A Distributed Greedy Heuristic for Computing Voronoi Tessellations With Applications Towards Peer-to-Peer Networks

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Outline

Motivation

We were creating a distributed network based off of Delaunay Triangulation and needed a fast distributed algorithm for calculating Delaunay peers. We ran into a couple of issues.

- Distributed algorithms for solving Delaunay triangulation don't really exist (every node does a global solution).
- Not any fast solutions if we start moving out of 2D Euclidean space.

This leaves approximation. However:

- Simple approximation doesn't guarantee a fully-reachable network (k-nearest neighbor, nodes in radius r).
- Other solutions [1] required prohibitively high sampling or other hidden time costs.

And nothing can handle moving nodes.

Voronoi Tessellation and Delaunay Triangulation

- Voronoi Tessellation
  - Partition space such that each point is mapped the 'voronoi generator' to which it is closest.
- Delaunay Triangulation
  - generate a triangulation, such that, for every triangle the circumcircle does not contain any other points

Voronoi Example

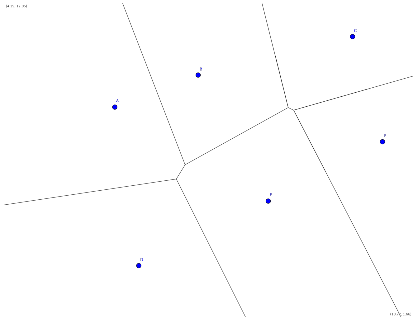

Figure: The space is partitioned, such that each point in a partition is closest to that partitions 'Voronoi generator'

Delaunay Example

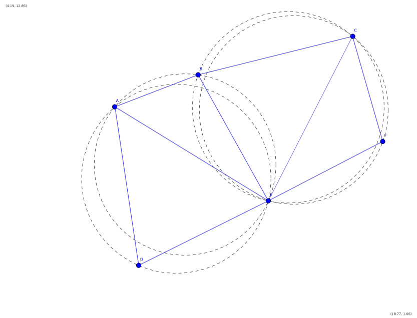

Figure: The space is partitioned, such that each point in a partition is closest to that partitions 'Voronoi generator'

Distributed Hash Tables

- Abstractly, a DHT is a mechanism for maintaining a large state in a decentralized network.
- In practice, the state is a large number of $(key, value)$ records.
- A Distributed hash table assigns those records to servers and routes request for those records to those servers.
- Current incarnations of Distributed hash tables assign servers and records locations in an arbitrary metric space.
- Servers are assigned responsibility for records that are “close” to them, and to peer with “nearby” servers.
- DHTs currently use a variety metric spaces.

Applications of DHTs

- *P2P file sharing* is by far the most prominent use of DHTs. The most well-known application is BitTorrent [4].
- *Distributed Domain Name Systems* (DNS) have been built upon DHTs [5] [7]. Distributed DNSs are much more robust that DNS to orchestrated attacks, but otherwise require more overhead.
- Distributed *machine learning* [6].
- Many *botnets* are now P2P based and built using well established DHTs [8]. This is because the decentralized nature of P2P systems means there's no single vulnerable location in the botnet.

Extant Varieties of DHT

- Ring Based DHTs
  - Chord
  - Pastry
  - Tapestry
- Tree Based DHTs
  - CAN
  - Kademlia

How are DHTs and Vonroi Tesselation/Delunay Trianguation related?

A Server is responsible for records "close" to it (Voronoi Triangulation) A Server peers with other servers that bound it's Voronoi Region (Delunay Triangulation) DHTs often have peers in excess of the Delaunay triangulation to shorten lookups, however the peers that are the Delunay neighbors

- Ring Based DHTs
  - Chord: a unidirectional modulus ring metric
  - Pastry, Symphony: bidirectional modulus ring
- Tree Based DHTs
  - CAN: Euclidean distance
  - Kademlia: XOR distance

Why do we need a distributed Voronoi heuristic?

- The different topologies DHTs utilize present optimization trade-offs (lookup latency, number of lookup hops, network robustness, availability, processing overhead)
- The primary effort in implementing a new metric space in a DHT is implementing Voronoi Regions/Delunay Triangulation algorithm in that metric.
- DGVH allows many metrics to be tested without requiring the design and development effort of generating an exact Voronoi Regions/Delunay Triangulation algorithm.

So we created a Distributed Greedy Voronoi Heuristic, or DGVH for short.

Distributed Greedy Voronoi Heuristic

- Geometrically intuitive method of approximating the one-hop delaunay peers of a Node
- Is guaranteed to form a connected mesh (unlike k-nearest heuristic)
- Can be utilized in any continuous metric space

DGVH Intuition

- The majority of Delunay links cross the corresponding Voronoi edges.
- We can test if the midpoint between two potentially connecting nodes is on the edge of the voronoi region.
- This intuition fails if the midpoint between two nodes does not fall on their voronoi edge.

DGVH Algorithim

```
1:  Given node $n$ and its list of *candidates*.
2:  *peers* $\leftarrow$ empty set that will contain $n$'s one-hop peers
3:  Sort *candidates* in ascending order by each node's distance to $n$
4:  Remove the first member of *candidates* and add it to *peers*
5:  for all $c$ in *candidates* do
6:      $m$ is the midpoint between $n$ and $c$
7:      if Any node in *peers* is closer to $m$ than $n$ then
8:          Reject $c$ as a peer
9:      else
10:         Remove $c$ from *candidates*
11:         Add $c$ to *peers*
12:     end if
13: end for
```

DGVH Example

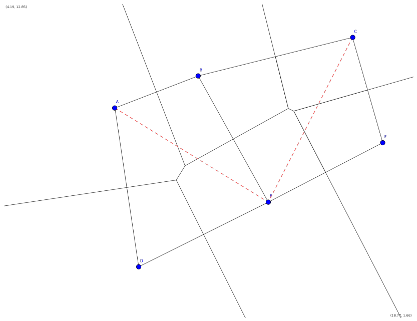

Figure: 'DGVH connects all nodes where the midpoint falls on the border of the voronoi regions'

Realistic Candidate set Size

- In application, a single node will not need to calculate the triangulation for every peer in the network, rather it will only calculate it's own peers.
- A smart "join" process will prevent the Candidate Set from reaching $O(n)$
- Expected size of the candidate set is $O(degree^2)$ which compromises current peers and 2-hop peers
- The average degree of many metric spaces is $O(1)$, then therefore DGVH will practically run in $O(1)$ time in those metric spaces.

Error Mitigation

- As DGVH is a heuristic, it will likely have errors when compared to a global Delaunay triangulation.
- This error rate is difficult to find analytically and will vary between metric spaces and distributions of locations
- A simple method of mitigating this error is to keep both one and two hop peers.

Experiment 1

In our first experiment, we wanted to test the accuracy of our heuristic.

- We generated a random graph and created the Delaunay triangulation using a global solution and DGVH.
- We found DGVH had approximately one error per node.

Our second set of experiments demonstrate that this error rate is sufficiently low for distributed applications.

Results

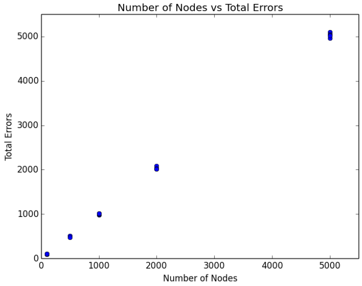

Figure: As the size of the graph increases, we see approximately 1 error per node. We can also see that the error rate and number of nodes has a linear relationship.

Experiment 2

Our second experiment were designed to test how well nodes could form a routing topology using DGVH.

- For each trial, we create a random graph.
- During the first two cycles, nodes are given 10 random connections.
- In each cycle (including the first two):
  - Each node gossips and runs DGVH.
  - 2000 random lookups from random nodes to random locations performed.
- The rate of successful lookups approaches 1.0 as time progresses.

Results

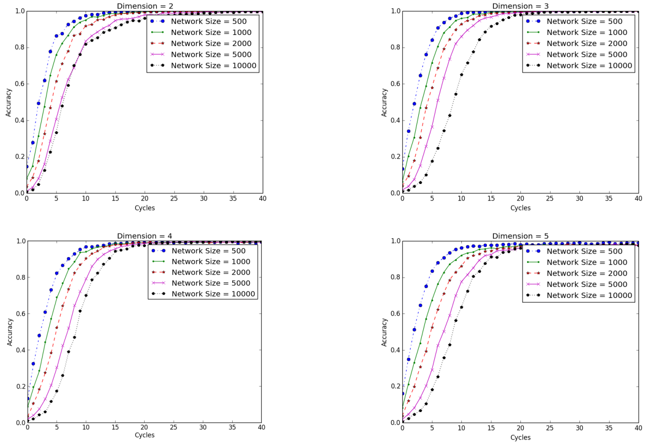

Figure: These figures show, starting from a randomized network, DGVH forms a stable and consistent network topology. The Y axis is the percentage of successful lookups out of 2000 queries and the X axis is the number of gossips cycles.

Other Applications

One type of distributed system that can use Voronoi tessellations are *wireless ad-hoc networks*.

- Solves the coverage-boundary problem [2].
- Can be used for sleep scheduling [3]

Conclusions

- DGVH provides a simple approximation Voronoi Triangulation / Delaunay Triangulation, of similar complexity to picking k-nearest node or nodes in distance k.
- Unlike other simple approximation methods, DGVH guarantees a fully connected graph.
- In practice, DGVH supplemented with K-nearest peers approximation provides an accurate, fast and distributable computation, with a fully connected graph as result.

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