Myriad of different LAN technologies co-existing in a WAN. For example:

- Fast Ethernet (100 Mbps)
- Gigabit Ethernet (1000 Mbps); 10 and 100 GigE

  → Purdue CS backbone: 10 Gbps

  → AT&T (tier-1 provider): 10+ Gbps
- WLAN (11, 54, 300 Mbps)
- 4G cellular (100 Mbps mobile, 1 Gbps stationary)

  → today: pre-4G

  → ITU-R
- WiMAX (tens of Mbps up to 1 Gbps)

  → wider area: several miles
- modem/DSL (cable and dial-up)

  → 12 Mbps (down)/2 Mbps (up), 50/10, higher

Note: WAN is a collection of LANs

$\rightarrow$ ultimately: everything happens at LANs

Each LAN, in general, speaks a different language

$\rightarrow$ message format (syntactic)

$\rightarrow$ behavioral (semantic)

Internetworking handles this problem by translating everything to IP (Internet Protocol)

$\rightarrow$ technical definition of **I**nternet

$\rightarrow$ collection of interconnected LANs speaking IP

But:

→ IP injects overhead

→ packet forwarding example: switches may choose not to speak IP

Hence:

→ IP (layer 3) is not necessary

→ large systems of layer 2 (LAN) switches

→ size limit: heterogeneity and management headache

→ today: L2 + L3

⟶ common attitude: avoid IP if possible

⟶ most devices speak IP in case needed

⟶ IP provides management benefit: naming

IP provides naming flexibility:

→ IP: v4 32-bit, v6 128-bit

→ in addition to 48-bit LAN addresses are hardwired and unique address per NIC

→ IP provides additional configurability

Common practice: assign similar addresses to network devices belonging to same organization

$\rightarrow$ ARIN in the U.S.

$\rightarrow$ blocks of contiguous addresses: makes routing easier

$\rightarrow$ e.g.: Purdue 128.10.$*$.$\star$, 128.210.$*$.$\star$

$\rightarrow$ LWSN B158: sslab01.cs.purdue.edu 128.10.25.101

$\rightarrow$ CS web server: www.cs.purdue.edu 128.10.19.20

$\rightarrow$ router bottleneck: table look-up speed

Another configurability benefit:

$\rightarrow$ private addresses

$\rightarrow$ e.g., 10.$*$.$*$.$*$, 192.168.$*$.$*$

$\rightarrow$ laptop WLAN IP address in LWSN: 10.184.43.63

$\rightarrow$ no one outside Purdue can reach laptop using 10.184.43.63

$\rightarrow$ how is it solved?

Naming: IP or LAN addresses are not enough

Communicating entities are *processes* running on host/router operating systems (Linux, Windows, IOS, etc.)

$\rightarrow$ IP only specifies host/server/router

$\rightarrow$ more accurately: one of the NICs attached to a device

$\rightarrow$ host with multiple NICs: multiple IP addresses

$\rightarrow$ multi-homed

Hence:

A name/address must also identify which process a message is destined for on a host

$\rightarrow$ OS/network convention: port number abstraction

$\rightarrow$ 16-bit

$\rightarrow$ address: pair (host IP, port number)

$\rightarrow$ well-known server port numbers (e.g., 80 for HTTP)

$\rightarrow$ is client app's port number important?

Network Performance

In computer networks, speed is at a premium

→ if slow, typically not used in practice

→ e.g., cryptographic protocols tend to be not turned on at routers

→ emphasis on lightweight network core

→ push heavyweight stuff toward the edge (i.e., host/server)

→ called end-to-end paradigm

→ has guided Internet design and evolution

Three yardsticks of performance:

- bandwidth: bps (bits-per-second)

  → throughput: includes software processing overhead

  → e.g., 802.11b WLAN: nominal bandwidth 11 Mbps, throughput around 6 Mbps

- latency: msec (millisecond)

  → signal propagation speed

  → approximately: speed of light

  → delay: includes software processing overhead and waiting time at routers (queueing)

  → delay at high speed routers: very small (μsec)

  → delay at WLAN AP: up to hundreds of millisecond

- jitter: delay variation

  → not good for real-time content (video, audio, voice)

Bandwidth vs. throughput:

bandwidth—maximum data transmission rate achievable at the hardware level; determined by signalling rate of physical link and NIC

throughput—maximum data transmission rate achievable at the software level; overhead of network protocols inside/outside OS is accounted for

reliable throughput—maximum reliable data transmission rate achievable at the software level; effect of recovery from transmission errors and packet loss accounted for

$\longrightarrow$ networks tend to be "leaky"

Meaning of "high-speed" networks:

- signal propagation speed is bounded by SOL (speed-of-light)

  $\rightarrow$ $\sim$300K km/s or $\sim$186K miles/s

  $\rightarrow$ optical fiber, copper: nearly same

- Ex.: latency: Purdue to West Coast

  $\rightarrow$ around 2000 miles: $\sim$10 msec ($= 2000/186000$)

  $\rightarrow$ lower bound

- Ex.: geostationary satellites: $\sim$22.2K miles

  $\rightarrow$ latency: $\sim$120 msec

  $\rightarrow$ end-to-end (one-way): $\sim$240 msec

  $\rightarrow$ round-trip (two-way): $\sim$480 msec

  $\rightarrow$ typically: $\sim$500 msec

- thus: a single bit cannot go faster

  $\rightarrow$ can only increase "bandwidth"

  $\rightarrow$ analogous to widening highway, i.e., more lanes

  $\rightarrow$ simulatenous transmission of multiple bits

  $\rightarrow$ hence "broadband" is a more accurate term

- interpretation: "high-speed" $\Leftrightarrow$ "many lanes"

  $\rightarrow$ what does it buy?

  $\rightarrow$ completion time of large files faster

  $\rightarrow$ in this sense, "higher" speed

Some units:

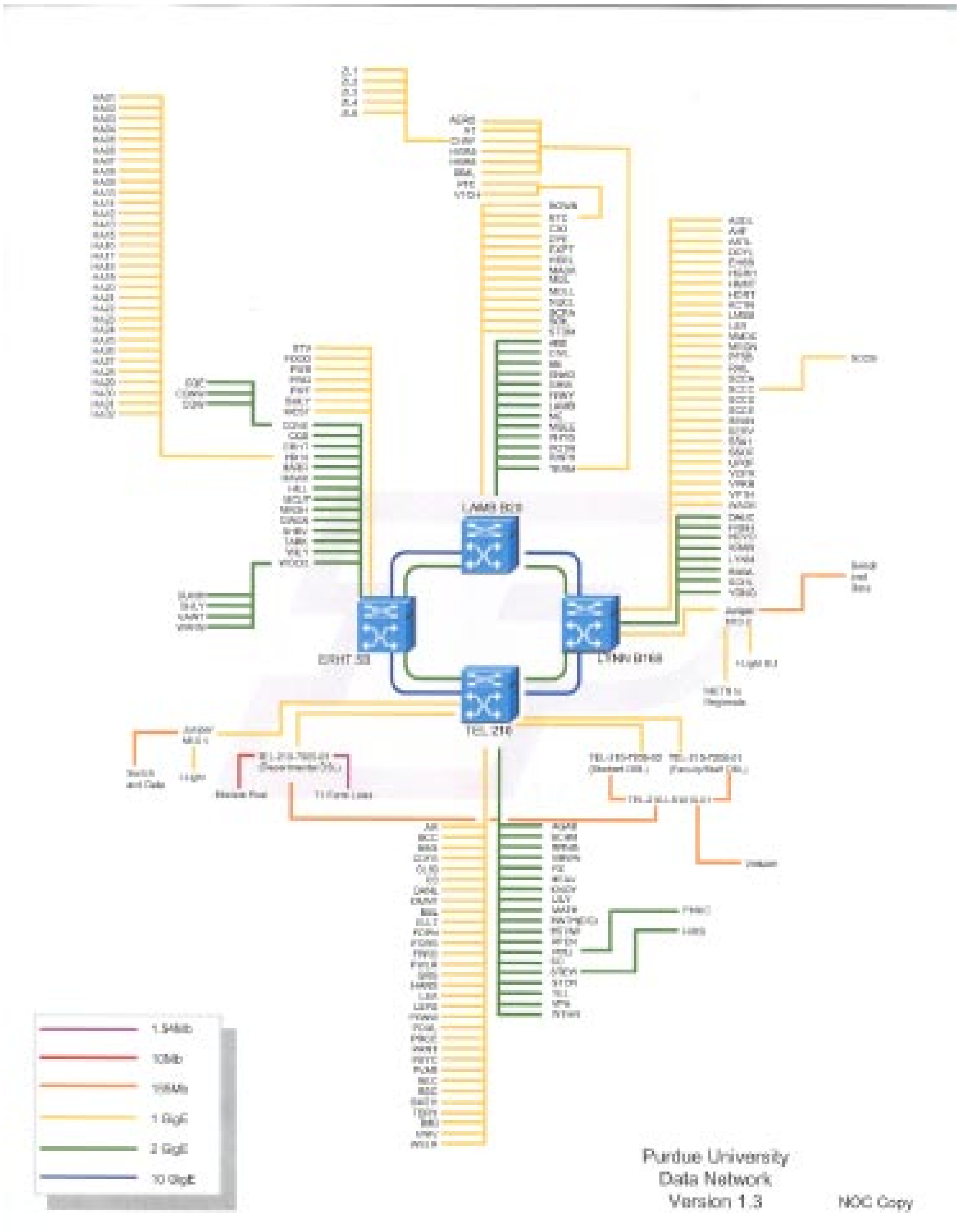
Tbps, Gbps, Mbps, Kbps:

10^{12}, 10^9, 10^6, 10^3 bits per second; indicates data transmission rate; influenced by clock rate (MHz/GHz) of signaling hardware

$\longrightarrow$ communication rate: factors of 1000

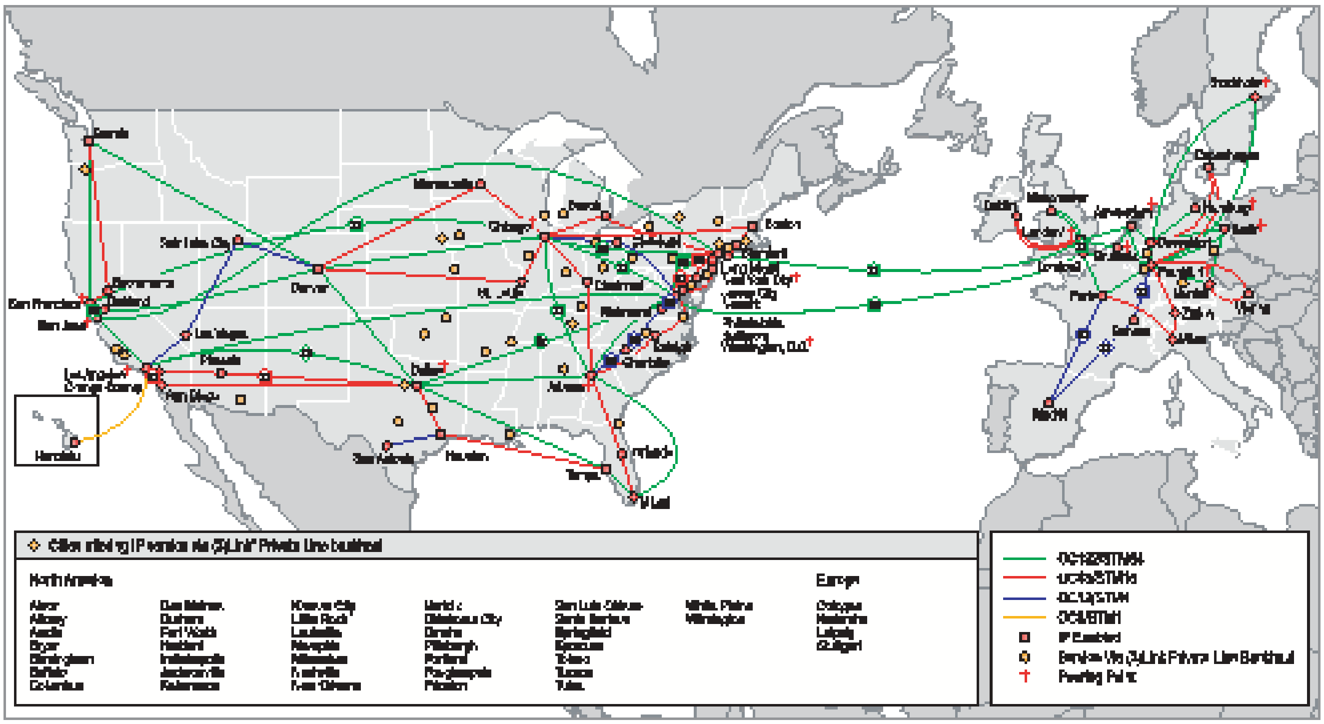
$\longrightarrow$ data size: 1 KB means 1024 bytes

Purdue's backbone network: ITaP



Level3 backbone network: www.level3.com

LEVEL 3 IP BACKBONE



→ 10 Gbps backbone (green): same speed as Purdue

→ outdated pic: faster backbone speeds now

What is traveling on the wires?

Mixture of:

bulk data (data, image, video, audio files), voice, streaming video/audio, real-time interactive data (e.g., games), etc.

→ around 90% of Internet traffic is TCP file traffic

→ HTTP web and P2P

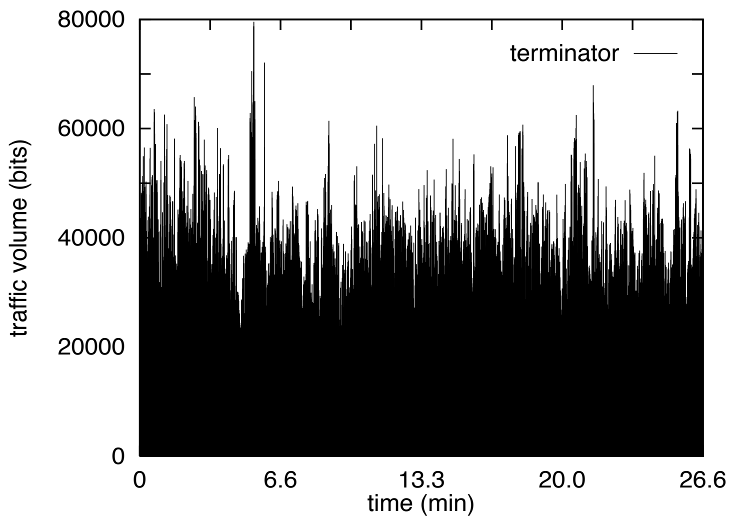
Multimedia (video/audio) streaming: on the rise

→ a minority but share is increasing

→ non-real-time: e.g., youtube, netflix

→ real-time: e.g., VoIP, video conferencing, games

Internet traffic is "bursty": MPEG compressed real-time video



Reason:

- video compression

  → utilize inter-frame compression

- across scenes, significant scenary changes

  → e.g., action movies

- within scenes, few changes

Burstiness is not good for networks: why?

Main source of traffic burstiness:

→ skewed file size

- 90/10 rule
- 90% of files are small, 10% are very large

  → "many mice, few elephants"

  → the few elephants make up 90% of total traffic

  → same for disk space

Real-world is inherently skewed . . .

How to make sense of all this?

Study of networks has three aspects:

- architecture

  $\rightarrow$ system design, real-world manifestation

- algorithms

  $\rightarrow$ how do the components work

- implementation

  $\rightarrow$ how are the algorithms implemented

Key concern: performance

$\rightarrow$ speed

$\rightarrow$ increasingly important: security and reliability