The Emergence of Networking Abstractions and Techniques in TinyOS

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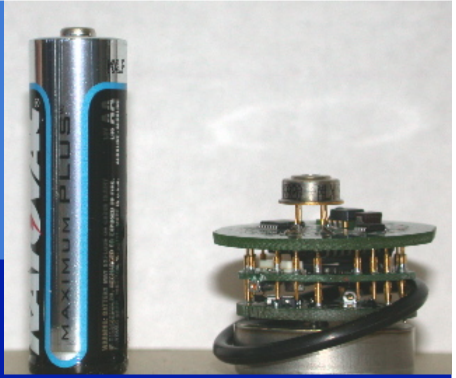
The Rise of Sensor Networks



- Sensornets:
  - tiny, cheap ⇒ Many, limited resource devices
  - embedded ⇒ Non-interactive, self-maintaining
  - power-constrained ⇒ Lifetime is a critical constraint
  - radio-equipped ⇒ Ad-hoc networking issues
- Promise to revolutionize industrial, scientific monitoring
- Emerg … Motes
  - In us … panies

Is sensornet system design (exemplified by TinyOS) substantially different than system design in conventional environments?

A Brief History of TinyOS

- TinyOS: initial versions developed at Berkeley in 2000
  - Perl scripts, cruft
- Moved to SourceForge in Summer 2001
- Intel-Berkeley heavily involved in development
  - Real programming language (nesC)
  - Many tools (simulators, gcc support, etc.)
- Now a large, community supported project
  - Berkeley, Intel, UCLA, Vanderbilt largest contributors

Methodology

- Using CVS, we study TinyOS evolution
  - Records covering 3 years, 10,000+ commits
- Focus on *networking*:
  - Software abstractions
    - General (e.g., active messages)
    - Application specialized (e.g., power management)
    - In-flux (e.g., epidemic dissemination protocols)
  - Unusual system design techniques, e.g.:
    - Cross-layer control
    - Static allocation discipline
- Highlight successes and failures
- *Not an analysis of programming model*

Outline

- TinyOS and Motes
- Single Hop Networking
- Multihop Networking
- Network Services
- Lessons and Conclusions

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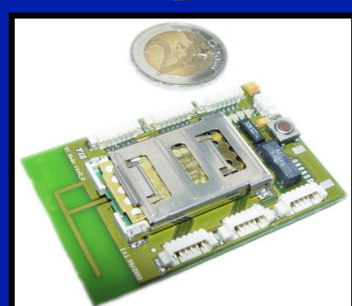
The Mote Platform

- 3 Generations: Rene, Mica, Mica2(Dot)

- Non-Berkeley Platforms:
  - Intel iMote
  - BTNode

64K RAM
512K Code
12 Mhz
38.6 kbps Radio



4K RAM
128K Code
8 Mhz
460 kbps Radio

TinyOS

- Programming model and language (nesC)
- Set of software abstractions
  - Single and multi-hop communication
  - Power management
  - Time Synchronization
  - Flash file system, timers, clocks, etc.
- Simple concurrency model
  - Hardware events (interrupts): fire asynchronously
    - E.g., timers, peripheral activity, reset
  - Tasks: "posted" to a queue (by events), execute serially
- No "kernel"; single application at a time
  - Each application includes its own set of OS services

Programming Model & nesC

- Component-based modularity
  - Components provide and require interfaces
  - Configurations wire components + configurations
  - Provides for easy composition, interposition
- Event-driven
  - Single (interruptable) thread of execution
    - Dictated by serial ordering of tasks
  - Tasks must be non-blocking, short-lived
    - Instead of blocking, use timer events or other interrupts
  - Upside: Mostly synchronization-free, only one stack
  - Downside: Complicates programs

Applications and Requirements

- Habitat Monitoring
  - E.g., TinyDB
  - Many-to-one routing
  - Collaborative, low sample rates, loose time sync, power management

- Localization
  - E.g., Vanderbilt shooter localization
  - Precise time sync, high sample rates
- Tracking
  - E.g., NEST Pursuer-Evader Games demo
  - Localization, any-to-any routing/collabora

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Single Hop Networking

- Fundamental link-layer primitive
  - Broadcast a message from A to nearby motes
    - Triv
  - Genera
- Active M
  - Messag
- Issues/T
  - Bit/byt
  - Hardwa
    - Rela
  - MAC layer (CSMA/TDMA/Hybrid)

```
Interface SendMsg {
 command result_t send(uint16_t addr,
                       uint16_t len,
                      TOS_MsgPtr msg);
 event result_t sendDone(TOS_MsgPtr msg,
                       result_t success);
}

Interface ReceiveMsg {
 event TOS_MsgPtr receive(TOS_MsgPtr msg);
}
```

The Rene Radio Stack

- RFM TR1000 Radio
- Hardware interface: read/write bit
- Software manages:
  - Timer interrupt to read/write bits
  - SEC/DED and CRC coding, DC balancing
- Interrupt rate limits to 10kbps
  - Encode/decode in tasks to limit per-interrupt time
  - 1-byte buffer limits task runtime to 1 byte time (~1.8ms)

- Low-power listening
  - Sample radio periodically, wake on transmission
- Synchronous acknowledgments
  - Sender and receiver switch roles without reacquiring channel
- Enabled by quick start up and switching times

The Mica2 Stack

- Chipcon CC1000 Radio
- 1-byte buffer with:
  - HW encoding
  - Interrupt per byte
  - CRC computation/checking in event handlers
  - Operation up to 38.6 kbps
  - 1 task per message
- Synchronous acknowledgements are impractical
  - Long send/receive switch time
    - another sender could acquire channel
- Low-power listen less effective than on RFM
  - On/off times much longer; can't sample channel as quickly

Trends & Observations

- SW/HW boundary moving towards HW
  - 802.15.4 provides packet-level interface
    - Encryption, authentication, acknowledgments, CRC
  - Decreases CPU load, software complexity
  - Decreases flexibility
    - E.g., link-layer acks infeasible on Mica2
- Fine line between useful and over-specified
  - E.g., bluetooth inappropriate for sensornets [Leopold et al, Sensys 2003]

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3 Types of Multihop Networking

- Many-to-one
  - “Tr
  - Rec
- One-t
  - Bro
  - Epi
  - Hyb
  - Lan
- Many-
  - Geo
  - Lan

```
interface Send {
 command result_t send(TOS_MsgPtr msg,
                                  uint16_t length);
 command void* getBuffer(TOS_MsgPtr msg,
                                  uint16_t* length);
 event result_t sendDone(TOS_MsgPtr msg,
                                  result_t success);
}
interface Intercept {
 event result_t intercept(TOS_MsgPtr msg,
                          void* payload,
                          uint16_t payloadLen);
}
```

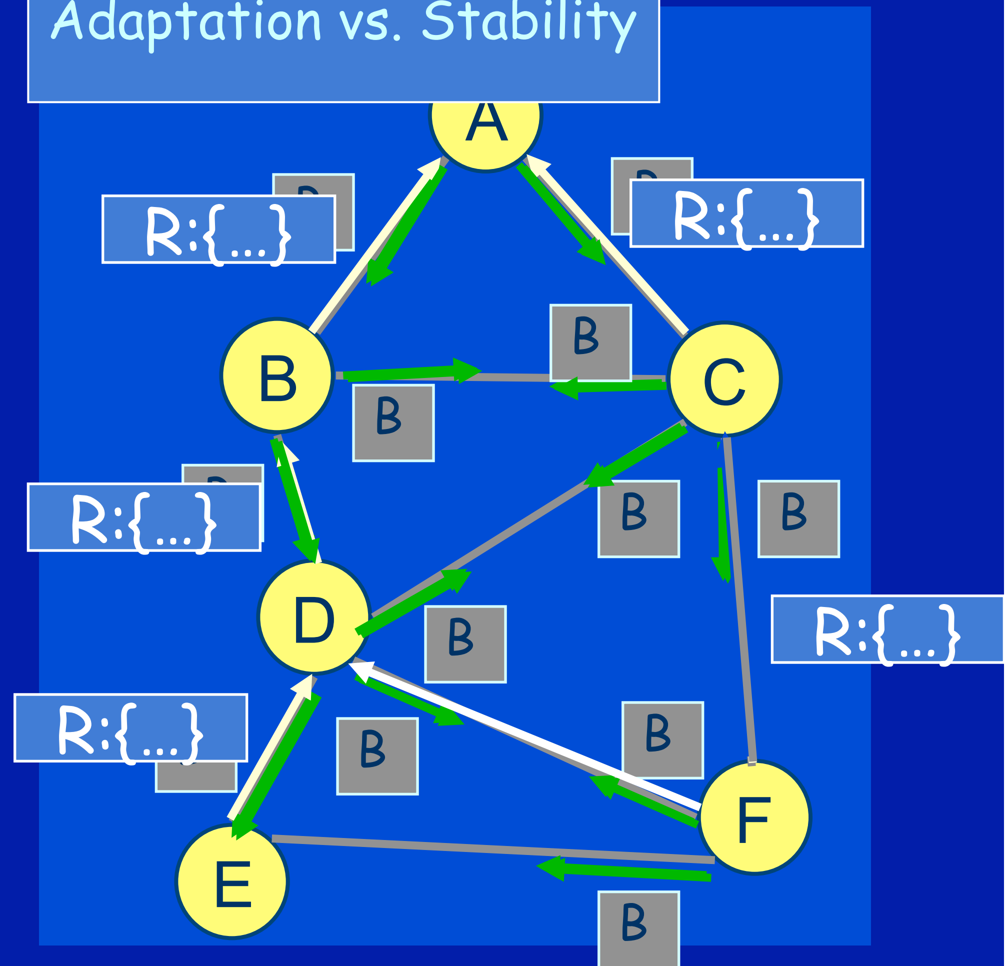
Many-to-1: AMROUTE vs. MultihopRouter

- AMRoute: Proto-routing
  - Pick first neighbor who transmits beacon as parent
- MultihopRouter
  - Estimate link-quality to neighbors
    - Using neighbor beacons
  - Pick path of fewest hops
    - Or fewest xmissions

Problems:
Bad Parent Selection
Asymmetric Links
Adaptation vs. Stability

Node D	
Neigh	Qual
B	.75
C	.66
E	.45
F	.82

Node C	
Neigh	Qual
A	.5
B	.44
D	.53
F	.35



Broadcast Floods and Epidemics

- Common app need: reliable dissemination
  - E.g., TinyDB queries, PEG parameters
- Floods
  - Used extensively
  - Effective way to reach most nodes
  - Randomize retransmits to avoid collisions
- Epidemics
  - Nodes "infect" neighbors with data, programs
  - Reach all nodes eventually
  - Requires careful tuning of transmit rate
- Hybrid
  - Flood + epidemic patchup
  - E.g., tinydb, network reprogramming algorithms

Trends & Observations

- Standard multihop interface has emerged
  - Including promiscuous “intercept” interface
- Common abstractions
  - Cross-layer neighbor table
    - Link state (e.g., qualities)
    - Network state (e.g., parent, depth, location)
  - Link quality estimation
    - Appears in MultihopRoute, DSDV, TinyDiffusion
  - Forwarding queue; app-configurable length
- Surprising
  - No receive queues
  - Segmentation/framing generally done by applications
  - Most apps are many-to-one

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  - Time Sync, Power Management
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Power Management & Scheduling

- `HPLPowerManagement` monitors processor state
  - Powers down when not in use
  - Brittle, platform specific technique
- Application uses `stop` interface to power down components
  - Uses timers to power back up
- Common forms of power management:
  - Low-power listening,
  - Scheduled operation (require synchronization)

- Power management is app-specific, with simple OS mechanism
  - Application knows when it should be on or off
- Versus traditional mobile environments
  - Where needs multiple apps, interactivity requirements conflict

Time Synchronization

- Many implementations
  - Vanderbilt, UCLA, Berkeley
  - Most rely on low-level events from radio
    - Cross-layer optimization
- Building a general purpose time sync is hard
  - Not for the reasons the research community is concerned with
  - Instead, due to interactions with application/OS timers
    - Similar to NTP observations
- Application controlled time-sync much easier
  - Application knows when changes are safe
  - E.g., TinyDB adjusts length of sleep intervals

Trends & Observations

- Application control of OS mechanism
  - Single app makes this more feasible
  - Low-interactivity enables aggressive policies
    - Tailored to each application
- Power management surprisingly rare in apps
  - Many apps are "demos", not "deployments"

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Widespread Abstractions

- AM, single, multihop interfaces are "standards"
  - Several link/many-to-one network implementations
- Time sync, power management: app specific policy
  - Standardized mechanisms
- Many abstractions still in-flux
  - E.g., many-to-many routing, epidemic protocols

- Some abstractions have never emerged
  - Where is distributed cluster formation?

Interesting Development Techniques

- Cross layer control
- Scheduling vs. snooping
- Static Resource Allocation

Conclusions

- So what's really different?
  - Limited memory constrains software design
    - E.g, RAM limitations imply a static discipline
  - Timing sensitive net services imply cross-layer control
    - E.g, time-sync, power-scheduling, localization
  - Single, non-interactive app
    - Services are different from their laptop counterparts
  - In-network processing vs. end-to-end connectivity
    - Traditional networking focuses on the latter

- Conclusion: TinyOS isn't solely a product of a crippled hardware platform!