CMPE 259
Wireless Sensor Networks: Data Aggregation

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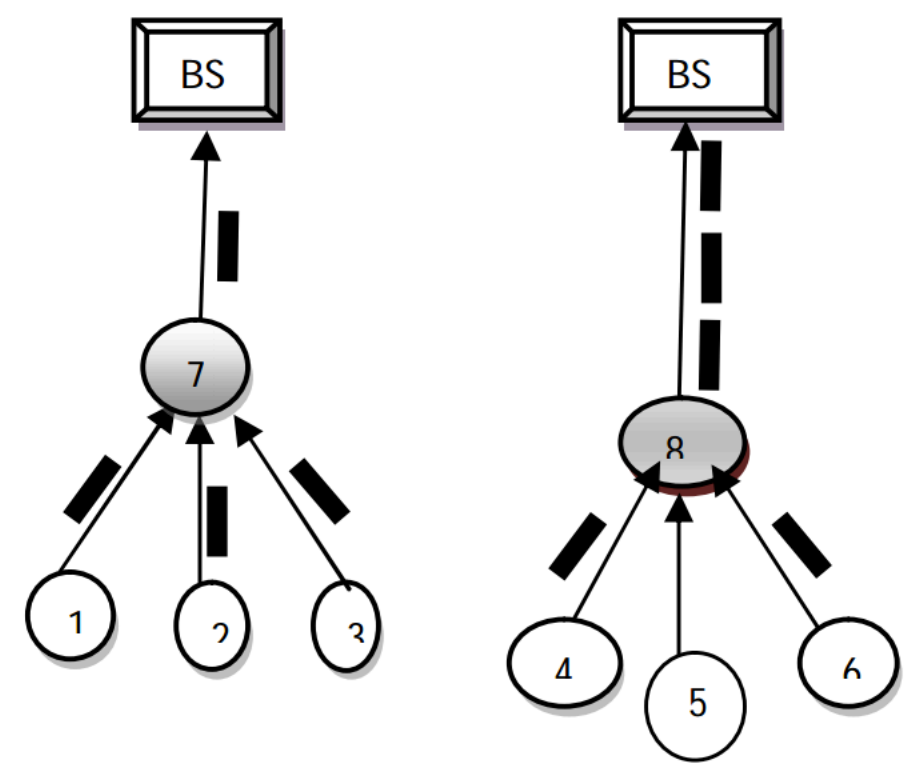
What is data aggregation?

- Aggregate data as it flows through the network
  - Concatenation
    - Raw data
    - Application independent
  - Fusion
    - Statistical computation
    - e.g. MAX/MIN/SUM/Moment
  - Reduction
    - Duplication of the same event
    - Temporal/spatial similar numerical value



Why data aggregation?

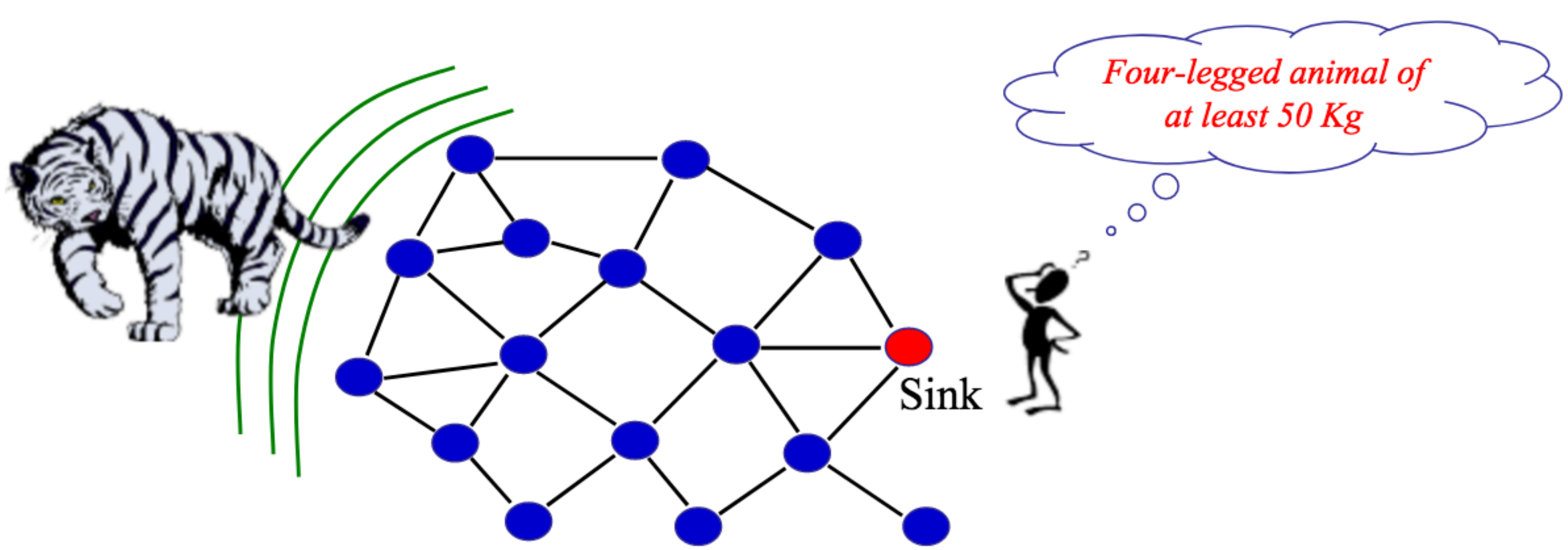
- Energy! Energy! Energy!
  - Assumptions:
    1. Computation consumes less energy than communication.
    2. Computation is not the bottleneck.
    3. The data is able to be aggregated.
  - Does these assumption always holds?
    - CV/VR/AR computational intensive tasks
    - Encrypted/compressed data

Why data aggregation?

- Bandwidth
  - CSMA
    - Less collision -> less power consumption
  - TDMA
    - Feasible scheduling
- Distributed information processing?
  - Load balance
- Privacy preserving?

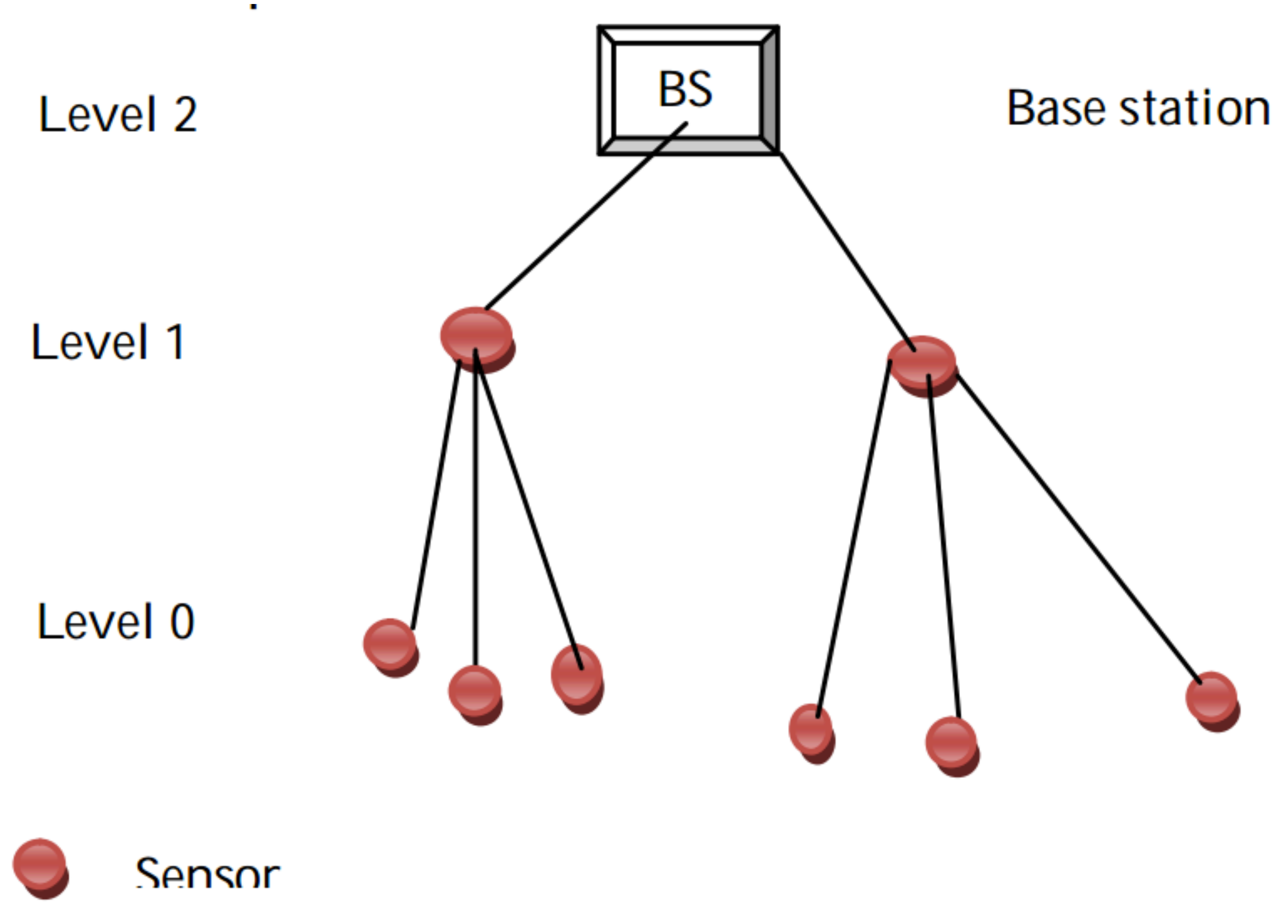
What data to aggregate?

- Periodic
  - continues real-time monitoring
    - e.g. environmental monitoring, energy monitoring
- Sporadic
  - dynamic event detection



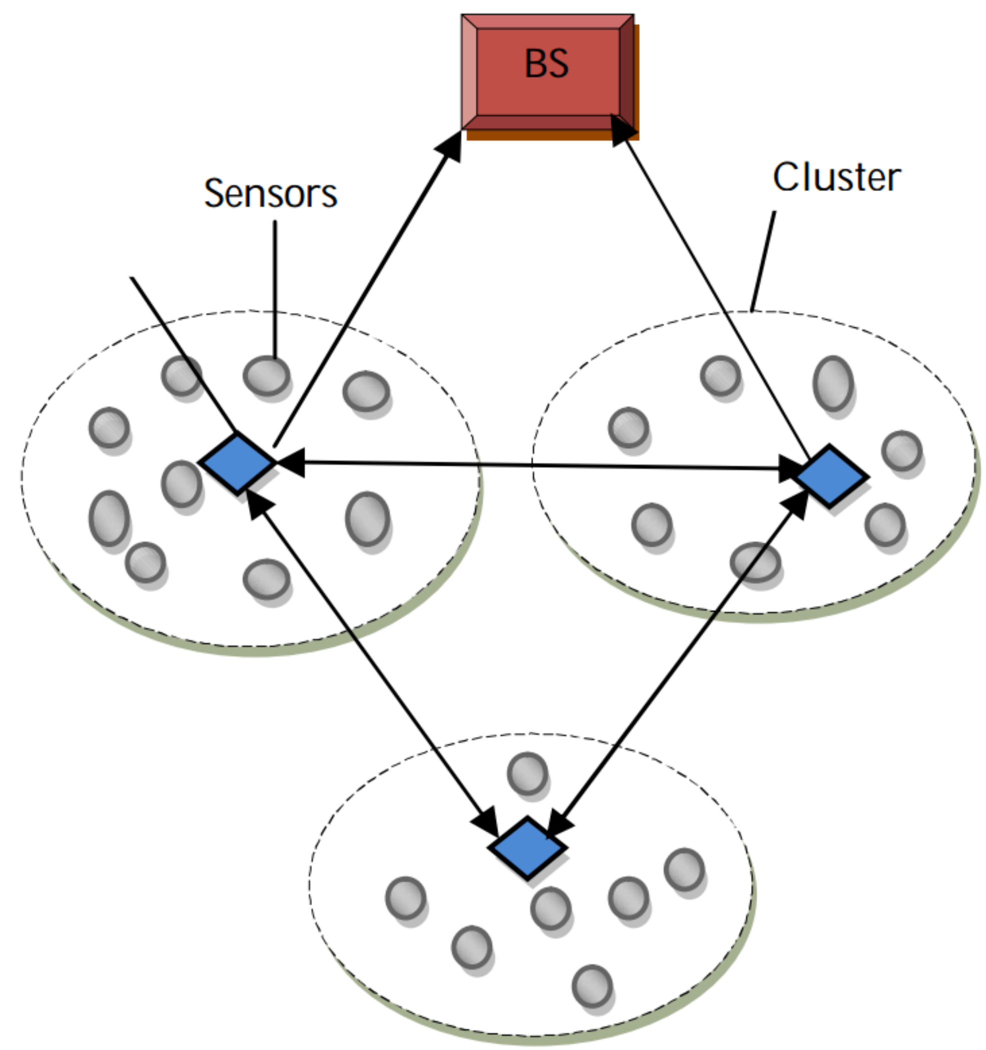
Where to aggregate?

- Aggregation Tree parent node [TinyDB]
  - Minimal spanning tree
  - Not robust



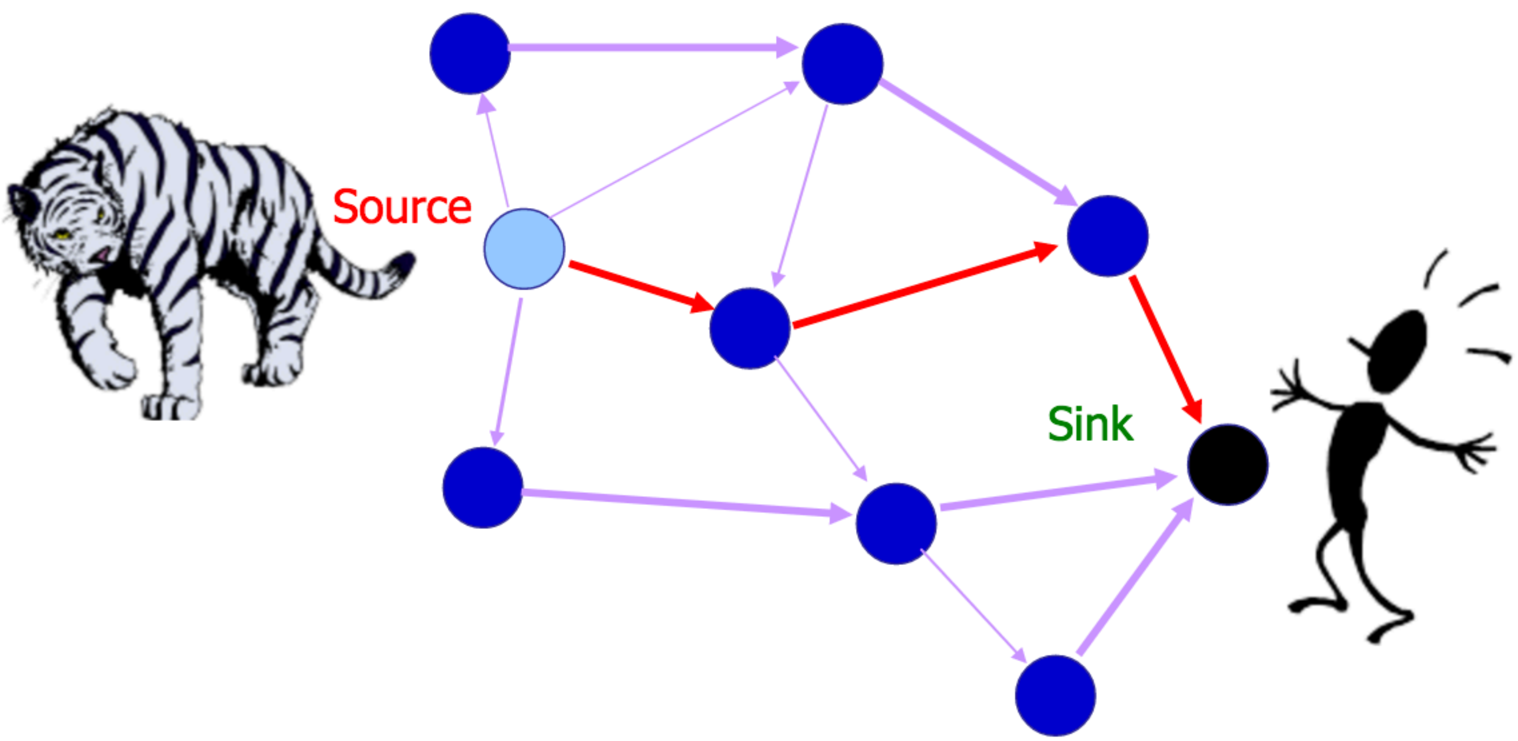
Where to aggregate?

- Cluster head [Cougar]
  - Hierarchical



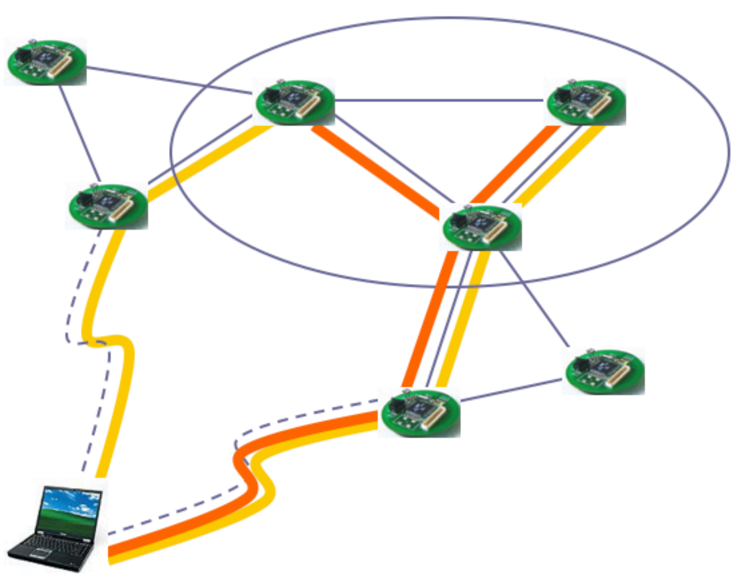
Where to aggregate?

- Multiple neighbor nodes [Directed Diffusion]
  - Robust
  - But duplications.



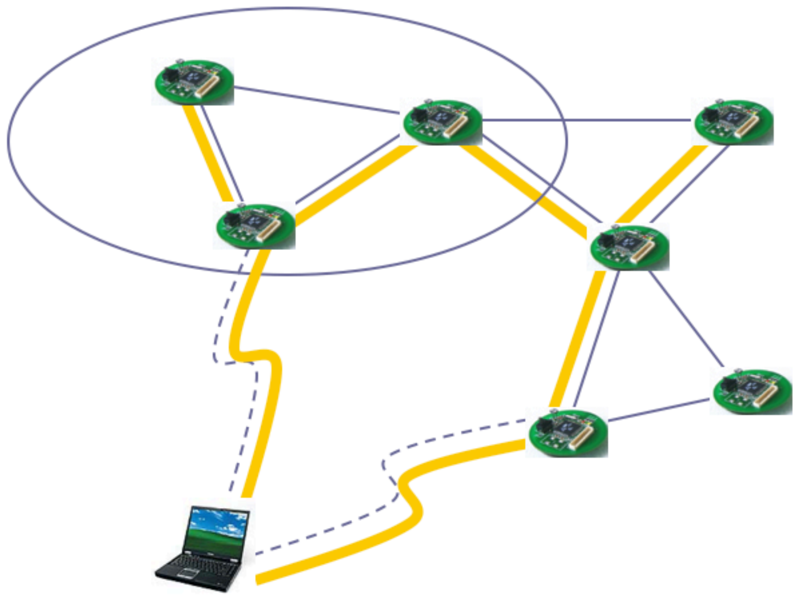
Aggregate structure

- Static structure
  - Routing on a pre-computed structure
  - Suitable for unchanging traffic pattern
  - Inappropriate for dynamic event



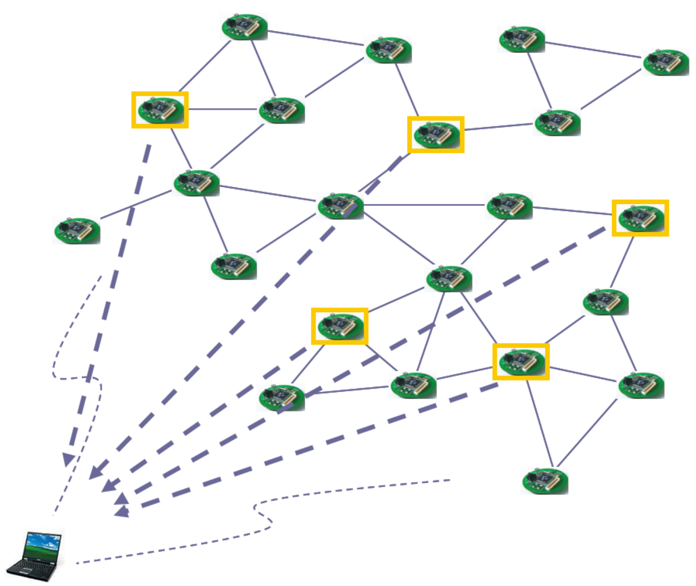
Aggregation structure

- Dynamic structure
  - Create a structure dynamically
  - Optimization for a subset of nodes
  - High control overhead for dynamic events



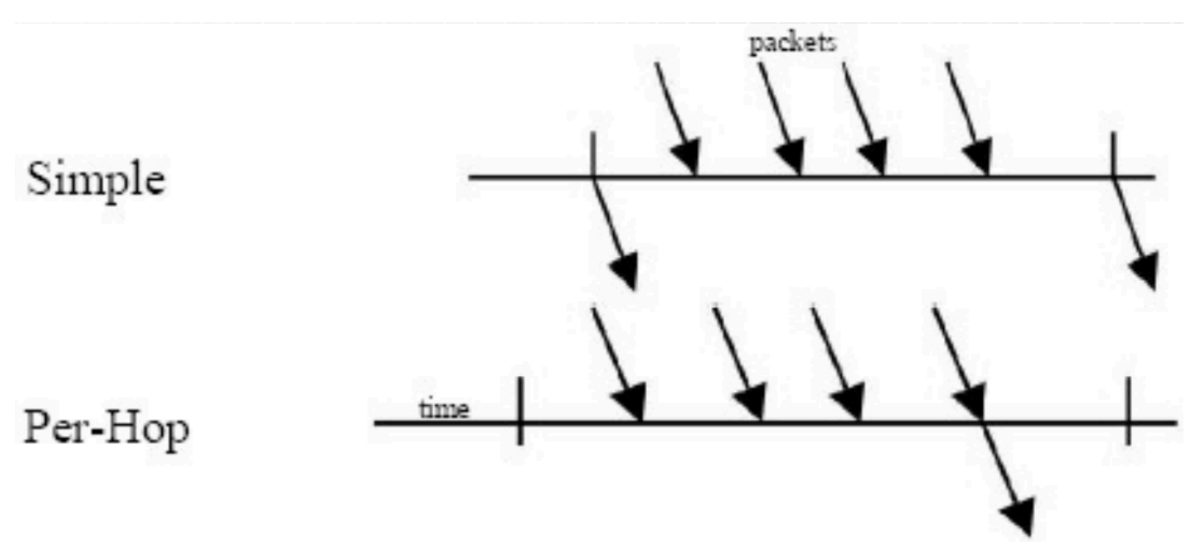
Aggregation structure

- Structure-free
  - Improve aggregation without any structure
  - Suitable for dynamic event scenarios
  - No guarantee of aggregation for all packets



When to aggregate? (periodic timing models)

- Periodic Simple Aggregation
  - each node wait a pre-defined period of time, aggregate all data item received, and send out a single packet containing the result
- Periodic Per-hop Aggregation
  - similarly to periodic simple, but transmits the aggregated data as soon as it hears from all its children
- Periodic Per-hop Adjusted Aggregation
  - nodes adjust their timeout based on their position in the data collection tree.



Performance metrics

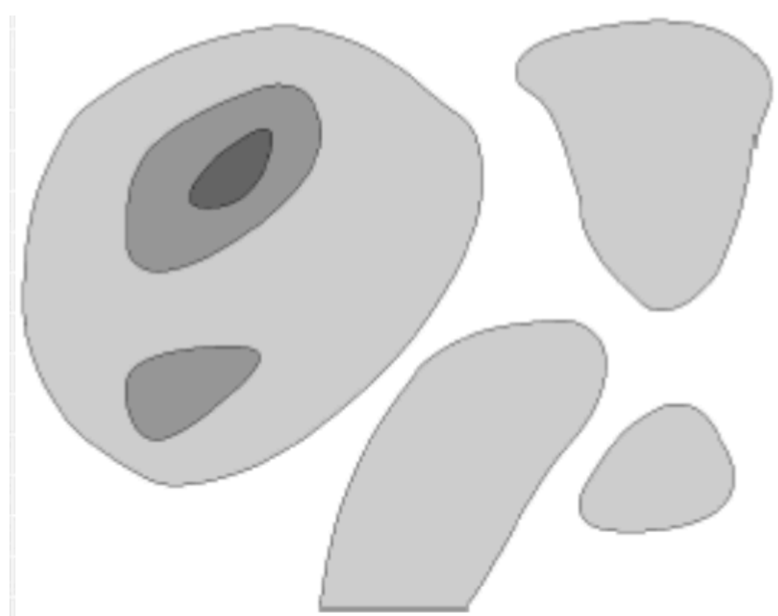
- Energy efficiency
- Latency
- Communication cost
- Data accuracy

Papaers overview

	data type	aggregation	Structure
Isoline	periodic data	Reduction	Structure-free
ToD	dynamic event	Fusion	Hybrid
Sparse	sparse event	Not specified	Dynamic tree

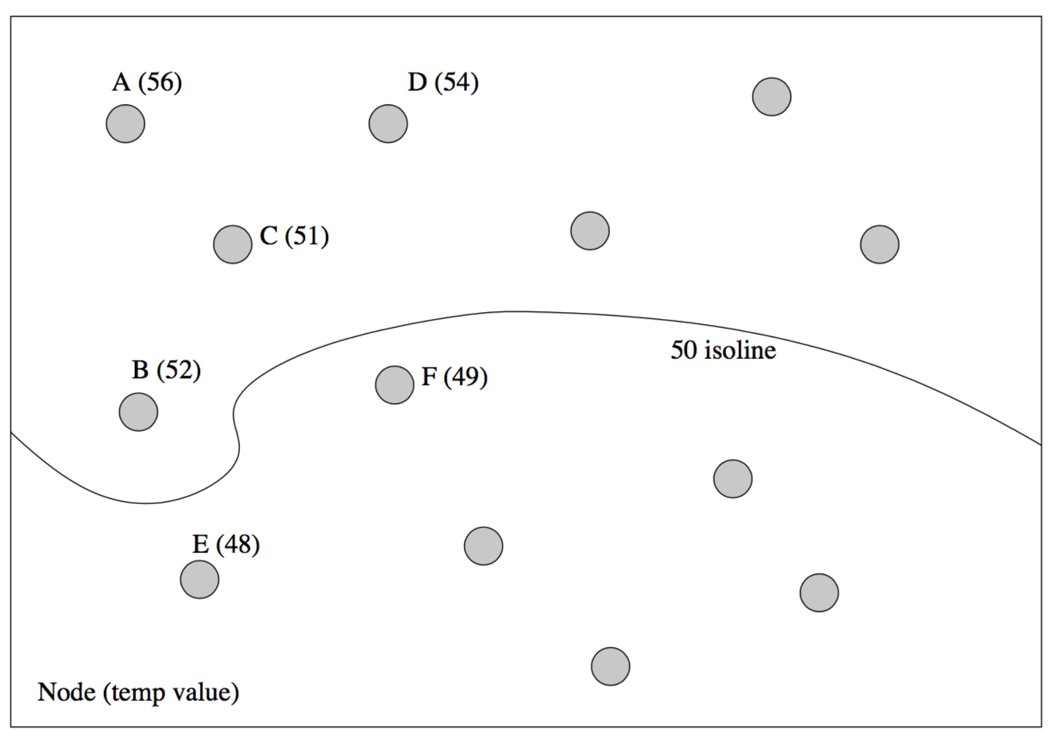
Efficient Continuous Mapping in Sensor Networks Using Isolines [isoline aggregation]

- Basic idea
  - Spatial correlation of data
  - Group nodes that report similar readings into **isoclusters**
- Key Operation: **Isoline** detection



Isoline detection

- Isolines
  - lines which pass through our network and have the same value.
  - Detection by local comparison with neighbor readings
  - Only node detecting isoline reports to sink



Continuous monitoring

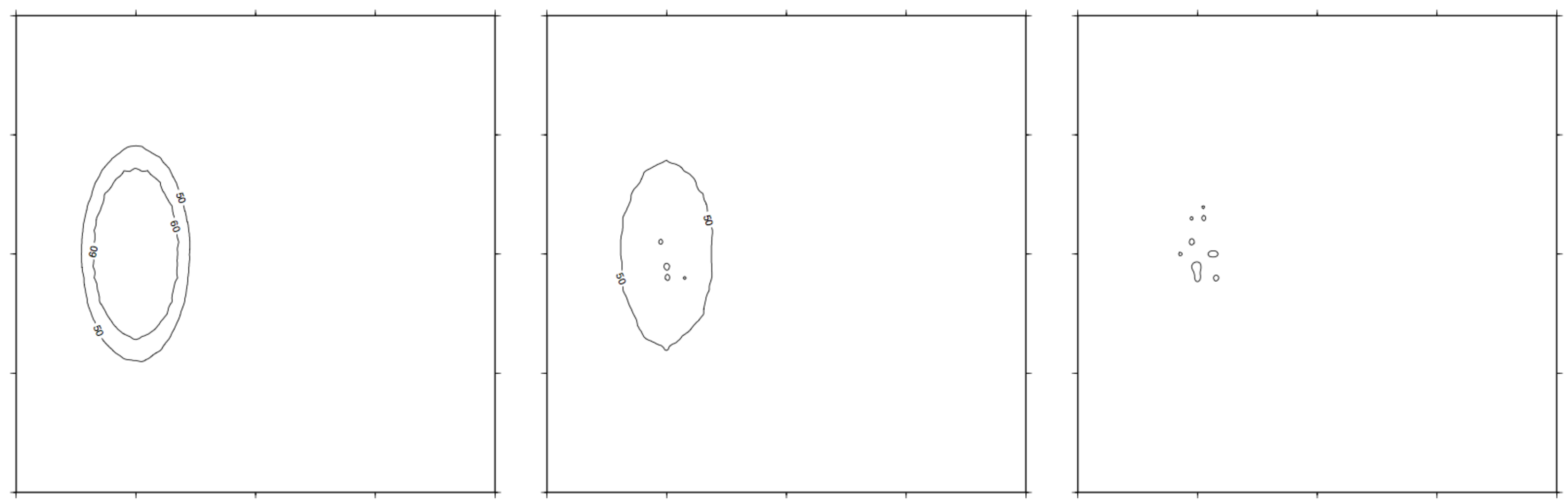
- Real-time data
- temporal correlation
  - If the isoline doesn't change or there is no nearby isoline, there is no report.

Simulation Setup

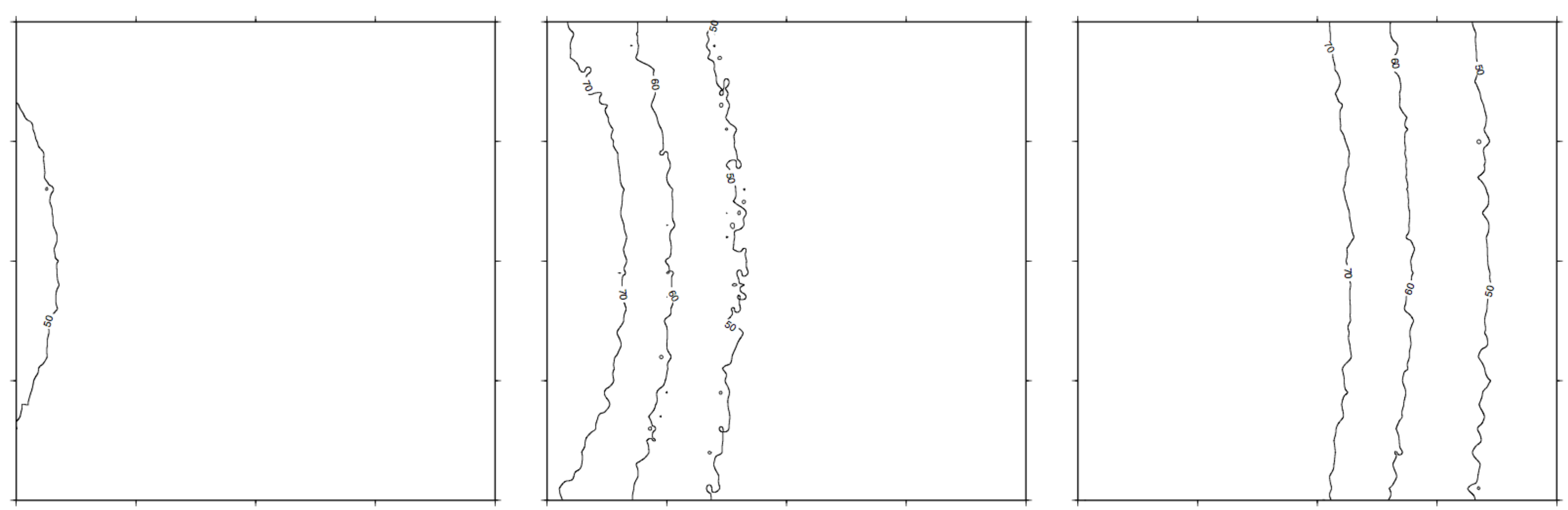
- Temperature continuous monitoring
  - 16*16 nodes grid, 400 m^2
  - CDMA: 40m transmission range
  - Reality is simulated by a matrix of 80*40 points
  - Initial centered at 45 degrees, Aggregated at interval of 10 degrees
- Comparison alternatives
  - No aggregation
  - No aggregation optimized: temporal data aggregation
  - polygon aggregation

Two scenarios

- Hotspot



- Front moving



t=4 t=7 t=11

Simulation result

- Hotspot
  - No aggregation and isoline aggregation send similar amount of data
    - Expensive initial data collection
  - Polygon aggregation sends more data
    - Aggregation happens down in the collection tree

	Similarity	KBytes sent
No Agg.	98.7 (sd 0.09)	180.0 (sd 5.4)
No Agg opt.	98.9 (sd 0.09)	21.1 (sd 0.4)
Polygons	98.1 (sd 0.49)	62.9 (sd 4.6)
Isolines	97.0 (sd 0.36)	15.3 (sd 1.2)

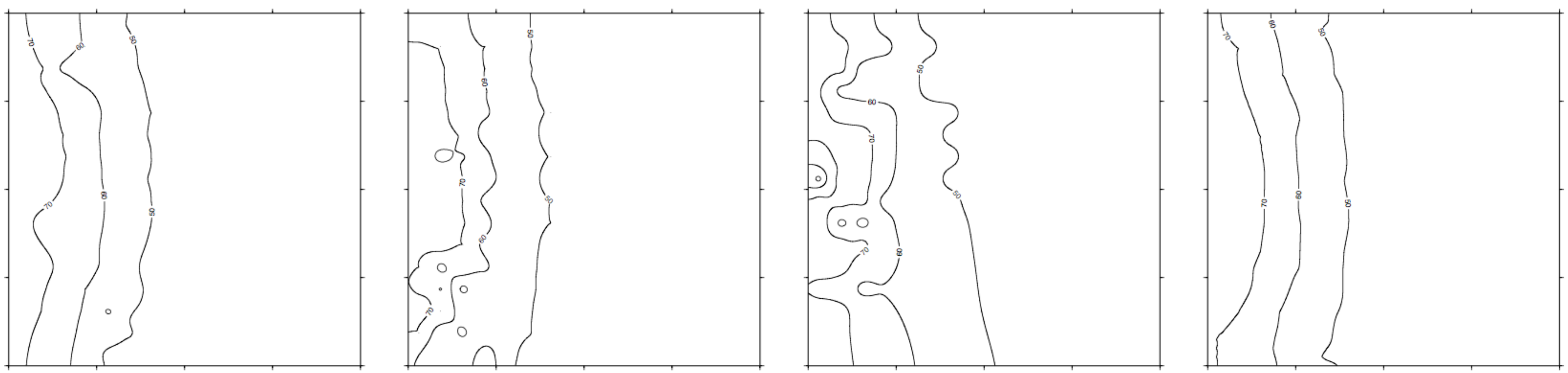
Simulation result

- Moving front
  - All nodes will eventually change value.
  - Error due to packet loss.

	Similarity	KBytes sent
No Agg.	93.2 (sd 1.72)	177.1 (sd 5.9)
No Agg opt.	89.3 (sd 0.70)	62.1 (sd 2.3)
Polygons	82.4 (sd 2.93)	77.0 (sd 3.6)
Isolines	96.7 (sd 0.50)	55.8 (sd 3.1)

Simulation result

- Moving front



None | None optimized | Polygon | Isoline

Conclusion

- Isolines are an effective method of aggregating information

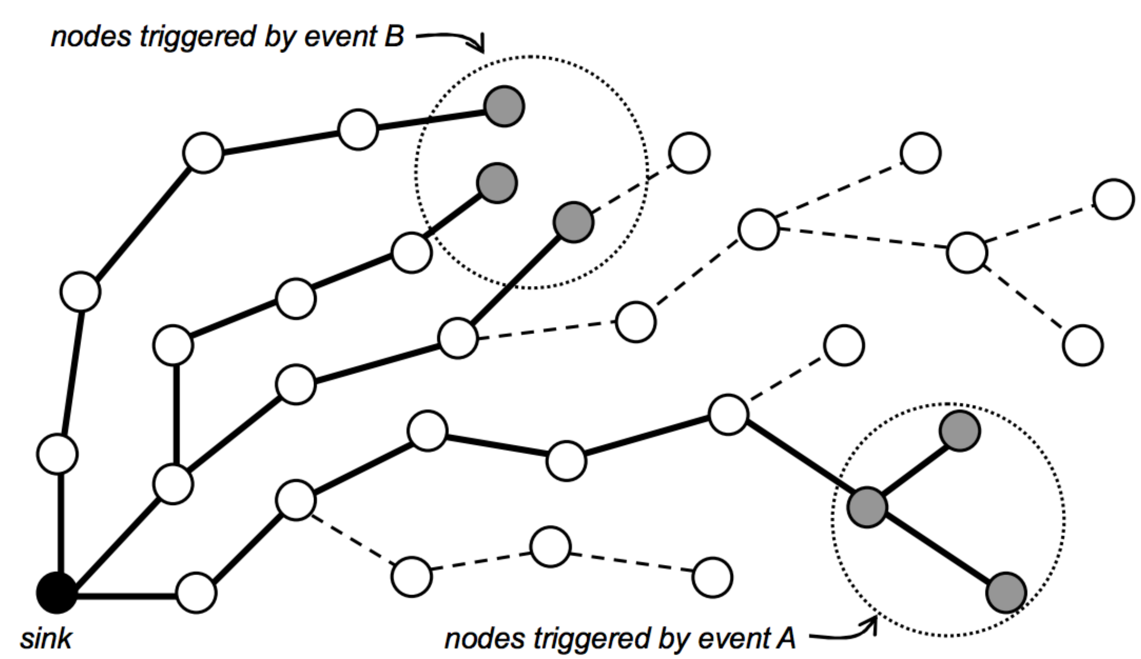
- What if…
  - Sparse deployment
  - Week spatial correlation

Scalable Data Aggregation for Dynamic Events in Sensor Networks

- Target: rare dynamic events
- Related work
  - Statistic Structure
    - Suitable for unchanging traffic pattern;
  - Dynamic Structure
    - High control overhead for dynamic events
  - Structure-Free
    - Suitable for dynamic event scenarios;
    - Not scalable

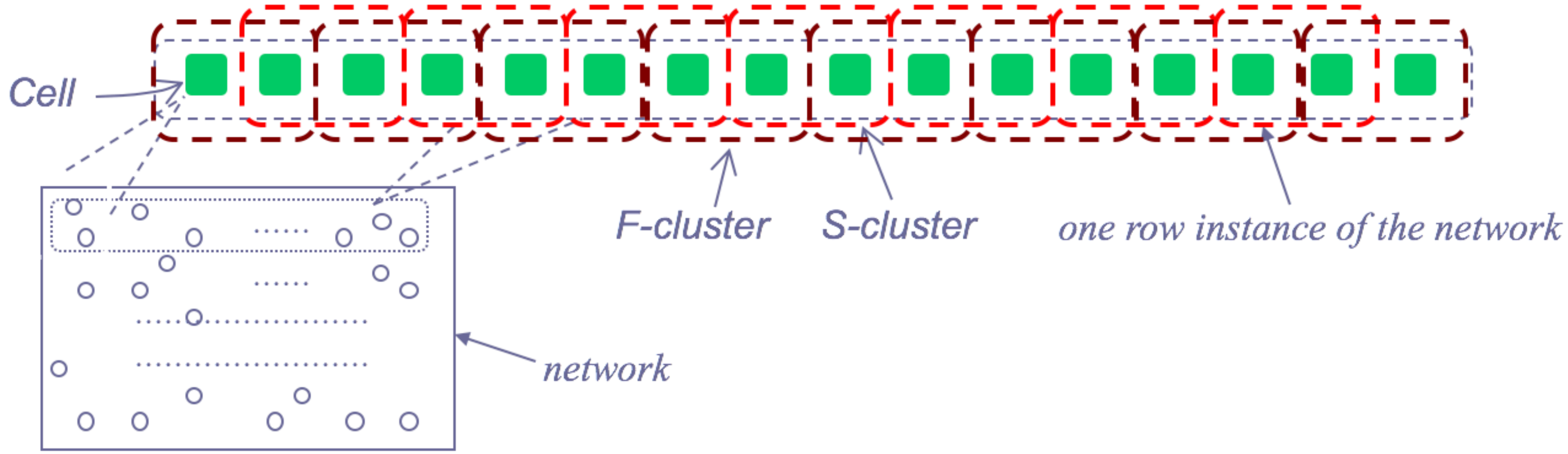
Approach:
Tree on Directed Acyclic Graph

- Combine benefits of structured and structure-free approaches
- Two-stage method
  - Structure-free data aggregation: early aggregation
  - Packet forwarding on an implicit structure: scalability



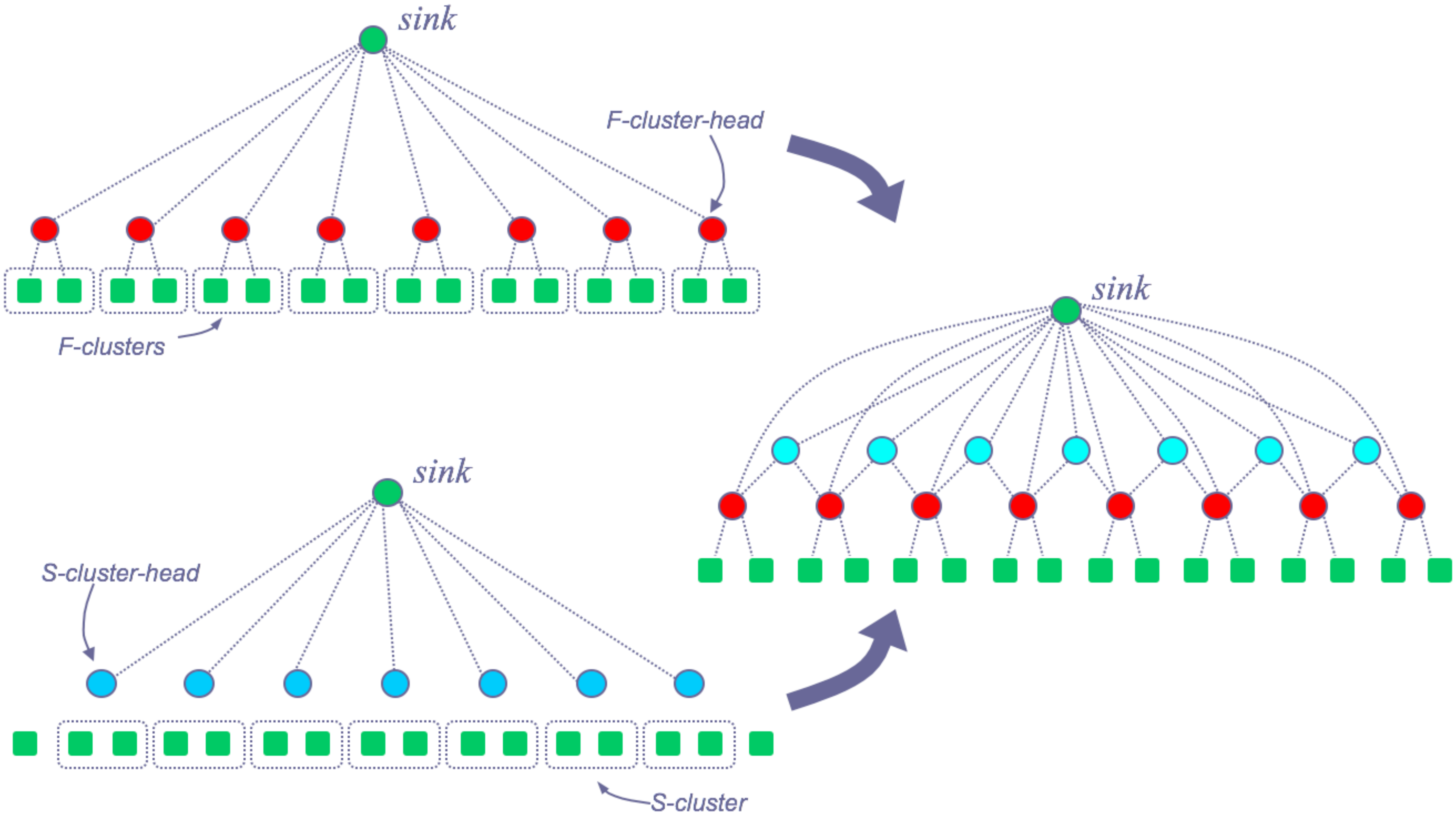
ToD - Tree on DAG

- One-Dimension illustration



- Definition
  - Cell: Cell size is the maximum diameter of events
  - F-cluster: First-level Cluster. Composed of multiple cells
  - S-cluster: Second-level Cluster. Composed of multiple cells
    - Interleaved with F-clusters

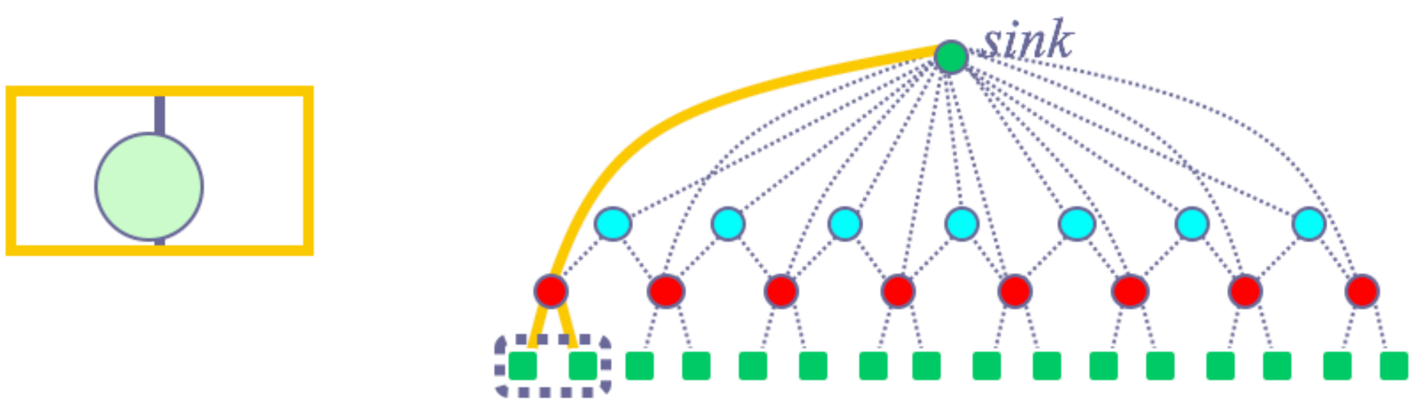
ToD - Tree on DAG



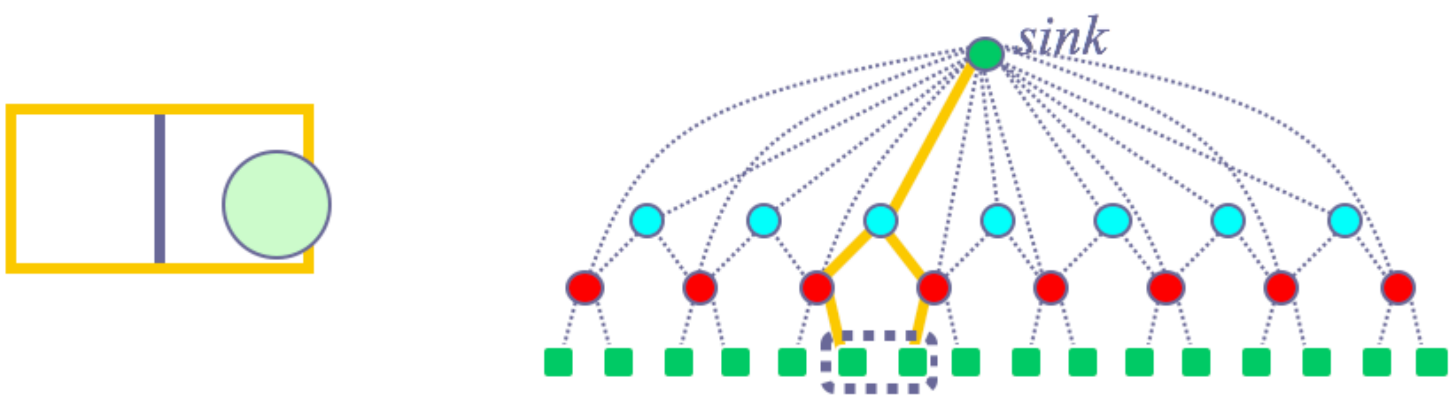
Dynamic Forwarding

- Rule 0: forward packets to F-cluster-head by structure-free data aggregation protocol [Infocom '06]

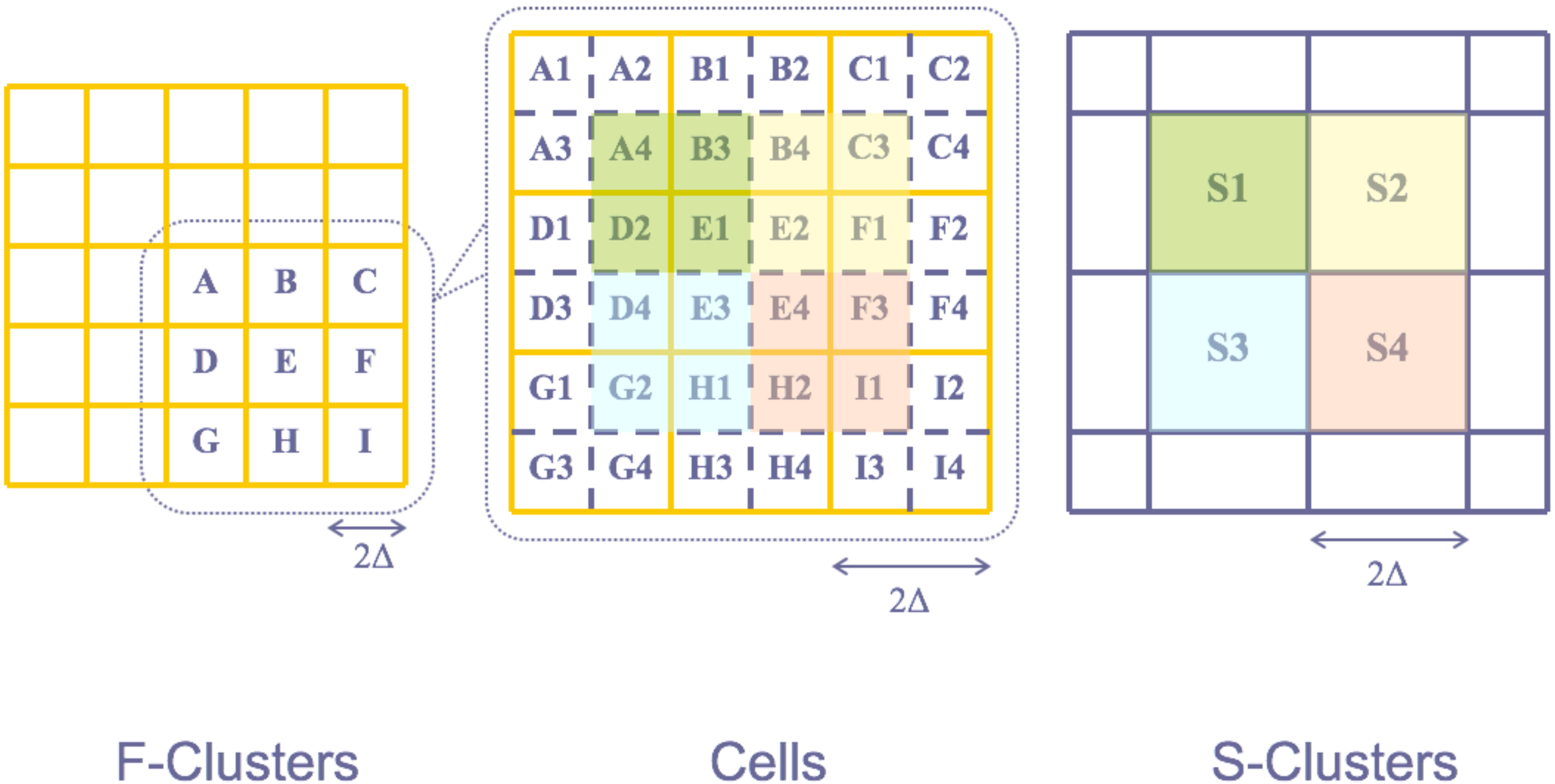
- Rule 1: event spans two cells, forward to sink

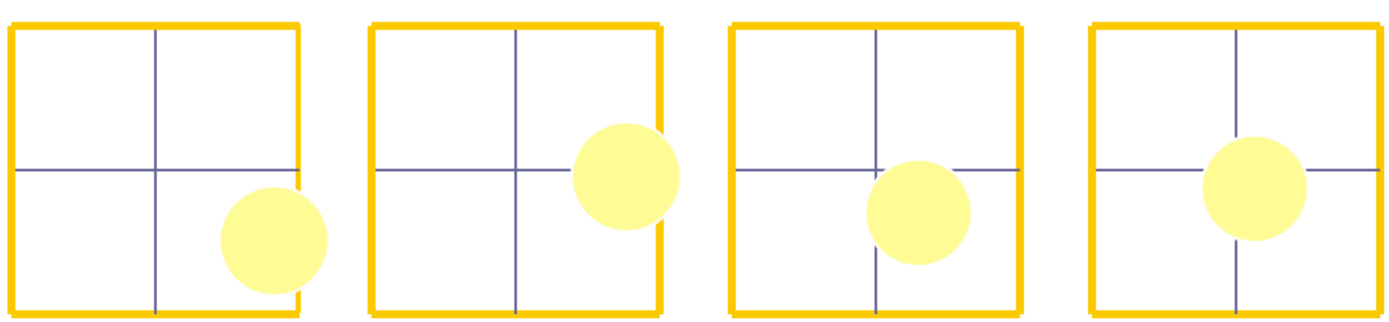


- Rule 2: event spans one cell, forward to S-cluster-head



Two-Dimension ToD Construction





Experimental Results

- Evaluated Protocols
  - ToD
  - Data Aware Anycast (DAA) (includes RW)
  - Shortest Path Tree (SPT)
  - SPT with Delay (SPT-D)
- Testbed Configuration
  - 105 Mica2-based motes
  - 15 * 7 grid network
  - TX Range: 2 grid-neighbor (max 12 neighbors)
- Evaluated Metric
  - Normalized Number of Transmissions

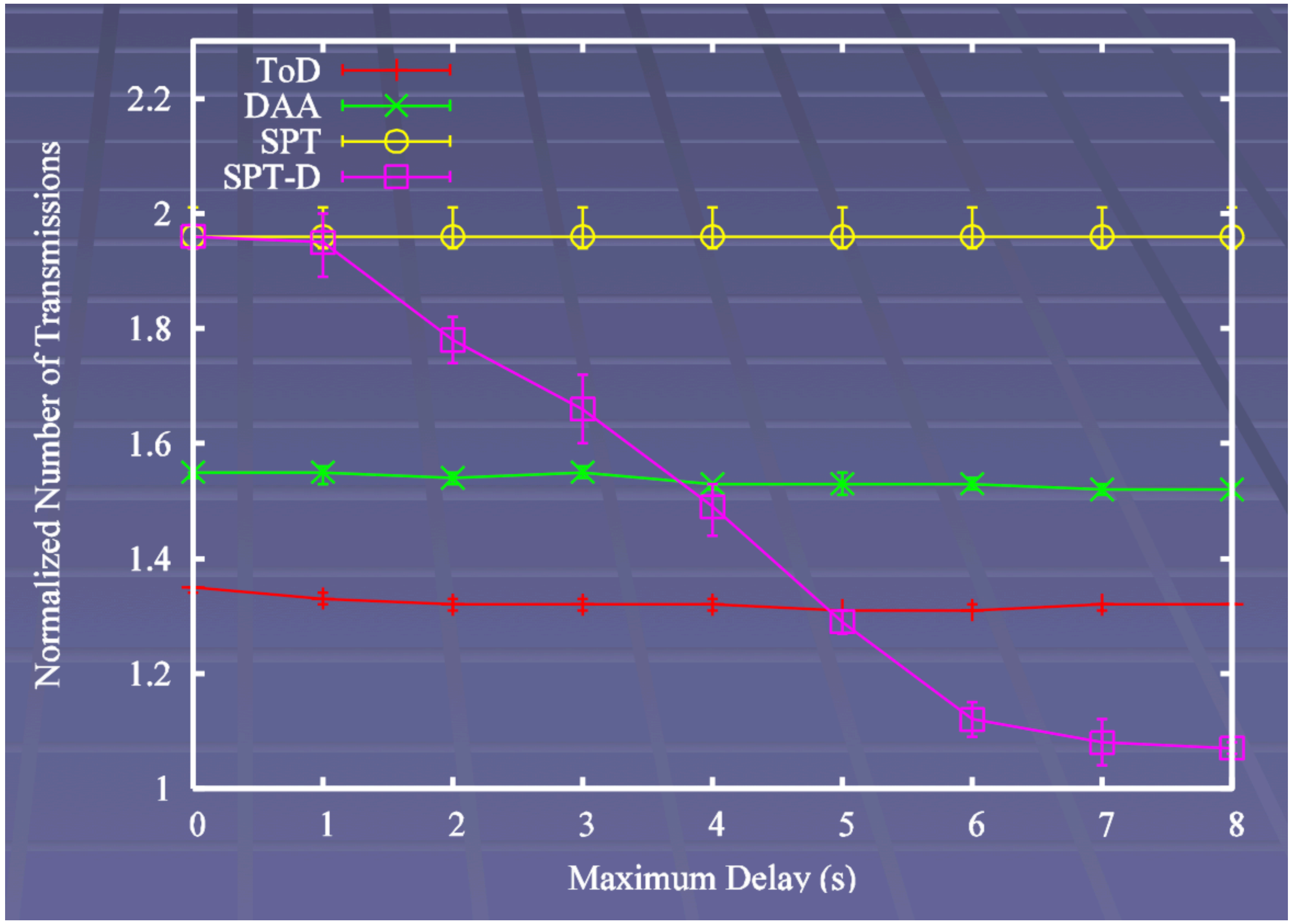
$$\frac{\textit{Number of Total Transmissions}}{\textit{Number of Contributing Sources}}$$

- Parameters
  - Maximum Delay
    - ToD, DAA, SPT-D
  - Event Size

Experiment Results - Delay

- All nodes are sources
- Data rate: 0.1 pkt/s
- Data payload: 20 bytes
- 2 F-clusters in ToD

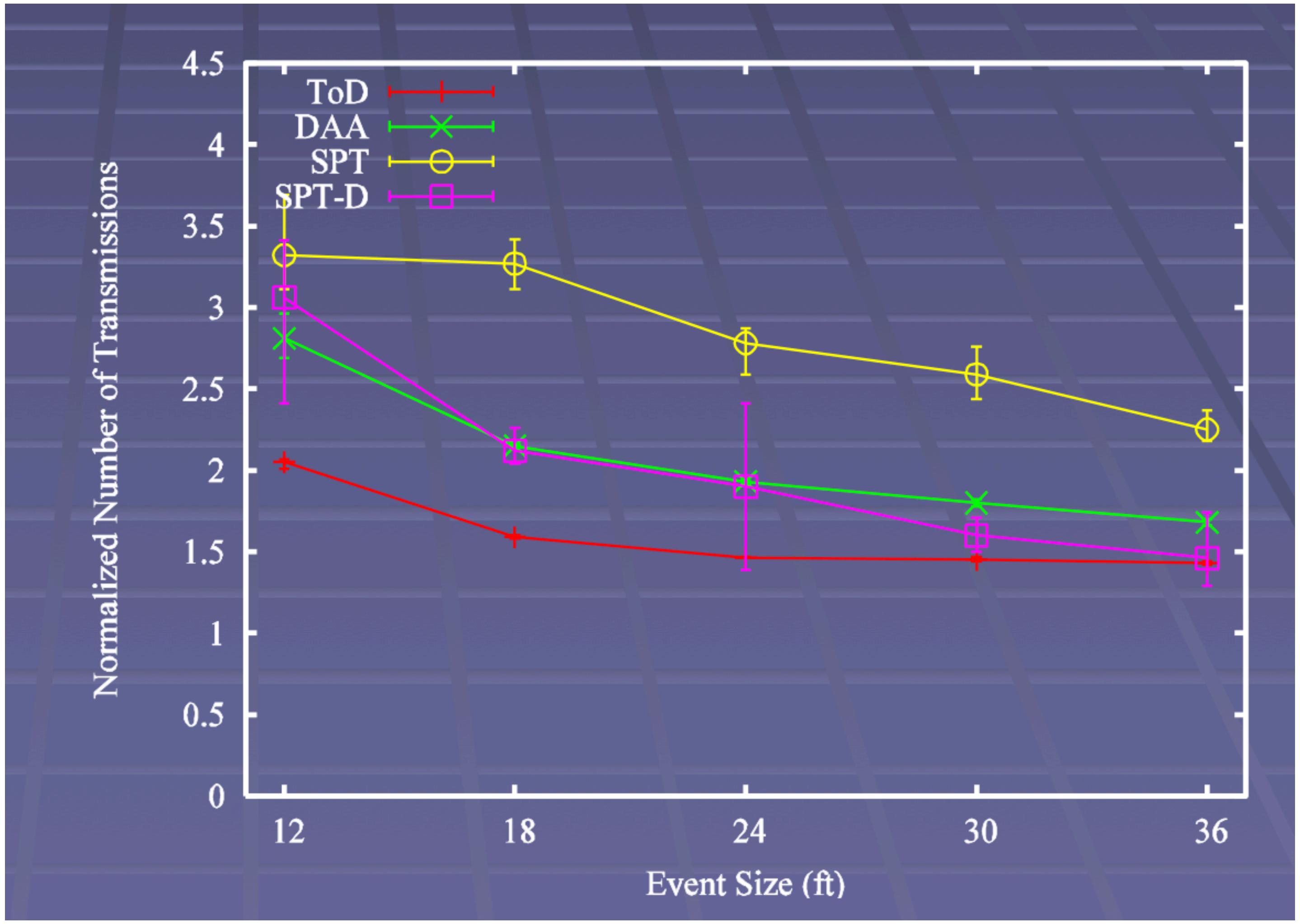
- Key observations
  - ToD performs better than DAA
  - SPT-D is sensitive to the delay



Experiment Results – Event Size

- 12 ~ 78 sources
- Data rate: 0.1 pkt/s
- Data payload: 20 bytes
- SPT-D delay: 6s

- Key observations
  - ToD performs best
  - High variation of SPT-D: Long stretch problem



Conclusion

- Structure-Free Aggregation
- Dynamic Forwarding on ToD for Scalability
- Efficient Aggregation without overhead of structure computation and maintenance

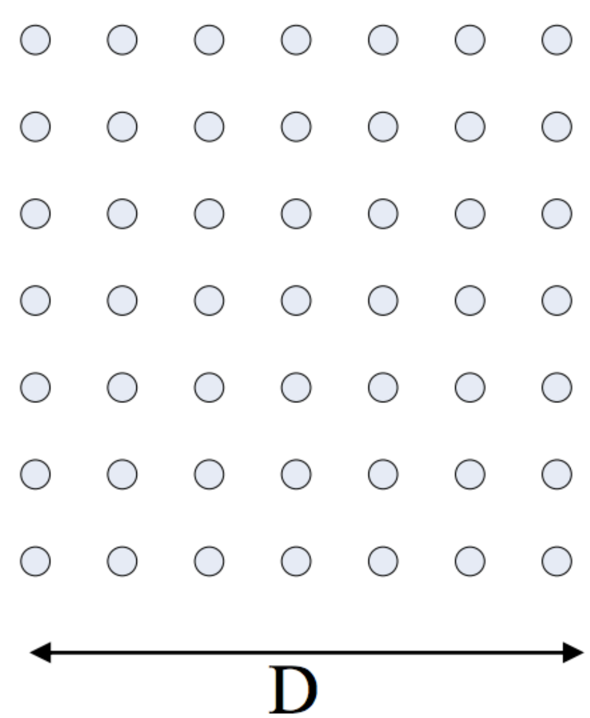
Sparse Data Aggregation in Sensor Networks

- Problem
  - Aggregate data from a sparse set of nodes.
    - Events are rare.
    - e.g. anomaly detection
  - No global information on where all these nodes are located.
- Goals:
  - Autonomously discover each other in a distributed fashion.
  - Ad hoc Aggregation structure

Network setup

- Sensor nodes are uniformly deployed inside a regular region.

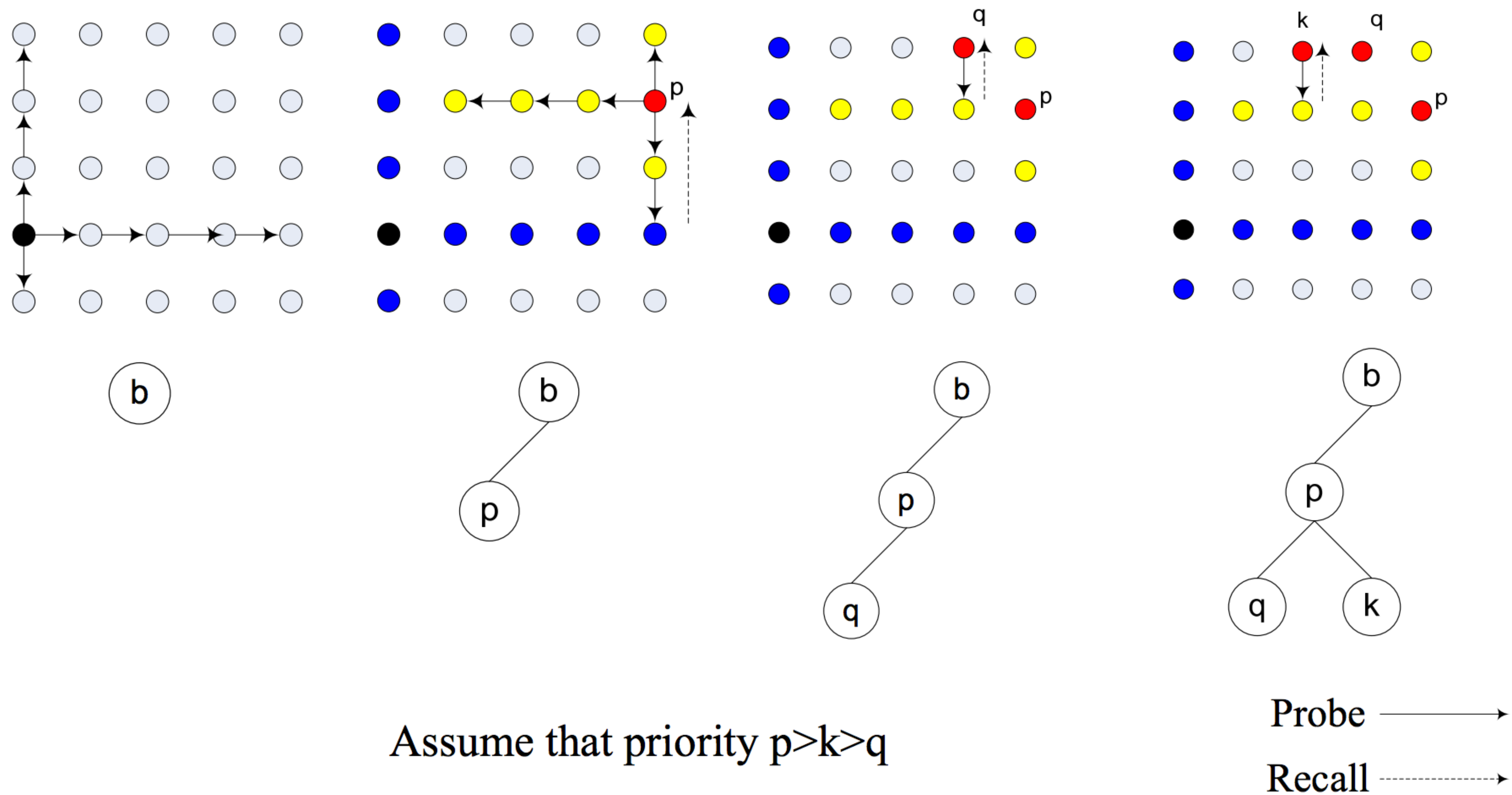
- The boundary of the field is known and connected to high-speed network.



Tree-based Sparse data aggregation

- Each hot-node has a unique priority number
- Base station node has the highest priority
- The hot nodes with data participate in the tree formation protocol composed of two sub-protocols:
    - The probe protocol: node ID + node priority number
    - The recall protocol: parent node ID.
- The hot nodes tries to find the nearest hot node with highest priority.
- Nearly optimal

Tree formation



Assume that priority p>k>q

slide source: http://www.st.ewi.tudelft.nl/~koen/wsn/2009/slides11.pdf

Routing

- The aggregation tree is a a logical structure: each node *p* knows its parent *q* in the tree.
- Routing can be done by several choices:
  - Send a packet from p to q along p's trail to the junction node w, then along q's trail to q.
  - Use some network-specific point-to-point routing mechanism.
  - Multi-path depend on the importance of the message.

slide source: http://www.st.ewi.tudelft.nl/~koen/wsn/2009/slides11.pdf

Probabilistic Aggregation

- Exponential distribution

$$f(x;\lambda) = \begin{cases} \lambda e^{-\lambda x}, & \text{if} \quad x \geq 0 \\ 0\,, & \text{if} \quad x < 0 \end{cases}$$

$$F(x;\lambda) = \begin{cases} 1 - e^{-\lambda x}, & \text{if} \quad x \geq 0 \\ 0\,, & \text{if} \quad x < 0 \end{cases}$$

- E[x] = 1/μ
- Var[x] = $1/\mu^2$

Probabilistic aggregation

Theorem 6.2. *If $x_1, x_2, \ldots, x_n$ are independent exponential random variables, where x_i has parameter λ_i, then*

$$\min(x_1, x_2, \ldots, x_n)$$

is an exponential random variable with parameter $\sum_{i=1}^{n} \lambda_i$.

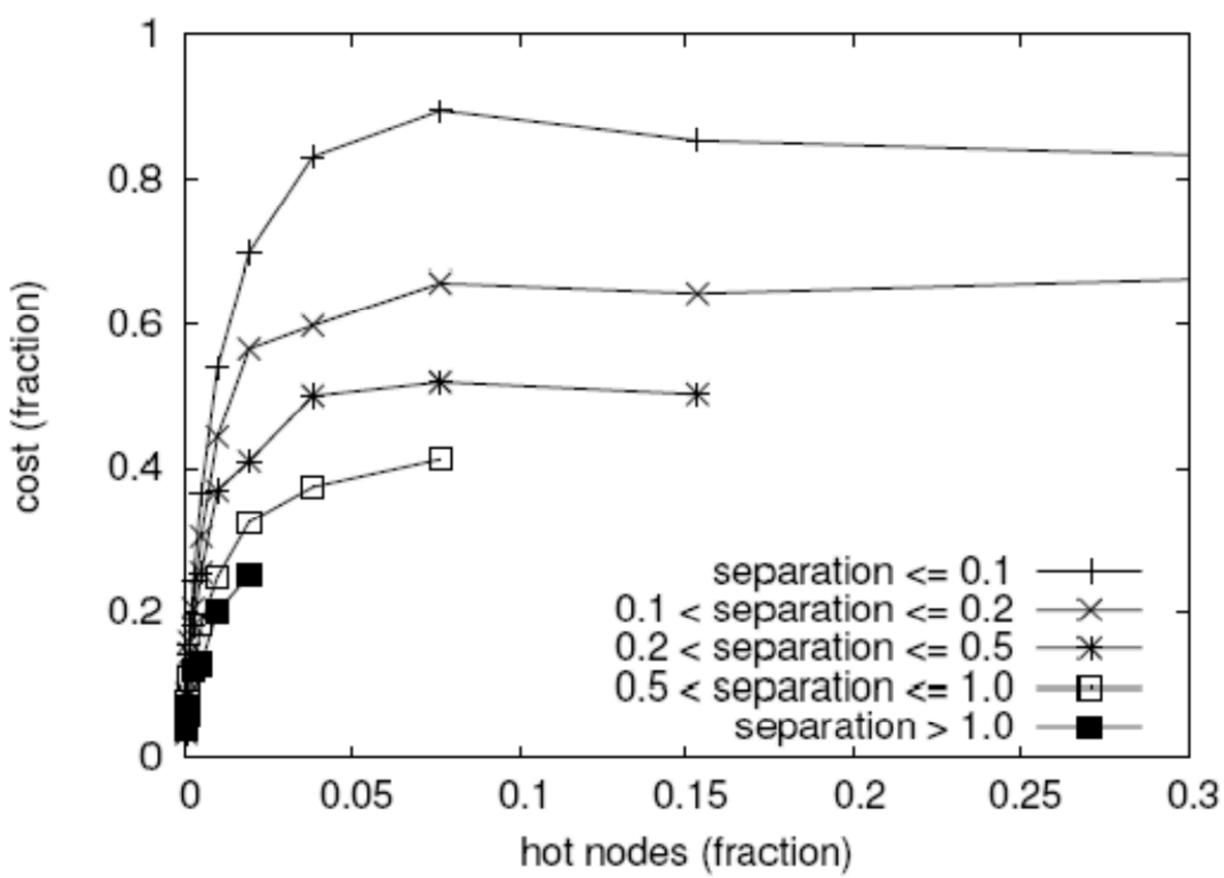
- E[$\min(x_1, x_2, \ldots, x_n)$] = $1/\sum_{i=1}^{n} \lambda_i$
- Robust to data loss/duplication

Simulation Setup

- Alternatives for comparison
  - Pull: query and answer (shortest path)
  - Push: nodes themselves report (shortest path)
- Communication cost
  - Proportional to Euclidian distance
  - Sparse aggregation: tree build + data transmission
  - Pull: Query + data transmission (w or w/o aggregation)
  - Push: data transmission (no aggregation)

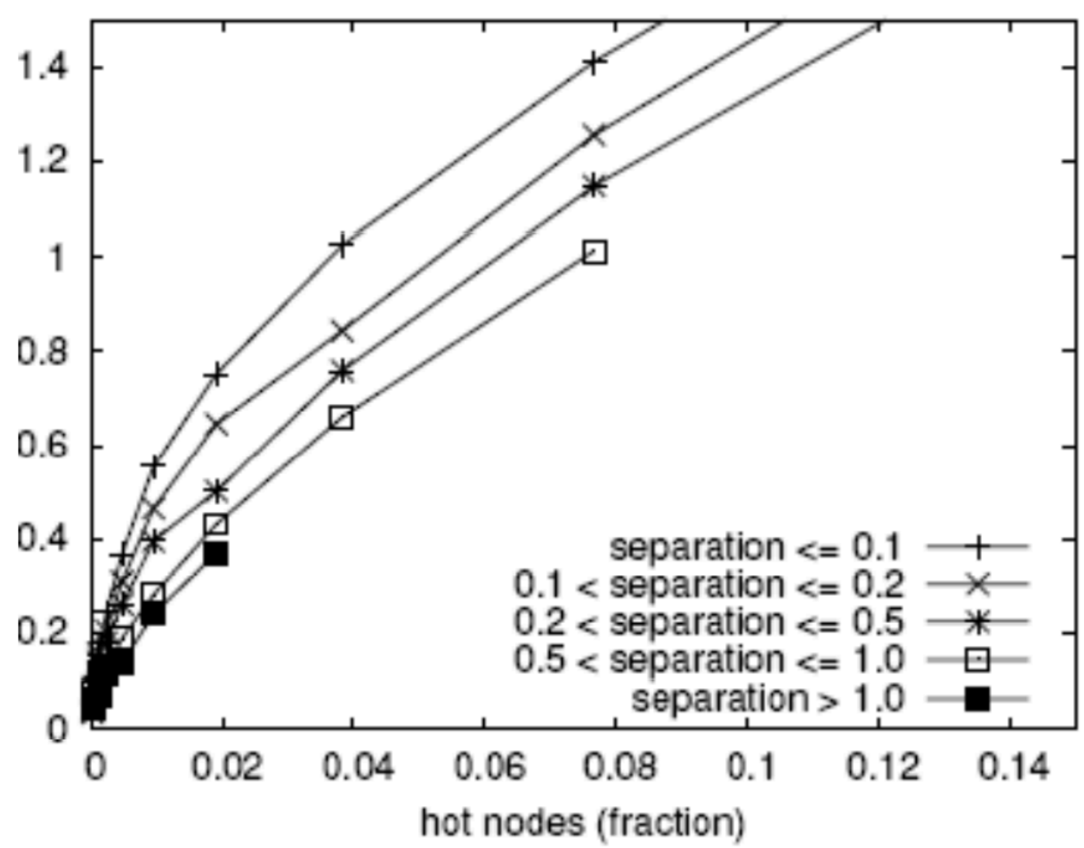
Simulation

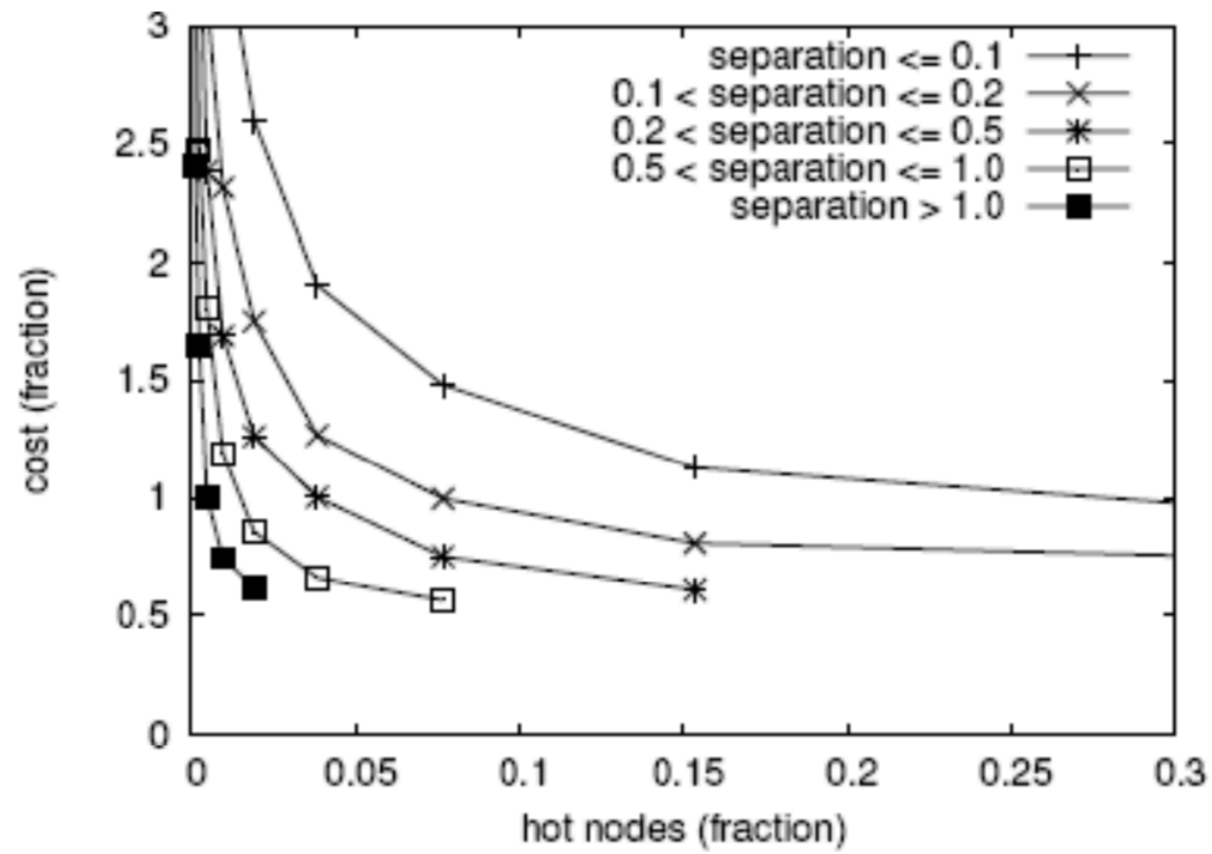
- Regular 100*100 grid
- separation ratio: ratio of the diameter of the hot nodes and the shortest distance between hot nodes and boundary



- Without in-network aggregation: better for all parameter settings.

Simulation





- With in-network “pull” aggregation: better when hot nodes are sparse.
- With in-network “push” aggregation: better unless the hot nodes are too few and their separation is small

slide source: http://www.st.ewi.tudelft.nl/~koen/wsn/2009/slides11.pdf

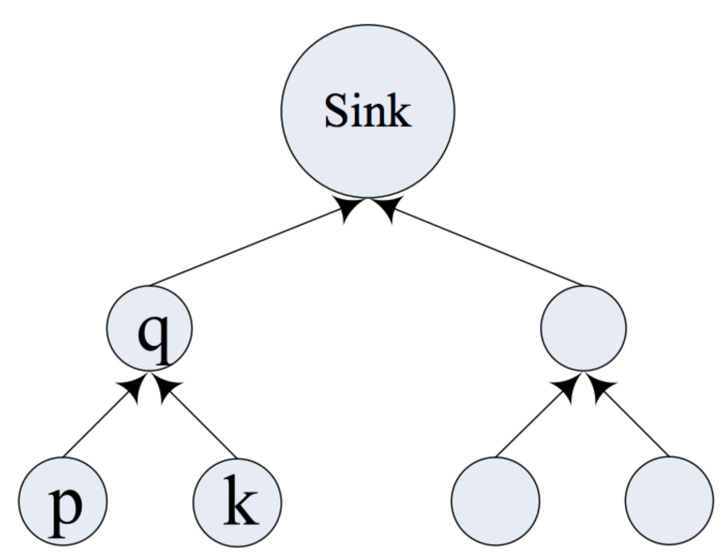
Conclusion

- Distributed Tree-based sparse data aggregation
- Communication is more efficient compared to the "pull" approach without in-network aggregation and the "push" approach with in approach with in-network aggregation network aggregation.
- Probabilistic aggregation

Limitations

- Not all boundary nodes are directed connected
- Grid deployment
- Timing is not discussed

q doesn't know whether it needs to wait for data from other nodes or not.



Recap

	data type	aggregation	Structure
Isoline	periodic data	Reduction	Structure-free
ToD	dynamic event	Fusion	Hybrid
Sparse	sparse event	Not specified	Dynamic tree


Thanks!