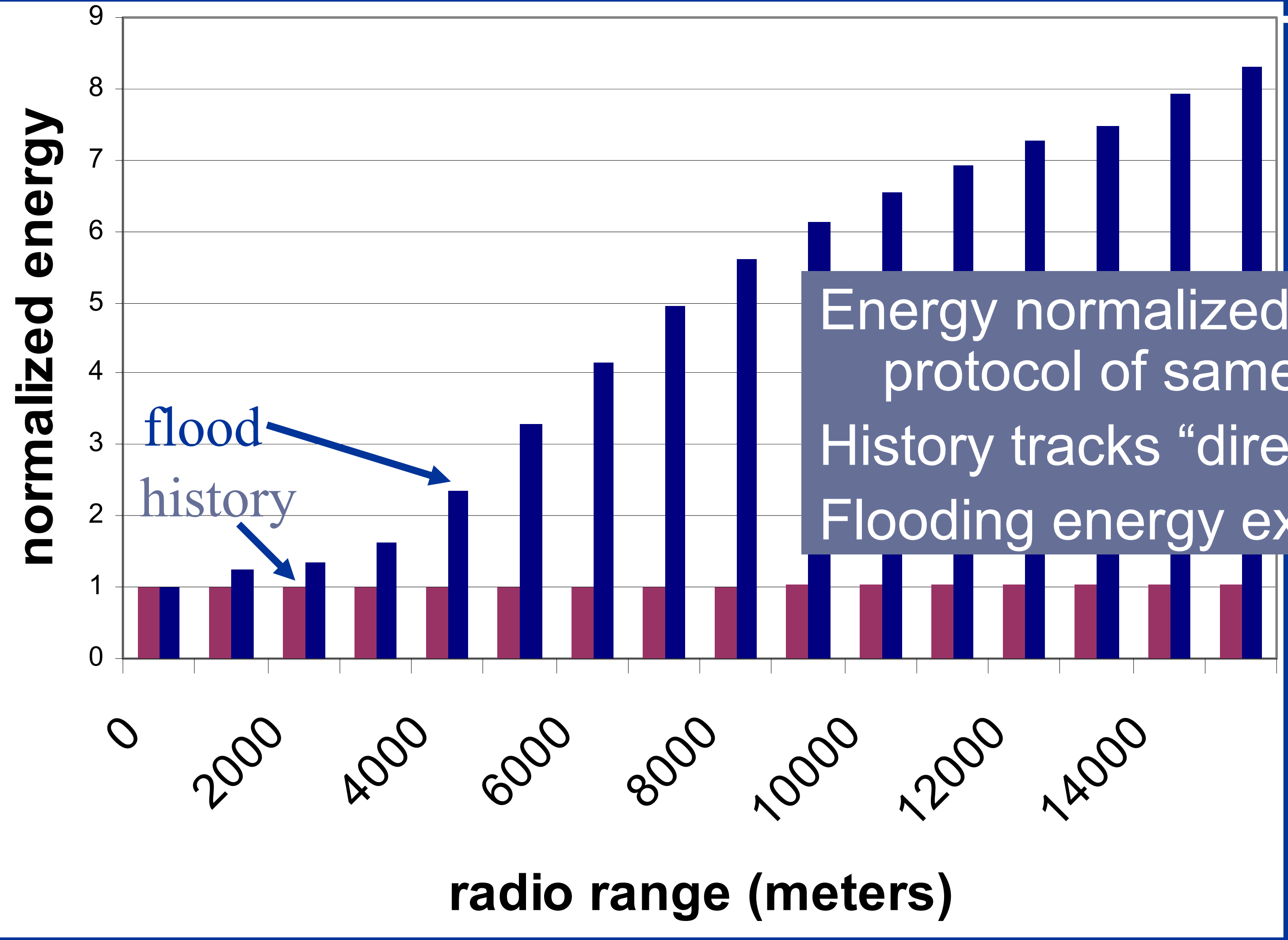
Protocol Success Rate: Constrained Bandwidth



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

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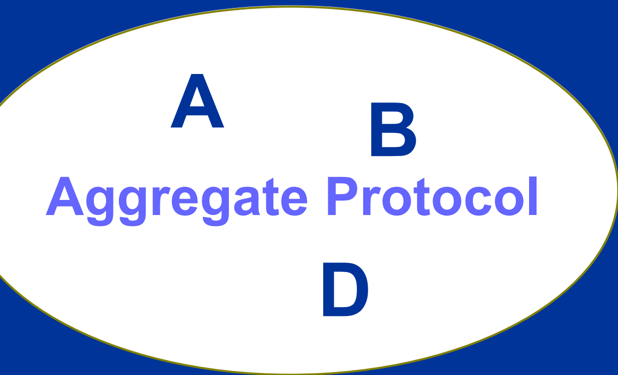
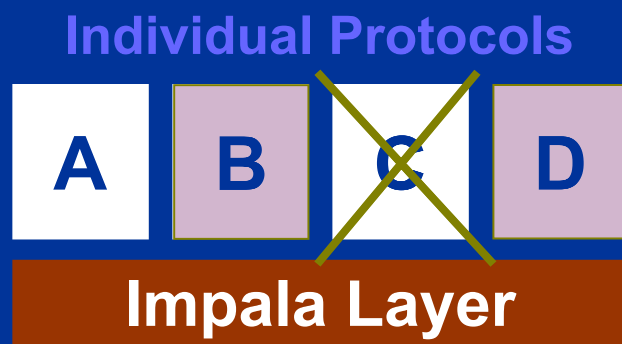
Impala: Middleware Support for Application/Protocol Modularity



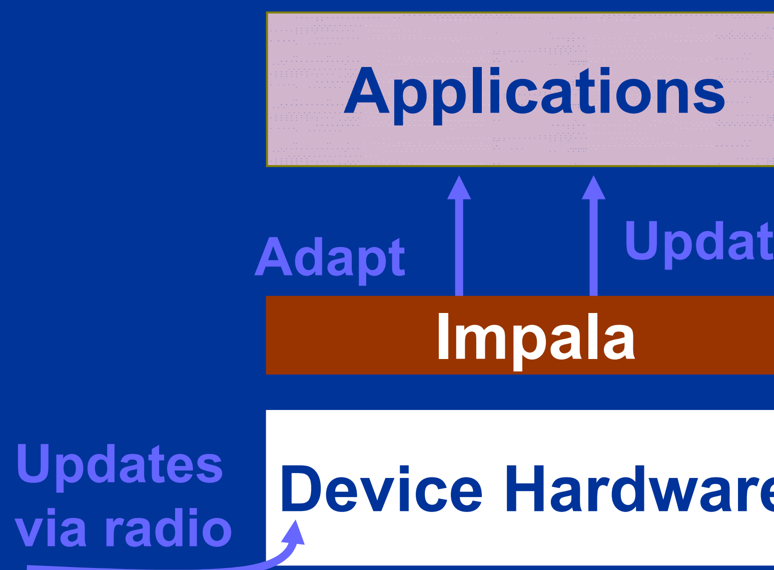


Monolithic Approach

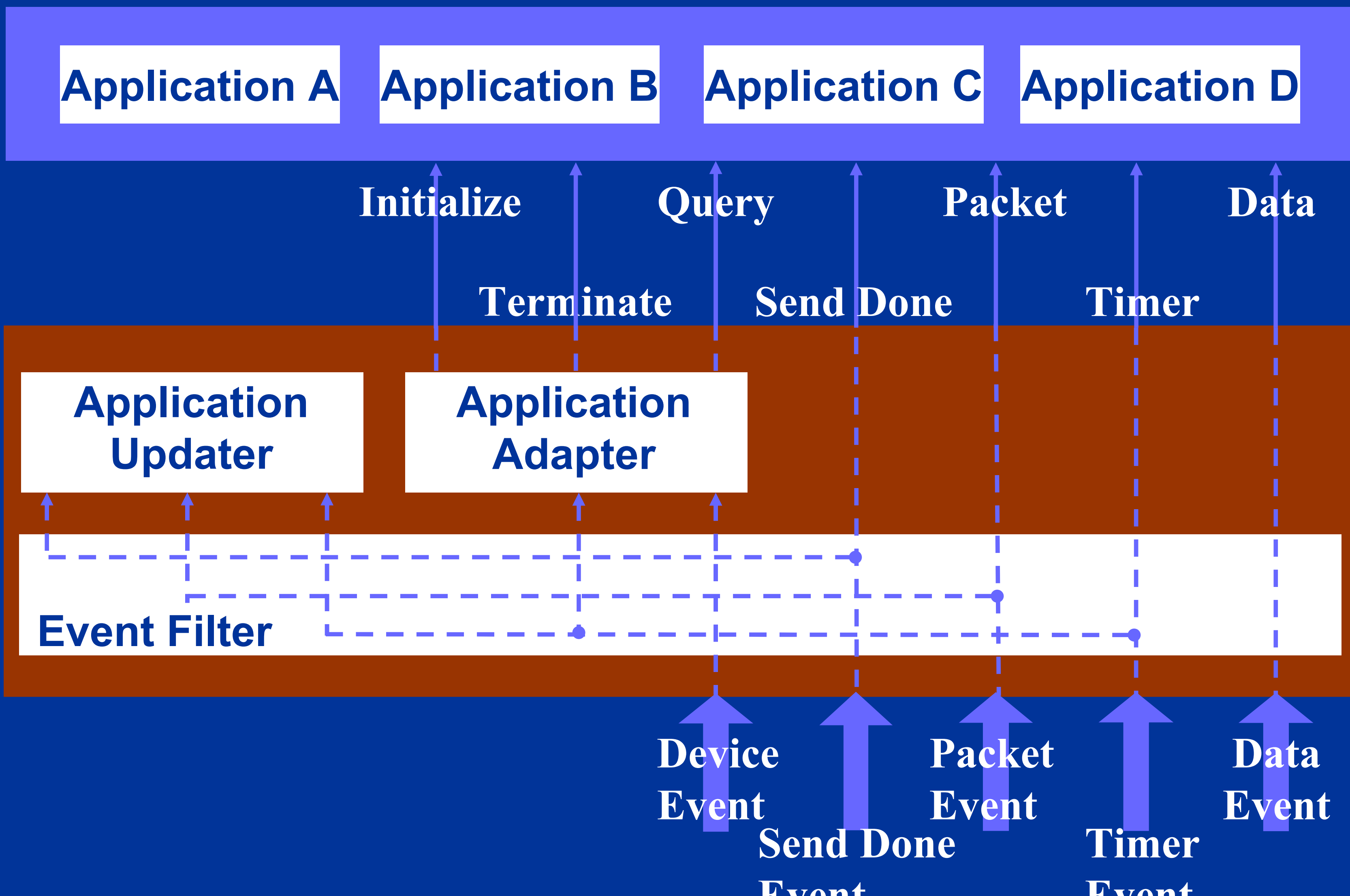
Layered Approach

Goals:

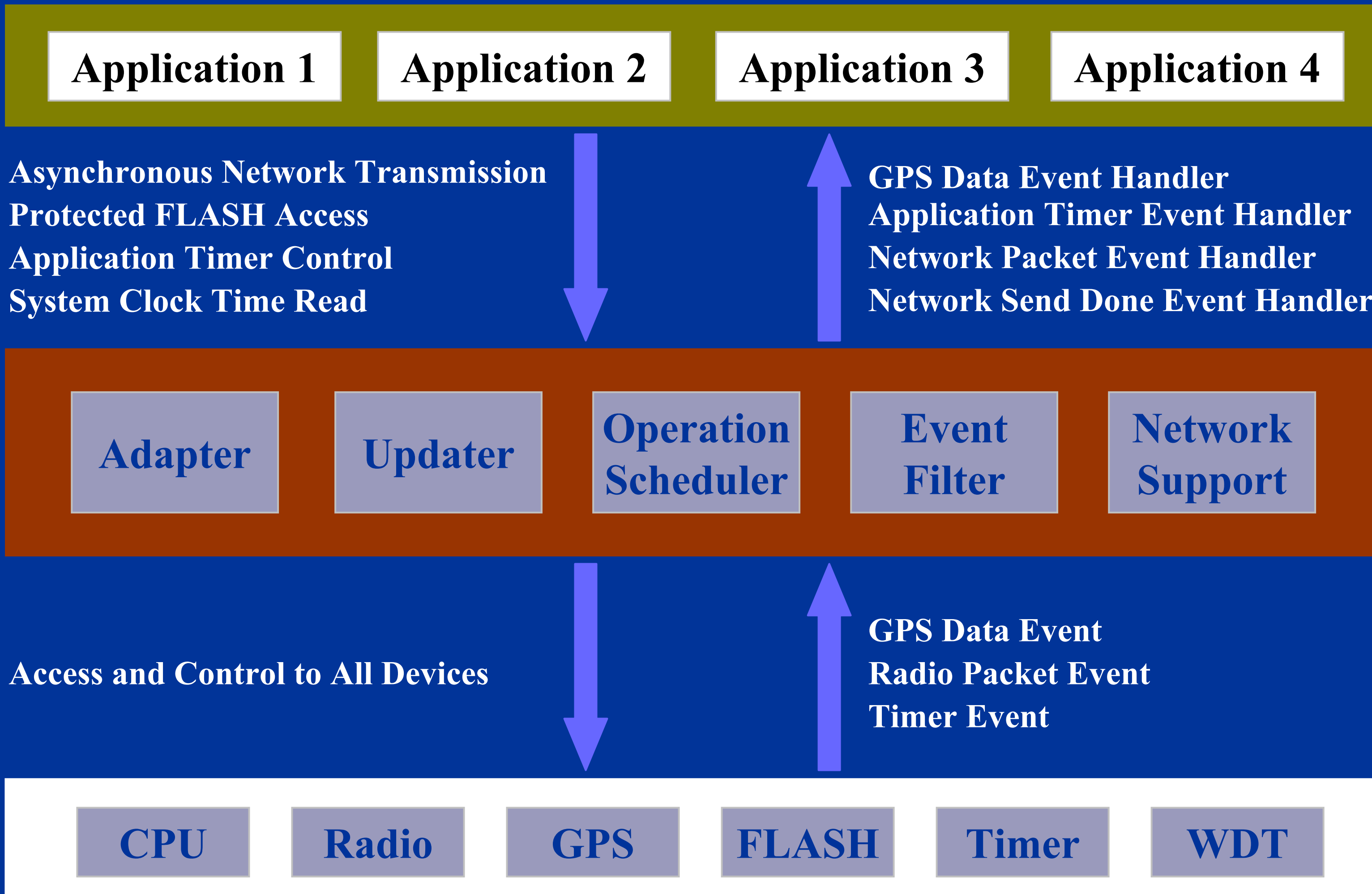
- Adaptive application software
- Remote software updates
  - ✓ Middleware adapts, updates apps, protocols dynamically
  - ✓ New protocols can be plugged in at any time



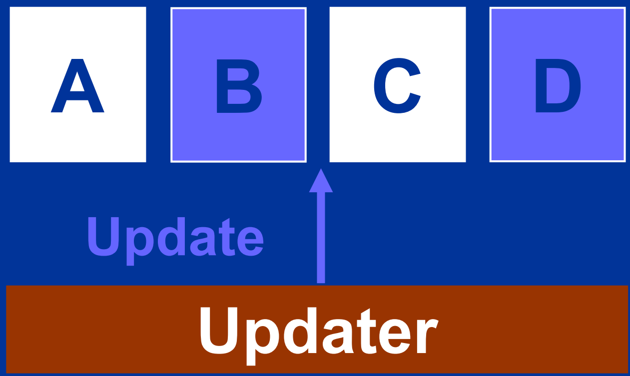
Impala Architecture & Programming Model



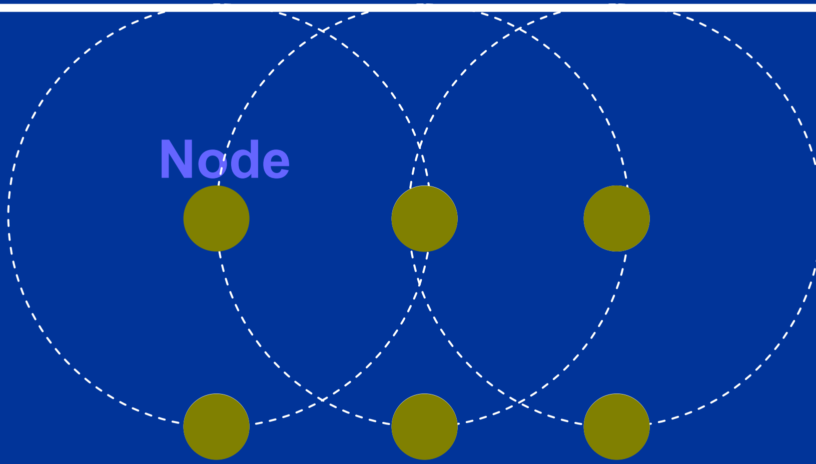
Impala Middleware Layer



Impala Code Updates



On a single sensor node



Full network

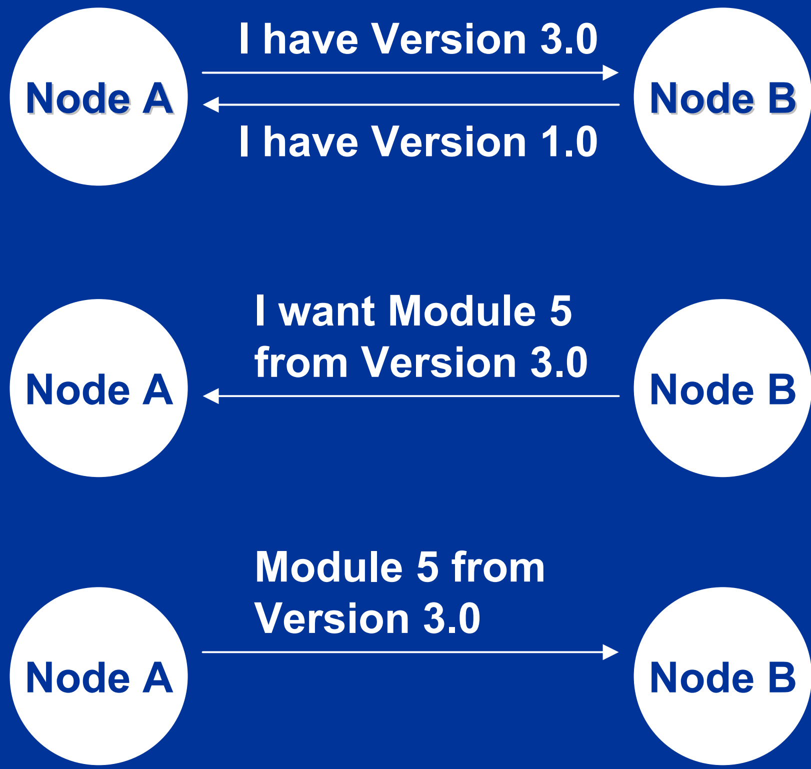
ZebraNet Characteristics

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

Design Implications

- Incomplete Updates
- Updates vs. Execution
- Out of order Updates

On-demand Software Transmission for Remote Software Update



Stage 1

Complete Version: 3.0

Incomplete Version:

Complete Version: 1.0

Incomplete Version:
2.0, 3.0

Stage 2

Complete Version: 3.0

Incomplete Version:

Complete Version: 1.0

Incomplete Version:
2.0 and 3.0

Stage 3

Complete Version: 3.0

Incomplete Version:

Complete Version: 3.0

Incomplete Version:

Repeat as needed …

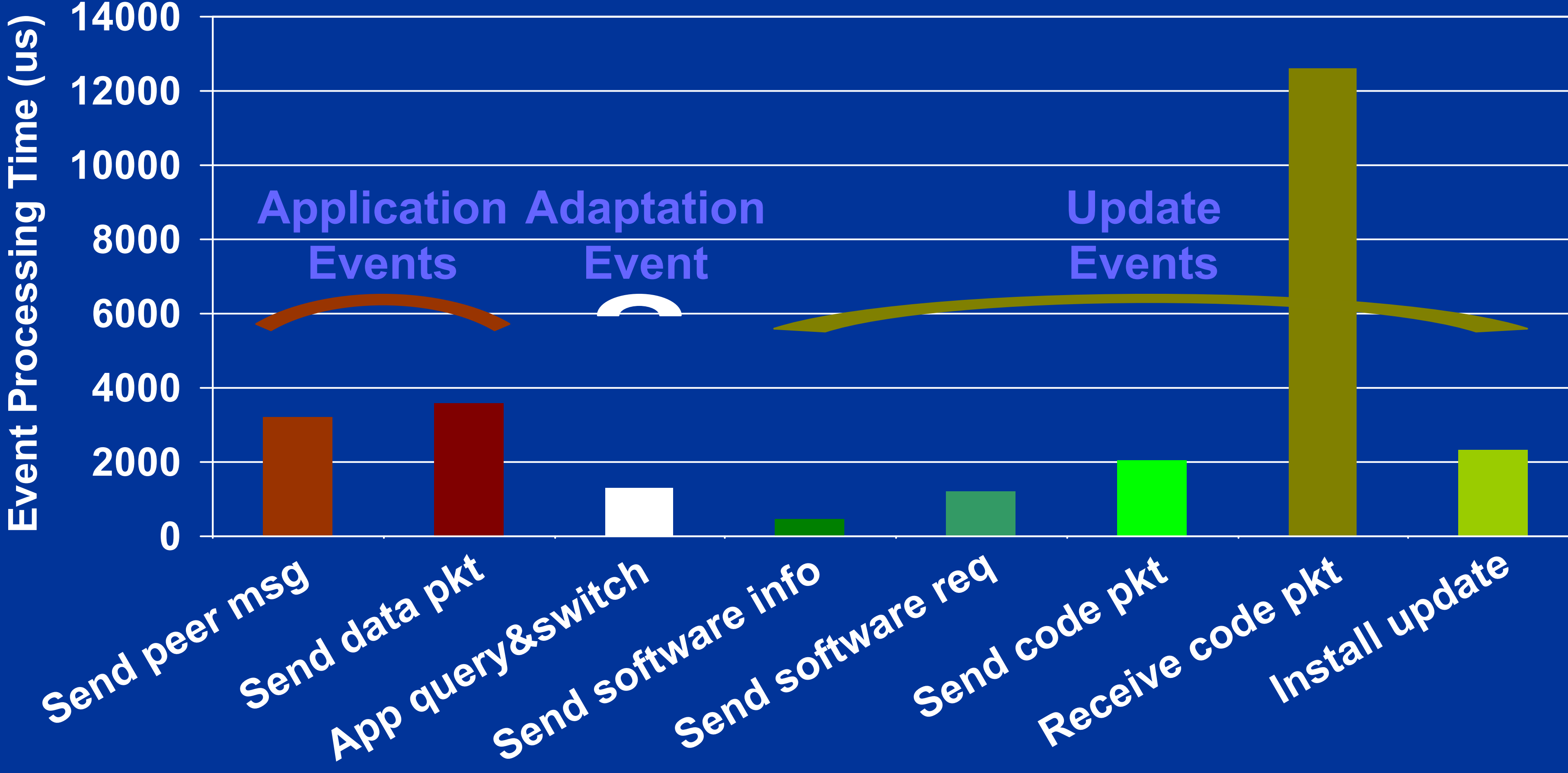
Repeat interval backs off if frequent updates not needed

Impala Implementations

- Initially prototyped on HP/Compaq iPAQ Pocket PC Handhelds
  - 206MHz CPU, 32MB flash RAM, 16MB flash ROM, running Linux
- Now (as of 2 weeks ago!) also implemented on ZebraNet hardware

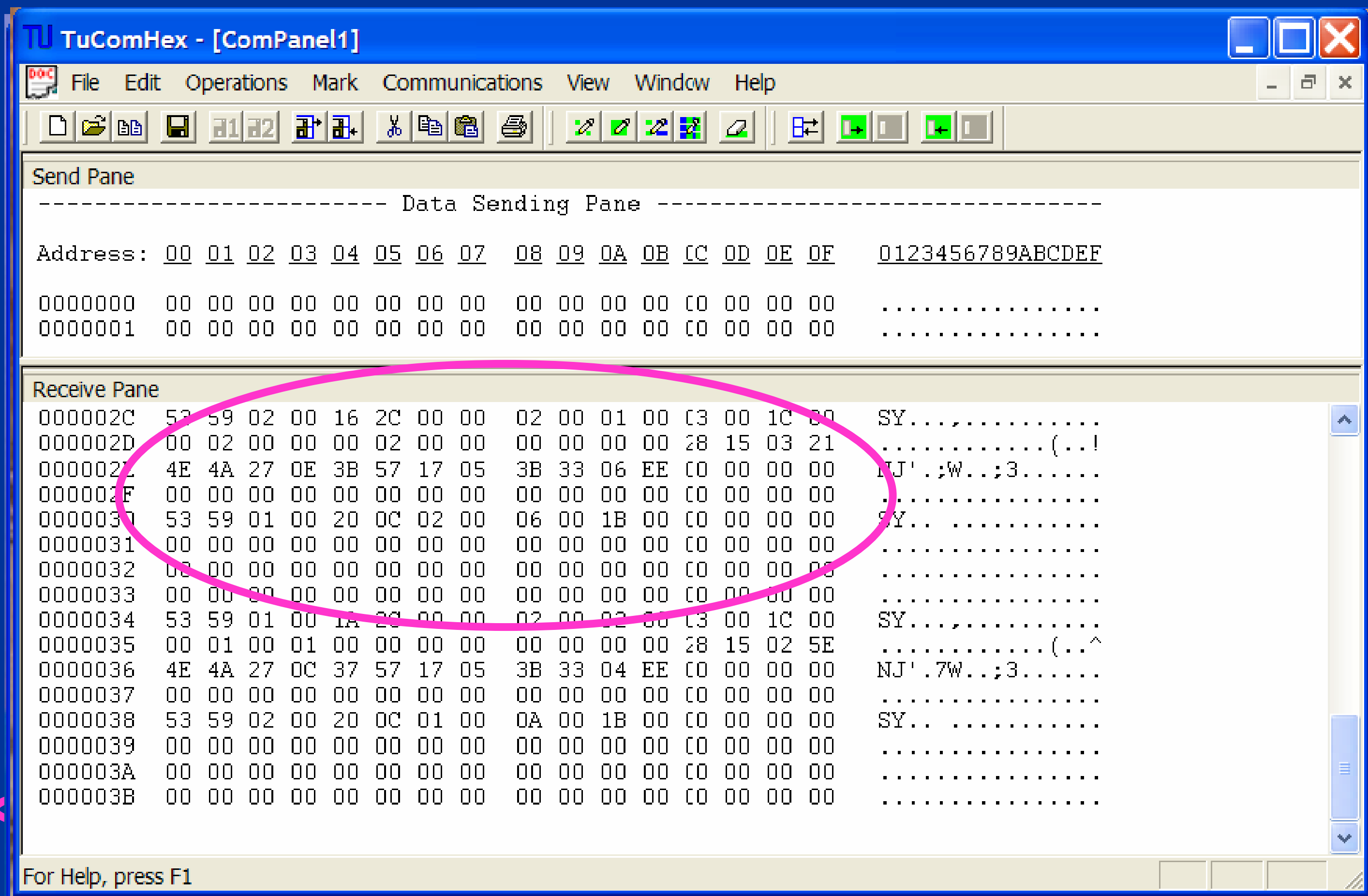
Event Processing Time Measurements

- Impala events require less time than app events except for receiving a code packet



Impala Screen Dumps

- Wait for GPS Lock
- Look for peers in range
- Send data to discovered peer



Impala Summary

- To be energy-efficient & long-running, sensor networks need to be modular, adaptable, repairable
- Impala middleware
  - Lightweight “OS” for sensor systems
  - Event handler & low-level services
- Prototype implementations and simulations demonstrate:
  - Low overhead
  - Efficient network reprogramming
  - Code updates

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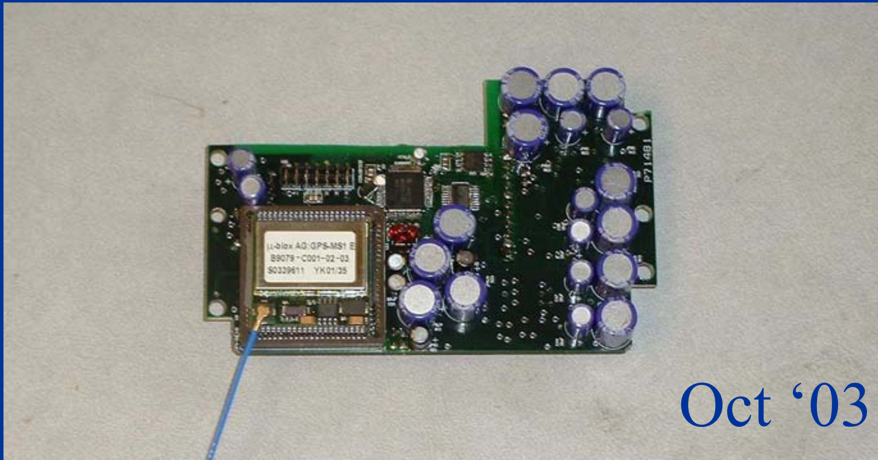
ZebraNet Hardware: Time-Lapse View…



Low-Power Hardware Strategies

- Lower-power parts
  - <5mW processor
  - <500mW GPS
- Shut-off or sleep mode for idle units
  - Individual high-efficiency switching power supplies for radio, GPS
  - Low-Drop-Out regulator for micro-controller
- Multiple clocks
  - 8MHz for performance-critical tasks; 32kHz for rest
- Software mode control to further reduce energy

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  - Software Layers and Abstractions: Impala
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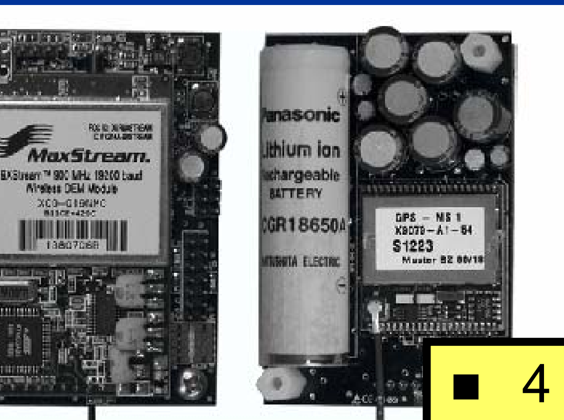
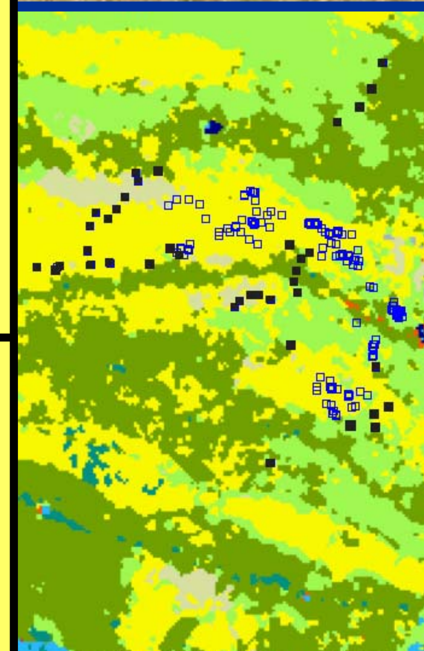
Other ongoing work…

- CPU design for sensor processing
  - Exploit unique application characteristics (highly-parallel, event-based, stream-oriented computation) to create high-perf, low-power computation model
- Analytical approach to mobility models, protocol design
  - Zebras vs. autos in NYC vs. military scenarios: Analysis techniques to automate sensible, protocol choices across range of mobilities
- Timekeeping techniques to optimize routefinding & route prefetch

ZebraNet Accomplishments To Date





- 4 hardware prototyping versions
- Full middleware design (Impala): networking, energy mgmt, remote software update
- 7-collar test deployment in January 2004 in central Kenya
- Early fine-grained data on animal movements

- For more info, see papers… ASPLOS02, PPOPP03, Mobisys04
- … and our webpage:

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

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

ebraNet Folks at Mpala Research Centre, ear Nanyuki, Kenya. January 2004.

- *Grads: Pei Zhang, Chris Sadler, Ting Liu, Ilya Fischoff,* Yong Wang, Philo Juang.
- Profs: *me, Dan Rubenstein, Steve Lyon,* Li-Shiuan Peh, Vince Poor.
- Undergrads: Julie Buechner, Chido Enyinna, Brad Hill, Kinari Patel, Karen Tang, Jeremy Wall
- Departments of EE, CS, and Biology at Princeton
- Funded by NSR ITR since 9/2002