The Impact of DHT Routing Geometry on Resilience and Proximity

Presented by Karthik Lakshminarayanan
at P2P Systems class
(Slides liberally borrowed from Krishna’s SIGCOMM talk)

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Motivation

- New DHTs constantly proposed
  - CAN, Chord, Pastry, Tapestry, Viceroy, Kademlia, Skipnet,
    Symphony, Koorde, Apocrypha, Land, Bamboo, ORDI …
- Each is extensively analyzed but in isolation
- Each DHT has many algorithmic details making it difficult to compare

Goals:
  a) Separate fundamental design choices from algorithmic details
  b) Understand their effect on reliability and efficiency

Approach: Component-based analysis

- Break DHT design into independent components
- Analyze impact of each component choice separately
  - compare with black-box analysis:
    • benchmark each DHT implementation
    • rankings of existing DHTs vs. hints on better designs

Different components of analysis

- Two types of components
  - Routing-level: neighbor & route selection
  - System-level: caching, replication, querying policy etc.
- Separating “routing” and “system” level issues
  - Good to understand them in isolation
  - Cons of this approach?
Outline

- DHT Design
- Compare DHT Routing Geometries
- Geometry’s impact on Resilience
- Geometry’s impact on Proximity

Three aspects of a DHT design

1) **Geometry**: a graph structure that inspires a DHT design
   - Tree, Hypercube, Ring, Butterfly, Debruijn

2) **Distance function**: captures a geometric structure
   - \( d(id1, id2) \) for any two node identifiers

3) **Algorithm**: rules for selecting neighbors and routes using the distance function

Chord DHT has Ring **Geometry**

- Nodes are points on a clock-wise Ring
- \( d(id1, id2) = \text{length of clock-wise arc between ids} = (id2 - id1) \mod N \)
**CAN => Hypercube Geometry**

- \( d(id_1, id_2) = \) #differing bits between \( id_1 \) and \( id_2 \)
- Nodes are the corners of a hypercube

```
000 001 010 011 100 101 110 111
```

\( d(001, 111) = 2 \)

**PRR => Tree**

- Nodes are leaves in a binary tree
- \( d(id_1, id_2) = \) height of smallest sub-tree with ids = \( \log N \) – length of prefix_match\( (id_1, id_2) \)

```
000 001 010 011 100 101 110 111
```

\( d(000, 011) = 2 \)

**Geometry Vs Algorithm**

- **Algorithm** : exact rules for selecting neighbors, routes
  - Chord, CAN, PRR, Tapestry, Pastry etc.
  - Inspired by geometric structures like Ring, Hyper-cube, Tree
- **Geometry** : an algorithm’s underlying structure
  - Distance function is the formal representation of Geometry
  - Chord, Symphony => Ring
  - Many algorithms can have same geometry

**Is the notion of Geometry clear?**

- Notion of geometry is vague (as the authors admit)
- It is really a distance function on an ID-space
  - Hypercube is a special case of XOR!
- Possible formal definitions?
Chord Neighbor and Route selection Algorithms

- Neighbor selection: \( i \)th neighbor at \( 2^i \) distance
- Route selection: pick neighbor closest to destination

Geometry => Flexibility => Performance

- Geometry captures *flexibility* in selecting algorithms
- Flexibility is important for routing performance
  - Flexibility in selecting routes leads to shorter, reliable paths
  - Flexibility in selecting neighbors leads to shorter paths

Outline

- Routing Geometry
- Comparing DHT Geometries
- Geometry’s impact on Resilience
- Geometry’s impact on Proximity

Geometries considered

<table>
<thead>
<tr>
<th>Geometry</th>
<th>Algorithm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ring</td>
<td>Chord, Symphony</td>
</tr>
<tr>
<td>Hypercube</td>
<td>CAN</td>
</tr>
<tr>
<td>Tree</td>
<td>PRR</td>
</tr>
<tr>
<td>Hybrid = Tree + Ring</td>
<td>Tapestry, Pastry</td>
</tr>
<tr>
<td>XOR ( d(id1, id2) = id1 \ XOR \ id2 )</td>
<td>Kademlia</td>
</tr>
</tbody>
</table>
Route selection flexibility allowed by Ring Geometry

- Chord algorithm picks neighbor closest to destination
- A different algorithm picks the best of alternate paths

Neighbor selection flexibility allowed by Ring Geometry

- Chord algorithm picks $i^{th}$ neighbor at $2^i$ distance
- A different algorithm picks $i^{th}$ neighbor from $[2^i, 2^{i+1})$

Metrics for flexibility

- **FNS**: Flexibility in Neighbor Selection
  $=$ number of node choices for a neighbor

- **FRS**: Flexibility in Route Selection
  $=$ avg. number of next-hop choices for all destinations

- Constraints for neighbors and routes
  - select neighbors to have paths of $O(\log N)$
  - select routes so that each hop is closer to destination

Flexibility of Ring

- $\log N$ neighbors at exponential distances
- $\text{FNS} = 2^{i+1}$ for $i^{th}$ neighbor
- Route along the circle in clock-wise direction
  \[
  \text{FRS} = \sum \frac{\log(\text{d}(000,J))}{N} = \log N
  \]
### Flexibility for Tree

- \( \log N \) neighbors in sub-trees of varying heights
- \( FNS = 2^{i-1} \) for \( i^{th} \) neighbor of a node
- Route to a smaller sub-tree with destination; \( FRS = 1 \)

### Flexibility for Hypercube

- Routing to next hop fixes one bit
- \( FRS = \text{Avg. (#bits destination differs in)} = \log N/2 \)
- \( \log N \) neighbors differing in exactly one bit; \( FNS = 1 \)

### Summary of flexibility analysis

<table>
<thead>
<tr>
<th>Flexibility</th>
<th>Ordering of Geometries</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neighbors (FNS)</td>
<td><strong>Hypercube ( &lt;&lt; ) Tree, XOR, Ring, Hybrid</strong> (1) ( (2^{i-1}) )</td>
</tr>
<tr>
<td>Routes (FRS)</td>
<td><strong>Tree ( &lt;&lt; ) XOR, Hybrid ( &lt; ) Hypercube ( &lt; ) Ring</strong> (1) ( (\log N/2) ) ( (\log N/2) ) ( (\log N) )</td>
</tr>
</tbody>
</table>

*How relevant is flexibility for DHT routing performance?*

### Outline

- Routing Geometry
- Comparing DHT Geometries
  - Geometry’s impact on Resilience
  - Geometry’s impact on Proximity
Static Resilience

Two aspects of robust routing

- Dynamic Recovery: how quickly routing state is recovered after failures
- Static Resilience: how well the network routes before recovery finishes
  - captures how quickly recovery algorithms need to work
  - depends on FRS

Evaluation:

- Fail a fraction of nodes, without recovering any state
- Metric: % Paths Failed

Static Resilience: Summary

- Tree << XOR ≈ Hybrid < Hypercube < Ring
  - What about trees with 2 neighbors?

- Addition of sequential neighbors helps resilience, but increases stretch

- Sequential neighbors offer more benefit, again at the cost of increased stretch

Outline

- Routing Geometry
- Comparing flexibility of DHT Geometries
- Geometry’s impact on Resilience
- Geometry’s impact on Proximity
  - Overlay Path Latency
  - Local Convergence

Flexibility in Route Selection matters for Static Resilience
Analysis of **Overlay Path Latency**

- **Goal:** Minimize end-to-end overlay path latency
- **Both FNS and FRS can reduce latency**
  - Tree has FNS, Hypercube has FRS, Ring & XOR have both

**Evaluation:**
- Using Internet latency distributions

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**Problems with existing Network Models**

- How to assign edge latencies to network topologies?
  - topology models: GT-ITM, Power-law, Mercator, Rocketfuel
  - no edge latency models, even for measured topologies
- **Solution:** A model using *only* latency distribution seen by a typical node

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**Simulations using latency distribution *only***

1) **Topology, Edge Latencies**

2) **Latency Distribution**

Simulate

- Simulated Overlay Path Latency Distribution

Compute

- Computed Overlay Path Latency Distribution

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**Which is more useful: FNS or FRS?**

- **Plain** << **FRS** << **FNS ≈ FNS+FRS**
- Neighbor Selection is much better than Route Selection
**Proximity results: Summary**

- Using neighbor selection is much better than using route selection flexibility
- Performance of FNS/FRS is independent of geometry beyond its support for neighbor selection
- In absolute terms, proximity techniques perform well (stretch of <2)

**Local convergence: Summary**

- Flexibility in neighbor selection helps much better than that in route selection
- Relevance of FRS depends on whether FNS restricted to a k-random sample closely approximates ideal FNS

**Limitations**

- Notion of geometry is vague (as the authors admit) – it is really a distance function on an ID-space
  - Hypercube is a special case of XOR!
- Not considered other factors that might matter
  - Algorithmic details, symmetry in routing table entries
- Metrics under consideration can bias results – eg. In ring, do not distinguish between OPT and slightly sub-optimal paths