EECS 369

Introduction to Wireless Sensor Network

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Geography-Aware Routing Protocols

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Recall: Taxonomy of Routing Protocols for Wireless Sensor Networks

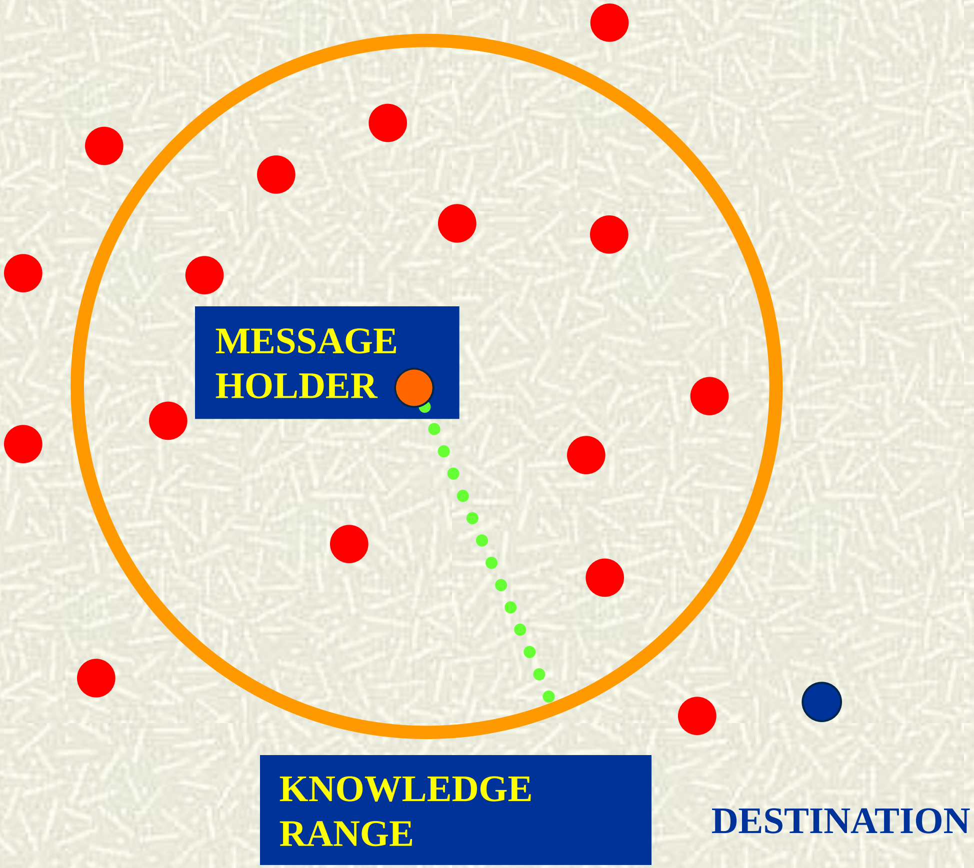
1. DATA CENTRIC PROTOCOLS
   e.g., Flooding, Gossiping, SPIN, Directed Diffusion,…
2. HIERARCHICAL PROTOCOLS
   e.g., LEACH, TEEN,…

3. =>LOCATION BASED (GEOGRAPHIC) PROTOCOLS
   1. GPSR
   2. TBF

      (see the corresponding papers)

   PLUS "Potpourri"…

Geographical Routing - Basics



Next Hop Selection

Given a DESTINATION, the node that is holding the message selects the next hop according to

1) Its own position

2) The position of the destination node

3) The position of its neighbors (nodes in the Knowledge Range)

DIFFERENT FORWARDING RULES ARE POSSIBLE!

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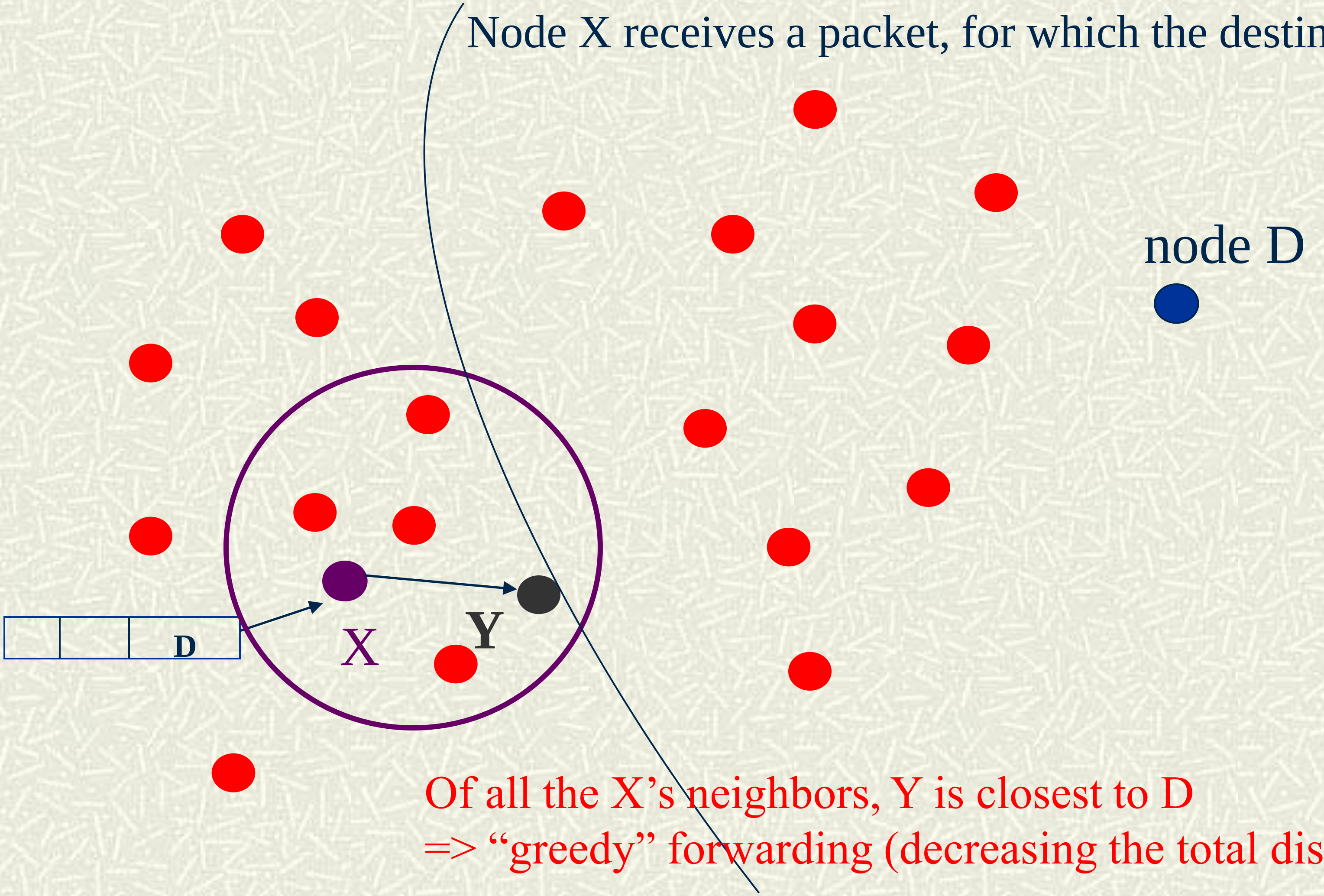
GPSR: Greedy Perimeter Stateless Routing

- **Key Assumptions:**
  - Nodes (routers) know their location

    (OUCH!) GPS, beacon, tri/multi-lateration…
  - (Roughly) Planar Topologies
  - Maybe: Registration/Lookup service mapping nodes to location
    - Sources can determine the addresses of their destinations and encode them as part of the packet(s).
  - Queries use the same "address-book"
    - (Implicit: Unit-disk graph model of communication range…)

GPSR - basics

Node X receives a packet, for which the destination is D



Of all the X's neighbors, Y is closest to D
=> "greedy" forwarding (decreasing the total distance)

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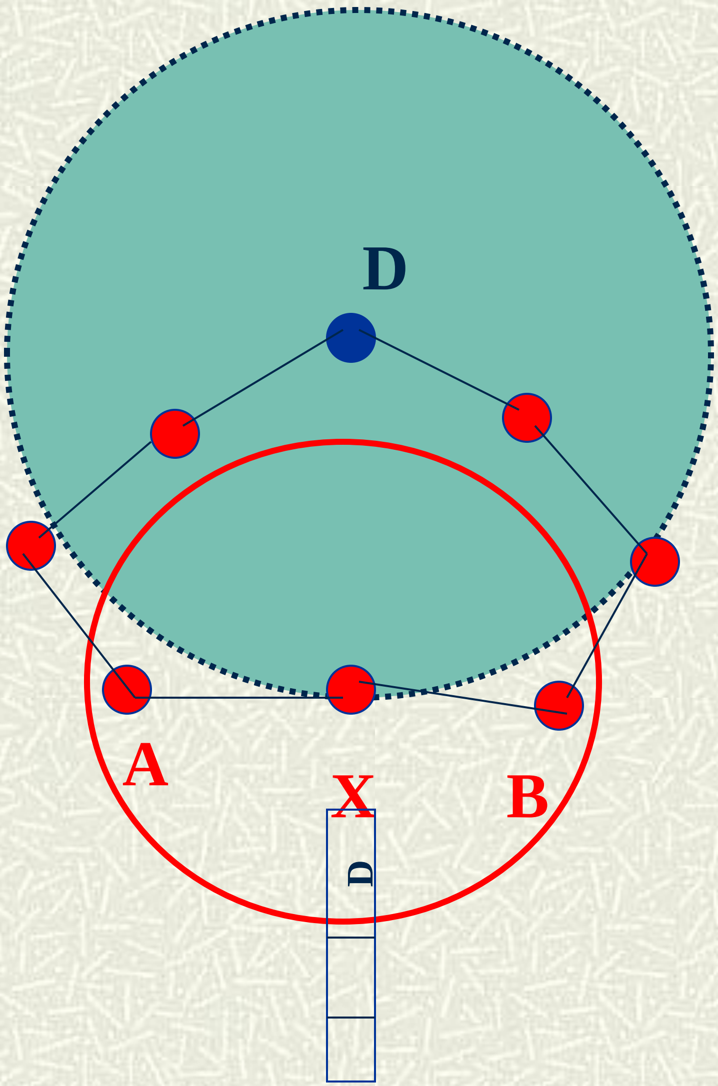
GPSR – basics

- Q: What if the neighborhood changes (e.g., nodes deplete their energy; new nodes enter the region; …)?
  - Periodically, each node transmits a beacon to the common, broadcast MAC address, containing (ID, location). Hence, the neighbors can update their data…
  - If the time during which a beacon has not been received from a given neighbor exceeds a pre-defined time-out interval, assume failure and delete it from neighborhood-table.
    - Two four-Bytes fields (float) for each of X and Y coordinates…
- NOTE: this is pro-active…
- To save on communication for beaconing, location info can be piggy-backed on the data packets
  - All?
  - Which ones?

BPSR – Problem(s) with the *"greedy"*…

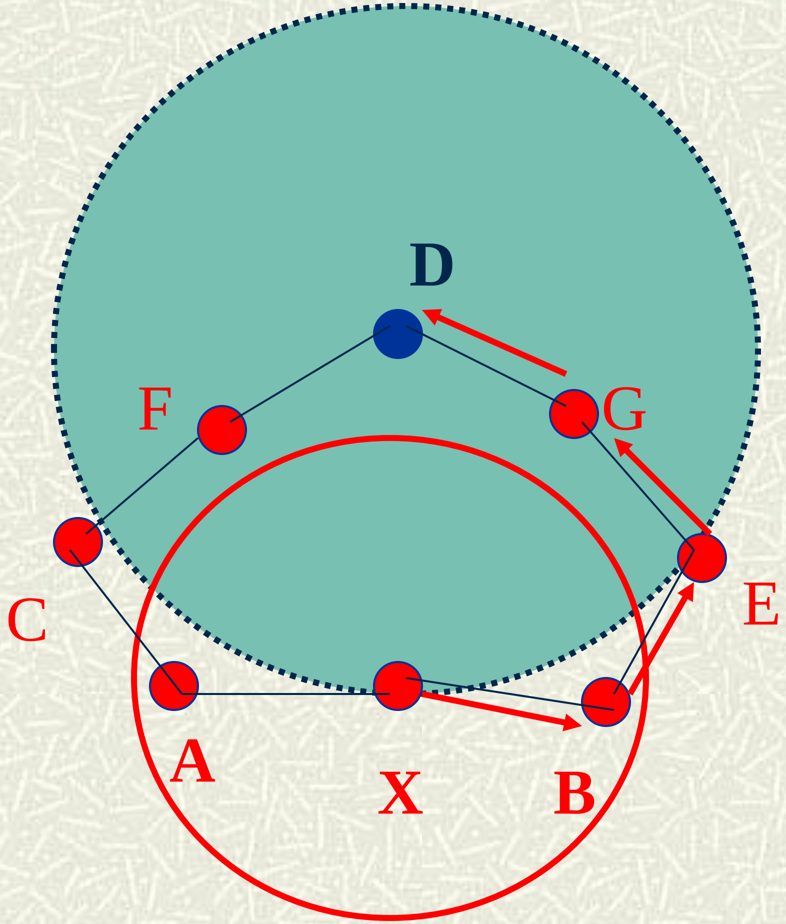
For the given network, assume that X receives a packet to be forwarded to the node D.



IF A & B are the only ones in Its communication range, since X Is closer to D than both of them ⇒the "pure" GPSR would NOT send the packet !!!

Hence, one type of problems are due to the, so called, **VOID regions**

GPSR – Problem(s) with the *"greedy"*…



Solution to ***voids:***

- Travel around the perimeter of the void, using as "road-segments" the edges between the nodes (view communication graph as a node)

-***Eventually/hopefully, get closer to the desired destination…***
(e.g., X->B->E->G->D)

OK, so this is kind'a graph-theoretic…
Ergo, it brings another problem: how
Are edges that are intersecting to be
treated (are they having an actual
vertex)

Solution: Enforce the ***PLANARITY…***

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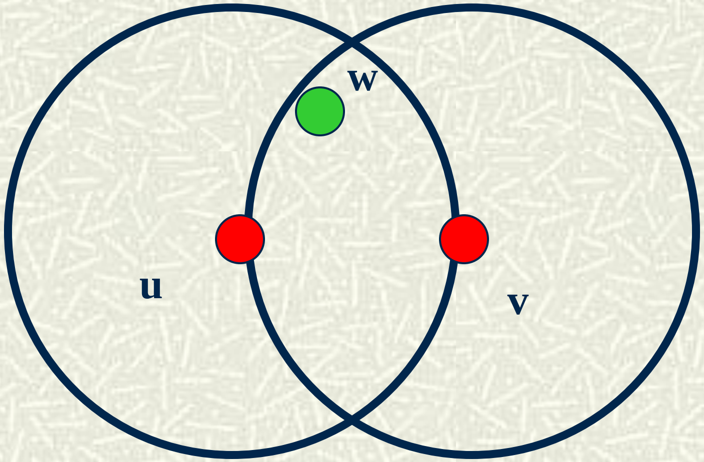
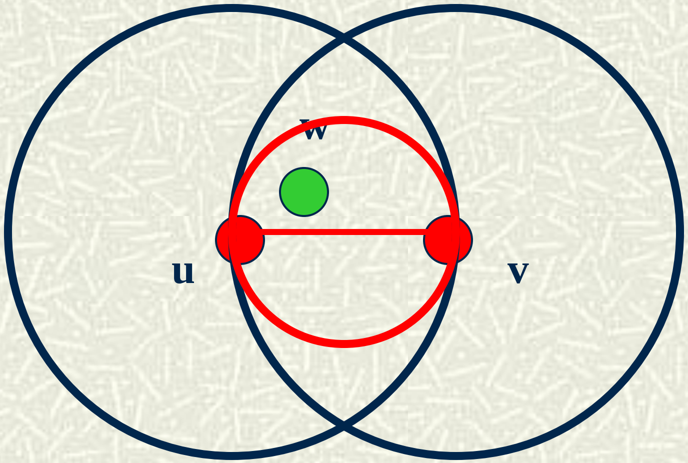
GPSR – Problem(s) with the *"greedy"*…

- Desideratum: reduce the number of "active" neighbors, while preserving the connectivity of the network as a whole.
  - This should be done in a manner to ensure min. amount of "links" to be traveled for whatever purpose needed…

- Two basic geometric techniques used for making a given graph planar, while ensuring that all the nodes that the connectivity is the same, with respect to the initial connectivity under the unit-disk model:
  - Relative Neighborhood Graph (RNG)
  - Gabriel Graph (GG)
    - (other methods, e.g., Yao graphs…)

GPSR – Planarization of Graphs:





GG:
An edge exists between u and v, if no other vertex is inside the circle whose diameter is uv

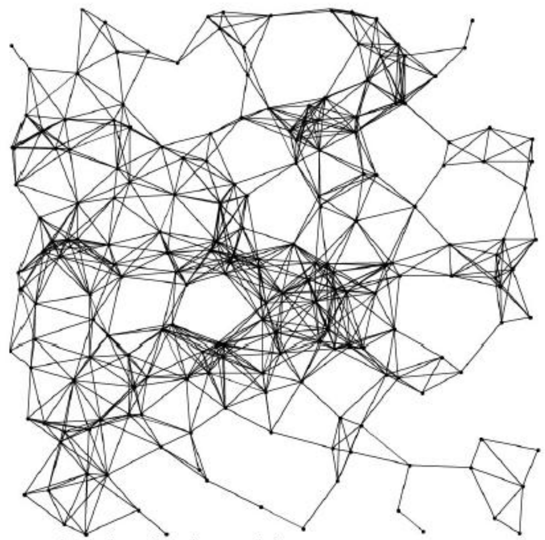
RNG:
An edge exists between u and v, if their distance is less than the max[(u,w),(v,w)] for any other such vertex w

e.g., no "witnesses" in the luna

e.g., no "witnesses" inside the circle

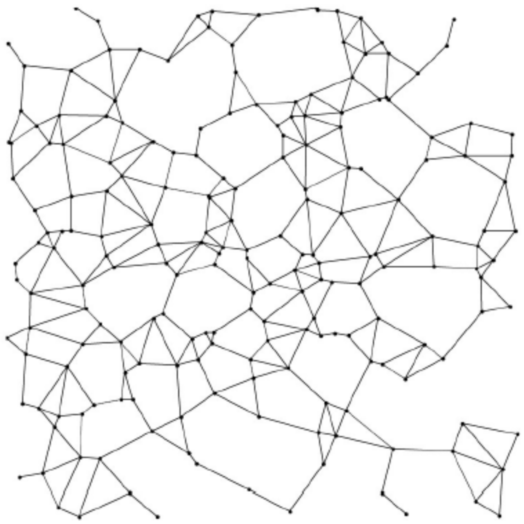
Clearly, GG more restrictive than RNG!!

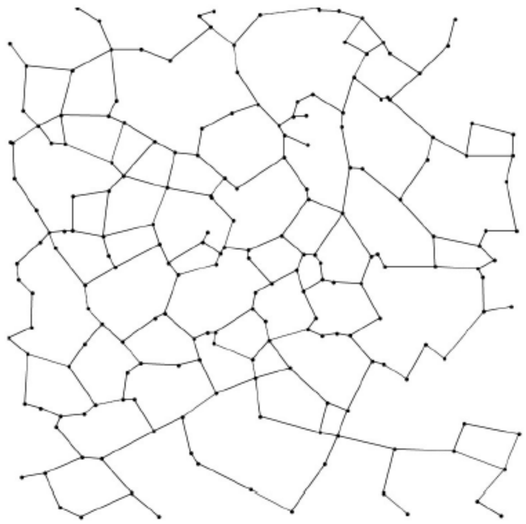
Quantitative Observations…



200 nodes randomly deployed in a 2000×2000 meters region.
Radio range =250meters

RNG





GG

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Back to the USSR…

OK, so given an initial network, assume that we are done with RNG-ization or GG-ization…

The typical packet can either:

forward greedily;

or

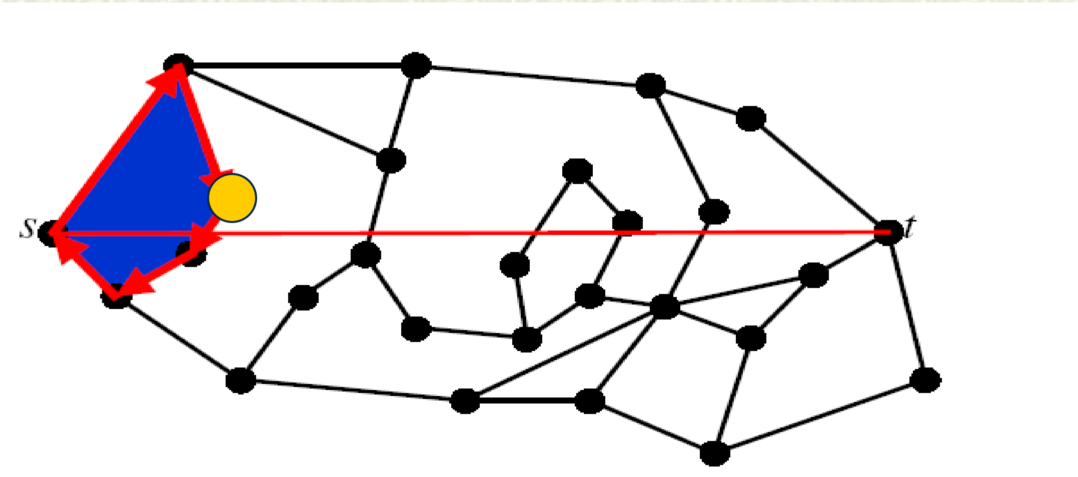
forward around perimeter…

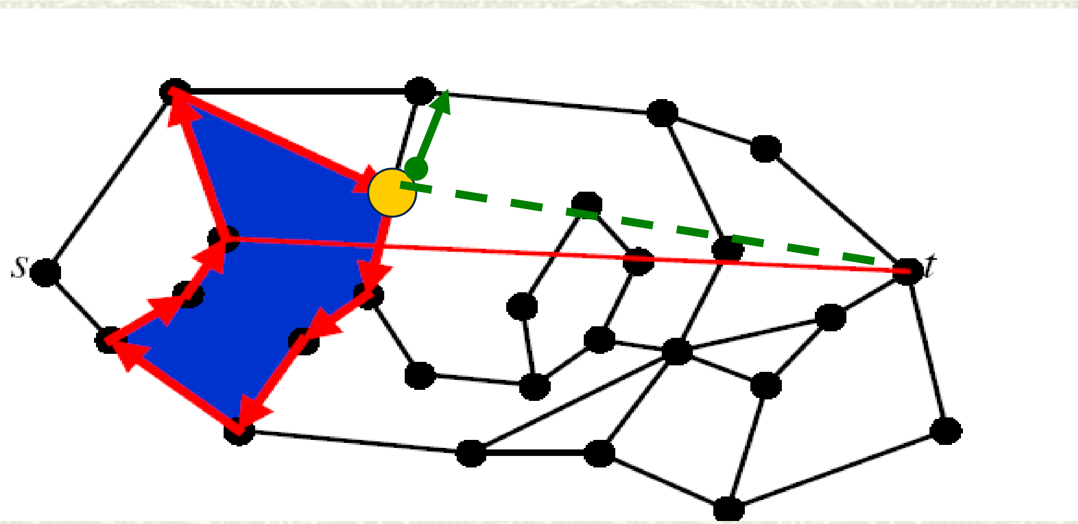
For the purpose of forwarding around the perimeter, the GPSR packet header has the following fields:…

D –destination location;
Lp – Location in which the packet entered the "perimeter" mode;
Lf – Location on xV in which the packet entered current face (TBE);
e0 – first edge traversed on the current edge;
M – packet mode (G/P)

So, just what is "walk around perimeter"???
AKA Face Routing…

- Keep left hand on the wall, walk until hit the straight line connecting source to destination.
- Then switch to the next face.





Und so weiter,
und so weiter…

…proceed "recursively"

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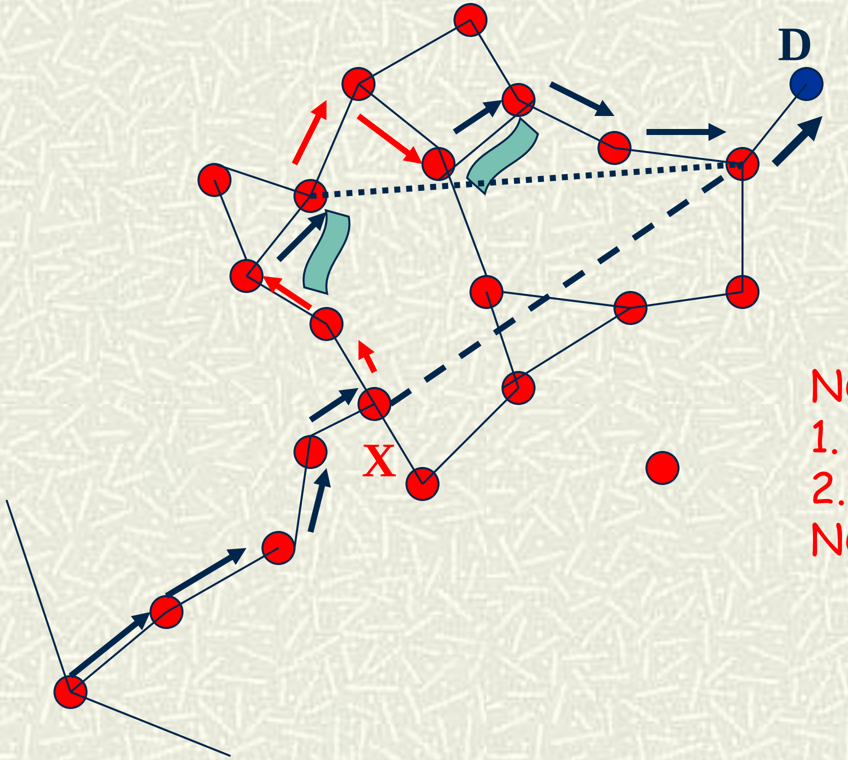
GPSR

Face: planar region bounded by the edges in a given graph (can be “open”)



When void encountered;
- “draw” the line XD;
-Pick the face at X intersected by XD;
-Select the edge on that face -> LHS;
-Traverse the edges on the boundary of that face -> RHS;
-At any point, if non-void (i.e., greedy-possible), do greedy;

NOTES:
1. Cycles can be detected (recall the header data)
2. Cycles can only happen when X and D are NOT in one connected component…

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Some Issues of GPSR…

- What if ***mobility*** is part of the game?
  - MAC failure feedback…
- Promiscuous use of network interface
  - Disable MAC address filtering (reason: every packet carries location data…)
- How realistic is the assumption about symmetric links (in turn, how good is the RNG/GG-ization of the connectivity graph)?
- Planarity of the graph?
  - Nodes move (in/out), deplete baterries => batch or incremental updates?

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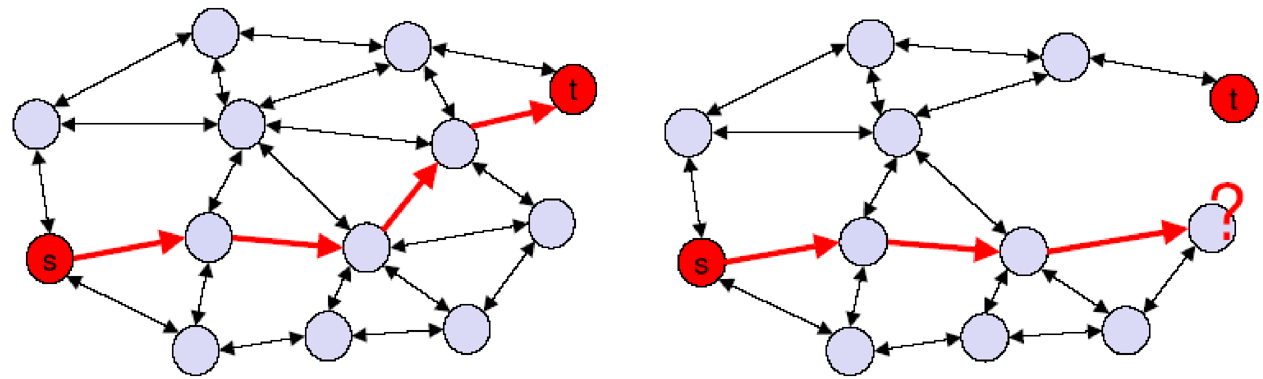
Some Issues with the GPSR…

Alternative "progress" measures

Issue++: Greed is not a good habit…
(face routing, although more "expensive" ensures that one cannot end up in a dead-end…)



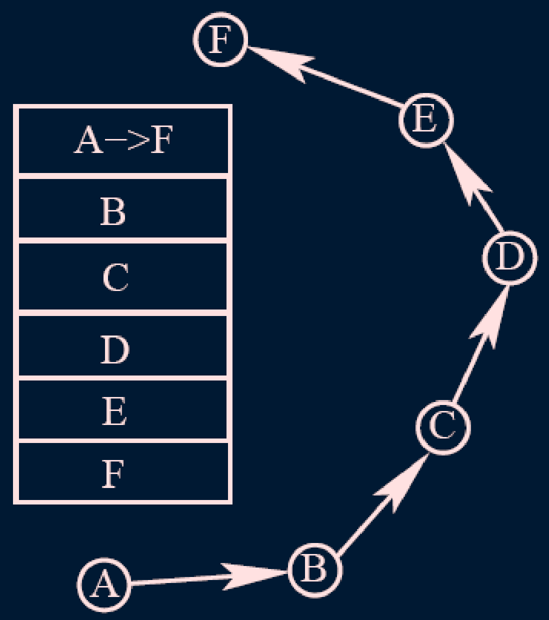
Send packets to the neighbor closest to the destination

Trajectory-Based Forwarding (TBF)

- A paradigm/general-recipe, rather than an actual implementation…
- Target = minimize the overheads which arise in:
  - Discovery
  - Construction of the route(s)
  - Scalability
    - Routing structure maintenance/update; space-time-flooding…
- Crux:
  - Instead of specifying
    - Destination, OR
    - Event/Region, OR
    - …
  - Specify the TRAJECTORY that the packets should follow…

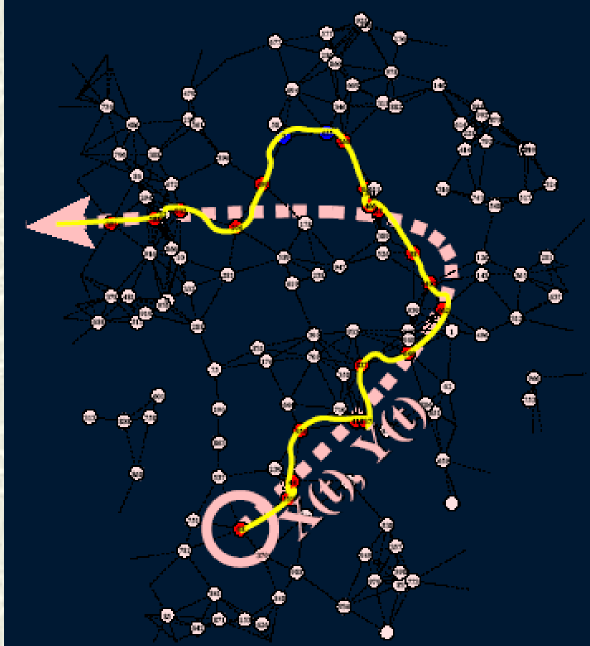
TBF – Basic Idea…

Ideally:



- discrete paths
- overhead≃path length
- mobility→updates

Possibility:



- continuous paths
- fixed overhead
- no maintenance

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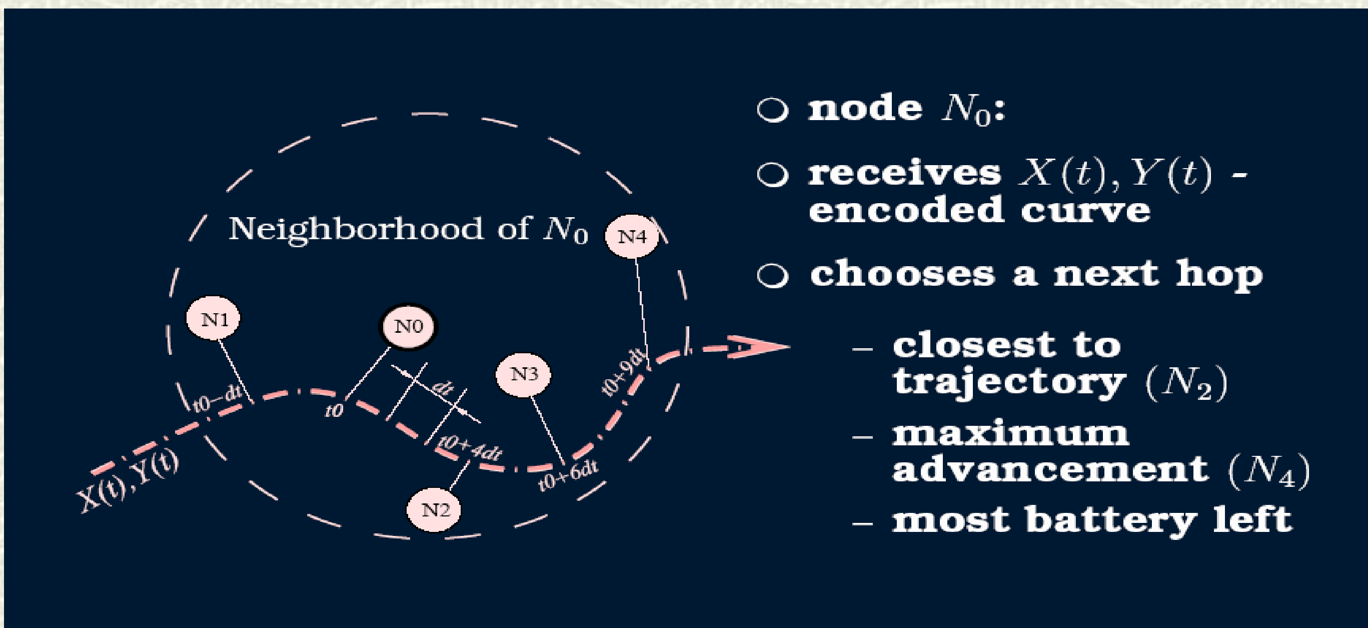
How TBF Forwards…

Needs to transmit the parameters of the curve representing the trajectory, e.g.,
$Ax^2 + Bx + C$ (in case the desired trajectory should resemble a parabola)

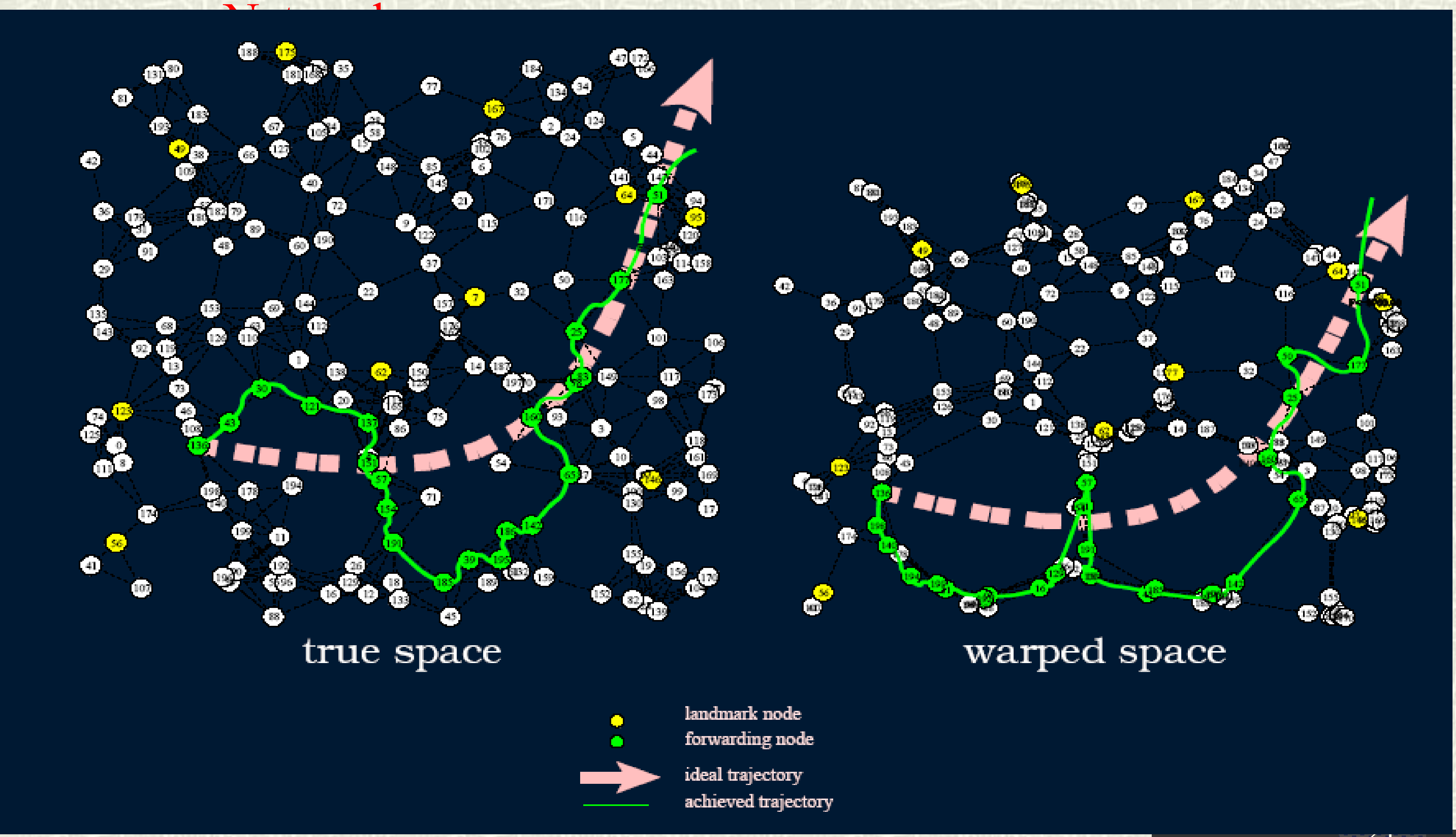
Problem: as the “nodes advance” (grain-of-salt-here), how do they know which value of x (or y) corresponds to them…

Hence, a better choice may be to represent the curve in a parametric form
$X = f_x(t), Y = f_y(t)$…



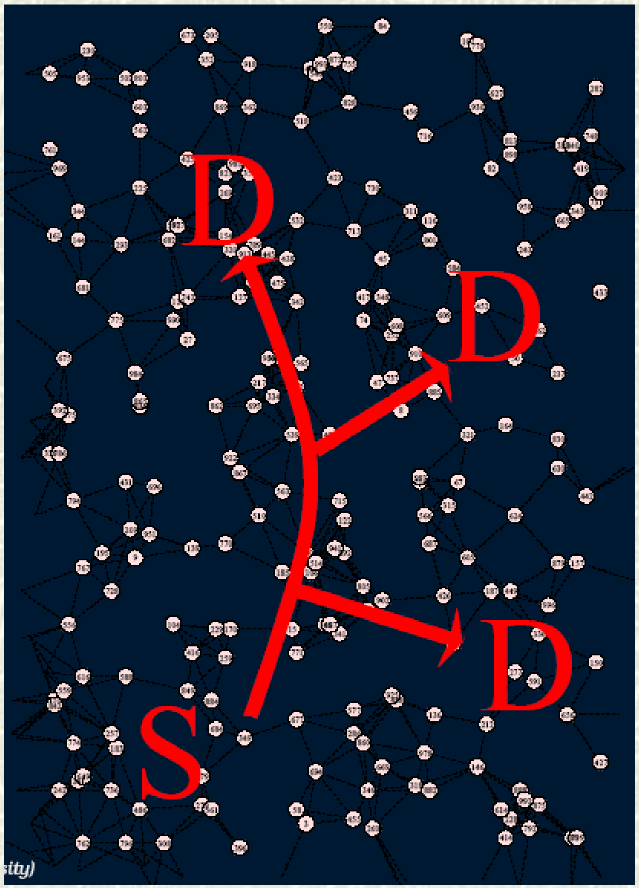
Possible Problems for TBF…

Sparse

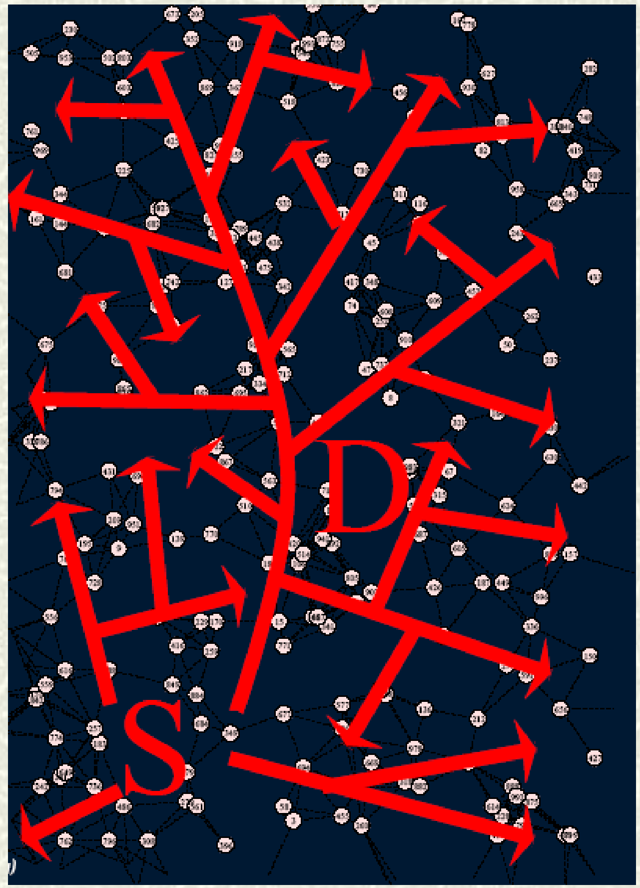


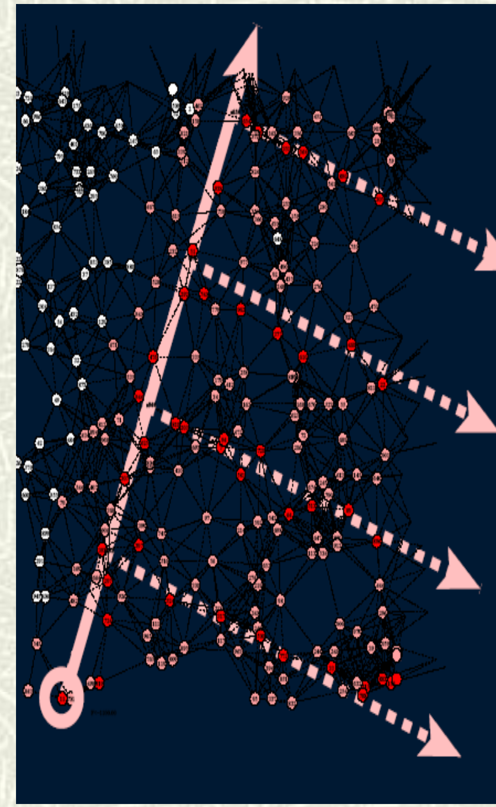
Extended Benefits of TBF…

TBF-Multicast



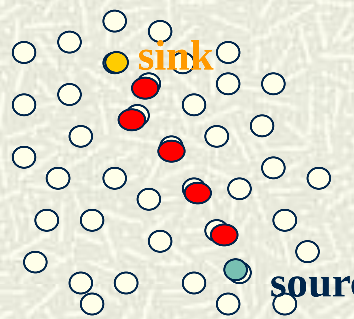
Recursively extend (a la fractal…) for flooding



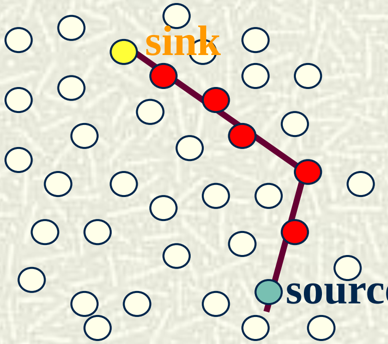


Broadcast version…

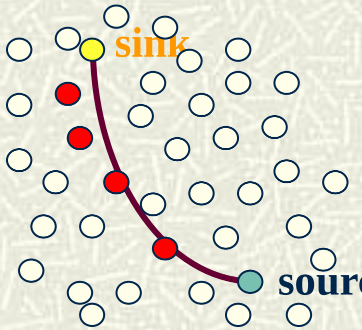
Potpourri: Single-Route Problems…



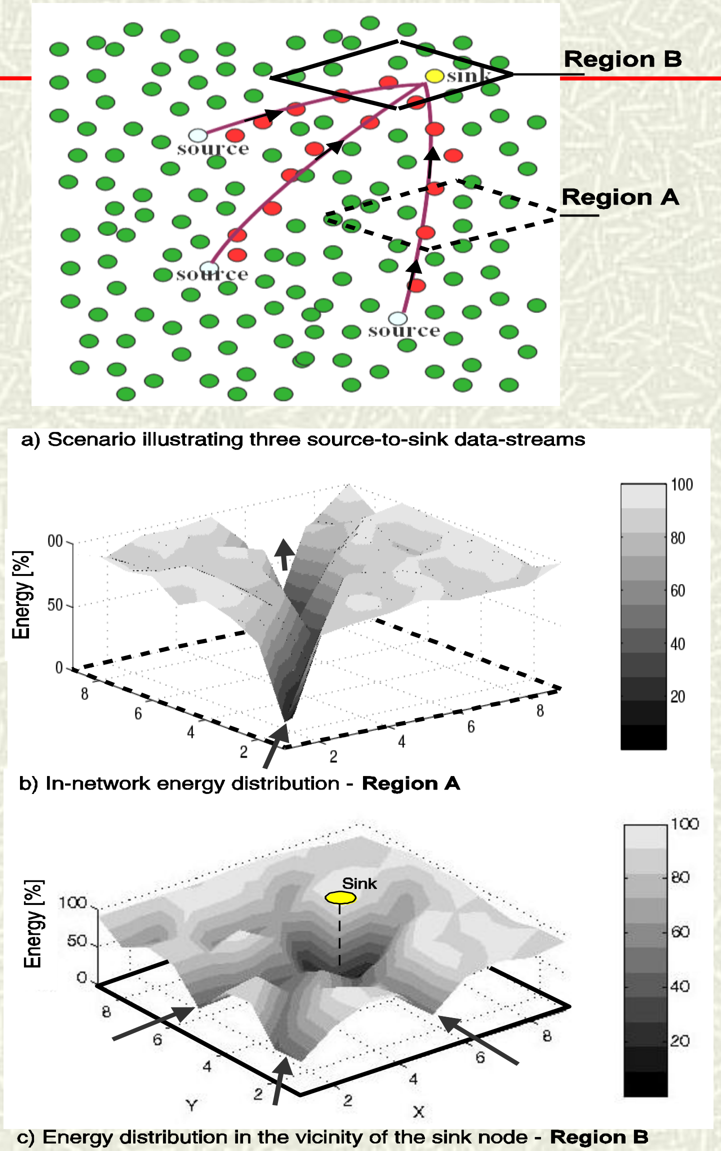
Shortest path (GPSR…)



TBF



TBF+



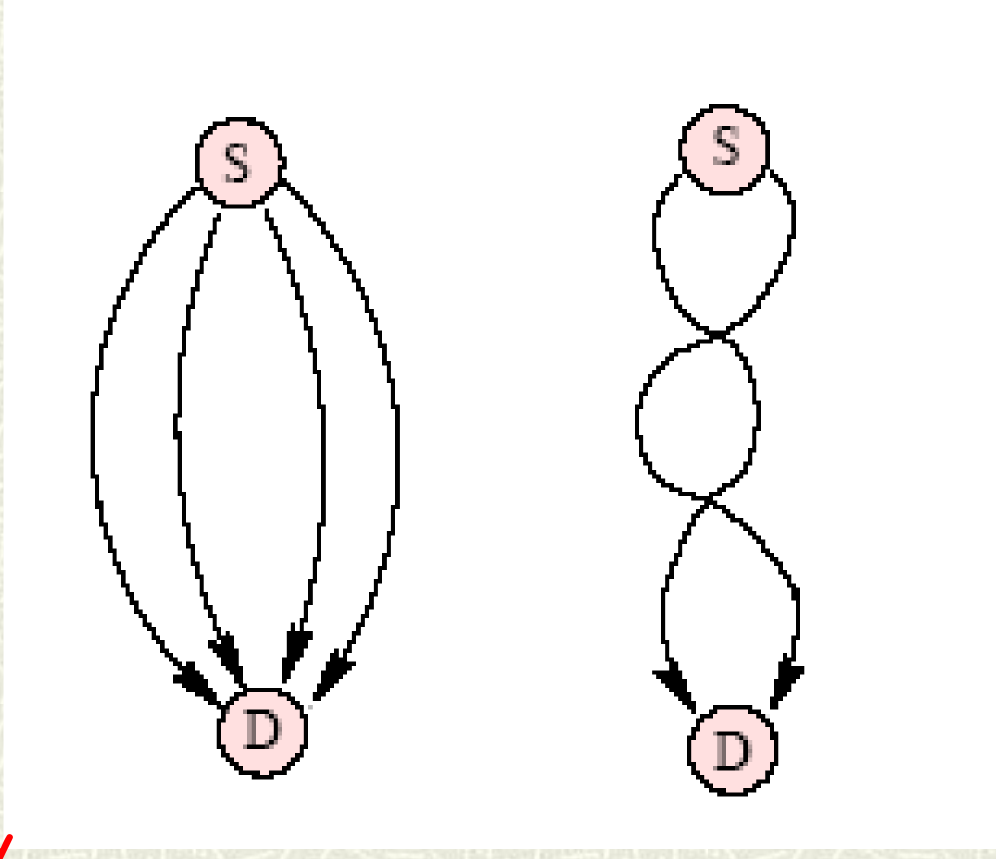
a) Scenario illustrating three source-to-sink data-streams

b) In-network energy distribution - **Region A**

c) Energy distribution in the vicinity of the sink node - **Region B**

Potpourri…

- Multi-Path Routing
  - Disjoint Paths
  - Breaded Paths



Goals:
I: Ensure robustness (i.e., the network is not quite reliable)
⇒ Ship a packet along > 1 route

II: Prolong the lifetime (careful about the definition…!!!) by alternating the routes used by consecutive packet (possibly, in batches…)

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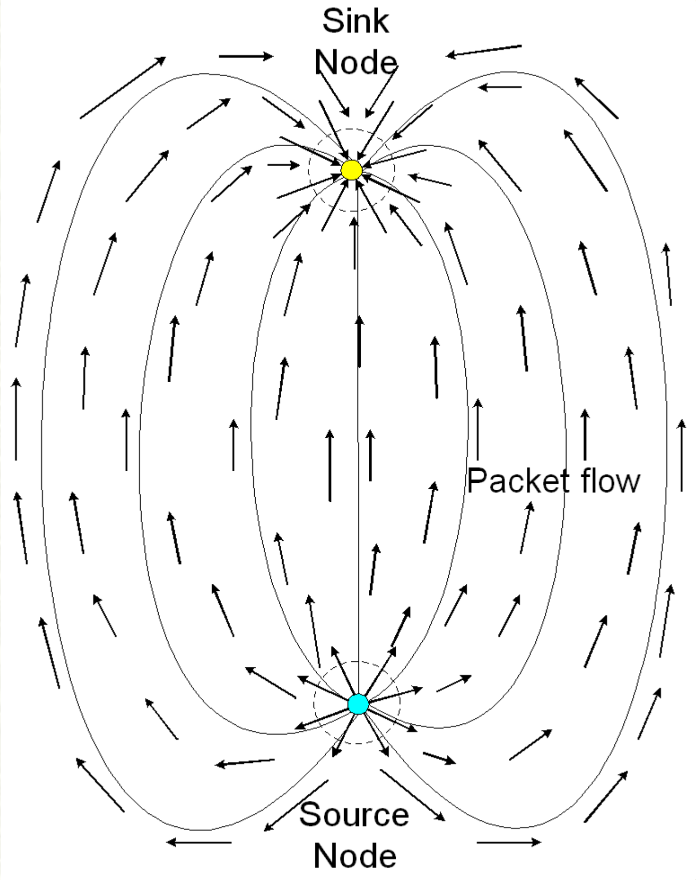
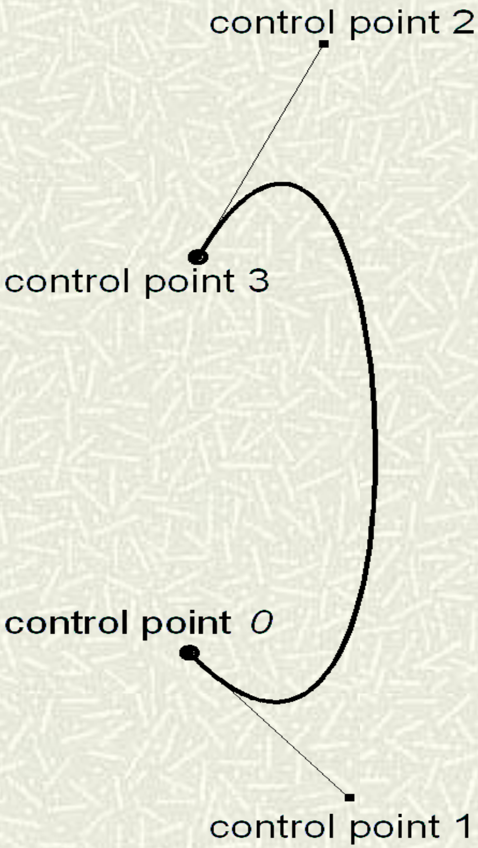
Bezier Curves



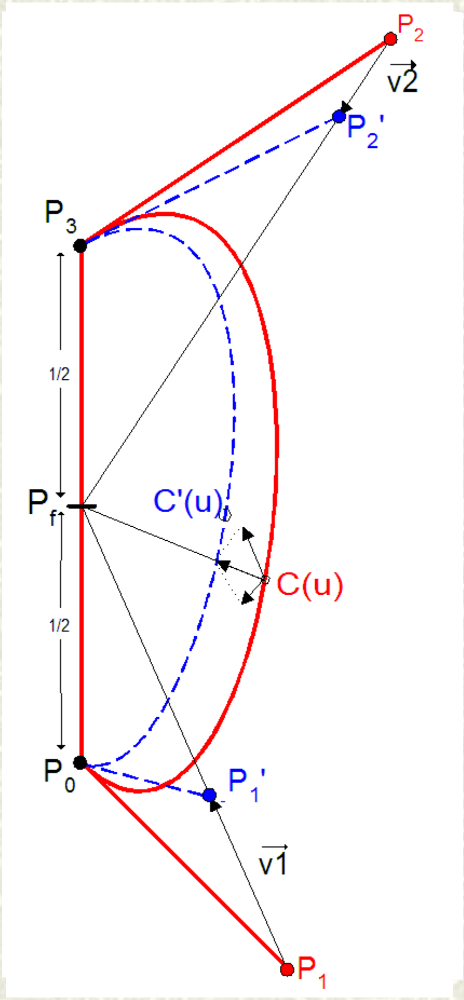


Sample: Cubic Bezier Curve

Bezier Curves **ARE Rational Polynomials!**

Properties[3]

- End-point interpolation
- Convex hull
- Pseudo-local control
- ***Affine invariance***



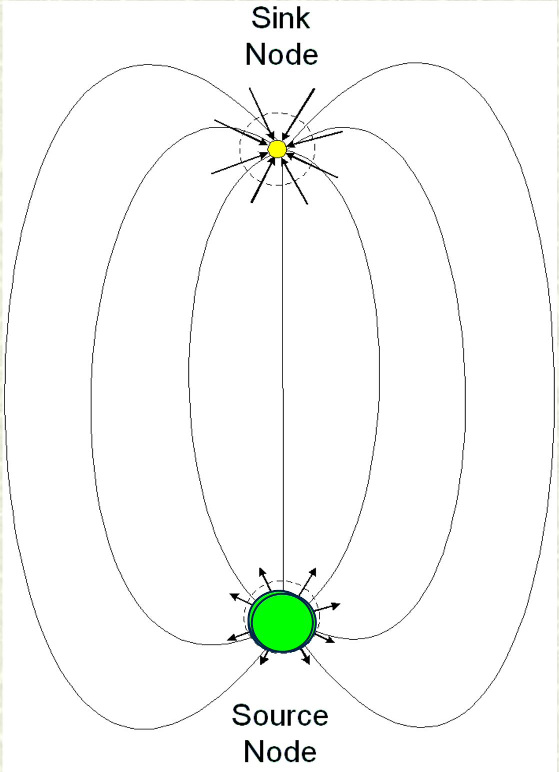
✓ $C(u) = \sum_{i=0}^{i=n} B_{i,n}(u) \cdot P_i, \quad u \in [0,1]$

✓ P_i are called **control points** of the generalized Bezier curve

Routing

Wake/Sleep Periods

- Remotely Activated Switch (RAS)
  - Controlled by the MAC layer
  - Usage of WAKE packets

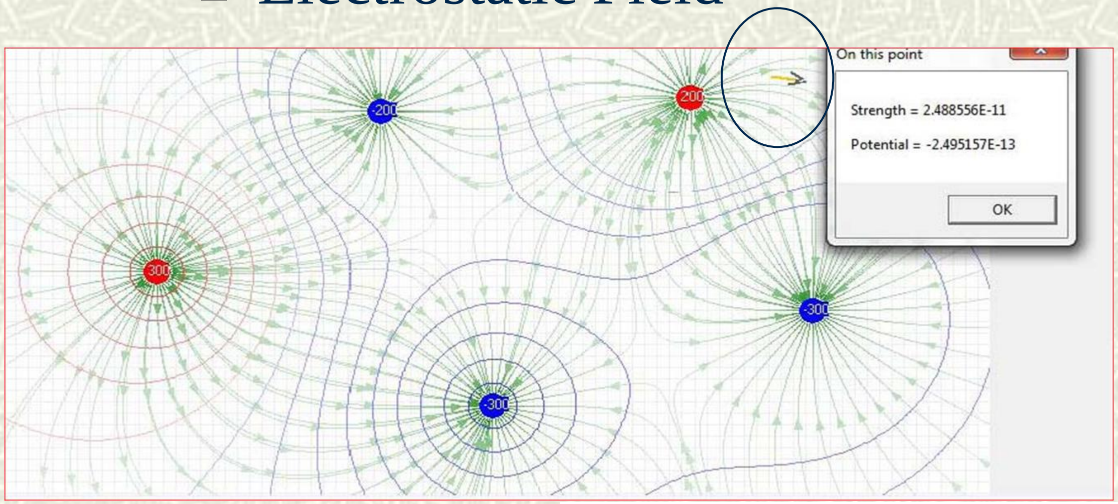


Data-packet

WAKE packet

Field-Based Routing

- How does one define “trajectory” in field-based settings?
  - Or, for that matter, a collection of trajectories
    - Without too much overhead on their “construction”…
- In this work:
  - Electrostatic Field



$$\mathbf{E}(\mathbf{r}) = \frac{1}{4\pi\epsilon_0}\sum_{i=1}^{N} sgn(i)\frac{|q_i|}{|\mathbf{r}_i - \mathbf{r}|^3}(\mathbf{r}_i - \mathbf{r})$$

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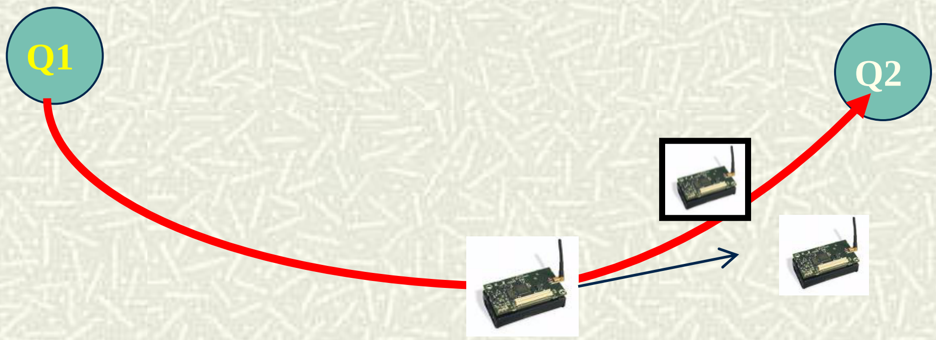
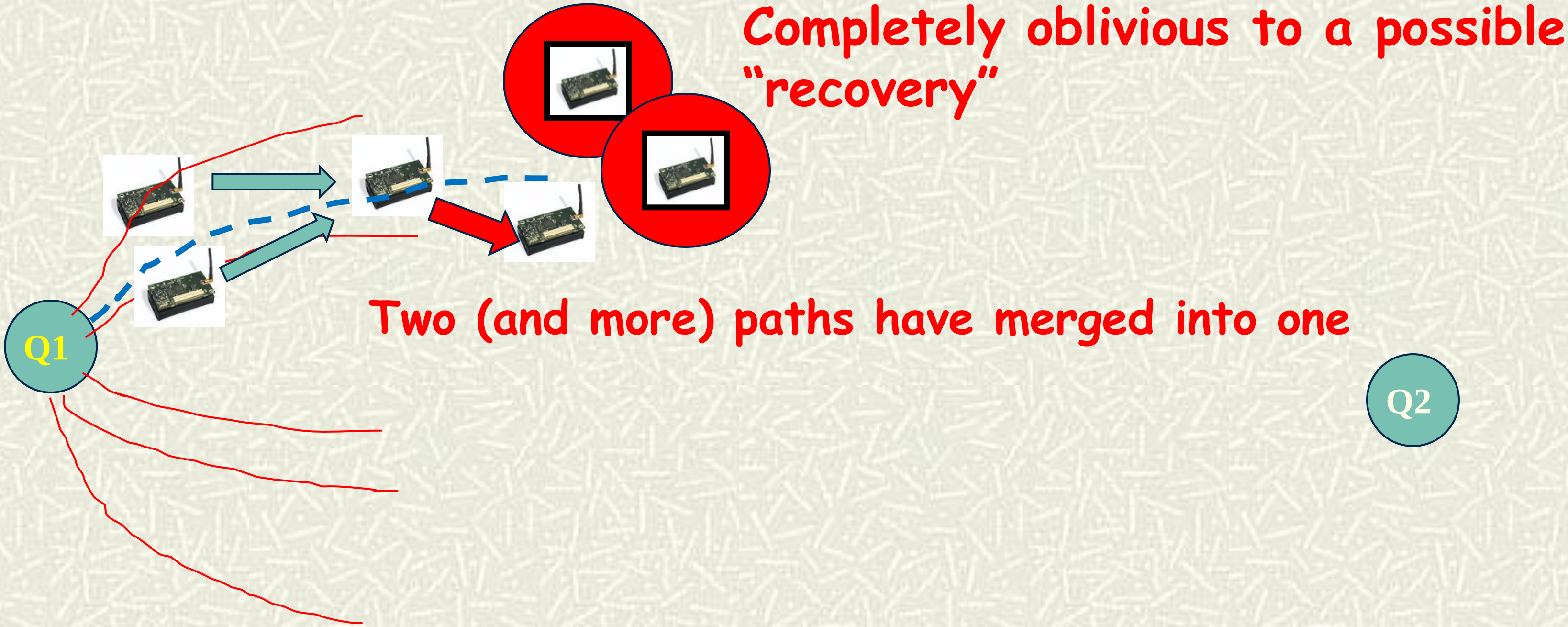
Electrostatic Field-based Routing (EFR)

- Multipath for a (source, sink) pair:
  - Determine the “charges”
    - E.g., application-based priority
  - Specify the geo-locations
  - Let each node calculate the field-value (vector)
    - **Use this to determine the next-hop**…
    - Node which is nearest to the field-line (and towards the sink)



EFR – Problems

- The distribution of nodes is hardly-ever:
  - Uniform and dense-enough
  - Uniform-enough along field line(s)

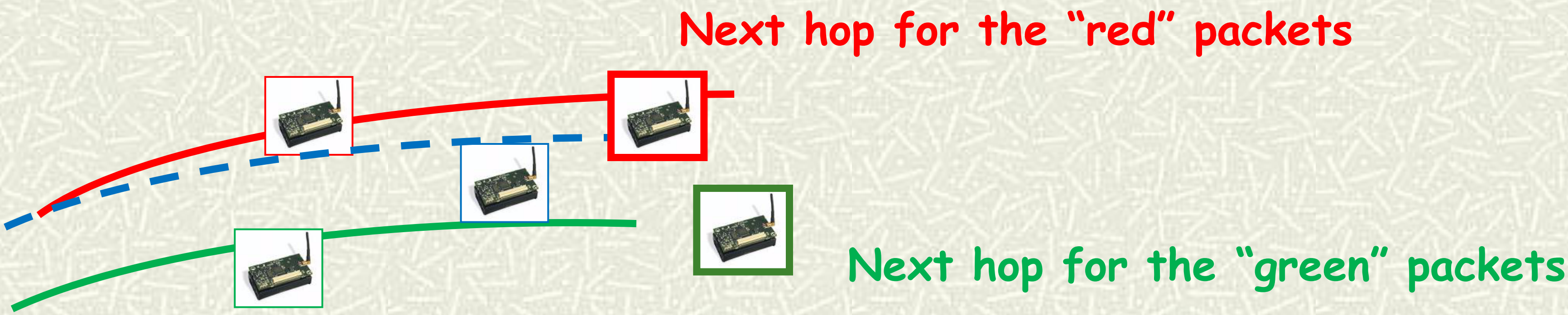


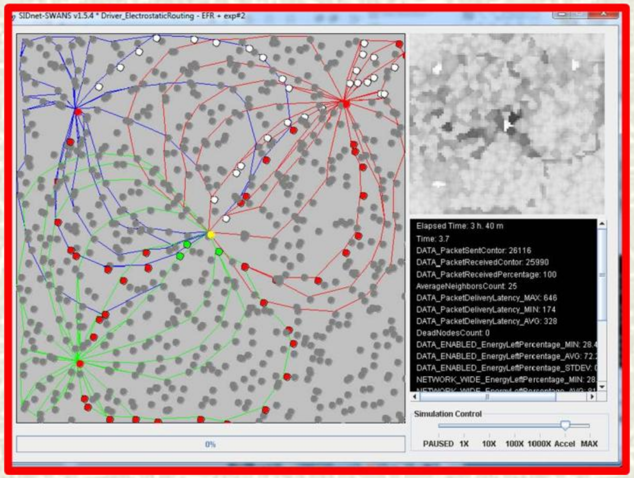
Persistent EFR (Load-Aware)

- Add a little "memory" to the packets…
  - Determine the location of the 1-hop neighbors
  - Calculate the (unique angle of the tangent to the) field-curve passing through their location
  - Transmit that along with the rest of the packet…

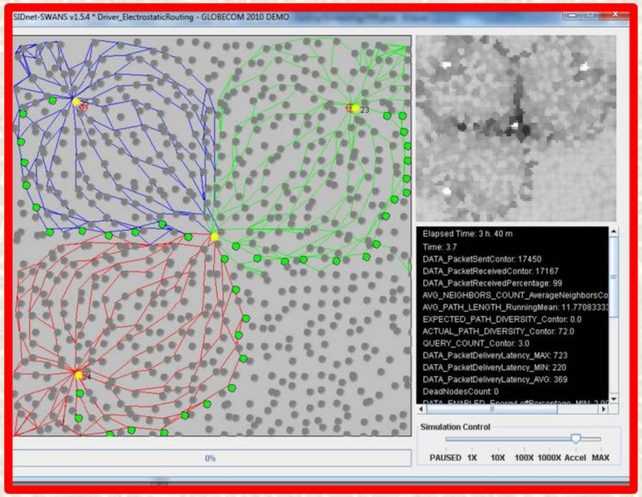
Persistent EFR (Load-Aware)

- **Enforce the "honor-the-ancestry"**
  - Closest to the original curve (and towards the sink).





Much better "spread-out"

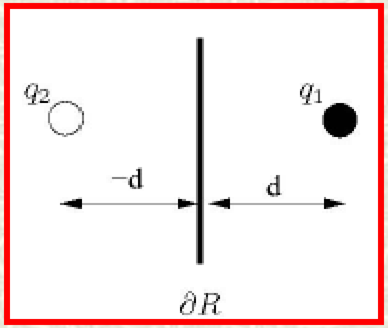


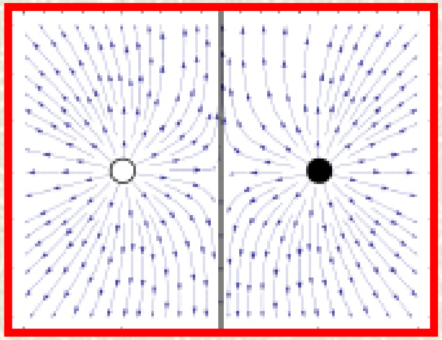
Persistent EFR (Load-Aware)

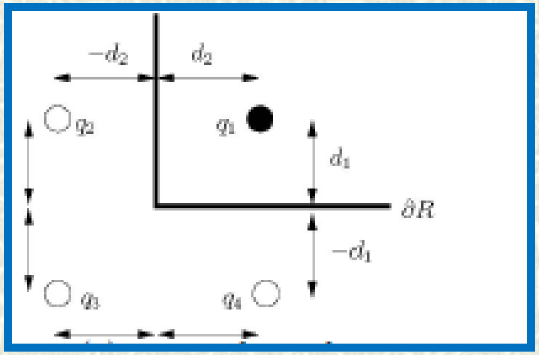
- Additional concern:
  - Boundary-effects (too many mergers)

Apply "method of images"
⇒ Add "virtual charges"

A couple of extra virtual-charges by the corners of the field…







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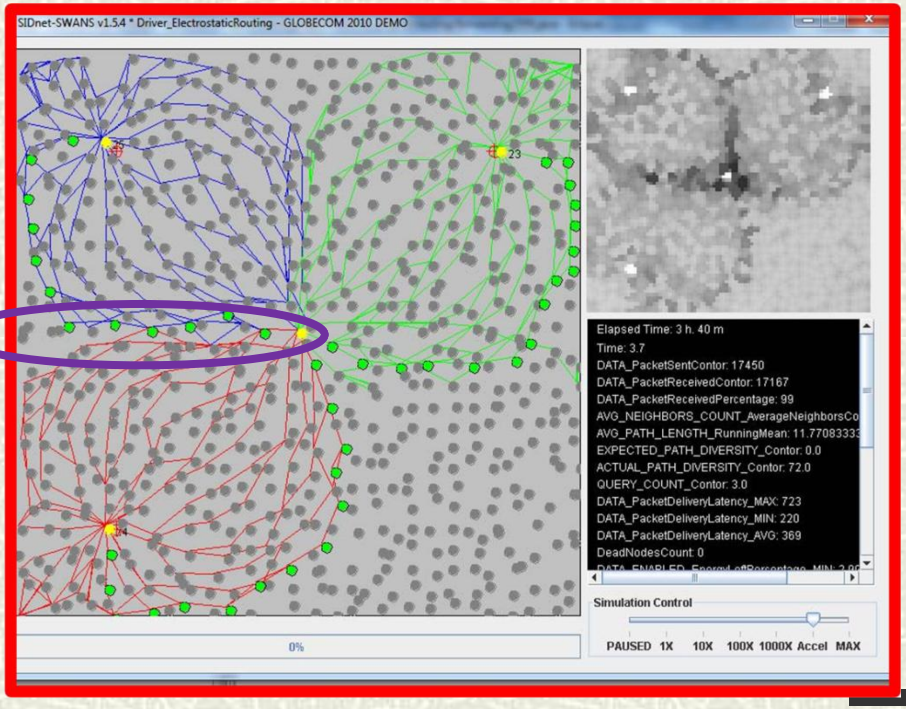
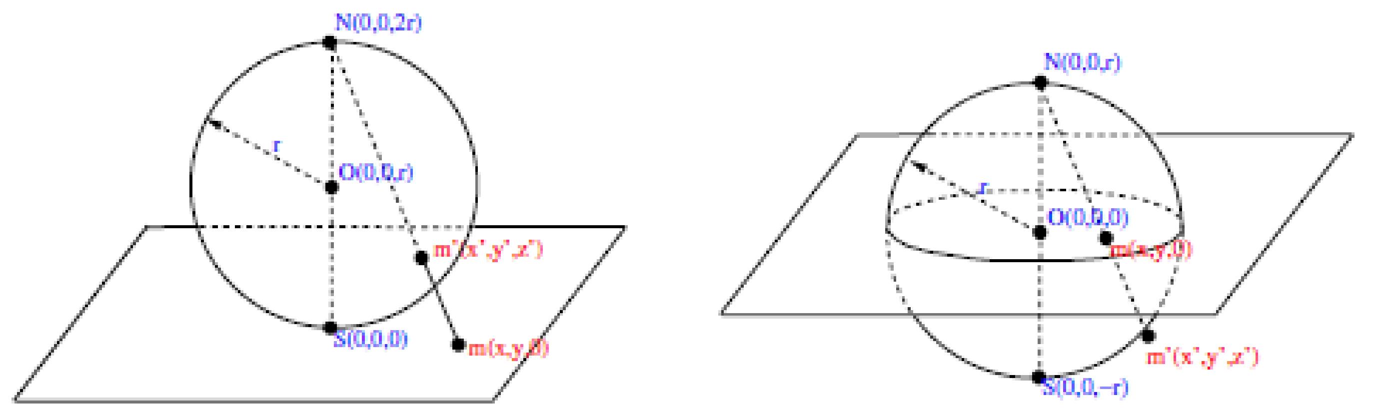
Persistent EFR (Load-Aware)

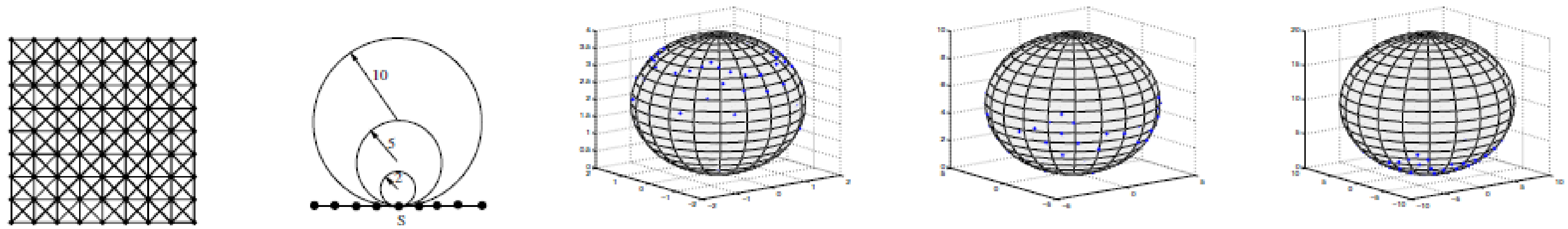
- When **multiple sources** are supposed to sample and transmit data to a given sink:
  - Nodes "on the boundary" will have to decide on behalf of which source they transmit…
    - **Need to carefully select the value of the charges of each source**



Other “Esoteric” Routings (Curveball)



(a) stereographic projection I (b) stereographic projection II



(a) 2D grid topology (b) size of sphere (c) on sphere ($r = 2$) (d) on sphere ($r = 5$) (e) on sphere ($r = 10$)

Fig. 3. The reversed stereographic projections of a grid network (9 × 9 grid in a 20 × 20 square area) to the sphere with various radii (2, 5 and 10).

Curveball Routing (Stereographic)

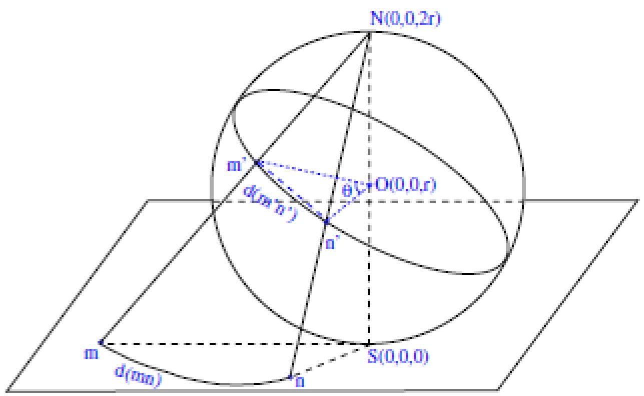


Fig. 4. The shortest distance between two points m' and n' on the sphere is the shorter segment of the greatest circle between m' and n'.

Bounding Property…

Circular Sailing

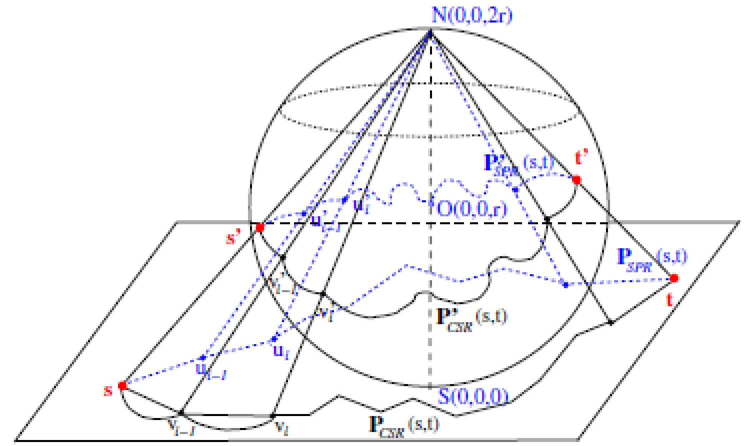


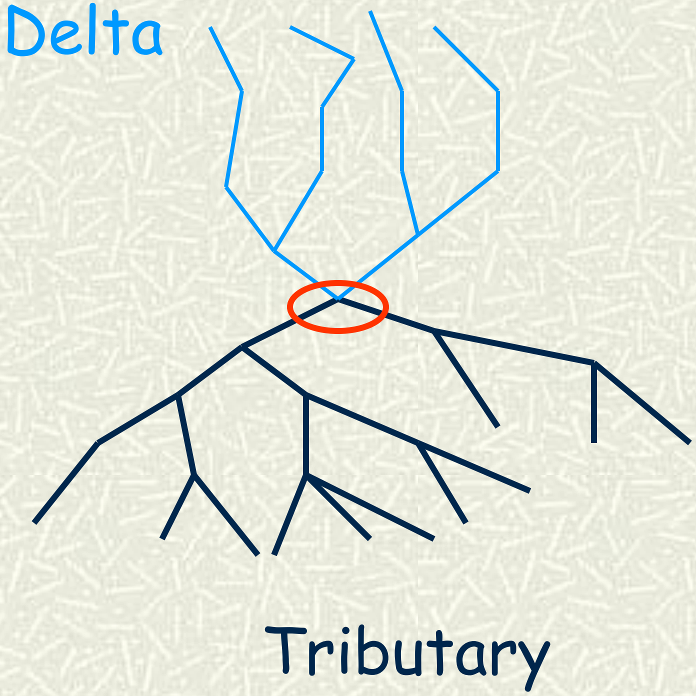
Fig. 7. The Euclidean path length of proposed CSR protocol is bounded by the Euclidean path length of shortest path routing.

Background and Motivation (multipaths)

- **Multipath routing**
  - Uses *simultaneously* (but) distinct routes to transmit the *same* information
  - Robustness/Reliability
- **Alternating path routing**
  - Uses a *sequence* of distinct routes to transmit *new(well, "subsequent")* information
  - Load-balancing
- **Alternating Multi-paths**
  - Combines the strategies of the first two.
  - ⇒ Robustness + Load-balancing

Background and Motivation (tributaries and deltas)

Much like in nature…



Original work (SIGMOD'05):

-In-network aggregate processing
-Reliability
  -When too many packets drop, "convert" a part of the tributary into a delta
  (and vice-versa)
-Demonstrated correctness/viability

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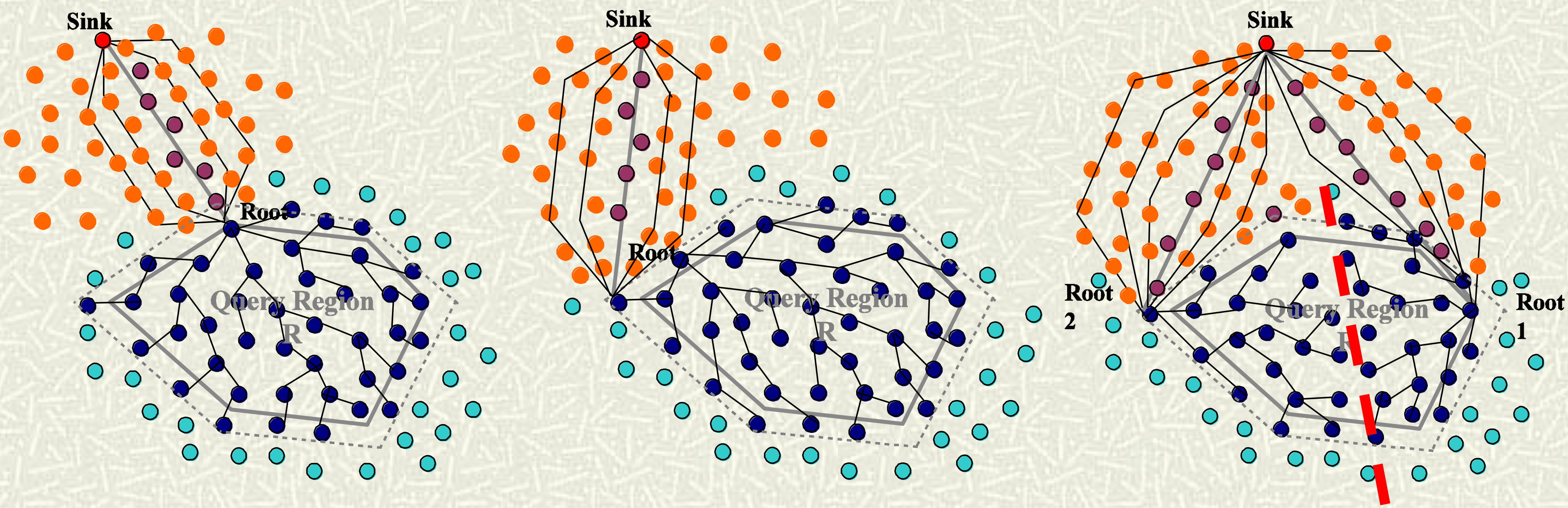
Background and Motivation

- **Goal:**
  - Overall lifetime extension of the network
- **Trade-off:**
  - Latency vs. load balancing
- **This work:**
  - Explore the possibility and impact of combining

    multiple trees and ***multiple-multipaths***

    for routing when processing a query with respect to a given region of interest

Basic Settings (Query Region and Answer Transmission)



a.) Shortest multipath

b.) Alternative multipath + tree

c.) Multiple trees and multipaths

One aggregation tree
+
multiple (k-short based)
paths

An alternate tree
+
multiple (k-short based)
paths

Disjoint trees
+
sets of
multiple (k-short based)
paths

1st variant

2nd variant

Alternation of Tributaries and Deltas

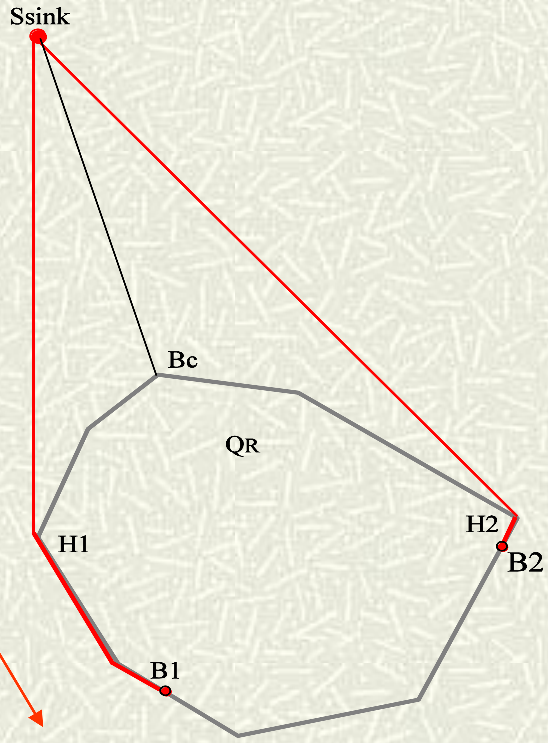
Initialization steps:

I. Query specification:

- the region of interest Q_R,
- the closest point to the sink $B_c(b_{cx},b_{cy})$ on (the boundary of) Q_R for initial shortest path establishment
- Additional tolerable delay bounds

II. Query propagation to B_c's nearest node (N_{Bc})

III. N_{Bc} triggers a tree construction mechanism, constrained by Q_R, rooted at N_{Bc}



Ex: boundaries for the roots of alternating trees

Alternation of Tributaries and Deltas ("construction")

"*Level_i* overlap" (parameter)

Given Tr1(root1) and Tr2(root2), where root1≠root2, their

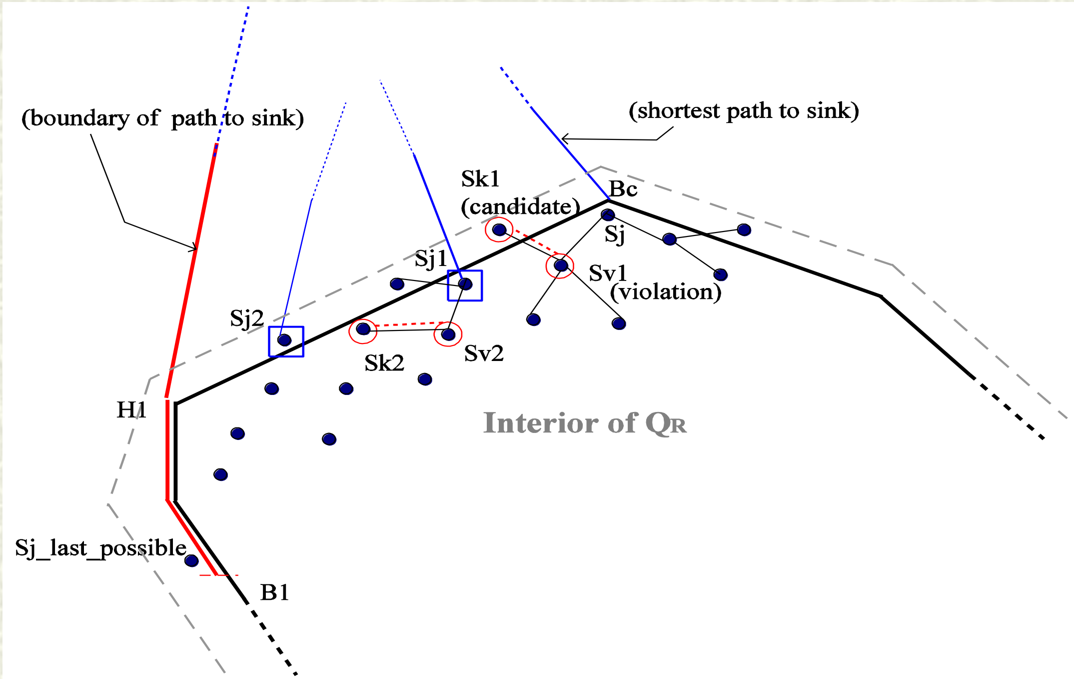
level_i overlap is the set of nodes that are at level_i in both Tr1 and Tr2

Intuitively, it provides a measure for "spreading" between adjacent alternative roots for the purpose of balancing the load *near the roots*

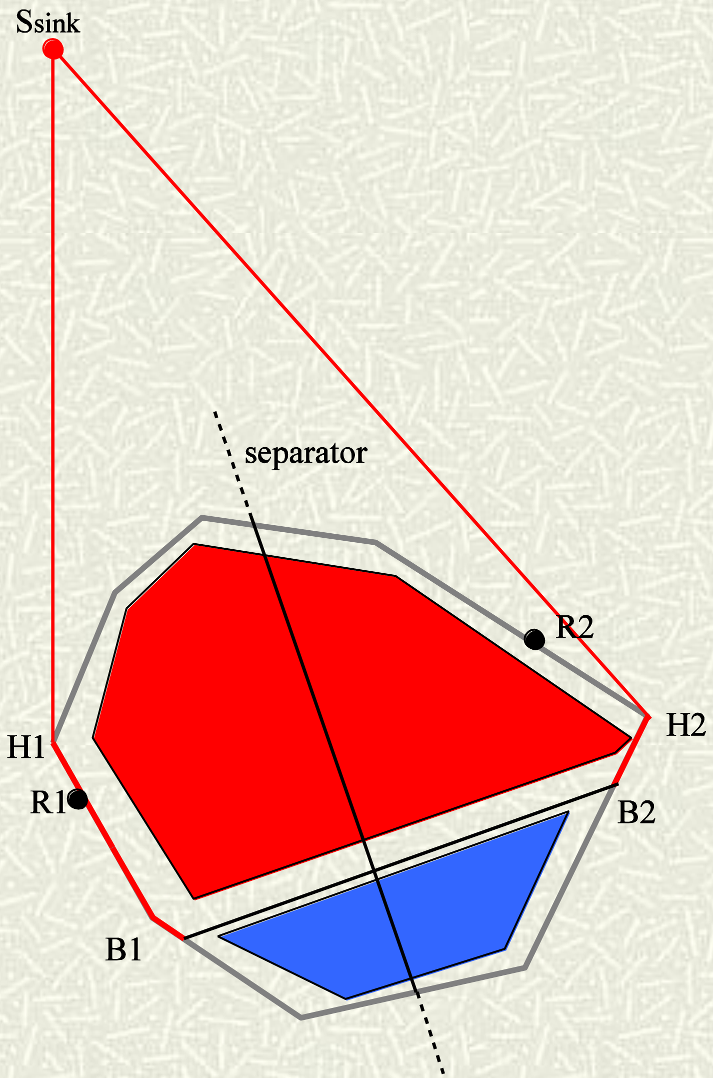
Selection of alternating trees/roots:

I. Determine the boundaries of the possible locations of the roots for the alternating trees

II. Within these boundaries, find a set of nodes that do not violate, pairwise, the *level_i* overlap



Concurrent Transmission with Disjoint Trees



Basic steps:

I. Partition Q_R in two sub-regions with balanced node count (Ham-Sandwich cut):

a. Color one region in "red", the other in "blue". "Red" region represent the admissible space of root nodes, with respect to the acceptable latency-parameter

b. Bisect red/blue areas in half using a separator line (O(n) for convex polygons)

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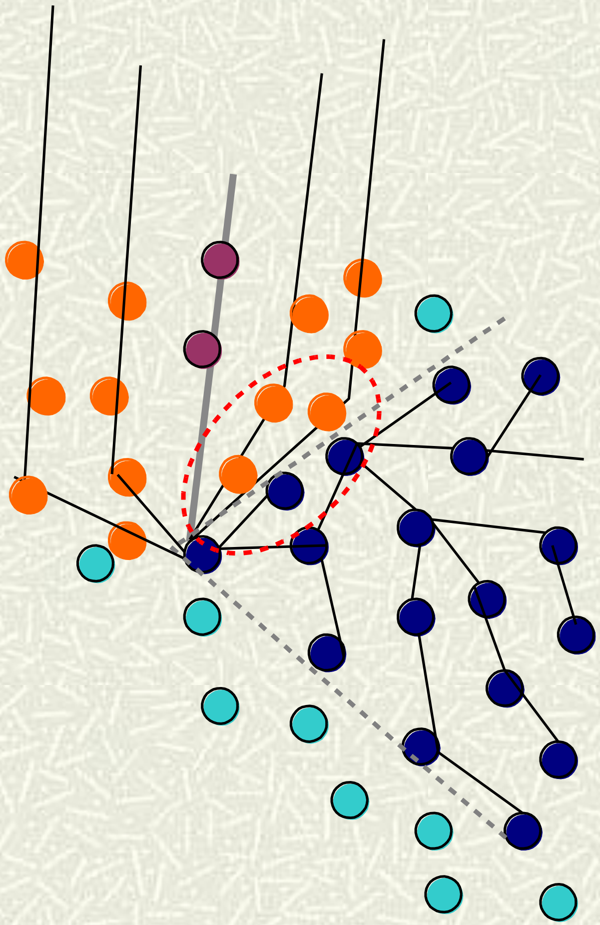
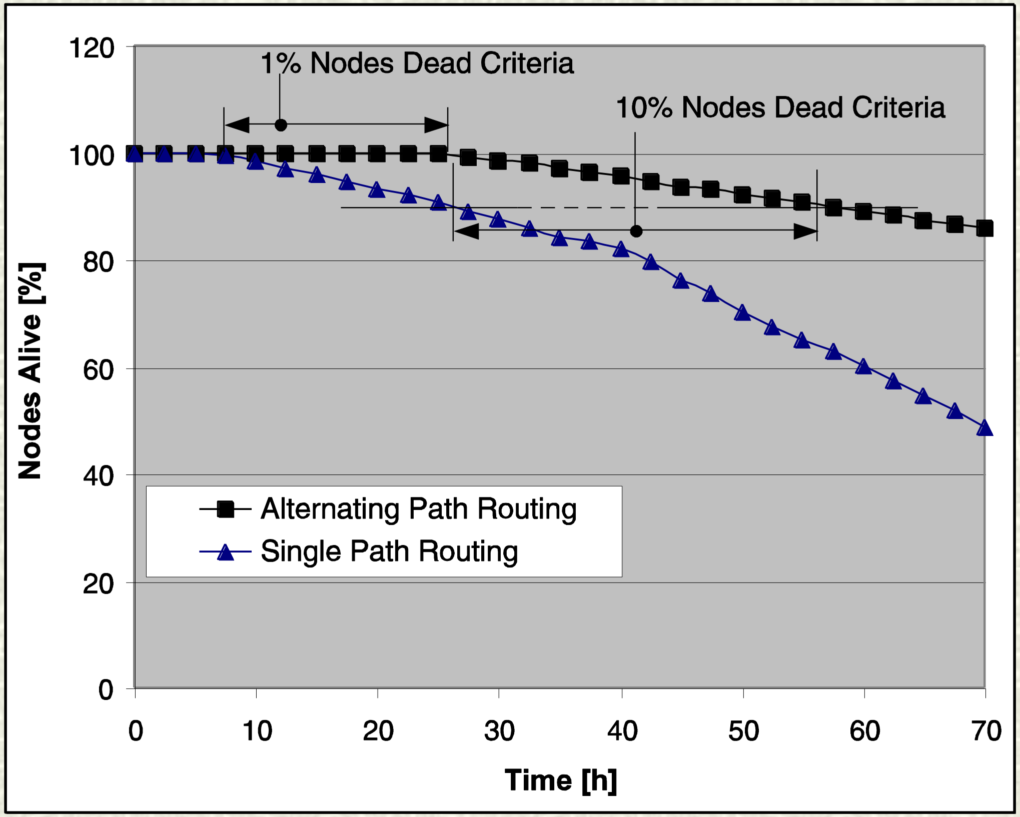
Practical Considerations

- Avoid (or, minimize) *sharing of nodes* by both Tributaries and Deltas (load balancing)
- *Frequency* of alternating of trees/path should be carefully chosen
- The *sequence of alternating* among the trees/paths becomes important in high-sampling rate queries (queuing effect among adjacent routes can yield prolonged contention along routes)

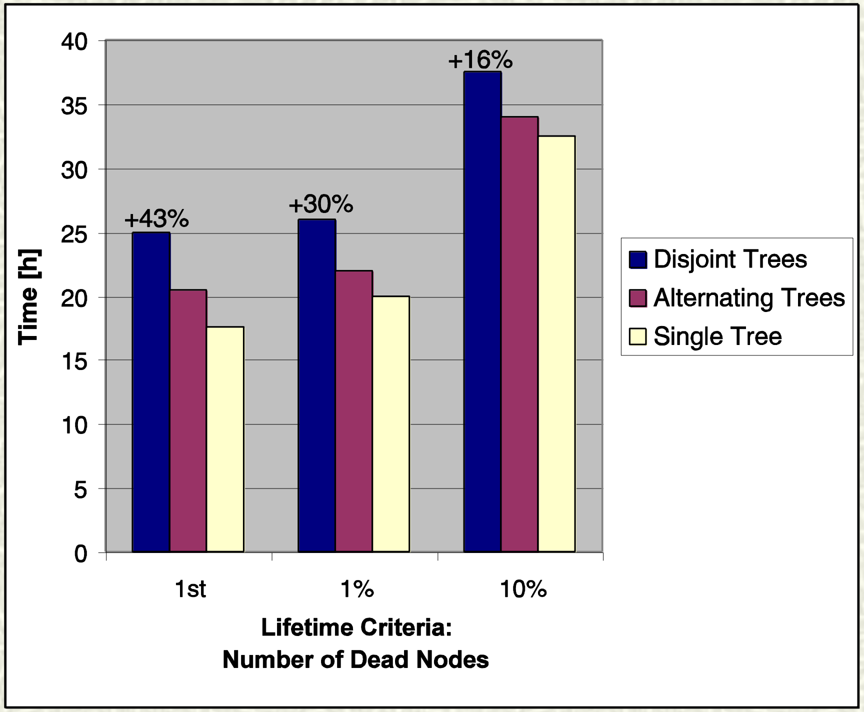


Experimental Evaluation

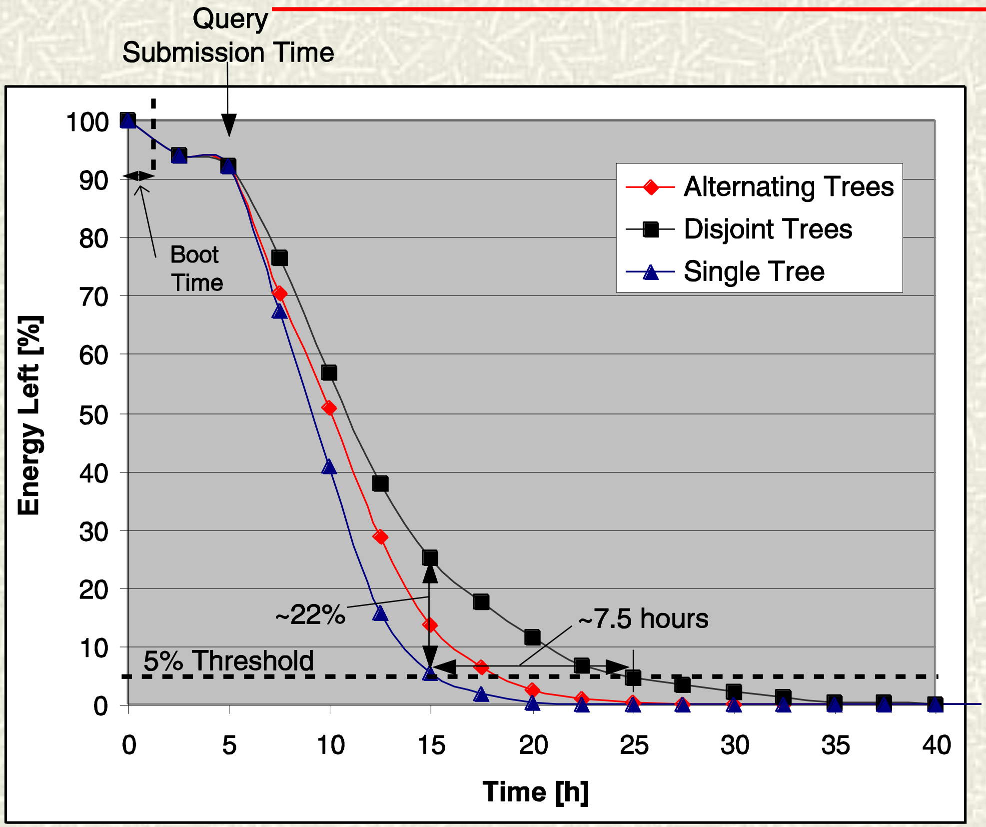
Lifetime: *single vs. alternating* (k-short based) multipaths



Overall lifetime



Experimental Evaluation



Time	0h	5h	10h	12.5h	**15h**	**17.5h**	20h	22.5h
Disjoint Trees	100	92	56.77	37.95	27.20	**17.46**	11.55	6.76
Alternating Trees	100	92	50.88	28.67	13.48	**6.47**	2.55	0
Single Tree	100	92	40.88	15.77	5.41	1.71	0	0

Minimum residual energy depletion rate over the entire network (coincides, not surprisingly with the root nodes' energy levels)