THE SECRET INSPIRATION FOR THE INTERNET

I SURE LIKE WRITING OFFENSIVE THINGS ANONYMOUSLY. IF ONLY THERE WAS A WAY TO REACH A WIDER AUDIENCE WITH MY FILTH...

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

from the who-comes-up-with-those 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

Executive Order -- Improving Critical Infrastructure Cybersecurity

EXECUTIVE ORDER

IMPRESSING 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 serious national security challenges we must confront. The national and economic security of the United States depends 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

- Outside plant
- Trans
- Pipelines
- Water
- Telecom

Connections:
- CO & data centers
- Towers & antennas
- Shared RoW
- Shared poles
- Flooding
- Fuel parts
- Recovery coordination
- Control

Date: 10/18/17

ITEP
Who runs communication systems and networks?

- **Incumbent local exchange carriers** ("ILEC")
- **Competitive local exchange carriers** ("CLEC")
- **Cable companies** ("MVPD")
- **Cellular providers** (3-4)
- **Rural local exchange carriers** ("RLEC")
- **Satellite providers**
- **Communities** ("muni networks")
- **Radio & TV stations**
- **Private land mobile radio** (public safety, transit, taxis, …)
- **Wholesaler providers** ("carriers’ carrier")

Numbers:
- ~1,000
- ~12
- ~2
- ~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

* incremental cost assuming legacy networks; “green field” cost is roughly the same
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

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

110/220V

~1915 (2 prong)

http://www.centennialbulb.org/cam.htm
Other long-lived interfaces

- Cigarette lighter (1956)
- Fuel nozzle
- SQL (1974)
- PDF (1982)
- Adobe (1993)
Interfaces: Paper-based information
Interfaces: Transportation

- 1435 mm
- 1830 (Stephenson)
- 1846 UK Gauge Act

About 60% of world railroad mileage
The two-layer model

content
apps & software
services

“Lower layers”
infrastructure
“the network”
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”

1. Physical
   analog-digital (bit stream)

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

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

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

5. Session
   authentication, permissions, restoration, state

6. Presentation
   serialization, encryption, compression

7. Application
   message format, human-machine interface

structured content

messages byte stream

packets (“frames”) thingStreamer

bit stream
Layering

L7

PHY (L1)

generality

email

any digital communications

secure, reliable, world-wide

functionality

unreliable bits over one link
The real model

Figure 42.1 - The 7 Layer OSI Network Model

*You are Here*

- Political
- Financial
- Application
- Presentation
- Session
- Transport
- Network
- Link
- Physical
The Internet Protocol Hourglass

small number of long-term stable interfaces

S. Deering
## Why four (core) layers?

<table>
<thead>
<tr>
<th>Layer</th>
<th>Colloquial name</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>PHY</td>
<td>photons &amp; electrons $\rightarrow$ bits</td>
</tr>
<tr>
<td>2</td>
<td>MAC</td>
<td>bits $\rightarrow$ packets on one technology</td>
</tr>
<tr>
<td>3</td>
<td>L3</td>
<td>packets <em>end-to-end</em>, on heterogeneous technologies, to <em>interface</em></td>
</tr>
<tr>
<td>4</td>
<td>L4</td>
<td>unreliable $\rightarrow$ reliable</td>
</tr>
<tr>
<td></td>
<td></td>
<td>host/interface $\rightarrow$ <em>application</em></td>
</tr>
<tr>
<td>(5)</td>
<td>Presentation, data</td>
<td>application data structure encoding</td>
</tr>
<tr>
<td>7</td>
<td>Application</td>
<td>Application behavior (email, web)</td>
</tr>
</tbody>
</table>
## Internet layer functions

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

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

Serialization = convert data structure into (linear) byte stream like C, without pointers…
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

```
{
    "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

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J. Kurose (Ch. 1)
Internet traffic flows today

backbone (transit)

Google
Facebook
YouTube
Yahoo
Live
Baidu

server farm

carpet access network (data center provider)

Level3
Cogent

CDN

Comcast
eyeball ISP

com. CDN

Akamai

content CDN

video conferencing

Netflix
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
Wireline & wireless

“almost all networks are 99% wired” exceptions?
It’s all spectrum - phone
It’s all spectrum - wires

4 kHz
10 MHz
1 GHz
200 - 347 THz
Classical division of spectrum

<table>
<thead>
<tr>
<th>Band</th>
<th>range</th>
<th>commonly called</th>
<th>sample current usage</th>
</tr>
</thead>
<tbody>
<tr>
<td>VLF</td>
<td>3-30 kHz</td>
<td></td>
<td>navigation, submarine</td>
</tr>
<tr>
<td>LF</td>
<td>30-300 kHz</td>
<td></td>
<td>WWVB (clock 60 kHz)</td>
</tr>
<tr>
<td>MF</td>
<td>300-3 MHz</td>
<td></td>
<td>AM radio</td>
</tr>
<tr>
<td>HF</td>
<td>3-30 MHz</td>
<td></td>
<td>short wave radio</td>
</tr>
<tr>
<td>VHF</td>
<td>30-300 MHz</td>
<td></td>
<td>TV 2-6, 7-13, FM radio, CB, LMR</td>
</tr>
<tr>
<td>UHF</td>
<td>0.3-3 GHz</td>
<td></td>
<td>LMR, TV 14-50, cellular, Wi-Fi</td>
</tr>
<tr>
<td>SHF</td>
<td>3-30 GHz</td>
<td>microwave</td>
<td>radars, Wi-Fi</td>
</tr>
<tr>
<td>EHF</td>
<td>30-300 GHz</td>
<td>mmWave</td>
<td>radars, satellite, p2p links</td>
</tr>
</tbody>
</table>
## Commercial wireless spectrum (US)

<table>
<thead>
<tr>
<th>LTE band class</th>
<th>frequency</th>
<th>origin</th>
<th>usage</th>
</tr>
</thead>
<tbody>
<tr>
<td>71</td>
<td>617-698 MHz</td>
<td>incentive auction (TV)</td>
<td>TMo, AT&amp;T, Dish</td>
</tr>
<tr>
<td>12 &amp; 13 (A, B, C)</td>
<td>700 MHz</td>
<td>digital dividend (TV)</td>
<td>AT&amp;T, TMo, VZ</td>
</tr>
<tr>
<td>14 (D)</td>
<td>700 MHz</td>
<td>digital dividend (TV)</td>
<td>FirstNet</td>
</tr>
<tr>
<td>5</td>
<td>850 MHz</td>
<td>cellular</td>
<td>AT&amp;T, US Cellular</td>
</tr>
<tr>
<td>4</td>
<td>1700 MHz</td>
<td>AWS</td>
<td>many</td>
</tr>
<tr>
<td>25</td>
<td>1900 MHz</td>
<td>PCS</td>
<td>many</td>
</tr>
<tr>
<td>30</td>
<td>2300 MHz</td>
<td>WCS</td>
<td>AT&amp;T</td>
</tr>
<tr>
<td>41</td>
<td>2500 MHz</td>
<td>EBS</td>
<td>Sprint</td>
</tr>
</tbody>
</table>
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
Spectrum for wireless broadband

Exhibit 13: Current Spectrum Available for Wireless Broadband Use

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

TOTAL LICENSED SPECTRUM = 753 MHz

Source: FCC and Wells Fargo Securities' estimates.
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

<table>
<thead>
<tr>
<th></th>
<th>Sprint</th>
<th>T-Mobile</th>
<th>AT&amp;T</th>
<th>Verizon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth</td>
<td>115</td>
<td>110</td>
<td>95</td>
<td>53</td>
</tr>
</tbody>
</table>

Source: MoffettNathanson estimates and analysis

Exhibit 24

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

<table>
<thead>
<tr>
<th></th>
<th>T-Mobile</th>
<th>Sprint</th>
<th>AT&amp;T</th>
<th>Verizon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth</td>
<td>79</td>
<td>61</td>
<td>52</td>
<td>38</td>
</tr>
</tbody>
</table>

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)

Not Shown
EA 173 (Guam and the Northern Mariana Isl.)
EA 175 (American Samoa)

EAs delineated by the Regional Economic Analysis Division
Bureau of Economic Analysis, U.S. Department of Commerce
January 1995
It's all spectrum - modem

The Sound of the Dialup: an Example Handshake

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(modem goes off hook)
(modem data 300 bps)
(modem data 1200 bps)
(modem data 2400 bps)

$c$ to $V.22$ connection
$c$ to $V.22$ connection
$c$ to $V.22$ connection

"Why don't we use $V.22$?"
"Why don't we use $V.22$?"
"Why don't we use $V.22$?"

"Call requests to escape from telephone into computer transfer mode."
"Call requests to escape from telephone into computer transfer mode."
"Call requests to escape from telephone into computer transfer mode."

"Call requests to escape from telephone into computer transfer mode."
"Call requests to escape from telephone into computer transfer mode."
"Call requests to escape from telephone into computer transfer mode."

(dial tone)
(dial tone)
(dial tone)
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
Phase modulation

\[
\frac{\pi}{2} \sin(f_1 t + \frac{\pi}{2} \sin(f_2 t))
\]
Quadrature amplitude modulation (QAM)
Shannon examples

- $\text{SNR (dB)} = 10 \log_{10} \left( \frac{S}{N} \right)$
- Telephone modem: $\text{SNR} = 20 \text{ dB (1:100)}$; frequency 4 kHz $\rightarrow 4,000 \log_2 (101) = 26.63 \text{ kb/s}$
- Noise can be larger than signal!
  - $\rightarrow$ negative SNR
- Less noise $\rightarrow$ 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 $\text{b/s/Hz}$, but can be much higher
Circuit switching: FDM versus TDM

Example:
4 users

FDM

TDM
All networks are similar

- packets
- time-division multiplexing
- modulation
- frequency division
- medium = spectrum
Reference architecture
**Broadband Access Technologies**

- **FBWA or 4G**
  - HFC
  - DSL
  - BPL
- **FTTHome FTTCurb**
- **Digital Subscriber Line**
  - Telco or ILEC
  - 10s of Mbps
  - Entertainment, data, voice
- **Fiber -- Passive Optical Network**
  - Telco or ILEC
  - ~75 Mb/s
  - Futureproof?
- **Hybrid Fiber Coax**
  - CableCo (MSO)
  - Entertainment, data, voice
  - 10s of 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)
- **Broadband Power Line**
  - PowerCo
  - Data, voice
  - ~few Mbps

Paul Henry (AT&T), FCC 2009
Local loop
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

Architectures Offered Today – Illustrative

Central Office

-48v

Feeder (F1)

SAI

Distribution (F2)

X

Drop

Customer

Homerun Copper Loop

Hybrid Loop

Fiber-to-the-Node “FTTN”

F1

RT

SAI

VRAD

Fiber-to-the-Curb “FTTC”

F1

HDT

Fiber-to-the-Premise “FTTP”

F1

PFP

F2

FST

Drop*

ONU = Optical Network Unit

HPF = Primary Point

HST = Fiber Serving Terminal

Drop* = FTTC copper drop < 500'

SAI = Serving Area Interface

X = Serving Terminal

RT = Remote Terminal

Copper

Fiber

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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

xDSL logical architecture

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

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

*data, TV transmitted at different frequencies over shared cable distribution network*
Cable architecture

<table>
<thead>
<tr>
<th>Headend</th>
<th>Distribution Hub</th>
<th>Optical Node</th>
<th>Coaxial Cable Plant / Subscriber Homes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-2 Headends Per Major Metro Area</td>
<td>Typically serves 20,000-100,000 homes</td>
<td>Typically serves 500 homes (today)</td>
<td></td>
</tr>
</tbody>
</table>

Source: Jefferies Research

<table>
<thead>
<tr>
<th>DOCSIS Version</th>
<th>Downstream Modulation Scheme</th>
<th>Upstream Modulation Scheme</th>
<th>Minimum Required Network Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>DOCSIS 2.0</td>
<td>256-QAM</td>
<td>64-QAM</td>
<td>N+6</td>
</tr>
<tr>
<td>DOCSIS 3.0</td>
<td>256-QAM</td>
<td>64-QAM</td>
<td>N+6</td>
</tr>
<tr>
<td>DOCSIS 3.1</td>
<td>512-QAM</td>
<td>128-QAM</td>
<td>N+4</td>
</tr>
<tr>
<td>DOCSIS 3.1</td>
<td>1024-QAM</td>
<td>256-QAM</td>
<td>N+2</td>
</tr>
<tr>
<td>DOCSIS 3.1</td>
<td>2048-QAM</td>
<td>512-QAM</td>
<td>N+1</td>
</tr>
<tr>
<td>DOCSIS 3.1</td>
<td>4096-QAM</td>
<td>1024-QAM</td>
<td>N+0</td>
</tr>
<tr>
<td>Full Duplex DOCSIS</td>
<td>4096-QAM</td>
<td>1024-QAM</td>
<td>N+0</td>
</tr>
</tbody>
</table>

Source: Jefferies Research
The favored method of adding capacity can be different depending on the situation. Node splits can involve more construction, engineering, and design work than adding narrowcast channels. Therefore, node splits are often used when a longer-term dramatic increase in capacity is required or when spectrum for additional narrowcast channels is unavailable. Adding narrowcast spectrum is a logical choice when channels are available to reallocate and smaller increments of capacity are required.

Mechanics of Node Splitting

To illustrate the operational aspects of node splitting and the associated equipment required, we walk through an example case in Chart 16 below. For purposes of the example, we assume this section of the network is at a "Node+4" architecture with 500 households in the service group. Based on our discussions with industry participants, Node+4 with 500 homes passed approximately represents the average cable access network in the 2016/2017 time frame.
Simplified access network diagram

Note: This diagram is a simplification of the actual network, which in actuality includes redundant network links, redundant network devices, and other details too complex to represent here.
DOCSIS 3.0 channel bonding

Logical Channel Bonding Technology

152 Mbps

• 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

OLT
Optical Line Terminal

ONT
Optical Network Terminal

Optical Couplers (WDM)

EDFA
Erbium Doped Fiber Amplifier

Optical Splitter

Upstream 1310 nm

Voice & Data, Downstream 1490 nm

Voice, Data & Video, 1490 nm, 1310 nm, 1550 nm

Video 1550 nm

1x32

Bandwidth & Services

Upstream
1310 nm
Voice & Data at 155 to 622 Mbps

Downstream
1490 nm
Voice, Data & VOD at 622 Mbps

1550 nm
Broadcast Video

54 MHz
Analog TV

864 MHz
Digital TV and HDTV

Brian Whitton, Verizon
Communication satellites

<table>
<thead>
<tr>
<th>Altitude (km)</th>
<th>Type</th>
<th>Latency (ms)</th>
<th>Sats needed</th>
</tr>
</thead>
<tbody>
<tr>
<td>35,000</td>
<td>GEO</td>
<td>270</td>
<td>3</td>
</tr>
<tr>
<td>20,000</td>
<td>MEO</td>
<td>35–85</td>
<td>10</td>
</tr>
<tr>
<td>10,000</td>
<td>MEO</td>
<td>35–85</td>
<td>10</td>
</tr>
<tr>
<td>5,000</td>
<td>LEO</td>
<td>1–7</td>
<td>50</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Band</th>
<th>Downlink</th>
<th>Uplink</th>
<th>Bandwidth</th>
<th>Problems</th>
</tr>
</thead>
<tbody>
<tr>
<td>L</td>
<td>1.5 GHz</td>
<td>1.6 GHz</td>
<td>15 MHz</td>
<td>Low bandwidth; crowded</td>
</tr>
<tr>
<td>S</td>
<td>1.9 GHz</td>
<td>2.2 GHz</td>
<td>70 MHz</td>
<td>Low bandwidth; crowded</td>
</tr>
<tr>
<td>C</td>
<td>4.0 GHz</td>
<td>6.0 GHz</td>
<td>500 MHz</td>
<td>Terrestrial interference</td>
</tr>
<tr>
<td>Ku</td>
<td>11 GHz</td>
<td>14 GHz</td>
<td>500 MHz</td>
<td>Rain</td>
</tr>
<tr>
<td>Ka</td>
<td>20 GHz</td>
<td>30 GHz</td>
<td>3500 MHz</td>
<td>Rain, equipment cost</td>
</tr>
</tbody>
</table>
Geostationary satellites (2)

"bent pipe"

VSATs using a hub.
HTS launches per year

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

**HTS Capacity Launches (Gbps)**

<table>
<thead>
<tr>
<th>Year</th>
<th>Gbps</th>
</tr>
</thead>
<tbody>
<tr>
<td>2004</td>
<td>11.0</td>
</tr>
<tr>
<td>2005</td>
<td>44.0</td>
</tr>
<tr>
<td>2006</td>
<td>10.0</td>
</tr>
<tr>
<td>2007</td>
<td>10.5</td>
</tr>
<tr>
<td>2008</td>
<td>5.4</td>
</tr>
<tr>
<td>2009</td>
<td>0.0</td>
</tr>
<tr>
<td>2010</td>
<td>72.3</td>
</tr>
<tr>
<td>2011</td>
<td>150.0</td>
</tr>
<tr>
<td>2012</td>
<td>156.7</td>
</tr>
<tr>
<td>2013</td>
<td>26.7</td>
</tr>
<tr>
<td>2014</td>
<td>40.5</td>
</tr>
<tr>
<td>2015</td>
<td>170.0</td>
</tr>
</tbody>
</table>

Source: NSR

David Hartshorn, 2014
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
- Aero terminal by Rockwell Collins
- Terminal Trucks and Trains
- Terminals for premises or Fixed locations
- Terminal for Ships
GSO protection

Novel Techniques to Protect GSO

- With “progressive pitching” the satellite (patent pending)
Exede beam map

http://www.wildbluertools.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
Example: Exede satellite plans

**LIBERTY 12**
- **Priority Data**: 12 GB
- **Includes**
  - Liberty Pass
  - Free Zone (3 am to 6 am daily)
- **Price**: $50/MO

**LIBERTY 25**
- **Priority Data**: 25 GB
- **Includes**
  - Liberty Pass
  - Free Zone (3 am to 6 am daily)
- **Price**: $75/MO

**LIBERTY 50**
- **Priority Data**: 50 GB
- **Includes**
  - Liberty Pass
  - Free Zone (3 am to 6 am daily)
- **Price**: $100/MO

Double your Priority Data speed w/ **Boost 25**
- **Cost**: $10/month on any plan
- **Speed**: Up to 25 MBPS download speed
- **Included**: Built-in WiFi Router
Project Loon

- LTE at 850 MHz
- solar powered
- wind layers
- < 20 km altitude
THE COST OF NETWORKS
Communications infrastructure upgrade

The need for deep fiber

Excessive operating expenditures caused by legacy network operations restrict carriers' ability to leverage IP networking advancements. Motivating carriers to fund fiber infrastructure likely requires a method to improve carrier margins and free up money for capital investment. As market share losses in both voice and broadband access mount, carriers have been aggressive in slashing costs. However, cost reduction opportunities are fundamentally limited without an ability to completely retire legacy TDM products and assets. Without the ability to shutter real estate and decommission support systems entirely, cost cutting alone cannot keep pace with customer loss and corresponding revenue declines. As legacy TDM wireline networks continue to descale, the percentage of fixed costs overwhelms the cost structure which could lead to even greater margin pressure.

Carriers are willing to invest in, and could potentially gain tremendous efficiency from deploying new IP networking architectures like Software Defined Networks and Network Function Virtualization (SDN NFV). However, the requirement to operate and maintain legacy TDM-based networks limits carriers' ability to take advantage of the savings and shift capital to deep fiber deployment.

The ratio of cash OPEX to CAPEX in Exhibit 8 depicts the predicament of operating a legacy network given ongoing market share loss. Operating two networks (legacy TDM and IP) forces the largest wireline carriers to spend, on average, five to six times as much on operating expenses as they do capital expenditures. High operating costs due to maintenance of legacy products and systems consume the vast majority of service revenues, leaving less for capital expenditures.

Wireline carriers have both a capital intensive and labor-intensive business model. Other labor-intensive industries such as construction, hospitality and agriculture typically have capital intensities below 5 percent compared to a typical wireline telecom carrier with the expected capital intensity of 14–18 percent.

Shifting OPEX dollars to capital investment in fiber deployment requires that carriers operate one network instead of two. Retirement of legacy TDM networks could greatly reduce the operating expenses to free up funds for fiber investment. TDM retirement also frees up capital previously reserved for maintenance of the legacy networks and systems.

Exhibit 8

2016 Average OPEX to CAPEX ratios

Wireless: 2.7X
Cable: 3.8X
Wireline: 5.2X

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

wastewater pipe
(3-5 km/week)
## Broadband network cost - FTTP

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

Crown Fibre Holdings (Govt. of New Zealand); provided by CTC
## Broadband network cost – Fiber middle mile

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

Data provided by CTC
## Middle mile cost example

### Independent 2" Conduit Run for Three User Co-Location

#### LABOR

<table>
<thead>
<tr>
<th>Category</th>
<th>Quantity</th>
<th>Unit</th>
<th>Low Cost/Unit</th>
<th>High Cost/Unit</th>
<th>Low Cost</th>
<th>High Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design</td>
<td>5,280</td>
<td>FT.</td>
<td>$0.08</td>
<td>$0.10</td>
<td>$422</td>
<td>$528</td>
</tr>
<tr>
<td>Engineering and Permits</td>
<td>0</td>
<td>FT.</td>
<td>$0.25</td>
<td>$0.25</td>
<td>$0</td>
<td>$0</td>
</tr>
<tr>
<td>Railroad Crossing</td>
<td>0</td>
<td>LOT</td>
<td>$5,000.00</td>
<td>$15,000.00</td>
<td>$0</td>
<td>$0</td>
</tr>
<tr>
<td>Directional Boring for 2&quot; Conduit</td>
<td>0</td>
<td>FT.</td>
<td>$8.00</td>
<td>$20.00</td>
<td>$0</td>
<td>$0</td>
</tr>
<tr>
<td>Directional Boring for 4&quot; Conduit</td>
<td>0</td>
<td>FT.</td>
<td>$11.00</td>
<td>$25.00</td>
<td>$0</td>
<td>$0</td>
</tr>
<tr>
<td>Trenching for 24&quot; - 36&quot; Depth</td>
<td>5,280</td>
<td>FT.</td>
<td>$5.00</td>
<td>$12.00</td>
<td>$26,400</td>
<td>$63,360</td>
</tr>
<tr>
<td>Place Conduit</td>
<td>15,840</td>
<td>FT.</td>
<td>$1.00</td>
<td>$1.75</td>
<td>$15,840</td>
<td>$27,720</td>
</tr>
<tr>
<td>Place Inner Duct</td>
<td>0</td>
<td>FT.</td>
<td>$0.50</td>
<td>$1.50</td>
<td>$0</td>
<td>$0</td>
</tr>
<tr>
<td>Place Vault</td>
<td>33</td>
<td>EACH</td>
<td>$500.00</td>
<td>$750.00</td>
<td>$16,500</td>
<td>$24,750</td>
</tr>
<tr>
<td>Place Fiber in Conduit</td>
<td>15,840</td>
<td>FT.</td>
<td>$1.25</td>
<td>$2.50</td>
<td>$19,800</td>
<td>$39,600</td>
</tr>
<tr>
<td>Install Splice Enclosure</td>
<td>3</td>
<td>EACH</td>
<td>$300.00</td>
<td>$500.00</td>
<td>$900</td>
<td>$1,500</td>
</tr>
<tr>
<td>Splice Fiber</td>
<td>648</td>
<td>EACH</td>
<td>$12.00</td>
<td>$30.00</td>
<td>$7,776</td>
<td>$19,440</td>
</tr>
<tr>
<td><strong>TOTAL LABOR</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$87,638</td>
<td>$176,898</td>
</tr>
</tbody>
</table>

#### MATERIALS

<table>
<thead>
<tr>
<th>Category</th>
<th>Quantity</th>
<th>Unit</th>
<th>Low Cost/Unit</th>
<th>High Cost/Unit</th>
<th>Low Cost</th>
<th>High Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>216 Count Fiber</td>
<td>18,216</td>
<td>FT.</td>
<td>$1.80</td>
<td>$2.50</td>
<td>$32,789</td>
<td>$45,540</td>
</tr>
<tr>
<td>Splice Kit</td>
<td>3</td>
<td>EACH</td>
<td>$500.00</td>
<td>$750.00</td>
<td>$1,500</td>
<td>$2,250</td>
</tr>
<tr>
<td>4&quot; Conduit and Materials</td>
<td>0</td>
<td>FT.</td>
<td>$2.98</td>
<td>$3.50</td>
<td>$0</td>
<td>$0</td>
</tr>
<tr>
<td>2&quot; Conduit and Materials</td>
<td>15,840</td>
<td>FT.</td>
<td>$0.88</td>
<td>$1.50</td>
<td>$13,939</td>
<td>$23,760</td>
</tr>
<tr>
<td>1&quot; Inner Duct</td>
<td>0</td>
<td>FT.</td>
<td>$0.30</td>
<td>$45.00</td>
<td>$0</td>
<td>$0</td>
</tr>
<tr>
<td>Vault</td>
<td>33</td>
<td>EACH</td>
<td>$450.00</td>
<td>$600.00</td>
<td>$14,850</td>
<td>$19,800</td>
</tr>
<tr>
<td>Tax and Freight</td>
<td>1</td>
<td>LOT</td>
<td>$6,307.80</td>
<td>$9,135.00</td>
<td>$6,308</td>
<td>$9,135</td>
</tr>
<tr>
<td><strong>TOTAL MATERIAL</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$69,386</td>
<td>$100,485</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Company</th>
<th>Revenue</th>
<th>Capital expenditures</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Comcast (US) [3Q14]</td>
<td>$11.04B</td>
<td>$1.644B</td>
<td>14.9</td>
</tr>
<tr>
<td>Telekom (DE) [3Q14]</td>
<td>€15.6B</td>
<td>$2.58B</td>
<td>16.5</td>
</tr>
<tr>
<td>Safaricom (KE) [H1FY15]</td>
<td>Ksh 79.34B</td>
<td>Ksh 12.37</td>
<td>15.5</td>
</tr>
</tbody>
</table>

Comcast’s Q2 2014 Capital Spending Trends

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

As of Aug. 2014. *Total excludes $13 million in discretionary capital. Total including discretionary spending was $1,493 mil. Source: Comcast. © 2014 SNL Kagan, a division of SNL Financial LC, estimates. All rights reserved.
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

DOCSIS 1.0
(40M/1M)

1995

“peak CATV”: 82% of HH

1997

DOCSIS 3.1
(10G/1G)

2008

2016
Network competition models

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

margin squeeze
Sharing models: US

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

+ WISP & satellite

DSL (ILEC)  
fiber (ILEC, CATV, overbuilder)  
HFC  
PHY (LTE)  
spectrum

ducts & poles (electric utilities or ILEC)  
towers
Sharing models: Canada, Europe, Australia

usually unbundled

unbundling varies
mostly not unbundled

DSL
fiber
HFC

products & poles (electric utilities or ILEC)
towers

PHY (LTE) spectrum
**Broadband competition challenges**

The lighter the blue, the fewer the options. You get the point.

The bar on the left reflects the availability of *wired* broadband using the FCC's current broadband definition of 4 Mbps. But let's be clear, this is "yesterday's broadband." Four megabits per second isn't adequate when a single HD video delivered to home or classroom requires 5 Mbps of capacity. This is why we have proposed updating the broadband speed required for universal service support to 10 Mbps.

But even 10 Mbps doesn't fully capture the increasing demand for better *wired* broadband, of which downstream speed is, of course, only one component. It's not uncommon for a U.S. Internet-connected household to have six or more connected devices—including televisions, desktops, laptops, tablets, and smartphones. When these devices are used at the same time, as they often are in the evenings, it's not hard to overwhelm 10 Mbps of bandwidth.

And consumer demand is growing; today over 60% of peak-time downloads are streaming audio and video. While today that video may be for entertainment, other applications are right behind. For instance, if we are to tackle healthcare costs, high-speed broadband video for remote examination, diagnosis and even surgery is important. If our students are to get a 21st Century education, high-speed broadband to the classroom is essential. And, increasingly, that high-speed will be in both directions.

As is proved here daily at 1776, high-speed connections are crucial not only for the kind of innovation that will educate our children and deliver quality health care, but also improve energy efficiency, fill the employment ranks, and maintain the United States as the world's innovation leader for the 21st Century.

The history of our time will be recorded as a period in which ever-increasing network performance made possible an ever-expanding list of capabilities for both consumers and businesses. This

---

*These data reflect speeds of 3 Mbps up / 768 kbps down, which the FCC uses as the best proxy for 4 Mbps / 1 Mbps. See, e.g., FCC, *Eighth Broadband Progress Report*, FCC 12-90, ¶ 29 (2010).*
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

- Backbone: largely unaffected by video
- Middle mile: ISP-owned vs. leased!
- Last mile: homes/service node for HFC
- Cellular: densification
- DSL: no
- Fiber: no

Lack of IXPs in LDCs!
Transit prices

$/Mbps

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)

Metro, nonmetro micropolitan, and nonmetro noncore counties, 2013

Source: USDA, Economic Research Service using data from the U.S. Census Bureau.

Counties changing metro status, 2003-2013

Source: USDA, Economic Research Service using data from the U.S. Census Bureau.
Broadband access by speed & geography

- 1 Gbps: 93.7%
- 25 Mbps: 7.0%
- 10 Mbps: 2.1%
- 3 Mbps: 0.7%

- Rural: 27.4%
- Small metro areas: 8.1%
- Suburbs: 2.9%
- City: 0.6%

15% of US population

No broadband access at 25 Mbps
Rural broadband US

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

- satellite
- WISP
- REC
- DSL (common)
- cable
- FTTH

HH/road mile
1 7 10 20 50 100 1000

Alaska roadmiles
1 1454
# Rural deployment options

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

<table>
<thead>
<tr>
<th>Application</th>
<th>Volume</th>
<th>Cost per unit</th>
<th>Cost / MB</th>
<th>Cost / TB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voice (13 kb/s GSM)</td>
<td>97.5 kB/minute</td>
<td>10c</td>
<td>$1.02</td>
<td>$1M</td>
</tr>
<tr>
<td>Mobile data</td>
<td>5 GB</td>
<td>$40</td>
<td>$0.008</td>
<td>$8,000</td>
</tr>
<tr>
<td>MMS (pictures)</td>
<td>&lt; 300 KB, avg. 50 kB</td>
<td>25c</td>
<td>$5.00</td>
<td>$5M</td>
</tr>
<tr>
<td>SMS</td>
<td>160 B</td>
<td>10c</td>
<td>$625</td>
<td>$625M</td>
</tr>
</tbody>
</table>
Problem likely capacity, not speed

Exhibit 13

Comcast: Median Bandwidth Usage per Household per Month, 2008 to 2016

Source: Comcast’s website, MoffettNathanson estimates and analysis
# The challenges of service differentiation

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

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

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