RESOURCE PROVISIONING AND NETWORK TRAFFIC

Network engineering:

- Feedback traffic control
  → closed-loop control (“adaptive”)
  → small time scale: msec
  → mainly by end systems
  → e.g., congestion control

- Resource provisioning
  → open-loop control (“in advance”)
  → large time scale: seconds, minutes, and higher
  → mainly by service providers

Question: what do ISPs do to keep customers happy and make money (or lose less money)?
What does Internet traffic look like?

"logging"

"traffic time series (at 10ms granularity)"
Aggregation (time):

→ analogous to computing sample mean

→ aggregation over multiple time scales

→ what to expect?
Throughput (bytes) vs Time (100s) for 100s Aggregation.
Throughput (bytes) vs Time (10s) for 10s Aggregation.
Throughput (bytes) vs Time (1s) for 1s Aggregation.
Throughput (bytes) vs Time (100ms) for 100ms Aggregation.

Zoom In
Deaggregation
Aggregation
Aggregated traffic becomes flat

→ “flat is good” rule for QoS provisioning
→ bandwidth dimensioning
→ technically: law of large numbers in action
→ not correlated in time
→ efficient and happy customers

Also aggregation over multiple users

→ called statistical multiplexing
→ assuming independence between different users
→ nice normal distribution shape
→ allows non-peak reservation
→ consider peak-to-mean ratio: less costly
Internet: self-similar

Telephony: Poisson-like

100s

zoom 10x

10s

1s

100ms

10ms
Internet: self-similar

Telephony: Poisson-like

peak
avrg
Back to Internet traffic:

→ what does it look like?

→ doesn’t become flat with time aggregation

→ stays bursty!

→ in a peculiar fashion: self-similar or fractal
Consequences:

→ cannot use “flat is good” method anymore
→ intrinsic trade-off between QoS and efficiency
→ bad news for QoS provisioning
→ traffic must be correlated in time (why?)
Tale of elephants and mice:

→ UNIX and WWW file systems

→ many small ones (mice)

→ a few very large ones (elephants)

→ 10% consumes 90% of bandwidth
Important empirical fact: time between session arrivals has been observed to be approximately exponentially distributed

→ e.g., TCP sessions, Web (HTTP) requests
→ refinements: additional burstiness (why?)

However, session lifetimes are not exponentially distributed!

→ tend of have “heavier” tails
→ exponential distribution: “light” tail
→ where have we seen heavier tails?
We know session arrivals are (approximately) Poisson; what about session lifetimes?

Important fact: TCP session lifetimes are heavy-tailed

\[ \Pr\{Z > x\} \approx x^{-\alpha} \]

\[ \text{as opposed to: } \Pr\{Z > x\} \approx e^{-bx} \]

\[ \text{exponent: } 1 < \alpha < 2 \text{ (closer to 1)} \]

\[ \text{note: different from Internet connectivity power-law} \]

\[ \text{much more likely session will last a long time} \]

\[ \text{has finite mean but infinite variance} \]

\[ \text{cat has a very fat tail ("too fat to carry")} \]

Why would TCP session lifetimes be heavy-tailed?

\[ \text{TCP traffic makes up bulk of Internet traffic} \]

\[ \text{greater than 80%} \]
How to check if files sizes are heavy-tailed?

Since $\Pr\{Z > x\} \approx x^{-\alpha}$, take logarithm on both sides:

$\rightarrow \log \Pr\{Z > x\} \approx -\alpha \log x$

$\rightarrow$ linear function with negative slope $-\alpha$

$\rightarrow$ holds true for large $x$

$\rightarrow$ what’s the slope $\alpha$?

$\rightarrow$ we don’t care about details of small sizes (why?)
Ex.: on/off model

\[
X_i(t) \quad \begin{array}{c|c|c|c|c|c|c}
& ON & OFF & ON & OFF & ON & OFF \\
\end{array} \\
X_2(t) \\
X_3(t) \\
X(t) \quad \text{time}
\]

→ on-period: TCP file transfer  
→ on-period length: file transfer completion time  
→ ignore internal details within on-period: sawtooth  
→ on-period could be VoIP session: CBR  
→ not exactly: a user talks only 40% of the time  
→ approximate view: ok by Amdahl’s law  
→ “don’t fret about small things”
Elephants in action:

→ at backbone router
Remarks:

• heavy-tailed on-times and resultant heavy-tailed queueing was a big surprise
  → grabbed CS, EE, statistics/probability, OR, some physicists, etc. by surprise!
  → huge scientific impact

• one technical aside: for heavy-tailed i.i.d. variables
  \[ \Pr\{Z_1 + \cdots + Z_n > x\} = \Pr\{\max\{Z_1, \ldots, Z_n\} > x\} \]
  → for large \( x \)
  → when the sum is large, one guy is to blame!
  → single long on-period picture: accurate
  → yields upper bound
  → starkly different from exponential: equal blame
  → implication to sampling and simulation: slow convergence
Sample mean convergence rate: exponential vs. Pareto

Exponential: rate=1/60

Pareto: alpha=1.2, b=10
Real-time VBR source profile

Consider traffic profile of compressed video (e.g., MPEG)

\[ \text{traffic volume (bits)} \]

\[ \text{time (min)} \]

\[ \rightarrow \text{periodic real-time application} \]

\[ \rightarrow \text{period } T = 1/f \ (f: \text{ frame rate}) \]
Burstiness structure:

→ burstiness persists across multiple time scales
Possible causes:

- Heavy-tailed scene durations
  \[\rightarrow\] facilitates inter-frame compression

- Repeating GOP pattern
  \[\rightarrow\] e.g., I B B P B B
Can the problem be solved?

→ no: as long as elephants and mice holds

Turns out to be a wide-spread phenomenon is sociology, networks, and elsewhere

→ size (population) of cities

→ popularity

→ frequency of words in books

→ etc.

In the real world:

→ norm: skewed distribution of sizes

→ power-law
User- and Session-Level Resource Provisioning

Basic set-up:

\[ \rightarrow \text{aggregate demand at access switch} \]

\[ \rightarrow n \text{ users or CPE (customer premises equipment)} \]

Set-up applies to:

- Telephone switch: TDM slot per session/user
- Dial-up modem pool: e.g., AOL Internet access
- Broadband access service: e.g., IP address pool
Remarks:

- LLN: principal engineering tool used by large transit providers and large access providers
  - “largeness” is key
  - even though components are random, system is well-behaved and predictable
  - apply at ingress/egress and backbone links
  - measurement-based tool: traffic matrix
QoS policy:

- Per-user (or flow) reservation for super-quality service
  \[\rightarrow\text{guaranteed service}\]
- Shared service classes (platinum, gold, silver, bronze)
  for good service
  \[\rightarrow\text{differentiated service}\]

Internet standards:

- IETF IntServ
  \[\rightarrow\text{RSVP protocol}\]
  \[\rightarrow\text{analogous to leasing a line}\]
- IETF DiffServ
  \[\rightarrow\text{different types of router behavior}\]
  \[\rightarrow\text{AF, EF, Cisco’s LLQ for VoIP}\]
Cisco 7206VXR router: packet loss rate

→ 8 classes

→ OC-3 link

→ varying offered load