Fractional Cascading in Wireless Sensor Networks

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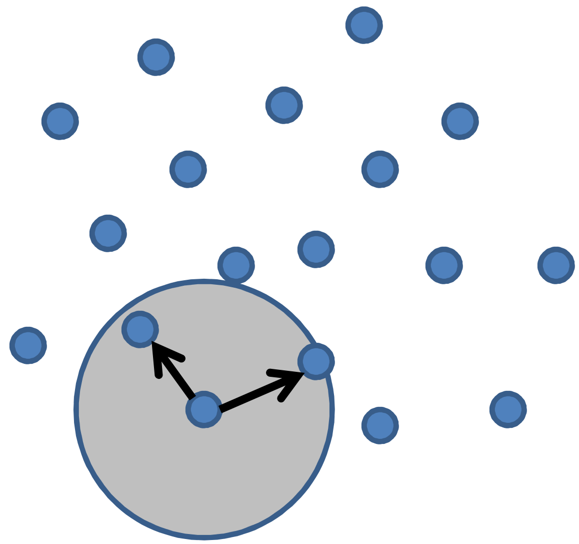
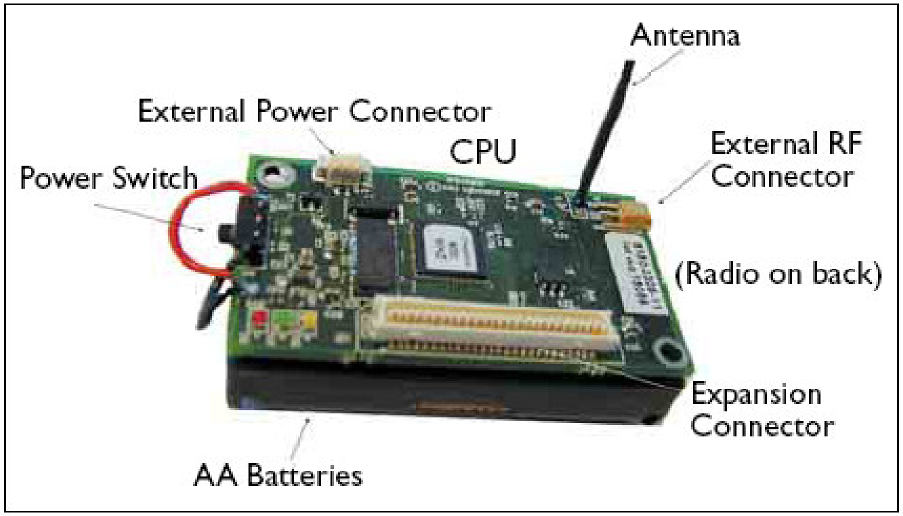
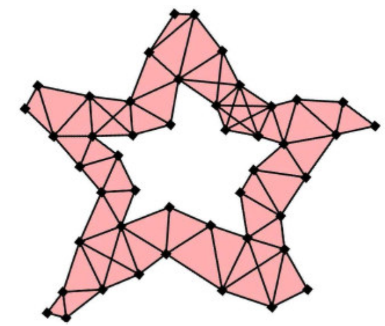
Sensor Networks

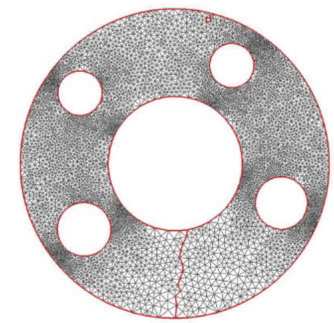
- Large number of small devices for environment monitoring



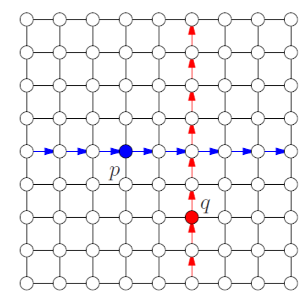


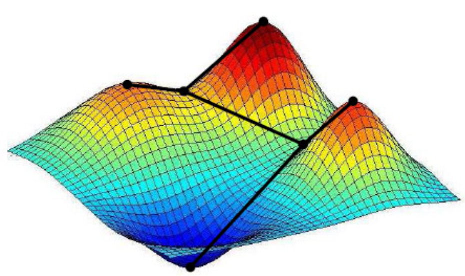
My recent work

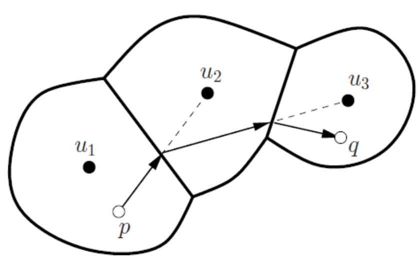


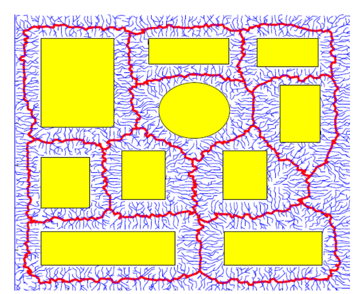


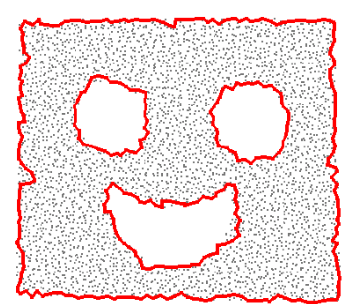
- Lightweight, distributed algorithms
  - Routing
  - Network localization
  - Data aggregation/processing
  - Resource management
  - Network hole detection
  - Mobility issues









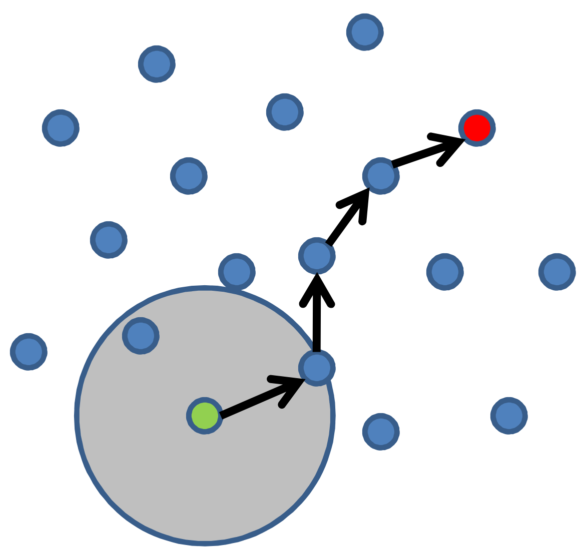


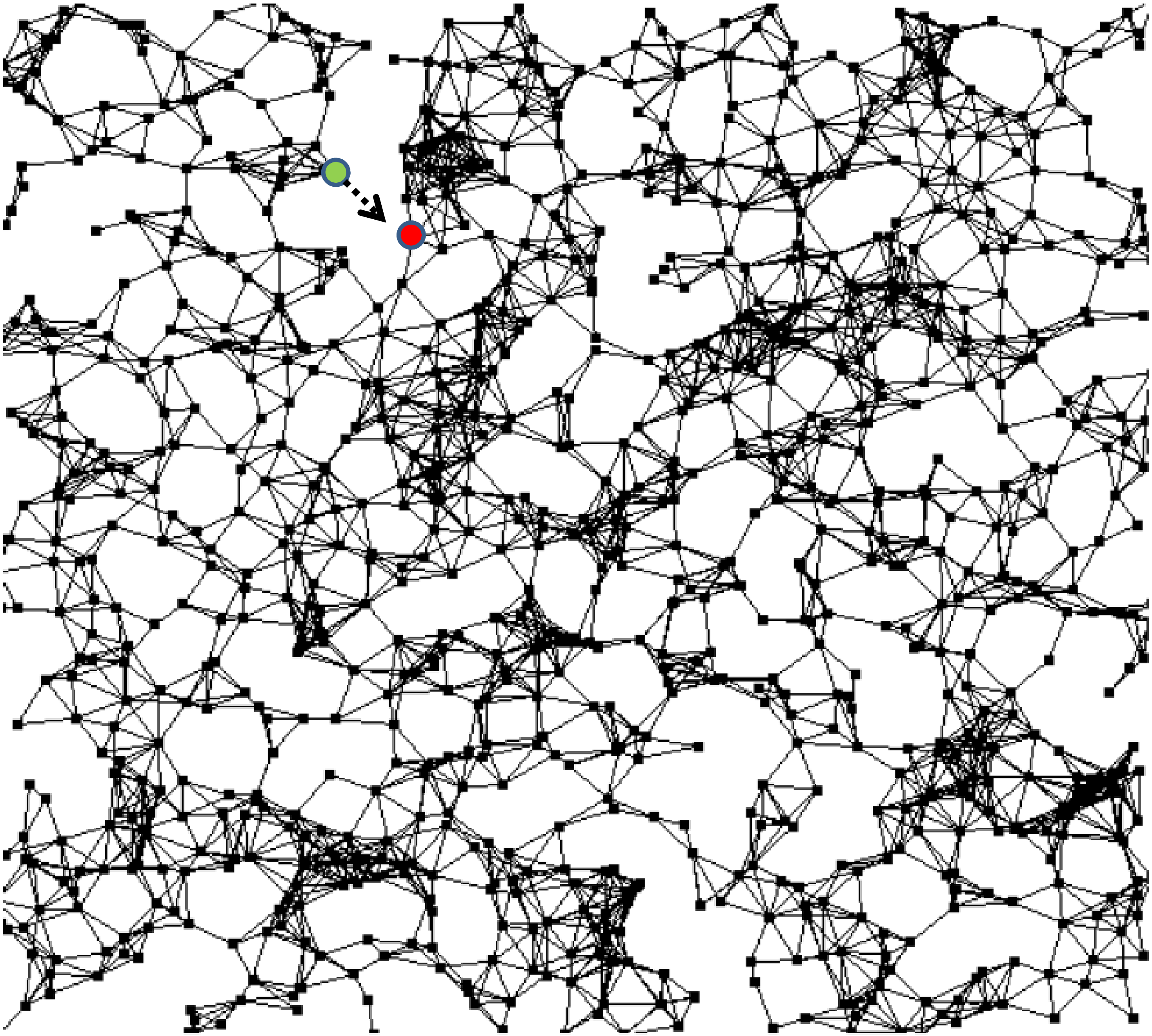
How much info should a node know about the network?

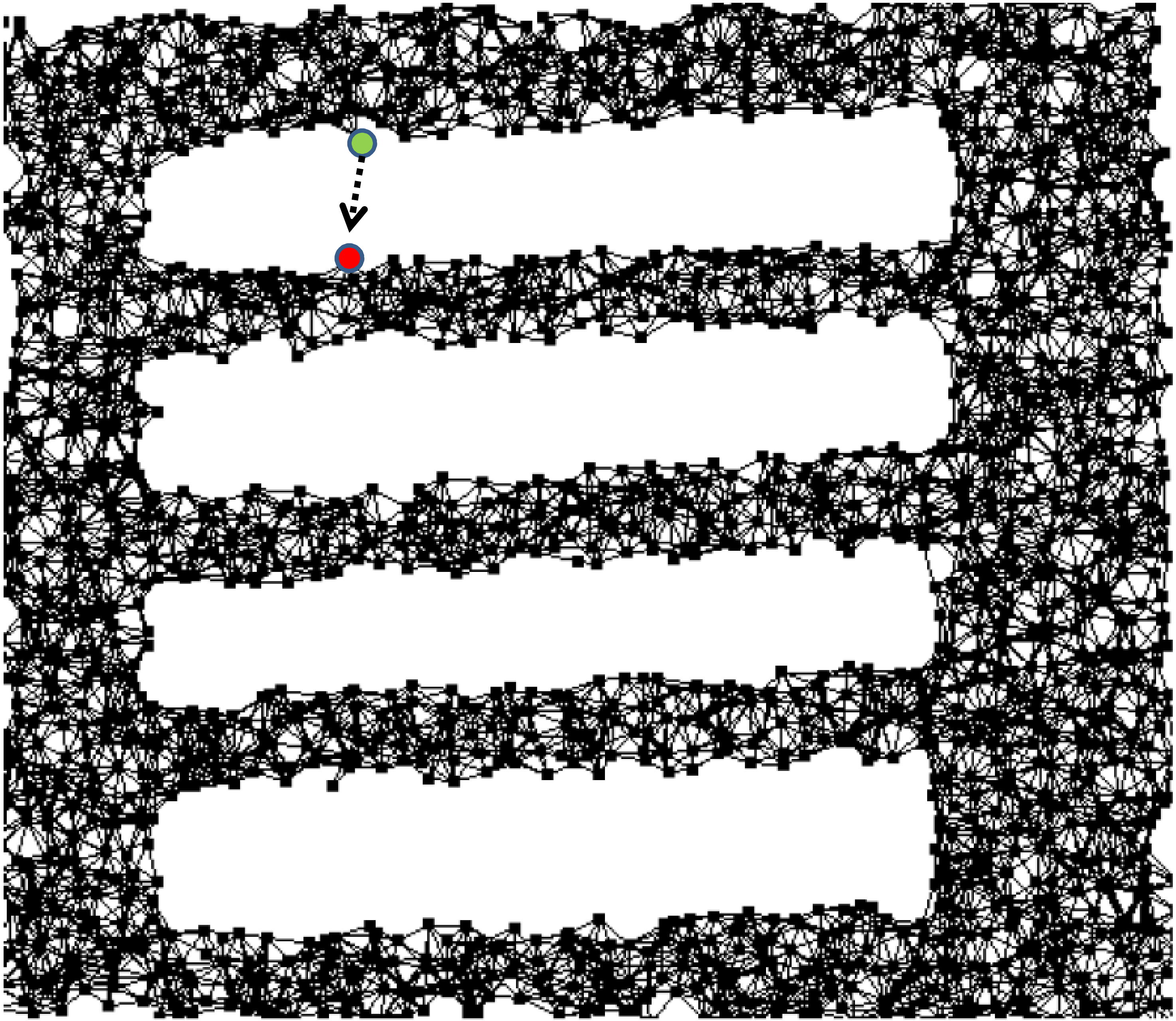
- Each node knows the entire network
  - Size of O(n), not scalable
- Each node only knows its local neighbors
  - Difficult to achieve global objectives
- Fractional cascaded information: more knowledge of nearby nodes, less information of faraway nodes.
  - O(log n) size information
  - Support near optimal routing schemes.

Problem I: routing

- Find a near shortest path from s to t.
- Suppose each node knows the location of itself, its neighbors and the destination.
- Geographical greedy forwarding: send to a neighbor closer to the destination.

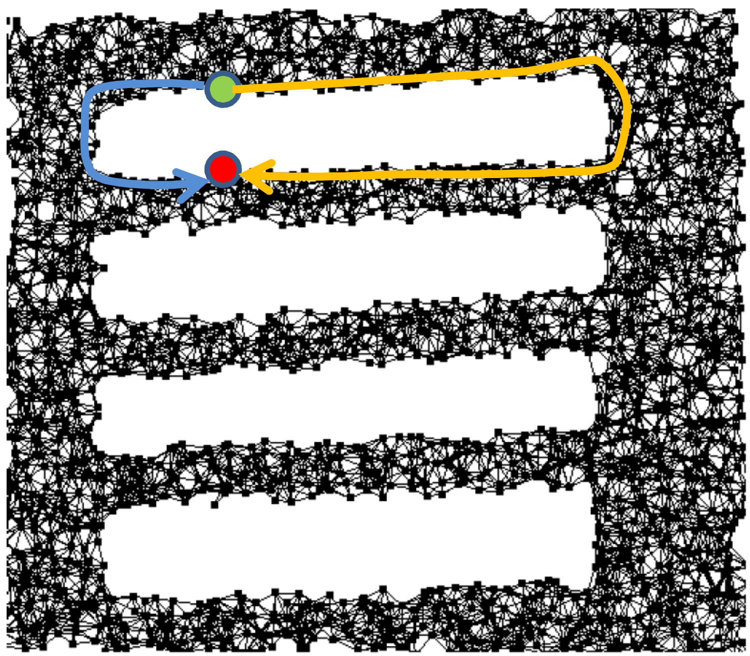






Routing local minimum

- A lot of literature on "how to get out of the local minimum."
  - Most of them do not guarantee path quality.



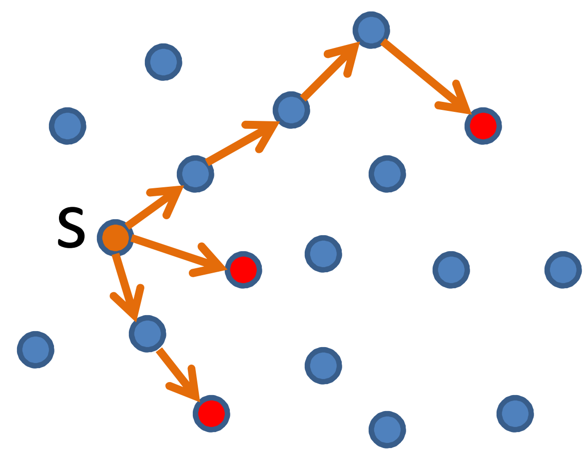
With only local information it is difficult to tell which path is shorter.

Routing local minimum

- The geographical distance |st| is not an accurate measure of the graph hop count distance σ(s, t).
- Our problem: given an approximate distance oracle, build routing tables s.t. some greedy method achieves 1+ε routing.
- Approach: each node stores paths to selected other nodes, called long links.
- Challenge: what long links to choose?

Build long links

- Each node build "long links" to all other nodes.
  - Achieves shortest path routing
  - Routing table size = Θ(n).
- Goal: select a few long links
  - Achieves 1+ε routing.
  - Routing table size is o(n).



What is next?

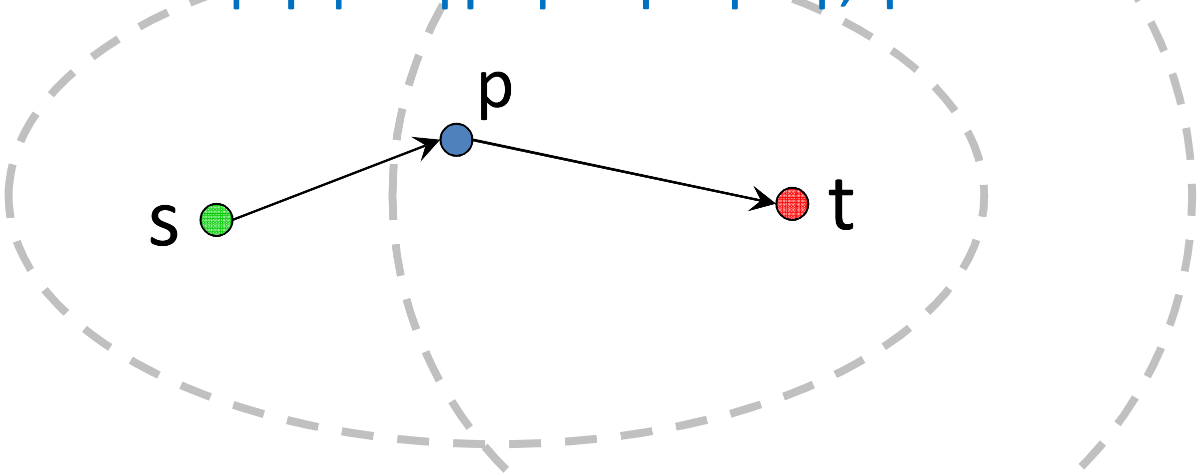
- I’ll first explain a local algorithm for routing in the plane.
  - With Euclidean coordinates, how to route to a destination?
- Then extend to the case of sensor networks when
  - The Euclidean distance only approximates the (unknown) hop count distance.

An easier case: routing in the plane

- Choose an intermediate node towards destination t
  - p should be closer to t.

    $|pt| \leq \beta \cdot |st|, \beta \leq 1.$
  - p should be near the shortest path.

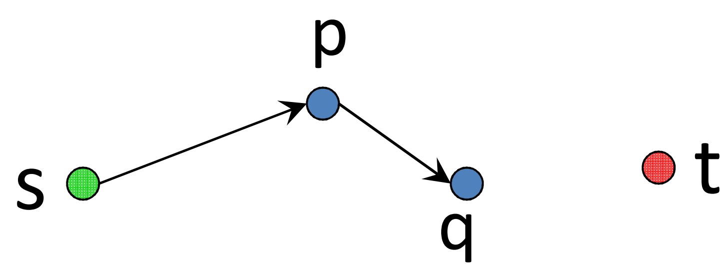
    $|sp| + |pt| \leq \gamma \cdot |st|, \gamma \geq 1.$



Near shortest path routing

- Recursively, we get 1+ε path:

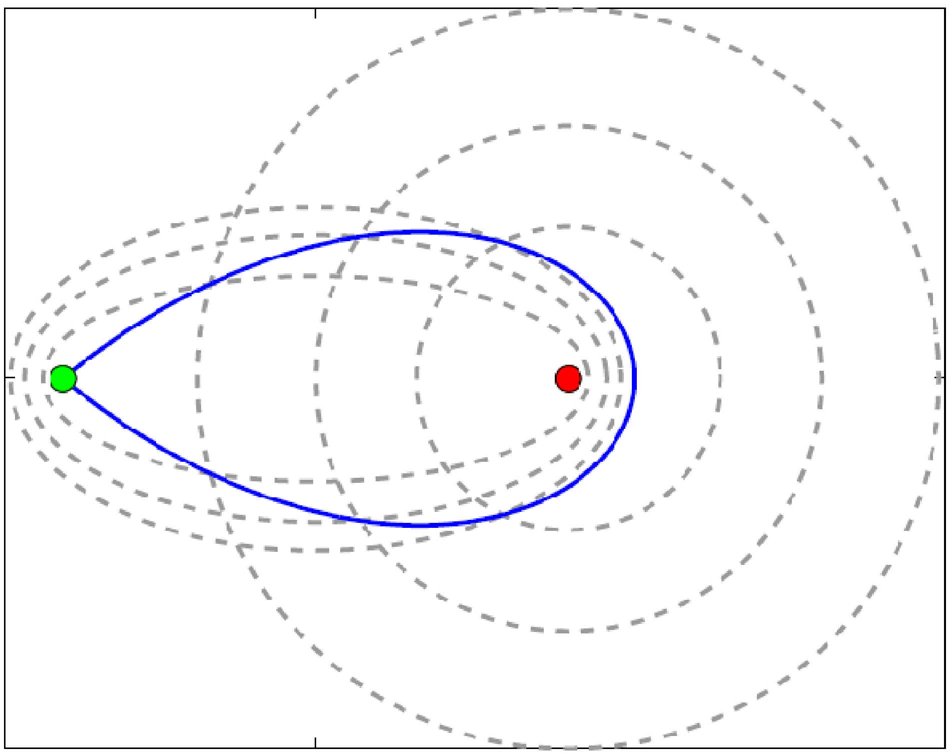
$$P(s, t) \leq (1+\varepsilon) \cdot |st|, \text{ if } (\gamma-1)/(1-\beta) \leq \varepsilon$$



- Only requirement: choose the next hop with the forwarding region.
  - $|pt| \leq \beta \cdot |st|$, $\beta \leq 1$.
  - $|sp| + |pt| \leq \gamma \cdot |st|$, $\gamma \geq 1$.

Forwarding region

- Near shortest path routing, if the next hop is within the forwarding region.

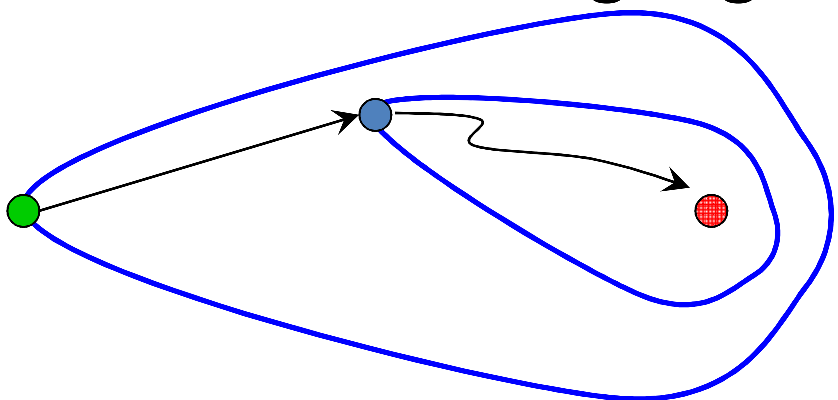


Boundary is defined by the intersection of
a ball: $|pt| \leq \beta |st|$ and
an ellipse: $|sp| + |pt| \leq \gamma |st|$

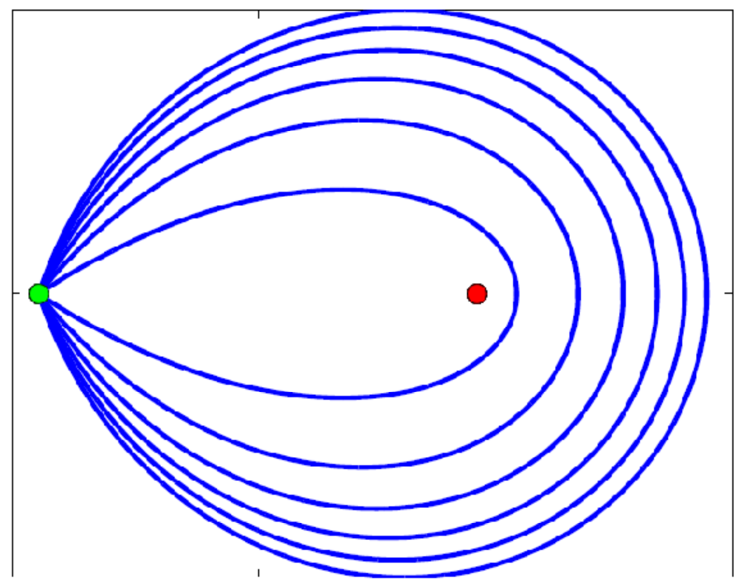
Local routing algorithm achieving a global objective.

Forwarding region properties

- The shape of the forwarding region is scale invariant.



- The larger ε, the fatter.



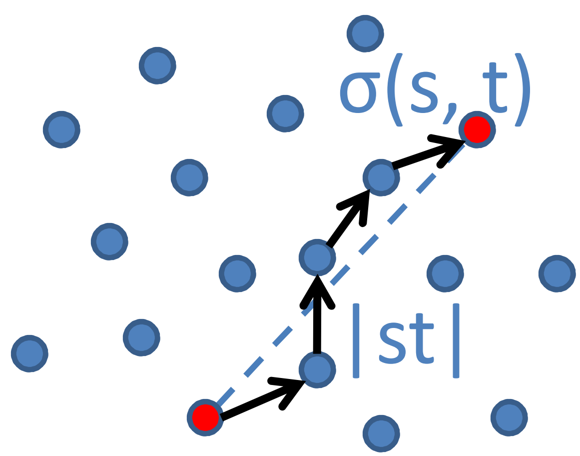
In the case of sensor networks

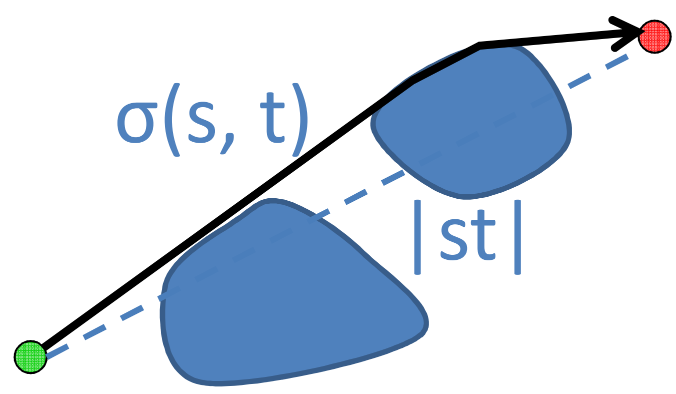
- Define forwarding region in the graph setting.
  - Replace Euclidean distance $|\cdot|$ by graph distance σ
  - Ball: $\sigma(p, t) \leq \beta \cdot \sigma(s, t)$, $\beta \leq 1$.
  - Ellipse: $\sigma(s, p) + \sigma(p, t) \leq \gamma \cdot \sigma(s, t)$, $\gamma \geq 1$.
- Problem: graph distance σ is unknown.
  - Approximated by Euclidean distances.
  - Approximated by landmark-based distances.

[Kleinberg, Slivkins and Wexler, FOCS 04]

Euclidean distance = approximate distance oracle

- Assumption: $\delta_1|st| \leq \sigma(s, t) \leq \delta_2|st|$, δ_1, δ_2 are two positive constants.
  - Local disturbances due to low sensor density
  - Global disturbances due to (fat) network holes

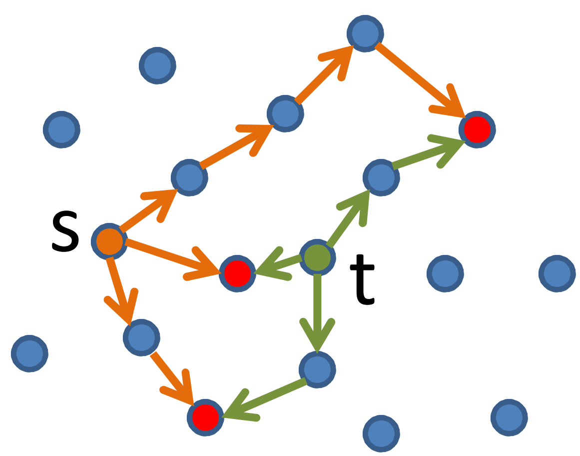




Landmark-based approximate distance oracle

- When Euclidean distances are not available
  - Each node measures hop counts to some landmarks L in the network
  - Use triangle inequality to bound σ (s, t).

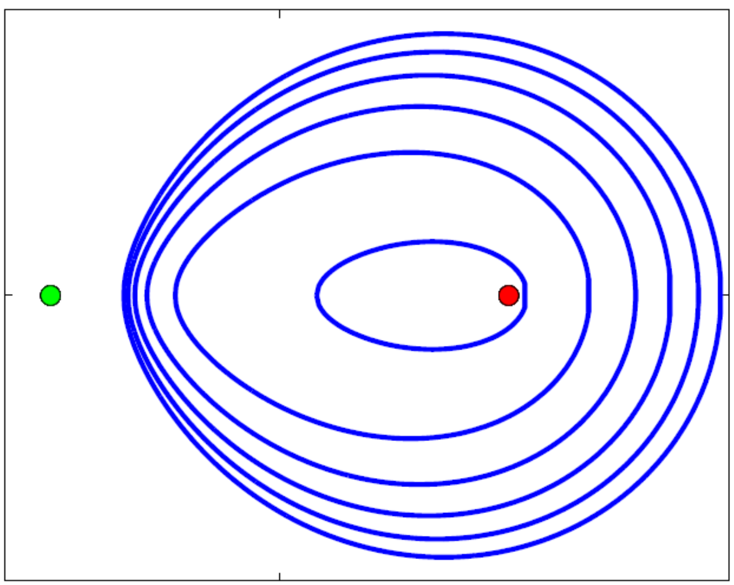
$\max_j |\sigma(s, l_j) - \sigma(l_j, t)| \leq \sigma(s, t) \leq \min_j \sigma(s, l_j) + \sigma(l_j, t)$



Kleinberg et.al. [FOCS 04] proved that with O(logn) landmarks this gives 1+ε approximation for most pairs.

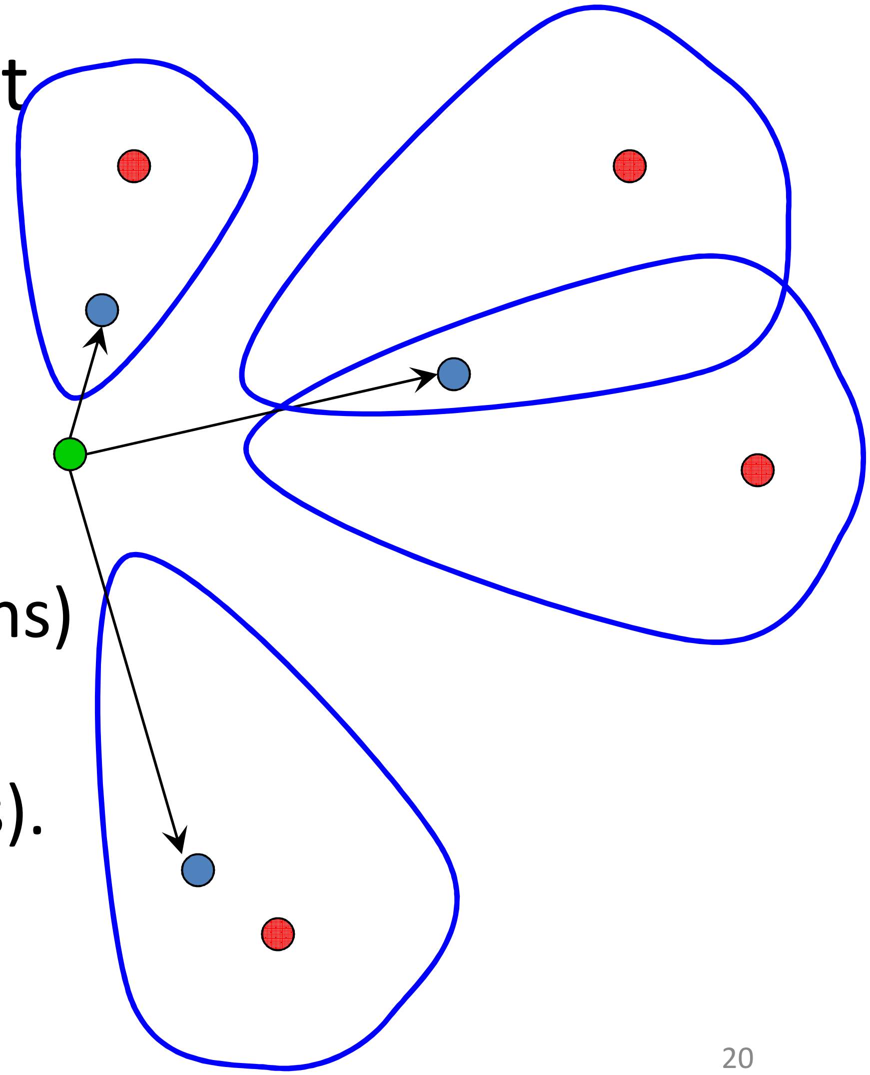
Forwarding region w/ approximate distance oracle

- Approximate distance $\delta_1|st| \leq \sigma(s, t) \leq \delta_2|st|$
  - Ball: $\delta_2|pt| \leq \beta \cdot \delta_1|st|$
  - Ellipse: $\delta_2|sp| + \delta_2|pt| \leq \gamma \cdot \delta_1|st|$



- Smaller.
- Does not include source s.

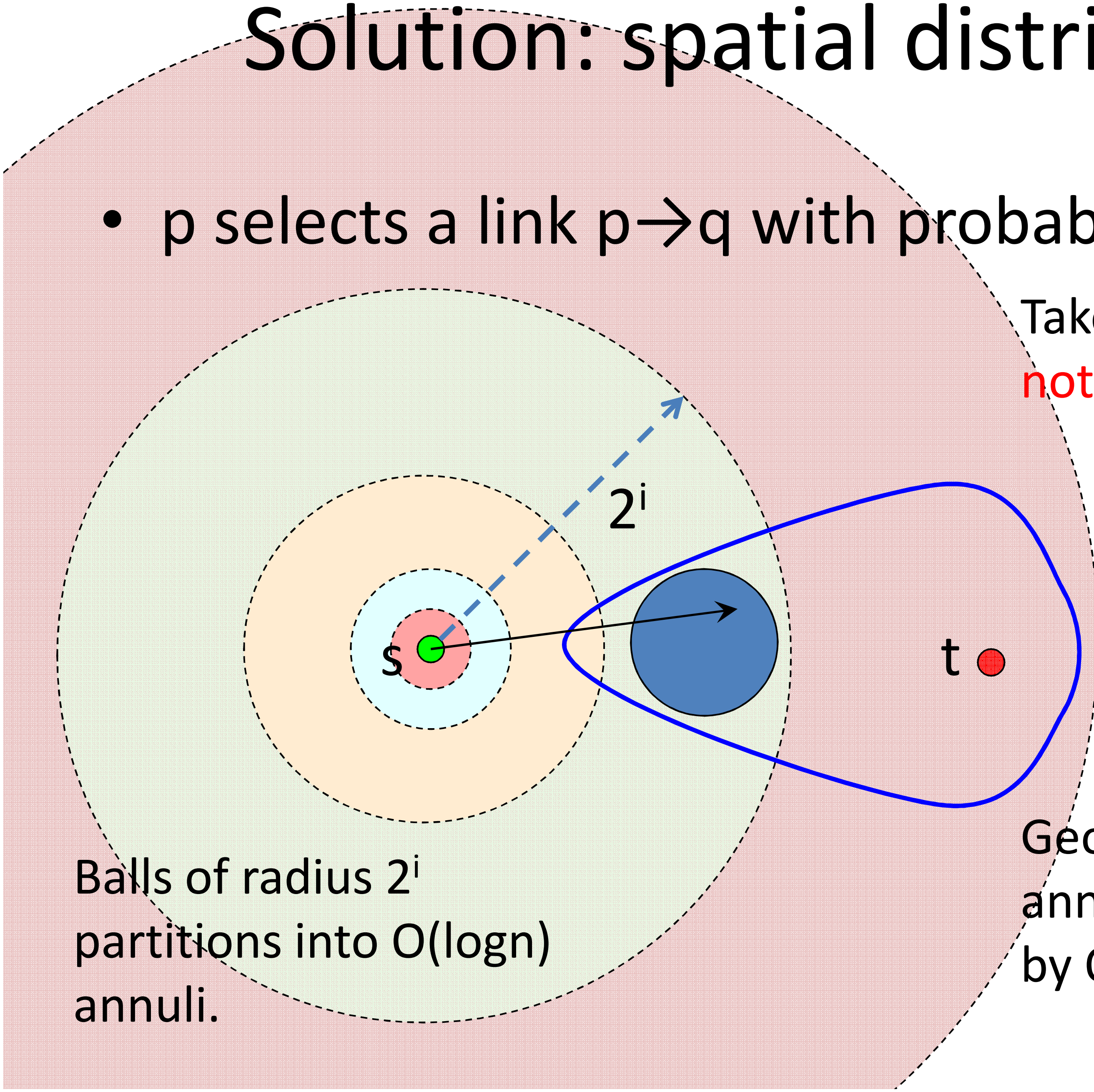
Select long links in forwarding regions



- Select long links such that every forwarding region contains one link.
- Intuition:
  - select more links nearby (smaller forwarding regions)
  - and fewer links faraway (larger forwarding regions).

Solution: spatial distribution

- p selects a link p→q with probability ~ $1/|pq|^2$



Take the largest annulus not including t.

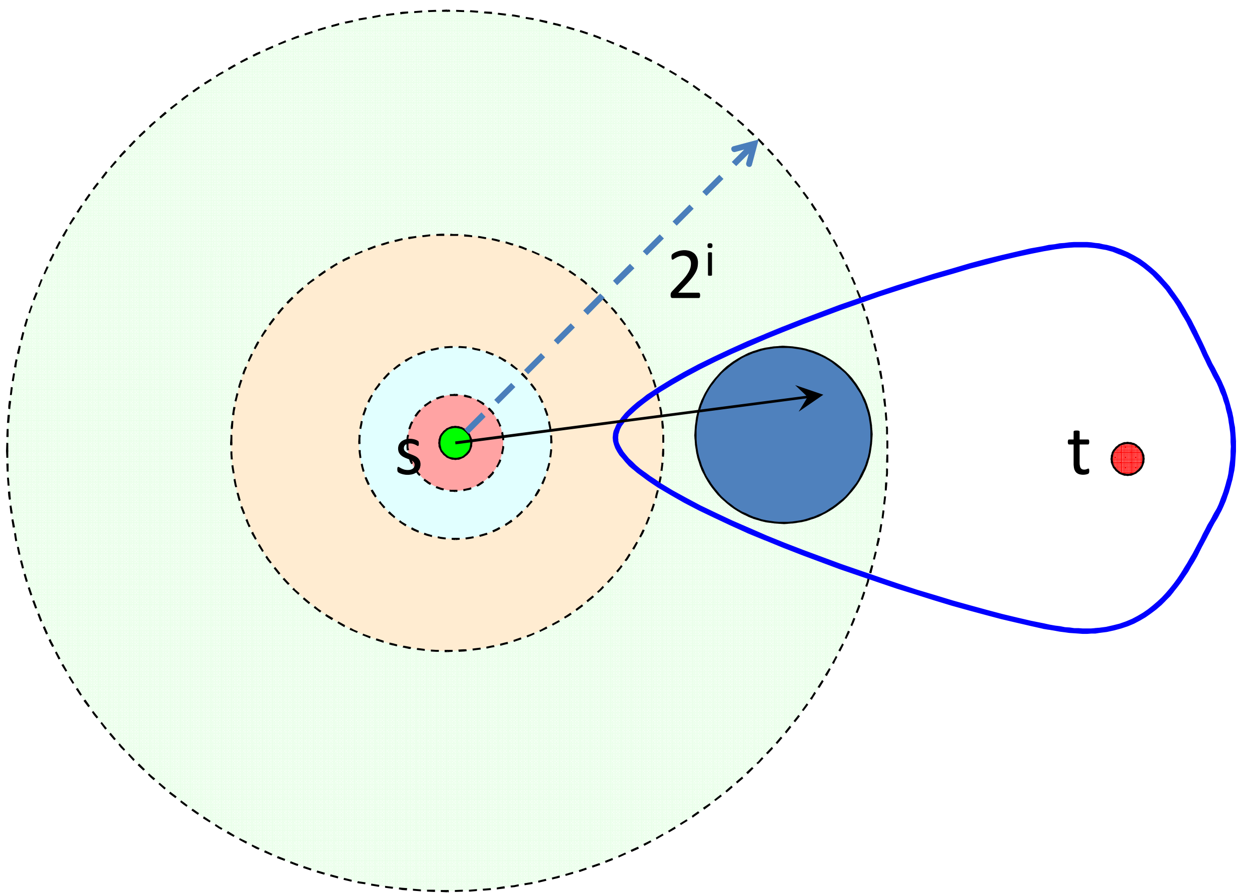
Inside this annulus there is a large ball B ~ Θ(|st|) inside the forwarding region.

Geometric packing: Each annulus can be covered by O(1) such balls.

Balls of radius 2^i partitions into O(logn) annuli.

Spatial distribution

- p selects a link p→q with probability ~ $1/|pq|^2$

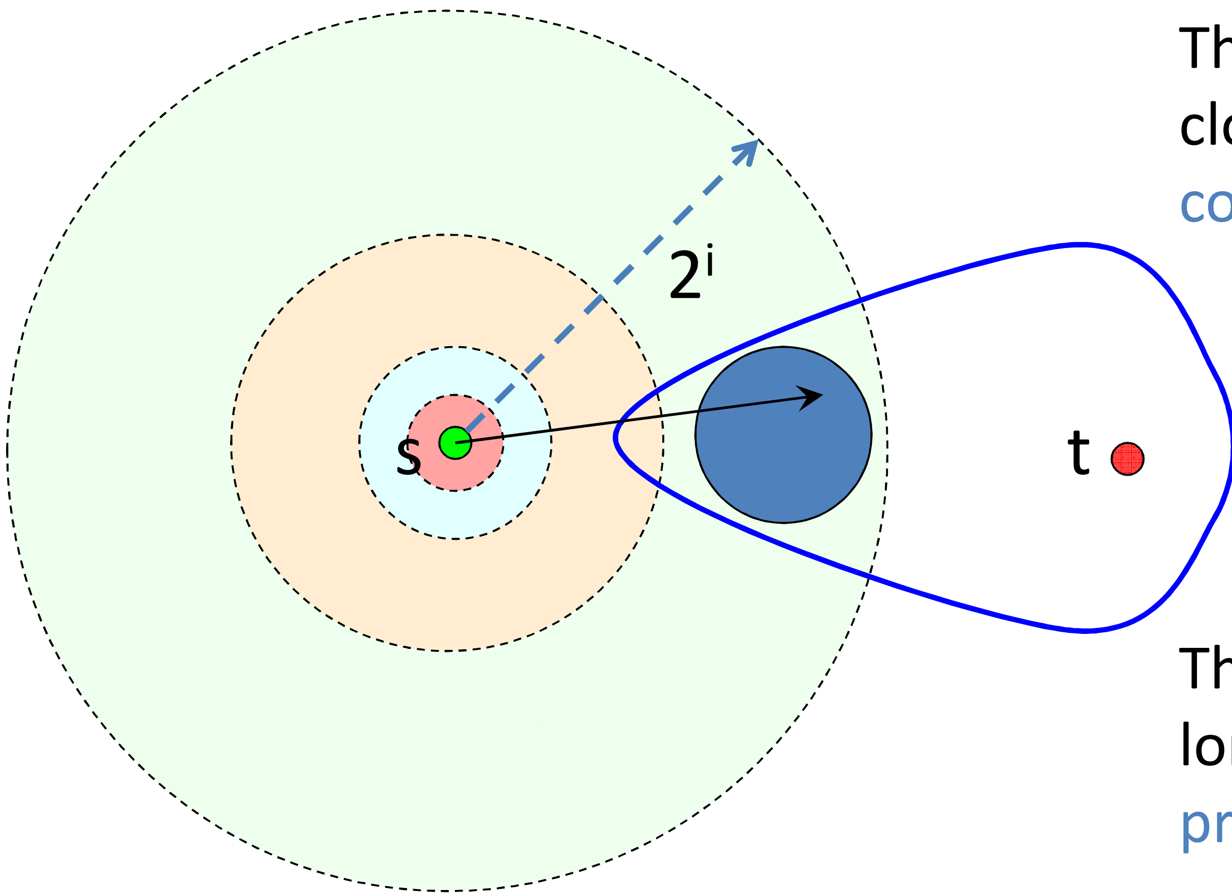


Each annulus has equal probability of getting a link. The ball B has prob ~ 1/logn of getting a link.

Balls and Bins: Select $O(\log^2 n)$ links such ball B has a long link with prob~$1-1/n^2$

Routing path

- Routing path: put the long links together.



The first long link gets closer to t by a constant fraction.

The path consists of O(logn) long links.

The path of O(logn) long links exists with prob ~ 1-1/n.

Graph setting

- Assumption: the graph has bounded growth rate ≈ sensors are deployed w/ uniform density.
- # nodes of r hops away from u = $\Theta(r)$
- # nodes within r hops from u = $\Theta(r^2)$
- Similar packing argument holds.

Routing scheme put together

- Preprocessing:
  - Each node selects $O(\log^2 n)$ long links
  - The paths realizing these long links are stored at the routing tables of the nodes on the paths.
  - Randomized scheme, no global coordination.
- Routing:
  - Recursively select a long link in the forwarding region.
  - Local routing algorithm.

Select long links

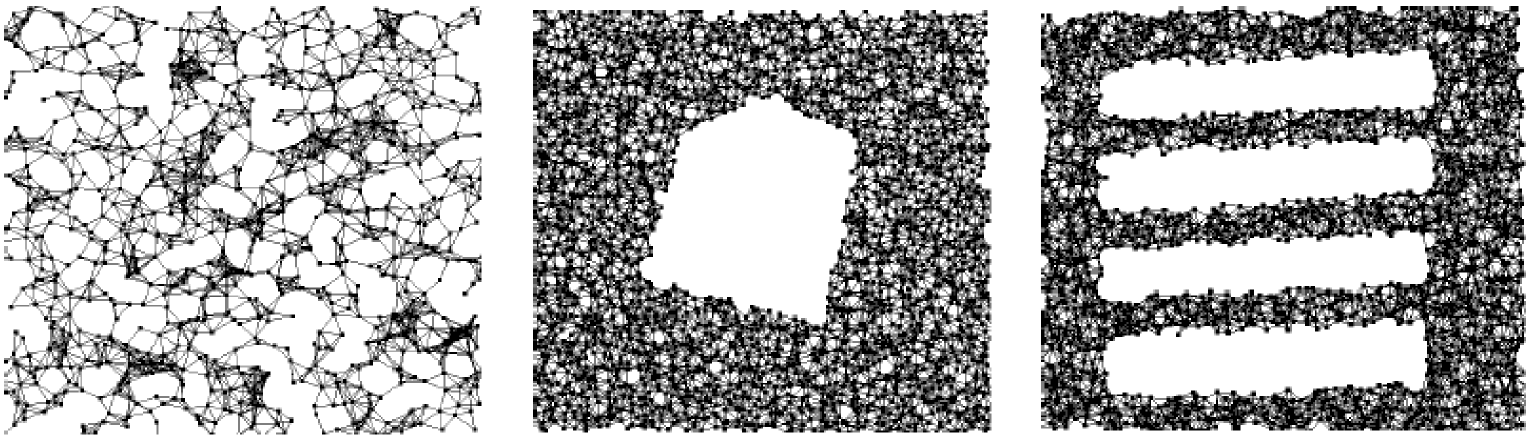
- Euclidean distance oracle
  - Sample a point with spatial distribution.
  - Round to the closest sensor node.
- Landmark-based distance oracle
  - $O(\log^2 n)$ random landmarks flood the network
  - Each node selects long links on the paths to these landmarks.

Construction of the routing tables

- Compute shortest paths
- Or, bootstrapping process:
  - All nodes first build the short “long links”
  - Use the short links to build longer “long links” (the same with standard routing operation)

Simulations

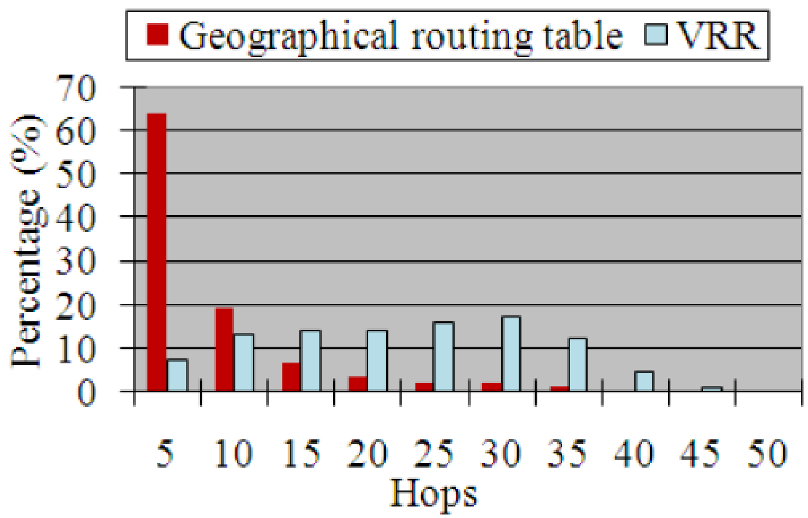
- Three topologies



- Compare with
  - Virtual Ring Routing (VRR): select long links uniformly randomly. [Caesar, et.al, SIGCOMM 06]
  - S4: stretch-3 landmark-based routing (first route to the landmark closest to t, when getting close, use routing table). [Mao, et.al, NSDI 07]

Our scheme v.s. VRR

- VRR: select randomly “long links”.
- We have smaller routing table, better stretch.



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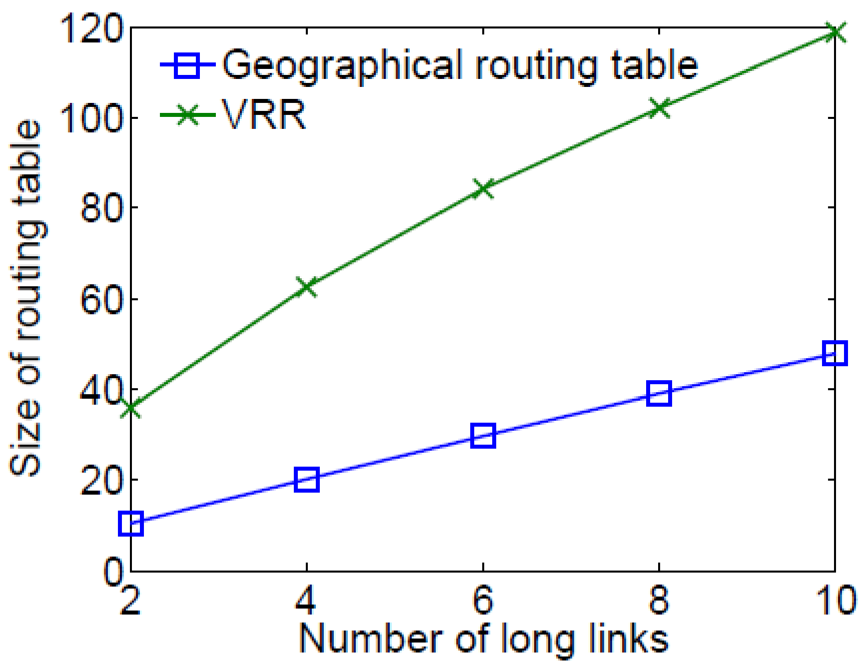
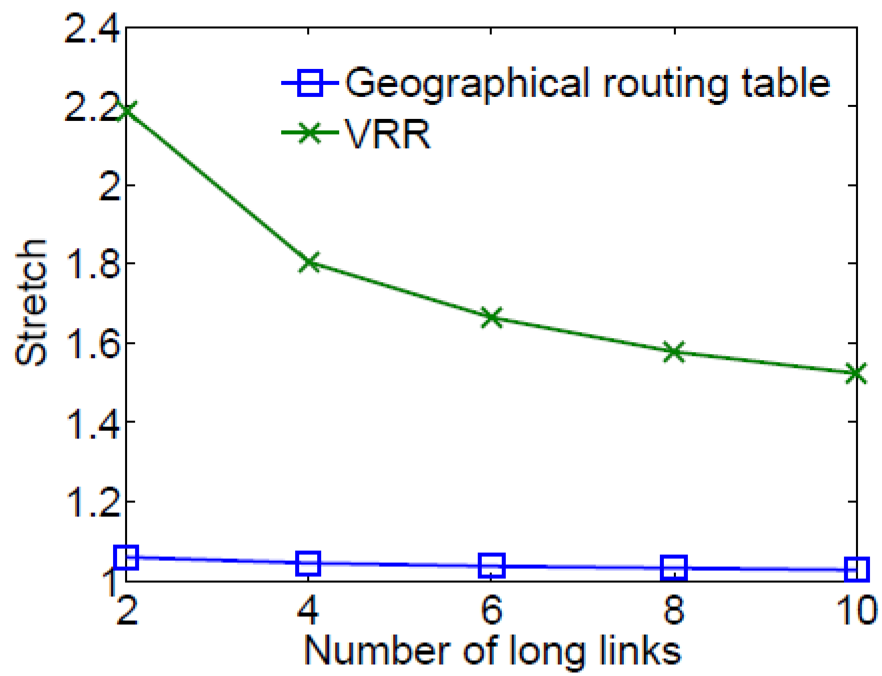


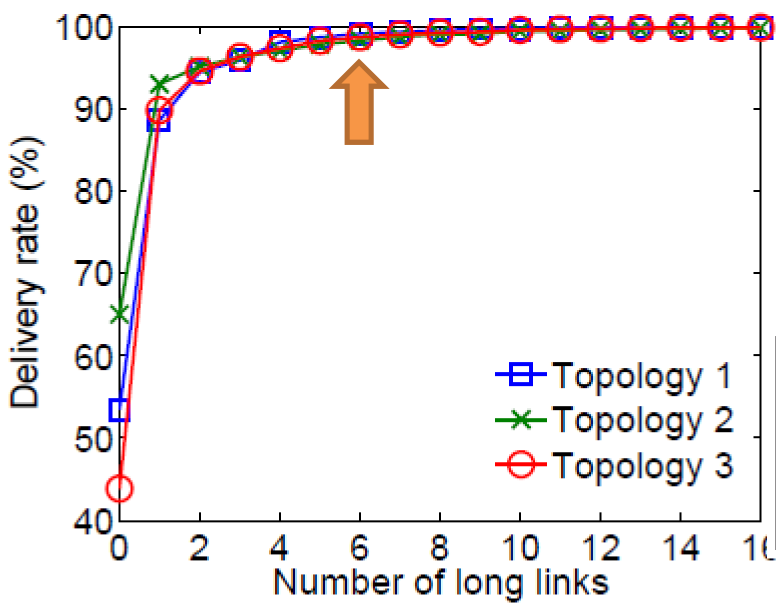
On average our "long links" are shorter.



Going "too far" hurts path stretch.

Routing stretch

- Comparable with S4 in stretch, with smaller routing table
- At a cost of small prob of delivery failure (i.e., need flooding)



Average stretch	Our scheme	S4	VRR
Topology 1	1.03	1.03	1.73
Topology 2	1.03	1.03	1.80
Topology 3	1.04	1.02	1.75

Size of routing table	Our scheme	S4	VRR
Topology 1	26.08	68.83	41.52
Topology 2	39.02	105.85	62.48
Topology 3	37.28	90.62	63.82

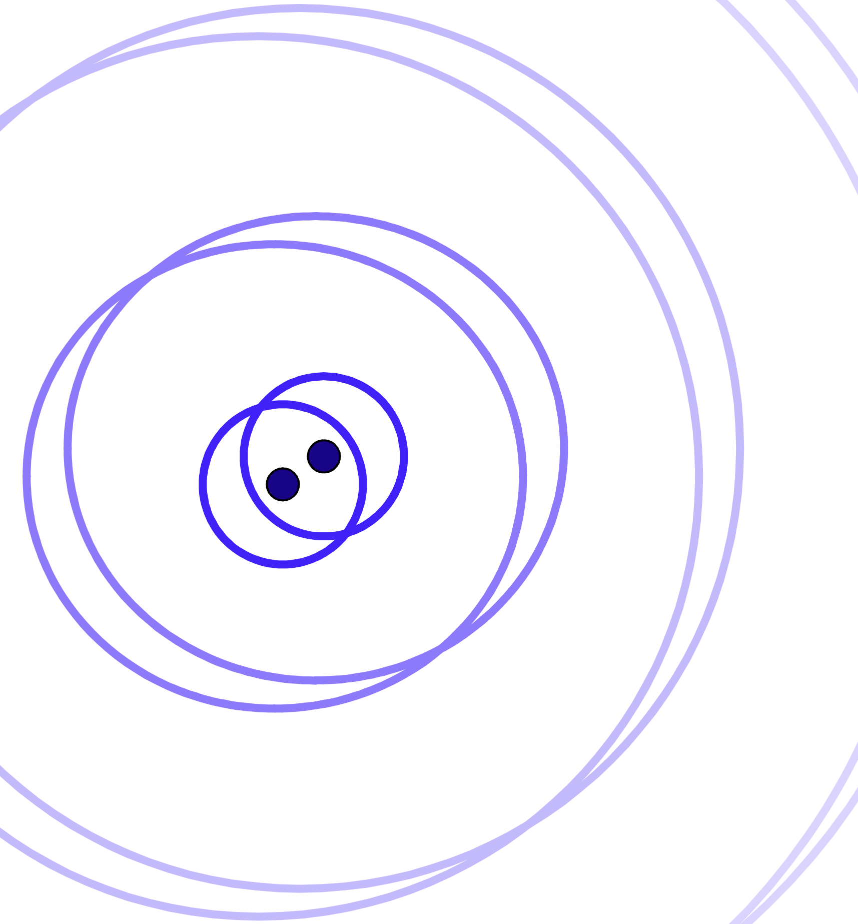
Summary of Part I

- Fractional cascaded information at each node to help routing.
- Strikes on scalability & locality while achieving globally optimal objectives.

- Part II: fractional cascaded information for data aggregation.

Multi-Resolution Representations

- Sensor nodes start with no knowledge of the global picture.
- Problem: Find aggregates (max, min, avg) for exponentially larger neighborhoods surrounding each node



Multi-resolutional data aggregation

- Each node keeps the aggregated information from all sensors within 2^i hops, i=1, 2, …, logn.
  - Locally relevant picture of the network
  - Data validation (is it an outlier?)
  - Support range queries
- How to construct it?
- Flooding works, with total $\Theta(n^2)$ messages.
- Our solution: use spatial gossip.

Gossip algorithms

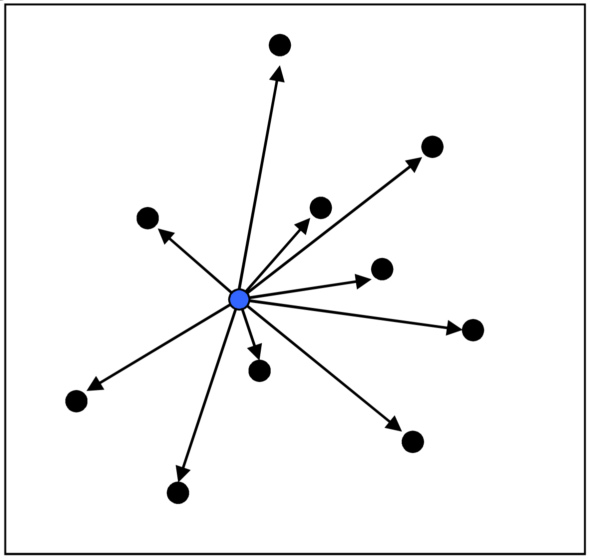
- In a round, each node:
  - Selects another node randomly
  - Exchanges information via multi-hop routing
  - Repeats every round

- Simple
- Distributed
- Robust to link dynamics, transmission errors

Types of Gossip

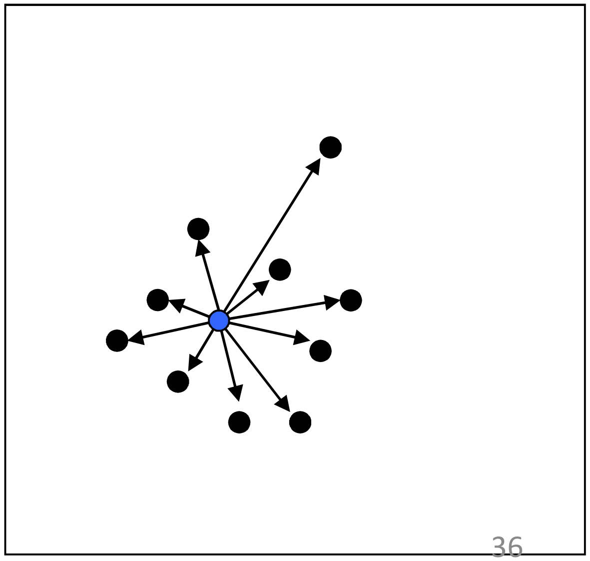
- Uniform/Geographic gossip
  - Select a node q uniformly randomly and gossip

[Dimakis, Sarwate, Wainwright, IPSN 06]



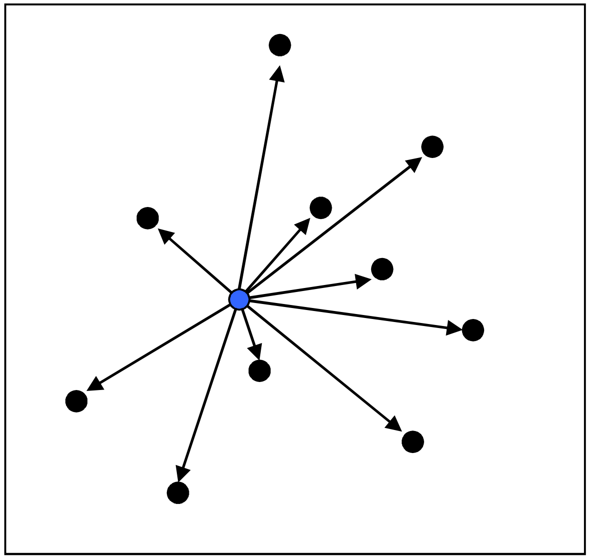
- Spatial Gossip
  - Select a node q at distance r with probability $1/r^{\alpha}$.

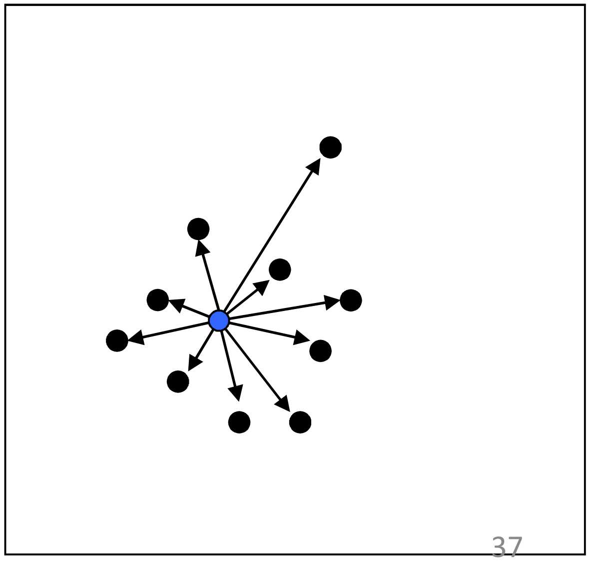
[Kempe, Kleinberg, Demers, STOC 01]



Communication Cost

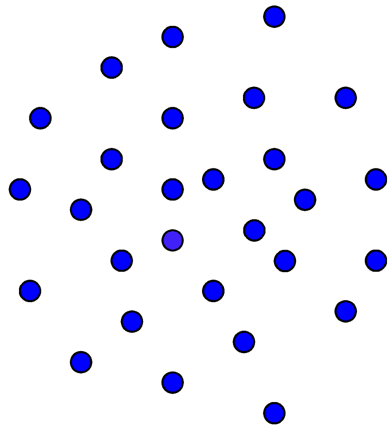
- Uniform/Geographic gossip
  - Cost per step ~ O(n√n)
  - # rounds for a message to reach everyone ~ O(logn)
- Spatial Gossip
  - Prob=$1/r^2$, cost per step ~O(n√n)
  - Prob=$1/r^3$, cost per step ~O(nlogn)
  - # rounds for a message to reach everyone ~ O(logn)





Spatial Gossip

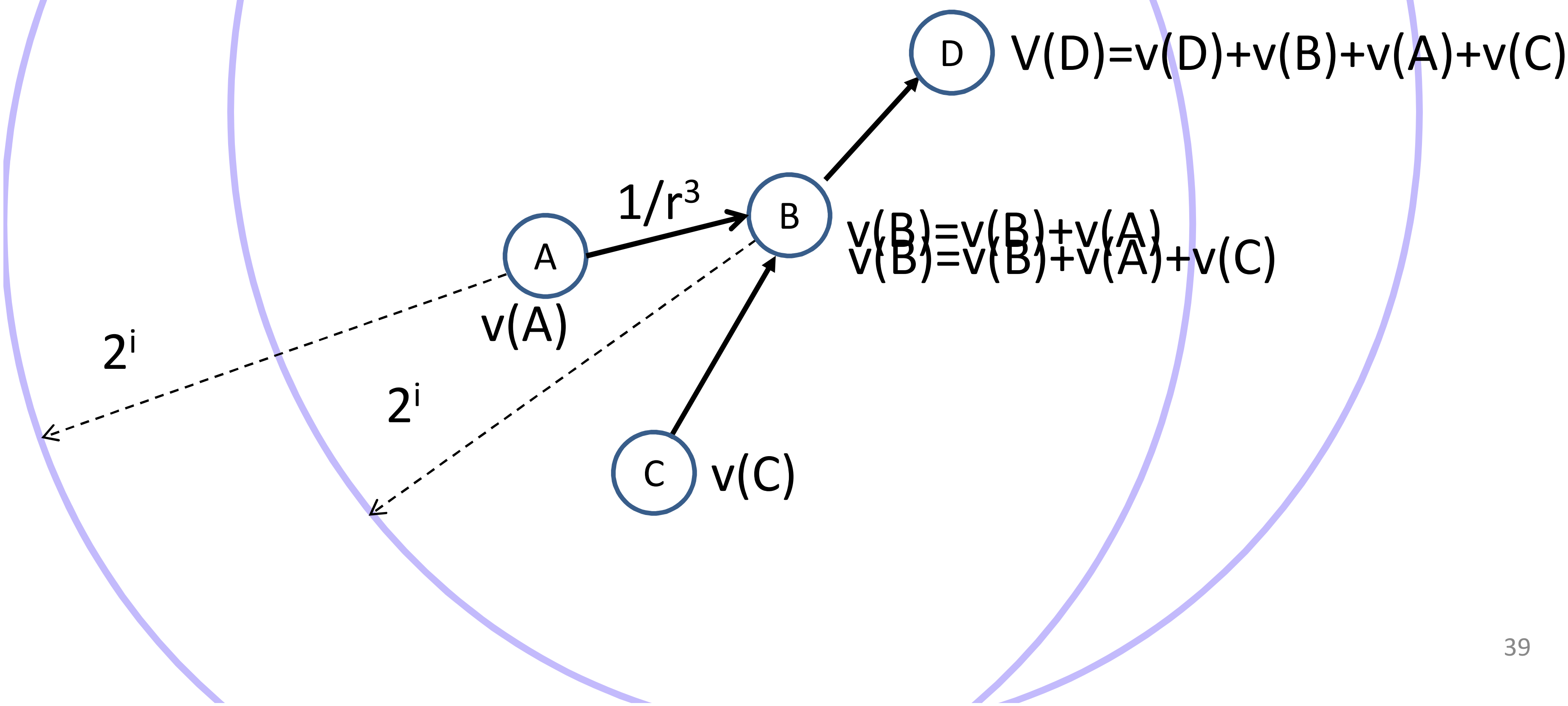
Expanding Neighborhood



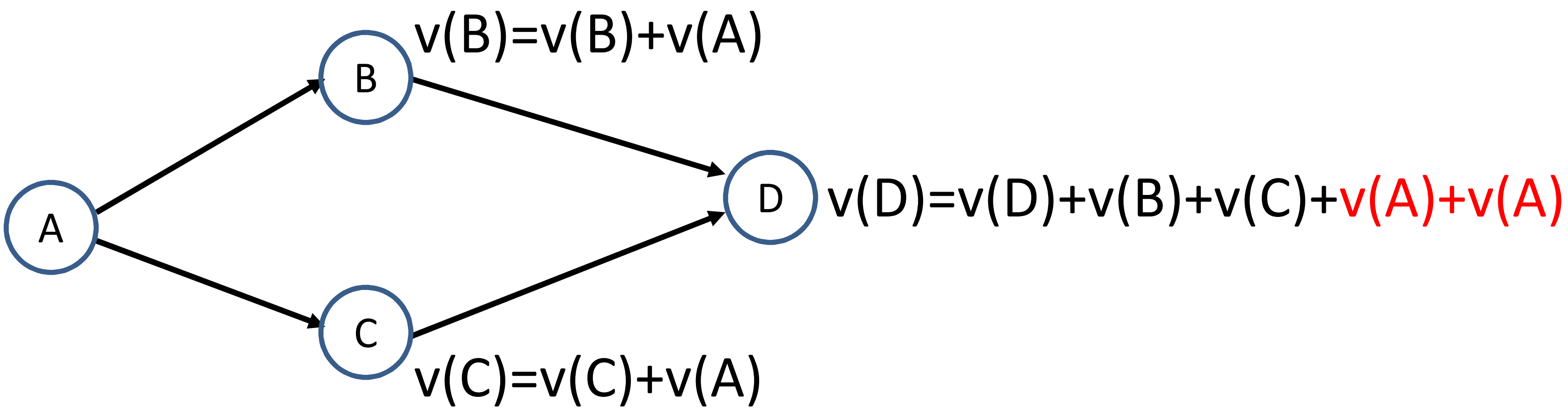
- Useful for multi-resolution aggregates

Using spatial gossip for aggregation

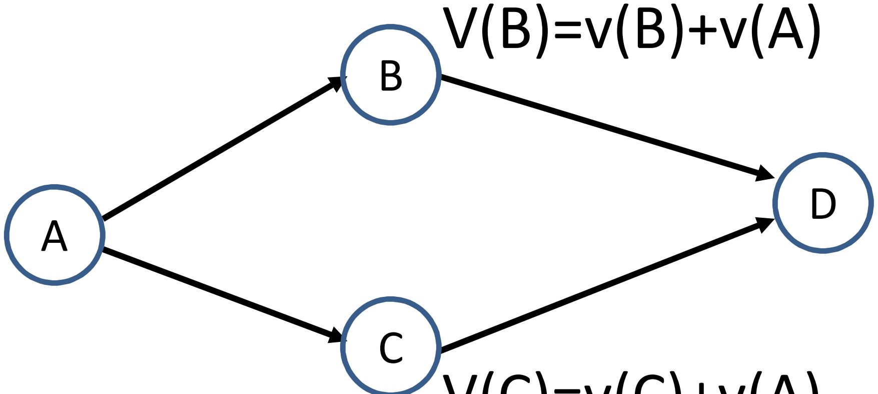
- Total logn phases
- In phase i we build aggregates for neighborhood of size 2^i around each node



Double counting?



Use Order and Duplicate Insensitive Aggregation



V(B)=v(B)+v(A)

V(C)=v(C)+v(A)

V(D)=v(D)+v(B)+v(C)+v(A)+v(A)
=v(D)+v(B)+v(C)+v(A)

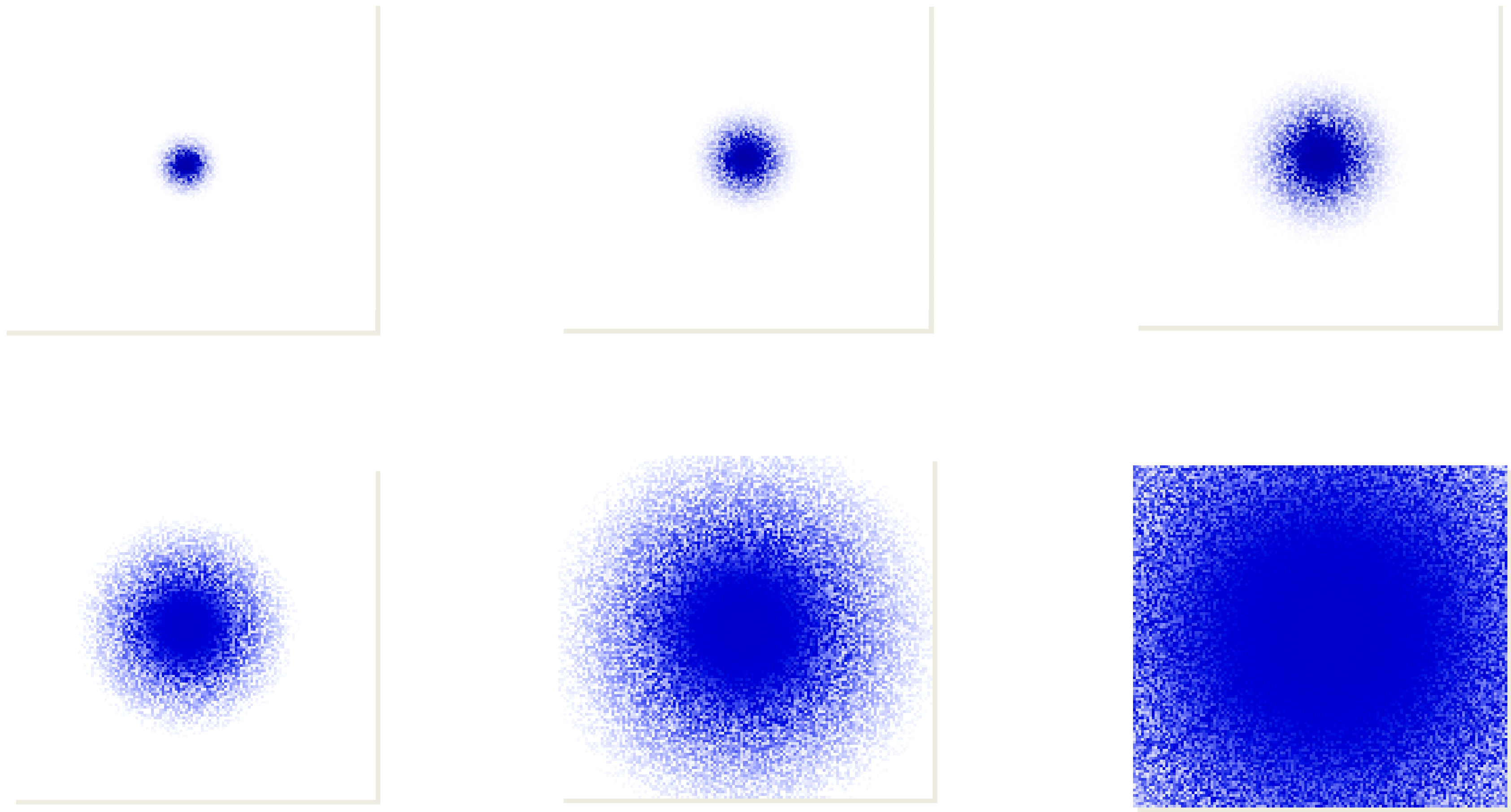
Order and Duplicate Insensitive Synopses

- The final aggregation does not change if a data value is aggregated multiple times.
- Min, Max are natural ODI aggregates
- ODI Synopses exist for other aggregates like sum, average, count..
  - Use probabilistic counting

Ref : Nath, Gibbons, Seshan, Anderson, SenSys 04

Considine, Kollios, Byers, ICDE 04

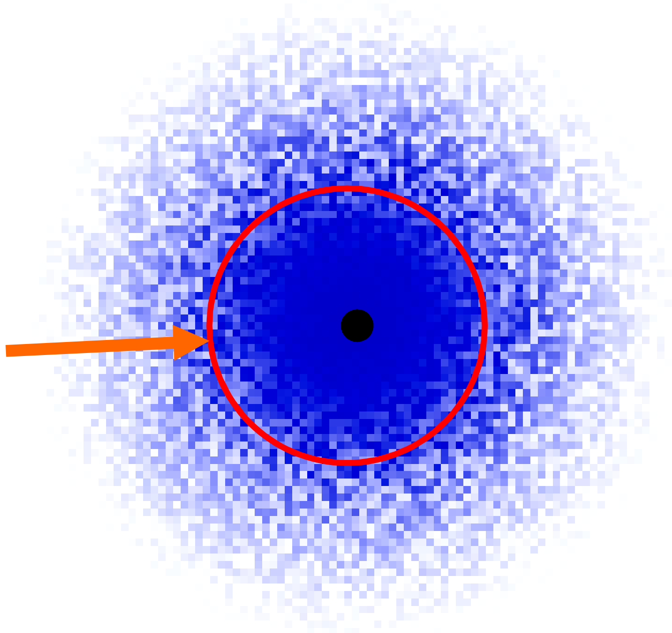
Data Distribution in Phases



Phases 1 to 6

Property 1 of Algorithm: Information Spreads Fast

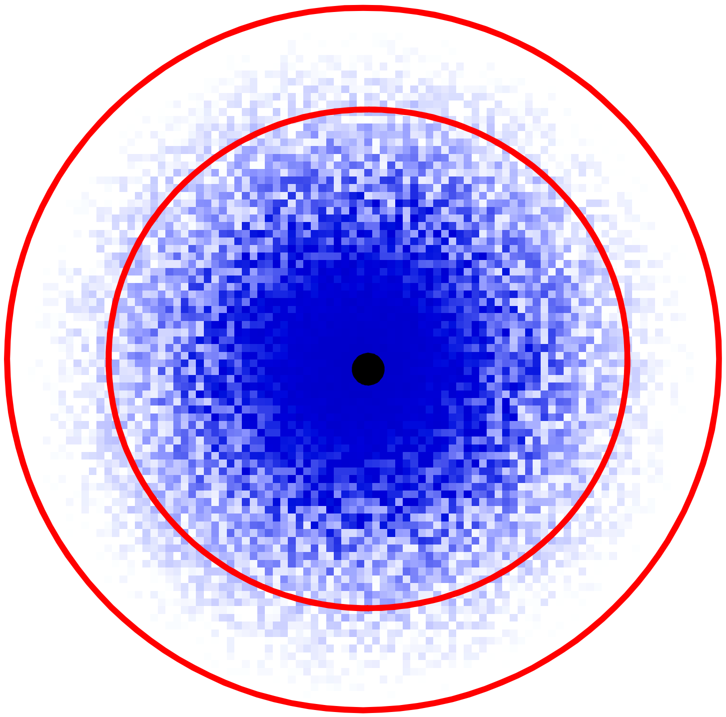
- In phase i, i=1, 2, …, logn, with $O(i^{3.4})$ rounds, information spreads to every node within 2^i distance, with high probability.



Ref : Kempe, Kelinberg, Demers STOC 01

Property 2: Information Does Not Spread Too Far

- In phase i, i=1, 2, …, logn, with $O(i^{3.4})$ rounds, information does not spread beyond distance $O(i^{3.4}2^i)$ for sure, and
- Does not spread beyond $O(i^{2.4}2^i)$ with high probability



Overall Efficiency

- $O(\log^{4.4} n)$ rounds.
- Total communication cost $O(n \log^{5.4} n)$.
- $O(\log n)$ aggregates per node simultaneously.

The Price of Accurate Computation

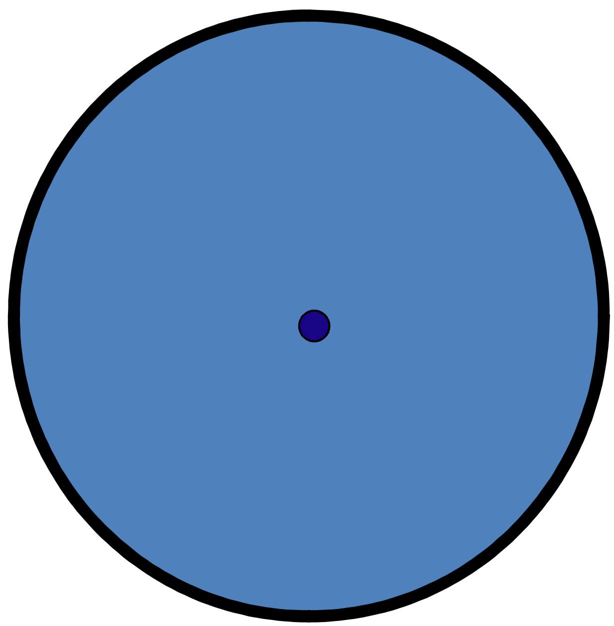
- Our aggregates are on fuzzy neighborhoods.
- Sharp multi-resolution aggregate computation requires a high communication cost of $\Omega(n\sqrt{n})$

Reduce the communication cost substantially by sacrificing a little on accuracy!

Range Queries

- User supplies a region, and asks for aggregate

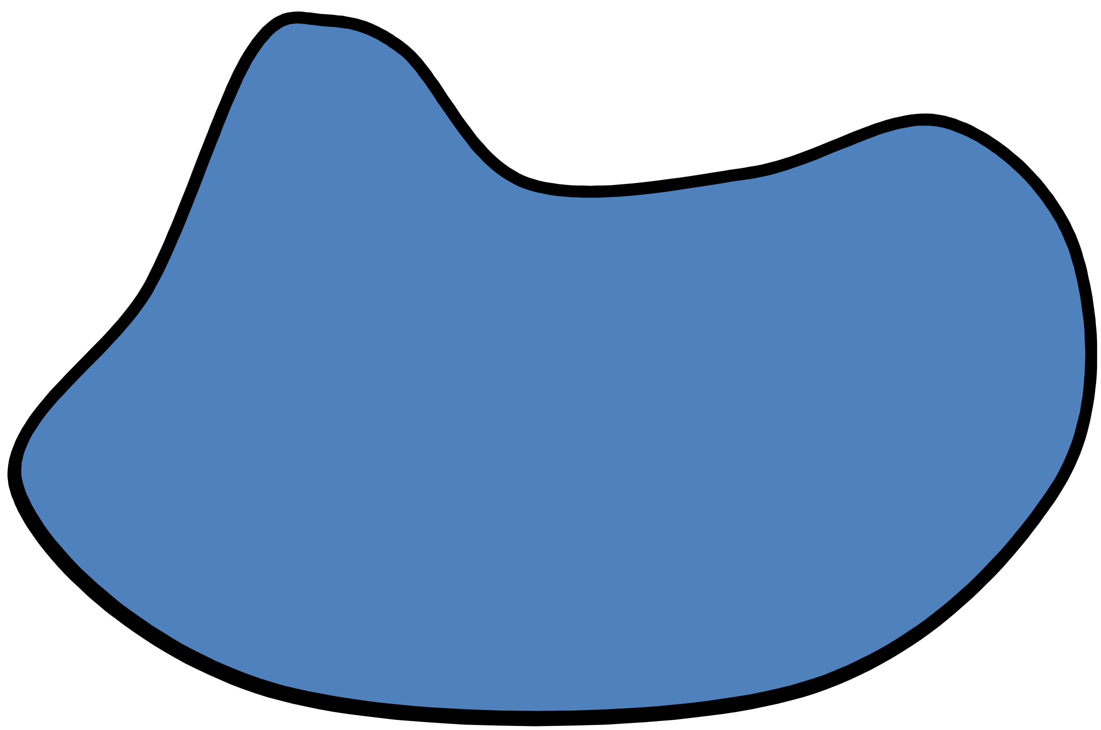
We pick a suitable node



And a suitable resolution level to cover the region

Range Queries

- Complex region
- Total communication cost ~ perimeter
- Cost of flooding ~ area of the region



Summary

- Information is most relevant in the spatial-temporal locale.
- Fractional cascading principle: diffuse information in a way cascaded with distances.
- Develop near optimal algorithms with low communication cost in a resource constrained network.

Questions or comments?

- Joint work with my students Rik Sarkar and Xianjin Zhu.
- Spatial distributions in routing table design for sensor networks, INFOCOM’09, mini-conference.
- Hierarchical spatial gossip for multi-resolution Representations in Sensor Networks, IPSN’07.
- Available at http://www.cs.sunysb.edu/~jgao