Internet ~1969 (ARPANET)

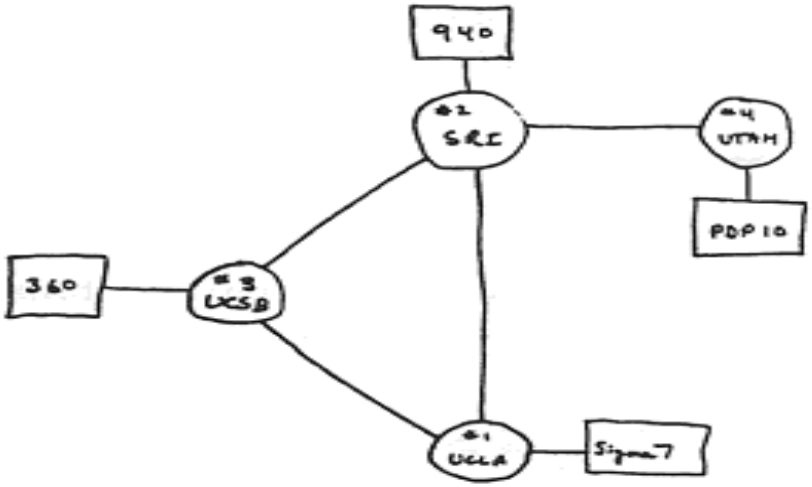
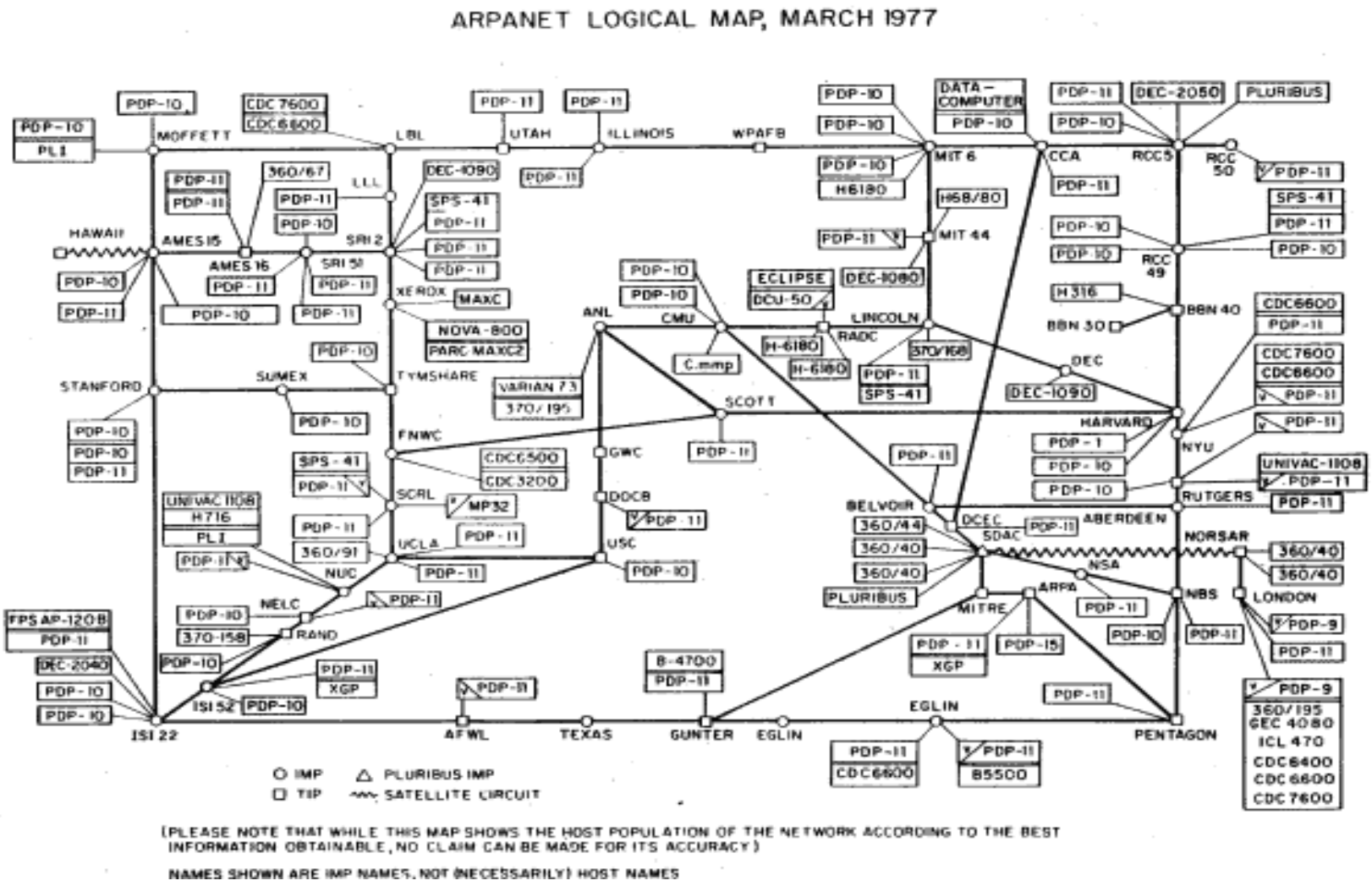


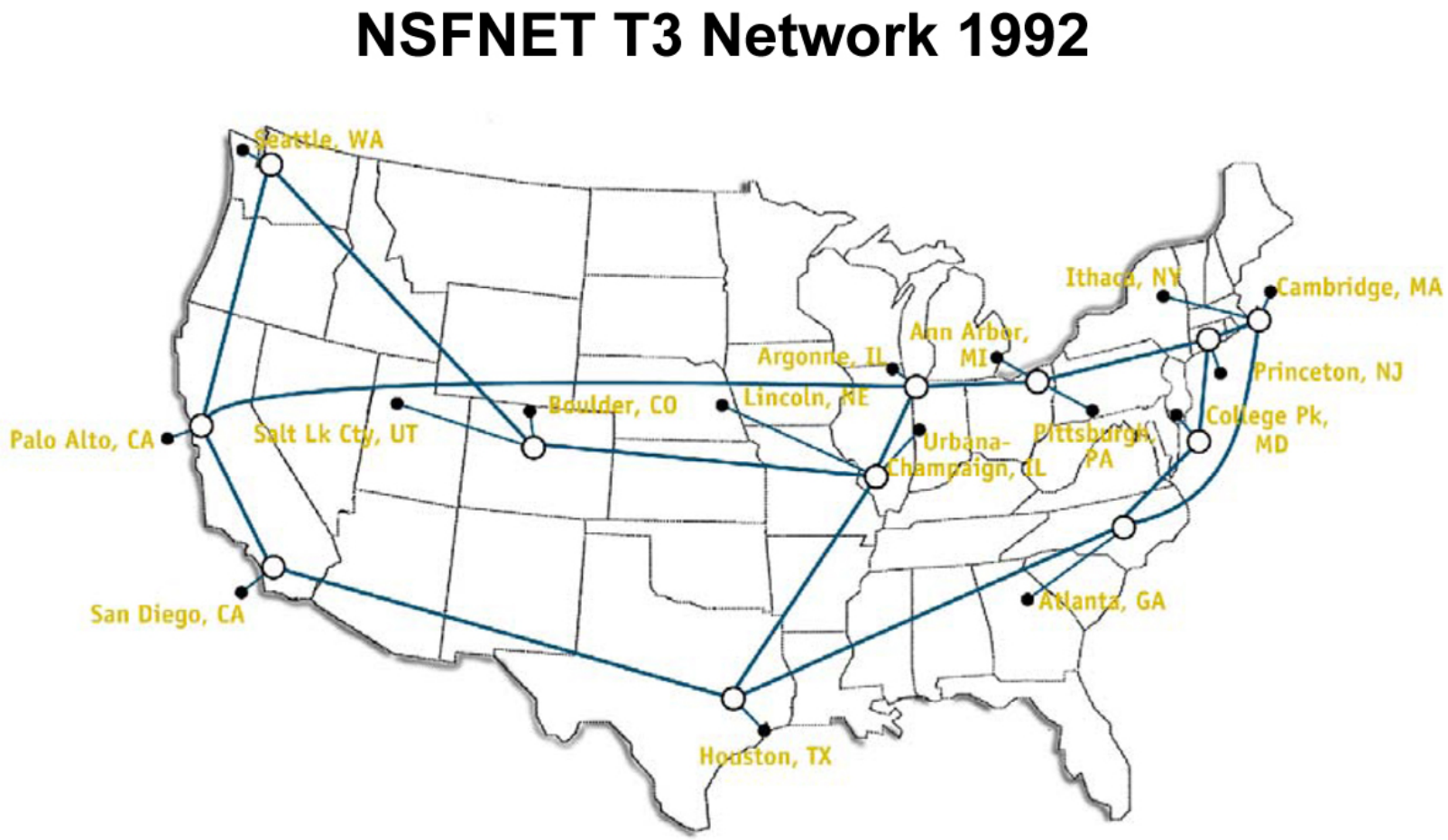
FIGURE 6.2 Drawing of 4 Node Network
(Courtesy of Alex McKenzie)

Internet ~1977 (ARPANET)



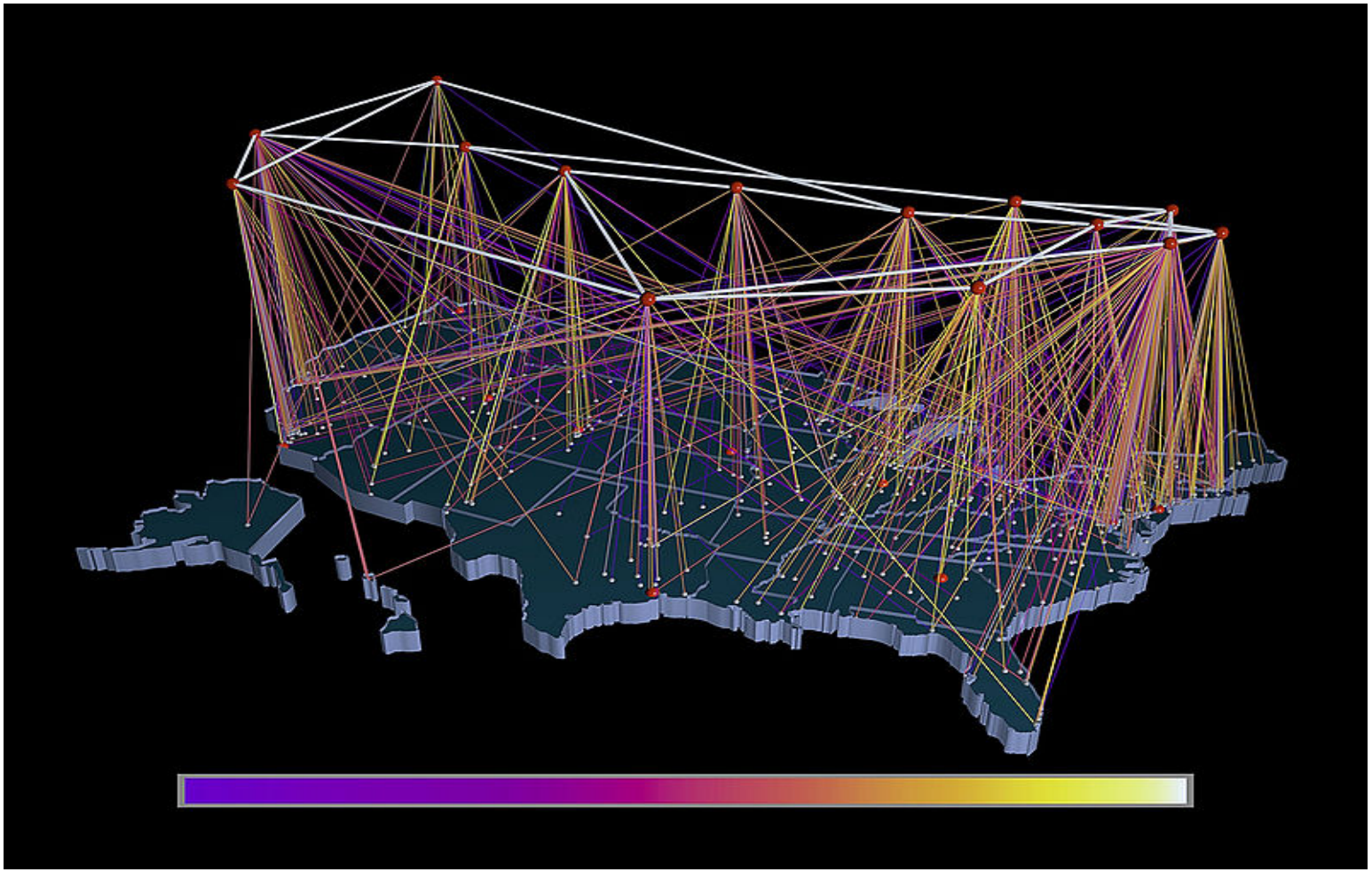
Source: ARPANET Completion Report, BNN,1977

Internet ~1991 (NSFNET)



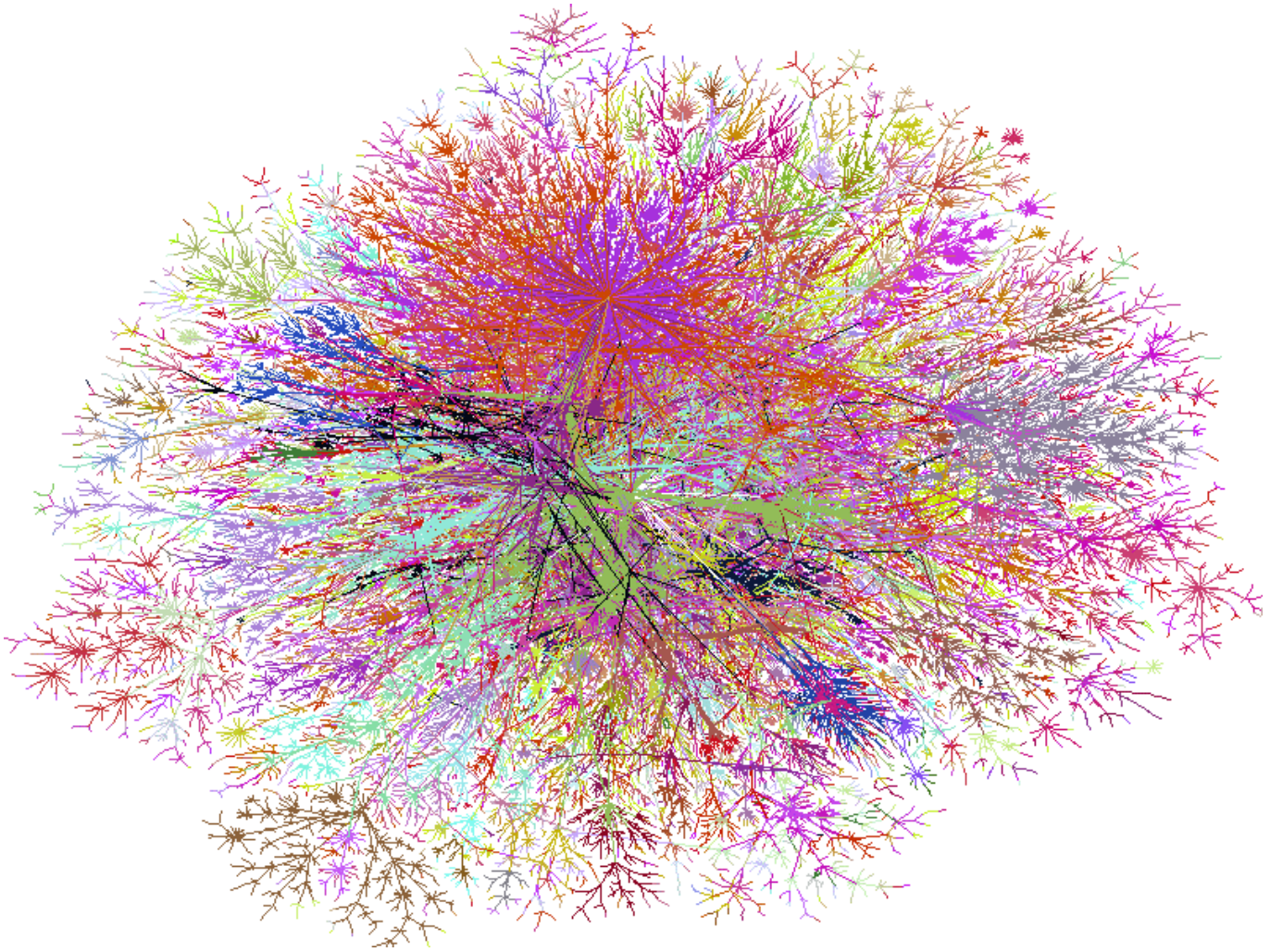
Merit Network, Inc. - Merit Network, Inc.(1992)

Internet ~1994 (NSFNET)



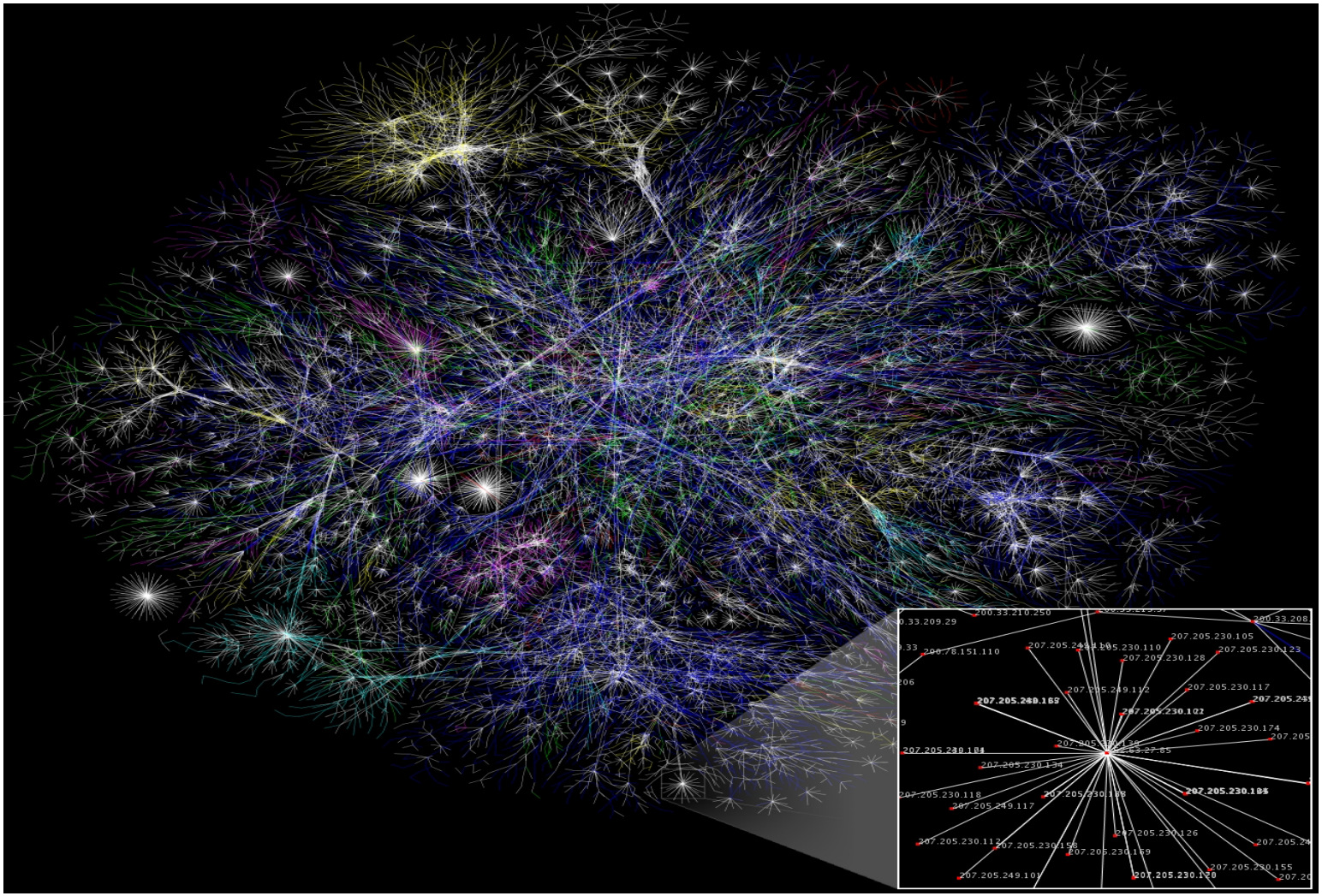
Source: https://en.wikipedia.org/wiki/National_Science_Foundation_Network

Public Internet ~2000



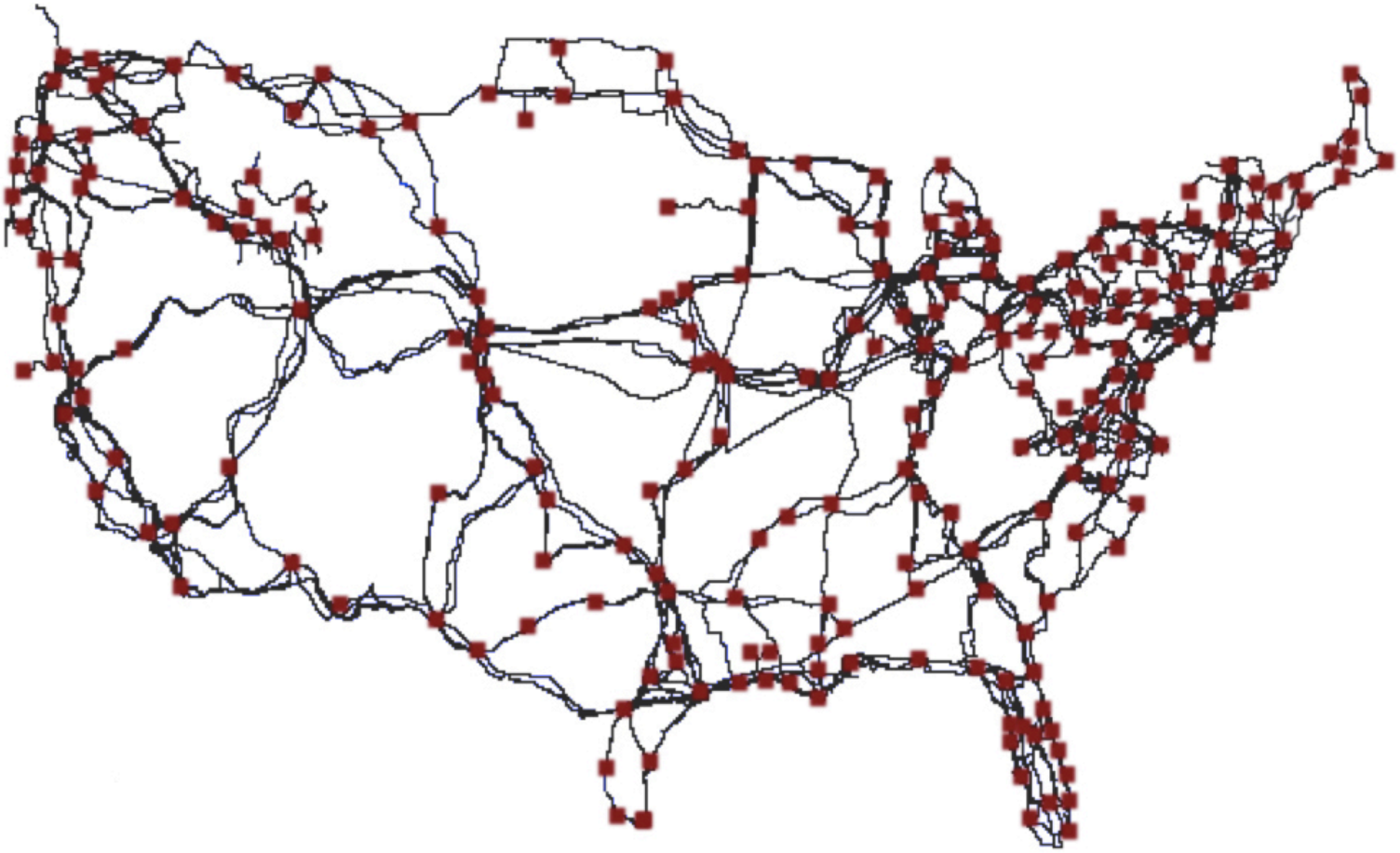
Source: Lumeta

Public Internet ~2010



Source: https://en.wikipedia.org/wiki/File:Internet_map_1024.jpg

US Internet ~2015



Source: ACM Sigcomm 2015

Objectives of our Work

- **Create and maintain a comprehensive catalog of the *physical Internet***
  - **Geographic locations of nodes (buildings that house PoPs, IXPs etc.) and links (fiber conduits)**
- **Extend with relevant related data**
  - **Traffic, active probes, BGP updates, weather, etc.**
- **Maintain portal for visualization and analysis**
- **Apply maps to problems of interest**
  - **Robustness, performance, security, etc.**

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Related Work

- Many prior Internet mapping efforts
  - Lots of traceroute-based studies
    - Data plane measurements to infer/map router topology
  - Many BGP update-based studies
    - Control plane measurements to infer/map AS topology
  - Some studies to infer/map the physical Internet
    - S. Gorman (2004) – FortiusOne (GeoCommons)
    - J.M. Kraushaar (FCC reports until 1998)
- Commercial activities
  - KMI Corp. (~early 2000)
  - TeleGeography, FiberLocator (NEF, Inc.)

The Physical Internet: Nodes

Back to Basics:
From Routers/Switches …

$$$$$

$$$$$$$

$

$$ to $$$$$

… to Racks/Cabinets/Cages …

… to Colocations (Colos) …

EQUINIX

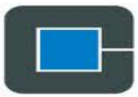
DIGITAL REALTY

Data Center Solutions

DuPont Fabros Technology

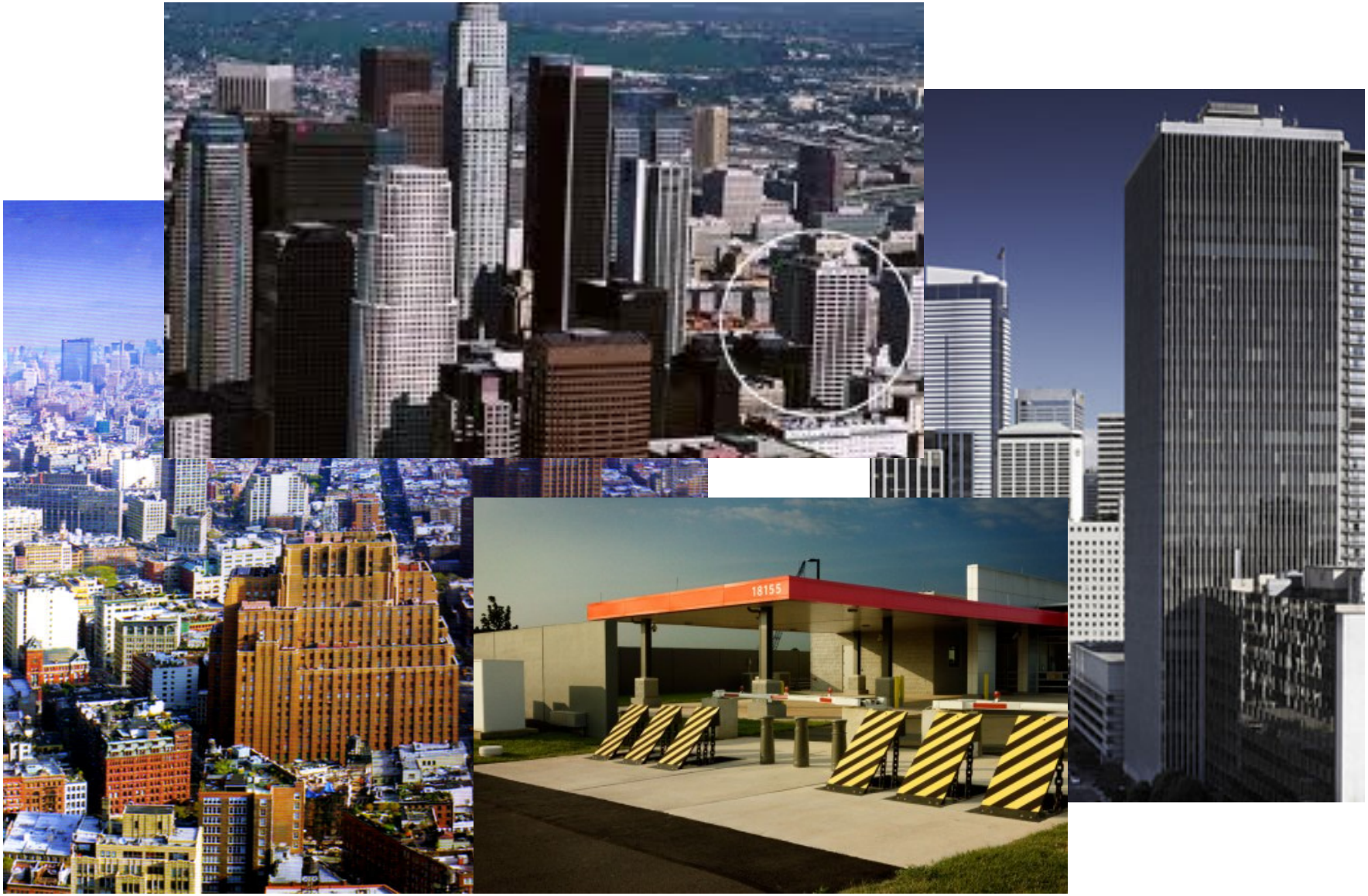
TELEHOUSE

HOME TO YOUR GLOBAL ICT SOLUTIONS



CORESITE

… to Carrier Hotels/Data Centers



The Physical Internet: Nodes

- **Major cities or metropolitan areas**
  - **Contain a majority of colocation facilities/data centers**
  - **Much is known about commercial colocation facilities/data centers**
  - **Places where long-haul fiber-optic cables originate/terminate**
- **Our map**
  - **Some 2000 colocation facilities/data centers**
  - **In 273 cities (nodes of our map)**

The Physical Internet: Links

The Physical Internet: Links

- **Long-haul links definition**
  - **Spans at least 30 miles or**
  - **Connects cities of population >= 100k people or**
  - **Shared by at least 2 providers**
- **Use maps of US infrastructure from 12 tier-1 and 4 major cable and 4 regional providers**
  - **Includes both geocoded and non-geocoded links**

Examples of Maps Used

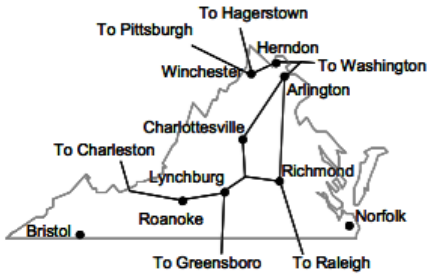
The Physical Internet: Links

- **Step #1: Identification**
  - **Utilize *search* to find maps of physical locations**
- **Step #2: Transcription**
  - **Begin with maps of ISPs that are geocoded**
  - **Add links of maps that are not geocoded**
- **Step #3: Verification**
  - **Check consistency with public records of rights of way (ROW), etc.**
- **Step #4: Infer conduit sharing**

Consistency Checks 1

AT&T

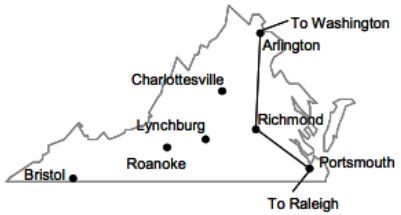
Address:	13630 Solstice Street Midlothian VA 23113
Telephone:	804-897-1734
Contact Person:	Chester Porter
Title:	Client Business Manager for VA
e-mail:	cdporter@att.com
Internet URL:	www.att.com
Offering:	"Full range of voice and data services, IT and professional services"



Source: KMI Corporation, Sept '01, www.kmicorp.com

Qwest

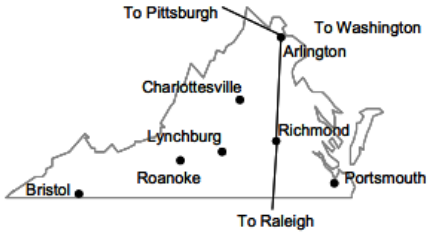
Address:	1306 Concourse Drive Suite 400 Linthicum MD 21090
Telephone:	410-694-4848
Contact Person:	Joel Prescott
Title:	National Account Manager
e-mail:	Joel.prescott@qwest.com
Internet URL:	www.qwest.com
Offering:	"Private line services, Internet, collocation, fiber leasing, engineering, construction, hosting, VPNs"



Source: KMI Corporation, Sept '01, www.kmicorp.com

Level 3

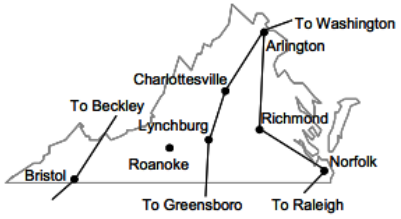
Address:	8270 Greensboro Drive Suite 900 McLean VA 22102
Telephone:	571-382-7427
Contact Person:	Laura Spining
Title:	Account Director
e-mail:	Laura.spining@level3.com
Internet URL:	www.level3.com
Offering:	"Private line transport services, optical waves, managed services for construction, engineering, fiber leasing, collocation, MPLS transport product"



Source: KMI Corporation, Sept '01, www.kmicorp.com

Worldcom

Address:	4951 Lake Brooke Drive Glen Allen VA 23060
Telephone:	804-527-6338
Contact Person:	Jim Nystrom
Title:	Director
e-mail:	Jim.nystrom@wcom.com
Internet URL:	www.wcom.com
Offering:	"Full array of voice and data services including private line, frame relay, ATM, Internet, Network Engineering and Managed Services, Worldcom is currently the enterprise service provider for the Commonwealth of Virginia including agencies, local and county government"



Source: KMI Corporation, Sept '01, www.kmicorp.com

Consistency Checks 2

AGREEMENT FOR THE LEASE OF CITY CONDUIT

and

LEASE OF THE PUBLIC RIGHT-OF-WAY FOR INSTALLATION OF CONDUIT AND FIBER OPTIC CABLE

between

THE CITY OF BOULDER AND ZAYO GROUP, LLC

This AGREEMENT FOR THE LEASE OF CITY CONDUIT AND LEASE ON THE PUBLIC RIGHT-OF-WAY FOR INSTALLATION OF CONDUIT AND FIBER OPTIC CABLE (this "Agreement") is made and entered into by and between the City of Boulder, Colorado (the "City") and Zayo Group, LLC, a Delaware limited liability corporation ("Zayo"). The City and Zayo may hereinafter be referred to individually as a "Party" or collectively as the "Parties."

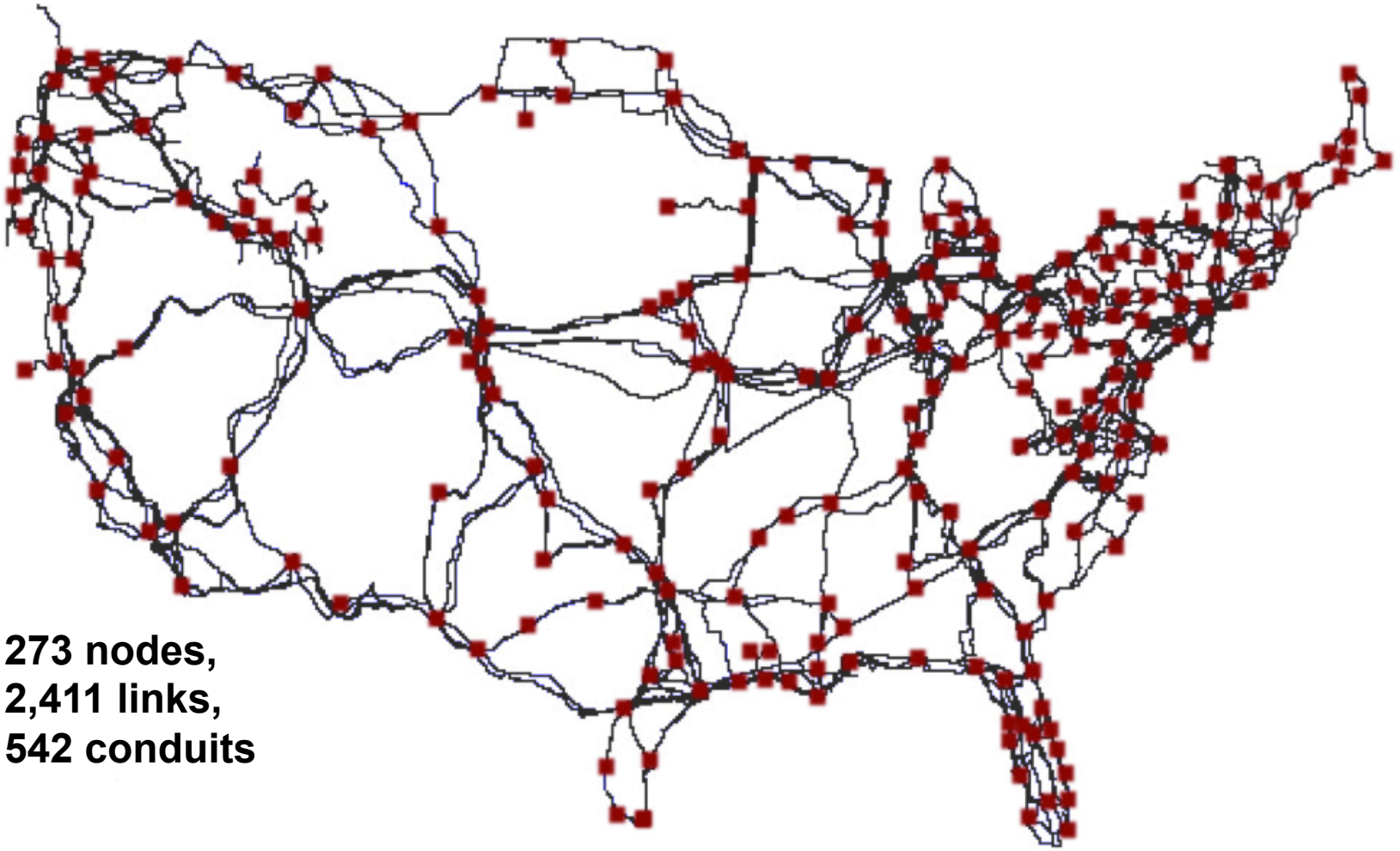
RECITALS

A. Zayo is a provider of telecommunications service, as defined in C.R.S. § 40-15-102, and, as such, holds a statewide franchise for the use of public rights-of-way pursuant to C.R.S. § 38-5.5-103 *et seq.*.

B. Zayo owns, operates and maintains metro fiber networks in multiple Colorado cities and desires to build a fiber optic network within Boulder to (i) serve large industrial, commercial and governmental clients within Boulder and (ii) connect to other municipalities along the Colorado Front Range and beyond. In order to accomplish this, Zayo wishes to lease unused conduit from the City.

C. The City owns certain underground conduit facilities, along with necessary handholes and manholes for access, located within the boundaries of the city of Boulder and depicted in red on **Exhibit A**, attached hereto and incorporated herein by this reference (the "City Duct System"). The City Duct System, which is 131,322 feet long, consists of as few as one and as many as four separate, but co-located, conduits that are typically used for routing wiring or fiber optic cable ("City Conduit").

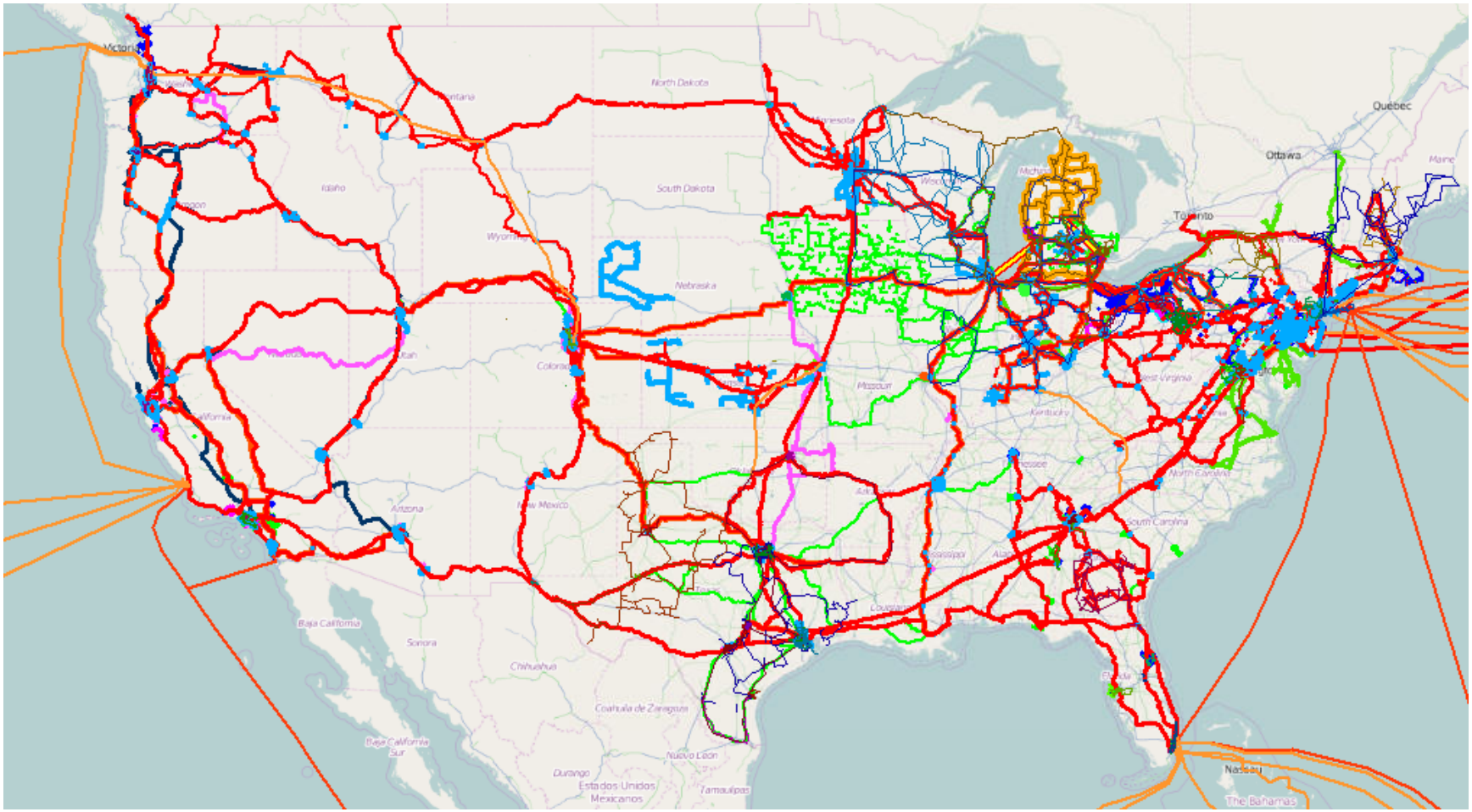
US Long-haul Infrastructure



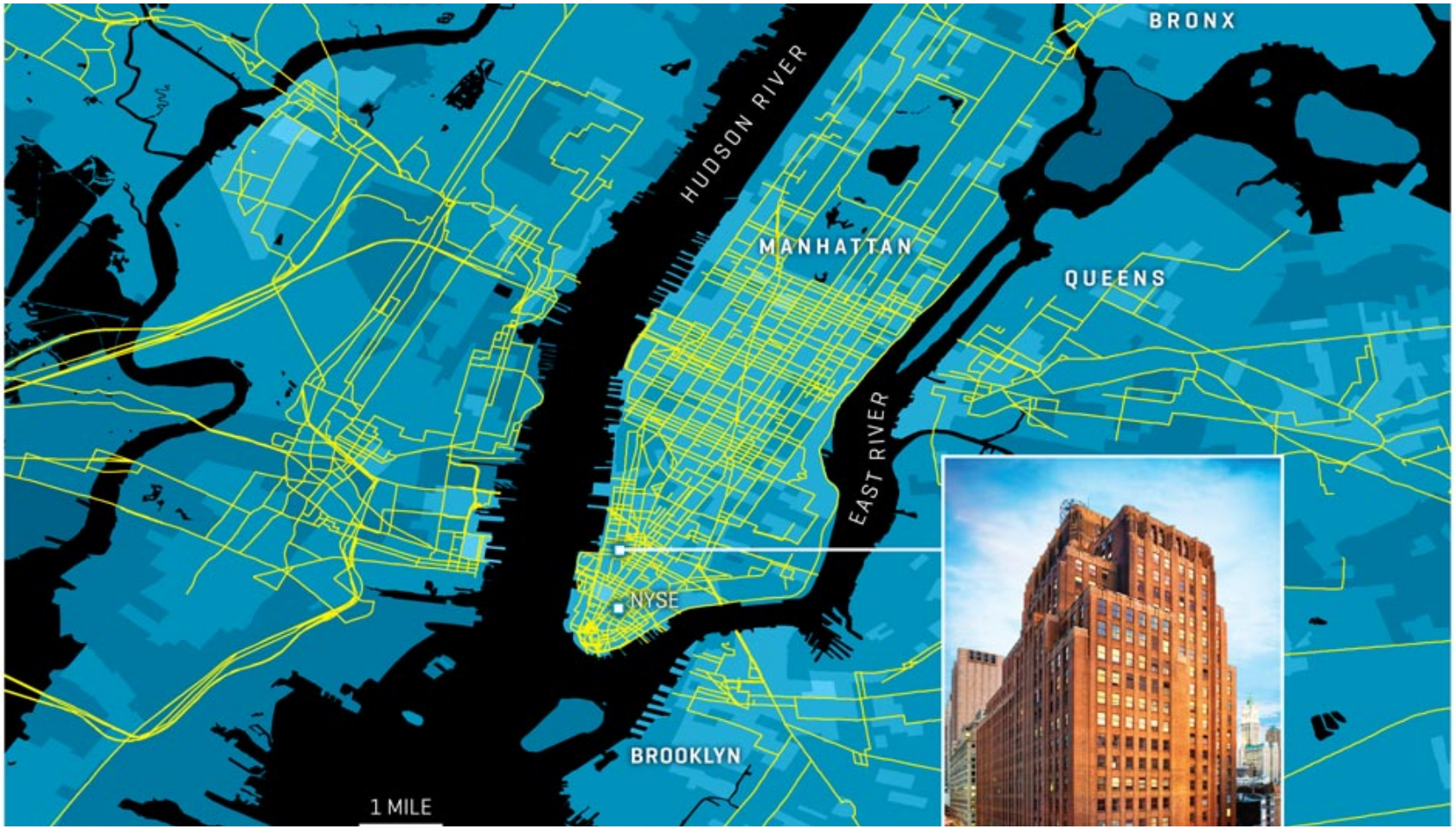
273 nodes,
2,411 links,
542 conduits

Some Missing Pieces …

Missing 1: Metro Fiber Maps

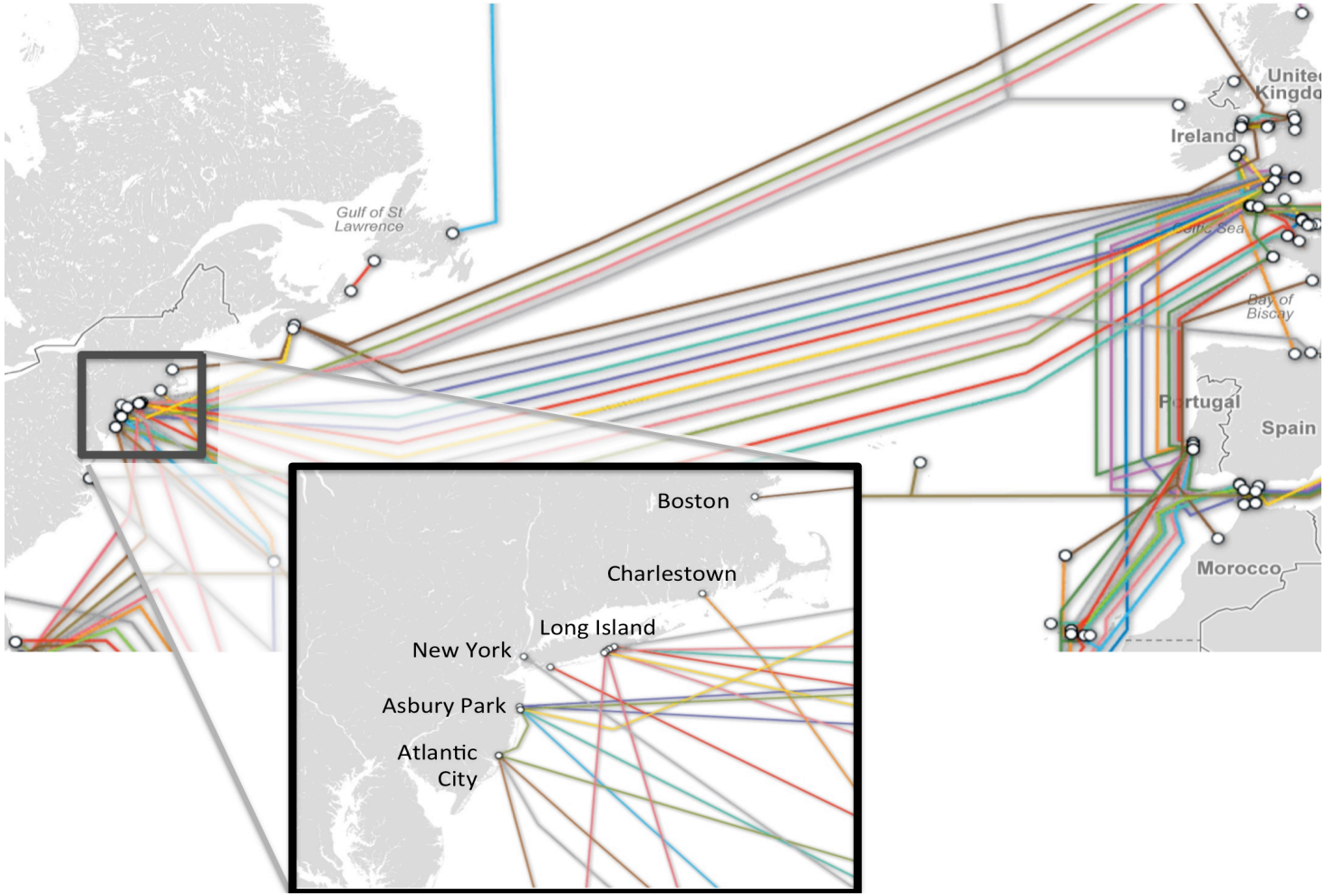


Example: NYC Metro Fiber



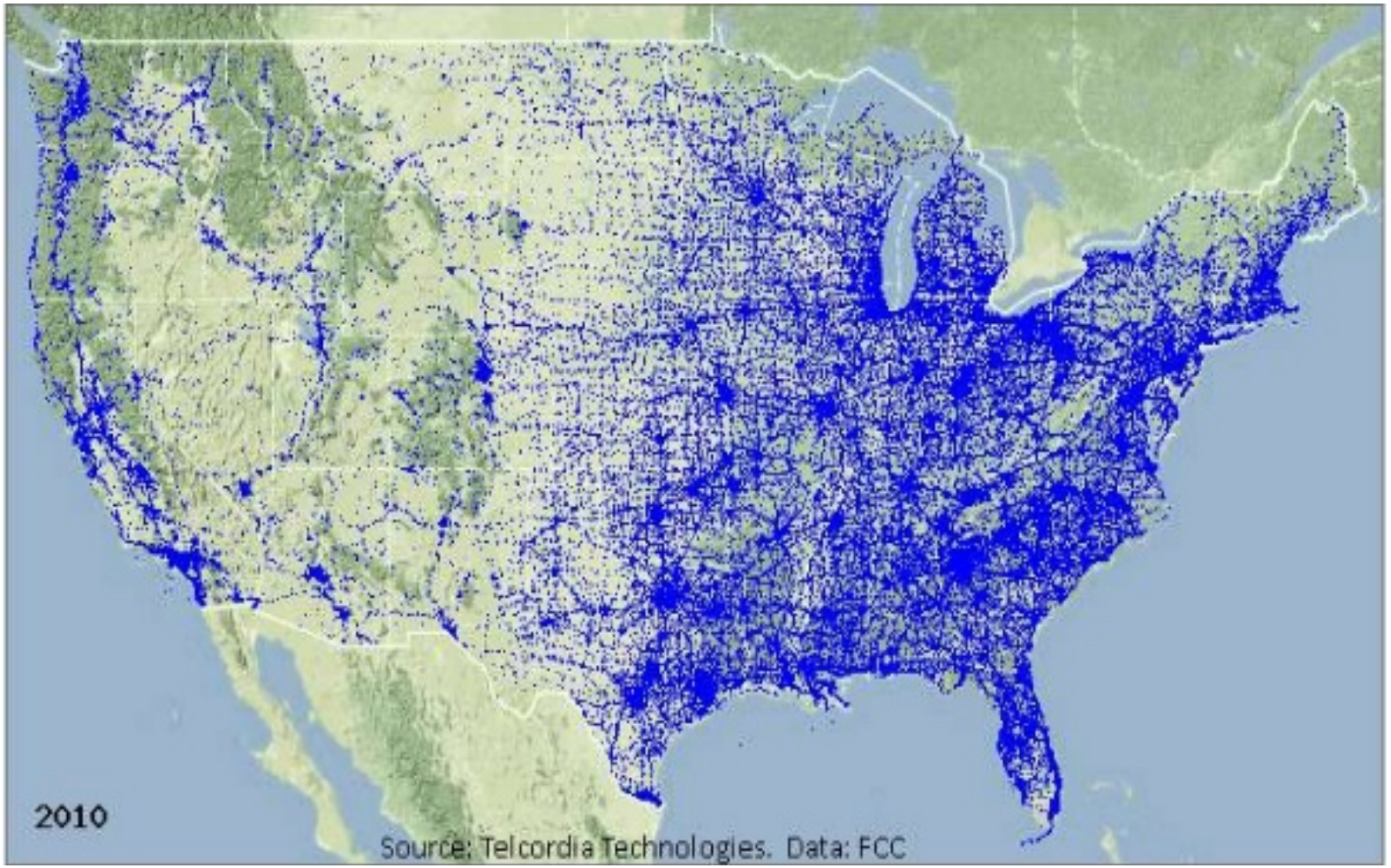
Source: http://ny.curbed.com/2012/7/17/10351100/mapping-manhattans-internet-with-underground-fiber-optics

Missing 2: Undersea Cables



Source: https://www.telegeography.com/telecom-resources/submarine-cable-map/

Missing 3: Cell Towers



Source: Telcordia Technologies, 2010

Some Questions of Interest

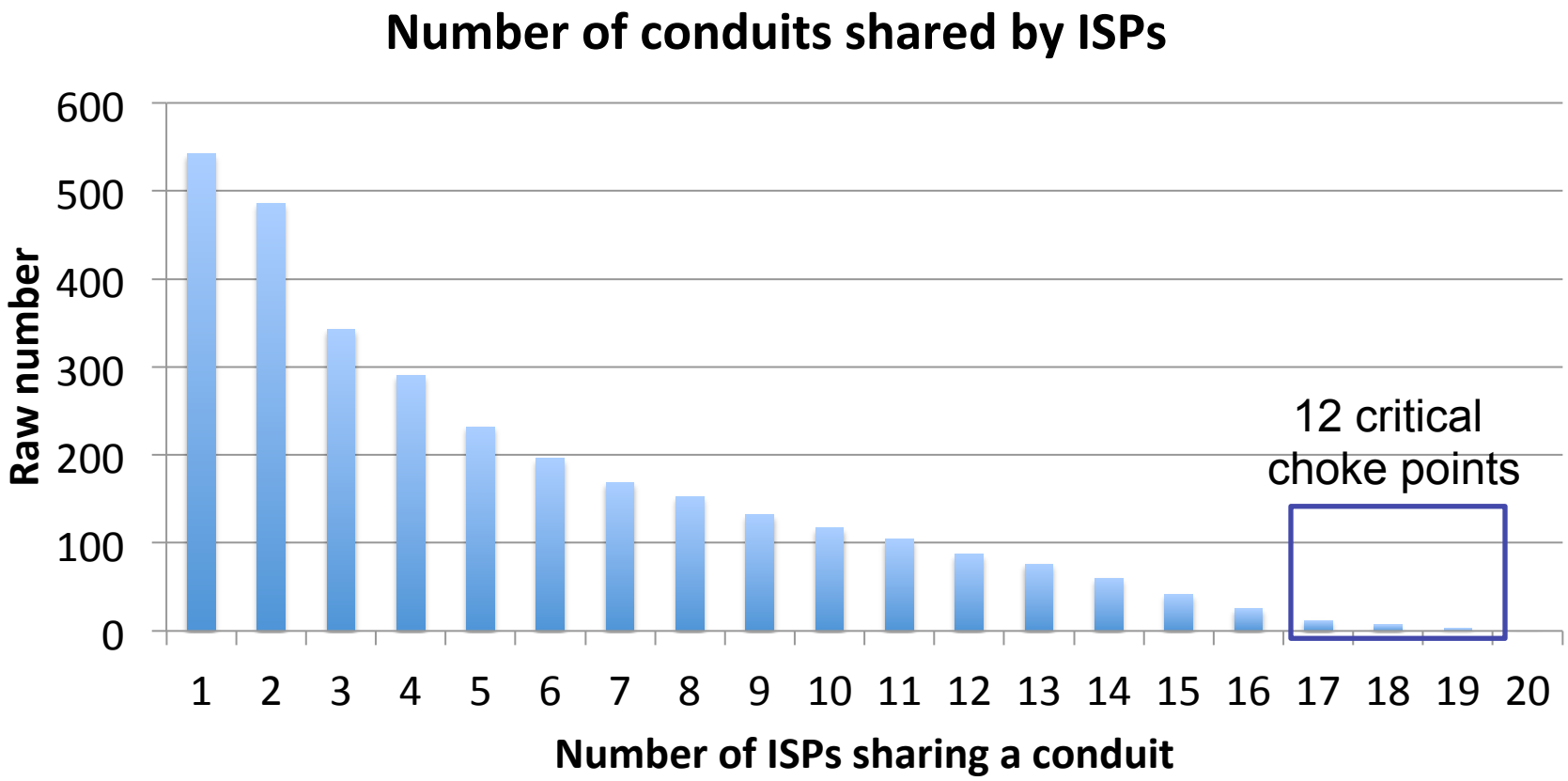
Question 1: Assessing Shared Risk

- **Striking characteristic of the constructed map is the amount of *conduit sharing***
- **Analyze shared risk using risk matrix**

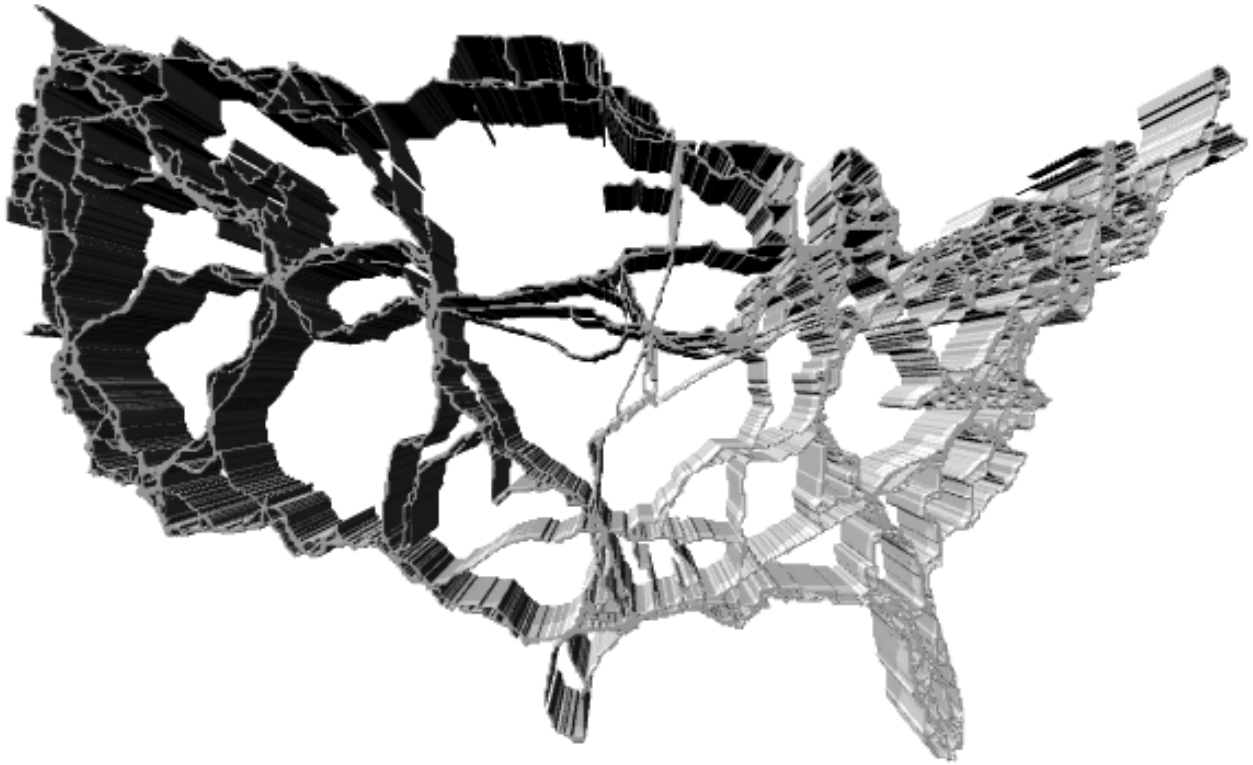
	c1	c2	c3
Level 3	2	2	1
Sprint	2	2	0

- **Notions of shared risk**
  - **Connectivity only**
  - **Connectivity plus inferred traffic**

Connectivity-only Risk



Connectivity plus Inferred Traffic



Dataset: Ono (BitTorrent clients) from Jan. 01, 2014 to Mar. 31, 2014;
Thickness number of probes traversing a conduit
Color number of ISPs sharing the conduits

Question 2:
Colocation With Other Infrastructure

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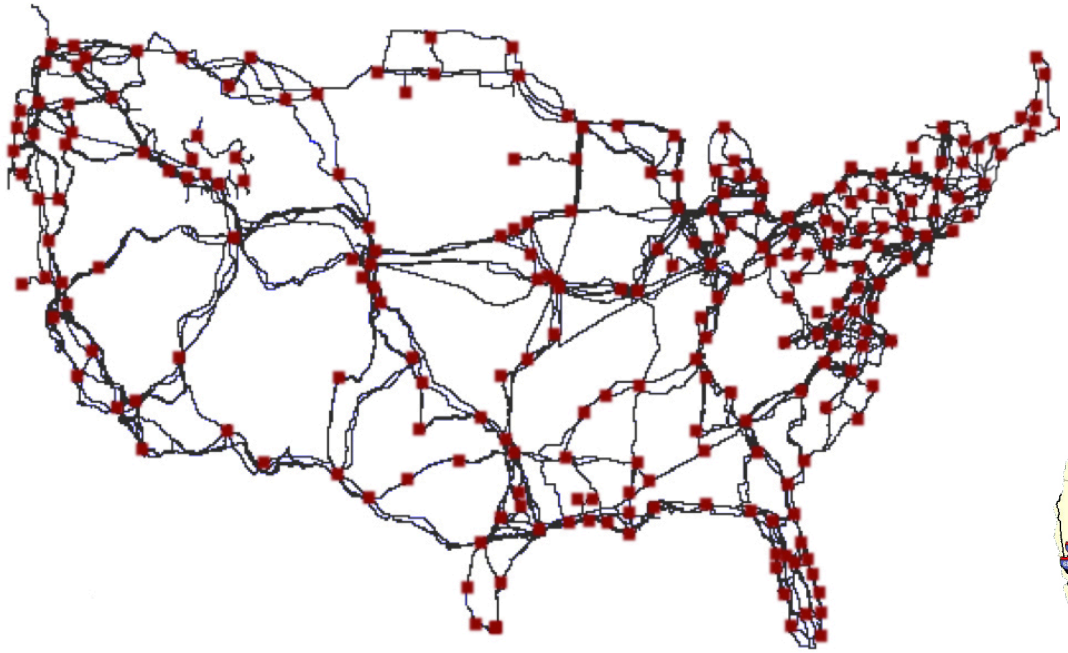
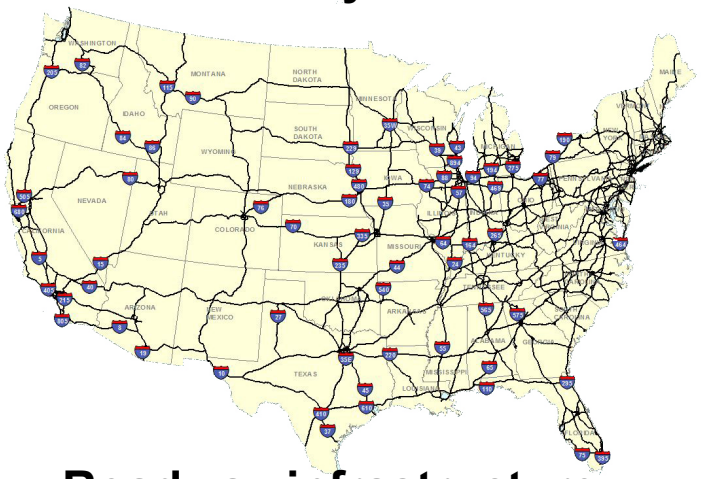
Colocation With Other Infrastructure



Railway infrastructure



Roadway infrastructure

Improving Infrastructure

- **We show that robustness and performance can be improved by adding just a few links in strategic places**
  - **Gain robustness to outages by reducing sharing**
  - **Better performance by minimizing propagation delay**
  - **Add new conduits or add new peers**

- **How to get there?**
  - **Regulation (e.g., Title II) may achieve the opposite?**
  - **Market forces (e.g., robustness as a competitive advantage)**

An Observation …

- **The physical Internet is resilient …**
  - **TCP/IP was designed so that the Internet can "live with" failures and "work/route around" them**
  - **TCP/IP allows for graceful degradation under failure while maintaining/providing basic services**

- **... but it helps to understand its "weak spots"**
  - **Where would more redundancy be beneficial?**
  - **Where would more (physical) security pay off?**
  - **Redundancy in view of prevailing market forces vs regulations**

… and Reminder ...

A bad actor whose objective is to do maximum damage to an industry/country/society relies critically on a fully functioning physical Internet infrastructure to reach the intended victims and harm them

… and the $100M(?) Question:

- **Secure the physical Internet infrastructure?**
  - **Submarine cable, landing stations**
  - **Colocation facilities, data centers**
  - **Long-haul fiber optic cables, cell towers, …**
- **Secure the logical Internet infrastructure?**
  - **IP (BGP hijacking)**
  - **TCP (low-volume DDoS)**
  - **SCADA protocols (corrupting power grid, gas supply, …)**

Thank you!

For portal access:
http://internetatlas.org
For account access:
http://www.predict.org