Reducing Latency for Linux Transport

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RITE – Reducing Internet Transport Latency

The EU-project RITE : Partners

Industry partners:

- British Telecommunications (UK)
- Alcatel-Lucent Bell (BE)
- Megapop (NO)

Academic partners:

- Simula Research Laboratory (NO)
- University of Oslo (NO)
- Karlstad University (SE)
- Institut Mines-Telecom (FR)
- The University Court of the University of Aberdeen (UK)

Internet Latency

Limitations of scope

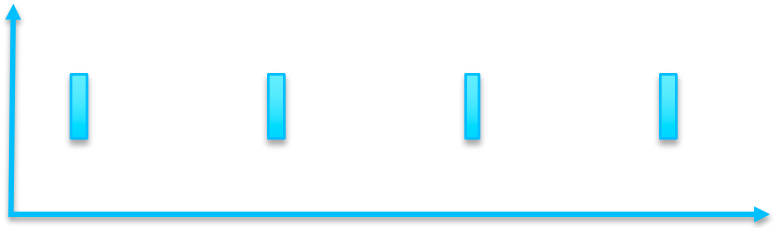
- The mechanisms we'll talk about is about
  - reliable, congestion-controlled transport
  - avoiding retransmissions
  - avoiding time wasted on getting up to speed
  - minimise queueing delay

Traffic patterns matter to latency

Short flows

Web traffic – most Internet traffic

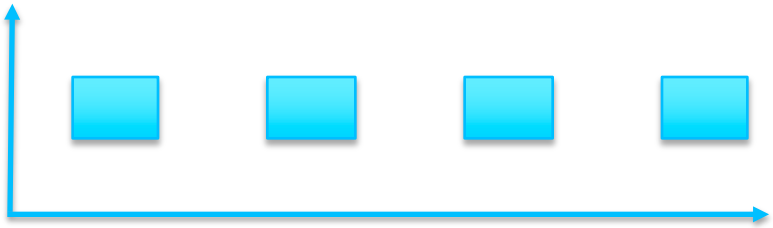
RTO Restart / TLP Restart



Thin streams

Interactive, real-time, sensors, games

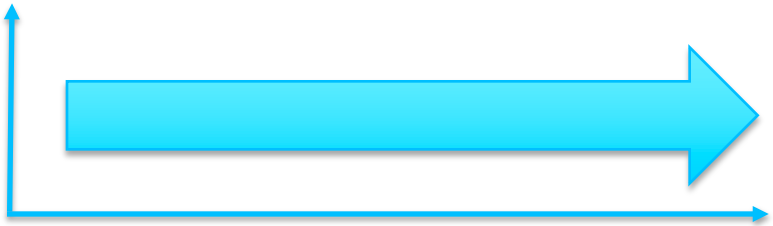
Redundant Data Bundling (RDB)



Bursty flows

HTTP segment streaming (Netflix)++

New CWV

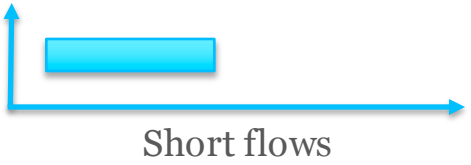


Greedy flows

Downloads

CAIA Delay Gradient (Linux edition)

TCP Tail Loss Recovery



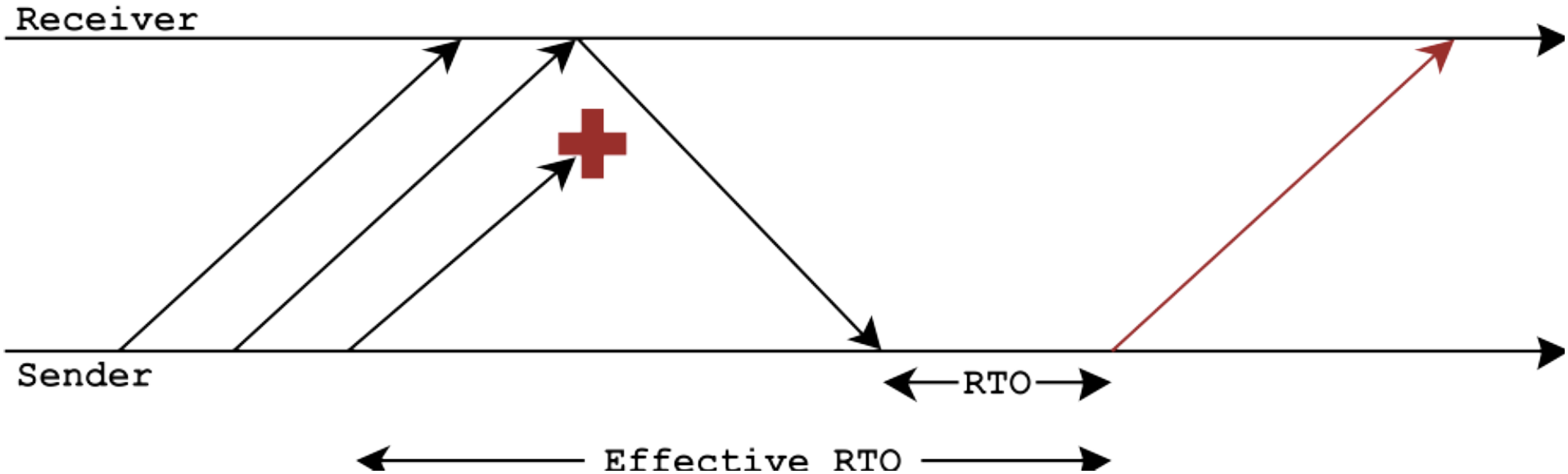
- The tail of transfers/bursts in TCP is critical for low latency
  - cannot use fast/early retransmit (FR/ER) for loss recovery
- For short and/or bursty flows this is really bad
  - tail constitutes large part of transfer
  - low latency is often important for applications sending this type of traffic

TCP Tail Loss Recovery

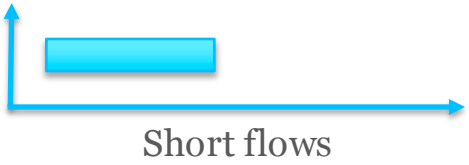
- A retransmission timeout (RTO) is used if FR/ER cannot be used
- RTO is a slow recovery mechanism based on the round-trip time (RTT) of the connection
- An RTO will cause larger congestion control impact than FR/ER

More Problems...

Short flows



RTO Restart (RTOR)



- An alternative way to restart TCP's RTO timer
  - removes the unnecessary offset
- RTOR is defined in "draft-ietf-tcpm-rtorestart-08"
  - approved by IETF for publication

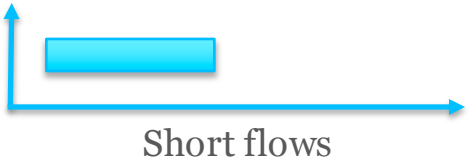
The Solution

When restarting the RTO, set:

```
RTO = RTO – T_earliest
```

where `T_earliest` is the transmission time of the earliest outstanding segment.

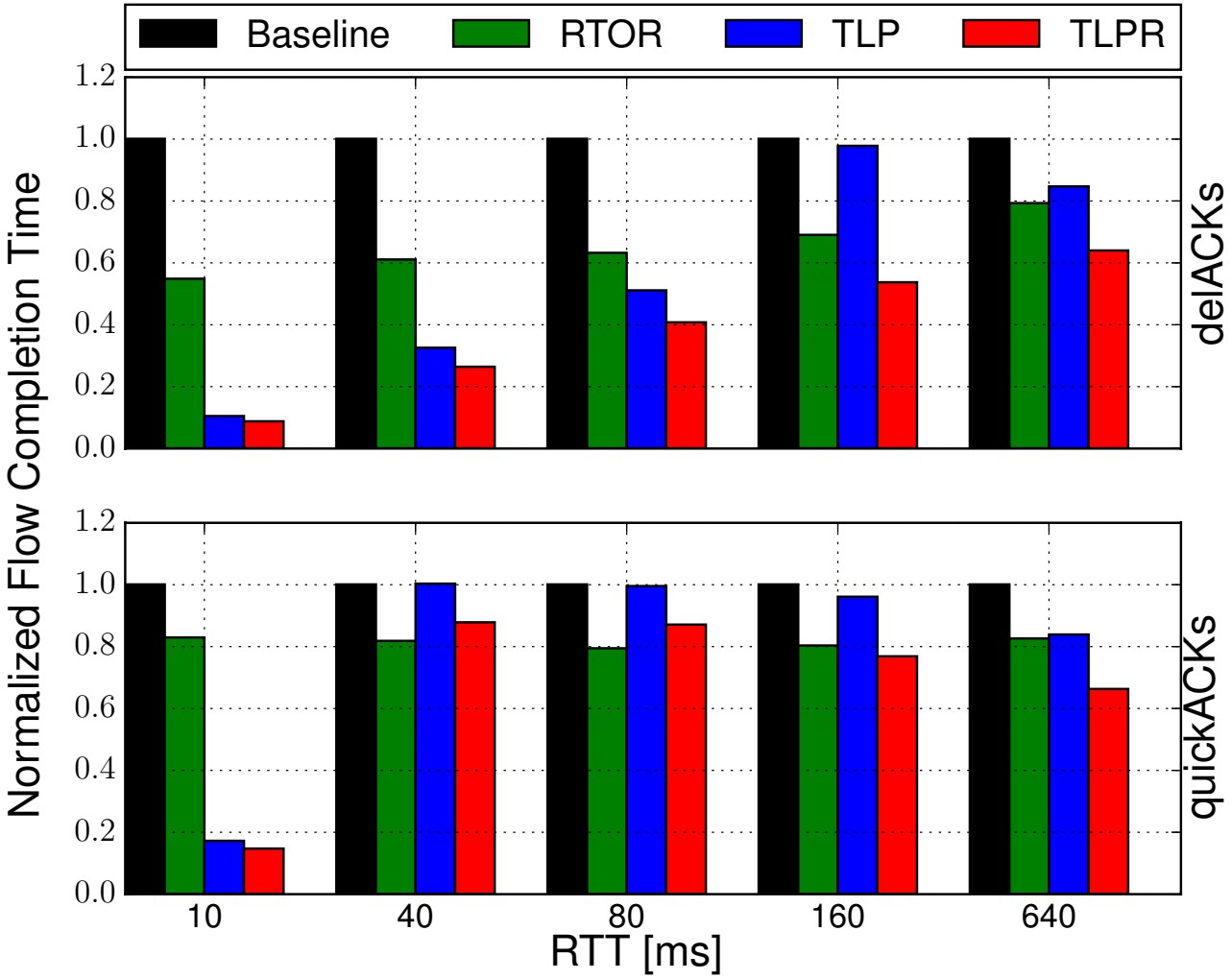
Tail Loss Probe Restart (TLPR)



- TLP is the “Linux” way of recovering from tail loss
- TLP tries to send new data/retransmit the latest transmitted segment on timeout
  - to trigger fast recovery instead of RTO
- The restart logic is the same as for the RTO
- TLP is defined in: “draft-dukkipati-tcpm-tcp-loss-probe-01”

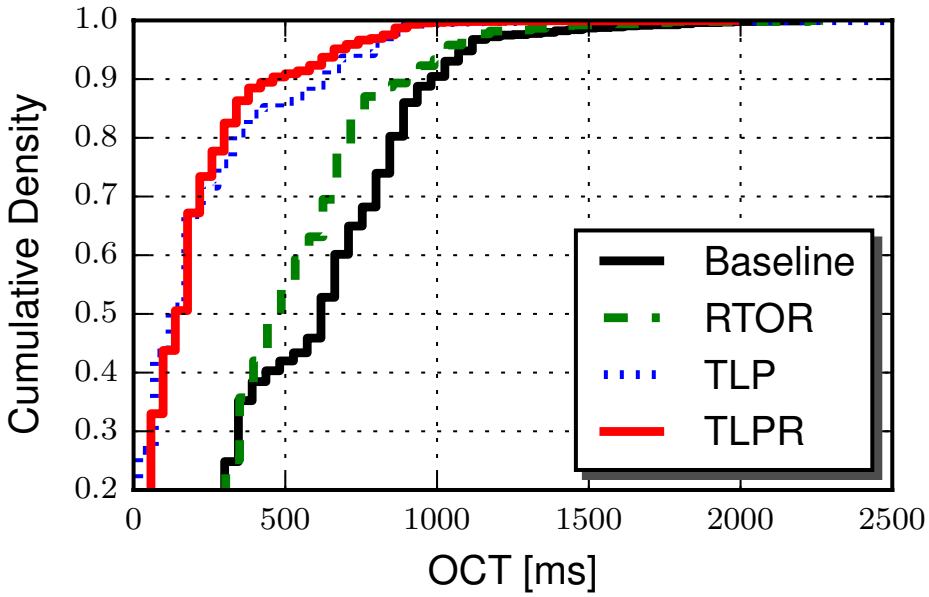
Losing the last segment

Short flows

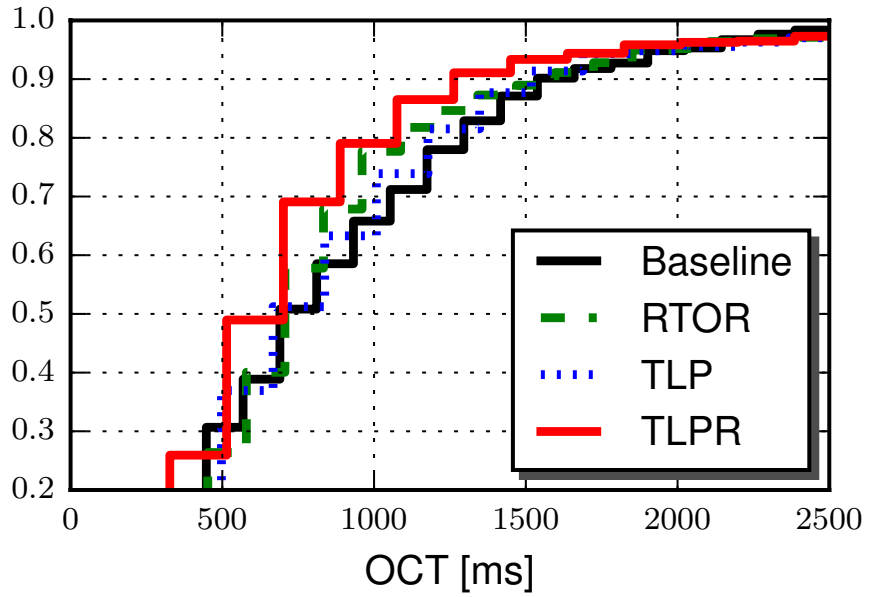


Web Page Downloads

Short flows



10ms RTT



160ms RTT

Changes to kernel (RTOR)

net/ipv4/tcp_input.c

```
void tcp_rearm_rto(struct sock *sk)
{
    […]
    else if (icsk->icsk_pending == ICSK_TIME_RETRANS &&
            sysctl_tcp_rto_restart &&
            tp->packets_out < sysctl_tcp_rto_restart &&
            (tp->packets_out + tcp_unsent_pkts(sk) <
             sysctl_tcp_rto_restart)) {
        struct sk_buff *skb = tcp_write_queue_head(sk);
        const u32 rto_time_stamp = tcp_skb_timestamp(skb);
        s32 delta = (s32)(tcp_time_stamp – rto_time_stamp);

        if (delta > 0 && rto > delta)
            rto -= delta;
    }
    inet_csk_reset_xmit_timer(sk, ICSK_TIME_RETRANS, rto,
                              TCP_RTO_MAX);
}
```

Changes to kernel (TLPR)

net/ipv4/tcp_output.c

```
bool tcp_schedule_loss_probe(struct sock *sk)
{
    […]
    if (tp->packets_out == 1)
        timeout = max_t(u32, timeout,
                        (rtt + (rtt >> 1) + TCP_DELACK_MAX));

        const u32 pto_time_stamp = tcp_skb_timestamp(skb);
        s32 delta = (s32)(tcp_time_stamp – rto_time_stamp);

        if (delta > 0 && timeout > delta)
            timeout -= delta;

    timeout = max_t(u32, timeout, msecs_to_jiffies(10));
    […]
    inet_csk_reset_xmit_timer(sk, ICSK_TIME_LOSS_PROBE, timeout,
                              TCP_RTO_MAX);
    […]
}
```

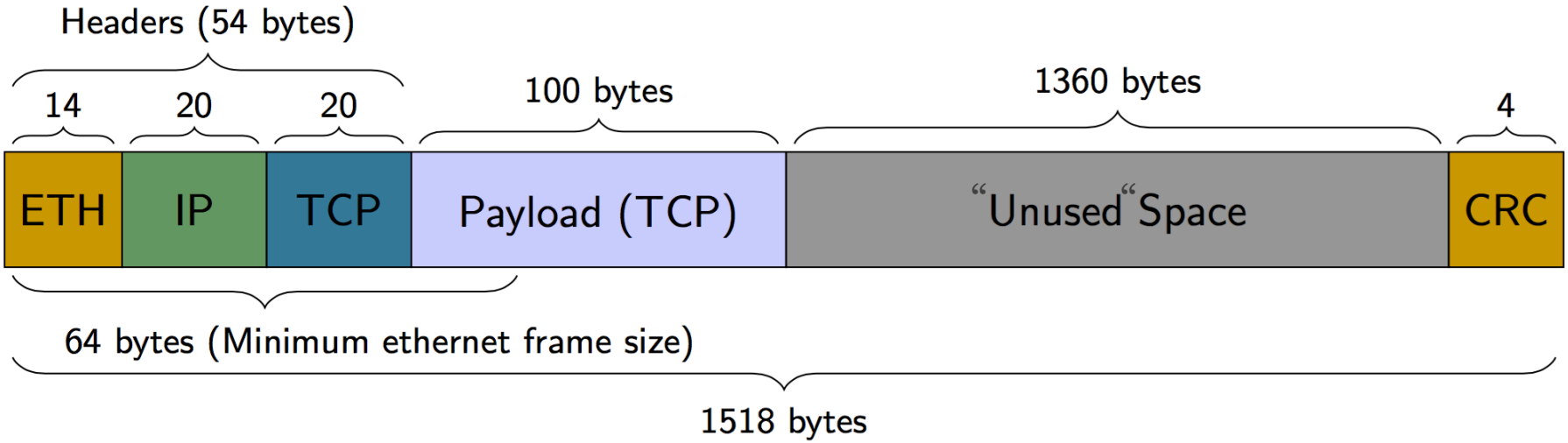
Redundant data bundling (RDB)

- Thin streams:
  - small packets
  - (relatively) high inter-transmission times between packets.
  - latency sensitive (traffic patterns arise due to timing/events/interaction)
- No backpressure →Not able to trigger fast retransmit

Application	Payload size			Packet inter-arrival time (ms)			
	avg	min	max	avg	med	min	max
Windows Remote Desktop	111	8	1417	318	159	1	12254
VNC (from client)	8	1	106	34	8	0	5451
VNC (from server)	827	2	1448	38	0	0	3557
Skype (2 users)	236	14	1267	34	40	0	1671
SSH text session	48	16	752	323	159	0	76610
Anarchy Online	98	8	1333	632	449	7	17032
World of Warcraft	26	6	1228	314	133	0	14855
Age of Conan	80	5	1460	86	57	0	1375

RDB – main principle

Thin streams

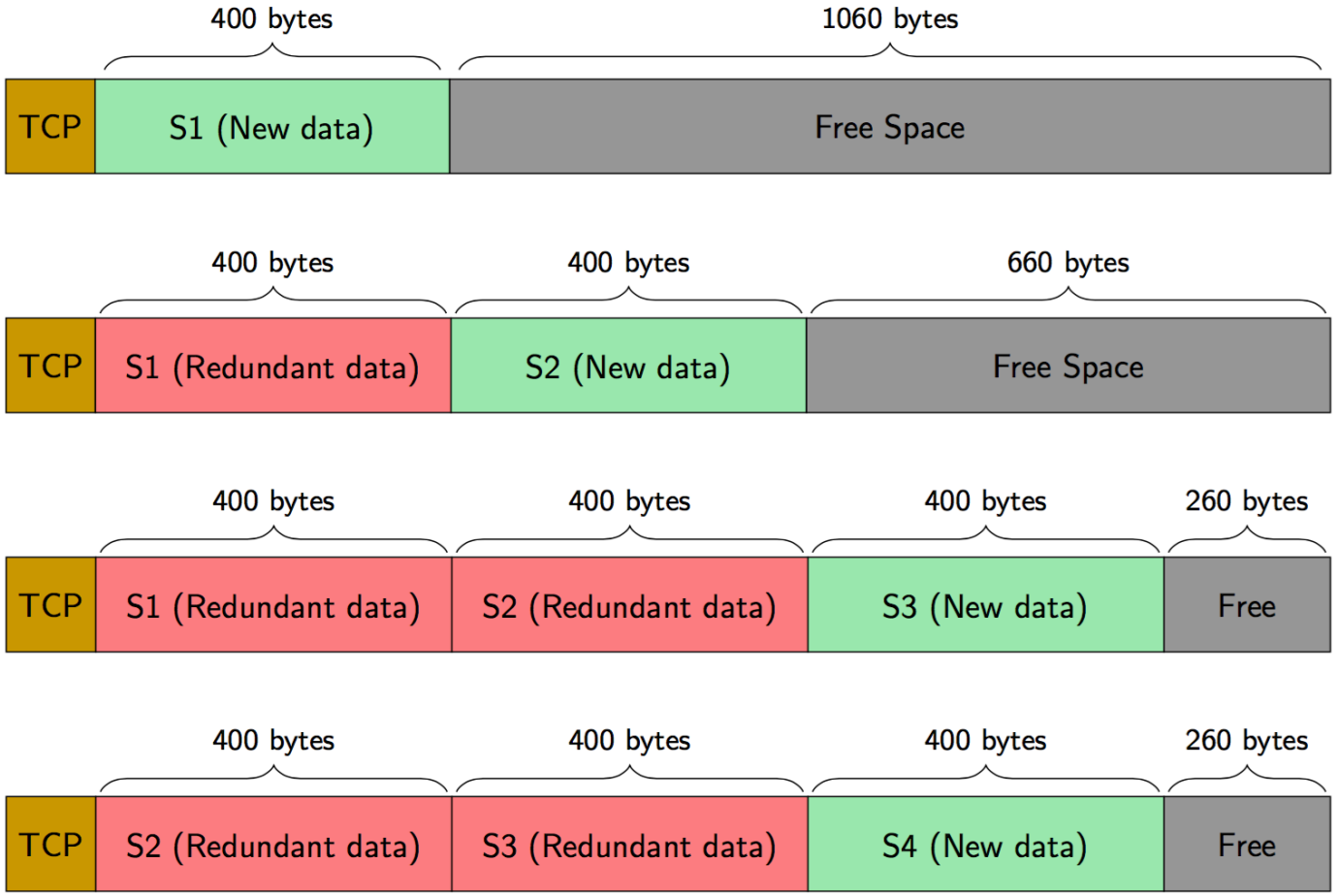


typical ethernet frame

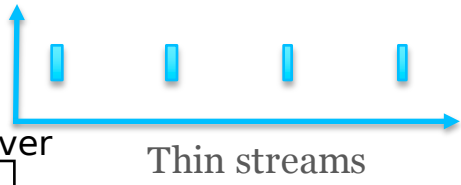
- send redundant data, but never send more packets.
- sender-side only mechanism.
- reduces retransmission latency and head-of-line blocking delay

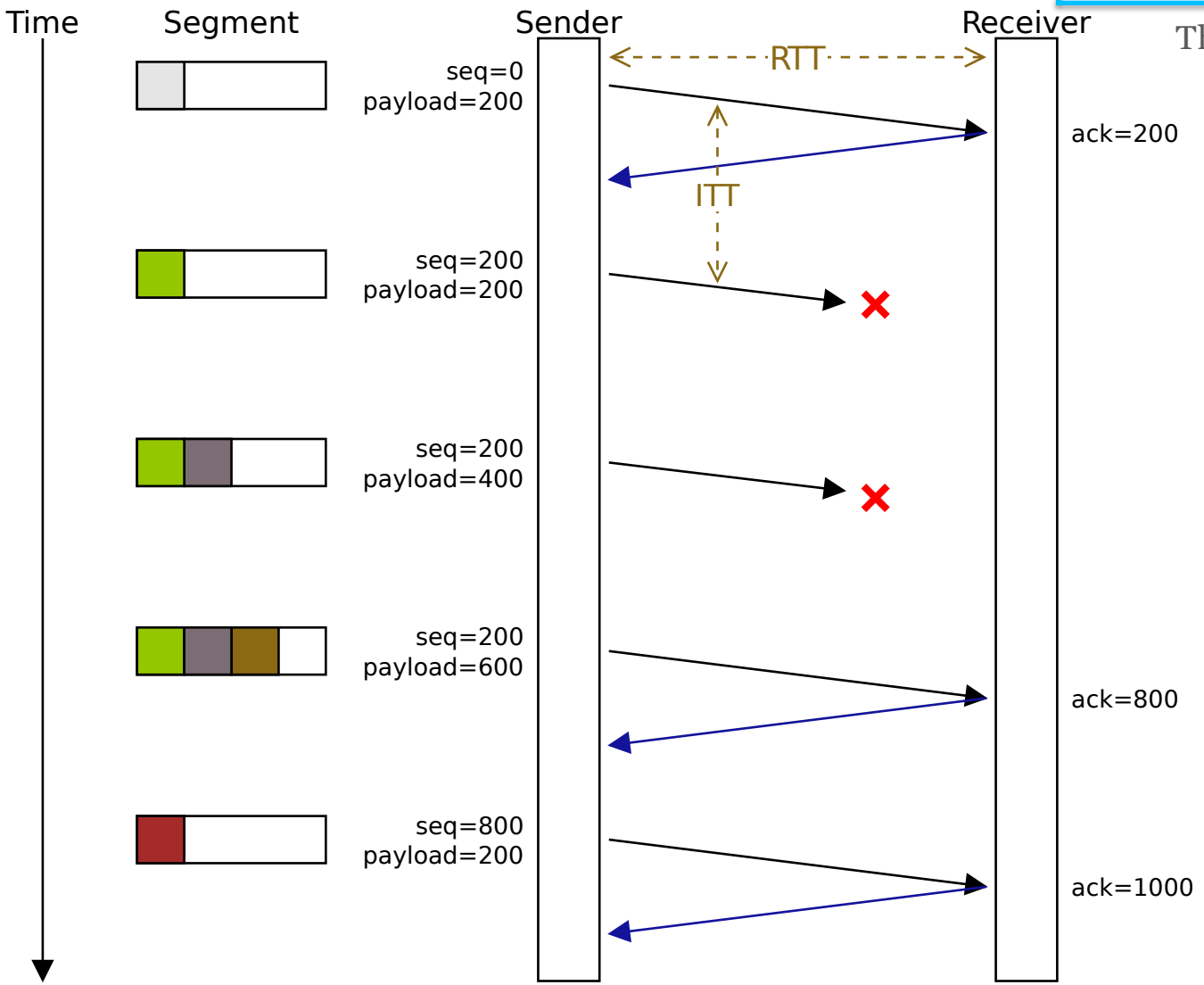
RDB – main principle

Example with four separate data segments showing how RDB organizes the data in each packet.

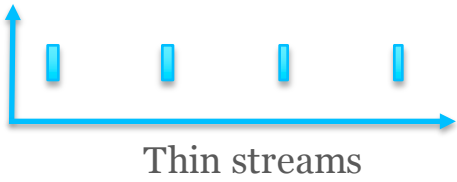


RDB: avoid retransmission delays





RDB: redundancy vs. latency gain



- Weigh redundancy against latency gain
- Protect against abuse
  - building a too high cwnd due to loss hiding

- Two key questions:
  1. When to bundle?
  2. How many redundant segments to allow?

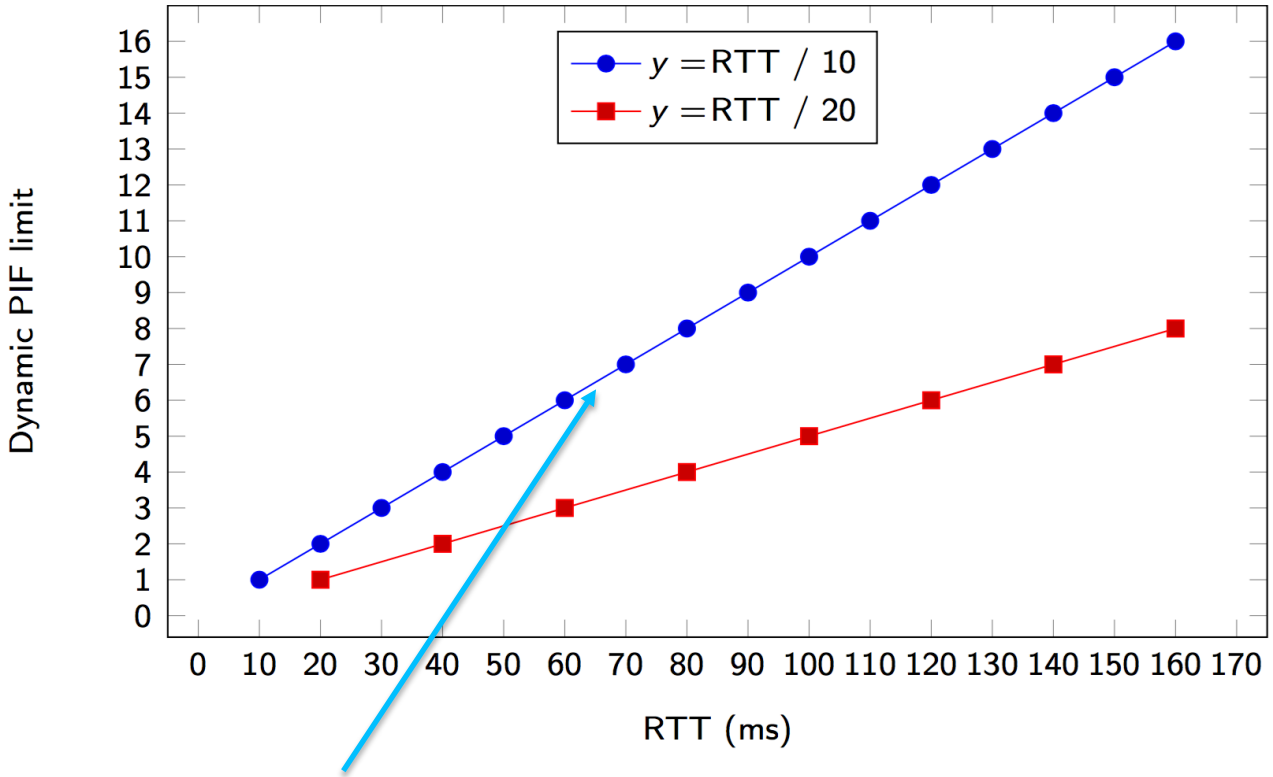
RDB: when to bundle?

- Use tcp_stream_is_thin (PIF < 4)?
  - big penalty for high-RTT flows.
  - a more precise name would be: can_trigger_fast_retransmit_within_one_rtt

```
/* Determines whether this is a thin stream (which may suffer from
 * increased latency). Used to trigger latency-reducing mechanisms.
 */
static inline bool tcp_stream_is_thin(struct tcp_sock *tp)
{
        return tp->packets_out < 4 && !tcp_in_initial_slowstart(tp);
}
```

RDB: Dynamic PIF limit

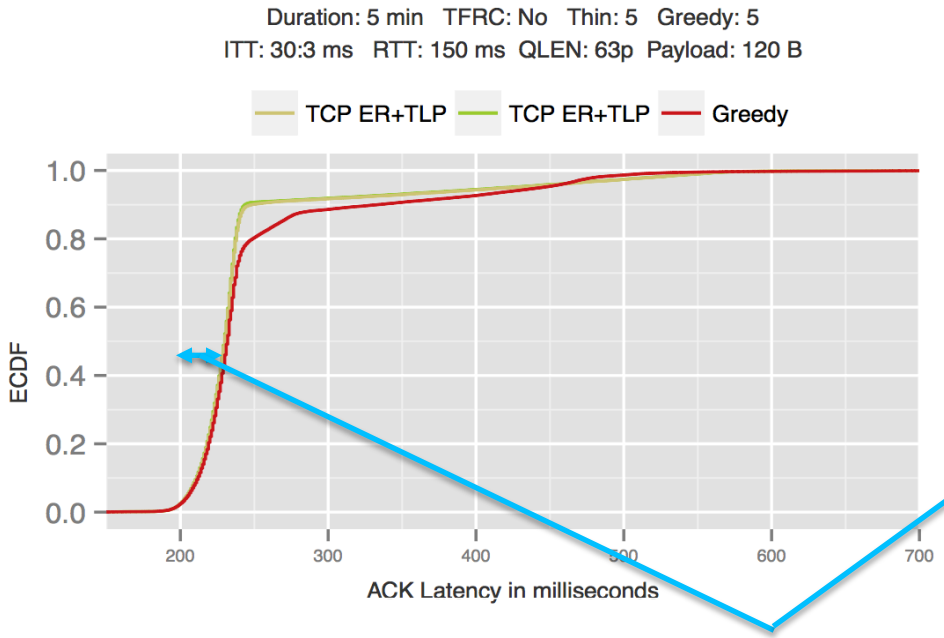
$$DPIFL = \frac{RTT_{min}}{ITT_{min}}$$

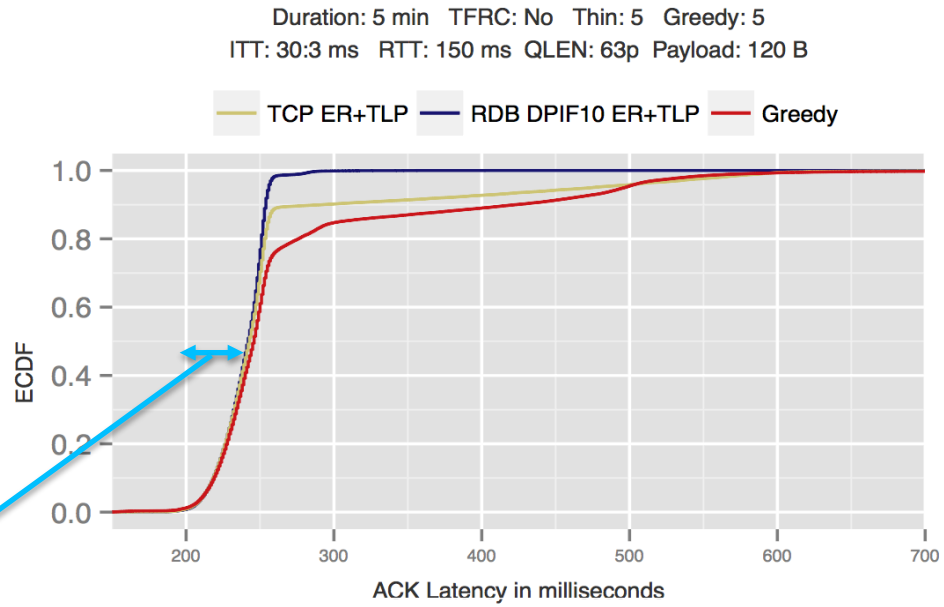


Choose TFRC-SP limit of 10ms ITT for thin streams [RFC4828].

RDB: how many segments?

- Avoid wantonly using capacity for redundancy.
- Recover faster from random loss.
- → allow RDB to only bundle only one segment.

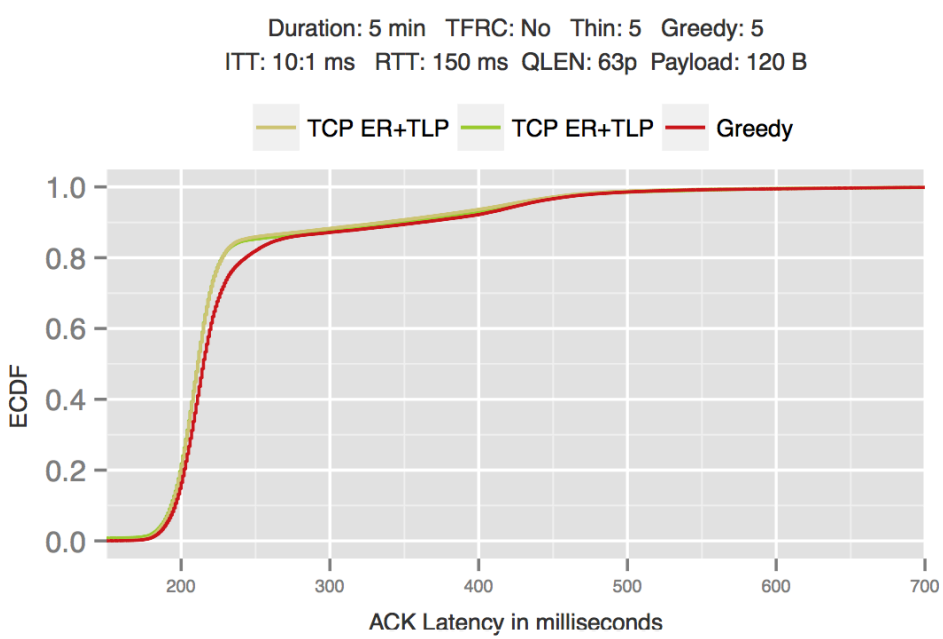


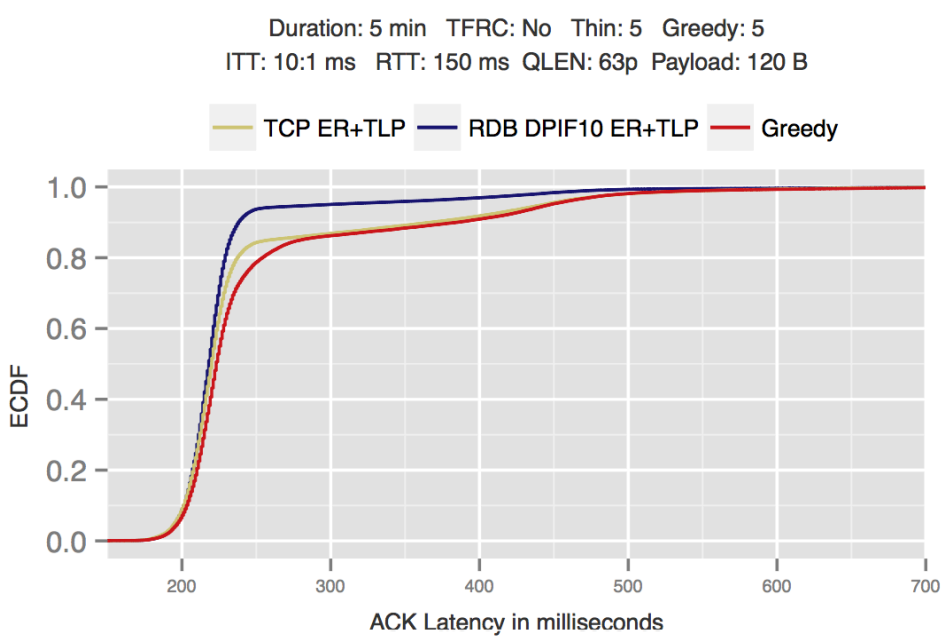


To bundle freely may contribute to added queueing delay
(an AQM would alleviate this situation)

RDB: how many segments?

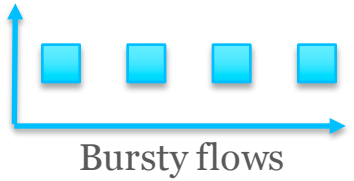
Thin streams





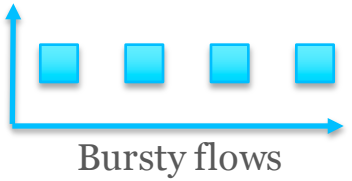
- a one segment limit helps avoid loss while keeping delay low.
- One may want to loosen the restrictions for special cases in order to further decrease latency.

New Congestion Window Validation (New-CWV)



- A method to control TCP cwnd for congestion-control in data-limited conditions
  - Data-limited do not consume the cwnd
  - Examples: interactive apps, web traffic, real-time flows
- Replaces RFC 2861 which was partially implemented in Linux
- It is defined in “draft-ietf-tcpm-newcwv” (TCPM WG item) approved by IETF for publication
- Implementations
  - For Linux (as a CC module and patch) http://github.com/rsecchi/newcwv
  - For FreeBSD https://bugs.freebsd.org/bugzilla/show_bug.cgi?id=191520

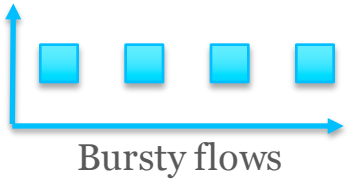
New-CWV Goals & Design



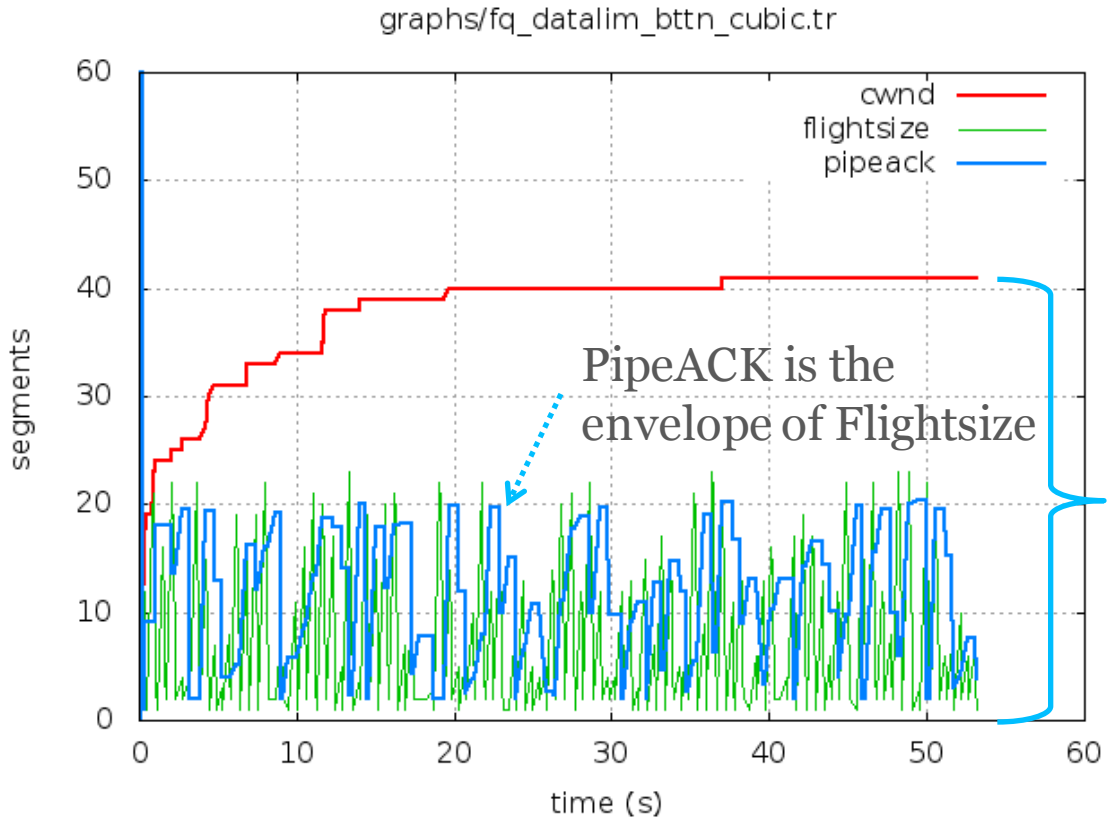
- New-CWV Goals
  - To reduce the latency in “bursty” applications
  - To remove the incentive for “ad-hoc” methods (eg “padding“)
  - To provide an incentive for the use of long-lived connections, rather than a succession of short-lived flows
  - To avoid a TCP sender growing a large "non-validated" cwnd (Linux did this already ☺)

- Design choices
  - TCP sender-side only modification
  - Change congestion control rules when the data to send is less than cwnd (non-validated periods)
  - Congestion control for data-limited flow independent from the RTT
  - Congestion control not based on the flightsize (it is not validated)

new-CWV method (1/3)

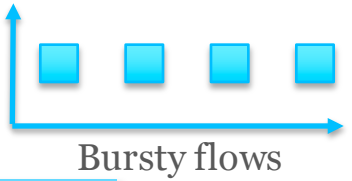


CC driven by available bandwidth evaluations (PipeACK)

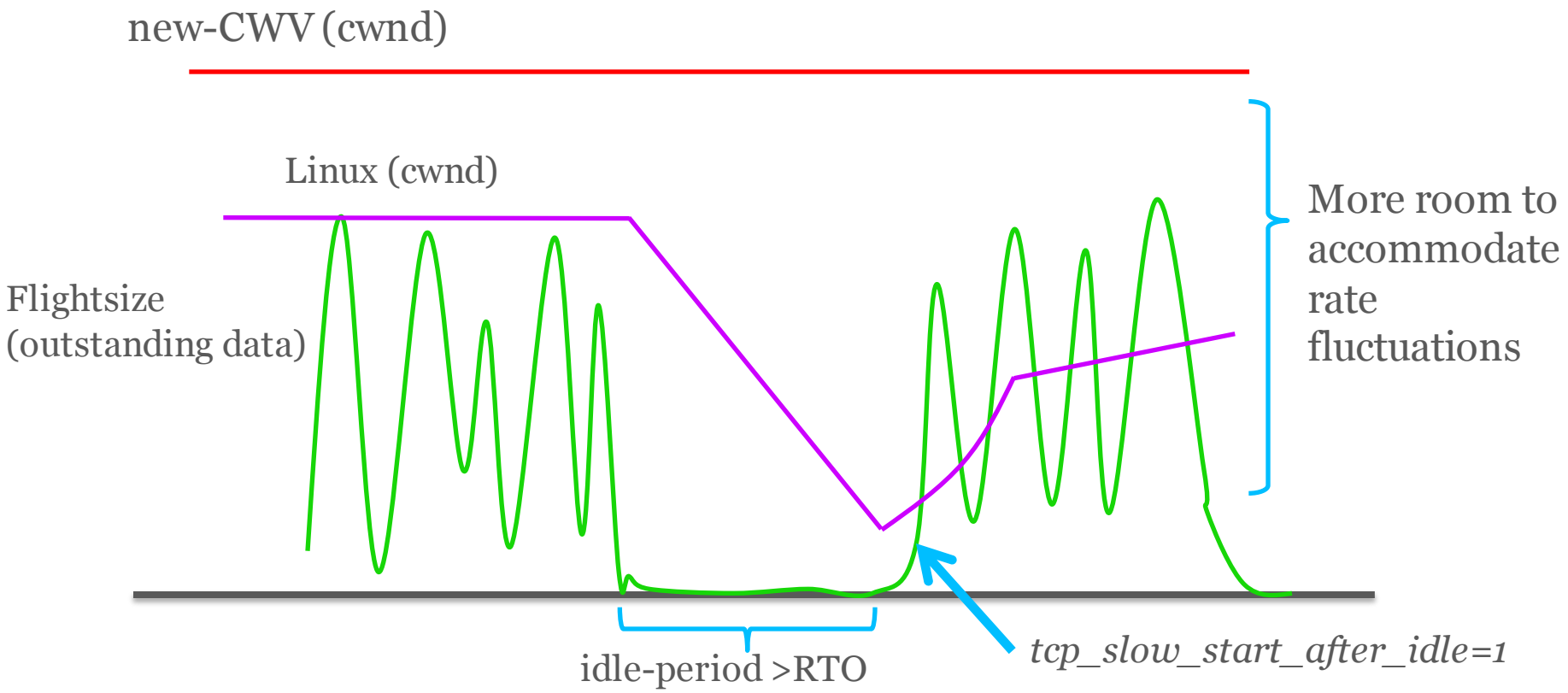


cwnd can grow up to 2 pipeACK

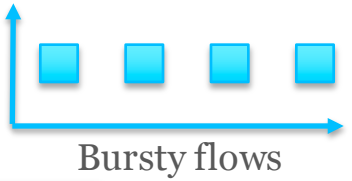
new-CWV method (2/3)



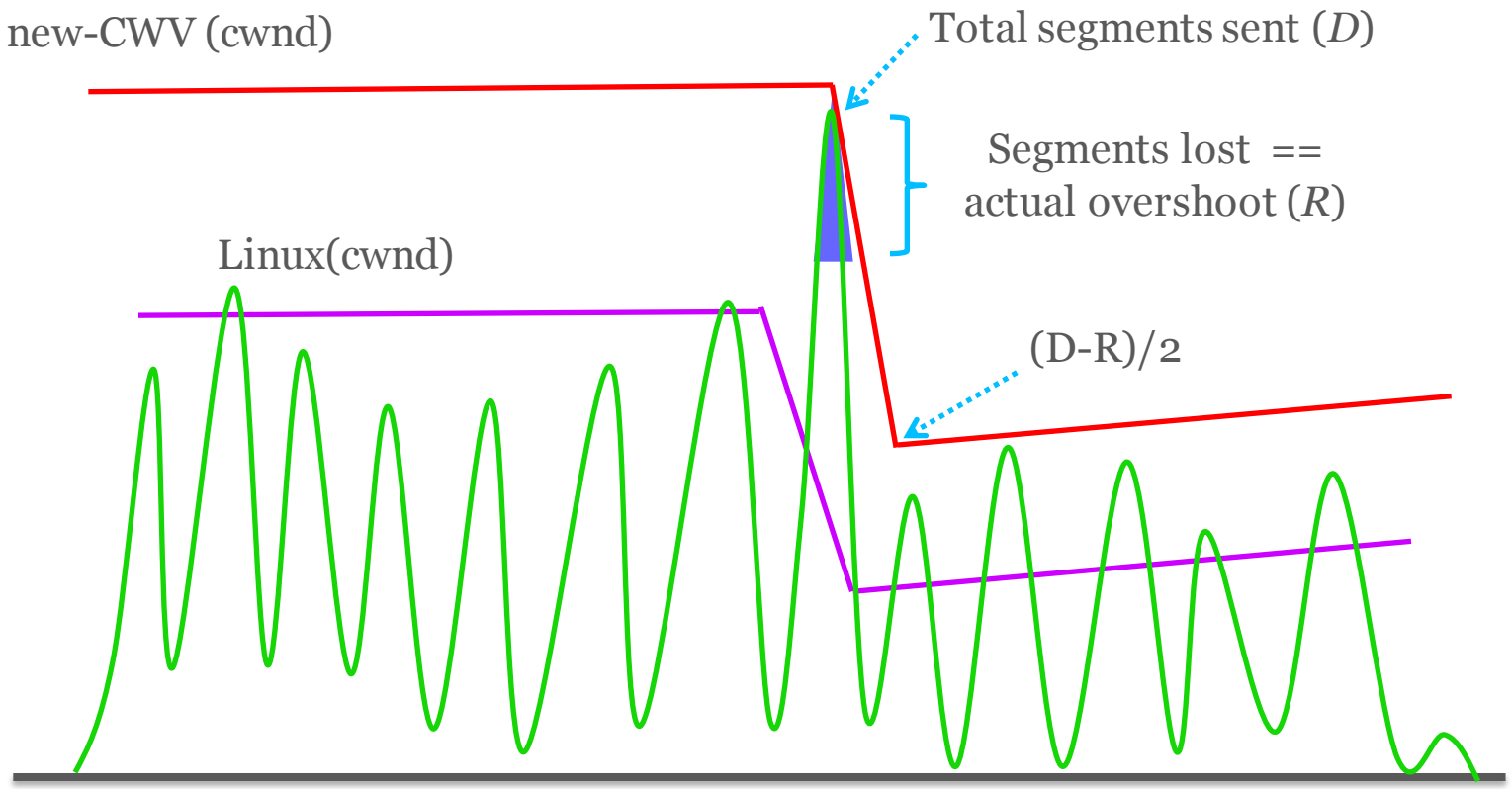
Avoid collapsing cwnd after periods > RTO if no congestion feedback



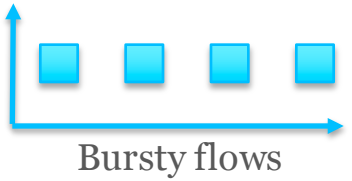
new-CWV method (3/3)



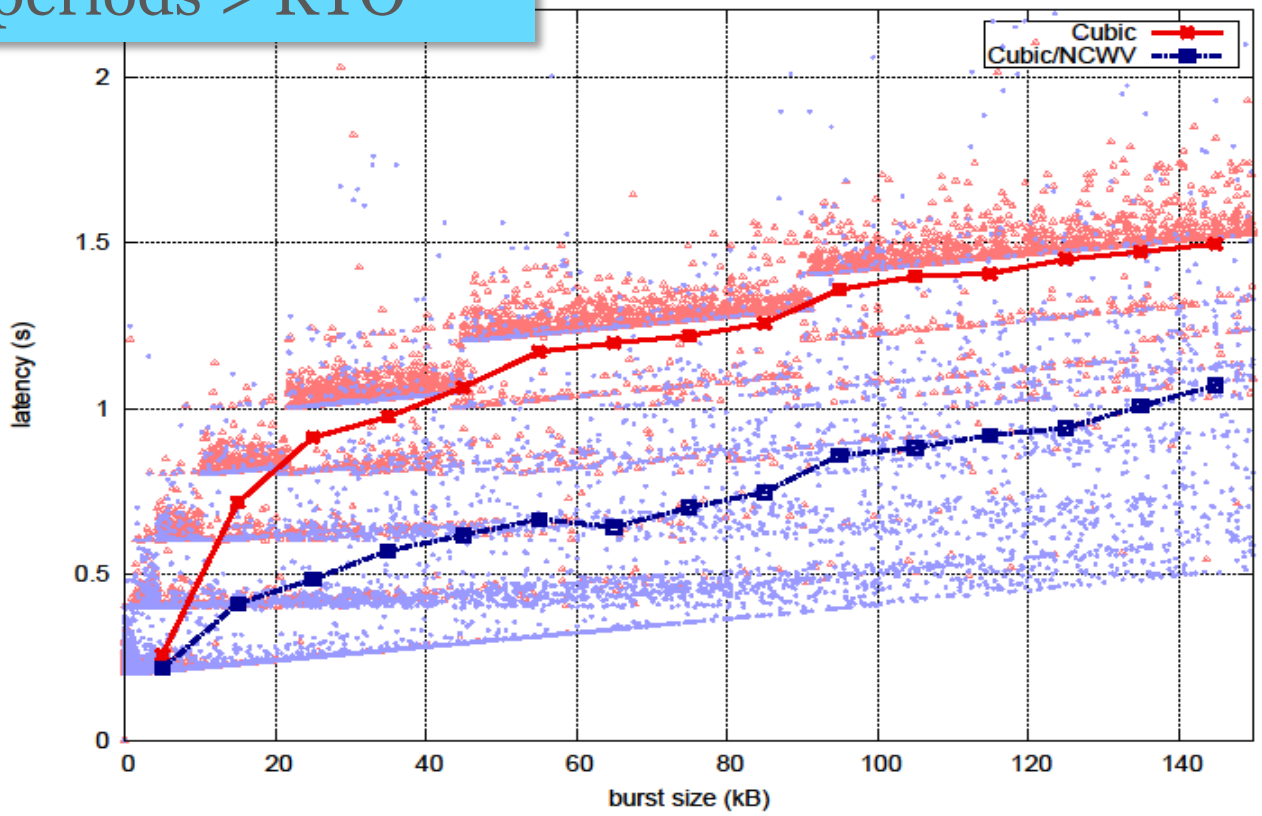
More accurate response to congestion feedbacks during data-limited periods



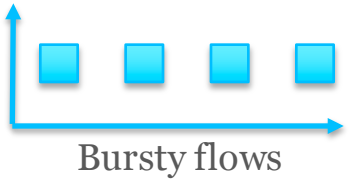
Experiments with TMIX replaying TCP connection from a wide-area traffic trace



Burst transmission latency after idle periods > RTO



Changes to Linux kernel



TCP headers: Socket descriptor & helper functions

include/linux/tcp.h

```
struct tcp_sock {
    [..]
    newcwv vars
};
```

New variables for the socket descriptor

```
static inline bool
tcp_is_cwnd_limited(sk)
{
   if ( flightsize>=cwnd ||
        pipeack>=cwnd) {
          return true;
   }
   return false;
}
```

Called by CC modules to determine if cwnd can be increased

TCP actions for outgoing packets:
Don't reduce cwnd

net/ipv4/tcp_output.c

```
tcp_event_data_sent(sk) {
   [...]
   tcp_newcwv_datalim_closedown(sk);
}
```

When packet are sent check if an RTO has passed from previous packet sent:

Reduce cwnd only after 5min rather than after one RTO as in CWV

CC common action: Initialise newcwv

net/ipv4/tcp_cong.c

```
tcp_init_congestion_control(sk) {
   [...]
   tcp_newcwv_reset(sk);
}
```

Init newcwv vars at start

Changes to Linux kernel: Recovery & PipeACK computation

net/ipv4/tcp_input.c

A **tcp_enter_recovery(sk)** {
[...]
if (pipeack<=2cwnd)

tcp_newcwv_enter_recovery(sk);
}

Loss detected (3dupacks):
1) store D
2) Cwnd = D/2

B **tcp_end_cwnd_reduction(sk)**
{
[...]
tcp_newcwv_end_recovery(sk);
tcp_newcwv_reset(sk);
}

At the end of recovery
1) cwnd=(D-R)/2
2) Restart newcwv

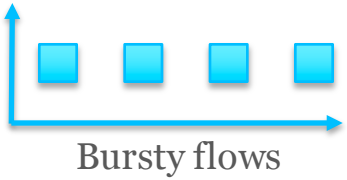
tcp_enter_loss(sk){
[...]
tcp_newcwv_reset(sk);
}

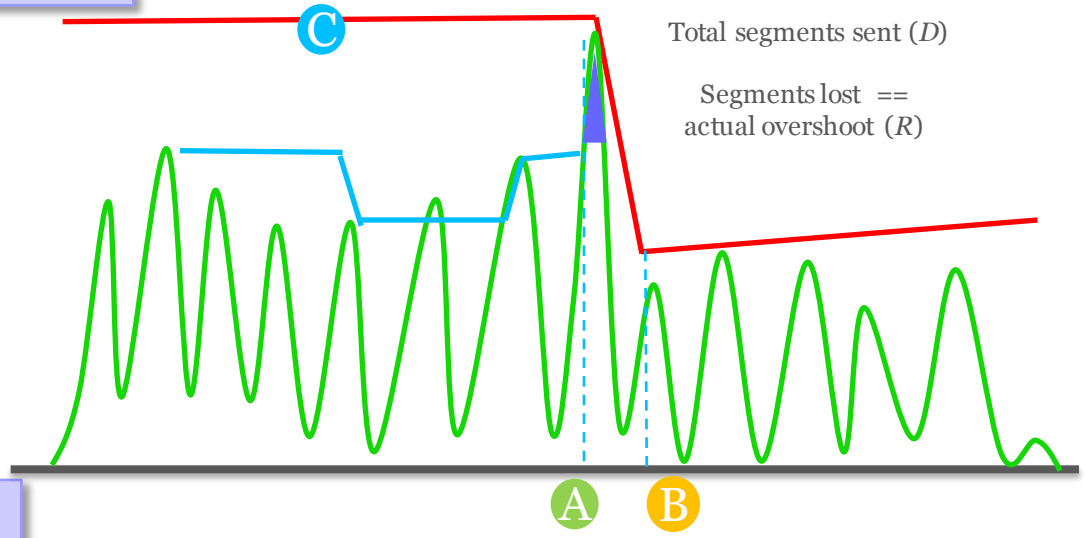
Timeout?
Restart newcwv

C **tcp_ack(sk)** {
[...]

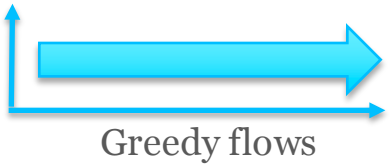
tcp_newcwv_update_pipeack(sk)
}

ACK received?
update
pipeACK





Caia Delay Gradient (CDG)



Developed by David Hayes / CAIA

Linux edition (by Kenneth Klette Jonassen)

Basic concepts

Delay-gradient as a congestion signal

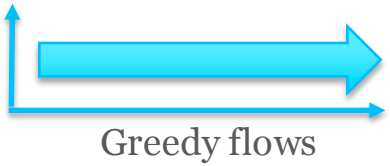
- RTT is a noisy signal
- RTTmin and RTTmax in a measured interval (1 RTT)

$$g_{\min,n} = \mathrm{RTT}_{\min,n} - \mathrm{RTT}_{\min,n-1}$$
$$g_{\max,n} = \mathrm{RTT}_{\max,n} - \mathrm{RTT}_{\max,n-1}$$

- Smoothed
  - moving average (configurable)
  - probabilistic back-off

- Queue State
  - $Q \in$ {full, empty, rising, falling, unknown}.

CDG: Delay-gradient probabilistic backoff



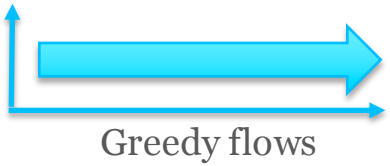
Why?

- Helps avoid synchronisation issues
- Helps smooth the noisy gradient signal.

Exponential

- Decisions are made once per RTT
- $P[\text{backoff}] = 1 - e^{-(\overline{g}_n/G)}$
- $\overline{P_{\text{RTT}}[\text{back-off}]} = \overline{P_{\text{RTT}}[\text{back-off}]}$
- Note: TCP's additive increase rate will still be RTT dependent.

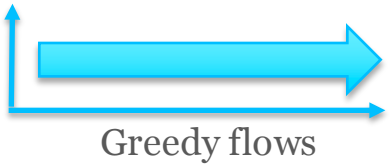
Co-existence with loss-based CC



- Maintains a “shadow congestion window”
  - switches to “New Reno” congestion avoidance when competing with loss-based CC flows.

- Also includes a loss-heuristic to detect random losses (not due to congestion).
  - disabled by default due to uncertainty to its accuracy (needs evaluation).

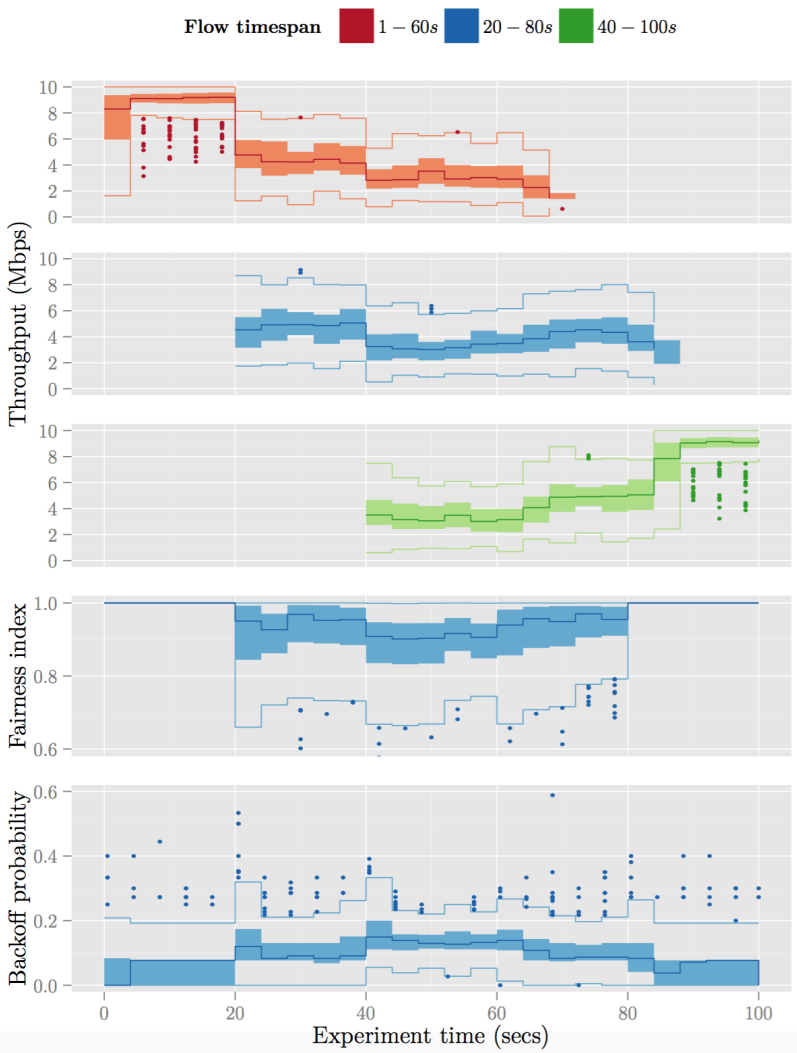
FreeBSD->Linux

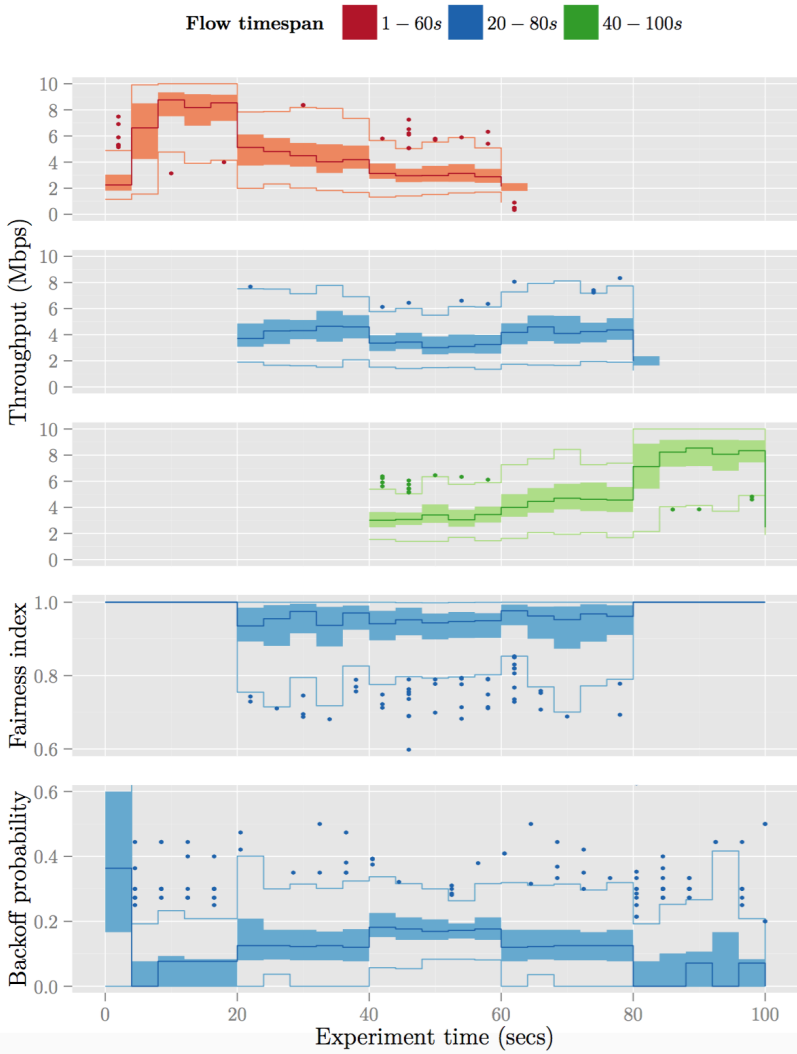


- CDG added to FreeBSD in 2013 (9.2).
- Some key differences in the Linux version by Kenneth:
  - Granularity of timers μsec in Linux, msec in FreeBSD
  - Using Hybrid Slow start and Proportional Rate Reduction.
  - Add toggle for shadow window mechanism. Suggested by David Hayes.
  - Add toggle for non-congestion loss tolerance.
  - Scaling parameter G is changed to a backoff factor;
    - conversion is given by: *backoff_factor* = 1000/(G * window).
  - Limit shadow window to 2 * cwnd, or to cwnd when application limited.
  - More accurate e^-x.
- CDG is available as a pluggable congestion control since 4.2

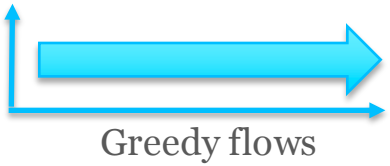
FreeBSD vs Linux performance

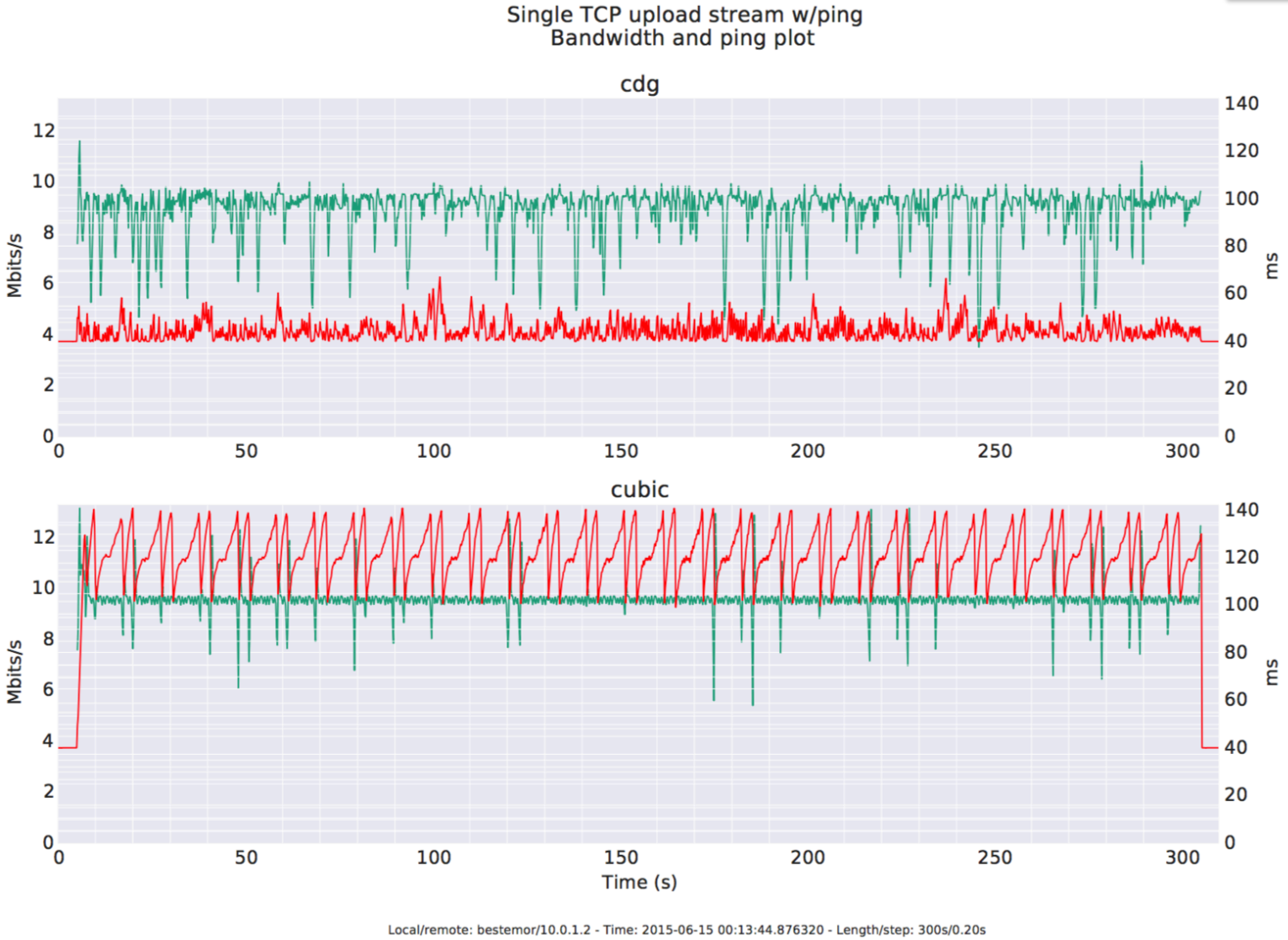
Greedy flows



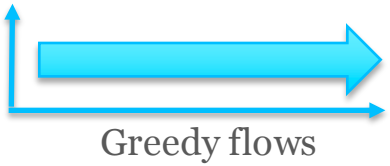


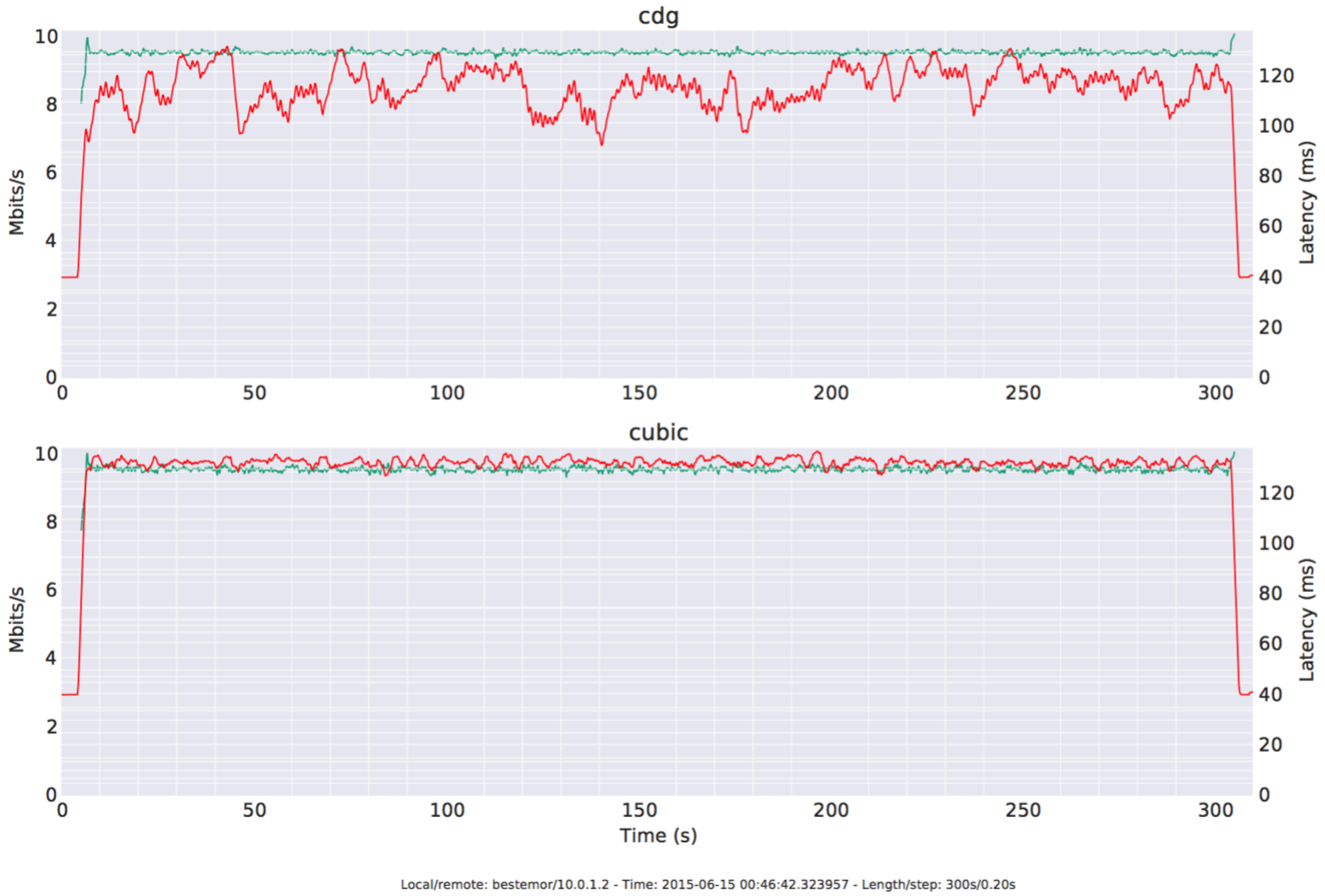
Delay compared to Cubic





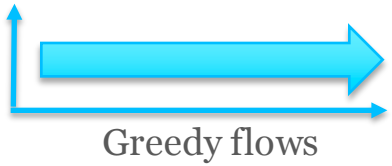
Delay compared to Cubic





L. Brakmo New Vegas tests

Loss competition turned on



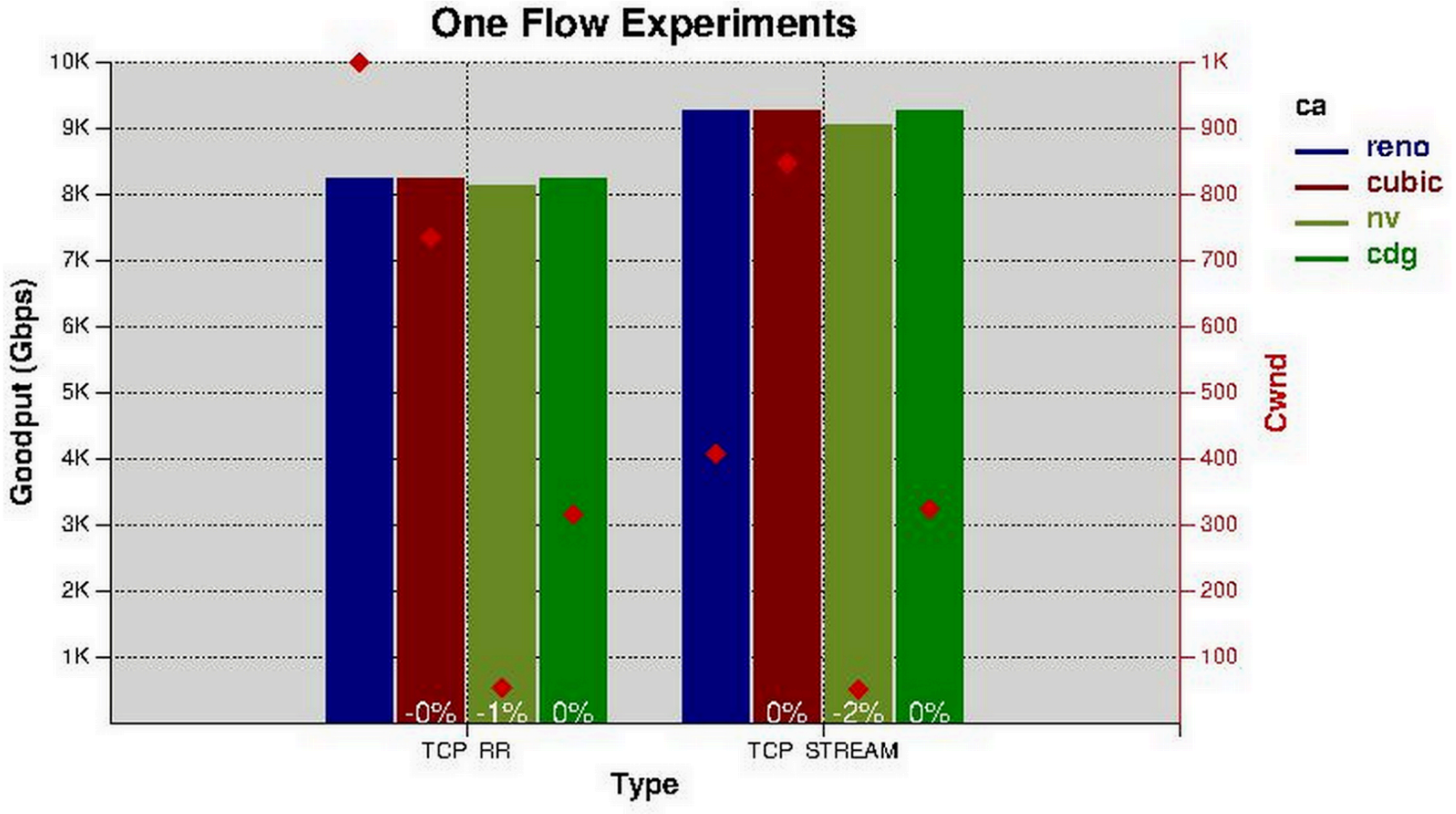


Chart 1: Rate and Cwnd for 1-flow experiments

L. Brakmo New Vegas tests: http://www.brakmo.org/networking/tcp-nv/TCPNV.html

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Questions?

- Patches and more info:
  http://www.riteproject.eu/resources

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