EE 122: Networks Performance & Modeling

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http://inst.eecs.berkeley.edu/~ee122/fa09
(Materials with thanks to Vern Paxson, Jennifer Rexford, and colleagues at UC Berkeley)

Outline
- Motivations
- Timing diagrams
- Metrics
- Little's Theorem
- Evaluation techniques

Motivations
- Understanding network behavior
- Improving protocols
- Verifying correctness of implementation
- Detecting faults
- Monitor service level agreements
- Choosing providers
- Billing

Timing Diagrams
- Sending one packet
- Queueing
- Switching
  - Store and forward
  - Cut-through

Definitions
- Link bandwidth (capacity): maximum rate (in bps) at which the sender can send data along the link
- Propagation delay: time it takes the signal to travel from source to destination
- Packet transmission time: time it takes the sender to transmit all bits of the packet
- Queuing delay: time the packet need to wait before being transmitted because the queue was not empty when it arrived
- Processing Time: time it takes a router/switch to process the packet header, manage memory, etc
### Sending One Packet

- **Bandwidth**: \( R \) bits per second (bps)
- **Propagation delay**: \( T \) sec

Transmission time = \( \frac{P}{R} \)

Propagation delay = \( T = \frac{\text{Length}}{\text{speed}} \)

- In free space: \( 1 \text{m/speed} = 3.3 \text{usec} \)
- In copper: \( 4 \text{usec} \)
- In fiber: \( 5 \text{usec} \)

### Sending one Packet: Examples

- **Example 1**
  - \( P = 1 \text{Kbyte} \)
  - \( R = 1 \text{Gbps} \)
  - \( 100 \text{Km, fiber} \Rightarrow T = 500 \text{usec} \)
  - \( \frac{P}{R} = 8 \text{usec} \)

- **Example 2**
  - \( P = 1 \text{Kbyte} \)
  - \( R = 100 \text{Mbps} \)
  - \( 1 \text{Km, fiber} \Rightarrow T = 5 \text{usec} \)
  - \( \frac{P}{R} = 80 \text{usec} \)

### Queueing

- The queue has \( Q \) bits when packet arrives \( \Rightarrow \) packet has to wait for the queue to drain before being transmitted

Queueing delay = \( \frac{Q}{R} \)

### Queueing Example

- \( P = 1 \text{Kbit}; R = 1 \text{Mbps} \Rightarrow \frac{P}{R} = 1 \text{ms} \)

Packet arrival

- Time (ms)
  - 0
  - 0.5
  - 1

Delay for packet that arrives at time \( t \):

\[ d(t) = \frac{Q(t)}{R} + \frac{P}{R} \]

- Packet 1: \( d(0) = 1 \text{ms} \)
- Packet 2: \( d(0.5) = 1.5 \text{ms} \)
- Packet 3: \( d(1) = 2 \text{ms} \)

### Switching: Store and Forward

- A packet is **stored** (enqueued) before being **forwarded** (sent)

### Store and Forward: Multiple Packet Example

Sender

- 10 Mbps
- 5 Mbps
- 100 Mbps
- 10 Mbps

Receiver
Switching: Cut-Through
A packet starts being forwarded (sent) as soon as its header is received.

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  - Metrics
  - Throughput
  - Delay
- Little's Theorem
- Evaluation techniques

Throughput
- Throughput of a connection or link = total number of bits successfully transmitted during some period \([t, t + T]\) divided by \(T\)
- Link utilization = (throughput of the link)/(link rate)
- Bit rate units: 1Kbps = \(10^3\) bps, 1Mbps = \(10^6\) bps, 1Gbps = \(10^9\) bps [For memory: 1 Kbyte = \(2^{10}\) bytes = 1024 bytes]
  - Some rates are expressed in packets per second (pps) → relevant for routers/switches where the bottleneck is the header processing

Example: Windows Based Flow Control
- Connection:
  - Send \(W\) bits (window size)
  - Wait for ACKs
  - Repeat
- Assume the round-trip-time is \(RTT\) seconds
- Throughput = \(W/RTT\) bps
- Numerical example:
  - \(W = 64\) Kbytes
  - \(RTT = 200\) ms
  - Throughput = \(W/RTT = 64,000/0.2 = 2.6\) Mbps

Throughput: Fluctuations
- Throughput may vary over time

Delay Related Metrics
- Delay (Latency) of bit (packet, file) from A to B
  - The time required for bit (packet, file) to go from A to B
- Jitter
  - Variability in delay
- Round-Trip Time (RTT)
  - Two-way delay from sender to receiver and back
- Bandwidth-Delay product
  - Product of bandwidth and delay → "storage" capacity of network
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Little's Theorem
- Assume a system at which packets arrive at rate $\lambda$
- Let $d$ be mean delay of packet, i.e., mean time a packet spends in the system
- Q: What is the mean (average) number of packets in the system ($N$)?

$$\lambda = \text{mean arrival rate}$$

$$d = \text{mean delay}$$

$$N = \lambda \times d$$

Example
- $\lambda = 1$
- $d = 5$

Little's Theorem: Proof Sketch
- What is the system occupancy, i.e., average number of packets in transit between 1 and 2?

Little's Theorem: Proof Sketch
- Average occupancy $= S/T$
Little's Theorem: Proof Sketch

Latest bit seen by time $t$

- $d(i)$ = delay of packet $i$
- $x(t)$ = number of packets in transit (in the system) at time $t$

$P = \text{packet size}$

$S = \sum S(i) = P \sum d(i)$

$T = \text{time}$

Average occupancy = (average arrival rate) x (average delay)

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Evaluation Techniques

- Measurements
  - gather data from a real network
  - e.g., ping www.berkeley.edu
  - realistic, specific
- Simulations: run a program that pretends to be a real network
  - e.g., NS network simulator, Nachos OS simulator
- Models, analysis
  - write some equations from which we can derive conclusions
  - general, may not be realistic
- Usually use combination of methods

Simulation

- Model of traffic
- Model of routers, links
- Simulation:
  - Time driven:
    - $X(t) = \text{state at time } t$
    - $X(t+1) = f(X(t), \text{event at time } t)$
  - Event driven:
    - $E(n) = n$-th event
    - $Y(n) = \text{state after event } n$
    - $T(n) = \text{time when event } n \text{ occurs}$
- Output analysis: estimates, confidence intervals
Simulation Example

- Use trivial time-driven simulation to illustrate statistical multiplexing
- Probabilistically generate the bandwidth of a flow, e.g.,
  - With probability 0.2, bandwidth is 6
  - With probability 0.8, bandwidth is 1
- Average bandwidth, $\text{avg} = 0.2 \times 6 + 0.8 \times 1 = 2$
- $\text{peak/avg} = 6/2 = 3$

One Flow

- $\text{peak} = 6$
- $\text{avg} = 2$
- $\text{peak/avg} = 6/2 = 3$

Two Flows

- $\text{agg_peak} = 7$
- $\text{agg_avg} = 3.75$
- $\text{agg_peak/agg_avg} = 7/3.75 = 1.86$
- $\text{agg_avg} = \text{average of aggregate bandwidth}$
- $\text{agg_peak} = \text{maximum value of aggregate bandwidth}$

50 Flows

- $\text{agg_peak} = 135$
- $\text{agg_avg} = 105.25$
- $\text{agg_peak/agg_avg} = 135/105.25 = 1.28$

Statistical Multiplexing

- As number of flows increases, $\text{agg_peak/agg_avg}$ decreases
  - For 1000 flows, $\text{peak/avg} = 2125/2009 = 1.057$
- Q: What does this mean?
- A: Multiplexing a large enough number of flows "eliminates" burstiness
  - Use average bandwidth to provision capacity, instead of peak bandwidth
  - E.g., For 1000 flows
    - Average of aggregate bandwidth = 2,000
    - Sum of bandwidth peaks = 6,000

Evaluation: Putting Everything Together

- Usually favor plausibility, tractability over realism
  - Better to have a few realistic conclusions than none (could not derive) or many conclusions that no one believes (not plausible)
Next Lecture

- Architecture, Layering, and the “End-to-End Principle”
- Read 1.4 & 1.5 of Kurose/Ross
- Pick up class computer account forms, if you haven’t done it already

- Project 1 (tiny world or warcrafts) out today
  - First part (client) due Oct 7 @ 11:59:59pm
  - Second part (server) due Oct 26 @ 11:59:59pm