Low-Power Sensor Networks

A Case Study in Seeking Distributed Predictability

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Predictable

- TinyOS and the specter of low-power
  - Limited resources and communication
  - Black box operation
- Systems are easy; predictable/dependable systems are hard
  - Large numbers, distributed through space
- Failures are inevitable: isolating them is paramount
  - Systems approach: TinyOS, TinyOS 2.0/T2
  - Networking approach: MNet
- This talk has nothing to say about real-time
  - More on why later

Outline

- A brief history of: 1.0, 1.1 and 2.0 (T2)
- T2 core structure, language/OS co-design
- MNet architecture
- Real Time?

In the Beginning

(1999)

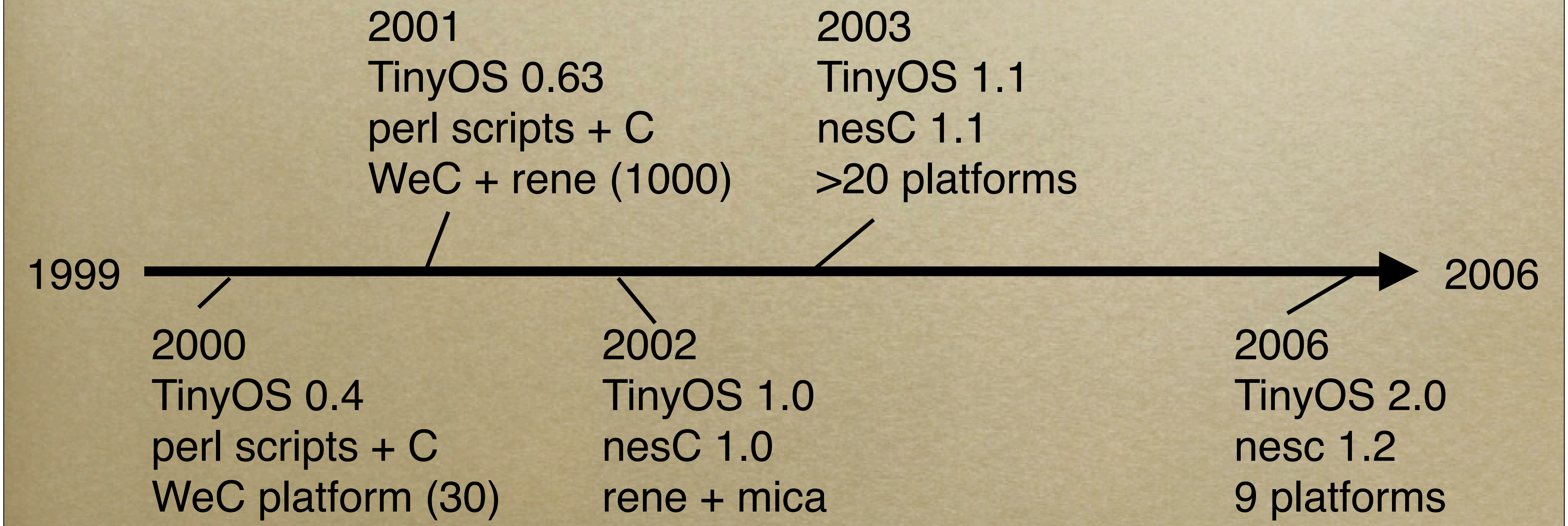
- Sensor networks are on the horizon...
- ... but what are they going to do?
  - What problems will be important?
  - What will communication look like?
  - What will hardware platforms look like?
- Having an operating system is nice...
- ... but how do you design one with these uncertainties?

The TinyOS Goals

(ASPLOS 2000)

- Allow high concurrency
- Operate with limited resources
- Adapt to hardware evolution
- Support a wide range of applications
- Be robust
- Support a diverse set of platforms

History



1999

2000
TinyOS 0.4
perl scripts + C
WeC platform (30)

2001
TinyOS 0.63
perl scripts + C
WeC + rene (1000)

2002
TinyOS 1.0
nesC 1.0
rene + mica

2003
TinyOS 1.1
nesC 1.1
>20 platforms

2006
TinyOS 2.0
nesc 1.2
9 platforms

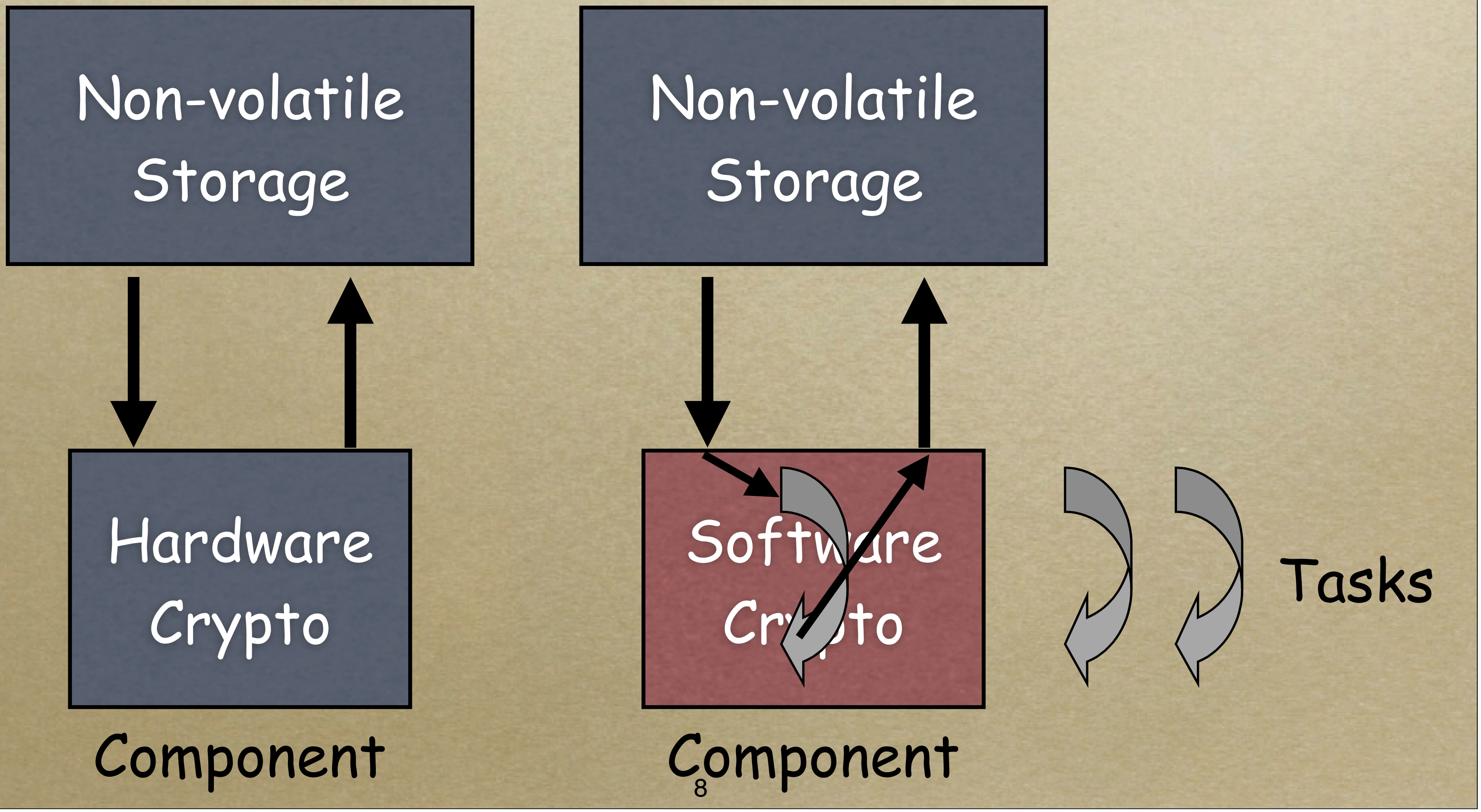
2006

TinyOS Basics

- A program is a set of components
  - Components can be easily developed and reused
    - Adaptable to many application domains
  - Components can be easily replaced
  - Components can be hardware or software
    - Allows boundaries to change unknown to programmer
- Hardware has internal concurrency
  - Software needs to be able to have it as well
- Hardware is non-blocking
  - Software needs to be so as well

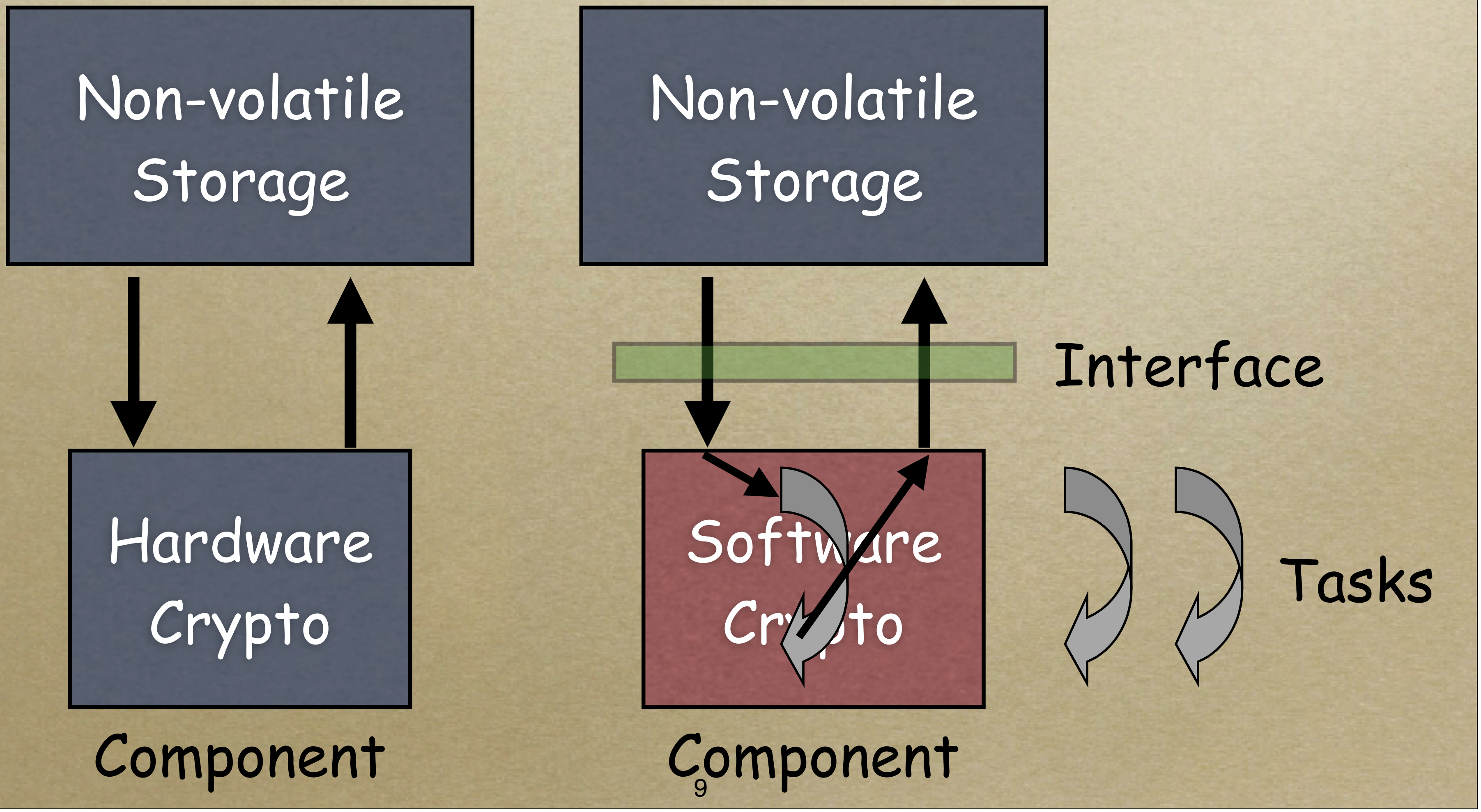
TinyOS Basics

(2000)



TinyOS Basics, Continued

(2002, nesC)



The TinyOS Goals

(A Scorecard, 2005)

- Allow high concurrency (A)
- Operate with limited resources (A-)
- Adapt to hardware evolution (B)
- Support a wide range of applications (B)
- Be robust (D)
- Support a diverse set of platforms (B-)

Robustness Drives Design

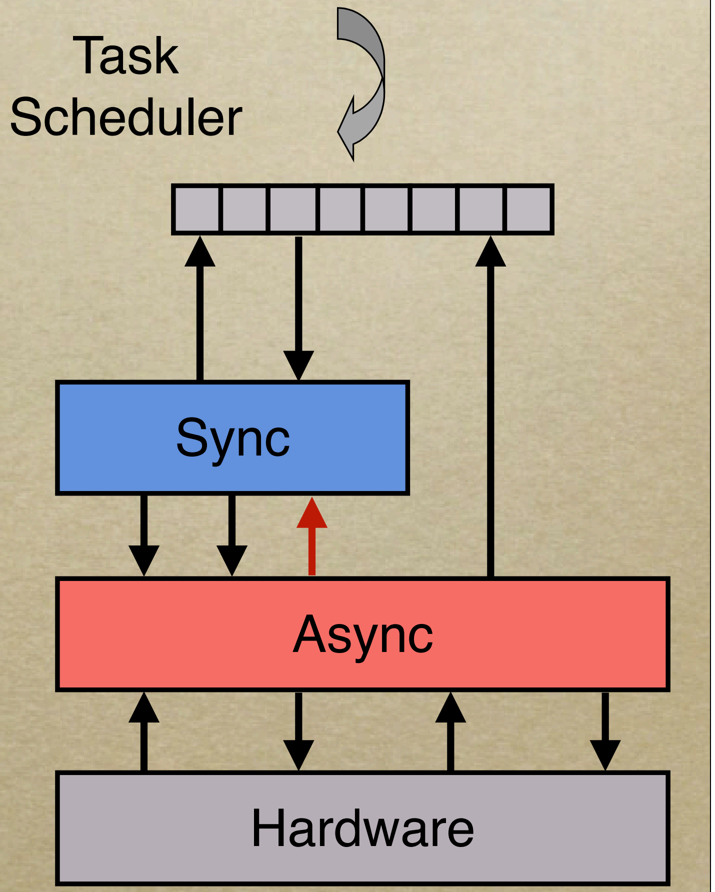
- Allow high concurrency (A)
- Operate with limited resources (A-)
- Adapt to hardware evolution (B)
- Support a wide range of applications (B)
- Be robust (D)
- Support a diverse set of platforms (B-)

TinyOS 0.6 -> TinyOS 1.0

- Introduce nesC language instead of perl + C
- Compilation benefits
  - Pre-nesC linked compiled components into an executable
  - The nesC compiler generates a single C file
    - Whole program analysis
    - Whole program optimization (code the native compiler likes)
    - Dead code elimination
- Interfaces
  - Establish programming abstraction as a language abstraction
  - Prevent bugs

TinyOS 1.0 -> TinyOS 1.1

- Major addition: async keyword
- Synchronous code: tasks (non-preemptive)
- async code is safe to call outside a task
  - Interrupt handlers are all async (preemptive code)
- To call sync code, async code must post a task
  - sync examples: start a ms timer, send a packet
  - async examples: start a 32kHz alarm, send a byte over a bus



Async vs. Sync

- Async code can preempt sync code
  - Might cause data races, `atomic` statements
- Sync code is written assuming no preemption
  - Sync code executes atomically with respect to other sync code
  - Simple, easy to write, no data races
- Tasks are the interface which transforms async to sync
- The explicit sync/async distinction allows nesC to detect all data races at compile time
- Fixed >100 data races in TinyOS (6 races/1000 lines)

Outline

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- MNet architecture
- Real Time?

TinyOS Evolution

- TinyOS 1.x improved component dependability
  - Adding language mechanisms for better checking
  - Low-level system code (few writers, many users)
  - OK to trade verbosity for dependability
  - Push checks to compile-time when possible
- TinyOS 2.0 takes the next step: system predictability

Failures of Implementation

- Components intended to be independent
- Unforeseen interactions
  - “The ADC hangs when I send packets!”
  - “Time synchronization gives crazy readings!”
  - “When I turn off the radio my application hangs!”
  - “When I boot with flash support the radio stops working!”

Failures of Structure

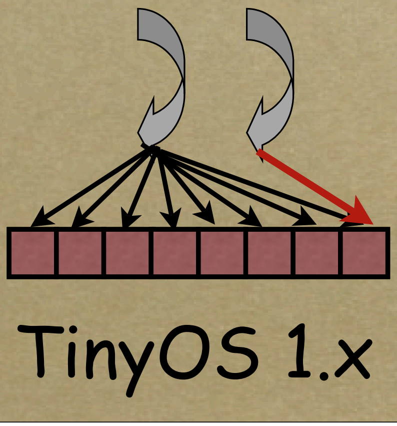
- TinyOS 1.x has no resource management
- Most operations can fail at any time (busy)
  - Packet transmission
  - Bus access
  - ADC sampling
- Depends on higher-level retries
  - Global “done” events (e.g., GenericComm.sendDone)
  - Fan-out has deterministic scheduling
- No component isolation

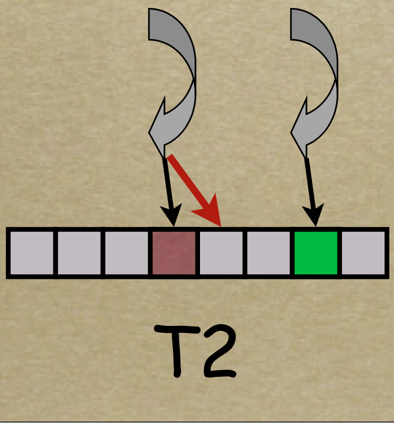
Allocation

- TinyOS has always followed a static allocation policy
  - Argument: dynamic allocation leads to dynamic failures
- One major 1.x exception: the task scheduler
  - Major source of failures
  - Inherent inter-component dependency

Concurrency Model

- T2 has the same basic concurrency model
  - Tasks, sync vs. async
- T2 changes the task semantics
  - TinyOS 1.x: post() can return FAIL, can post() multiple times (shared slots)
  - T2: post returns FAIL iff the task is already in the queue (single reserved slot per task)

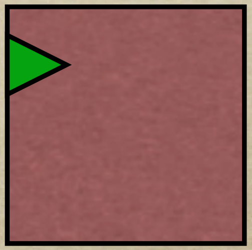




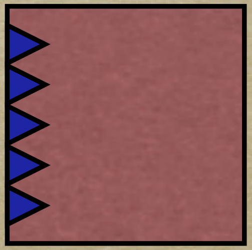
Static Binding

- Run-time vs. compile time parameters

```
interface CC2420Register {
  command uint16_t read(uint8_t reg);
  command uint8_t write(uint8_t reg, uint16_t val);
  command uint8_t strobe();
}
component CC2420C {
  provides interface CC2420Register;
}
```



```
interface CC2420StrobeReg {
  command uint8_t strobe();
}
component CC2420C {
  provides interface CC2420StrobeReg as SNOP;
  provides interface CC2420StrobeReg as STXONCCA;
   ....
}
```



Static Allocation

- You know what you’ll need: allocate it at compile-time (statically)
- Depending on probabilities is a bet
  - I.e., “it’s very unlikely they’ll all need to post tasks at once” = “they will”
- You know what components will use a resource, can allocate accordingly
  - In some cases, static allocation can **save** memory
  - Less defensive programming/error handling

Predictability Saves Memory

```
module Foo {
  bool busy;

  command result_t request() {
    if (!busy() &&
        post fooTask() == SUCCESS) {
      busy = TRUE;
      return SUCCESS;
    }
    else {
      return FAIL;
    }
  }
```

TinyOS 1.x

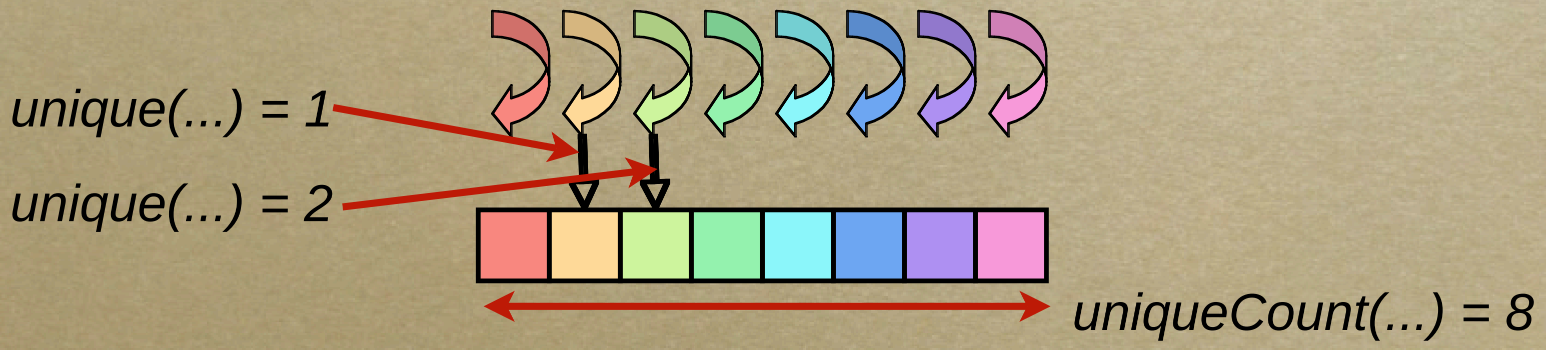
```
module Foo {
  ~~bool busy;~~

  command result_t request() {
    return post fooTask();
  }
```

T2

The Power of Counting

- Basic language mechanism that TinyOS provides
- Ability to count elements in an application at compile time
  - unique(key): for each key, returns a unique number starting at 0
  - uniqueCount(key): returns number of calls to unique(key)
- Each needed service or abstraction can use its own key
  - Tasks: unique(“TinySchedulerC.BasicTask”), etc.



unique(...) = 1

unique(...) = 2

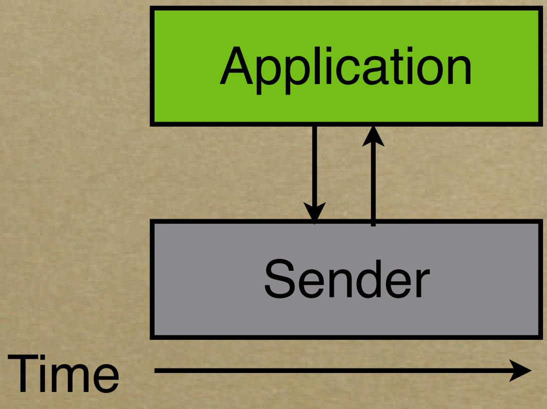
uniqueCount(...) = 8

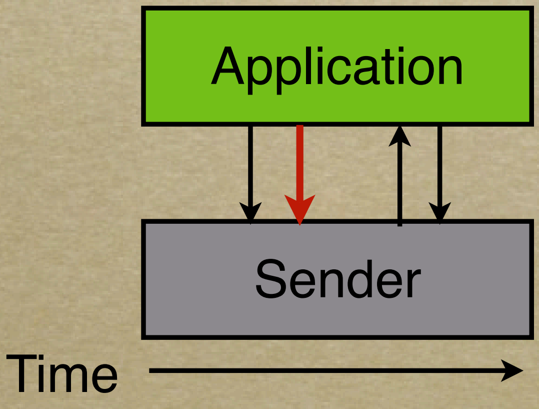
Basic OS Requirement: QoS

- Flaw in many protocols: under load, routing fails
  - Data packets overflow queues
  - Control packets are lost, routes disintegrate
- Priorities are difficult: they can break promises
  - I've agreed to forward this data packet, but have to drop it now...
  - Defining priorities across many protocols can be difficult
- Want to promise a minimum quality of service
  - Control traffic receives at least k/n of the available bandwidth
  - A control packet has to wait for at most x packets

QoS Through an OS Interface

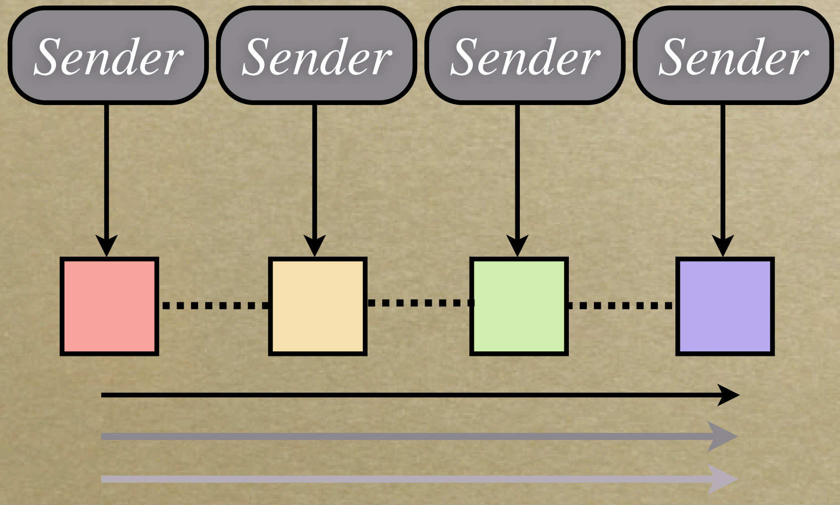
- Every component that needs to send a packet instantiates an instance of a packet sending service
  - Broadcast, collection, unicast, etc.
- Each instance of the service can have at most one outstanding packet at any time
- Like tasks, send fails if and only if a packet is already pending





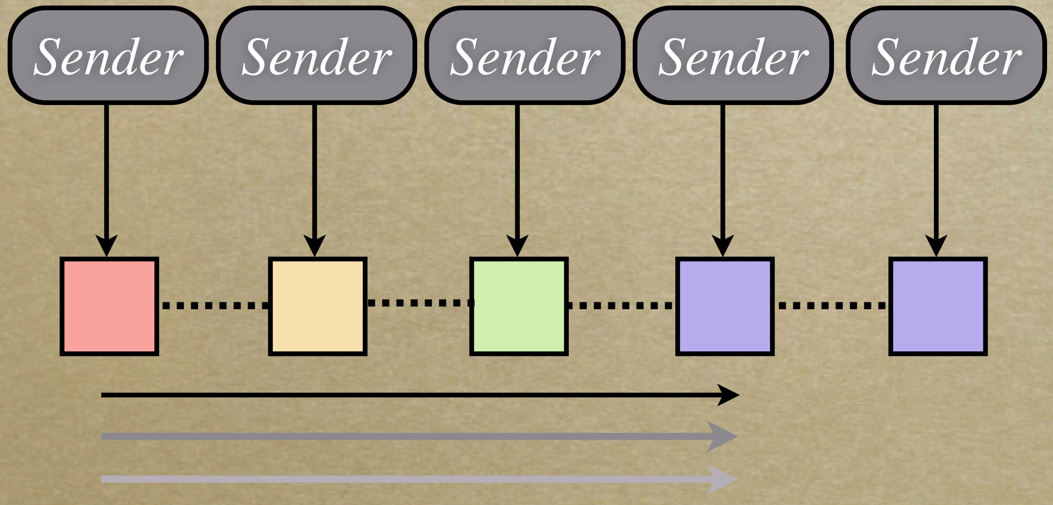
QoS Through Counting

- Each instance allocates a queue entry with unique(...)
- The service has a queue of length uniqueCount(...)
- Implementation scans through the queue for pending packets



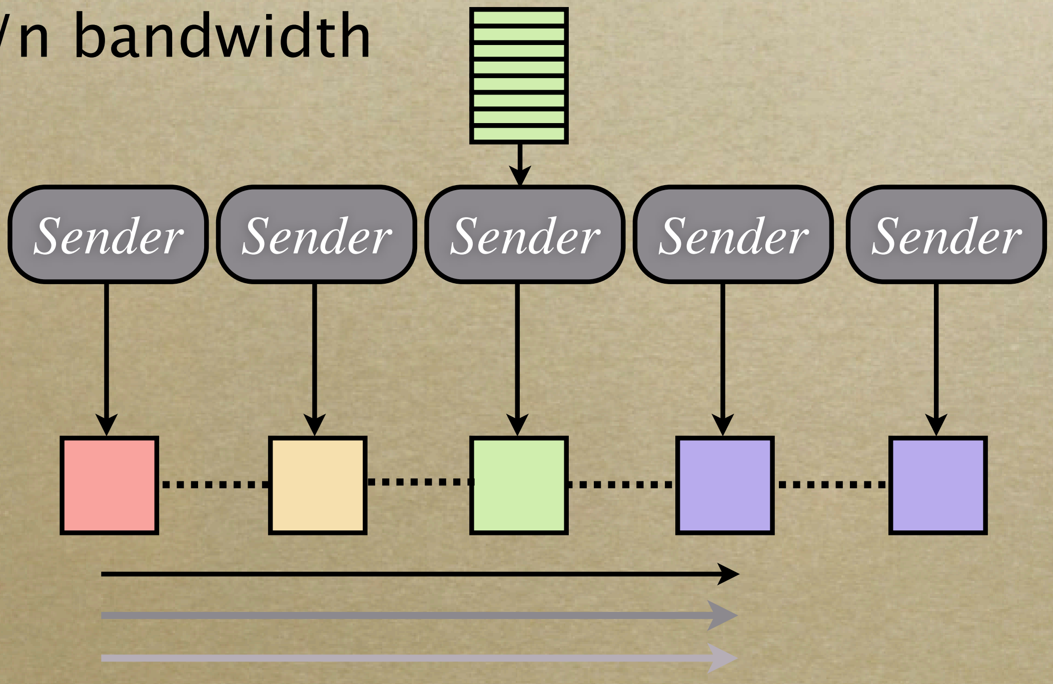
Extending the Model

- A protocol can allocate more than one sender for a greater share



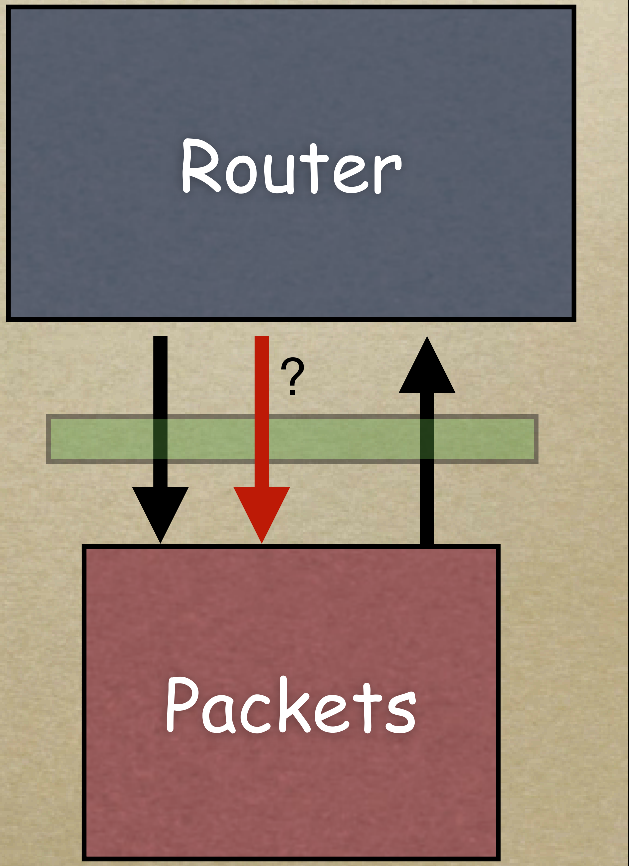
Extending the Model

- A protocol can allocate more than one sender for a greater share
- A protocol can introduce its own queue
- Still uses k/n bandwidth



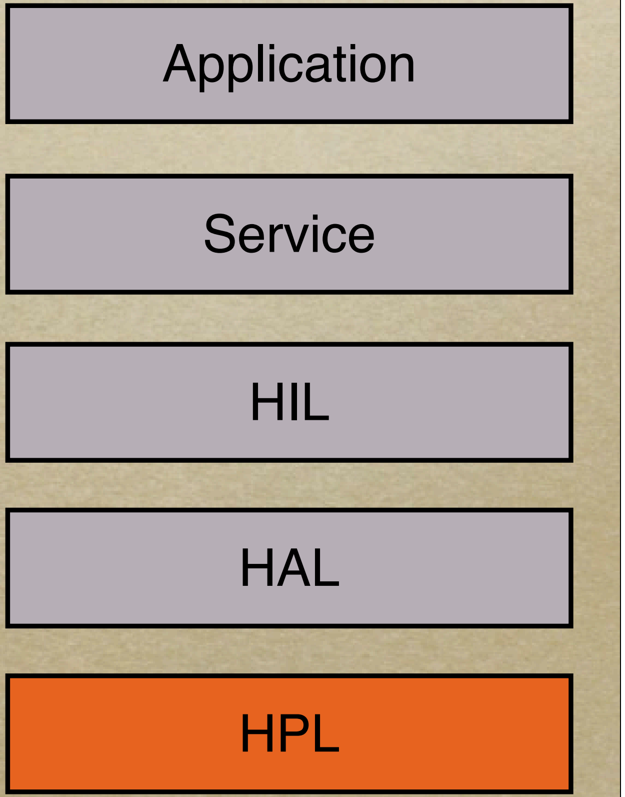
More Defensive Programming

- Interfaces allow programs to easily swap component implementations
  - Exchange SerialAMSenderC for AMSenderC
- Interfaces are weakly specified
  - Allow implementation differences
  - E.g., 1.x SendMsg vs 2.0 Send
- Weak specifications lead to defensive programming
  - More code -> more errors
  - Wastles resources



Interface Contracts

- Specify valid call patterns with annotations
  - Per-interface basis (heavy reuse)
  - Both sides of the interface
- Base case: hardware abstractions follow contracts
- Inductive static, dynamic, run-time checking
  - Run-time approach has detected several serious bugs in 1.x (which turn out to be impossible by design in 2.0)



Application

Service

HIL

HAL

HPL

Outline

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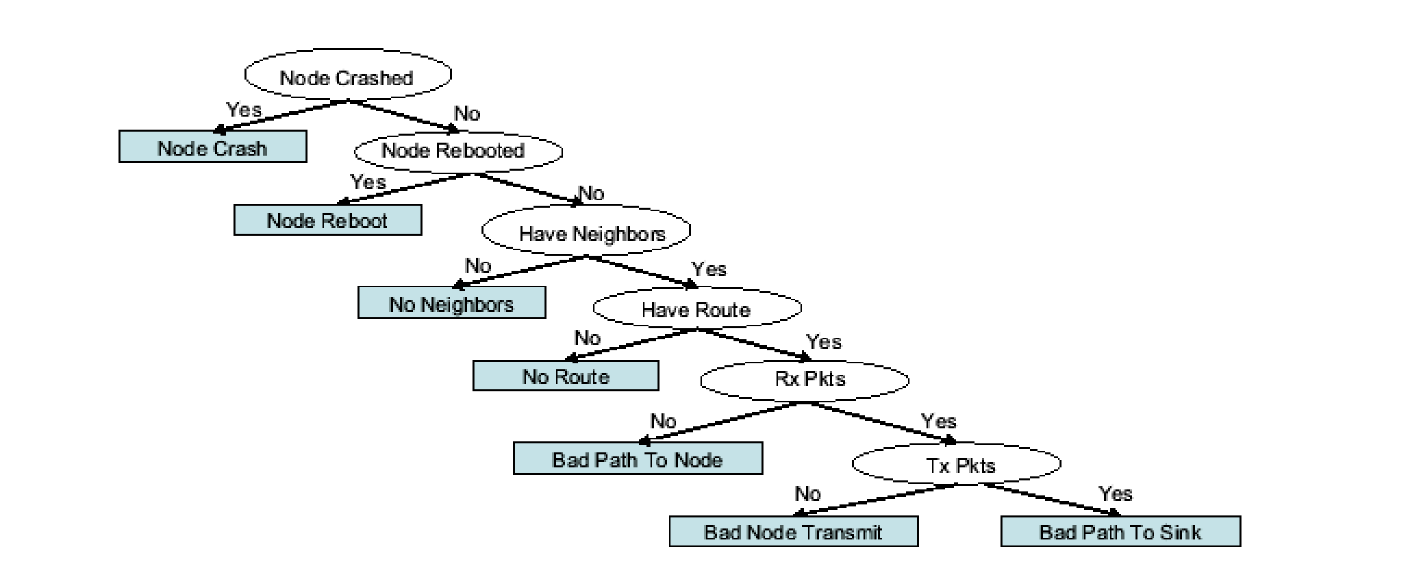
Sensornets Are Hard

- Sensor networks often fail/operate poorly
  - Great Duck Island network: median yield 58% [SenSys 2004]
  - Redwood network: median yield 40% [SenSys 2005]
  - Volcano network: median yield:68% [OSDI 2006]
- Survey of causes
  - Protocol conflicts/interference
  - Collisions and congestion induced loss
  - Neighbor management (with layer 2 scheduling, e.g. TMAC)
  - Don't know!
- Low-power, limited resources make complete logging prohibitively expensive...

Management

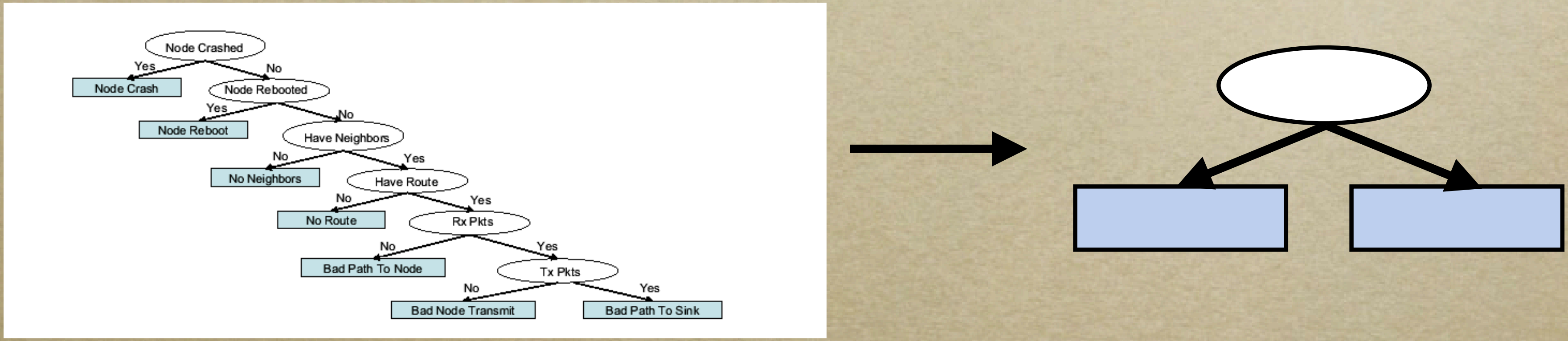
- Give operators a peek into the sensornet black box
- SNMS [EWSN 2005]: lightweight get/set
- Sympathy [SenSys 2005]: expert system



MNet Principle

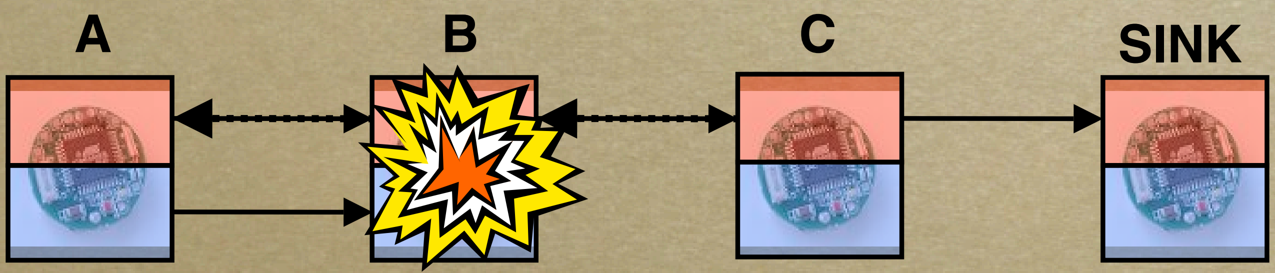
- The difficulty in deploying and developing sensornets is part of the essence of this class of systems.
  - Large numbers, limited energy, distributed over space, different views of the environment, noise, local optimizations, etc.
  - This is more than an artifact.
- MNet principle: Improve visibility into the internal operation of the network.
  - Quantify: Minimize the energy required to identify the cause of network behavior.
- Case study: network protocols.

Goal


Node Crashed
Yes
No
Node Crash
Node Rebooted
Yes
No
Node Reboot
Have Neighbors
No
Yes
No Neighbors
Have Route
No
Yes
No Route
Rx Pkts
No
Yes
Bad Path To Node
Tx Pkts
No
Yes
Bad Node Transmit
Bad Path To Sink

Inter-Protocol Interference

- Snooping is a common routing approach
  - Implicit acks, rate control, backpressure, etc.
- Vulnerable to inter-protocol interference
  - Reduces energy efficiency, can even cause failures
- One misbehaving protocol can prevent anyone else from performing well



Isolation

- Isolating behaviors simplifies reasoning.
  - Basic technique in systems: apply to networks
- If any protocol X, Y, Z can a protocol to fail, then we have a larger (more expensive) state space to explore
- We need a way to isolate protocols from one another, so they can operate concurrently but not interfere.
- Mechanism: grant-to-send (GTS)

Grant-To-Send

- A transmitter may embed a quiet time in a packet.
- No-one except the destination may transmit for the duration of the quiet time (including transmitter).
- Sending a packet grants the channel to the receiver.

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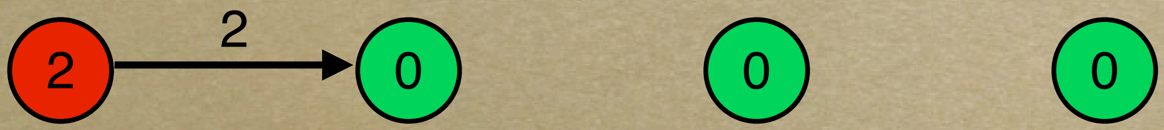

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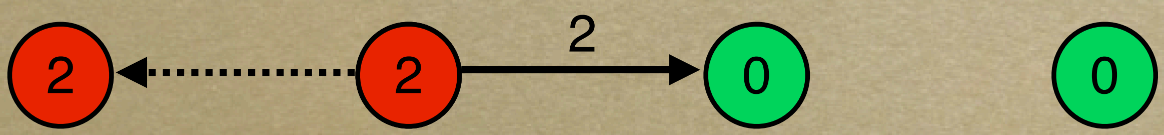

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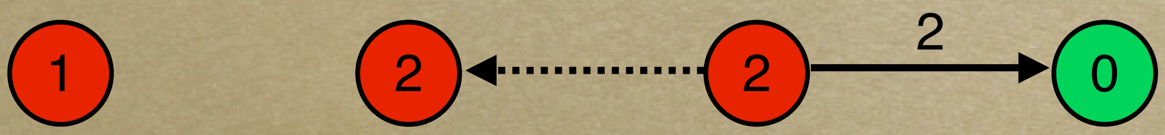

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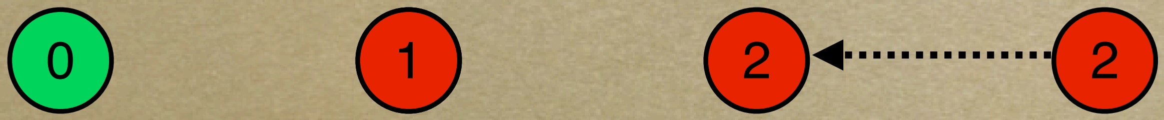

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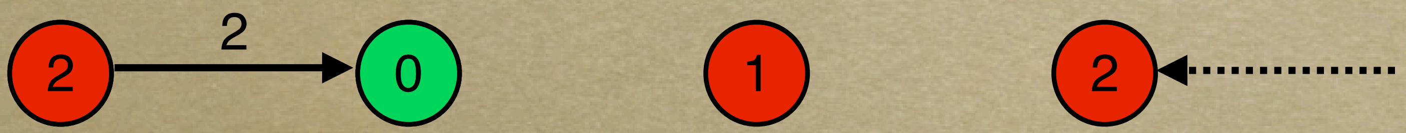


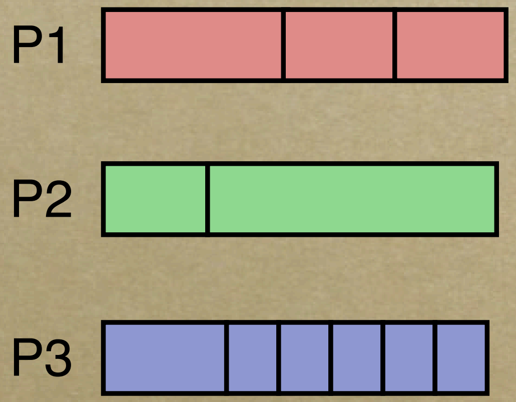
Fairness

- Isolation is insufficient.
  - The simplest approach is to not let anyone do anything.
- Every protocol should receive its fair share of the network bandwidth.
- Wireless is inherently distributed
  - Different views of the channel
  - Perfect fairness is not always possible (but we can be close)
- Mechanism: fair queueing
  - GTS times represent channel utilization
  - Naturally fit into fair queueing

Fair Queueing

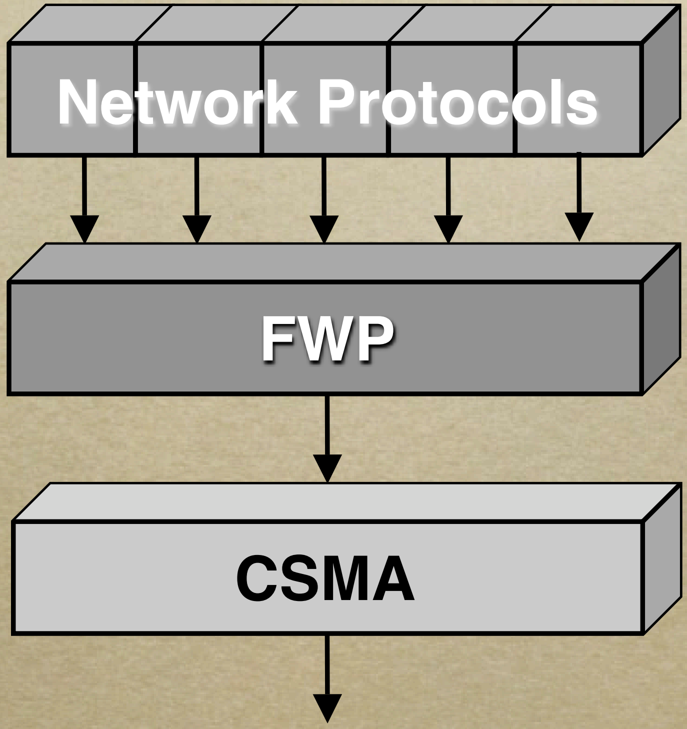
(Demers, Shenker, and Keshav)

- Send protocol which has lowest channel utilization.



Fair Waiting Protocol

- Uses Grant-To-Send mechanism
- Sits between CSMA layer and network layer
- Fair queueing according to the channel occupation
  - Considers the grant duration as a channel occupation

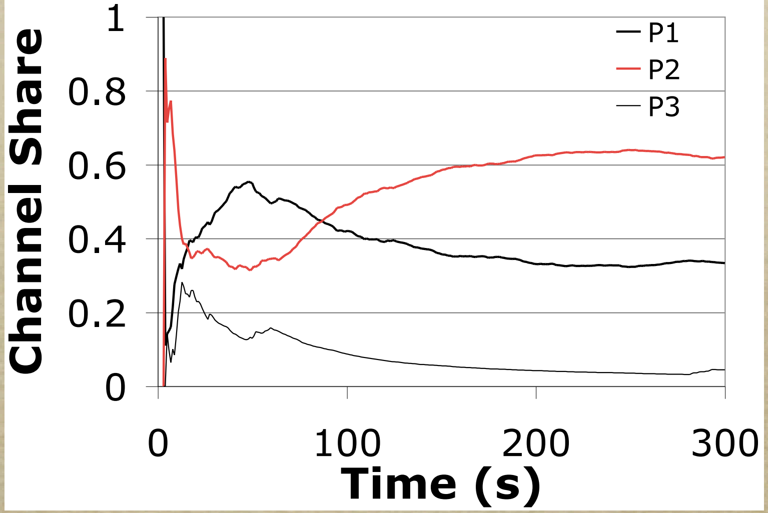


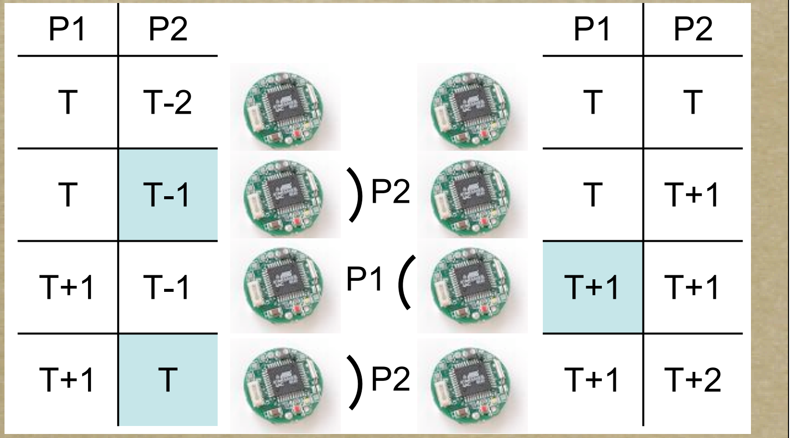
Single-Hop Uniform Lossless Load

- Ideal case without collisions and packet losses
- Perfect fairness among nodes and protocols
  - CSMA allows all nodes to have equal chance of transmission
  - All nodes agree on channel usages of protocols, thus perfect fairness among protocols
- Perfect Isolation
  - Every node waits until the current quiet time expires

Loss

- Lost packets can cause inconsistent view of the channel occupation times of protocols
- Experimental Setting:
  - Five nodes in single-hop range
  - Three protocols with different quiet times (20ms / 40ms / 80ms)
- Normalized share of one node
- High channel fairness: 0.99 (Jain's Fairness Index)
- However, individual nodes are servicing protocols unevenly
- "Ping-pong Effect"



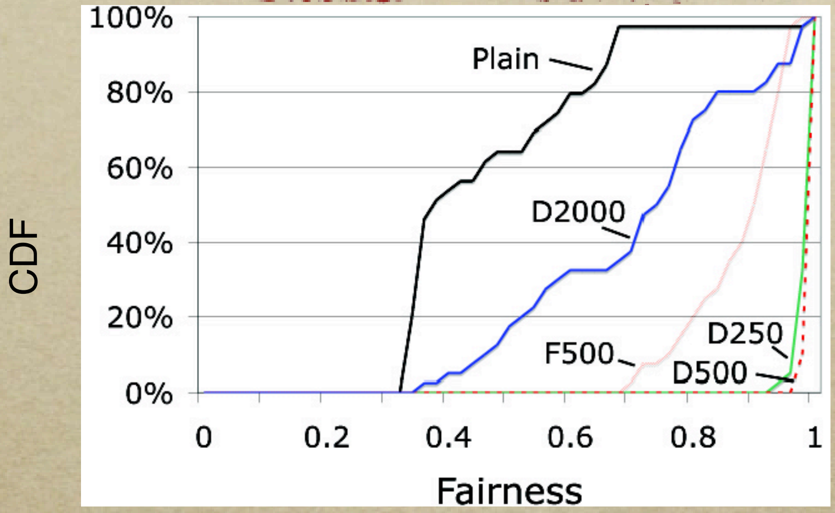


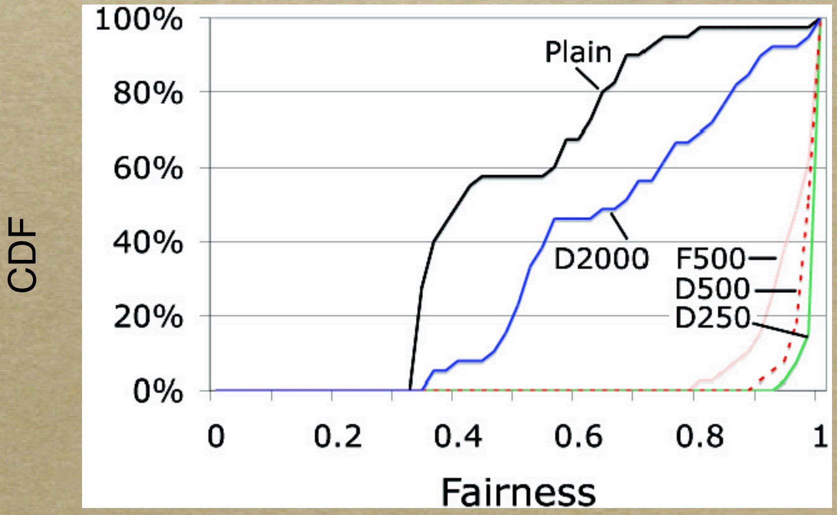
P1	P2
T	T-2
T	T-1
T+1	T-1
T+1	T

P1	P2
T	T
T	T+1
T+1	T+1
T+1	T+2

Multihop Uniform Load

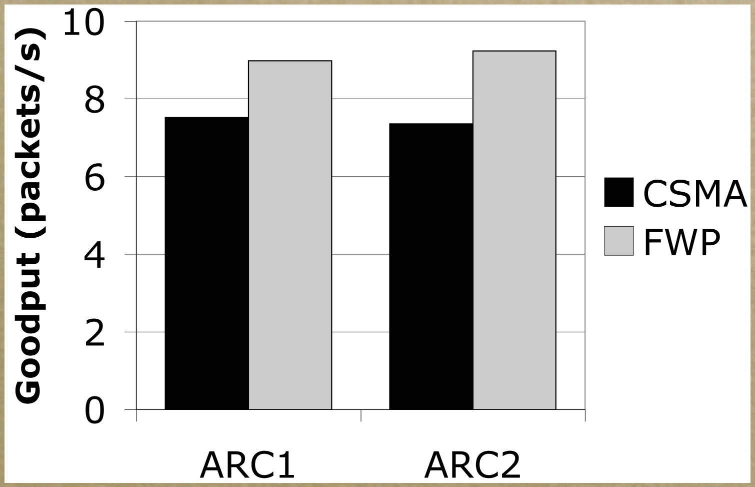
- Uniform loads on 40 nodes on motelab
  - 20 / 40 / 80 ms (Fig. 1)
  - 20 / 60 / 140 ms (Fig. 2)
- Plain (no decay)
  - Global fairness : 0.997
  - Poor transmit fairness
- Decaying every 500 ms
  - Global Fairness : 0.995
  - Best transmit fairness
- Understanding the decaying period better is a future work

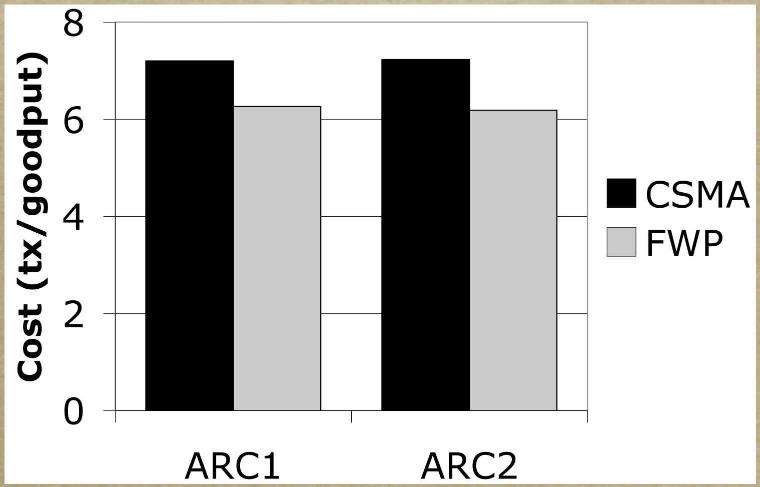




Real Loads - ARC

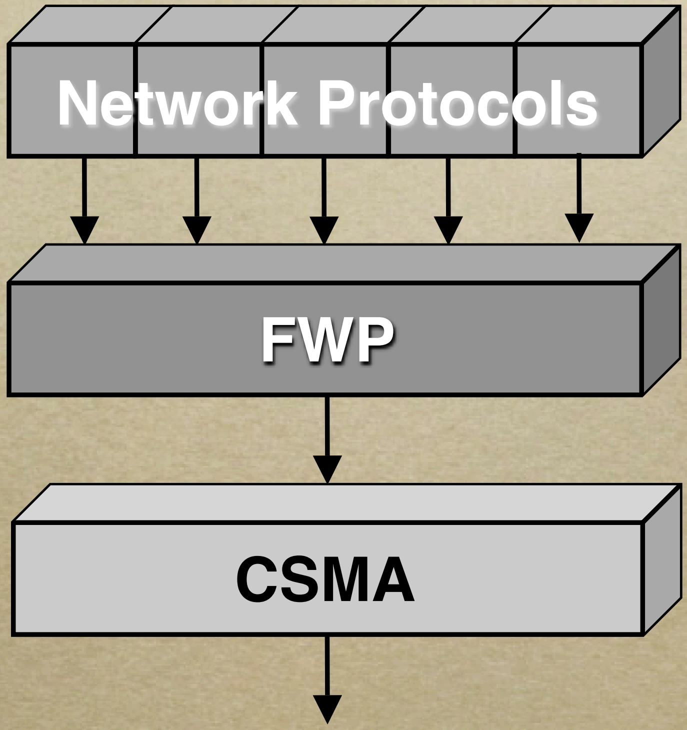
- ARC: rate-limiting collection protocol [Mobicom 2001]
- Goodput and cost for two separate ARC instances running in the presence of two other protocols (PSFQ and Trickle)
- FWP increases ARC goodput by 23-30% and decreases cost by 5-10%





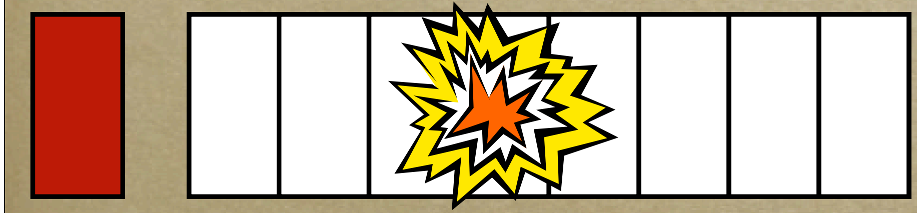
Network Protocols

- FWP isolates network protocols from each other
- How do we isolate causes within a protocol?
- Apply minimization principle to higher layers



Case Study: Collection

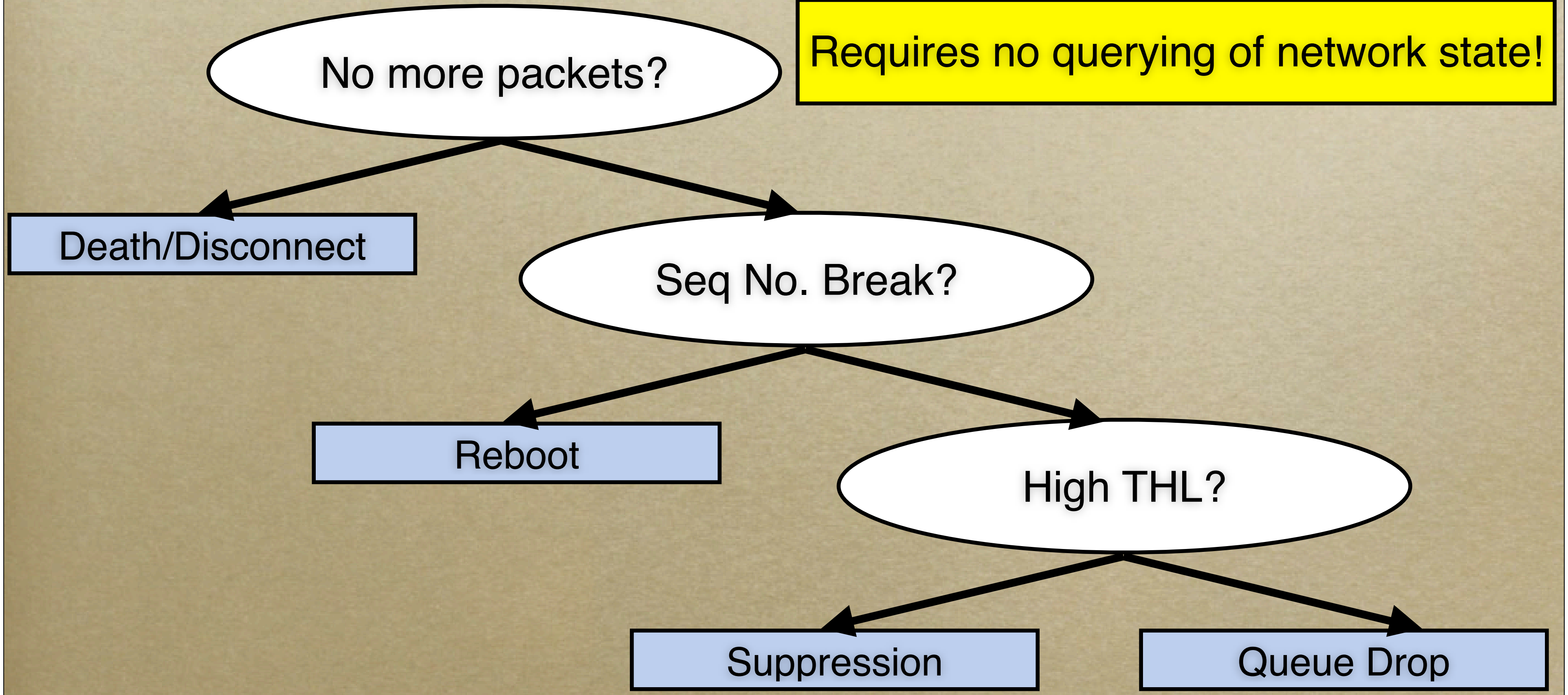
- 5 principal causes of packet loss



1. Retransmit timeout
2. Queue drop
3. False positive duplicate suppression
4. Reboot
5. Kaboom!

Origin sequence numbers, THL field

Decision Tree



Requires no querying of network state!

MNet Architecture

- Elevate management and visibility to an architectural principle and design goal
- Isolation of causes
- Fairness (protocol, node, application...)
- FWP as the narrow waist

Outline

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- Real Time?

The Real-Time Tension

- Real-time is inherently unfair
  - Some people get to go first!
  - Understanding *why* something failed is hard (Mars Rover)
  - Necessitates local operations and internal decisions
  - Makes it more difficult to understand the internal operation of the system
- Optimal scheduling of a scarce resource
  - Uncommon in sensornets because utilization is so low...
  - Event-driven, not periodic workloads
- Wireless is an inherent challenge
  - Outside of your control

Predictability

- Being able to assume things will behave in a certain way
- Breaking outside current approaches
  - Language-OS co-design
  - Static, dynamic, run-time approaches
- Predictable networks, not just systems
  - Network is increasingly cause of failure
  - Wireless more so...

Questions