Vivaldi
Practical, Distributed Internet Coordinates

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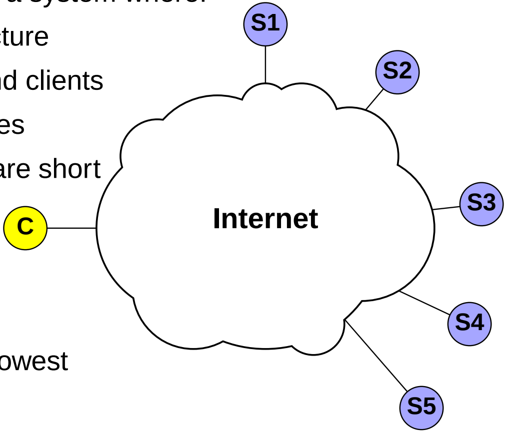
Problem: Predicting Round Trip Times on Internet

Example: server selection in a system where:

- no centralized infrastructure
- nodes act as servers and clients
- many thousands of nodes
- exchanges with server are short
- server choice changes for each exchange



Want to choose server with lowest round trip time to client.

How?

Possible Solutions

- Can avoid predictions, wasting time or bandwidth:
  - measure RTT on demand
  - measure RTT in advance
  - talk to multiple servers at once
- Can predict using synthetic coordinates as in GNP (Infocom 2002).

Synthetic Coordinates with GNP

GNP assigns Euclidean coordinates to nodes such that coordinate distance predicts round trip time.

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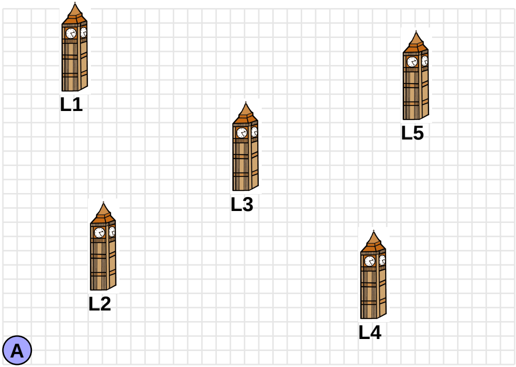
L1	(40,320)	
L2	(60,180)	
L3	(160,250)	
L4	(250,160)	
L5	(280,300)	



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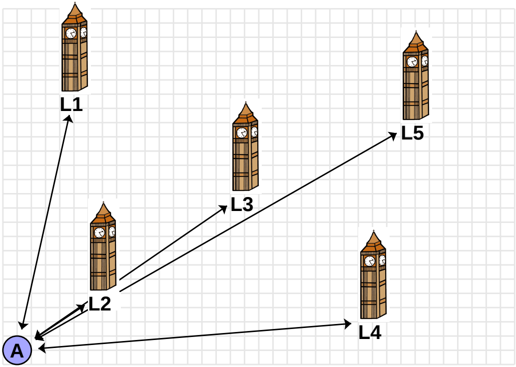

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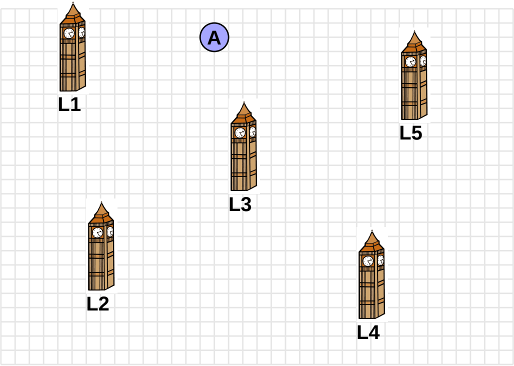

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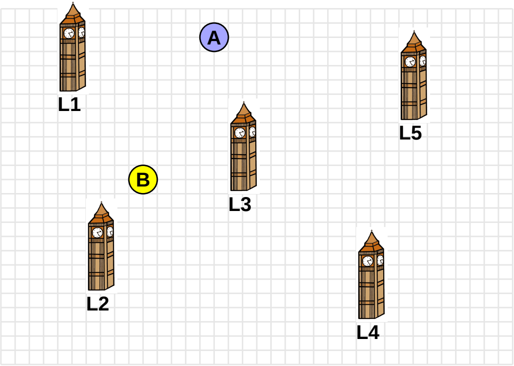


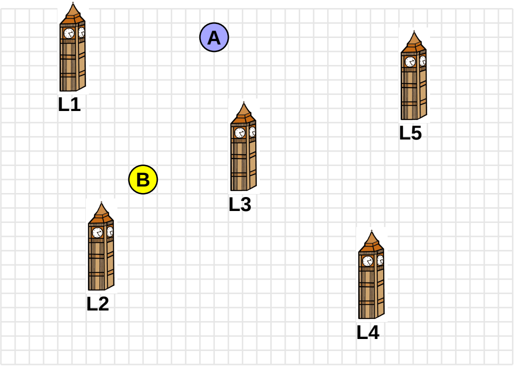
Synthetic Coordinates with GNP

GNP assigns Euclidean coordinates to nodes such that coordinate distance predicts round trip time.

Node A pings landmarks to compute its own position.

Node B does the same.

RTT between A and B
is predicted by the distance
between their coordinates,
without direct measurement.



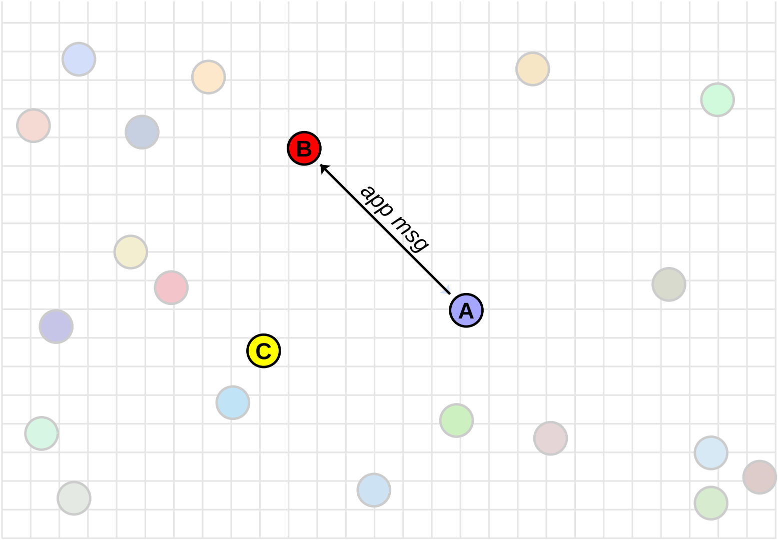
Vivaldi Overview

Vivaldi is a decentralized method for computing synthetic coordinates

- Piggyback on application traffic
- Node updates its own coordinates in response to sample
- Each node need only contact a small fraction of the other nodes

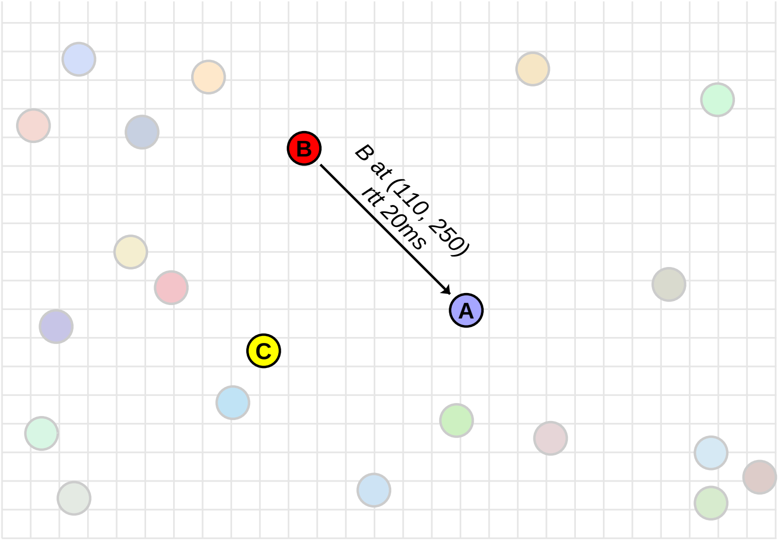
Vivaldi Example

Follow node A through a sequence of communications.



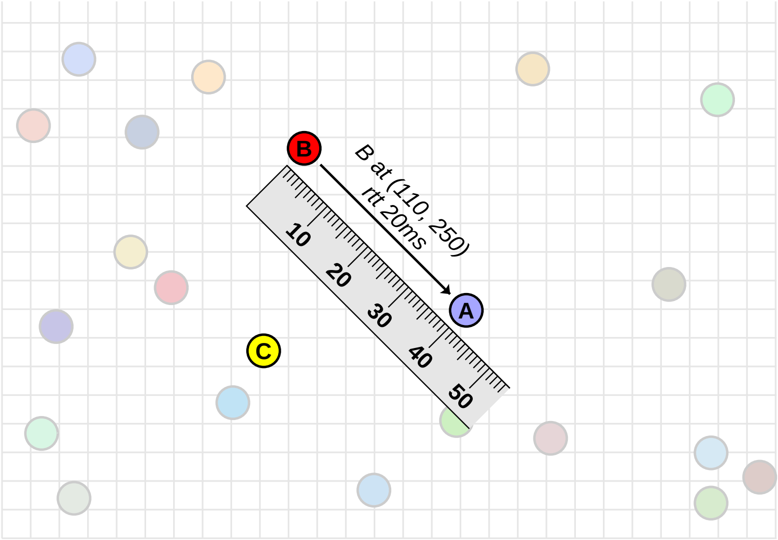
Vivaldi Example

A obtains B's coordinates, RTT.



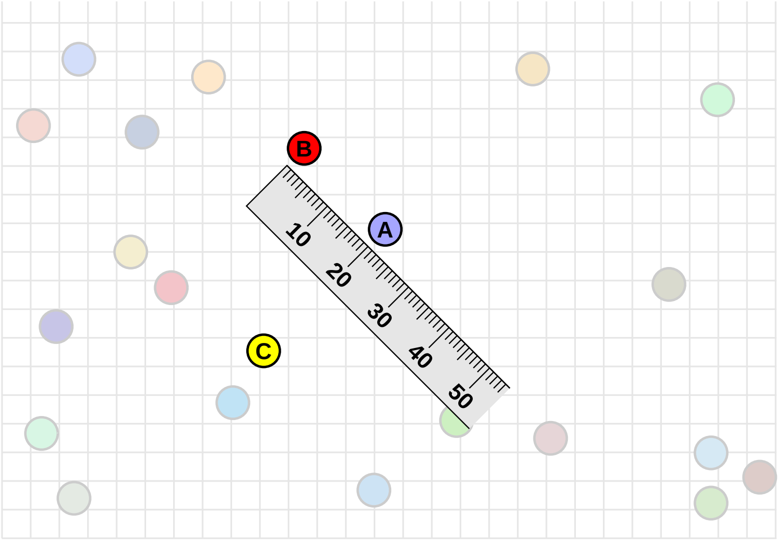
Vivaldi Example

A computes distance to B in coordinate space.



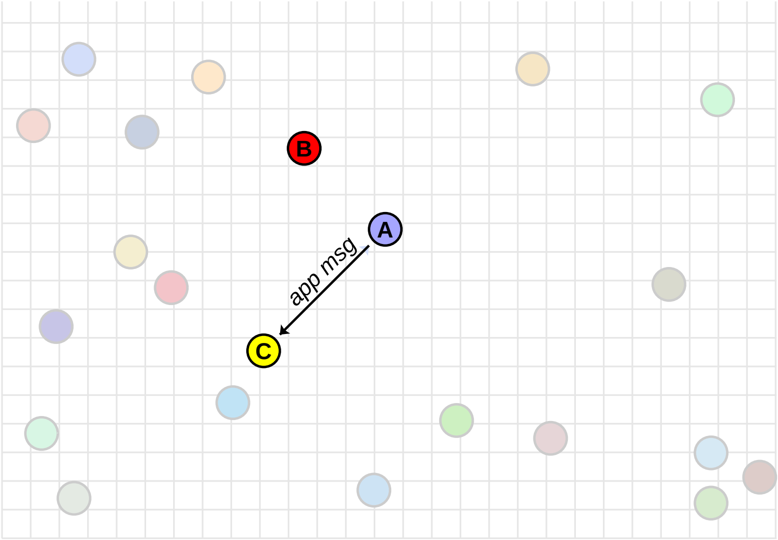
Vivaldi Example

A adjusts coordinates so distance matches actual RTT.



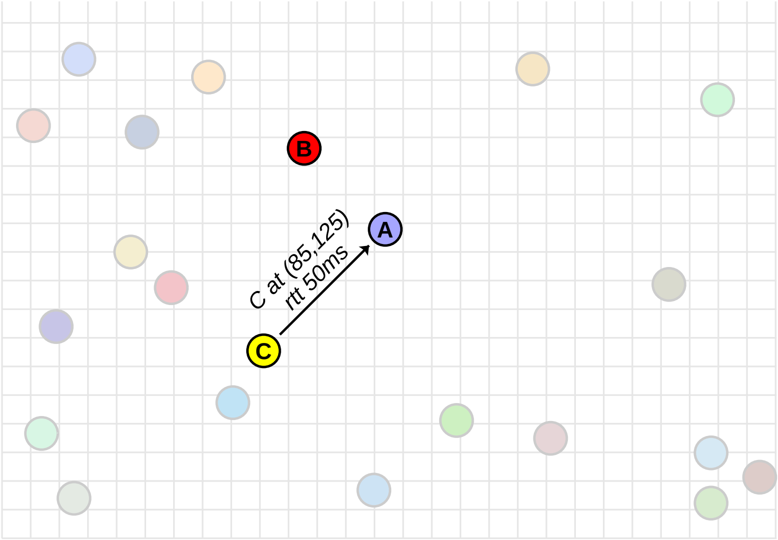
Vivaldi Example

Follow node A through communication with C.



Vivaldi Example

A obtains C's coordinates, RTT.



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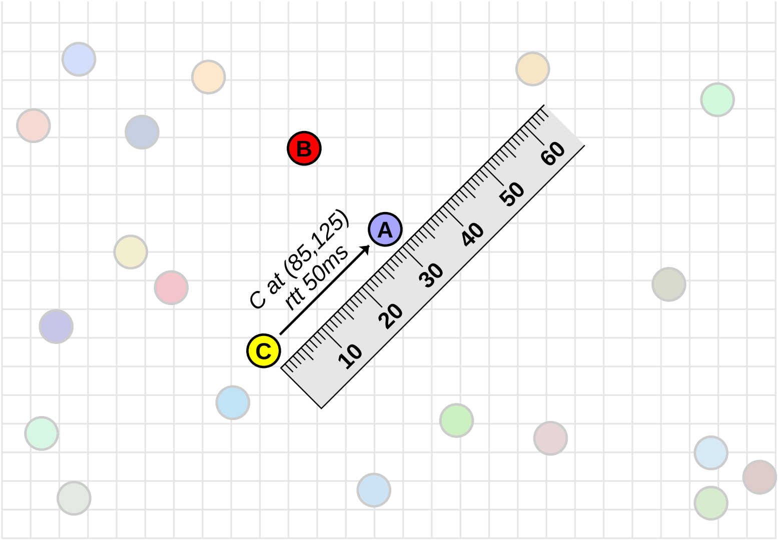
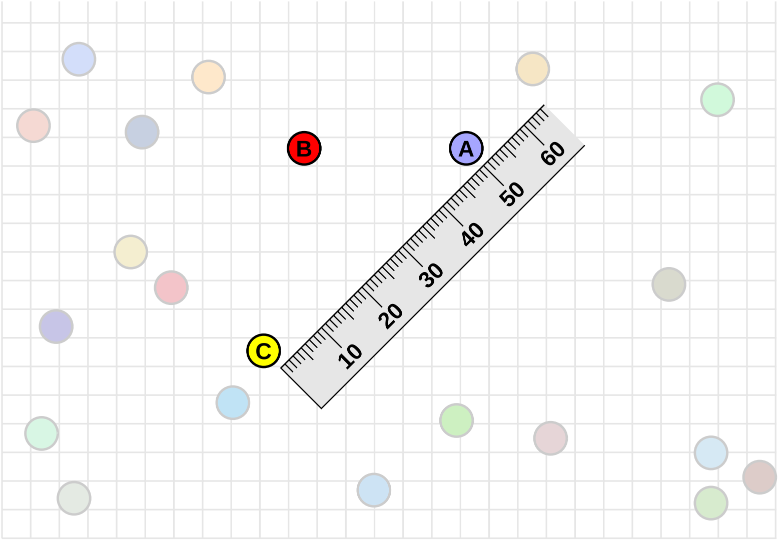


Vivaldi Example

A adjusts coordinates so distance matches actual RTT.
(Now A is wrong distance from B.)



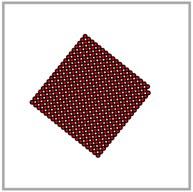
Challenges of Decentralization

Without centralized control, must consider:

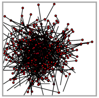
- will the system converge to an accurate coordinate set?
- how long will the system take to converge?
- will the system be disturbed by new nodes joining the system?

Tuning Vivaldi: Convergence

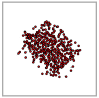
- Run Vivaldi on round trip times derived from grid.



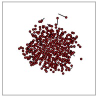
- As described, algorithm never converges.



- To cause convergence, damp motion.

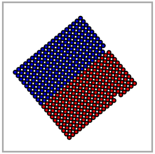


- To speed convergence, vary damping with estimate of prediction accuracy.

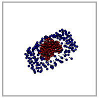


Tuning Vivaldi: Naive Newcomers

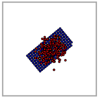
- Run Vivaldi on round trip times derived from grid.
  Blue nodes start first, stabilize.
  Red nodes join the system.



- High-accuracy nodes are displaced by new, low-accuracy nodes joining the system



- To avoid this, vary damping with ratio of local node's accuracy and sampled node's accuracy.



Vivaldi Algorithm

Given the coordinates, round trip time, and accuracy estimate of a node:

- Update local accuracy estimate.
- Compute ‘ideal’ location.
- Compute damping constant δ using local and remote accuracy estimates.
- Move δ of the way toward the “ideal” location.

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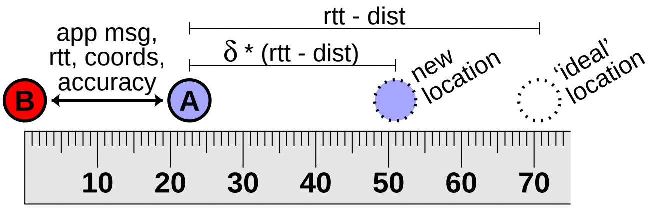


Evaluating Synthetic Coordinates on the Internet

- Cannot evaluate by comparing to “correct” coordinate set.
- Evaluate *predictions* made using a coordinate set.
- Predictions of Internet will never be perfect.
    - violations of triangle inequality, ...

Evaluating Vivaldi on the Internet

- How accurate are Vivaldi's predictions?
- How quickly does Vivaldi converge to a coordinate set?
- How quickly can Vivaldi adapt to network changes?
- How does choice of coordinate space affect error?
- How does Vivaldi work in real-world apps?

Evaluation Methodology

Use simulator seeded with real Internet measurements.

- pairwise RTTs for 192 PlanetLab nodes
- use RTT matrix as input to simulator
- run various algorithms on simulator

Each Vivaldi node queries others as fast as it can

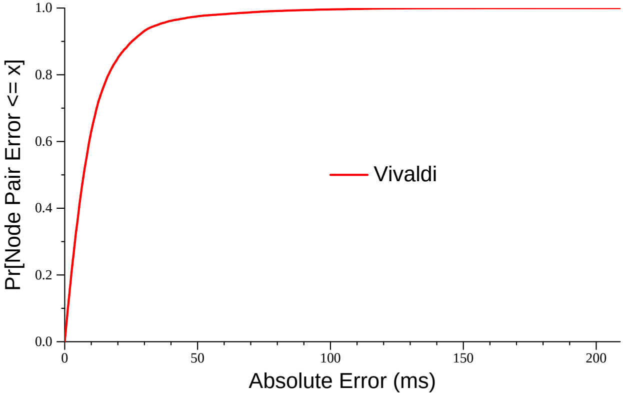
- one message outstanding at a time
- each node has a small fixed neighbor set

Vivaldi's Absolute Prediction Error

Look at distribution of absolute prediction error, defined as

$$|\text{actual RTT} - \text{predicted RTT}|,$$

over all node pairs in the system.



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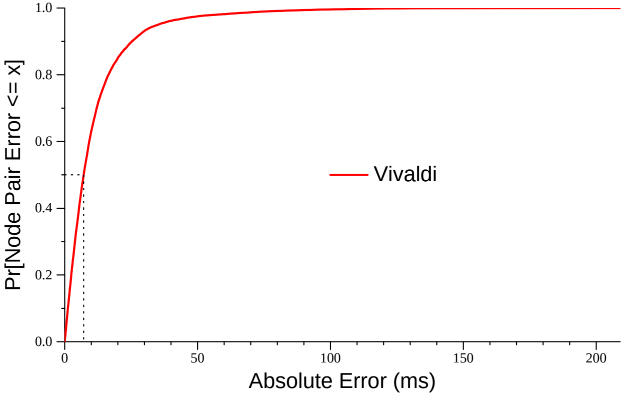

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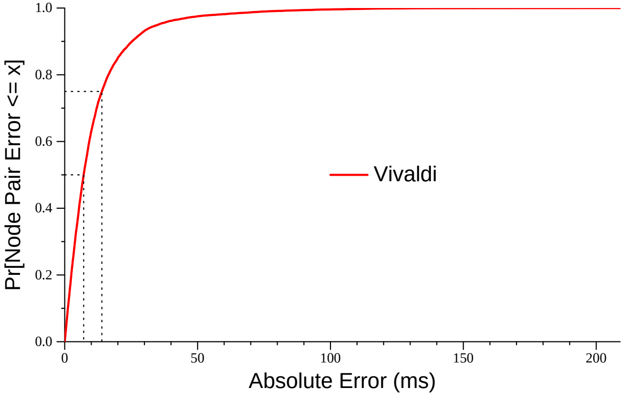

Vivaldi's Relative Prediction Error

Look at relative error, defined as

$$\frac{|\text{actual RTT} - \text{predicted RTT}|}{\min(\text{actual RTT}, \text{predicted RTT})},$$

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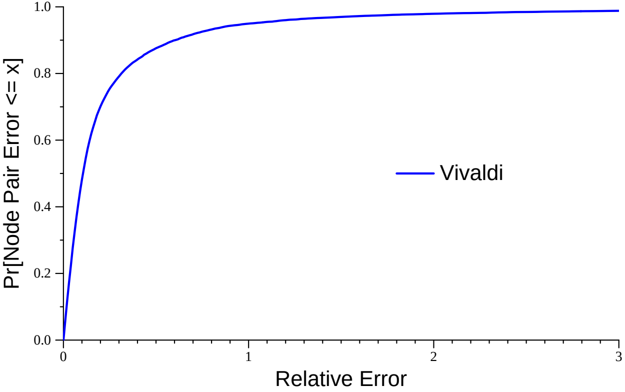

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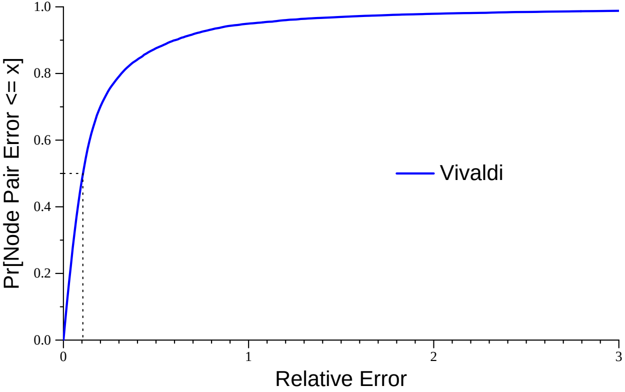

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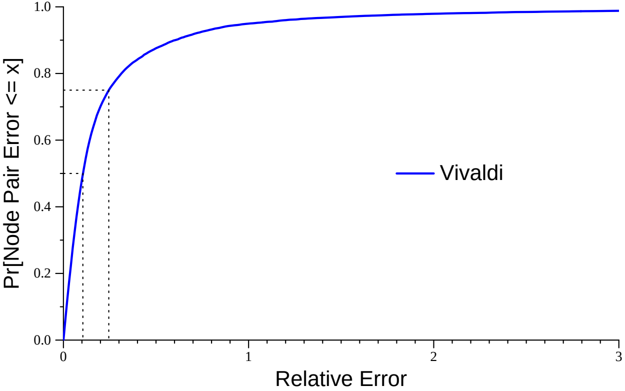
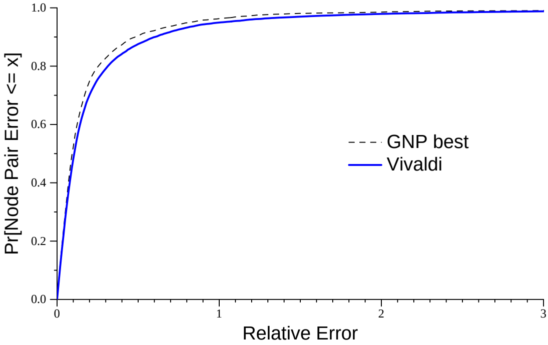


Vivaldi Compared to GNP on Relative Error

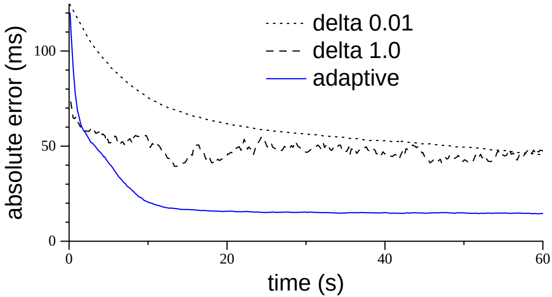
Compare to GNP's predictions.

- GNP sensitive to landmark choice. Use best of 64 random landmark sets.



Vivaldi's Convergence Time

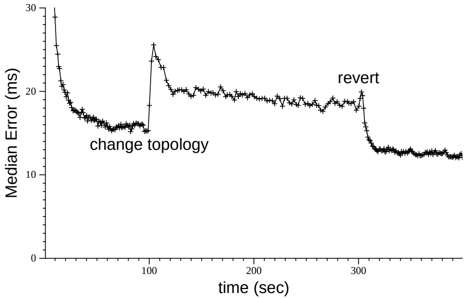
- Depends on choice of δ, the damping constant.



- Using adaptive δ, Vivaldi converges in under 20 seconds (60 measurements per node).

Vivaldi's Time to Adapt to Network Changes

- Vivaldi nodes are always adjusting their coordinates.
- Test adapting speed with synthetic topology change: lengthen one link by factor of ten.



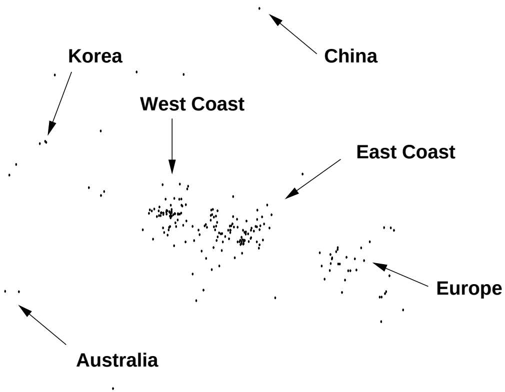
- Vivaldi adapts in about twenty seconds.

Other Coordinate Spaces

- *A priori*, it's not clear why *any* coordinate system should fit the Internet well.
- GNP showed that Euclidean coordinates work well.
- Why do they work?
- Are there better coordinate systems?
  - Obvious other candidates: globe, 3D, 4D, ...

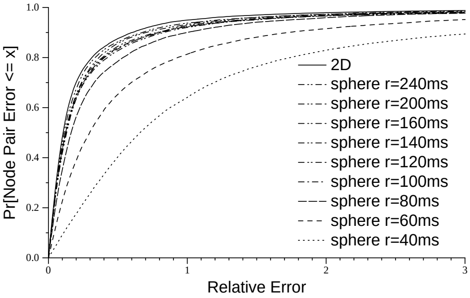
Vivaldi's 2D Assignment for PlanetLab

Placement in 2D mirrors physical geography.



Globe Coordinates vs. 2D Euclidean

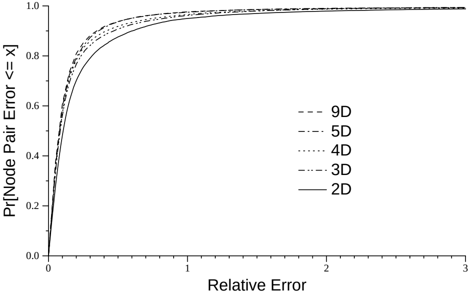
- Globe coordinates (latitude, longitude) place nodes on surface of a sphere.
- Great circle distance between two nodes on the sphere depends on radius.



- Coordinate sets are using one part of the sphere as a rough approximation to a 2D plane.

Higher Euclidean Dimensions

- If two are good, more should be better.



- Why are they better?

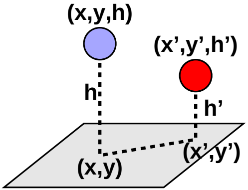
Higher Euclidean Dimensions Explained

- In 2D, some nodes need to be farther away from all others.
- In 3D, these “hard-to-place” nodes can move up or down from the 2D plane to get away from everyone.
- Each new dimension adds an independent direction.
- Accomodates per-node overhead: server load, access links.

Problem: how can we accomodate “hard-to-place” nodes without an arbitrary number of dimensions?

Height Vectors

- Give “hard-to-place” nodes their own way to get away from everyone.
- Height vectors place nodes at some height above a 2D transit plane.
- Directly models per-node overhead.

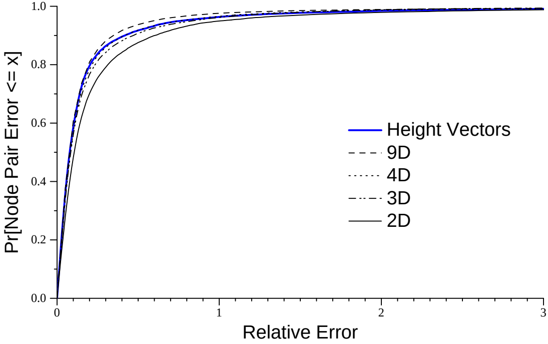


- Distance from (x, y, h) to (x', y', h') is

$$h + \sqrt{(x - x')^2 + (y - y')^2} + h'.$$

Height Vectors Work Well

- Height Vectors outperform 2- and 3-D Euclidean.



- Works to view Internet as geographically-accurate core with access links attached.

Real-World Application

- Vivaldi is easy to deploy, because it:
  - requires no infrastructure
  - is simple to implement
  - piggybacks on application-level communication
- We modified DHash to use Vivaldi.
  - block fetch time on PlanetLab reduced by 40% (NSDI 2004).
- Vivaldi is also used by:
  - Bamboo Distributed Hash Table
  - SWORD Resource Discovery system

Related Work

- Other location techniques (IDMaps, IP2Geo) use static data (AS maps, guesses at physical location).
- Centralized coordinate systems (GNP, Lighthouse) need well-known landmark nodes.
- Decentralized coordinate systems (PIC, NPS) have been developed concurrently.
- Tang and Crovella (IMC 2003) analyze best Euclidean models to use; Shavitt and Tankel (Infocom 2004) suggest using hyperbolic geometries.

Conclusions

- Vivaldi:
  - accurately predicts round trip time
    between node pairs not directly measured.
  - works without centralized infrastructure.
  - improves the performance of a real system.
- Height vectors are a promising coordinate space for the Internet.