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Network Simulation and Testing

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Traffic Papers

- V. Paxson, and S. Floyd, Wide-Area Traffic: The Failure of Poisson Modeling. IEEE/ACM Transactions on Networking, Vol. 3 No. 3, pp. 226-244, June 1995
- M. E. Crovella and A. Bestavros, Self-Similarity in World Wide Web Traffic: Evidence and Possible Causes. IEEE/ACM Transactions on Networking, Vol 5, No. 6, pp. 835-846, December 1997
- Anja Feldmann; Anna C. Gilbert; Polly Huang; Walter Willinger, Dynamics of IP traffic: A study of the role of variability and the impact of control. In the Proceeding of SIGCOMM '99, Cambridge, Massachusetts, September 1999
- Vern Paxson. End-to-end internet packet dynamics. ACM/IEEE Transactions on Networking, 7(3):277-292, June 1999

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Identifying Internet Traffic

Failure of Poisson
Self-similar Traffic
Practical Model
Packet Dynamics

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The Problem

- What is the traffic workload like?
- Call/packet arrival rate as a process
- What kind of process is it?
- Very old problem and a lot of work

Because

- Traces are available
- Researchers care about
  - The validness of their assumption
  - The network traffic being independent Poisson
- Operation people care a lot about
  - The amount of buffer/bandwidth to provision for their networks
  - The profit comes from satisfying customers with minimum infrastructure cost

Telephone Network

- Assumptions
  - Poisson call arrivals
  - Exponential call duration
- Wonderful Property
  - Poisson mixing with Poisson is still Poisson
  - Average rate well-characterize a call
- The whole queueing theory

Data Network?

- Wide-Area Traffic: The Failure of Poisson Modeling
- V. Paxson, and S. Floyd
- IEEE/ACM Transactions on Networking, Vol. 3 No. 3, pp. 226-244, June 1995

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A Study of the Wide-Area Traffic

- Two units of examination
  - Connections vs. packets
- A sizeable number of traces
  - ~4M connections, ~26M packets
  - Different location and different time
- Inter-arrival processes
  - TCP connections
  - Telnet packets
  - FTPDATA connections
- Going self-similar

Unit of Observation

- Telephone network
  - Circuit-switched
  - The unit is circuit, i.e., a call
  - People picking up the phone and talk for a while
- Data network
  - Packet-switched
  - The unit is packet
  - Another unit is connection, comparable to call
  - People starting up an FTP connection and send data for a while

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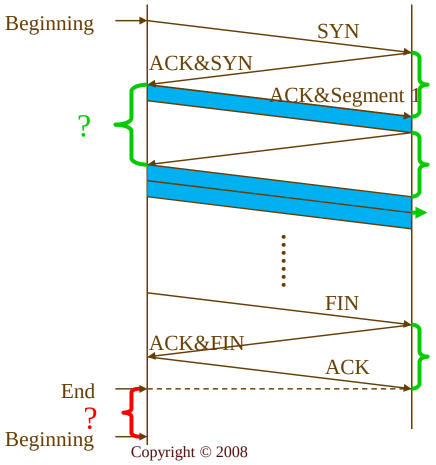
Packet $\subset$ Connection

- Hosts send/receive packets over a channel at the transport layer
  - Reliable: TCP
  - Non-reliable: UDP
- Packets from various channels multiplex at the network layer
  - IP Routers switched on the packets

Inter-Arrival Process:

A Little Exercise



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TCP Connection Arrival Poisson?

Depends

Application Dependent

- TELNET
  - Users typing 'telnet cc.ee.ntu.edu.tw'
- FTP
  - User typing 'ftp cc.ee.ntu.edu.tw'
- FTPDATA burst
  - User typing 'mget net-simtest-*.ppt'
- FTPDATA
  - Each individual TCP transfer
- NNTP & SMTP
  - Machine initiated and/or timer-driven

Independent and Poisson?

	Y/N
TELNET	
FTP	
FTPDATA	
FTPDATA burst	
SMTP	
NNTP	

Quick Summary

- TELNET and FTP
  - Independent and Poisson
  - Both the 1-hour and 10-min scales
- FTPDATA bursts and SMTP
  - At the 10-min interval
  - Not 'terribly far' from Poisson
  - SMTP inter-arrival is not independent
- FTPDATA, NNTP
  - Clearly not Poisson

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Before One Can Explain

- Human-initiated process
  - Independent and Poisson
- Non-human-initiated process
  - Well, who knows

Explanations I

- TELNET and FTP
  - User initiated
  - Users typing 'telnet cc.ee.ntu.edu.tw'
  - User typing 'ftp cc.ee.ntu.edu.tw'
- FTPDATA bursts
  - User typing 'mget net-simtest-*.ppt'
  - Actually, taking the closely-spaced connections... (<= 4 sec)
- FTPDATA
  - TCP connections

Explanations II

- NNTP
  - Flooding to propagate network news
  - Arrival of news trigger another
  - Periodical and implementation/configuration dependent
- SMTP
  - Mailing list
  - Timer effects from the DNS queries

TELNET Packets Poisson?

No, heavy-tailed!

Show in 4 Ways

- Distribution of packet inter-arrival time
  - Exponential processes ramp up significantly slower
- Packet arrival pattern in seconds and 10 seconds
  - Exponential processes are smoother at the 10sec scale
- Variance-time plot
  - Change of variance to time scale
  - Var of exponential processes decays quickly
- Packet arrival rate process in seconds
  - By the sole visual effect
  - Exponential processes are less spiky

Full TELNET model?

Poisson connection arrival
Heavy-tailed packet arrival within a connection

FTPDATA

- Connection arrival is not Poisson
  - Clustered in bursts
- Burst sizes in bytes is quite heavy-tailed
  - A 0.5% of bursts contribute to 50% of the traffic volume

OK. We know it's not Poisson. But what?

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Going Self-Similar

- Well, since other evidences suggest so
- And it's the next good thing

- Go straight into producing self-similar traffic

Producing Self-Similar Traffic

- ON/OFF sources
  - Fix ON period rate
  - ON/OFF period length heavy-tailed
- M/G/∞
  - Customer arrival being Poisson
  - Service time being heavy-tailed with infinite variance
- Authors' own model
  - Pseudo-self-similar
  - Not long-range dependent though

Performance Implication

- Low-priority traffic starvation
  - Shall the high-priority traffic being long-range dependent (bursty)
- Admission control based on recent traffic failing
  - 'Congestions haven't happened for a long while' does not mean it won't happen now

The Real Message

Poisson is no longer sufficient!

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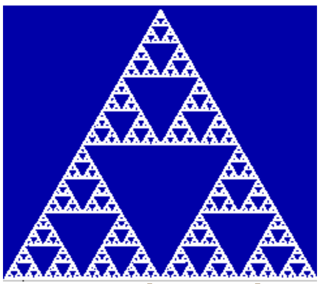
Self-Similar What?

- Self-similarity in World Wide Web Traffic: Evidence and Possible Causes
- Mark E. Crovella; Azer Bestavros
- IEEE/ACM Transactions on Networking, Vol 5, No. 6, pp. 835-846, December 1997

Self-Similar Process



Serpgask Triangles

Definition

- X: a stationary time series
- $X^{(m)}$: the m-aggregates
  - Summing the time series over non-overlapping blocks of m
- X is H-self-similar if
  - $X^{(m)}$ has the same distribution for all positive m

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Same Distribution?

- Same autocorrelation function
  - $r(k) = E[(X_t - \mu)(X_{t+k} - \mu)]/\sigma^2$
- $r(k) \sim k^{-\beta}$
  - $k \rightarrow \infty$
  - $0 < \beta < 1$

Significance of $k^{-\beta}$

- Long-range dependence
  - Just another way of characterizing the same thing
- Power-law decay
  - Slower than exponential decay
  - Therefore traffic does not smooth up
- $\beta < 1$
  - r(k) does not converge
  - Sum of r(k) infinite, I.e., variance infinite

Just FYI

- The Hurst parameter: $1 - \beta/2$

Tests for Self-Similarity

- Variance-time plot
  - A line with slope $-\beta > -1$
- R/S plot
  - Rescaled range grows as the number points included
  - A line with slope H an the log-log scale
- Periodogram
  - Power spectrum to frequency
  - A line with slope $\beta - 1$ at the log-log scale
- Whittle estimator
  - Confidence to a form
  - FGN or Fractional ARIMA

Pareto Review

- Exponential
  - $f(x) = ce^{-cx}$
- Heavy-tailed
  - $F(x) \sim x^{-c}$, $0 < c < 2$
  - Hyperbolic
- Pareto
  - $f(x) = ck^c x^{-c-1}$
  - $F(x) = 1 - (k/x)^c$
  - A line at the log-log scale of F(x) plot

In Addition to the Theory

- Show consistency of being self-similar in all sorts of tests
- Implication to traffic engineering

Why Self-Similar?

- Theory suggests
  - Fix rate ON/OFF process
  - Heavy-tailed length
- Looking into the length
  - The ON time: transmission time
  - The OFF time: silent time

Physical Cause

- Heavy-tailed transmission time
  - Heavy-tailed file sizes
  - Magic of the nature
  - E.g., book size in library

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So, enough Math. Just tell me what to do!

It depends!

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Cutting to the Chase

- The structural model
  - user level: Poisson arrival and heavy-tailed duration
  - network level: TCP closed-loop feedback control and ack clocking
  - Variability: delay and congestion
- Let simulators track the complex behavior

Why not FGN?

- IP Traffic Dynamics: The Role of Variability and Control
- Anja Feldmann; Anna C. Gilbert; Polly Huang; Walter Willinger
- In the Proceeding of SIGCOMM '99, Cambridge, Massachusetts, September 1999

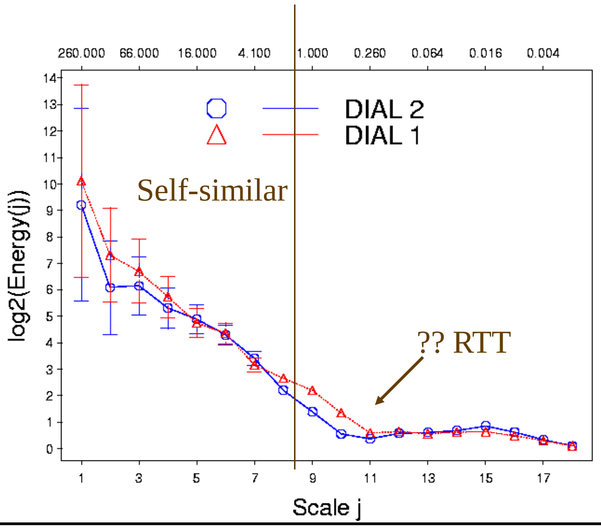
Wavelet Analysis

- FFT
  - Frequency decomposition
  - f_j, Fourier coefficient
  - Amount of the signal in frequency j
- WT: wavelet transform
  - Frequency (scale) and time decomposition
  - $d_{j,k}$, wavelet coefficient
  - Amount of the signal in frequency j, time k

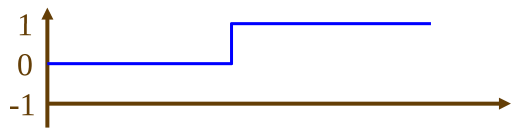
Self-similarity

- Energy function
  - $E_j = \Sigma(d_{j,k})^2/N_j$
  - Weighted average of the signal strength at scale j
- Self-similar process
  - $E_j = 2^{j(2H-1)}\ C$ <- the magic!!
  - $\log_2 E_j = (2H-1)\ j + \log_2 C$
  - **linear** relationship between $\log_2 E_j$ and j

'Shape' of Self-Similarity



Wavelet Example



00 00 00 00 11 11 11 11

s_1	0 0 0 0 2 2 2 2	0 0 0 0 0 0 0 0	d_1
s_2	0 0 4 4	0 0 0 0	d_2
s_3	0 8	0 0	d_3
s_4	8	8	d_4

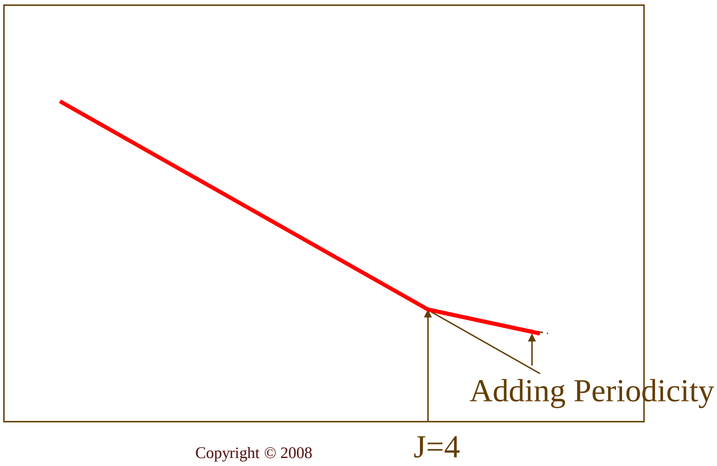
Adding Periodicity

- packets arrive periodically, 1 pkt/2^3 msec
- coefficients cancel out at scale 4

10 00 00 00 10 00 00 00

s_1	1 0 0 0 1 0 0 0	1 0 0 0 1 0 0 0	d_1
s_2	1 0 1 0	1 0 1 0	d_2
s_3	1 1	1 1	d_3
s_4	2	0	d_4

Visualization



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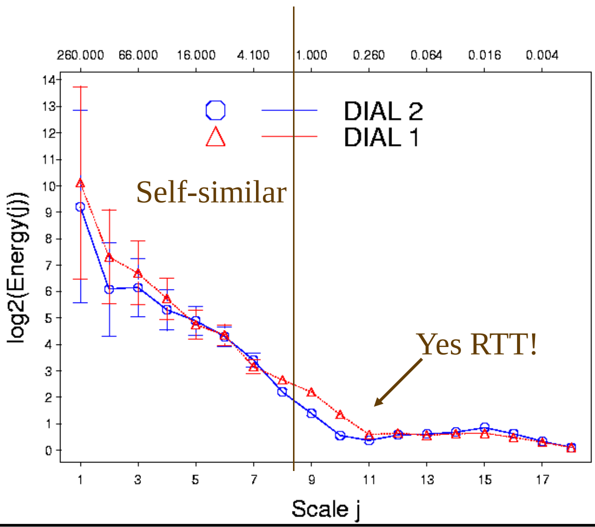
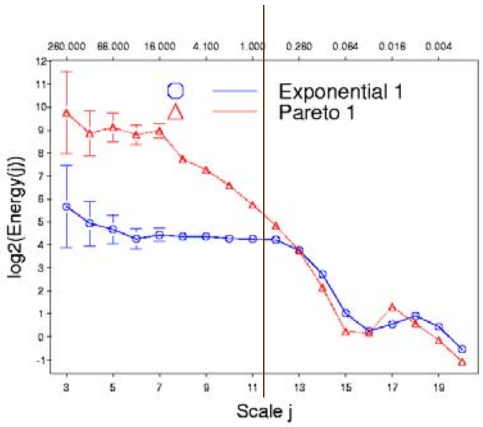
'Shape' of self-similarity



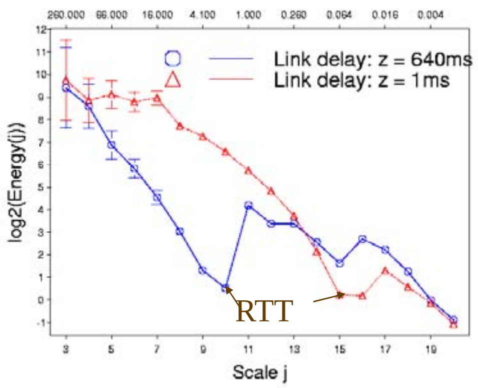
Large Scale

- Heavy-tailed connection duration

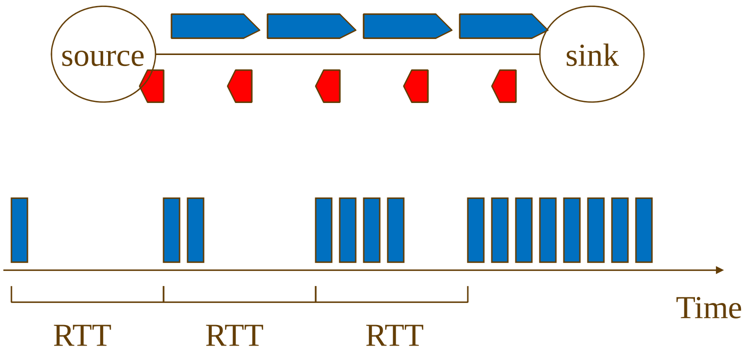


Medium Scale

- TCP close-loop control



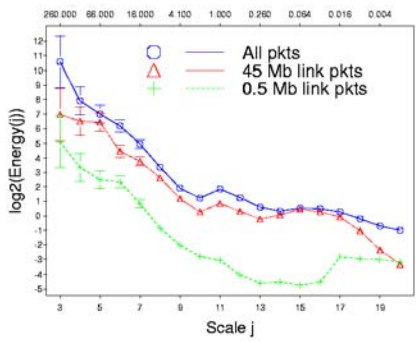
TCP Flow Control



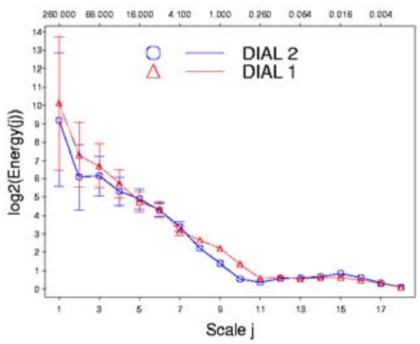
Variability

- Delay and congestion (bandwidth & load)

Simulation



Measurement



Internet Traffic is *Weird*!

- Different properties at different time scales
  - Large scales: self-similarity
  - Medium scale: periodicity
  - Small scale: ??? (possibly multifractal)

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New Queuing Theory?

- For chaotic Internet traffic
- Only pen and paper

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NO!

- Probably not in the near future
- Confirmed by the experts

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A Few Reasons

- Not exactly self-similar (FGN - big no no)
- 'Shape' of self-similarity changes with the network conditions
- Don't know what self-similar processes add up to (mathematically intractable)
- Don't know what those strange small-scale behavior is exactly

Therefore

- The structural model
  - User level: Poisson arrival and heavy-tailed duration
  - Network level: TCP closed-loop feedback control and ack clocking
  - Variability: delay and congestion
- Let simulators track the complex behavior

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It's not a perfect world…

Web Surfing Failures

- The 'window' waving forever?
- An error message saying network not reachable
- An error message saying the server too busy
- An error message saying the server is down
- Anything else?

Network Specific Failures

- The 'window' waving forever?
- An error message saying network not reachable
- An error message saying the server too busy
- An error message saying the server is down
- Anything else?

The Causes

- The 'window' waving forever
  - Congestion in the network
  - Buffer overflow
  - Packet drops
- An error message saying network not reachable
  - Network outage
  - Broken cables, Frozen routers
  - Route re-computation
  - Route instability

Back to the Problem

- But how non-perfect is the Internet?
- Equivalent of
  - **Packets can be dropped**
    - **How frequent**
    - **How much**
  - Routes may be unstable
    - How frequent
    - For how long

Significance

- Knowing the characteristics of packet drops and route instability helps
  - Design for fault-tolerance
  - Test for fault-tolerance

Packet Dynamics

- End-to-End Internet Packet Dynamics
- Vern Paxson
- ACM/IEEE Transactions on Networking, 7(3):277-292, June 1999

Emphasis in Reverse Order

- Real subject of study
  - Packet loss
  - Packet delay
- Necessary assessment
  - The unexpected
  - Bandwidth estimation

Measurement

- Instrumentation
  - 35 sites, 9 countries
  - Education, research, provider, company
- 2 runs
  - N1: Dec 1994
  - N2: Nov-Dec 1995
  - 21 sites in common

Measurement Methodology

- Each site running NPD
  - A daemon program
  - Sender side sends 100KB TCP transfer
- Sender and receiver sides both
  - *tcpdump* the packets
- Noteworthy
  - Measurement occurred in Poisson arrival
    - Unbiased to time of measurement
  - N2 used big max window size
    - Prevent window size to limit the TCP connection throughput

Packet Loss

- Overall loss rate:
  - N1 2.7%, N2 5.2%
  - N2 higher, because of big max window?
    - I.e. Pumping more data into the network therefore more loss?
- Big max window in N2 is not a factor
  - By separating data and ack loss
  - Assumption: ack traffic in a half lower rate
    - Won't stress the network
  - Ack loss: N1 2.88%, N2 5.14%
  - Data loss: N1 2.65%, N2 5.28%

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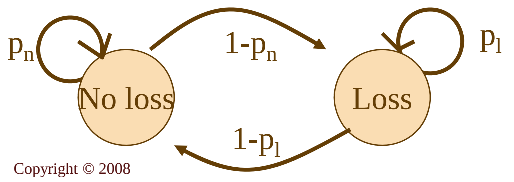
Quiescent vs. Busy

- Definition
  - Quiescent: connections without ack drops
  - Busy: otherwise
- About 50% of the connections are quiescent
- For connections are busy
  - Loss rate: N1 5.7%, N2 9.2%

Towards a Markov Chain Model

- For hours long
  - No-loss connection now indicates further no-loss connection in the future
  - Lossy connection now indicates further lossy connections in the future
- For minutes long
  - The rate remains similar



Another Classification

- Data
  - Loaded data: packets experiencing queueing delay due to own connection
  - Unloaded data: packets not experiencing queueing delay due to own connection
  - Bottleneck bandwidth measurement is needed here to determine whether a packet is loaded or not
- Ack
  - Simply acks

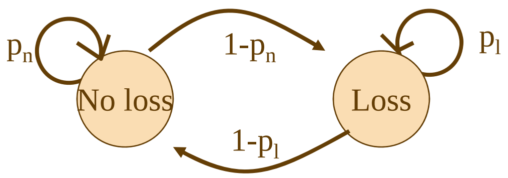
3 Major Observations

- Although loss rate very high (47%, 65%, 68%), all connections complete in 10 minutes
- Loss of data and ack not correlated
- Cumulative distribution of per connection loss rate
  - Exponential for data
  - Not so exponential for ack
  - Adaptive sampling contributing to the exponential observation?

More on the Markov Chain Model

- The loss rate Pu
  - The rate of loss
- The conditional loss rate Pc
  - The rate of loss when the previous packet is lost
- Contrary to the earlier work
  - Losses are busty
  - Duration shows pareto upper tail
  - (Polly: maybe more log-normal)

You might ask…p_l ,p_n?



Values for the p_l's

	N1	N2
Loaded data	49%	50%
Unloaded data	20%	25%
Ack	25%	31%

Possible Invariant

- Conditional loss rate
- For the value remains relatively close over the 1 year period

- More up-to-date data to verifying this?
- The loss burst size log normal?
- Both interesting research questions

Packet Delay

- Looking at one-way transit times (OTT)
- There's model for OTT distribution
  - Shifted gamma
  - Parameters changes with regards to time and path...
- Internet path are asymmetric
  - OTT one way often not equal OTT the other way

Timing Compression

- Ack compressions are rare and small events
- So not really pose threads on
  - Ack clocking
  - Rate estimation based control
- Data compression even rarer
  - Estimation needs to do outlier filtering

Queueing Delay

- Variance of OTT over different time scales
  - For each time scale τ
  - Divide the time into intervals of τ
  - For all 2 neighboring intervals L, R
    - m_L the median of OTT in interval L
    - m_R the median of OTT in interval R
    - Calculate $(m_L - m_R)$
- Variance of OTT at τ scale is median of all $(m_l - m_r)$
- Can you suggest another way?

Finding the Dominant Scale

- Looking for τ whose queueing variance is large
  - Where control most needed
- For example, if τ is smaller than RTT
  - Then TCP doesn't need to bother adapting to queueing fluctuations

Oh Well

- Queueing delay variations occur
  - Dominantly on 0.1-1 sec scales
  - But non-negligible on larger scales

Share of Bandwidth

- Pretty much uniformly distributed

Conclusions on Analysis

- Behavior
  - Very wide range, not one typical
  - Loss: 2 vs. 5%, strong correlation in time
  - Delay: queueing delay variation at 0.1-1sec scale

Conclusions on Design

- Measurement methodology
  - TCP-based measurement shown viable
  - Sender-side only inferior
- TCP implementation
  - Sufficiently conservative

Questions?

On the Review Forms

- Novelty
  - New idea
- Clarity
  - The problem
- Correctness
  - Evaluation
- Importance, significance, relevance
  - How much impact?
  - Would things change?

OK for Beginners

- Clarity
  - Easiest
  - Judging the writing
- Correctness
  - Easy
  - Judging the experiments and technical content

Challenging for the Advanced

- Novelty
  - Hard
  - Need to follow/read enough papers in the area
- Importance
  - Hardest
  - Need to have breadth and know enough development in the area

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Questions?

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