NETWORK TECHNOLOGY REVIEW

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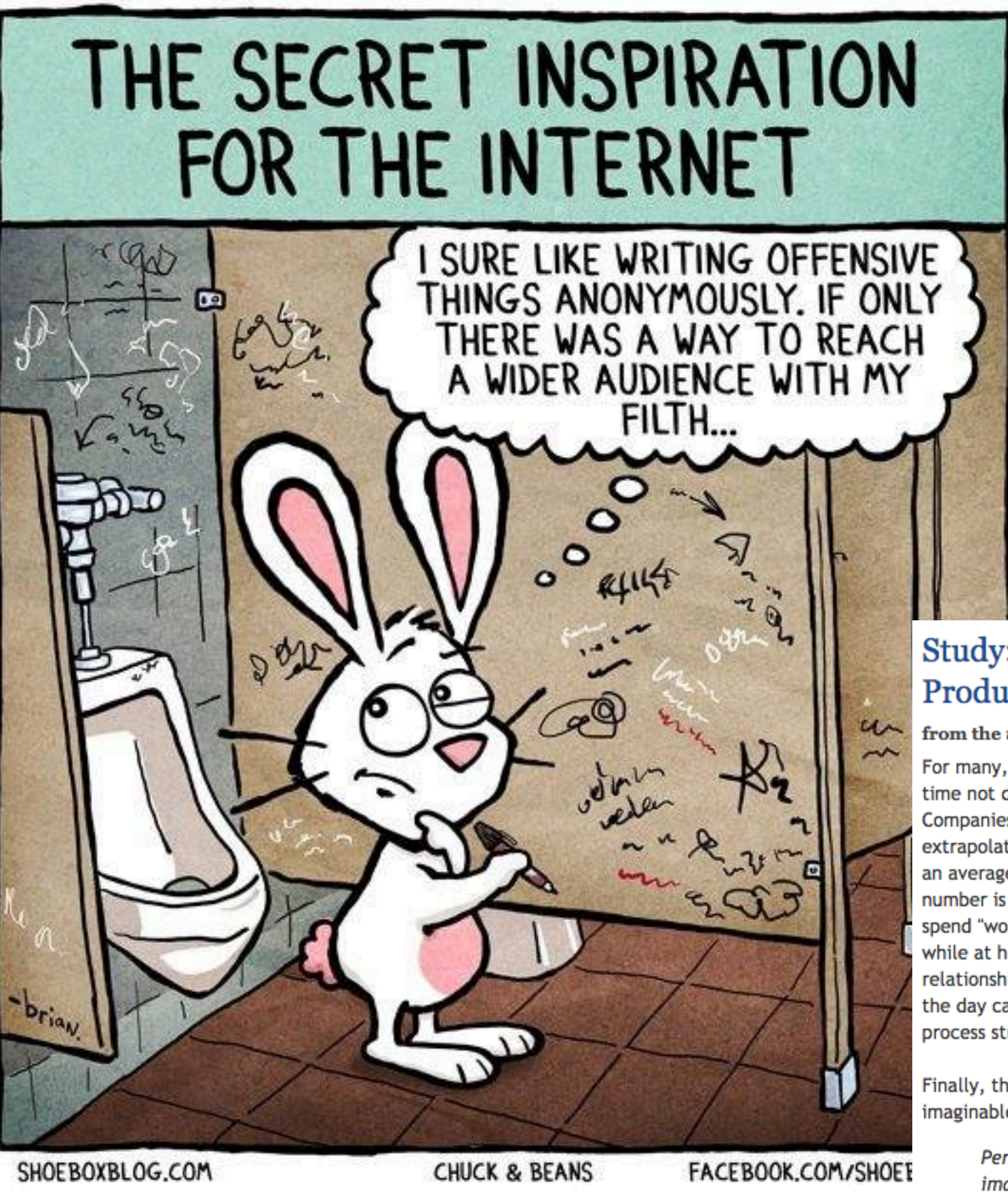
Fall 2017

material drawn from various online sources, reports & author



Study: Viewing Cat Videos At Work Can Make You More Productive

from the *who-comes-up-with-these?* dept

For many, many years, we've pointed out just how silly all those studies are that claim that any time not directly spent working -- such as on "personal surfing" -- was somehow lost productivity. Companies who sold filters to businesses often would put out these exaggerated "studies" that extrapolated the amount of time that people spend doing "non-work" things at work, multiply it by an average employee's hourly salary, and claim that much money was "lost productivity." That number is obviously bogus. First of all, it doesn't take into account the amount of time people spend "working" when they're not at the office either (many of us check our emails, for example, while at home). It also ignores the much more important point that productivity is not an exact relationship to time worked in many jobs. In fact, being non-stop focused on work every minute of the day can certainly be a *drag* on productivity, because it doesn't give your brain time off to process stuff, and doesn't give you a good way to focus in on what you need to do.

Finally, there's a study to help point this out... and it does so in the most internet-awesome way imaginable. The study has found that staring at cute images can actually *help* productivity:

> *Performance indexed by the number of successful trials increased after viewing cute images (puppies and kittens; M ± SE = 43.9±10.3% improvement) more than after viewing images that were less cute (dogs and cats; 11.9±5.5% improvement). In the*

DIVIDING THE PROBLEM

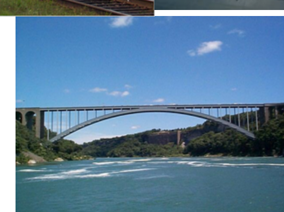
The great infrastructure

- Technical structures that support a society → "civil infrastructure"
  - Large
  - Constructed over generations
  - Not often replaced as a whole system
  - Continual refurbishment of components
  - Interdependent components with well-defined interfaces
  - High initial cost

water

energy

transportation



communication

The Internet as core civil infrastructure

For Immediate Release February 12, 2013

Executive Order -- Improving Critical Infrastructure Cybersecurity

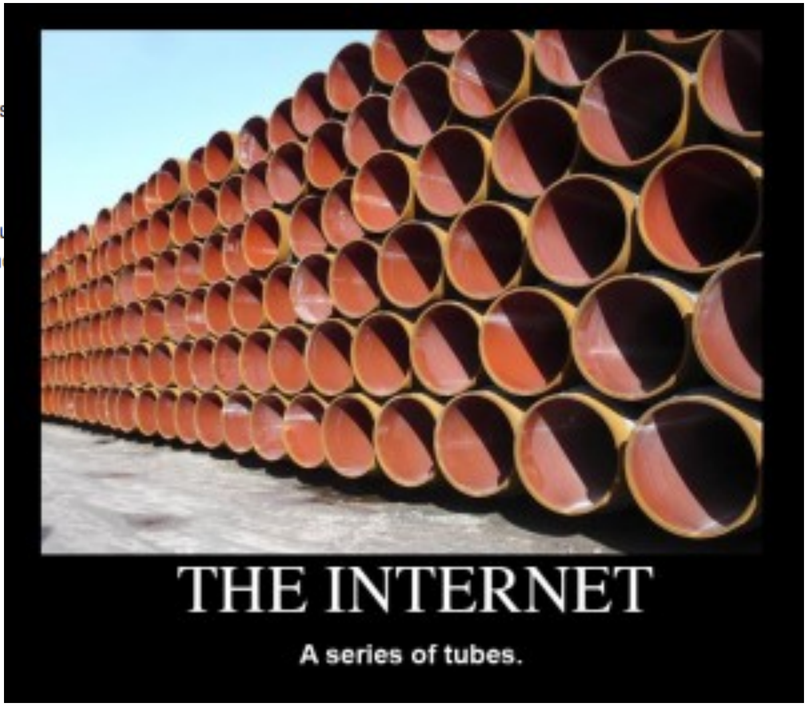
EXECUTIVE ORDER

\- - - - - - -

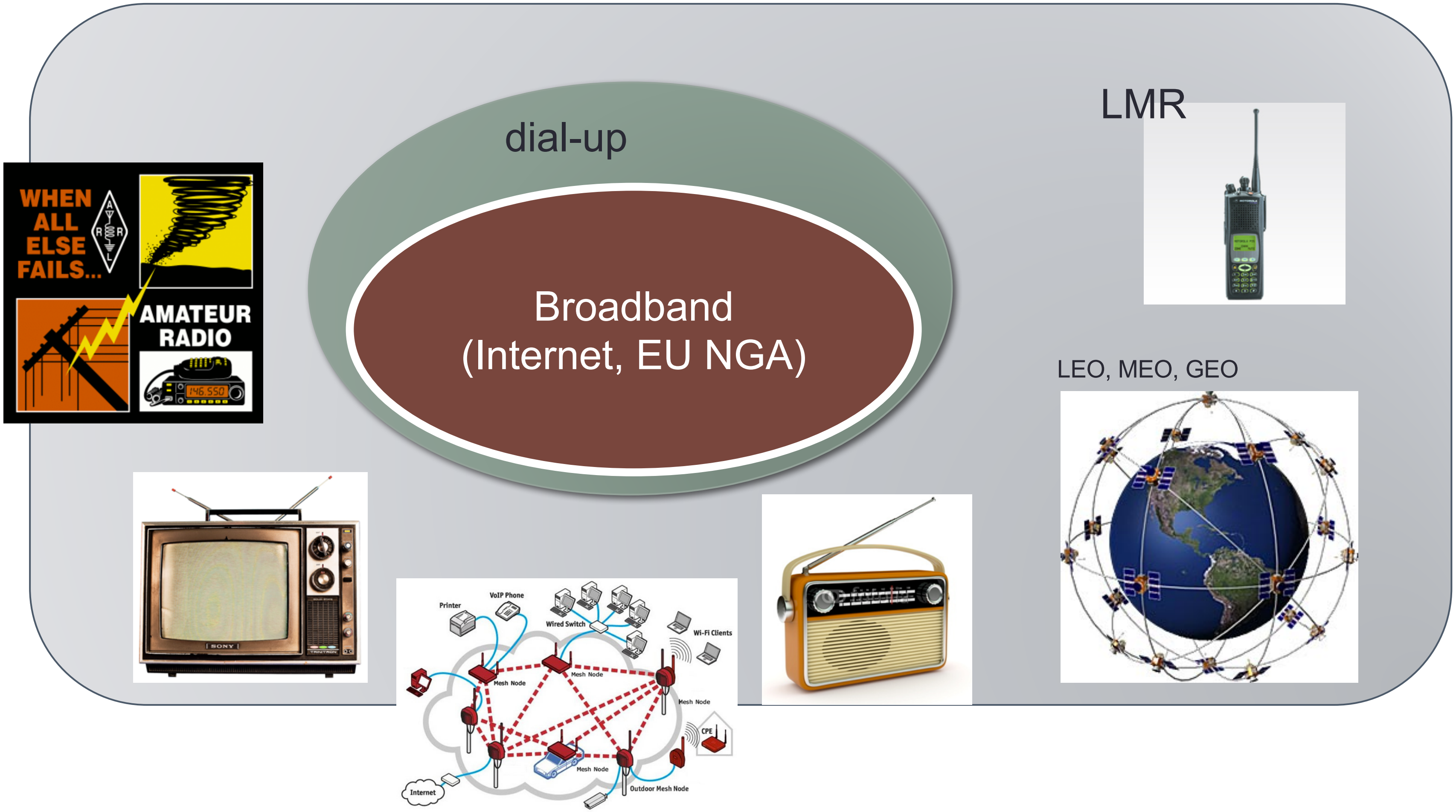
IMPROVING CRITICAL INFRASTRUCTURE CYBERSECURITY

By the authority vested in me as President by the Constitution and the laws of the United States of America, it is hereby ordered as follows:

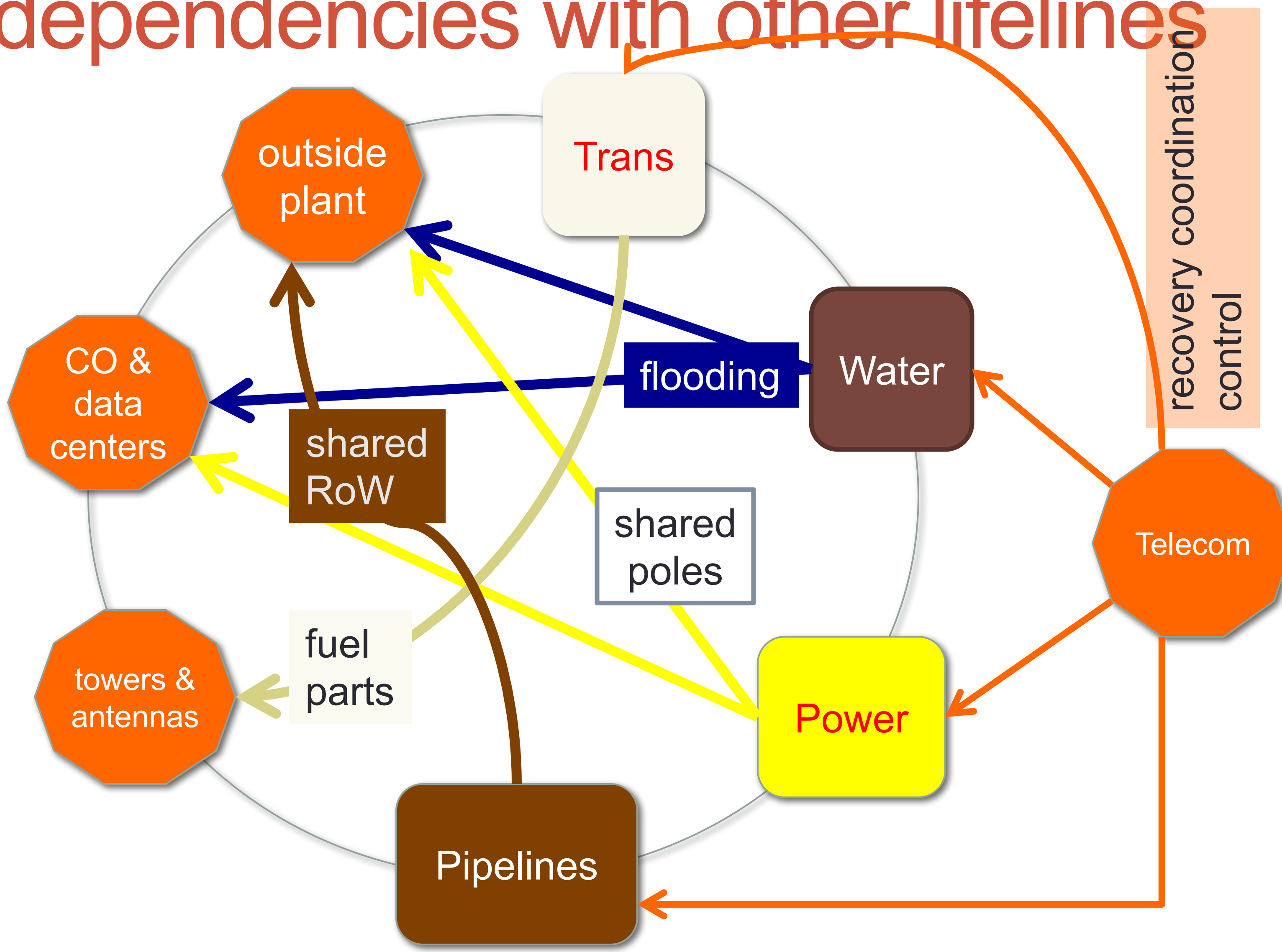
Section 1. Policy. Repeated cyber intrusions into critical infrastructure demonstrate the need for improved cybersecurity. The cyber threat to critical infrastructure continues to grow and represents one of the most seriou national security challenges we must confront. The national and economic security of the United States depen on the reliable functioning of the Nation's critical infrastructure in the face of such threats. It is the policy of the



Broadband, Internet, communications



Interdependencies with other lifelines



Who runs communication systems and networks?

incumbent local exchange carriers ("ILEC")

at&t verizon windstream.

competitive local exchange carriers ("CLEC")

rural local exchange carriers ("RLEC")

~1,000

CABLEVISION

cable companies ("MVPD")

~12

COMCAST

T · · Mobile ·

Sprint

cellular providers (3-4)

at&t verizon

Level(3) COMMUNICATIONS

wholesaler providers ("carriers' carrier")

zayo GROUP cogent

DIRECTV dish NETWORK

satellite providers

HUGHES Connect to the future.

~2

communities ("muni networks")

radio & TV stations (1,784 TV, 15,470 radio)

private land mobile radio (public safety, transit, taxis, …)

with ~90% marketshare

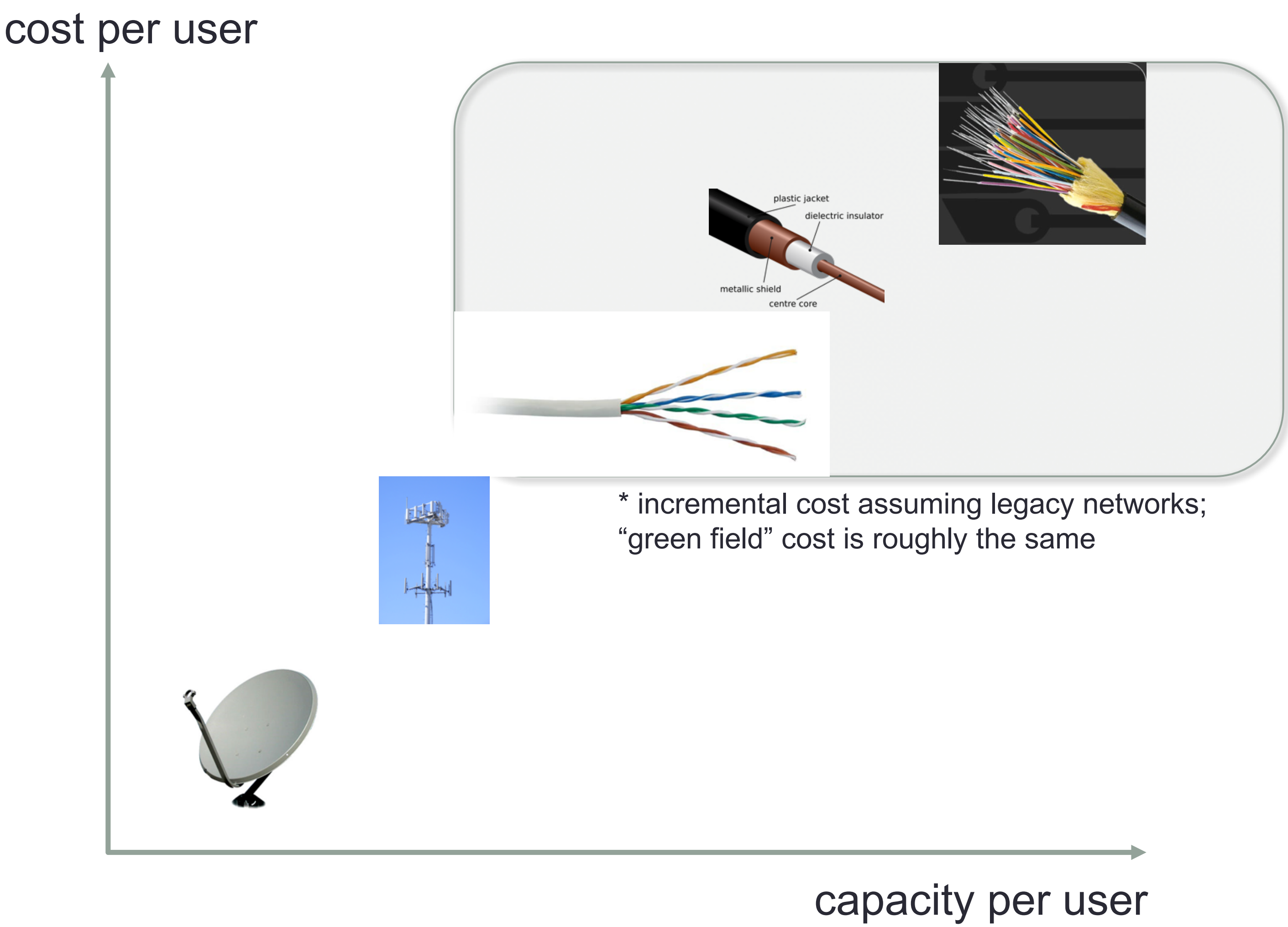
What do communications networks do that's different?

- Any-to-any: multiparty, coordination & cooperation, conflict
  - less of a concern in (say) civil engineering
- Economics: network effect, scale effects
- Challenges:
  - geographic distribution
  - long-lived
  - different industries participating
  - remote attacks through infrastructure itself

What problems do networks solve?

- Diversity in technologies
  - wired vs. terrestrial wireless vs. satellite
  - trade-off capacity vs. cost vs. distance
- Variation in load
  - intermittent demand → shared networks
  - cannot design capacity for top 5 minutes of load
- “Noise”
  - electric noise
  - radio interference
- Human adversaries
  - denial-of-service attacks
  - information theft
  - impersonation

Network trade-offs



A bit of (US) history

- 1895-1901: G. Marconi demonstrates wireless communications
- 1912: *Titanic*
- Radio Act of 1912
  - all radio stations licensed
  - monitor distress channel (500 kHz)
- Radio Act of 1927
  - deal with AM ("medium wave") chaos → licensing "in the public interest"

Communications as a *regulated industry*

- free-market economies, subject to government regulation
  - "why" (and objections) later
- telephony: federally regulated since 1910
- broadcasting: 1927
- telecommunications: 1934
  - but dates back to Interstate Commerce Act of 1887 (railroads)
  - cousins: railroads, electricity, air service, …
  - specialized administrative agency for sector-specific regulation
    - vs. general regulation (environmental, safety, employment, contracts, consumer protection, …)

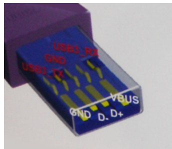
Interfaces: Energy

110/220V

NEMA 1-15R

~1915 (2 prong)

- Lots of other (niche) interfaces
- Replaced in a few applications



1901

http://www.centennialbulb.org/cam.htm

Other long-lived interfaces

1878

Cigarette lighter
(1956)

1993

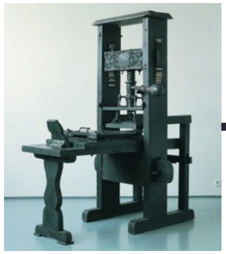
fuel nozzle

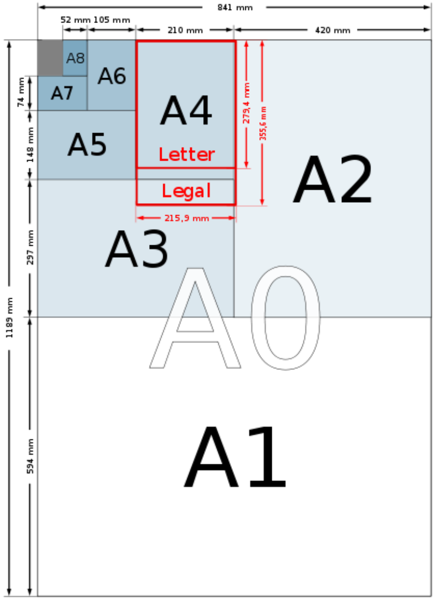
1982

1992

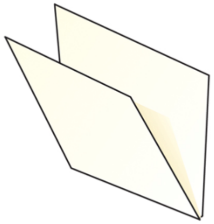
SQL
1974

Interfaces: Paper-based information





1798, 1922 (DIN)



Interfaces: Transportation

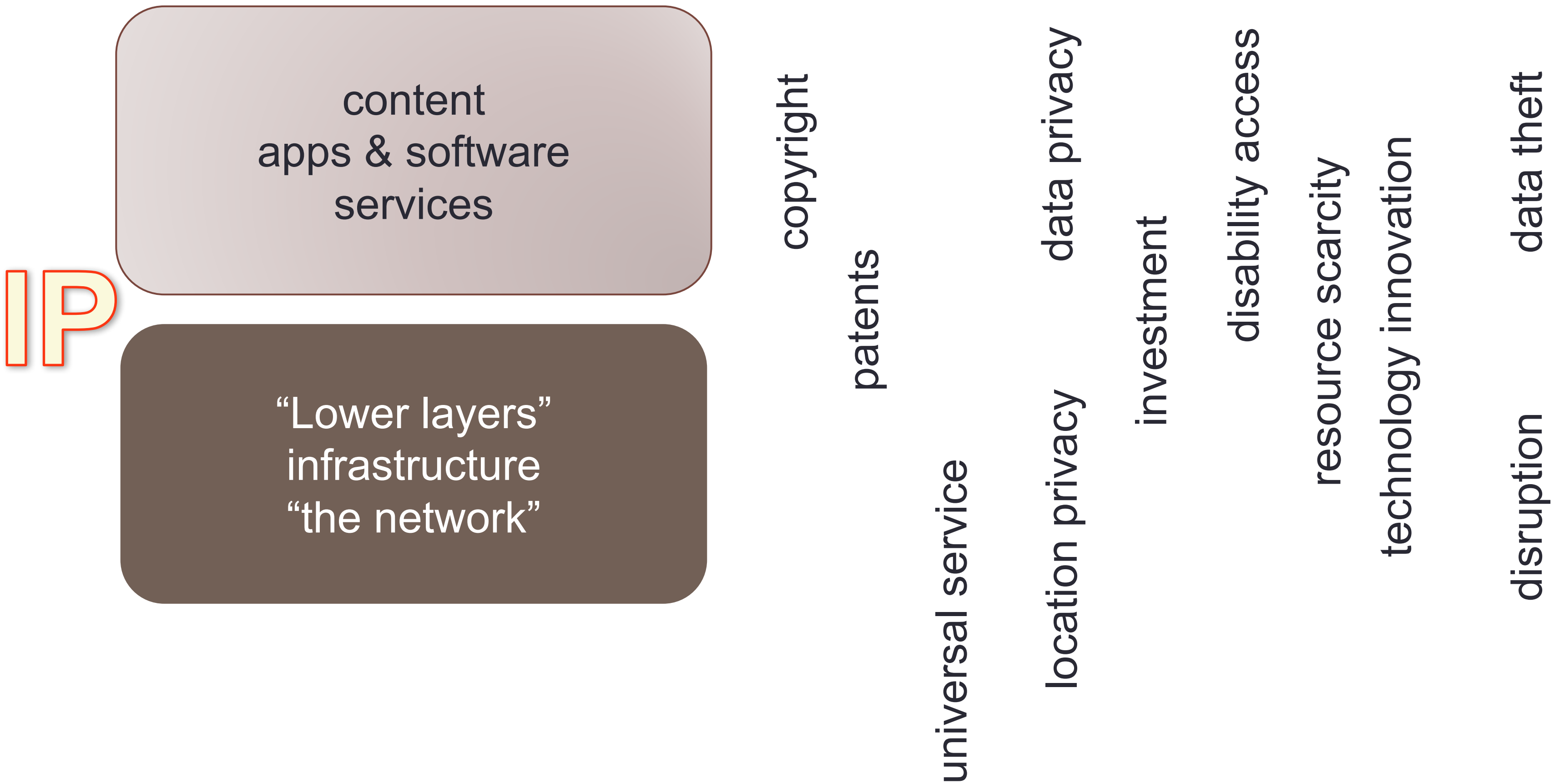
1435 mm

About 60% of world railroad mileage

1830 (Stephenson)
1846 UK Gauge Act

12'

The two-layer model



Why layering?

- Perform functions once
  - upper layers rely on lower layers
  - in theory (see: “end-to-end principle”)
- Common in engineering and society
  - postal system, operating systems & other APIs, buildings, …
  - but not always formal or deep
  - model of a (legal) contract
- Change implementation without affecting relying parties
  - minimize communications, “information hiding”, “isolation”
  - “black box”
- Topological and administrative scoping
  - single *physical* connection technology
  - single vs. multiple *administrative* domains

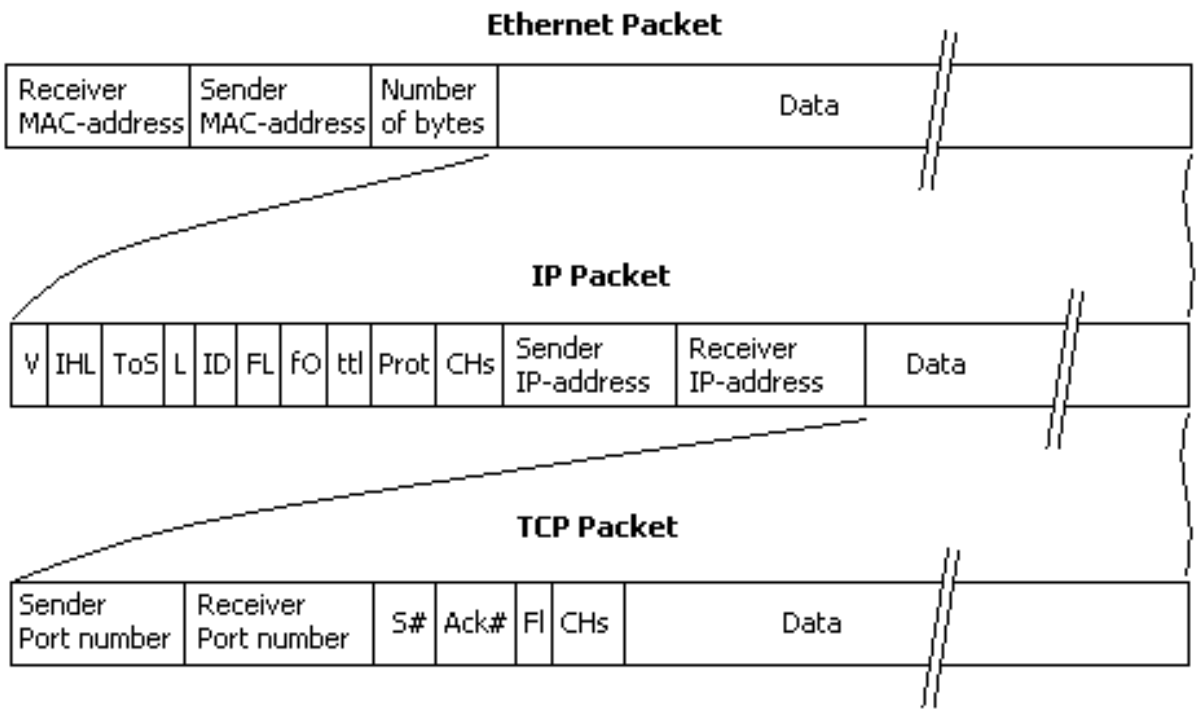
OSI model background

- Introduced in 1978 and revised in 1984
  - first formal attempt to codify engineering practice
  - slice big problem into manageable areas of concern
- Formulates the communication process into structured layers
- There are seven layers in the model → the 7-Layer model

The function of a layer

- Each layer deals with a subset of aspects of networking
  - e.g., Layer 1 deals with the communication media
- Each layer communicates with the adjacent layers
  - In both directions
  - Example: Network layer communicates with:
    - transport layer
    - data link layer
- Each layer formats the data packet
  - Example: adds or deletes addresses

Layers → wrapping



applies to other “networks” – FireWire, USB, SCSI, SS7 (telecom), …

The (theoretical) layered approach to communication

"OSI model"

7. Application
message format, human-machine interface

6. Presentation
serialization, encryption, compression

5. Session
authentication, permissions, restoration, state

4. Transport
end-to-end reliability, flow & congestion control

3. Network
network addressing, end-to-end routing

2. Data Link
link flow control, error detection, framing

1. Physical
analog-digital (bit stream)

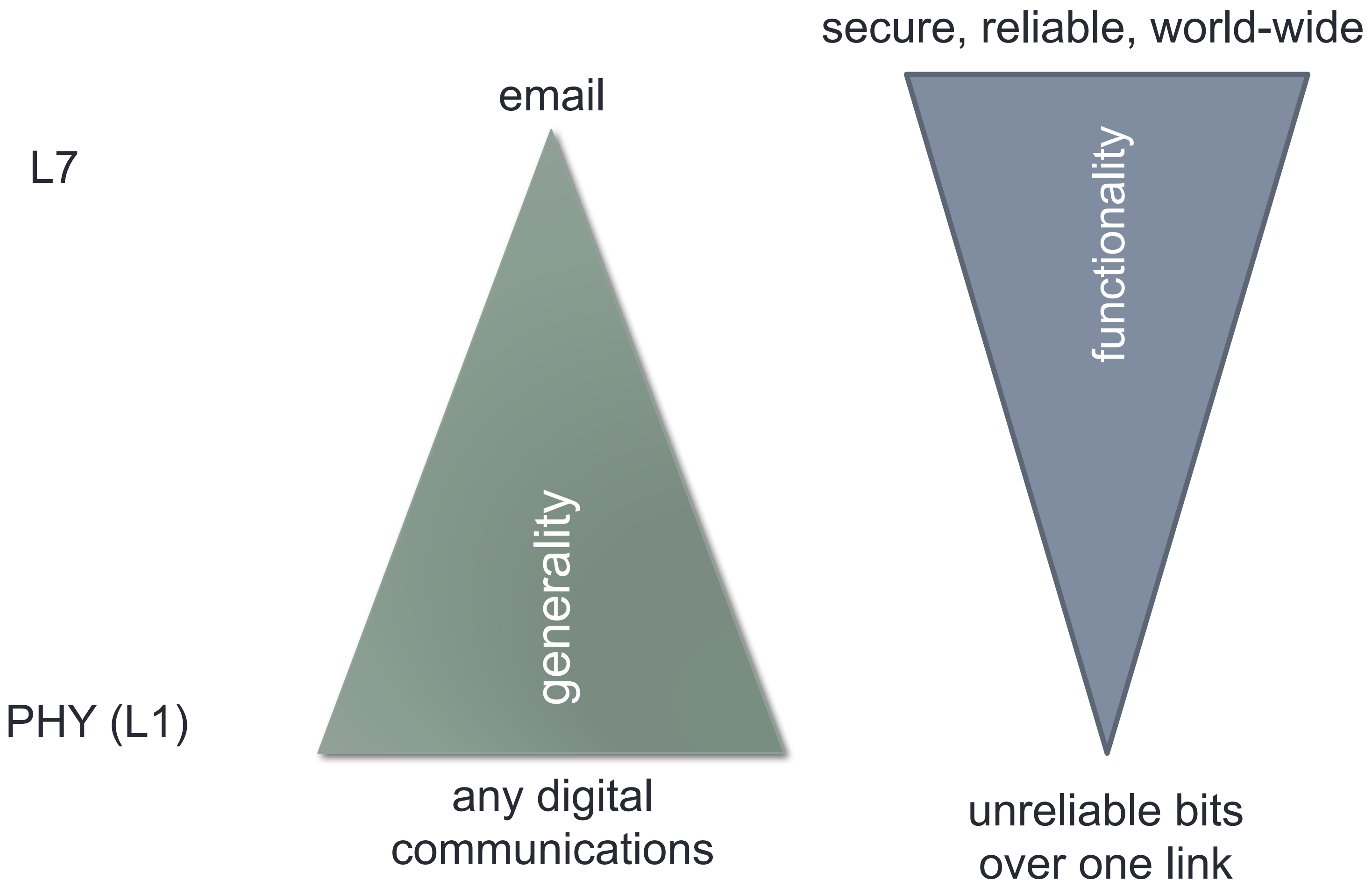
structured content

messages byte stream

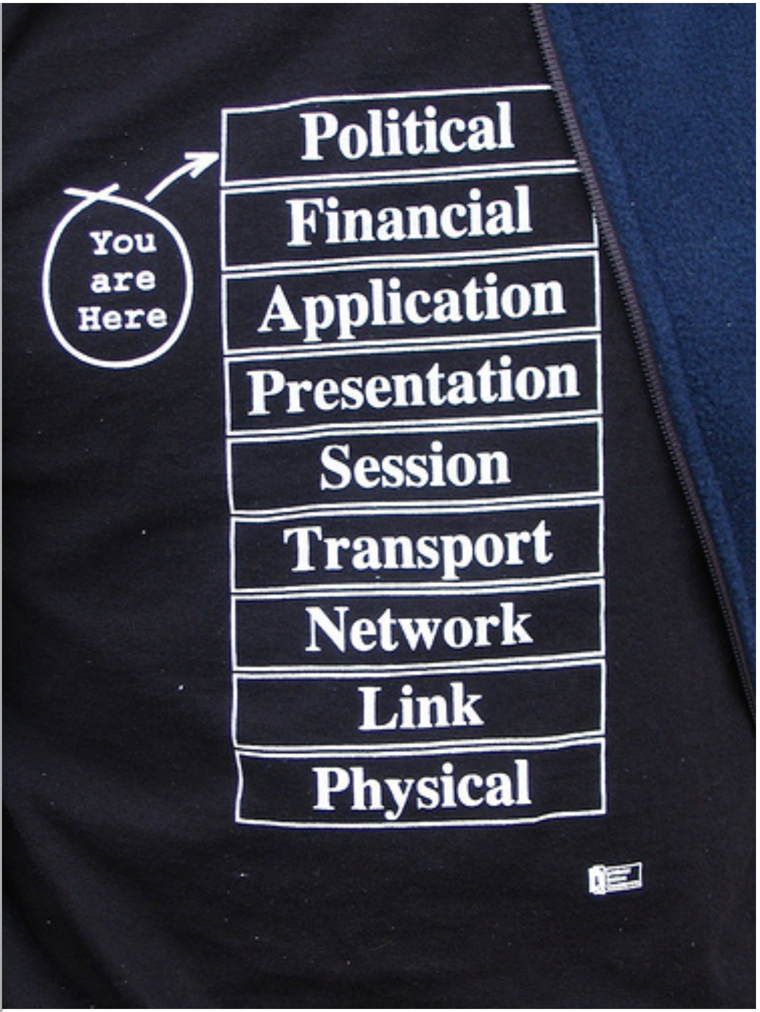
packets ("frames")

bit stream

Layering

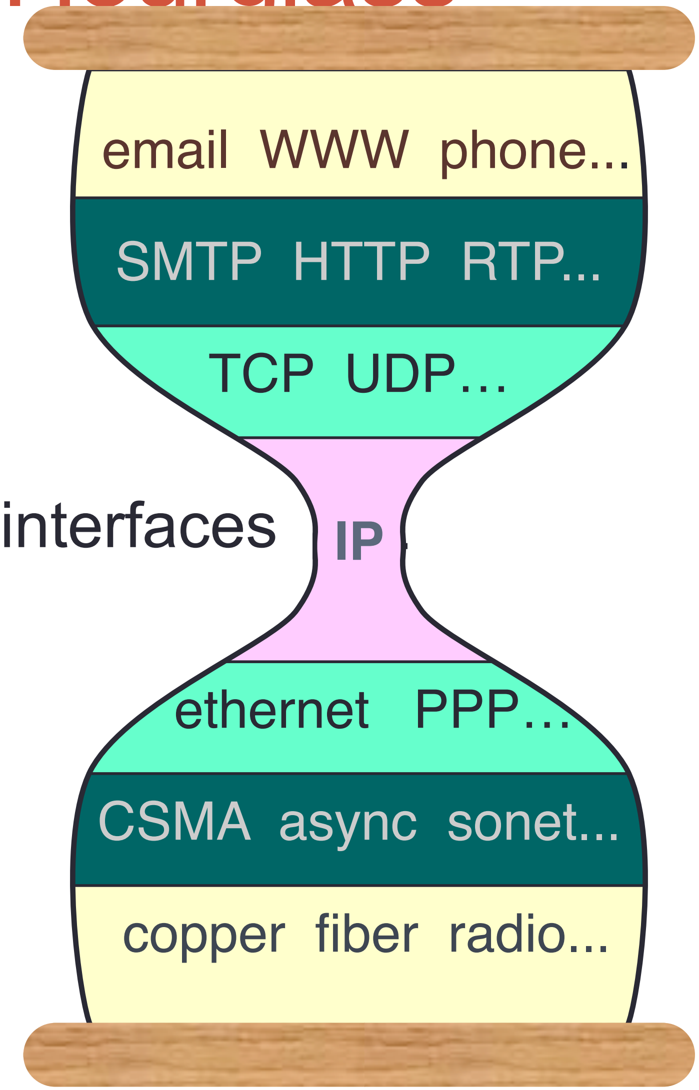

secure, reliable, world-wide
email
L7
functionality
generality
PHY (L1)
any digital
communications
unreliable bits
over one link

The real model



The Internet Protocol Hourglass

small number of long-term stable interfaces



S. Deering

Why four (core) layers?

Layer	Colloquial name	Function
1	PHY	photons & electrons → **bits**
2	MAC	bits → **packets** on one technology
3	L3	packets **end-to-end**, on heterogeneous technologies, to **interface**
4	L4	unreliable → **reliable** host/interface → **application**
(5)	Presentation, data	application data structure encoding
7	Application	Application behavior (email, web)

Internet layer functions

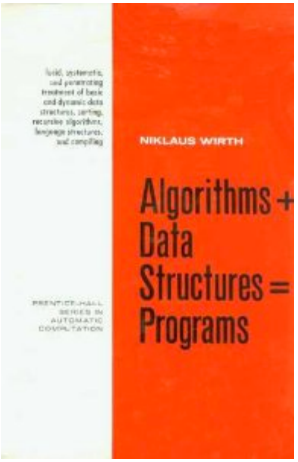
Layer	Key protocols	Control protocol	Transmission technologies	Administrative domains	Main function	Addresses
PHY	Ethernet, 4G		single, but may be diverse (fiber, copper)	1	analog-to-digital	none
MAC	Ethernet	3GPP	same	1	framing	MAC address
network	IPv4, IPv6	DHCP, OSPF, BGP	agnostic	many	end-to-end delivery	IP addresses
transport	UDP, TCP	built-in	agnostic	2 (ends)	reliability, congestion control	ports
application	HTTP, RTP	SIP	agnostic (except for properties)	2 (ends)	framing, description, sessions	URLs, email addresses

Node functions

- Error detection
  - bit errors are detected with high probability
- Error correction
  - bit errors are repaired via redundancy (“forward error correction”)
- ARQ
  - lost or corrupted packets are re-transmitted
- Flow control
  - prevent fast sender overwhelming slow receiver
- Congestion control
  - prevent fast sender overwhelming slower network

"Algorithms + Data Structures = Programs"

Protocols + serialization = networking



1976

human protocols:

- "what's the time?"
- "I have a question"
- air traffic control
- introductions

… specific messages sent

… specific actions taken when message received, or other events

network protocols:

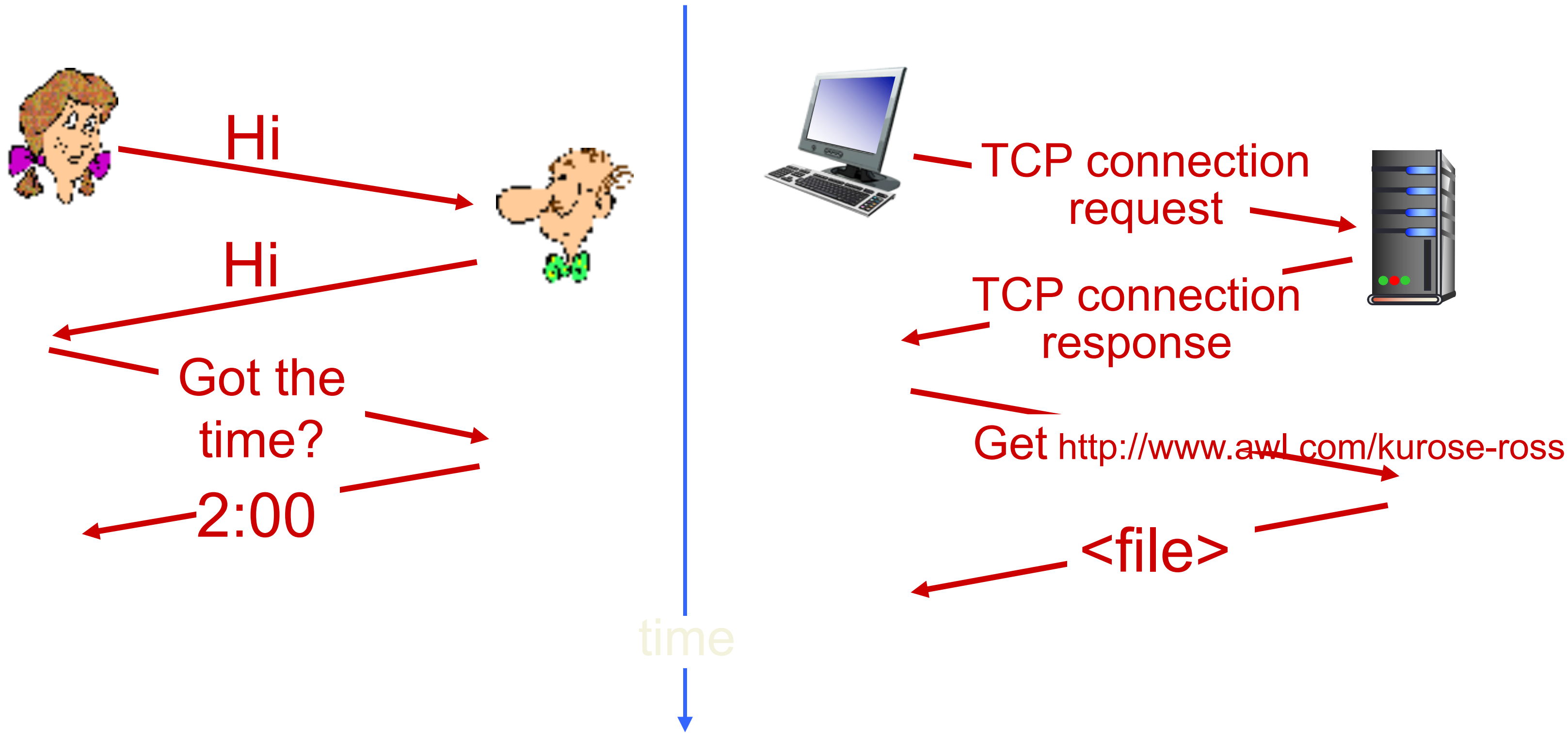
- machines rather than humans
- all communication activity in Internet governed by protocols

Protocols

- Protocols define format & order of messages sent and received among network entities
  - and actions taken on message transmission or receipt
- Often includes notions of time
  - what happens if there is no response?
- Similar to Application Programming Interfaces (APIs)
  - size_t fwrite (const void * ptr, size_t size, size_t count, FILE * stream);
  - differences?
- Can also consider a “contract”
  - “if I provide you X, you will provide Y”

What's a protocol?

a human protocol and a computer network protocol:



Q: other human protocols?

Serialization: turning data structures into bytes

- Internal data structures (data bases, arrays, lists, dictionaries, …) need to be transported across network or stored in a file
  - efficiently, without too much empty space
  - without memory references
  - without depending on computer architecture of sender
- Networks and files are sequences of bytes ("byte stream")
- → convert internal structure into nested text elements
  - references ("pointers") by name or identifier, not memory location

Serialization: ASN.1

```
FooProtocol DEFINITIONS ::= BEGIN

    FooQuestion ::= SEQUENCE {
        trackingNumber INTEGER,
        question       IA5String
    }

    FooAnswer ::= SEQUENCE {
        questionNumber INTEGER,
        answer         BOOLEAN
    }

END
```

serialization = convert data structure into (linear) byte stream

like C, without pointers…

```
myQuestion FooQuestion ::= {
    trackingNumber     5,
    question           "Anybody there?"
}
```

30 13 02 01 05 16 0e 41 6e 79 62 6f 64 79 20 74 68 65 72 65 3f

Serialization: RFC 822

```
Delivered-To: hgs10@lionmailmx.cc.columbia.edu
Received: by 10.140.158.132 with SMTP id e126csp131562qhe;
        Thu, 28 Aug 2014 14:01:48 -0700 (PDT)
Return-Path: etickets@amtrak.com
Return-Path: etickets@amtrak.com
Received: from unknown (HELO etvswas01p) ([10.14.128.202])
   by phlsmtprelay01.amtrak.com with ESMTP; 28 Aug 2014 16:55:42 -0400
Date: Thu, 28 Aug 2014 17:01:30 -0400 (EDT)
From: etickets@amtrak.com
To: HGS@cs.columbia.edu, HENNING.SCHULZRINNE@FCC.GOV
Message-ID: <633700356.JavaMail.TDDServerProd@amtrak.com>
Subject: Amtrak: eTicket and Receipt for Your 09/10/2014 Trip
MIME-Version: 1.0
Content-Type: multipart/mixed;
       boundary="----=_Part.1409259690306”
MIME-Version: 1.0
Content-Type: multipart/mixed;
```

Serialization: XML


```
<note>
  <id>1</id>
  <name>A green door</name>
  <price>12.50</price>
  <tags>
    <tag>home</tag>
    <tag>green</tag>
  </tags>
</note>
```

Serialization: JSON

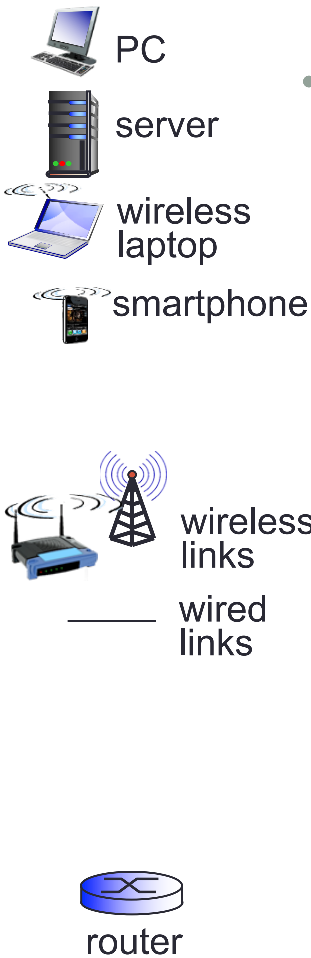
```json
{
  "id": 1,
  "name": "A green door",
  "price": 12.50,
  "tags": ["home", "green"]
}
```

The problems with layering

- Doesn't capture whole story
  - control protocols
- Information hiding
  - inefficiency: more than needed
- Information and implementation leakage
- Ossification
- Duplication
  - "If you want it done right, you have to do it yourself"

INTERNET ARCHITECTURE

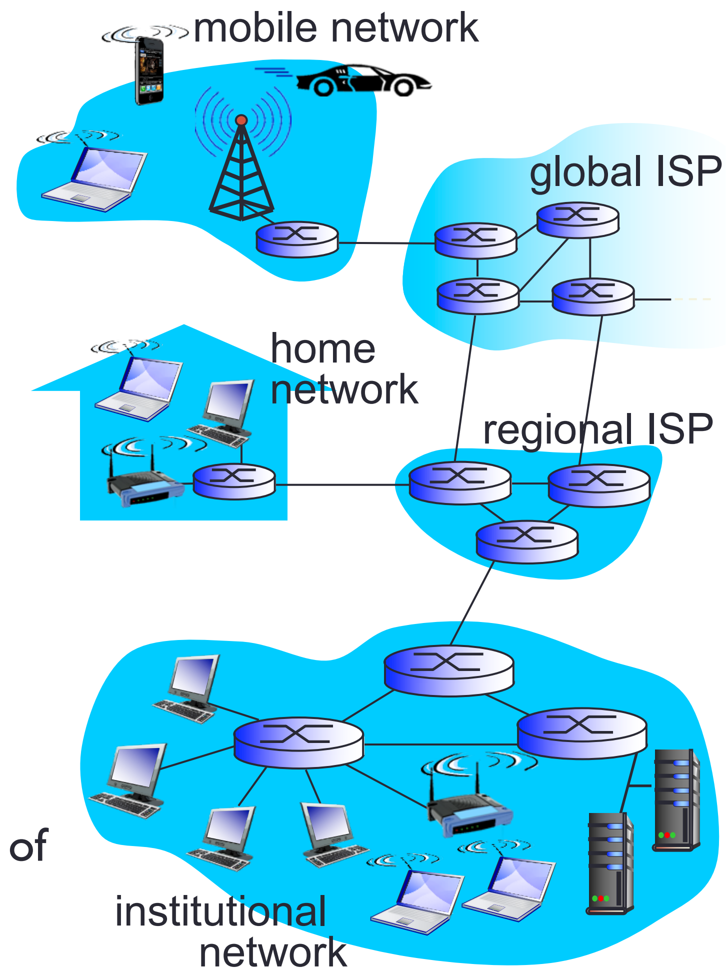
What's the Internet: "nuts and bolts" view



- millions of connected computing devices: *hosts*
  - running *network apps*

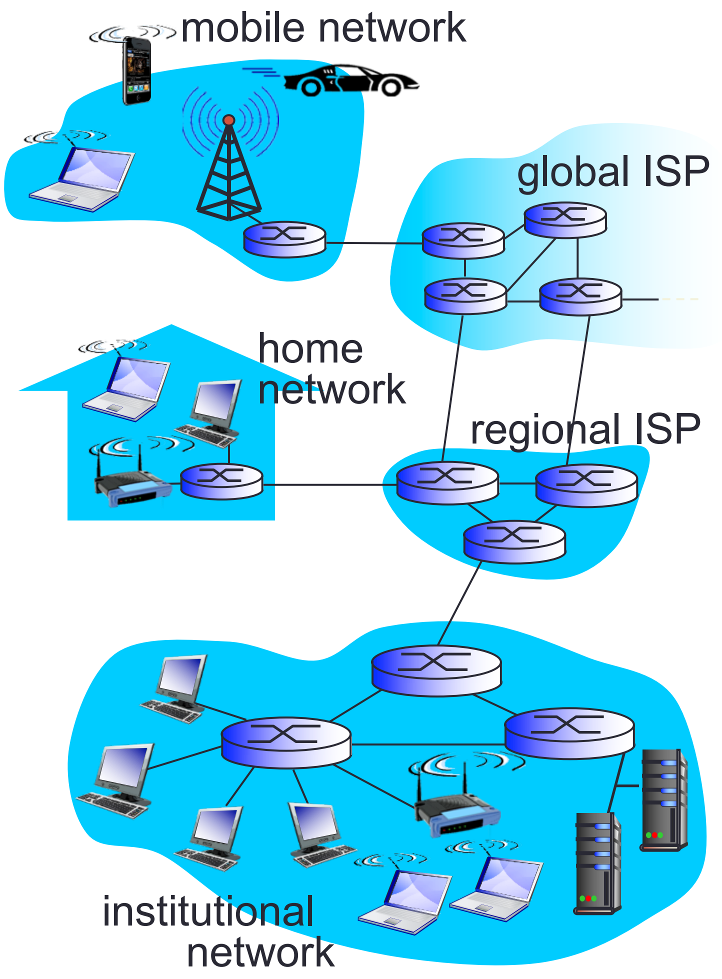
❖ *communication links*
  - fiber, copper, radio, satellite
  - transmission rate: *bandwidth*

❖ *routers:* forward packets (chunks of data)

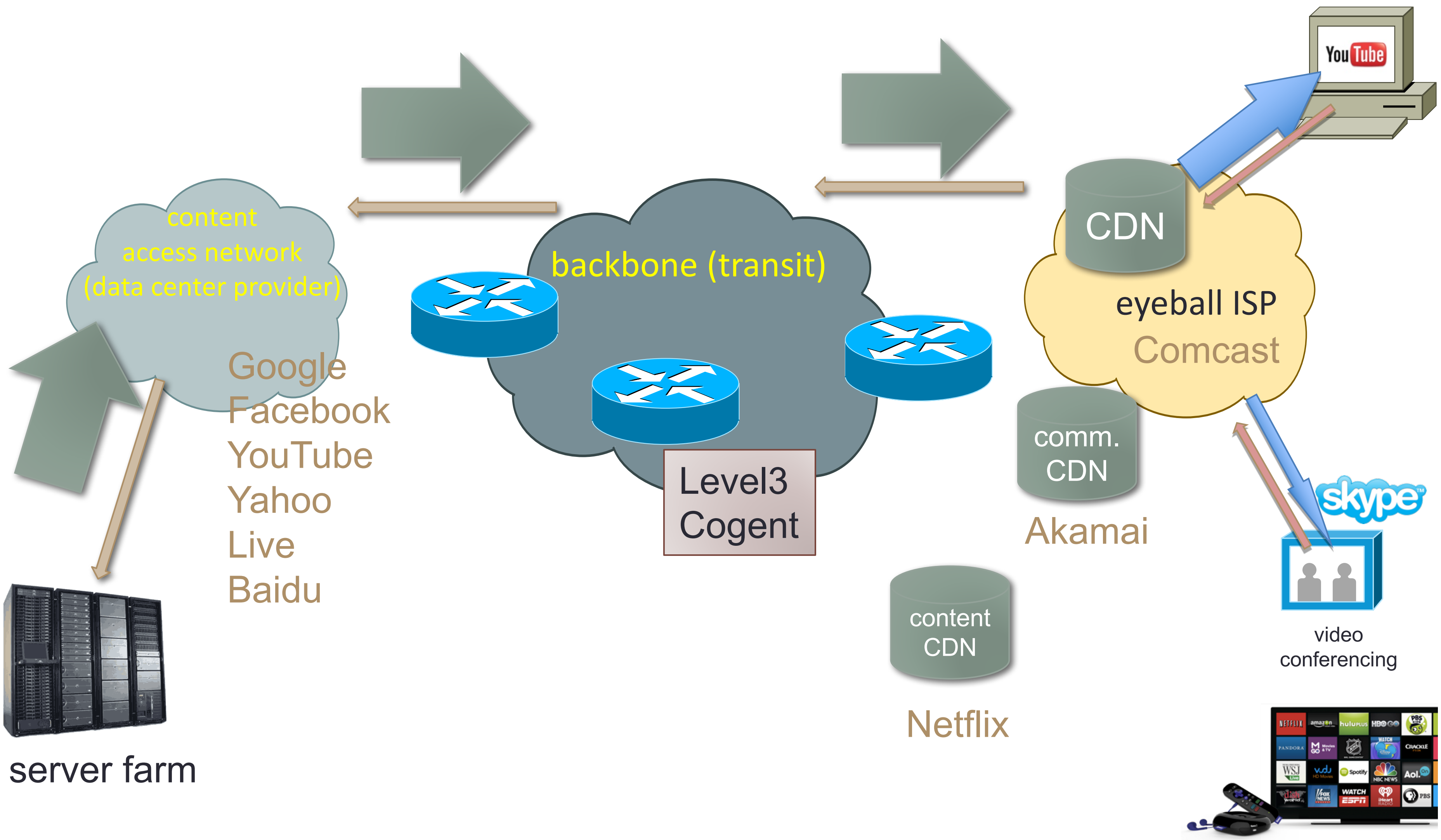


Internet: "Nuts & bolts" view

- *protocols* control sending, receiving of msgs
  - e.g., TCP, IP, HTTP, Skype, Ethernet
- *Internet: "network of networks"*
  - loosely hierarchical
  - public Internet versus private intranet
- Internet standards
  - RFC: Request for comments
  - IETF: Internet Engineering Task Force



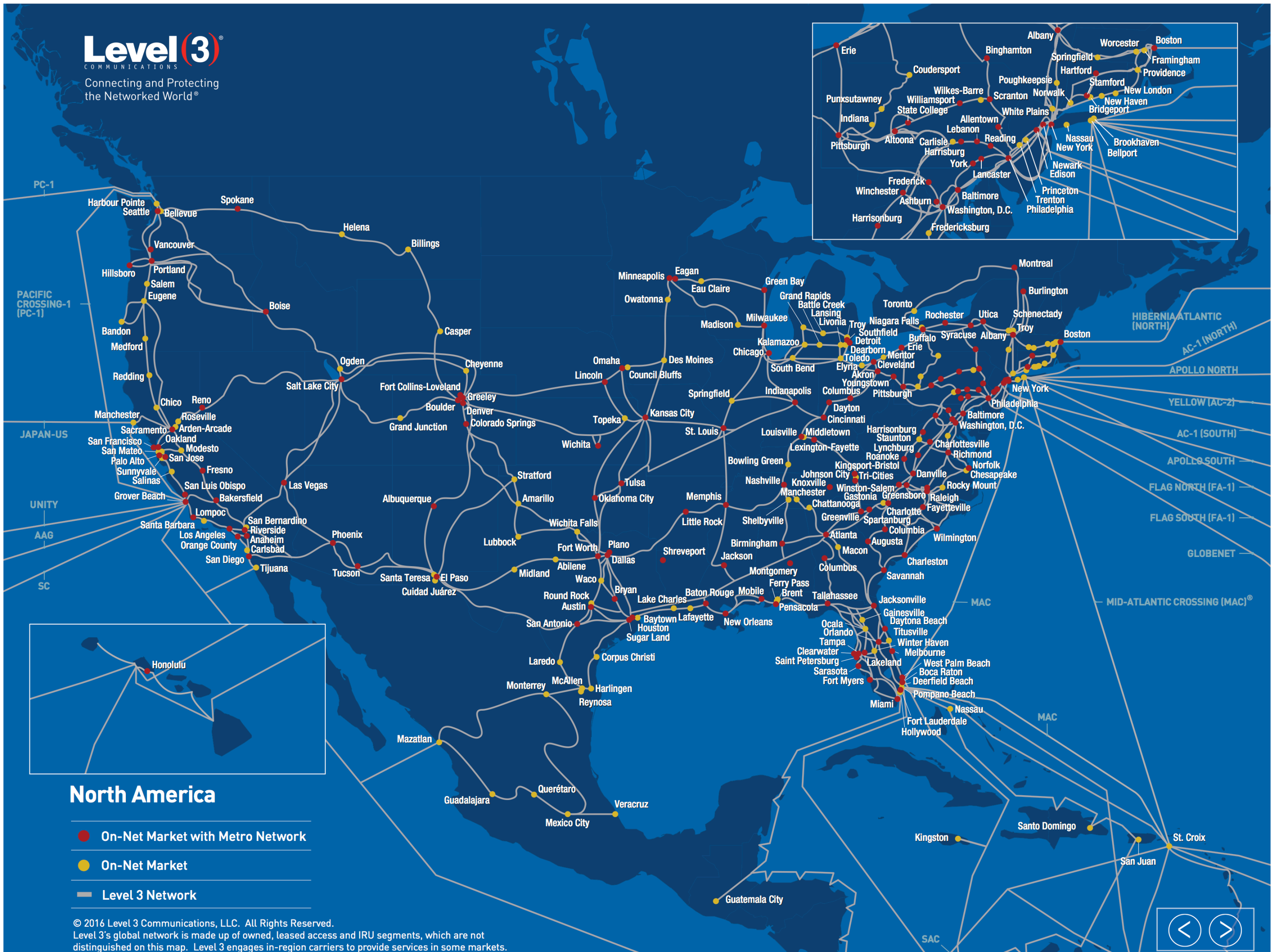
Internet traffic flows today



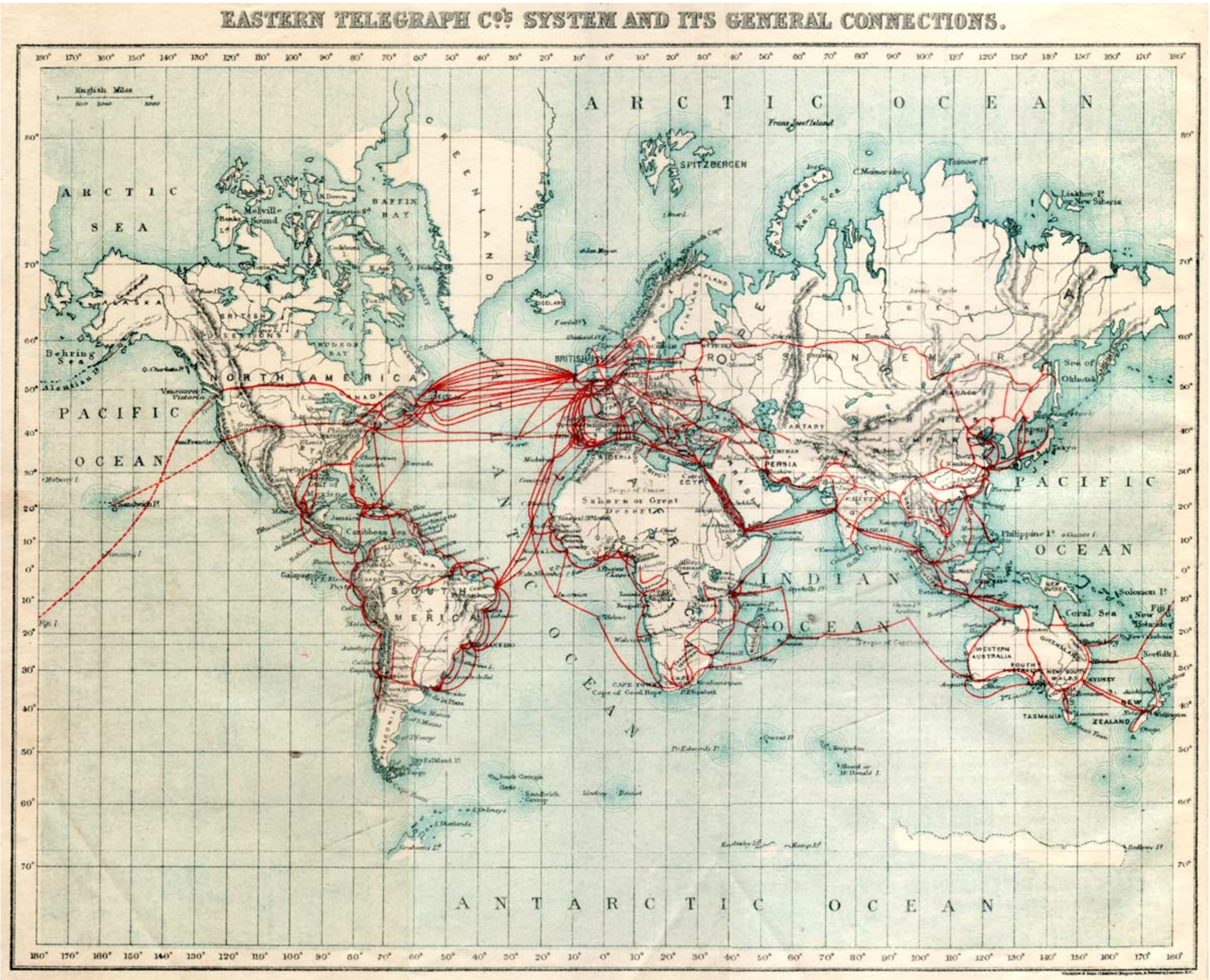
Network types

- Access
  - “last mile”
- Regional or metro
  - “metro fiber”, “metro Ethernet”
- Wholesale
  - connect points-of-presence across
  - may also provide access to commercial buildings & data centers
- Trans-oceanic
  - often, owned separately (consortium), but integrated into wholesale networks

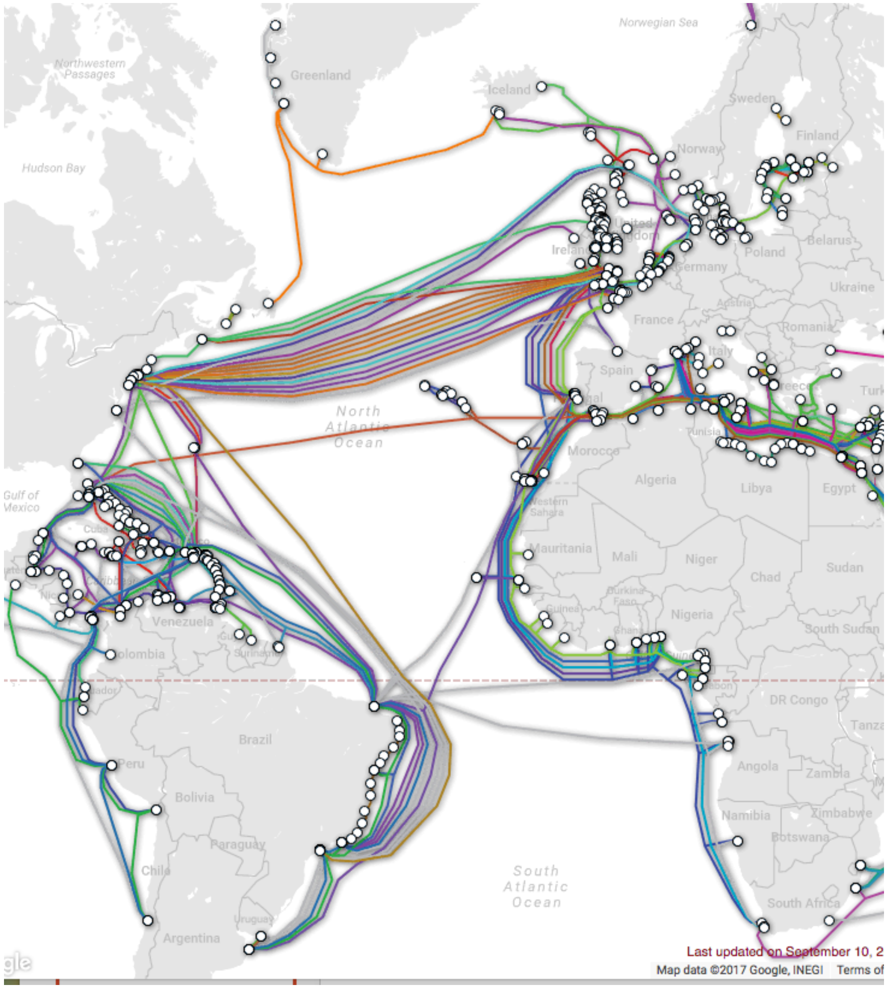
A backbone network

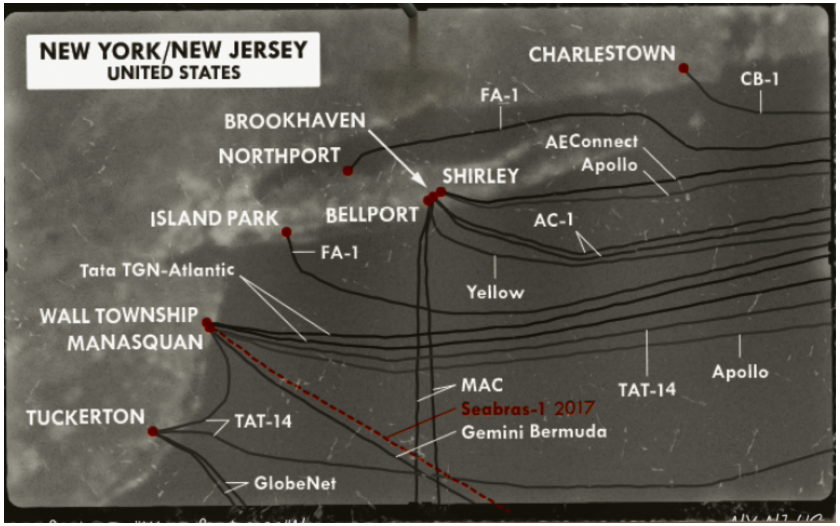


1901 “data” backbone



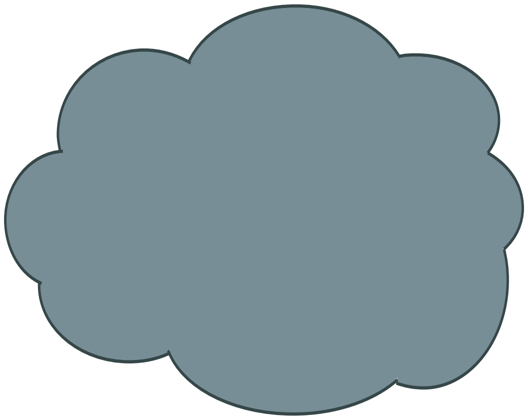
Submarine cable map





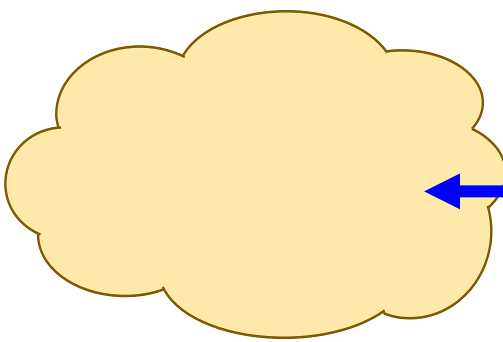
http://www.telegeography.com/

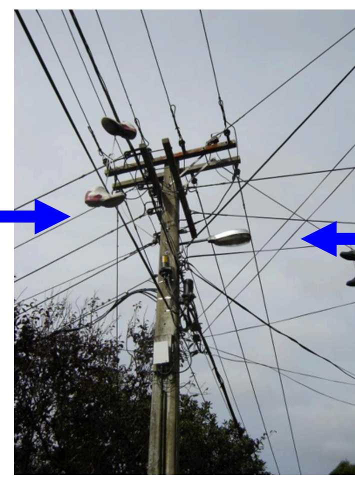
Wireline & wireless

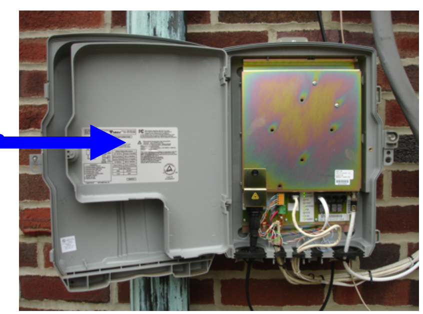


100’ to ~3 miles

fiber or copper
(rarely, microwave)

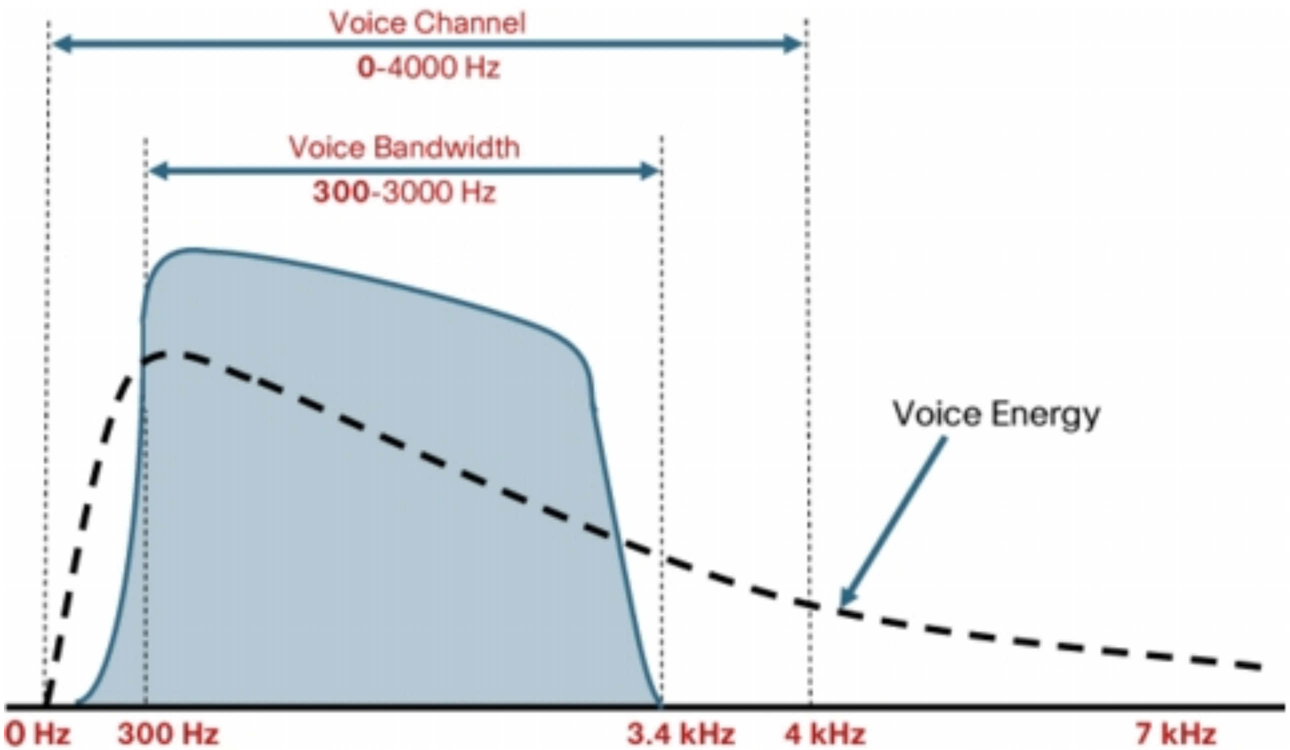






“almost all networks are 99% wired”
exceptions?

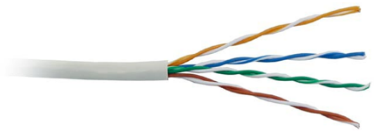
It's all spectrum - phone



It's all spectrum - wires

4 kHz

copper



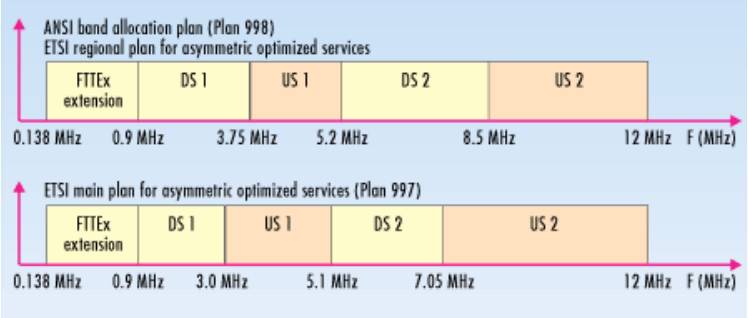
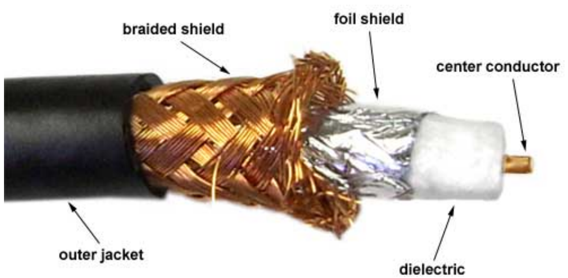


FIGURE 2: QAM uses the 4-band standard VDSL band allocation schemes. Plan 998 is optimized for countries with asymmetric needs, and Plan 997 is optimized for countries with symmetric needs.

10 MHz

COAXIAL CABLE



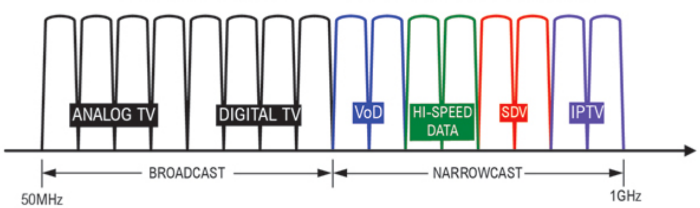
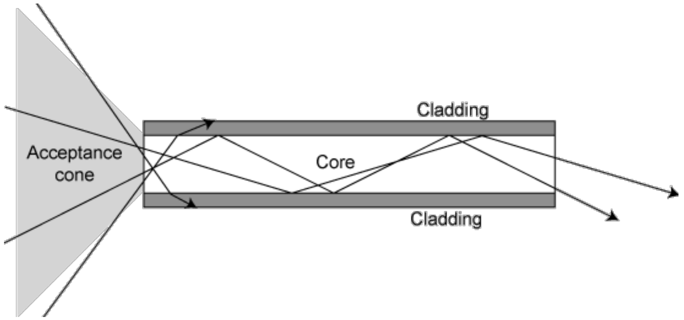
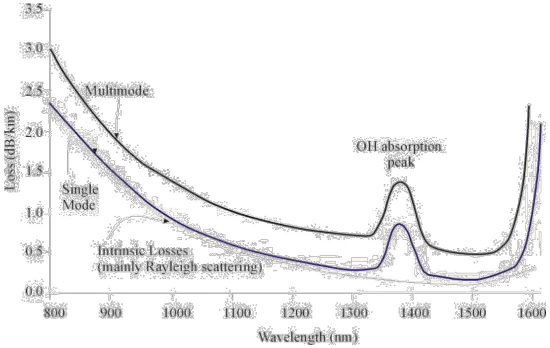


Figure 1: Cable TV spectrum includes broadcast and narrowcast services.

1 GHz

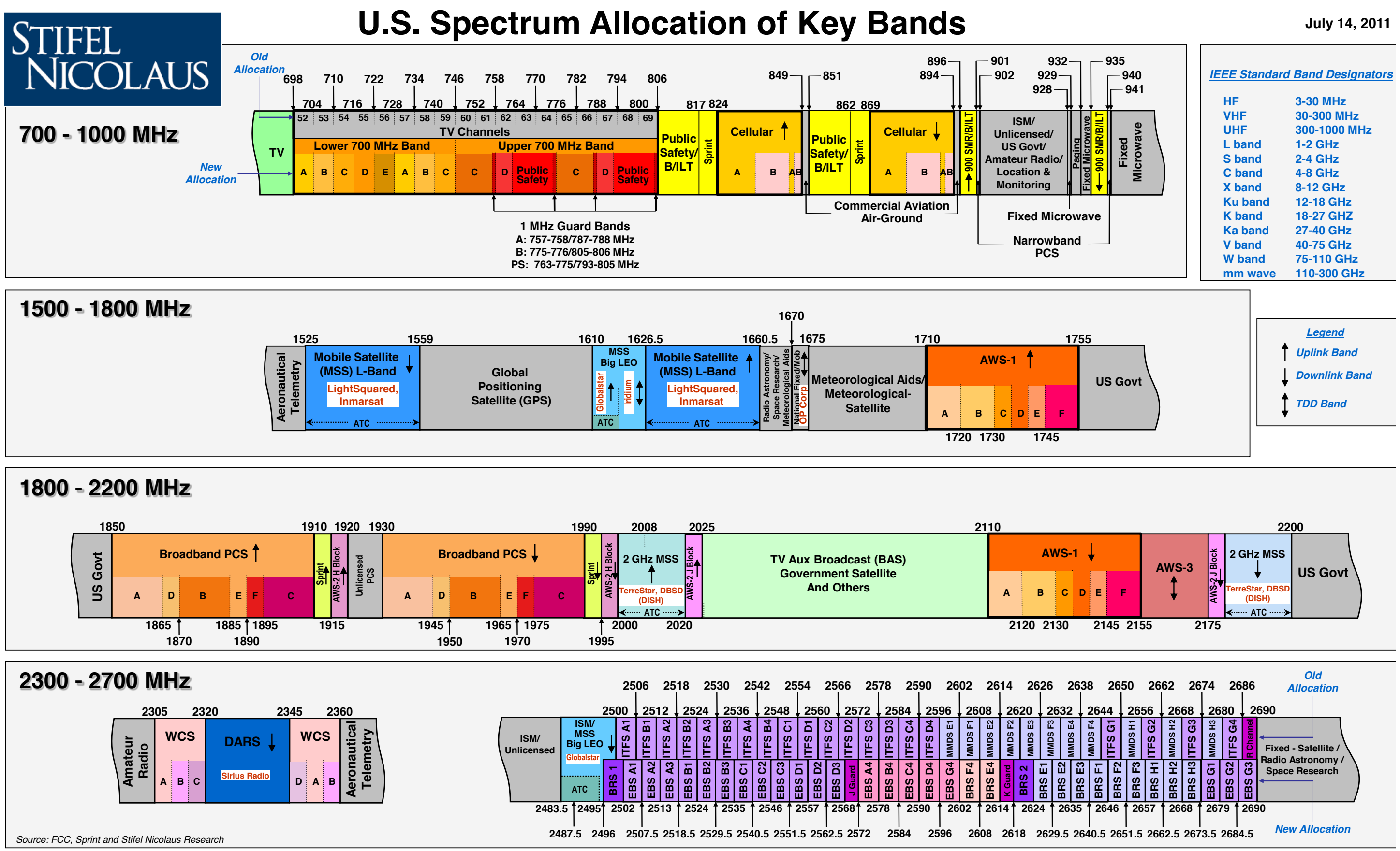




200 - 347 THz

Classical division of spectrum

Band	range	commonly called	sample current usage
VLF	3-30 kHz		navigation, submarine
LF	30-300 kHz		WWVB (clock 60 kHz)
MF	300-3 MHz		AM radio
HF	3-30 MHz		short wave radio
VHF	30-300 MHz		TV 2-6, 7-13, FM radio, CB, LMR
UHF	0.3-3 GHz		LMR, TV 14-50, cellular, Wi-Fi
SHF	3-30 GHz	microwave	radars, Wi-Fi
EHF	30-300 GHz	mmWave	radars, satellite, p2p links

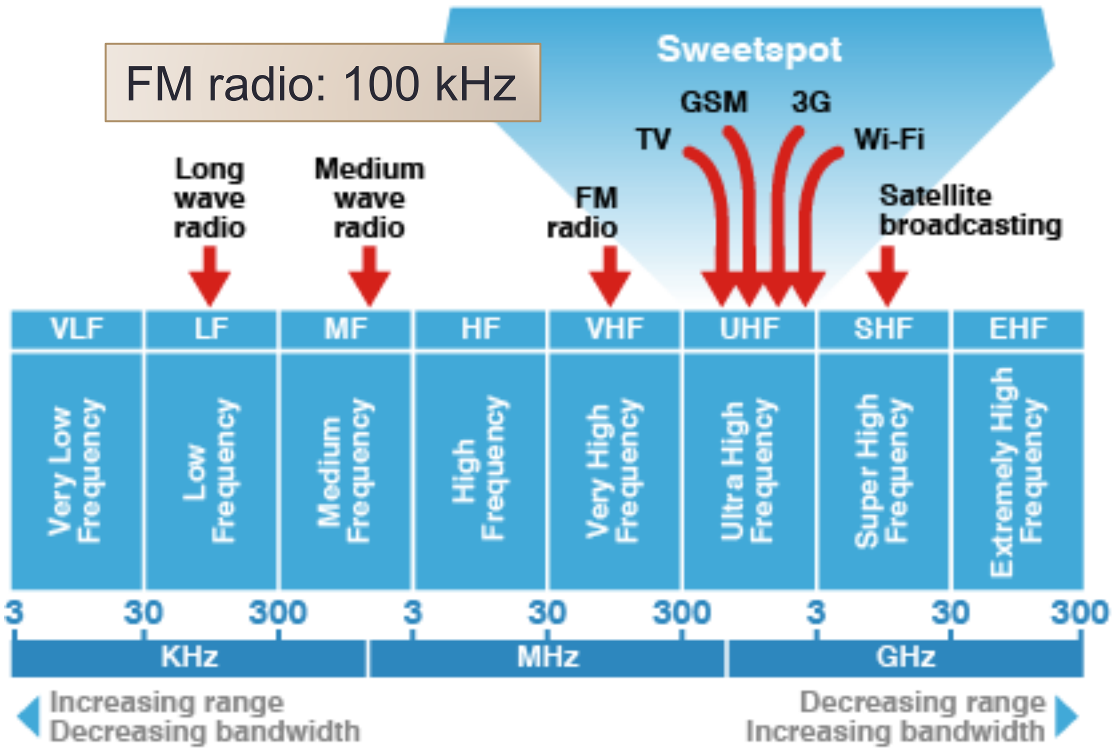

STIFEL NICOLAUS
U.S. Spectrum Allocation of Key Bands
July 14, 2011
700 - 1000 MHz
Old Allocation
New Allocation
TV
TV Channels
Lower 700 MHz Band
Upper 700 MHz Band
Public Safety
Public Safety/ B/ILT
Sprint
Cellular
Commercial Aviation Air-Ground
ISM/ Unlicensed/ US Govt/ Amateur Radio/ Location & Monitoring
Paging Fixed Microwave
900 SMR/B/ILT
Fixed Microwave
Narrowband PCS
1 MHz Guard Bands
A: 757-758/787-788 MHz
B: 775-776/805-806 MHz
PS: 763-775/793-805 MHz
IEEE Standard Band Designators
HF 3-30 MHz
VHF 30-300 MHz
UHF 300-1000 MHz
L band 1-2 GHz
S band 2-4 GHz
C band 4-8 GHz
X band 8-12 GHz
Ku band 12-18 GHz
K band 18-27 GHZ
Ka band 27-40 GHz
V band 40-75 GHz
W band 75-110 GHz
mm wave 110-300 GHz
1500 - 1800 MHz
Aeronautical Telemetry
Mobile Satellite (MSS) L-Band
LightSquared, Inmarsat
ATC
Global Positioning Satellite (GPS)
MSS Big LEO
Globalstar
Iridium
Radio Astronomy/ Space Research/ Meteorological Aids
Meteorological Aids/ Meteorological-Satellite
AWS-1
US Govt
Legend
Uplink Band
Downlink Band
TDD Band
1800 - 2200 MHz
US Govt
Broadband PCS
Sprint
AWS-2 H Block
Unlicensed PCS
2 GHz MSS
TerreStar, DBSD (DISH)
AWS-2 J Block
TV Aux Broadcast (BAS) Government Satellite And Others
AWS-1
AWS-3
2300 - 2700 MHz
Amateur Radio
WCS
DARS
Sirius Radio
Aeronautical Telemetry
ISM/ Unlicensed
ISM/ MSS Big LEO
Globalstar
ATC
Fixed - Satellite / Radio Astronomy / Space Research
Old Allocation
New Allocation
Source: FCC, Sprint and Stifel Nicolaus Research

Commercial wireless spectrum (US)

LTE band class	frequency	origin	usage
71	617-698 MHz	incentive auction (TV)	TMo, AT&T, Dish
12 & 13 (A, B, C)	700 MHz	digital dividend (TV)	AT&T, TMo, VZ
14 (D)	700 MHz	digital dividend (TV)	FirstNet
5	850 MHz	cellular	AT&T, US Cellular
4	1700 MHz	AWS	many
25	1900 MHz	PCS	many
30	2300 MHz	WCS	AT&T
41	2500 MHz	EBS	Sprint

It's all spectrum - radio

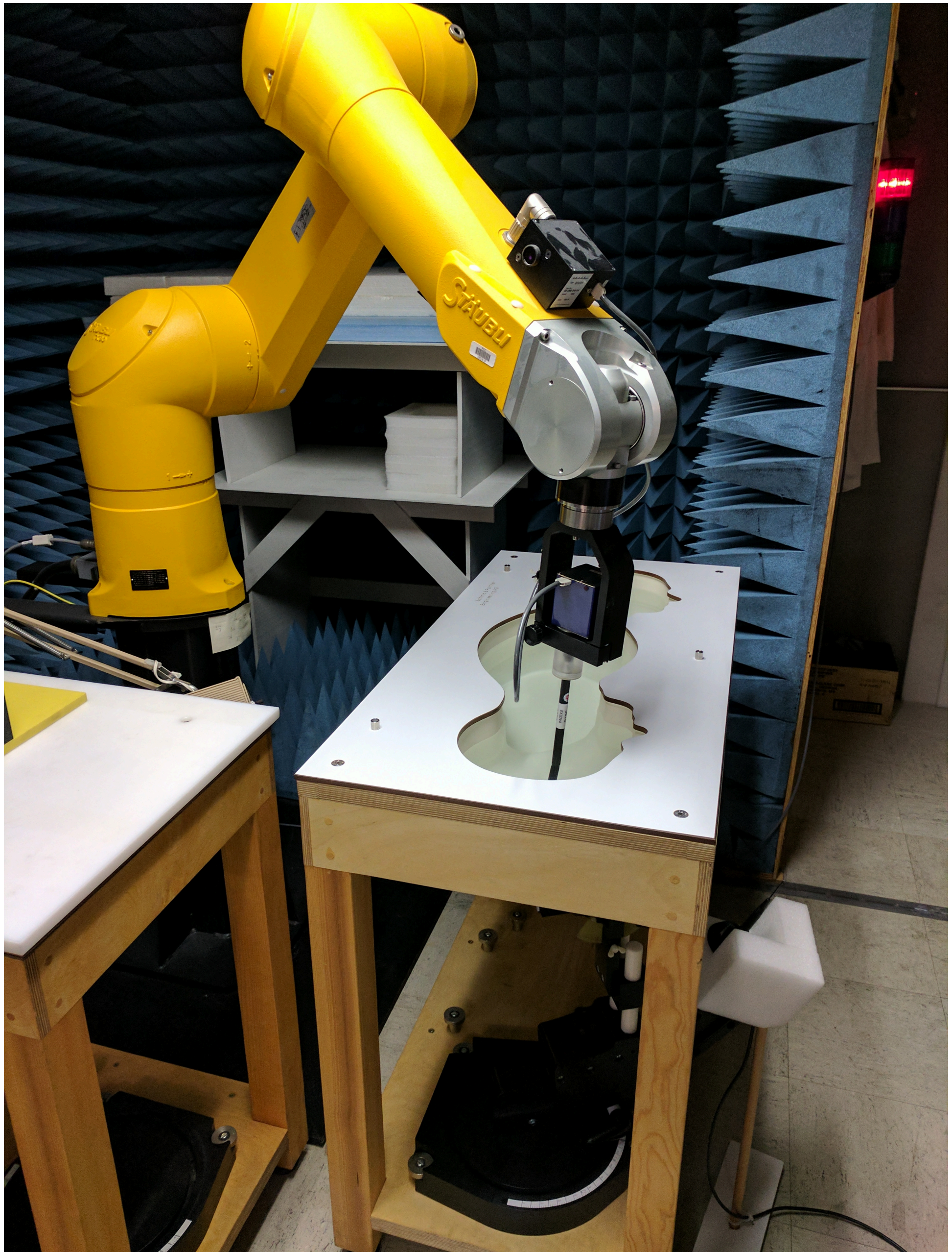
FM radio: 100 kHz

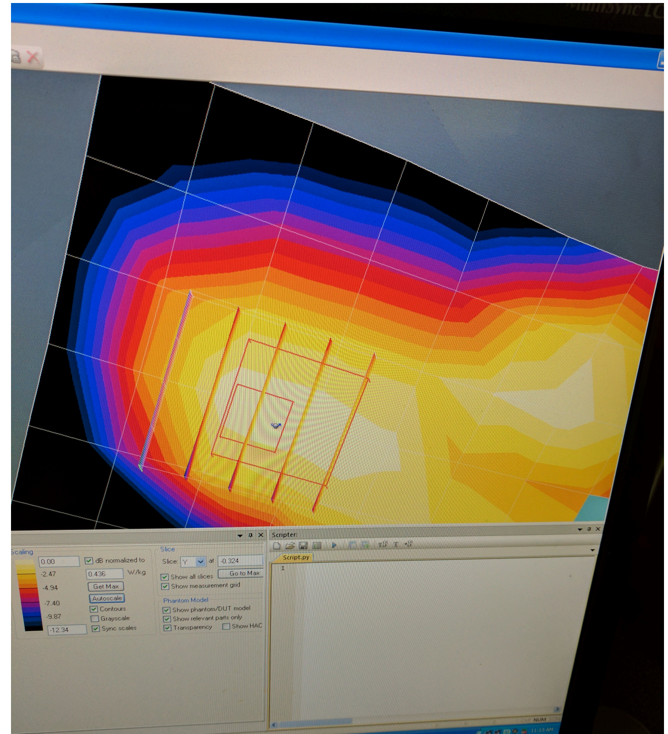


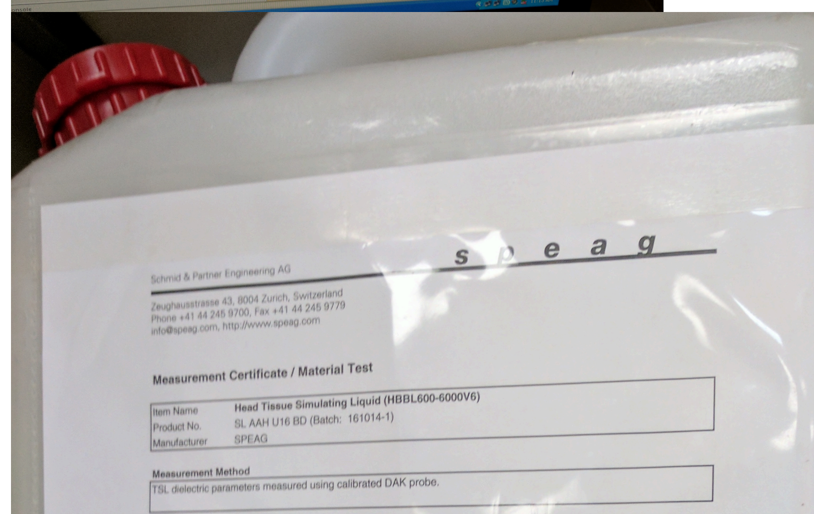
AM radio: 9 or 10 kHz

TV: 5 or 6 MHz

typical cell channel: 5-10 MHz


STÄUBLI




speag
Schmid & Partner Engineering AG
Zeughausstrasse 43, 8004 Zurich, Switzerland
Phone +41 44 245 9700, Fax +41 44 245 9779
info@speag.com, http://www.speag.com
Measurement Certificate / Material Test
Item Name Head Tissue Simulating Liquid (HBBL600-6000V6)
Product No. SL AAH U16 BD (Batch: 161014-1)
Manufacturer SPEAG
Measurement Method
TSL dielectric parameters measured using calibrated DAK probe.

Spectrum for wireless broadband

Exhibit 13: Current Spectrum Available for Wireless Broadband Use

Spectrum Band	Size	Location	Allocated	Current Deployment	Primary Holders
Cellular	50 MHz	824-849 MHz 869-894 MHz	1980s	2G 3G	AT&T Verizon U.S. Cellular
Broadband PCS	140 MHz	Uplink: 1850-1920 MHz Downlink: 1930-2000 MHz	mid-1990s	Primarily 3G	AT&T Verizon Sprint T-Mobile DISH (H)
SMR	14 MHz	817-824 MHz 862-869 MHz	2004 (reconfig.)	LTE (formerly iDEN)	Sprint
BRS/EBS	194 MHz	2496-2690 MHz	2005 (transition plan)	WiMAX TDD-LTE	Sprint
AWS-1	90 MHz	Uplink: 1710-1755 MHz Downlink: 2110-2155 MHz	2006	Primarily LTE	AT&T Verizon T-Mobile
700 MHz	70 MHz	Lower: 698-748 MHz Upper: 746-806 MHz	2008	Primarily LTE	T-Mobile (A) AT&T (B/C/D/E) DISH (E) Verizon (Upper C)
AWS-4	40 MHz	2000-2020 MHz 2180-2200 MHz	2013 (waiver)	n/a	DISH
WCS	20 MHz	2305-2315 MHz 2345-2355 MHz	2013 (T-SIRI deal)	n/a	AT&T
AWS-3	65 MHz	1695-1710 MHz 1755-1780 MHz 2155-2180 MHz	2015	n/a	AT&T DISH Verizon T-Mobile
600 MHz	70 MHz	617-652 MHz 663-698 MHz	2017	n/a	T-Mobile DISH Comcast

TOTAL LICENSED SPECTRUM = 753 MHz

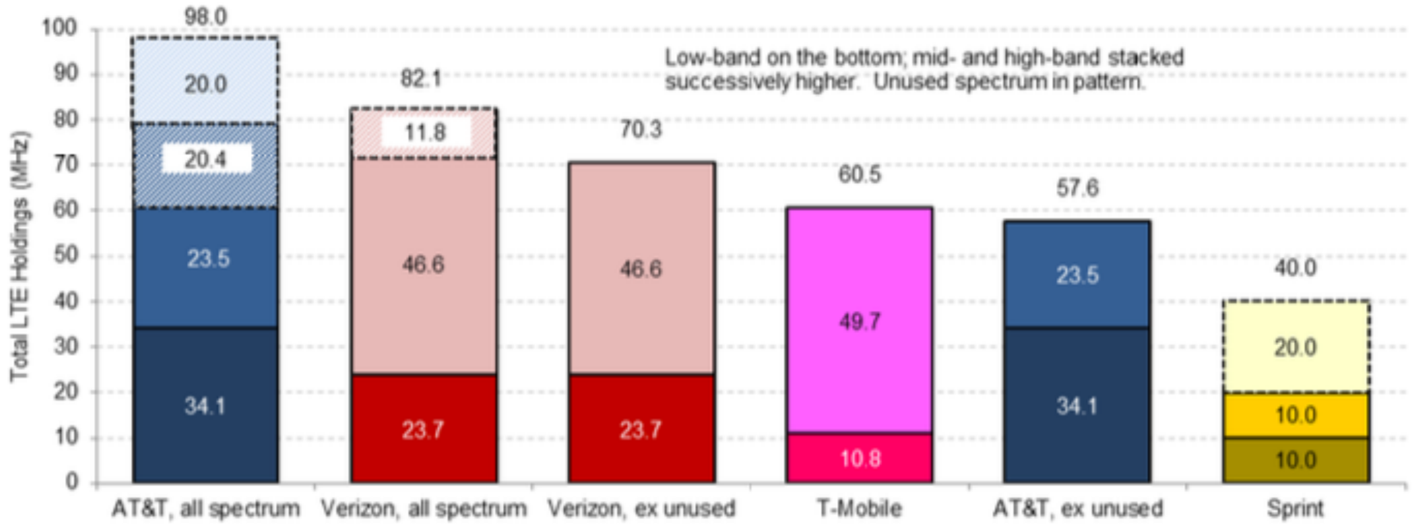
Source: FCC and Wells Fargo Securities' estimates.

Wells-Fargo 2017

LTE holdings

Exhibit 19

Big Four: Estimated Current LTE Holdings by Band, With and Without Unused Spectrum

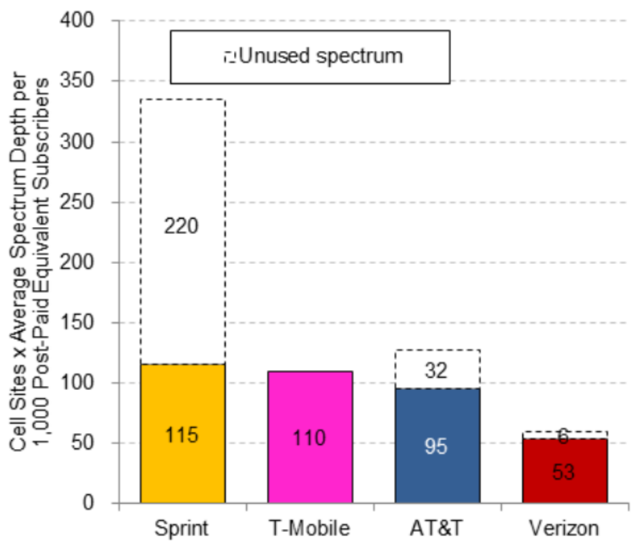


Source: Allnet, Fierce Wireless, MoffettNathanson estimates and analysis

Spectrum per user

Exhibit 23

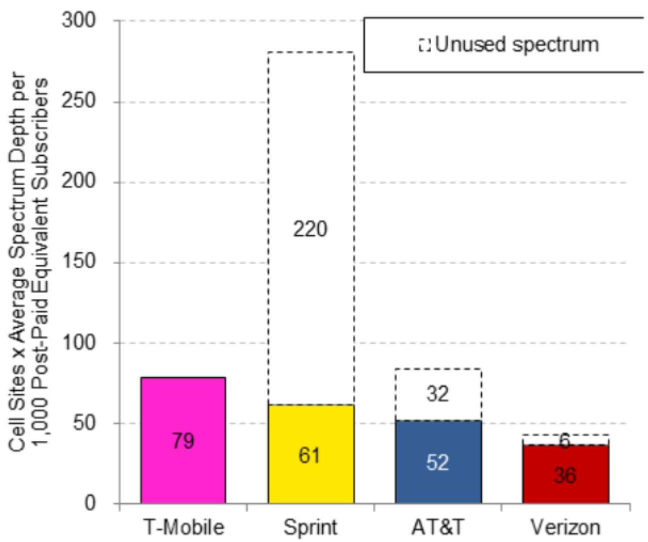
Big Four: Total Spectrum x Cell Site per Post-Paid Equivalent Subscriber



Source: MoffettNathanson estimates and analysis

Exhibit 24

Big Four: Total LTE Spectrum x Cell Site per Post-Paid Equivalent Subscriber

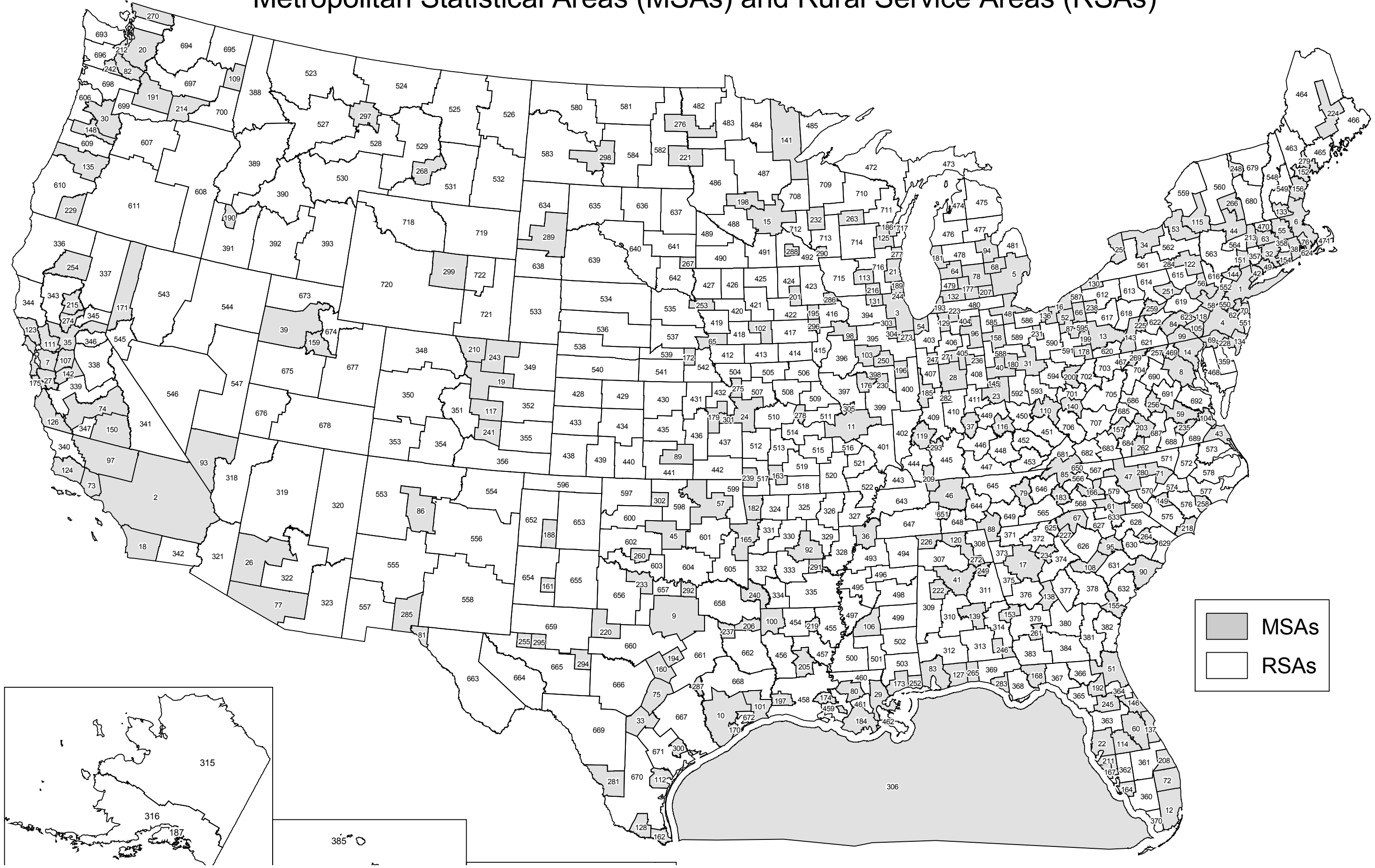


Source: MoffettNathanson estimates and analysis

Geographic sizing: CMA

Cellular Market Areas (CMAs)

Metropolitan Statistical Areas (MSAs) and Rural Service Areas (RSAs)

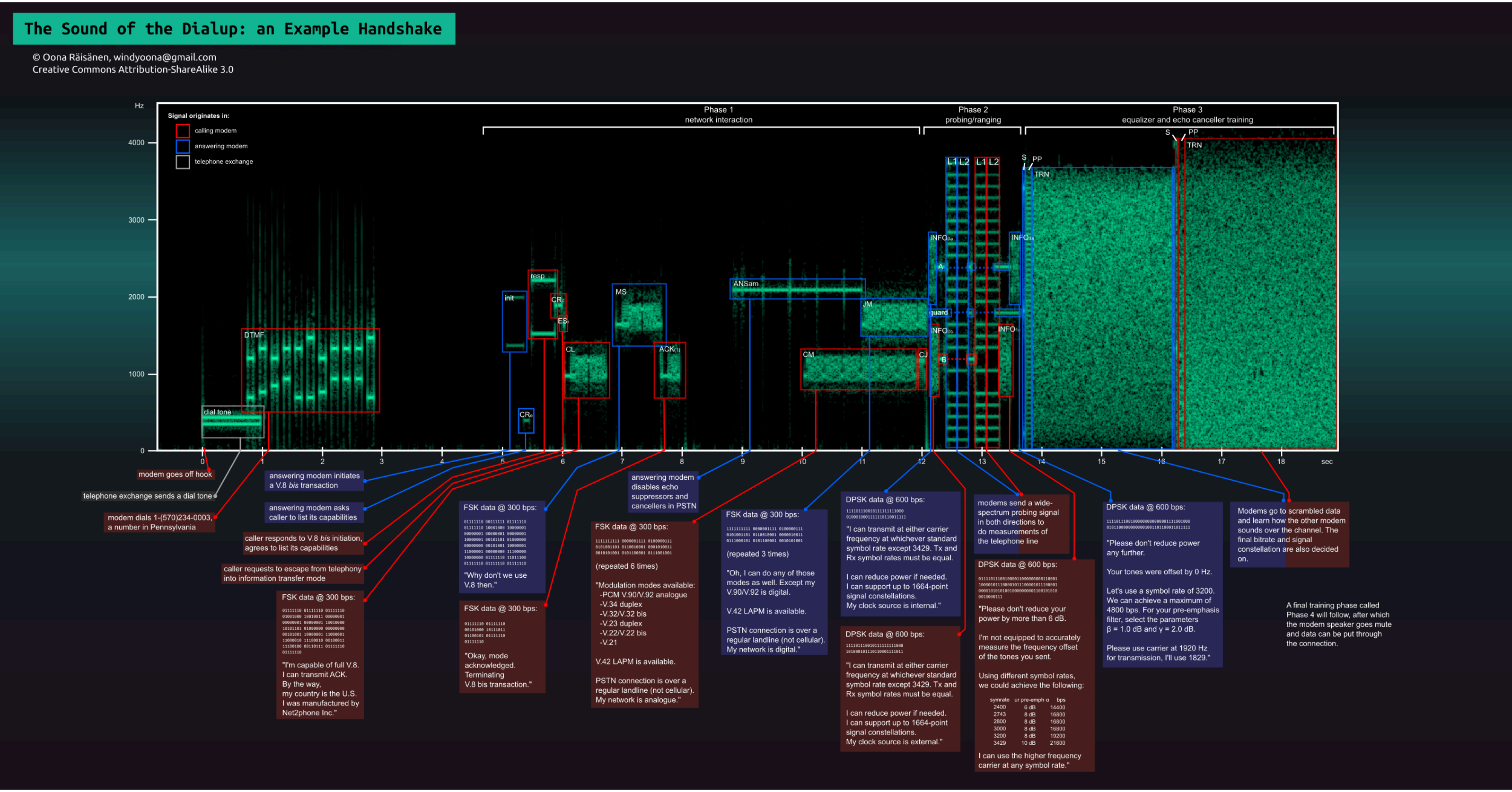


Spectrum geography: EA

Economic Areas (EAs)

EAs delineated by the Regional Economic Analysis Division
Bureau of Economic Analysis, U.S. Department of Commerce
January 1995

It’s all spectrum - modem



Fundamental limit to channel capacity

$$C = B\log_2\left(1 + \frac{S}{N}\right)$$

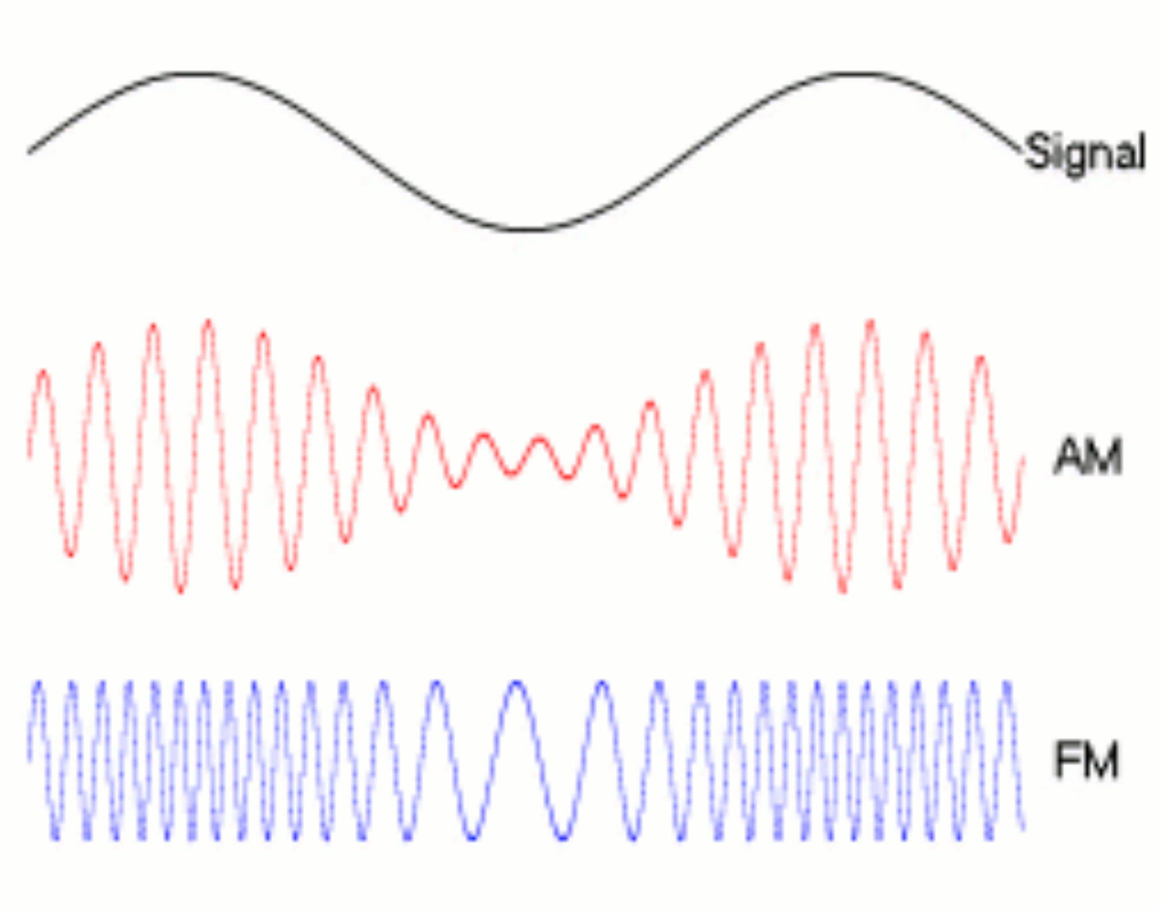
channel capacity (bits/second)

bandwidth (Hz)

signal-to-noise ratio (typically, dB)

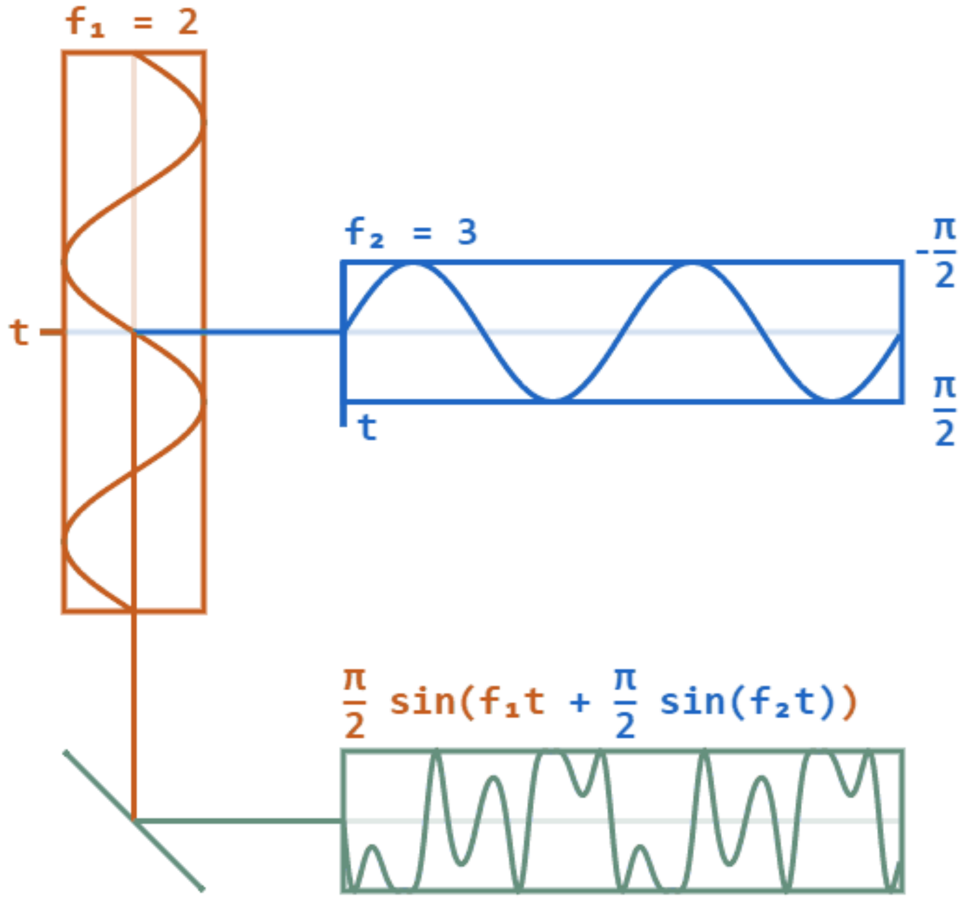
Shannon-Hartley limit

Amplitude, frequency & phase modulation



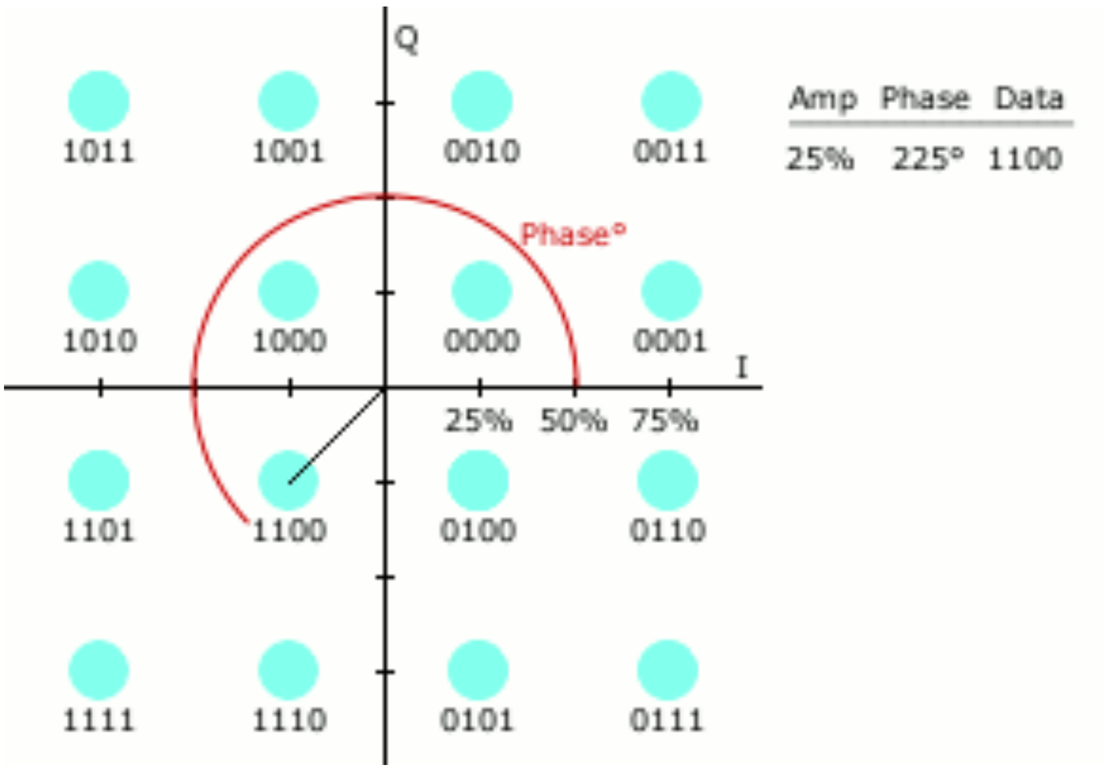
Wikipedia

Phase modulation



Wikipedia

Quadrature amplitude modulation (QAM)



Wikipedia

Shannon examples

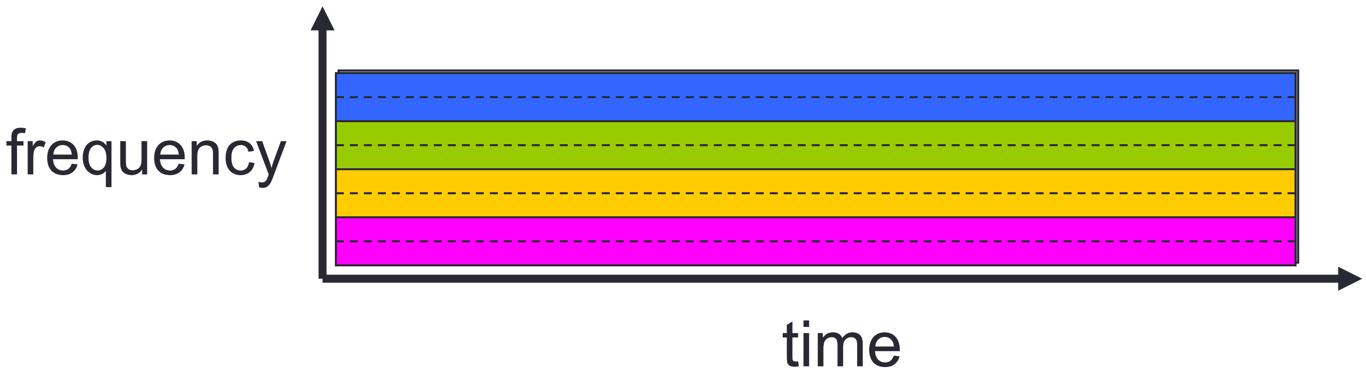
- SNR (dB) = 10 $\log_{10}$ (S/N)
- Telephone modem: SNR = 20 dB (1:100); frequency 4 kHz → 4,000 $\log_2$ (101) = 26.63 kb/s
- Noise can be larger than signal!
  - → negative SNR
- Less noise → higher signal power
- Only true for simple channel models
  - "additive Gaussian white noise" (AWGN)
- Spectral efficiency: bits per second per Hz
  - often, around 1-2 b/s/Hz, but can be much higher

Circuit switching: FDM versus TDM

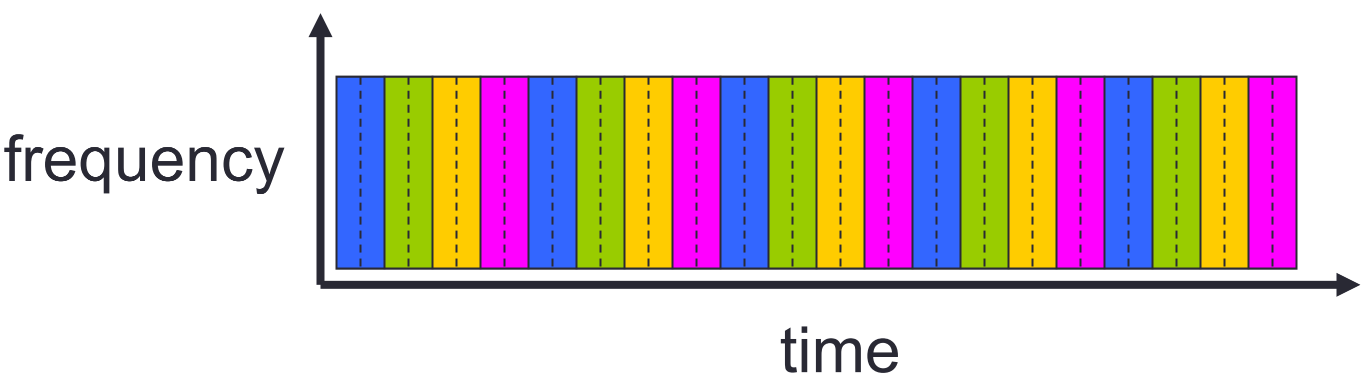
Example:

4 users 

FDM



TDM



All networks are similar

packets

time-division multiplexing

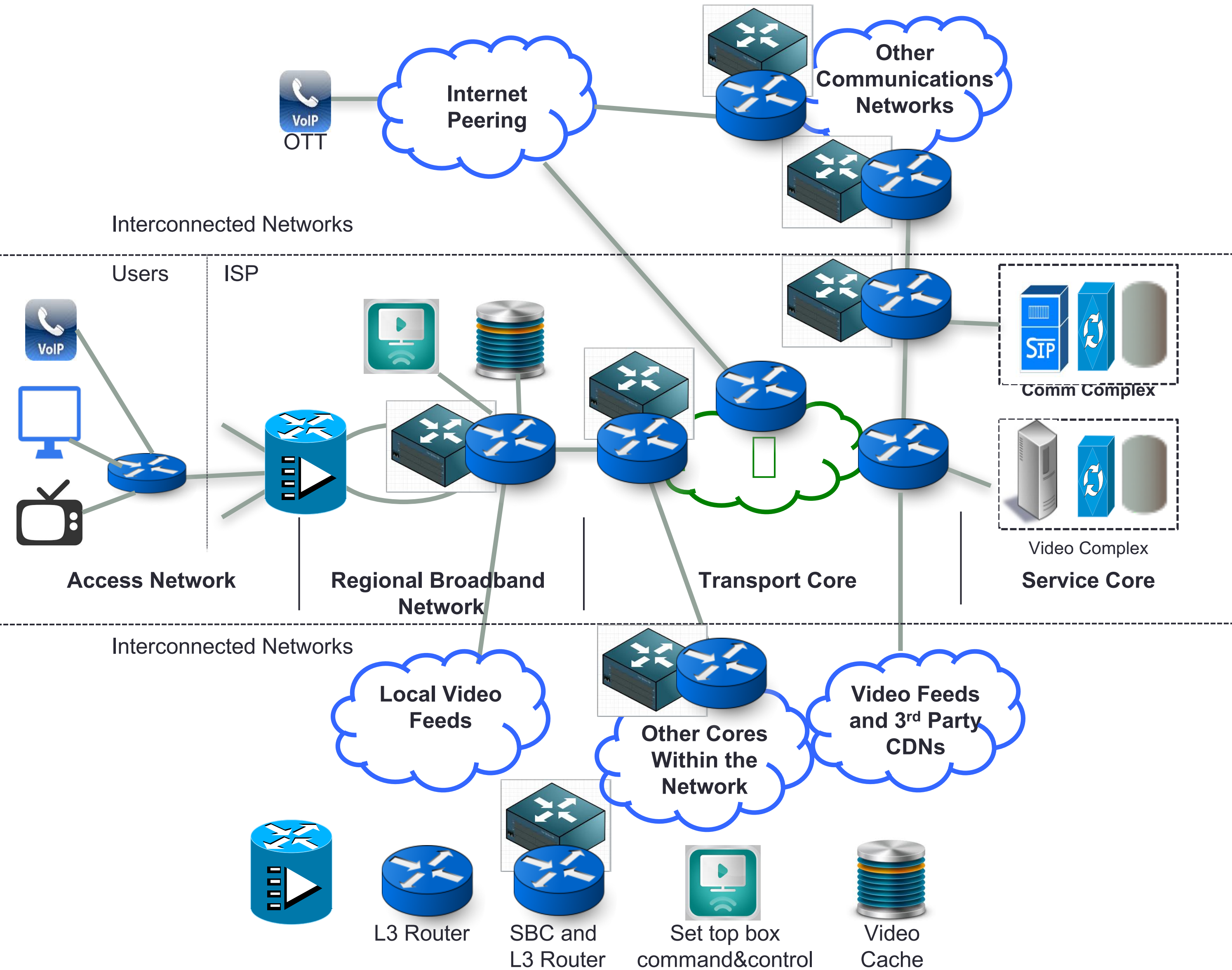
packets

modulation

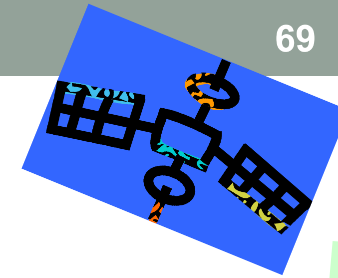
frequency division

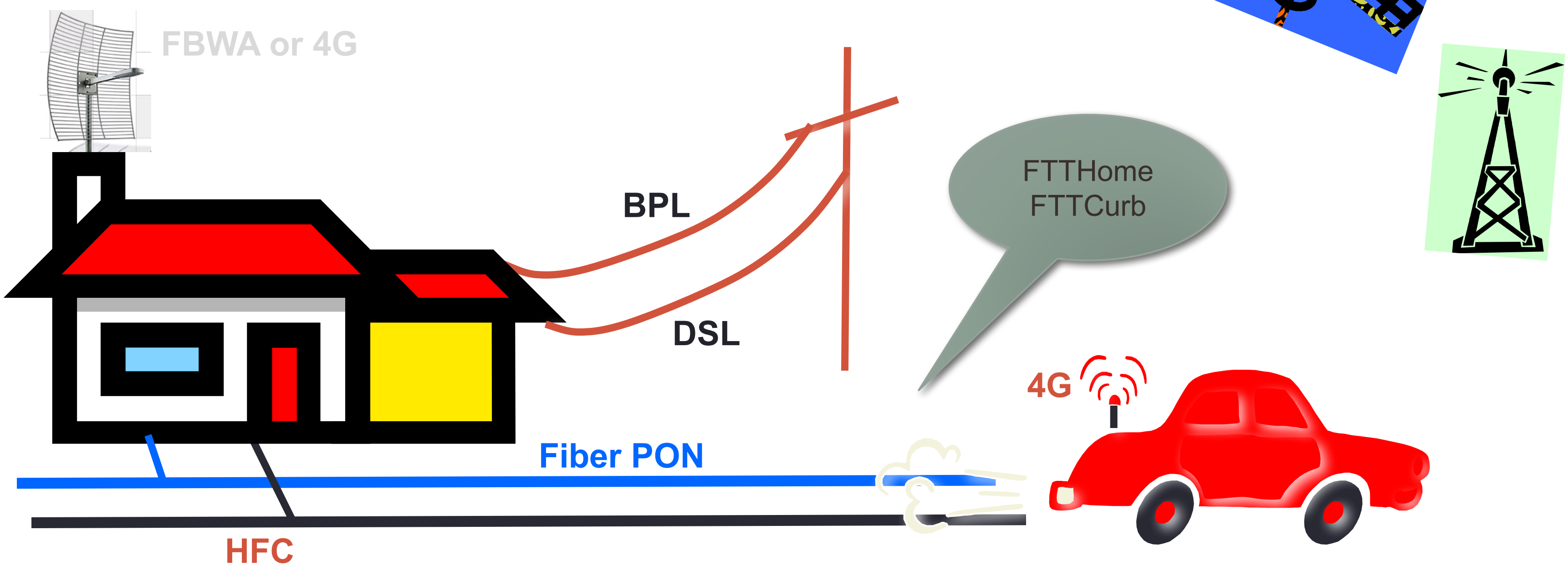
medium = spectrum

Reference architecture



Broadband Access Technologies





Digital Subscriber Line
- Telco or ILEC
- 10s of Mbps
- Entertainment, data, voice

Hybrid Fiber Coax
- CableCo (MSO)
- Entertainment, data, voice
- 10s of Mbps

Fiber -- Passive Optical Network
- Telco or ILEC
- ~75 Mb/s
- Futureproof?

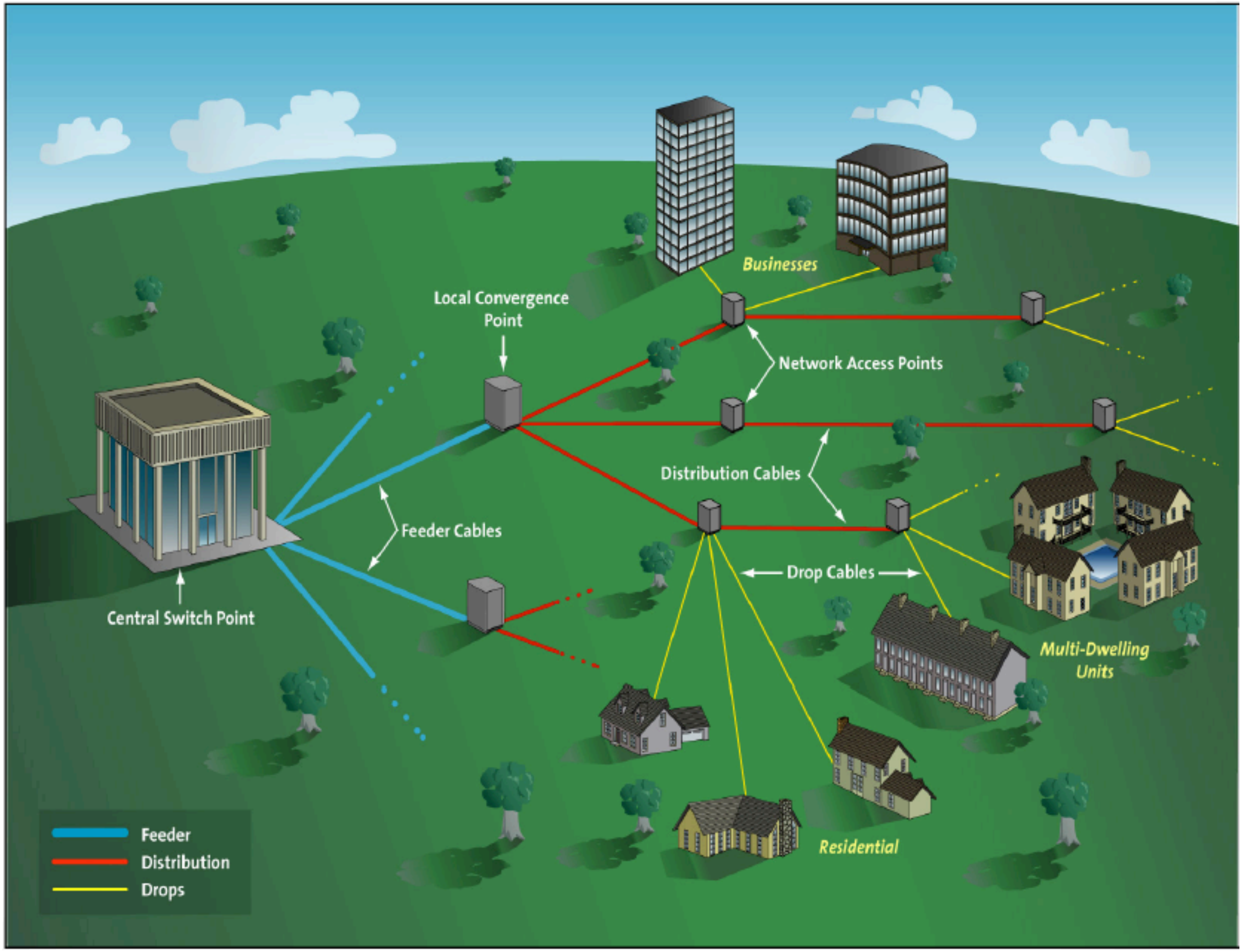
Broadband Power Line
- PowerCo
- Data, voice
- ~few Mbps

Fixed Broadband Wireless Access
- Wireless ISP
- WiMAX or LTE:
  - -10s of Mbps
- Satellite: few Mbps

4G/LTE
- Cellular operators
- 5-10 Mbps (100 kph)

Paul Henry (AT&T), FCC 2009

Local loop

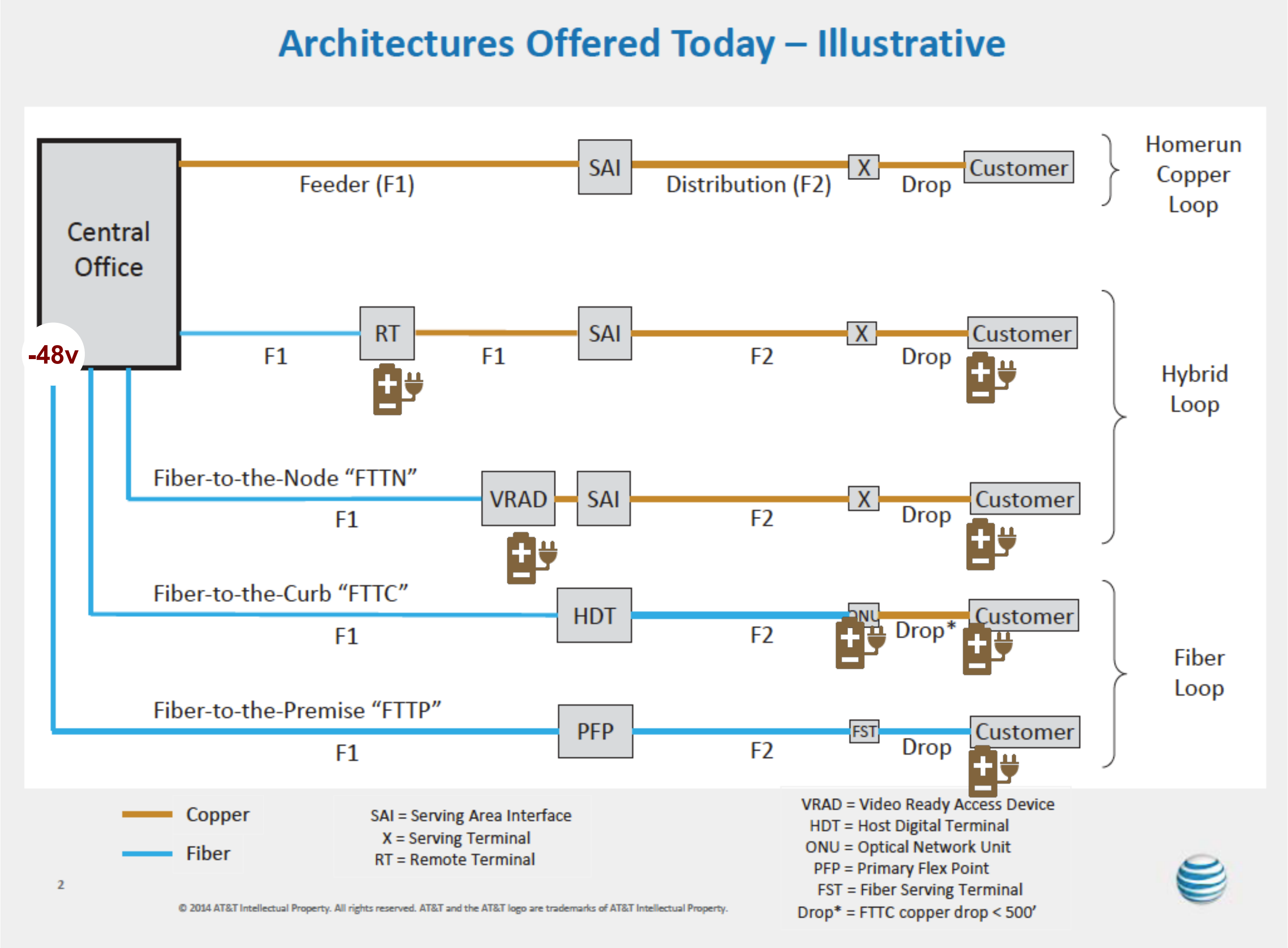

Businesses
Local Convergence Point
Network Access Points
Distribution Cables
Feeder Cables
Drop Cables
Central Switch Point
Multi-Dwelling Units
Residential
Feeder
Distribution
Drops

Physical architecture

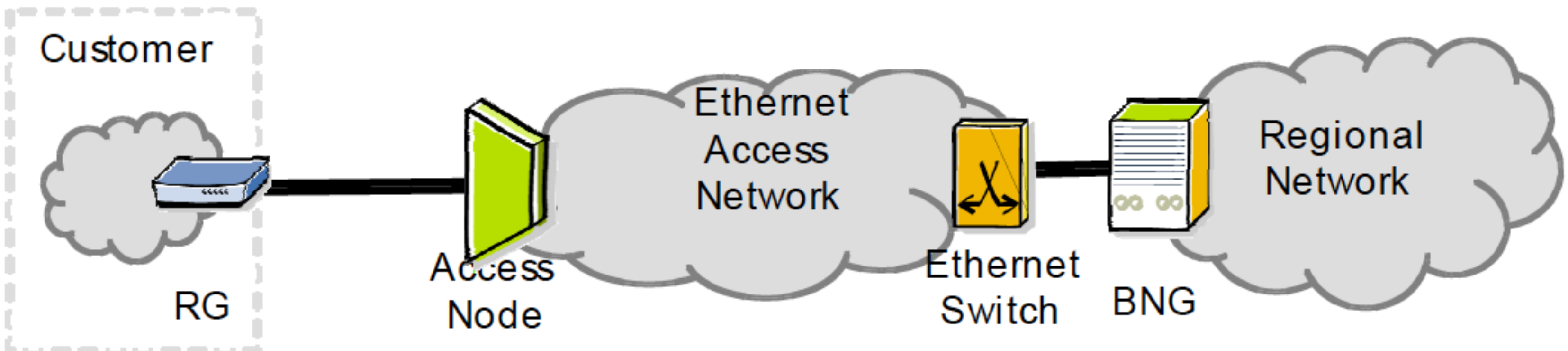
- Feeder Cables
  - Carries traffic serving multiple endpoints form an “office” to a neighborhood (local convergence point, LCP, or serving area interface, SAI)
- Distribution Cables
  - Carry traffic for one or more households from LCP to the curb (network access point)
- Drop Cables (above ground) or service wire (underground)
  - Carry traffic from curb to dwelling unit

- Depending upon the architecture
  - Cables may be fiber, twisted pair or coax
  - Local convergence point and/or network access point could host a patch panel, a DSLAM, an optical splitter, an Ethernet switch, or a fiber/coax interface.

Broadband access



Logical architecture



- Access network extends from Residential Gateway (RG) to Broadband Network Gateway (BNG)
- Flow management between AN and RG depends upon the architecture
- Flow management in the Ethernet Aggregation Network similar across architectures but may differ from how flows are managed between the AN and the RG
- In Metro Network flows are typically distinguished by layer 3 QoS tags and/or separate VPNs

http://www.broadband-forum.org/technical/download/TR-101_Issue-2.pdf

xDSL logical architecture

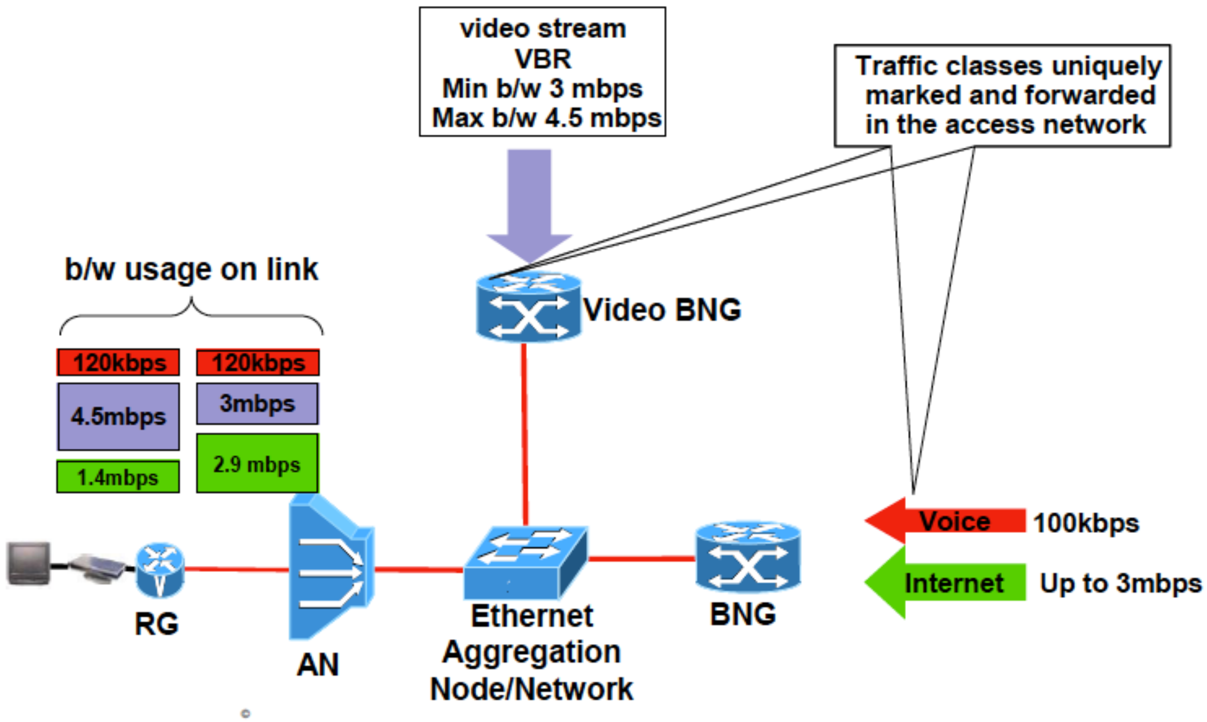
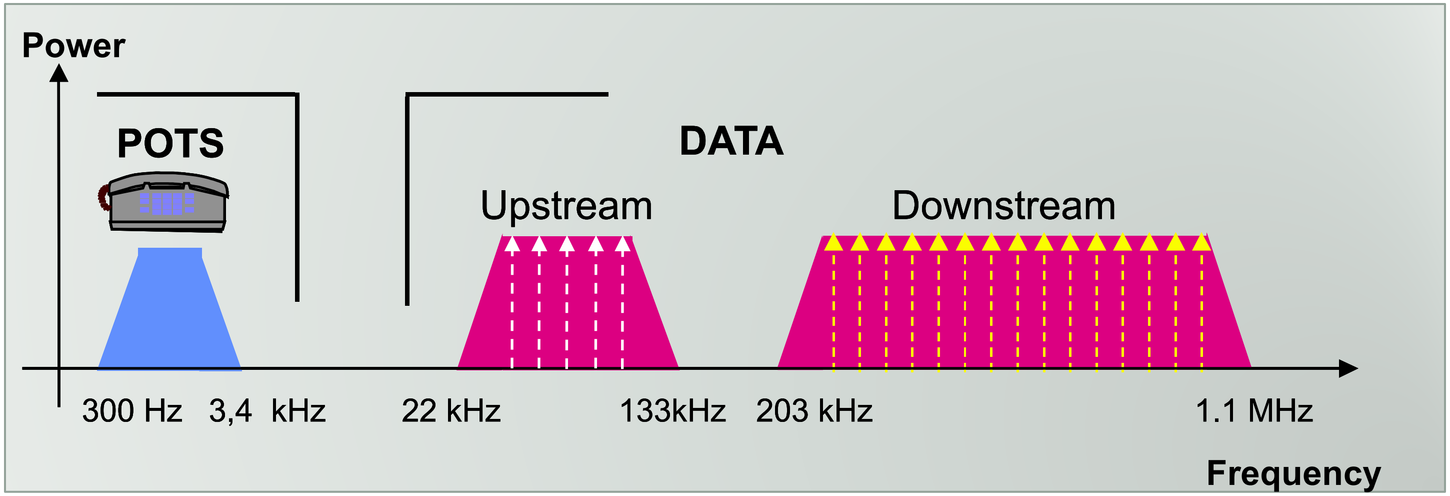


Figure 12 – Example distributed precedence and scheduling model with dual nodes

http://www.broadband-forum.org/technical/download/TR-101_Issue-2.pdf

ADSL (ITU G.992.1)

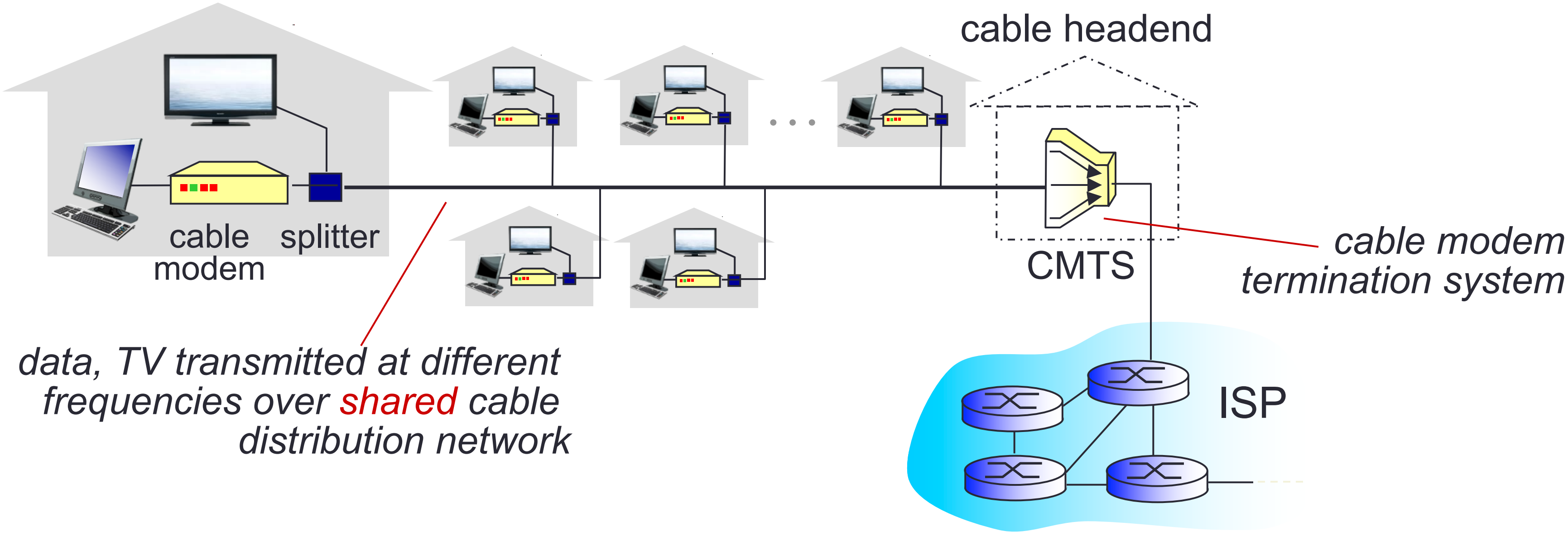
ADSL spectral power repartition (PSTN)



FDD: Frequency Division Duplexing

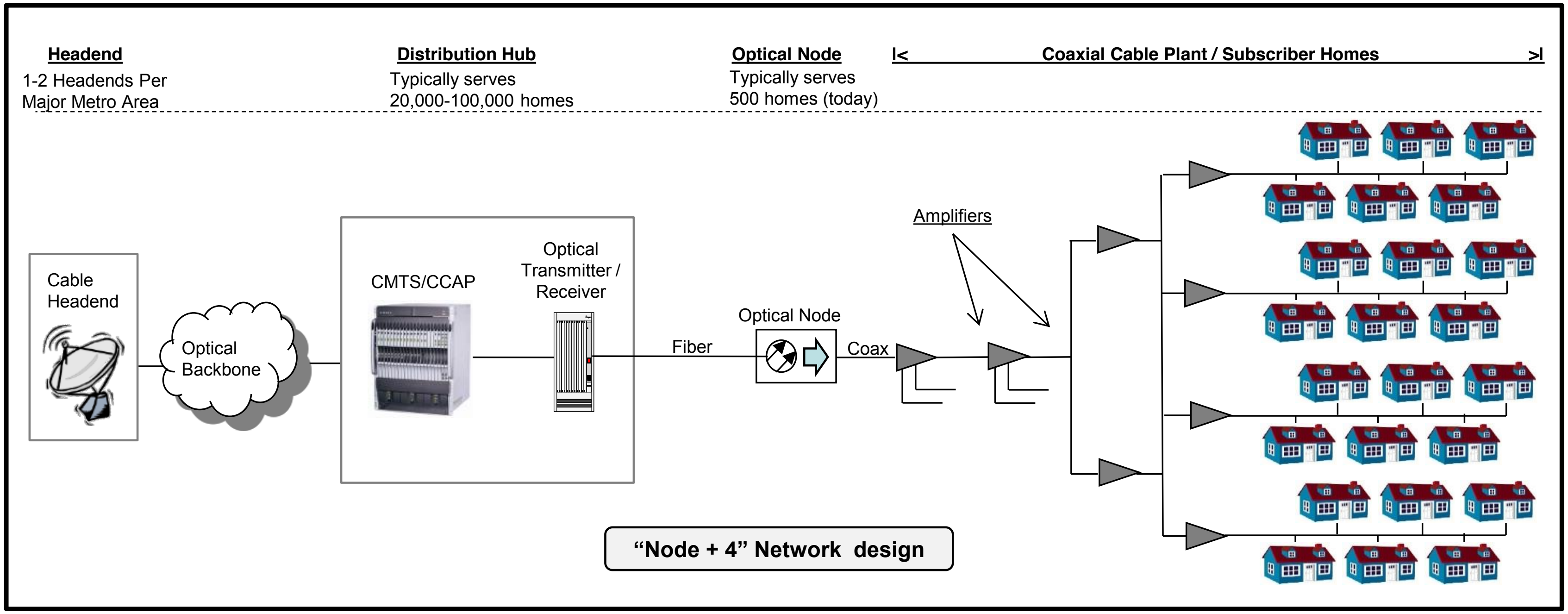
➔ no interference between up and down

Access: cable network



- HFC: hybrid fiber coax
  - asymmetric: up to 30Mbps downstream transmission rate, 2 Mbps upstream transmission rate
- network of cable, fiber attaches homes to ISP router
  - homes *share access network* to cable headend
  - unlike DSL, which has dedicated access to central office

Cable architecture

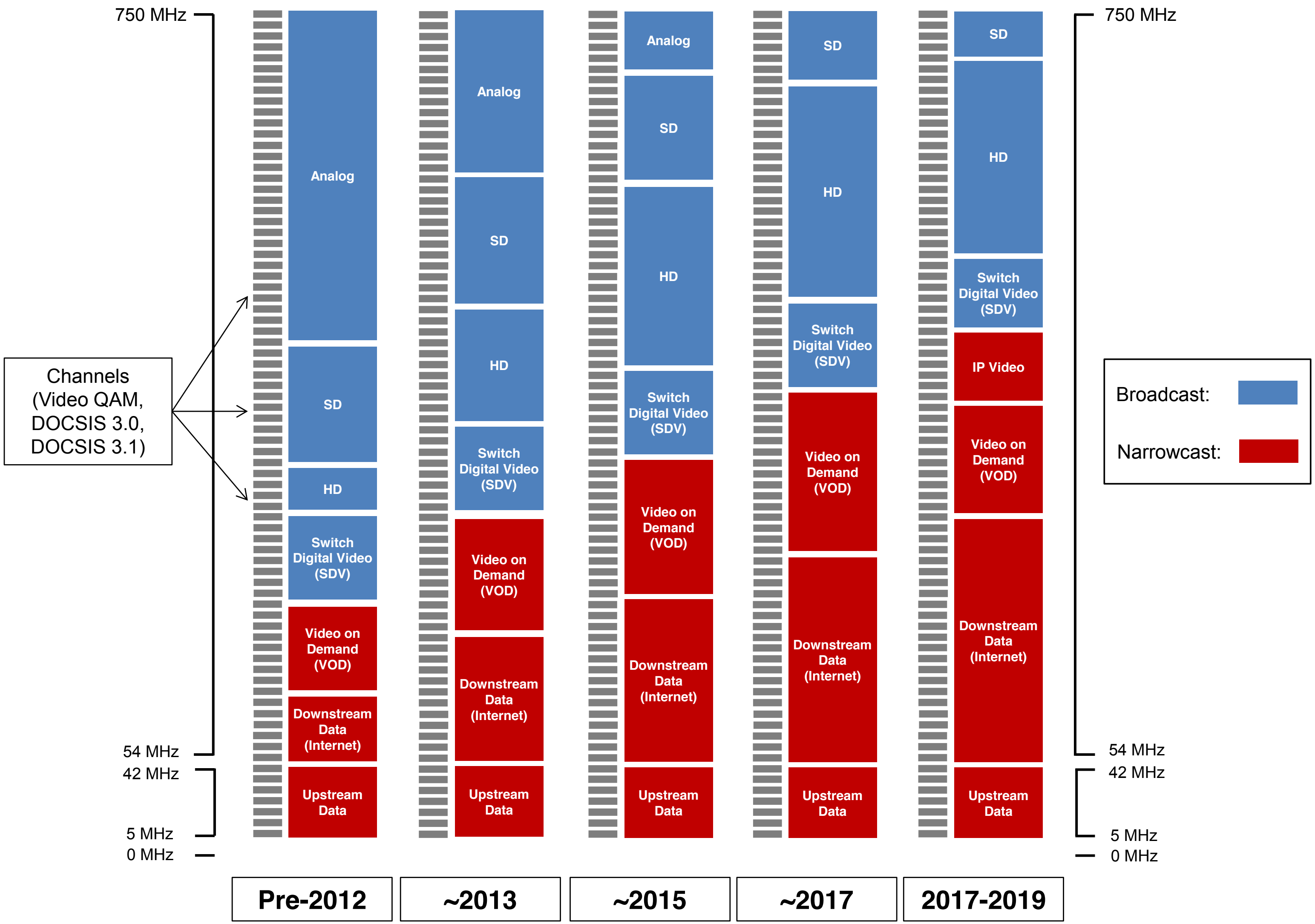


Source: Jefferies Research

DOCSIS Version	Downstream Modulation Scheme	Upstream Modulation Scheme	Minimum Required Network Design
DOCSIS 2.0	256-QAM	64-QAM	N+6
DOCSIS 3.0	256-QAM	64-QAM	N+6
DOCSIS 3.1	512-QAM	128-QAM	N+4
DOCSIS 3.1	1024-QAM	256-QAM	N+2
DOCSIS 3.1	2048-QAM	512-QAM	N+1
DOCSIS 3.1	4096-QAM	1024-QAM	N+0
Full Duplex DOCSIS	4096-QAM	1024-QAM	N+0

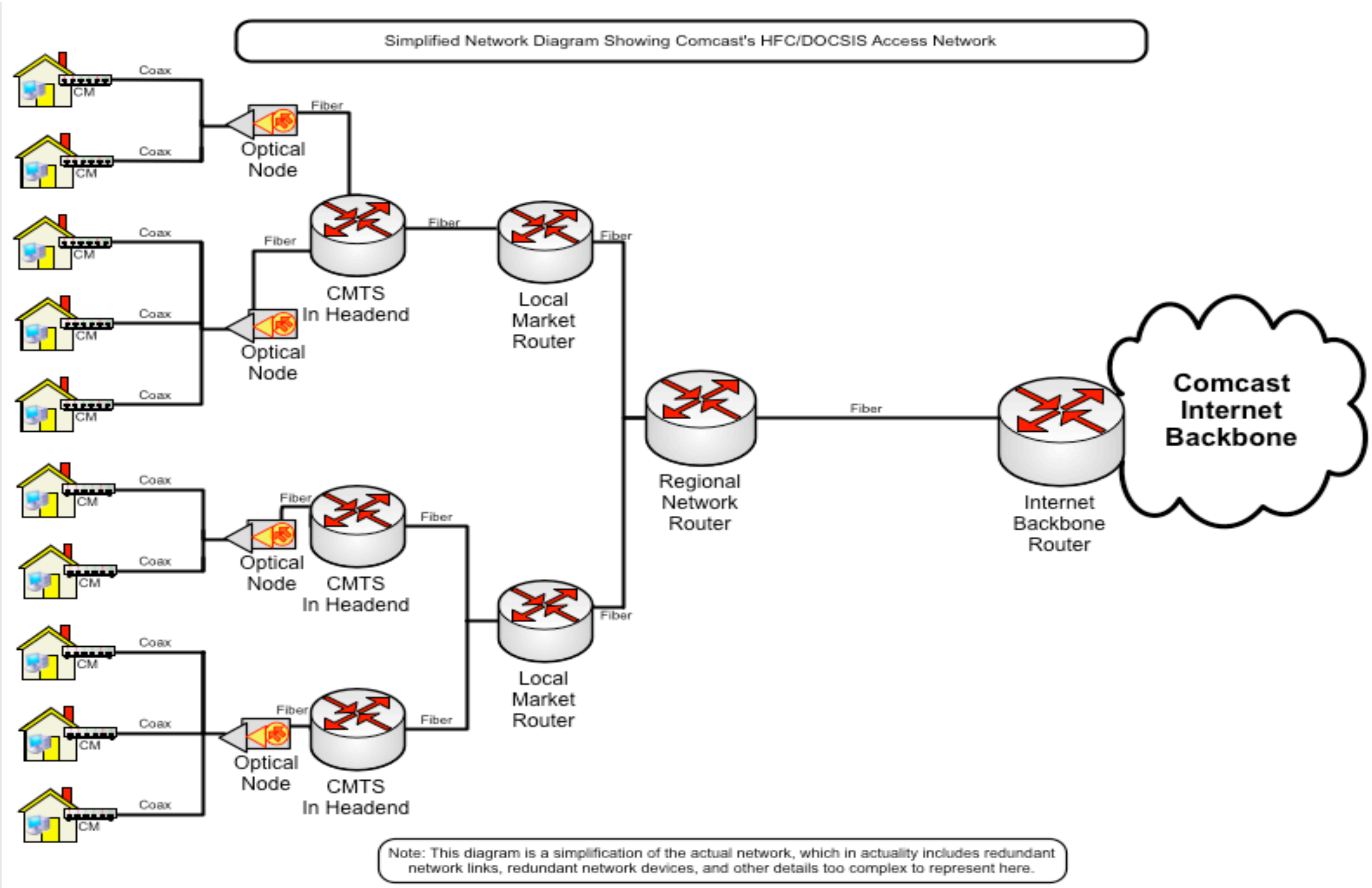
Source: Jefferies Research

Cable spectrum



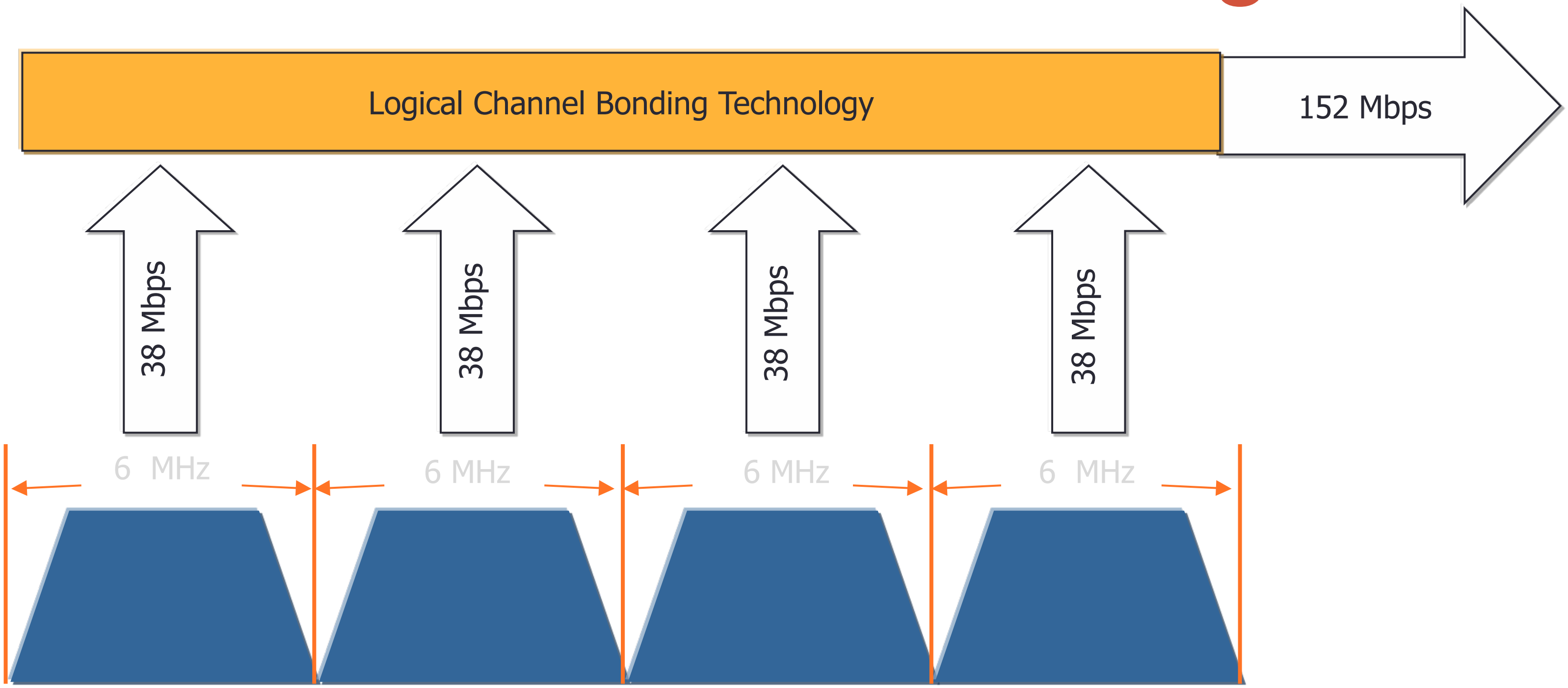
Source: Jefferies Research

Simplified access network diagram



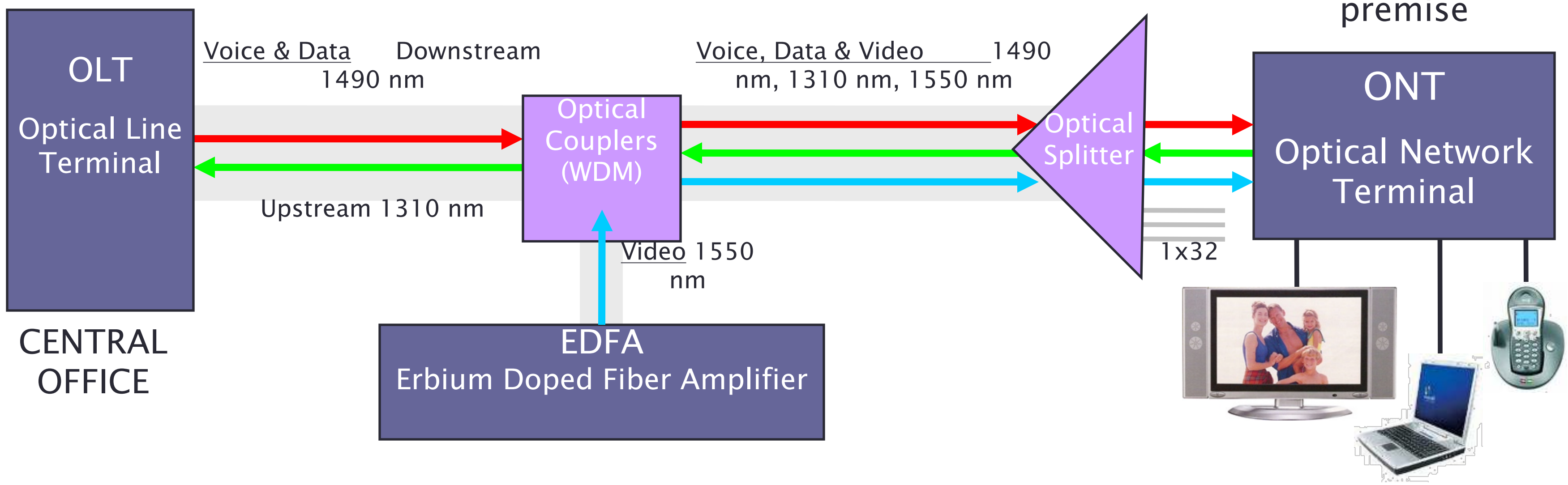
Jason Livingood (Comcast) FCC 2009

DOCSIS 3.0 channel bonding

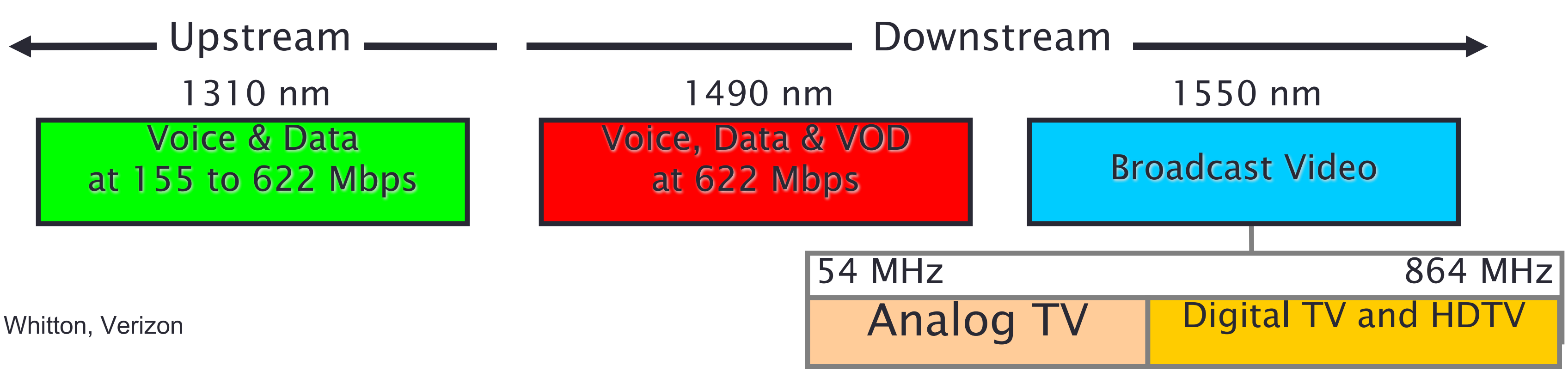


- DOCSIS 2.0 is limited to single channel's capacity
- DOCSIS 3.0 employs packet bonding across multiple channels
    - Initially will bond 4 channels
    - 8 channel-capable silicon coming soon
    - Upstream bonding in 2010
    - Increased speeds 100Mbps+

Verizon's FTTP architecture

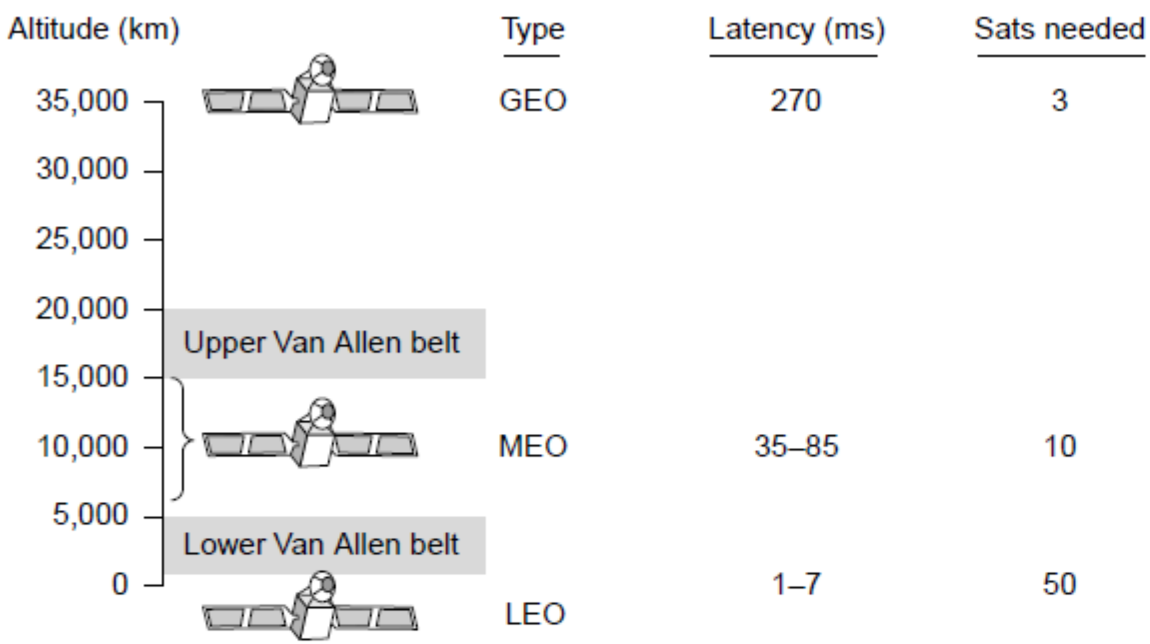


Bandwidth & Services



Brian Whitton, Verizon

Communication satellites

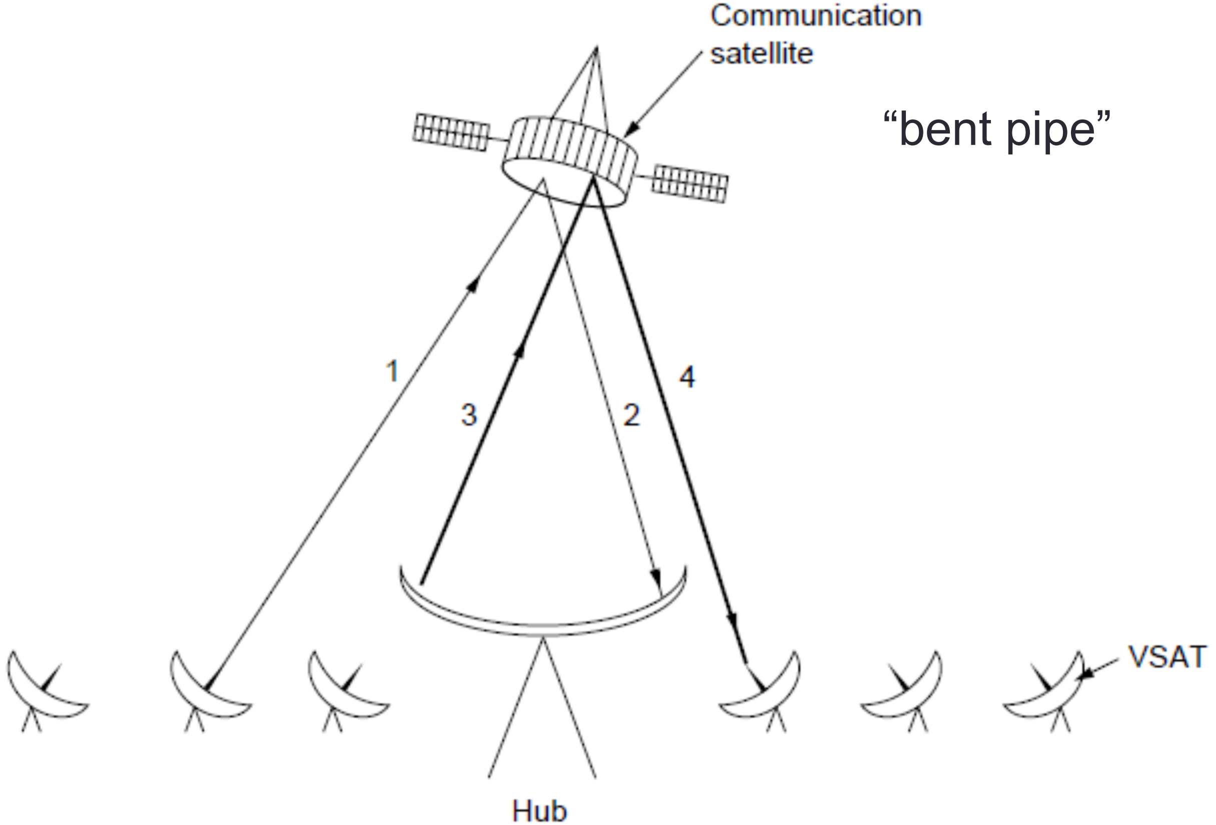


Communication satellites, some properties, including: altitude above earth, round-trip delay time, number of satellites for global coverage.

Satellite frequency bands

Band	Downlink	Uplink	Bandwidth	Problems
L	1.5 GHz	1.6 GHz	15 MHz	Low bandwidth; crowded
S	1.9 GHz	2.2 GHz	70 MHz	Low bandwidth; crowded
C	4.0 GHz	6.0 GHz	500 MHz	Terrestrial interference
Ku	11 GHz	14 GHz	500 MHz	Rain
Ka	20 GHz	30 GHz	3500 MHz	Rain, equipment cost

Geostationary satellites (2)

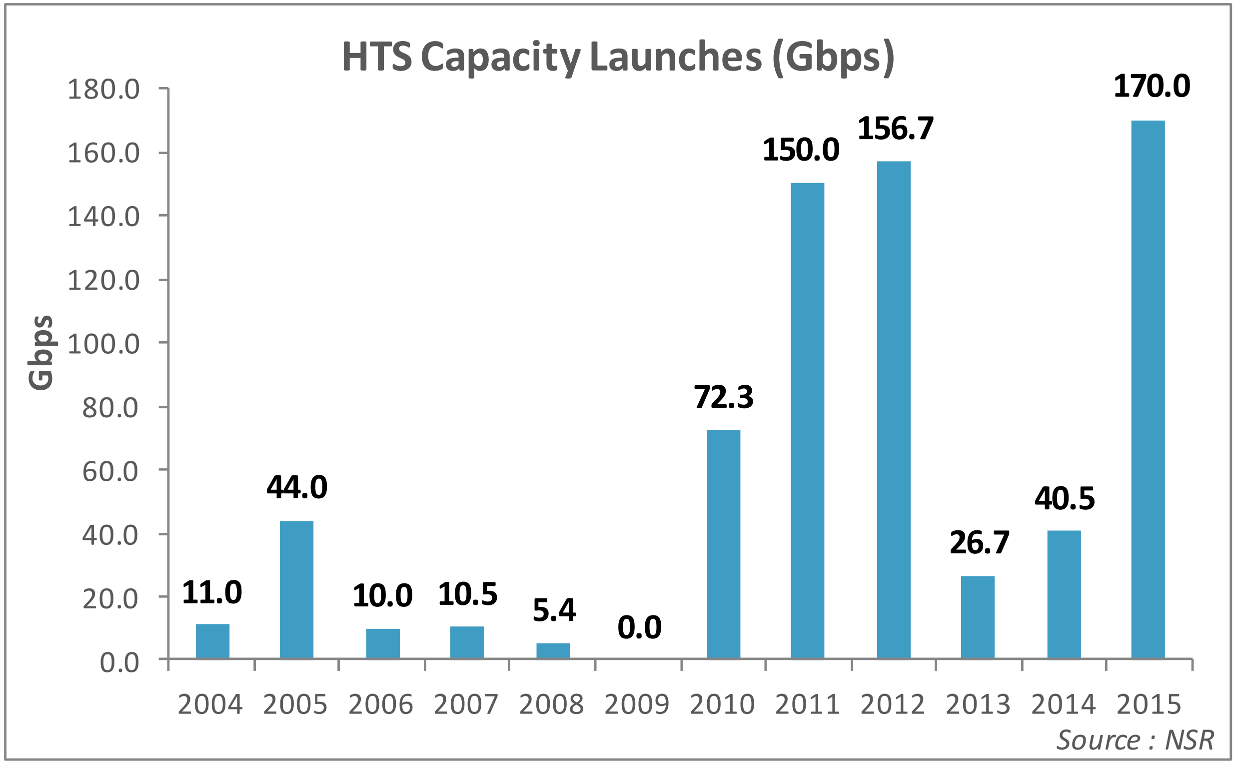


"bent pipe"

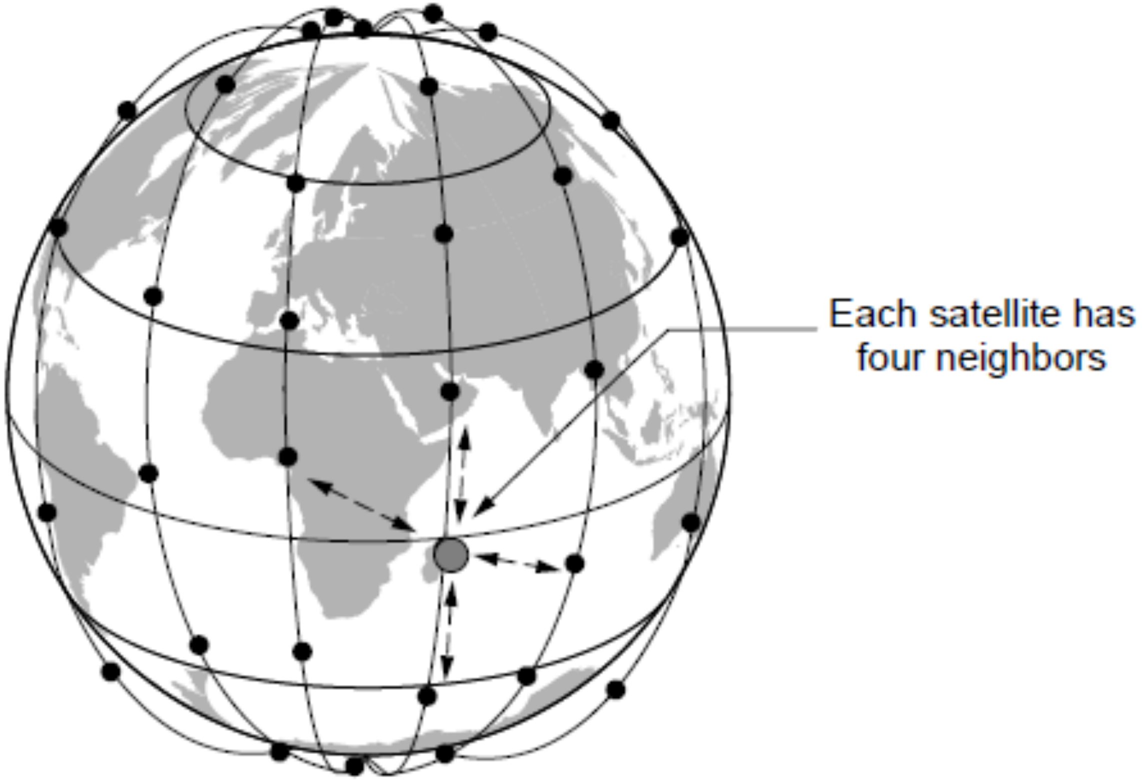
VSATs using a hub.

HTS launches per year

Dedicated HTS	Hybrid Payload HTS
Thaicom 4	Anik F2
WildBlue 1	AMC-15
Spaceway 3	AMC-16
Ka-Sat	Ciel-2
ViaSat-1	Hylas 1
Jupiter-1	Arabsat 5C
Inmarsat 5F2	YahSat 1B
Inmarsat 5F1	Hylas 2
Inmarsat 5F3	Hispasat AG1
NBN Co 1A	Express AM5
GSAT-11	Astra 2F
NBN Co 1B	Express AM6
	Amazonas 3
	Astra 2E
	Thor 7
	Astra 2G
	Jabiru-1



Low-Earth orbit satellites

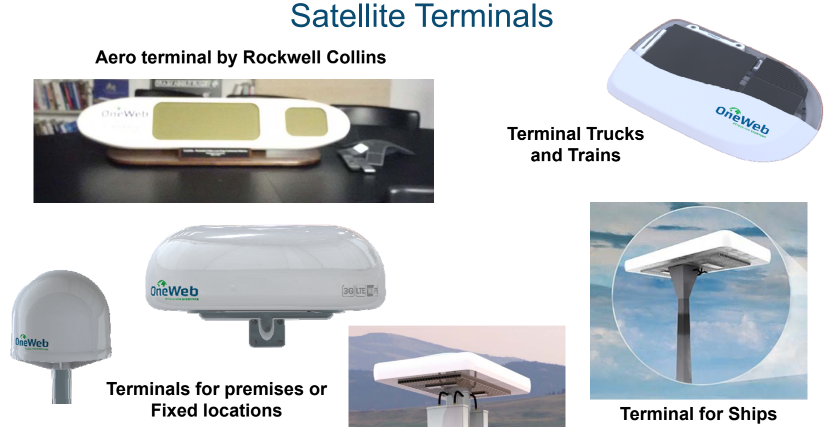


The Iridium satellites form six necklaces around the earth.

OneWeb (2018+)

- LEO – 1,200 km orbit
- 648 satellites in 18 orbital planes
  - 50-70 gateway sites
- Ku & Ka-band spectrum
- Service area: 1,080 by 1,080 km per satellite
  - 7.5 Gb/s

Satellite Terminals

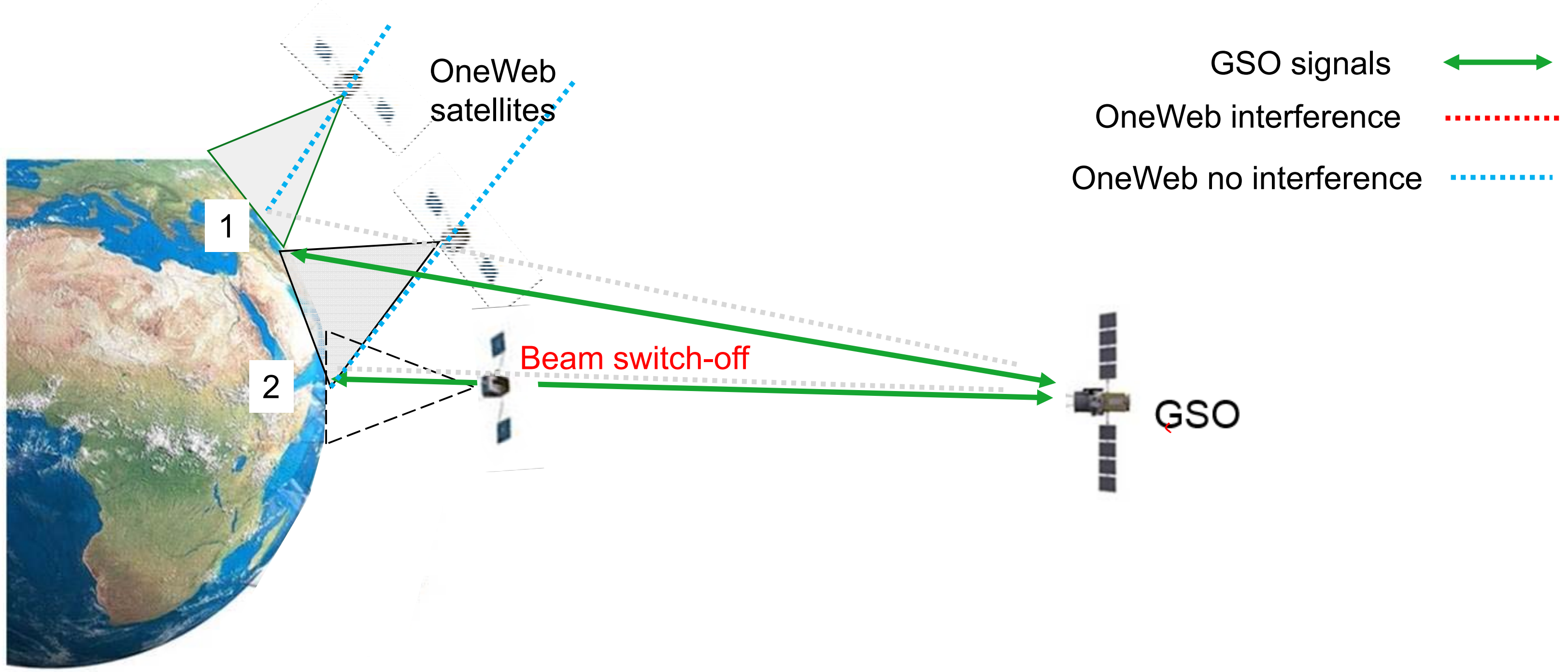


OneWeb presentation at *International Satellite Symposium 2016*

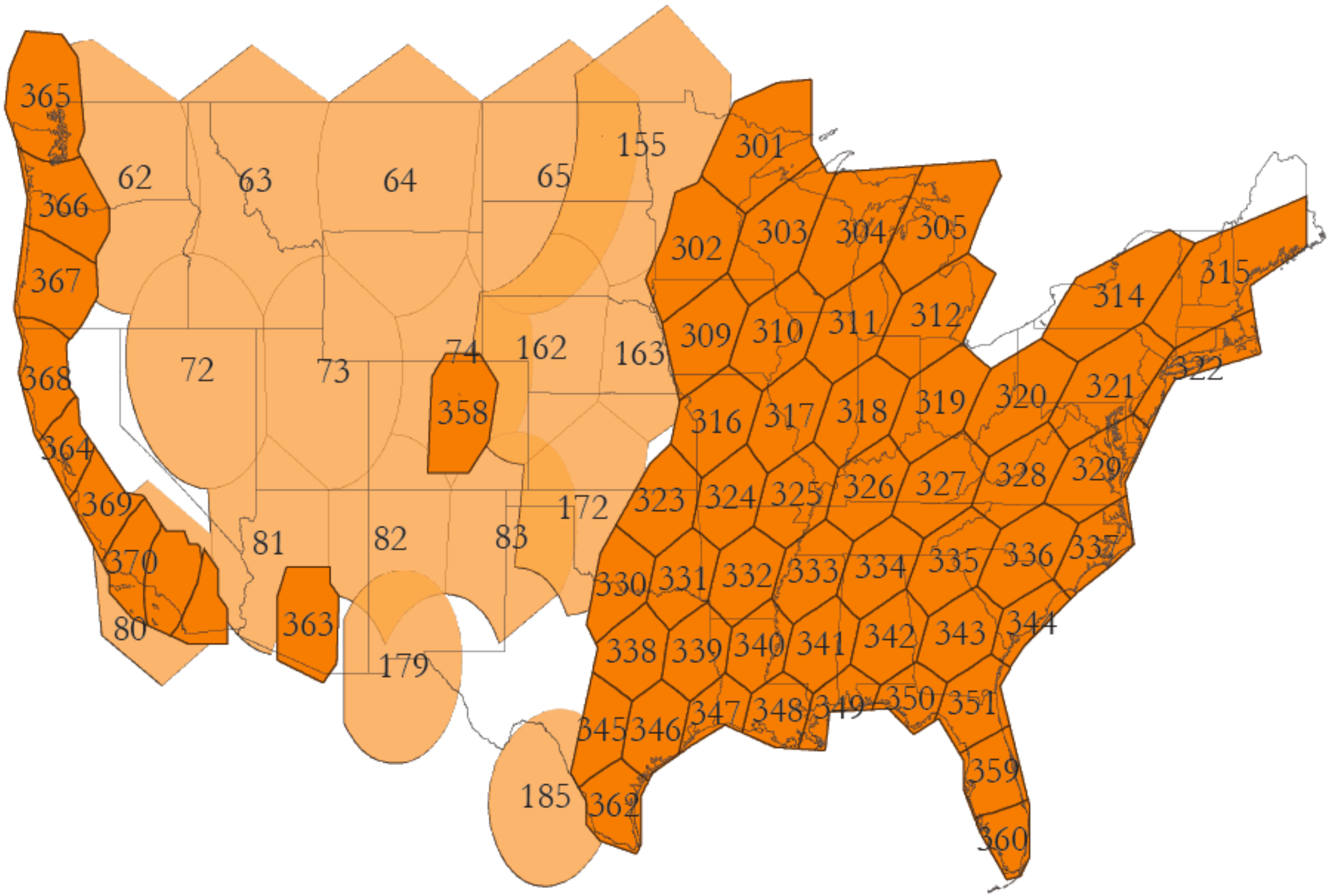
GSO protection

Novel Techniques to Protect GSO

- **With "progressive pitching" the satellite (patent pending)**



Exede beam map



http://www.wildbluetools.com/content/dealer/email/Beam_map-high-mid-low.html

Satellite

Advantages

- Near-universal geographic availability
  - low incremental cost
    - satellite terminal + installation
- Resilient after natural disasters
  - often used as backup

Disadvantages

- Latency
  - MBA 2014: RTT 671 ms
- Temporary disruptions
  - sun alignment
  - rain fade
- Capacity
  - Viasat-1: 140 Gb/s (for 300,000 customers)
  - usually, usage-capped

Oklahoma County, OK

Example: Exede satellite plans

LIBERTY 12	LIBERTY 25	LIBERTY 50
PRIORITY DATA[1]	PRIORITY DATA	PRIORITY DATA
12 GB	25 GB	50 GB
INCLUDES	INCLUDES	INCLUDES
Liberty Pass	Liberty Pass	Liberty Pass
Don't fear your data allowance	Don't fear your data allowance	Don't fear your data allowance
+	+	+
Free Zone	Free Zone	Free Zone
3 am to 6 am daily	3 am to 6 am daily	3 am to 6 am daily
$50/MO	$75/MO	$100/MO
+ LIBERTY PASS INCLUDED[1] Click to learn more	+ LIBERTY PASS INCLUDED[1] Click to learn more	+ LIBERTY PASS INCLUDED[1] Click to learn more
+ FREE ZONE INCLUDED Click to learn more	+ FREE ZONE INCLUDED Click to learn more	+ FREE ZONE INCLUDED Click to learn more
ORDER NOW	ORDER NOW	ORDER NOW

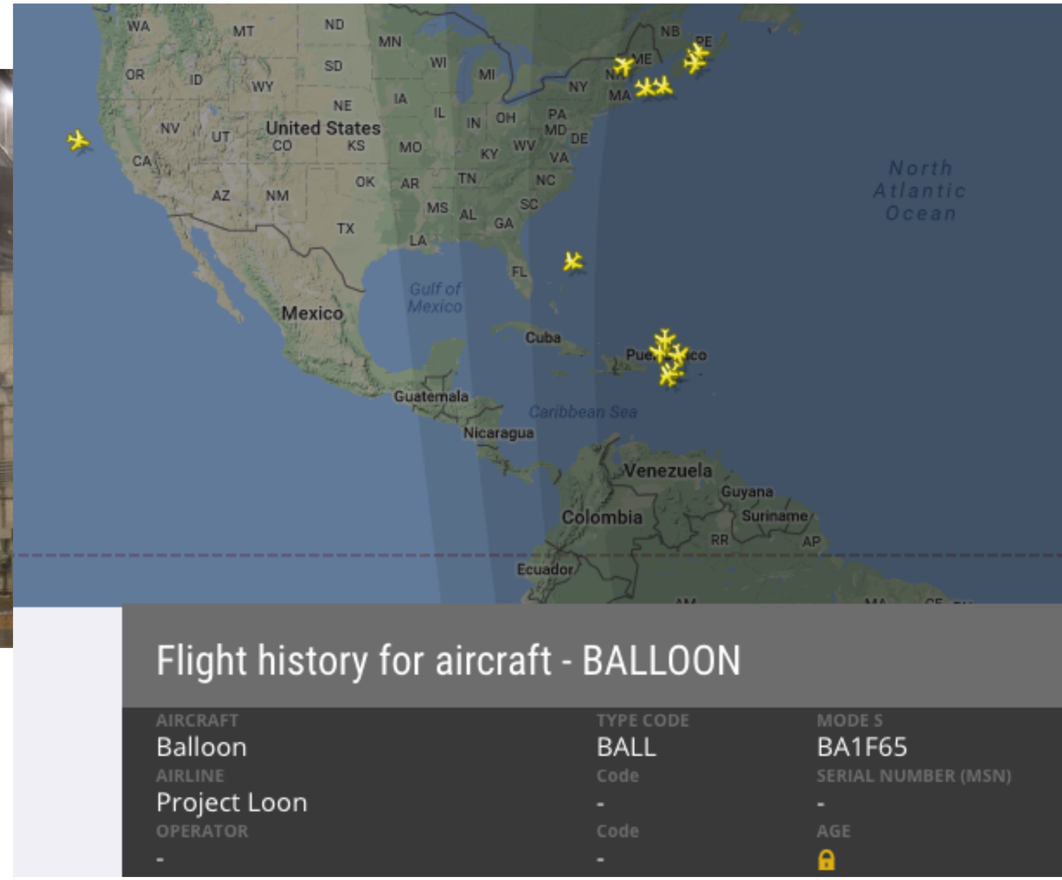
Double your Priority Data speed w/ **Boost 25**

UP TO 25 MBPS DOWNLOAD SPEED

$10/month on any plan

Built-in WiFi Router included

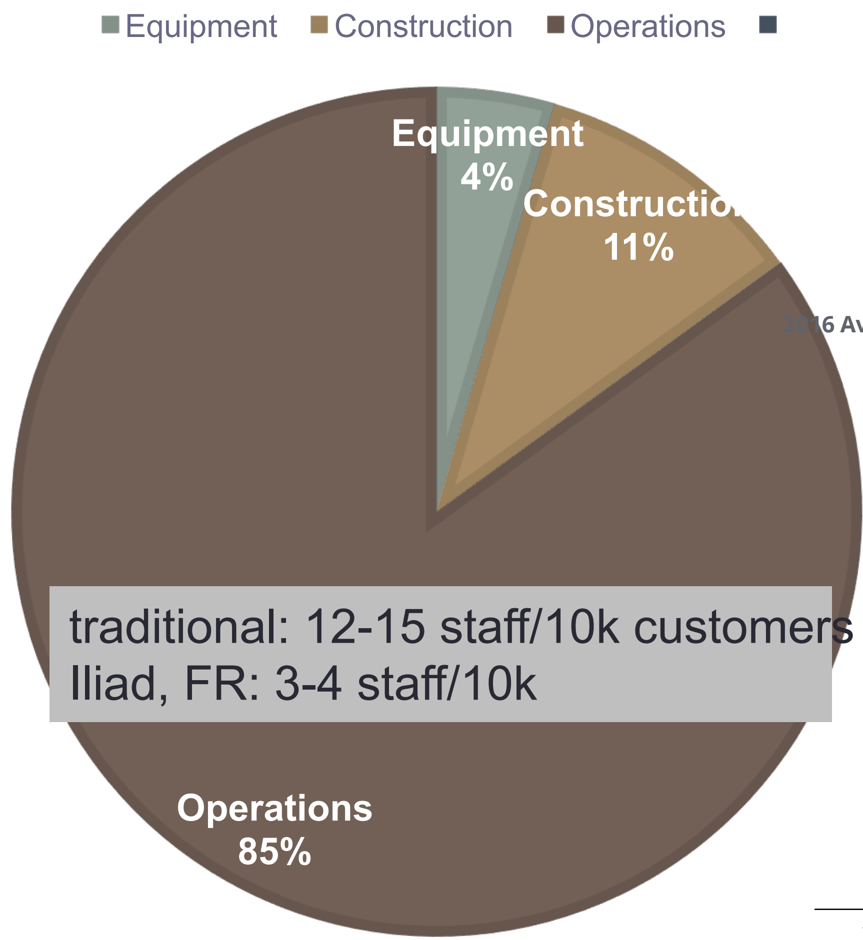
Project Loon



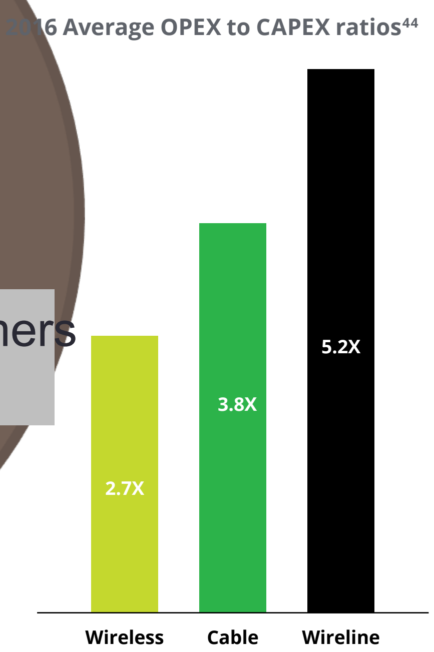
- LTE at 850 MHz
- solar powered
- wind layers
- < 20 km altitude

THE COST OF NETWORKS

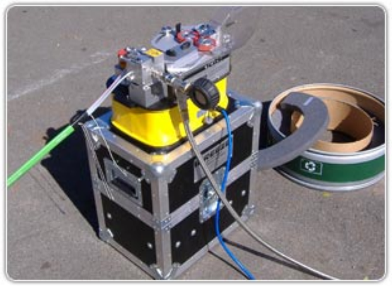
Network economics, (over)simplified

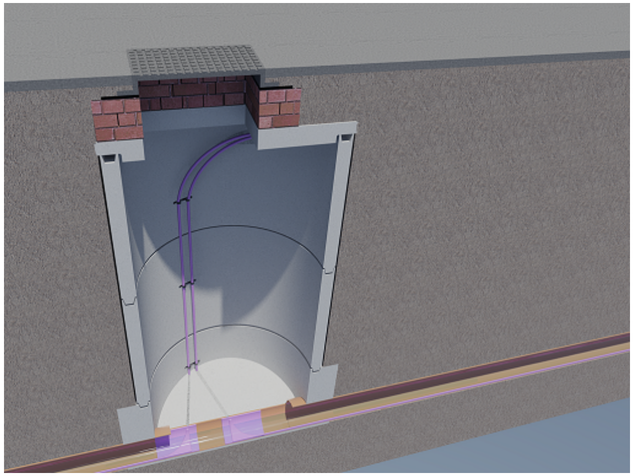


traditional: 12-15 staff/10k customers
Iliad, FR: 3-4 staff/10k



Fiber deployment





wastewater pipe
(3-5 km/week)

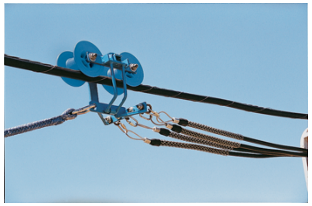
Broadband network cost - FTTP

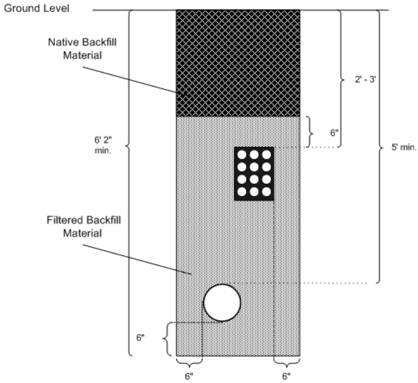
Category	Details	Outside plant
FTTP in existing right-of-way	All underground, not including drops or electronics	$1,200…$1,300 per passing
	40% aerial, 60% underground, not including drops or electronics	$1,000…$1,100 per passing
FTTP drops	Range of distances and complexity	$300…$700 per connected home

Crown Fibre Holdings (Govt. of New Zealand); provided by CTC

Broadband network cost – Fiber middle mile

Category	Details	Outside plant	Source
aerial, new attachment	Northeastern city municipal utility; 96% aerial, 4% underground; 87.6 miles	$30,000/mile	Public utility (actual cost)
aerial overlash	Major metropolitan area (U.S. east coast)	$15,000/mile	
buried	Mixed suburban/urban locations and pot/bore construction	$89,000/mile	Washington, D.C.-area BTOP project (actual cost)





Data provided by CTC

Middle mile cost example

Independent 2" Conduit Run for Three User Co-Location

LABOR

Category	Quantity	Unit	Low Cost/Unit	High Cost/Unit	Low Cost	High Cost
Design	5,280	FT.	$0.08	$0.10	$422	$528
Engineering and Permits	0	FT.	$0.25	$0.25	$0	$0
Railroad Crossing	0	LOT	$5,000.00	$15,000.00	$0	$0
Directional Boring for 2" Conduit	0	FT.	$8.00	$20.00	$0	$0
Directional Boring for 4" Conduit	0	FT.	$11.00	$25.00	$0	$0
Trenching for 24" - 36" Depth	5,280	FT.	$5.00	$12.00	$26,400	$63,360
Place Conduit	15,840	FT.	$1.00	$1.75	$15,840	$27,720
Place Inner Duct	0	FT.	$0.50	$1.50	$0	$0
Place Vault	33	EACH	$500.00	$750.00	$16,500	$24,750
Place Fiber in Conduit	15,840	FT.	$1.25	$2.50	$19,800	$39,600
Install Splice Enclosure	3	EACH	$300.00	$500.00	$900	$1,500
Splice Fiber	648	EACH	$12.00	$30.00	$7,776	$19,440
TOTAL LABOR					**$87,638**	**$176,898**
MATERIALS						
Category	**Quantity**	**Unit**	**Low Cost/Unit**	**High Cost/Unit**	**Low Cost**	**High Cost**
216 Count Fiber	18,216	FT.	$1.80	$2.50	$32,789	$45,540
Splice Kit	3	EACH	$500.00	$750.00	$1,500	$2,250
4" Conduit and Materials	0	FT.	$2.98	$3.50	$0	$0
2" Conduit and Materials	15,840	FT.	$0.88	$1.50	$13,939	$23,760
1" Inner Duct	0	FT.	$0.30	$45.00	$0	$0
Vault	33	EACH	$450.00	$600.00	$14,850	$19,800
Tax and Freight	1	LOT	$6,307.80	$9,135.00	$6,308	$9,135
TOTAL MATERIAL					**$69,386**	**$100,485**

CTC, 2009 (“Brief Engineering Assessment: Efficiencies available through simultaneous construction and co-location of communications conduit and fiber”)

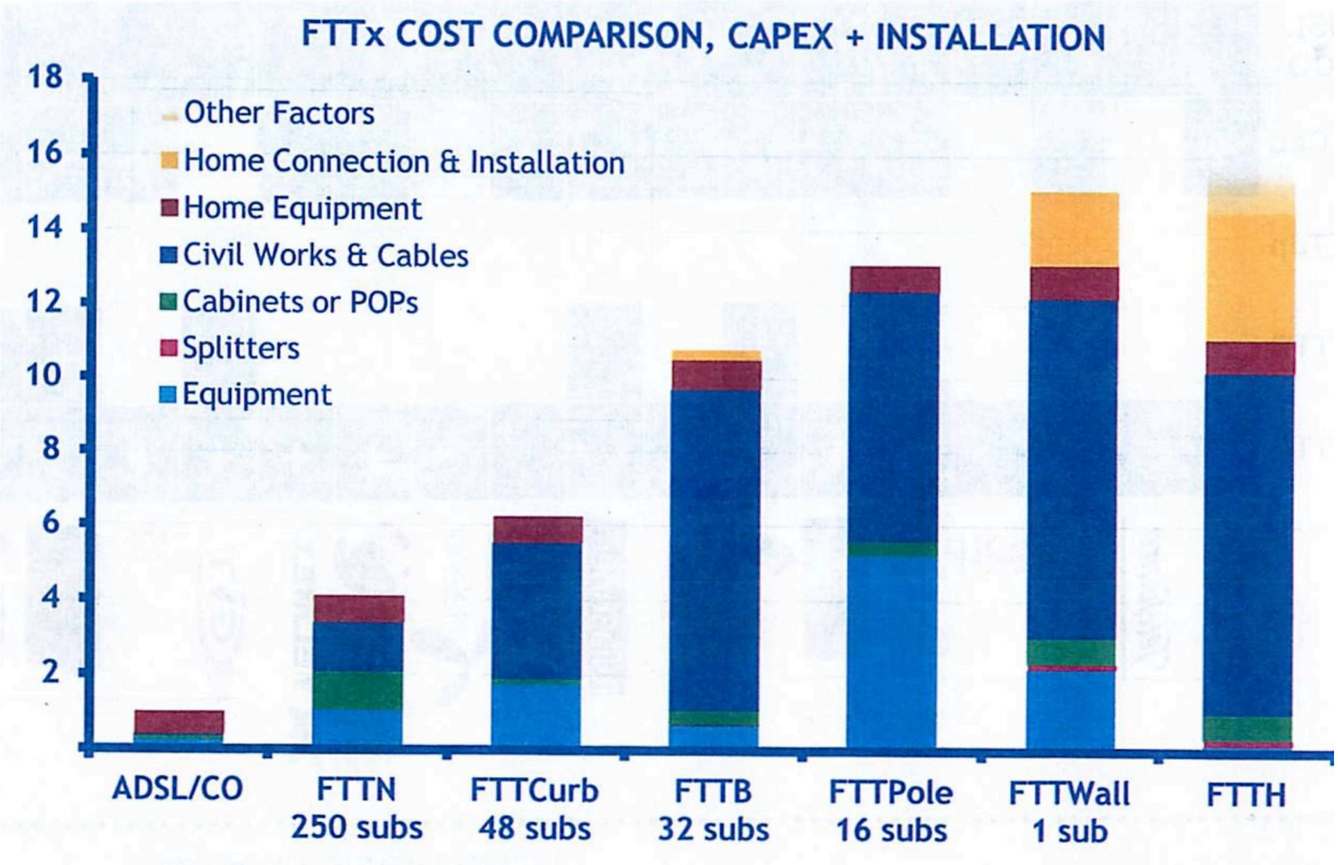
More fiber observations

- Fiber middle-mile cost: $50-70k/mile
- Fiber cost: 144 strands = $10k/mile, 48 strands = $4.7k/mile
- Common characteristics:
  - avoid active elements in network → power, maintenance → PON
  - recently: avoid anything except fiber (including splitters)
    - cf. wireless last mile approach
  - fiber home run, even if PON (Google Fiber, Stockholm)
- Fiber cost higher for buried, but cheaper if conduit or aerial
- Recent FTTH:
  - avoid indoor installation (cf. Verizon FiOS)
  - one box in home (ONT + 802.11ac), not ONT + MoCa STB

FTTH estimates

- Bell Alliant in Western Canada has now passed over half a million homes with fiber home, the largest deployment in North America after Verizon. Their latest financial report showed capex of less than $500 per home passed.
- Verizon reported costs fell below $700/home passed several years ago and headed to $600. Add the cost of actually installing a large fraction of those homes, and your cost per home passed by the network comes closer to $1,000.
- Installing each home at Verizon added $500-600. Digging lawns and drilling holes into the homes is labor intensive.
- Includes equipment whose price is rapidly dropping. Early Verizon gear cost $300-400/home, but today they are probably paying half that.
  - Very large fiber builds in China are paying less than $100/home.

FTTx cost vs. DSL



Alcatel-Lucent, 2013

Capital investment

Company	Revenue	Capital expenditures	%
Comcast (US) [3Q14]	$11.04B	$1.644B	14.9
Telekom (DE) [3Q14]	€15.6B	$2.58B	16.5
Safaricom (KE) [H1FY15]	Ksh 79.34B	Ksh 12.37	15.5

Comcast's Q2 2014 Capital Spending Trends

Category	Growth CapEx ($ mil.)	% of Total (%)	Maintenance CapEx ($ mil.)	% of Total (%)	Total CapEx* ($ mil.)	% of Total (%)
Consumer Premises Equipment	668	65	72	16	740	50
Network Infrastructure	107	10	287	64	394	27
Support Capital	48	5	89	20	137	9
Commercial	209	20	0	0	209	14
Total*	**1,032**	-	**448**	-	**1,480**	-

As of Aug. 2014. * Total excludes $13 million in discretionary capital. Total including discretionary spending was $1,493 mil. Source: Comcast.

Accidental broadband

DSL patents — 1988-1991

94.2% of US households have phone service — 1993

G.992.2 ADSL — 1999

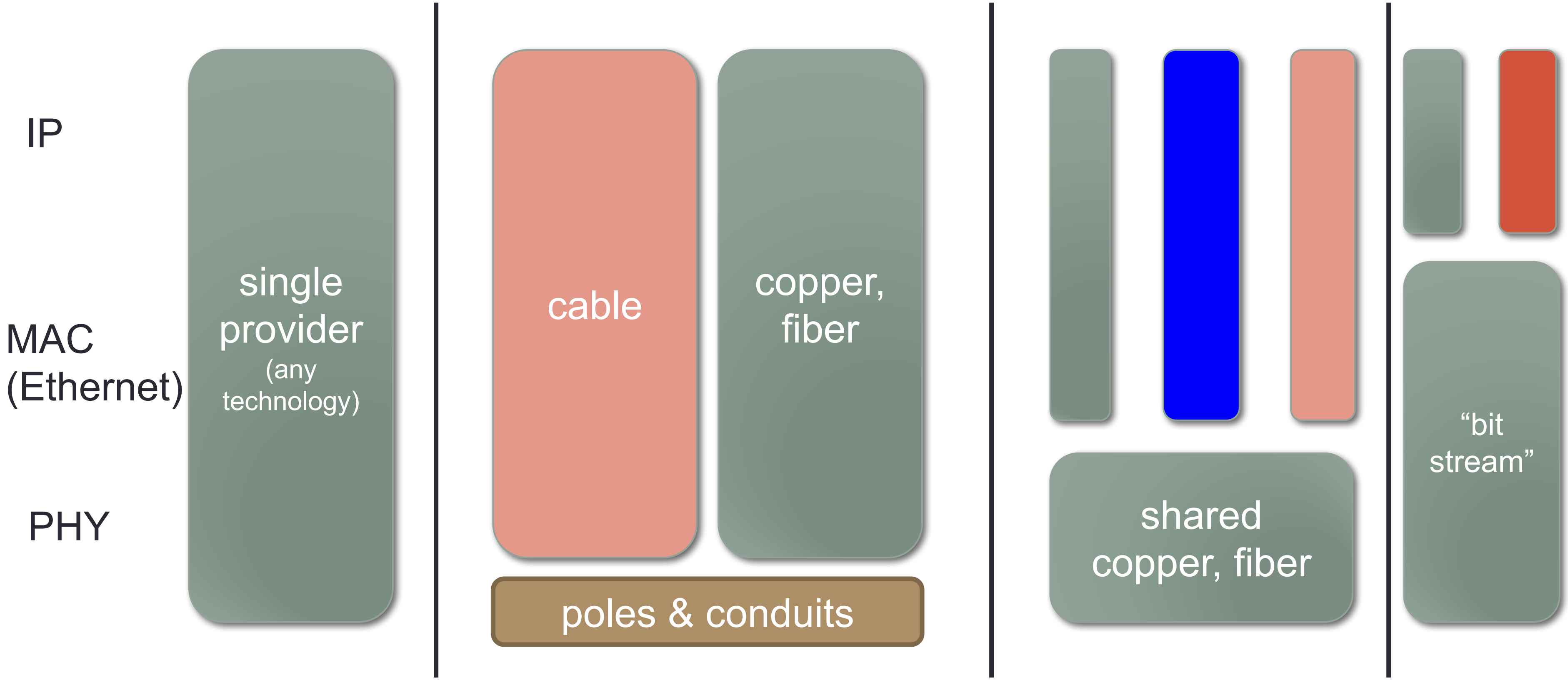
62.1 million US households have cable TV — 1995

DOCSIS 1.0 (40M/1M) — 1997

“peak CATV”: 82% of HH — 2008

DOCSIS 3.1 (10G/1G) — 2016

Network competition models



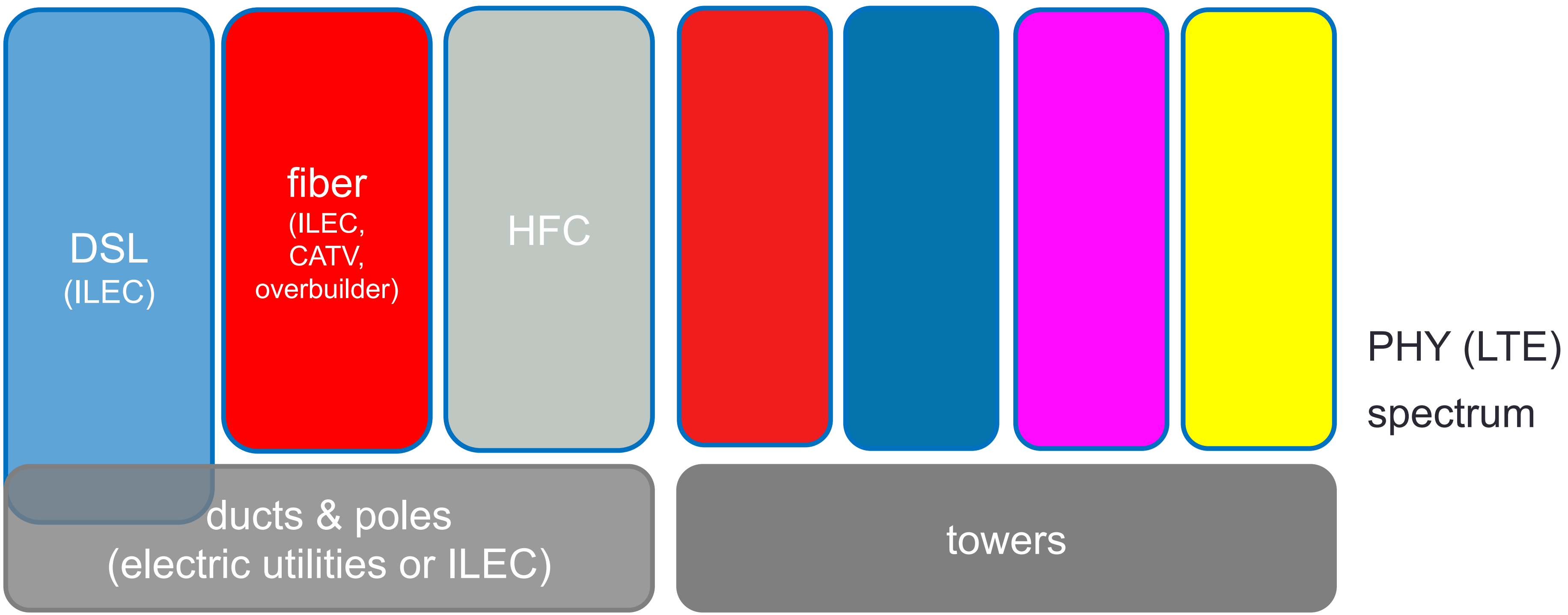
- regulated: pricing? behavior?
- how many entrants? where?

margin squeeze

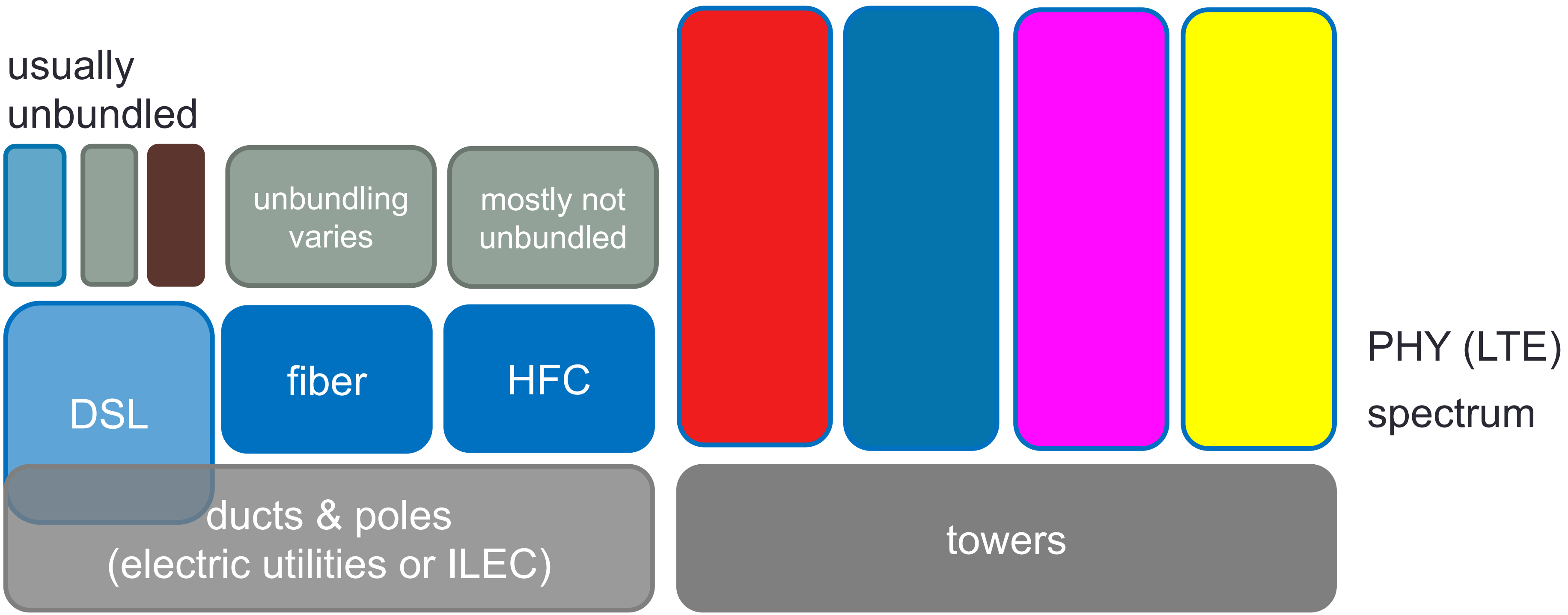
sharing (incumbent + new entrant) vs. neutral third party

Sharing models: US

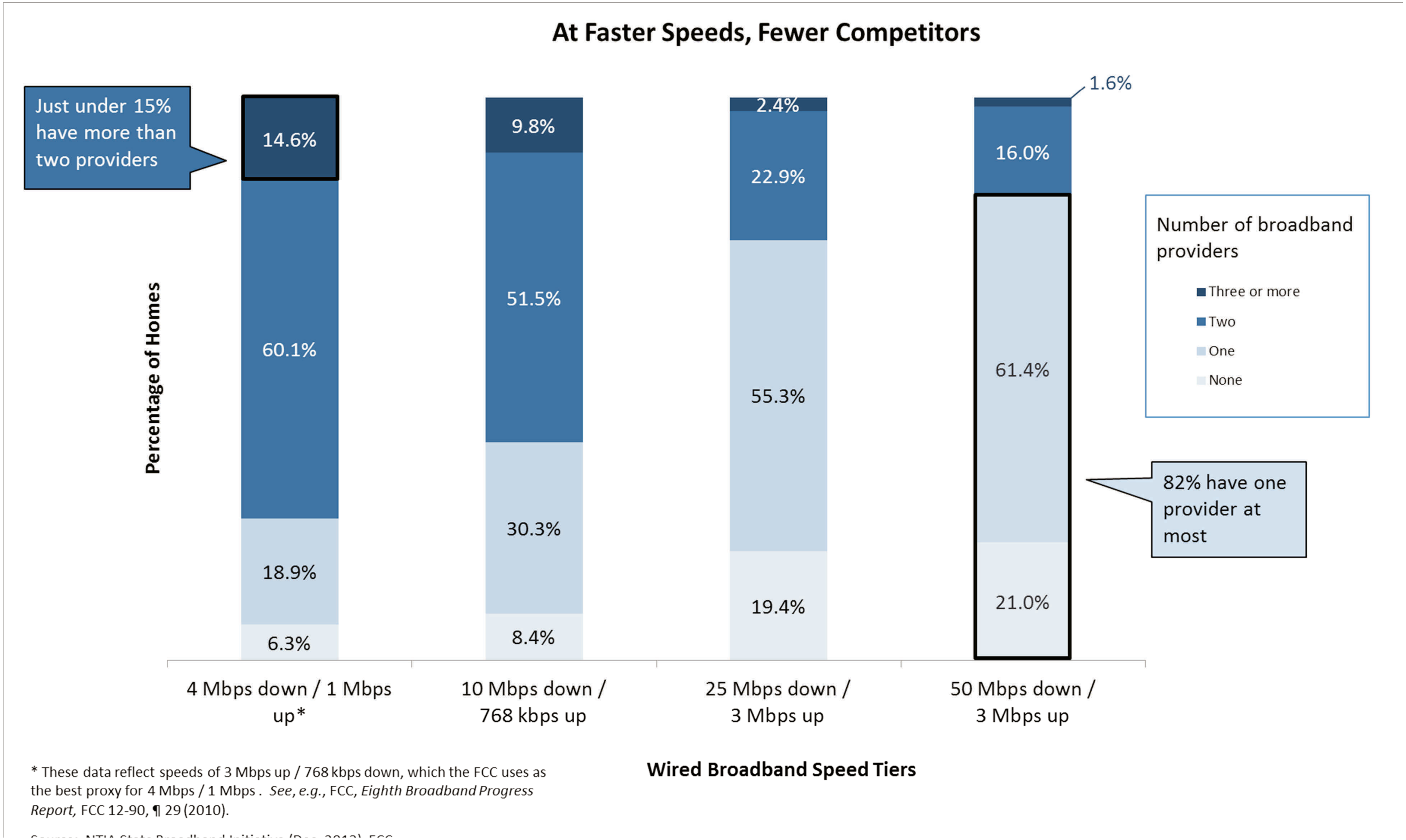
+ *WISP & satellite*



Sharing models: Canada, Europe, Australia



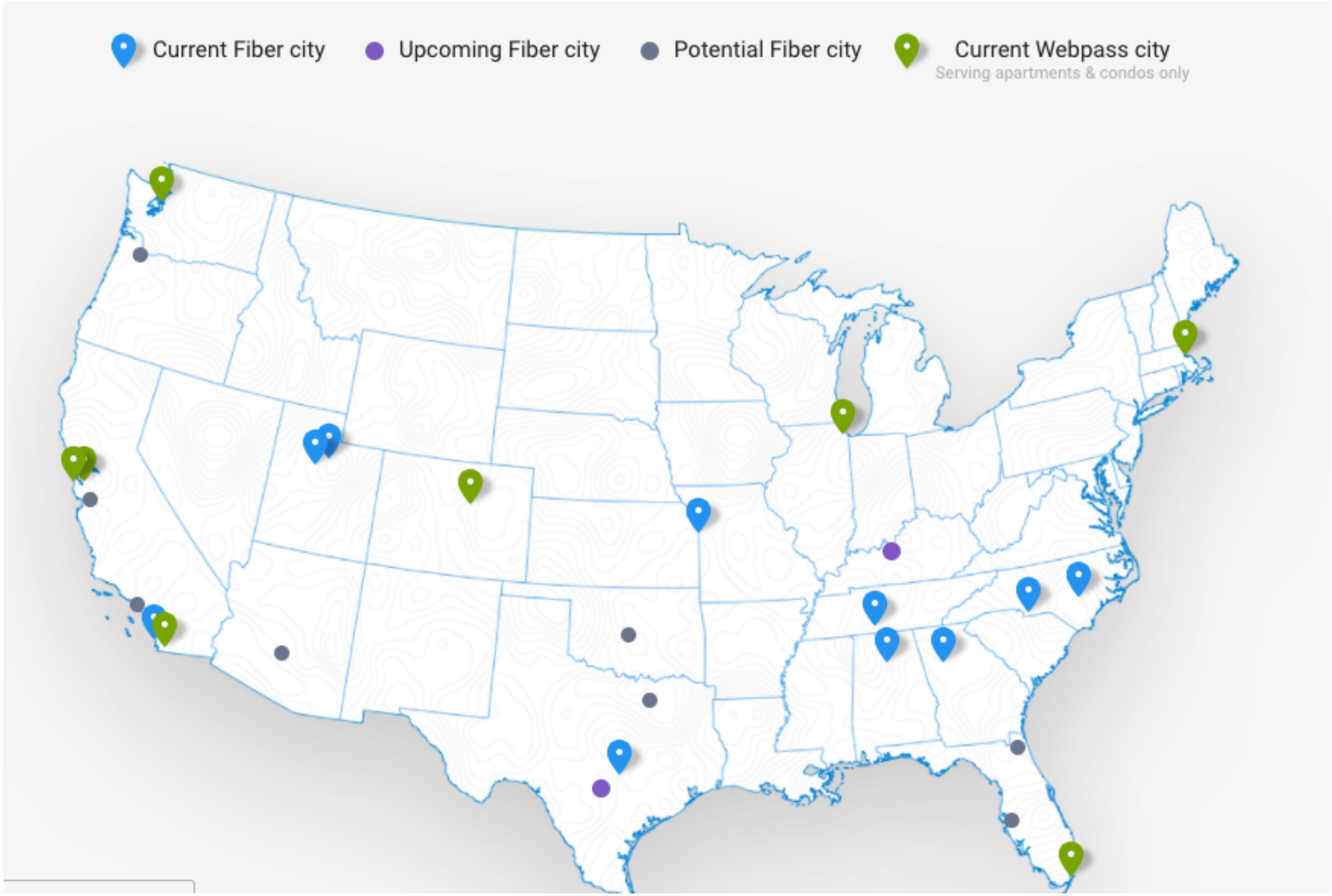
Broadband competition challenges



The difficulty of competition

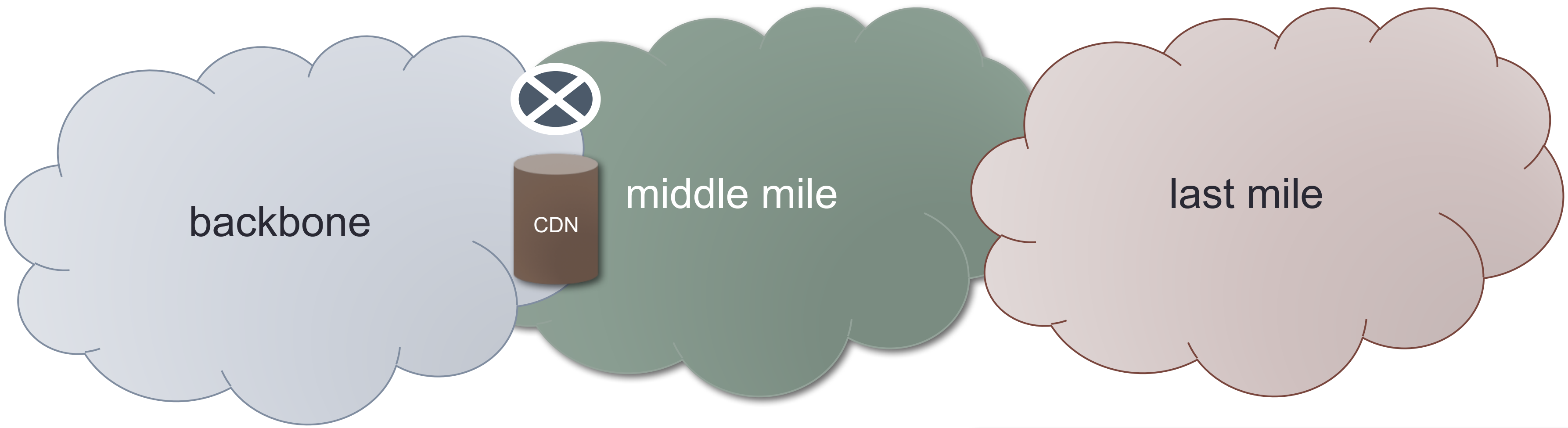
- Static vs. dynamic (new entrants)
  - existing, converging infrastructures
    - coax cable + copper + wireless
- Difficulties for new entrants (“overbuilder”)
  - capital investment vs. amortized network
  - legal barriers
  - customer acquisition (“sticky” customers)
  - incumbent pricing

Google Fiber



Network costs

yes, but mostly electronics



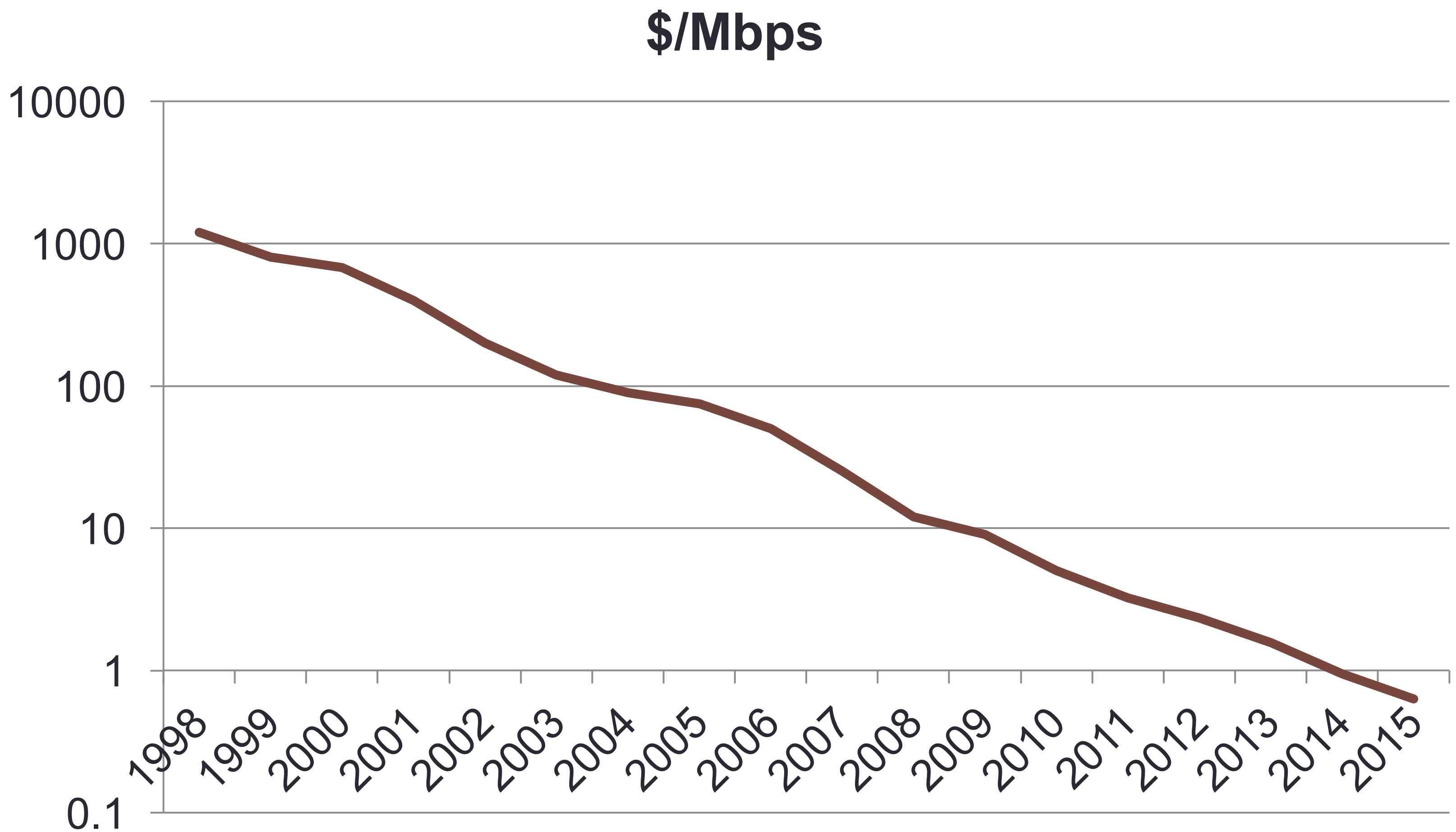
largely unaffected by video

ISP-owned vs. leased!

lack of IXPs in LDCs!

DSL	no
HFC	homes/service node
fiber	no
cellular	densification

Transit prices



http://drpeering.net/white-papers/Internet-Transit-Pricing-Historical-And-Projected.php

Bandwidth costs

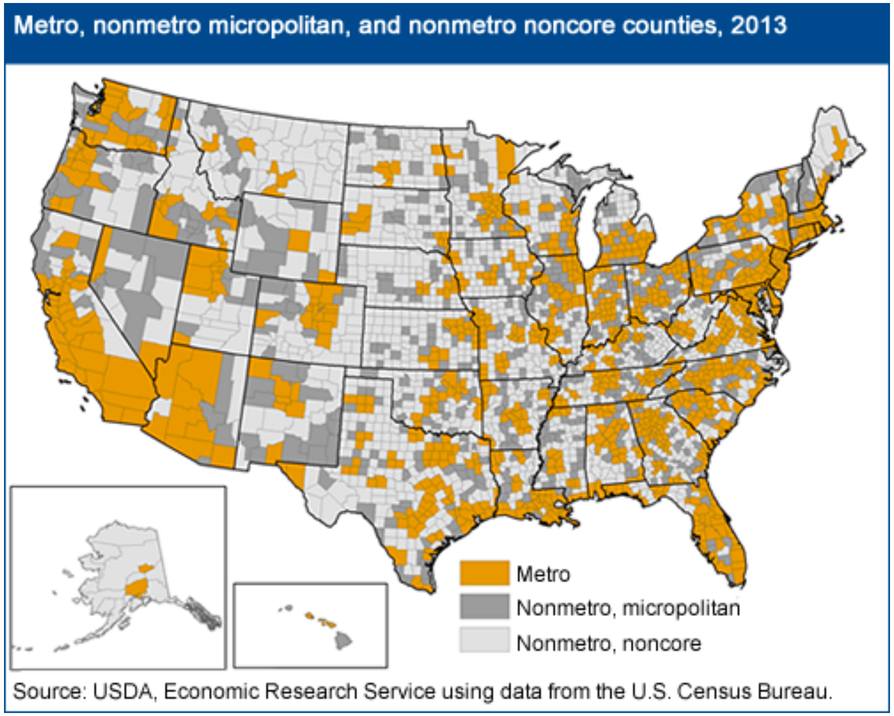
- Amazon EC2
  - $50 - $120/TB out, $0/TB in
- CDN (Internet radio)
  - $600/TB (2007)
  - $7-20/TB (Q1 2014 – CDNpricing.com)
- NetFlix (7 GB DVD)
  - postage $0.70 round-trip → $100/TB
- FedEx – 2 lb disk
  - 5 business days: $6.55
  - Standard overnight: $43.68
  - Barracuda disk: $91 - $116/TB
- DVD-R (7 GB)
  - $0.25/disk → $35/TB

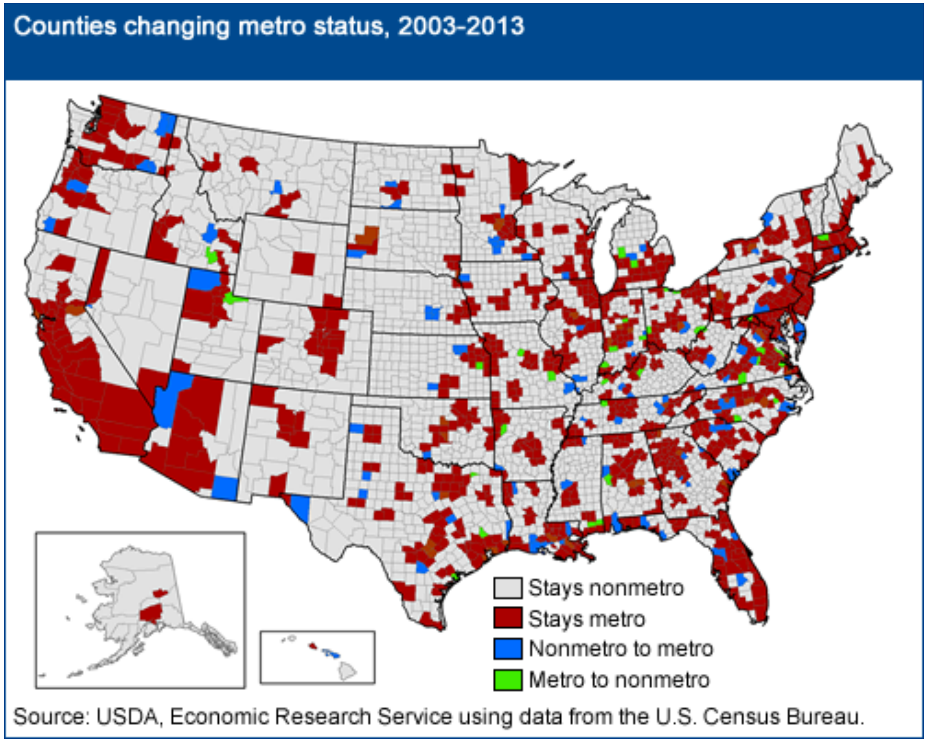
RURAL BROADBAND

What is rural?

- Census:
  - Urban = Urbanized Areas (UAs) of 50,000 or more people
    - OR Urban Clusters (UCs) of **2,500 to 50,000** people.
    - core of population density of 1000 people/mi^2
      - all of NJ: 1210 / mi^2
  - Rural = everywhere else
- OMB:
  - Metropolitan Statistical Areas (MSAs): >= one urbanized area of >= 50,000 population, plus adjacent territory that has a high degree of social and economic integration with the core as measured by commuting ties.
  - Micropolitan Statistical Areas: >= one urban cluster of at least 10,000 but less than 50,000 population, plus adjacent territory that has a high degree of social and economic integration.
- USDA
  - based on counties

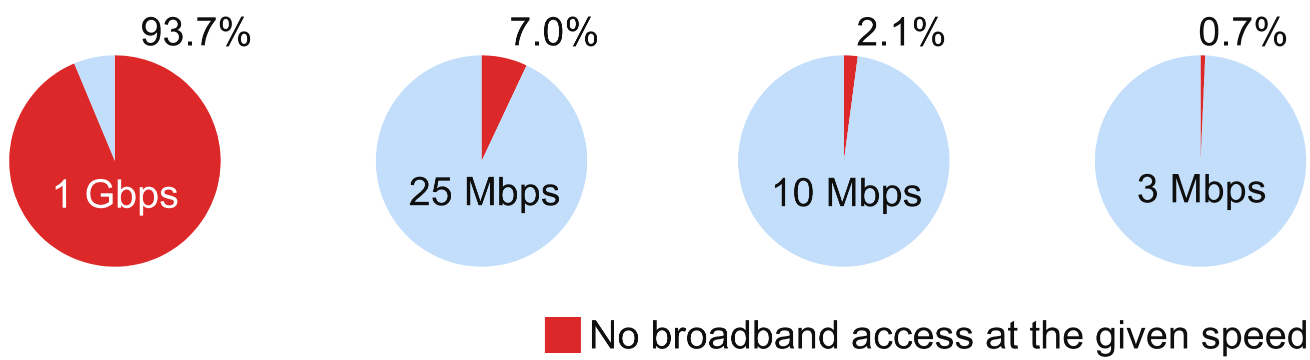
Rural areas (USDA)

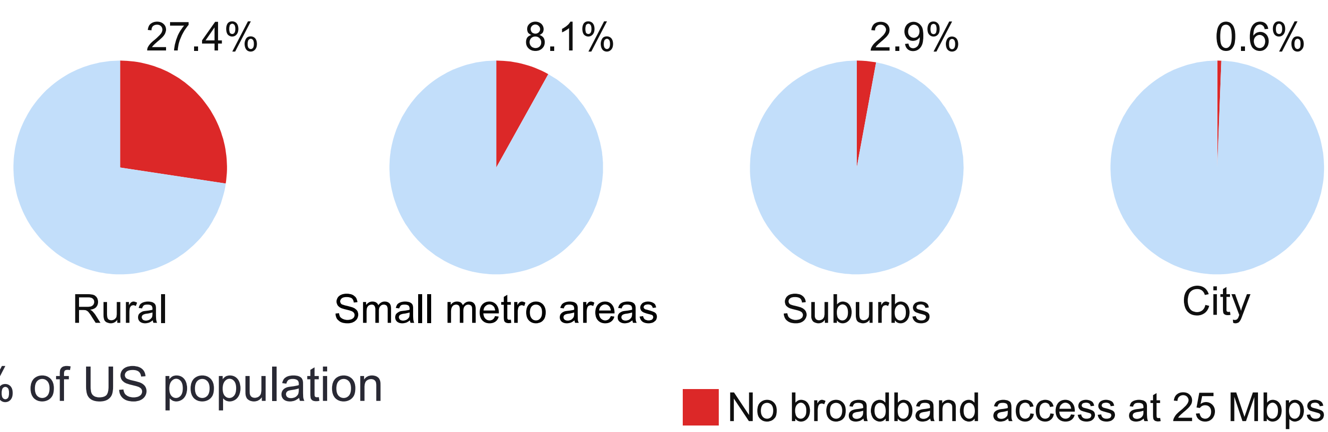




Broadband access by speed & geography

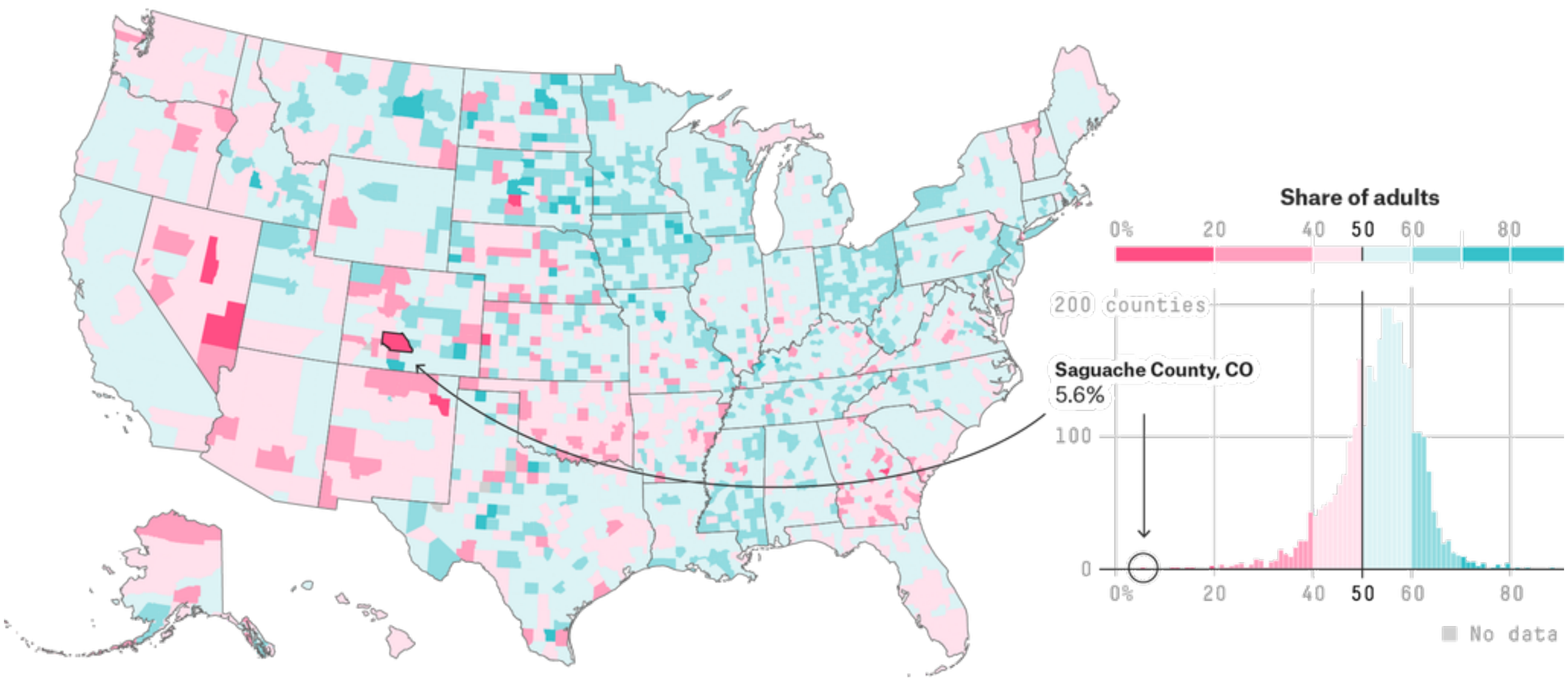
BROOKINGS





15% of US population

Rural broadband US



County shares are estimated using data from a 1 percent sample of 240 million voting-age Americans provided by Catalist, an election data firm. Internet connections faster than dial-up include those via DSL, cable, fiber-optic, satellite, etc.

FiveThirtyEight

SOURCE: ARIZONA STATE UNIVERSITY'S CENTER FOR POLICY INFORMATICS

Rural electrification

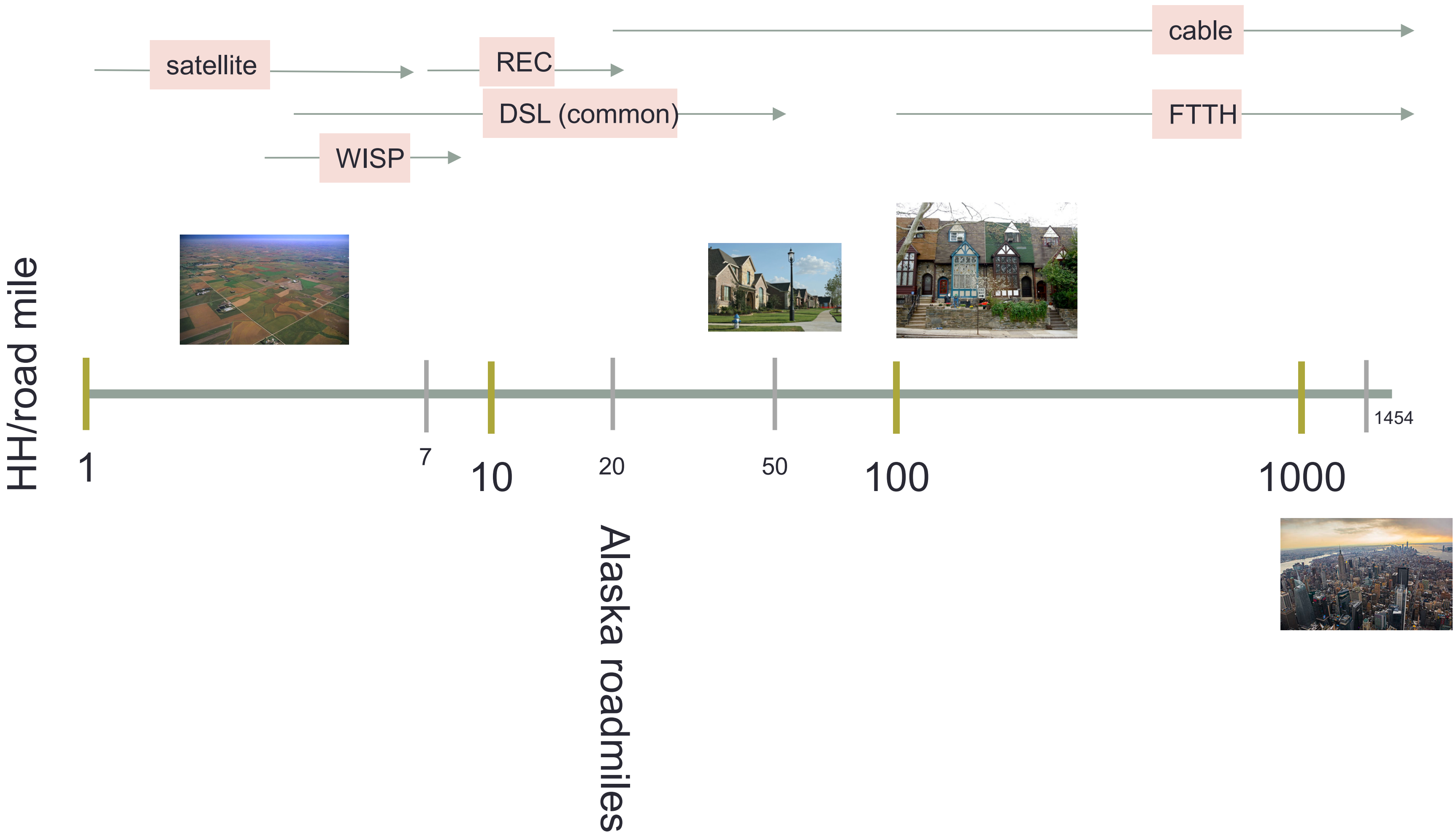
- Early 1920s, between 2 and 3% (likely less)
  - 1921: DC had 98.2%, MA 97.8%
- "In 1935, only 10.9% of American farms (744,000) enjoyed central station power, compared with Germany and Japan at 90%, France between 90 and 95%, and New Zealand at 60%."
- "In 1940, just four and a half years after Roosevelt signed Executive Order No. 7037 (followed by 1936 "Rural Electrification Act"), 25% of American farms had been electrified."
- 1950: 90% had been electrified nationally
- Today: 850 distribution coops serving 14 M homes

Rural electrification

- “In 1935, Morris Llewellyn Cooke, a mechanical engineer who had devised efficient rural distribution systems for power companies in New York and Pennsylvania, had written a report that detailed a plan for electrifying the nation's rural regions. Appointed by Roosevelt as the REA's first administrator, Cooke applied an engineer's approach to the problem, instituting what was known at the time as "scientific management"—essentially systems engineering. Rural electrification became one of the most successful government programs ever enacted. Within 2 years it helped bring electricity to some 1.5 million farms through 350 rural cooperatives in 45 of the 48 states. By 1939 the cost of a mile of rural line had dropped from $2,000 to $600. Almost half of all farms were wired by 1942 and virtually all of them by the 1950s.”
- Cost of aerial **fiber** installation: $14k/mile material, $39k/mile installation (Singer, 2017)
- USDA loans at 5% (hardship rate) for telecom
  - but currently Treasure rate is lower (2.81% for 30 years)
  - others at rates equivalent to municipal bonds

$10,958
in 2017

Density determines network choices



Rural deployment options

Technology	Capacity in rural areas (typical)	Advantage	Disadvantage
DSL	< 5 Mb/s	mostly deployed	speed increase requires active components deep in network
4G LTE	~ 5 Mb/s	existing deployment, MF II	limited capacity (current avg.: 2.1 GB/month)
5G (3.5 GHz, not mmWave)	depends on deployment model	saves fiber drop	spectrum OpEx
satellite (current geo)	12 Mb/s nominal	no incremental deployment cost	expensive, capacity-limited, latency
HFC ("cable")	25-100 Mb/s	low upgrade cost to 1 Gb/s+	85% of households
FTTH & FTTC	100 Mb/s – 1 Gb/s	20 year life time passive outside plant	cost to deploy

COST RECOVERY

Consumer expenditures

"Americans spent $116 more a year on telephone services in 2011 than they did in 2007, according to the Labor Department, even as total household expenditures increased by just $67.

Meanwhile, spending on food away from home fell by $48, apparel spending declined by $141, and entertainment spending dropped by $126. The figures aren't adjusted for inflation." (WSJ 2012)

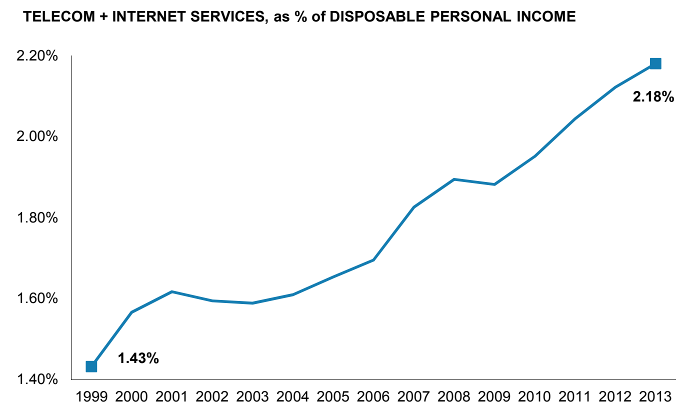
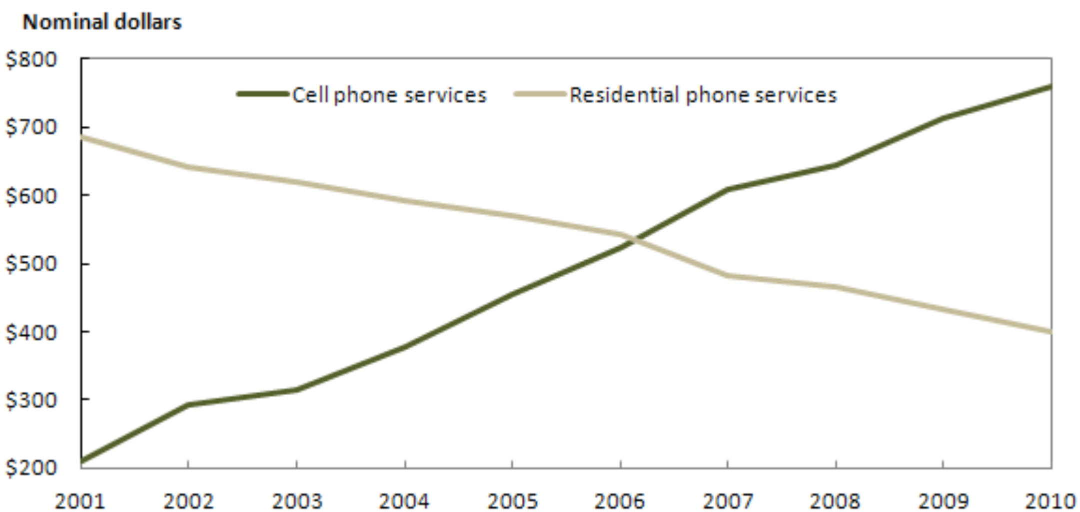


Chart 1. Average annual expenditures on cell phone and residential phone services, 2001–2010



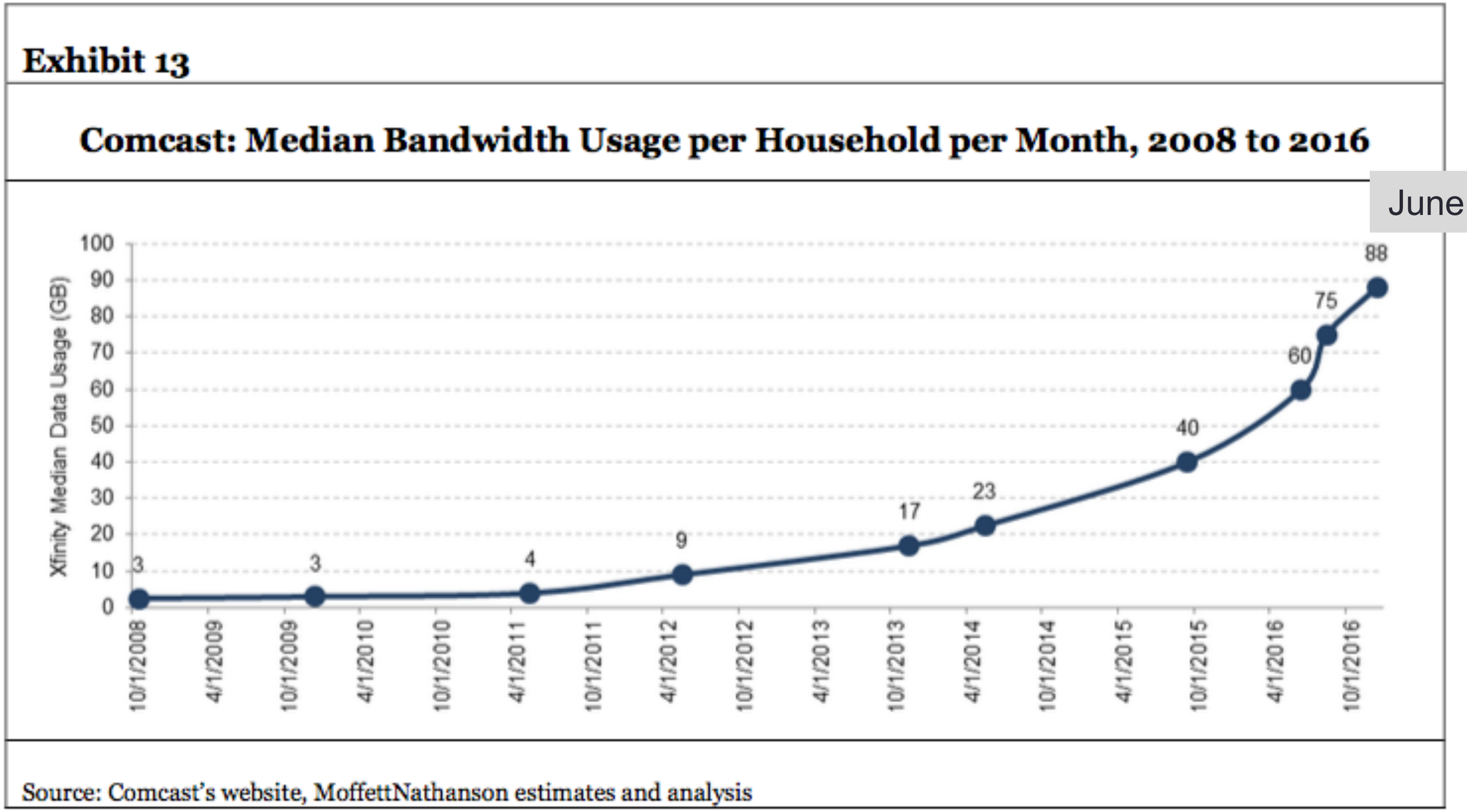
SOURCE: U.S. Bureau of Labor Statistics, Consumer Expenditure Survey

The value of bits

- Technologist: A bit is a bit is a bit
- Economist: Some bits are more valuable than other bits
  - e.g., $(email) >> $(video)

Application	Volume	Cost per unit	Cost / MB	Cost / TB
Voice (13 kb/s GSM)	97.5 kB/minute	10c	$1.02	$1M
Mobile data	5 GB	$40	$0.008	$8,000
MMS (pictures)	< 300 KB, avg. 50 kB	25c	$5.00	$5M
SMS	160 B	10c	$625	$625M

Problem likely capacity, not speed



June 2017: 100 GB

The challenges of service differentiation

Method	Used by	Advantage	Drawbacks	Customer dislike estimate
Speed tiers	C, DSL	Differentiates basic usage modes	Less effective above 10 Mb/s	😦
Usage-based charging (caps, metered)	M, (C, DSL), LD	• heavy vs. light users • encourages Wi-Fi use	• complaints about meter accuracy • adaptive applications (4G bill shock) • pay for ads • hard to predict	😦😦😦
Application-based charging	M	• Easier to predict • Business model	• Affects content competition • barriers to entry	😦😦😦
Differentiated privacy	AT&T, NetZero	• Full functionality	• Low-income users may not be attractive to advertisers	😦 or 😦😦😦

The challenges of service differentiation

Method	Used by	Advantage	Drawbacks	Customer dislike estimate
Priority	?	Better experience for VoIP	Other experience must be bad → economy class in airline	?
Time-of-day	LD, Sat	• Approximates congestion • Easy to understand	• Not optimally efficient • Possible bill shock	😦😦
Congestion-based	?	Encourages time shifting	• Limited shift • Unpredictability	😦😦😦😦

The words you won't say on your deathbed are, "If only I had spent more time watching the bandwidth meter (or phone bill)."

Cable TV vs. Internet

- Lots of advocates of "fairness" for metering
- Very few advocate scaling the monthly TV fee (Europe) or the cable TV fee by hours watched
  - eminently feasible with STBs
  - content tiers but not viewing tiers
- "but cost of cable TV does not depend on viewers"
- not really: content cost to MVPD is based on popularity