InterTubes: A Study of the US Long-haul Fiber-optic Infrastructure

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November 7, 2025

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Introduction

The Internet has been around since 1969, and it is hard to imagine what the world today would be like without it

Despite this, not much research or focus has been placed on the physical infrastructure that we take advantage of daily

Contributions

1. Internet Infrastructure Map of the United States
2. Risk Assessment of the Current Infrastructure
3. How to Improve the Current Infrastructure

Related Work

The physical Internet and its robustness has been studied extensively

- Robustness
- Vulnerability
- Survivability
- Resilience
- Reachability
- Security
- Fault Detection
- Routing Protocols

Other papers have tried to plot the existing infrastructure, but were uncertain in quality, lacked important details, and cannot be reproduced

Additionally, other appears have analyzed the network with geocoded maps, but this paper avoids the difficulties with router locations

Mapping Core Long Haul Infrastructure

One of the main contributions is to identify long haul fiber routes

Long haul link: spans 30 miles, connects populations of 100,000 or shared by 2 providers

Map Building Process

1. Use maps from tier-1 ISPs and cable providers with full link geography
2. Validate links with publicly available records
3. Use maps from tier-1 ISPs and cable providers with only endpoint geography
4. Further validation using public records

Build an Initial Map

Utilize explicit geocoded links from the Internet Atlas project

Detailed maps from 5 tier-1 ISPs and 4 major cable providers

- 267 nodes
- 1258 links
- 512 conduits

Table 1: Number of nodes and long-haul fiber links included in the initial map for each ISP considered in step 1.

ISP	AT&T	Comcast	Cogent	EarthLink	Integra	Level 3	Suddenlink	Verizon	Zayo
Number of nodes	25	26	69	248	27	240	39	116	98
Number of links	57	71	84	370	36	336	42	151	111

Check the Initial Map

The next step is to validate the initial information with public data

Specifically look for

- Government agency filings
- Environmental impact statements
- Documentation from third party fiber services
- Indefeasible rights of use agreements
- Press releases

Links are considered valid if they match with known ROW's or are grouped with other links

Build an Augmented Map

Maps from large ISPs are once again utilized, but this time the links are not geocoded

Ex: Link from Atlanta ↔ Orlando

They assume that these links follow existing road or railway, and place them accordingly

Utilized maps from 7 tier-1 ISPs and 4 large regional ISPs

- CenturyLink,
- Cox
- Deutsche Telekom
- HE
- Inteliquent
- NTT
- Sprint
- Tata
- TeliaSonera
- TWC
- XO

Validate the Augmented Map

Nearly identical validation to that in step 2 is performed after the augmentation

Individual Link Illustration

Sprint has link between Los Angeles ↔ San Francisco, but no info on link geography

Search "los angeles to san francisco fiber iru at&t sprint" in Internet Atlas repository

Learn that AT&T and Sprint share that route

Resource Illustration

Documents reveal: (1) Sprint uses level 3 fibers in Detroit (2) a white paper reveals link location and sharing details for Sprint fiber (3) several ISPs including Sprint were apart of the "coastal project" (4) fiber settlement website established for class action settlements

The US Long Haul Fiber Map

273 nodes, 2411 links, 542 conduits

Features

1. Dense deployments
2. Long haul hubs
3. Absence of infrastructure
4. Parallel deployments
5. Spurs

State that the map is not complete, but sufficient for study. Want to share that their results are reproducible

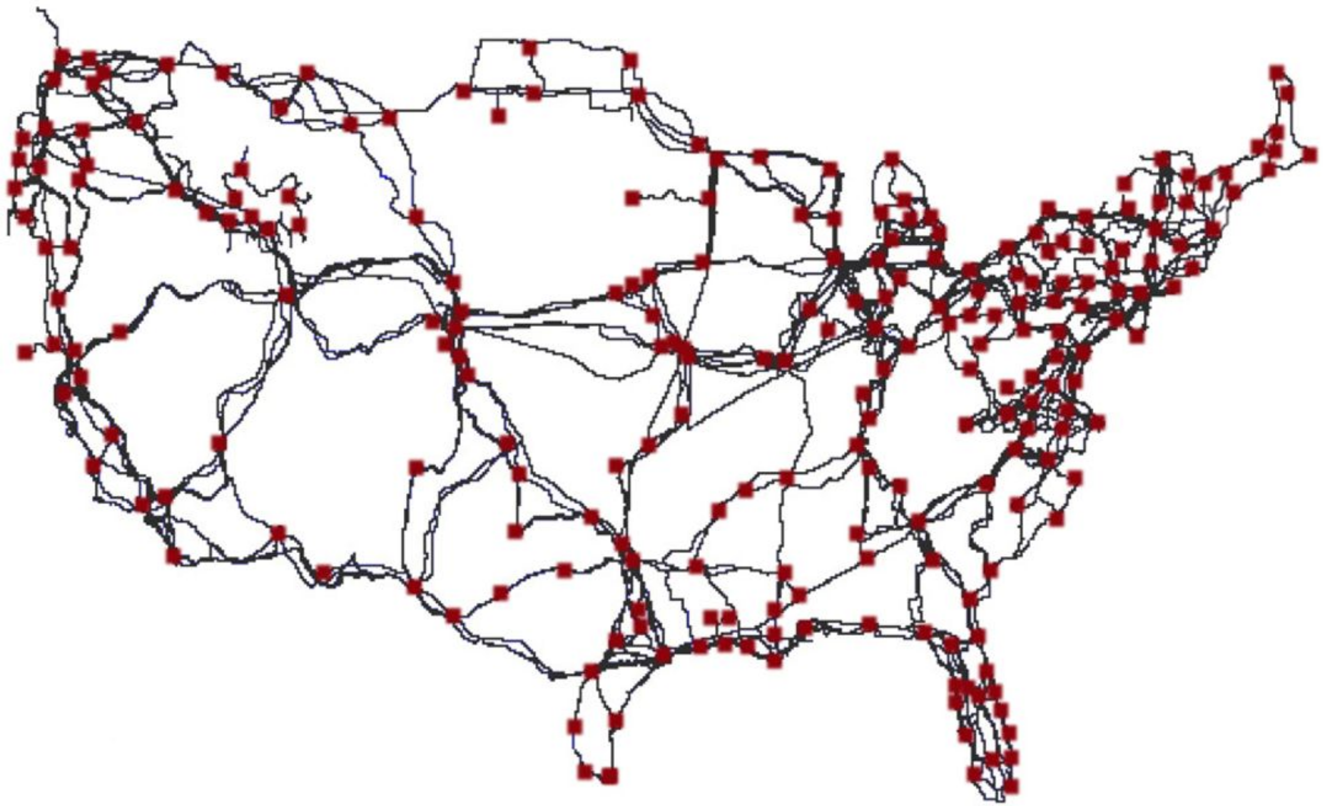


Figure 1: Location of physical conduits for networks considered in the continental United States.

Geography of Fiber Deployments

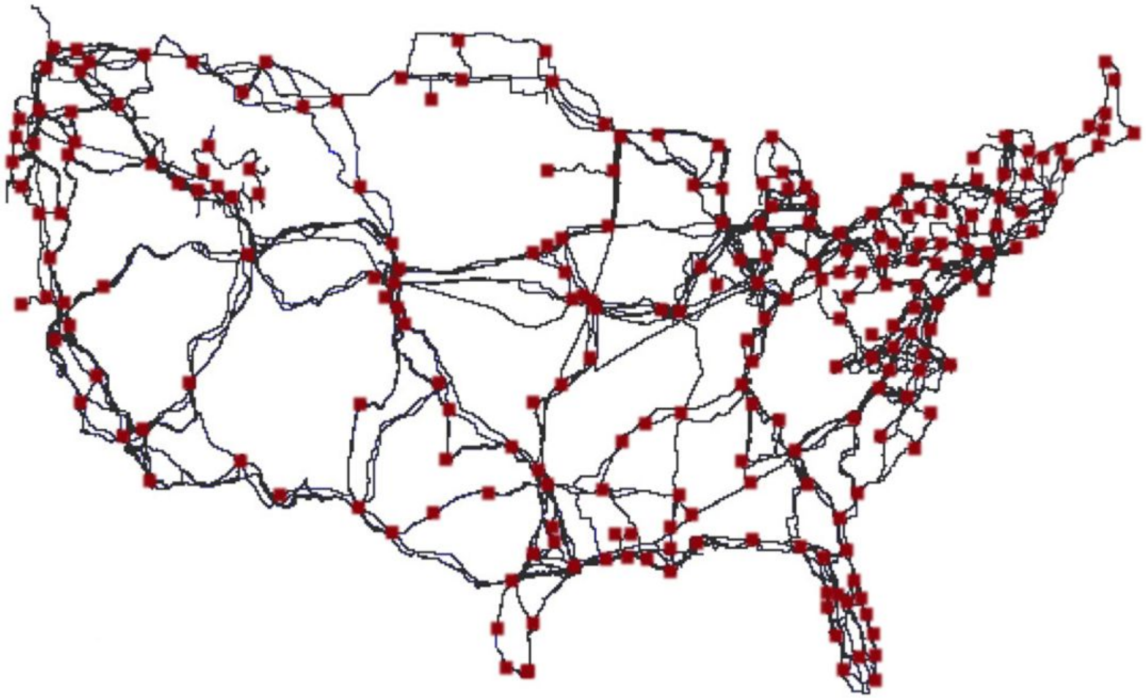
Relationship between long haul infrastructure map and transportation networks

Figure 2: NationalAtlas roadway infrastructure locations.

Figure 3: NationalAtlas railway infrastructure locations.

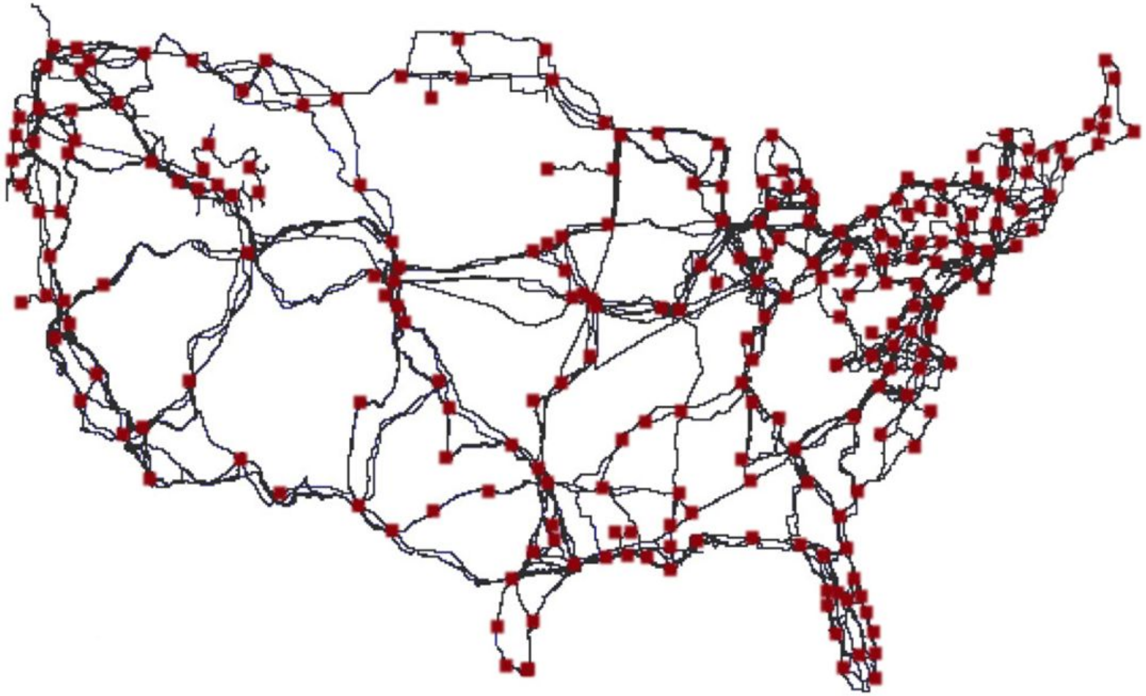
Geography of Fiber Deployments

Figure 2: NationalAtlas roadway infrastructure locations.



Geography of Fiber Deployments

Figure 3: NationalAtlas railway infrastructure locations.



Geography of Fiber Deployments

Use polygon overlap analysis to quantify the similarity between long haul links infrastructure and transportation networks

Chart shows that it is very common for long haul links to be co-located with rail and road ways

More common to run beside roads rather than rails

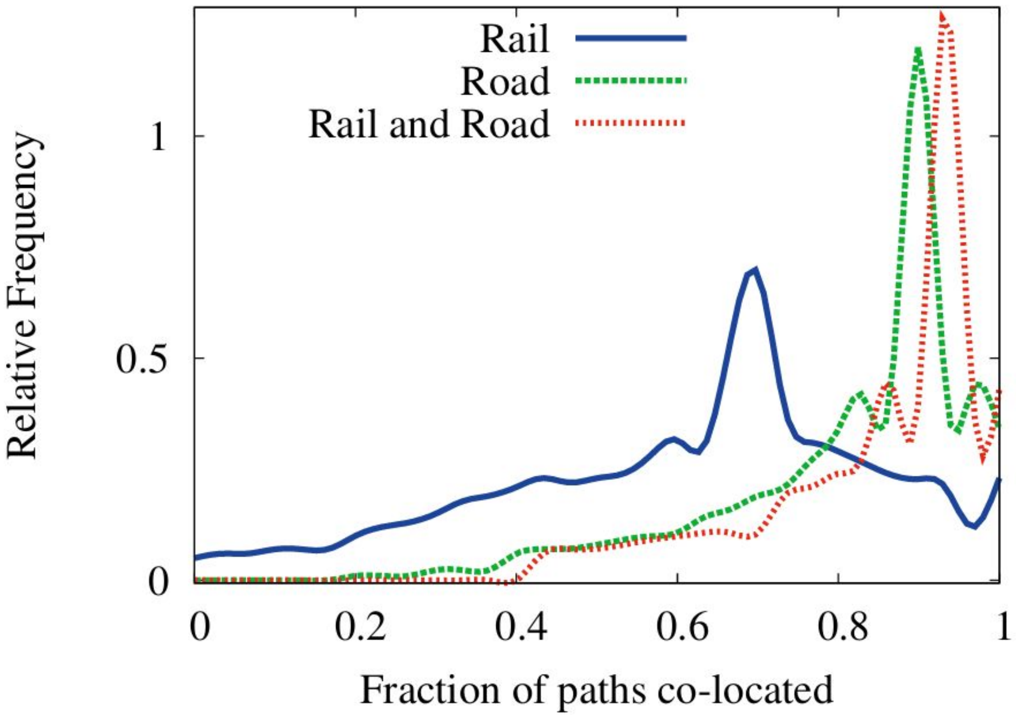


Figure 4: Fraction of physical links co-located with transportation infrastructure.

Geography of Fiber Deployments

Despite the previous results, there are cases where the long haul links are not co-located with transportation infrastructure

As an explanation it is possible that these links are co-located with natural gas or oil pipelines

Verified that the long haul link between Anaheim and Las Vegas runs beside a refined products pipeline

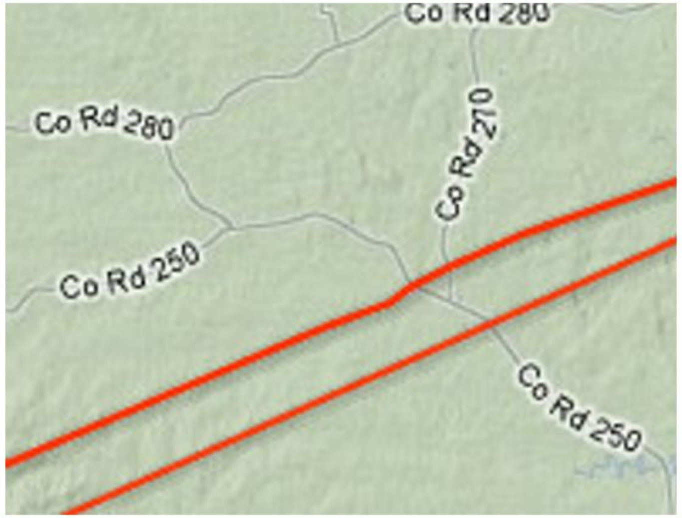


Figure 5: Satellite image validated right-of-way outside of Laurel, MS. (Left) - Level 3 Provided fiber map. (Right) - Google Maps satellite view.

Assessing Shared Risk

With conduit sharing being very common, assessment on the inherent risk is made

Types of Assessment

1. Connectivity Only
2. Connectivity and Traffic

Risk Matrix

Rows: ISPs | Columns: Physical Conduits
Integers represent number of ISPs sharing a conduit

1. Level 3 chosen as initial ISP
2. Extract conduit endpoints across city pairs
3. c1 = SLC ↔ Denver, c2 = SLC ↔ Sacramento, c3= Sacramento ↔ Palo Alto (SLC = Salt Lake City)
4. Assign 1 for all conduits that are apart of Level 3
5. Then add Sprint as another ISP
6. Increment all entries if Sprint has this conduit
7. Repeat for all ISPs

	c1	c2	c3
Level 3	1	1	1

	c1	c2	c3
Level 3	2	2	1
Sprint	2	2	0

Risk Metric (Connectivity Only)

X-axis: # of ISPs sharing | Y-axis: # of Conduits

Notable Results

- 542 total conduits on generated map
- 89.67% of conduits are shared by 2 or more ISPs
- 63.28% of conduits are shared by 3 or more ISPs
- 53.50% of conduits are shared by 4 or more ISPs
- 12 conduits are shared by 17 or more ISPs

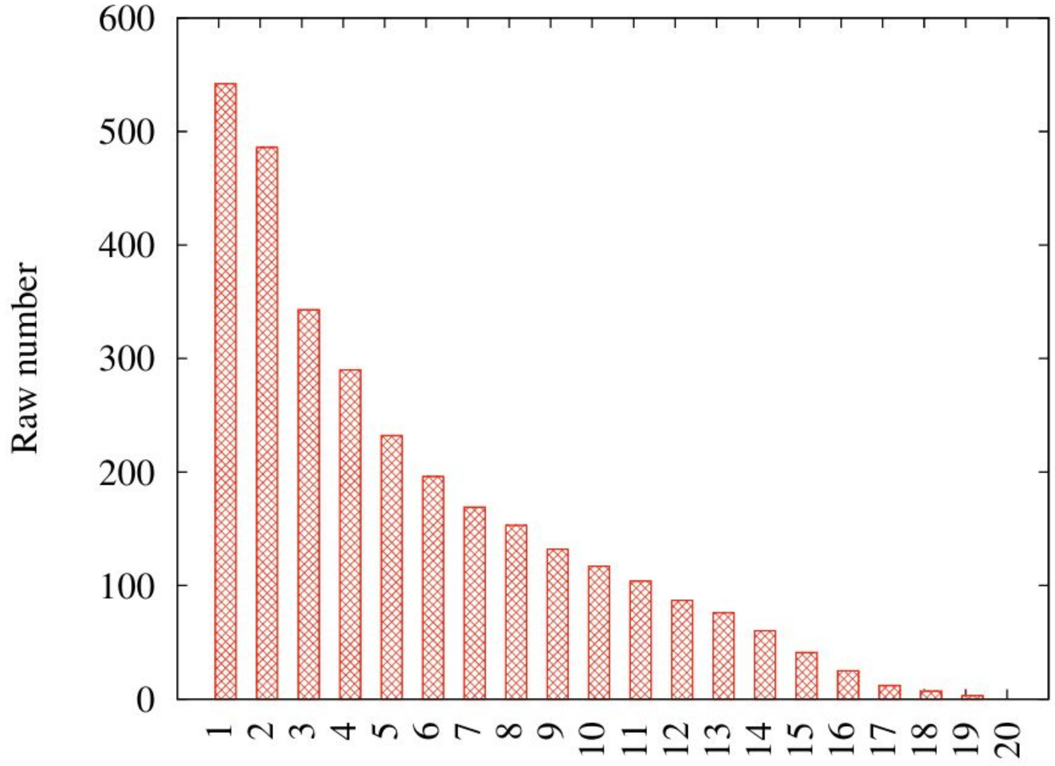


Figure 6: ISP Ranking.

Risk Metric (Connectivity Only)

Rank individual ISPs based on sharing risk

Use the Risk Matrix and average the values across each row

X-axis: ISPs
Y-axis: Average # of shared ISPs for the ISP

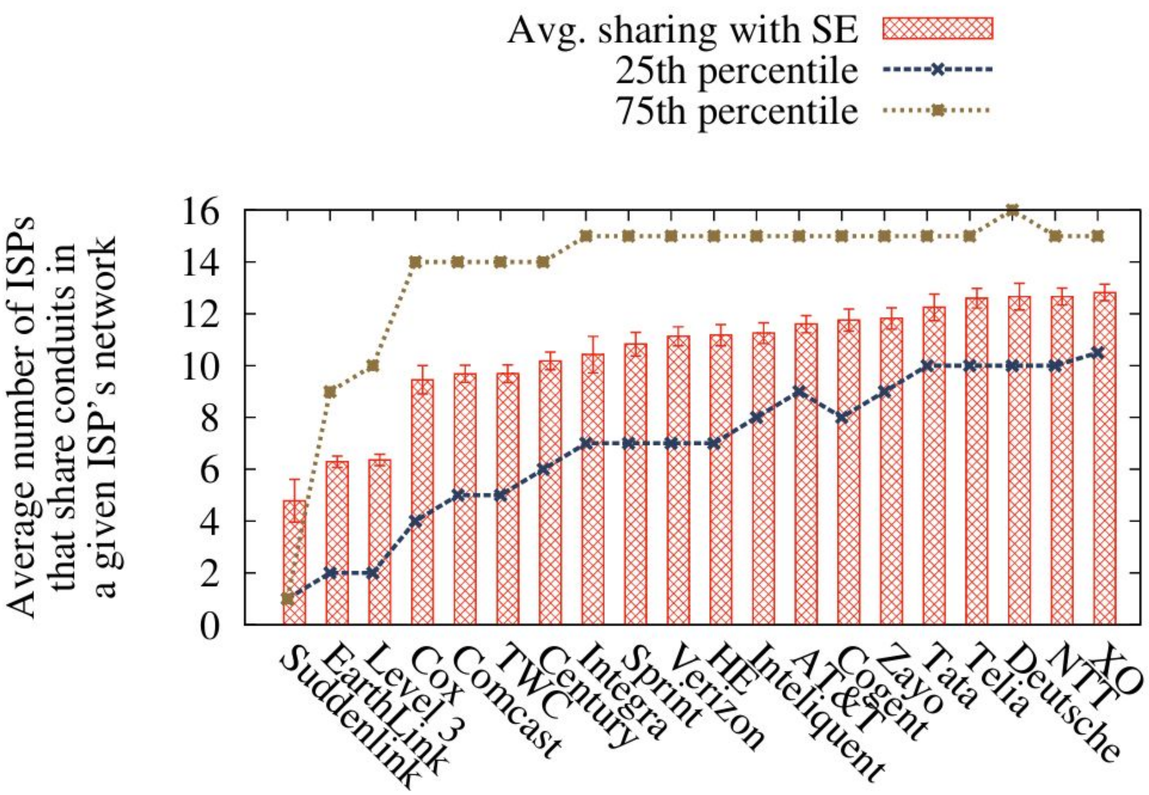


Figure 7: The raw number of shared conduits by ISPs.

Risk Metric (Connectivity and Traffic)

Assessed popularity of different routes on the Internet using data from 4,908,223 traceroutes in diverse locations

Table 2: Top 20 base long-haul conduits and their corresponding frequencies of west-origin to east-bound traceroute probes.

Location	Location	# Probes
Trenton, NJ	Edison, NJ	78402
Kalamazoo, MI	Battle Creek, MI	78384
Dallas, TX	Fort Worth, TX	56233
Baltimore, MD	Towson, MD	46336
Baton Rouge, LA	New Orleans, LA	46328
Livonia, MI	Southfield, MI	46287
Topeka, KS	Lincoln, NE	46275
Spokane, WA	Boise, ID	44461
Dallas, TX	Atlanta, GA	41008
Dallas, TX	Bryan, TX	39232
Shreveport, LA	Dallas, TX	39210
Wichita Falls, TX	Dallas, TX	39180
San Luis Obispo, CA	Lompoc, CA	32381
San Francisco, CA	Las Vegas, NV	22986
Wichita, KS	Las Vegas, NV	22169
Las Vegas, NV	Salt Lake City, UT	22094
Battle Creek, MI	Lansing, MI	15027
South Bend, IN	Battle Creek, MI	14795
Philadelphia, PA	Allentown, PA	12905
Philadelphia, PA	Edison, NJ	12901

Table 3: Top 20 base long-haul graph conduits and their corresponding frequencies of east-origin to west-bound traceroute probes.

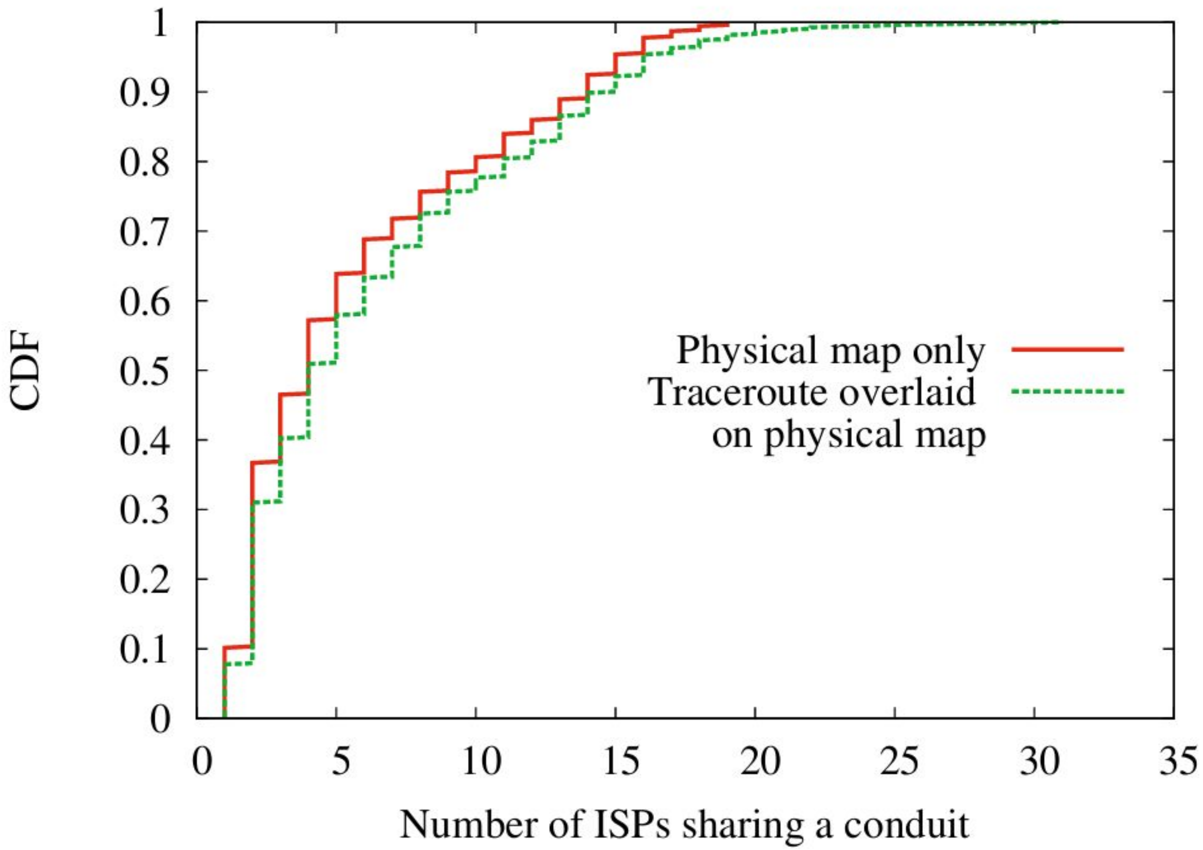
Location	Location	# Probes
West Palm Beach, FL	Boca Raton, FL	155774
Lynchburg, VA	Charlottesville, VA	155079
Sedona, AZ	Camp Verde, AZ	54067
Bozeman, MT	Billings, MT	50879
Billings, MT	Casper, WY	50818
Casper, WY	Cheyenne, WY	50817
White Plains, NY	Stamford, CT	25784
Amarillo, TX	Wichita Falls, TX	16354
Eugene, OR	Chico, CA	12234
Phoenix, AZ	Dallas, TX	9725
Salt Lake City, UT	Provo, UT	9433
Salt Lake City, UT	Los Angeles, CA	8921
Dallas, TX	Oklahoma City, OK	8242
Wichita Falls, TX	Dallas, TX	8150
Seattle, WA	Portland, OR	8094
Eau Claire, WI	Madison, WI	7476
Salt Lake City, UT	Cheyenne, WY	7380
Bakersfield, CA	Los Angeles, CA	6874
Seattle, WA	Hillsboro, OR	6854
Santa Barbara, CA	Los Angeles, CA	6641

Risk Metric (Connectivity and Traffic)

Compares the CDF of the conduit frequency observed from their map with that observed through the traceroute process

Shows that an even greater risk is inherent when considering traffic

The traceroute also revealed that there is more conduit sharing than observed on the map



Mitigating Risks

With the risk determined and analyzed, solutions are suggested to improve the infrastructure

Two Optimization Analyses

1. Increasing Network Robustness (I & II)
2. Reducing Propagation Delay

Increasing Network Robustness (I)

To increase robustness, the goal is to reduce impact of fiber cuts due to fiber sharing

Relying on the existing infrastructure (no new links), robustness can be increased by …

1. Utilizing existing conduits that are not used by the ISP
2. Choosing ISPs to peer with at certain locations to increase diversity

Optimized Path between two city nodes *i* and *j* defined as …

$$OP_{i,j}^{robust} = \min_{P_{i,j} \in \mathscr{E}^A} SR\left(\mathbf{P_{i,j}}\right)$$

where $\mathscr{E}^{\mathrm{A}}$ is the set of all possible paths from the risk matrix

Increasing Network Robustness (I)

Analysis began on the 12 conduits that are shared by 17 or more ISPs

Path Inflation =

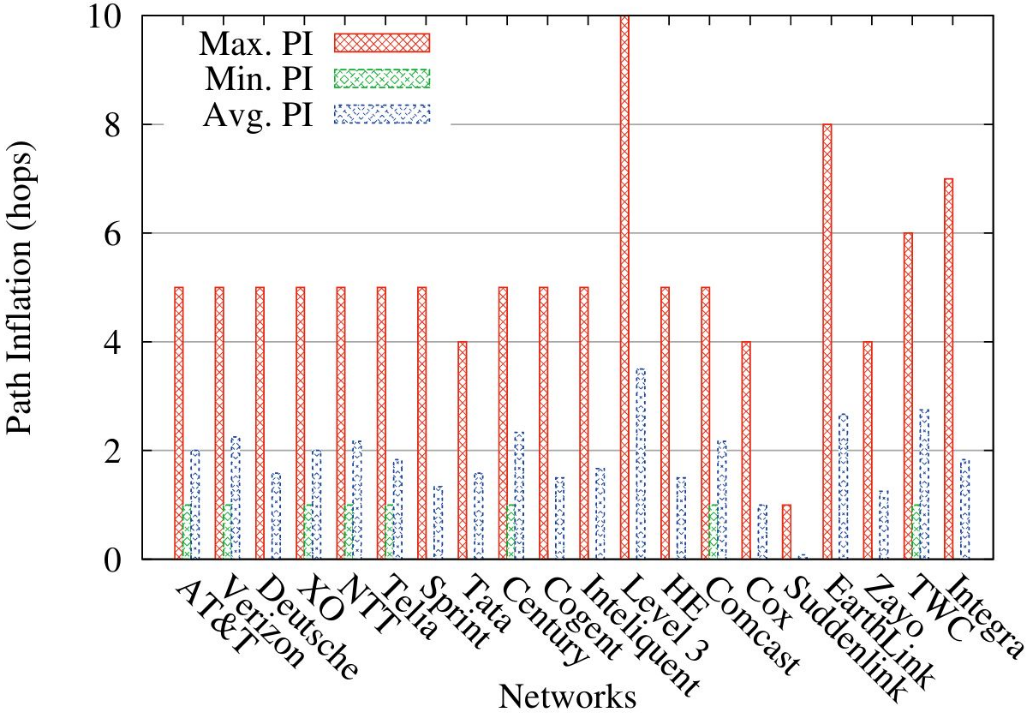
(# of hops in original path) - (# of hops in optimized path)

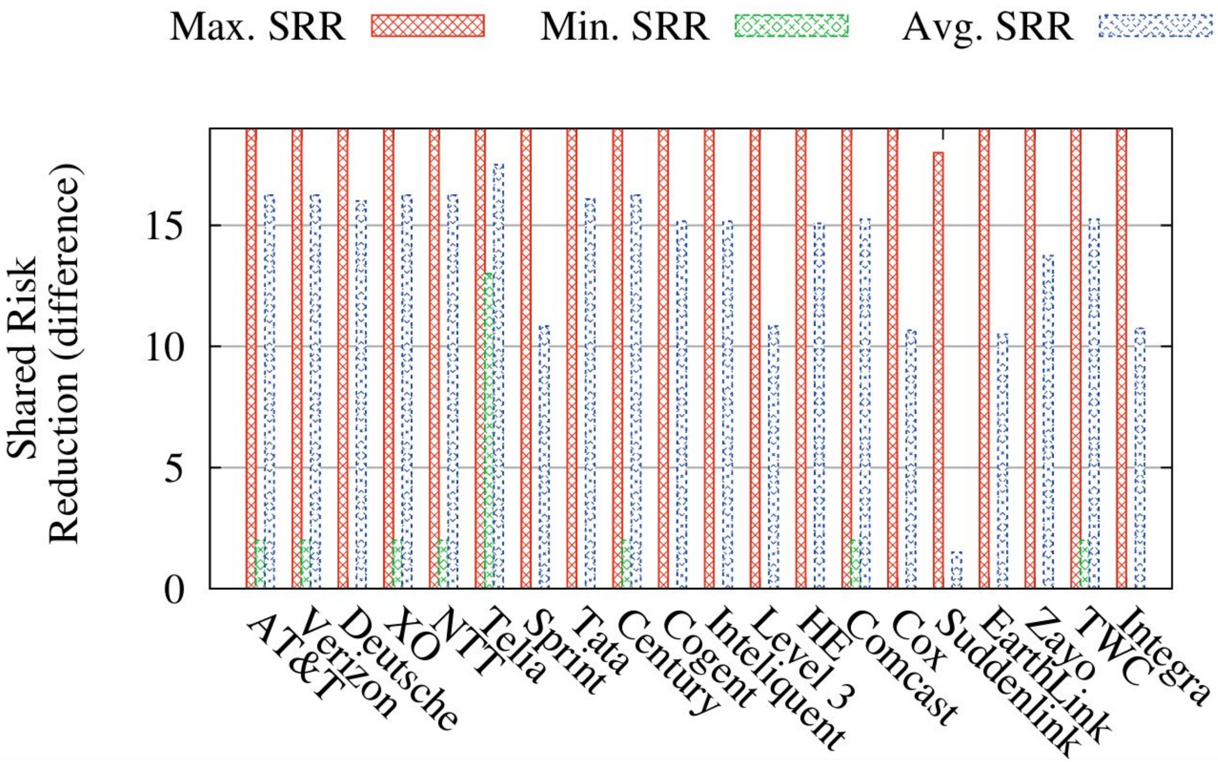
Shared Risk Reduction (SRR) =

(# of ISPs sharing conduit on original path) - (# of ISPs sharing conduit on optimized path)

Increasing Network Robustness (I)

Results show only adding one or two more links can lead to a significant decrease in risk





Increasing Network Robustness (II)

Also consider the increased robustness of adding *k* new city-to-city conduits

They consider the link map as a graph $G = (V, E)$ and look to find a new set of edges that has …

1. Greatest reduction in risk
2. Smallest deployment cost

Let $\hat{E}$ be the set of edges not in G and $\hat{A}$ the reduced matrix for $\hat{G} = (V, E \cup S)$ where $S \in \hat{E}$ s.t.

$$S = arg\max(\lambda_A - \lambda_{\hat{A}})$$

where $\lambda = \sum_{i=1,j=1}^{m,n} SRR_{i,j} + \sum_{i=1,j=1}^{m,n} DC_{i,j}$ and $DC_{i,j}$ is the shortest alternate path

Increasing Network Robustness (II)

Resulting figure shows the improvement ratio

Improvement Ratio =

average shared risk after adding links /
average shared risk before adding links

ISPs like Tata with smaller footprints see the largest improvement from deploying fiber at diverse locations

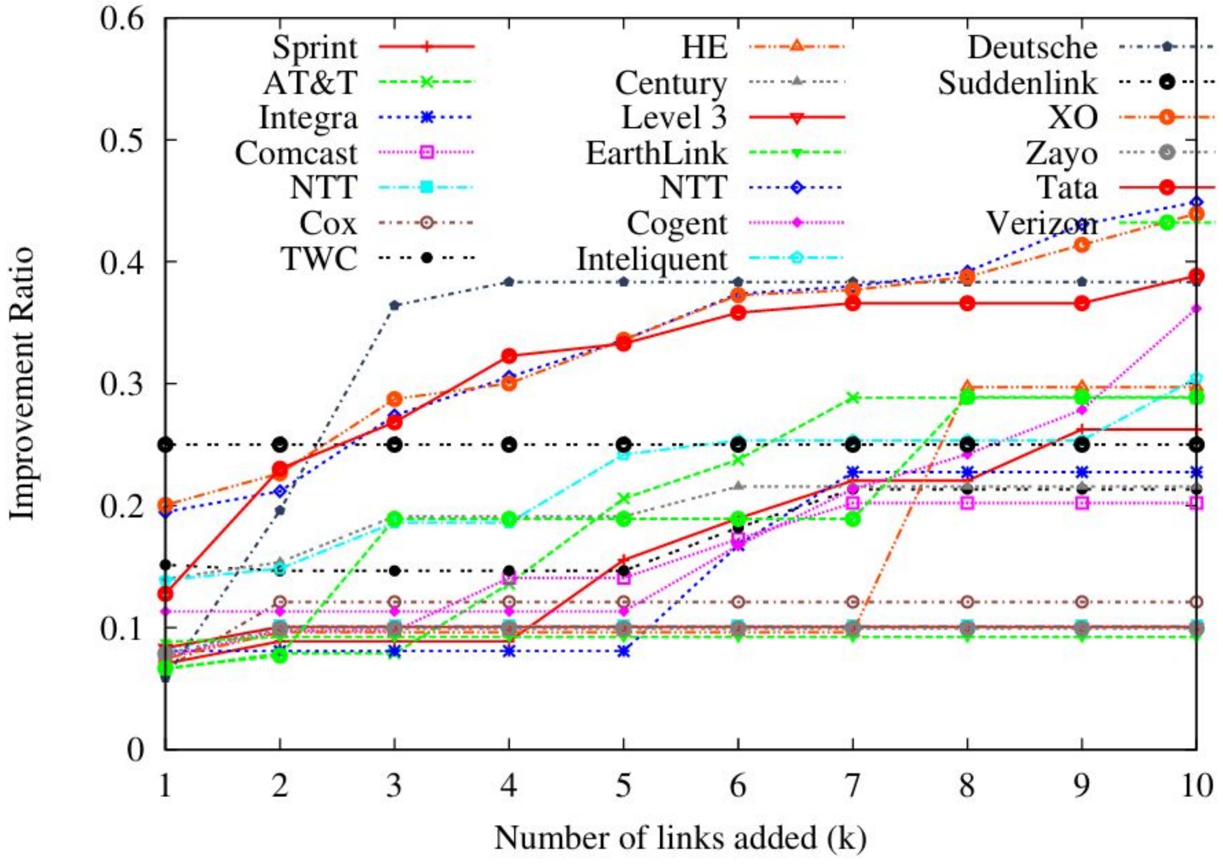


Figure 11: Potential improvements to ISP

Reducing Propagation Delay

CDF of different delays was plotted …

Best Paths: Best or shortest delay across
 an existing physical path

LOS: Delay if conduits were installed
 for direct line-of-sight

Average: Average delay across all
 physical paths

ROW: Delay if conduits were added
 to existing ROWs

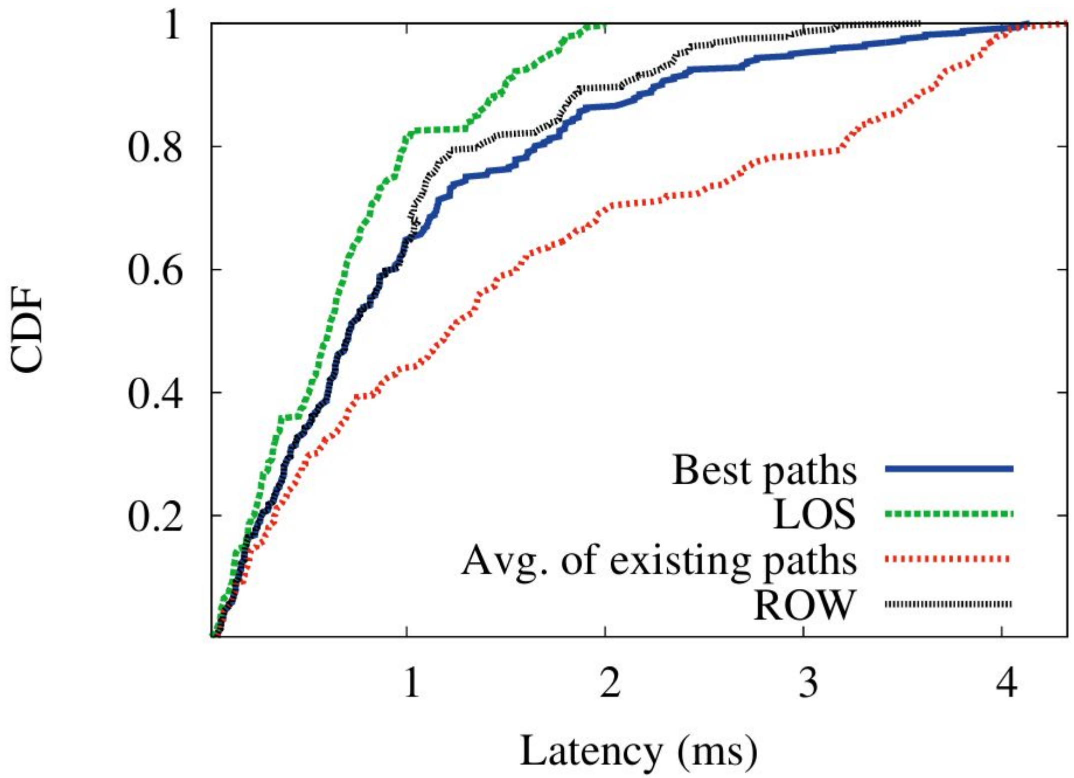


Figure 12: Comparison of best links against avg. latencies of links, ROW links and LOS links.

Some links travel further than needed

65% of best paths are best ROW paths

Implications for Service Providers

The base map gives ISPs a way to make informed decisions about managing their infrastructure

- Local deployment
- Route Selection
- Peering
- Competitive Insight
- Backup Paths

The map provides a good starting point to add metro-level information or undersea international cables to get a better understanding of the Internet on a global scale

The FCC and Title II

Title II of the US Communications Act of 1934 gives the FCC the ability to elect ISPs as "common carriers"

The physical infrastructure of the common carriers will become available to third parties, increasing the amount of sharing on the conduits

In the larger topic of network neutrality, the sharing of pre-existing infrastructure is beneficial, but it is argued that the risk is something that should be more considered

Enriching US Long Haul Infrastructure

The analysis on the addition of new, strategically-placed conduits shows that risk and delays can be significantly reduced

Although their data shows that conduits are being deployed at a steady rate, they do not necessarily line up with the proposed links to improve the overall network

Adapting the idea of Internet Exchange Points (IXPs) to conduits is a proposed solution

Discussion and Future Work

Contributions

1. Internet Infrastructure Map of the United States
2. Risk Assessment of the Current Infrastructure
3. How to Improve the Current Infrastructure

Future Work

- Update and add metro-level, undersea links to map
- Further link comparison with other infrastructure (e.g. pipelines or rivers)
- Analysis on the security and risk associated with cyber attacks

Questions?