Wireless Sensor Networks
7. Geometric Routing

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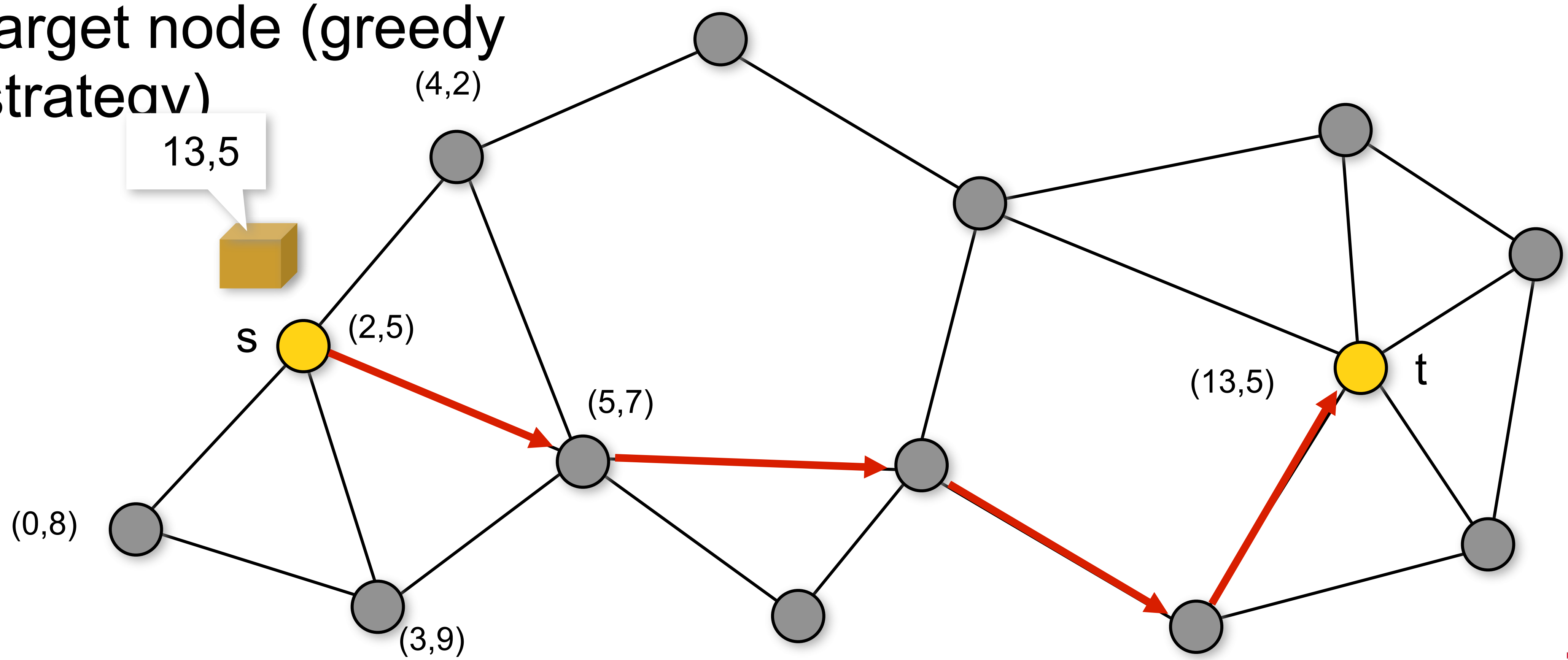
Literature - Surveys

- Stefan Rührup: Theory and Practice of Geographic Routing. In: Hai Liu, Xiaowen Chu, and Yiu-Wing Leung (Editors), Ad Hoc and Sensor Wireless Networks: Architectures, Algorithms and Protocols, Bentham Science, 2009
- Al-Karaki, Jamal N., and Ahmed E. Kamal. Routing techniques in wireless sensor networks: a survey. Wireless communications, IEEE 11.6 (2004): 6-28.

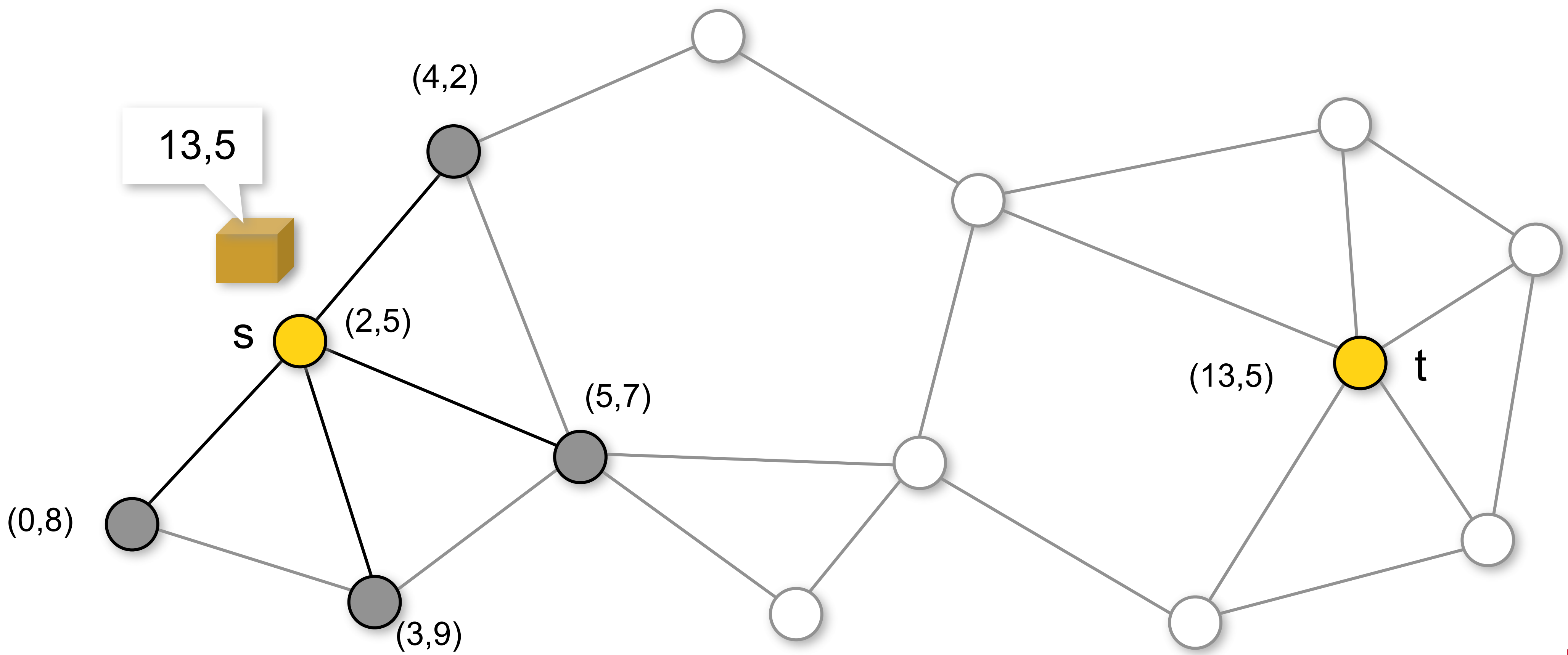
Geometric Routing

- Routing target:
  - geometric position
- Idea
  - send message to the neighbor closest to the target node (greedy strategy)
- Advantagements
  - only local decisions
  - no routing tables
  - scalable



Position Based Routing

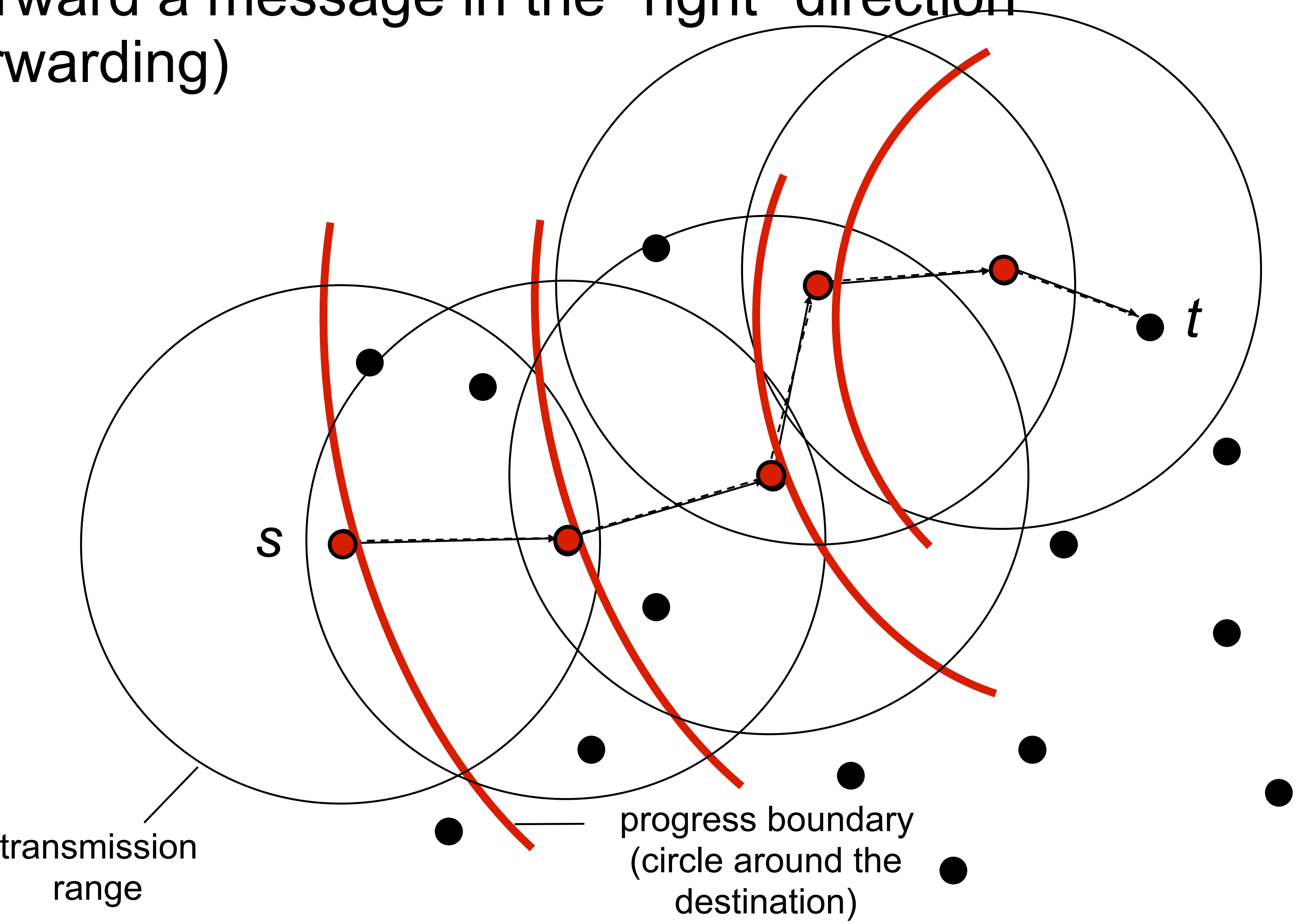
- Prerequisites
  - Each node knows its position (e.g. GPS)
  - Positions of neighbors are known (beacon messages)
  - Target position is known (location service)



Greedy forwarding and recovery

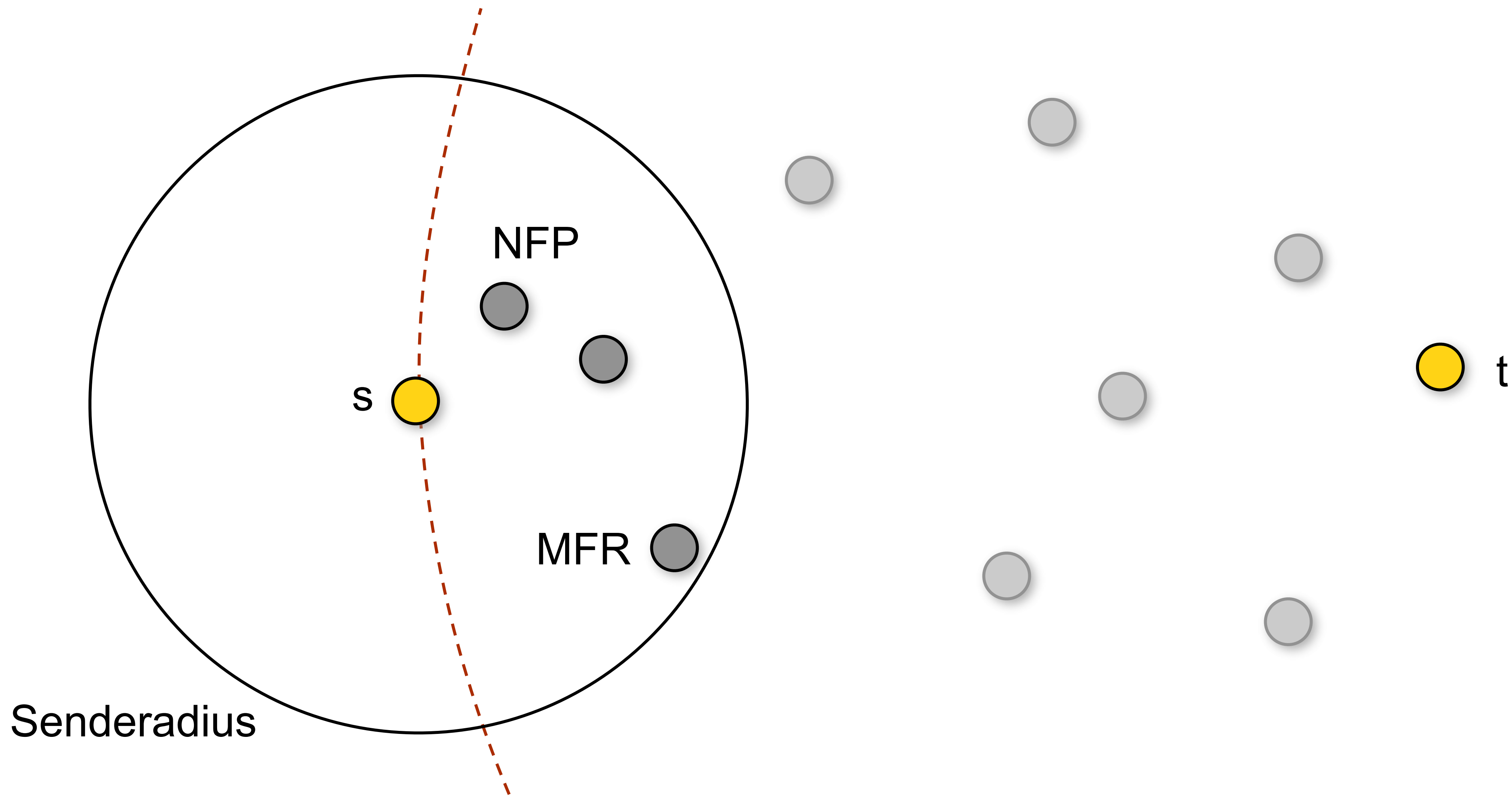
- With position information
  - one can forward a message in the "right" direction (greedy forwarding)

no routing tables,
no flooding!



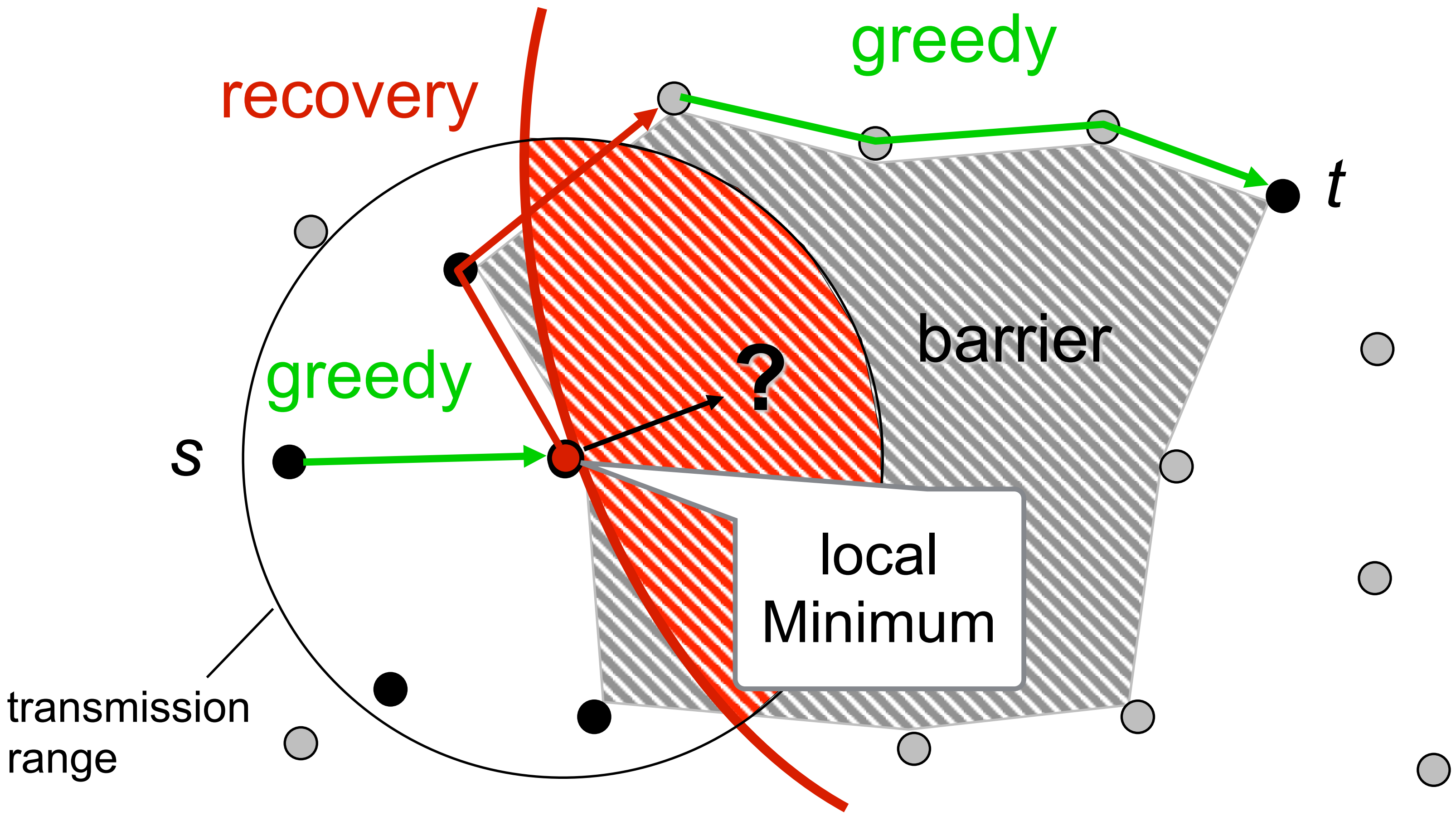
First Approaches

- Routing in packet radio networks
- Greedy strategies:
  - MFR: Most Forwarding within Radius [Takagi, Kleinrock 1984]
  - NFP: Nearest with Forwarding Progress [Hou, Li 1986]



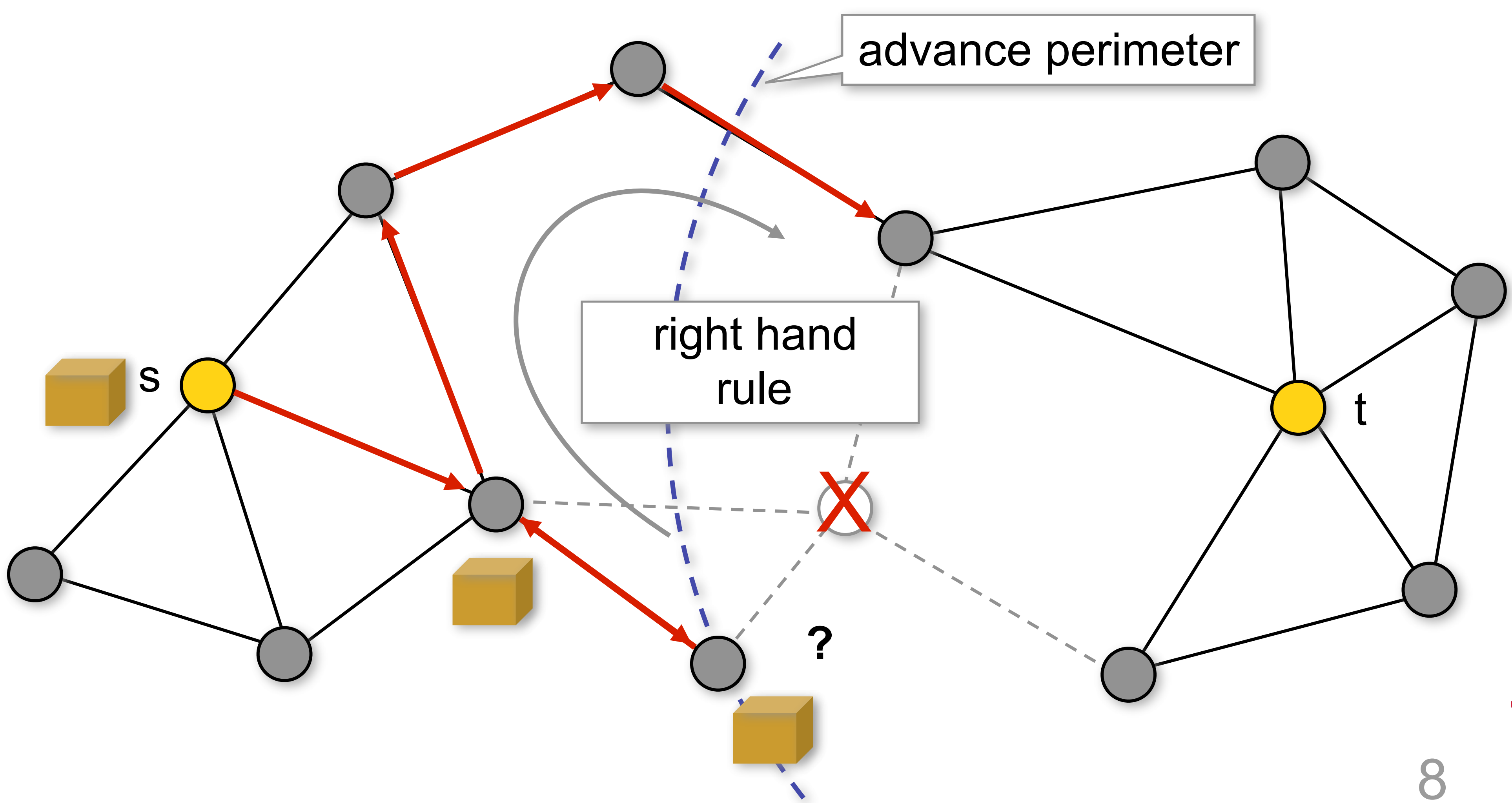
Greedy forwarding and recovery

- Greedy forwarding is stopped by barriers
  - (local minima)
- Recovery strategy:
  - Traverse the border of a barrier until a forwarding progress is possible (right-hand rule)
  - routing time depends on the size of barriers



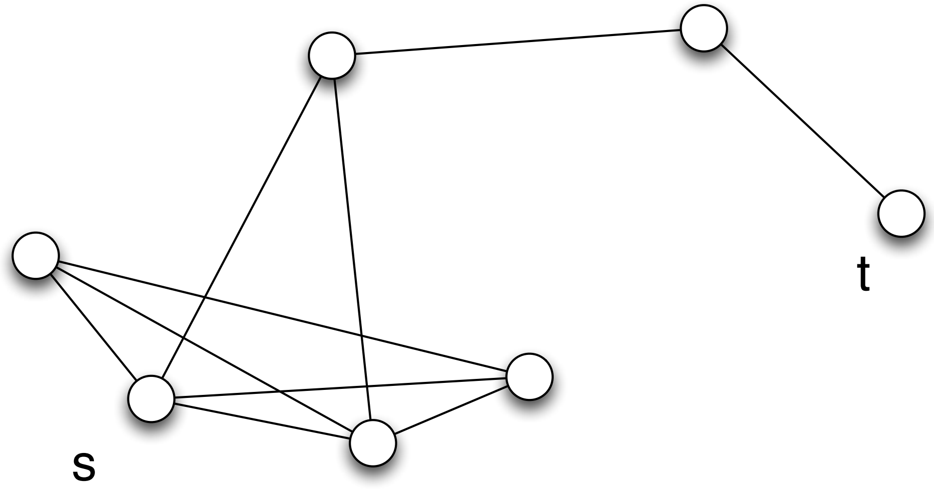
Position Based Routing

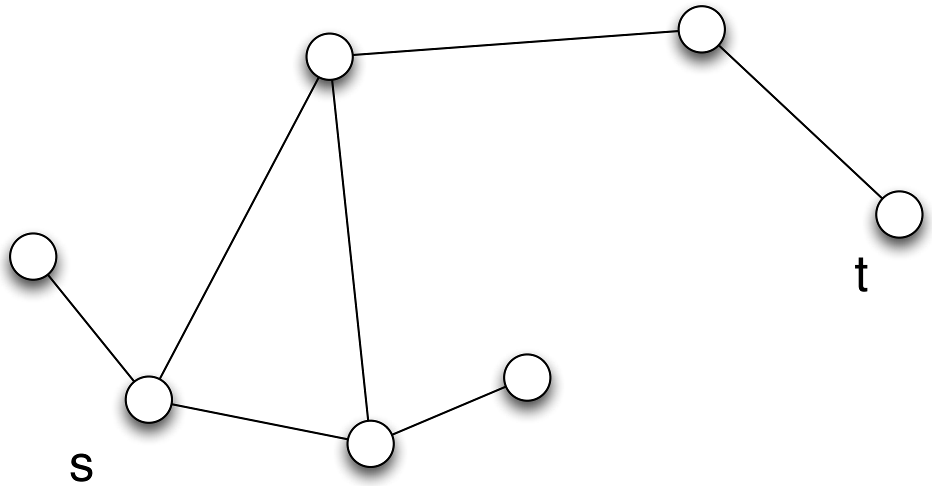
- Combination of greedy routing and recovery strategy
- Recovery from local minima (right hand rule)
  - Example: GPSR [Karp, Kung 2000]
    - B. Karp and H. T. Kung, “GPSR: Greedy Perimeter Stateless Routing for Wireless Sensor Networks,” Proc. MobiCom 2000, Boston, MA, Aug. 2000.



Greedy forwarding and recovery

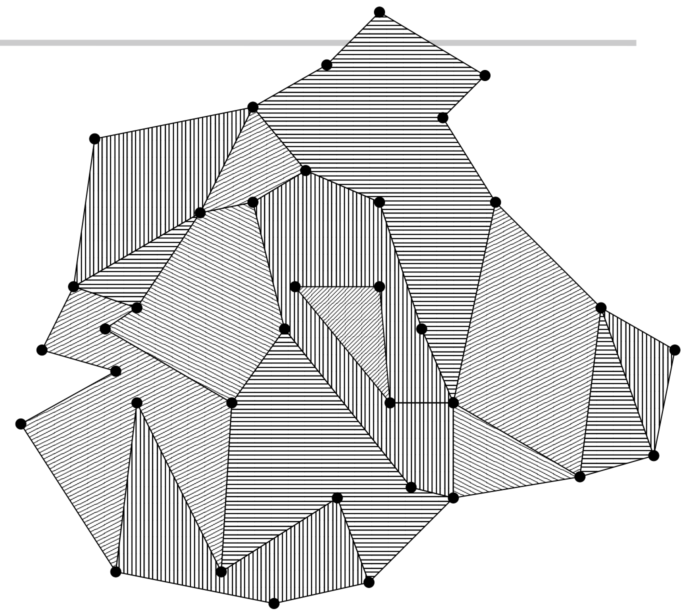
- Right-hand rule needs planar topology
  - otherwise endless recovery cycles can occur
- Therefor the graph needs to be made planar
  - erase crossing edges
- Problem
  - needs communication between nodes
  - must be done careful in order to prevent graph from becoming disconnected

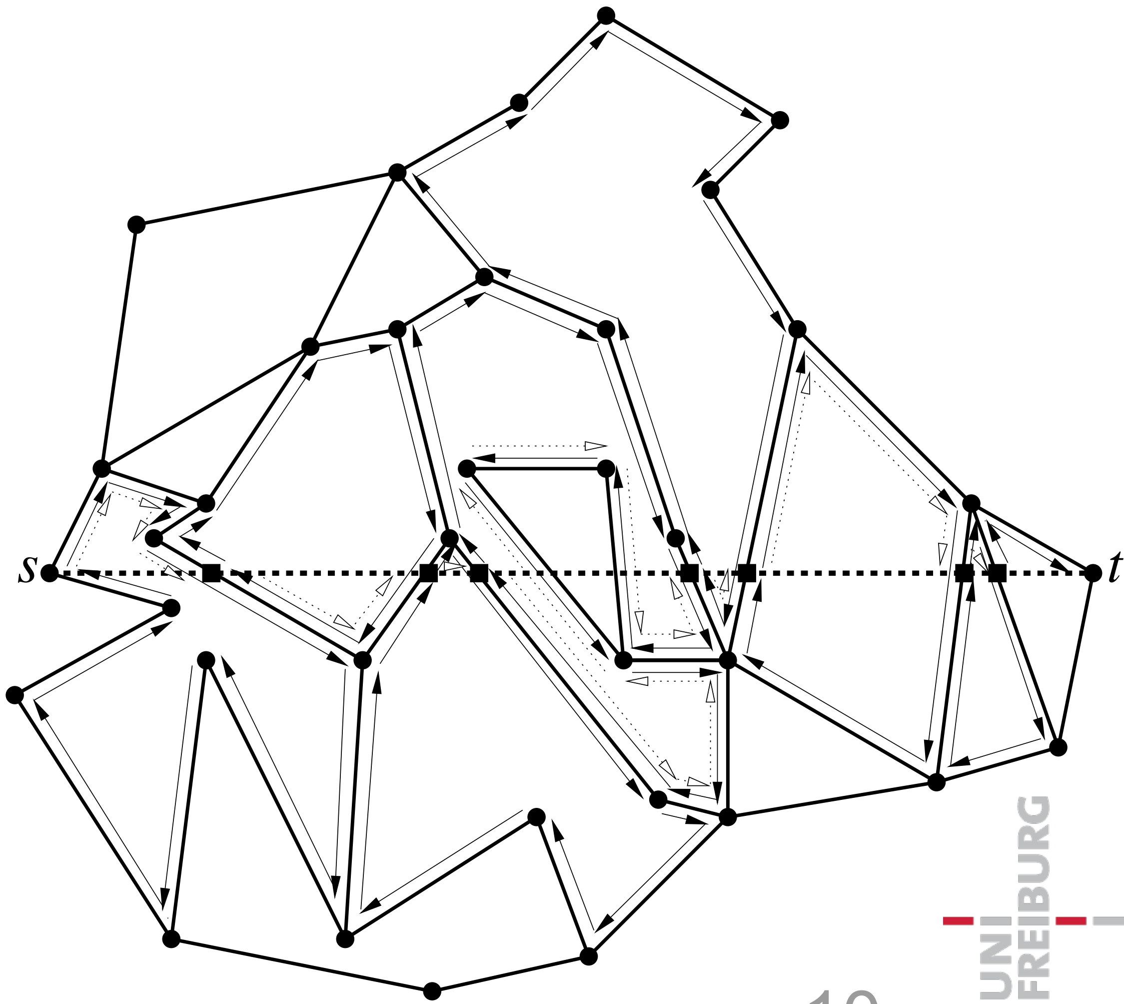




Problems of Recovery

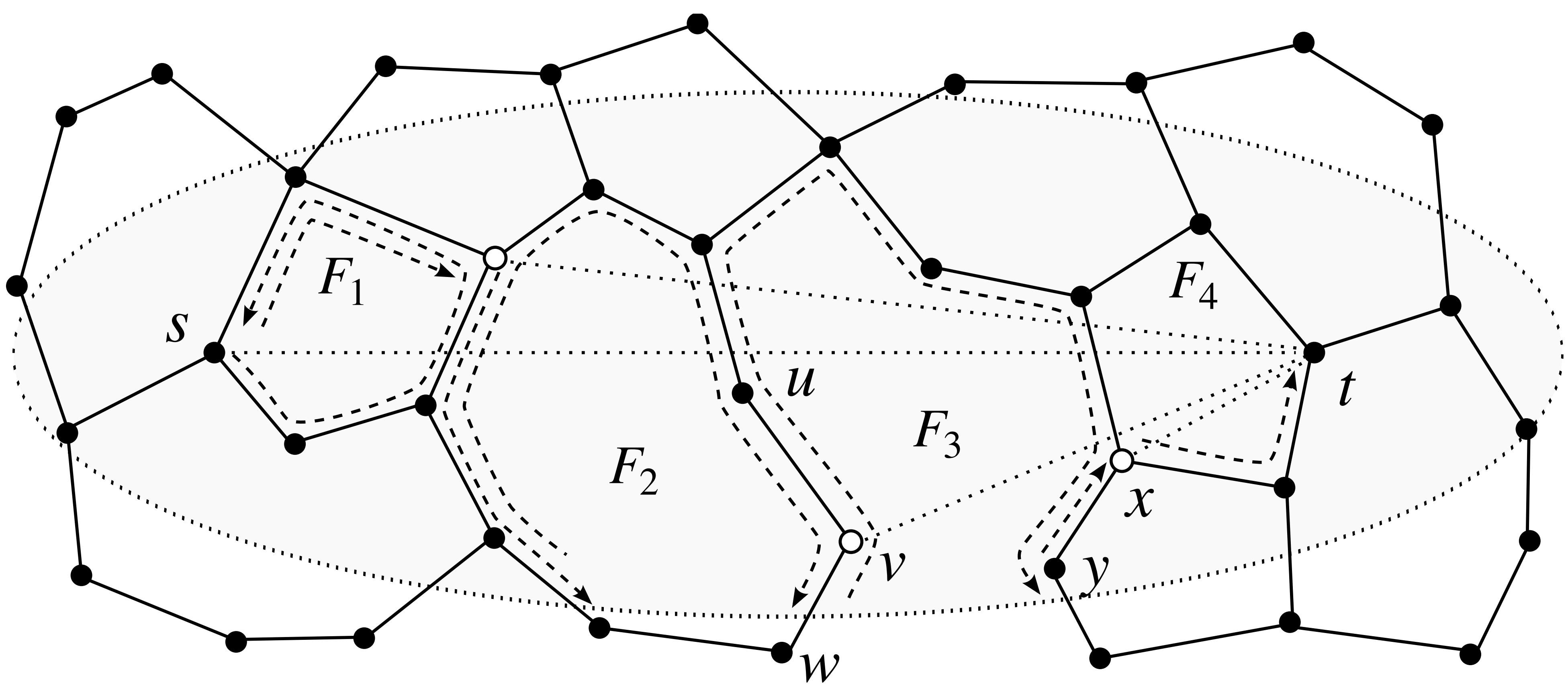
- Recovery strategy can produce large detours
- Solutions
  - Follow recovery strategy until the situation has absolutely improved
    - e.g. until the target is closer
  - Follow a thread
    - Face Routing strategy, GOAFR
    - Kuhn, Wattenhover, Zollinger, Asymptotically Optimal Geometric Mobile Ad-Hoc Routing, DIAL-M 2002





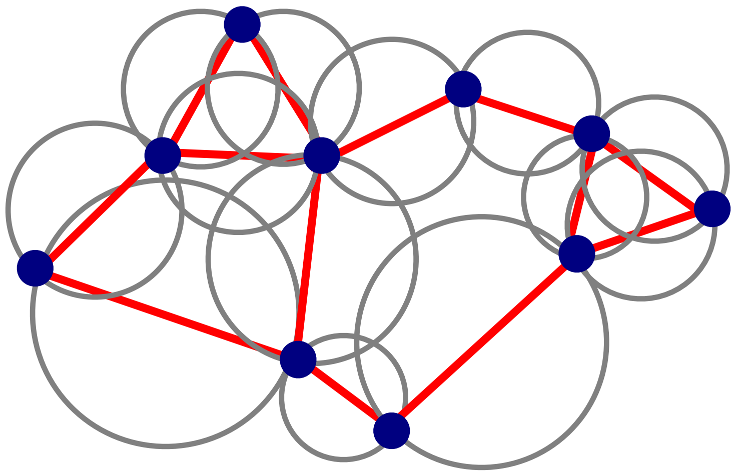
GOAFR: Adaptive Face Routing

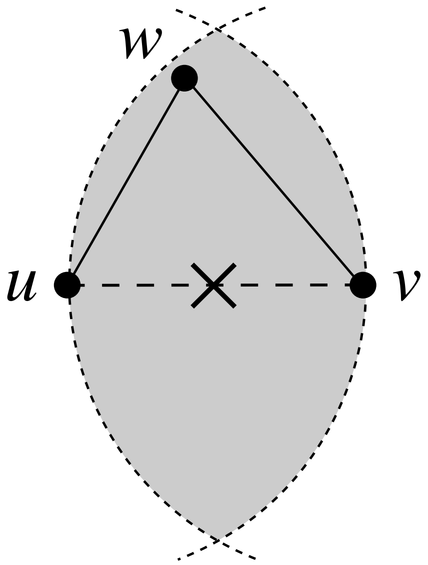
- Adaptive Face Routing
  - Faces are traversed completely while the search area is restricted by a bounding ellipse
  - Recovery strategy + greedy forwarding

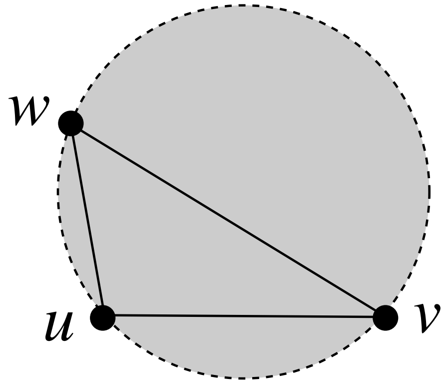


Planarization

- Construction of planar subgraph
  - Gabriel graphs
    - edges where closed disc of which line segment (u,v) is a diameter contains no other elements of S
  - Relative Neighborhood Graph
    - edges connecting two points whenever there does not exist a third point that is closer to both
  - Delaunay Triangulation
    - only triangles such that no point is inside the circumcircle

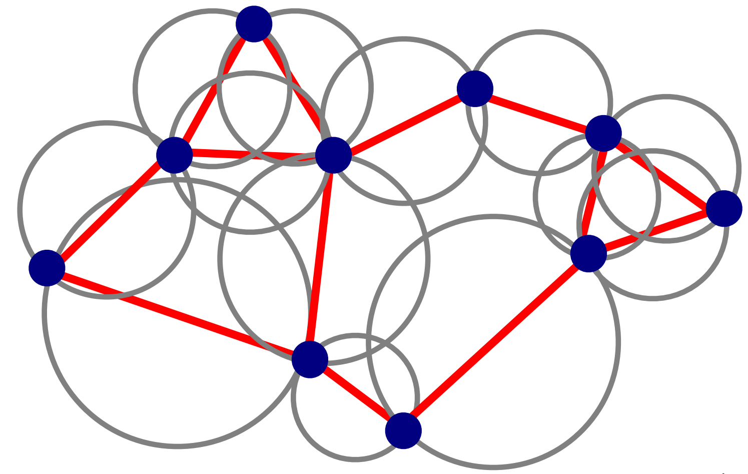




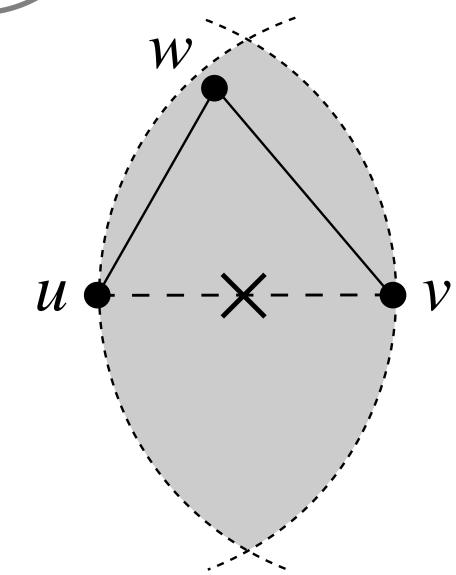


Adaptive Face Routing

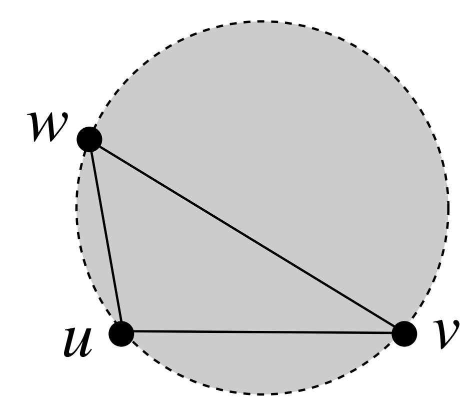
- Spanning ratio/stretch factor
  - max{shortest path(u,v)/ geometric distance(u,v)}
- Gabriel graphs $\Theta(\sqrt{n})$



- Relative Neighborhood Graph
  $\Theta(n)$



- Delaunay Triangulation $\frac{4\pi}{3\sqrt{3}}$
  - but possibly long edges
  - because the convex hull is always a sub-graph of the DT



- A lot of better techniques studied in literature

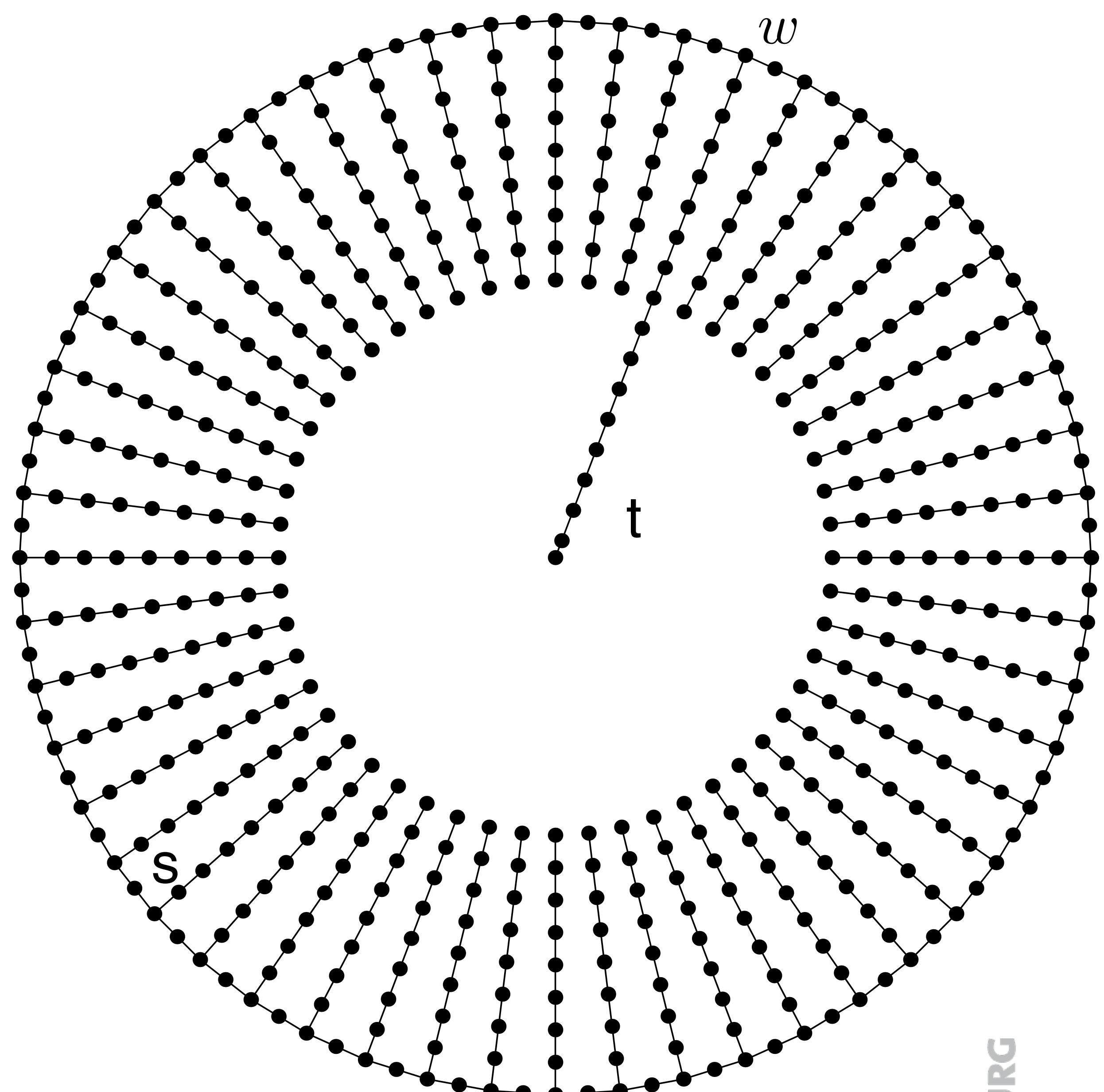
Lower Bound for Geometric Routing

- Kuhn, Wattenhover, Zollinger, Asymptotically Optimal Geometric Mobile Ad-Hoc Routing, DIAL-M 2002

d = length of shortest path

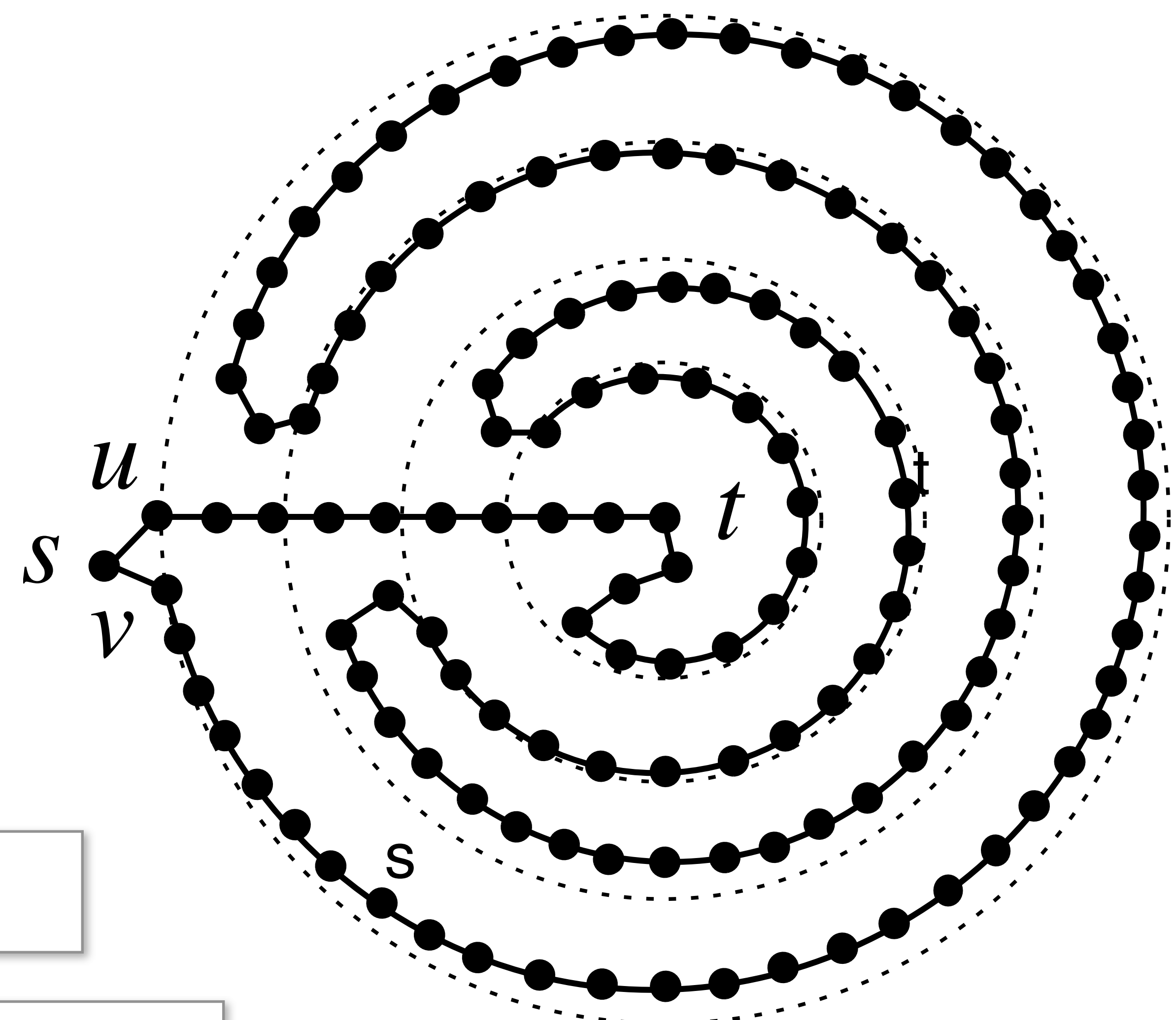
time = #hops, traffic = #messages

Time: $\Omega(d^2)$



Lower Bound for Greedy Routing

- J.Gao,L.J.Guibas,J.E.Hershberger,L.Zhang, A.Zhu,“Geometric spanner for routing in mobile networks,” in 2nd ACM Int. Symposium on Mobile Ad Hoc Networking & Computing (MobiHoc), 2001, pp. 45–55.



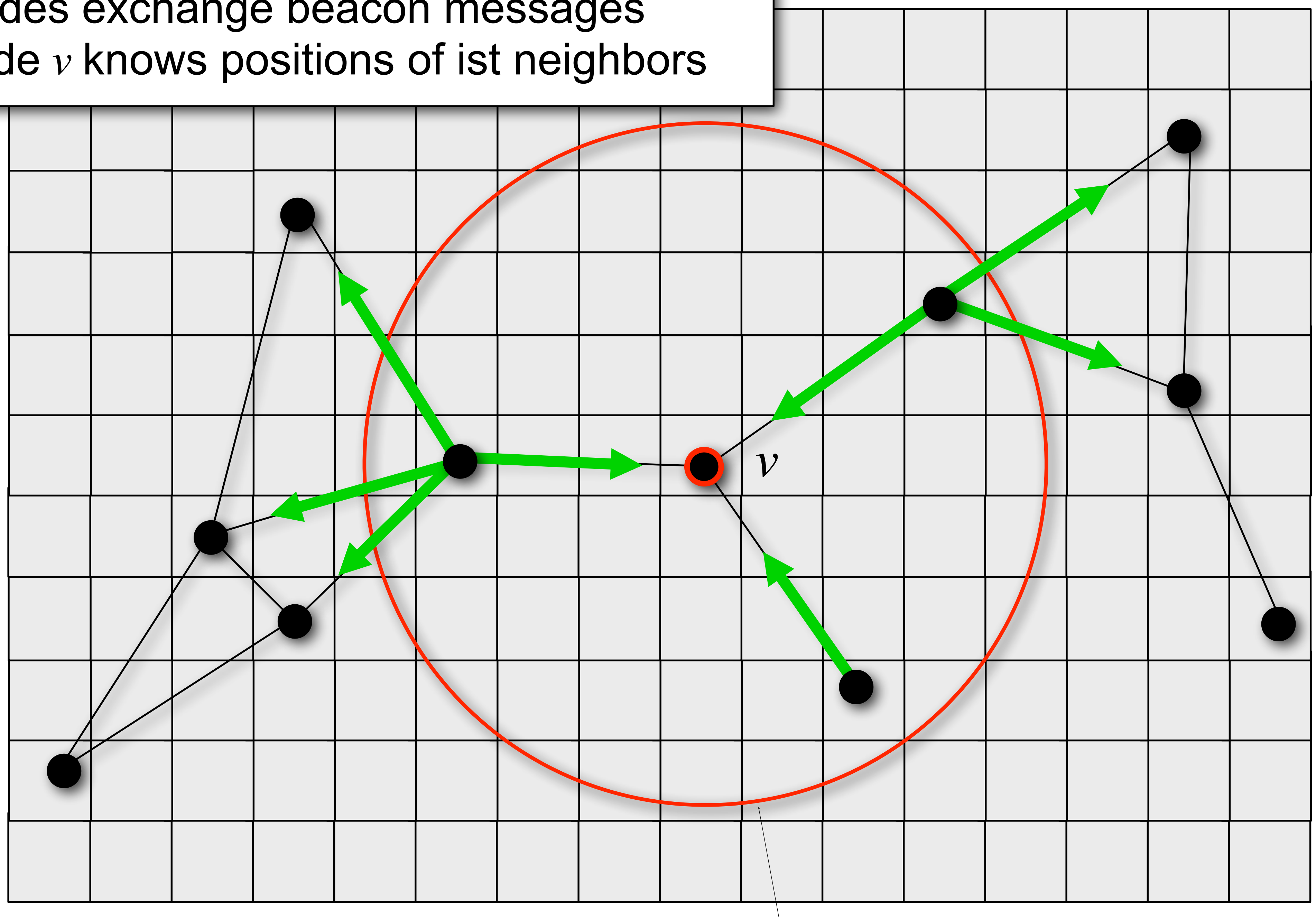
Time: $\Omega(d^2)$

d = length of shortest path

time = #hops, traffic = #messages

A Virtual Cell Structure

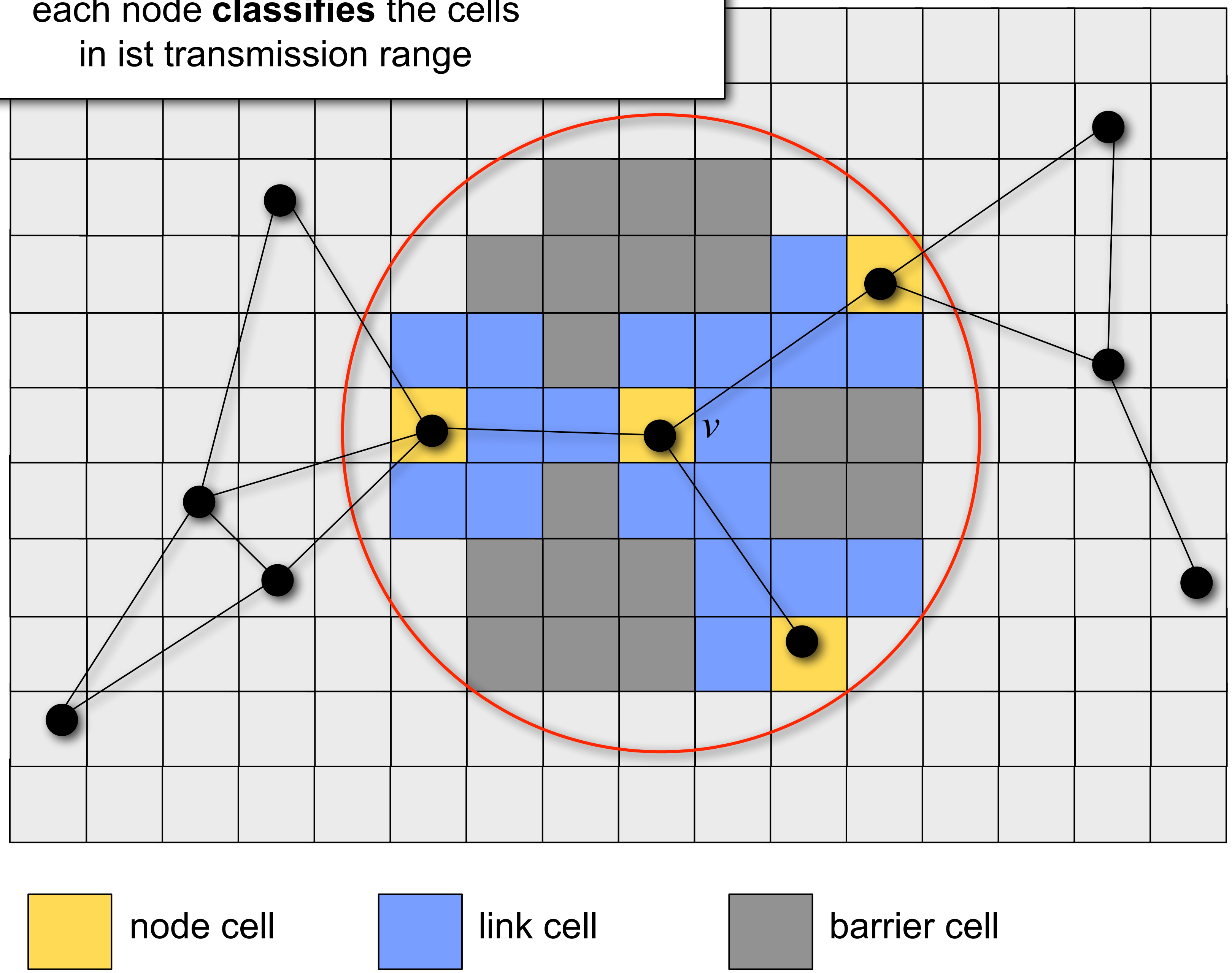
nodes exchange beacon messages
⇒ node v knows positions of ist neighbors



Rührup et al. Online Multi-Path Routing in a Maze, ISAAC 2006

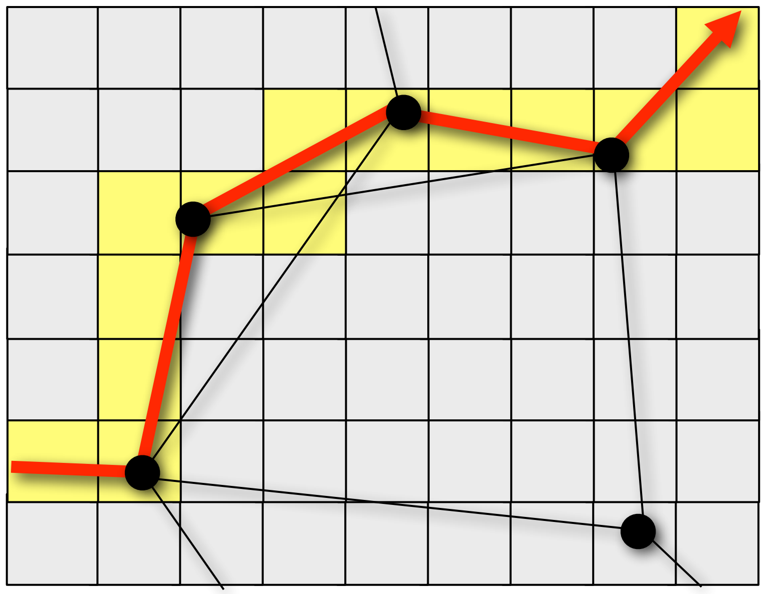
A Virtual Cell Structure

each node **classifies** the cells
in ist transmission range

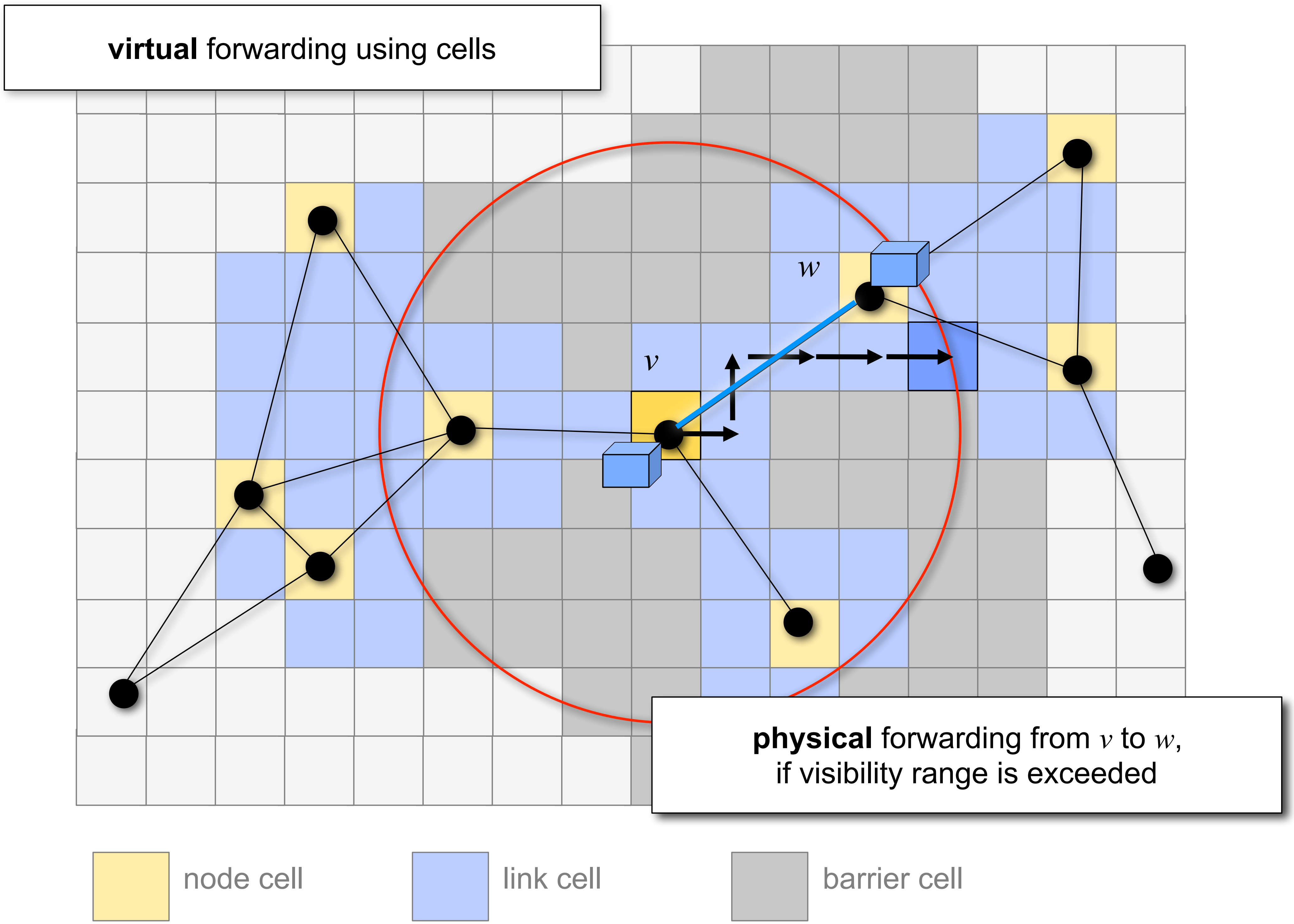


Routing based on the Cell Structure

- Routing based on the cell structure uses cell paths cell path
  - = sequence of orthogonally neighboring cells
- Paths
  - in the unit disk graph and cell paths are equivalent up to a constant factor
- no planarization strategy needed
  - required for recovery using the right-hand rule



Routing based on the Cell Structure



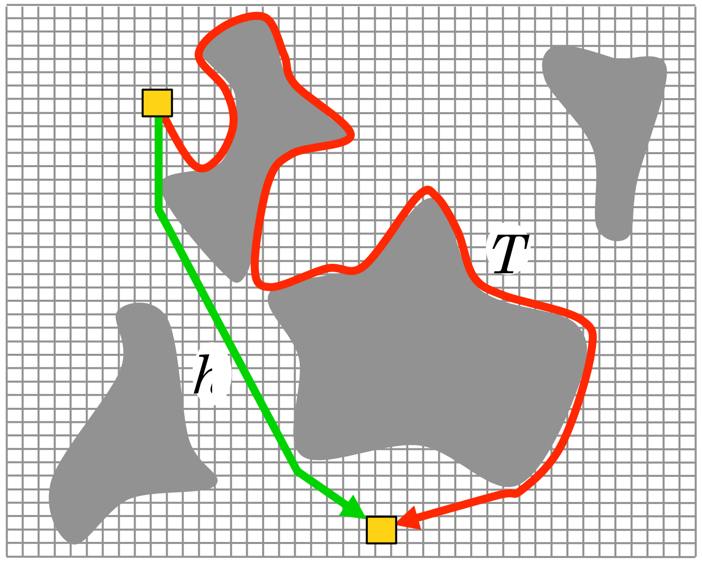
Performance Measures

- competitive ratio: $\dfrac{\text{solution of the algorithm}}{\text{optimal offline solution}}$

- competitive time ratio of a routing algorithm
  - h = length of shortest barrier-free path
  - algorithm needs T rounds to deliver a message

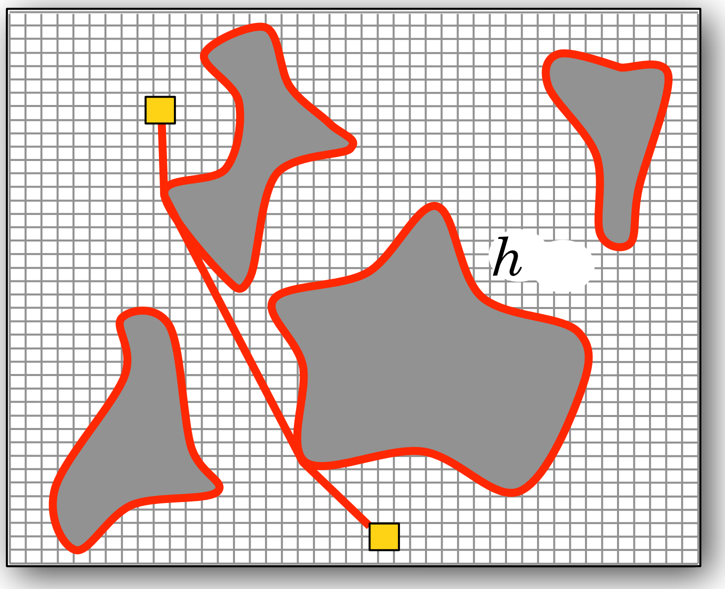
$$\mathcal{R}_t := \frac{T}{h}$$

single-path



Comparative Ratios

- optimal (offline) solution for traffic:
  - h messages (length of shortest path)
- Unfair, because
  - offline algorithm knows the barriers
  - but every online algorithm has to pay exploration costs
- exploration costs
  - sum of perimeters of all barriers (p)
- comparative traffic ratio



$$\mathcal{R}_{Tr} := \frac{M}{h + p}$$

M = # messages used
h = length of shortest path
p = sum of perimeters

Comparative Ratios

- measure for time efficiency:
  - competitive time ratio

$$\mathcal{R}_t := \frac{T}{h}$$

- measure for traffic efficiency:
  - comparative traffic ratio

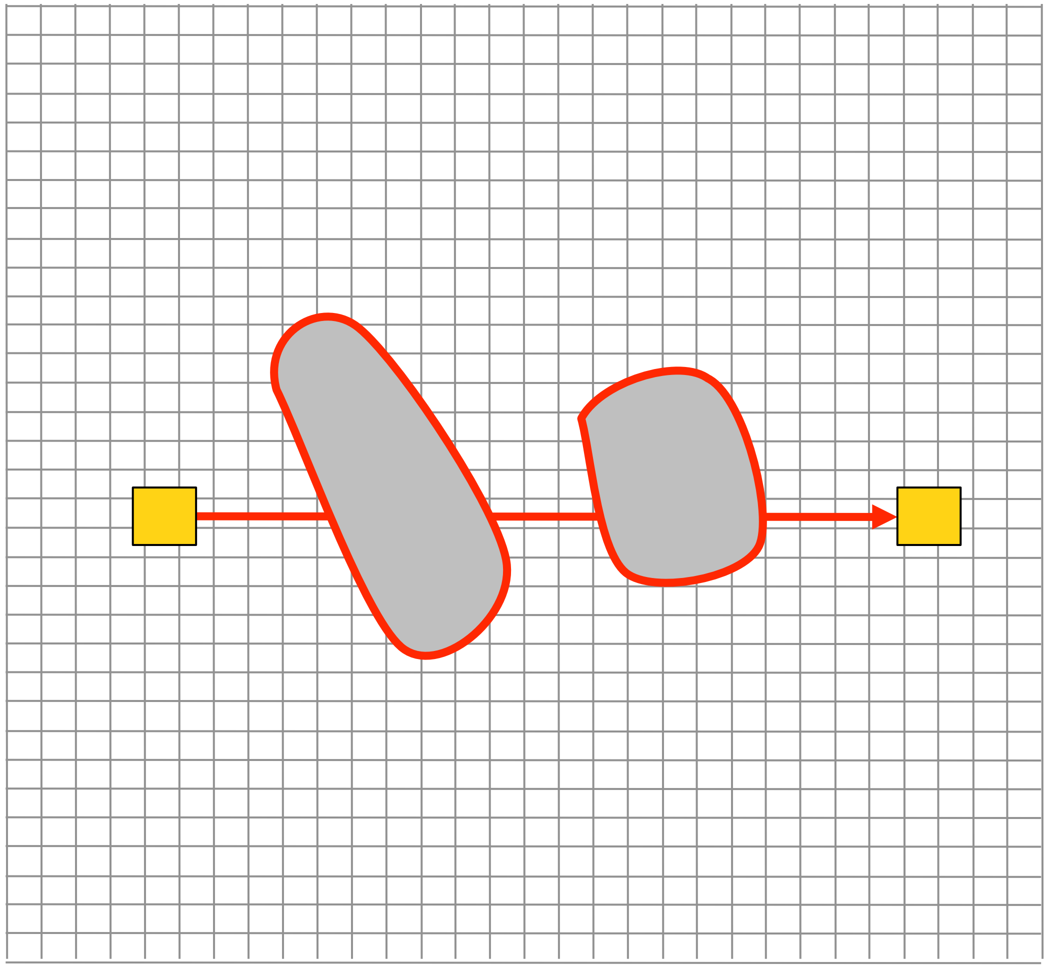
$$\mathcal{R}_{Tr} := \frac{M}{h+p}$$

- Combined comparative ratio
  - time efficiency and traffic efficiency

$$\mathcal{R}_c := \max\{\mathcal{R}_t, \mathcal{R}_{Tr}\}$$

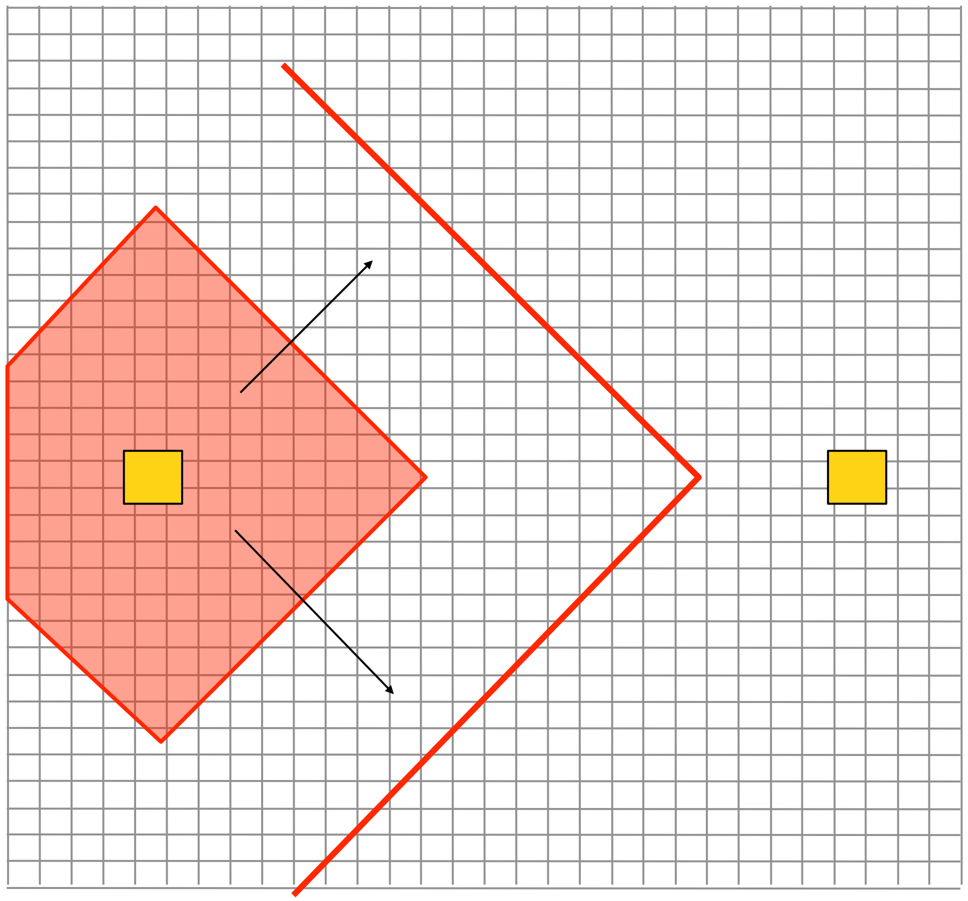
Single Path Strategy

- no parallelism
  - traffic-efficient (time = traffic)
  - example: GuideLine/Recovery
- follow a guide line connecting source and target
- traverse all barriers intersecting the guide line
- Time and Traffic: $\mathcal{O}(h+p)$



Multi-path Strategy

- speed-up by parallel exploration
  - increasing traffic
  - example: Expanding Ring Search
- start flooding with restricted search depth
- if target is not in reach then
  - repeat with double search depth
- Time $\mathcal{O}(h)$
- Traffic $\mathcal{O}(h^2)$



Algorithms under Comparative Measures

	time	traffic
GuideLine/Recovery (single-path)	$\mathcal{O}(h+p)$	
Expanding Ring Search (multi-path)	$\mathcal{O}(h)$	$\mathcal{O}(h^2)$

$$\mathcal{R}_t := \frac{T}{h}$$

$$\mathcal{R}_{Tr} := \frac{M}{h+p}$$

Is that good?

It depends ... on the	scenario	time ratio	traffic ratio	combined ratio
GuideLine/Recovery (single-path)	maze $p = h^2$	$\mathcal{O}(h)$	$\mathcal{O}(1)$	$\mathcal{O}(h)$
Expanding Ring Search (multi-path)	open space $p < h$	$\mathcal{O}(1)$	$\mathcal{O}(h)$	$\mathcal{O}(h)$

The Alternating Algorithm

- uses a combination of both strategies:

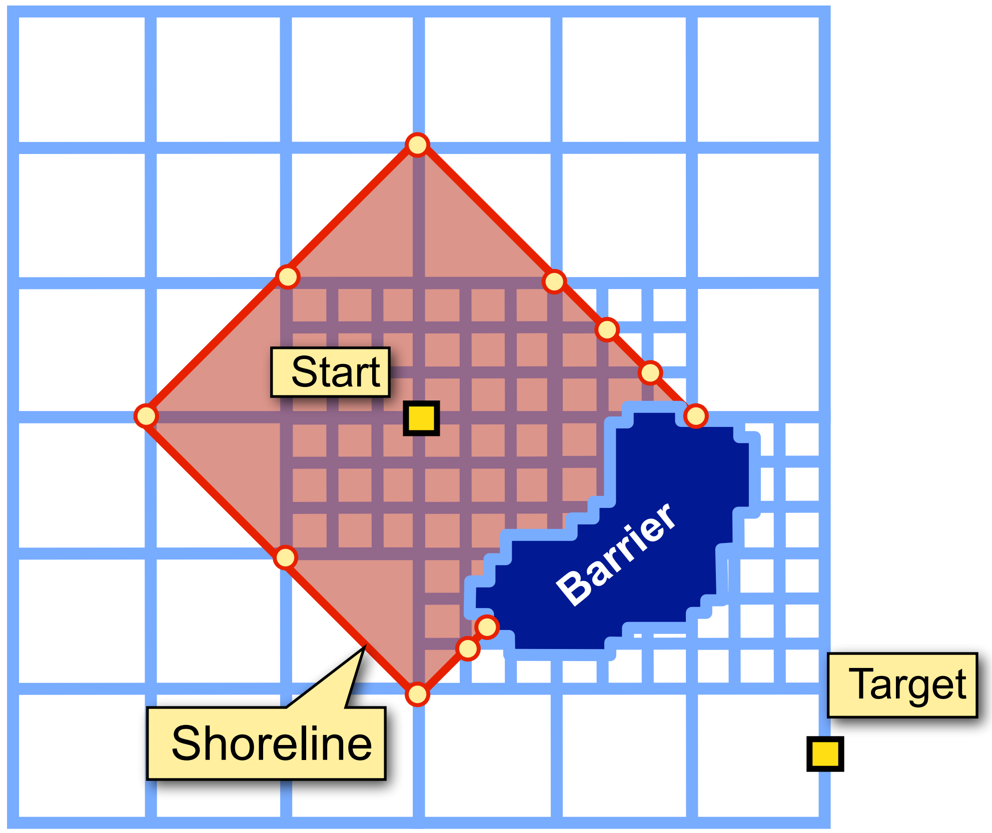
1. i = 1
2. d = 2^i
3. start GuideLine/Recovery with time-to-live = $d^{3/2}$
4. if the target is not reached then
   start Flooding with time-to-live = d
5. if the target is not reached then
   i = i+1
   goto line 2

- Combined comparative ratio: $\mathcal{R}_c = \mathcal{O}(\sqrt{h})$

The JITE Algorithmus

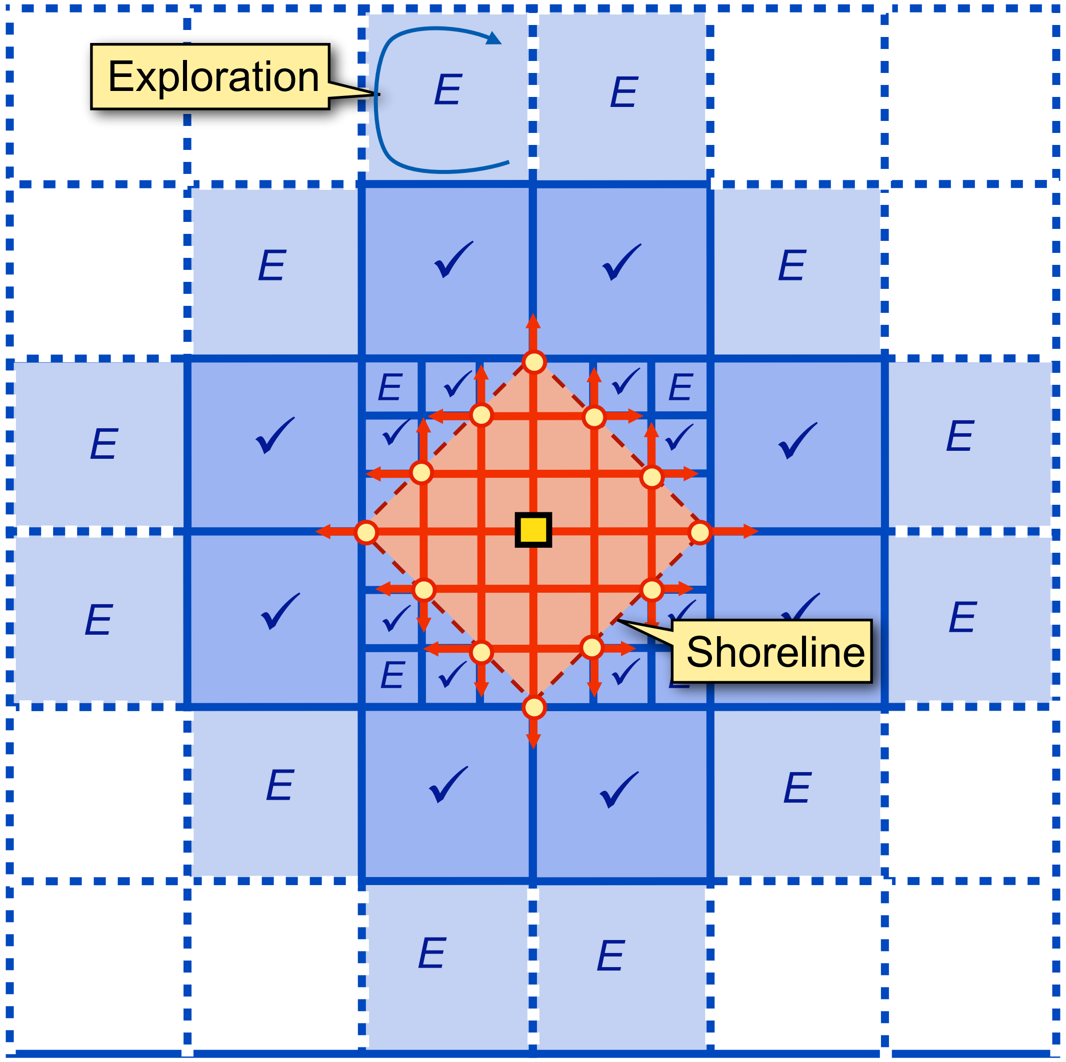
Rührup et al. Online Multi-Path Routing in a Maze, ISAAC 2006

- Complex algorithm
- Message efficient parallel BFS (breadth first search)
  - using Continuous Ring Search
- Just-In-Time Exploration (JITE)
  - construction of search path instead of flooding
- Search paths surround barriers
- Slow Search
  - slow BFS on a sparse grid
- Fast Exploration
  - Construction of the sparse grid near to the shoreline



Slow Search & Fast Exploration

- Slow Search visits only explored paths
- Fast Exploration is started in the vicinity of the BFS-shoreline
- Exploration must be terminated before a frame is reached by the BFS-shoreline



Performance of Geometric Routing Algorithms

Strategy	Time	Traffic	Comb. Comp. Ratio
Exp. Ring Search [9, 18]	$\mathcal{O}(d)$	$\mathcal{O}(d^2)$	$\mathcal{O}(d)$
Lucas' Algorithm [13]	$\mathcal{O}(d+p)$	$\mathcal{O}(d+p)$	$\mathcal{O}(d)$
Alternating Strategy [20]	$\mathcal{O}(d^{3/2})$	$\mathcal{O}(\min\{d^2, d^{3/2}+p\})$	$\mathcal{O}(\sqrt{d})$
Selective Flooding [21]	$d \cdot 2^{\mathcal{O}\left(\sqrt{\frac{\log d}{\log\log d}}\right)}$	$\mathcal{O}(d) + p\, d^{\mathcal{O}\left(\sqrt{\frac{\log\log d}{\log d}}\right)}$	$d^{\mathcal{O}\left(\sqrt{\frac{\log\log d}{\log d}}\right)}$
JITE (this paper)	$\mathcal{O}(d)$	$\mathcal{O}((d+p)\log^2 d)$	$\mathcal{O}(\log^2 d)$
Online Lower Bound (cf. [3])	$\Omega(d)$	$\Omega(d+p)$	$\Omega(1)$

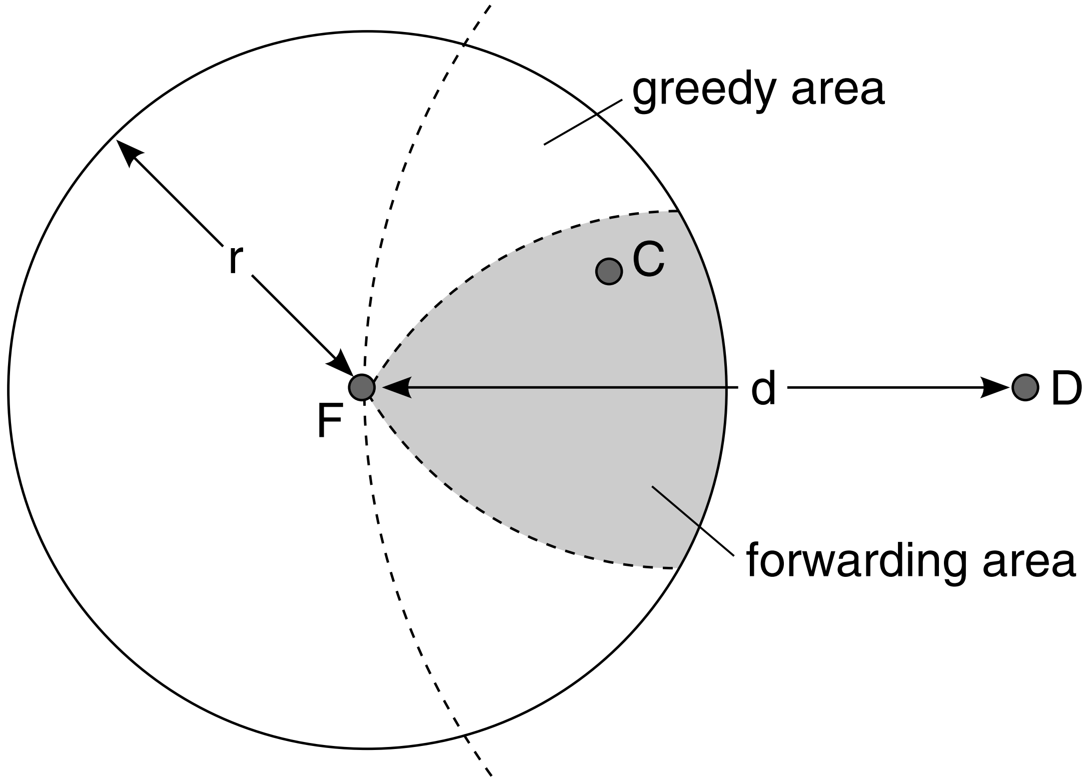
Rührup et al. Online Multi-Path Routing in a Maze, ISAAC 2006

Beacon-Less Geometric Routing

- Literature
  - M. Heissenbüttel and T. Braun, A novel position-based and beacon-less routing algorithm for mobile ad-hoc networks, in 3rd IEEE Workshop on Applications and Services in Wireless Networks, 2003, pp. 197–209.
  - M. Heissenbüttel, T. Braun, T. Bernoulli, and M. Wälchli, BLR: Beacon-less routing algorithm for mobile ad-hoc networks," Computer Communications, vol. 27 (11), pp. 1076–1086, Jul. 2004.
  - H. Kalosha, A. Nayak, S. Rührup, and I. Stojmenovic, Select-and-protest-based beaconless georouting with guaranteed delivery in wireless sensor networks, in 27th Annual IEEE Con- ference on Computer Communications (INFOCOM), Apr. 2008, pp. 346–350.

Beaconless Routing

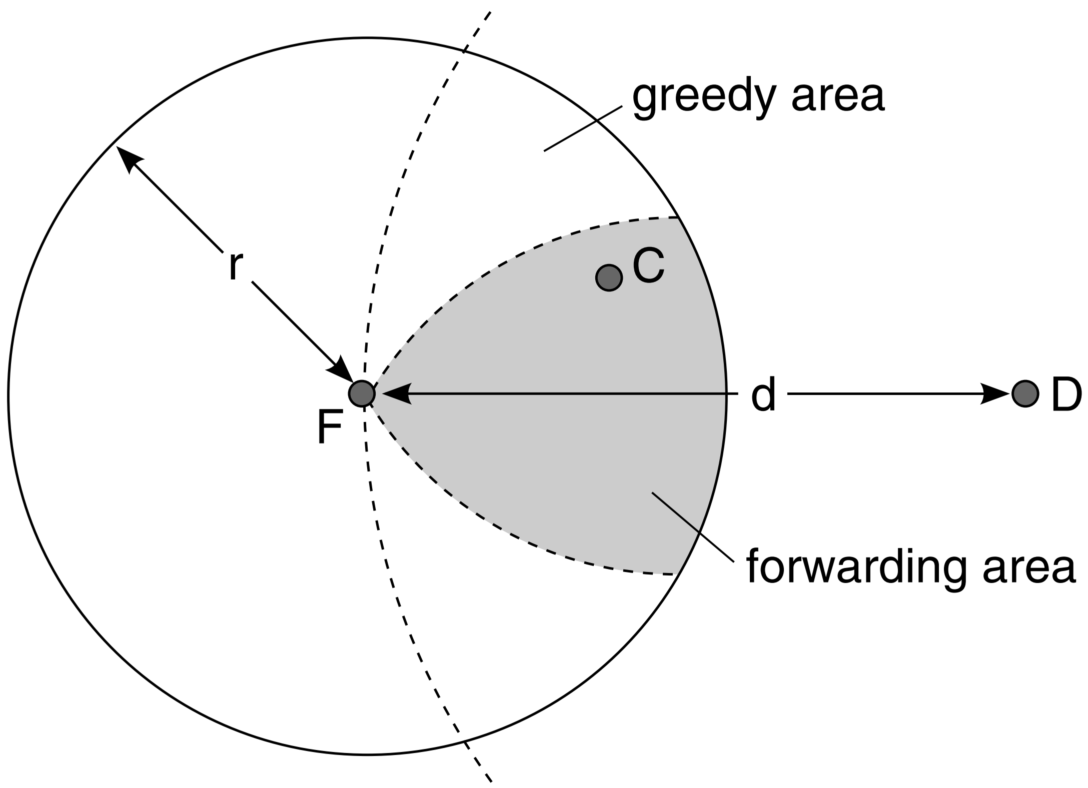
- Givens
  - Each node knows its position
  - A node knows the position of the routing target
  - No beacons
  - The neighborhood is unknown
  - Nodes listen to messages
  - Sparse routing information in packets
- The Idea
  - A packet carries the source and target coordinates
  - Only good located sensor answers



H. Kalosha et al. Select-and-protest-based beaconless georouting with guaranteed delivery in wireless sensor networks InfoCom 2008

Beaconless Routing
The Roles

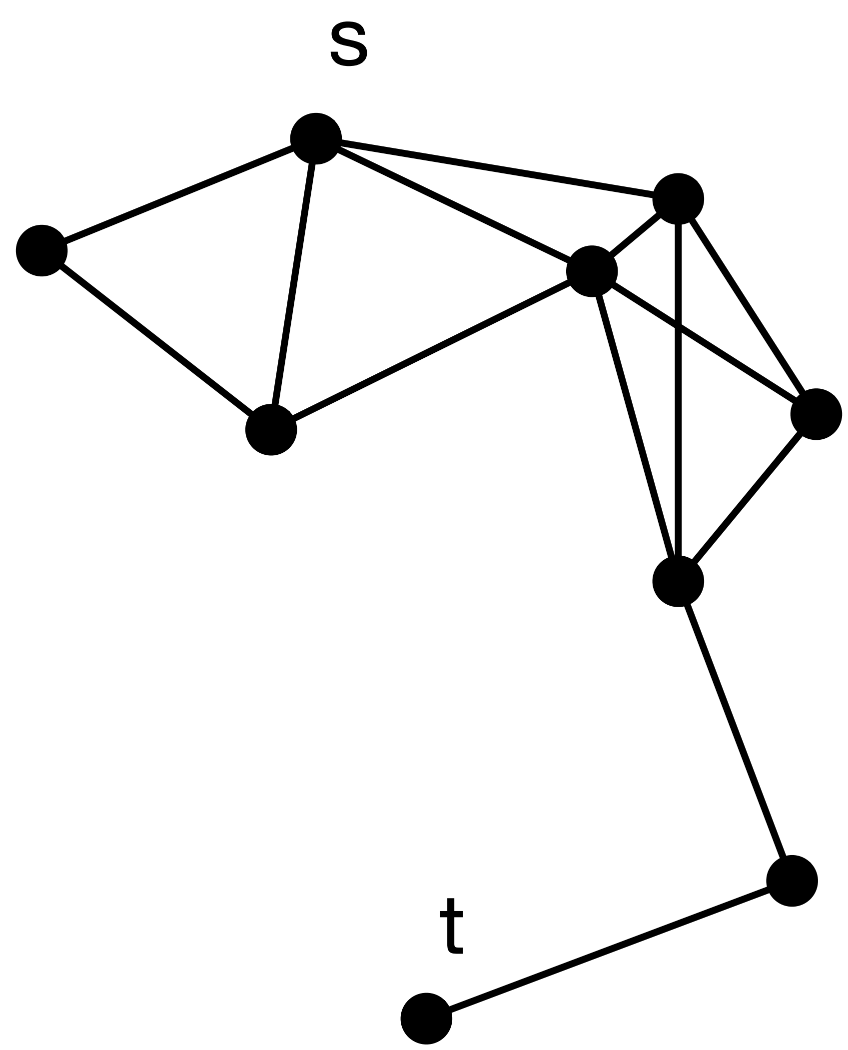
- Forwarder
  - node currently holding the packet
- Forwarding Area
  - nodes in this area are allowed to accept the packets
- Candidates
  - nodes in the forwarding area
  - most suitable candidate chosen by contention
- Timer
  - each candidate has a time based on a delay function
  - The delay function has as parameters the coordinate of the forwarder the target and the own position



H. Kalosha et al. Select-and-protest-based beaconless georouting with guaranteed delivery in wireless sensor networks InfoCom 2008

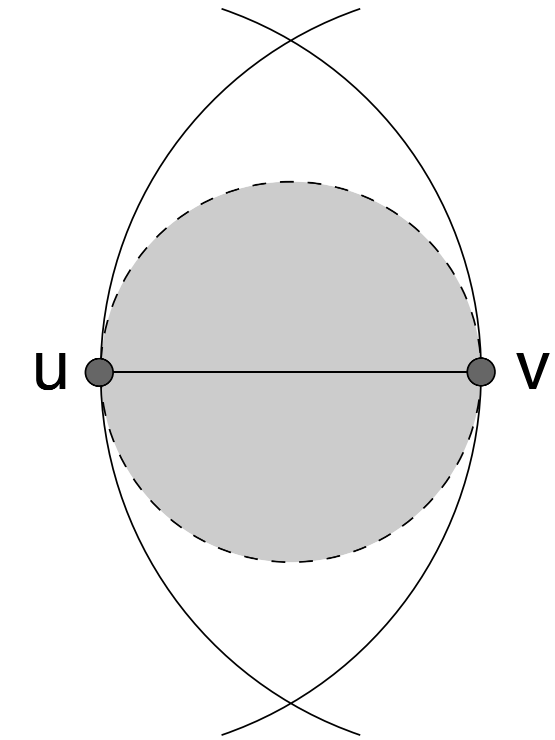
Beaconless Routing Problem: Recovery Strategy

- Greedy Routing works perfectly
- But recovery strategy is problematic
  - How to construct local planar subgraphs on the fly
  - How to determine the next edge of a planar subgraph traversal
- Rules
  - no beacons allowed to solve this problem
  - but interaction with the neighborhood



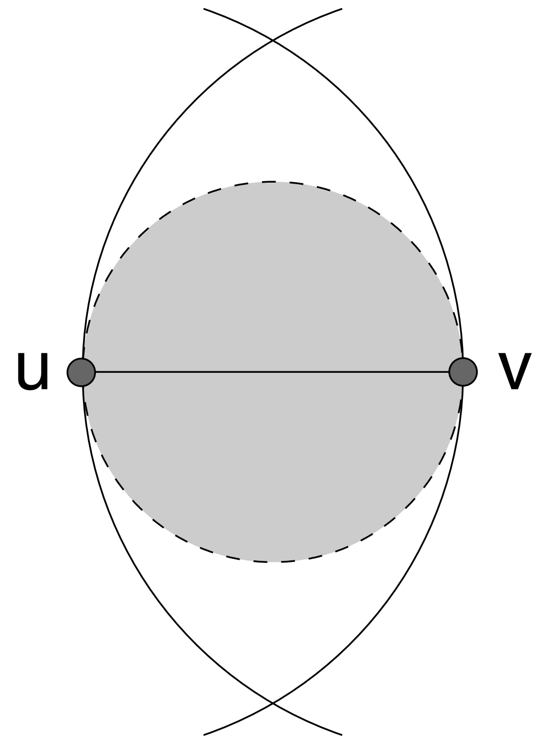
Possible Recovery Strategies

- BLR Backup Mode
  - Literature
    - M. Heissenbüttel, T. Braun, T. Bernoulli, and M. Wälchli, BLR: Beacon-less routing algorithm for mobile ad-hoc networks," Computer Communications, vol. 27 (11), pp. 1076–1086, Jul. 2004.
- Algorithm
  - Forwarder broadcast to **all** neighboring nodes
  - **All** neighbors reply
  - Construct a local planar subgraph (Gabriel Graph)
  - Forward using right-hand-rule
- BLR guarantees delivery
  - but needs reaction of all neighbors (pseudo-beacons)



Possible Recovery Strategies

- NB-FACE
  - Literature
    - M. Narasawa, M. Ono, and H. Higaki, “NB-FACE: No-beacon face ad- hoc routing protocol for reduction of location acquisition overhead,” in 7th Int. Conf. on Mobile Data Management (MDM’06), 2006, p. 102.
- Algorithm
  - Delay function depends on the angle between forwarder candidate and previous hop,
    - such that the first candidate in clockwise or counter-clockwise order responds first.
  - If this node is not a neighbor of the Gabriel graph, then other nodes **protest**
- NB-Faces also guarantees delivery
  - this strategy was improved by Kalosha et al. in order to decrease the number of messages



Location Service

- How to inform all nodes about the position of the destination node(s)
- Categories
  - Flooding-based location dissemination
    - fastest and simplest way
    - yet many messages
  - Quorum-based and home-zone-based strategies
    - reduces communication overhead
  - Movement-based location dissemination
    - location information is spread only locally
    - table of location and time stamps is exchanged when to nodes come close to each other
    - only applicable to mobile networks

Quorum based Location Services

- Location information at group of nodes
- Nodes need to be contacted to obtain information
- E.g. consider grid (Stojmenovic, TR 99)
  - Destination information information is stored on a row
  - Node needs to ask all nodes in a column to receive this information
  - reduces traffic by a factor of $O(n^{1/2})$
- Grid Location Service (Li et al. MobiCom 00)
  - location servers distributed by a hierarchical subdivision of the plane

Home based Location Services

- Each node has a home-zone
  - in this home zone (possibly far away)
  - another nodes is responsible for relaying position information
- Geographic Hash Tables (Ratnasami et al. 02)
  - Node and location are key-value pair
  - key is assigned to a location by a hash function
  - In this location the home zone router is responsible for storing this information
  - Each node updates his information at the home zone router
  - Nodes looking for a node contact home zone router

Summary

- Geometric Routing is a scalable alternative with only local information
- Recovery strategies
  - are necessary since barriers might occur
- Planarization
  - underlying communication graph should be planar
  - erase edges or use cell structure
- Beacon- and baconless Routing
- Location Service is necessary
- Real-world Solutions
  - Flooding
  - Alternating algorithm
  - Greedy with right-hand recovery
  - Greedy with flooding recovery

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