NETWORK TECHNOLOGY REVIEW

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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-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; $M \pm SE = 43.9\pm10.3\%$ improvement) more than after viewing images that were less cute (dogs and cats; $11.9\pm5.5\%$ 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

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 depend 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

- Broadband (Internet)
- Dial-up
- LMR
Interdependencies with other lifelines

- CO & DC
- towers & antennas
- shared RoW
- fuel parts
- Pipelines
- Trans
- Power
- Water
- Telecom
- shared poles
- flooding
- recovery coordination
- control
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
- Wholesaler providers ("carriers’ carrier")
- Communities ("muni networks")
- Radio & TV stations
- 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
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, …)
The Internet as core civil infrastructure

• Involved in all information exchange
  • (in a few years)

• Crucial to
  • commerce
  • governance
  • coordination
  • inter-personal communication

• Assumed to just be there
  • “plumbing”, “pipes”, …
Interfaces: Energy

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

1878

Cigarette lighter (1956)

1982

fuel nozzle

1992

SQL

1993

1974

PDF

Adobe

10/24/15

ITEP 2015
Interfaces: Paper-based information

1798, 1922 (DIN)
Interfaces: Transportation

About 60% of world railroad mileage

1435 mm

1830 (Stephenson)

1846 UK Gauge Act

12’
The two-layer model

content
apps & software
services

"Lower layers" infrastructure "the network"

copyright
patents

data privacy
investment
disability access
resource scarcity
technology innovation
data theft
disruption

universal service
location privacy
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
The (theoretical) layered approach to communication

1. Physical
   analog-digital (bit stream)

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

3. Network
   network addressing, routing

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

5. Session
   authentication, permissions, restoration, state

6. Presentation
   serialization, encryption, compression

7. Application
   message format, human-machine interface

"OSI model"
Division of layers

1. Physical
2. Data Link
3. Network
4. Transport
5. Session
6. Presentation
7. Application

Upper Layers

Middle Layer

Lower Layers
The real model

Layer 9: Politics
Layer 8: Money
Layer 7: Application
Layer 6: Presentation
Layer 5: Session
Layer 4: Transport
Layer 3: Network
Layer 2: Data Link
Layer 1: Physical

Figure 4.1 - The 7 Layer OSI Network Model (www.netlab.co.uk)
The Internet Protocol Hourglass

small number of long-term stable interfaces
# 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 → <strong>bits</strong></td>
</tr>
<tr>
<td>2</td>
<td>MAC</td>
<td>bits → <strong>packets</strong> on one technology</td>
</tr>
<tr>
<td>3</td>
<td>L3</td>
<td>packets <strong>end-to-end</strong>, on heterogeneous technologies, to <strong>interface</strong></td>
</tr>
<tr>
<td>4</td>
<td>L4</td>
<td>unreliable → <strong>reliable</strong> host/interface → <strong>application</strong></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: ASN.1

```
FooProtocol DEFINITIONS ::= BEGIN
  FooQuestion ::= SEQUENCE {
    trackingNumber INTEGER,
    question       IA5String
  }
  FooAnswer ::= SEQUENCE {
    questionNumber INTEGER,
    answer          BOOLEAN
  }
END

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

serialization = convert data structure into (linear) byte stream

like C, without pointers...
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: converting data structures into a byte stream

XML

```xml
<?xml version="1.0"?>
<dept-tickets>
  <dept-chief>Greg Sanguinetti</dept-chief>
  <dept-id>123890289</dept-id>
  <ticket id="034567910" code="301">
    <offender>
      <name>John Smith</name>
      <license-number>10003887</license-number>
      <plate-number>0AE8976</plate-number>
    </offender>
    <offence-date>09/30/2005</offence-date>
    <location>
      <state>CA</state>
      <city>SG</city>
      <intersection>West Tasman Dr.-Great America Pkwy</intersection>
    </location>
    <officer>
      <officer-name>Paul Greene</officer-name>
      <officer-badge>7652523</officer-badge>
      <cruiser-plate-number>6TXY9823</cruiser-plate-number>
    </officer>
    <description>Failure to stop at red light</description>
    <fine>100</fine>
  </ticket>
  ...
</dept-tickets>
```

JSON

```json
{
  "firstName": "John",
  "lastName": "Smith",
  "isAlive": true,
  "age": 25,
  "height_cm": 167.6,
  "address": {
    "streetAddress": "21 2nd Street",
    "city": "New York",
    "state": "NY",
    "postalCode": "10021-3100"
  },
  "phoneNumbers": [
    {
      "type": "home",
      "number": "212 555-1234"
    },
    {
      "type": "office",
      "number": "646 555-4567"
    }
  ],
  "children": [],
  "spouse": null
}
```
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

- Server farm
- Content access network (data center provider)
  - Google
  - Facebook
  - YouTube
  - Yahoo
  - Live
  - Baidu
- Backbone (transit)
  - Level3
  - Cogent
- CDN
  - Akamai
  - Comcast
  - Eyeball ISP
- Content CDN
  - Netflix
- Video conferencing

ITEP 2015
10/24/15
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

It's all spectrum - wires

**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.

**Figure 3**: Cable TV spectrum includes broadcast and narrowcast services.

<table>
<thead>
<tr>
<th>Frequency Band</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>200 - 347 THz</td>
<td>Wavelengths</td>
</tr>
<tr>
<td>4 kHz</td>
<td>CATV spectrum</td>
</tr>
<tr>
<td>10 MHz</td>
<td>UP to 158 QAM channels</td>
</tr>
<tr>
<td>1 GHz</td>
<td>Broadcast, Narrowcast</td>
</tr>
</tbody>
</table>

**Figure 4**: Coaxial cable components: outer jacket, braided shield, foil shield, center conductor, cladding, core, acceptance cone, and dielectric.
It’s all spectrum - modem

The Sound of the Dialup: an Example Handshake

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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
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
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
Circuit switching: FDM versus TDM

**FDM**

- Frequency
- Time

**TDM**

- Frequency
- Time

**Example:**

4 users

![Diagram showing FDM and TDM](image-url)
All networks are similar

- packets
- time-division multiplexing
- modulation
- frequency division
- medium = spectrum
Reference architecture

Interconnected Networks

Users

Access Network

Regional Broadband Network

Transport Core

ISP

Interconnected Networks

Local Video Feeds

Other Cores Within the Network

Video Feeds and 3rd Party CDNs

Interconnected Networks

L3 Router

SBC and L3 Router

Set top box command & control

Video Cache
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?

- **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

- **FTTHome**
- **FTTCurb**
Local loop
Physical architecture

- **Feeder Cables**
  - Carries traffic serving multiple endpoints from 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

Fiber-to-the-Node “FTTN”
Fiber-to-the-Curb “FTTC”
Fiber-to-the-Premise “FTTP”

Central Office

Feeder (F1)
SAI
VRAD
HDT
PFP

Distribution (F2)
SAI

Customer

Customer

Homerun Copper Loop

Hybrid Loop

Fiber Loop

-48v

Copper
Fiber

SAI = Serving Area Interface
X = Serving Terminal
RT = Remote Terminal

VRAD = Video Ready Access Device
HDT = Host Digital Terminal
ONU = Optical Network Unit
PFP = Primary Flex Point
FST = Fiber Serving Terminal
Drop* = FTTC copper drop < 500’

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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

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*
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

- 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+
Typology of FTTH

1. P2P
   - Ethernet

2. P2MP
   - Active Ethernet

3. PON
   - TDMA-PON
     - EPON
     - BPON
     - GPON
   - (T)WDM-PON
     - NG-PON2

- DDoE
Glossary

- **P2P**: Point-to-point (individual links from CO to premises)
- **P2MP**: Point-to-multipoint (feeder to neighborhood, then branching)
- **PON**: Passive Optical Network (optical signal on feeder passively split)
- **TDMA-PON**: PON where traffic to multiple households multiplexed in time
- **(T)WDM-PON**: PON using combination of Wavelength Division Multiplexing and TDMA
- **EPON**: Ethernet Passive Optical Network
- **DPoE**: DOCSIS Provisioning over EPON
- **BPON**: Broadband Passive Optical Network (ATM based)
- **GPON**: Gigabit Passive Optical Network (Generic Framing)
- **NG-PON**: Next Generation PON
Verizon’s FTTP architecture

OLT (Optical Line Terminal) to ONT (Optical Network Terminal) via Optical Couplers (WDM) and Optical Splitter.

Central Office

OLT

Voice & Data: 1490 nm
Downstream 1310 nm
Upstream 1310 nm

Video: 1550 nm

EDFA (Erbium Doped Fiber Amplifier)

ONT

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

Customer premise

Bandwidth & Services

Upstream
1310 nm
Voice & Data at 155 to 622 Mbps

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
Active Ethernet

- Active Ethernet uses single fiber from CO to neighborhood where there is an active Ethernet Switch
- Variant of P2P because there is a direct link (P2P) from the neighborhood Ethernet switch to the premise
PON standards

- Two different families of standards for PON networks
  - IEEE standards
    - EPON or Ethernet in the First Mile (EFM)
      - Based on Ethernet framing over fiber
      - Flow management similar to xDSL using VLAN tagging
      - Video carried as IPTV
  - ITU Standards
    - ATM-based (*deprecated but significant installed base*)
      - BPON (G.983)
        - 622 Mbps down/155 Mbps up
    - Packet based
      - GPON (G.984) (*Most common in the U.S. today*)
        - 1.2 Gbps and 2.4 Gbps down/155 Mbps, 622 Mbps, 1.2 Gbps and 2.4 Gbps up
      - XG-PON (10G-PON) (G.987)
        - 10 Gbps down/2.5 Gbps up
      - NG-PON2 (G.989) *emerging standard*
        - Combines WDM and TDMA to support both P2P and P2MP
Typical Fiber GPON Access Architecture for providing voice, data and video

- OLT (Data) and EDFA (Video) output are combined using a WDM in the Fiber Distribution Frame (FDF) and transmitted to the Outside Plant over a feeder fiber
- A splitter located at the Fiber Distribution Hub (FDH) splits the optical power evenly to be shared between 32 or 64 customers
- Each 1x32(64) splitter feeds 32(64) distribution fibers to serve 32(64) homes in a neighborhood. The drop fiber connects the ONT to the distribution fiber at the Fiber Distribution Terminal (FDT)
- Separate wavelength for linear video (1550 nm)
- Voice and data carried as cells/packets (1490 nm down/1310 nm up)
PON architecture
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>25,000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15,000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10,000</td>
<td>MEO</td>
<td>35–85</td>
<td>10</td>
</tr>
<tr>
<td>5,000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</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.
Geostationary satellites (1)

<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>

The principal satellite bands
Geostationary satellites (2)

VSATs using a hub.

“bent pipe”
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)

Source: NSR

David Hartshorn, 2014
Low-Earth orbit satellites

The Iridium satellites form six necklaces around the earth.
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

EXEDE12 PLANS

CLASSIC PLANS

10 GB Month $49.99 Month

15 GB Month $79.99 Month

25 GB Month $129.99 Month
Broadband cost

70%

30%
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></td>
<td>40% aerial, 60% underground, not including drops or electronics</td>
<td>$1,000…$1,100 per passing</td>
</tr>
<tr>
<td>FTTP drops</td>
<td>Range of distances and complexity</td>
<td>$300…$700 per connected home</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**

<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><strong>Labor</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<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” 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” 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” - 36” 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>$87,638</td>
<td>$176,898</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Materials</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<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” 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” 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” 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>$69,386</td>
<td>$100,485</td>
<td></td>
<td></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></td>
<td><strong>448</strong></td>
<td></td>
<td><strong>1,480</strong></td>
<td></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.
Engineering and business opportunities

- Capital investment surprisingly small
- Academic and industry research focuses on 15%, rather than 85%
- Three likely models in different countries:
  1. public conduits (& fiber) + private Internet access
     - community & electric utilities
  2. structurally-separated into transmission, interconnection & connect
  3. vertically integrated (monopoly & duopoly) provider
Network competition models

- single provider (any technology)
- cable
- copper, fiber
- poles & conduits
- shared copper, fiber
- "bit stream"

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

Sources: ITU, State of Broadband (Oct. 2013); FCC.
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

[Map of Google Fiber coverage areas in the United States, showing current, upcoming, and potential cities.]
Network costs

- **backbone**
  - yes, but mostly electronics
  - largely unaffected by video

- **middle mile**
  - ISP-owned vs. leased!

- **last mile**
  - DSL: no
  - HFC: homes/service node
  - fiber: no
  - cellular: densification

- lack of IXPs in LDCs!
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
Transit prices

$/Mbps

http://drpeering.net/white-papers/Internet-Transit-Pricing-Historical-And-Projected.php
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>
# 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                                                   • encourages Wi-Fi use</td>
<td>• complaints about meter accuracy</td>
<td>😞😞😞</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• adaptive applications (4G bill shock)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• pay for ads</td>
<td></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                                                       • Business model</td>
<td>Affects content competition</td>
<td>😞😞😞</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• barriers to entry</td>
<td></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>😞😞😞</td>
</tr>
</tbody>
</table>

10/24/15
ITEP 2015
102
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