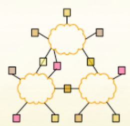
15-446 Distributed Systems Spring 2009



L-22 Sensor Networks

Overview

- Ad hoc routing
- Sensor Networks
- Directed Diffusion
- Aggregation
  - TAG
  - Synopsis Diffusion

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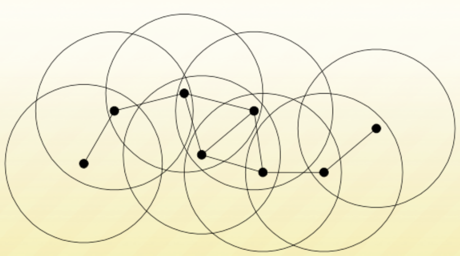
Ad Hoc Routing

- Goal: Communication between wireless nodes
  - No external setup (self-configuring)
  - Often need multiple hops to reach dst



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Ad Hoc Routing

- Create multi-hop connectivity among set of wireless, possibly moving, nodes
- Mobile, wireless hosts act as forwarding nodes as well as end systems
- Need routing protocol to find multi-hop paths
  - Needs to be dynamic to adapt to new routes, movement
  - Interesting challenges related to interference and power limitations
  - Low consumption of memory, bandwidth, power
  - Scalable with numbers of nodes
  - Localized effects of link failure

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Challenges and Variants

- Poorly-defined "links"
  - Probabilistic delivery, etc. Kind of n^2 links
- Time-varying link characteristics
- No oracle for configuration (no ground truth configuration file of connectivity)
- Low bandwidth (relative to wired)
- Possibly mobile
- Possibly power-constrained

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Problems Using DV or LS

- DV protocols may form loops
  - Very wasteful in wireless: bandwidth, power
  - Loop avoidance sometimes complex
- LS protocols: high storage and communication overhead
- More links in wireless (e.g., clusters) - may be redundant → higher protocol overhead

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Problems Using DV or LS

- Periodic updates waste power
  - Tx sends portion of battery power into air
  - Reception requires less power, but periodic updates prevent mobile from "sleeping"
- Convergence may be slower in conventional networks but must be fast in ad-hoc networks and be done without frequent updates

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Proposed Protocols

- Destination-Sequenced Distance Vector (DSDV)
  - DV protocol, destinations advertise sequence number to avoid loops, not on demand
- Temporally-Ordered Routing Algorithm (TORA)
  - On demand creation of hbh routes based on link-reversal
- Dynamic Source Routing (DSR)
  - On demand source route discovery
- Ad Hoc On-Demand Distance Vector (AODV)
  - Combination of DSR and DSDV: on demand route discovery with hbh routing

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DSR Concepts

- Source routing
  - No need to maintain up-to-date info at intermediate nodes
- On-demand route discovery
  - No need for periodic route advertisements

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DSR Components

- Route discovery
  - The mechanism by which a sending node obtains a route to destination
- Route maintenance
  - The mechanism by which a sending node detects that the network topology has changed and its route to destination is no longer valid

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DSR Route Discovery

- Route discovery - basic idea
  - **Source** broadcasts route-request to **Destination**
  - Each node forwards request by adding own address and re-broadcasting
  - Requests propagate outward until:
    - Target is found, or
    - A node that has a route to Destination is found

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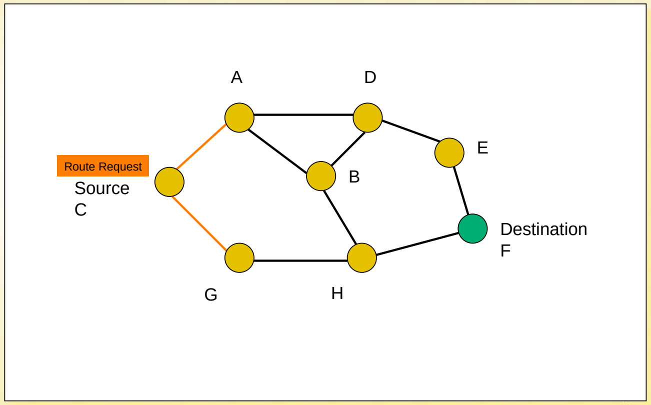
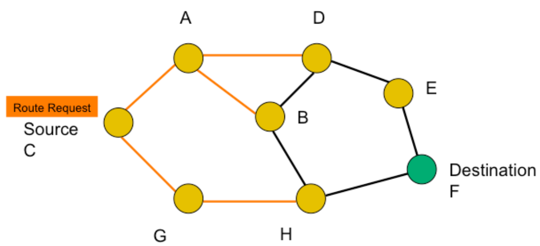
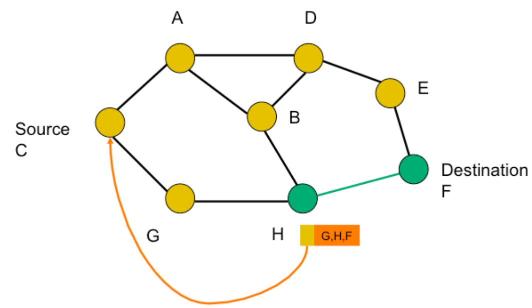
C Broadcasts Route Request to F



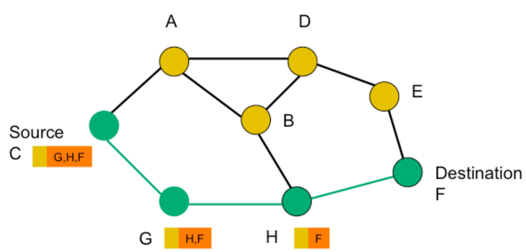
C Broadcasts Route Request to F



H Responds to Route Request



C Transmits a Packet to F



Forwarding Route Requests

- A request is forwarded if:
  - Node is not the destination
  - Node not already listed in recorded source route
  - Node has not seen request with same sequence number
  - IP TTL field may be used to limit scope
- Destination copies route into a Route-reply packet and sends it back to **Source**

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Route Cache

- All source routes learned by a node are kept in Route Cache
  - Reduces cost of route discovery
- If intermediate node receives RR for destination and has entry for destination in route cache, it responds to RR and does not propagate RR further
- Nodes overhearing RR/RP may insert routes in cache

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Sending Data

- Check cache for route to destination
- If route exists then
  - If reachable in one hop
    - Send packet
  - Else insert routing header to destination and send
- If route does not exist, buffer packet and initiate route discovery

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Discussion

- Source routing is good for on demand routes instead of a priori distribution
- Route discovery protocol used to obtain routes on demand
  - Caching used to minimize use of discovery
- Periodic messages avoided

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  - Synopsis Diffusion

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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

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Smart-Dust/Motes

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




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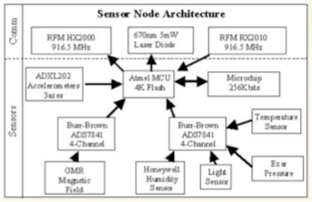
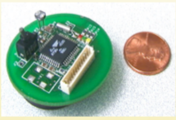
Berkeley Motes

- 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





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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

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Sensor Net Sample Apps

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

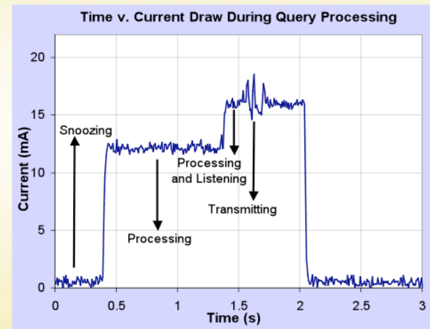
Earthquake monitoring in shake-test sites.

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

Traditional monitoring apparatus.

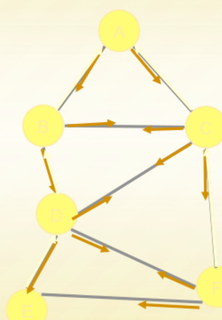
Metric: Communication

- 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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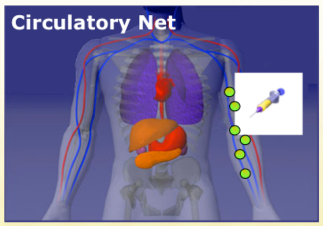
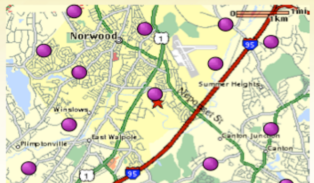
The long term goal

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





Disaster Response

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

Requires robust distributed systems of tens of thousands of devices.

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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?

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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

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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

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Interest and Event Naming

- Query/interest:
  1. Type=four-legged animal
  2. Interval=20ms (event data rate)
  3. Duration=10 seconds (time to cache)
  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

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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

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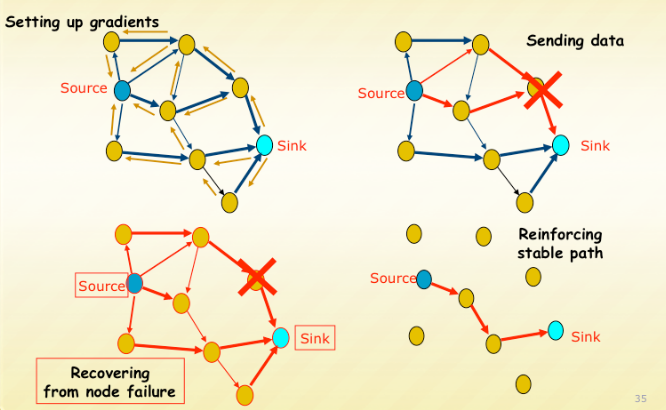
Illustrating Directed Diffusion



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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
- (In paper: pipelining, grouping)

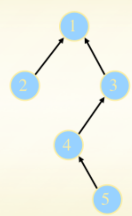
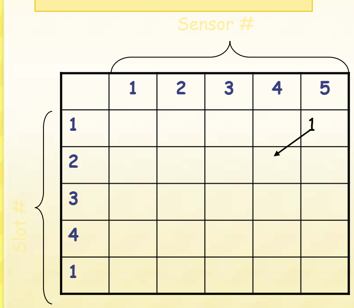
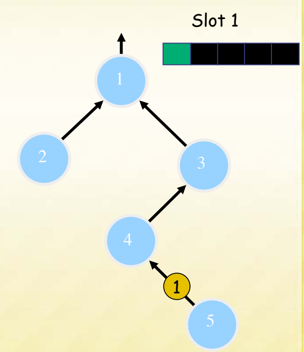


Illustration: Aggregation

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





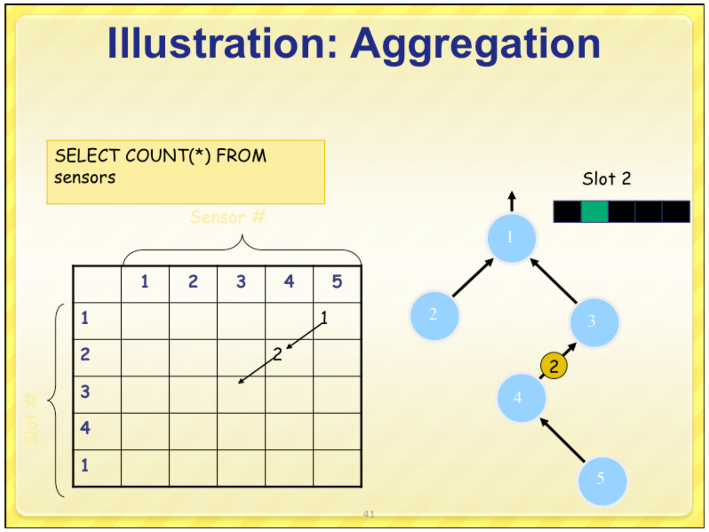


Illustration: Aggregation
SELECT COUNT(*) FROM sensors
Sensor #
Slot #
Slot 2

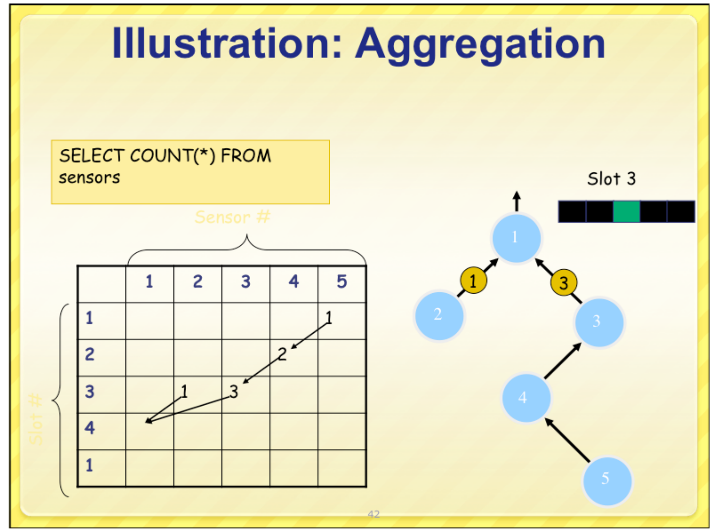


Illustration: Aggregation
SELECT COUNT(*) FROM sensors
Sensor #
Slot #
Slot 3

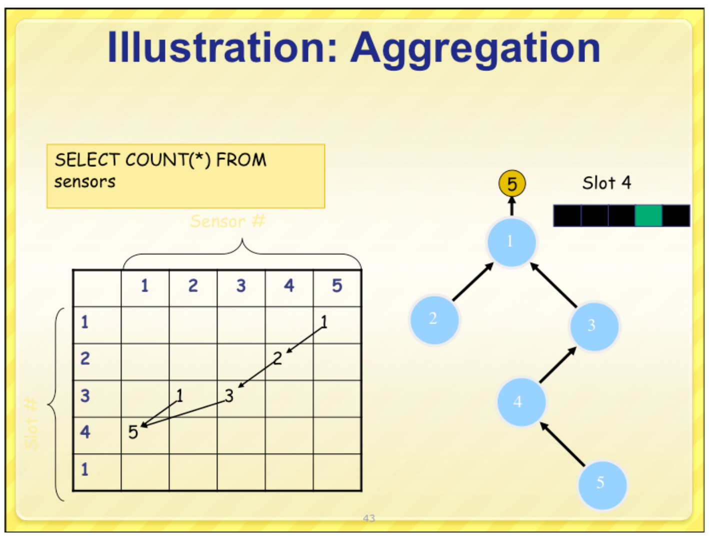


Illustration: Aggregation
SELECT COUNT(*) FROM sensors
Sensor #
Slot #
Slot 4

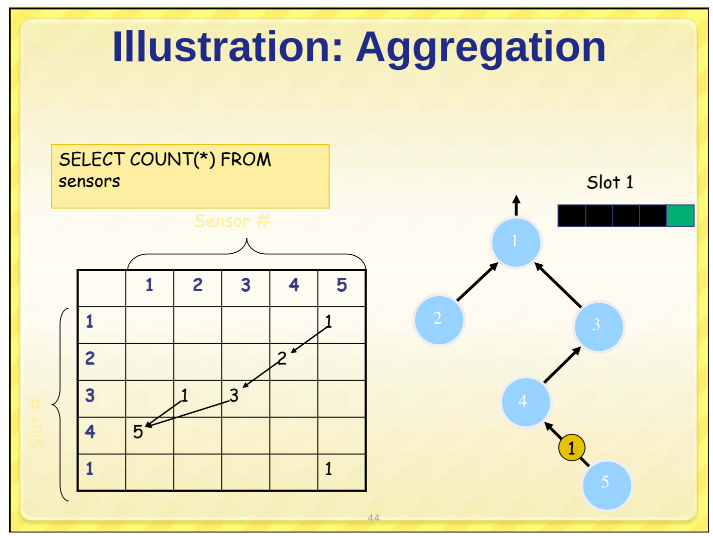


Illustration: Aggregation
SELECT COUNT(*) FROM sensors
Sensor #
Slot #
Slot 1

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, spatial union/intersection, histograms, etc.
  - Compactness of PSR

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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

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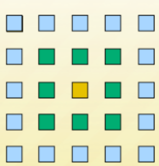
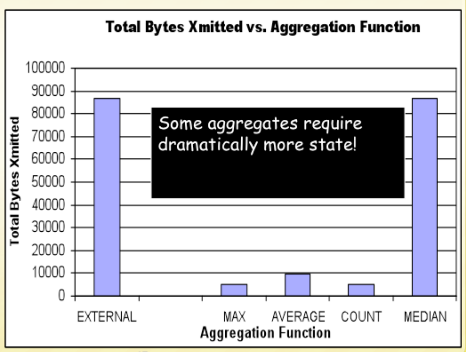
Benefit of In-Network Processing

Simulation Results
2500 Nodes
50x50 Grid
Depth = ~10
Neighbors = ~20





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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

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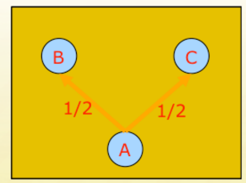
Optimization: Hypothesis Testing

- 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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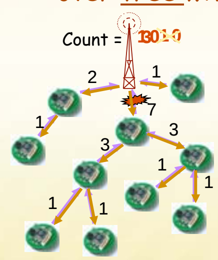
Aggregation in Wireless Sensors

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

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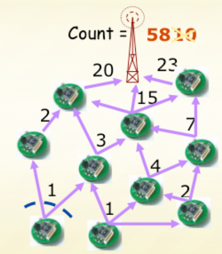
Exploiting Broadcast Medium



✓ Robust multi-path
✓ Energy-efficient

✗ Double-counting
✗ Different ordering

Challenge

➢ Challenge: order and duplicate insensitivity (ODI)

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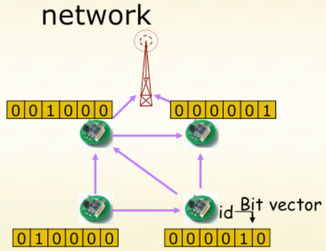
A Naïve ODI Algorithm

- Goal: count the live sensors in the network



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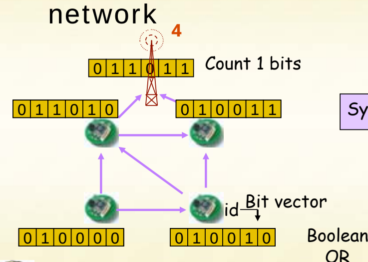
Synopsis Diffusion (SenSys'04)

- Goal: count the live sensors in the network



Challenge

Synopsis should be small

Approximate COUNT algorithm: logarithmic size bit vector

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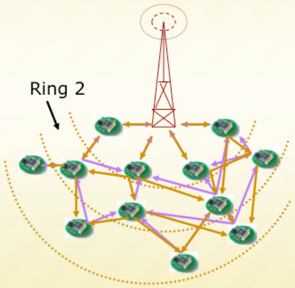
Synopsis Diffusion over Rings

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



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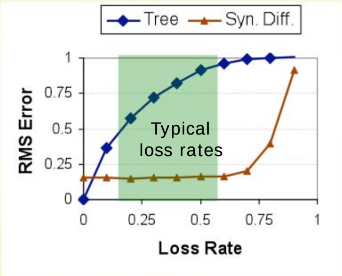
Evaluation

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

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