CE693: Adv. Computer Networking

L-13 Sensor Networks

Acknowledgments: Lecture slides are from the graduate level Computer Networks course thought by Srinivasan Seshan at CMU. When slides are obtained from other sources, a a reference will be noted on the bottom of that slide. A full list of references is provided on the last slide.

Sensor Networks

- Directed Diffusion
- Aggregation
- Assigned reading
  - TAG: a Tiny AGgregation Service for Ad-Hoc Sensor Networks
  - Directed Diffusion: A Scalable and Robust Communication Paradigm for Sensor Networks

Outline

- Sensor Networks
- Directed Diffusion
- TAG
- Synopsis Diffusion

Smart-Dust/Motes

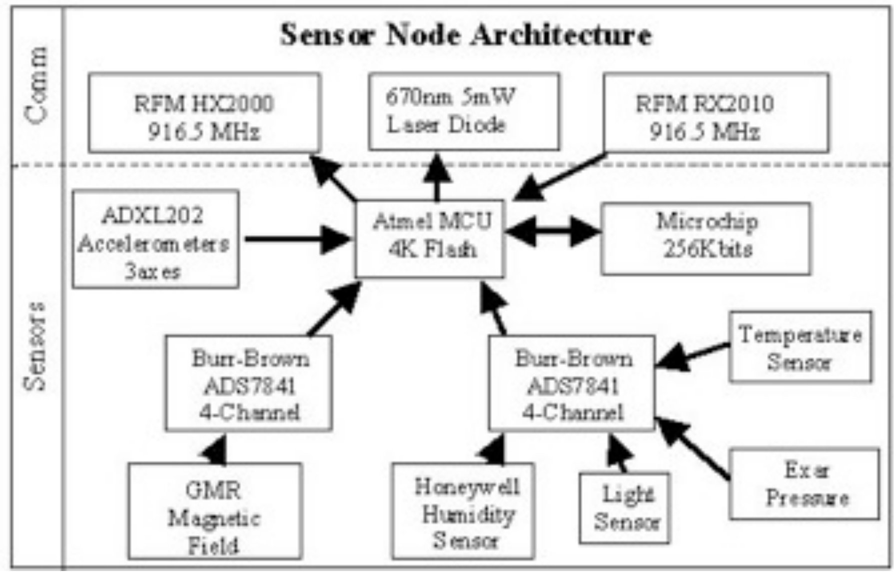
- First introduced in late 90’s by groups at UCB/UCLA/USC
  - Published at Mobicom/SOSP conferences
- Small, resource limited devices
  - CPU, disk, power, bandwidth, etc.
- Simple scalar sensors – temperature, motion
- Single domain of deployment (e.g. farm, battlefield, etc.) for a targeted task (find the tanks)
- Ad-hoc wireless network

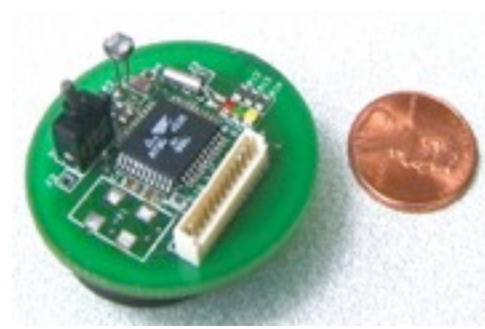
Smart-Dust/Motes

- Hardware
  - UCB motes
- Programming
  - TinyOS
- Query processing
  - TinyDB
  - Directed diffusion
- Power management
  - MAC protocols
  - Adaptive topologies

Berkeley Motes

- Devices that incorporate communications, processing, sensors, and batteries into a small package
- Atmel microcontroller with sensors and a communication unit
  - RF transceiver, laser module, or a corner cube reflector
  - Temperature, light, humidity, pressure, 3 axis magnetometers, 3 axis accelerometers





Berkeley Motes (Levis & Culler, ASPLOS 02)

Mote Type	WeC	rene2	rene2	dot	mica
					
Date	9/99	10/00	6/01	8/01	2/02
Microcontroller					
Type	AT90LS8535		ATMega163		ATMega103
Prog. mem. (KB)	8		16		128
RAM (KB)	0.5		1		4
Nonvolatile storage					
Chip	24LC256				AT45DB041B
Connection type	I2C				SPI
Size (KB)	32				512
Default Power source					
Type	Li	Alk		Li	Alk
Size	CR2450	2xAA		CR2032	2xAA
Capacity (mAh)	575	2850		225	2850
Communication					
Radio	RFM TR1000				
Rate (Kbps)	10	10	10	10	10/40
Modulation type	OOK				OOK/ASK

Sensor Net Sample Apps

Habitat Monitoring: Storm petrels on great duck island, microclimates on James Reserve.

Earthquake monitoring in shake-test sites.

Traditional monitoring apparatus.

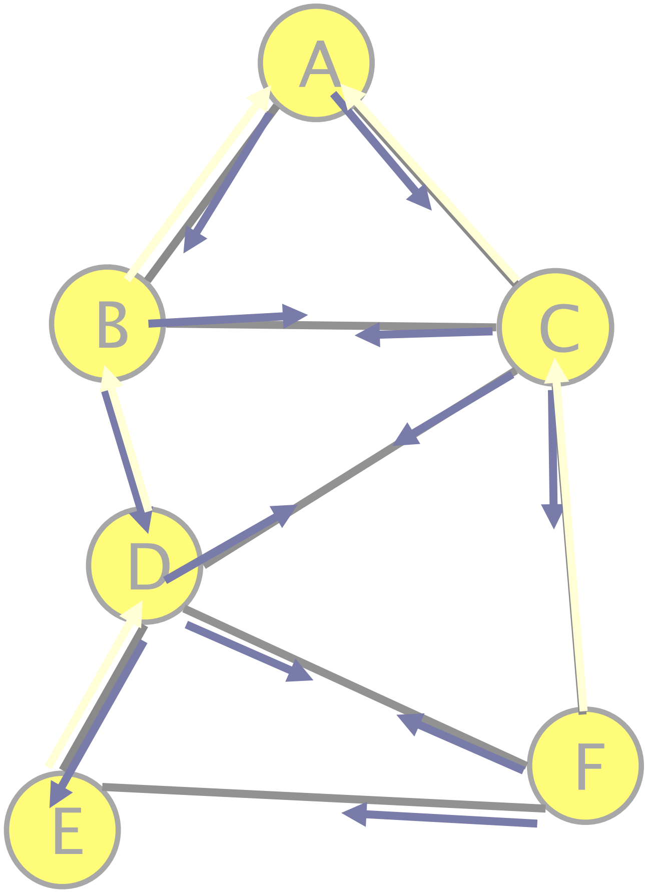
Vehicle detection: sensors along a road, collect data about passing vehicles.

Metric: Communication

- Lifetime from one pair of AA batteries
  - 2-3 days at full power
  - 6 months at 2% duty cycle
- Communication dominates cost
  - < few mS to compute
  - 30mS to send message

Communication In Sensor Nets

- Radio communication has high link-level losses
  - typically about 20% @ 5m
- Ad-hoc neighbor discovery
- Tree-based routing



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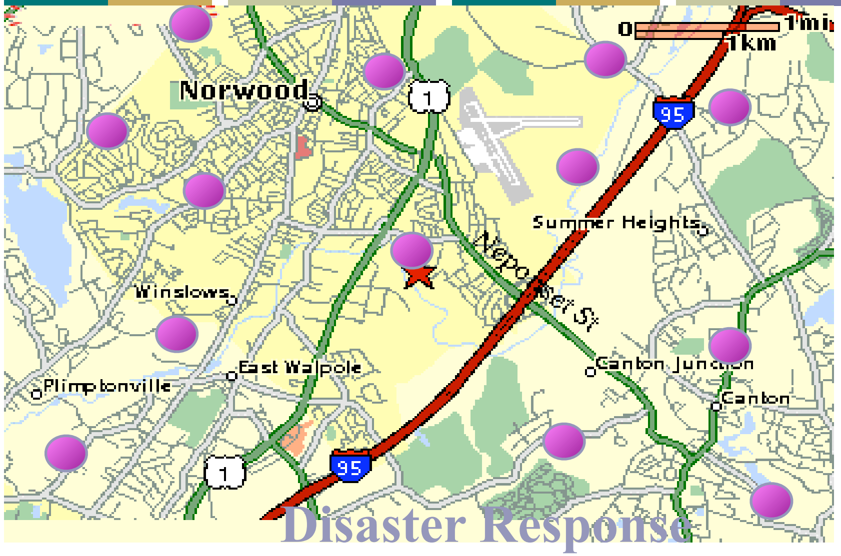
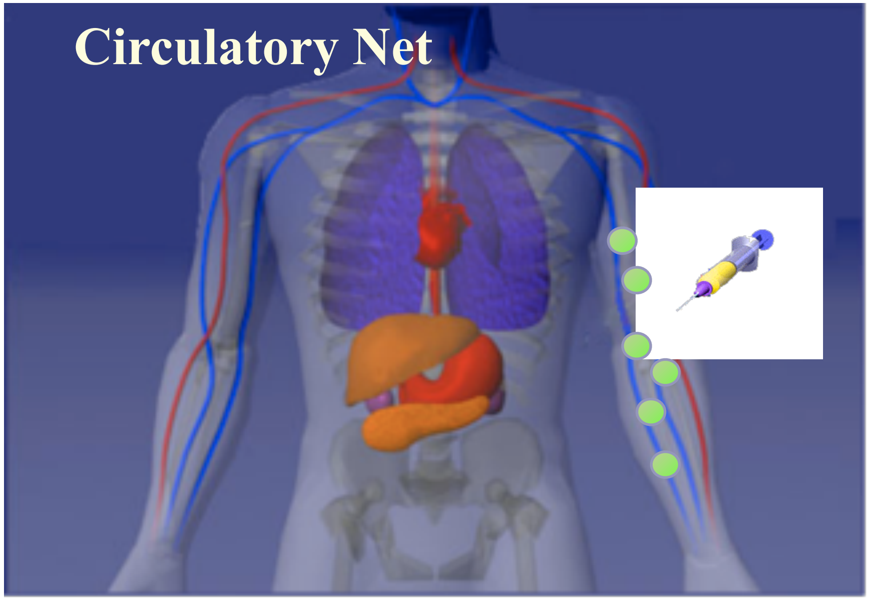
The long term goal

Embed numerous distributed devices to monitor and interact with physical world: in work-spaces, hospitals, homes, vehicles, and “the environment” (water, soil, air…)





Network these devices so that they can coordinate to perform higher-level tasks.

Requires robust distributed systems of tens of thousands of devices.

Motivation

- Properties of Sensor Networks
  - Data centric, but not node centric
  - Have no notion of central authority
  - Are often resource constrained
- Nodes are tied to physical locations, but:
  - They may not know the topology
  - They may fail or move arbitrarily
- Problem: How can we get data from the sensors?

Directed Diffusion

- Data centric – nodes are unimportant
- Request driven:
  - Sinks place requests as interests
  - Sources are eventually found and satisfy interests
  - Intermediate nodes route data toward sinks
- Localized repair and reinforcement
- Multi-path delivery for multiple sources, sinks, and queries

Motivating Example

- Sensor nodes are monitoring a flat space for animals
- We are interested in receiving data for all 4-legged creatures seen in a rectangle
- We want to specify the data rate

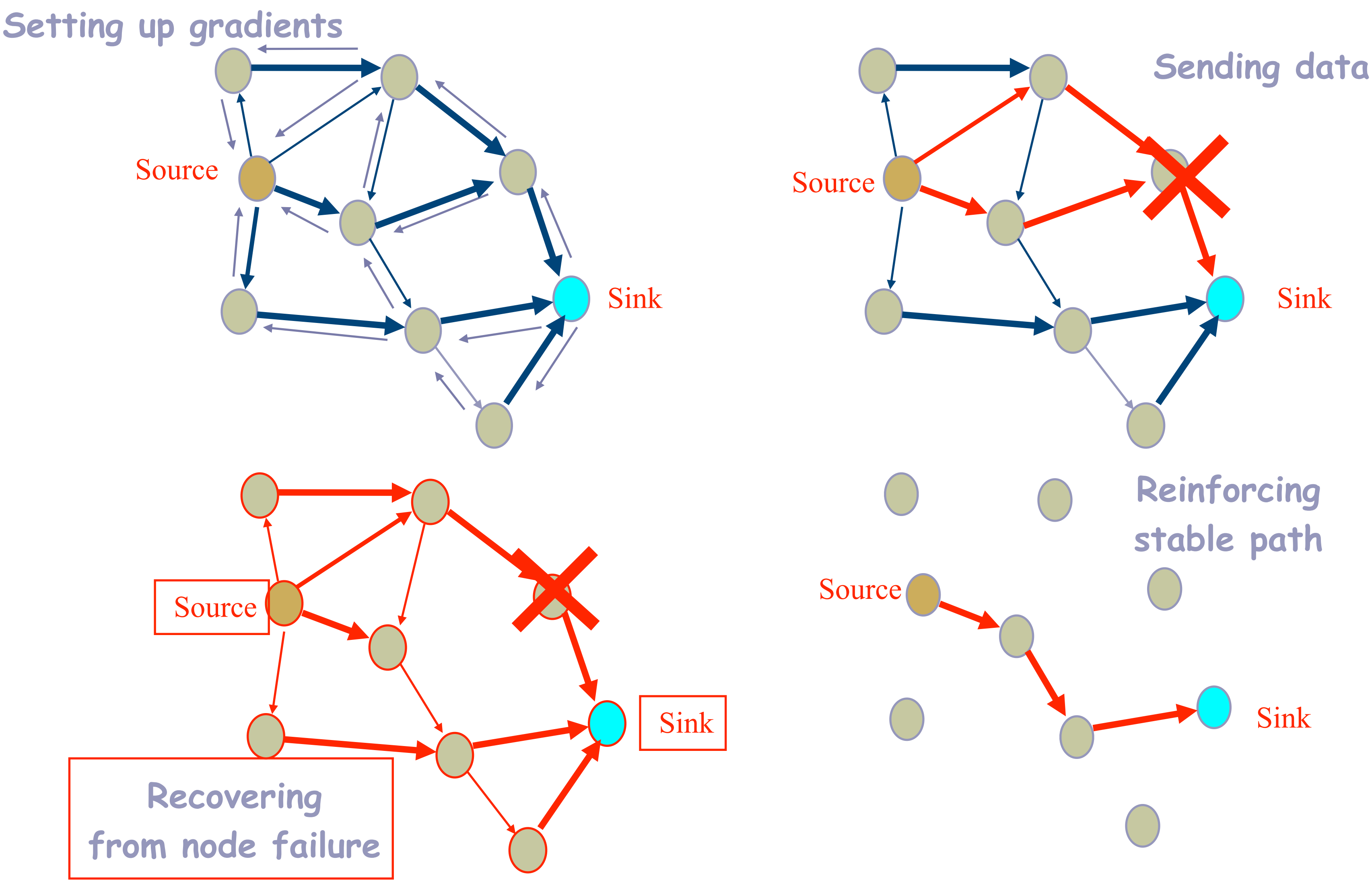
Interest and Event Naming

- Query/interest:
  1. Type=four-legged animal
  2. Interval=20ms (event data rate)
  3. Duration=10 seconds (time to cache this query)
  4. Rect=[-100, 100, 200, 400]
- Reply:
  1. Type=four-legged animal
  2. Instance = elephant
  3. Location = [125, 220]
  4. Intensity = 0.6
  5. Confidence = 0.85
  6. Timestamp = 01:20:40
- Attribute-Value pairs, no advanced naming scheme

Diffusion (High Level)

- Sinks broadcast interest to neighbors
- Interests are cached by neighbors
- Gradients are set up pointing back to where interests came from at low data rate
- Once a sensor receives an interest, it routes measurements along gradients

Illustrating Directed Diffusion



Summary

- Data Centric
  - Sensors net is queried for specific data
  - Source of data is irrelevant
  - No sensor-specific query

- Application Specific
  - In-sensor processing to reduce data transmitted
  - In-sensor caching

- Localized Algorithms
  - Maintain minimum local connectivity – save energy
  - Achieve global objective through local coordination

- Its gains due to aggregation and duplicate suppression may make it more viable than ad-hoc routing in sensor networks

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TAG Introduction

- Programming sensor nets is hard!
- Declarative queries are easy
  - Tiny Aggregation (TAG): In-network processing via declarative queries
- In-network processing of aggregates
  - Common data analysis operation
  - Communication reducing
    - Operator dependent benefit
  - Across nodes during same epoch
- Exploit semantics improve efficiency!

- Example:
    - Vehicle tracking application: 2 weeks for 2 students
    - Vehicle tracking query: took 2 minutes to write, worked just as well!

```
SELECT MAX(mag)
FROM sensors
WHERE mag > thresh
EPOCH DURATION 64ms
```

Basic Aggregation

- In each epoch:
  - Each node samples local sensors once
  - Generates **partial state record (PSR)**
    - local readings
    - readings from children
  - Outputs PSR during its comm. slot.

- At end of epoch, PSR for whole network output at root

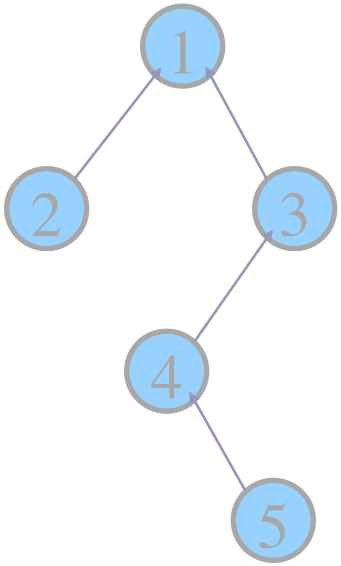


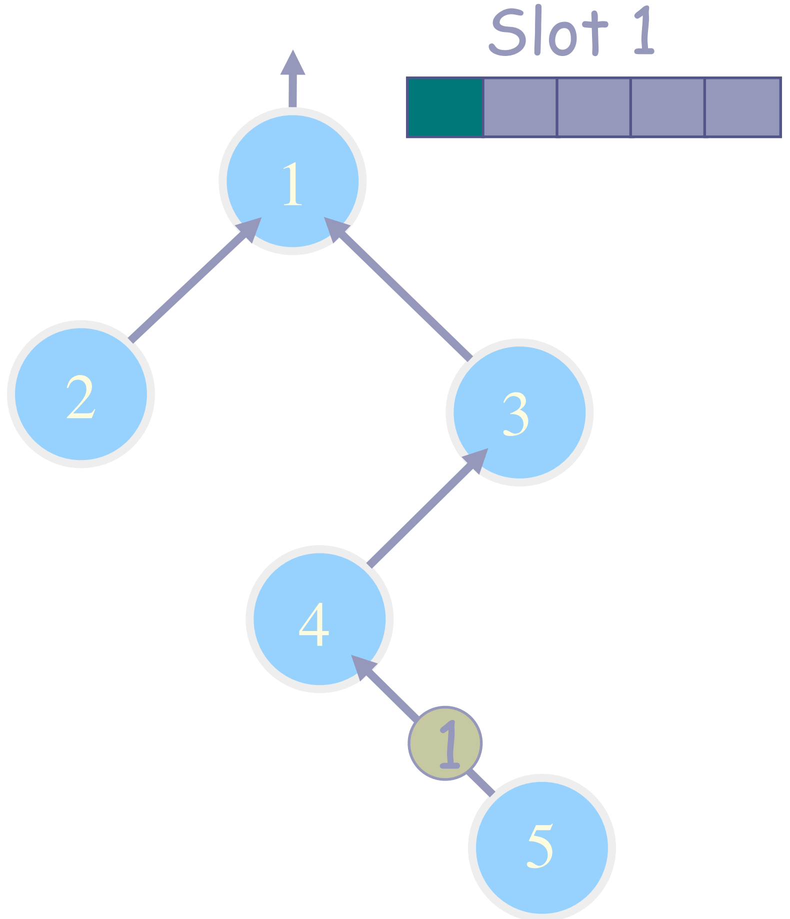
Illustration: Aggregation

```
SELECT COUNT(*)
FROM sensors
```

Sensor #

Slot #

	1	2	3	4	5
1					1
2					
3					
4					
1					



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2				2	
3					
4					
1					

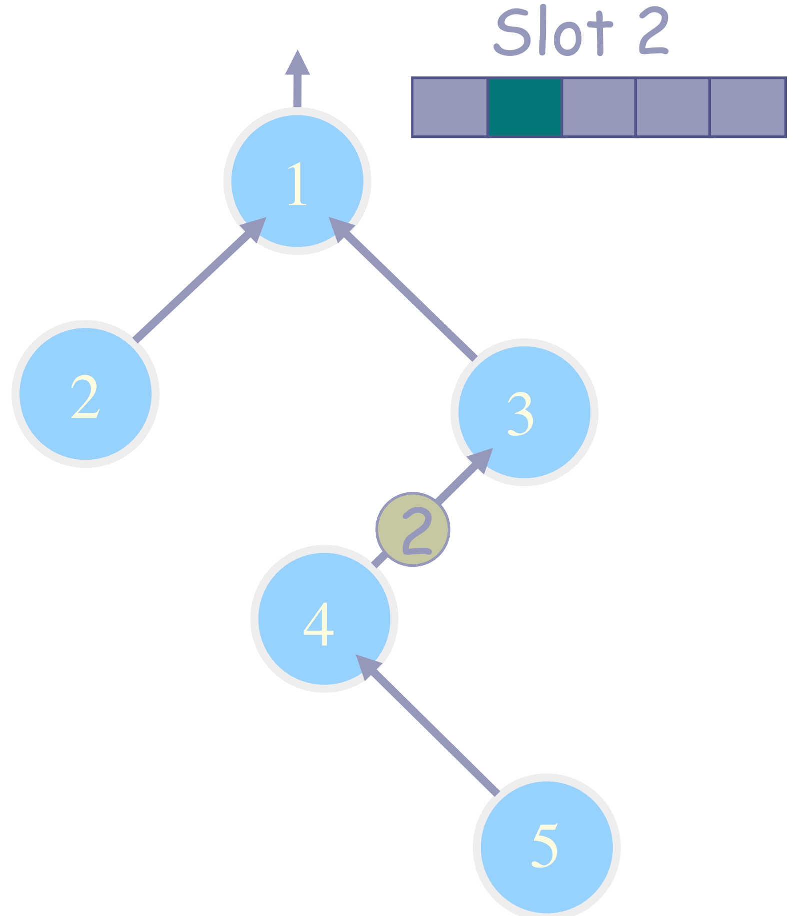

Illustration: Aggregation

SELECT COUNT(*)
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Sensor #

Slot #	1	2	3	4	5
1					1
2				2	
3		1	3		
4					
1					

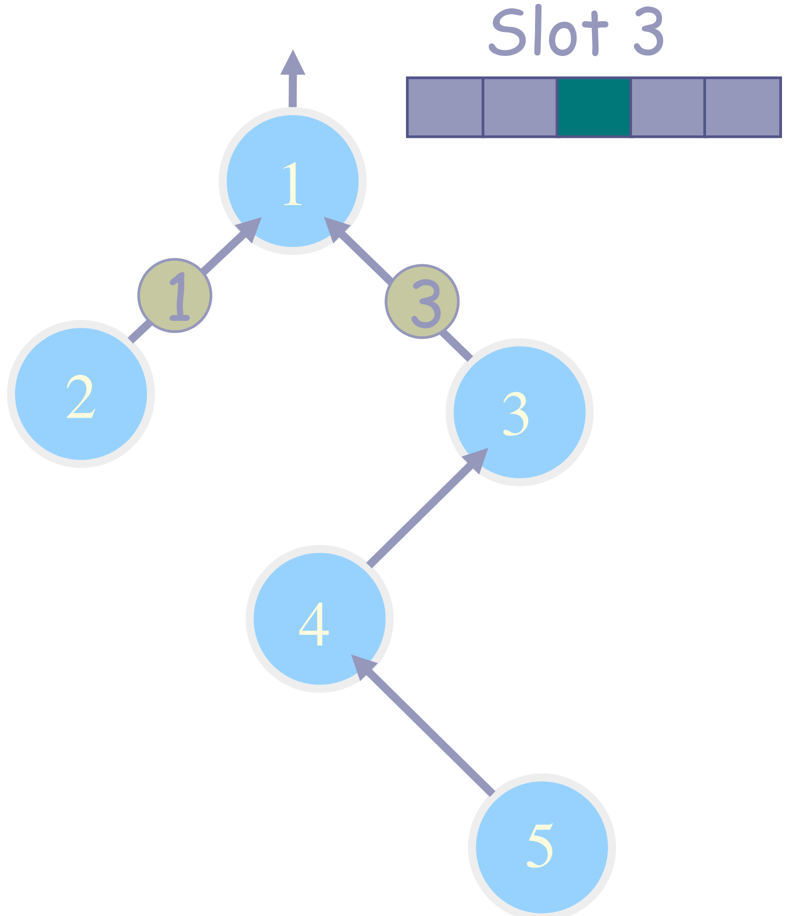

Illustration: Aggregation

```
SELECT COUNT(*)
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```

Sensor #

Slot #

	1	2	3	4	5
1					1
2				2	
3		1	3		
4	5				
1					

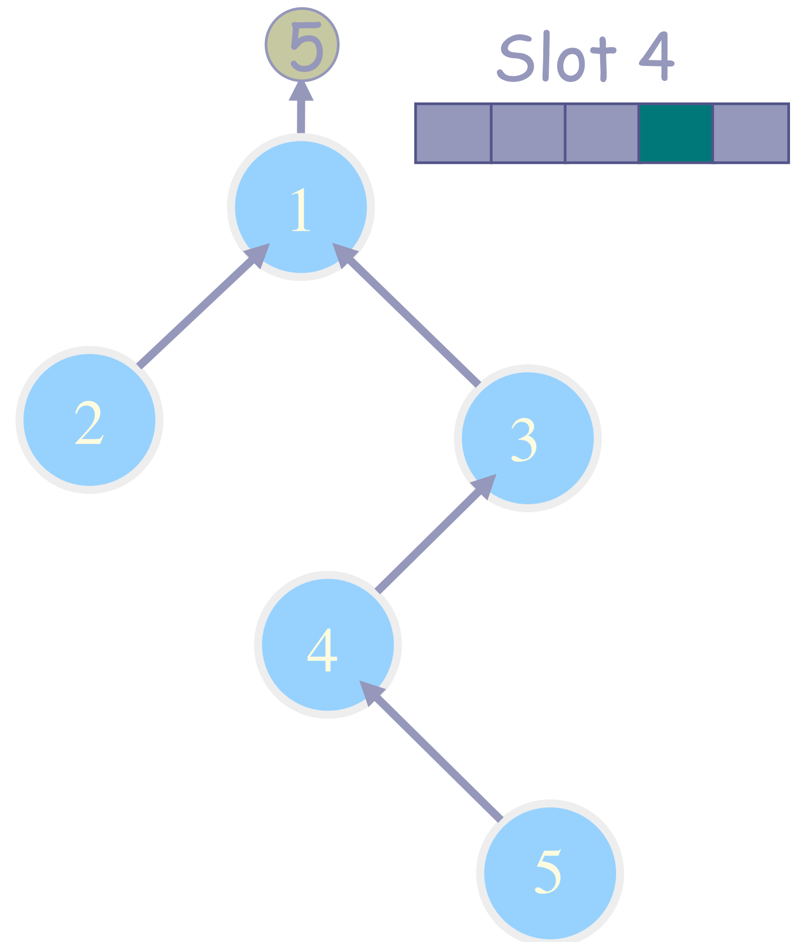
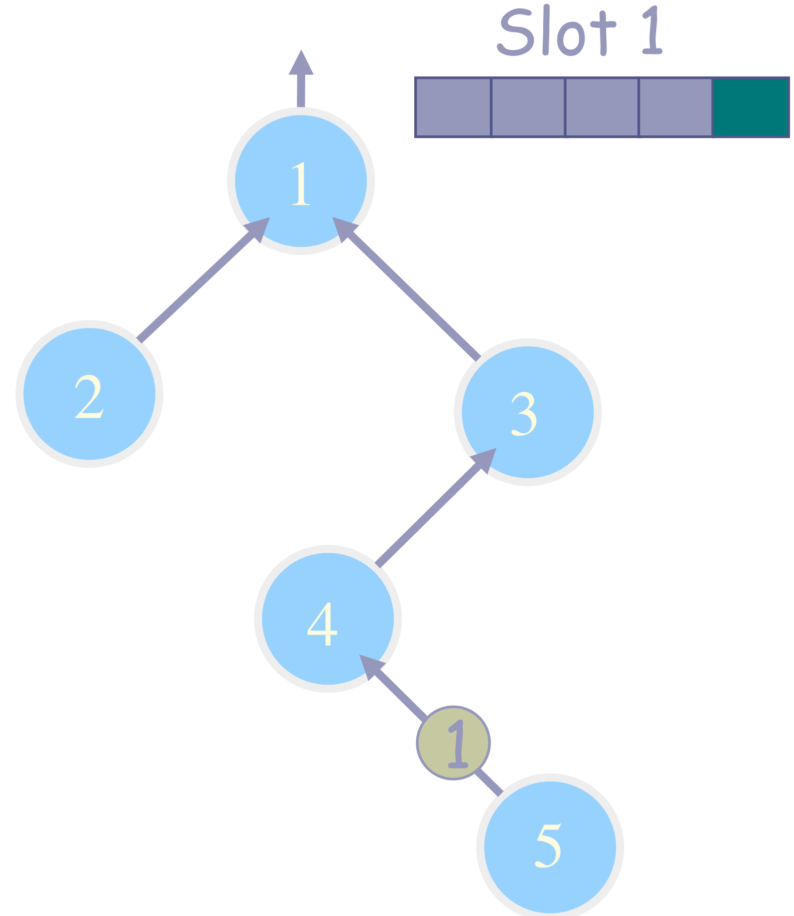


Illustration: Aggregation

```
SELECT COUNT(*)
FROM sensors
```

Sensor #

Slot #	1	2	3	4	5
1					1
2				2	
3		1	3		
4	5				
1					1



Types of Aggregates

- SQL supports MIN, MAX, SUM, COUNT, AVERAGE
- Any function *can* be computed via TAG
- In network benefit for many operations
  - E.g. Standard deviation, top/bottom N, histograms, etc.
  - Compactness of PSR

Taxonomy of Aggregates

- TAG insight: classify aggregates according to various functional properties
  - Yields a general set of optimizations that can automatically be applied

Property	Examples	Affects
Partial State	MEDIAN : unbounded, MAX : 1 record	Effectiveness of TAG
Duplicate Sensitivity	MIN : dup. insensitive, AVG : dup. sensitive	Routing Redundancy
Exemplary vs. Summary	MAX : exemplary COUNT: summary	Applicability of Sampling, Effect of Loss
Monotonic	COUNT : monotonic AVG : non-monotonic	Hypothesis Testing, Snooping

Benefit of In-Network Processing

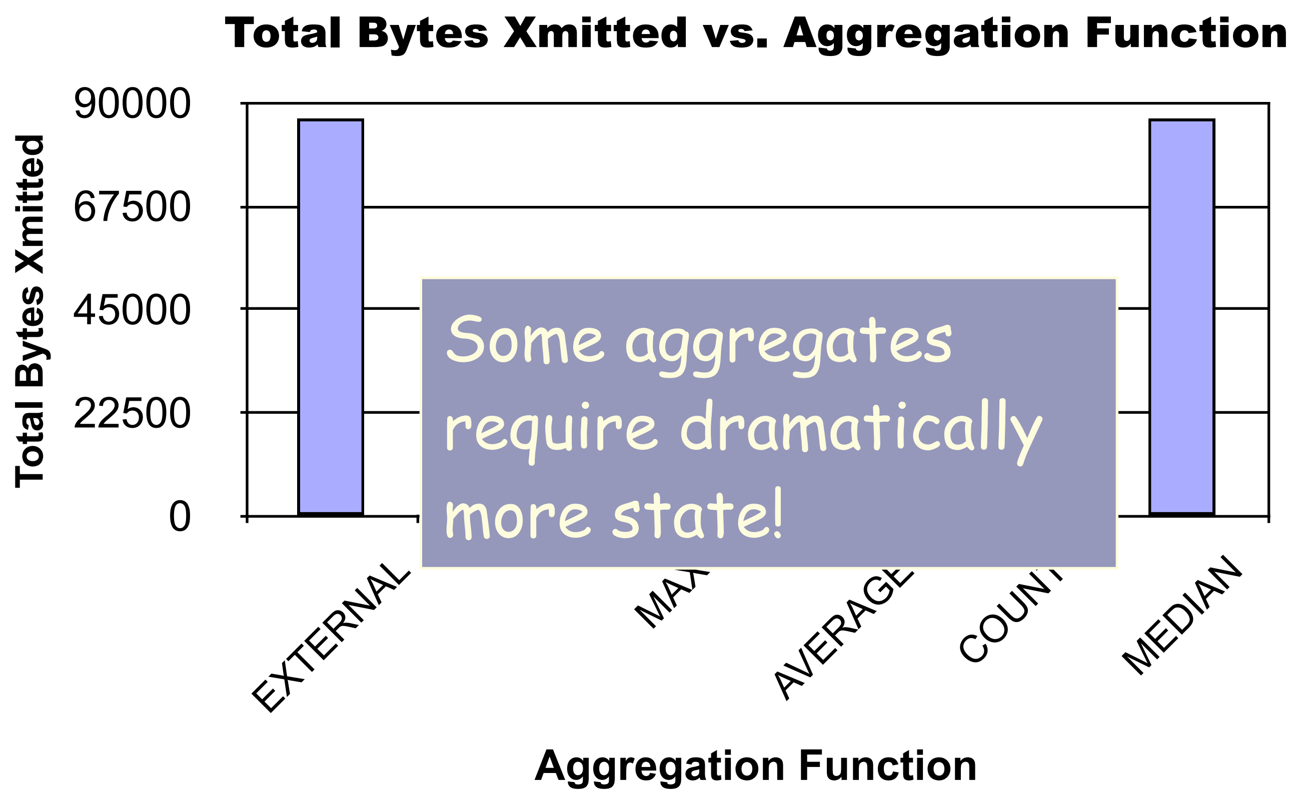
<u>Simulation Results</u>

2500 Nodes

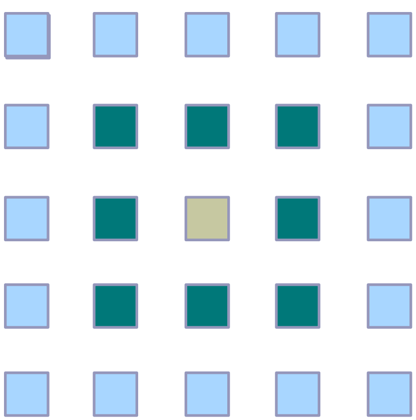
50x50 Grid

Depth = ~10

Neighbors = ~20



Some aggregates require dramatically more state!



Optimization: Channel Sharing ("Snooping")

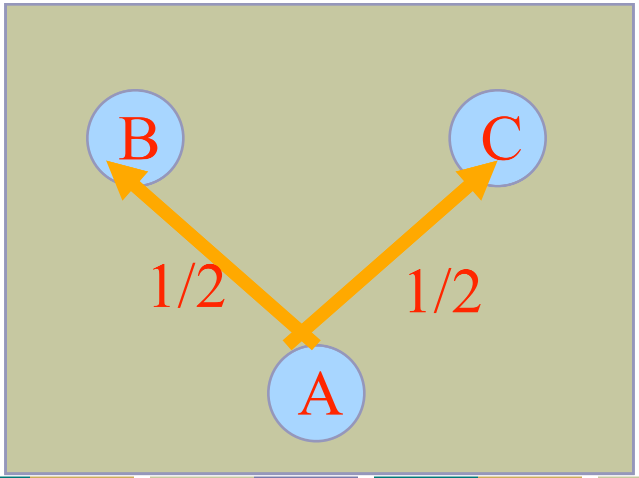
- Insight: Shared channel enables optimizations
- Suppress messages that won't affect aggregate
  - E.g., MAX
  - Applies to all exemplary, monotonic aggregates

Optimization: Hypothesis Testing

- Insight: Guess from root can be used for suppression
  - E.g. ‘MIN < 50’
  - Works for monotonic & exemplary aggregates
    - Also summary, if imprecision allowed
- How is hypothesis computed?
  - Blind or statistically informed guess
  - Observation over network subset

Optimization: Use Multiple Parents

- For duplicate insensitive aggregates
- Or aggregates that can be expressed as a linear combination of parts
  - Send (part of) aggregate to all parents
    - In just one message, via broadcast
  - Decreases variance



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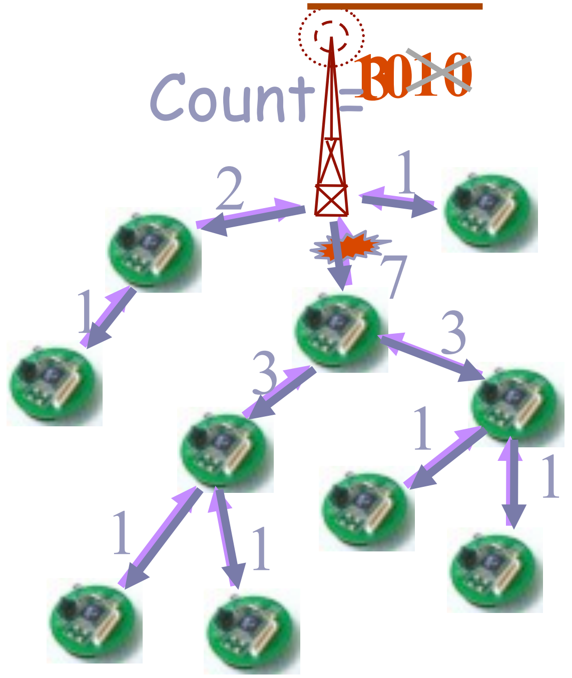
Aggregation in Wireless Sensors

Aggregate data is often more important

In-network aggregation

over tree with unreliable communication



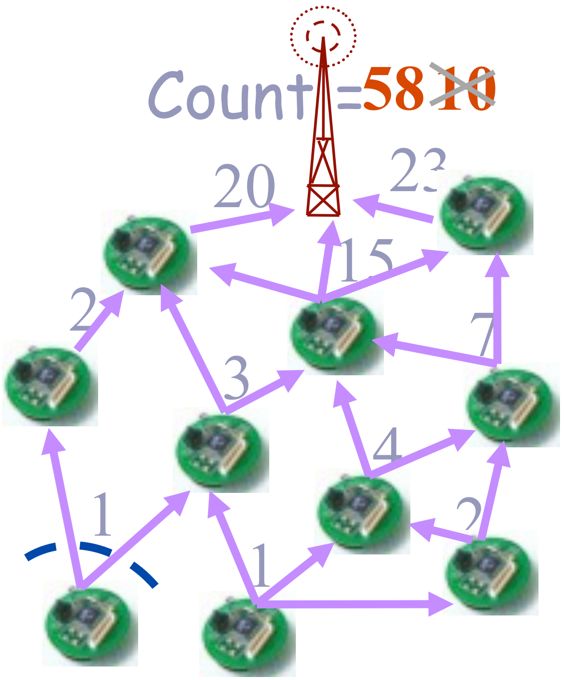
Used by current systems,
TinyDB [Madden et al. OSDI'02]
Cougar [Bonnet et al. MDM'01]

Not robust against
node- or link-failures

Traditional Approach

- Reliable communication
  - E.g., RMST over Directed Diffusion [Stann'03]
- High resource overhead
  - 3x more energy consumption
  - 3x more latency
  - 25% less channel capacity
- Not suitable for resource constrained sensors

Exploiting Broadcast Medium



- ✓ Robust multi-path
- ✓ Energy-efficient

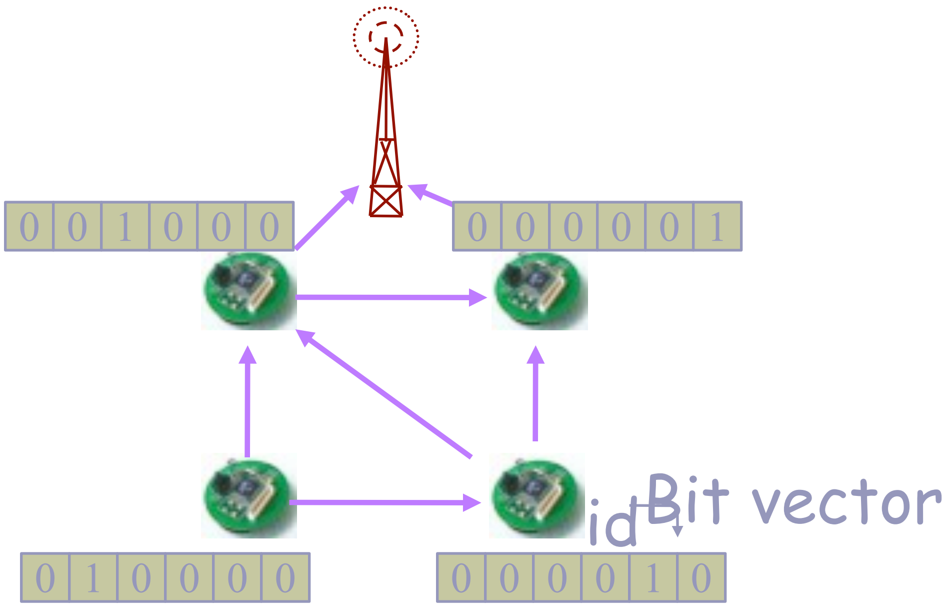
- ✘ Double-counting
- ✘ Different ordering

Challenge

➢ Challenge: order and duplicate insensitivity (ODI)

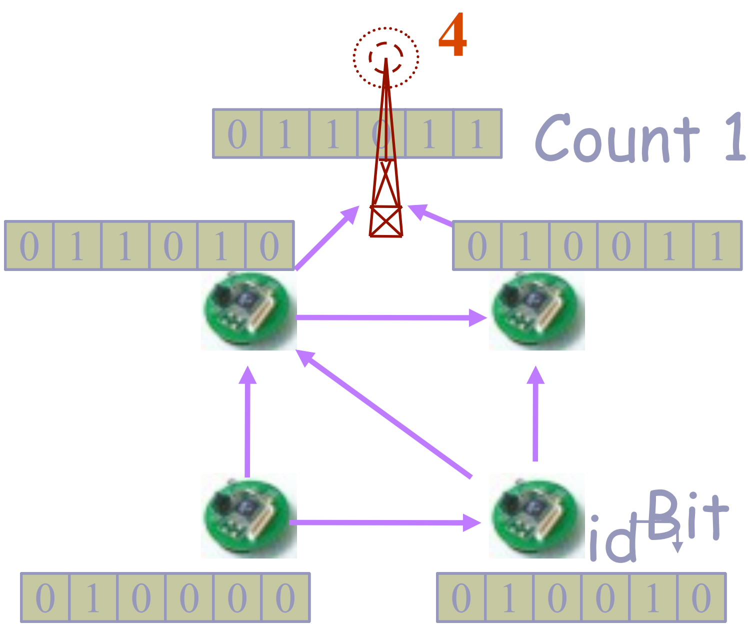
A Naïve ODI Algorithm

- Goal: <u>count</u> the live sensors in the network



Synopsis Diffusion (SenSys'04)

- Goal: <u>count</u> the live sensors in the network



Count 1 bits

Challenge

Synopsis should be small

id

Bit vector

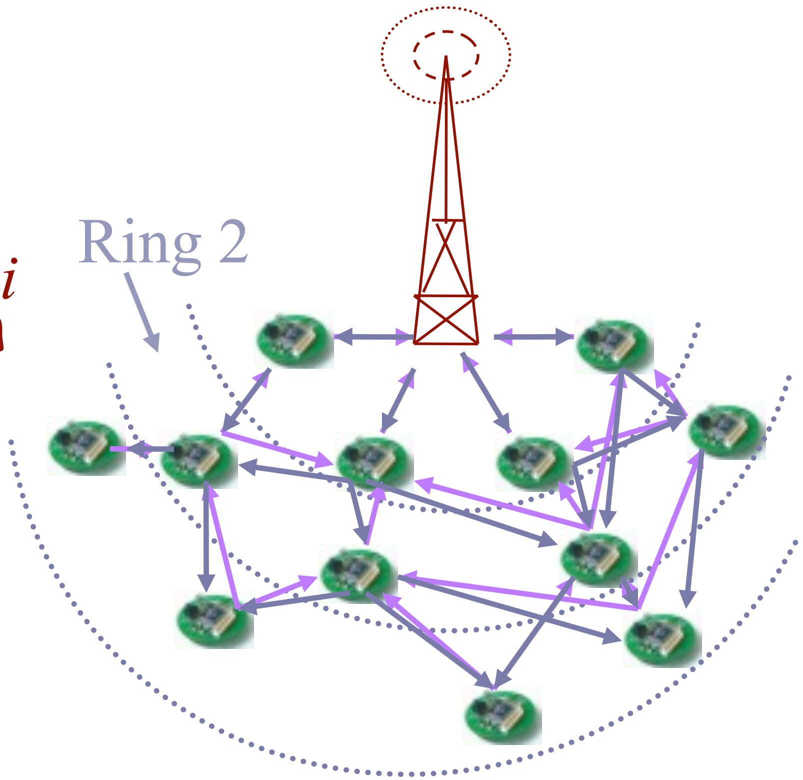
Boolean

OR

Approximate COUNT algorithm: logarithmic size bit vector

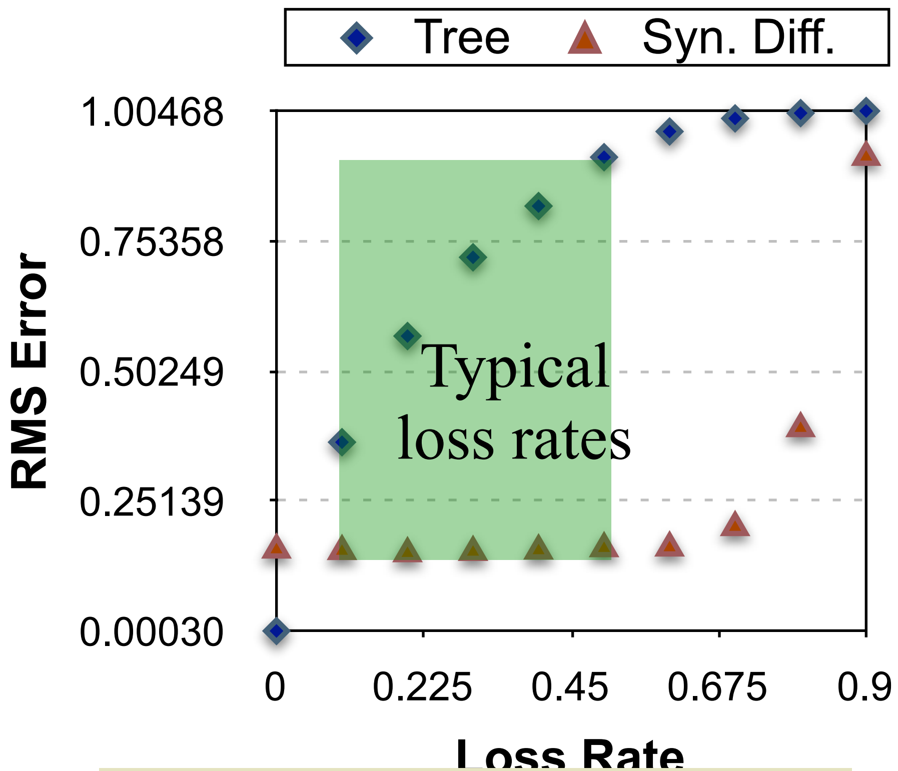
Synopsis Diffusion over Rings

- A node is in ring i if it is i hops away from the base-station
- <u>Broadcasts</u> by nodes in ring i are received by neighbors in ring i-1
- Each node transmits once = optimal energy cost (same as Tree)



Evaluation

Approximate COUNT with Synopsis Diffusion



Scheme	Energy
Tree	41.8 mJ
Syn. Diff.	42.1 mJ

Per node energy

More robust than Tree

Almost as energy efficient as Tree

Next Lecture

- Data center networks
- Required readings
  - PortLand: A Scalable Fault-Tolerant Layer 2 Data Center Network Fabric [Sigcomm09]
  - Safe and Effective Fine-grained TCP Retransmissions for Datacenter Communication [Sigcomm09]