Network Metrology: Bandwidth

This class

- Introduction
- Definitions of bandwidth metrics
- End-to-end measurement approaches
- Flooding
- Advanced probing
- Summary

Bandwidth captures network speed

- Bandwidth
  - Data rate of network link or path

- Why measure bandwidth?
  - Main commercial metric (e.g., in SLA)
  - Important for many applications
    - TCP congestion control
    - Video streaming
    - File transfer

Nominal Physical link capacity

- Definition:
  - Theoretical maximum transmission rate a link can support

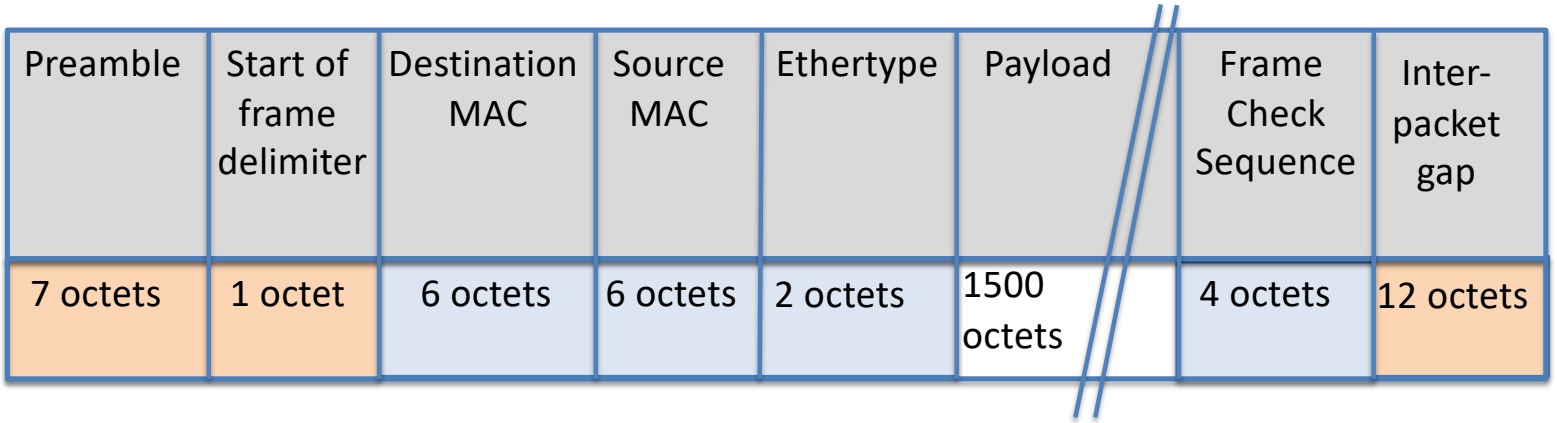
Examples physical capacities

- Local networks
  - 100BaseTX Ethernet: 100 Mbps
  - WiFi 802.11g: 54 Mbps; 802.11n: 130 ~ 150 Mbps (max 600 Mbps)
- Residential access (downstream)
  - ADSL2+: 24 Mbps
  - Cable: 30 Mbps
- Backbone links
  - OC-192: 10 Gbps
  - OC-768: 40 Gbps

Physical versus IP link capacity

- IP-layer capacity < nominal capacity
  - Coding schemes
  - Framing bits, overhead
  - Medium access control

Example: 100BaseTX Ethernet



Preamble	Start of frame delimiter	Destination MAC	Source MAC	Ethertype	Payload	Frame Check Sequence	Inter-packet gap
7 octets	1 octet	6 octets	6 octets	2 octets	1500 octets	4 octets	12 octets

- IP capacity (assuming max-size packets):
  - $\frac{1500}{1538} * 100\ Mbps = 97.5 Mbps$

Our focus

- Measurements at the IP layer and above
  - IP layer capacity
  - End-to-end capacity of a TCP connection

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Bandwidth-Related Metrics

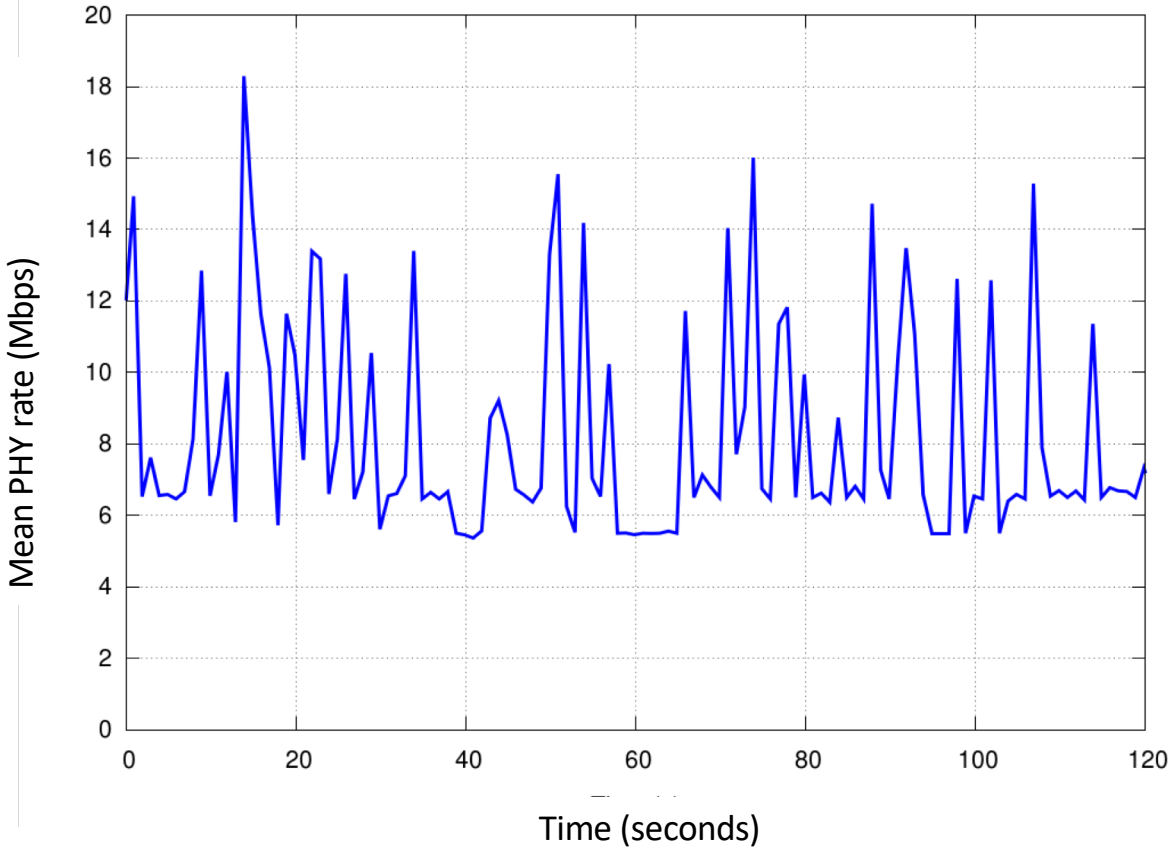
- Capacity
  - Single Link
  - End-to-End Path
- Available Bandwidth
  - Single Link
  - End-to-End Path
- Bulk Transfer Capacity (BTC)
  - End-to-End Path

Link capacity

- Link capacity ($C(\Delta t)$) = IP-layer capacity
  - Maximum IP-Layer transfer rate of maximum-sized packets
  - IP-layer capacity depends on size of packet relative to layer-2 overhead

Link capacity can vary over time

- E.g., WiFi 802.11n rate adaption



End-to-end capacity

- End-to-end capacity
  - Maximum possible capacity of the path
  - The link with the smallest capacity is called the ***narrow*** link.

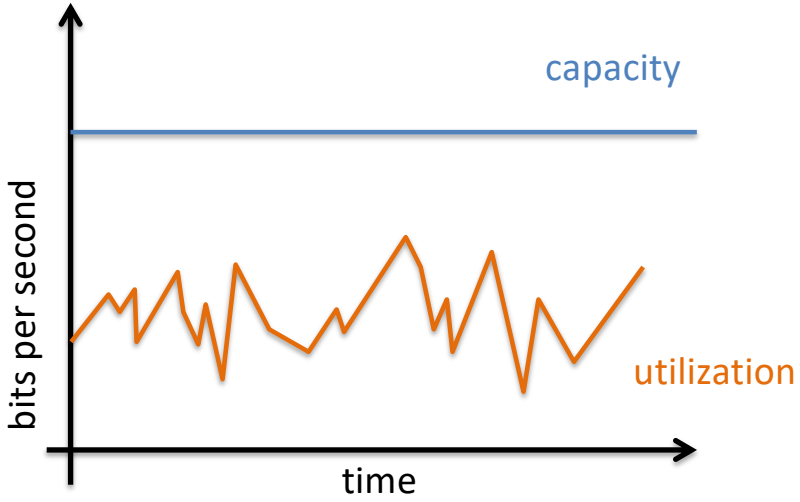
- What is the end-to-end capacity in this example?

Bandwidth-Related Metrics

- Capacity
  - Single Link
  - End-to-End Path
- Available Bandwidth
  - Single Link
  - End-to-End Path
- Bulk Transfer Capacity (BTC)
  - End-to-End Path

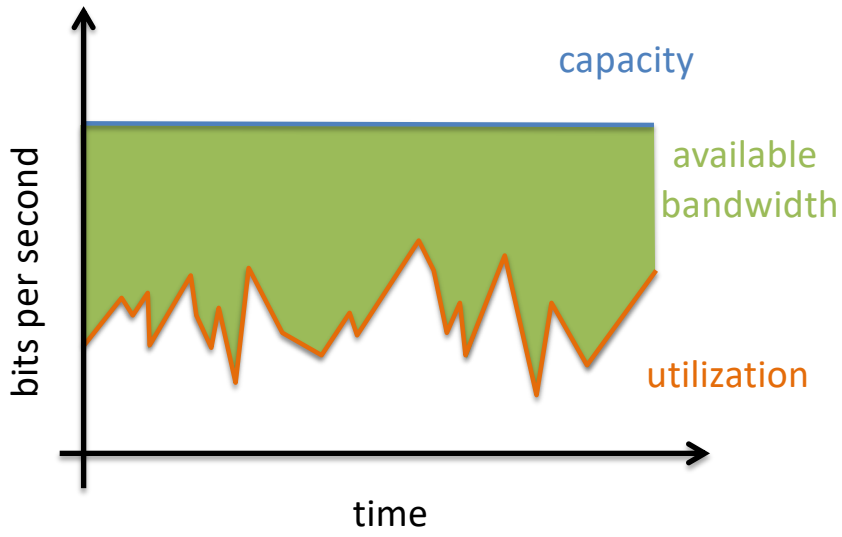
Link utilization

- Link utilization (u(Δt))
  - u(Δt) = Average bits transmitted on the link during Δt
  - Percent utilization = % link capacity that is utilized



Link available bandwidth

- Available bandwidth at a given time interval Δt:
  - $A(\Delta t) = C(\Delta t) - u(\Delta t)$



End-to-end available bandwidth

- End-to-end available bandwidth
  - $A = \min_{i=1 \ldots H} A_i$
  - Minimum available bandwidth of all hops
  - Link with smallest available bandwidth is known as the ***tight*** link

C_1: 100 Mbps
u_1: 80 Mbps
A_1: 20 Mbps

C_2: 30 Mbps
u_2: 3 Mbps
A_2: 27 Mbps

- What is the end-to-end available bandwidth in this example?

Bandwidth-Related Metrics

- Capacity
  - Single Link
  - End-to-End Path
- Available Bandwidth
  - Single Link
  - End-to-End Path
- Bulk Transfer Capacity (BTC)
  - End-to-End Path

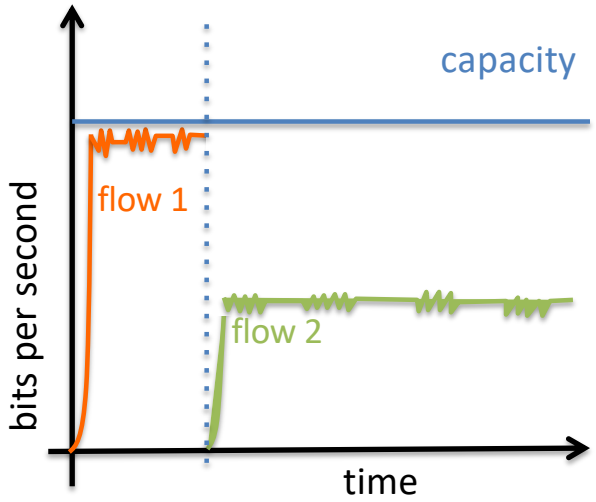
Bulk transfer capacity

- Bulk transfer capacity
  - Throughput of single TCP connection during bulk transfer

- 90% percent of traffic on the Internet is carried by TCP/IP.

Available bandwidth ≠ what is available for new connections

- Cross traffic may vary when new flows appear



Bulk transfer capacity depends on many factors

- Transfer size
- TCP variant and configuration
- Congestion on reverse (ACK) path
- Cross traffic

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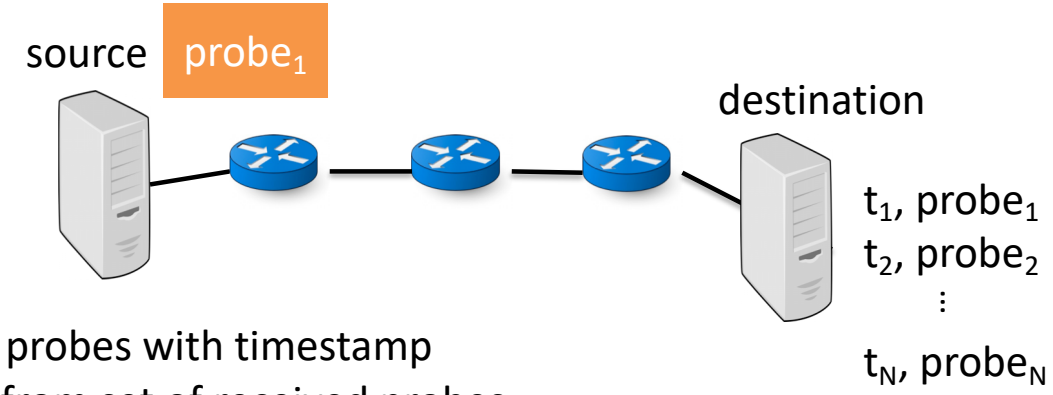
Our focus: active methods

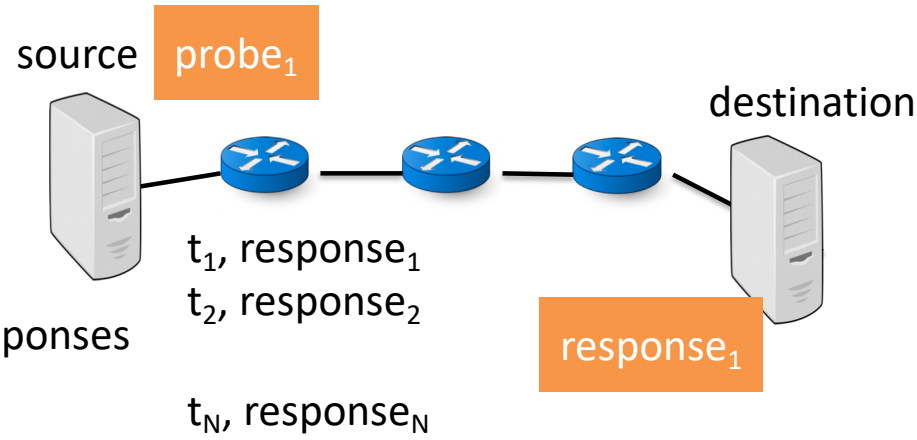
- Active methods measure properties of e2e paths
  - Metrics: capacity, available bandwidth, bulk transfer capacity
  - Measure any path with access to source and/or destination
- Passive methods require access to network equipment
  - Metrics: configured capacity, utilization
  - Measure single links or small number of links

Active measurement with control of source and destination of paths

- Source host
  - Issues probes
- Destination host
  - Records received probes with timestamp
  - Estimate metrics from set of received probes



Active measurement with control of source of paths only



- Source host
  - Issues probes
  - Estimate metrics from responses
- Limitation
  - Hard to distinguish properties of forward and reverse paths

Probing method

Flooding

- Issue large number of probes to “fill” path
- Pro
  - Measure what users can get
- Con
  - Large overhead affect network and users

Advanced methods

- A number of methods in literature
  - Packet pair, size-delay, self-induced congestion
- Pro
  - Less overhead than flooding
- Con
  - Rely on assumptions that don’t always hold in practice

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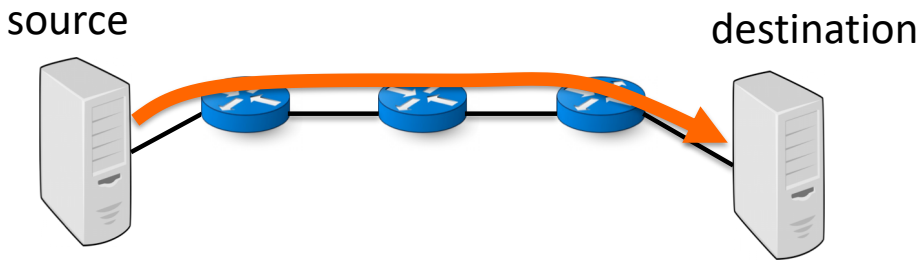
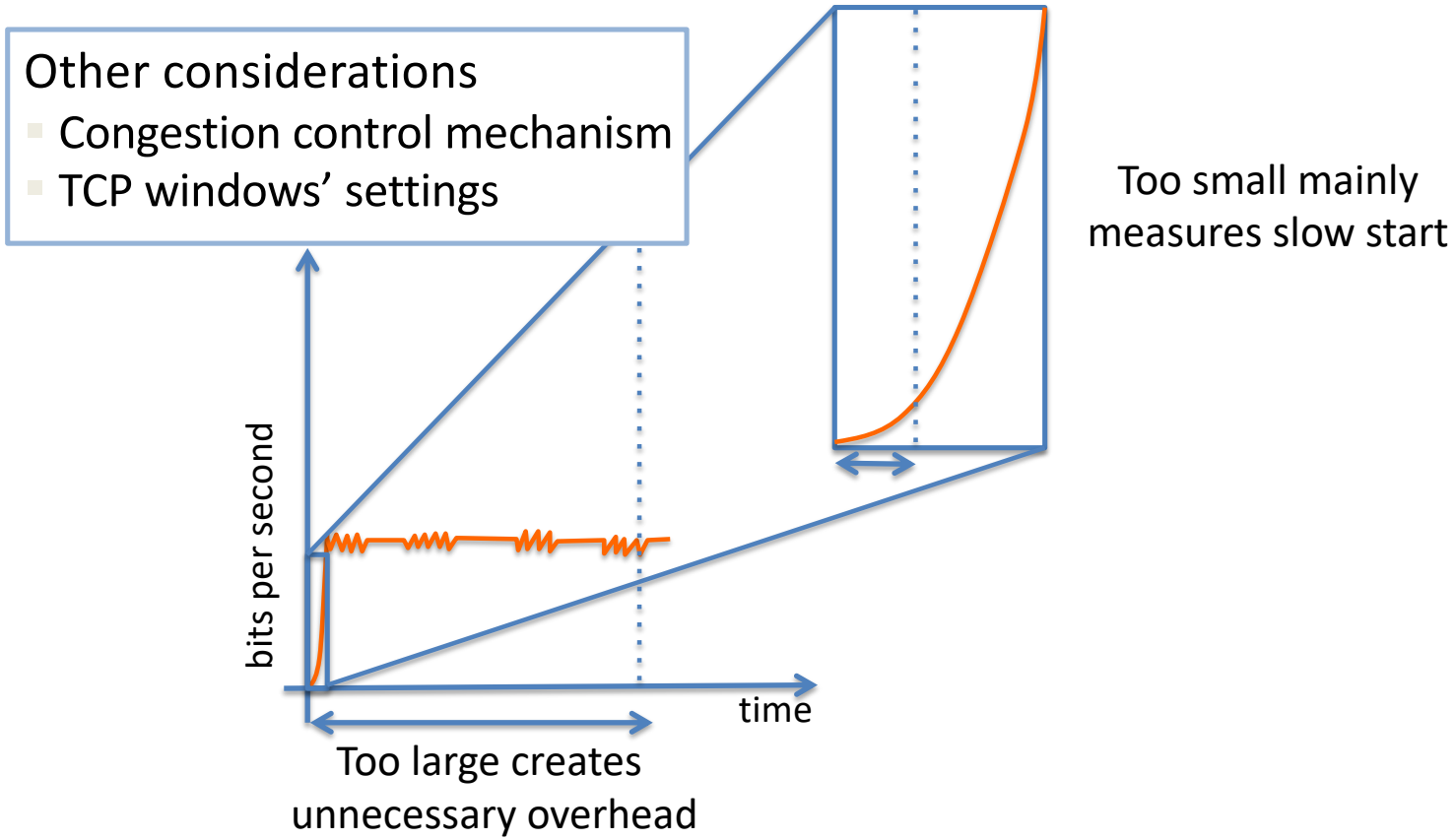
Bulk transfer capacity (BTC)

- Basic method
  - Send as much data as possible over a single TCP connection from source to destination



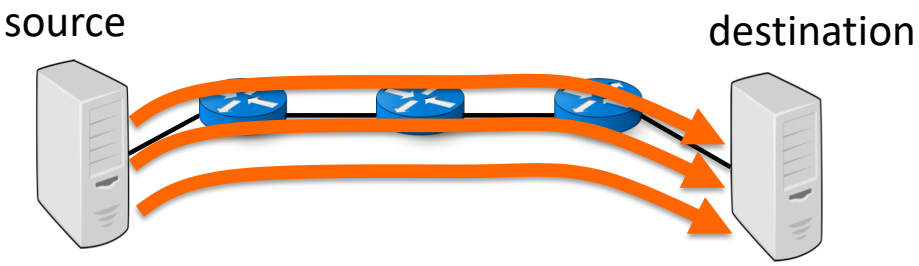
  - BTC = $\frac{\text{data size (in bits)}}{\text{transfer time}}$

Consideration: Transfer size



Available bandwidth

- Basic method
  - Send as much data as possible from source and measure rate at destination
    - Over multiple TCP connections or UDP



  - A = $\frac{\text{data size (in bits)}}{\text{transfer time}}$

Considerations

- TCP versus UDP
  - UDP not biased by congestion/flow control
  - Flooding with UDP may create too much congestion and bias results
  - Multiple TCP connections reduces bias
- Multi-threaded TCP
  - How many threads?
  - Which size transfers?
- UDP
  - How to pick sending rate?

Measure path capacity with flooding

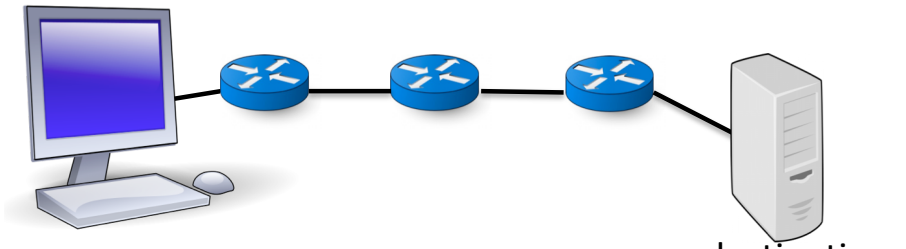
- Hard to measure capacity with a single measurement
- Solution: estimate from multiple measurements
  - Maximum available bandwidth over time approximates path capacity

Flooding tools and services for measuring available bandwidth

- iperf/iperf3
  - Control of client and server
  - Configurable tests
- Services for measuring broadband Internet: Speedtest
  - Fixed set of servers
  - Fixed tests

iperf3: Vantage points

- Installation at client and server
  - Public servers exist



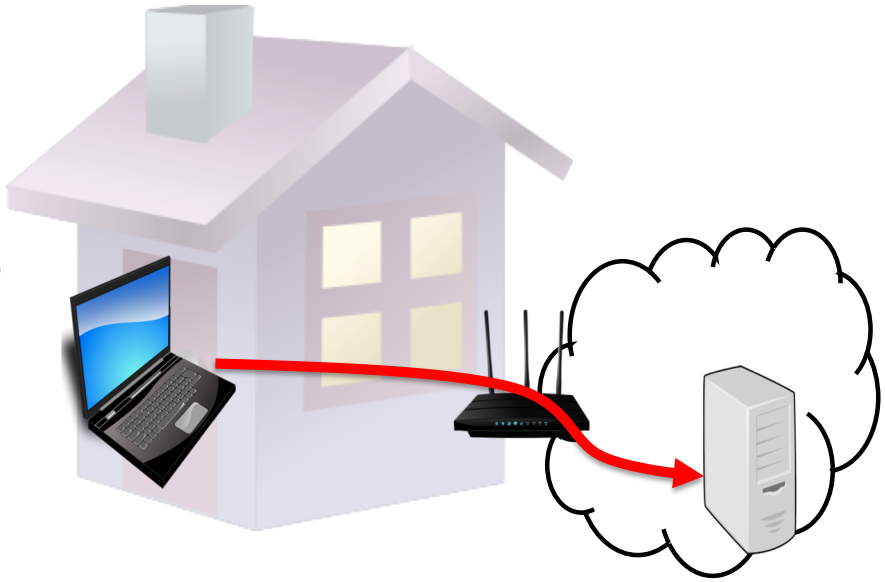
iperf3: Test configuration

- Protocol
  - TCP (default)
    - Configuration of window size (`-w`), congestion control (`-C`)
    - Multi-threaded TCP (`-P`): parallel streams
  - UDP (`-u`)
- Rates, timing
  - Bandwidth (`-b`)
  - Time to transmit (`-t`)
  - Bytes to transmit (`-n`)

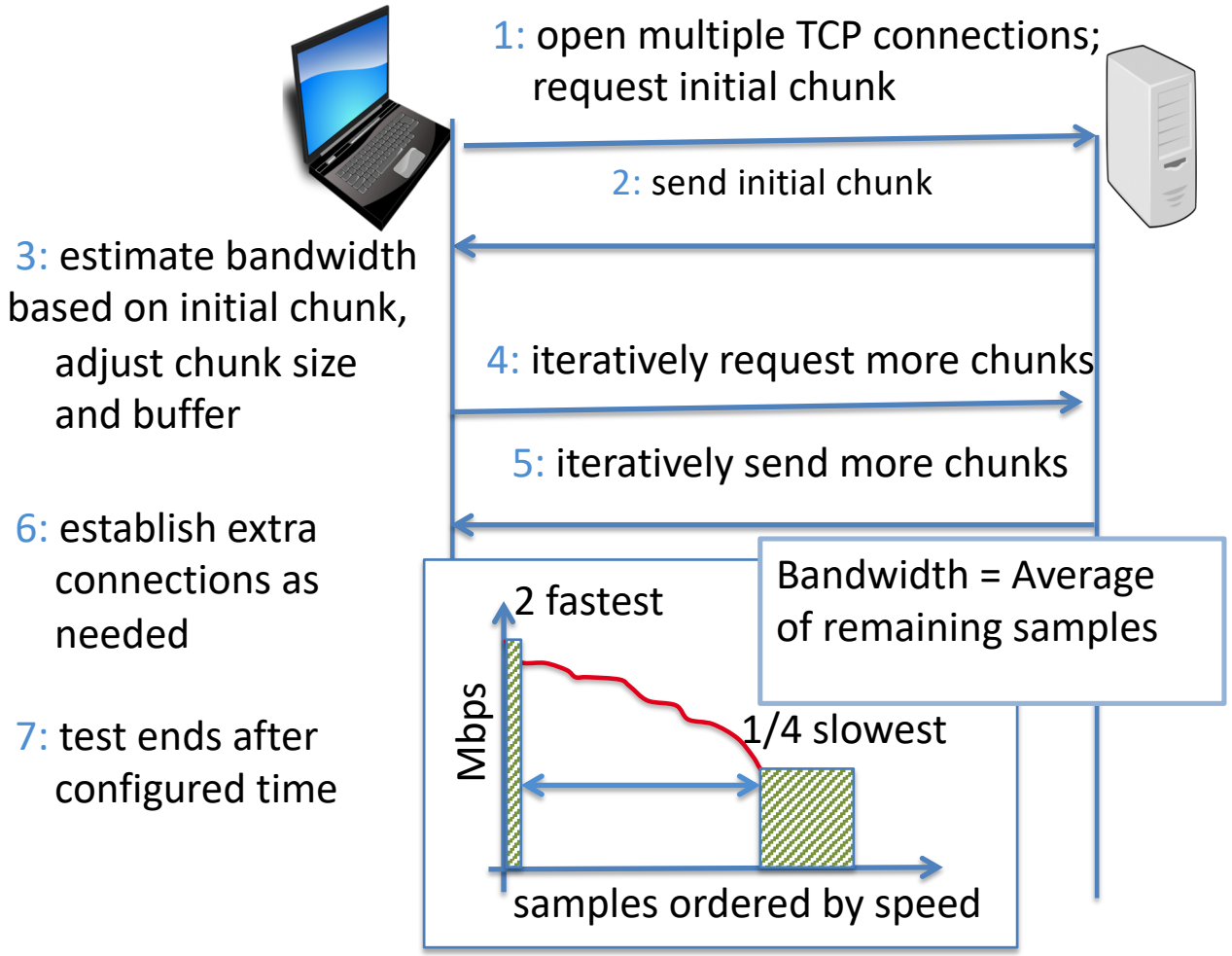
```
$ iperf3 -u -t 10 -b 100Mbit --get-server-output -c 192.168.1.174
Connecting to host 192.168.1.174, port 5201
[  4] local 192.168.1.231 port 51069 connected to 192.168.1.174 port 5201
[ ID] Interval           Transfer     Bandwidth       Total Datagrams
[  4]   0.00-1.00   sec  10.8 MBytes  90.2 Mbits/sec  1379
               ⋮
[  4]   9.00-10.00  sec  12.0 MBytes   100 Mbits/sec  1532
- - - - - - - - - - - - - - - - - - - - - - - - -
[ ID] Interval           Transfer     Bandwidth       Jitter    Lost/Total Datagrams
[  4]   0.00-10.00  sec   118 MBytes  99.0 Mbits/sec  0.839 ms  2034/15114 (13%)
[  4] Sent 15114 datagrams

Server output:
Accepted connection from 192.168.1.231, port 58542
[  5] local 192.168.1.174 port 5201 connected to 192.168.1.231 port 51069
[  5]   0.00-1.00   sec  7.05 MBytes  59.2 Mbits/sec  1.190 ms  226/1129 (20%)
               ⋮
[  5]   9.00-10.00  sec  11.4 MBytes  95.9 Mbits/sec  2.670 ms  74/1537 (4.8%)
```

Measuring residential broadband: Speedtest

- Well-placed servers
  - In major ISPs
- Client
  - User devices
    - Affected by WiFi, home traffic



Example: Speedtest's download test



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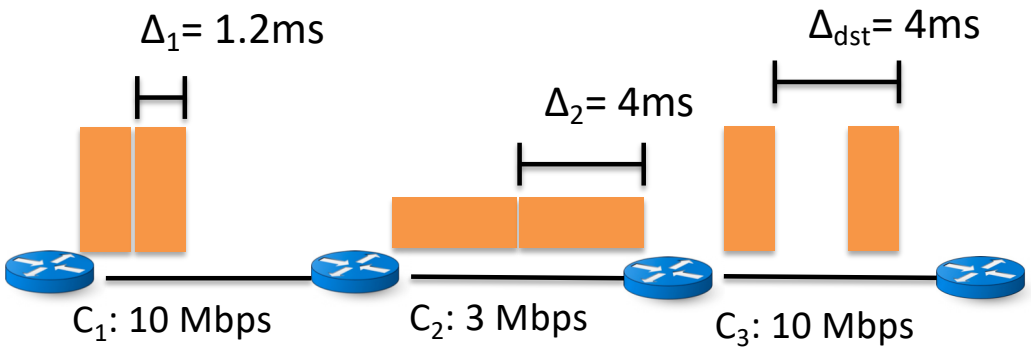
Capacity with packet pairs

- Basic method
  - Send a pair of equal-sized packets back-to-back and measure the inter-packet gap at destination



probe size (L) = 1500 bytes

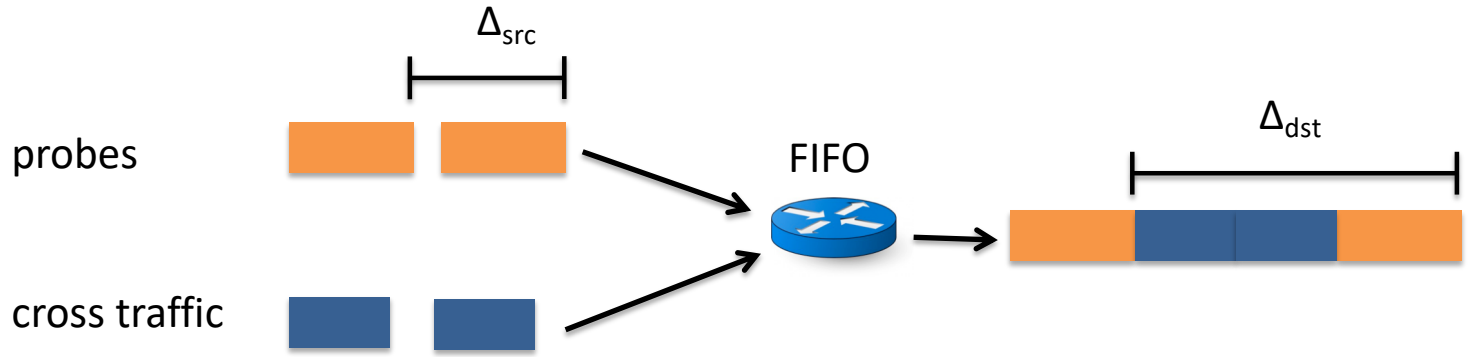
  - End-to-End Capacity: $C = \frac{L}{\Delta_{dst}}$

Considerations

- Probe size and interval
  - Probe rate should be greater than capacity of bottleneck link
  - Small probes, back-to-back
- Cross traffic will modify inter-probe gap
  - Send multiple probe pairs
  - Probe pairs with minimum delay give best estimates
- Gaps hard to measure at high capacity
  - E.g. 1500-byte probes at 1 Gbps = 12 μs

Available bandwidth with packet pairs

- Basic method
  - Use pairs of probes to measure capacity and cross traffic



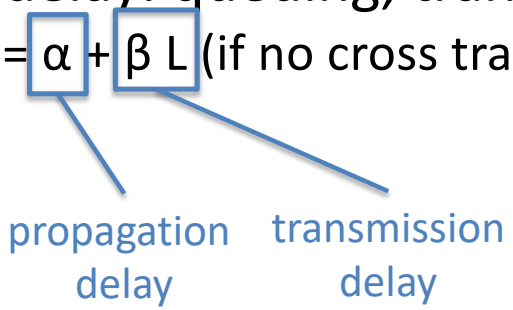
  - $A = C * \left[1 - \frac{\Delta_{dst} - \Delta_{src}}{\Delta_{src}}\right]$

Considerations

- Bottleneck router's queue not empty between probes
  - Send back-to-back probes
- Requires FIFO queuing
  - Not always true, e.g. CoDel

Capacity with size-delay: Intuition

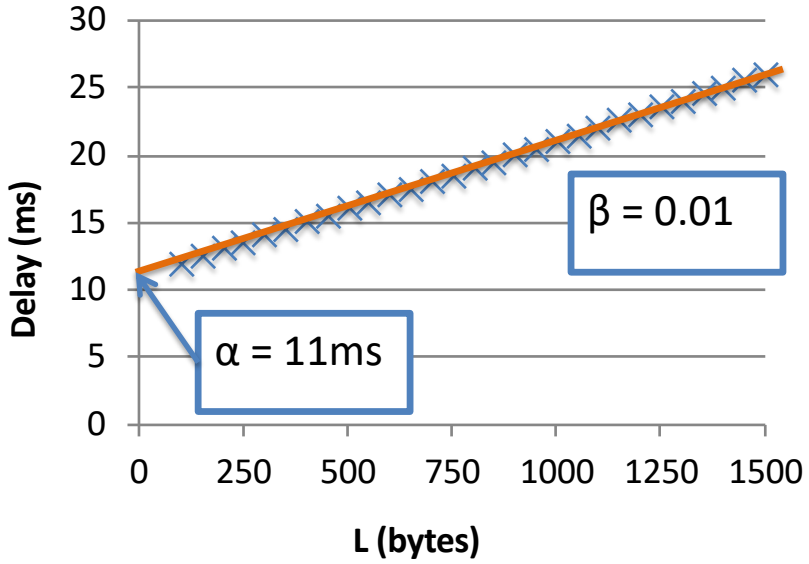
- Probe delay: queuing, transmission, propagation
  - $T(L) = \alpha + \beta L$ (if no cross traffic)



  - Only transmission delay affected by capacity and probe size

Capacity with size-delay: Basic method

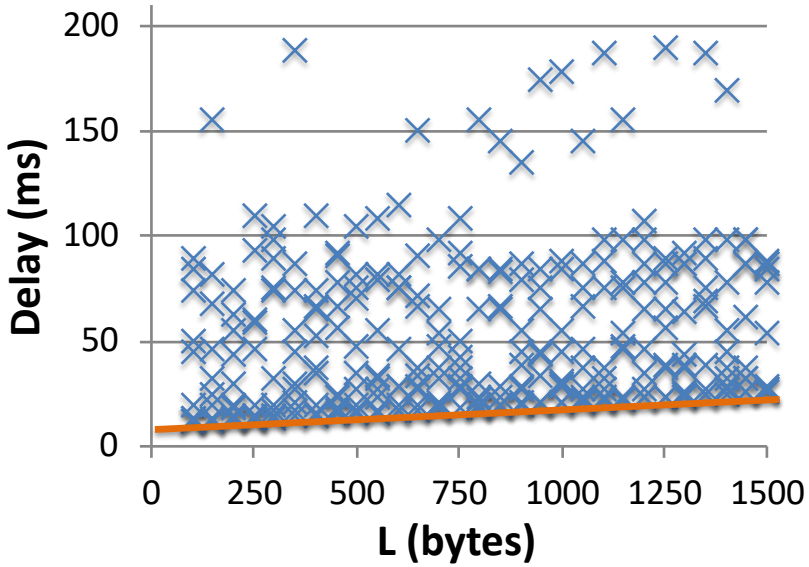
- Send RTT probes with varying packet sizes
  - Estimate α and β



$$C = \frac{1}{\beta}$$

Considerations

- Presence of cross traffic will break assumptions
  - Send many probes per L and take minimum

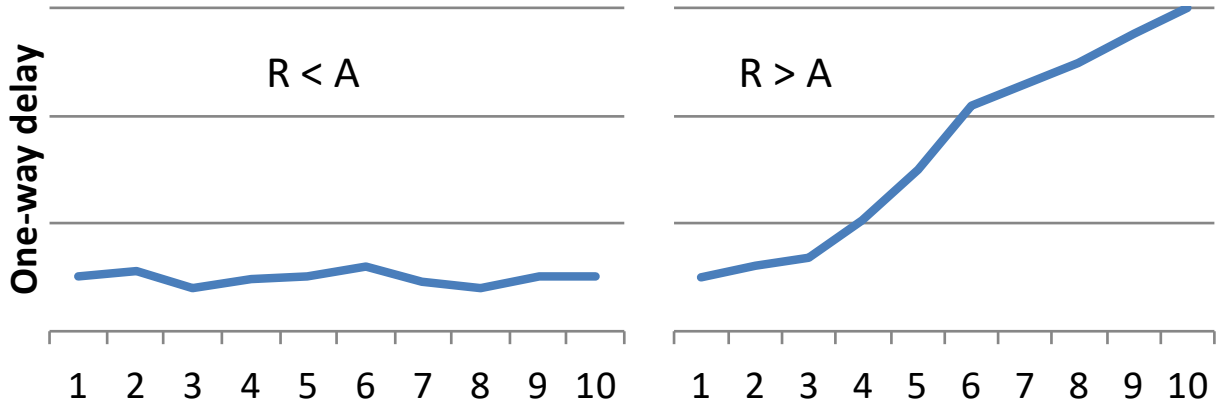


Considerations

- Presence of cross traffic will break assumptions
  - Send many probes per hop and take minimum
- Packet size may vary in the network
  - Layer-2 header sizes are different across technologies

Available bandwidth with self-induced congestion

- Basic method
  - Send train of equal-sized probes with rate R



  - Search R (binary or exponentially increasing)

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Which metric to select?

- Bulk transfer capacity
  - Captures bandwidth of applications with a single large transfer
- Available bandwidth
  - Captures available bandwidth of a path
    - Some applications use multiple connections
    - Multiple users share a single Internet access
- Capacity
  - Upper bound on available bandwidth

Measuring bulk transfer capacity

- Method: Flooding
- Considerations
  - Transfer size
  - TCP version and configuration

Measuring available bandwidth

- Method: Flooding
  - Direct measurement of available bandwidth
  - Large overhead (getting worse with higher link capacities)
- Method: Packet pair, self-induced congestion
  - Lower overhead
  - Results not exactly what new connections will get
  - Assumptions don’t always hold

Measuring capacity

- Method: Flooding
  - Measure available capacity
  - High overhead, require repeated measurements
- Method: Packet pairs, size-delay
  - Low overhead
  - As capacity increases, delay diffs are smaller and sensitive to errors

Internship proposals

- https://team.inria.fr/muse/join-us-2/

References

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