Scalable localized **routing** in wireless sensor networks

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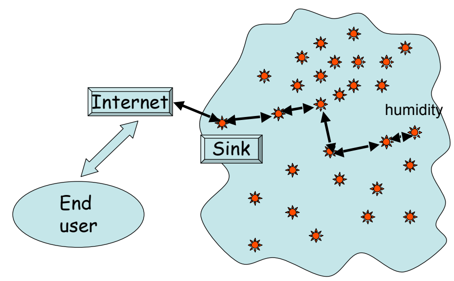
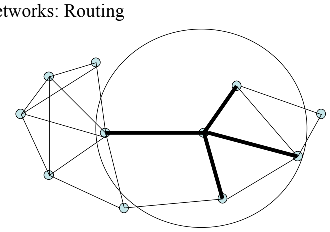
Sensors route reports to a fixed sink …



Multi-hop networks: Routing

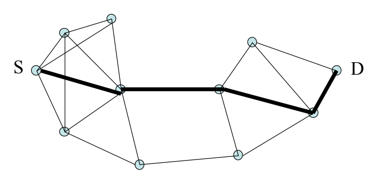


Sensor networks
Position information

Unit disk graphs
radius

•Routing: source → destination

Multi-hop networks: Routing



Sensor networks
Position information

Unit disk graphs
radius

•**Routing**: source → destination

Routing with/out position information ?

Sensors can function efficiently only with position information
GPS and location estimation advanced rapidly
(cubic cm sensor with 7mm x 7mm x 2mm GPS)

Sink can flood network with/out its own position
Routes can be learned while flooding, or
Only position of sink is learned and used

Reactive routing

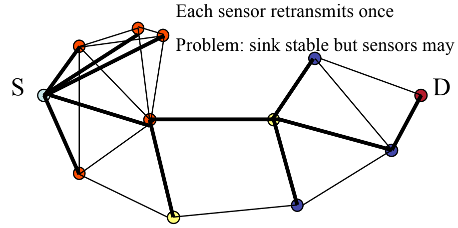
- Source floods route discovery (short) message
- Destination node replies back to source upon receiving discovery message(s) using memorized hops (**AODV**) or paths (**DSR**) (ad hoc networks)
- Source sends full message using recorded path
- Multi-paths for QoS
- Route discovery message may contain accumulated delay, congestion, power, cost etc. along paths;
  best path selected at destination
- Local route maintenance; expanding ring search

Route discovery by flooding

S → ● → ● → ● → ● D

Each sensor retransmits once

Problem: sink stable but sensors may sleep

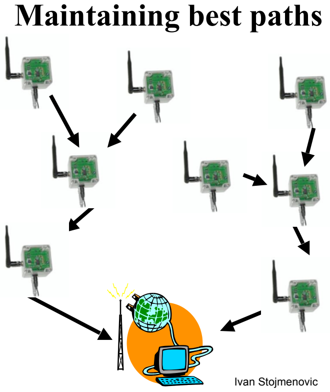


DSR, AODV in ad hoc networks, position info not needed = '**directed diffusion**' sensors Intanagonwiawat, Govindan, Estrin 2000

Proactive routing

- Routing table contains the first hop/neighbor toward each destination
- **Bellman-Ford**: Each node exchanges its routing tables with all its neighbors, and
- Best neighbors N for route from S to D is one that minimizes: cost of link S to N + cost N to D (from routing table in N)
- **OLSR** (Optimized Link State Routing): link changes are flooded + Dijkstra's shortest path
- MPR (MultiPoint Relay) to reduce flooding

Maintaining best paths to the sink: BF



Cost of each link to neighbors is updated

Summary cost of reporting to sink is included in message

Best neighbor minimizes cost to it + path cost from neighbor

Link changes require several iterations to find new best path

Xue Zhang JCST 2008

Routing by partial flooding

Position info not needed (but available)

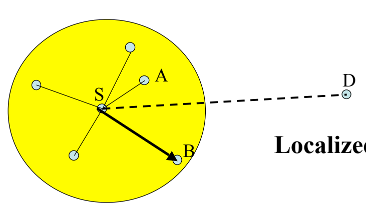
Synchronized sleep schedule

Implemented with >1000 nodes in Hangzhou forest: **GeoOrbitts** (Yunhao Liu, XiangYang Li, Jianhui Zhang…)

Every received report from node X is retransmitted by neighbor Y if:
Y has smaller accumulated cost for reporting to the sink, and
Y did not retransmit same report already (ID memorized)

Nodes already awake have small additional cost to retransmit or listen
If packet size is relatively small and reports are relatively rare then there are no collision issues; no energy hole issue

Greedy position based localized routing



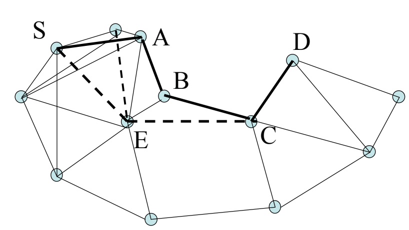
Localized protocol

S knows only position of itself, its neighbors and destination D

S forwards to neighbor B closest to D

Finn 1987

Greedy: SABCD vs shortest path SECD



Localized vs. globalized protocol

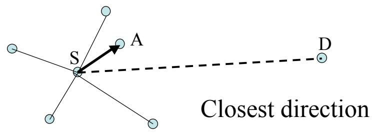
SP: slow convergence of BF, or message overhead to maintain global information at each node (mobility and/or sleep/active periods changes)

DIRectional routing methods

Basagni, Chlamtac, Syrotiuk, Woodward MOBICOM'98 (DREAM)

Ko, Vaidya MOBICOM '98 (LAR)

Kranakis, Singh, Urrutia CCCG'99 (compass routing)



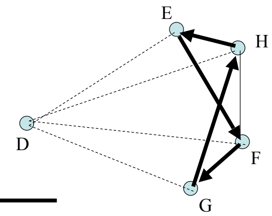
Closest direction

Send to ***all*** neighbors within angular range from direction [BCSW,KV]

location update schemes [BCSW, KV]

Flooding rate (# of messages vs SP) ??

DIR is not loop-free !



Transmission radius

Greedy and MFR are loop free Stojmenovic 1998

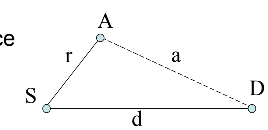
Is hop count the best metric ?

- Power consumption
- Reluctance (avoiding nodes with low energy)
- Power_reluctance
- Delay
- Expected hop count (realistic physical layer)
- COST - selected metric

Cost to progress ratio framework

- Progress: measures advance toward destination
- Progress = |SD|-|AD|=d-a
- Select neighbor A that minimizes cost(SA)/progress(A)
- Hop count: cost=1
- →Maximize advance

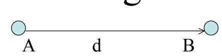
Stojmenovic IEEE Network 2006

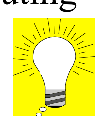


Parameterless behavior

- Cost-to-progress ratio framework has no added parameters such as thresholds
- Threshold based approach: eliminate 'bad' links, drop packet if there is no 'good' neighbor
- What if a solid path has just one weak 'bridge'?
- Experiments so far indicate that threshold based approaches are inferior for all threshold values - either high failure rate or suboptimal since there is no notion of 'best' neighbor

Power saving localized routing





Constant power → minimize hop count

power $=u(d)= d^{\alpha} + c$ → minimize total power

$2\leq\alpha\leq6$ model by Rodoplu, Meng 1999

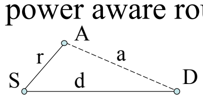
Many articles assume $c=0$; in practice $c>0$ since power is needed to run hardware at each node, and correct reception requires minimal transmission power (no energy free transmission at zero distance)

reluctance $f(A)$ to forward packets =

$=1/g(A)$ $g(A)$ in [0,1] lifetime → minimize total cost

Power_reluctance $= f(A)u(d)$

Localized power aware routing



Kuruvila, Nayak, Stojmenovic 2004

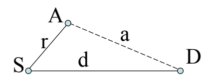
***Power progress:* minimize $(r^{\alpha}+c)/(d-a)$**

Iterative power progress:

select *B* if *power(SB)+power(BA) < power(SA)*

(Iterative) Projection power progress

‘Reluctance’ routing algorithm



Stojmenovic, Lin 1998

Rediscovered by: Yu, Govindan, Estrin: GEAR, TR-01-0023, Aug. 2001.

f(A)= **reluctance** =1/g(A)   g(A) in [0,1] lifetime

A = neighbors of S that minimizes f(A) + f’(S)*s/R

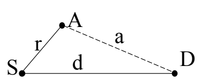
(cost of A + average cost around S * ideal number of hops from A to D)

If D is neighbor of S *then* deliver to D *else* forward to A

Reluctance/progress*: minimize *f(A)/(|SD|-|SA|)

Kuruvila, Nayak, Stojmenovic 2004 (no added parameters)

Power_reluctance routing



Stojmenovic, Lin 1998

A = neighbors of S that minimizes u(r) + v(s)

If D is neighbor of S and u(d) < min [u(r) + v(s)]

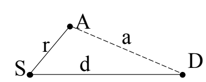
then deliver to D *else* {A = neighbor of S that minimizes f(A)u(r) + v(s)f’(S); forward to A }

Power*reluctance/progress:* minimize *f(A)power(SA)/(|SD|-|SA|)

Kuruvila, Nayak, Stojmenovic 2004 (no added parameters)

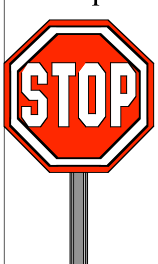
Physical layer impact

- Expected hop count (counting all transmissions and possibly acknowledgements)
- F(SA)= expected hop count from S to A
- **Minimize F(SA)/(d-a)**
- Kuruvila, Nayak, Stojmenovic 2004
- Delay; QoS routing; Bitrate



- If position information is available, it replaces Bellman-Ford approach (e.g. GeoOrbitts)

Loop-free with guaranteed delivery



Stop if message is to be returned to neighbor it came from (no further choices)= ***concave node***

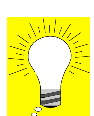
MFR, DIR, Greedy

Backtracking/Flooding Greedy/MFR:

Concave nodes flood message to *one/all* neighbors and then reject further copies of the same message

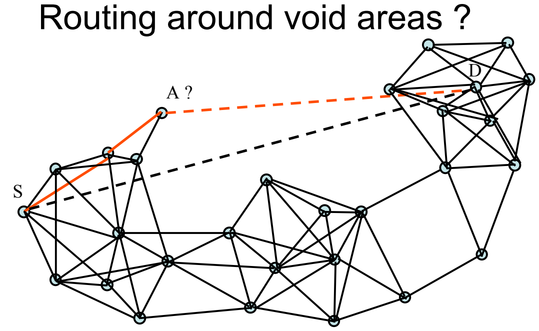
Loop-free methods that guarantee delivery, reasonable flooding rate

But nodes memorize past traffic



Stojmenovic, Lin 1999

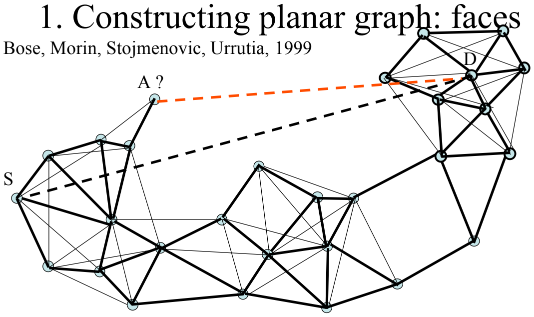
Routing around void areas ?



Recovery, perimeter, face mode

1. Constructing planar graph: faces

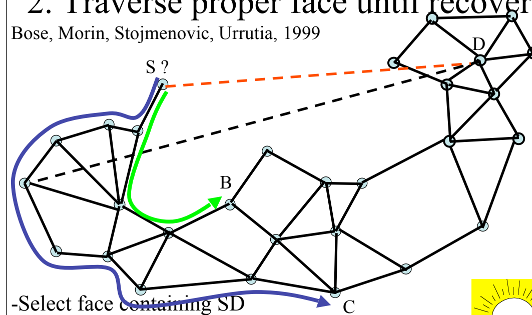
Bose, Morin, Stojmenovic, Urrutia, 1999



Some planar graphs (Gabriel graph) can be constructed without message exchange!

2. Traverse proper face until recovery

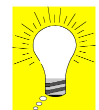
Bose, Morin, Stojmenovic, Urrutia, 1999



-Select face containing SD

- Follow that face by **left** hand or **right** hand rule

until recovery (= closer node reached)



GFG= Greedy-FACE-Greedy

REPEAT:

Greedy until delivery or a failure node A,|AD|=d

FACE until delivery or B reached, |BD|<d,

Greedy … until delivery or loop

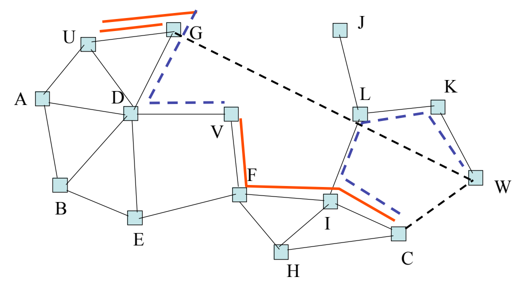
No traffic memorization, localized, close to SP

→ ***scalable*** !! Bose, Morin, Stojmenovic, Urrutia, 1999

Karp and Kung MOBICOM 2000 duplicated (with citation)

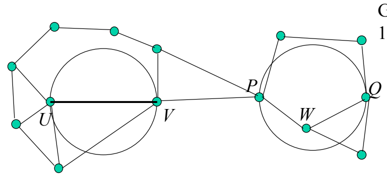
GPSR= GFG (added MAC, mobile nodes)

Greedy, GFG (greedy-face-greedy)



Gabriel graph

Gabriel, Sokal 1984



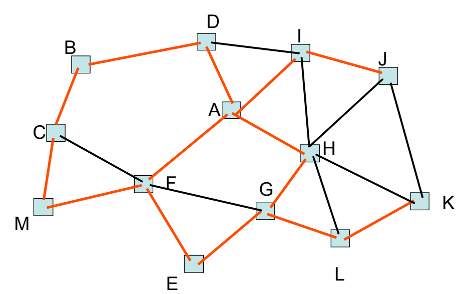
Gabriel graph GG(S) contains an edge (U,V) iff the disk with diameter (U,V) contains no other point from the same network

= distance from other points to center of UV is > |UV|/2

= Acute angles for all joint neighbors → in GG

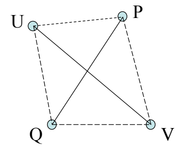
GG(S) is planar and connected (contains MST)

RNG, **GG**



Gabriel graph is planar

Planar graph = no two edges intersect



Proof by contradiction: Assume

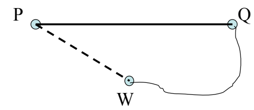
UV, PQ ∈ GG(S), UV ∩ PQ

→∠ PUQ < π /2, ∠ PVQ < π /2,

∠ UPV < π /2, ∠ UQV < π /2,

→ Sum of angles in UPVQ < 2π

Gabriel graph contains MST



By contradiction: Assume

PQ ∈MST, PQ ∉ GG;

→ ∃W, PW<PQ, QW<PQ, PW∉ MST

Replace PQ by PW in MST

→ new MST has smaller sum of edge lengths. contradiction

→ Gabriel graph connected

Unit (connected) graph contains MST

Kruskal's algorithm to construct MST:

Sort all edges by their length, from shortest to longest.

Consider each edge in that order for inclusion in MST:

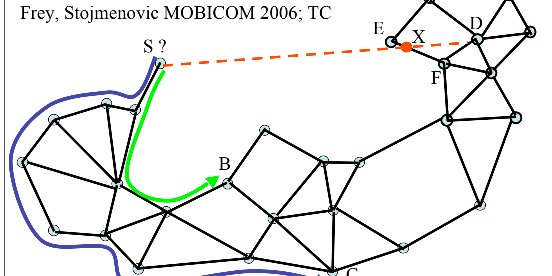
Include it in MST if its addition does not create a cycle.

Unit graph edges considered before any other edge. After their consideration, MST is already connected, and no more edges can be added.

→ GG(S) ∩ U(S) planar and connected!

Traversal of selected face leads to recovery

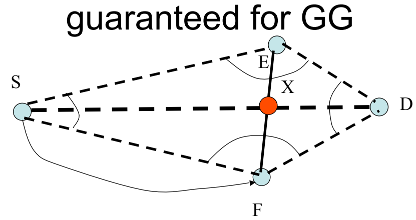
Frey, Stojmenovic MOBICOM 2006; TC



-Line SD intersects the face in X on an edge EF

- E or F is closer to D than A (if nothing else found before)

Getting closer on the face is guaranteed for GG



∠S < π/2, ∠D< π/2 since EF is in GG → ∠E > π/2 or ∠F > π/2

∠F > π/2 → |SD| > |FD| → F is closer to D than S

Frey, Stojmenovic MOBICOM 2006 IEEE TC 2010

Conclusions on GFG

- Imprecise location information is challenge for georouting with guaranteed delivery
- Georouting in 3D has no guaranteed delivery
- Unit disk graph is required in theory; however GG has no R in definition
- For planar graphs GFG still always works,
  but GPSR by Karp and Kung does not

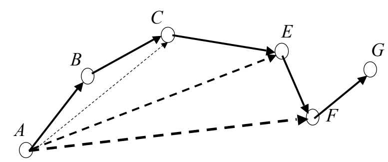
  Frey, Stojmenovic 2006
- For other metrics, there is still no alternative to GG based face routing for recovery mode, which prefers close neighbors (except shortcuts, dominating sets..)

Robustness of GFG

- GFG requires unit graph = equal transmission radius, no obstacles, nodes in plane
- Extension for fuzzy unit graphs = connected if distance < r, nor connected if distance >R, may or may not be connected otherwise, R/r < 1.41 Barriere, Fraigniaud, Narajanan, and Opatrny 2001
- Loop-free for static nodes; loops can be created by mobile nodes but exit can be found by adding timestamp of the last intersection with imaginary line SD and ignoring links created afterwards

Shortcut procedure in FACE mode

Datta, Stojmenovic, Wu 2001



ABCE replaced by AF

2-hop information needed

Beaconless greedy routing

- Füßler, Widmer, Käsemann, Mauve, Hartenstein 2003
- Heissenbüttel Braun 2003
- No ‘hello’ messages
- S transmits packet containing position of destination
- Each receiving node sets timeout based on its distance to destination
- If a packet from a neighbor received while waiting, cancel retransmission
- Otherwise retransmit at end of timeout
- Details for reducing the # of paths searched, e.g.
- Sender asks for help, and sends full message only to neighbor that responded first

Beaconless routing with guaranteed delivery

- Select and Protest Based …
- Kalosha, Nayak, Ruehrup, Stojmenovic, IEEE INFOCOM 2008 + IEEE/ACM ToN 2010
  - Routing with **Beaconless Forwarder Planarization** (**BFP**)
  - Routing with **Angular Relaying** (**AR**) recovery
- **BFP**: In face mode, nodes respond to S based on **distance to S**, not distance to D
- Closer neighbors respond sooner, but neighbors protests if it is not in GG
- **AR**: time delay proportional to **angle from previous direction** in face mode: sweep line (sweep curve)
- Protest message if not next edge (not on GG).

BFP: Select and protest example

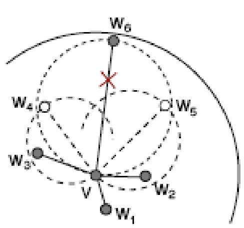
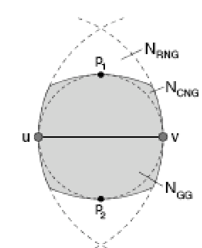


Fig. 5: BFP: Nodes respond in the order w_1, w_2, w_3, w_6; w_4 and w_5 are hidden. w_4 protests against w_6.

Circular neighborhood graph



Constant number of protests (max 13)

Fig. 8: The proximity region for circlunar neighborhood is between RNG lune and Gabriel circle.

Contention based georouting

- With guaranteed delivery, minimal communication overhead and shorter paths
- Ruehrup and Stojmenovic 2010 IEEE IPDPS
- Without prior planarization
- RTS-CTS-DATA in both greedy & face modes
- Sweep Circle method in face mode
- Radius *r/2* sensitive to UDG (less heterogeneity)

Rolling ball of radius r/2

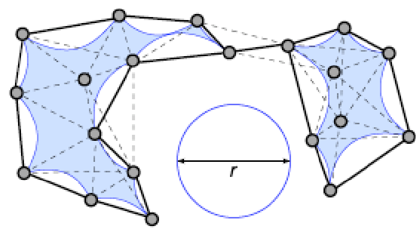


Figure 2: Unit disk graph with radius r, α-hull (shaded area) and α-shape (solid edges) with $\alpha = -\frac{2}{r}$ *of a point set.*

Sweep circle

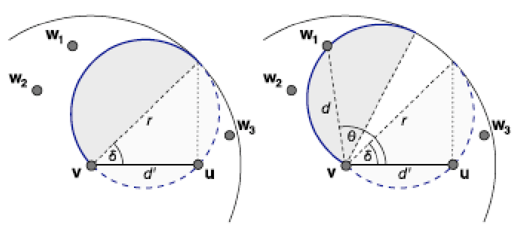


Figure 3: Sweep Circle starting at current node v with u as previous hop and δ being the start angle. The relative position of candidate w_1 *is given by distance d and angle θ.*

Initialization in recovery mode

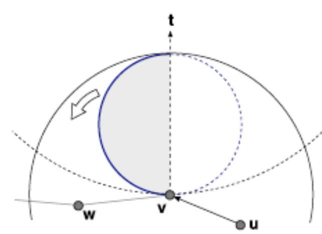
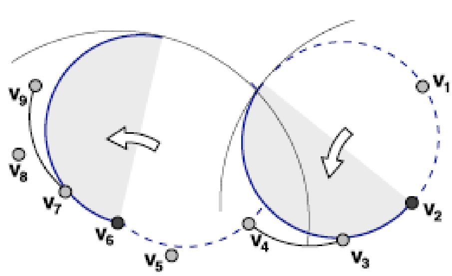


Figure 4: Initialization of the RS algorithm when starting the sweep at a local minimum node v.

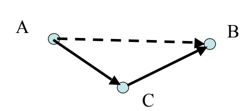
Traversal vs Gabriel graph



(b) Sweep Circle Traversal

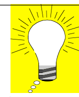
QoS routing

- Find a route which satisfies delay, bandwidth etc. QoS criteria
- Huang, Dai, Wu 2004
- Localized routing, maximizes *progress/cost*
- *Progress* =advance on the projection to destination
- *Cost* from QoS criterion used
- *Backward checking* = iterative improvement



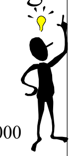
Instead of routing to B, route to C if cost(AC)+cost(CB) < cost (AB)

QoS DFS routing



- Depth First Search with Greedy to sort neighbors, and O(1) memory in each node, guarantee delivery
- bandwidth criterion = edge elimination
- delay criterion = hop count + more bandwidth
- new connection time criterion
- Jain, Puri and Sengupta; Stojmenovic, Russell, Vukojevic 1999
- Power and cost addition: Vukojevic, Stojmenovic 2005

Power/cost aware localized routing with guaranteed delivery



Combine greedy and recovery phases
greedy only power optimized: Stojmenovic, Datta 2000

- Both greedy and recovery phases power optimal
- Replace edge in GG by shortest weighted path: Wu, Candan
- Construct CDS (connected dominating set), run face on CDS, apply shortest weighted path: Simplot-Ryl et all, 2008
- Competitive with respect to globalized solutions

Assisted routing

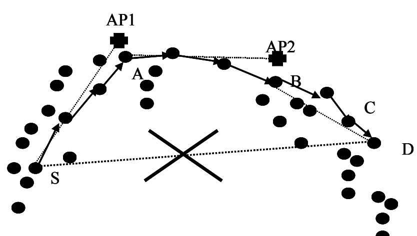
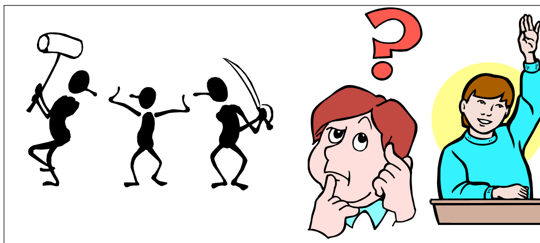


Figure 4: the operation of AGPF

Blazevic, Giordano, Le Boudec 2000



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