Geo-Routing
Chapter 2

ETH
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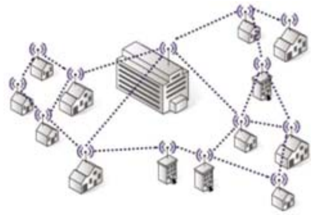
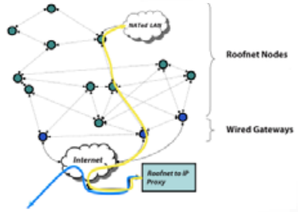
Application of the Week: Mesh Networking (Roofnet)



- Sharing Internet access
- Cheaper for everybody
- Several gateways → fault-tolerance
- Possible data backup
- Community add-ons
  - I borrow your hammer, you copy my homework
  - Get to know your neighbors



Rating

- Area maturity

  First steps — Text book

- Practical importance

  No apps — Mission critical

- Theoretical importance

  Not really — Must have

Overview

- Classic routing overview
- Geo-routing
- Greedy geo-routing

- Euclidean and Planar graphs
- Face Routing
- Greedy and Face Routing
- 3D Geo-Routing

Classic Routing 1: Flooding

- What is Routing?
- „Routing is the act of moving information across a network from a source to a destination.“ (CISCO)

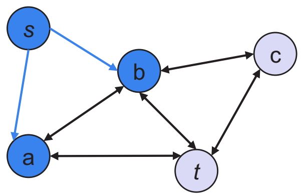
- The simplest form of routing is “flooding”: a source *s* sends the message to all its neighbors; when a node other than destination *t* receives the message the first time it re-sends it to all its neighbors.

+ simple (sequence numbers)

– a node might see the same message more than once. (How often?)

– what if the network is huge but the target *t* sits just next to the source *s*?

- We need a smarter routing algorithm



Classic Routing 2: Link-State Routing Protocols

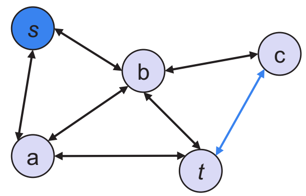
- Link-state routing protocols are a preferred iBGP method (within an autonomous system) in the Internet

- Idea: periodic notification of all nodes about the complete graph
- Routers then forward a message along (for example) the shortest path in the graph

+ message follows shortest path

– every node needs to store whole graph, even links that are not on any path

– every node needs to send and receive messages that describe the whole graph regularly



Classic Routing 3: Distance Vector Routing Protocols

- The predominant method for wired networks
- Idea: each node stores a routing table that has an entry to each destination (destination, distance, neighbor)
- If a router notices a change in its neighborhood or receives an update message from a neighbor, it updates its routing table accordingly and sends an update to all its neighbors

+ message follows shortest path

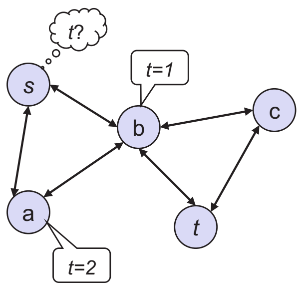
+ only send updates when topology changes

– most topology changes are irrelevant for a given source/destination pair

– every node needs to store a big table

– count-to-infinity problem

Dest	Dir	Dst
a	*a*	1
b	*b*	1
c	*b*	2
t	*b*	2



Discussion of Classic Routing Protocols

- Proactive Routing Protocols

- Both link-state and distance vector are “proactive,” that is, routes are established and updated even if they are never needed.

- If there is almost no mobility, proactive algorithms are superior because they never have to exchange information and find optimal routes easily.

- Reactive Routing Protocols

- Flooding is “reactive,” but does not scale

- If mobility is high and data transmission rare, reactive algorithms are superior; in the extreme case of almost no data and very much mobility the simple flooding protocol might be a good choice.

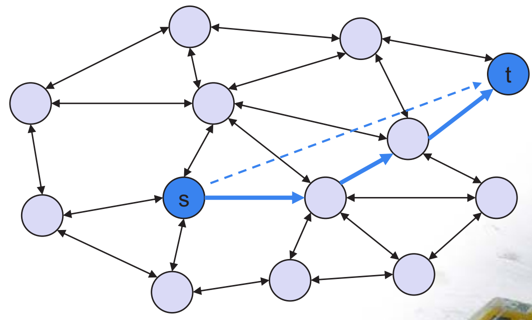
There is *no* “optimal” routing protocol; the choice of the routing protocol depends on the circumstances. Of particular importance is the mobility/data ratio.

Routing in Ad-Hoc Networks

- Reliability
  - Nodes in an ad-hoc network are not 100% reliable
  - Algorithms need to find alternate routes when nodes are failing
- Mobile Ad-Hoc Network (MANET)
  - It is often assumed that the nodes are mobile (“Car2Car”)
- 10 Tricks → 2^{10} routing algorithms
- In reality there are almost that many proposals!
- Q: How good are these routing algorithms?!? Any hard results?
- A: Almost none! Method-of-choice is simulation…
- “If you simulate three times, you get three different results”

Geometric (geographic, directional, position-based) routing

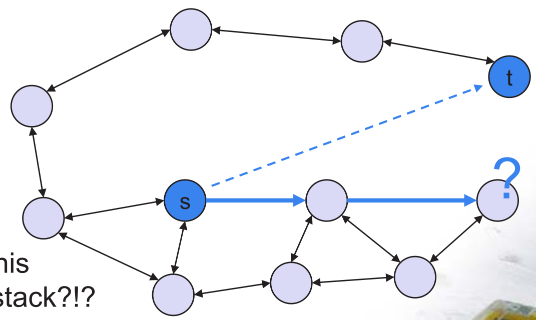
- …even with all the tricks there will be flooding every now and then.
- In this chapter we will assume that the nodes are location aware (they have GPS, Galileo, or an ad-hoc way to figure out their coordinates), and that we know where the destination is.
- Then we simply route towards the destination



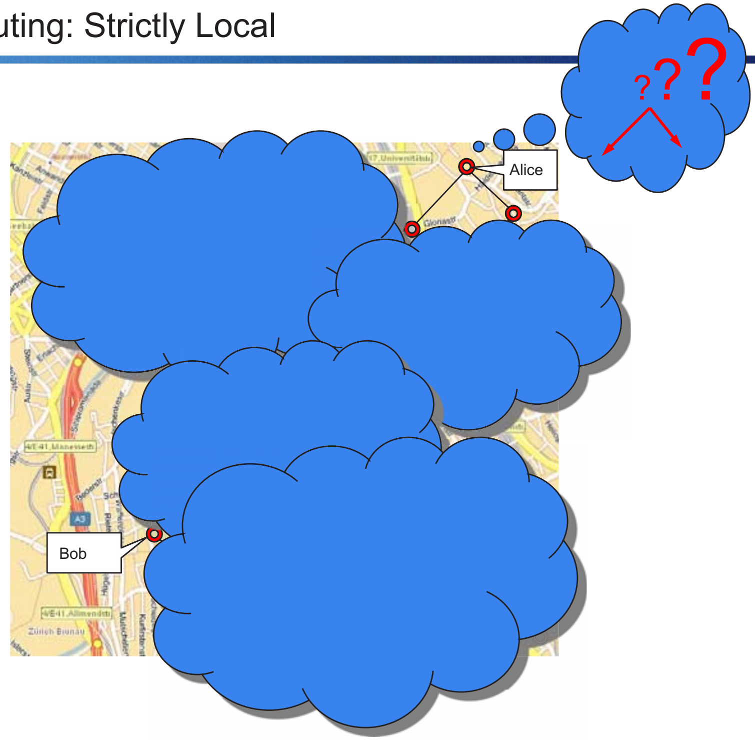
Geometric routing

- Problem: What if there is no path in the right direction?
- We need a guaranteed way to reach a destination even in the case when there is no directional path…
- Hack: as in flooding nodes keep track of the messages they have already seen, and then they backtrack* from there

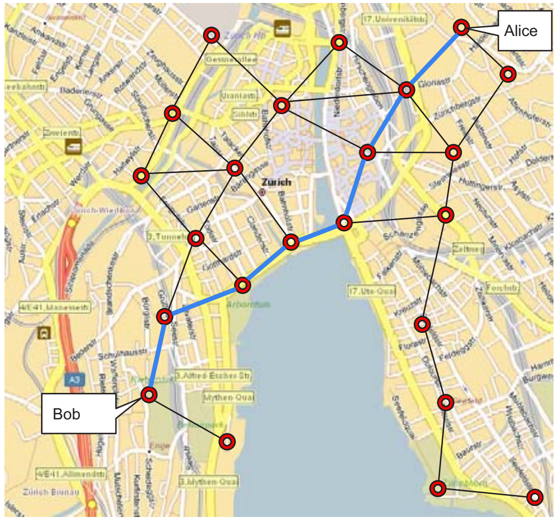
*backtracking? Does this mean that we need a stack?!?



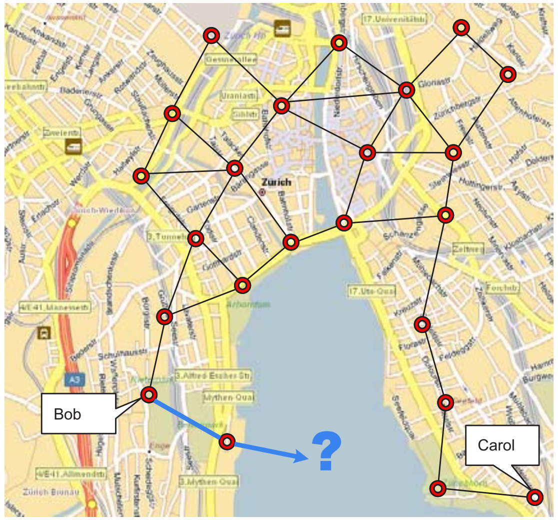
Geo-Routing: Strictly Local



Greedy Geo-Routing?



Greedy Geo-Routing?



What is Geographic Routing?

- A.k.a. geometric, location-based, position-based, etc.

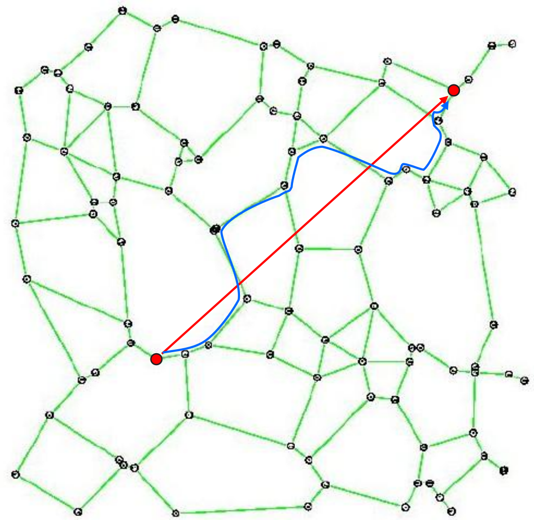
- Each node knows its own position and position of neighbors
- Source knows the position of the destination
- No routing tables stored in nodes!

- Geographic routing makes sense
  - Own position: GPS/Galileo, local positioning algorithms
  - Destination: Geocasting, location services, source routing++
  - Learn about ad-hoc routing in general

Greedy routing

- Greedy routing looks promising.

- Maybe there is a way to choose the next neighbor and a particular graph where we always reach the destination?

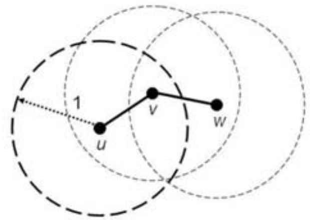


Examples why greedy algorithms fail

Can you think of a network in which greedy routing fails?

Euclidean and Planar Graphs

- Euclidean: Points in the plane, with coordinates, e.g. UDG
- UDG: Classic computational geometry model, special case of disk graphs
- All nodes are points in the plane, two nodes are connected iff (if and only if) their distance is at most 1, that is $\{u,v\} \in E \Leftrightarrow |u,v| \leq 1$

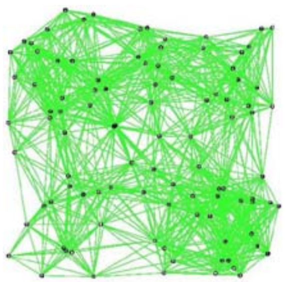


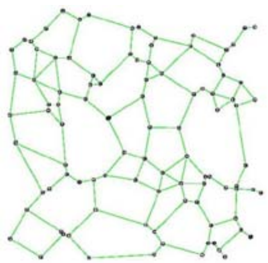
+ Very simple, allows for strong analysis
– Not realistic: “If you gave me $100 for each paper written with the unit disk assumption, I still could not buy a radio that is unit disk!”
– Particularly bad in obstructed environments (walls, hills, etc.)

- Natural extension: 3D UDG

Euclidean and Planar Graphs

- Planar: can be drawn without “edge crossings” in a plane

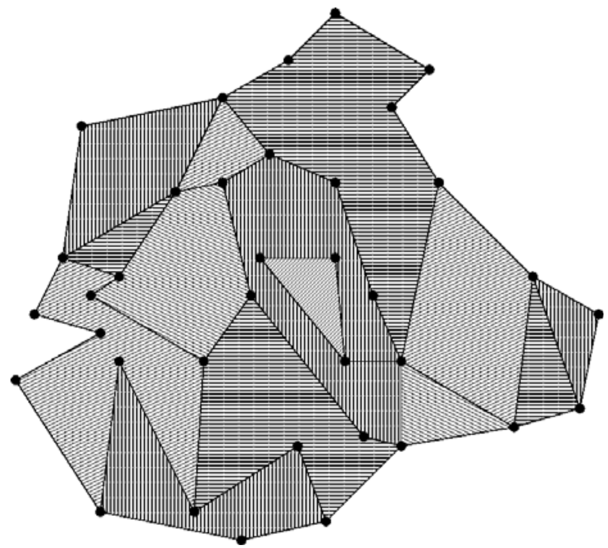




- A planar graph already drawn in the plane without edge intersections is called a plane graph. In the next chapter we will see how to make a Euclidean graph planar.

Breakthrough idea: route on faces

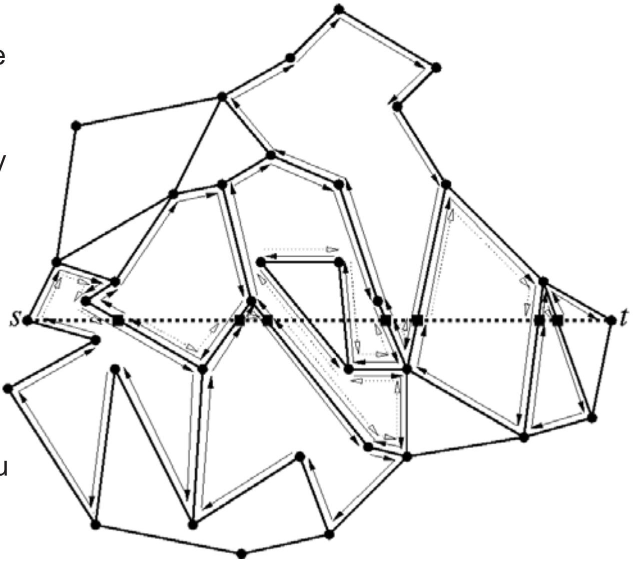
- Remember the faces…
- Idea:
  Route along the boundaries of the faces that lie on the source–destination line



Face Routing

0. Let f be the face incident to the source s, intersected by (s,t)

1. Explore the boundary of f; remember the point p where the boundary intersects with (s,t) which is nearest to t; after traversing the whole boundary, go back to p, switch the face, and repeat 1 until you hit destination t.

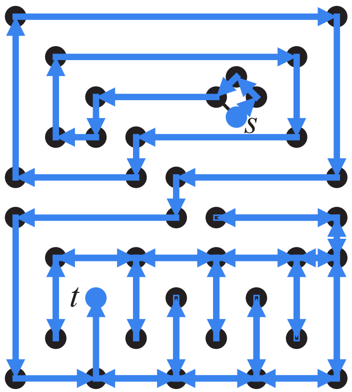


Face Routing Properties

- All necessary information is stored in the message
  - Source and destination positions
  - Point of transition to next face
- Completely local:
  - Knowledge about direct neighbors‘ positions sufficient
  - Faces are implicit

- Planarity of graph is computed locally (not an assumption)
  - Computation for instance with Gabriel Graph

Face Routing Works on *Any* Graph



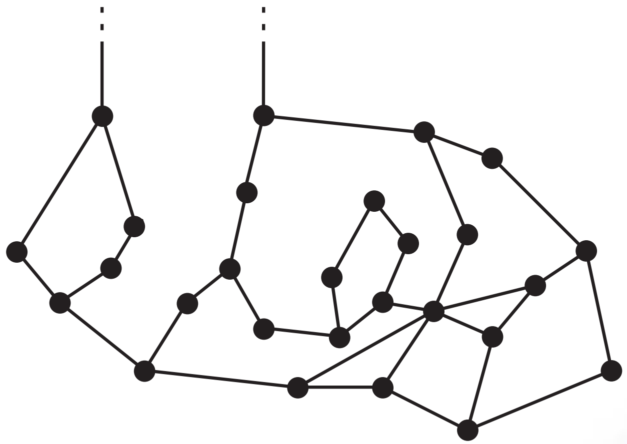
Face routing is correct

- Theorem: Face routing terminates on any simple planar graph in O(n) steps, where n is the number of nodes in the network
- Proof: A simple planar graph has at most 3n–6 edges. You leave each face at the point that is closest to the destination, that is, you never visit a face twice, because you can order the faces that intersect the source—destination line on the exit point. Each edge is in at most 2 faces. Therefore each edge is visited at most 4 times. The algorithm terminates in O(n) steps.

Definition: $f \in O(g) \rightarrow \exists\, c>0, \forall\, x>x_0: f(x) \le c\cdot g(x)$

Face Routing

- Theorem: Face Routing reaches destination in O(n) steps
- But: Can be very bad compared to the optimal route



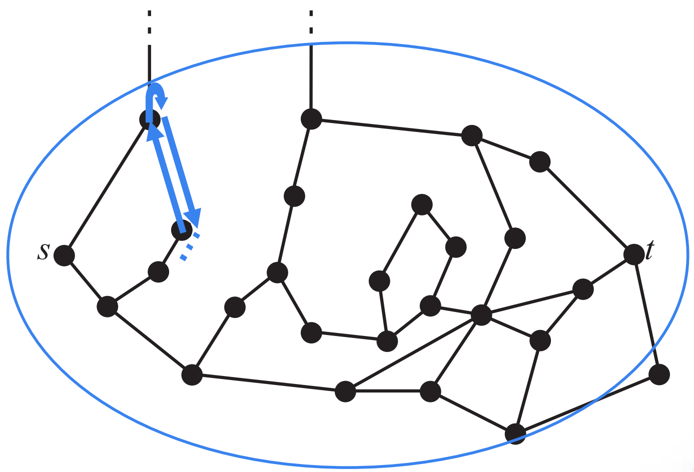
Is there something better than Face Routing?

How can we improve Face Routing?

Is there something better than Face Routing?

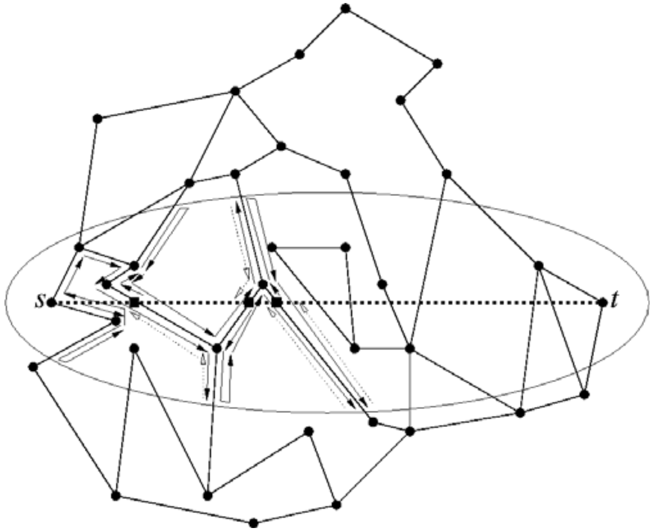
- How to improve face routing? A proposal called “Face Routing 2”
- Idea: Don’t search a whole face for the best exit point, but take the first (better) exit point you find. Then you don’t have to traverse huge faces that point away from the destination.
- Efficiency: Seems to be practically more efficient than face routing. But the theoretical worst case is worse – $O(n^2)$.
- Problem: if source and destination are very close, we don’t want to route through all nodes of the network. Instead we want a routing algorithm where the cost is a function of the cost of the best route in the unit disk graph (and independent of the number of nodes).

Bounding Searchable Area



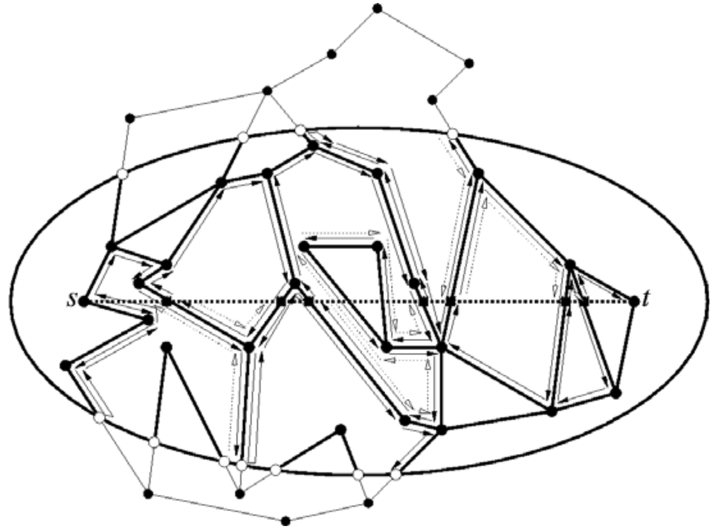
Adaptive Face Routing (AFR)

- Idea: Use face routing together with “growing radius” trick:
- That is, don’t route beyond some radius r by branching the planar graph within an ellipse of exponentially growing size.



AFR Example Continued

- We grow the ellipse and find a path



AFR Pseudo-Code

0. Calculate G = GG(V) ∩ UDG(V)
   Set c to be twice the Euclidean source—destination distance.

1. Nodes w ∈ W are nodes where the path s-w-t is larger than c. Do face routing on the graph G, but without visiting nodes in W. (This is like pruning the graph G with an ellipse.) You either reach the destination, or you are stuck at a face (that is, you do not find a better exit point.)

2. If step 1 did not succeed, double c and go back to step 1.

- Note: All the steps can be done completely locally, and the nodes need no local storage.

The $\Omega(1)$ Model

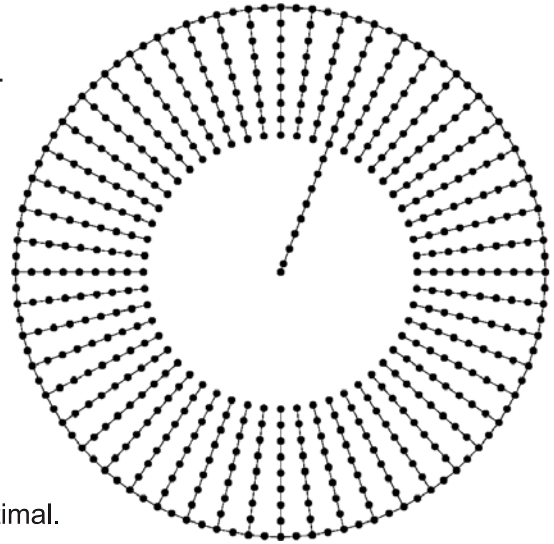
- We simplify the model by assuming that nodes are sufficiently far apart; that is, there is a constant d_0 such that all pairs of nodes have at least distance d_0. We call this the $\Omega(1)$ model.
- This simplification is natural because nodes with transmission range 1 (the unit disk graph) will usually not “sit right on top of each other”.
- Lemma: In the $\Omega(1)$ model, all natural cost models (such as the Euclidean distance, the energy metric, the link distance, or hybrids of these) are equal up to a constant factor.
- Remark: The properties we use from the $\Omega(1)$ model can also be established with a backbone graph construction.

Analysis of AFR in the $\Omega(1)$ model

- Lemma 1: In an ellipse of size c there are at most $O(c^2)$ nodes.
- Lemma 2: In an ellipse of size c, face routing terminates in $O(c^2)$ steps, either by finding the destination, or by not finding a new face.
- Lemma 3: Let the optimal source—destination route in the UDG have cost c*. Then this route c* must be in any ellipse of size c* or larger.
- Theorem: AFR terminates with cost $O(c^{*2})$.
- Proof: Summing up all the costs until we have the right ellipse size is bounded by the size of the cost of the right ellipse size.

Lower Bound

- The network on the right constructs a lower bound.
- The destination is the center of the circle, the source any node on the ring.
- Finding the right chain costs $\Omega(c^{*2})$, even for randomized algorithms
- Theorem: AFR is asymptotically optimal.



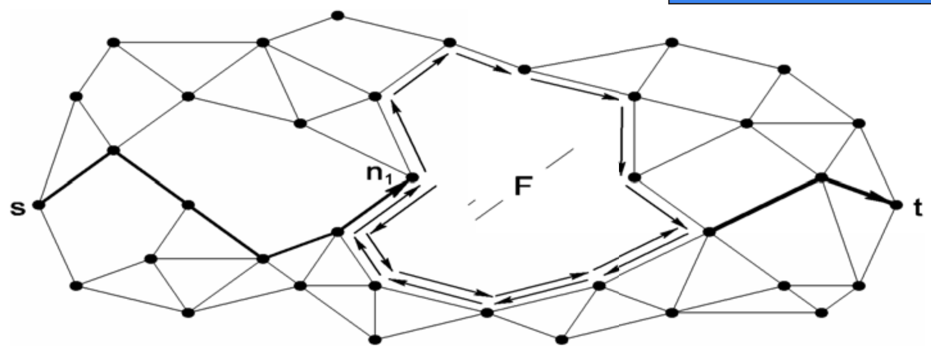
Non-geometric routing algorithms

- In the $\Omega(1)$ model, a standard flooding algorithm enhanced with growing search area idea will (for the same reasons) also cost $O(c^{*2})$.
- However, such a flooding algorithm needs O(1) extra storage at each node (a node needs to know whether it has already forwarded a message).
- Therefore, there is a trade-off between O(1) storage at each node or that nodes are location aware, and also location aware about the destination. This is intriguing.

GOAFR – Greedy Other Adaptive Face Routing

- Back to geometric routing…
- AFR Algorithm is not very efficient (especially in dense graphs)
- Combine Greedy and (Other Adaptive) Face Routing
  - Route greedily as long as possible
  - Circumvent "dead ends" by use of face routing
  - Then route greedily again

Other AFR: In each face proceed to point closest to destination

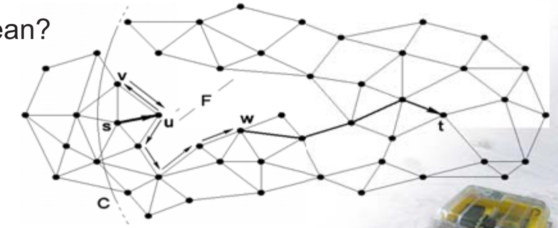


GOAFR+ – Greedy Other Adaptive Face Routing

- Early fallback to greedy routing:
  - Use counters p and q. Let u be the node where the exploration of the current face F started
    - p counts the nodes closer to t than u
    - q counts the nodes *not* closer to t than u
  - Fall back to greedy routing as soon as p > $\sigma \cdot$ q (constant σ > 0)

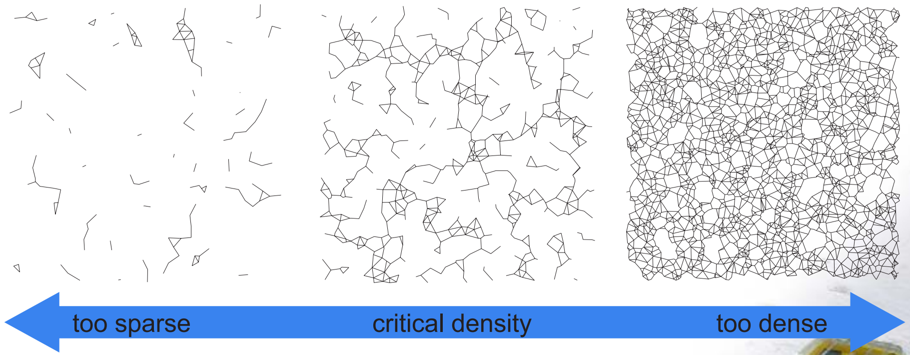
Theorem: GOAFR is still asymptotically worst-case optimal…
…*and* it is efficient in practice, in the average-case.

- What does "practice" mean?
  - Usually nodes placed uniformly at random



Average Case

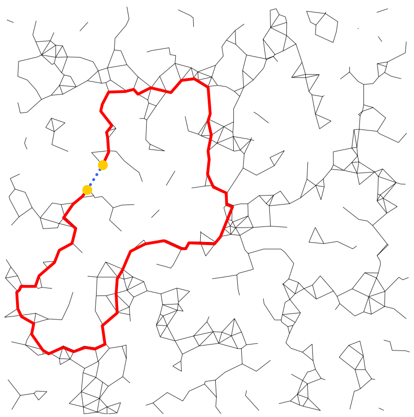
- Not interesting when graph not dense enough
- Not interesting when graph is too dense
- Critical density range ("percolation")
  - Shortest path is significantly longer than Euclidean distance



Critical Density: Shortest Path vs. Euclidean Distance

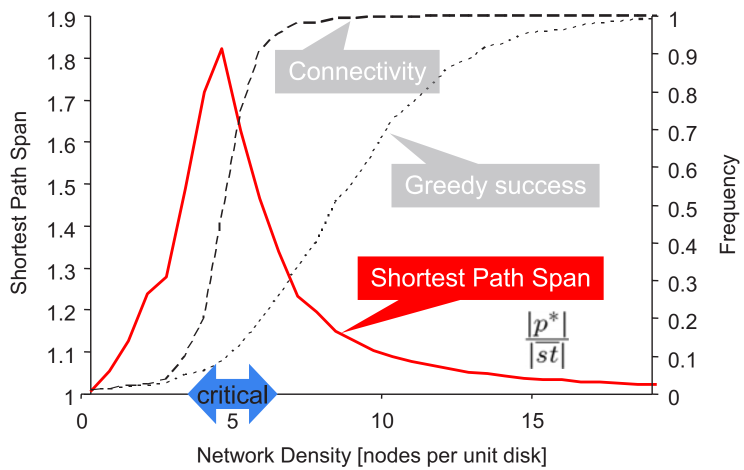
- Shortest path is significantly longer than Euclidean distance

$$\frac{|p^*|}{|st|}$$

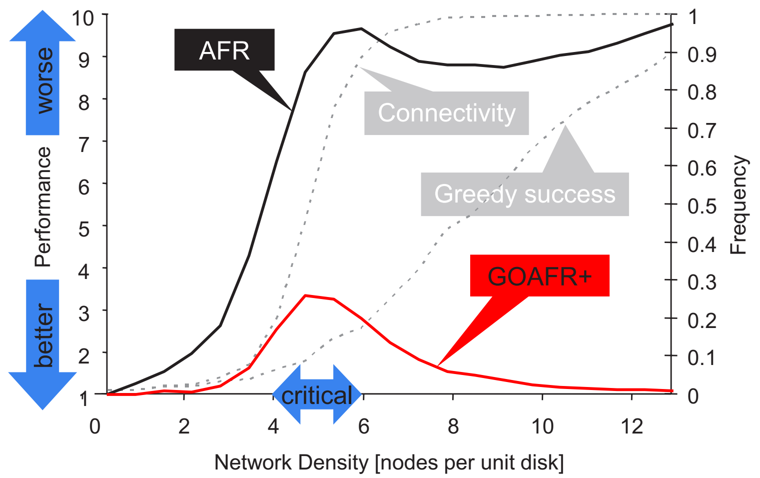


- Critical density range mandatory for the simulation of any routing algorithm (not only geographic)

Randomly Generated Graphs: Critical Density Range



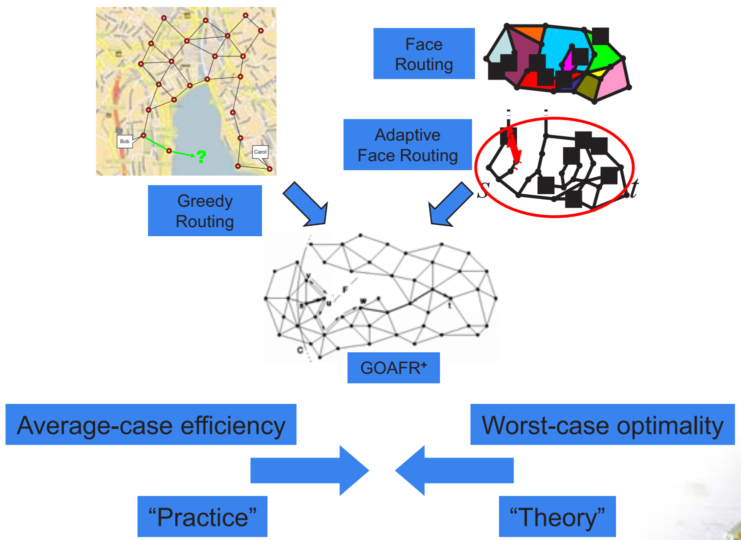
Simulation on Randomly Generated Graphs



A Word on Performance

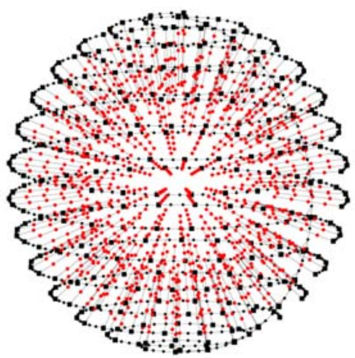
- What does a performance of 3.3 in the critical density range mean?
- If an optimal path (found by Dijkstra) has cost c, then GOAFR+ finds the destination in 3.3·c steps.
- It does *not* mean that the *path* found is 3.3 times as long as the optimal path! The path found can be much smaller…
- Remarks about cost metrics
  - In this lecture "cost" c = c hops
  - There are other results, for instance on distance/energy/hybrid metrics
  - In particular: With energy metric there is no competitive geometric routing algorithm

GOAFR: Summary



3D Geo-Routing

- The world is not flat. We can certainly envision networks in 3D, e.g. in a large office building. Can we geo-route in three dimensions? Are the same techniques possible?
- Certainly, if the node density is high enough (and the node distribution is kind to us), we can simply use greedy routing. But what about those local minima?!?
- Is there something like a face in 3D?
- The picture on the right is the 3D equivalent of the 2D lower bound, proving that we need at least OPT^3 steps.



3D Geo Routing

How would you do 3D routing?

Routing with and without position information

- Without position information:
  - Flooding
    → does not scale
  - Distance Vector Routing
    → does not scale
  - Source Routing
    - increased per-packet overhead
    - no theoretical results, only simulation
- With position information:
  - Greedy Routing
    → may fail: message may get stuck in a “dead end”
  - Geometric Routing
    → It is assumed that each node knows its position

Summary of Results

- If position information is available geo-routing is a feasible option.
- Face routing guarantees to deliver the message.
- By restricting the search area the efficiency is OPT^2.
- Because of a lower bound this is asymptotically optimal.
- Combining greedy and face gives efficient algorithm.
- 3D geo-routing is impossible.
- Even if there is no position information, some ideas might be helpful.

- Geo-routing is probably the only class of routing that is well understood.
- There are many adjacent areas: topology control, location services, routing in general, etc.

Open problem

- Geo-routing is one of the best understood topics. In that sense it is hard to come up with a decent open problem. Let’s try something wishy-washy.

- We have seen that for a 2D UDG the efficiency of geo-routing can be quadratic to an optimal algorithm (with routing tables). However, the worst-case example is quite special.

- Open problem: How much information does one need to store in the network to guarantee only constant overhead?
  - Variant: Instead of UDG some more realistic model
  - How can one maintain this information if the network is dynamic?