The Impact of DHT Routing
Geometry on Resilience and
Proximity

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Motivation

• New DHTs constantly proposed
  – CAN, Chord, Pastry, Tapestry, Viceroy, Kademlia, Skipnet,
    Symphony, Koonde, 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

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Chord DHT has Ring **Geometry**

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Chord **Distance** function captures Ring

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

- $d(id1, id2) = \#\text{differing bits between } id1 \text{ and } id2$
- Nodes are the corners of a hypercube

PRR => Tree

- Nodes are leaves in a binary tree
- $d(id1, id2) = \text{height of smallest sub-tree with ids} = \log N - \text{length of prefix_match}(id1, id2)$

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>Kademila</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
- **FNS** = $2^{i-1}$ for $i^{th}$ neighbor
- Route along the circle in clock-wise direction
  \[ FRS = \sum \log \left( d(000, J) \right) / N = \log N \]
Flexibility for Tree

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

Flexibility for Hypercube

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

Summary of flexibility analysis

<table>
<thead>
<tr>
<th>Flexibility</th>
<th>Ordering of Geometries</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neighbors (FNS)</td>
<td>Hypercube &lt;&lt; Tree, XOR, Ring, Hybrid</td>
</tr>
<tr>
<td>Routes (FRS)</td>
<td>Tree &lt;&lt; XOR, Hybrid &lt;&lt; Hypercube &lt;&lt; Ring</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

Does flexibility affect Static Resilience?

Tree << XOR ≈ Hybrid < Hypercube < Ring
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

*Flexibility in Route Selection matters for Static Resilience*

Outline

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

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
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

Simulations using latency distribution only

1) Topology, Edge Latencies

Simulate
Simulated Overlay
Path Latency Distribution

2) Latency Distribution

Compute
Computed Overlay
Path Latency Distribution

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