End-to-End Available Bandwidth: Measurement Methodology, Dynamics, and Relation with TCP Throughput

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Talk Overview

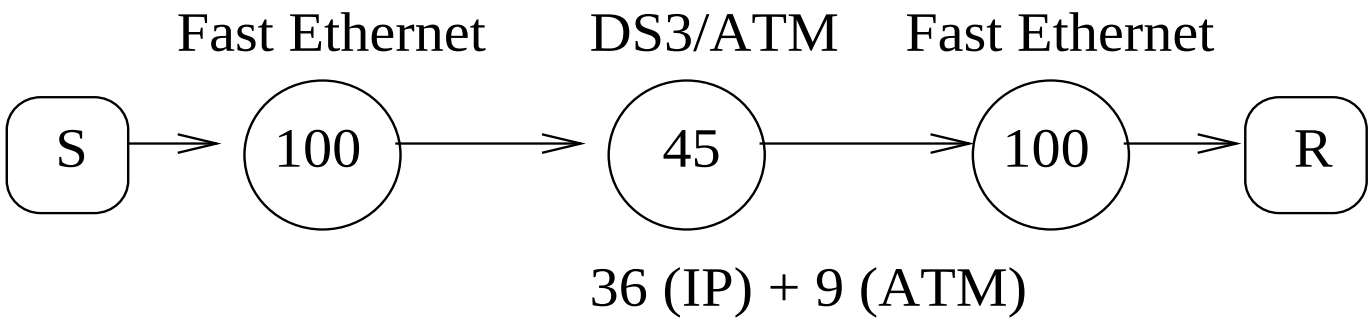
- Capacity and available bandwidth (avail-bw)
- Avail-bw estimation methodology (SLoPS) and tool (Pathload)
- Verification of Pathload
- Using Pathload to examine avail-bw variability

Capacity and Available bandwidth

- Path capacity C: maximum possible end-to-end throughput.

  It is defined as $C = \min_{i=0\ldots H} \{C_i\}$, where, C_i is capacity of link i

  Narrow Link: the link with minimum capacity



- Avail-bw: spare capacity in the path.

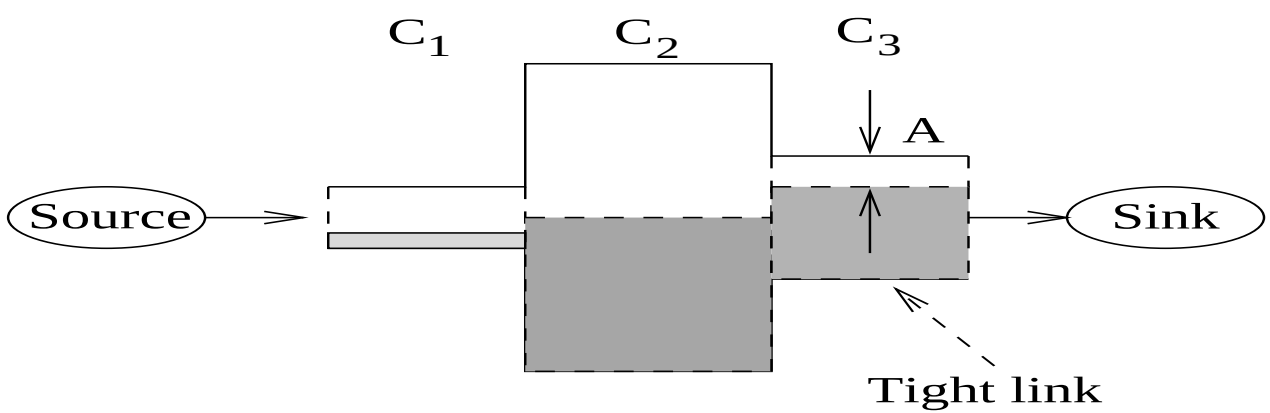
  maximum end-to-end throughput given cross traffic load. It is a time-varying metric, defined as average over certain time interval.

  Tight Link: the link with minimum available bandwidth.

Definition of avail-bw

- u_i : average utilization of link i in a time interval of length τ ($0 <= u_i <= 1$)
- *Avail-bw of link i*: $A_i = C_i (1-u_i)$

  End-to-end avail-bw: $A=\min_{i=0\ldots H} A_i = \min_{i=0\ldots H} C_i(1-u_i)$
- Time interval length τ : averaging timescale

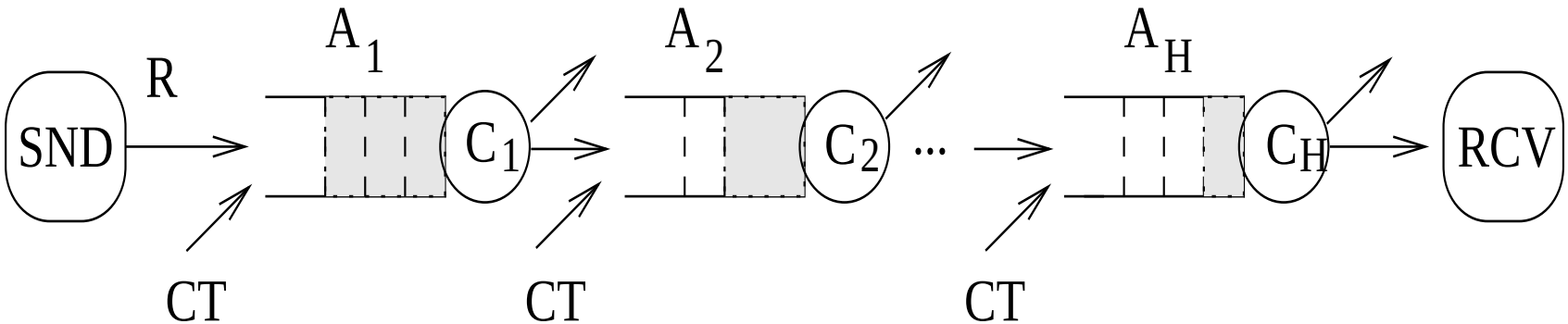


- Avail-bw is limited by tight-link

Previous work on avail-bw estimation

- Measure throughput of bulk TCP transfer
  - A bulk TCP's throughput is not avail-bw.
  - TCP saturates path (i.e., intrusive measurements)
- Carter & Crovella: dispersion of long packets trains (cprobe)
- Ribeiro et al.: estimation technique for single-queue paths
- Melander et al.: attempt to estimate capacity & avail-bw of every link in path

Self-loading Periodic Streams (SLoPS)



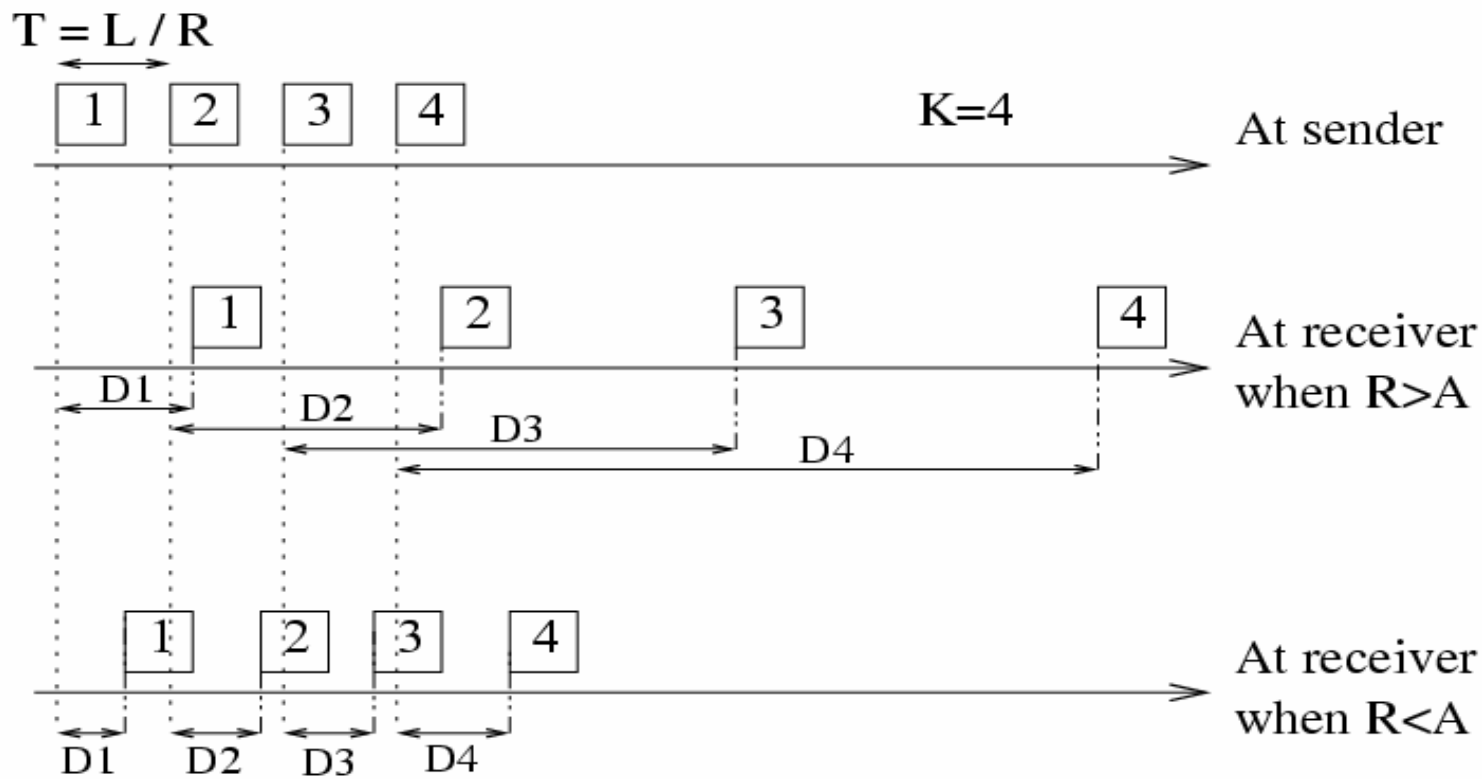
- *SND* sends a periodic UDP packet stream of rate *R*
- Stream characteristics: K packets, size L, period T, rate R=L/T
- *RCV* Measured One-Way Delay (OWD): $D^K = T_{arrive}^{RCV} - T_{send}^{SND}$
- OWD variation: $\Delta D^k = D^{k+1} - D^k$ (independent of clock offset)
- With a stationary & fluid model for the cross traffic, and FIFO queues:

  If $R > A = \min A_i$, then $\Delta D^k > 0$ for $k=1,\ldots,K-1$

  Else, $\Delta D^k = 0$ for $k=1,\ldots,K-1$

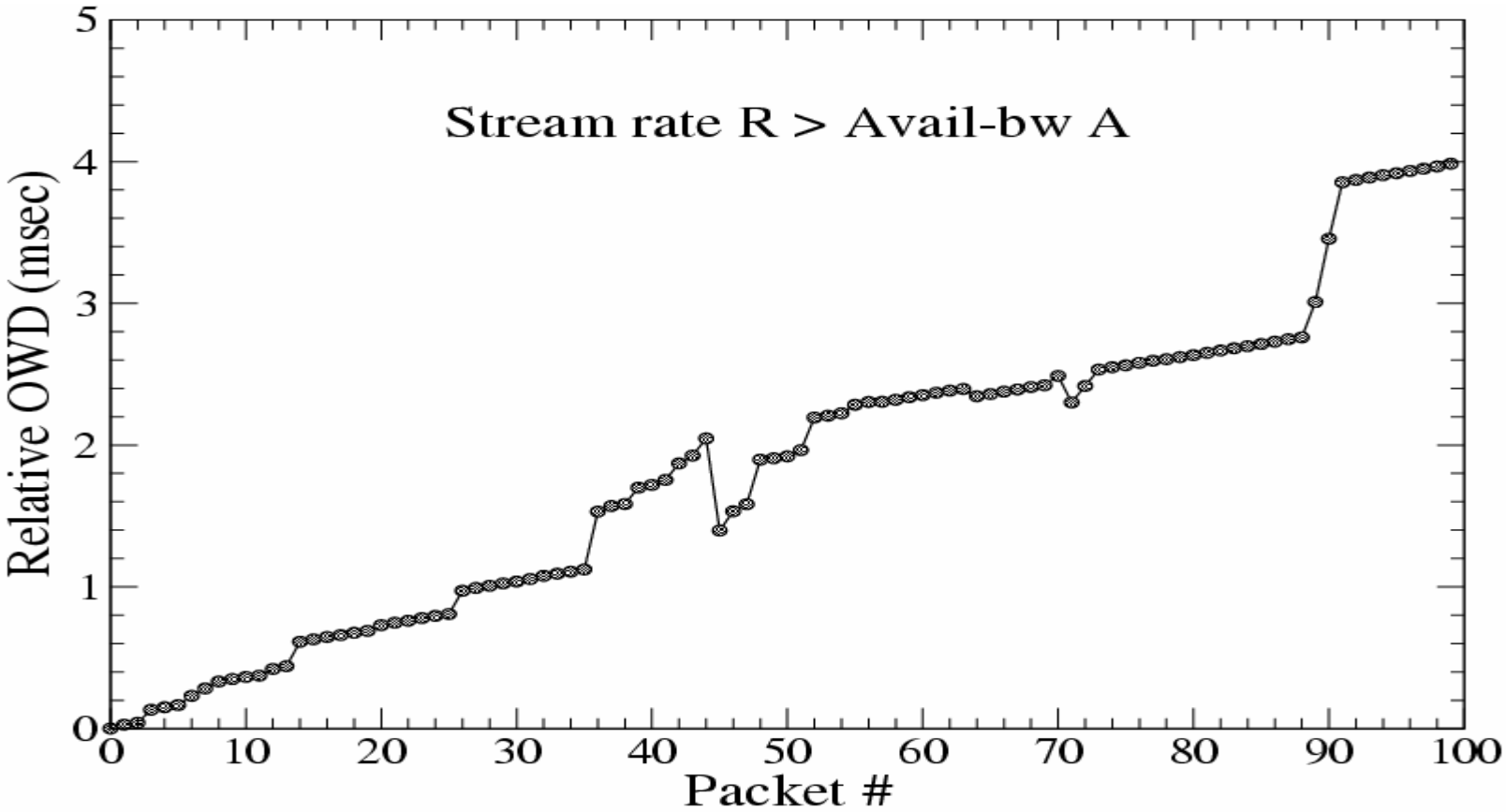
Illustration of basic idea

- Periodic stream: K packets, period T, packet size L, rate: R=L/T



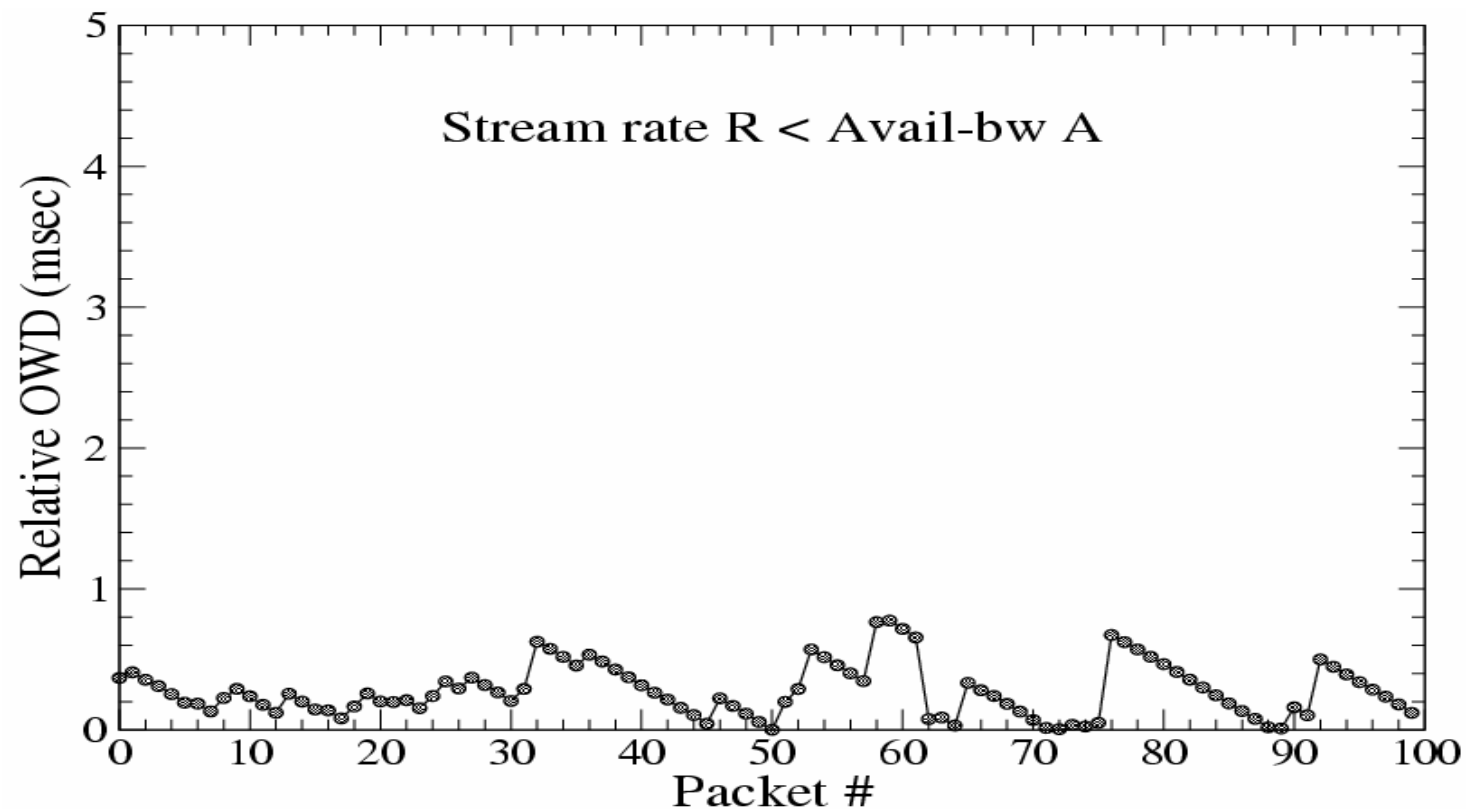
Increasing delay trend: R> A

- Path: Univ-Oregon to Univ-Delaware (12-hops)
- A=73Mbps (MRTG), R=96Mbps (K=100packets, T=100µs, L=1200B)



Non-increasing delay trend: R<A

- Path: Univ-Oregon to Univ-Delaware (12-hops)
- A=74Mbps (MRTG), R=37Mbps (K=100 packets, T=100μs, L=462B)



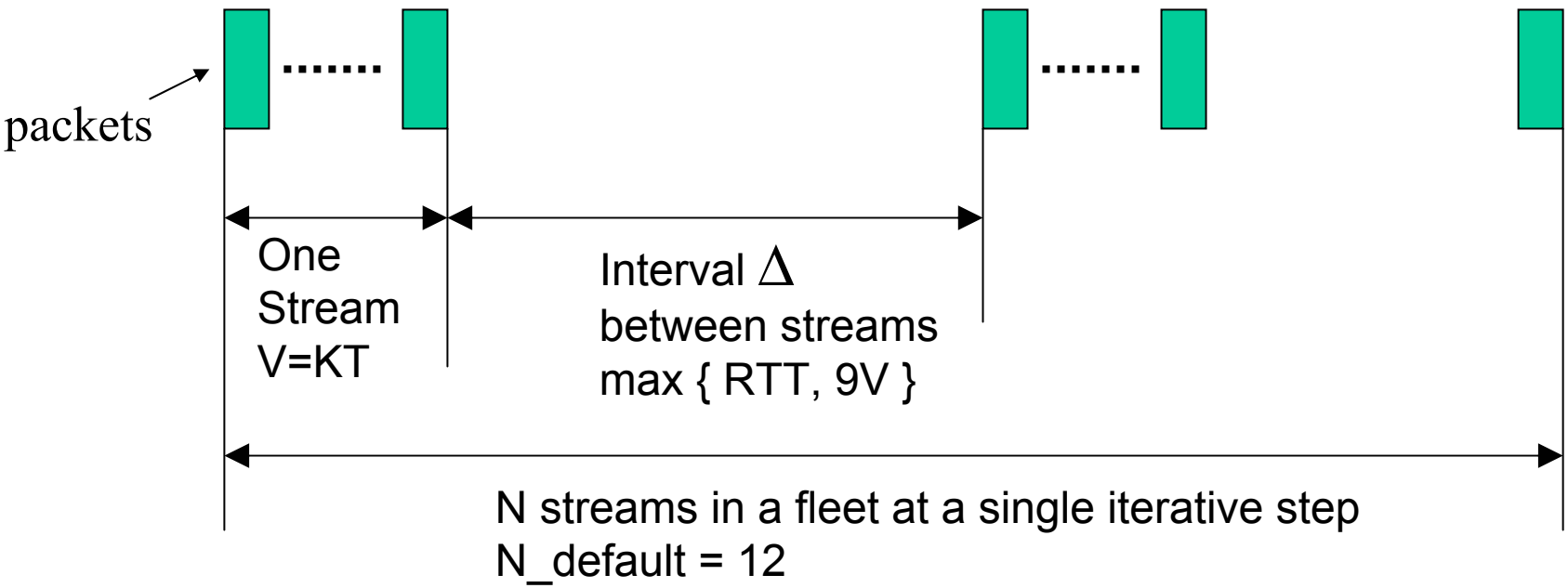
Iterative rate adjustment to measure A

- Source: send n-th periodic stream with rate R(n)
- Receiver: measure delays D^k for k=1…K
- Receiver: check for increasing delay trend, notify source
- Source:
  - If delays show increasing trend (R(n) > A), $R^{max} = R(n)$;
  - If delays show non-increasing trend (R(n) < A), $R^{min} = R(n)$;
  - $R(n+1) = (R^{max} + R^{min})/2$;

- Exit when $R^{max} - R^{min} <= \omega$ (ω: estimate resolution)

Rate-adjustment Algorithm

In actual implementation: a fleet of N streams sent out at time *n* to infer if $R(n)>A$, $R(n)<A$, *or* $R(n) >< A$. Then, the iterative algorithm determines the rate $R(n+1)$ of the next fleet.



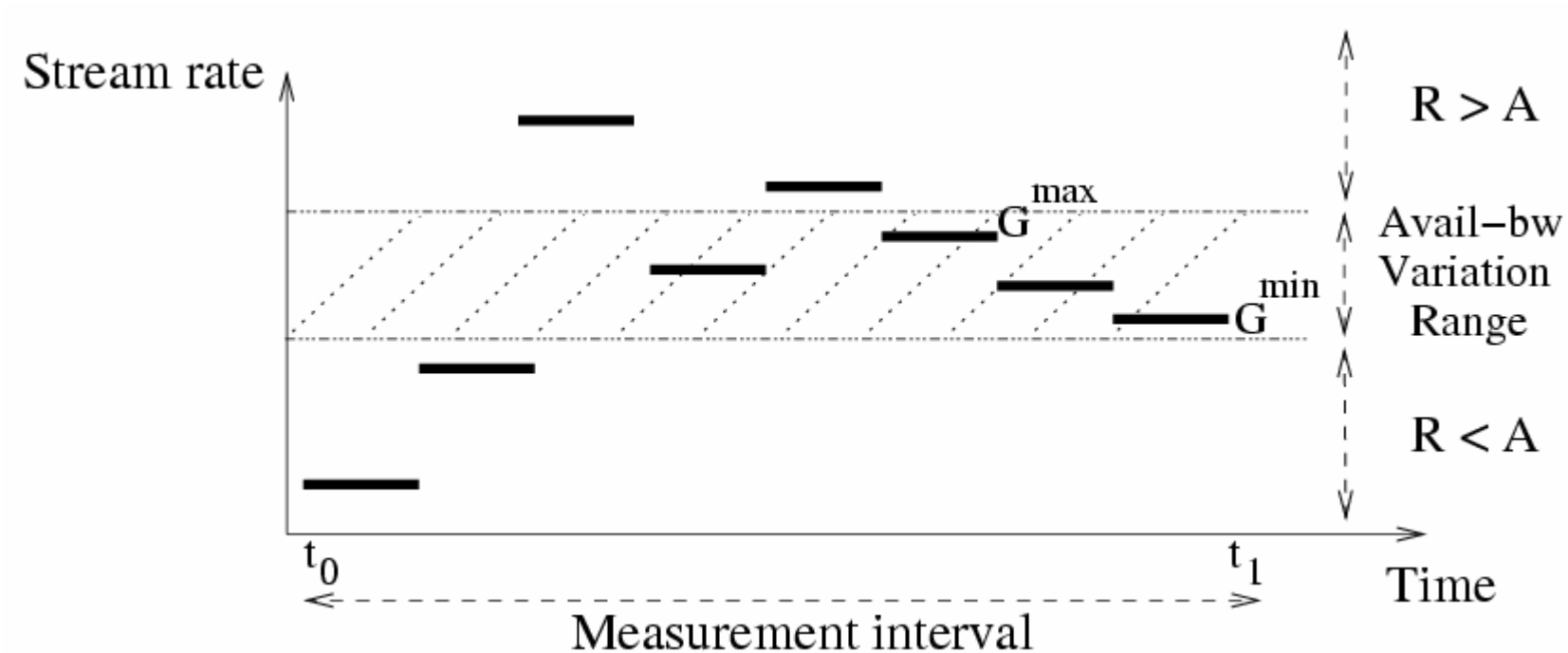
Measurement Latency? Time scale?

K_default=100, if L=800B, T=100μsec, a stream lasts 10msec.

Using default parameters, if A≈100Mbps, Δ=100ms, the tool takes 15 seconds to converge.

Rate-adjustment Algorithm, Grey-region, and avail-bw variability

- Measurement stream rate can fall into avail-bw variation range



- Pathload reports grey-region boundaries [G^{min}, G^{max}]
- Relative width of grey-region: quantify avail-bw variability

Detection of increasing trend in a single stream

Pairwise Comparison Test (PCT)

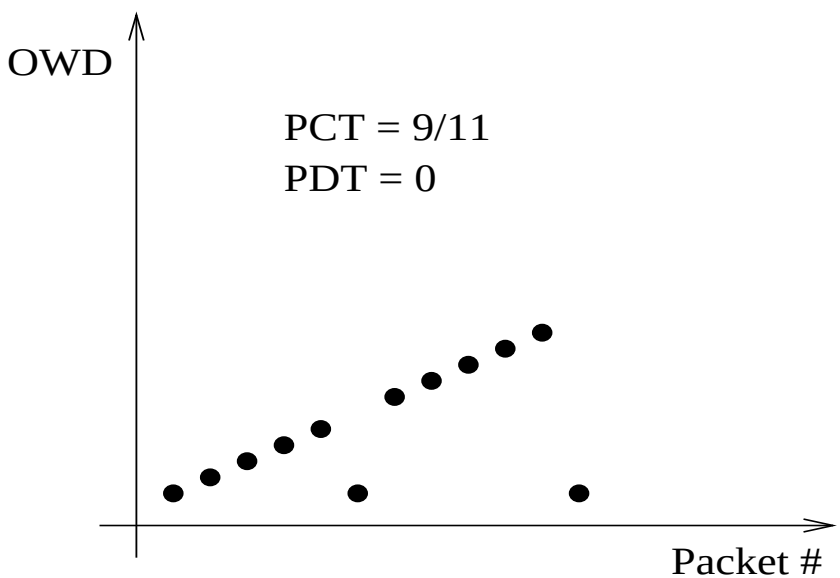
$$PCT = \frac{\sum_{k=2}^{K} I(D^k > D^{k-1})}{K-1}$$

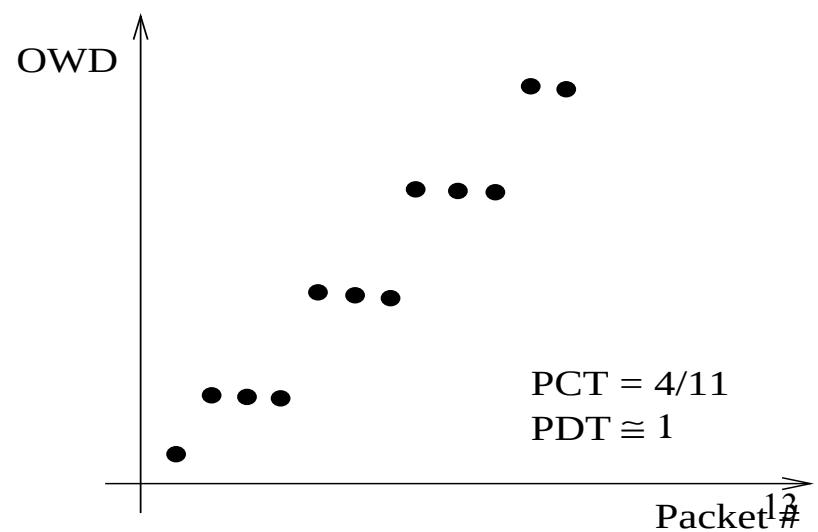
$0 <= PCT <= 1$

Pairwise Difference Test (PDT)

$$PDT = \frac{D^K - D^1}{\sum_{k=2}^{K} \left| D^k - D^{k-1} \right|}$$

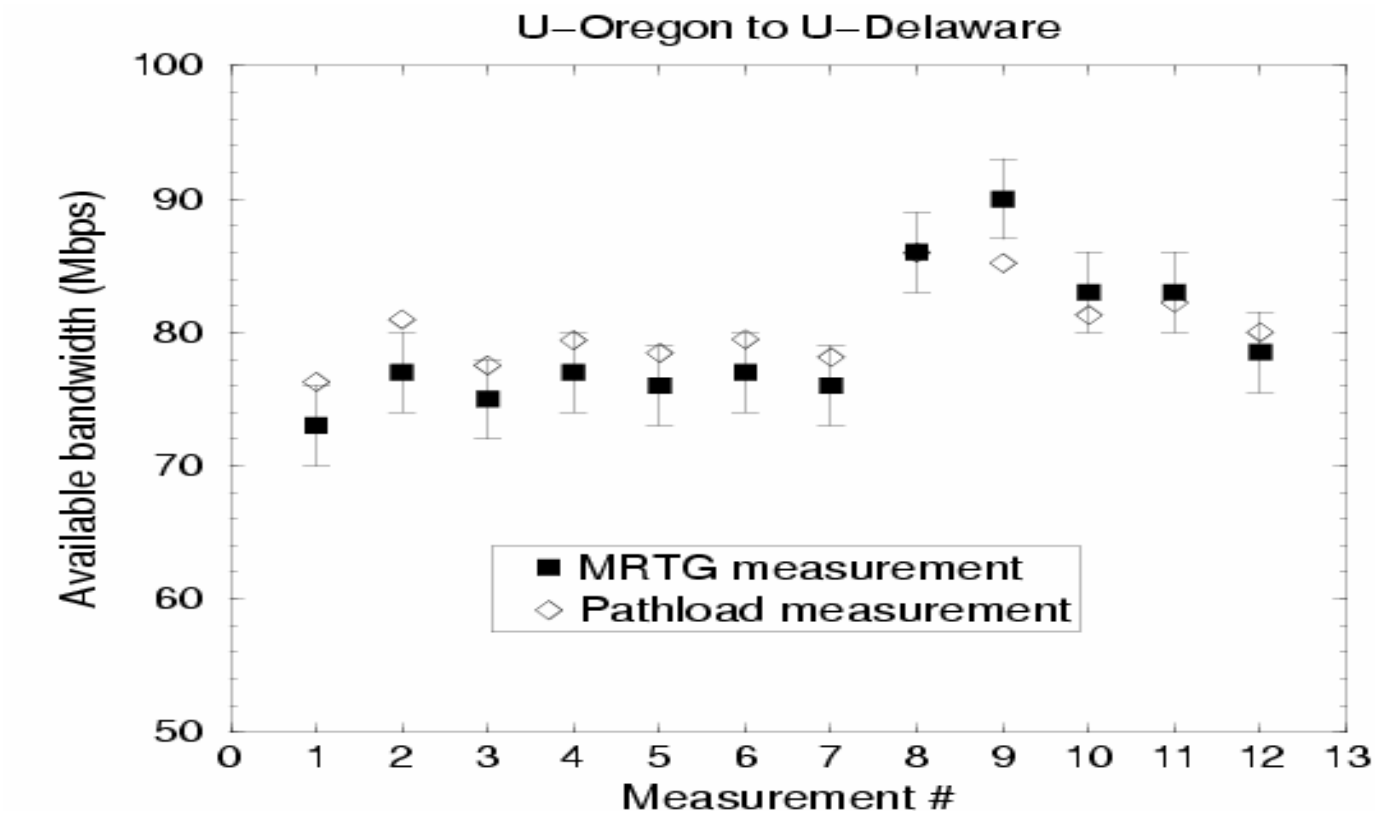
$-1 <= PDT <= 1$





Experiment verification

- From Univ-Oregon to Univ-Delaware
- Tight link: U-Oregon GigaPoP link (C=155Mbps)
- Compare Pathload estimate (average of consecutive runs for 5 mins) with 5-min average avail-bw from MRTG readings.

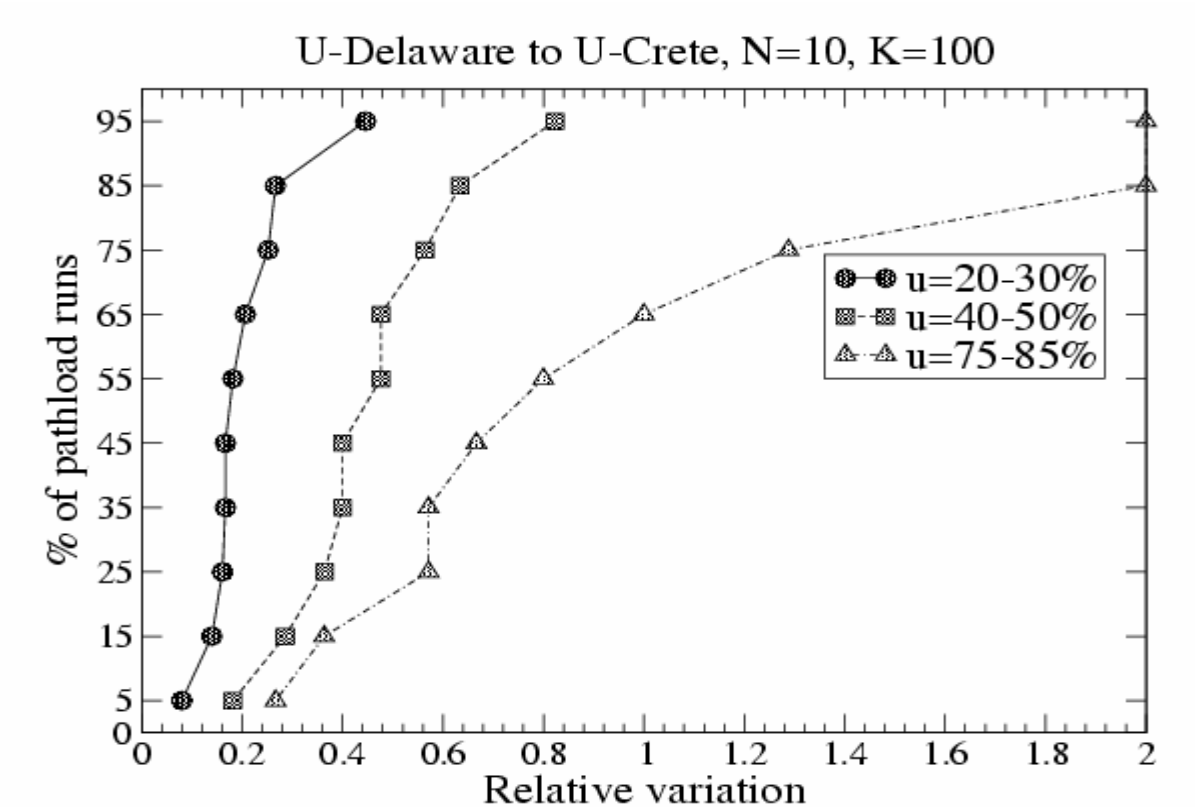


Pathload: latency and intrusiveness

- For RTT=100msec and A≈100Mbps, Pathload takes approx 15 seconds to converge
- Pathload does not cause:
  - Significant reduction in avail-bw (less than 10%)
  - Significant increase in queuing delays
- It is not intrusive: does not cause significant increases in network utilization, delays, or losses.
- To achieve non-intrusiveness:
  - Short measurement streams (K=100)
  - Introduce delay ('silence period') between streams

Avail-bw variability versus traffic load

- Relative variation index: $\rho = \dfrac{R^{\max} - R^{\min}}{(R^{\max} + R^{\min})/2}$



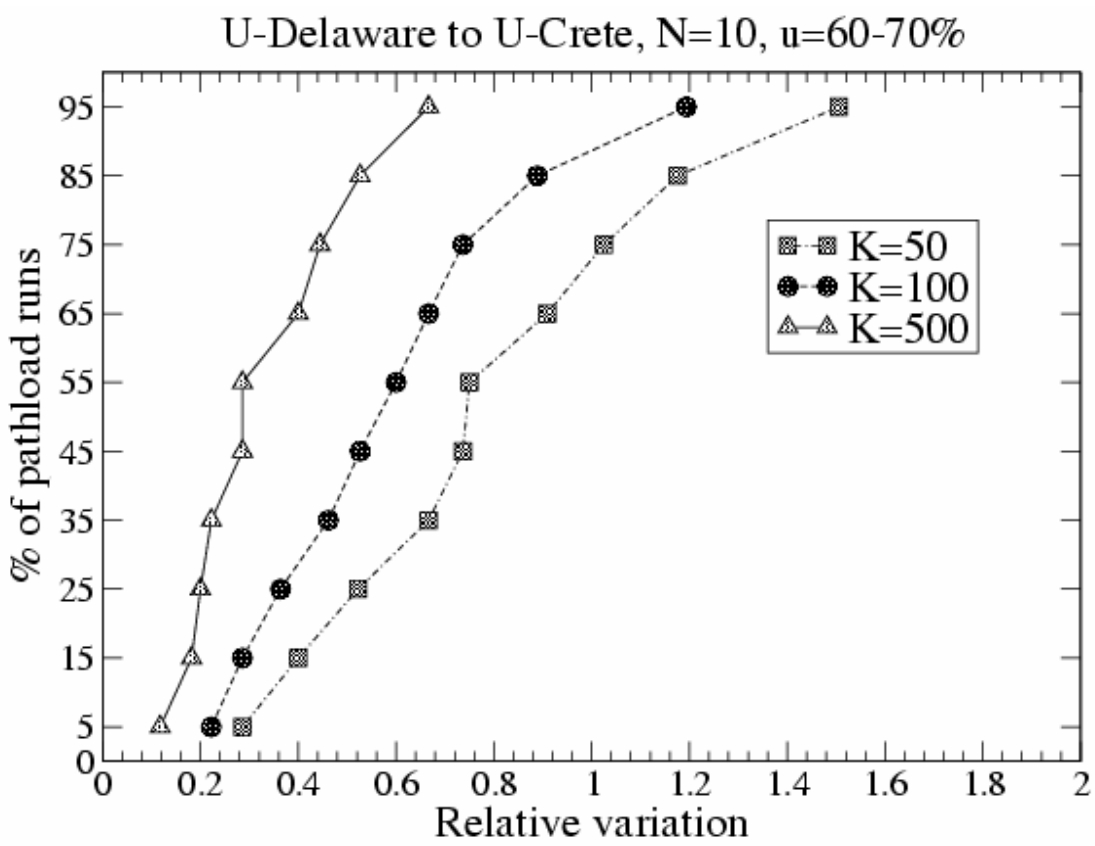
CDF of ρ.

C=12.4Mbps.

110 runs.

- Heavier tight link utilization leads to higher avail-bw variability

Avail-bw variability versus stream length



CDF of ρ.

C=12.4Mbps.

The stream duration for R=A(=4.5Mbps), L=200B, T=356μs is:

18ms for K=50,
36ms for K=100,
180ms for K=500

- Longer probing streams observe lower avail-bw variability
- But also, longer streams can be more intrusive

Future directions

- Sensitivity analysis for several Pathload parameters
- Apply avail-bw estimation in high-throughput TCP bulk transfers
- Apply avail-bw in overlay network routing optimizations
- Pathload is currently available at www.pathrate.org

Comments

- What can we take away from this paper?
  - Using binary search to find out the avail-bw by sending out probing packets.
  - More … ?
- What I like about this paper?
  - Basic idea is simple and easy to be implemented.
    Looking at the trend of delays of a periodic stream.
  - Algorithm is well designed.
  - Actual experiments to verify methodology.
  - Pathload is used to estimate the variability of avail-bw.
  - More …. ?

Questions

- Not intrusive?
  - Only gives a single experiment. Difficult to justify.
  - How about if lots of users are using pathloads?
- Almost all parameters are empirical.
  - Could be difficult to tune them under different scenarios.
  - Difficult to draw general conclusions.
- Difficult to predict converge time.
  - In their reported experiments, converge time for a single fleet of streams is [10, 30] seconds.
- Works well when there is only one tight link.
- Stationary assumption.
- More…. ?

Some interesting research problems?

Thank you!