Last-Mile Internet Access

CS249i: The Modern Internet

Stanford University

How do you get access to the Internet at home?

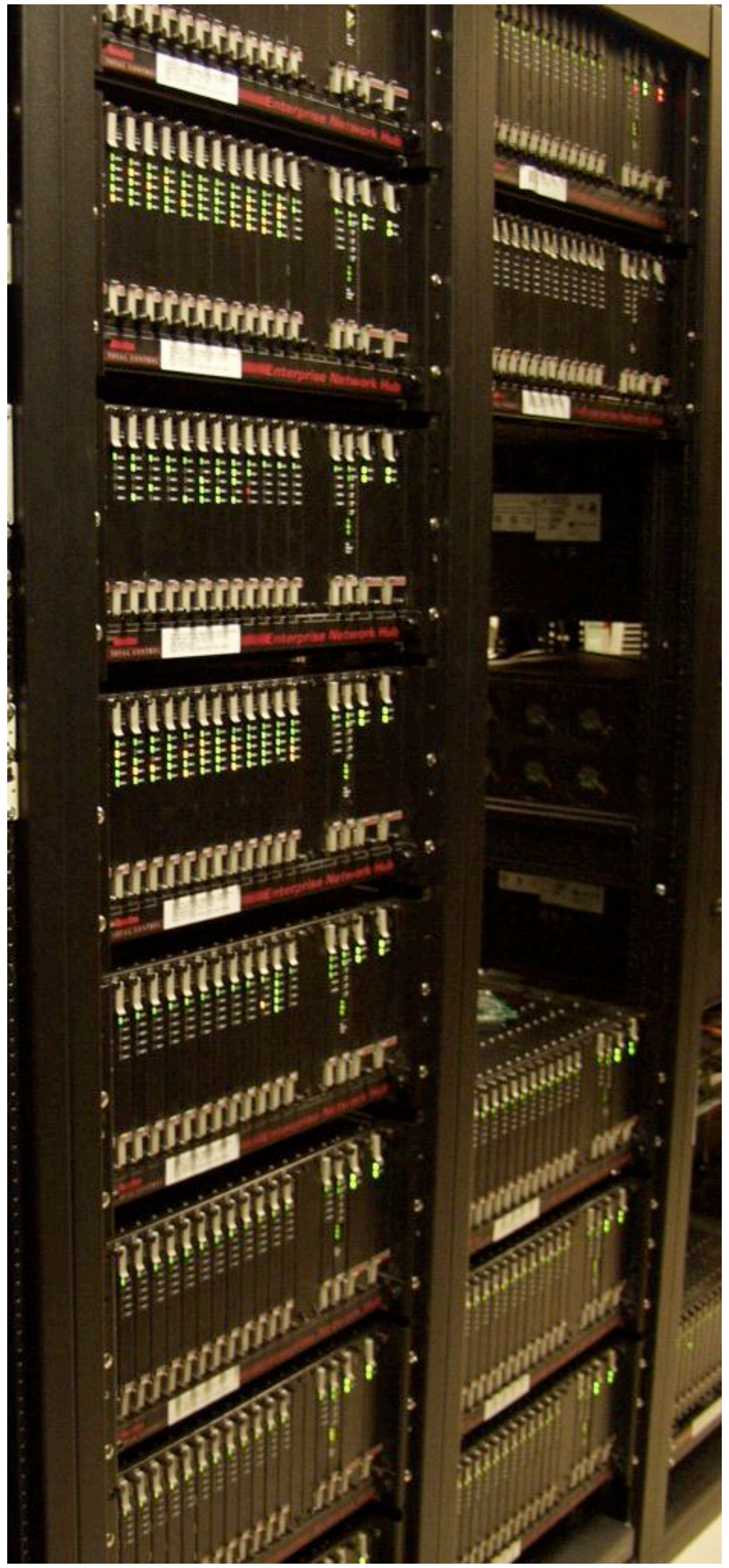
🌍 Last Mile Access

The Last Mile

- The final leg between the telecommunications network (cable, Internet, whatever) and the end-user (home, university, cellphone, etc.)
- Tends to be the *most* bandwidth constrained, since it costs lost of $$$ to invest in infrastructure everywhere
  - Last “miles” problem

A Brief Last Mile History

- In the early 90s, 56K dial-up was the way to connect to the Internet
    - Could leverage the existing telephone network to connect homes to the Internet
- …but 56Kbps is slow. Like, really, really, really slow.
    - Restricted by the modems themselves



A Brief Last Mile History

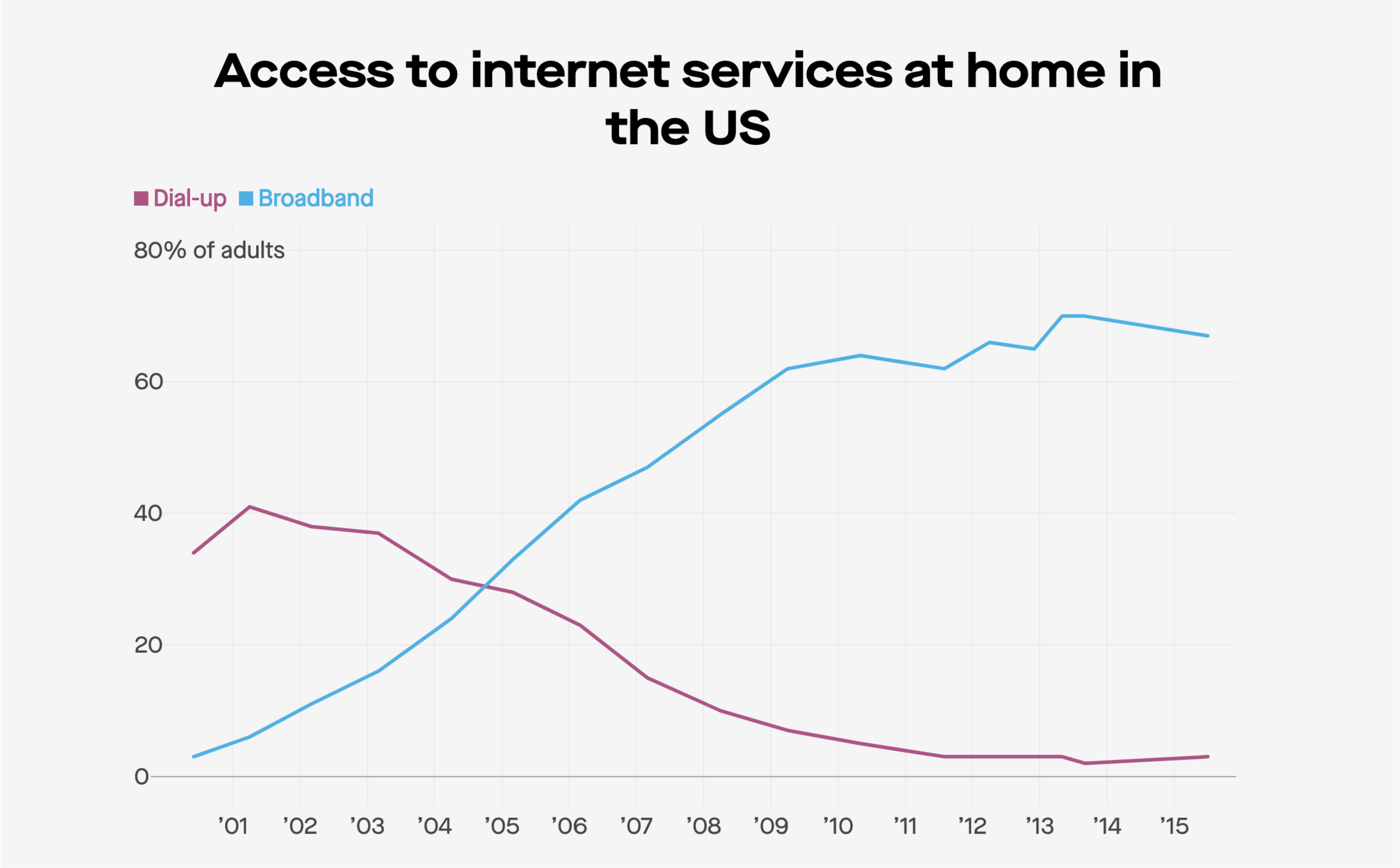
- After dial-up, the next innovation was DSL – digital subscriber line (late 90s)
- Core innovation here was using a *different* frequency channel (and thus, different hardware) that would enable people to use the phone + Internet at the same time
    - Could push up to 256K speeds in beginning, Bell Labs pushed 10 Gbps* in 2014
    - Much of the world *still* uses DSL

*Over a distance of 30 meters

A Brief Last Mile History

- Finally… cable Internet! (later 90s, early 2000s)
- Core idea: We have a big cable network for Television… why don't we use that for Internet?
  - Typically copper, or hybrid copper / fiber
- 80% of Americans use cable Internet to connect to broadband
  - "Broadband" defined by the FCC as stable, 25Mbps download, 3Mbps upload, but cable companies have used it to mean so much that it means nothing anymore

Last Mile in the US



21 million

Americans don’t have access to broadband Internet access in 2020

https://docs.fcc.gov/public/attachments/DOC-357699A1.pdf

Broadband Is Largely Inaccessible to Those Who Need it Most

Because of high prices and low accessibility, poor and rural communities are the least likely to subscribe to high-speed internet.

2.6 billion

People don’t have Internet access around the world.

https://www.itu.int/en/mediacentre/Pages/PR-2023-11-27-facts-and-figures-measuring-digital-development.aspx

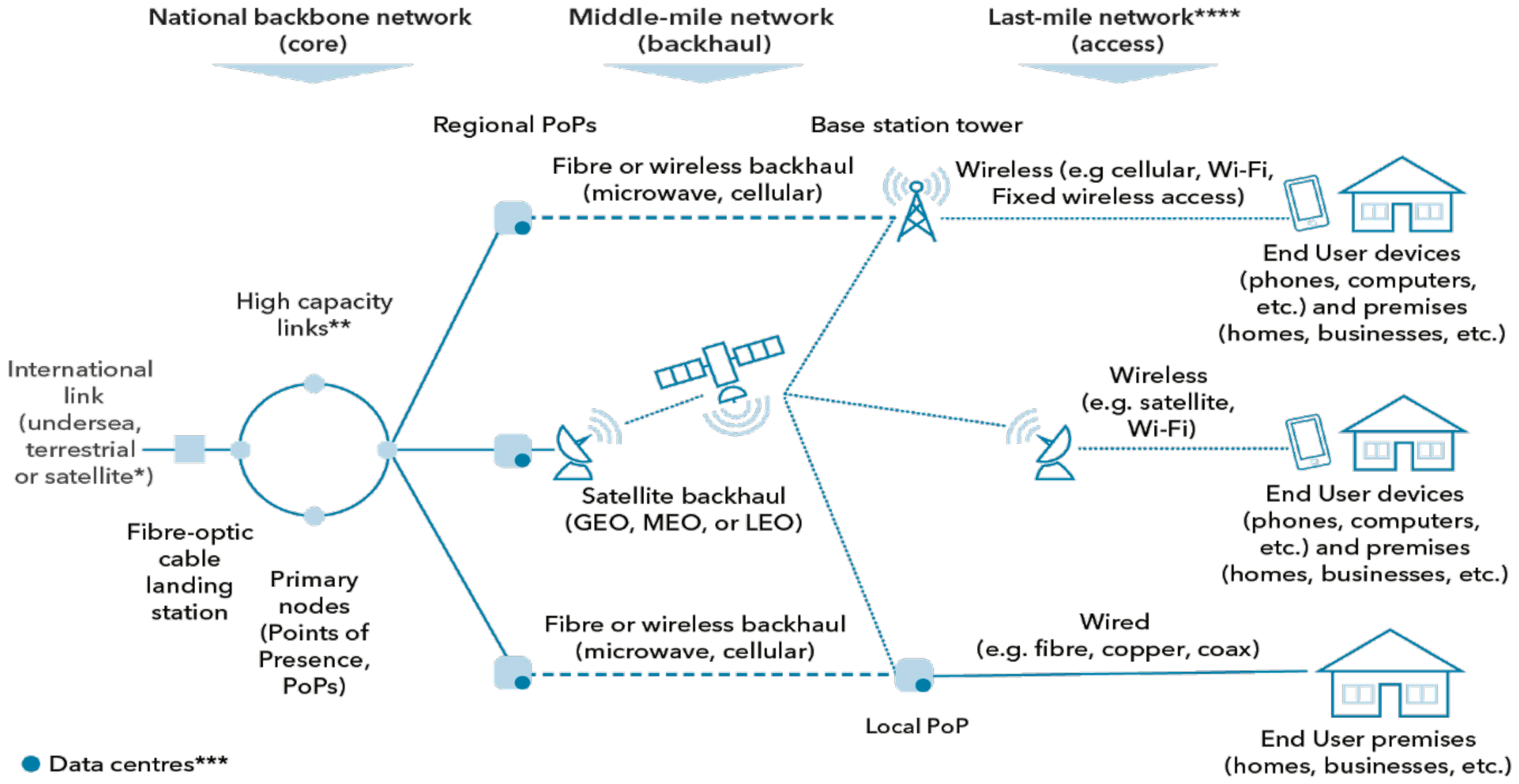
The Last Mile Problem

How do we connect people around the world to the Internet who currently don't have access?

Two Main Areas of Investment

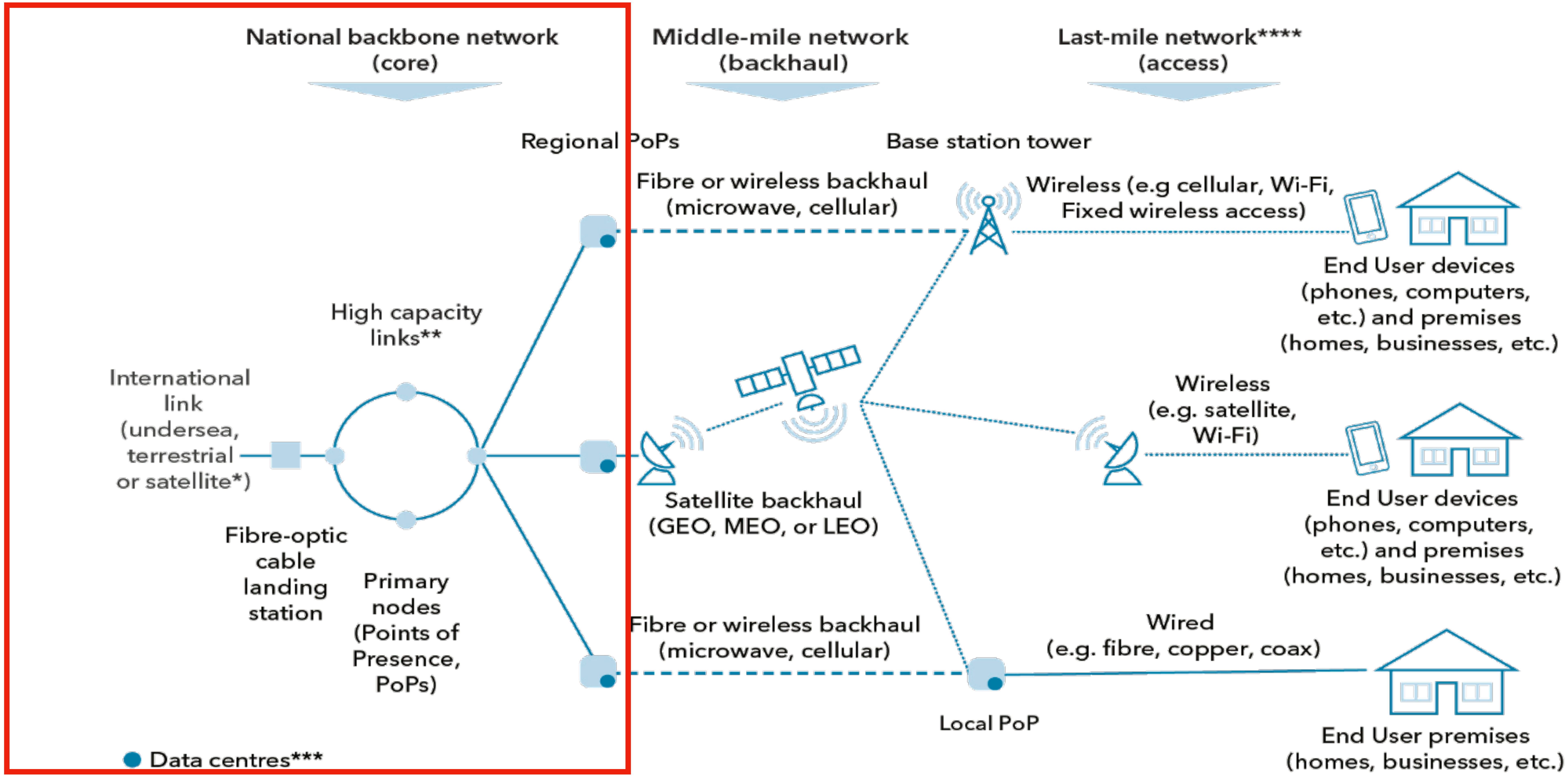
- Wired investment (Cables)
  - Typically copper, coax at last mile, but could be fiber in developed regions
  - Fiber in backhaul / backbone
- Wireless investment
  - Satellite
  - Cell Towers
  - New moonshots

Example Telecom Topology



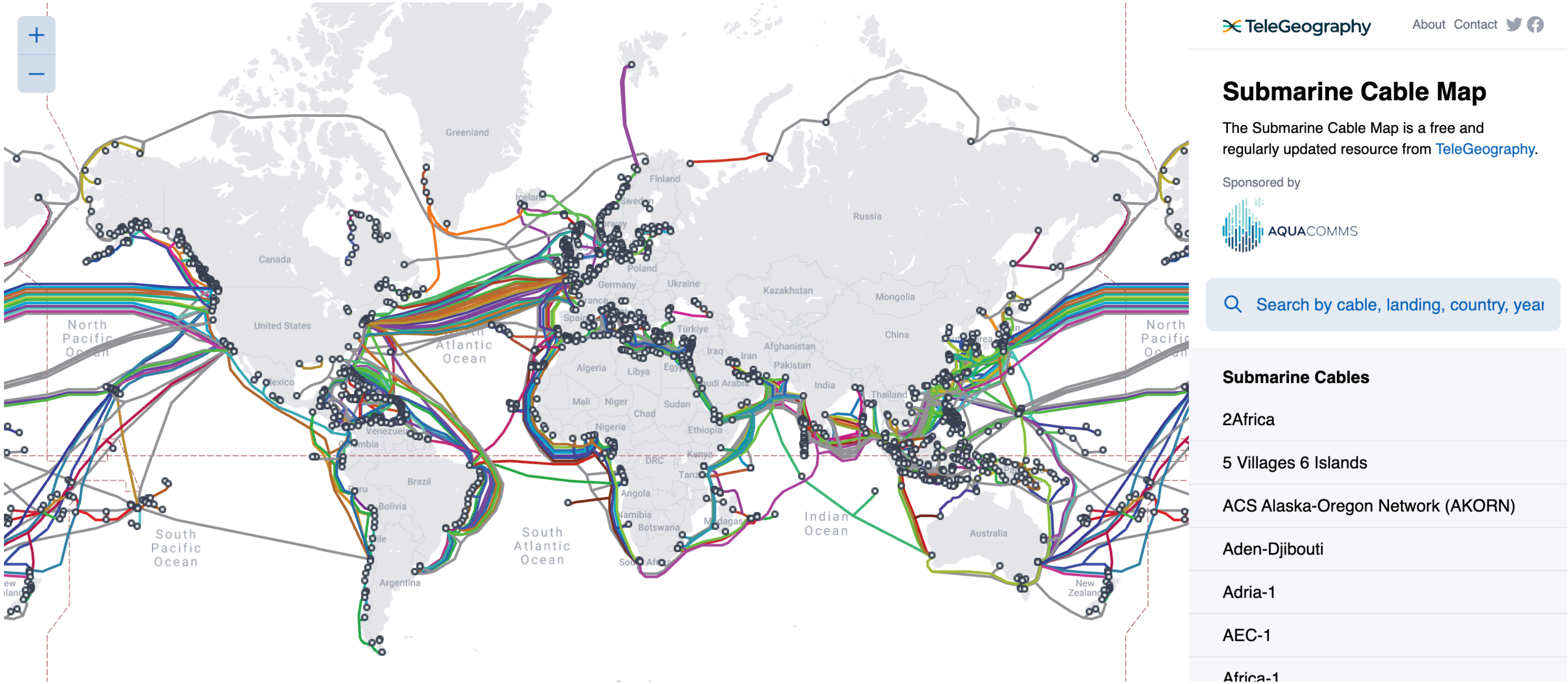
International Telecommunications Union

Example Telecom Topology



International Telecommunications Union

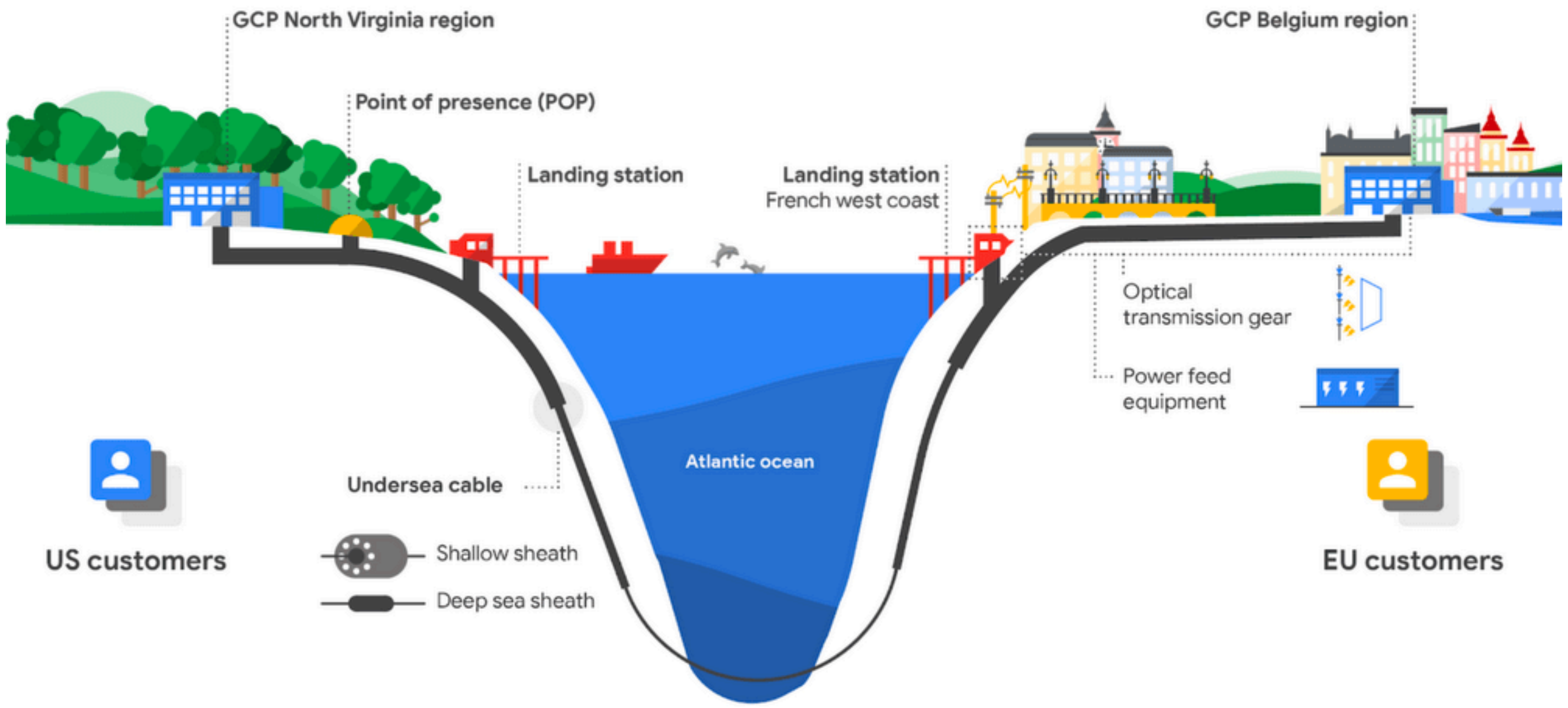
Submarine Cable Map

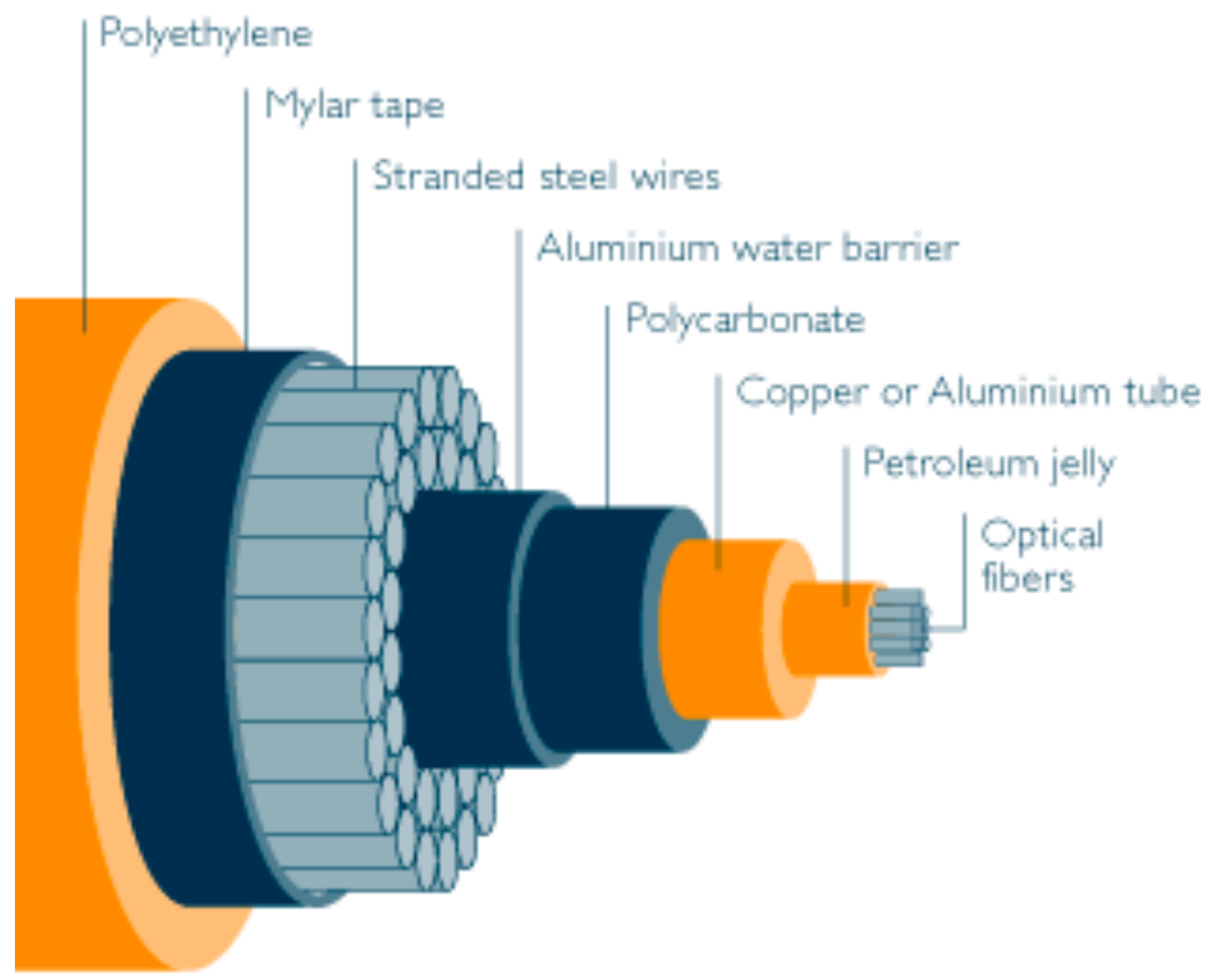


SeaCom

- In 2009, SeaCom launched in Africa, providing the eastern coast of country with its first broadband submarine cable system
    - Connects Eastern Africa to France, India
- Cost **$650 million** to build
    - Privately operated, currently 75% African-owned
- Designed to deliver 12 Tbit/s to Eastern Coast

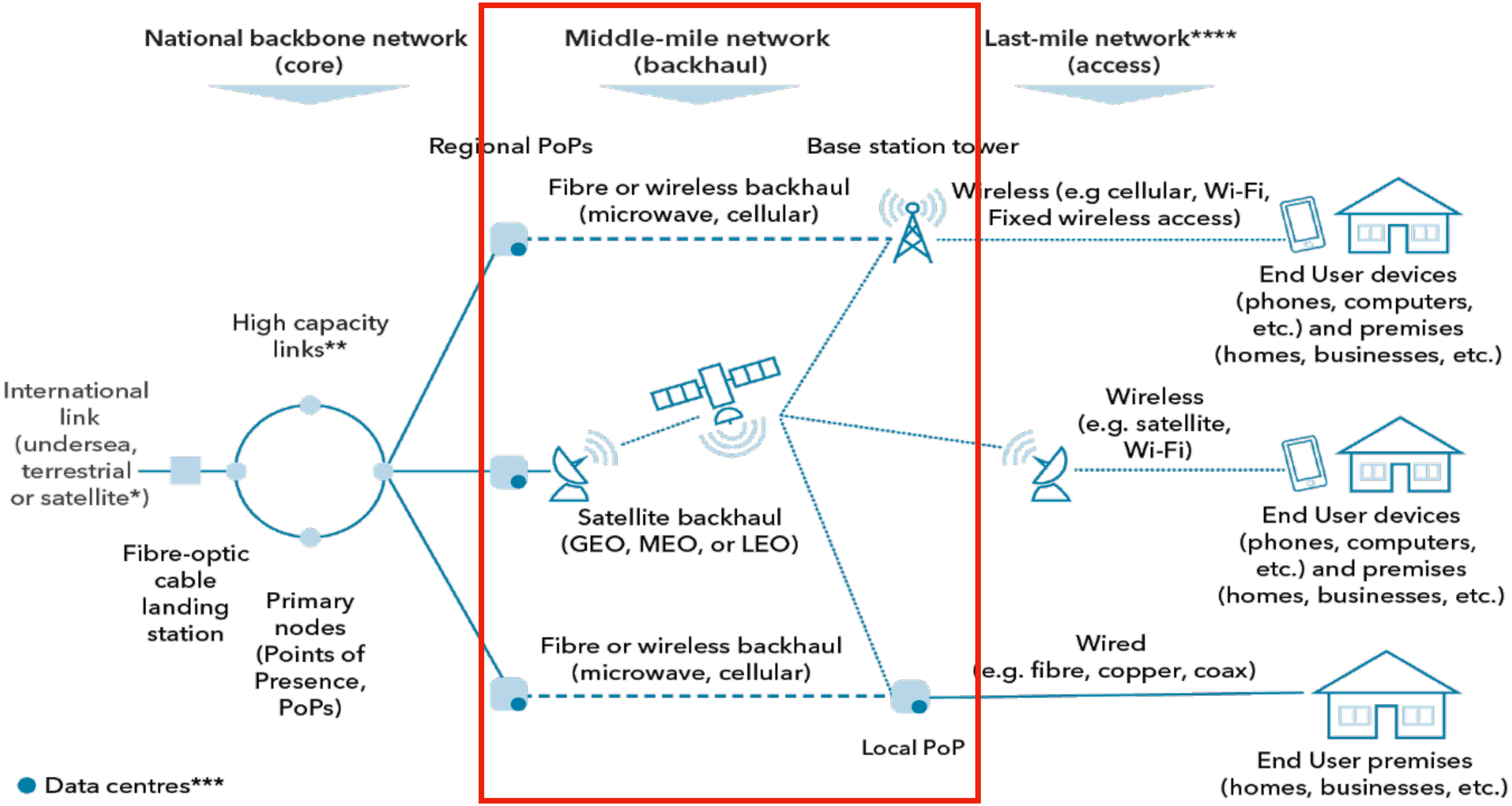
Submarine Cables





https://dgtlinfra.com/submarine-cables-fiber-link-internet/

Example Telecom Topology



International Telecommunications Union

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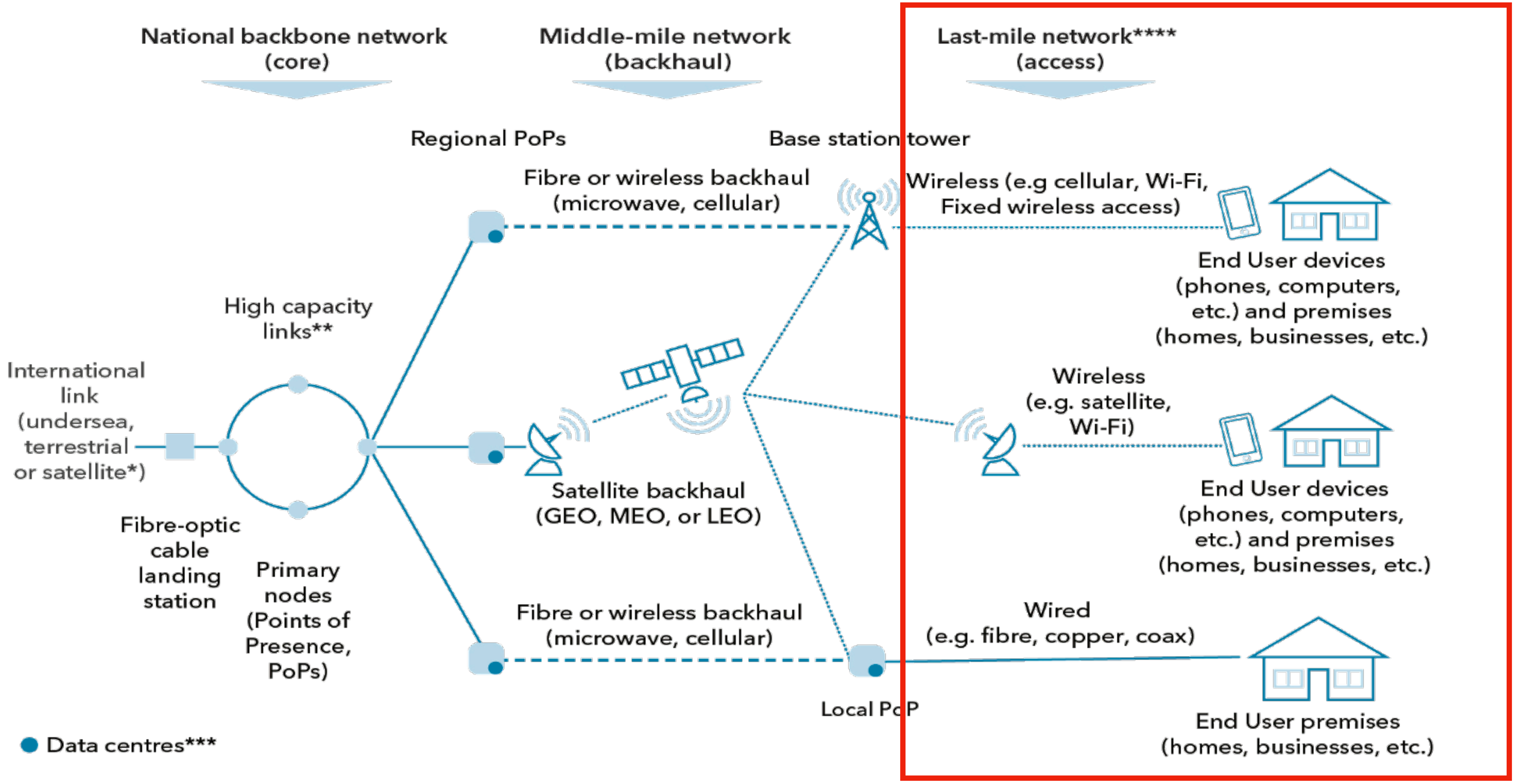


International Telecommunications Union

🌾 Modern Last Mile Investment

Fiber to the Premises

- Fiber to the premises is increasing in availability in densely populated areas in the west
  - Major US, European players, e.g., Google, Verizon
  - Smaller players are getting in as well!
- **Why doesn't everyone have fiber?**
  - Costly: $27,000 per mile of fiber (Dept of Transportation)

Fiber

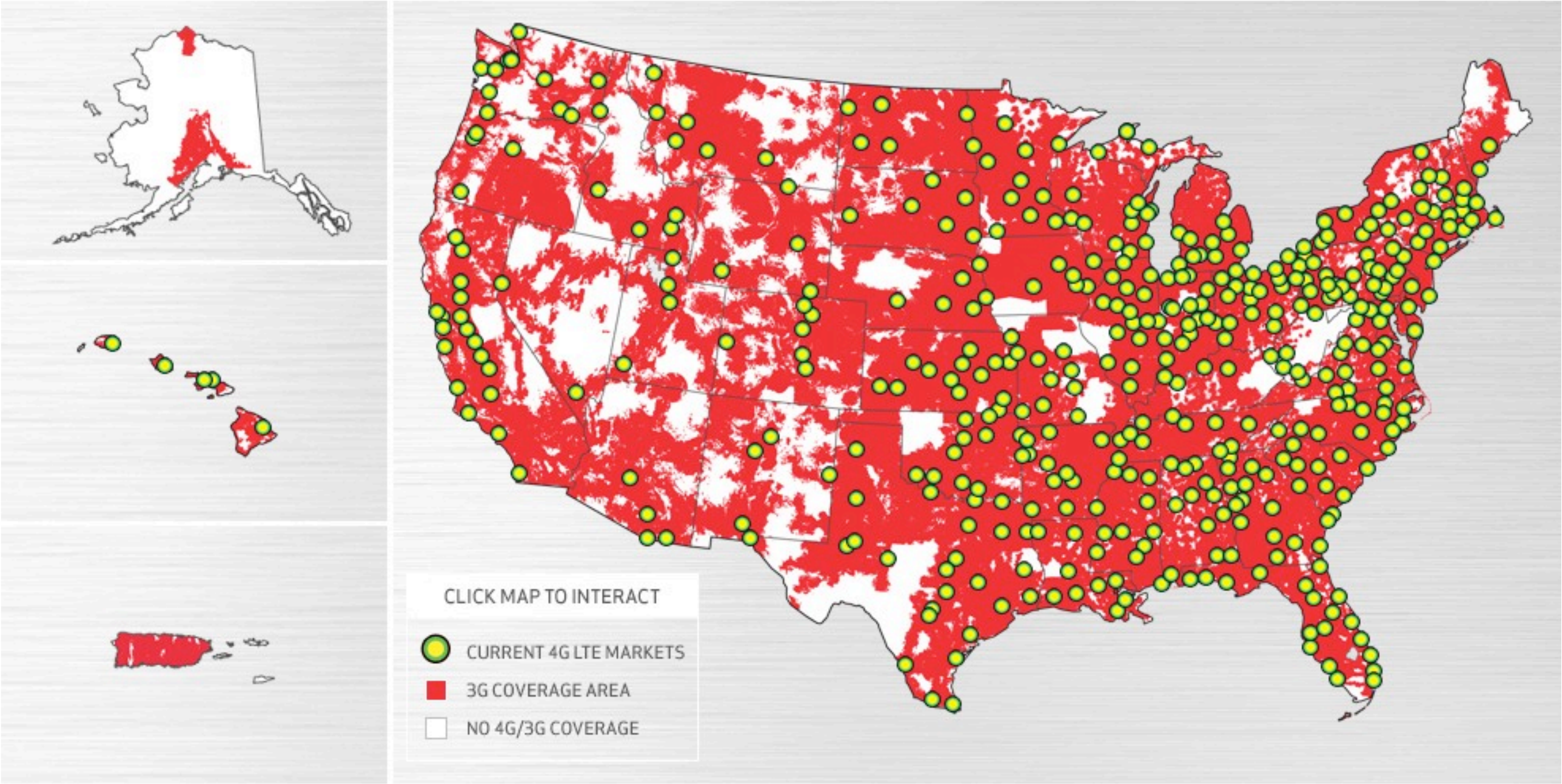
fios by verizon

“Dig Once” Policies

- "Dig once” policies are simple: When you are doing other infrastructure projects (e.g., construction, sewage), build in the broadband connection you need then instead of separately
  - Goldman Sachs estimates nationwide fiber would cost $140 billion dollars, “Dig Once” would save $126 billion of those
- Only 16 states have implemented policies (CA included!)
- Nationwide legislation is stonewalled. **Why?**
  - “Dig once” policies can enable small, regional providers low cost access to building fiber, which some national telecom providers (cough cough, AT&T, Verizon, Comcast) **lobby against.**

Mobile Networks

- Cell towers have exploded in popularity in the last 20 years as a cheaper alternative to broadband access than fiber
- 4G networks are offering **broadband** speeds, but these are expensive to build
  - Est. $200,000 to build a single cell tower capable of 4G communication
- Although many networks have nationwide *availability,* this doesn't solve the in-home access problem



Verizon 4g Coverage Map

Mobile Cellular Generations

- 1G - basic voice calling services
- 2G - Voice calls, text messages, limited browsing
- 3G - Broadband access, video conferencing, GPS
- 4G - High speed apps, mobile TV, wearable devices
- 5G - HD streaming, IoT, autonomous vehicles

3GPP™
A GLOBAL INITIATIVE

Mobile Cellular Generations

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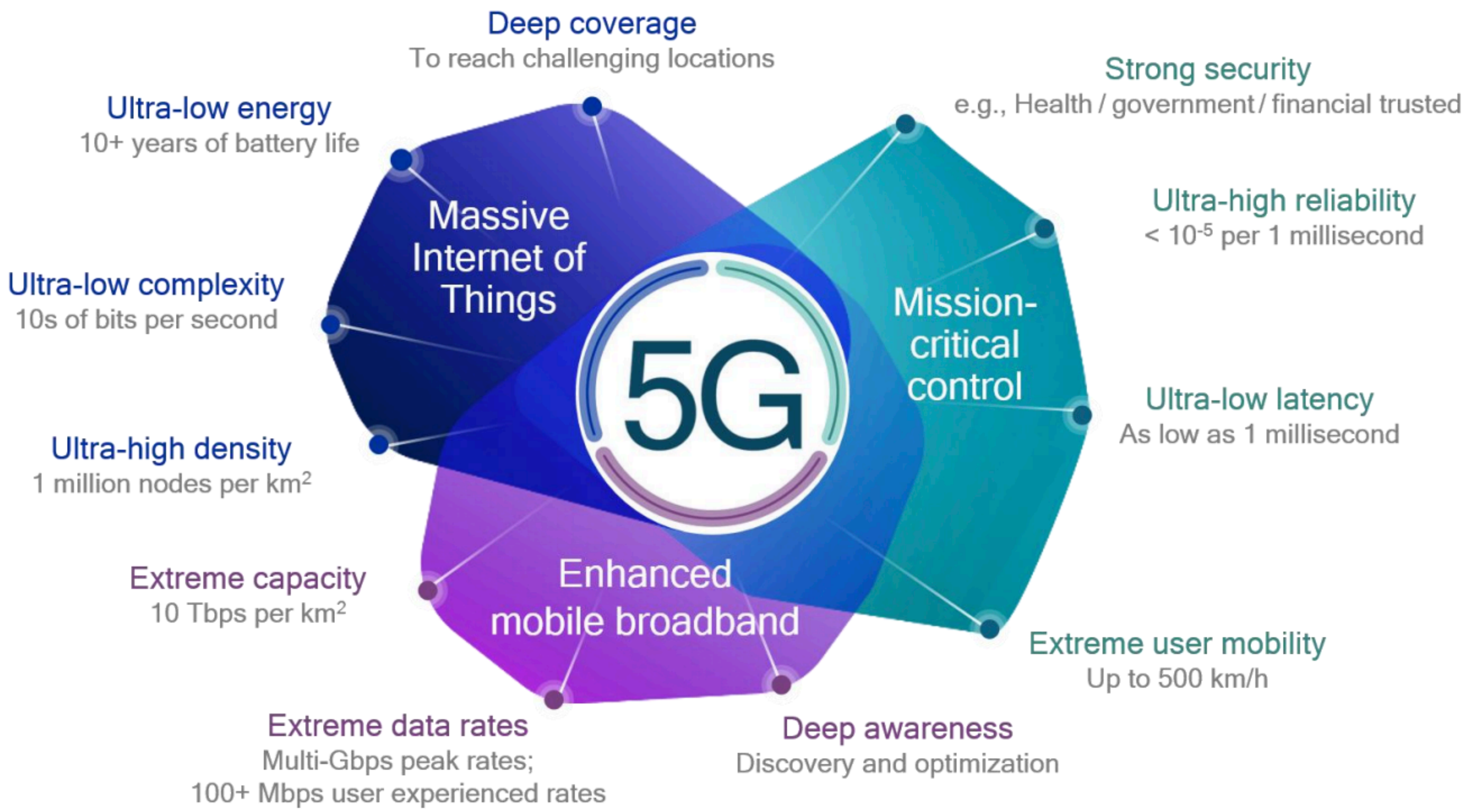
- 4G LTE

5G Networks

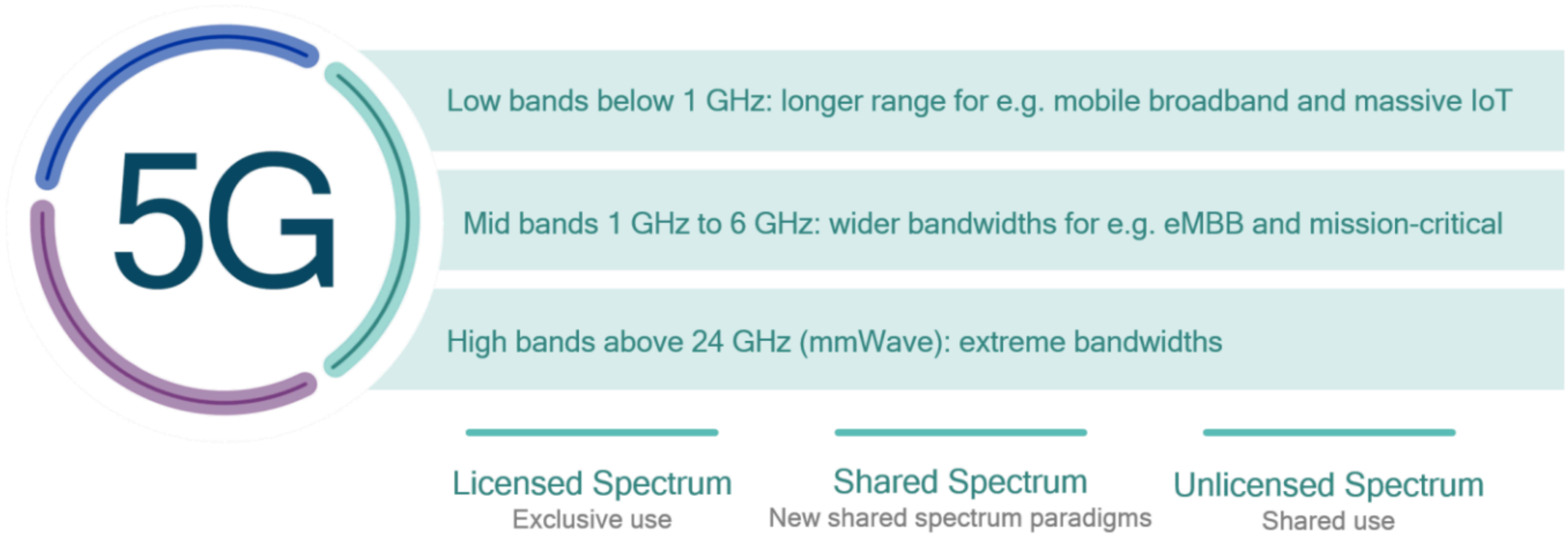
- More than just increased bandwidth compared to 4G
- 5G networks are expected to (eventually) support:
  - **Enhanced Mobile Broadband:** extreme data rates, extreme capacity
  - **Mission-Critical Control:** ultra-low latency, ultra-high availability, extreme mobility
  - **Massive Internet-of-Things:** devices with ultra-low energy, ultra-high density



https://www.qualcomm.com/content/dam/qcomm-martech/dm-assets/documents/whitepaper-making-5g-nr-a-reality.pdf

5G New Radio

- Improvements in how data is multiplexed onto the radio spectrum
- New frequency bands
  - Higher frequency generally means faster data rates, but less coverage and range

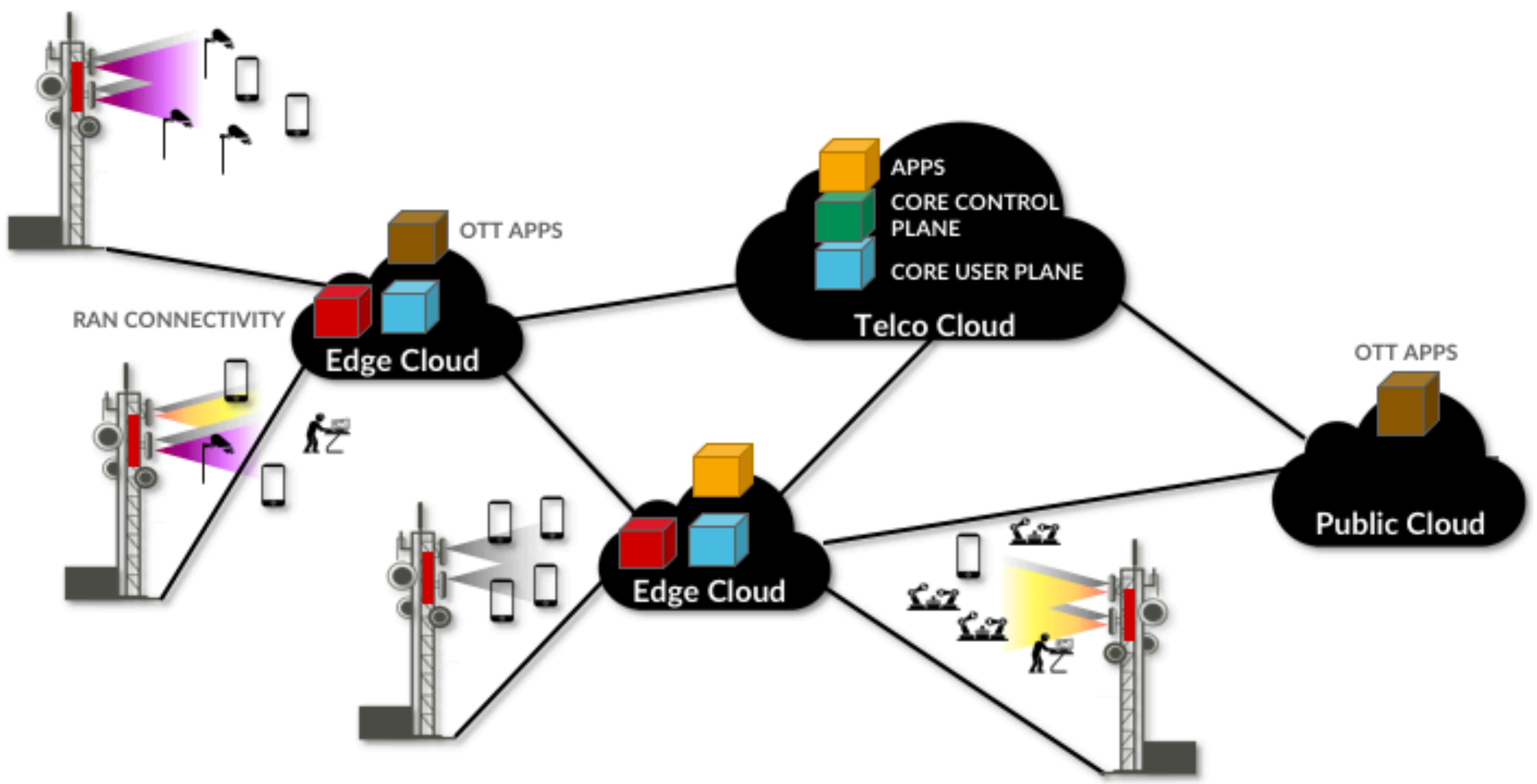


Carriers:	Low-Band 5G Freq:	Mid-Band 5G Freq:	High-Band 5G Freq:
AT&T 5G	850 MHz: Band n5	3.4 GHz: Band n2 3.7 GHz: Band n77	24 GHz: Band n258 28 GHz: Band n261 39 GHz: Band n260
Verizon Wireless 5G	850 MHz: Band n5 1700/2100 MHz: Band n66 1900 MHz: Band n2	3.7 GHz: Band n77	28 GHz: Band n261 39 GHz: Band n260
T-Mobile 5G	600 MHz: Band n71	2.5 GHz: Band n41 3.4 GHz: Band n2 3.7 GHz: Band n77	24 GHz: Band n258 28 GHz: Band n261 39 GHz: Band n260 47 GHz: Band n262 (Pending)
U.S. Cellular 5G	600 MHz: Band n71	3.4 GHz: Band n77 3.7 GHz: Band n77	24 GHz: Band n258 28 GHz: Band n261 39 GHz: Band n260
Cricket Wireless 5G	850 MHz: Band n5	3.7 GHz: Band n77	39 GHz: Band n260
Boost Mobile 5G	N/A	2.5 GHz: Band n41	N/A
Metro by T-Mobile 5G	600 MHz: Band n71	N/A>	28 GHz: Band n261 39 GHz: Band n260

This table is subject to change, as more frequencies are auctioned off for use.

Cloudification of Access

- Cellular networks have historically been extremely opaque
  - proprietary hardware, slow to innovate
- Industry is re-architecting the access network using the principles of SDN
  - Run 5G network functions in the cloud rather than on purpose-built appliances
  - **Win-win:** network operators get faster innovation and CAPEX savings that, cloud providers get low-latency connectivity to a bunch of end-users and their devices



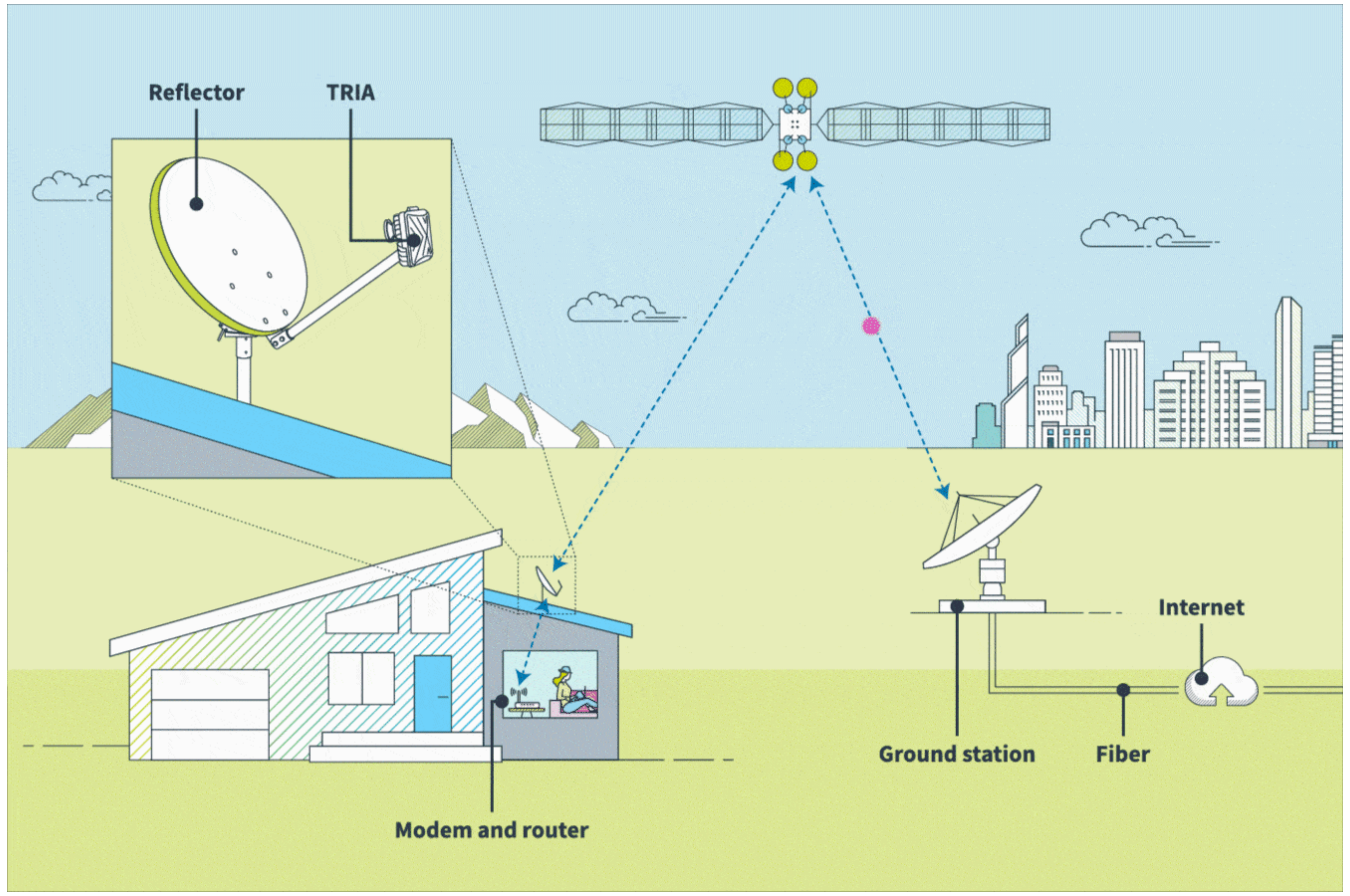
https://5g.systemsapproach.org/cloud.html

Problems with Cell Towers

- Many companies aren't willing to invest in regions without large enough populations
- Cellular frequencies are allocated by country (e.g., FCC)
  - This results in "line-of-sight" as a rough principle
- Even when $$$ exists to build cell towers, they may not be effective in regions with difficult topologies, like hills

Satellite Internet

- Works through a connection of satellites (often privately operated) that are flying in geostationary orbit (35Km above)
- Connections are SLOW, very high latency
- Usually extremely costly to build, deploy, and operate, and thus costly to purchase
  - 25Mbps from Comcast is $30/mo
  - 25Mbps from ViaSat is $150/mo



https://www.viasat.com/about/newsroom/blog/how-it-works-the-technology-behind-satellite-internet/

The Fight for TV Spectrum

- In ~2007, researchers in major technology companies (e.g., Microsoft, Google, Dell, HP, Samsung) started to investigate lower band channels for long range communication for Internet connectivity
- **Why?**

The Fight for TV Spectrum

- In ~2007, researchers in major technology companies (e.g., Microsoft, Google, Dell, HP, Samsung) started to investigate lower band channels for long range communication for Internet connectivity
- **Why?**
    - Can travel greater distances (longer wavelengths @ same power level)
    - Can move throw many obstacles (energy transfer is lower for lower frequency waves)
    - Cheaper to deploy, requires fewer base stations

UNITED STATES FREQUENCY ALLOCATIONS

THE RADIO SPECTRUM

RADIO SERVICES COLOR LEGEND

- AERONAUTICAL MOBILE
- AERONAUTICAL MOBILE SATELLITE
- AERONAUTICAL RADIONAVIGATION
- AMATEUR
- AMATEUR SATELLITE
- BROADCASTING
- BROADCASTING SATELLITE
- EARTH EXPLORATION SATELLITE
- FIXED
- FIXED SATELLITE
- INTER-SATELLITE
- LAND MOBILE
- LAND MOBILE SATELLITE
- MARITIME MOBILE
- MARITIME MOBILE SATELLITE
- MARITIME RADIONAVIGATION
- METEOROLOGICAL
- METEOROLOGICAL SATELLITE
- MOBILE
- MOBILE SATELLITE
- RADIO ASTRONOMY
- RADIODETERMINATION SATELLITE
- RADIOLOCATION
- RADIOLOCATION SATELLITE
- RADIONAVIGATION
- RADIONAVIGATION SATELLITE
- SPACE OPERATION
- SPACE RESEARCH
- STANDARD FREQUENCY AND TIME SIGNAL
- STANDARD FREQUENCY AND TIME SIGNAL SATELLITE

ACTIVITY CODE

- FEDERAL EXCLUSIVE
- FEDERAL/NON-FEDERAL SHARED
- NON-FEDERAL EXCLUSIVE

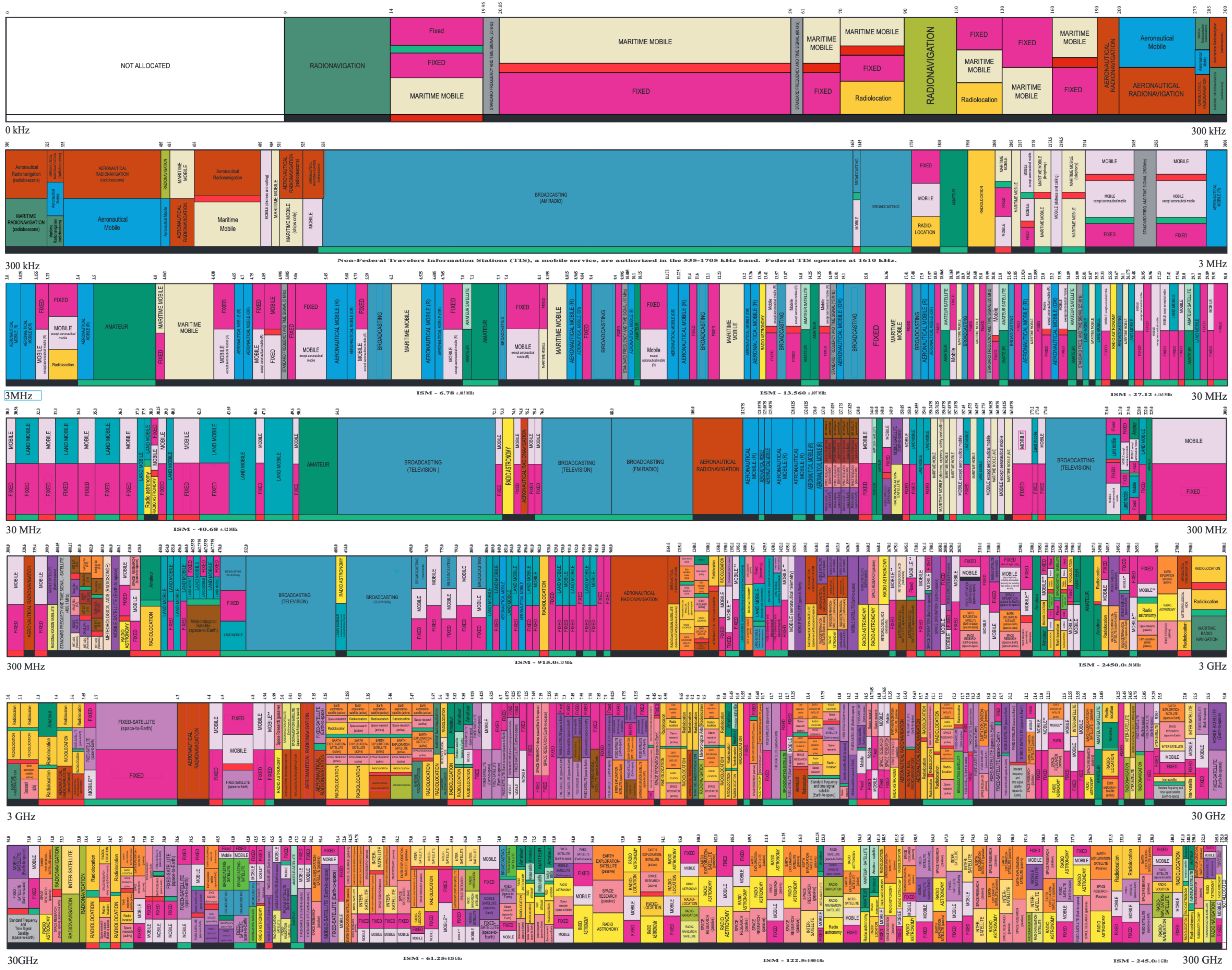
ALLOCATION USAGE DESIGNATION

SERVICE	EXAMPLE	DESCRIPTION
Primary	FIXED	Capital Letters
Secondary	Mobile	1st Capital with lower case letters

This chart is a graphic single-point-in-time portrayal of the Table of Frequency Allocations used by the FCC and NTIA. As such, it may not completely reflect all aspects, i.e. footnotes and recent changes made to the Table of Frequency Allocations. Therefore, for complete information, users should consult the Table to determine the current status of U.S. allocations.

U.S. DEPARTMENT OF COMMERCE
National Telecommunications and Information Administration
Office of Spectrum Management

JANUARY 2016



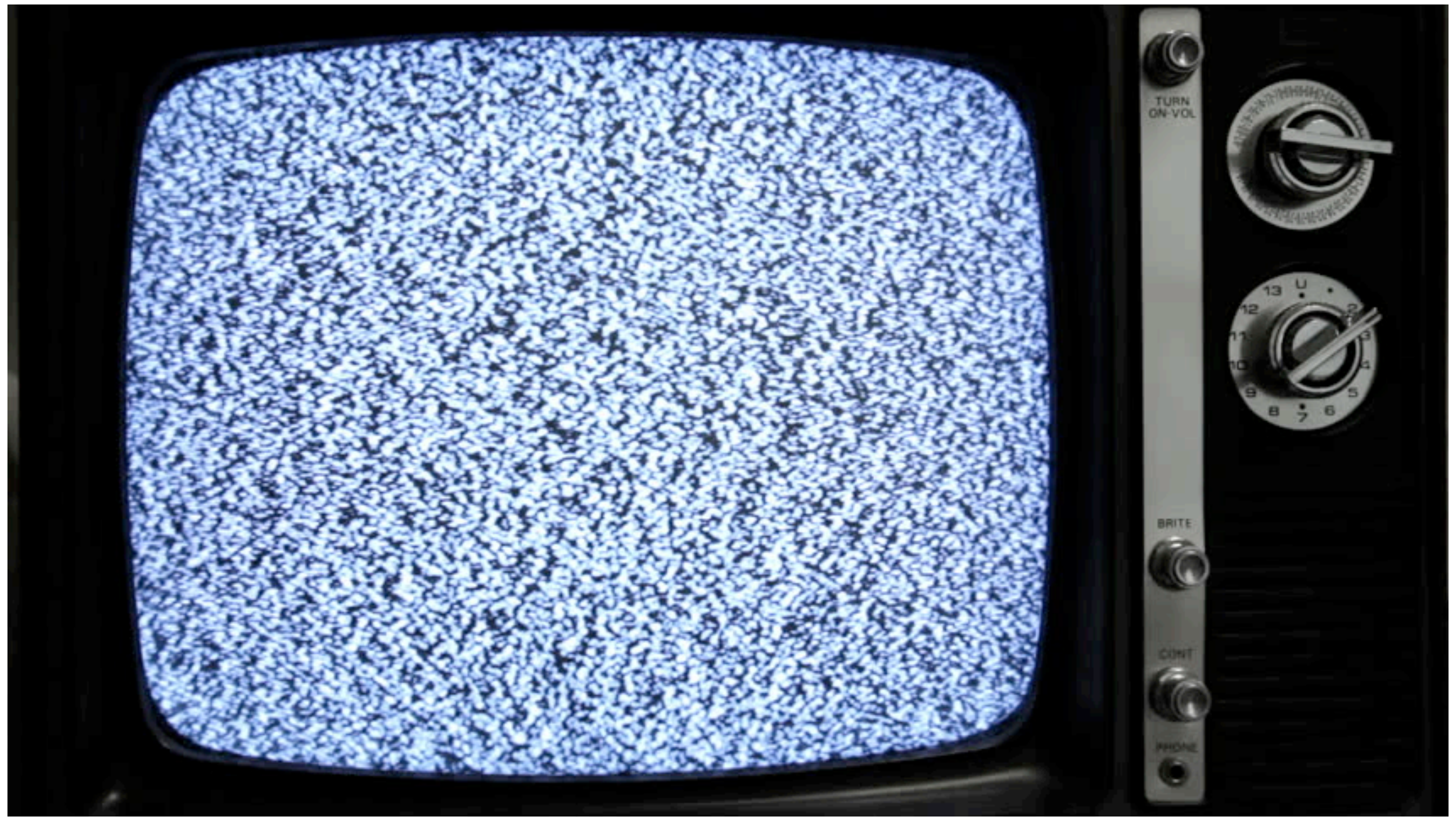
* EXCEPT AERONAUTICAL MOBILE (R)

** EXCEPT AERONAUTICAL MOBILE

PLEASE NOTE: THE SPACING ALLOTTED THE SERVICES IN THE SPECTRUM SEGMENTS SHOWN IS NOT PROPORTIONAL TO THE ACTUAL AMOUNT OF

TV White Spaces

- Core idea: use the unused part of the TV broadcast spectrum to deliver Internet to rural areas *without Line-of-Sight requirements*
- Dynamic spectrum allocation, which happens all behind-the-scenes to the user
  - e.g., if a frequency comes online and is detected, move to a different frequency band
- Receivers can be built much cheaper than (e.g., 100s of dollars)



Case Study: Essex County, NY

The Drama with TV White Spaces

- TV people were very upset about reclaiming some of their space (even unused)
  - Chance for interfering with existing TV broadcasting
  - Giant political headache
- FCC ruling in 2019 says these concerns are baseless, but has hampered innovation and money into these technologies for most of the last decade

NATIONAL ASSOCIATION OF BROADCASTERS

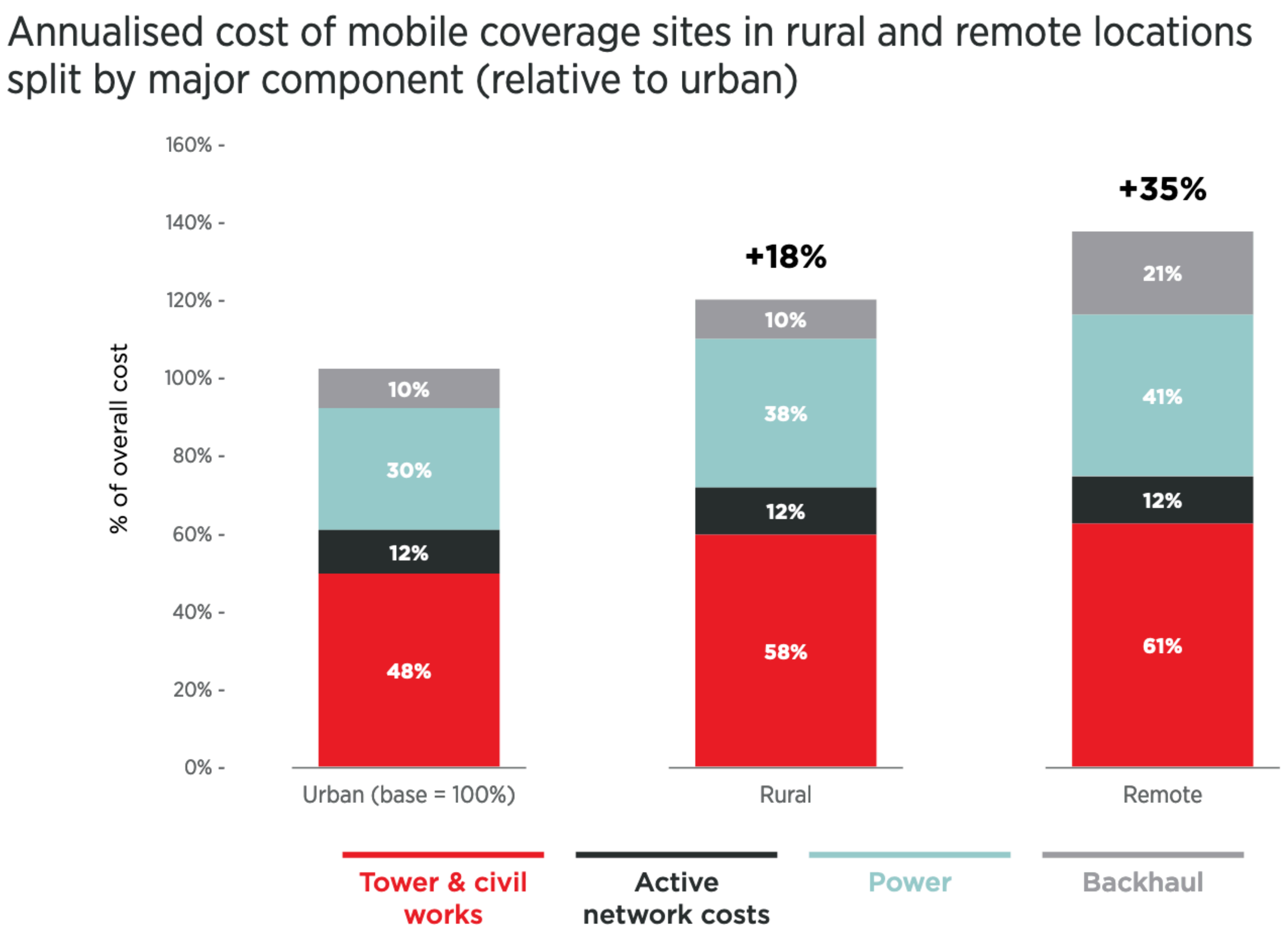
Before the
Federal Communications Commission
Washington, D.C. 20554

In the Matter of	)	
	)	
Amendment of Part 15 of the Commission's Rules for Unlicensed White Space Devices	)	ET Docket No. 16-56 RM-11745
	)	
Amendment of Part 15 of the Commission's Rules for Unlicensed Operations in the Television Bands, Repurposed 600 MHz Band, 600 MHz Guard Bands and Duplex Gap, and Channel 37	)	ET Docket No. 14-165
	)	
Expanding the Economic and Innovation Opportunities of Spectrum Through Incentive Auctions	)	GN Docket No. 12-268

Moonshots

Case Study: RuralStar in Ghana

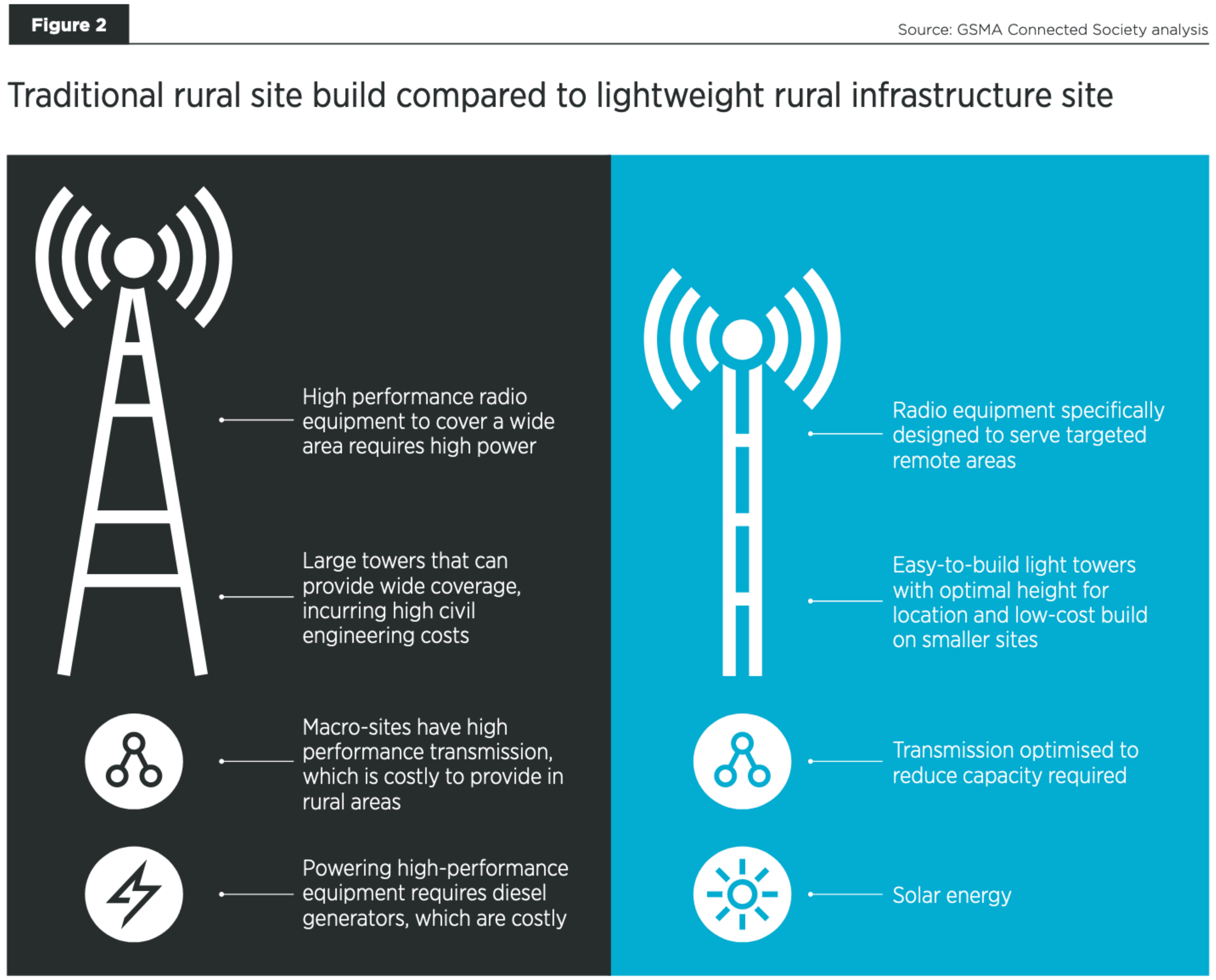
- Mobile heavily invested, but doesn't reach 5M (18%) of people in Ghana
- Huawei developed RuralStar, a lightweight cell tower that can connect to existing mobile backhaul *without* line-of-sight requirements at much lower cost. **How?**
    - Focused on main pain points: tower & civil works, and power consumption



https://www.gsma.com/mobilefordevelopment/wp-content/uploads/2019/02/Huawei_RuralStar_MTN_Ghana_Rural_Innovation_Connectivity_Case_Study_Nov18.pdf

Case Study: RuralStar in Ghana

- Base is made of wood, not metal, so much lighter to transport across the country and easier to set up
- Uses Non-Line-of-Sight (NLOS) relay, essentially low-band communication that can travel farther distances and set up multiple hops
- Leverage solar energy as a main power source, highlights how renewable energy plays a role in costs
- Increased coverage from 83% -> 95% in Ghana



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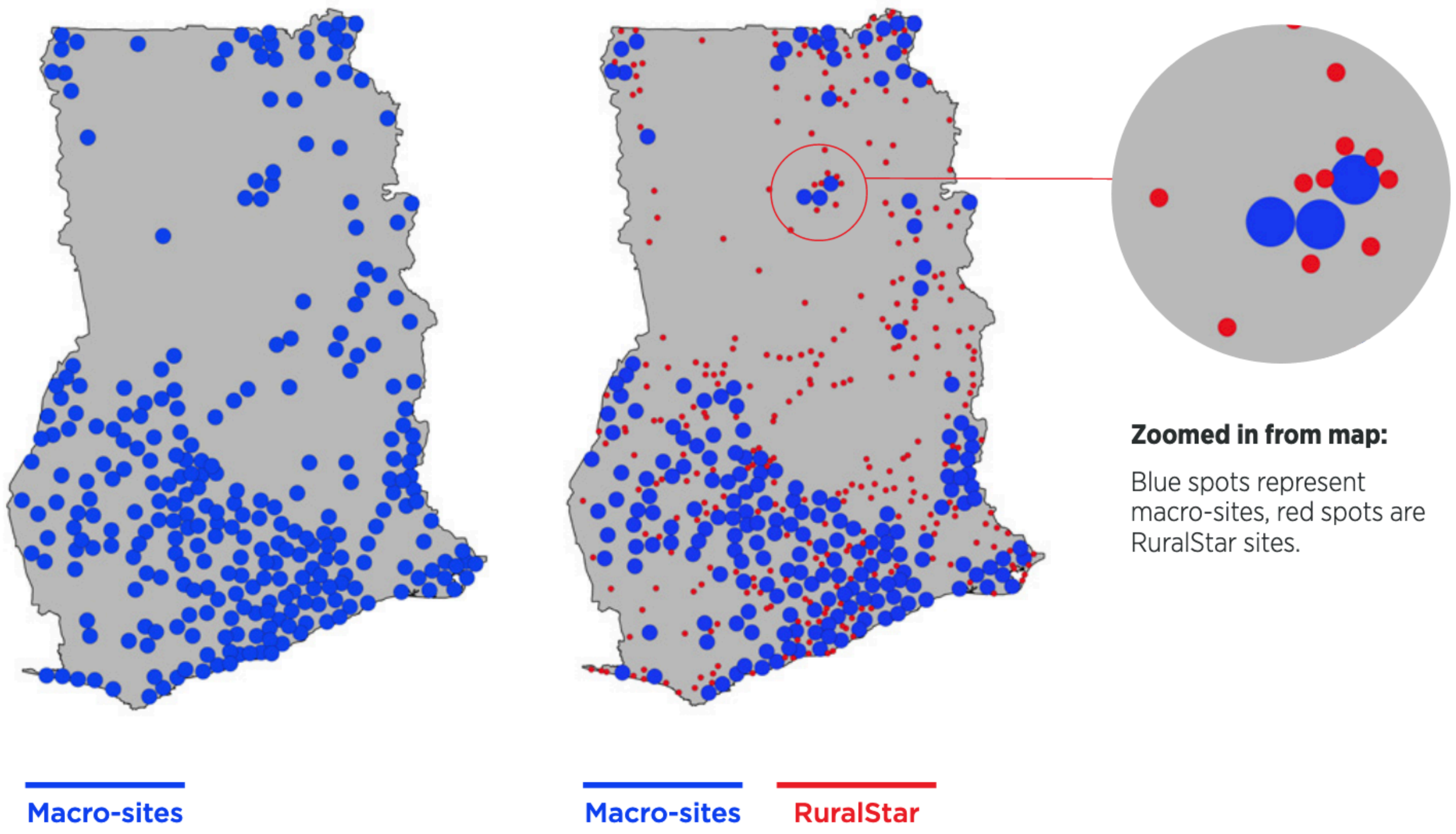

Figure A: *Scenario utilising macro-sites only (no RuralStar)*

Figure B: *Scenario combining macro-sites and RuralStar*

https://www.gsma.com/mobilefordevelopment/wp-content/uploads/2019/02/Huawei_RuralStar_MTN_Ghana_Rural_Innovation_Connectivity_Case_Study_Nov18.pdf

Project Loon

- Core idea: Put receivers on balloons that are flying in the stratosphere (~ 12 miles above the earth) to provide 3G —> LTE Service to rural areas

- Balloon would connect to a base station receiver on the ground that was connected to fiber backhaul

- One balloon could service ~4633 sq mile region, 200x avg. cell tower range

    - First launch was in New Zealand in 2014

- Aimed for 1 Gbps speeds directly to end-users

- **Died in January 2021**

Project Taara

- For terrain with clear line-of-sight, but difficulty laying cable
  - Too much cost to set up, too many natural bodies in the way (water, short hills)
- Shoots a very narrow beam of invisible light (20+ km) to receive 10 – 100 Gbps transmission of data
- Free Space Optical Communications
  - “Fiber without the cables”
- Piloted in India, Africa

Case Study: Taara in Andhra Pradesh

StarLink

- “Satellite internet constellation” that aims to provide satellite Internet access to “most of the earth”
- Idea: Instead of having a small handful of satellites at very high altitude, have many in in Low Earth Orbit (~100 – 1000 miles)
- Wants to deliver 50% of all backhaul traffic, 10% of Internet traffic in cities
  - Up to 100-300 Mbps speeds, targeting 10 Gbps
  - Latency is generally high
- They estimate will cost $10B to simply build the infrastructure
- Surpassed 2.2M users as of December 2023

💬 Final Thoughts

What are the Barriers to Widespread Access?

- Technical barriers
  - How do we build communication systems that can handle non-standard terrain? What other mechanisms of network delivery can we try?
    - Taara is trying light-through-the-air
- Business barriers
  - How can we make infrastructure investment cost effective for businesses?
    - RuralStar developed the poles out of wood instead of metal, decreasing transportation costs and building costs significantly
  - Coverage vs. Access
- Political barriers
  - Advocating for policies (local + state level!) that promote Internet access in our local communities