Network Security and Measurement

- Bandwidth, Capacity, and Congestion -

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Agenda

How can we quantify key properties and performances of a network?

Models for assessing networks

Measurement approaches to capacity

Measurement approaches to bandwidth

METRICS AND MEASURABLES

Quantifying Key Properties of a Network

What do we need to know and why?

- Capacities of the network to explore its potentials
- Utilization to asses its provisioning
- Current network performance to adapt applications
- Congestion for troubleshooting
- Bandwidth monitoring to gain operational experience

The Perspective of a Network Link

Terms and Phenomena

Available Bandwidth is the IP data rate that a network link can transfer.

Capacity is the maximum possible bandwidth that a network link can deliver.

Cross Traffic utilization is the difference between capacity and available bandwidth.

Congestion occurs when the available bandwidth falls below transmission demands.

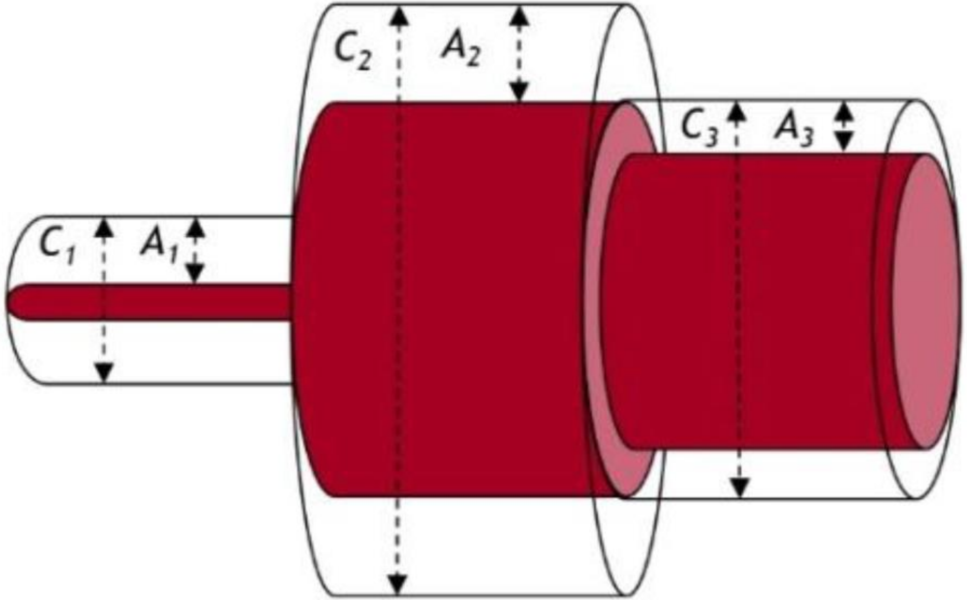
Controlled Traffic Flows adapt to available bandwidth.

A network is composed from a Mesh of Links.

Heterogeneous Link Transitions

Capacities (C_i) and network utilization vary between links, and with them the available bandwidths (A_i).

The end-to-end capacity (C) and available bandwidth (A) along a path are the minima of the respective components (C_i) and (A_i) $(over\ i)$.



Measurements of Interest

Network Characteristics and Performances

Capacities, link composition,
heterogeneous link transitions, bottlenecks

Measurements of Interest

Network utilization, available bandwidths, congestion and delays

Network Characteristics and Performances

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Bulk Transfer Capacity

Orthogonal metric on layer 4: Throughput of a single TCP connection

Depends on various transport features:

- Implementations and configurations at endpoints: buffers, algorithms, ...
- Adaptation of the probe flow
- Adaptations (or not) of the competing flows

Requires large data transfers: highly intrusive

Tools: *iperf, netperf*

Sources of Network Delay

Serialization delay – the time needed to place a packet on a link. Its duration is proportional to the ratio *packet-size/link-capacity.*

Propagation delay – the time needed for a bit to traverse the link. Its duration is proportional to the ratio *link-spread/link-speed.*

Queuing delay – the time needed to store a packet in queues and buffers of routers and switches while the outgoing port is blocked. Its duration depends on link transitions and competing traffic.

MEASUREMENT MODELS

Two Fundamentally Different Approaches

How to quantify the complex behavior

Probing at Rates

Systematically testing out available bandwidth.

Packet Spacing

Analyzing sequenced packets in the network.

Probe Rate Model (PRM)

Based on ideas by Bellovin and Jacobson

Probes between two controlled endpoints

- measure one-way delay

Varying probing rates

- induce a congestion on the path
- infer the starting point of the congestion

Produces a congesting load, intrusive

Underlying Idea

Packets traveling on sufficient bandwidth admit an about constant delay.

Packet rates (R) that exceed the available bandwidth (A) will see queuing delays.

The PRM objective is to find the probing rate at which the delay starts to rise.

The ‘ideal’ transition point marks the available bandwidth: R = A

Probe Gap Model

Based on ideas of Jacobson, Keshav, and Bolot

Inject individual packet pairs with gap

- measures dispersion of packets

Tight links increase dispersion

- identify minimal gap

Limitation

- quantifies only a single tight link
- sensitive to varying cross traffic

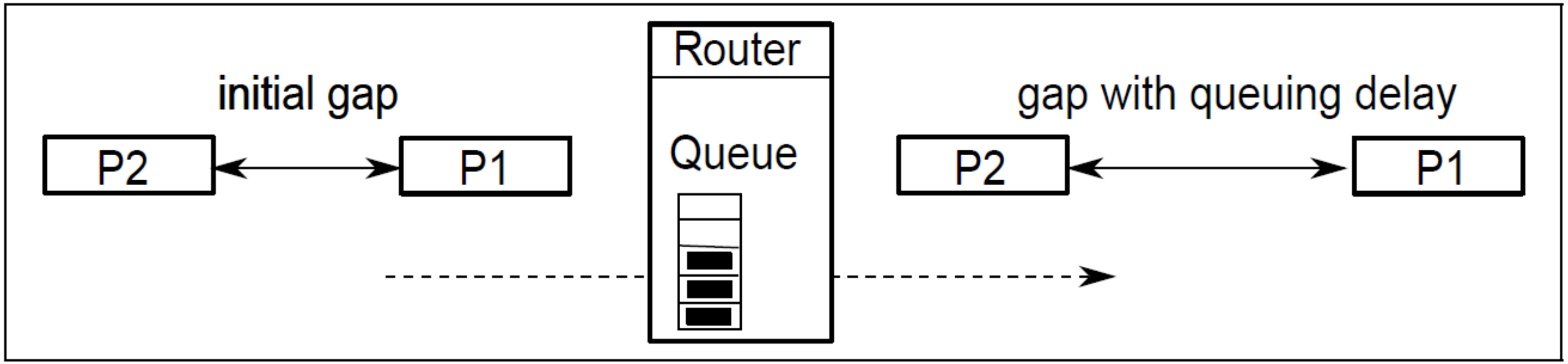
Little traffic overhead, not intrusive

Underlying Idea

In a balanced, uncongested network, inter-packet gaps remain constant.

Link serialization at bottleneck links will add dispersion.

Increasing queuing delays from congested networks also add dispersion and will lower the capacity estimates.



MEASURING CAPACITY

Variable Packet Size (VPS) Probing

PGM approach for measuring the capacity of each hop along a path

Procedure:

- Measure RTTs to each hop as a function of packet sizes (minima to exclude queuing)
- Use increasing TTL values (like traceroute)

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- Use increasing TTL values (like traceroute)
- Extract the delay portion that is proportional to the packet size: The serialization delay

Problem: store-and-forward layer-2 switches introduce serialization delays beyond capacities

The VPS Method

The RTT $T_i(L)$ at the i-th hop consists of a size-independent part α_i and the serialization proportional to the packet size L:

$$T_i(L) = \alpha + \sum_{k=1}^{i} \frac{L}{C_k} = \alpha + \beta_i L$$

with C_k the capacity of the k-th hop, β_i the slope of the minimum RTT.

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Measuring the slopes β_i at each hop, allows us to calculate all capacities:

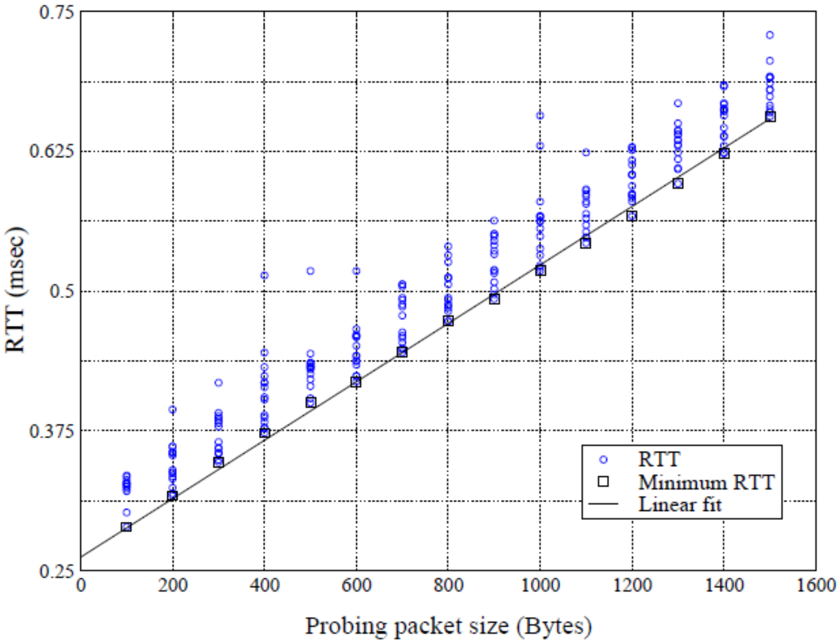
$$C_i = \frac{1}{\beta_i - \beta_{i-1}} \quad \text{since} \quad \beta_i = \sum_{k=1}^{I} \frac{1}{C_k}$$

Example

Probes measured for a first hop

Minimum RTTs selected

Linear interpolation



Packet Pair/Train Dispersion (PPTD) Probing

PGM method for measuring end-to-end capacity.

A sequence of packet pairs of fixed gap Δ_{in} is sent from the source to the receiver and the dispersion Δ_{out} is measured.

The dispersion after a link of capacity C_i will be

$$\Delta_{out} = \max\left(\Delta_{in}, \frac{L}{C_i}\right)$$

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After a packet pair traversed each link of a path, the dispersion Δ_R reads

$$\Delta_R = \max_{i=0,\ldots,H}\left(\frac{L}{C_i}\right) = \frac{L}{\min_{i=0,\ldots,H}(C_i)} = \frac{L}{C}$$

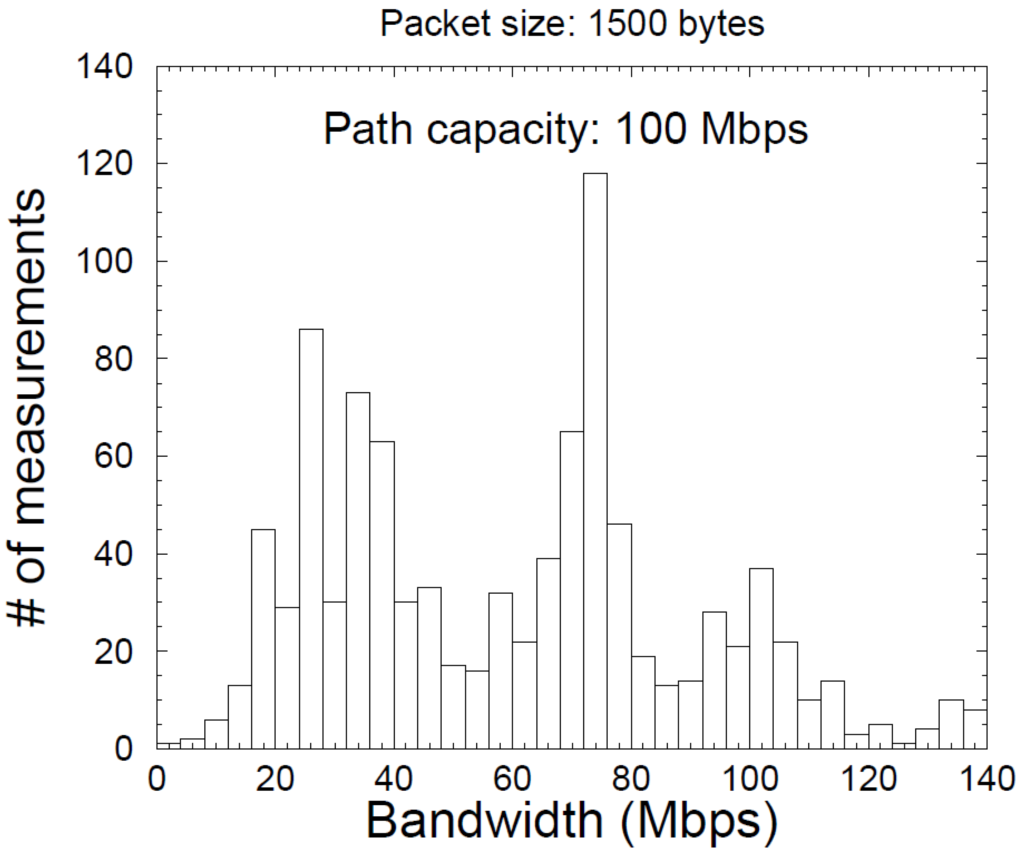
where C is the end-to-end capacity of the path.

Sending multiple packet pairs can mitigate the effect of cross traffic.

Example

Measuring a realistic wide-area link with real traffic load can lead to significant outliers and capacity underestimation.

Selecting the maximum capacity after statistical filtering can mitigate errors.



MEASURING AVAILABLE BANDWIDTH

Self-Loading Periodic Streams (SLoPS)

Poster PRM method to measure end-to-end available bandwidth.

The sender sends a “periodic stream” of equal-sized packets (≈ 100) at a given rate R.

Sender and receiver measure the one-way delays, which only increase under congestion.

R is varied in a binary search to approach the maximum without increasing delays.

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Under varying cross traffic, a “grey region” is determined.

Trains of Packet Pairs (ToPP)

Combination of PRM and PGM to determine the available bandwidth and tight link capacity

ToPP sends many packet pairs at gradually increasing rates from the source to the sink.

The receiver measures the dispersion of the packet pairs.

All packets have the same length L.

Increasing packet rates lead to decreasing initial packet gaps, which eventually will lead to increasing dispersions, if overload occurs.

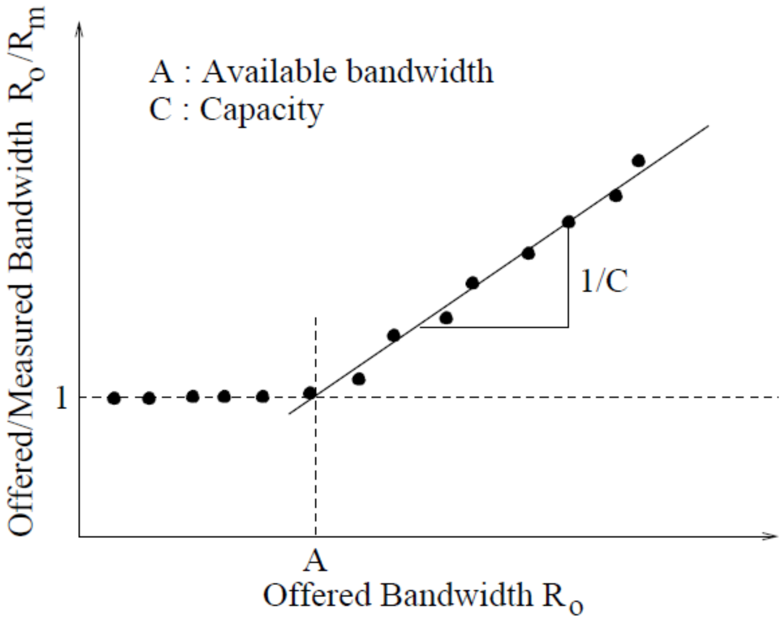
The ToPP Method

The packet gap Δ_s at the sender defines an offered bandwidth of $R_0 = \frac{L}{\Delta s}$.

The measured dispersion corresponds to a rate R_m.

The maximum R_0 such that $R_0 \approx R_m$ corresponds to the available bandwidth A

The slope of the relative bandwidth decay is inverse proportional to the end-to-end capacity.



Résumé

- All approaches have limitations, multiple refinements exist
- Expect high statistical fluctuations – the higher the larger the network distance
- Data post-processing needs to follow the specific measurement approach
- Some measurements can be piggybacked, e.g., on application data exchange

Literature

Ravi Prasad, Constantinos Dovrolis, Margaret Murray, and Kimberly C. Claffy (2003).

Bandwidth Estimation: Metrics, Measurement Techniques, and Tools. *IEEE Network*, 17(6):27-35.

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Bandwidth estimation: metrics, measurement techniques, and tools

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Abstract— **In a packet network, the terms “bandwidth” or “throughput” often characterize the amount of data that the network can transfer per unit of time. Bandwidth estimation is of interest to users wishing to optimize end-to-end transport performance, overlay network routing, and peer-to-peer file distribution. Techniques for accurate bandwidth estimation are also important for traffic engineering and capacity planning support. Existing bandwidth estimation tools measure one or more of three related metrics: capacity, available bandwidth, and bulk transfer capacity (BTC). Currently available bandwidth estimation tools employ a variety of strategies to measure these metrics. In this survey we review the recent bandwidth estimation literature focusing on underlying techniques and methodologies as well as open source bandwidth measurement tools.**

with high bandwidth links and low packet transmission latencies.

Bandwidth is also a key factor in several network technologies. Several applications can benefit from knowing bandwidth characteristics of their network paths. For example, peer-to-peer applications form their dynamic user-level networks based on available bandwidth between peers. Overlay networks can configure their routing tables based on the bandwidth of overlay links. Network providers lease links to customers and usually charge based on bandwidth purchased. Service-Level-Agreements (SLAs) between providers and customers often define service in terms of available bandwidth at key interconnection (network boundary) points. Carriers plan capacity upgrades in