Trace-Routing in 3D Wireless Sensor Networks: A Deterministic Approach with Constant Overhead

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2D PLANE, 3D VOLUME, AND 3D SURFACE SENSOR NETWORKS

Sensor network settings

- 2D plane: crop sensing in fields or wildlife tracking on plains
- 3D volume: underwater or space reconnaissance
- 3D surface: seismic monitoring on ocean floors or in mountainous regions
Routing in Large Scale 3D Sensor Networks

- Routing algorithm must be scalable
- Constraints in storage and computation capacities at individual sensor nodes
- Large scale in sensor quantity
- Goal: realizes Deterministic routing with Constant Overhead (or DISCO routing) in 3D networks
- Constant overhead: signifies the storage, communication and computation required for routing are bounded by a constant at each sensor node
- Deterministic and guaranteed: a routing path can be determined without random search, to guarantee packet delivery between any pair of nodes
OUR MAIN CONTRIBUTIONS

- The conventional table-driven routing is obviously non-DISCO because the size of a routing table grows with the size of the network.
- Most on-demand routing algorithms developed for mobile ad hoc networks are not DISCO either because they result in non-constant communication overhead for route discovery.
- Protocols that aggregate data from sensors to sink(s) are predominantly DISCO, do not support generic communication between any peers in the network.
The earliest endeavor to achieve DISCO in large-scale peer-to-peer wireless sensor networks is geometric routing [13-20].

What is geometric greedy routing?
- A node always forwards a packet to one of its neighbors, which is the closest to the destination of the packet.

Why geometric greedy routing?
- Both computation complexity and storage space bounded by a small constant.
- Scalable to large networks with stringent resource constraints on individual nodes.
LIMITATIONS OF CURRENT GREEDY ROUTING SCHEMES

- Face routing (alternatives/enhancements)
  - Exploit the fact that a void in a 2D planar network is a face with a simple line boundary
  - Surprising challenges for extending to 3D although increasing space dimension appears irrelevant to network protocol
LIMITATIONS OF CURRENT GREEDY ROUTING SCHEMES

- Topology control — a critical communication range is suggested to avoid local minimum [29]: theoretically sound but the critical communication range is often too large for practical sensor networks

- Dimension reduction—project to a 2D plane to apply face routing [6,7]: no guarantee (face routing on projected plane does not ensure a packet to actually move out of void in the 3D network)
LIMITATIONS OF CURRENT GREEDY ROUTING SCHEMES

- Structures-based
  - 3D partial unit Delaunay triangulation [5]: divide the network into closed subspaces such that a local minimum recovered within a few subspaces only
  - GDSTR-3D [10]: If a local minimum is reached, forward packet along a spanning tree of convex hulls
  - Distributed multi-dimensional tree structure [30]
  - Random walk under a spherical dual graph structure [8]
  - Certain structure must be maintained by individual sensors, which are often non-locally-deterministic [8][5] or requires non-constant storage space [10][30]
LIMITATIONS OF CURRENT GREEDY ROUTING SCHEMES

- Greedy embedding [21-27]
  - Provides theoretically sound solutions to ensure the success of greedy routing
  - Unfortunately, none of the greedy embedding algorithms can be extended from 2D to general 3D networks
- Proven results [28]
  - There does not exist a deterministic algorithm that can guarantee delivery based on local information only in general 3D networks
HARMONIC MAP APPROACH (MOBIHOC’11)

(a) A 3D sensor network (Network model 1).
(b) Local minimums in nodal greedy routing.
(c) Unit tetrahedron cells (UTCs).
(d) Volumetric Harmonic mapping.
(e) A greedy routing path in mapped domain.
(f) A greedy routing path in original network.
CONTRIBUTIONS

- Realizes DISCO
- **Constant overhead**: signifies the storage, communication and computation required for routing are bounded by a constant at each sensor node
- **Deterministic and guaranteed**: a routing path can be determined without random search, to guarantee packet delivery between any pair of nodes
- Conflicts with the proven result? No.
- Works for networks with no or one hole only
**TRACE-ROUTING**

- **U**: an Euclidean volume in 3D space, which is enclosed by a set of boundaries $B = \{B_k | 0 \leq k \leq K\}$, where $B_0$ is the outer boundary and $B_k$ ($k > 0$) is an inner boundary of $U$.

- **L(p, q)**: a straight line segment from Point p to Point q.
DEFINITIONS

**Definition 1.** Let $C(s, d)$ be a sequence of line segments, $C(s, d) = \langle L(p_0, p_1), L(p_1, p_2), \ldots, L(p_{m-1}, p_m) \rangle$, where $p_0 = s$ and $p_m = d$. We call $C(s, d)$ a routing path connecting $s$ and $d$, if and only if

- $L(p_i, p_{i+1})$ does not intersect with $L(p_j, p_{j+1})$, $\forall i \neq j$, $i + 1 \neq j$ and $i \neq j + 1$; and
- $L(p_i, p_{i+1})$ does not penetrate any boundary of $U$, $\forall L(p_i, p_{i+1}) \in C(s, d)$.

**Definition 2.** We call $V(p, \delta)$ the $\delta$-vicinity of Point $p$, if $\forall \hat{p}$ in $V(p, \delta)$, $L(p, \hat{p})$ is completely contained in $U$ and $|L(p, \hat{p})| \leq \delta$ where $\delta$ is a given positive real number.
DEFINITION 3. A routing path $C(s,d)$ is a geometric greedy path (or greedy path for conciseness), denoted as $C(s,d,\delta)$, if $\forall$ $p_i$ on $C(s,d,\delta)$, $p_{i+1}$ is the closest point in $V(p_i,\delta)$ to Destination $d$. 
**Definition 4.** Point $p_{\text{min}}$ is a local minimum for Destination $d$ under a given $\delta$, if $p_{\text{min}} \neq d$ and $L(p_{\text{min}}, d) \leq L(p, d) \forall p \in V(p_{\text{min}}, \delta)$. 

![Diagram showing the definition of a local minimum with points $p_{\text{min}}$, $d$, and $V(p_{\text{min}}, \delta)$.]
**Lemma 1.** If there does not exist a geometric greedy routing path \( C(s, d, \delta) \) between \( s \) and \( d \) under a given \( \delta \), \( L(s, d) \) must intersect at least one of the boundaries of \( U \).

**Lemma 2.** Greedy routing only fails at local minimums and local minimums are always on the boundaries of holes.
As shown by Lemma 2, if greedy routing fails, it must stuck at a local minimum, and such local minimum must be on a boundary of U.

Let $p_{\text{min}}$ denote the local minimum, and assume it is on Boundary $B_i$.

Now we construct an arbitrary plane that contains $L(p_{\text{min}}, d)$. It intersects $B_i$, resulting in one or multiple traces. By examining the traces, we have the following observation.

**Lemma 3.** A trace on a boundary surface is a closed loop with no self-intersection.
**Lemma 4.** In an s-con volume, the trace containing $p_{\text{min}}$ must also contain $p_0$ and there is a loop-free path from $p_{\text{min}}$ to $p_0$ along this trace.
We construct a simple algorithm, dubbed trace-routing as follows:

When geometric greedy routing reaches a local minimum $p_{\text{min}}$ on Boundary $B_i$, it chooses a cutting plane that is determined by $p_{\text{min}}$, Destination $d$, and another point.

The plane intersects $B_i$, yielding a trace that contains $p_{\text{min}}$.

The routing path advances along the trace in clockwise or counterclockwise direction until it reaches a point that is closer to Destination $d$ than $p_{\text{min}}$ is. Then geometric greedy routing follows.
While trace-routing has been introduced above to escape from local minimums, it remains challenging to adapt the concepts and ideas to a practical sensor field.

A sensor network is under a discrete setting, which presents an approximation of the 3D volume only, rendering part of the earlier discussed methods and results invalid.

Lemma 2 has shown that local minimums are always on the boundaries of holes in a continuous 3D Euclidean volume. Unfortunately, this result no longer holds in discrete settings.

Sensor nodes rarely reside perfectly on the trace computed in a continuous space, calling for approximated solutions.

The routing algorithm must be distributed without the knowledge of the global boundary information.
We first establish a tetrahedral structure based on discrete sensors as discussed in [31]

**Lemma 5.** Given an internal local minimum $p_{\text{min}}$, the routing path can move out the local minimum by using local information in $2\delta$-vicinity of $p_{\text{min}}$, where $\delta$ is the maximum radio transmission range.

**Lemma 6.** Given a tetrahedral structure of the 3D sensor network and a plane that intersects a triangular boundary surface of the tetrahedral structure, a closed-loop trace can be constructed deterministically.
**Theorem 2.** A deterministic routing path can be identified by following the trace constructed according to Lemma 6 to escape from local minimums.

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**Algorithm 1: Trace-Routing Algorithm**

**Input:** Local minimum $p_{min}$, Destination $d$;

1. Define Plane $\Delta$ based on $p_{min}$, $d$ and an arbitrary node $p \in V(p_{min}, \delta)$;
2. $p_{cur} \leftarrow p$, $p_{pre} \leftarrow p_{min}$;
3. **while** $|L(p_{cur}, d)| \geq |L(p_{min}, d)|$ **do**
   4. Identify a boundary node $\hat{p} \in V(p_{cur}, \delta)$ such that $L(\hat{p}, p_{cur})$ intersects Plane $\Delta$ and forms the largest angle with $L(p_{pre}, p_{cur})$;
5. $p_{pre} \leftarrow p_{cur}$; $p_{cur} \leftarrow \hat{p}$;
SIMULATIONS RESULTS

- 3D sensor networks in different sizes (ranging from 1,800 to 11,000 nodes) and shapes are simulated.
- Compared with GDSTR-3D [10] and HVE [31].
  - Since HVE works in networks with one hole only, we focus on the comparison between TR and GDSTR-3D in most simulation scenarios.
- Performance metrics:
  - Delivery ratio
  - Stretch factor (the ratio of the actual greedy routing path length to the shortest path length).
EXAMPLE ROUTING PATHS
EXAMPLE ROUTING PATHS
STRETCH FACTOR

<table>
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<th>Models</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
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<td>1.09</td>
<td>1.04</td>
<td>1.21</td>
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<td>1.10</td>
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<td>GDSTR-3D</td>
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<td>1.23</td>
<td>1.29</td>
<td>1.25</td>
<td>1.07</td>
<td>1.19</td>
<td>1.20</td>
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</tbody>
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Percent of Total Routing Paths (x100%)

Routing Path Stretch

- 0.05
- 0.1
- 0.15
- 0.2
- 0.25
- 0.3
- 0.35

[1.0−1.05] [1.05−1.1] [1.1−1.15] [1.15−1.2] [1.2−1.5] [1.5−2.0] [2.0−2.5] > 2.5
NETWORK DYNAMICS

![Network Dynamics Graph](image)

- **Delivery Ratio** vs. **Time Intervals**
- Lines represent different algorithms:
  - TR
  - GDSTR-3D
  - HVE
ROBUSTNESS TO SENSOR COORDINATES ERRORS
TRACE-ROUTING LIMITATION

- Work for all networks? No
- Guaranteed delivery for S-Con only
  - A 3D volume $U$ is s-con (Strong-CON-nected), if and only if the intersection of any plane and $U$ is a connected graph on the plane
- May work for Non-S-Con networks with properly chosen cutting plane
SUMMARY

- Investigate DISCO routing in 3D wireless sensor networks
- Does not exist a DISCO algorithm for general 3D networks
- Proposed Trace-Routing
  - Formally show its correctness under continuous and discrete settings
  - Numerically show its performance in terms of stretch factor and success rate under various network conditions