Location-based Routing in Sensor Networks I

Jie Gao
Computer Science Department
Stony Brook University
Papers


Routing in ad hoc networks

- Obtain route information between pairs of nodes wishing to communicate.
- **Proactive protocols**: maintain routing tables at each node that is updated as changes in the network topology are detected.
  - Heavy overhead with high network dynamics (caused by link/node failures or node movement).
  - Not practical for ad hoc networks.
Routing in ad hoc networks

- **Reactive protocols**: routes are constructed on demand. No global routing table is maintained.
- Due to the high rate of topology changes, reactive protocols are more appropriate for ad hoc networks.
  - Ad hoc on demand distance vector routing (AODV)
  - Dynamic source routing (DSR)
- However, both depend on flooding for route discovery.
Geographical routing

- **“Data-centric” routing**: routing is frequently based on a nodes’ attributes and sensed data, rather than on pre-assigned network address.
- **Geographical routing** uses a node’s location to discover path to that route.
Geographical routing

- Assumptions:
  - Nodes know their geographical location
  - Nodes know their 1-hop neighbors
  - Routing destinations are specified geographically (a location, or a geographical region)
  - Each packet can hold a small amount \( O(1) \) of routing information.
  - The connectivity graph is modeled as a unit disk graph.
Geographical routing

- The source node knows
  - The location of the destination node;
  - The location of itself and its 1-hop neighbors.
- Geographical forwarding: send the packet to the 1-hop neighbor that makes most progress towards the destination.
  - No flooding is involved.
- Many ways to measure “progress”.
  - The one closest to the destination in Euclidean distance.
  - The one with smallest angle towards the destination: “compass routing”.
Greedy progress

compass routing

greedy distance routing

x

y

y'

d
Compass routing may get in loops

- Compass routing may get in a loop.

Send packets to the neighbor with smallest angle towards the destination.
Geographical routing may get stuck

- Geographical routing may get stuck at a node whose neighbors are all further away from the destination than itself.

Send packets to the neighbor closest to the destination.
How to get around local minima?

• Use a planar subgraph: a straight line graph with no crossing edges. It subdivides the plane into connected regions called faces.
Face Routing

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

- All necessary information is stored in the message
  - Source and destination positions
  - The node when it enters face routing mode.
  - The first edge on the current face.

- Completely local:
  - Knowledge about direct neighbors’ positions is sufficient
  - Faces are implicit. Only local neighbor ordering around each node is needed.

“Right Hand Rule”
What if the destination is disconnected?

- Face routing will get back to where it enters the perimeter mode.
- Failed – no way to the destination.
- Guaranteed delivery of a message if there is a path.
Face routing needs a planar graph.

Compute a planar subgraph of the unit disk graph.

- Preserves connectivity.
- Distributed computation.
A detour on Delaunay triangulation
Delaunay triangulation

- First proposed by B. Delaunay in 1934.
- Numerous applications since then.
Voronoi diagram

- Partition the plane into cells such that all the points inside a cell have the same closest point.
Delaunay triangulation

- Dual of Voronoi diagram: Connect an edge if their Voronoi cells are adjacent.
- Triangulation of the convex hull.
Delaunay triangulation

- “Empty-circle property”: the circumcircle of a Delaunay triangle is empty of other points.
- The converse is also true: if all the triangles in a triangulation are locally Delaunay, then the triangulation is a Delaunay triangulation.
Greedy routing on Delaunay triangulation

• Claim: Greedy routing on DT never gets stuck.
Delaunay triangulation

- For an arbitrary point set, the Delaunay triangulation may contain long edges.
- Centralized construction.

- If the nodes are uniformly placed inside a unit disk, the longest Delaunay edge is $O((\log n/n)^{1/3})$. [Kozma et al. PODC’04]

- Next: 2 planar subgraphs that can be constructed in a distributed way: relative neighborhood graph and the Gabriel graph.
Relative Neighborhood Graph and Gabriel Graph

- **Relative Neighborhood Graph (RNG)** contains an edge $uv$ if the lune is empty of other points.
- **Gabriel Graph (GG)** contains an edge $uv$ if the disk with $uv$ as diameter is empty of other points.
- Both can be constructed in a distributed way.
Relative Neighborhood Graph and Gabriel Graph

- Claim: MST \( \subseteq \) RNG \( \subseteq \) GG \( \subseteq \) Delaunay

- Thus, RNG and GG are planar (Delaunay is planar) and keep the connectivity (MST has the same connectivity of UDG).
MST $\subseteq$ RNG $\subseteq$ GG $\subseteq$ Delaunay

1. RNG $\subseteq$ GG: if the lune is empty, then the disk with uv as diameter is also empty.
2. GG $\subseteq$ Delaunay: the disk with uv as diameter is empty, then uv is a Delaunay edge.
MST $\subseteq$ RNG $\subseteq$ GG $\subseteq$ Delaunay

3. MST $\subseteq$ RNG:
   - Assume uv in MST is not in RNG, there is a point w inside the lune. $|uv|>|uw|$, $|uv|>|vw|$.
   - Now we delete uv and partition the MST into two subtrees.
   - Say w is in the same component with u, then we can replace uv by wv and get a lighter tree. $\Rightarrow$ contradiction.

RNG and GG are planar (Delaunay is planar) and keep the connectivity (MST has the same connectivity of UDG).
An example of UDG

200 nodes randomly deployed in a 2000×2000 meters region. Radio range = 250 meters
An example of GG and RNG
Two problems remain

- Both RNG and GG remove some edges → a short path may not exist!

- The shortest path on RNG or GG might be much longer than the shortest path on the original network.

- Even if the planar subgraph contains a short path, can greedy routing and face routing find a short one?
Tackle problem I:
Find a planar spanner
Find a good subgraph

• Goal: a planar spanner such that the shortest path is at most $\alpha$ times the shortest path in the unit disk graph.
  – Euclidean spanner: The shortest path length is measured in total Euclidean length.
  – Hop spanner: The shortest path length is measured in hop count.

• $\alpha$: spanning ratio.
  – Euclidean spanning ratio $\geq \sqrt{2}$
  – Hop spanning ratio $\geq 2$.

• Let’s first focus on Euclidean spanner.
Delaunay triangulation is an Euclidean spanner

- DT is a 2.42-spanner of the Euclidean distance.
- For any two nodes uv, the Euclidean length of the shortest path in DT is at most 2.42 times |uv|. 
**Restricted Delaunay graph**

- Keep all the Delaunay edges no longer than 1.
- Claim: RDG is a 2.42-spanner (in total Euclidean length) of the UDG.
- Proof sketch: If an edge in UDG is deleted in RDG, then it’s replaced by a path with length at most 2.42 longer.
Construction of RDG

- Easy to compute a superset of RDG: Each node computes a local Delaunay of its 1-hop neighbors.
  - A global Delaunay edge is always a local Delaunay edge, due to the empty-circle property.
  - A local Delaunay may not be a global Delaunay edges.

- What if the superset has crossing edges?
Crossing Lemma

- **Crossing lemma**: if two edges cross in a UDG, then one node has edges to the three other nodes in UDG.

\[
|uw| \leq |wp| + |up| \\
|vx| \leq |vp| + |xp| \\
|wu| + |vx| \leq |wx| + |ux| \leq 2
\]

Also, \( |wv| + |ux| \leq |wx| + |ux| \leq 2 \)

There must be 2 edges on the quad adjacent to the same node.
Detect crossings between local delaunay edges

- By the crossing Lemma: if two edges cross in a UDG, one of them has 3 nodes in its neighborhood and can tell which one is not Delaunay.

- Neighbors exchange their local DTs to resolve inconsistency.
  - A node tells its 1-hop neighbors the non-Delaunay edges in its local graph.
  - A node receiving a “forbidden” edge will delete it from its local graph.

- Completely distributed and local.
RDG construction

- 1-hop information exchange is sufficient.
  - Planar graph;
  - All the short Delaunay edges are included.
  - We may have some planar non-Delaunay edges but that does not hurt spanning property.
More on RDG construction

- RDG can be constructed without the full location information.

- Only local angle information suffices.

- Key operation: If two edges in the unit-disk graph cross, remove the one that is not in the Delaunay triangulation.

- How to tell that an edge is not in the Delaunay triangulation?
Removing non-Delaunay edges

If two edges AB, CD cross, there are only three cases:

(i)  
(ii) 
(iii)
Removing non-Delaunay edges

If two edges AB, CD cross, there are only three cases:

(i) 

(ii) 

(iii) 

With angle info, the shape is fixed! Node C can tell which edge is not Delaunay.
Removing non-Delaunay edges

Case (i) : Use the “empty-circle” test of Delaunay triangulation

\[ |AC| > 1 \geq |CD| \]
\[ |BC| > 1 \geq |CD| \]

Conclusion: The edge AB is not a Delaunay edge.
Find a hop spanner

• Restricted Delaunay graph is not a hop spanner.
  • Take $n$ nodes uniformly in a segment of length 1. The hop count can be as large as $n-1$.
• Reduce the density of the sensors.
  • Use clustering to reduce density.
  • Compute RDG on the subset to get a hop spanner.
  • Clustering also reduce interference and enables efficient resource reuse such as bandwidth.
Reduce node density

- Find a subset of nodes, called clusterheads
  - Each node is directly connected to at least 1 clusterhead.
  - No two clusterheads are connected.
- Use a greedy algorithm. Pick a node as a clusterhead, remove all the 1-hop neighbors, continue.
- Constant density: $\leq 6$ clusterheads in any unit disk.
  - The angle spanned by two clusterheads is at least $\pi/3$. 

\[ \pi/3 \]
Connect clusterheads by gateways

- For two clusterheads, if their clients have an edge, then we pick one pair as gateway nodes.

- Notice that clusterheads $x, y$ are within 3 hops to have a pair of gateways.

- There are constant clusterheads and gateways inside any unit disk.
Path on clusterheads and gateways

- For two nodes $u, v$ that are $k$ hops away, there is a path through clusterheads and gateways with at most $3k+2$ hops.

- Construct RDG on clusterheads and gateways, which have constant bounded density.

Shortest path
A Routing Graph Sample

Select clusterheads

Clusterheads select gateways

RDG on clusterheads & gateways
Restricted Delaunay graph

- Claim: (RDG on clusterheads and gateways + edges from clients to clusterheads) is a constant hop spanner of the original UDG.

- Proof sketch:
  - The shortest path $P$ in the unit disk graph has $k$ hops.
  - Through clusterheads and gateways $\exists$ a path $Q$ with $\leq 3k+2$ hops.
  - $Q$’s total Euclidean length is $\leq 3k+2$.
  - The shortest path on the RDG, $H$, has Euclidean length $\leq 2.42 \times (3k+2)$.
  - By constant density property a region with width 1 and length $2.42 \times (3k+2)$ has $O(k)$ nodes inside. So # hops of $H$ is $O(k)$.
  - This concludes the hop spanner property.
Restricted Delaunay graph

RNG

RDG

Clusterhead
Gateway
Restricted Delaunay graph

RNG

RDG

Clusterhead
Gateway