Vern Paxson's Paper
"End-to-End
Internet Packet
Dynamics", 1997/99

How often are packets dropped?

How often are packets reordered?

Why these questions?

I. Understand the Internet

"When you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind;"

- Lord Kelvin

II. Model the Internet

III. Enable more accurate evaluation through simulations

IV. Lead to a better application/systems design

How often are packets dropped?

How often are packets reordered?

How to answer these questions?

Collect lots of packet traces

Analyze the traces

**Trace collection:**

large number of flows

a variety of sites

many packets per flow

use TCP

Time between measurement is Poisson distributed

PASTA Theorem. Intuitively, if we make n observations and k observation is in some state S and n-k in another state, then we can assume prob of observing S is approximately k/n.

**Two traces:**

N1: Dec94
N2: Nov-Dec95

use tcpdump at sender + receiver

**100 kB**

Size of file transfered

**21**

Number of sites

**20800**

Number of trace pairs

**Part 1:**
The Unexpected

Packet Reordering

1
2
5
3
4

2 reorderings

N1 N2

**36% 12%**

Percentage of connections with at least one out-of-order delivery

N1 N2

**2% .3%**

Percentage of data packets out-of-order

N1 N2

**.6% .1%**

Percentage of ACK packets out-of-order

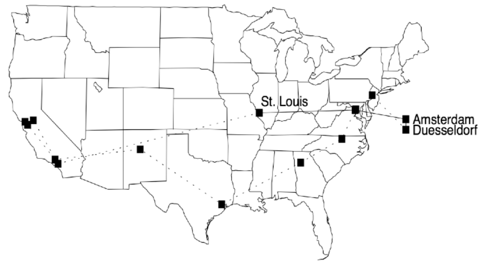
Data packets are usually sent closer together.

From To

**15% .2%**

Percentage of packets out-of-order
to and from U of Colorado in N1.

**Route fluttering:**
alternate packets
can take different
route to dest.




Taken from Paxson's PhD Thesis: Alternate routes
are taken for packets from WUSTL to U Mannheim

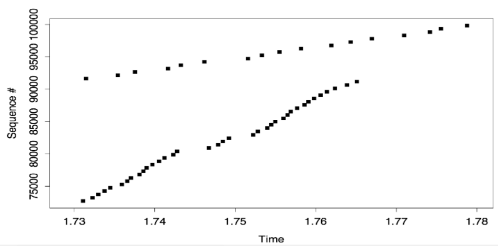



Fig 1 from the paper, showing large gap
and two slopes.

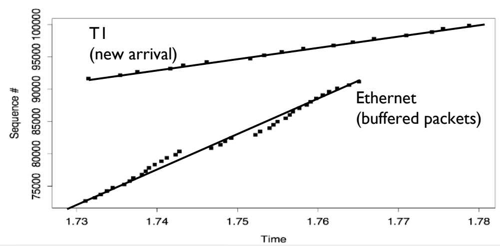
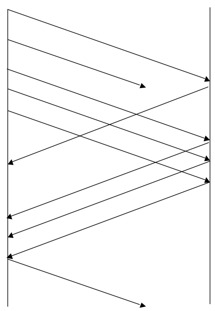


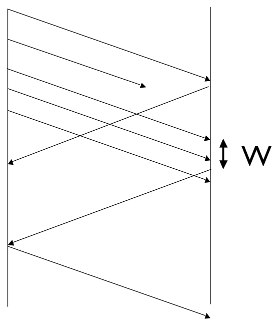

Fig 1 from the paper, showing large gap
and two slopes.

Impact of Packet
Reordering



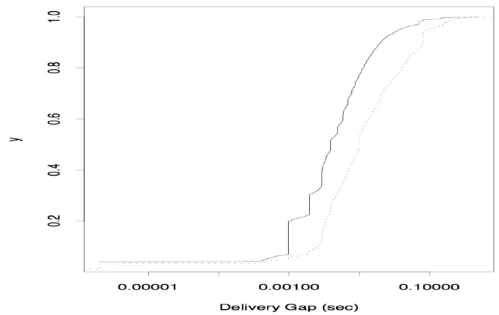
$N_d = 3$ is a conservative choice.

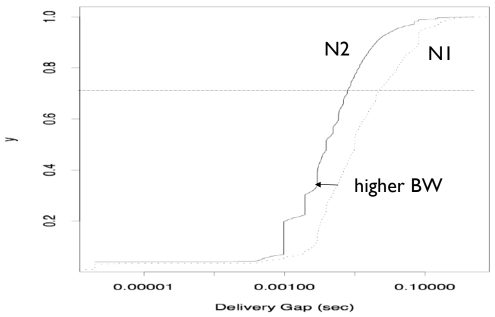
What if receiver wait longer before sending dup ack?




1
2
5
3
4

**Delivery Gap:**
time between receiving an out-of-order packet and the packet sent before it.





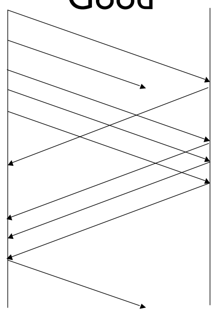

N1 N2

**20ms** **8ms**

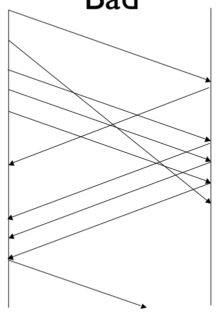
Waiting time with which 70% of
out of order delivery would be identified.

Is needless retransmission a problem?

Good



Bad



N1 N2

**22** **300**

Number of good retransmissions
for every bad retransmission.
$N_d$ = 3, W = 0

N1 N2

**~7 100**

Number of good retransmissions
for every bad retransmission.
$N_d = 2$, $W = 0$

N1 N2

**15 300**

Number of good retransmissions
for every bad retransmission.
$N_d = 2$, $W = 20ms$

Packet Corruption

**1** in **5000**

packet is corrupted

**1** in **65536**

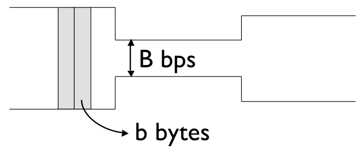
corrupted packet goes undetected
using TCP checksum

**1** in **300**million

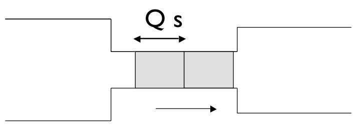
Internet packet is corrupted
and is undetected.

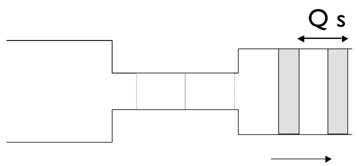
**Part 2:**
Bottleneck
Bandwidth

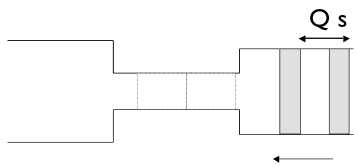
Packet Pair

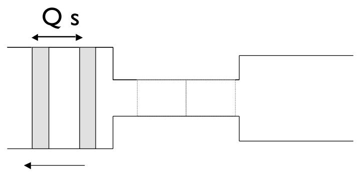



$Q \times B = b$






Problems with Packet Pair

1. Asymmetric Link

2. ACK Compression

3. Out of order delivery

4. Clock resolution

## 5. Changing bottleneck bandwidth

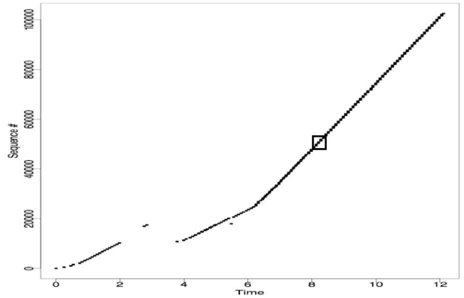



Fig 2 from the paper, showing changing bandwidth.

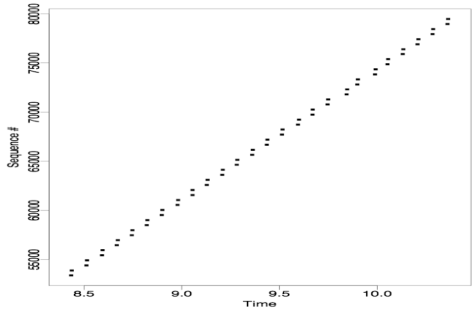


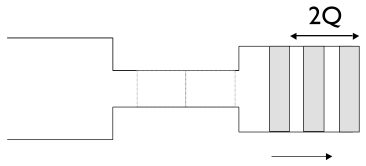

Fig 3 from the paper, showing multi-channel links.

## 6. Multi-channel Links

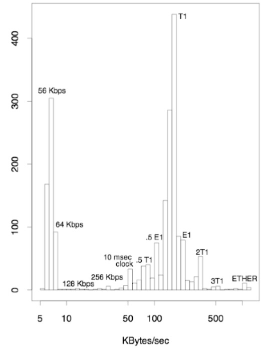
Asymmetric links
ACK compression
Out-of-order delivery
Clock resolution
Changes in bottleneck bandwidth
Multi-channel links

**Measure at receiver:**
Asymmetric links
ACK compression

**Packet bunch:**
Out-of-order delivery
Clock resolution
Changes in bottleneck bandwidth
Multi-channel links




Collect multiple estimates, take the most freq occurrence (modes) as the bottleneck bandwidth.




**Part 3:**
Packet Loss

| N1 | N2 |
|---|---|
| **2.7%** | **5.2%** |

Percentage of packets that were lost.

| N1 | N2 |
|---|---|
| **50%** | **50%** |

Percentage of loss free connections

N1 N2

**5.7% 9.2%**

Loss rate on lossy connections

**17%**

Loss rate on connections from EU to US

Are packet losses independent?

Compute:

$P^u$ = Pr [ p lost ]

$P^c$ = Pr [ p lost | prev pkt lost ]

$P^u$ $P^c$

**2.8% 49%**

Loss rate for “queued data pkt” on N1

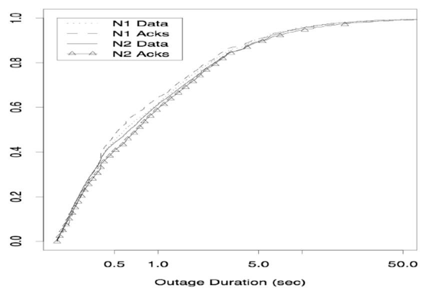
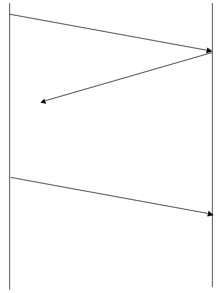


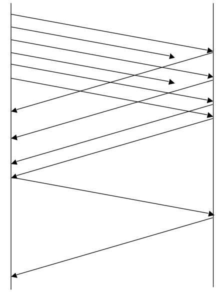

Fig 6 from the paper, showing outage duration.

Are retransmission redundant?

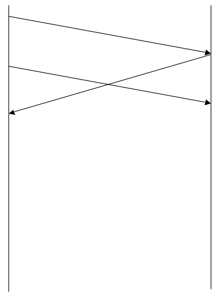
Unavoidable



Coarse Feedback



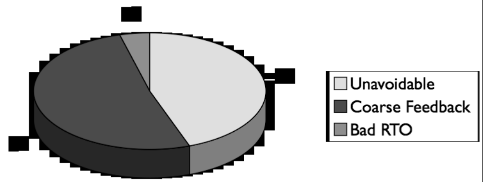
Bad RTP



N1 N2

**26% 28%**

Percentage of retransmissions that are redundant




Type of redundant retransmission in N1.

**Part 4:**
Packet Delay

OTT is not well approximated as RTT/2

Estimating Available Bandwidth

$Q_b$: time to transit the bottleneck

$\psi_i$: expected time spend queuing behind predecessor (derived from sending time)

$\gamma_i$: diff between packet OTT and min OTT

$$\beta = \frac{\sum_i (\psi_i + Q_b)}{\sum_i (\gamma_i + Q_b)}$$

$\beta$ = 1 means all bandwidth is available.

$\beta$ = 0 means none of the bandwidth is available.

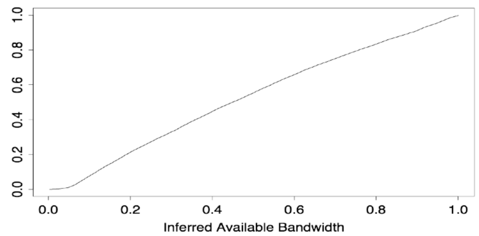



Fig 10 from the paper, showing distribution of available bandwidth.

All numbers in the paper is not important (the Internet has changed!).

Measurement is difficult but useful

Many new techniques needed (e.g to measure bottleneck bandwidth)

We can improve current design (e.g. TCP if we know more about reordering)

We can identify problem (e.g. packet corruption)

We can better model the behavior (e.g. bursty packet loss)

We can infer many info from just a packet trace (e.g. available bandwidth)