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

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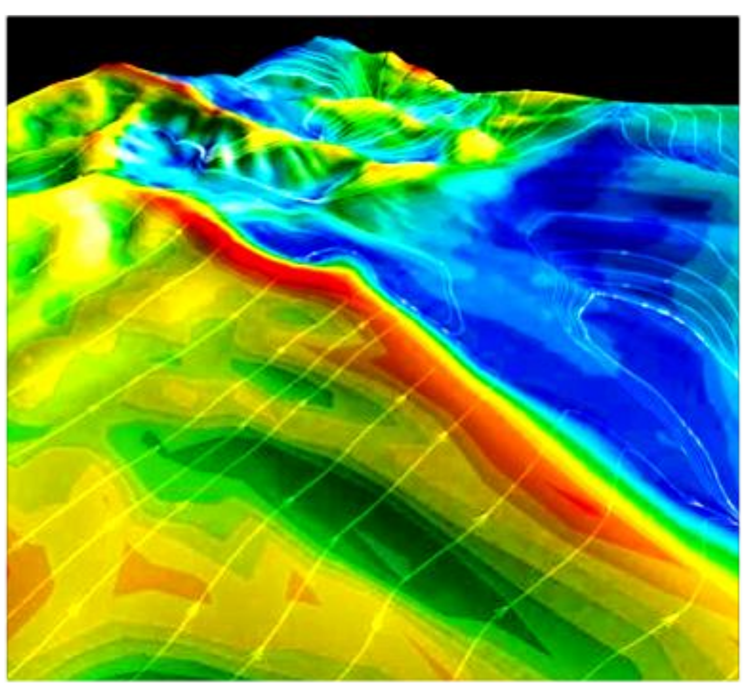
2D PLANE, 3D VOLUME, AND 3D SURFACE SENSOR NETWORKS

- 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
  - <u>Constant overhead</u>: signifies the storage, communication and computation required for routing are bounded by a constant at each sensor node
  - <u>Deterministic and guaranteed</u>: a routing path can be determined without random search, to guarantee packet delivery between any pair of nodes

OUR MAIN CONTRIBUTIONS

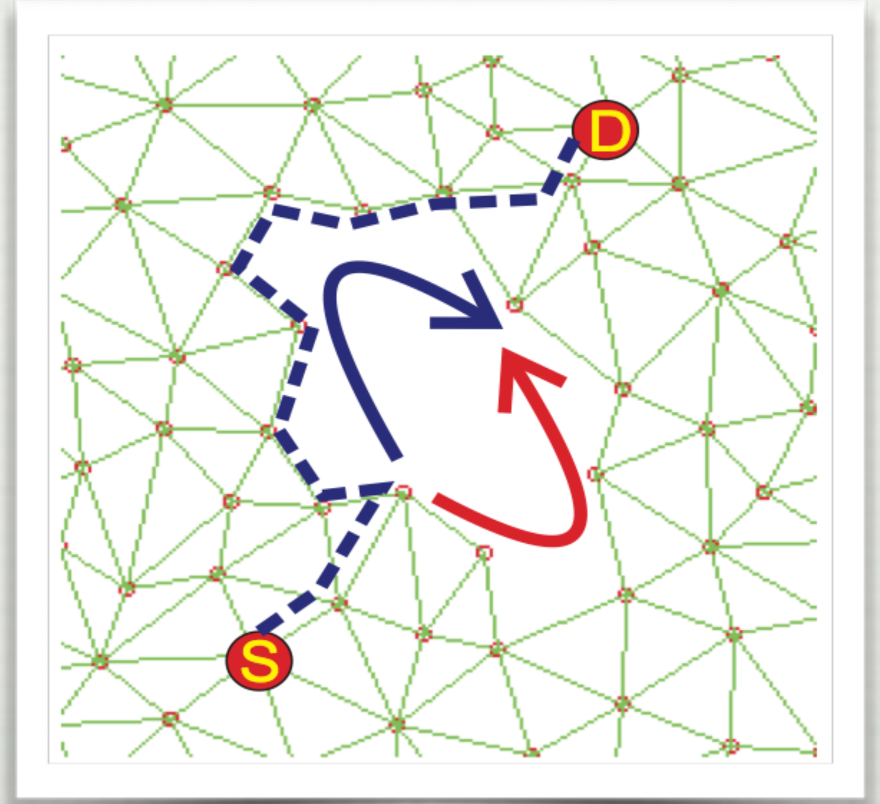
- The conventional table-driven routing is obviously non-DISCO
  - because the size of a routing table grows with the size of the network
- Most on-demand routing algorithms developed for mobile ad hoc networks are not DISCO either
  - because they result in non-constant communication overhead for route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

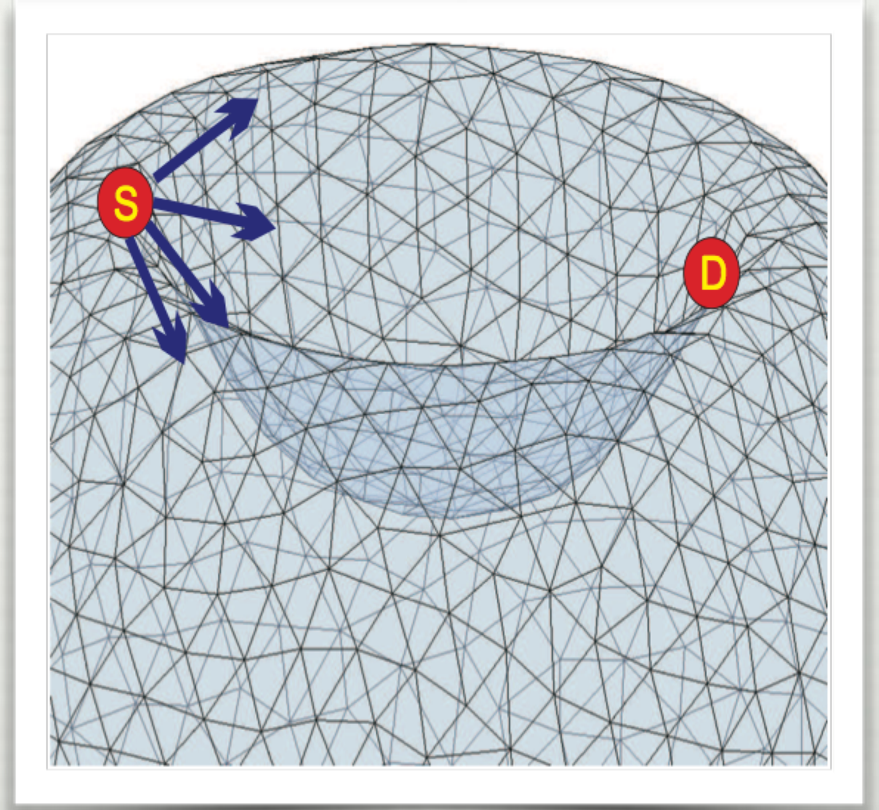
GREEDY ROUTING

- The earliest endeavor to achieve DISCO in large-scale peep-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]: <u>no guarantee</u> (face routing on projected plane does not ensure a packet to actually move out of void in the 3D network)

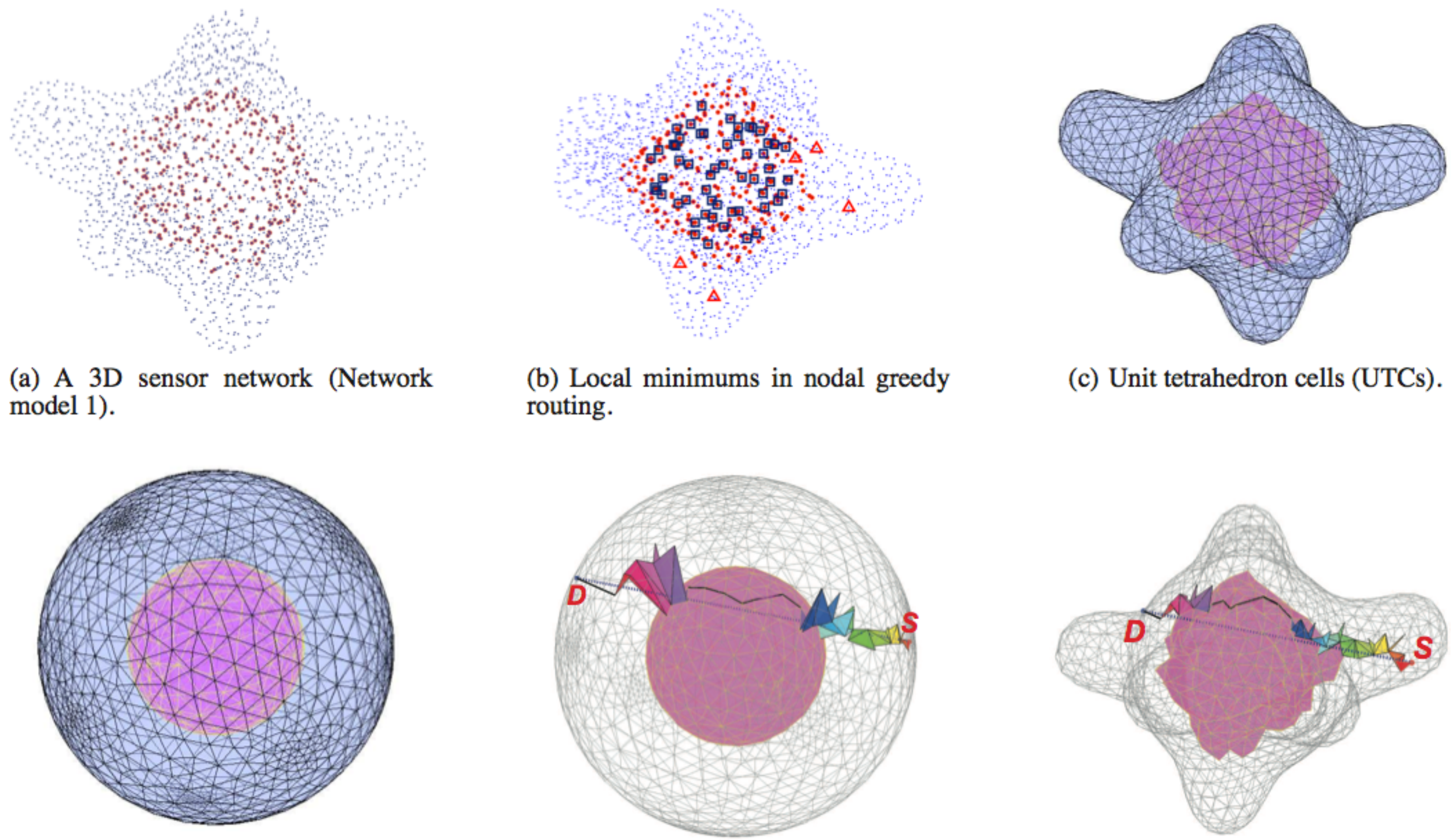
LIMITATIONS OF CURRENT GREEDY ROUTING SCHEMES

- 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 <u>non-locally-deterministic</u> [8][5] or requires <u>non-constant storage space</u> [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.

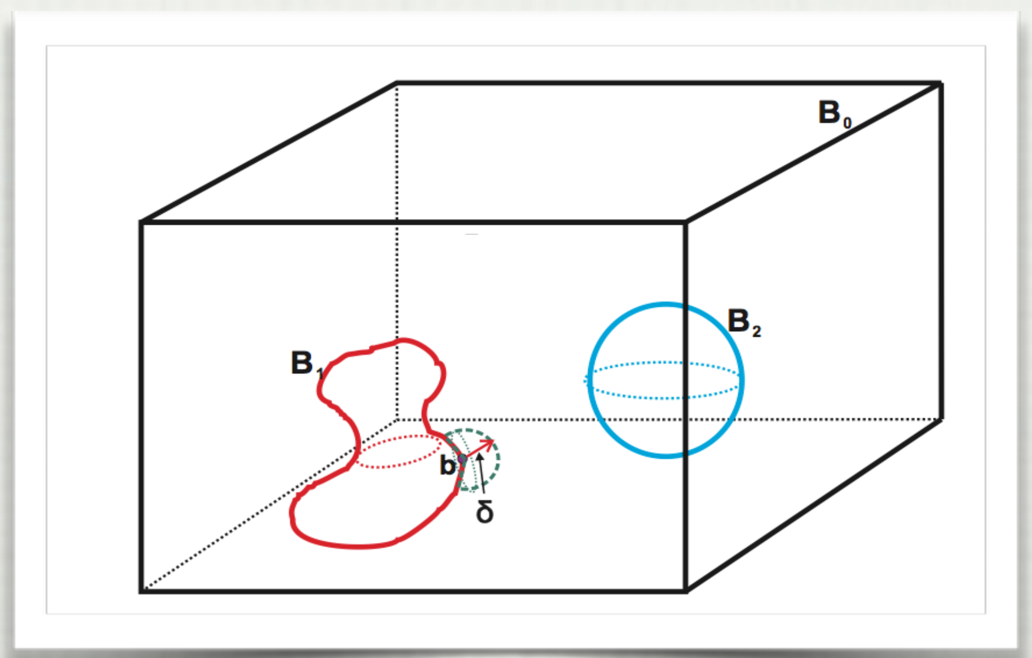
(f) A greedy routing path in original network.

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 $B=\{B_k \mid 0 \le k \le K\}$, 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

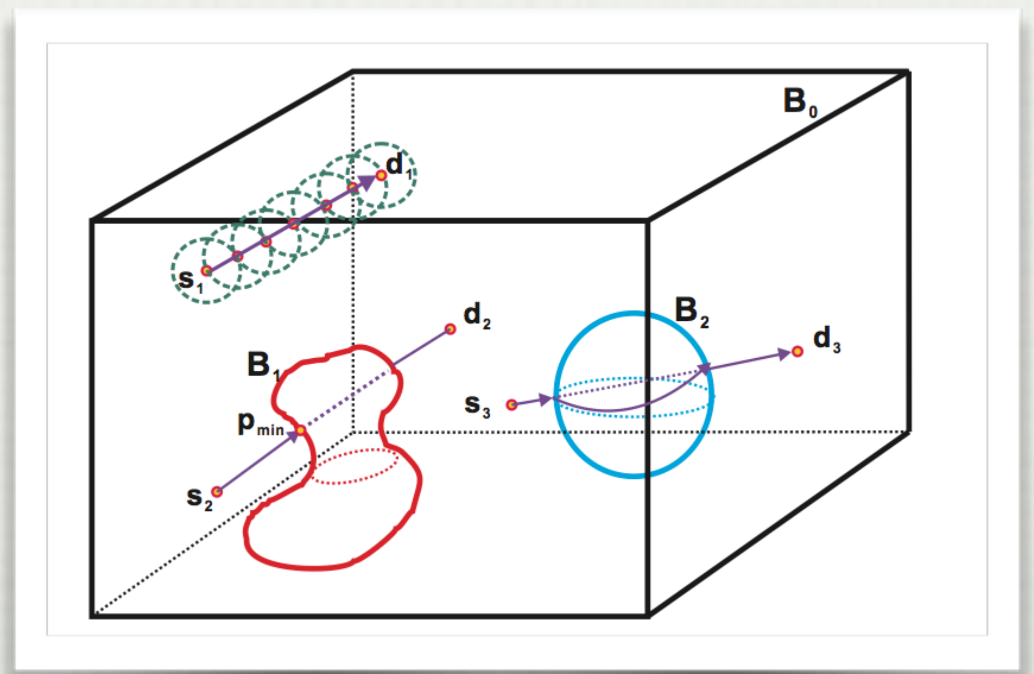
DEFINITION 1. *Let* $C(s,d)$ *be a sequence of line segments,* $C(s,d) = \langle L(p_0, p_1), L(p_1, p_2), .., L(p_{m-1}, p_m)\rangle$*, where* $p_0 = s$ *and* $p_m = d$*. We call* $C(s,d)$ *a routing path connecting* s *and* d*, if and only if*

- $L(p_i, p_{i+1})$ *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* δ*-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* δ *is a given positive real number.*

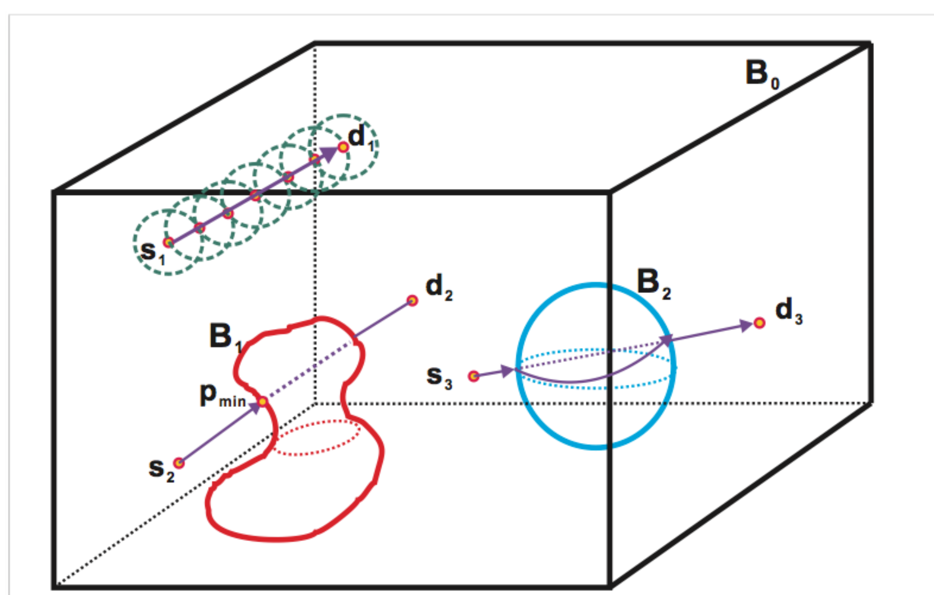
DEFINITIONS

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.



DEFINITIONS

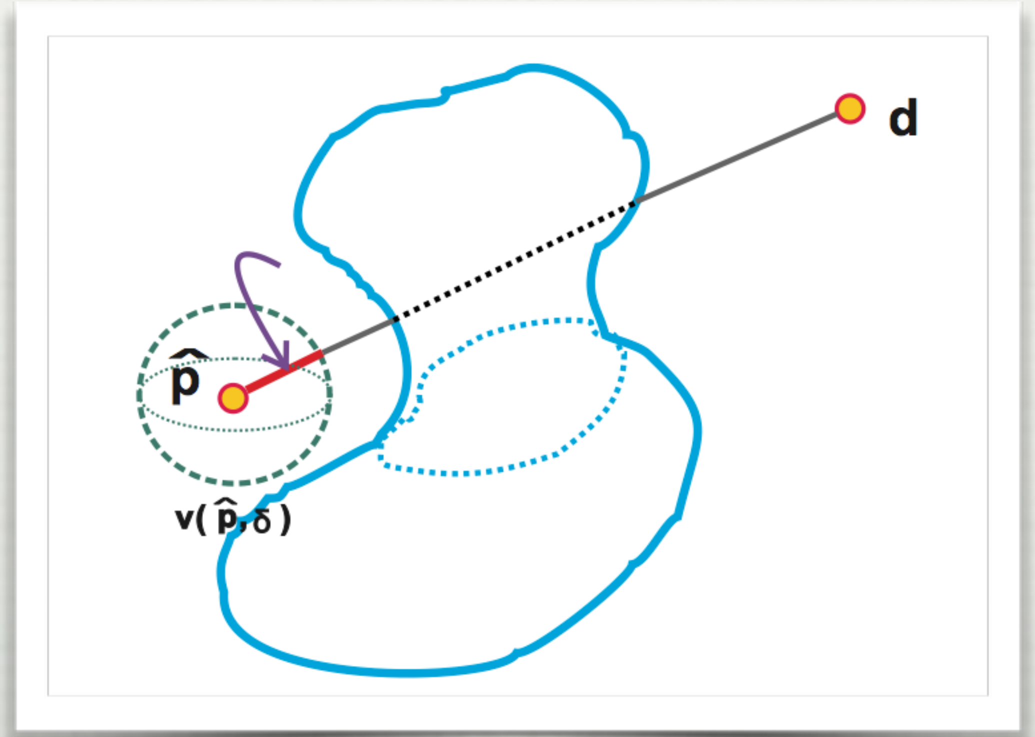
DEFINITION 4. *Point p_{min} is a local minimum for Destination d under a given δ, if $p_{min} \neq d$ and $L(p_{min}, d) \leq L(p, d)\ \forall\, p \in V(p_{min}, \delta)$.*



TRACE-ROUTING ALGORITHM

LEMMA 1. *If there does not exist a geometric greedy routing path $C(s, d, \delta)$ between s and d under a given δ, $L(s, d)$ 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.*



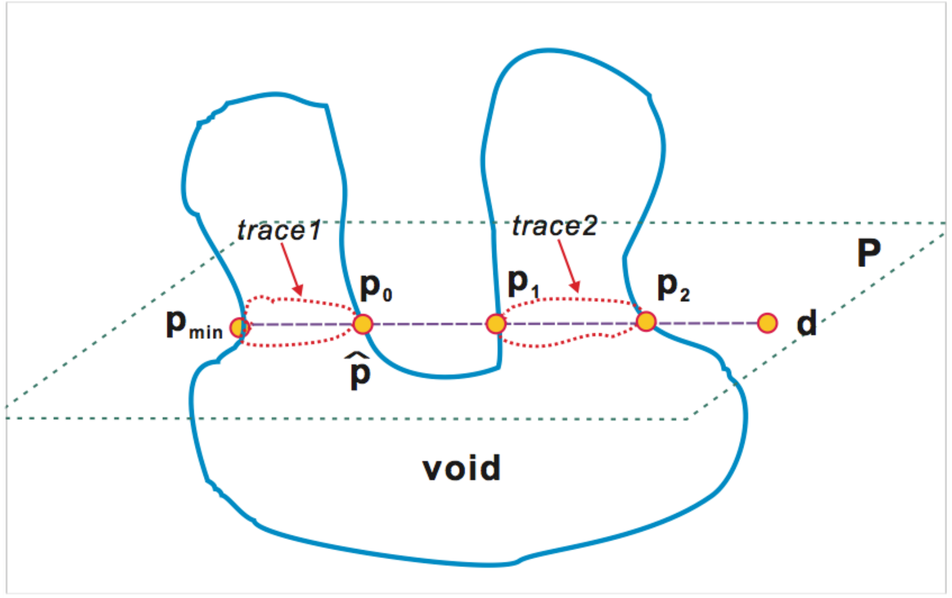
TRACE-ROUTING ALGORITHM

- 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_{min} denote the local minimum, and assume it is on Boundary B_i.
- Now we construct an arbitrary plane that contains $L(p_{min}, d)$. 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.*

TRACE-ROUTING ALGORITHM

LEMMA 4. *In an s-con volume, the trace containing p_{min} must also contain p_0 and there is a loop-free path from p_{min} to p_0 along this trace.*



TRACE-ROUTING ALGORITHM

THEOREM 1. *There exists a deterministic algorithm with constant storage, communication and computation overhead, which can always successfully navigate the routing path out of local minimums in an s-con volume.*

- We construct a simple algorithm, dubbed trace-routing as follows:
  - When geometric greedy routing reaches a local minimum p_{min} on Boundary B_i, it chooses a cutting plane that is determined by p_{min}, Destination d, and another point.
  - The plane intersects B_i, yielding a trace that contains p_{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_{min} is. Then geometric greedy routing follows.

DISCRETE SENSOR NETWORK SETTING

- 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 long 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

DISCRETE SENSOR NETWORK SETTING

- We first establish a tetrahedral structure based on discrete sensors as discussed in [31]

LEMMA 5. *Given an internal local minimum p_{min}, the routing path can move out the local minimum by using local information in 2δ-vicinity of p_{min}, where δ 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.*

DISCRETE SENSOR NETWORK SETTING

THEOREM 2. *A deterministic routing path can be identified by following the* trace *constructed according to Lemma 6 to escape from local minimums.*

Algorithm 1: Trace-Routing Algorithm

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

Define Plane Δ based on p_{min}, d and an arbitrary node $p \in V(p_{min}, \delta)$;

$p_{cur} \leftarrow p$, $p_{pre} \leftarrow p_{min}$;

while $|L(p_{cur}, d)| \geq |L(p_{min}, d)|$ **do**

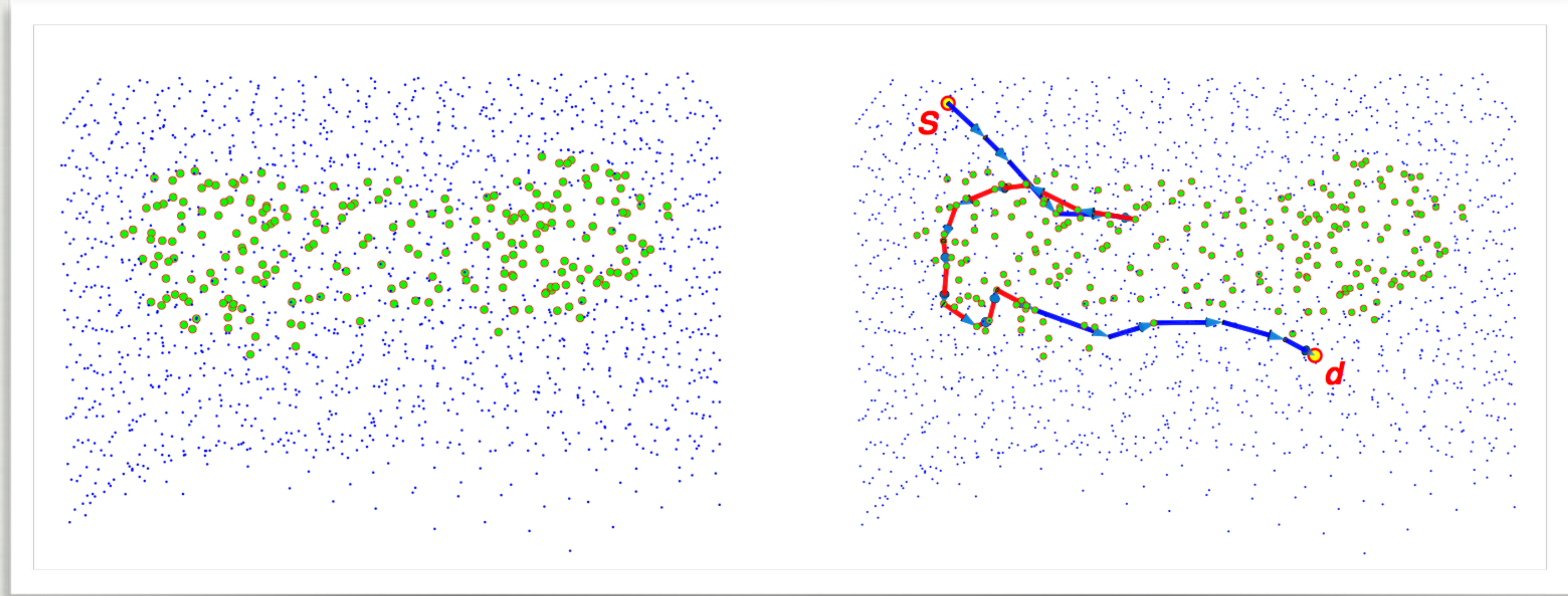
  Identify a boundary node $\hat{p} \in V(p_{cur}, \delta)$ such that $L(\hat{p}, p_{cur})$ intersects Plane Δ and forms the largest angle with $L(p_{pre}, p_{cur})$;

  $p_{pre} \leftarrow p_{cur}$; $p_{cur} \leftarrow \hat{p}$;

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



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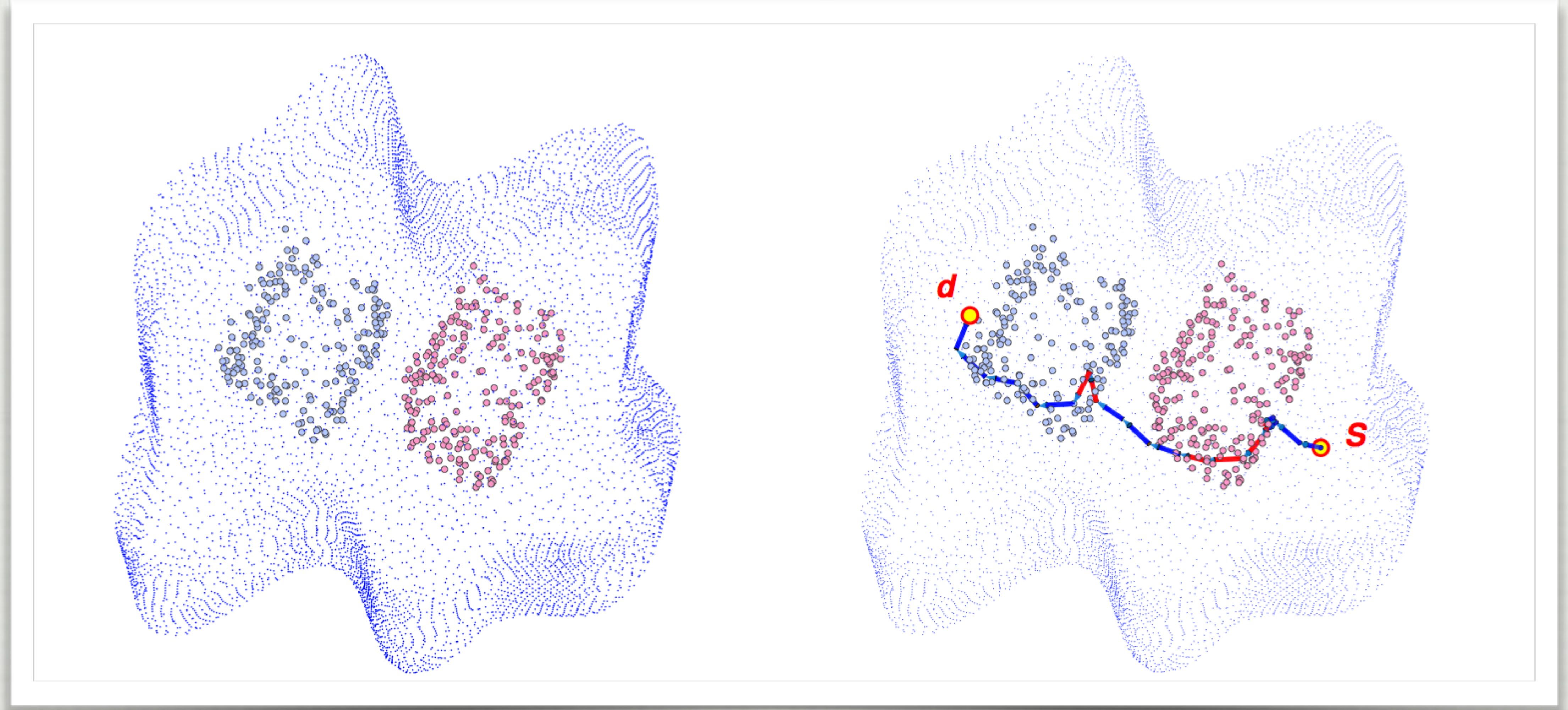
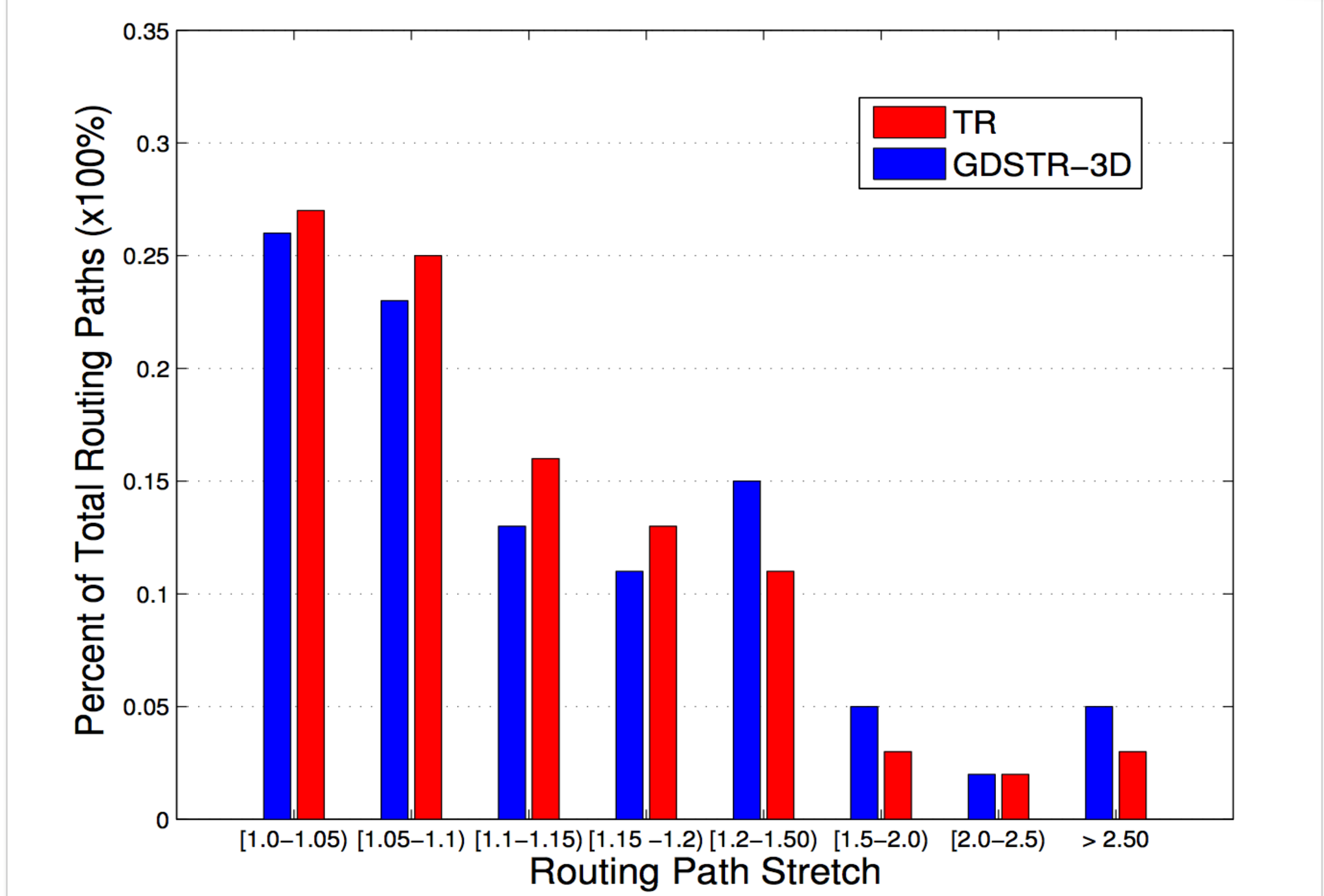
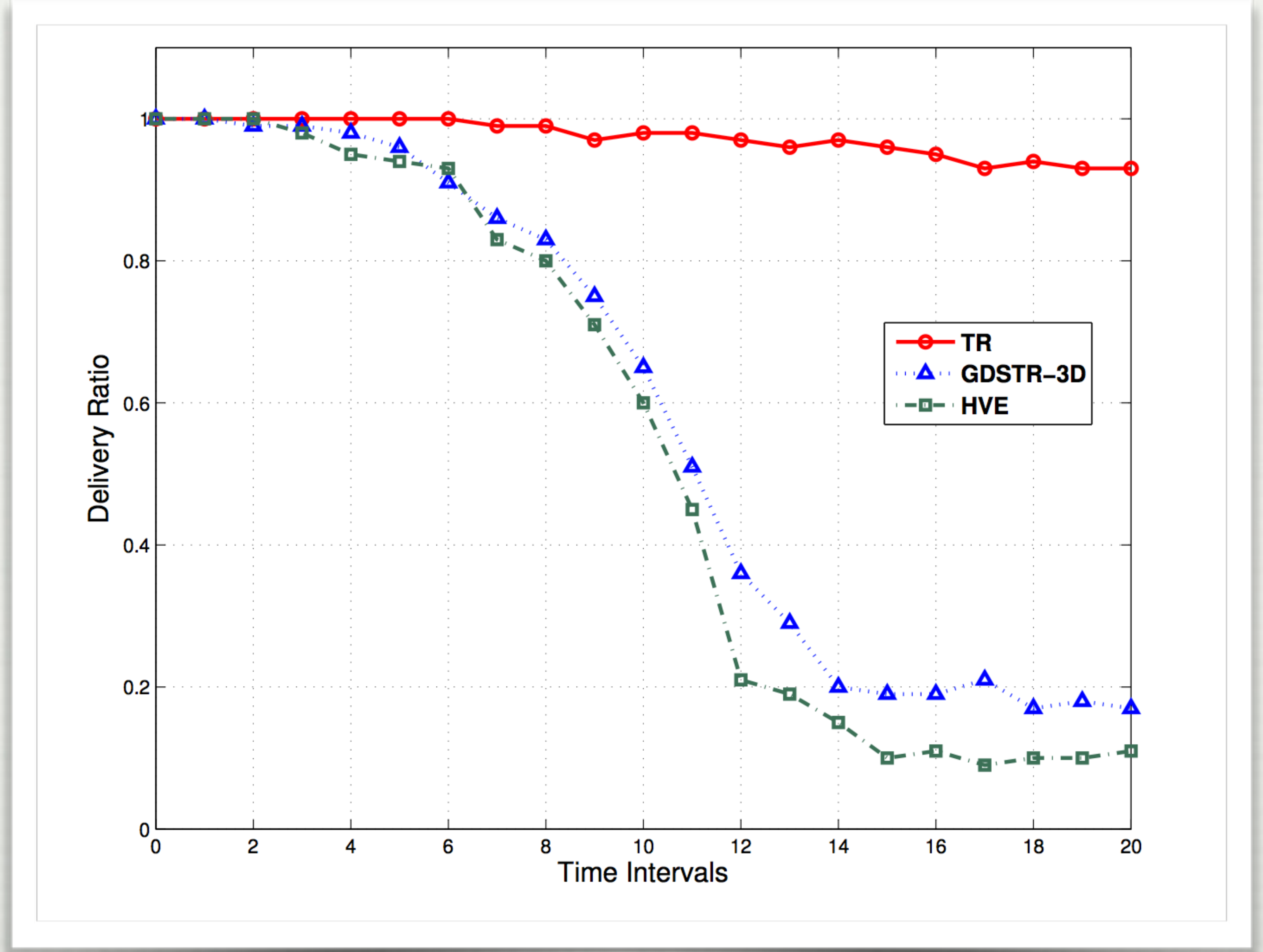


STRETCH FACTOR

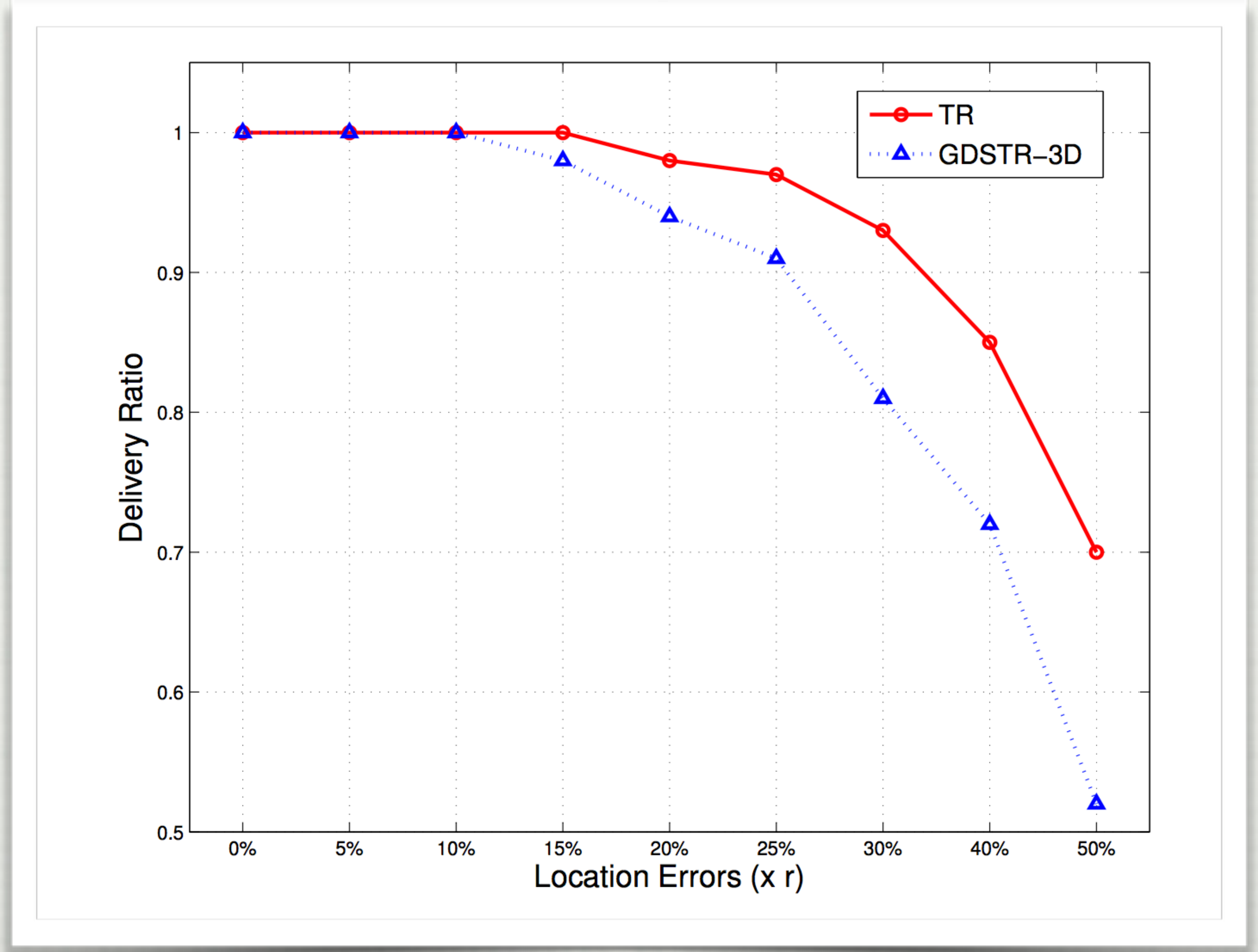
Models	1	2	3	4	5	6	Ave.
TR	1.05	1.09	1.04	1.21	1.08	1.11	1.10
GDSTR-3D	1.14	1.23	1.29	1.25	1.07	1.19	1.20



NETWORK DYNAMICS



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