Overlay networks for wireless ad hoc networks

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Motivation

Wireless ad hoc networks have many important applications:

- search and rescue missions
- emergency situations
- military applications

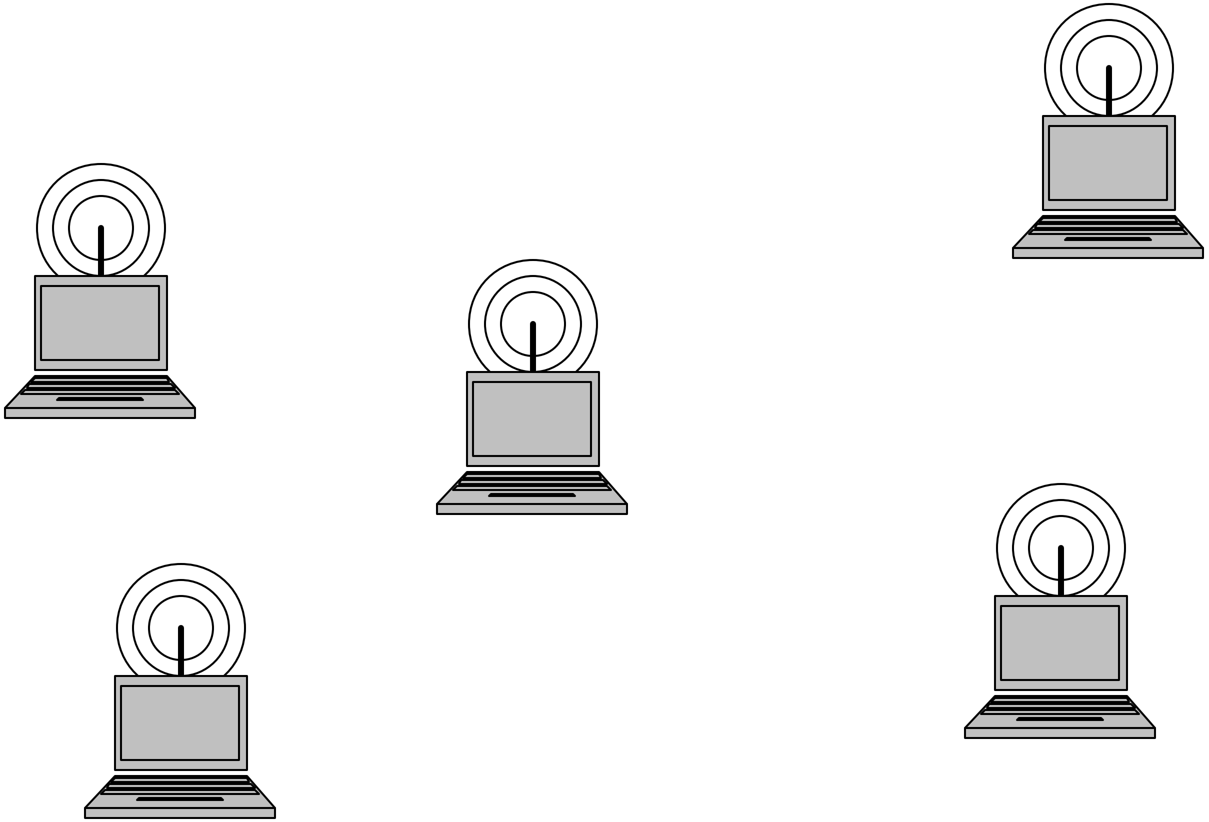
- Signal processing and MAC: OK
- Scheduling: somewhat OK
- Routing: HARD!!

Outline

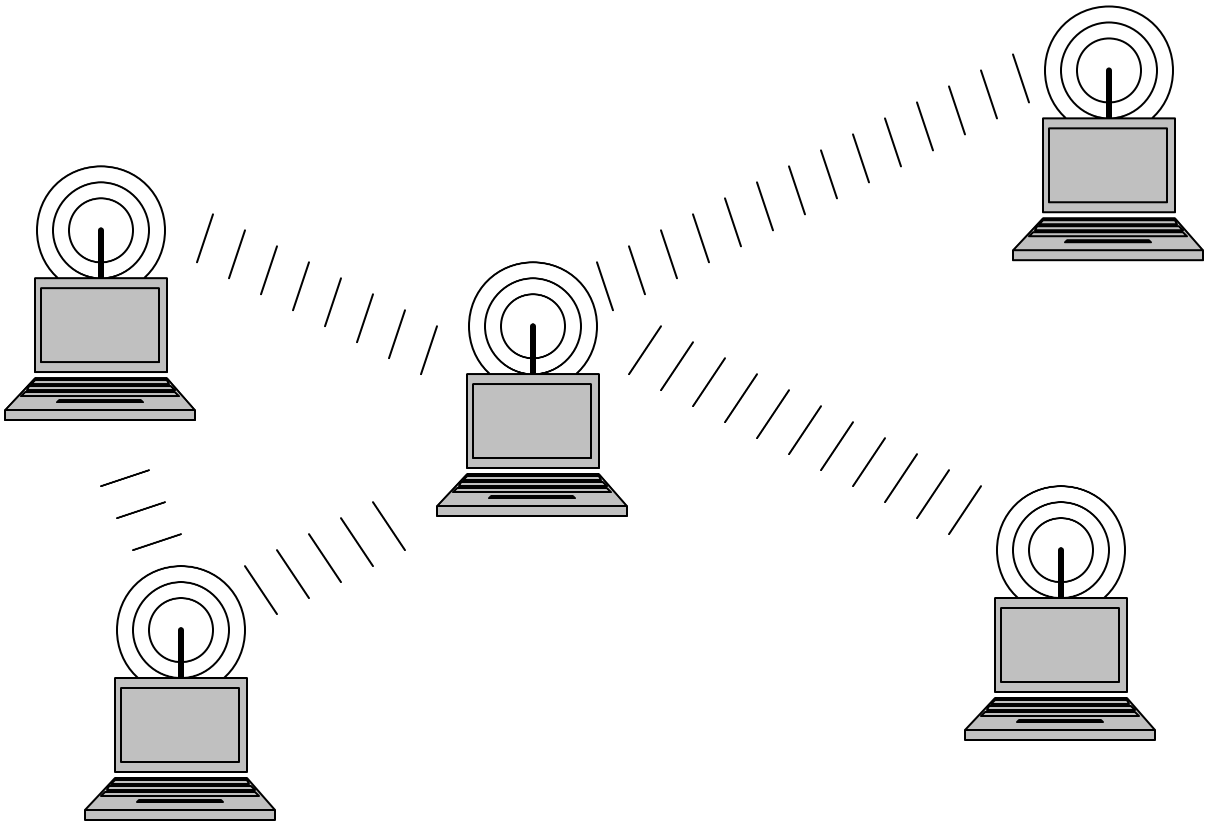
In this talk:

- Basic model and goals
- Basic approach (graph spanners)
- Basic results about spanners
- Examples
- Extensions and problems
- Realistic wireless models and protocols
- References

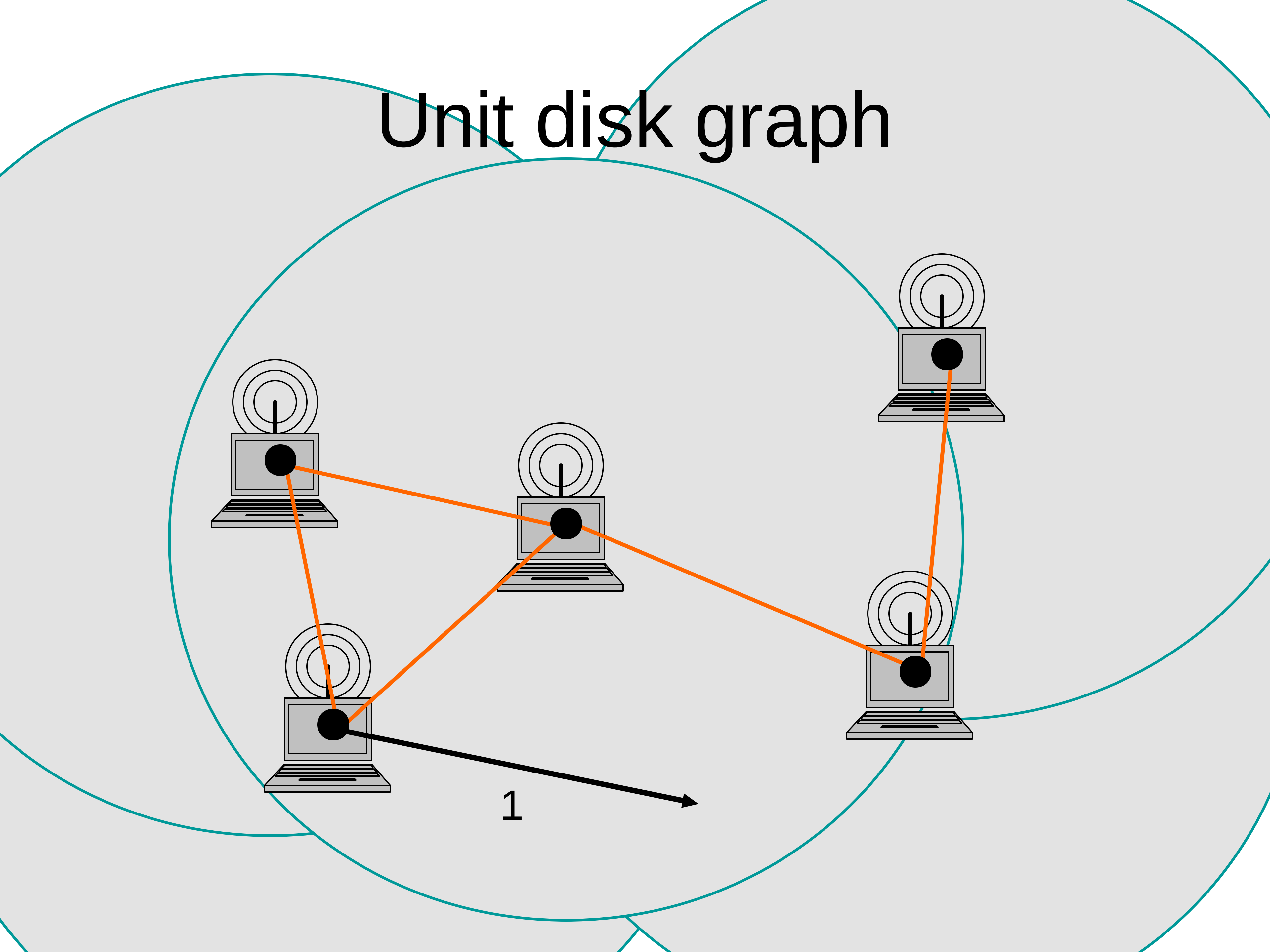
Wireless ad hoc network



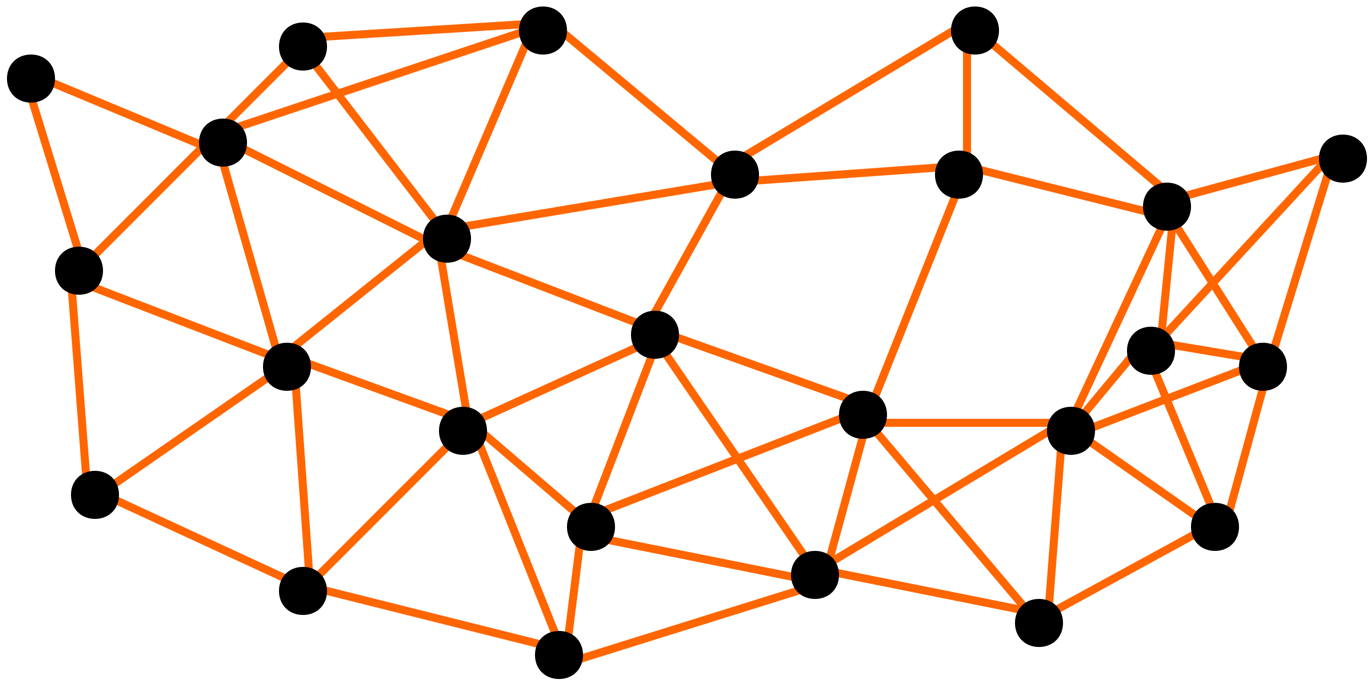
Overlay network



Unit disk graph



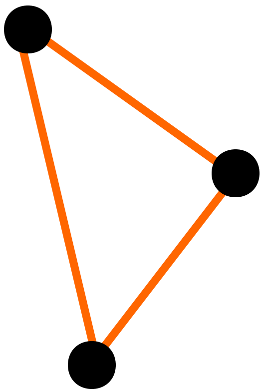
Unit disk graph

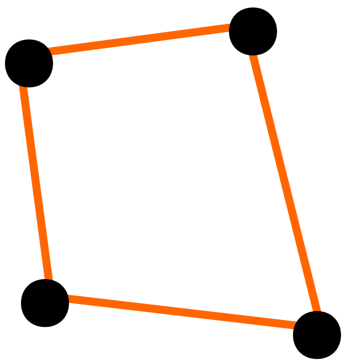


[illegible]

Sparsification is not trivial!

Every node connects to two nearest neighbors.





- < 0.074 log n nearest neighbors: disconnected w.h.p.
- > 5.1774 log n nearest neighbors: connected w.h.p.

if nodes distributed uniformly at random in convex reg.

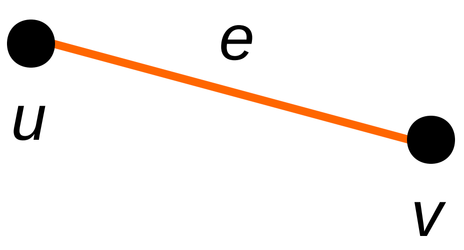
Goals of Sparsification

- Guarantee connectivity
- Guarantee energy-efficient paths resp. paths with high success probability
- Maintain self-routing network (no preprocessing for path selection)

- General strategy: graph spanners

Assumptions

Node set V distributed in 2-dim Euclidean space



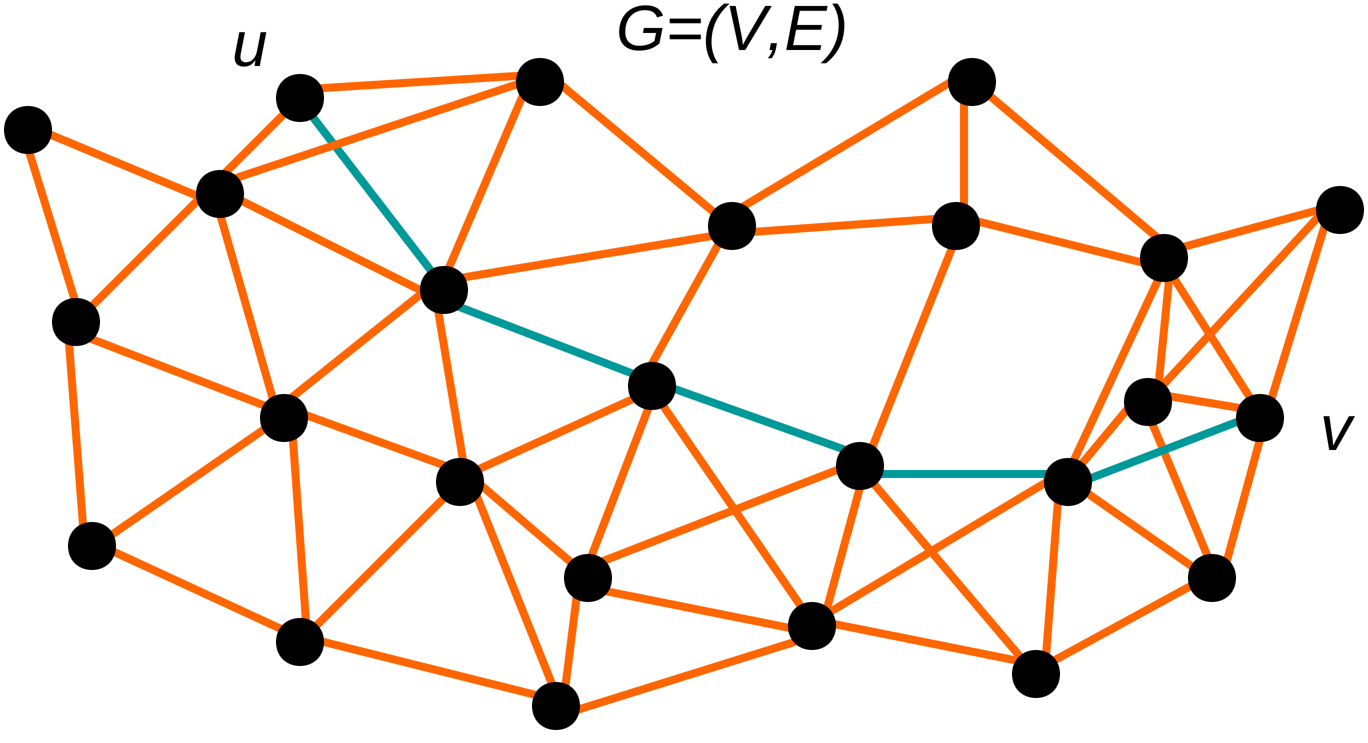
Euclidean distance: $||u\ v||$ or $||e||$

Power consumption: $||u\ v||^{\delta}$ for some $\delta > 2$

δ–cost of path $p=(e_1,\ldots,e_k)$:

$$||p||^{\delta} = \sum_{i=1}^{k} ||e_i||^{\delta}$$

Distance



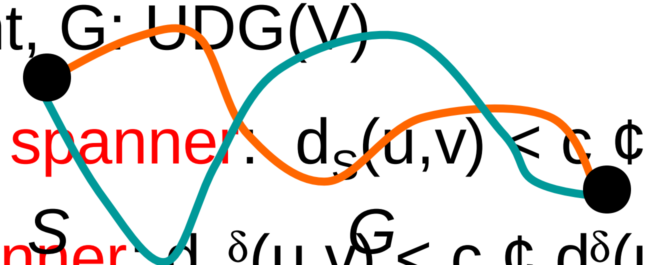
$d_G^\delta(u,v)$: min $||p||^\delta$ over all paths p from u to v in G

Unit disk graph UDG(V): simply $d^\delta(u,v)$

UDG Spanners

Basic idea: S is spanner of graph G for some δ: subgraph of G with $d_S^{\delta}(u,v)$ ¼ $d_G^{\delta}(u,v)$ for all u,v 2 V

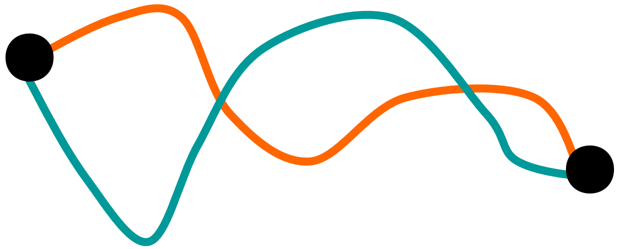
c>1 constant, G: UDG(V)



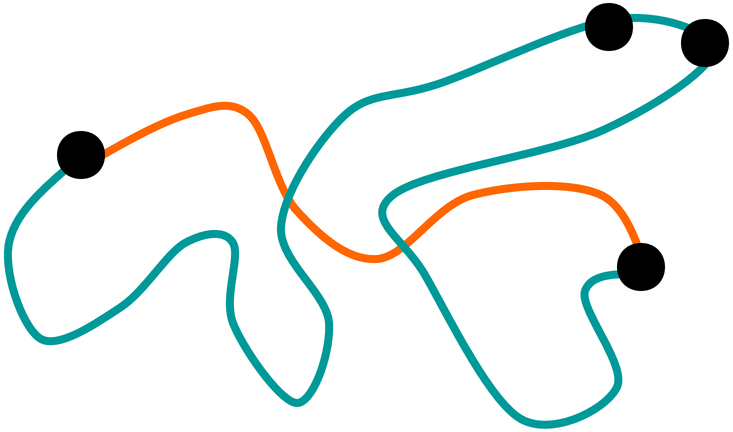
- Geometric spanner: $d_S(u,v)$ < c ¢ d(u,v)
- Power spanner: $d_S^{\delta}(u,v)$ < c ¢ $d^{\delta}(u,v)$, δ>2
- Weak spanner: path p from u to v within disk of diameter c ¢ d(u,v)
- Topological spanner: $d_S^{0}(u,v)$ < c ¢ $d^{0}(u,v)$

UDG Spanners

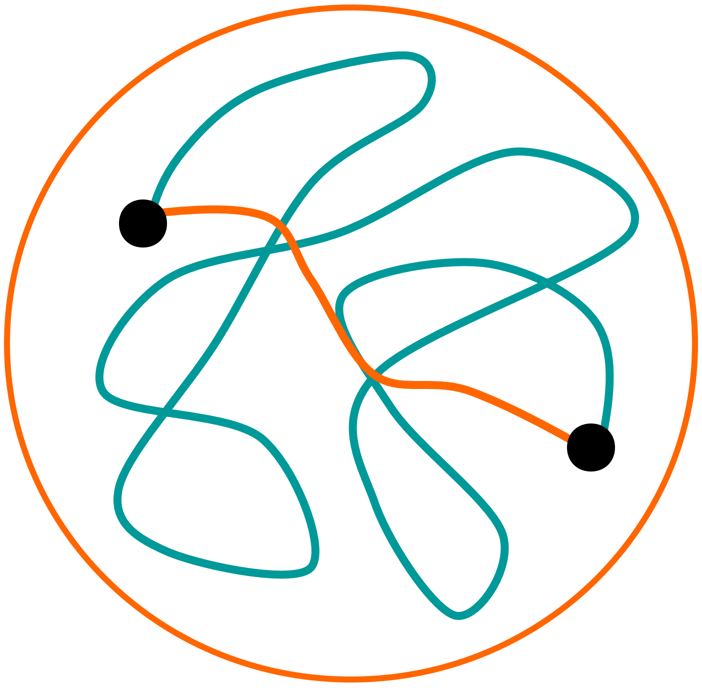
Geometric spanner:



Power spanner:

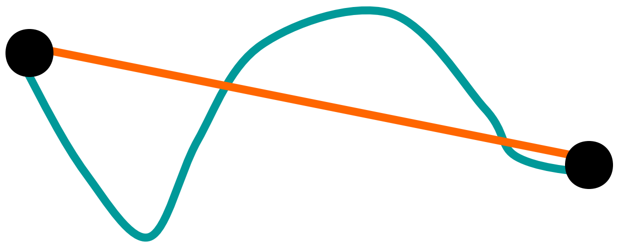


Weak spanner:

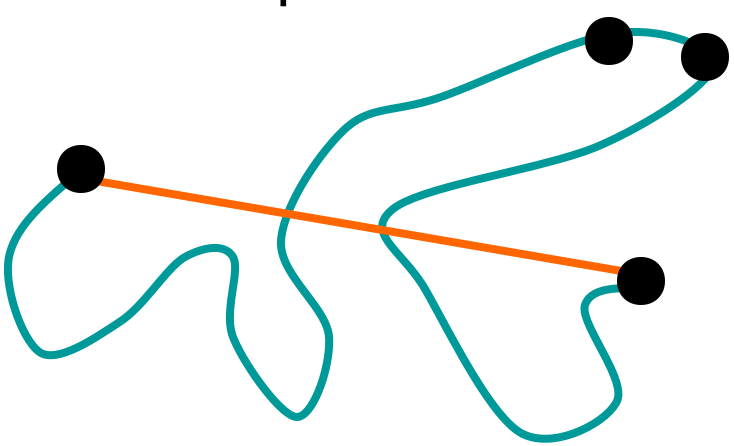


Spanners

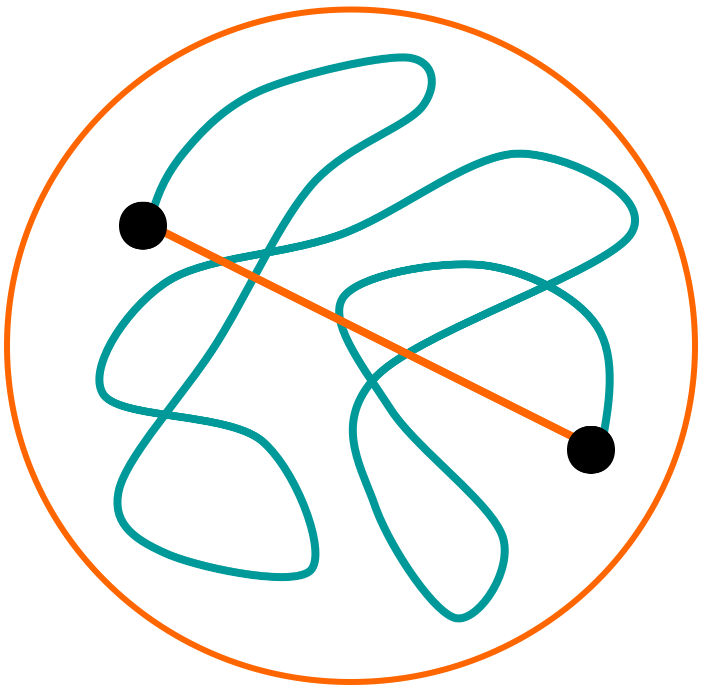
Geometric spanner:



Power spanner:



Weak spanner:



UDG Spanners

We want: c>1 constant

- Geometric spanner: $d_S(u,v) < c$ ¢ $||u v||$
- Power spanner: $d_S^{\delta}(u,v) < c$ ¢ $||u v||^{\delta}$, $\delta \geq 2$
- Weak spanner: path p from u to v within disk of diameter c ¢ $||u v||$
- Constrained spanner: there is a path p satisfying constraint above and $||e|| <= ||u v||$ for all e 2 p

E(constrained spanner) Å UDG(V): spanner of UDG(V)

Spanner Properties

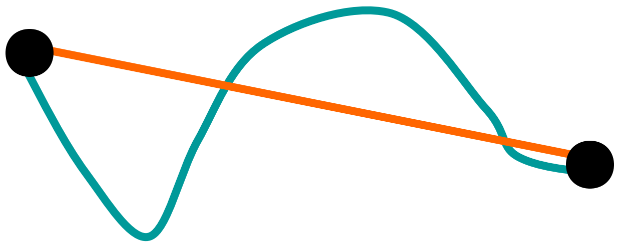
geometric) power) weak spanner

geometric) weak) power spanner

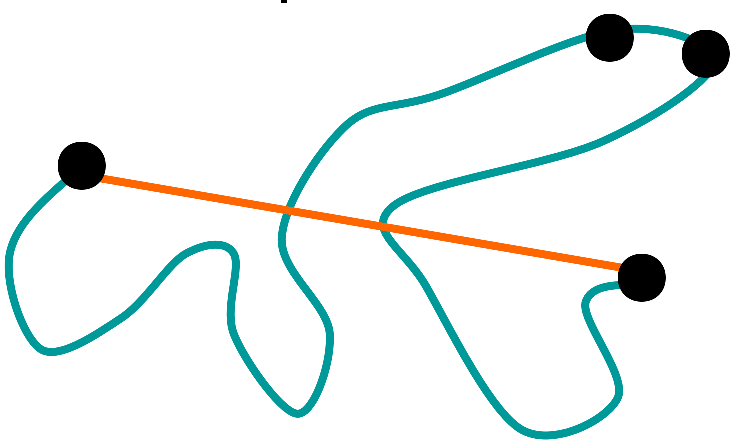
- Geometric spanner) power spanner
- Geometric spanner) weak spanner
- Weak spanner)/ geometric spanner
- Power spanner)/ weak spanner
- Weak spanner) power spanner

Spanners

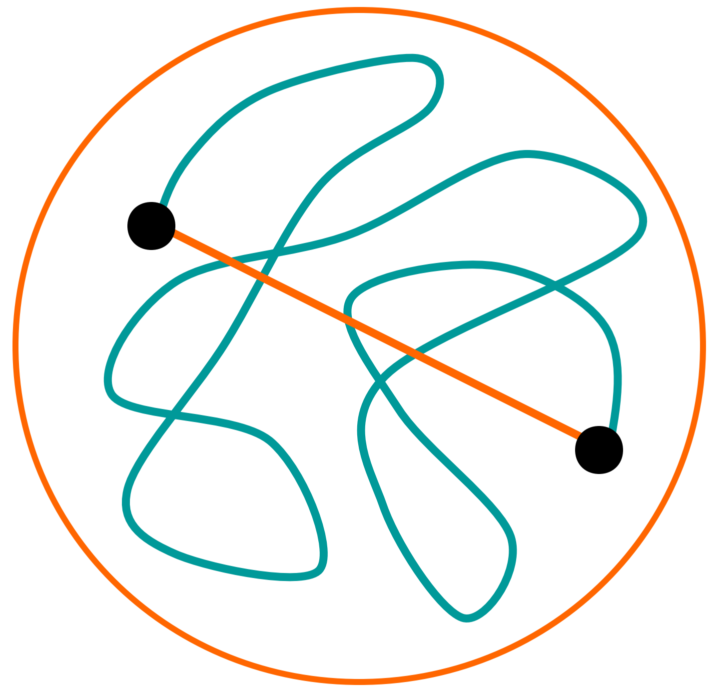
Geometric spanner:



Power spanner:



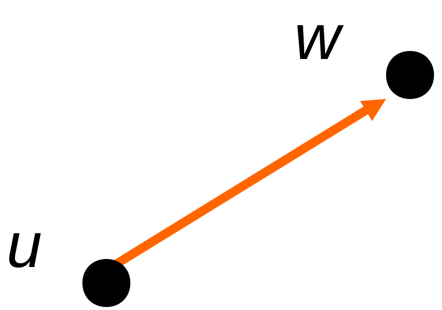
Weak spanner:

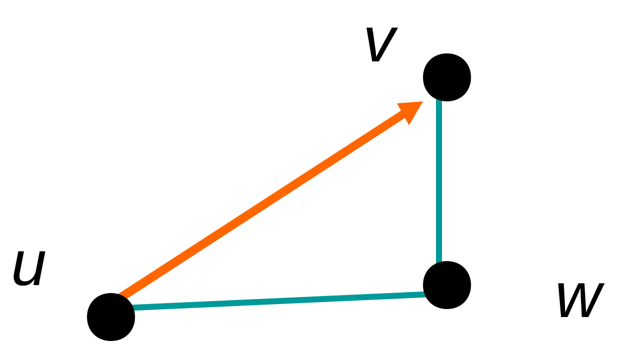


Proximity graphs

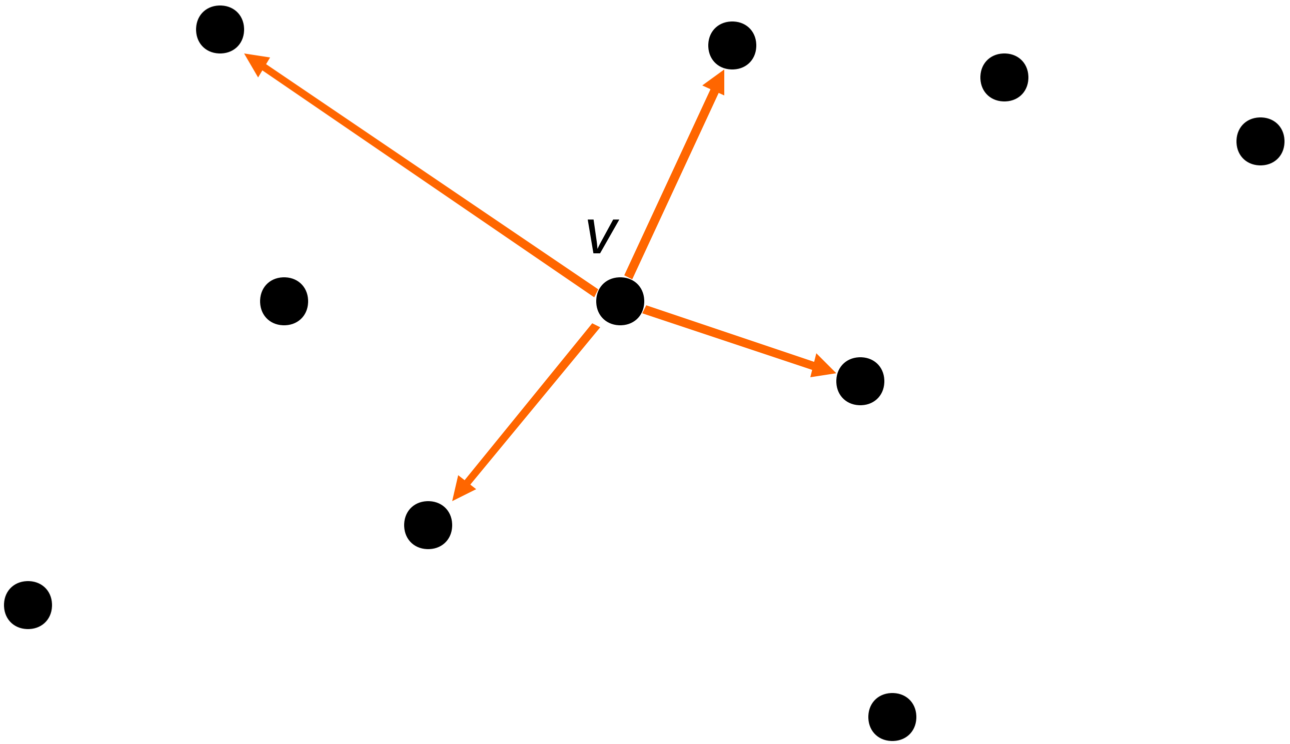
G=(V,E) is proximity graph of V if 8 u,w 2 V:

- either (u,w) 2 E
- or (u,v) 2 E for some v: ||v w|| < ||u w||





Example

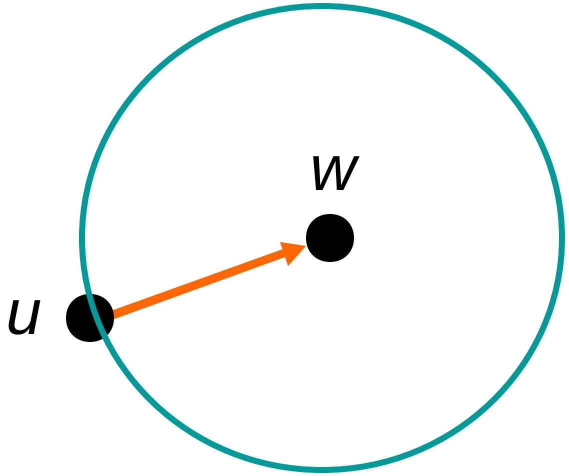


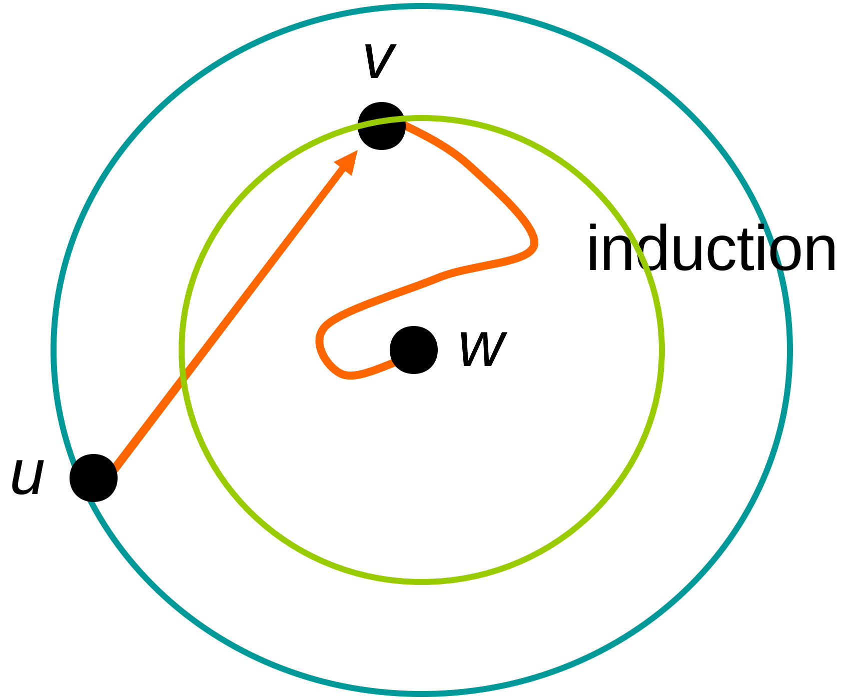
Proximity graphs

Every proximity graph of V is a weak 2-spanner.

Proof: by induction on distance

min distance:

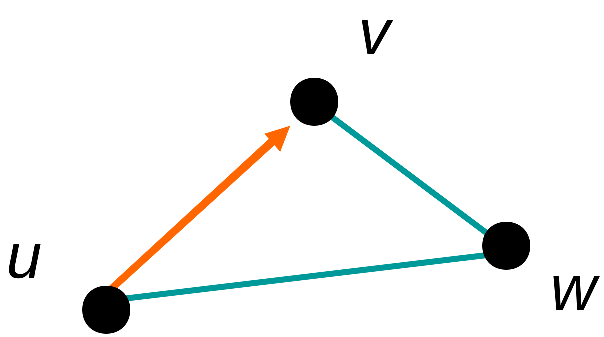




Relative neighborhood graphs

G=(V,E) is a RNG of V if for all u,w 2 V:

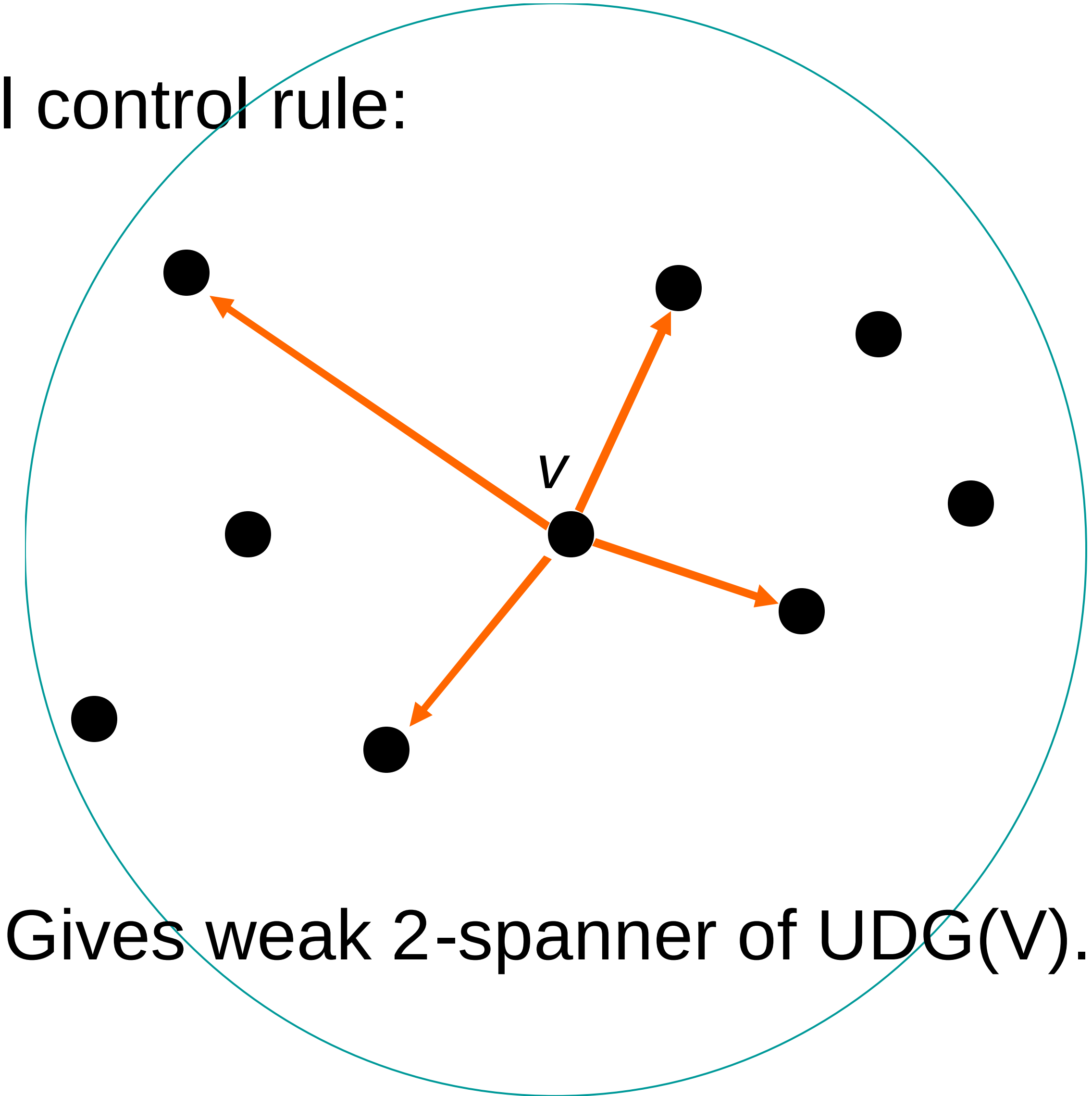
- either (u,w) 2 E
- or (u,v) 2 E for some v:
  ||u v|| <= ||u w|| and ||v w|| < ||u w||



RNG: constrained proximity graph

Relative neighborhood graphs

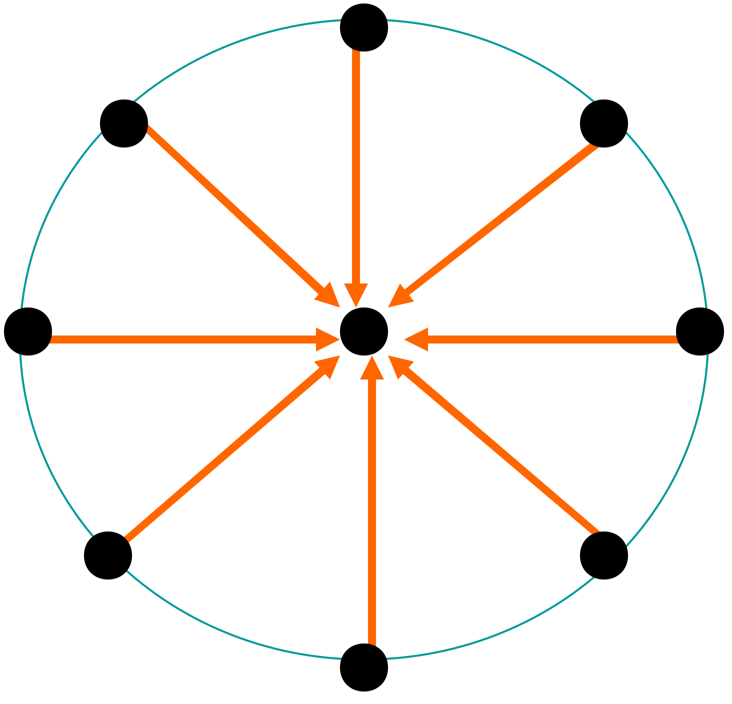
Local control rule:



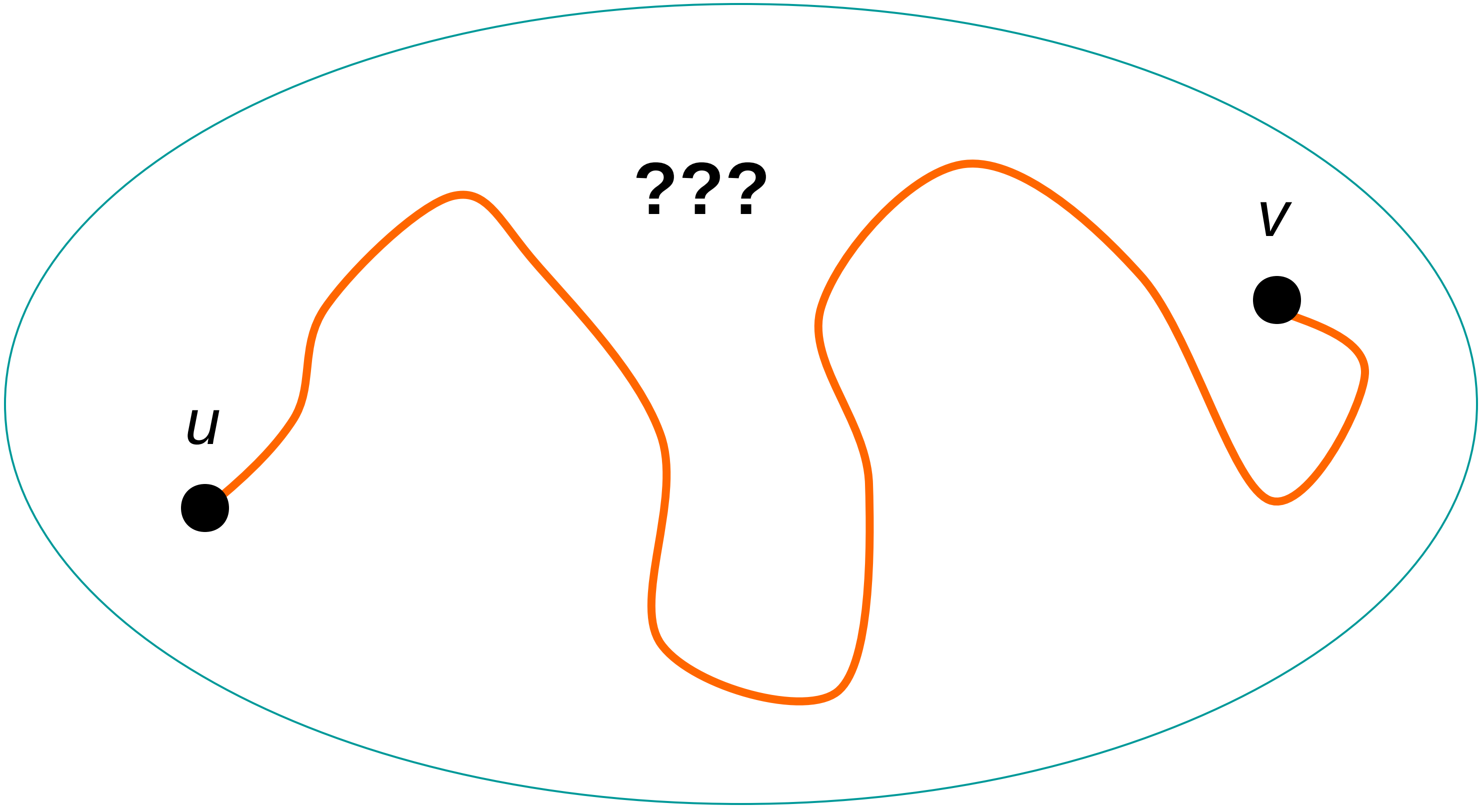
Gives weak 2-spanner of UDG(V).

Relative neighborhood graphs

Problem: Minimal RNGs have outdegree at most 6 but indegree can be large.



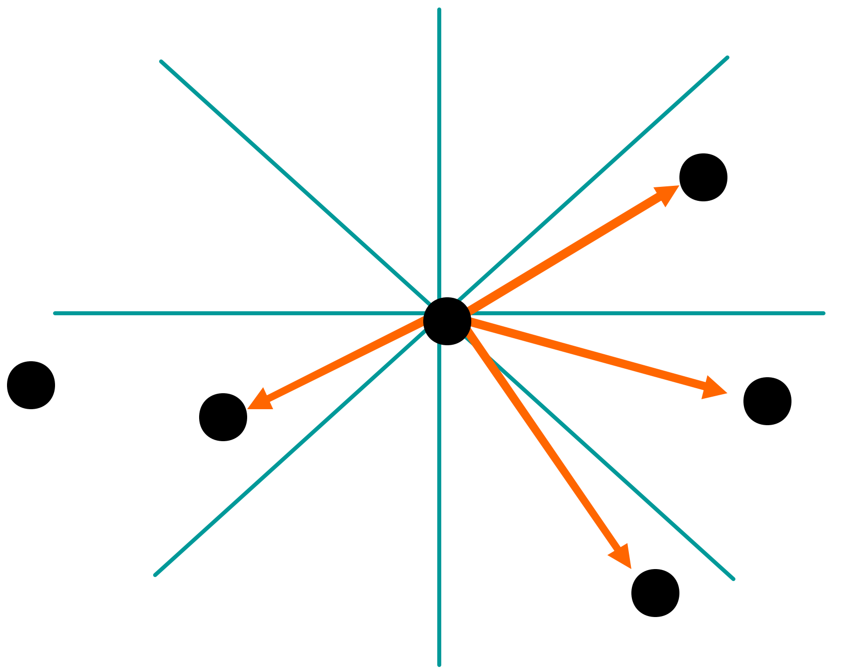
Routing in RNGs



BeWhaitestapplesAcavieltGiPS?gths

Sector-based spanners

Yao graph or θ-graph (special RNG):

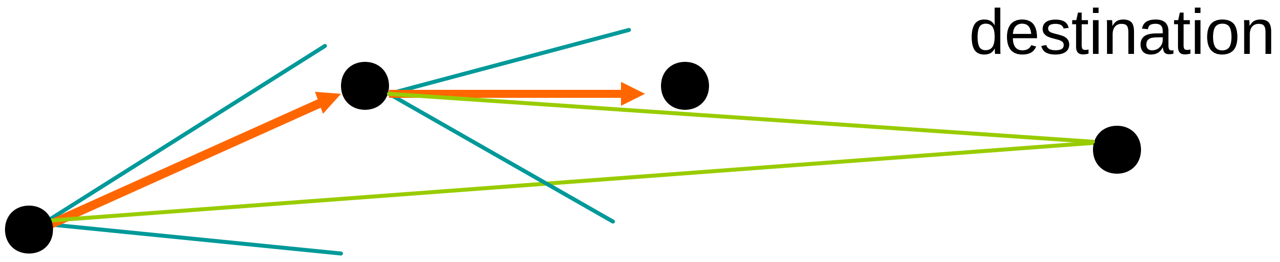


Rule: Connect to nearest node in each sector

Sector based spanners

θ–graphs with >6 sectors are geometric spanners

Routing:

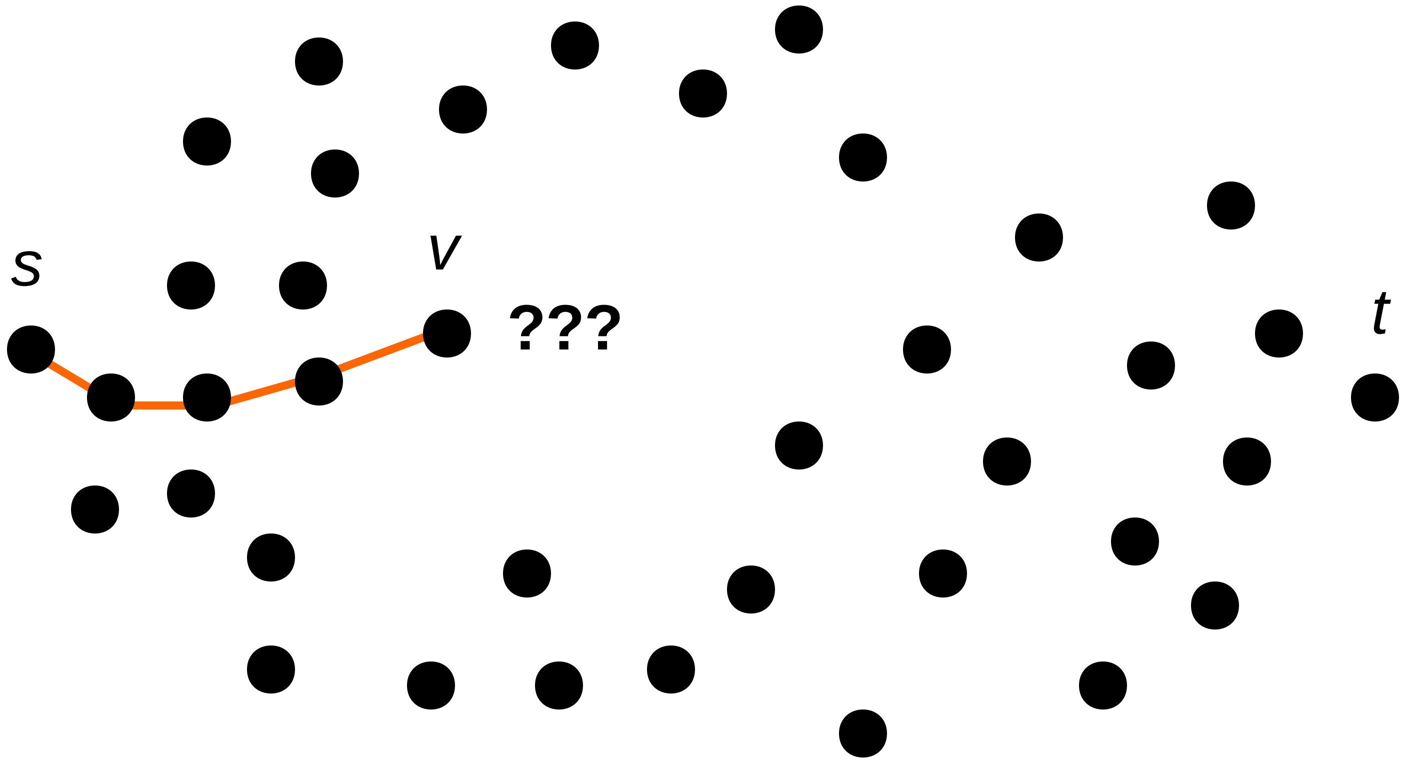


Go to node in sector of destination.

Requires dense node distribution, GPS!

Sector based graphs

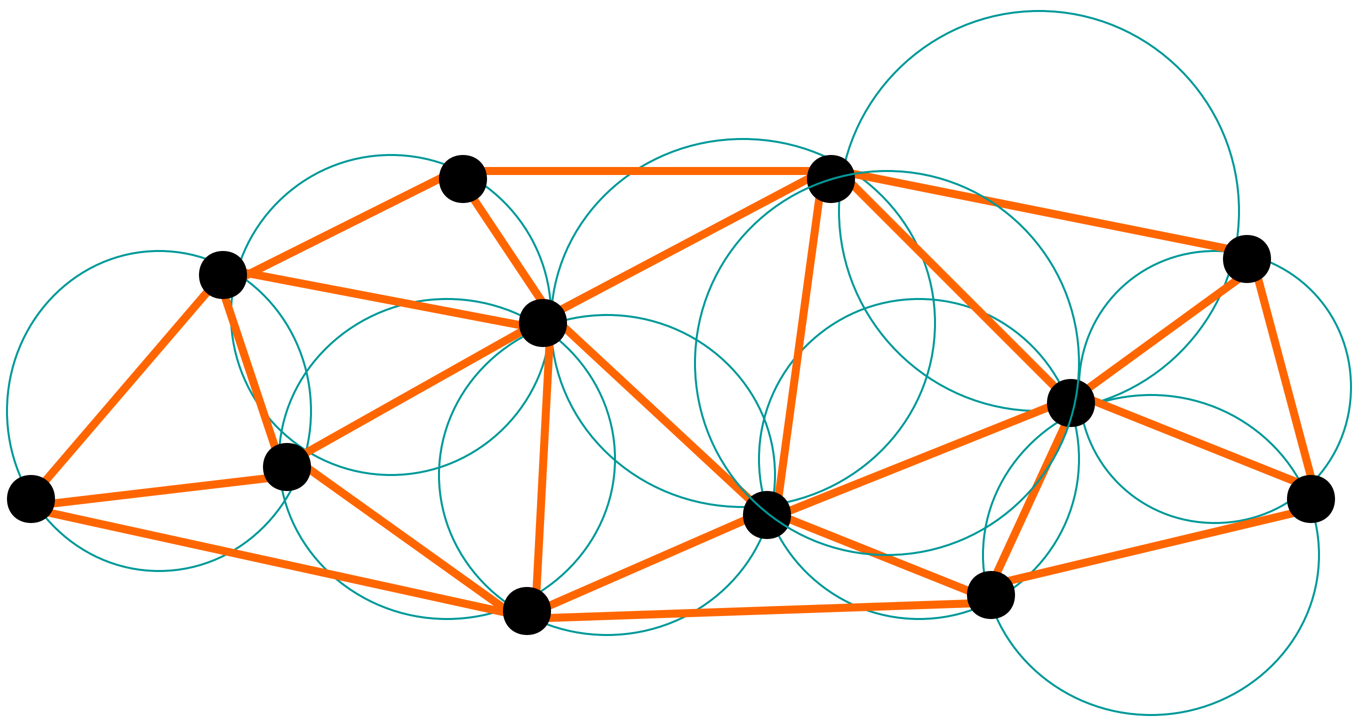
Distribution not dense:



Delaunay-based spanners

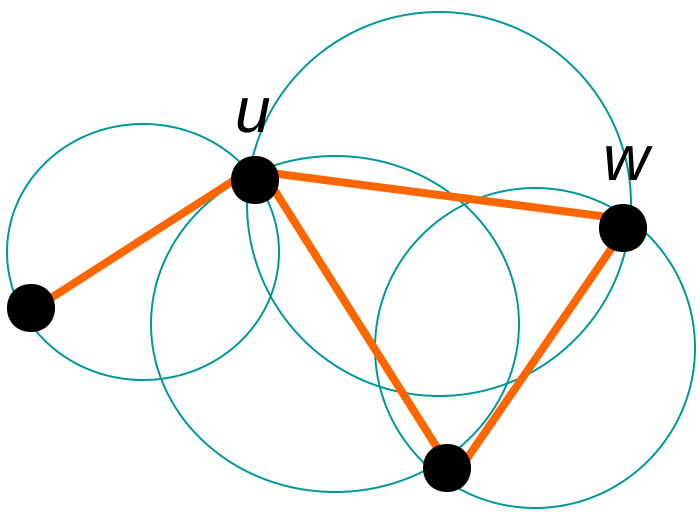
Idea: use variants of Delaunay graph

Delaunay graph Del(V) of V: contains all {u,v}: 9 w 2 V where O(u,v,w) does not contain any node of V



Delaunay-based spanners

Gabriel graph GG(V) of V: contains all {u,w} with no v 2 V s.t. $||u\ v||^2 + ||v\ w||^2 < ||u\ w||^2$

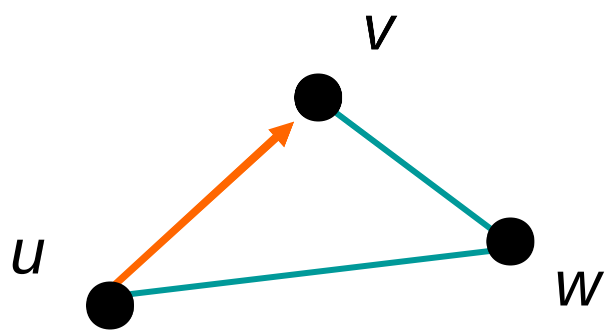


GG(V) ½ Del(V)

Relative neighborhood graph

G=(V,E) is a RNG of V if for all u,w 2 V:

- either (u,w) 2 E
- or (u,v) 2 E for some v:
  ||u v|| <= ||u w|| and ||v w|| < ||u w||

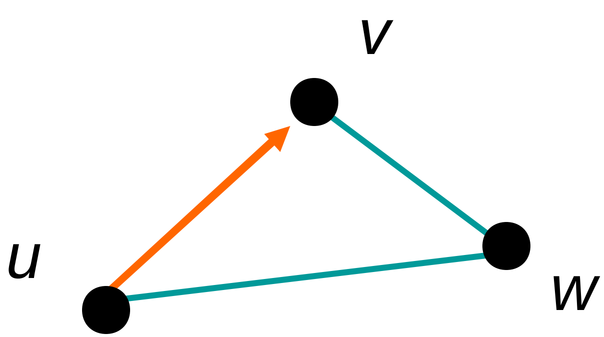


RNG: constrained proximity graph

RNG for path loss

The GG satisfies for all u,w 2 V:

- either (u,w) 2 E
- or (u,v) 2 E for some v:
  c(u,v) <= c(u,w) and c(v,w) < c(u,w)



GG: constrained proximity graph for path loss with δ=2

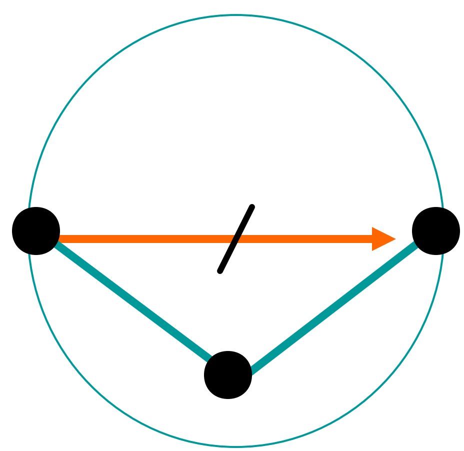
Delaunay-based spanners

GG(V) is an optimal power spanner.

Proof: Let p be energy-optimal path for {u,v}.
Consider any edge {x,y} in p.

{x,y} 2 GG(V):

{x,y} 2/ GG(V):

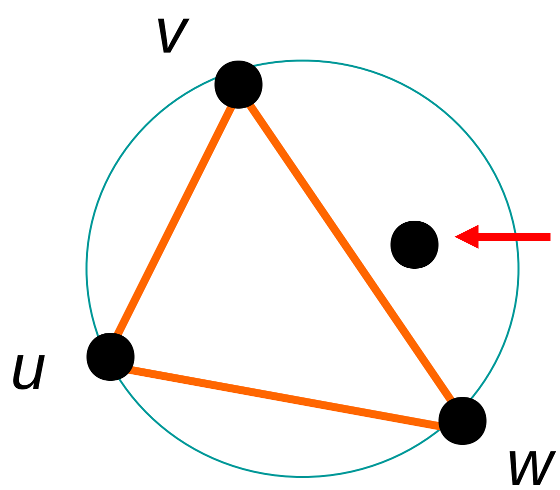


Contradiction!

Delaunay-based spanners

Problem with Gabriel graphs: can have high degree, can be poor geometric spanner

Alternative: k-localized Delaunay graphs $LDel^{(k)}(V)$



No node in k-neighborhood of u,v,w in UDG(V)

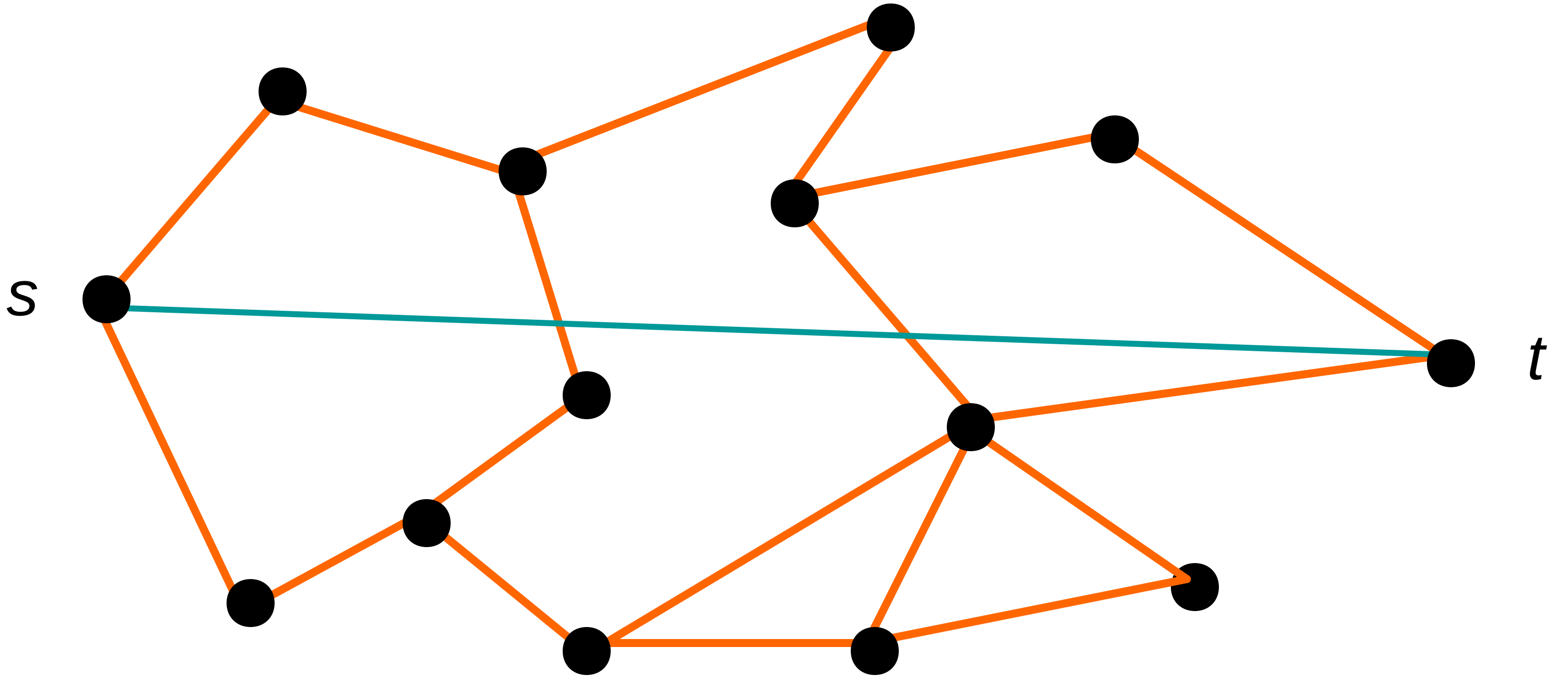
Delaunay-based spanners

- $LDel^{(1)}(V)$: not planar
- $LDel^{(2)}(V)$: planar and geometric spanner

Planarity important for routing!

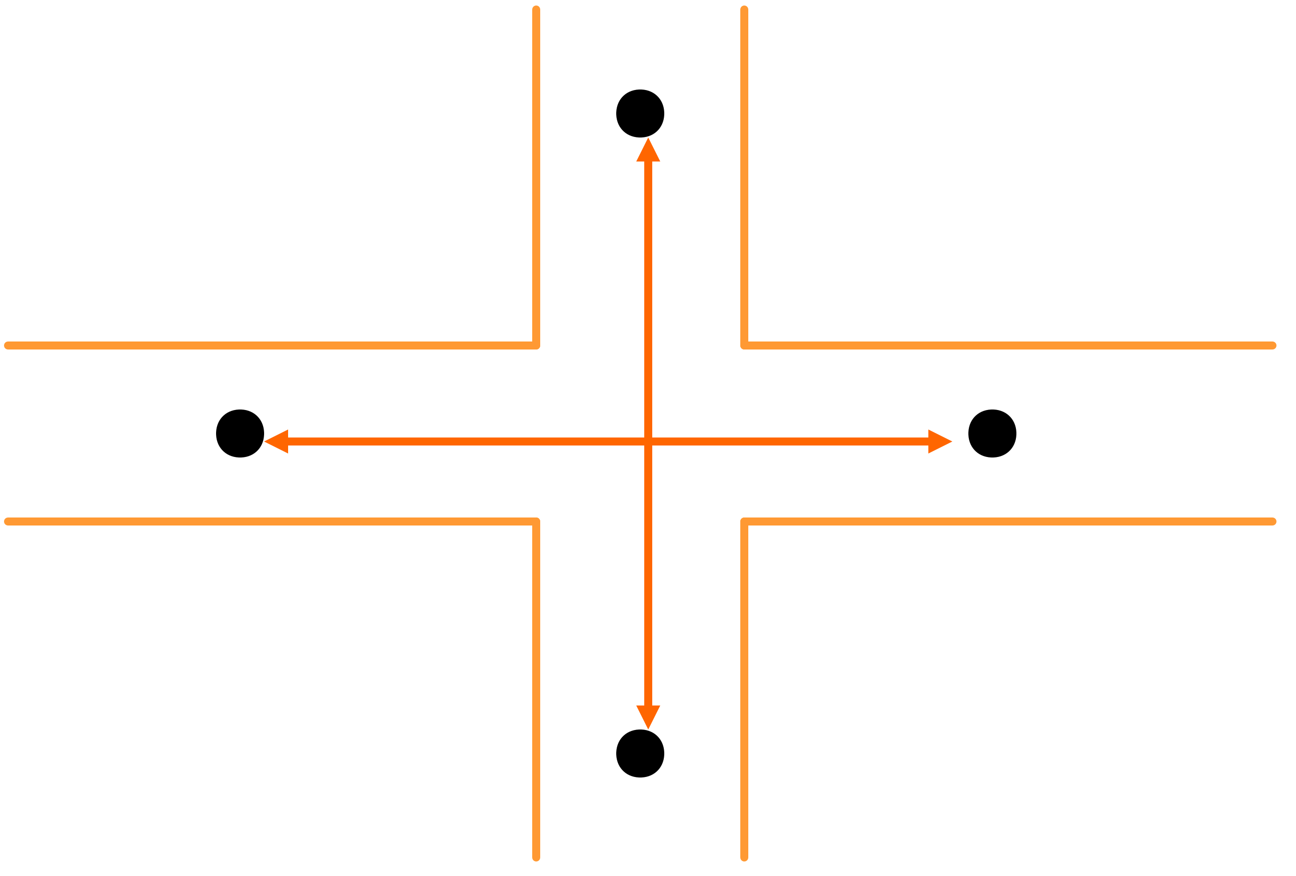
Routing in planar graphs

Face routing:



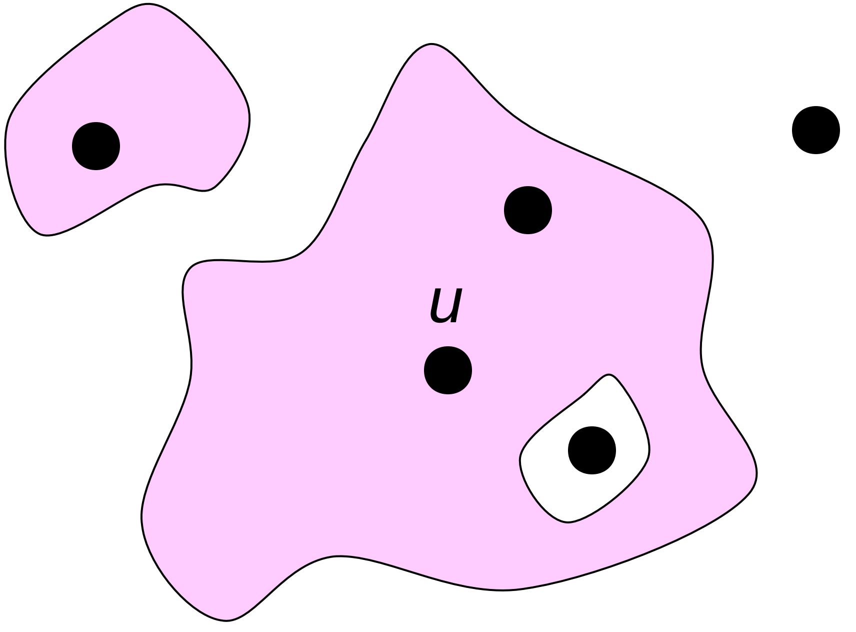
That’s nice, but do these strategies work in practice???

Problem: Unit Disk Model



In reality, hard to maintain planar overlay network.

Reality



Cost function c and constant δ>0 s.t. for any two points v and w

- c(v,w) 2 [(1-δ) ¢ ||v w||, (1+δ) ¢ ||v w||]
- c(v,w) = c(w,v)

Realistic wireless model

When using cost function c:

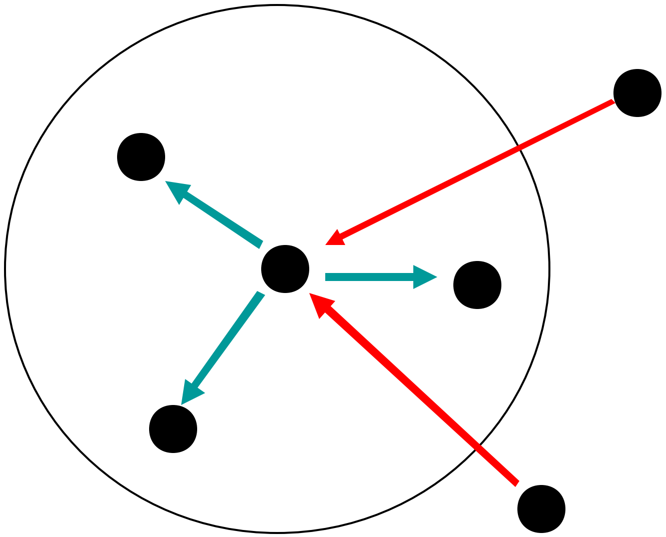
- Proximity graphs: OK
- Relative neighborhood graphs: OK
- θ-graphs: $\theta < \arccos (\delta^2+1/2)/(1-\delta^2)$, $\delta < 1/2$
- Gabriel graphs, localized Delaunay graphs: not planar but other spanner results OK

- Face routing extendable to more realistic model?
- Is GPS necessary?

Problem: GPS

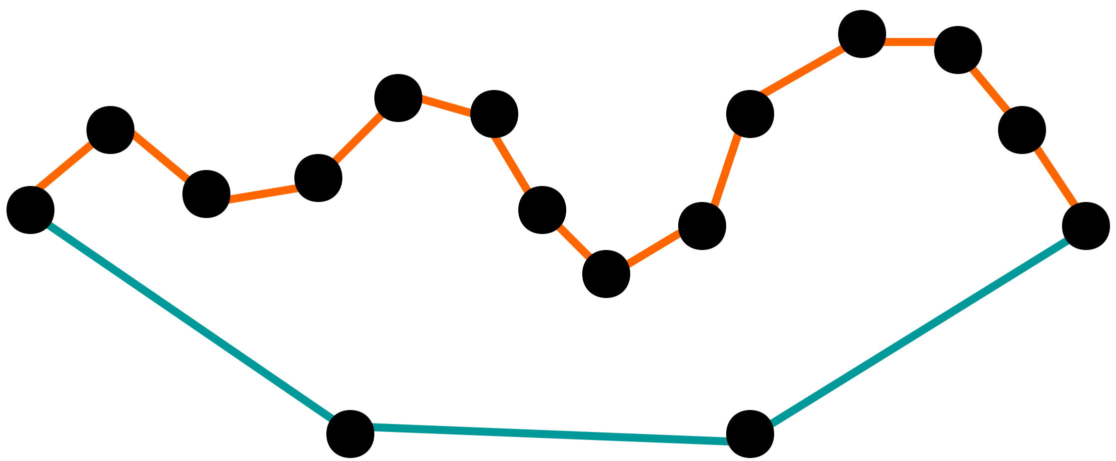
GPS not necessary for topology control, but
can we avoid GPS for routing?

Possible solution: use force approach

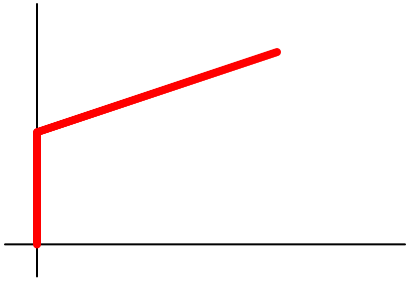


Problem: Cost Model

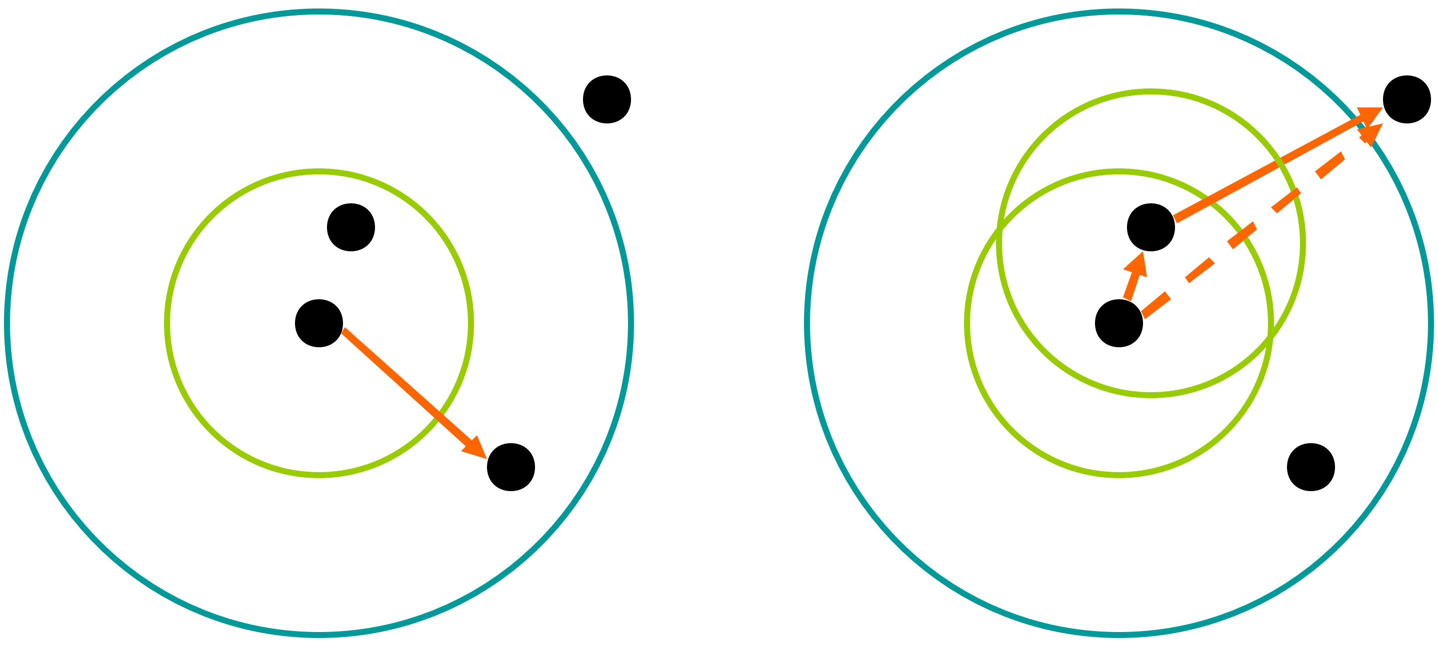
Power spanner prefers over



Energy consumption:



Solution

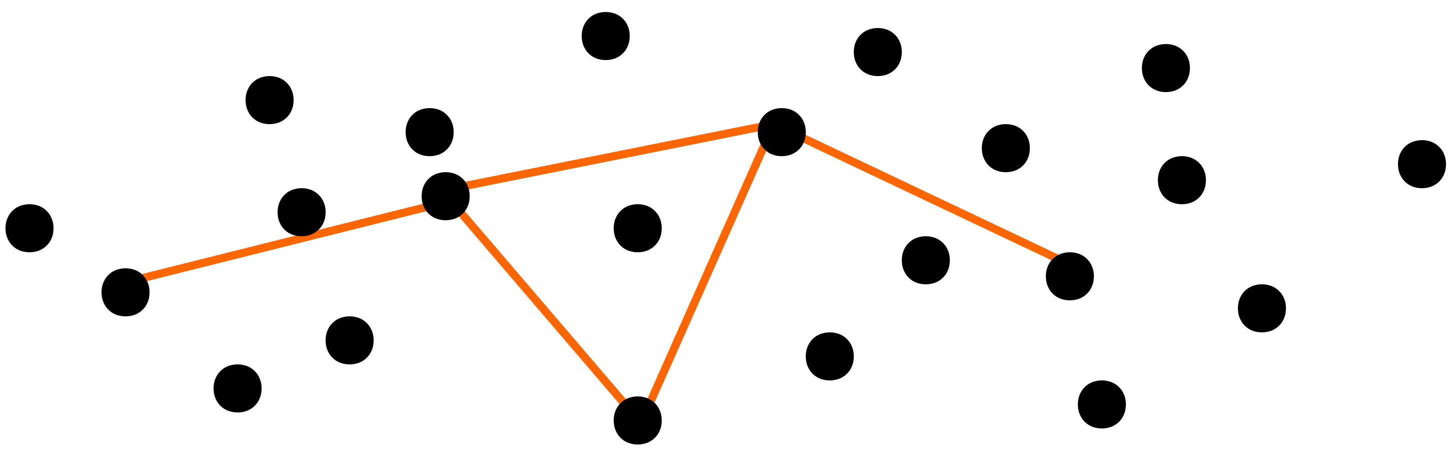


Only allow long edges (except last).

Problem: Contention

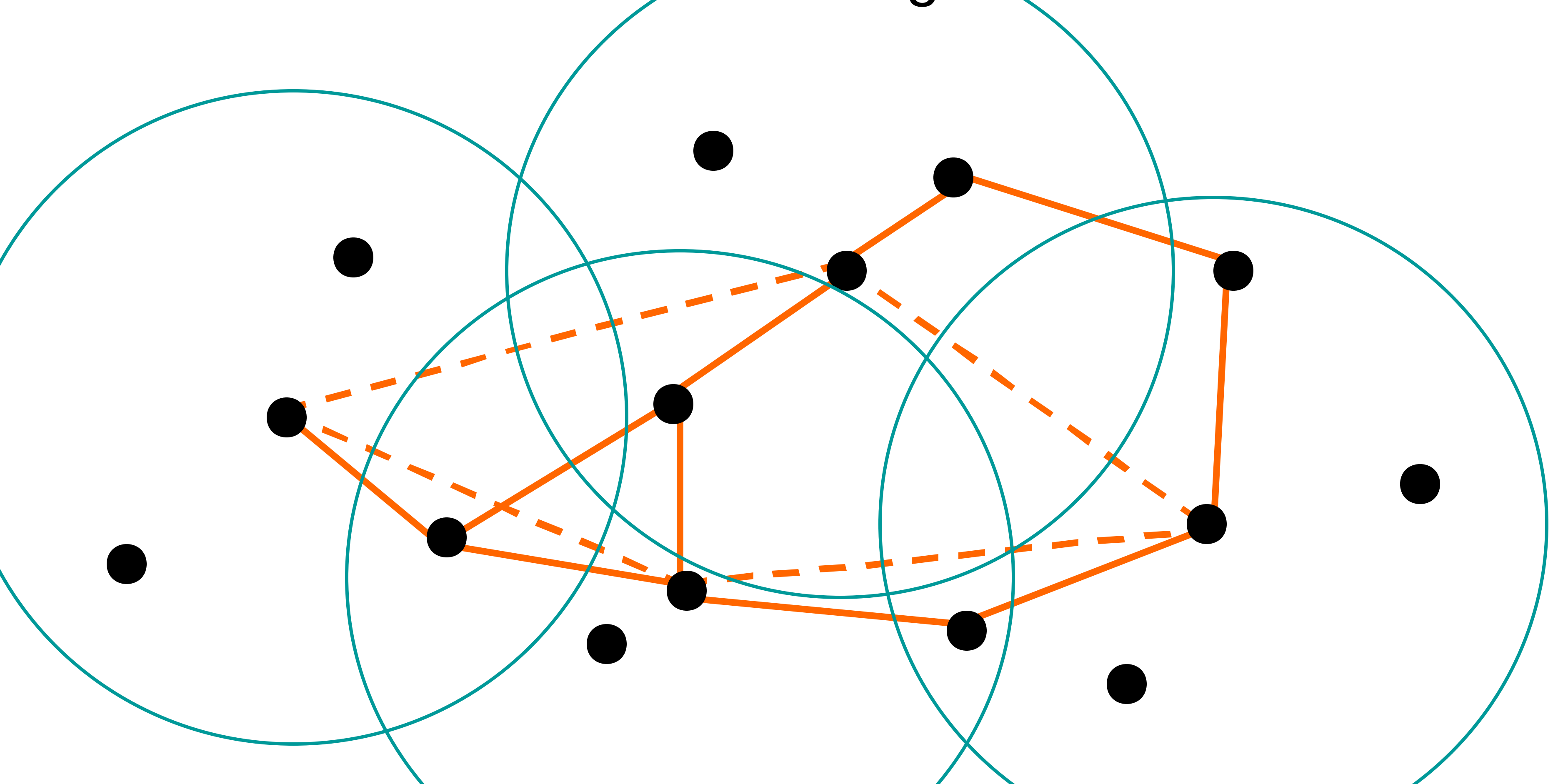
Still too much contention because every node participates in routing.

Better to have highway system (i.e., only few nodes act as relay nodes).



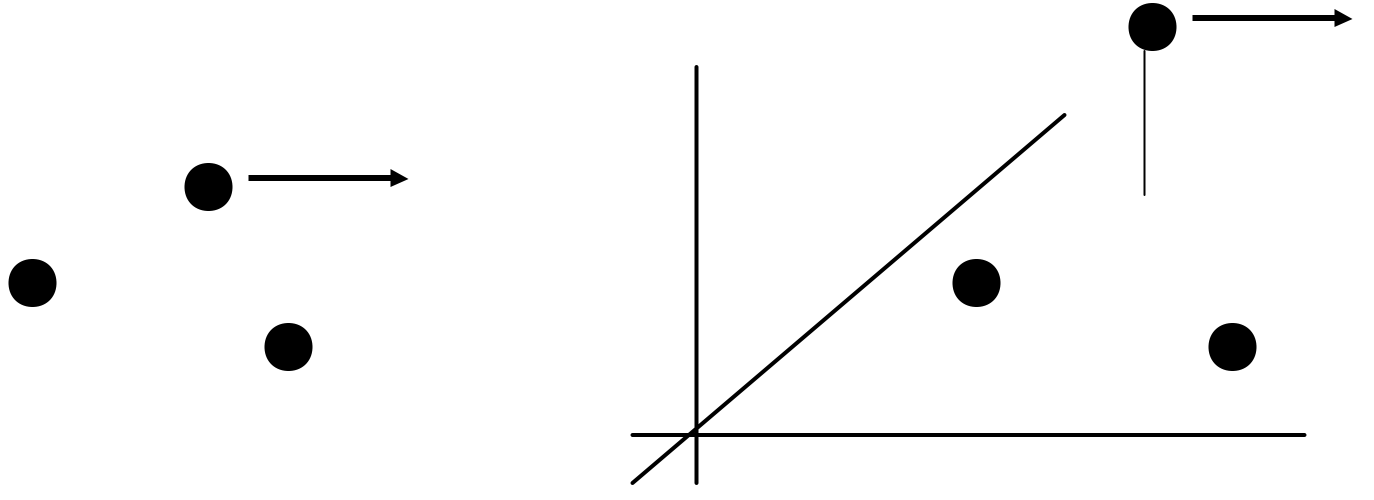
Solution

Construct dominating set: every ● has ● within its transmission range

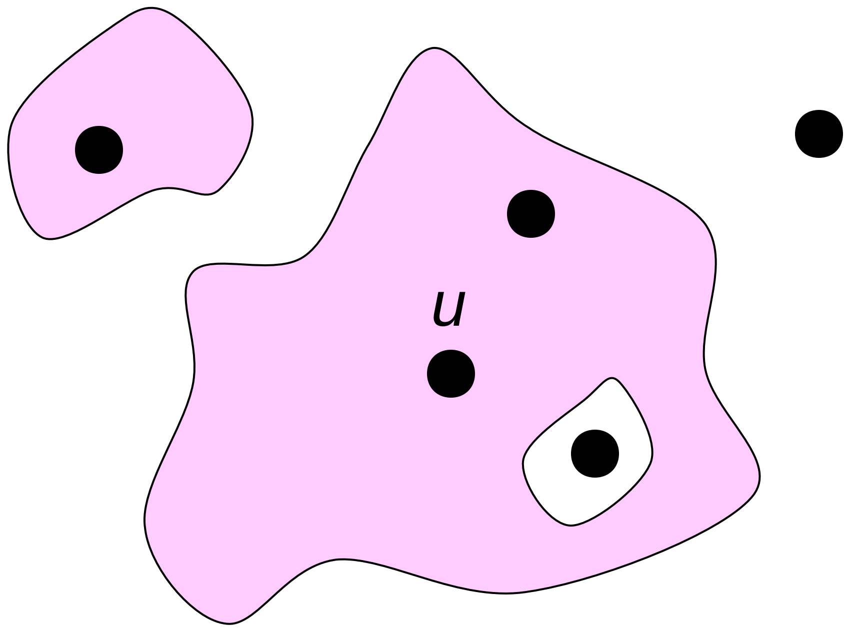


Problem: Mobility

Solution: view mobility as another dimension



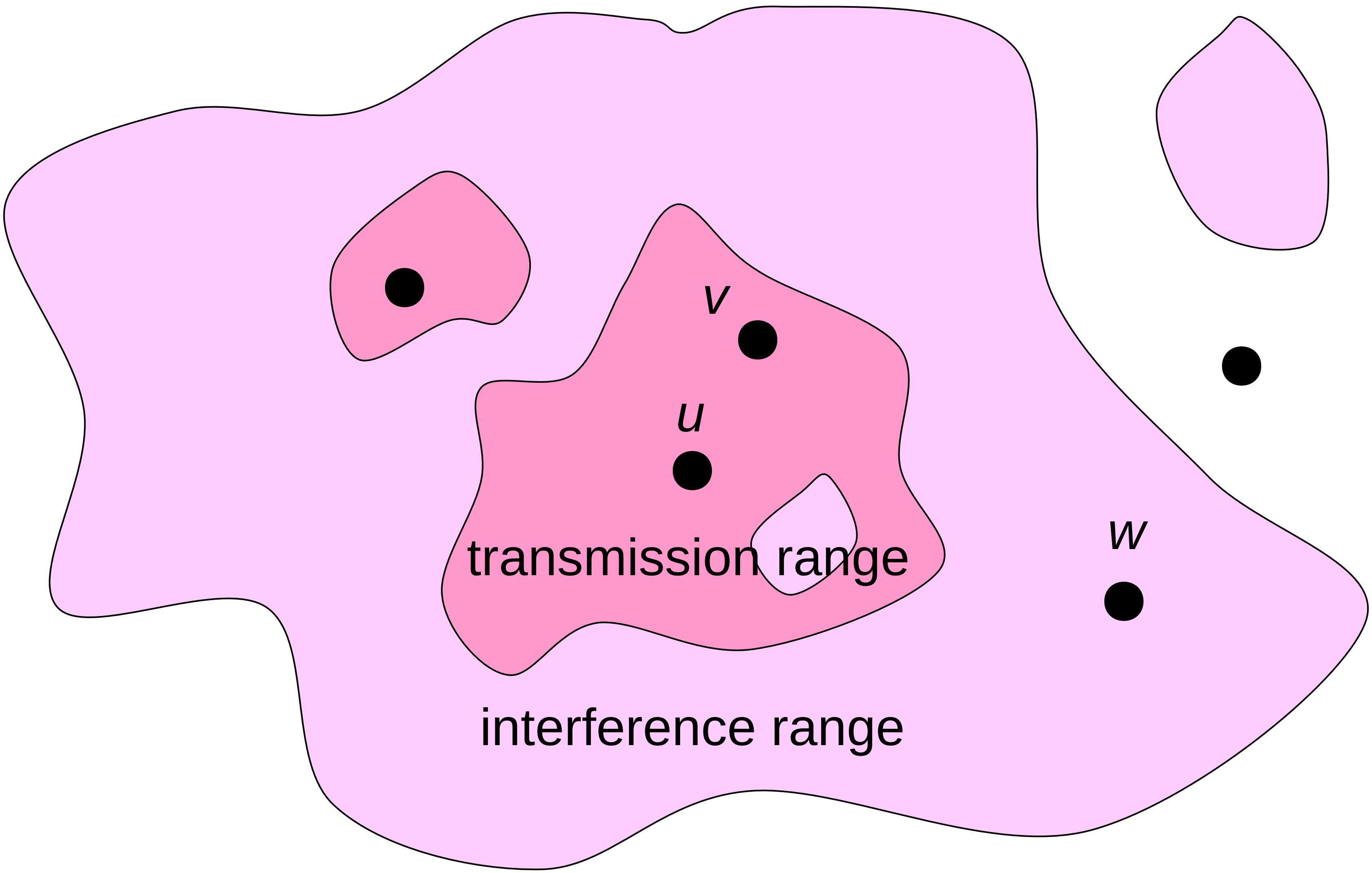
Problem: Protocol Design



Cost function c and constant δ>0 s.t. for any two points v and w

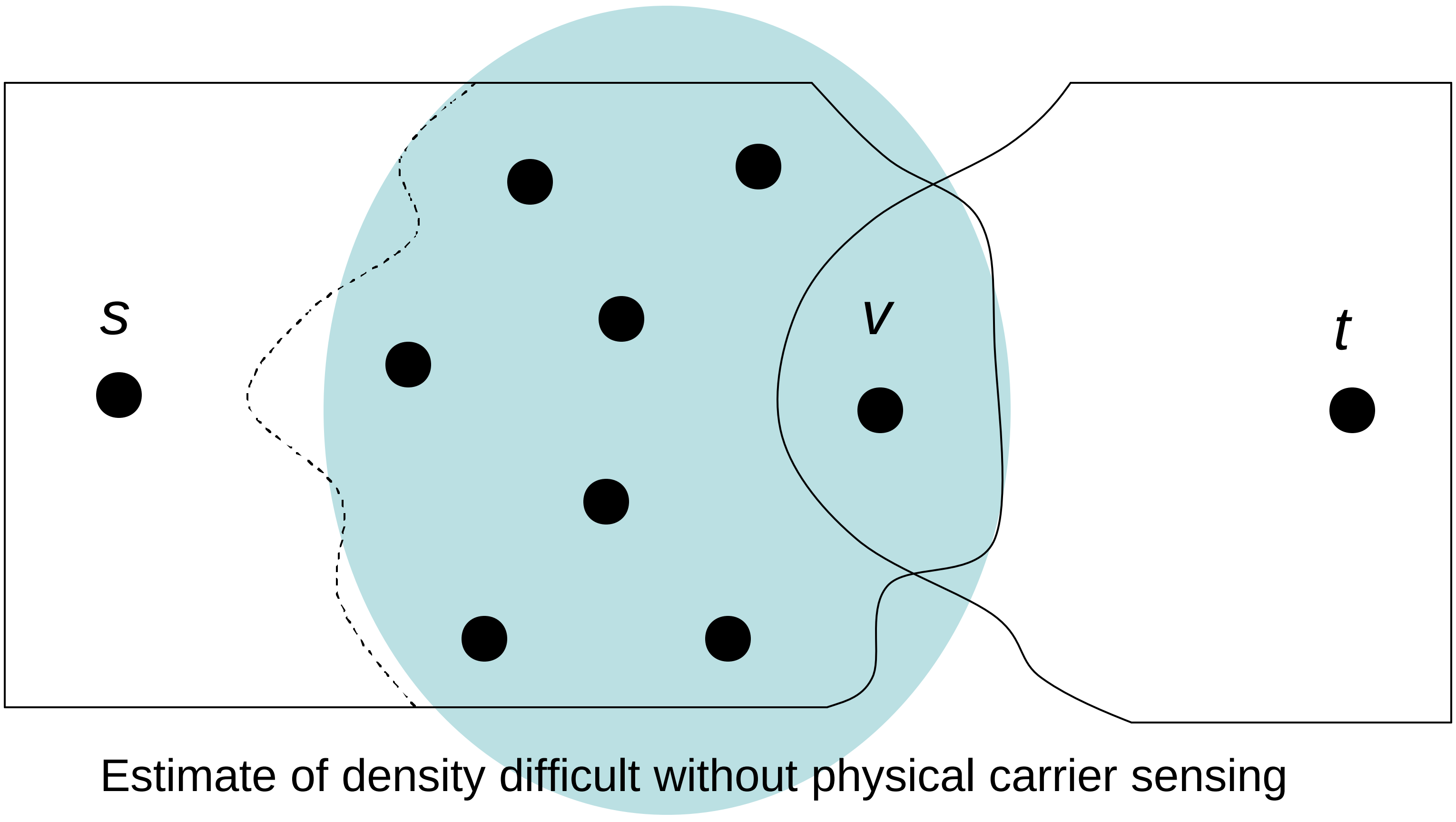
- c(v,w) 2 [(1-δ) ¢ ||v w||, (1+δ) ¢ ||v w||]
- c(v,w) = c(w,v)

Realistic wireless model



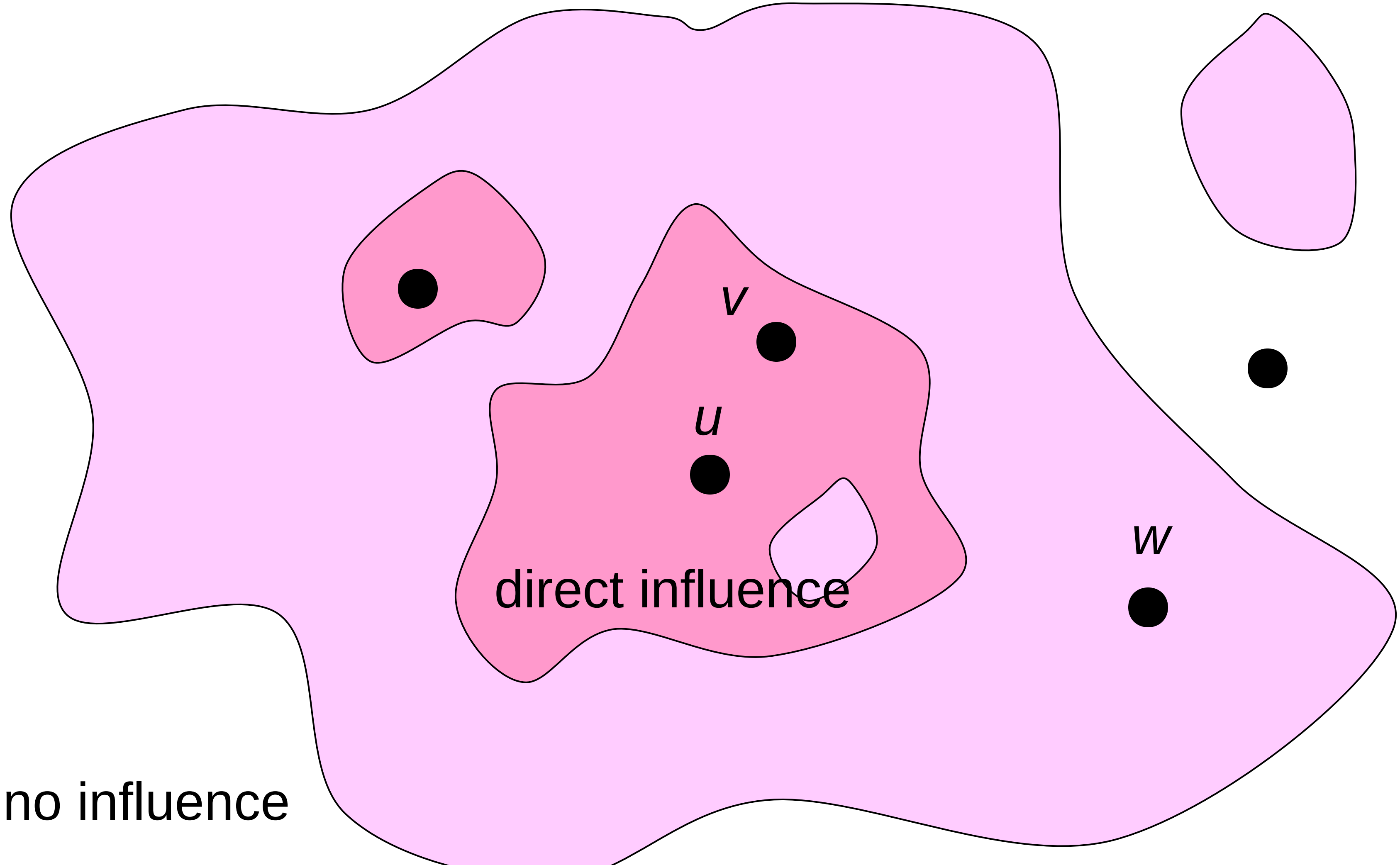
Realistic wireless model

Design of algorithms much more complicated!



Estimate of density difficult without physical carrier sensing

Physical carrier sensing



Future problems

Overlay networks are hot topic!

Problems:

- Local self-stabilization
- Robustness against adversarial behavior
- Distributed optimization
- Unified network model (???)

References

Surveys:

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Sector-based spanners:

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Lists are not meant to be comprehensive but should be sufficient to get started in this field.