To send or not to send?..

How TCP Congestion Control algorithms work

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About me

- In IT since 2005
- Working for Unitop (IT integration)
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  - Twitter: @Packet_vlad
  - Q&A: https://ask.wireshark.org
  - Blog: packettrain.net
  - Social group https://vk.com/packettrain (Russian)

PCAPs

http://files.packettrain.net:8001/SF18/

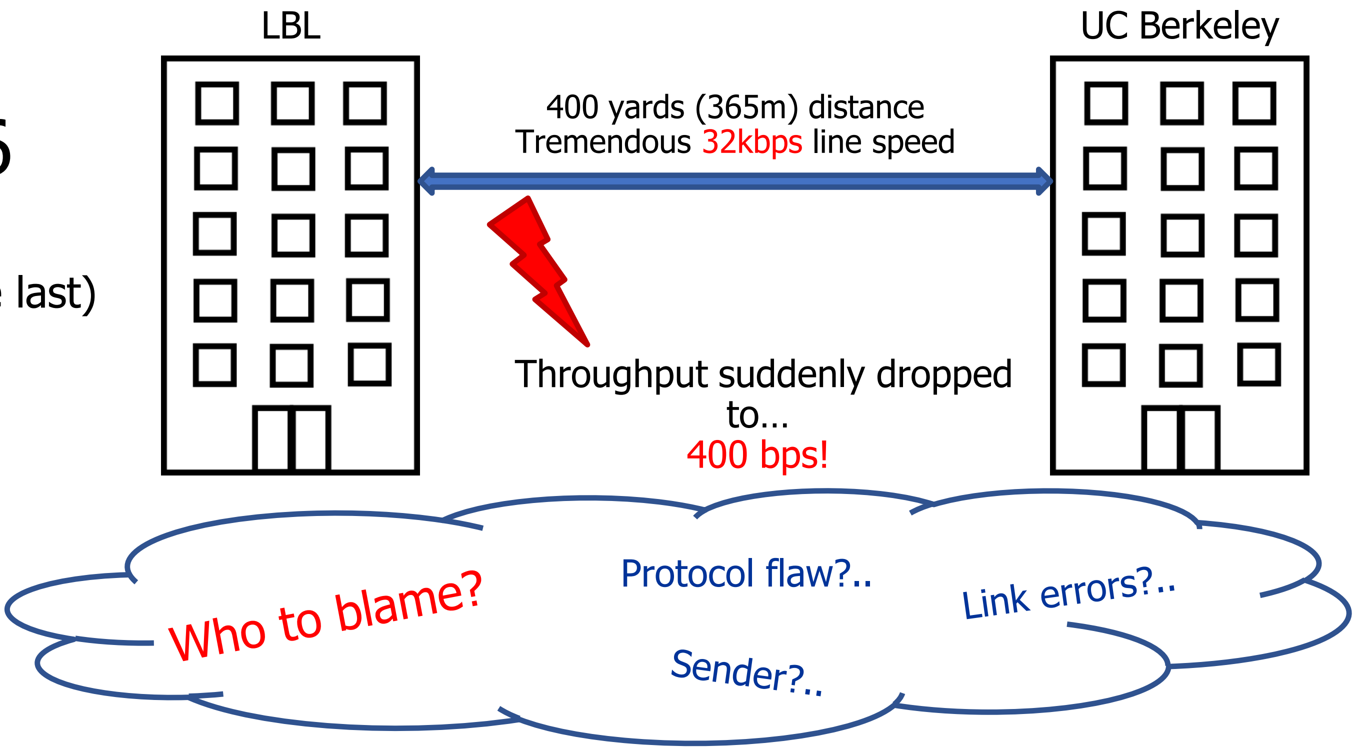
Login = password = sf18eu

(caution: size!!)

The beginning..

Oct 1986

The first (but not the last) occurrence.



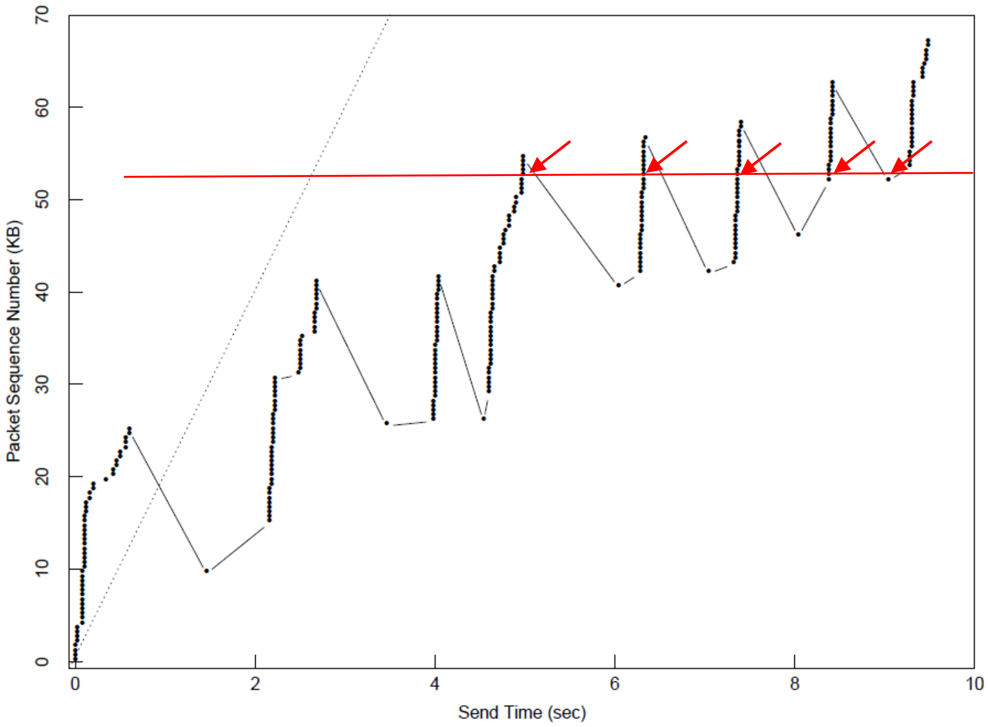
Let’s capture!

What was on the wire?

The sender (4.2 BSD) floods the link with tons of **unnecessary retransmissions**.

* because it sends on own full rate and have inaccurate RTO timer

* some packets were retransmitted 5+ times!



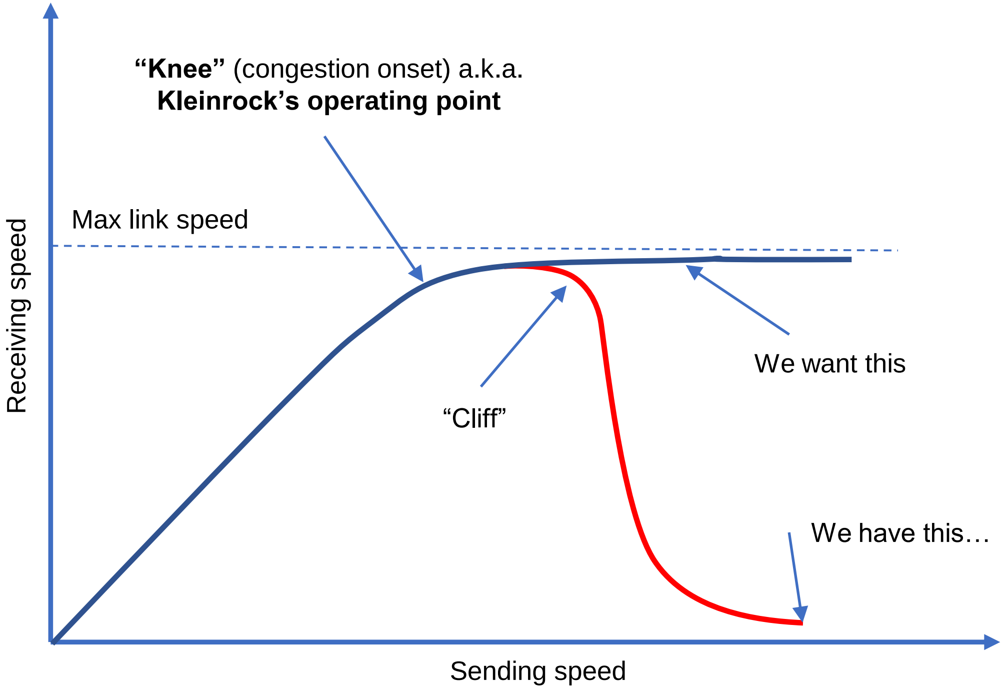
Congestion collapse

This is called **"congestion collapse"** – when goodput decreases by huge factor – up to 1000x!

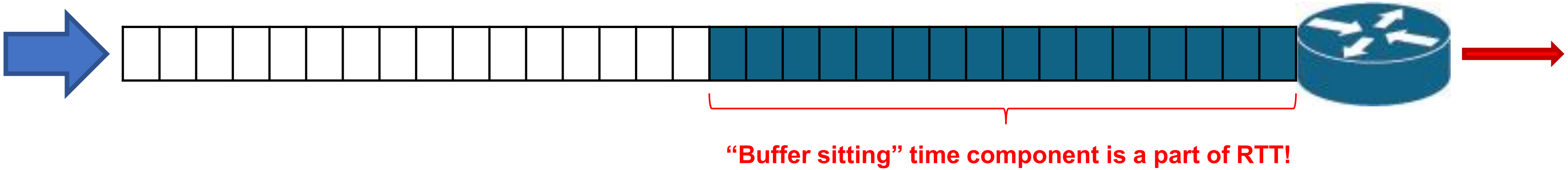
[Fact: it was predicted by Nagle in 1984 before it occurred in real life]

- Bad news: it NEVER disappears without taking countermeasures.

- So a sender has to slow down its rate … or we just add more buffer to router?



Large buffers?



- *"Let's never drop a packet" approach.*
- But… buffers could be large, but not endless.
- Good for absorbing bursts, but doesn't help **if long-term incoming rate > outgoing rate.**
- Actually make things worse (high latency, **"bufferbloat"**) – so we don't want to have even endless buffers if we could.

Key point

Buffer is good for absorbing short spikes of traffic or for short-lived connections, but becomes a problem for long-lived ones.

How to handle it?

Main decision made in [J88]:

<u>“Smart endpoint, Dumb internet”</u>

A sender (endpoint) has to slow down its transmission speed for some time giving up self-interest for the interest of the whole system.

Modified sender should be capable to handle congestion without any assistance from network nodes (though sometimes we’d like to have it… see later).

Senders are recommended to use agreed reaction to congestion signal.

Focus on sender

Window-based or rate-based control??

Signaling (how do we know there is a congestion)??

Priority to delay or utilization??

Increment rule if there is no congestion??

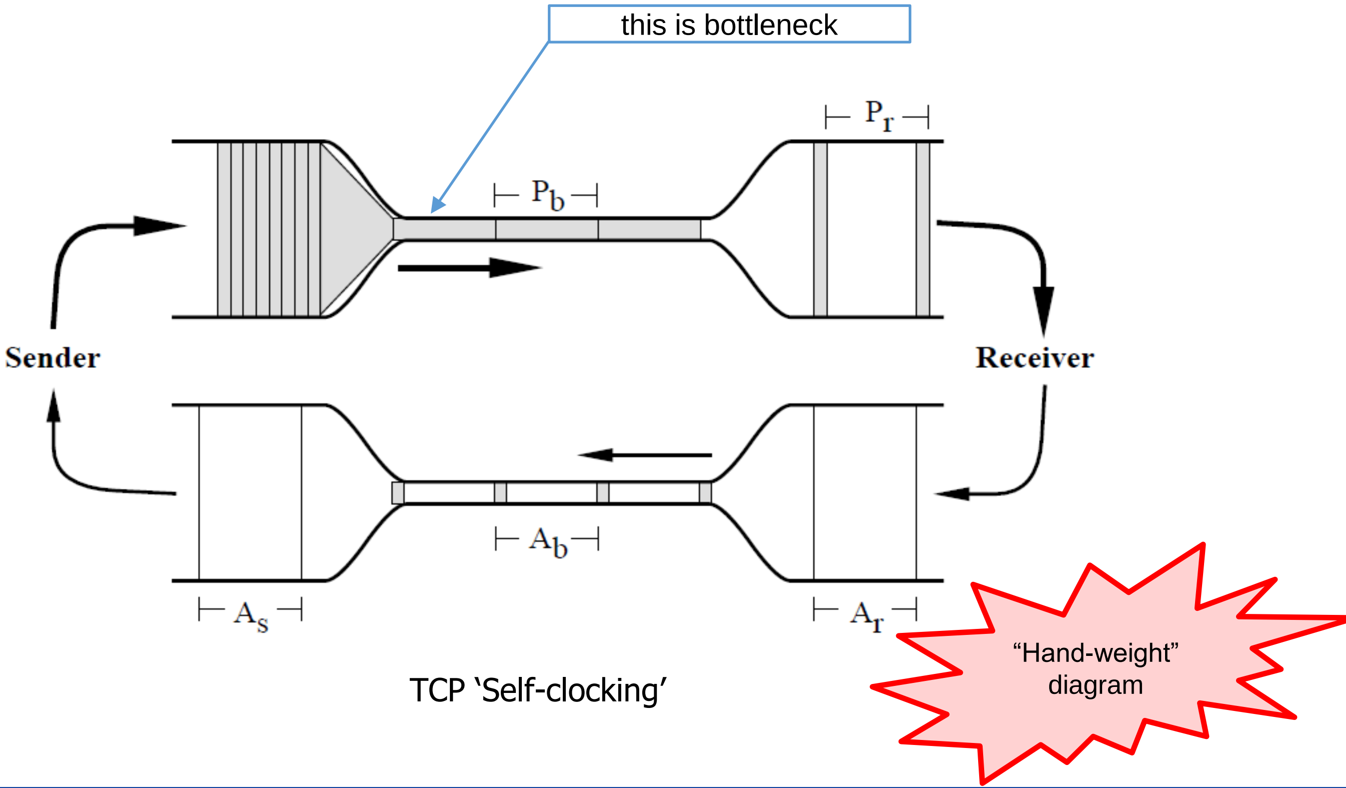
Decrement rule if there IS congestion??

Fairness??

TCP Self-clocking

Equilibrium state is good, but…
only if:
- you are the only one sender,
- you're already in it,
- there are no other variables.

Looks unrealistic.



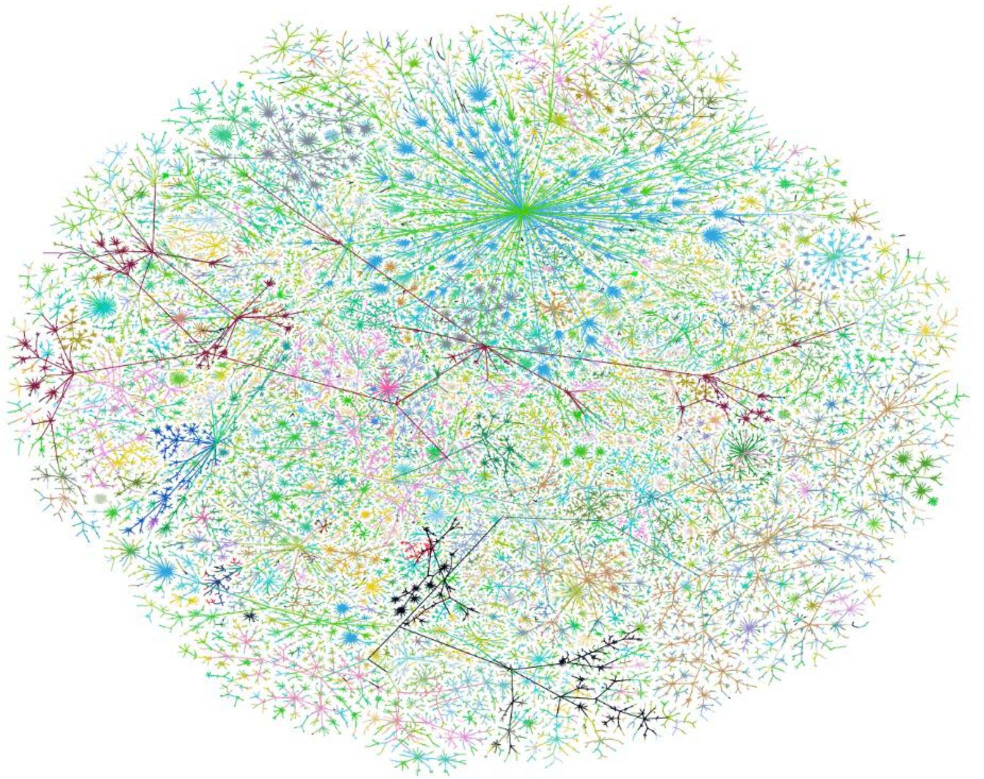
TCP 'Self-clocking'

But in real world...

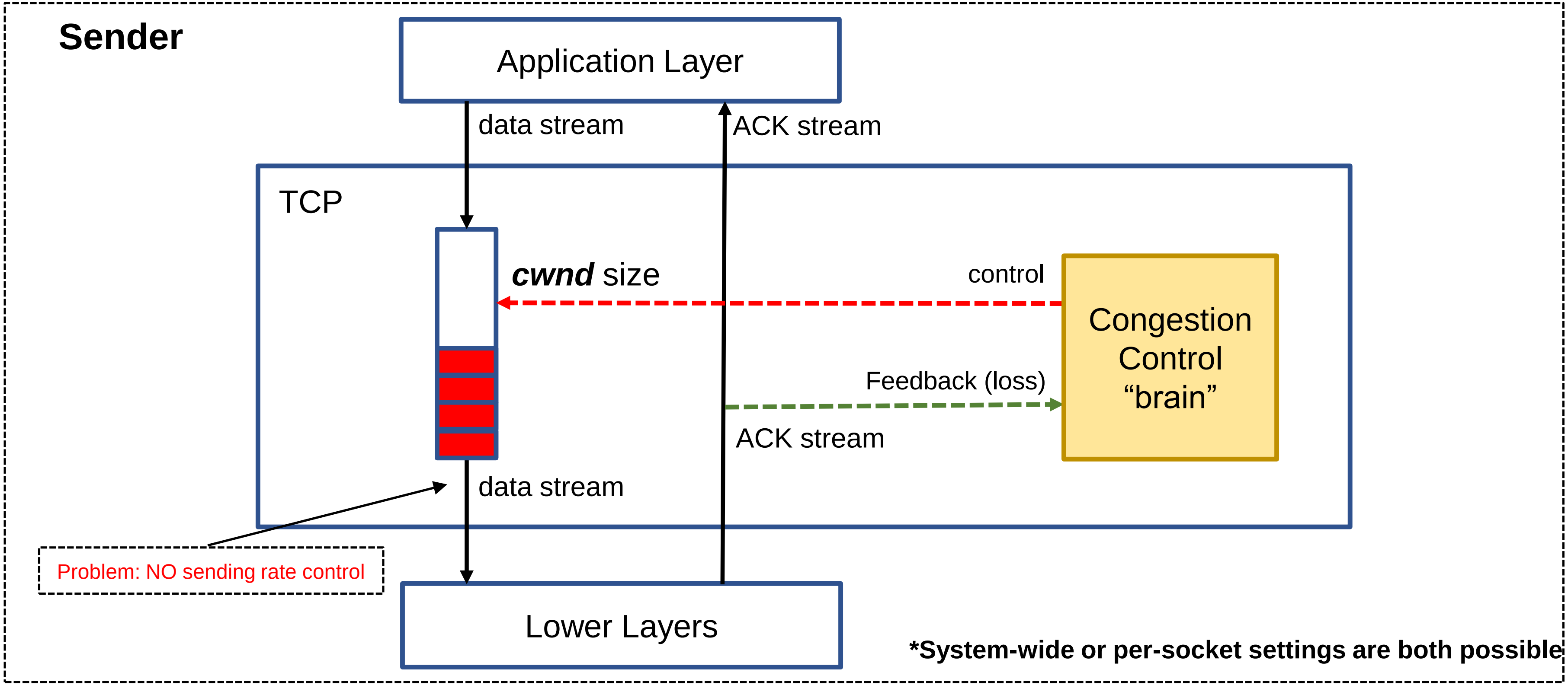
What about this topology?

- Random data transfer occurrence
- Random link parameters
- Unknown path

TCP has to do it's job in **such** environment.



Design by [J88]



***System-wide or per-socket settings are both possible**

First solution by [J88]

1. Window-based control – hello, ***cwnd***! –
   W=min(*cwnd*, *awnd*), * where W – number of unacknowledged packets; we also assume there are no constraints in ***awnd*** in this session.

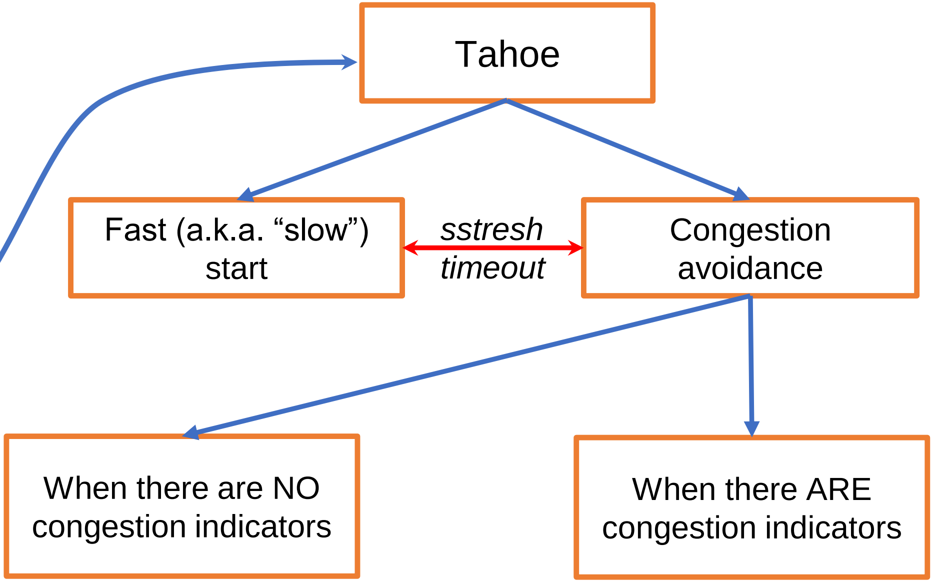
2. Feedback: packet loss as network congestion indicator

3. Action profile: several stages for different purpose each

4. RTO estimation enhancement

5. Fast retransmit mechanism

6. Focus on protection from collapse, not efficiency etc.



Tahoe – “slowfast kickstart”

Three tasks:

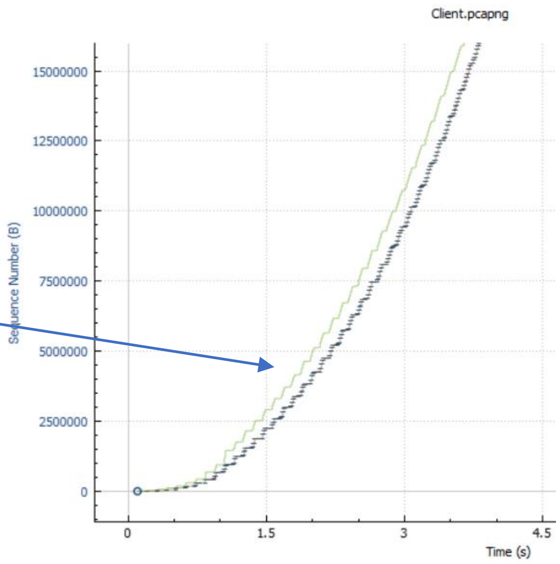
1. **Establishing feedback circuit (main one!)**
2. “Fast and dirty” probe for bandwidth.
3. Determining initial ***sstresh*** value for further use (**important!**)

“It is always exponential shape!!”
Oh rly?? What about…(trace)

Operation:

1. Start from initial window IW.
2. For every ACKed SMSS increase ***cwnd*** by one SMSS.

*Refer to slides from Christian Reusch for details.



Fun fact

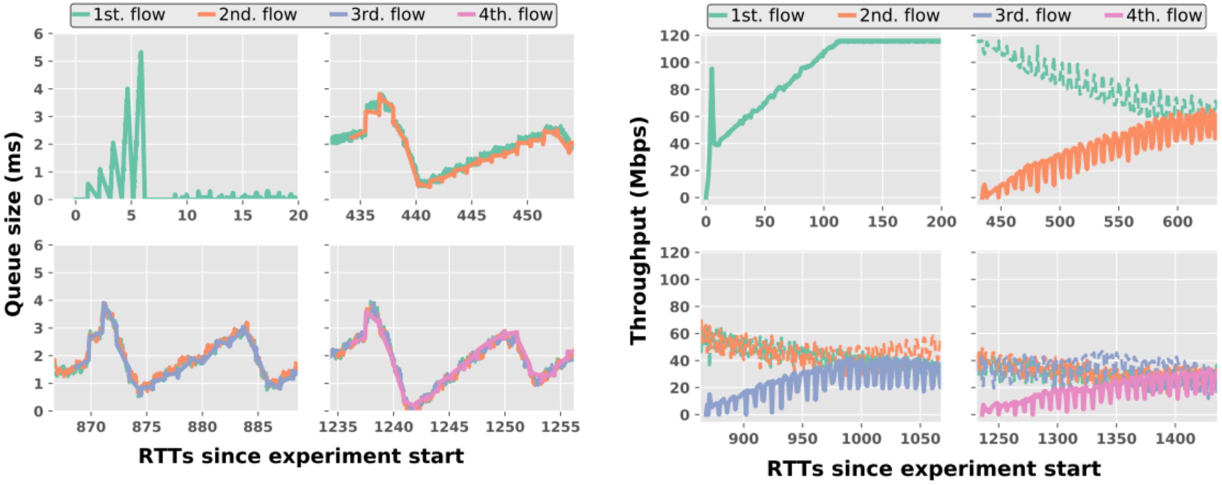
Initial window size nowadays usually equals 10 packets.
Refer to this link: https://iw.netray.io/stats.html
You can change it in Linux OS: #ip route change default via ip.address dev eth0 initcwnd 15
And in Windows OS: https://andydavies.me/blog/2011/11/21/increasing-the-tcp-initial-congestion-window-on-windows-2008-server-r2/

Slow start problems

Do you think it's the best option?

Questions/problems:

1. Too slow.
2. Too fast.
3. Behavior on extra-low queue scenarios.
4. Spikes in queuing delay.
5. "Bad luck" drop.

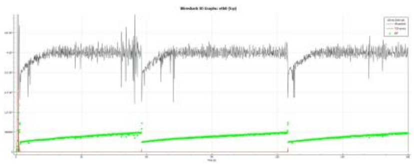


Alternative approach is being developed ("Paced chirping" by Joakim Misund, Bob Briscoe and others)

Fun Facts

Tahoe was created using “bottom-up” approach: packet-level rules first, macroscopic shape (flow-level) second.

All subsequent CA algorithms (almost) were developed using the opposite “top-down” approach: flow-level first (this is **what I want to achieve**), packet-level rules second (**this is how I achieve that**).



Flow level

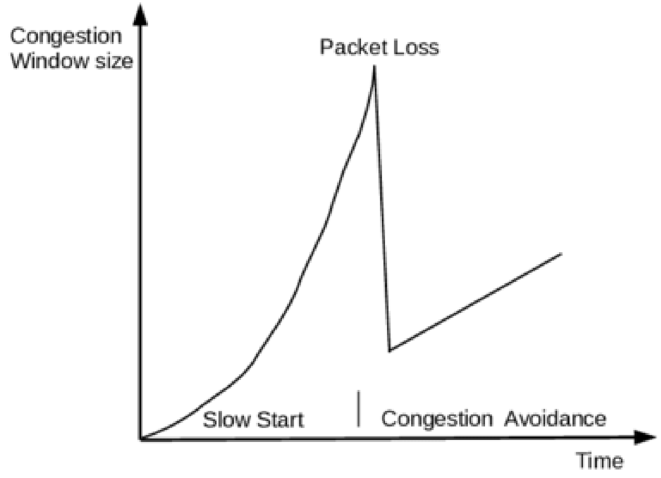
Packet level

$$cwnd = \begin{cases} cwnd + a & \text{if congestion is not detected} \\ cwnd * b & \text{if congestion is detected} \end{cases}$$

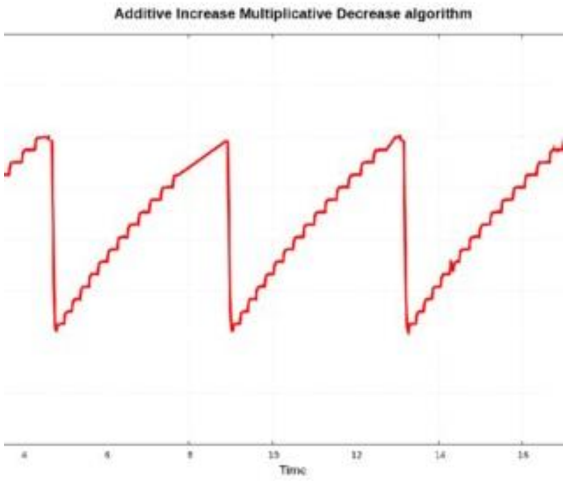
Fun fact

Fun fact

As ***cwnd*** increases/decreases at least by SMSS value, its real graph never contains inclined line segments, but only horizontal or vertical segments! So:



This is technically inaccurate! But totally OK to see the whole picture



In fact it is **"staircase-shaped"**

Tahoe – Congestion avoidance

Core ideas:

1. Uses packet loss as a sign of congestion (feedback type/input).
2. Uses AIMD approach as action profile (control/output).

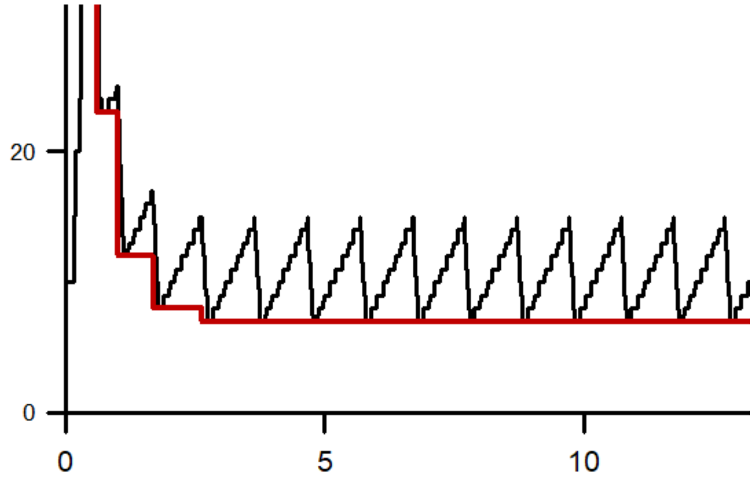
Has two modes (as any other algorithm):

1. With no observed signs of congestion.
2. With signs of congestion detected.

***cwnd* control rules:**

$$cwnd = \begin{cases} cwnd + a & \text{if congestion is not detected} \\ cwnd * b & \text{if congestion is detected} \end{cases}$$

For Tahoe, Reno $a = \frac{1}{cwnd}$; $b = 0.5$



*Refer to Christian's session for more details

Fun Facts

True or False?
- AIMD is an obsolete congestion control algorithm, nowadays we have better ones.

True or False?
- All congestion control algorithms since Tahoe react to packet loss.

True or False?
- ***cwnd*** in Reno in Congestion Avoidance phase grows as straight line until packet loss is detected.

Fun Facts

True or False?

- AIMD is an obsolete congestion control algorithm, nowadays we have better ones – Partially true!
- True: AIMD itself is not a congestion control algorithm, this is just an approach, pattern to behave while in congestion control stage. Many modern algorithms also use AIMD approach, but it's being eventually switched from. Remember also: AIMD ≠ Reno

True or False?

- All congestion control algorithms react to packet loss – FALSE!
- True: There many kinds of congestion control algorithms. Many of them indeed react to packet loss, but many others use different feedback type – delay. So, transition to congestion avoidance state could be done with no observed packet loss at all!

True or False?

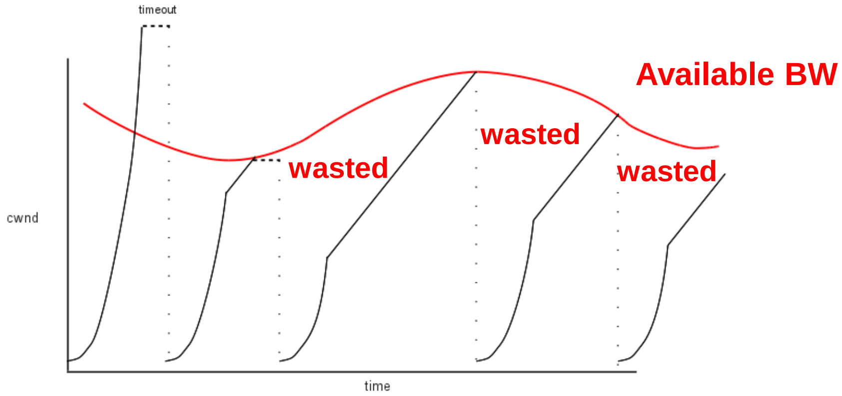
- ***cwnd*** in Reno (CA stage) grows as straight line until packet loss is detected – FALSE!
- True: In addition to "staircase-shape" although this line looks straight, it is not! The more ***cwnd*** size is, the less slope of this line is (refer to "Convergence" slide to see it!). Chances are we'll reach packet loss too early to spot this.

Let’s rate it!

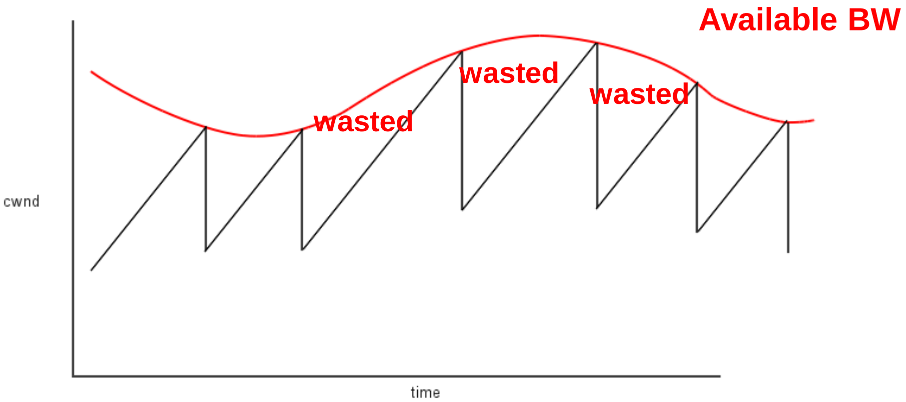
Well, how to decide which algorithm is better?

1. Efficiency (how full and steady is bottleneck utilization?)
2. Fairness (how do we share bottleneck capacity?)
3. Convergence capability (how fast do we approach equilibrium state? How much do we oscillate later?)
4. “Collateral damage” (buffer overflow event rate, self-inflicted latency)

Efficiency



Tahoe: bad



Reno: better, but not ideal

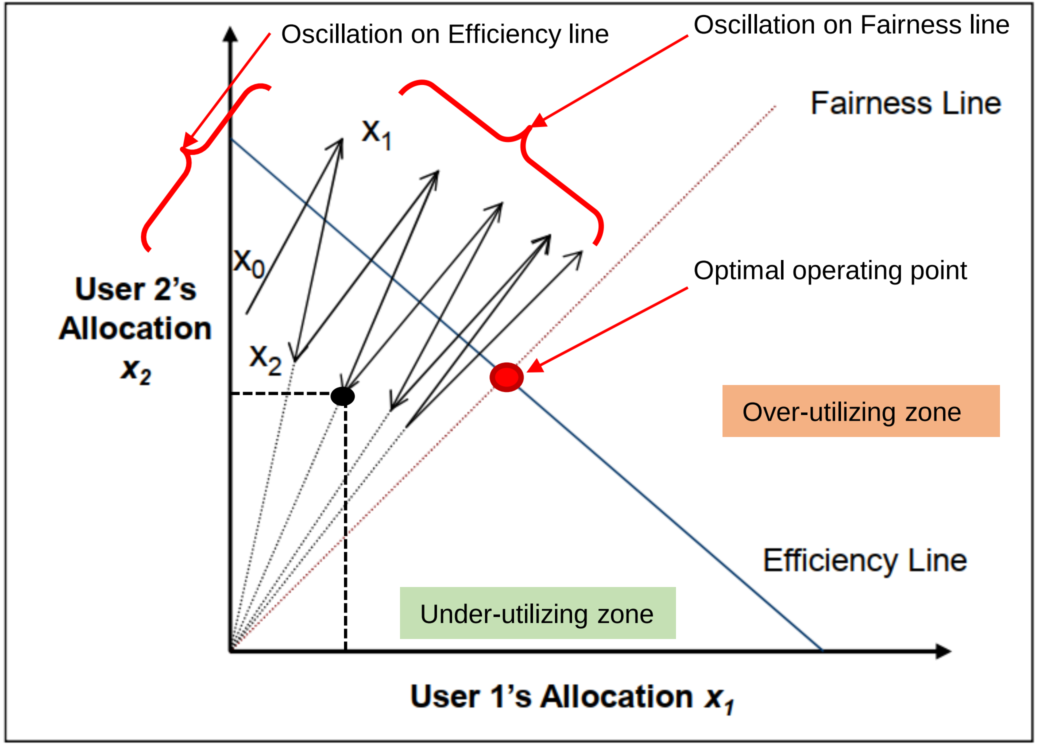
Fairness, convergence

Caution! Backup slide!

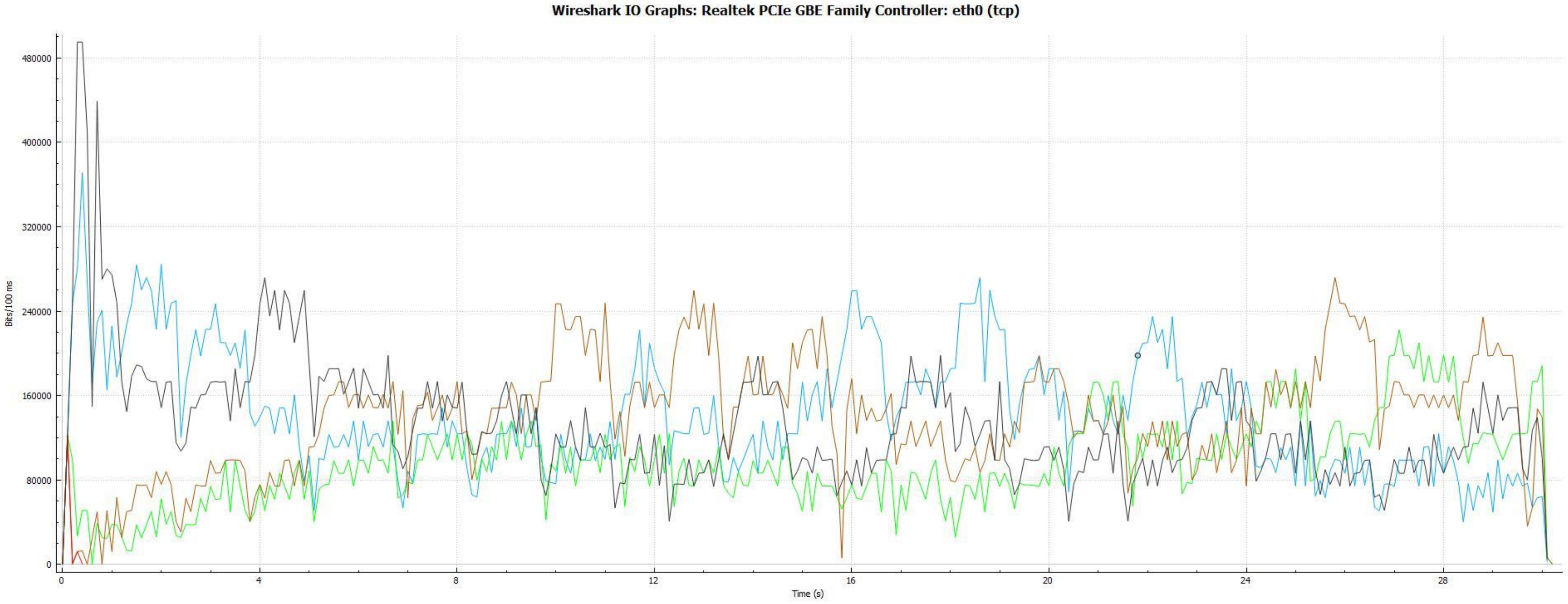
Introducing: **Phase graph**

Shows efficiency, fairness and convergence.

Here: an example for two senders.



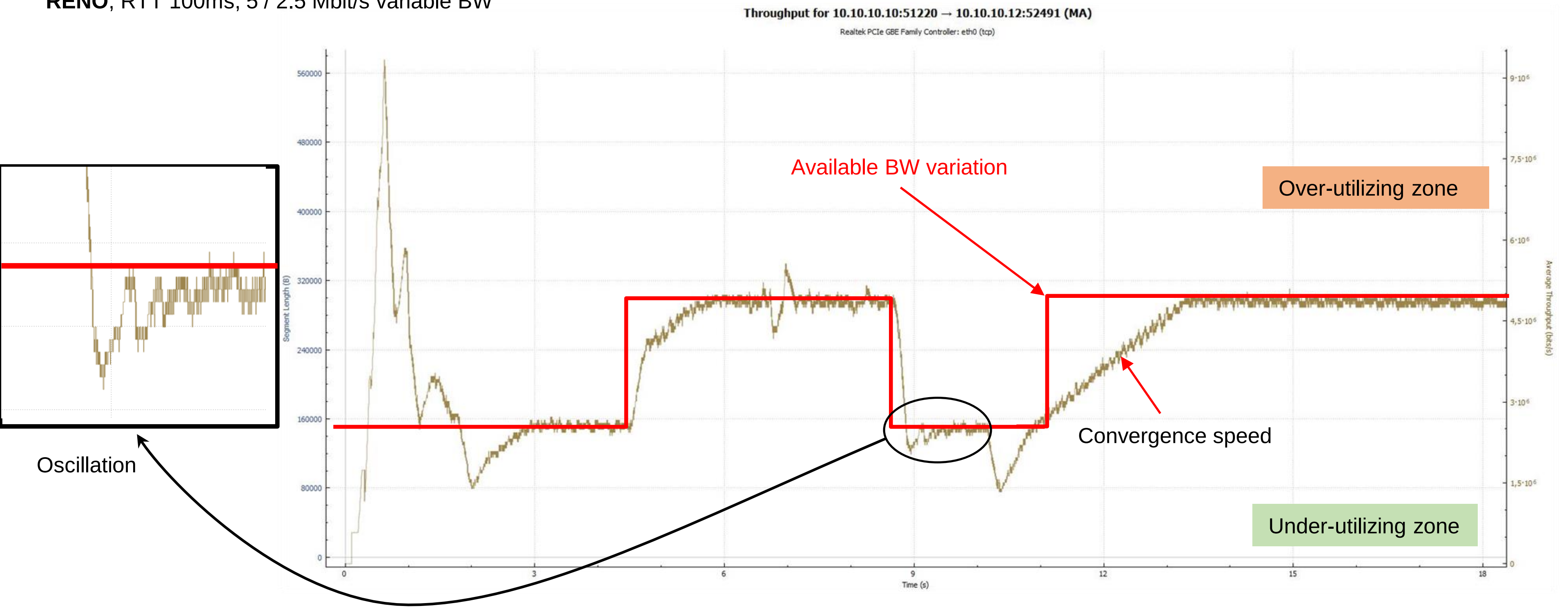
Fairness (5 streams Reno)



But what about non-TCP protocols? See later..

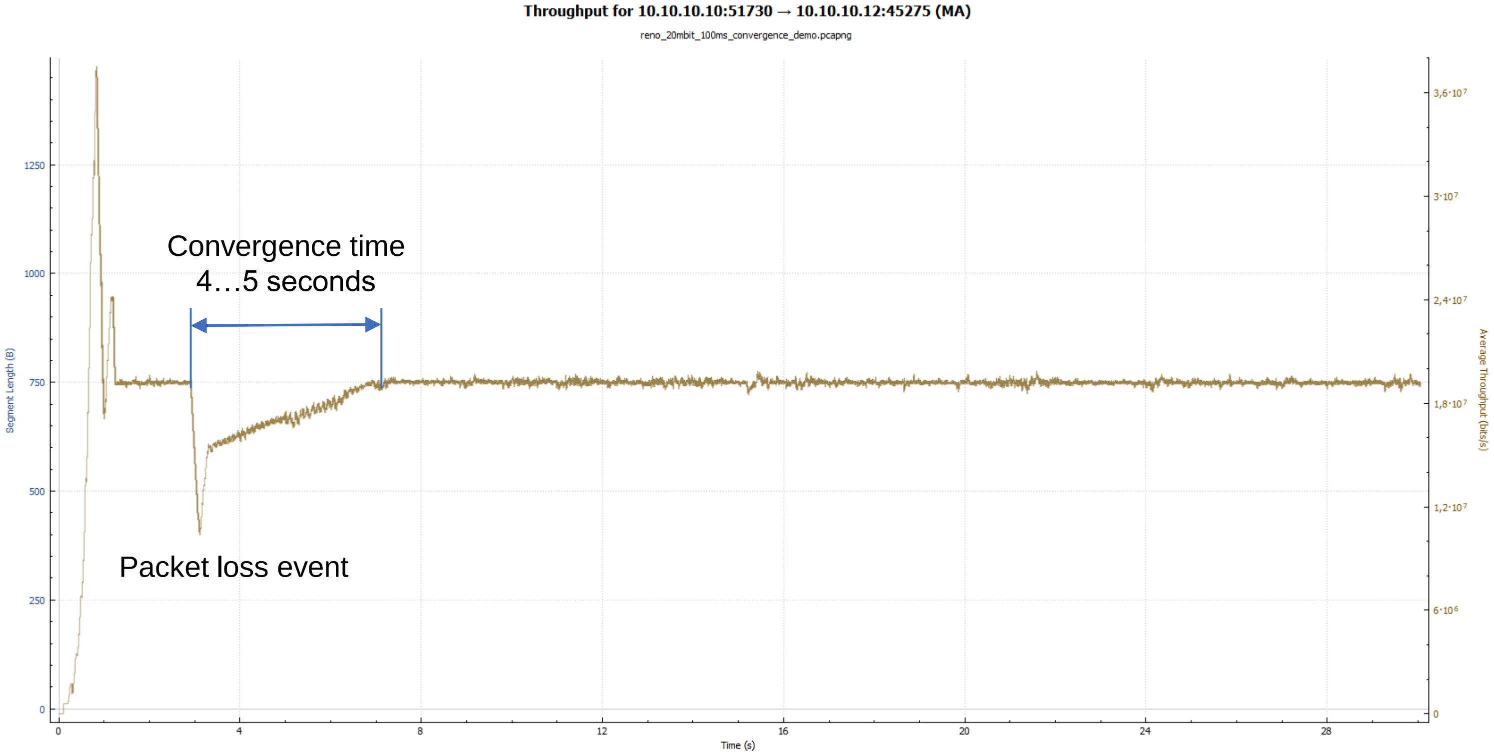
Convergence (1 stream)

RENO, RTT 100ms, 5 / 2.5 Mbit/s variable BW



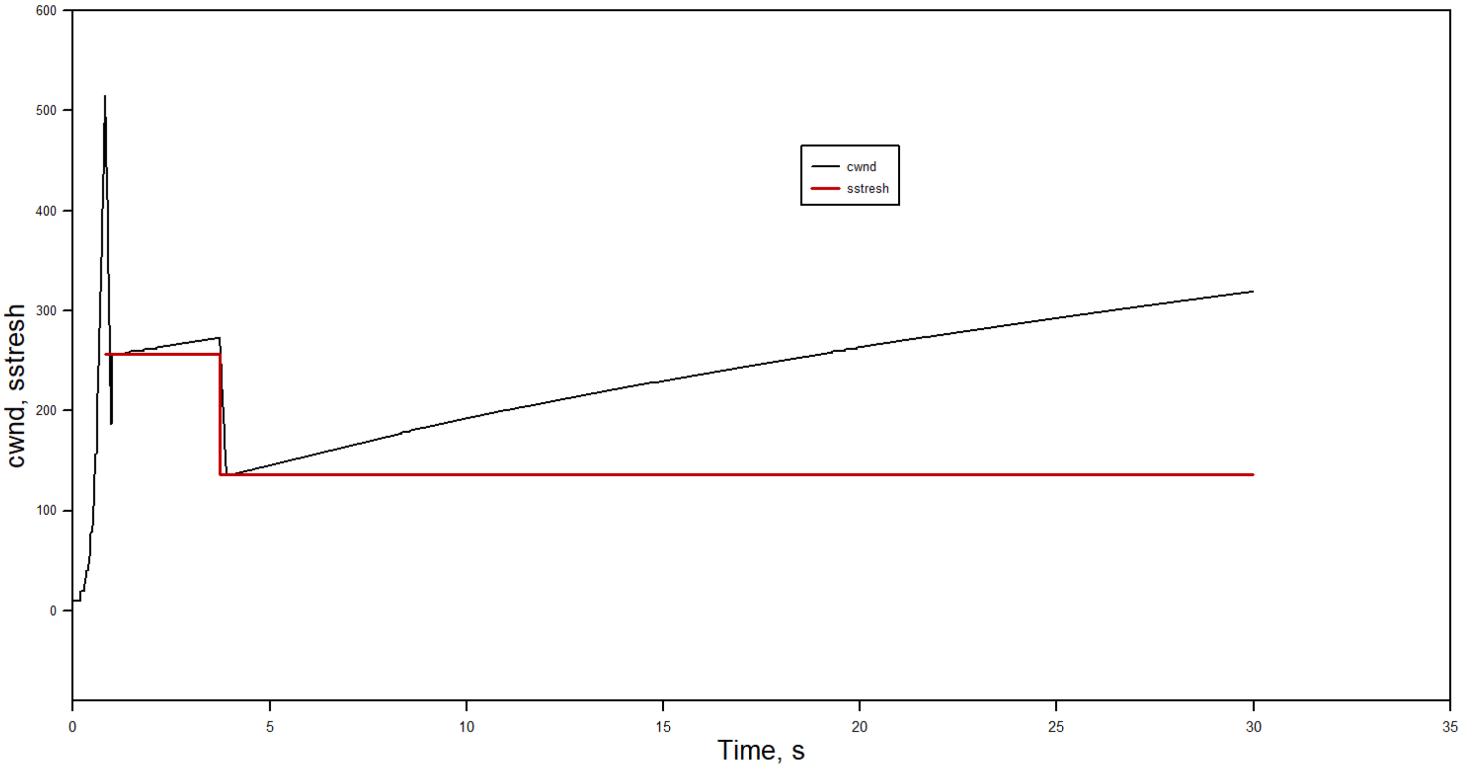
Convergence (1 stream)

RENO, RTT 100ms,
20 Mbit/s constant BW



Convergence (1 stream)

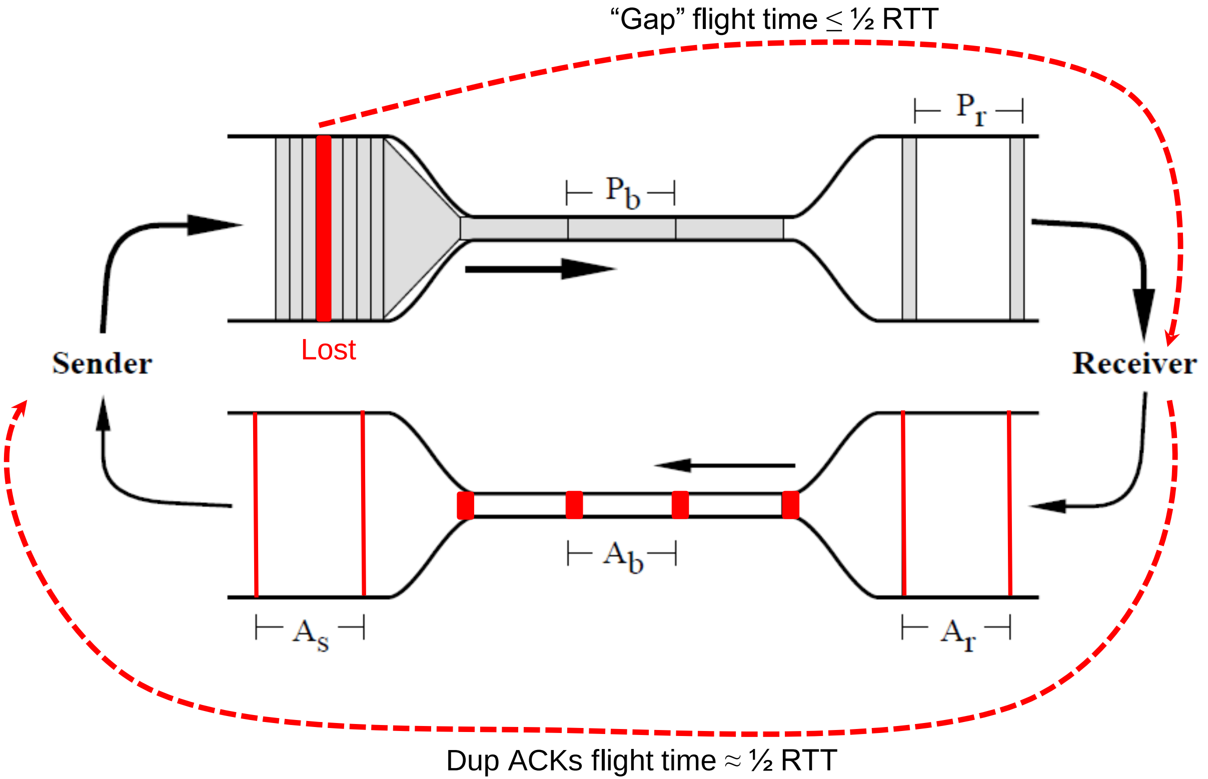
RENO, RTT 100ms,
20 Mbit/s constant BW



Complex challenges - 1

“Late news!”

- The sender will know about “data leaving network rate” not instantly, but only after ½ RTT.
- With packet drop at the beginning of a path – it’s getting worse.
- All this time the sender was sending more and more packets! Probably already starting to slide down the cliff.
- It is getting worse when RTT increases.



Complex challenges - 2

Non-TCP-compatible flows, unresponsive flows ("fairness" and " TCP friendliness").

- ✓ Non-TCP-compatible is a flow which reacts to congestion indicators differently, not like TCP.
- ✓ Unresponsive is a flow which does not react to congestion indicators at all.

"Fairness"	"TCP friendliness"
This is how TCP flows with the same CA algorithm share bottleneck BW with each other. A part of it is "RTT fairness".	This is how non-TCP flows or TCP flows with different CA algorithms share bottleneck bandwidth.

2 possible solutions of this problem:

- ✓ TCP friendly rate control [RFC5348] concept – intentional rate limiting. *** a part of many modern CA algorithms.**
- ✓ Call for help ("network assisted congestion control").

TCP friendly rate control

<u>Core idea</u>: create an equation for T (sending rate, packets/RTT) with argument *p* (<u>packet loss coefficient</u>).

$$T=f(p)$$

For standard TCP (Reno) the equation is:

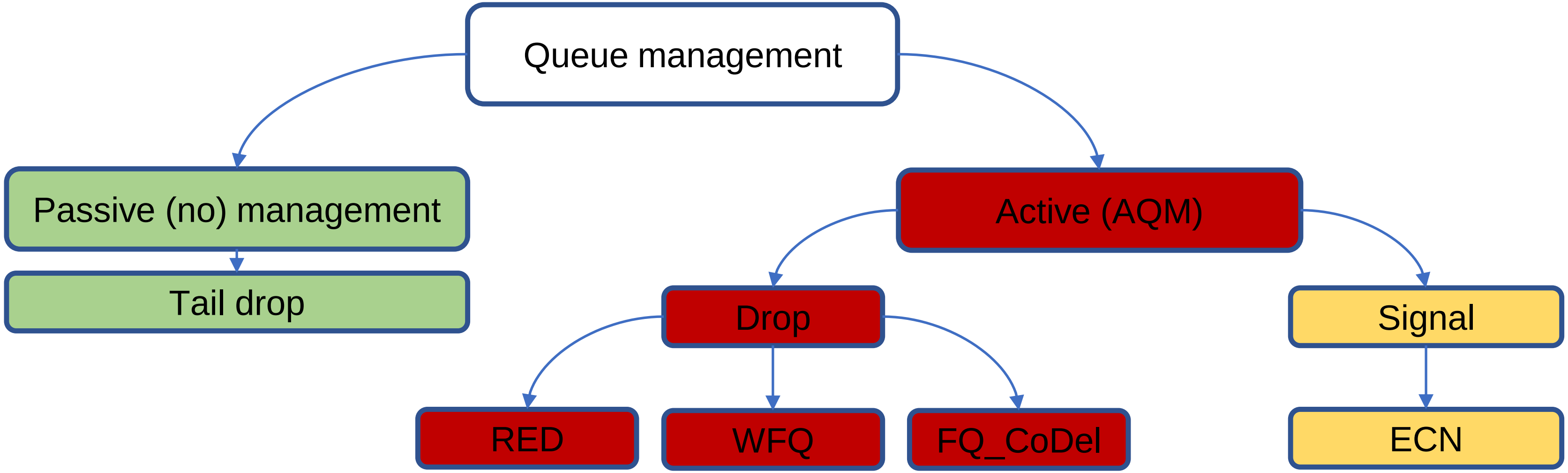
$$T=\frac{1.2}{\sqrt{p}}$$

- ✓ Comparing actual T to “Reno –T” we can analyze *relative fairness* i.e. how aggressive protocol is vs. standard TCP.
- ✓ Equations might be much more complex and take into account RTT, packet size.

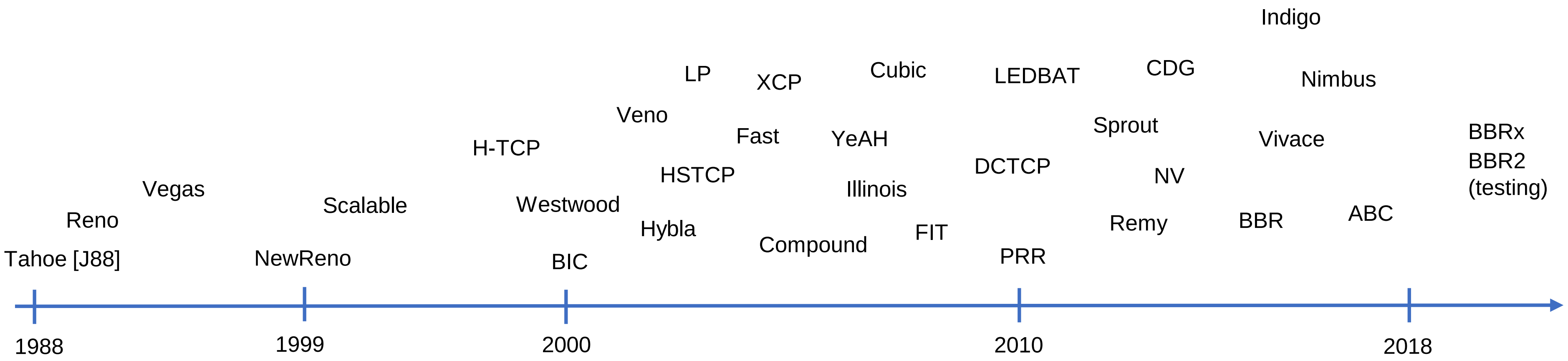
Call for help!

Sometimes this isn't enough so to **ask network for help** is a good idea!

- ✓ Routers know their own state (buffer load, link speed).
- ✓ Router can separate different kinds of flows.



Timeline


Tahoe [J88]
Reno
Vegas
NewReno
Scalable
H-TCP
Westwood
BIC
Veno
Hybla
HSTCP
LP
XCP
Fast
Compound
Cubic
YeAH
Illinois
FIT
LEDBAT
DCTCP
PRR
Sprout
CDG
NV
Remy
Indigo
Nimbus
Vivace
BBR
ABC
BBRx
BBR2
(testing)
1988
1999
2000
2010
2018

Reno (1998)

Core idea:
Tahoe + "Fast Recovery".

What do we address: non-optimal behavior during loss recovery.

Operation:
- Send Fast retransmission and then:
- Set ***sstresh*** to ***cwnd***/2, set ***cwnd*** to ***sstresh***+3.
- Increase ***cwnd*** on 1 SMSS for every received next Dup ACK ("inflate phase").
- Decrease ***cwnd*** to ***sstresh*** after receiving higher ACK ("deflate phase").

Reason: we treat Dup ACKs stream as ***good*** sign (because packets somewhere are leaving our network!) But we are stuck with "unacknowledged" window edge because of packet loss and can't use capacity becoming available. So let's manipulate ***cwnd*** temporarily for this period and bring things back when it ends.

New Reno [RFC3782]

<u>Core idea:</u>

“The Classics”

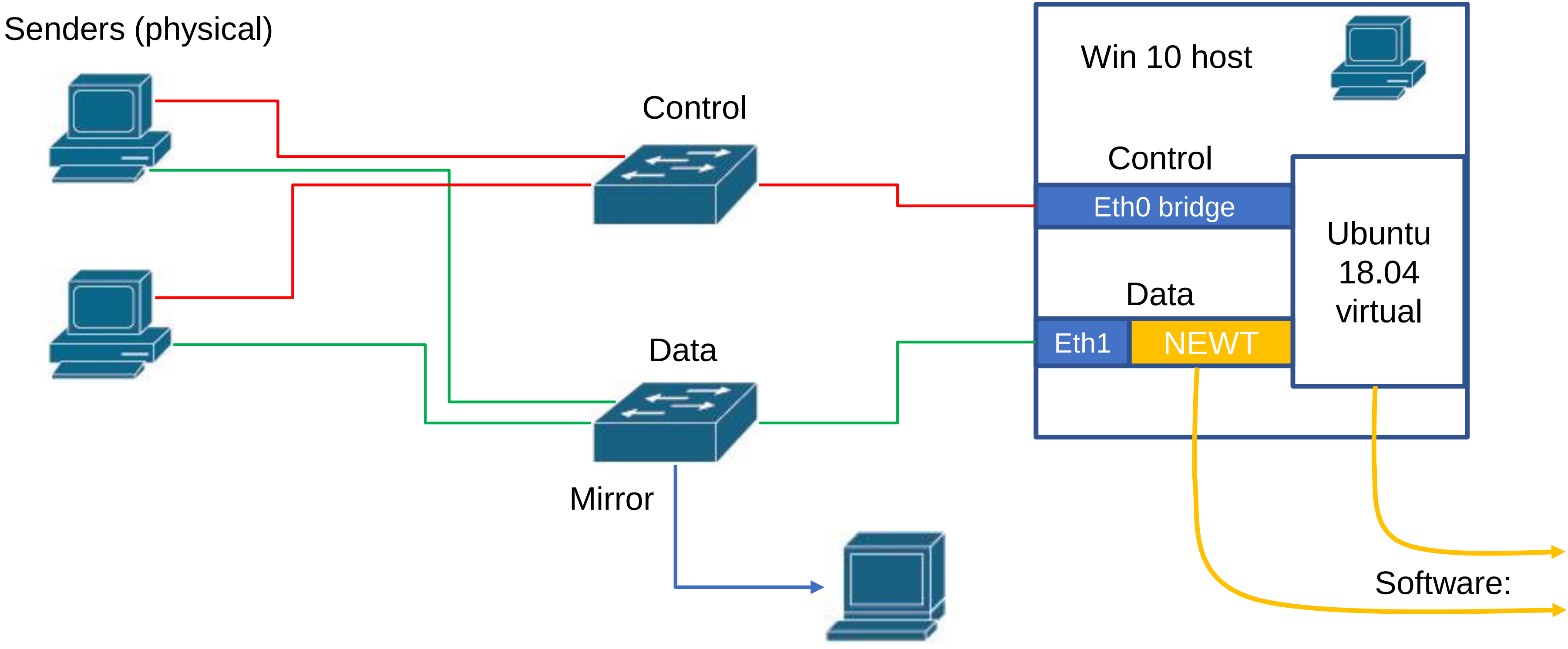
This is the same Reno + improved packet loss handling (**only for multiple segments loss**).

<u>What do we address:</u> loss burst.

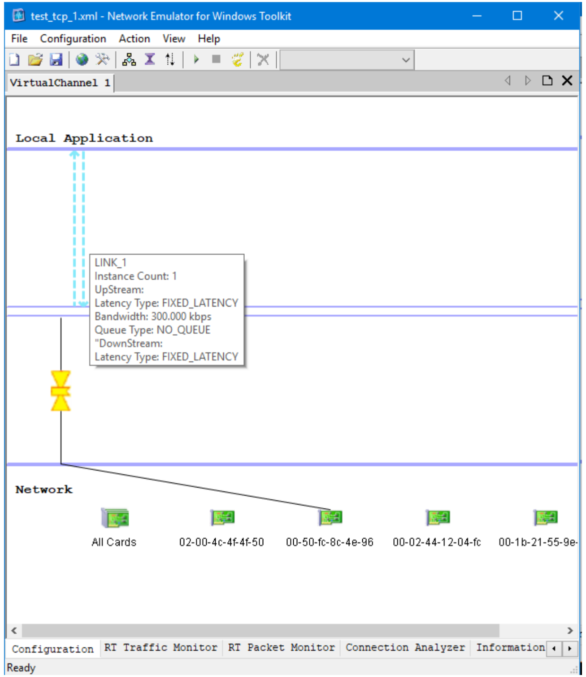
<u>Reason:</u>
If multiple segments were lost, this can mess up our “inflate-deflate” strategy. We’ll deflate ***cwnd*** even if we receive *partial ACK* (higher than the one in Dup ACK stream, but lower than packet we sent last before loss). Therefore we’ll deflate ***cwnd*** too early!

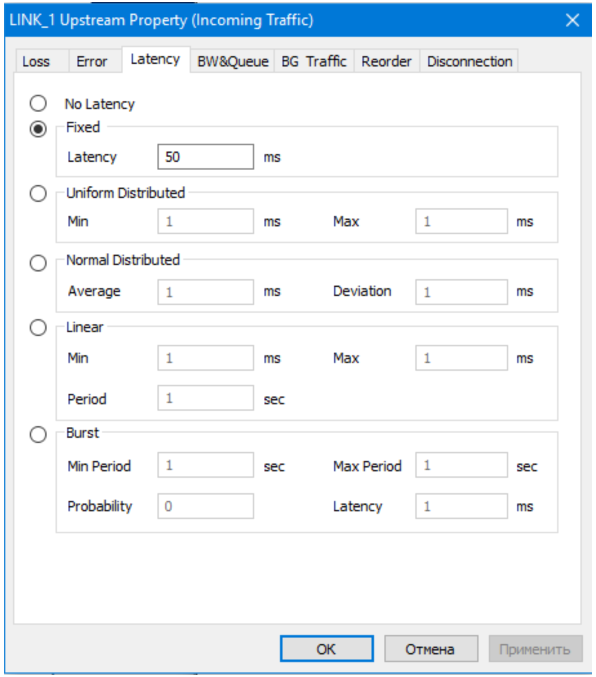
<u>Solution:</u>
- Remember highest SEQ at the moment of packet loss detection (“Recovery point”).
- Do NOT deflate ***cwnd*** unless we receive an ACK for Recovery Point.

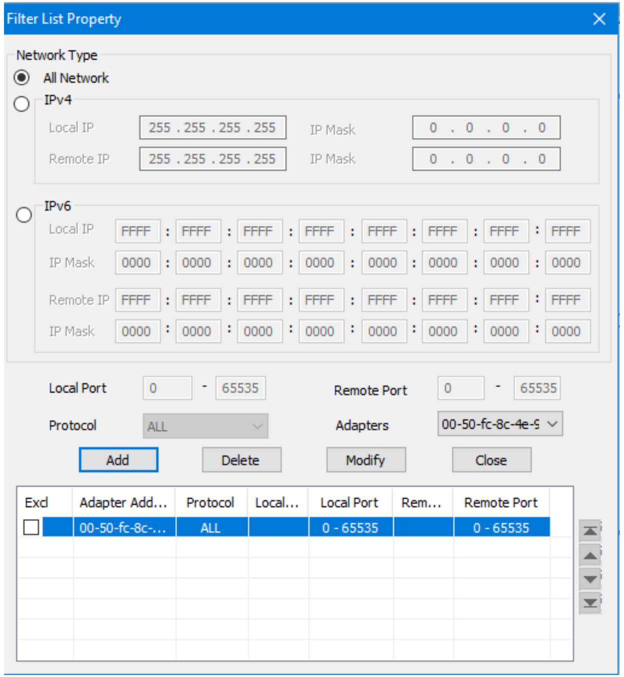
Testbed


Senders (physical)
Control
Data
Mirror
Win 10 host
Control
Eth0 bridge
Data
Eth1
NEWT
Ubuntu
18.04
virtual
Software:

Software 1 - NEWT





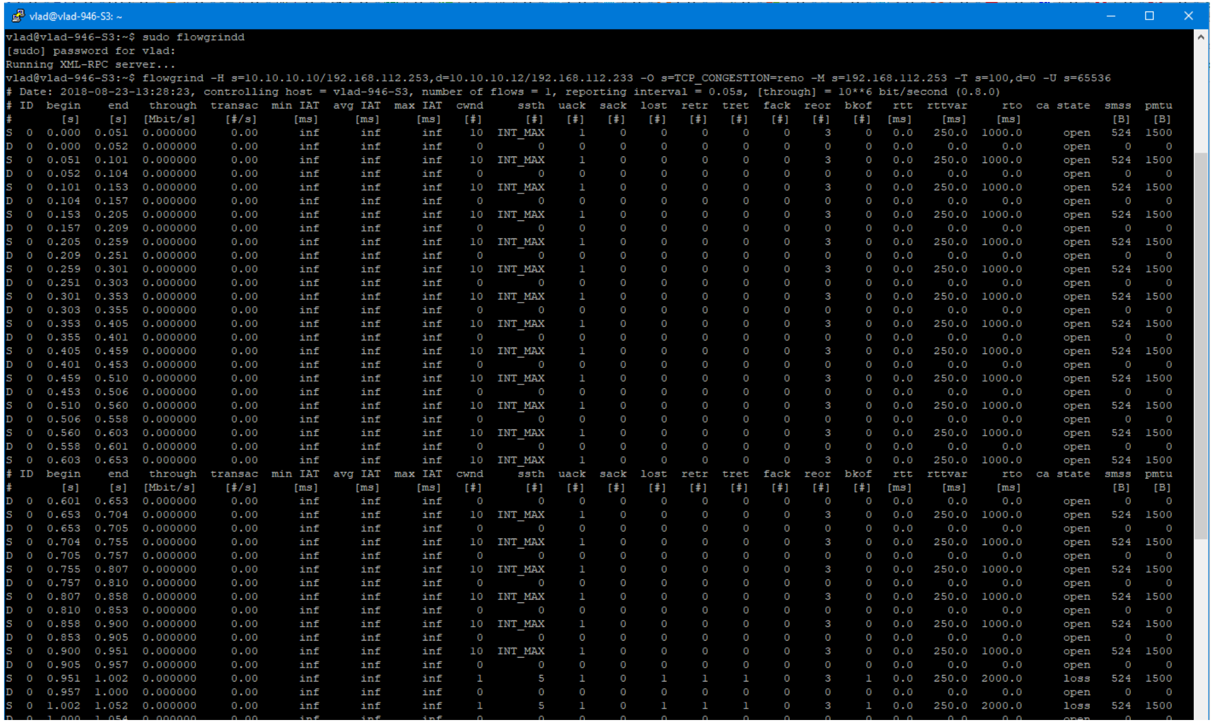


https://blog.mrpol.nl/2010/01/14/network-emulator-toolkit/

Software 2 - flowgrind

- ✓ Allows separation between control and data traffic.
- ✓ Large number of monitored values (including current ***cwnd*** and ***sstresh*** size, yeah!)
- ✓ Various traffic generation patterns.
- ✓ Individual TCP flow parameters setting.
- ✓ An ability to start flow from any PC running flowgrind daemon.
- ✓ Possibility to redirect output table to text file for parsing.

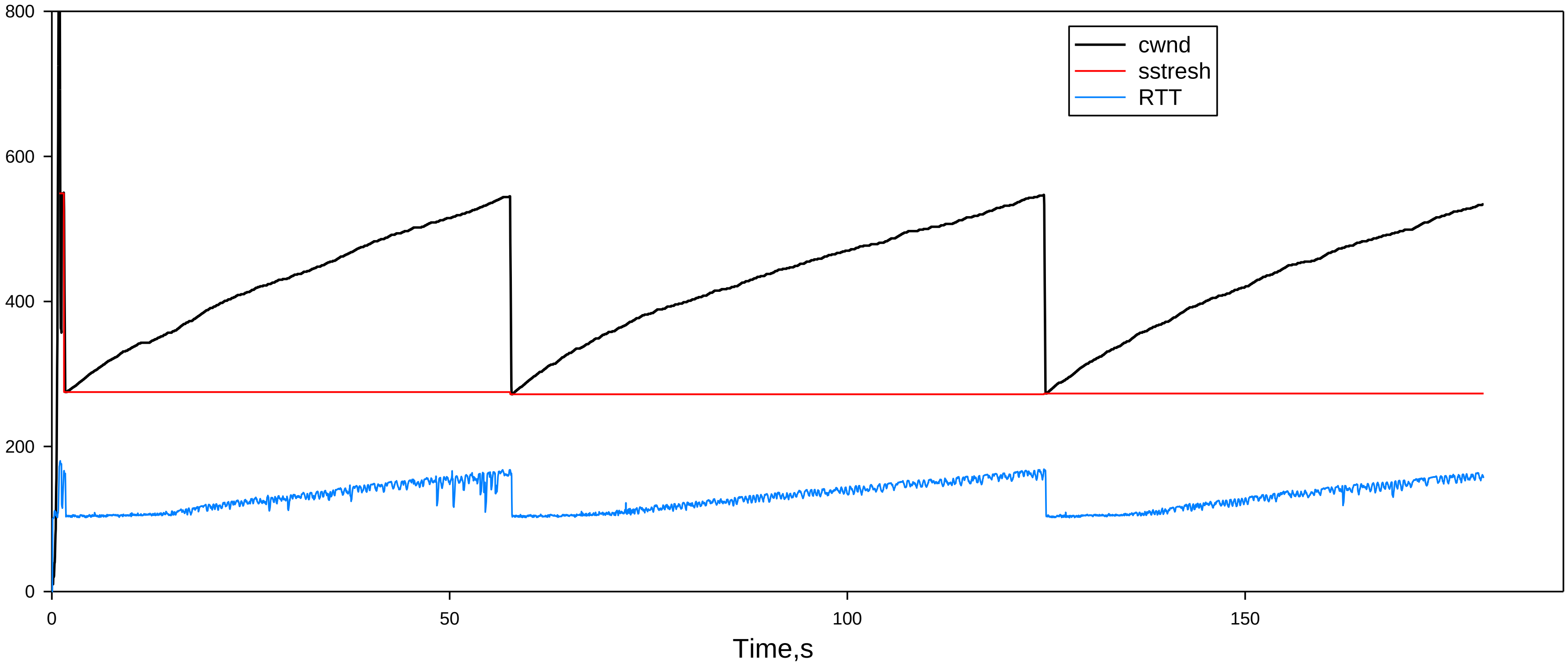
- Sensitive to incorrect arguments (often gets stuck and reboot is needed).
- Problems with NAT'ed endpoints.
- No Windows version = no Compound TCP.



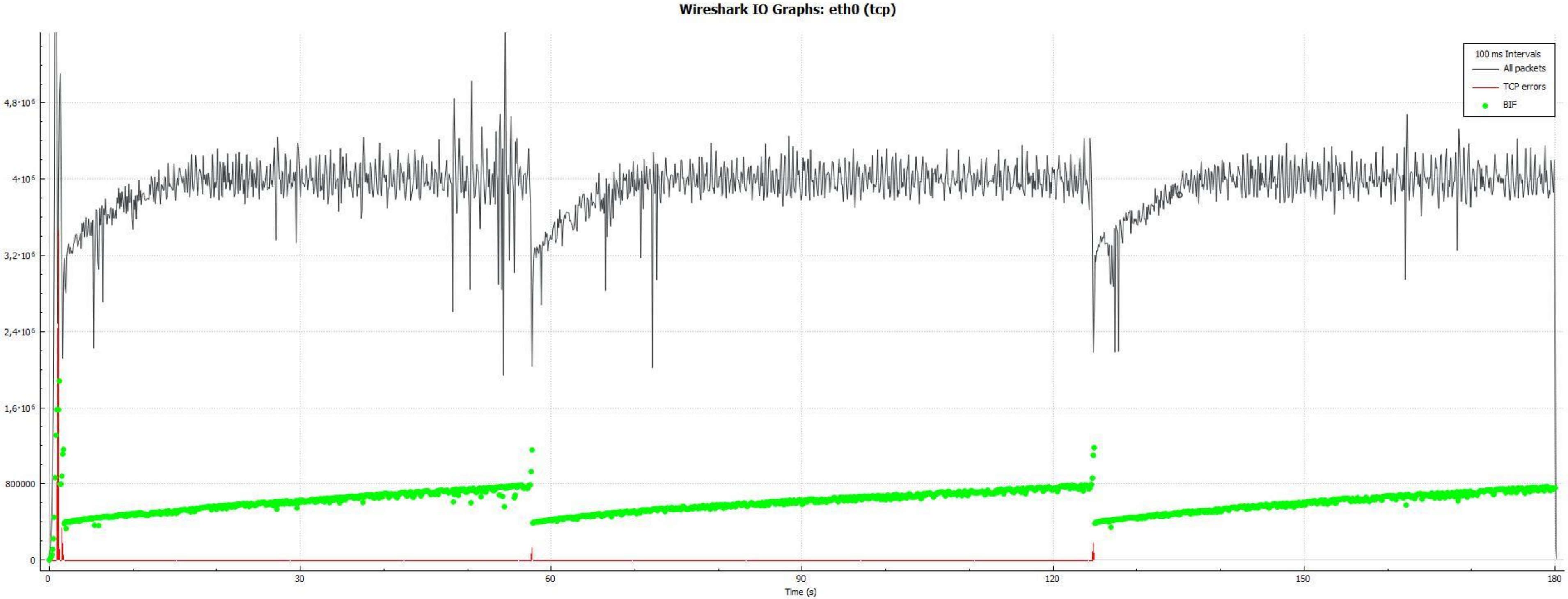
```
vlad@vlad-946-S3: ~
vlad@vlad-946-S3:~$ sudo flowgrindd
[sudo] password for vlad:
Running XML-RPC server...
vlad@vlad-946-S3:~$ flowgrind -H s=10.10.10.10/192.168.112.253,d=10.10.10.12/192.168.112.233 -O s=TCP_CONGESTION=reno -M s=192.168.112.253 -T s=100,d=0 -U s=65536
# Date: 2018-08-23-13:28:23, controlling host = vlad-946-S3, number of flows = 1, reporting interval = 0.05s, [through] = 10**6 bit/second (0.8.0)
# ID begin   end   through  transac min IAT avg IAT max IAT cwnd    ssth uack sack lost retr tret fack reor bkof  rtt rttvar    rto ca state smss pmtu
#        [s]   [s]  [Mbit/s]   [#/s]    [ms]    [ms]    [ms]  [#]     [#]  [#]  [#]  [#]  [#]  [#]  [#]  [#]  [#] [ms]   [ms]   [ms]            [B]  [B]
S  0 0.000 0.051 0.000000     0.00     inf     inf     inf   10 INT_MAX    1    0    0    0    0    0    3    0  0.0  250.0 1000.0     open  524 1500
D  0 0.000 0.052 0.000000     0.00     inf     inf     inf    0       0    0    0    0    0    0    0    0    0  0.0    0.0    0.0     open    0    0
S  0 0.051 0.101 0.000000     0.00     inf     inf     inf   10 INT_MAX    1    0    0    0    0    0    3    0  0.0  250.0 1000.0     open  524 1500
D  0 0.052 0.104 0.000000     0.00     inf     inf     inf    0       0    0    0    0    0    0    0    0    0  0.0    0.0    0.0     open    0    0
S  0 0.101 0.153 0.000000     0.00     inf     inf     inf   10 INT_MAX    1    0    0    0    0    0    3    0  0.0  250.0 1000.0     open  524 1500
D  0 0.104 0.157 0.000000     0.00     inf     inf     inf    0       0    0    0    0    0    0    0    0    0  0.0    0.0    0.0     open    0    0
S  0 0.153 0.205 0.000000     0.00     inf     inf     inf   10 INT_MAX    1    0    0    0    0    0    3    0  0.0  250.0 1000.0     open  524 1500
D  0 0.157 0.209 0.000000     0.00     inf     inf     inf    0       0    0    0    0    0    0    0    0    0  0.0    0.0    0.0     open    0    0
S  0 0.205 0.259 0.000000     0.00     inf     inf     inf   10 INT_MAX    1    0    0    0    0    0    3    0  0.0  250.0 1000.0     open  524 1500
D  0 0.209 0.251 0.000000     0.00     inf     inf     inf    0       0    0    0    0    0    0    0    0    0  0.0    0.0    0.0     open    0    0
S  0 0.259 0.301 0.000000     0.00     inf     inf     inf   10 INT_MAX    1    0    0    0    0    0    3    0  0.0  250.0 1000.0     open  524 1500
D  0 0.251 0.303 0.000000     0.00     inf     inf     inf    0       0    0    0    0    0    0    0    0    0  0.0    0.0    0.0     open    0    0
S  0 0.301 0.353 0.000000     0.00     inf     inf     inf   10 INT_MAX    1    0    0    0    0    0    3    0  0.0  250.0 1000.0     open  524 1500
D  0 0.303 0.355 0.000000     0.00     inf     inf     inf    0       0    0    0    0    0    0    0    0    0  0.0    0.0    0.0     open    0    0
S  0 0.353 0.405 0.000000     0.00     inf     inf     inf   10 INT_MAX    1    0    0    0    0    0    3    0  0.0  250.0 1000.0     open  524 1500
D  0 0.355 0.401 0.000000     0.00     inf     inf     inf    0       0    0    0    0    0    0    0    0    0  0.0    0.0    0.0     open    0    0
S  0 0.405 0.459 0.000000     0.00     inf     inf     inf   10 INT_MAX    1    0    0    0    0    0    3    0  0.0  250.0 1000.0     open  524 1500
D  0 0.401 0.453 0.000000     0.00     inf     inf     inf    0       0    0    0    0    0    0    0    0    0  0.0    0.0    0.0     open    0    0
S  0 0.459 0.510 0.000000     0.00     inf     inf     inf   10 INT_MAX    1    0    0    0    0    0    3    0  0.0  250.0 1000.0     open  524 1500
D  0 0.453 0.506 0.000000     0.00     inf     inf     inf    0       0    0    0    0    0    0    0    0    0  0.0    0.0    0.0     open    0    0
S  0 0.510 0.560 0.000000     0.00     inf     inf     inf   10 INT_MAX    1    0    0    0    0    0    3    0  0.0  250.0 1000.0     open  524 1500
D  0 0.506 0.558 0.000000     0.00     inf     inf     inf    0       0    0    0    0    0    0    0    0    0  0.0    0.0    0.0     open    0    0
S  0 0.560 0.603 0.000000     0.00     inf     inf     inf   10 INT_MAX    1    0    0    0    0    0    3    0  0.0  250.0 1000.0     open  524 1500
D  0 0.558 0.601 0.000000     0.00     inf     inf     inf    0       0    0    0    0    0    0    0    0    0  0.0    0.0    0.0     open    0    0
S  0 0.603 0.653 0.000000     0.00     inf     inf     inf   10 INT_MAX    1    0    0    0    0    0    3    0  0.0  250.0 1000.0     open  524 1500
# ID begin   end   through  transac min IAT avg IAT max IAT cwnd    ssth uack sack lost retr tret fack reor bkof  rtt rttvar    rto ca state smss pmtu
#        [s]   [s]  [Mbit/s]   [#/s]    [ms]    [ms]    [ms]  [#]     [#]  [#]  [#]  [#]  [#]  [#]  [#]  [#]  [#] [ms]   [ms]   [ms]            [B]  [B]
D  0 0.601 0.653 0.000000     0.00     inf     inf     inf    0       0    0    0    0    0    0    0    0    0  0.0    0.0    0.0     open    0    0
S  0 0.653 0.704 0.000000     0.00     inf     inf     inf   10 INT_MAX    1    0    0    0    0    0    3    0  0.0  250.0 1000.0     open  524 1500
D  0 0.653 0.705 0.000000     0.00     inf     inf     inf    0       0    0    0    0    0    0    0    0    0  0.0    0.0    0.0     open    0    0
S  0 0.704 0.755 0.000000     0.00     inf     inf     inf   10 INT_MAX    1    0    0    0    0    0    3    0  0.0  250.0 1000.0     open  524 1500
D  0 0.705 0.757 0.000000     0.00     inf     inf     inf    0       0    0    0    0    0    0    0    0    0  0.0    0.0    0.0     open    0    0
S  0 0.755 0.807 0.000000     0.00     inf     inf     inf   10 INT_MAX    1    0    0    0    0    0    3    0  0.0  250.0 1000.0     open  524 1500
D  0 0.757 0.810 0.000000     0.00     inf     inf     inf    0       0    0    0    0    0    0    0    0    0  0.0    0.0    0.0     open    0    0
S  0 0.807 0.858 0.000000     0.00     inf     inf     inf   10 INT_MAX    1    0    0    0    0    0    3    0  0.0  250.0 1000.0     open  524 1500
D  0 0.810 0.853 0.000000     0.00     inf     inf     inf    0       0    0    0    0    0    0    0    0    0  0.0    0.0    0.0     open    0    0
S  0 0.858 0.900 0.000000     0.00     inf     inf     inf   10 INT_MAX    1    0    0    0    0    0    3    0  0.0  250.0 1000.0     open  524 1500
D  0 0.853 0.905 0.000000     0.00     inf     inf     inf    0       0    0    0    0    0    0    0    0    0  0.0    0.0    0.0     open    0    0
S  0 0.900 0.951 0.000000     0.00     inf     inf     inf   10 INT_MAX    1    0    0    0    0    0    3    0  0.0  250.0 1000.0     open  524 1500
D  0 0.905 0.957 0.000000     0.00     inf     inf     inf    0       0    0    0    0    0    0    0    0    0  0.0    0.0    0.0     open    0    0
S  0 0.951 1.002 0.000000     0.00     inf     inf     inf    1       5    1    0    1    1    1    0    3    1  0.0  250.0 2000.0     loss  524 1500
D  0 0.957 1.000 0.000000     0.00     inf     inf     inf    0       0    0    0    0    0    0    0    0    0  0.0    0.0    0.0     open    0    0
S  0 1.002 1.052 0.000000     0.00     inf     inf     inf    1       5    1    0    1    1    1    0    3    1  0.0  250.0 2000.0     loss  524 1500
```

http://manpages.ubuntu.com/manpages/bionic/man1/flowgrind.1.html

NewReno on 40Mbps_100ms link

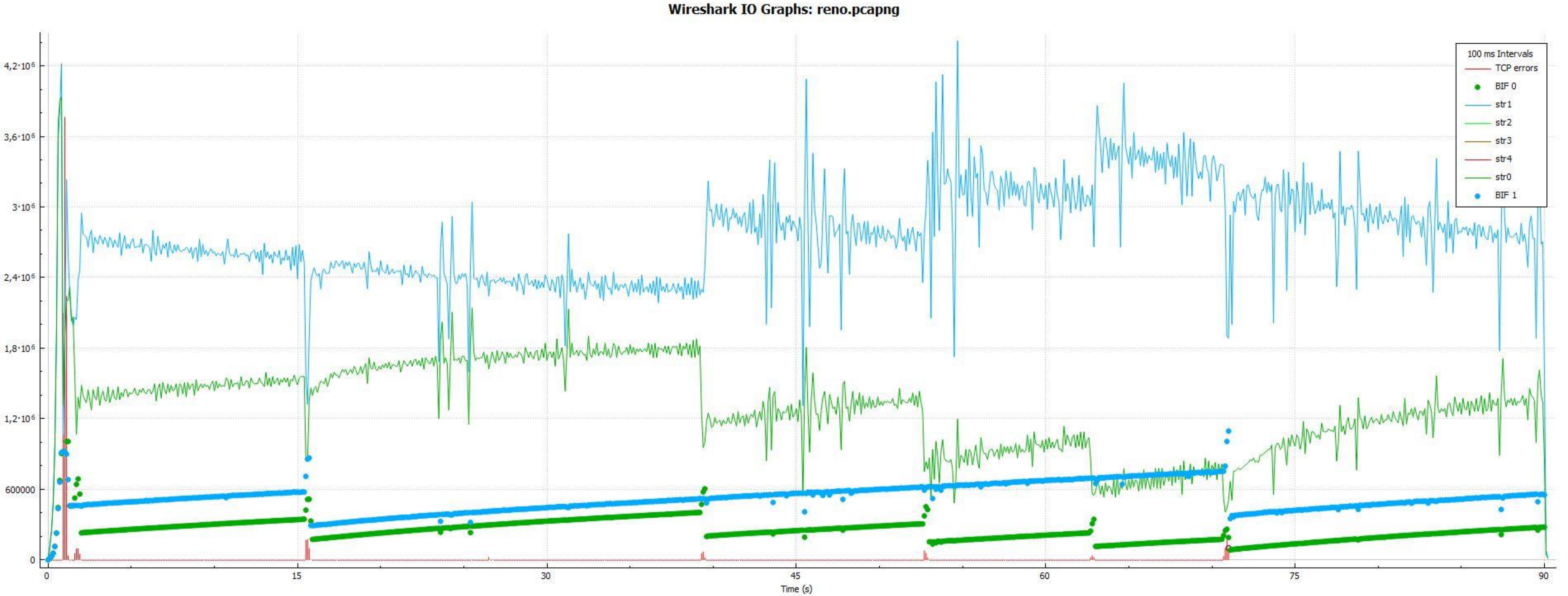


NewReno



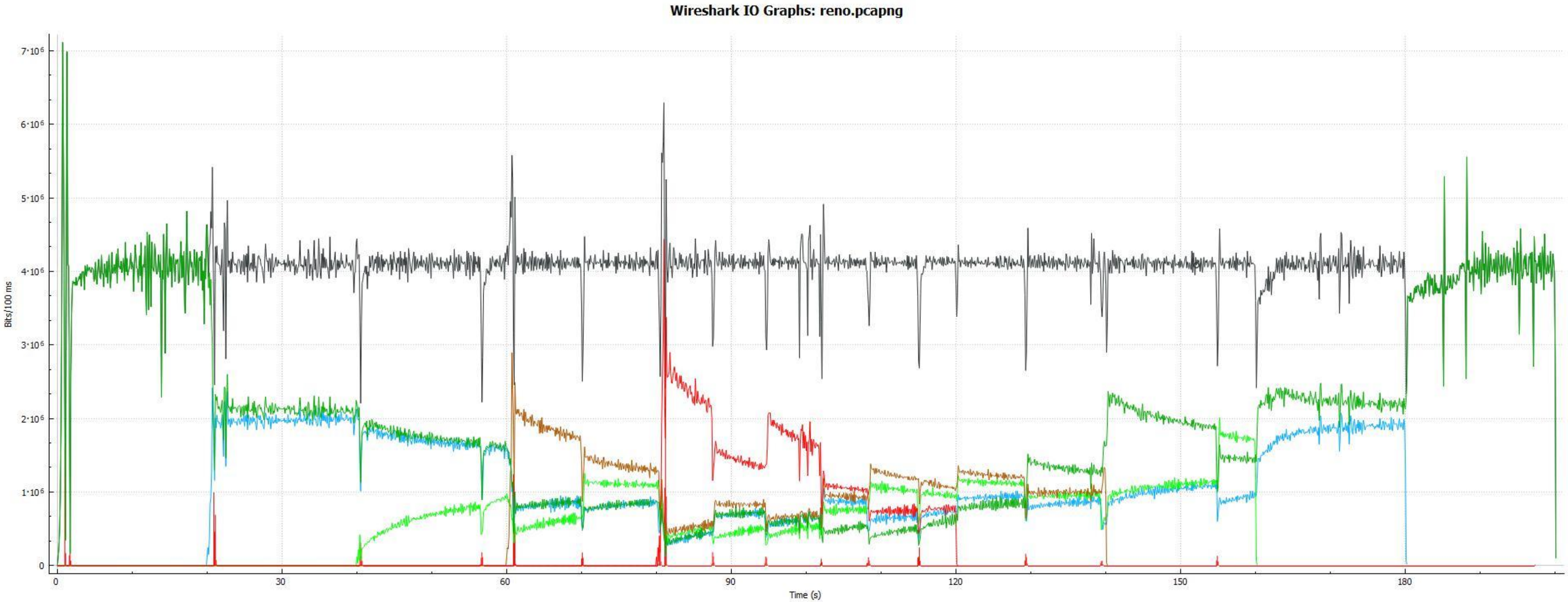
Collateral damage: Almost 3 Buffer overflows / 797k Total Packets

NewReno



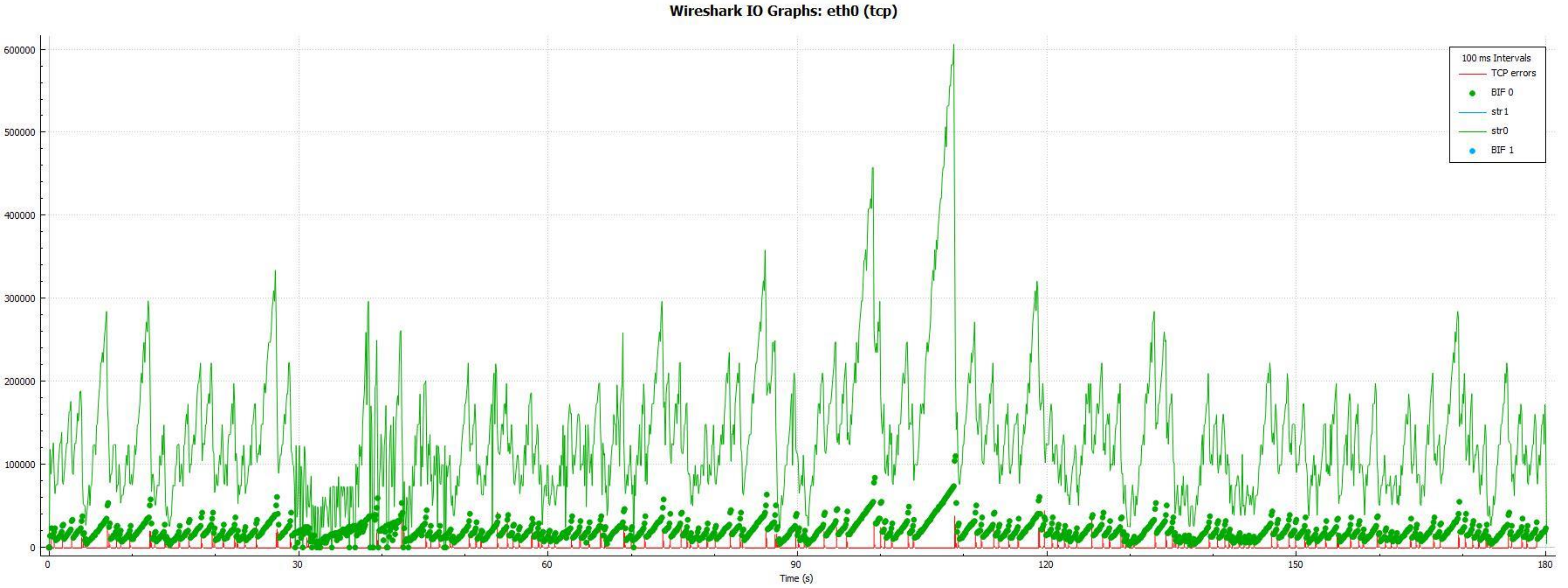
vs. Reno Friendliness

NewReno



5-stream convergence

NewReno



1% loss link behavior

Further progress

Several problems were observed with Reno:

- ✓ NewReno was doing its job fine those days, but later with the raise of LFN and wireless it became clear that…

- × It can't work efficiently on high-BDP links (because ***cwnd*** fixed additive increase algorithm is too slow and ½ ***cwnd*** drop is too much). To utilize fully 1Gbps link with 100ms RTT it needs packet loss rate of $2x10^{-8}$ or less. With 1% loss in this link it can't go faster than 3Mbps. After packet loss event it needs 4000 RTT cycles to recover.

- × It treats any packet loss as congestion indicator (not good for wireless networks).

- × Often visits "cliff" area doing damage (this is common among all loss-based algorithms).

- × Has 1-Bit congestion indicator → inevitable high oscillation level (this is common among all loss-based algorithms).

Further progress

How to make CC algorithm perform better? What to play with?
Remember feedback type and control? Let’s play with them!

Feedback type:

- Packet loss
- Delay
- Both of them
- ACKs inter-arrival timing
- ACKing rate
- Explicit signals (ECN)

CA – feedback types

Packet Loss

- (New)Reno
- Tahoe
- BIC
- CUBIC
- Scalable
- HSTCP

Delay

- Vegas
- Fast TCP
- CDG
- Hybla
- LP

Packet Loss + Delay

- Compound
- H-TCP
- Veno
- Westwood
- Illinois
- Yeah TCP

Explicit signals

- CLTCP
- XCP
- DCQCN
- DCTCP
- D^{3}TCP

CA – control (action) tweaking

What about control?

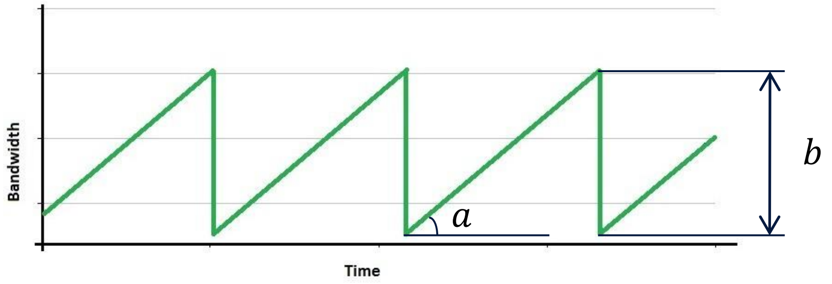
Step 1. Playing with AIMD factors (“knobs turning”)

We can play with a factor

$$cwnd = \begin{cases} cwnd + a & if\ congestion\ is\ not\ detected \\ cwnd\ * b & if\ congestion\ is\ detected \end{cases}$$

We can play with b factor

Therefore changing angle and “drop height”.



Step 2. Adding more variables

Not constant a, but a=f(something)
Same with b.

Step 3. Shifting from AIMD to entirely different model

(The most recent approach).

Scalable TCP – first "high BDP" try

Core ideas: **"Psycho"** [Source]

1. Aimed to deal with high BDP (first and simplest attempt to do it).
2. Uses packet loss as feedback (loss-based).
3. Uses MIMD approach as action profile (!).

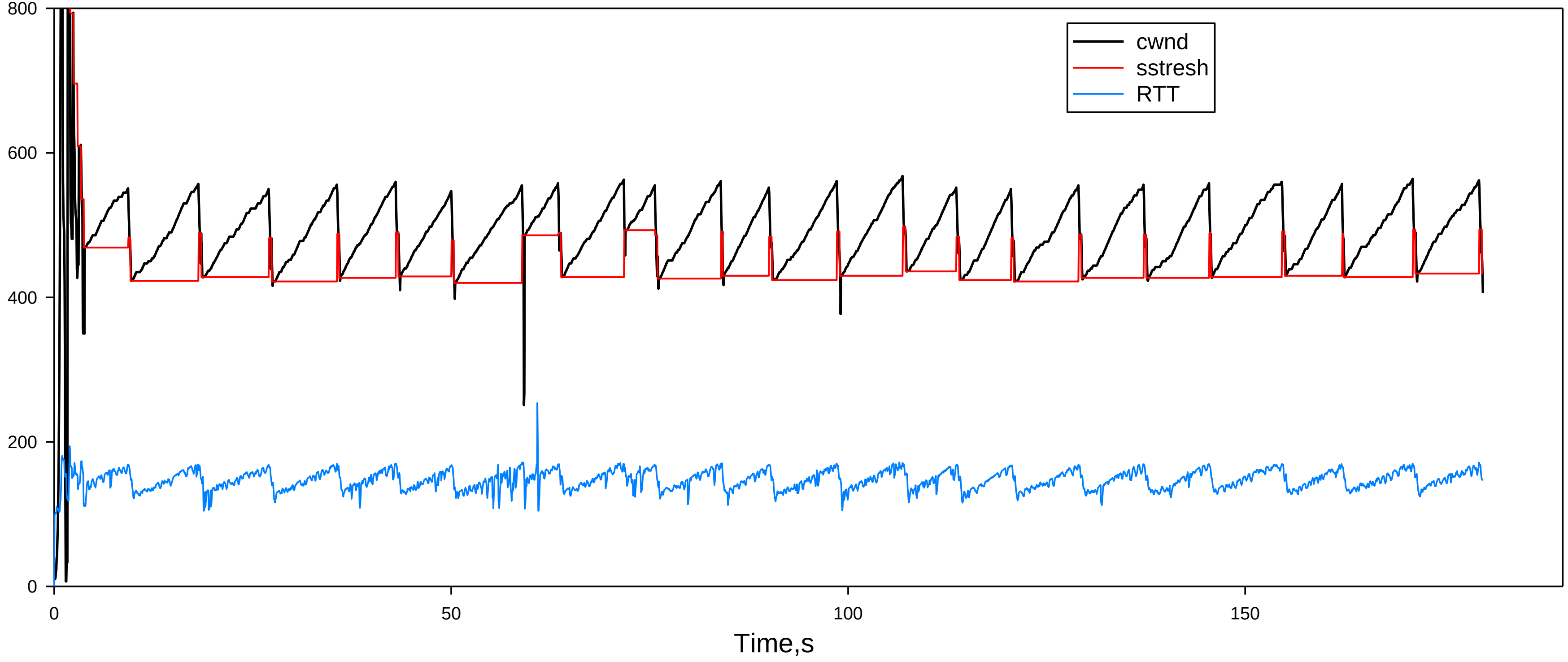
"Scalable" means "**better scalability**"

***cwnd* control rules:**

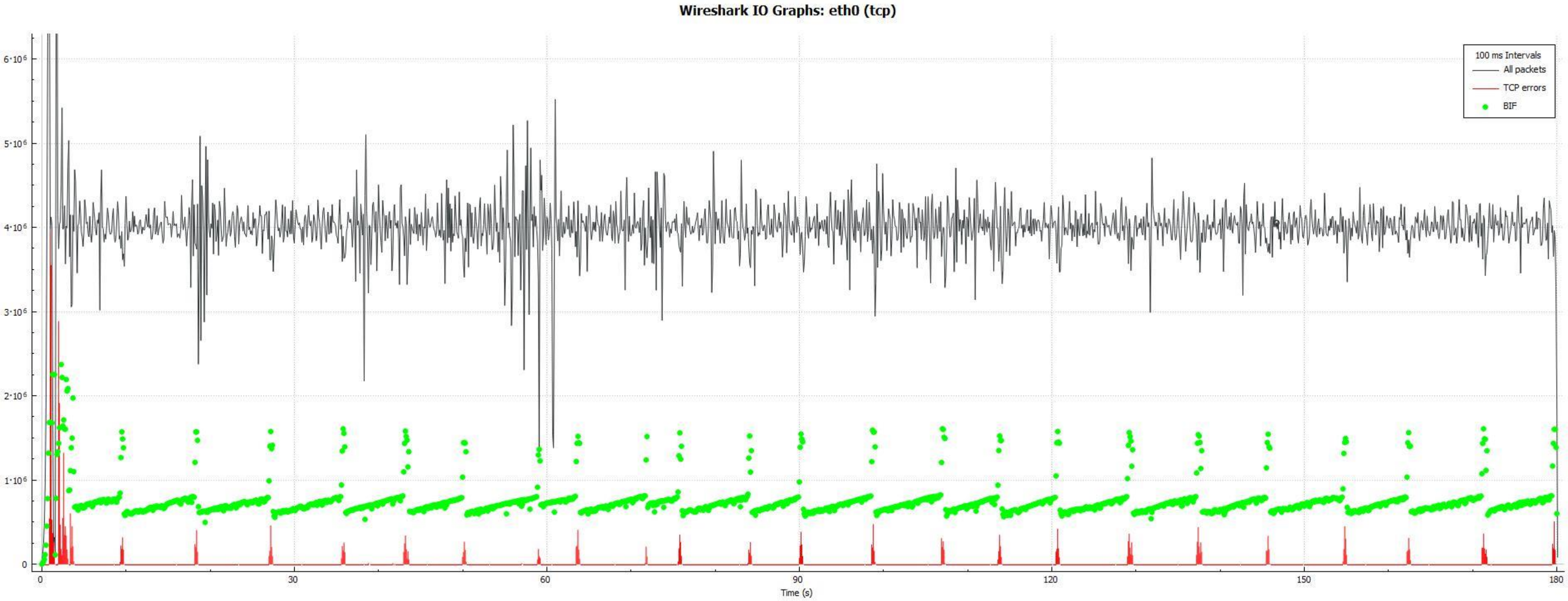
$$cwnd = \begin{cases} cwnd + 0.01 * cwnd & if\ congestion\ is\ not\ detected \\ cwnd * 0{,}875 & if\ congestion\ is\ detected \end{cases}$$

- ✓ Much more efficient than Reno in high BDP networks.
- ✓ Recovery time after packet loss (200ms RTT, 10Gbps link) – 2,7 sec.
- × RTT fairness, TCP friendliness – terrible. Kills Reno easily.

Scalable TCP

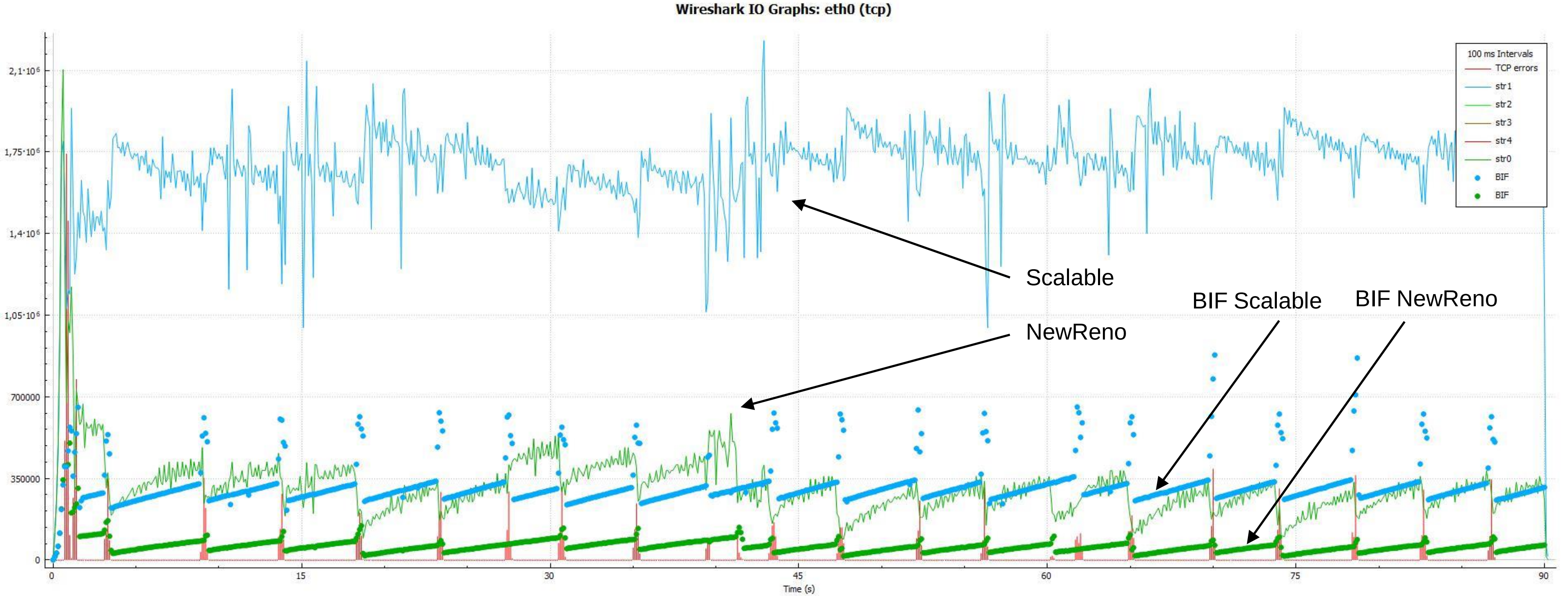


Scalable TCP



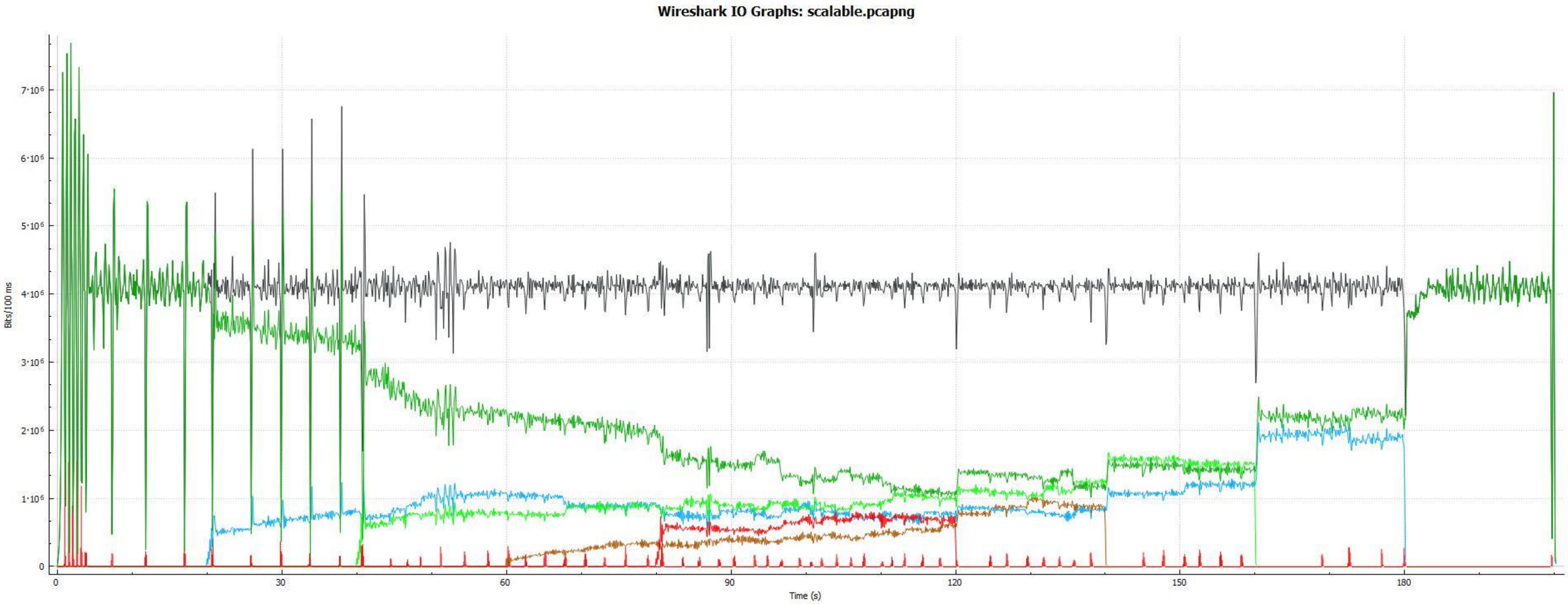
Collateral damage: 23 Buffer overflows / 812k Total Packets

Scalable vs NewReno



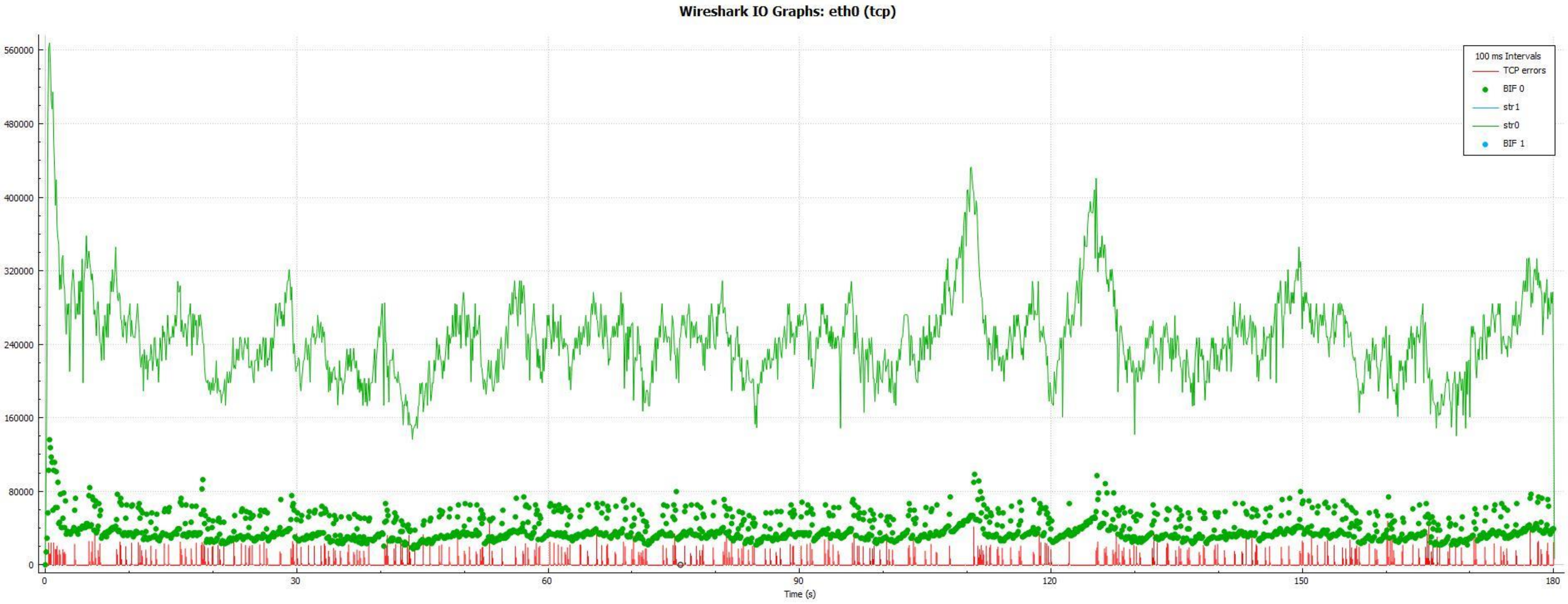
It's unfair to say the least. 20Mbps, 100ms link.

Scalable



5-stream convergence

Scalable



1% loss link behavior

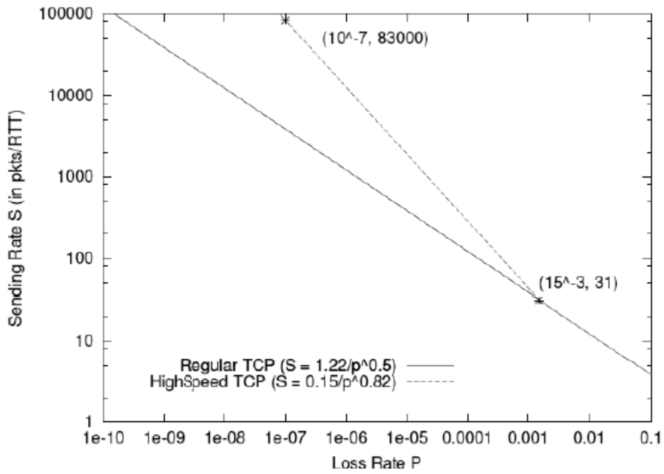
Highspeed TCP [RFC 3649]

Core ideas:

"Medicated psycho"

Source

1. Aimed to deal with high BDP.
2. Uses packet loss as feedback (loss-based).
3. Uses AIMD approach as action profile.
4. "Let's live with Reno on low-BDP, but take what it can't take on high-BDP"



***cwnd* control rules:**

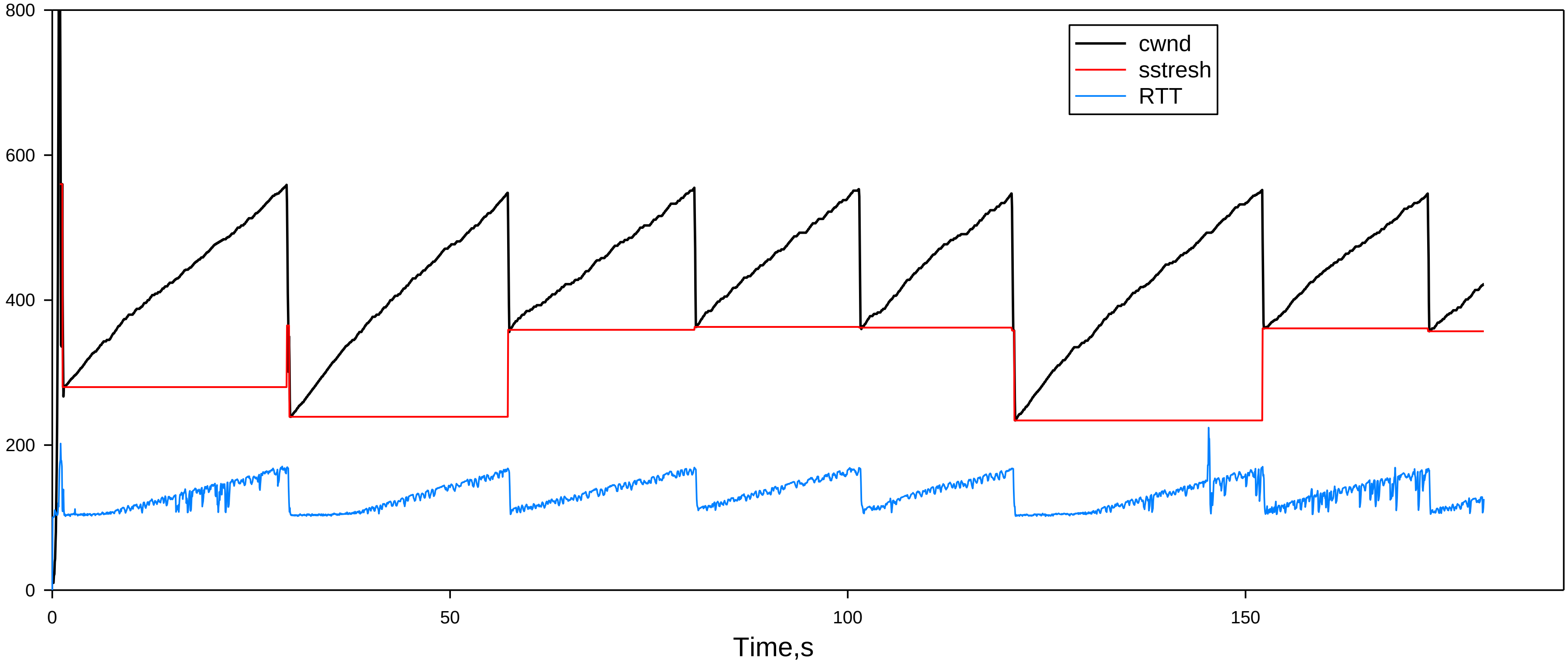
$$cwnd = \begin{cases} cwnd + a(cwnd)/cwnd & \text{if congestion is not detected} \\ cwnd - b(cwnd) * cwnd & \text{if congestion is detected} \end{cases}$$

Formula: $\mathbf{a}(w) = 2P_0 W_0^2\, \mathbf{b}(w)/(2 - \mathbf{b}(w))$

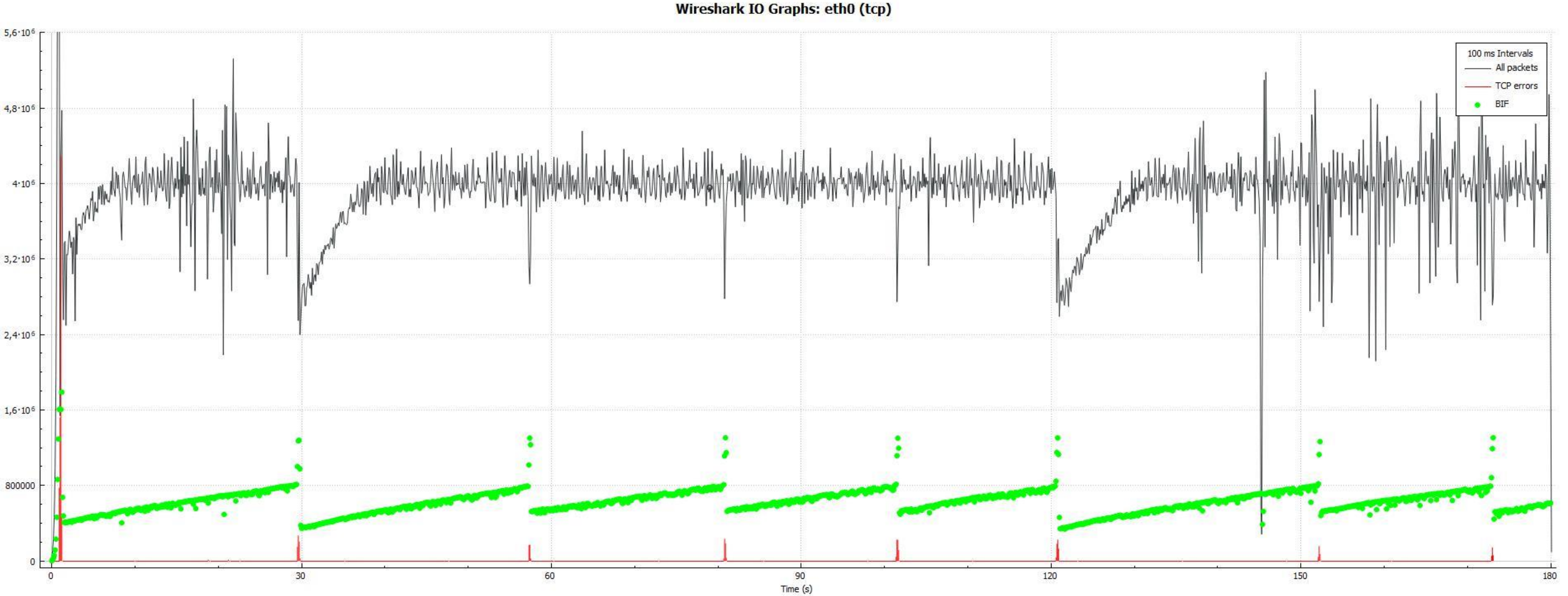
Main point is: a, b values depend on current ***cwnd*** size. If ***cwnd*** is less than 38*SMSS -> act as Reno (more bits in input!)

- Behaves less aggressive if a path is not LFN (for TCP friendliness).
- × RTT fairness - still bad.

Highspeed TCP

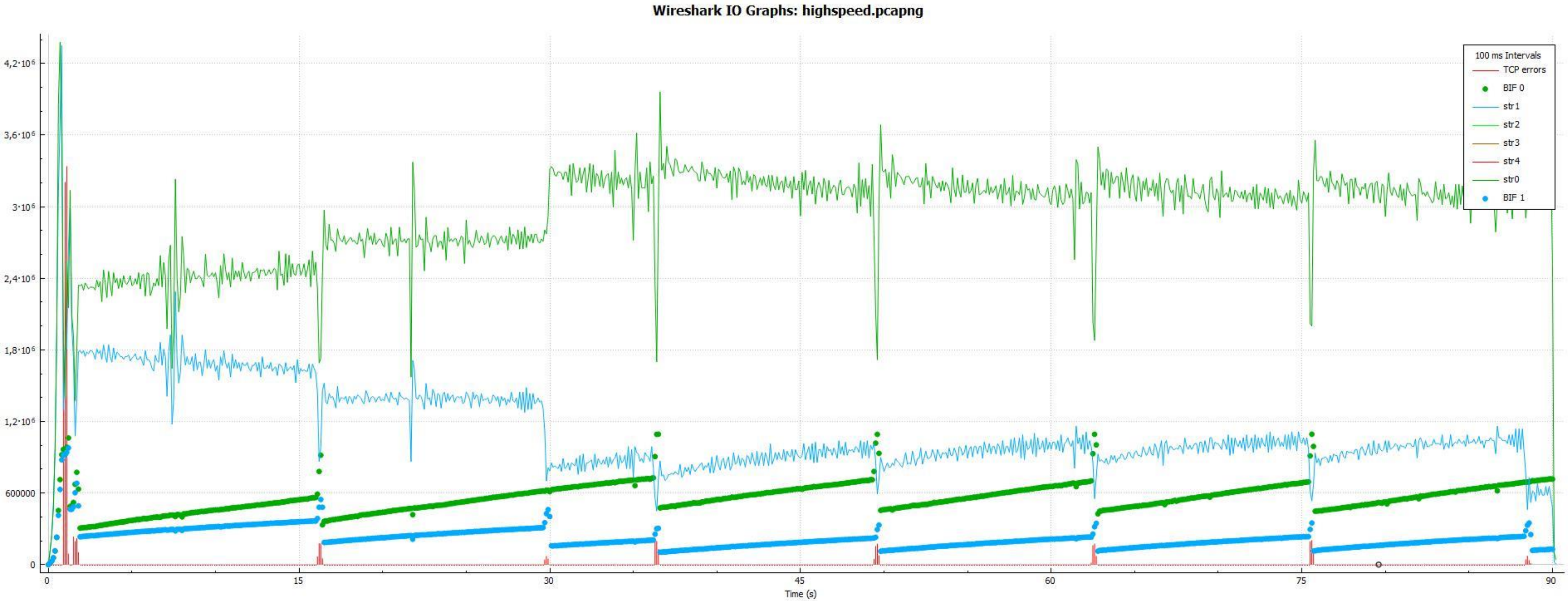


Highspeed TCP



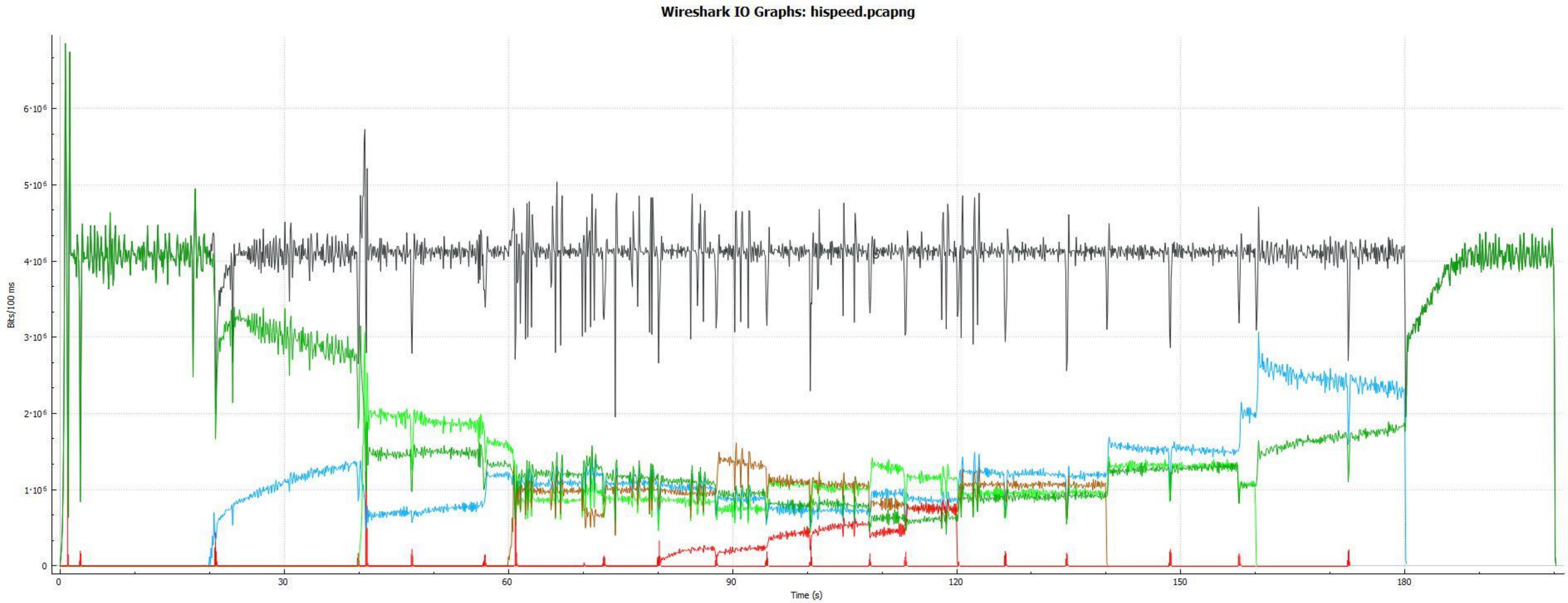
Collateral damage: 7 Buffer overflows / 790k Total Packets

Highspeed TCP



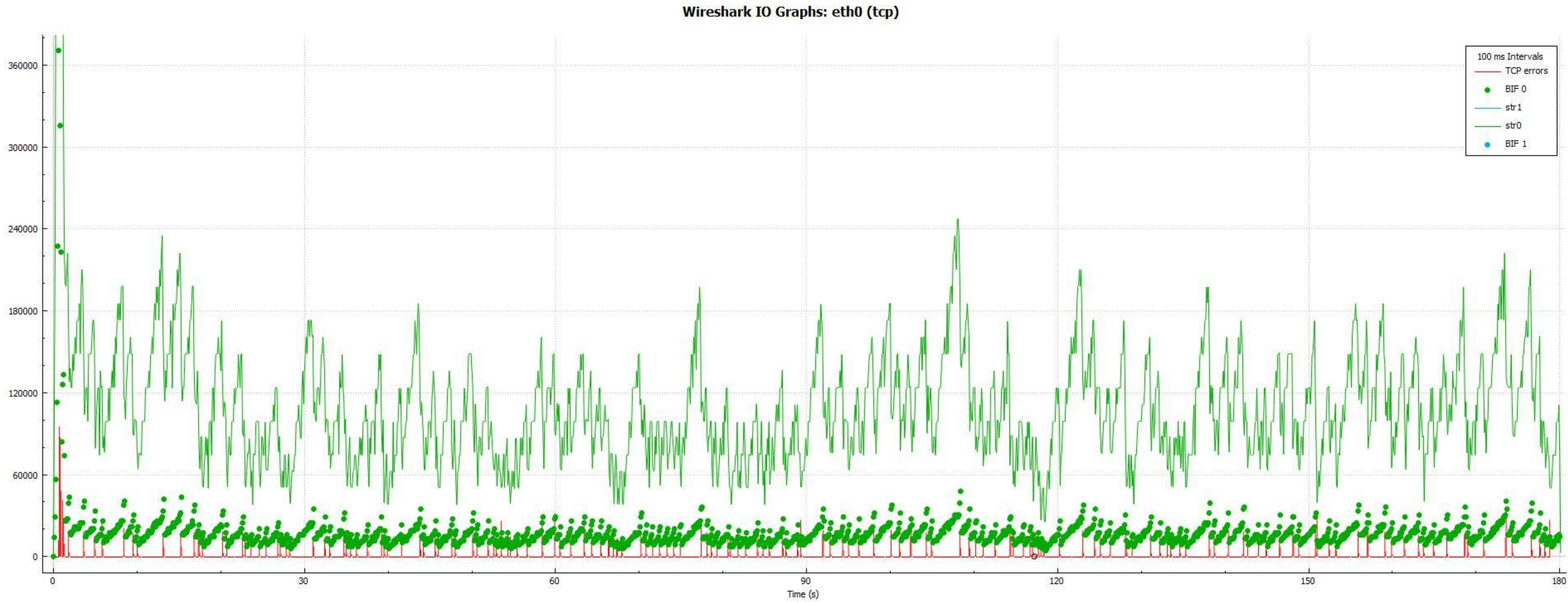
vs. Reno Friendliness

Highspeed TCP



5-stream convergence

Highspeed TCP



1% loss link behavior

CUBIC TCP

Core ideas:

"Ready-Steady-Go!"

Source

1. Aimed to deal with high BDP.
2. Uses packet loss as feedback.
3. Uses cubic function as action profile (concave/convex parts).
4. Default for all Linux kernels > 2.6.18, implemented in Windows since Win10.

***cwnd* control rules:**

In case of packet loss:

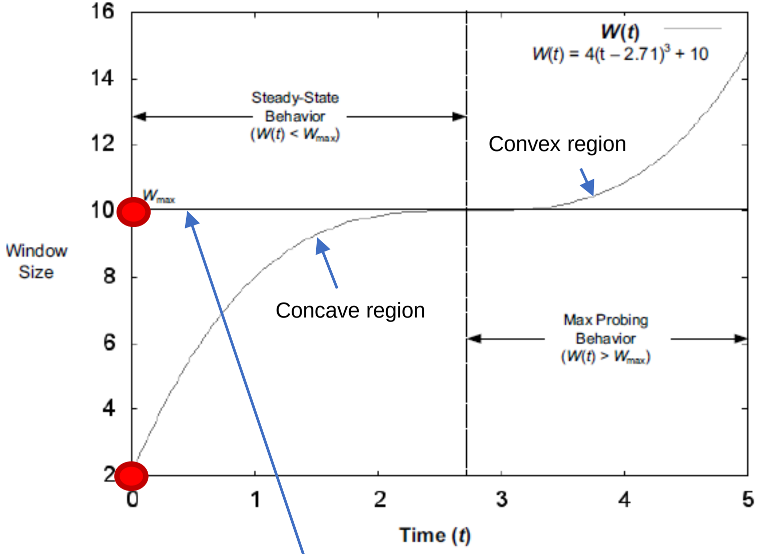
1. Set W_{max} to ***cwnd***;
2. Set ***cwnd, sstresh*** to *(1 - β)*cwnd* where default *β=0.8*
3. Grow ***cwnd*** using cubic function:

$$W(t) = C(t - K)^3 + W_{max} \qquad \text{where:} \qquad K = \sqrt[3]{\frac{\beta W_{max}}{C}}$$

Main point: approach last packet loss point slowly and carefully, but if there is no more packet loss here – begin ramp up to use possibly freed up resources.

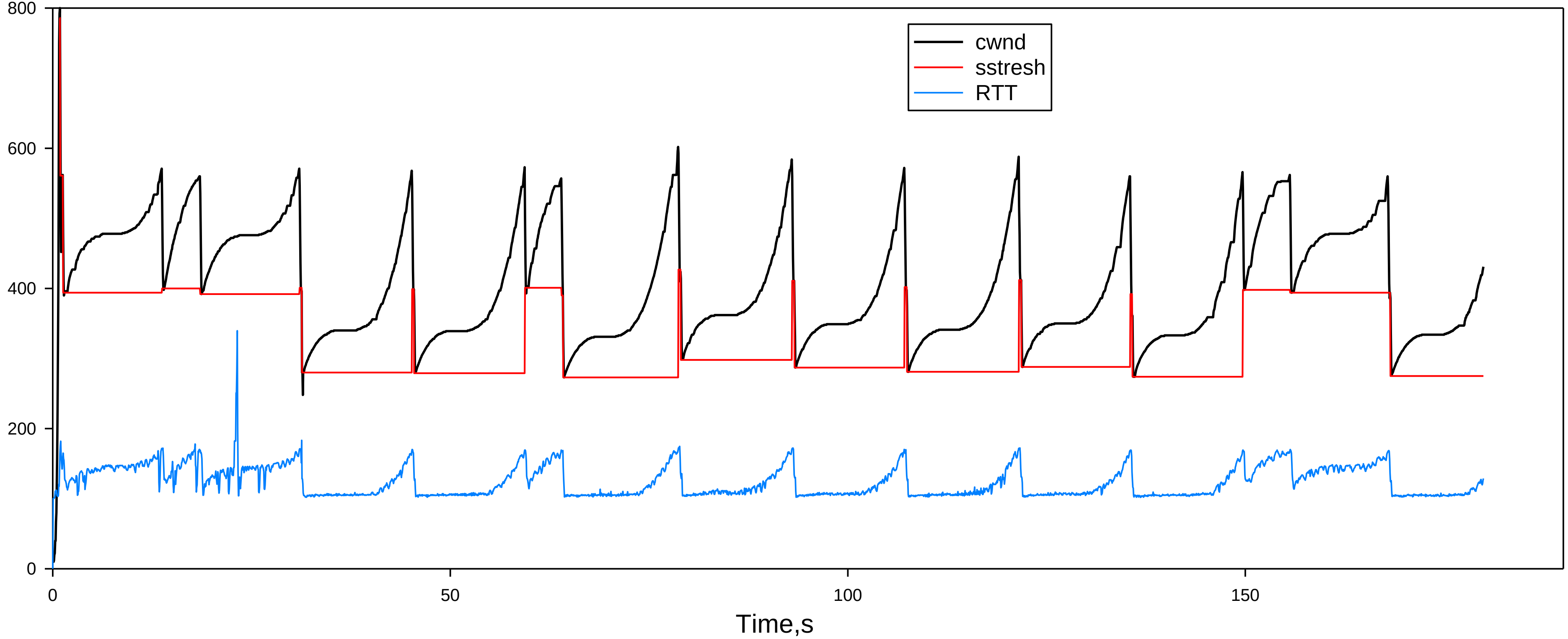
Additional techniques used: TCP friendly region, Fast convergence, Hybrid slow start.

- ✓ Coexistence with Reno on non-LFN links – moderate
- ✓ RTT fairness - good

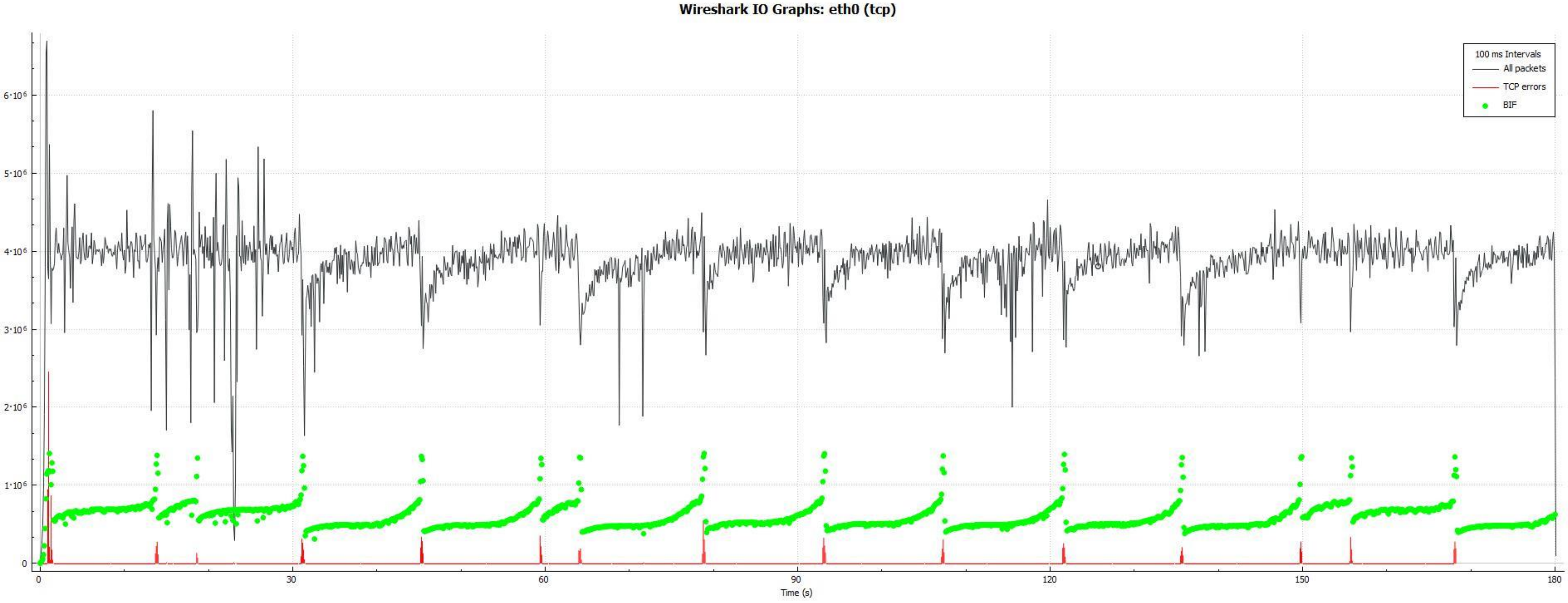


Last remembered value where packet loss happened

CUBIC TCP

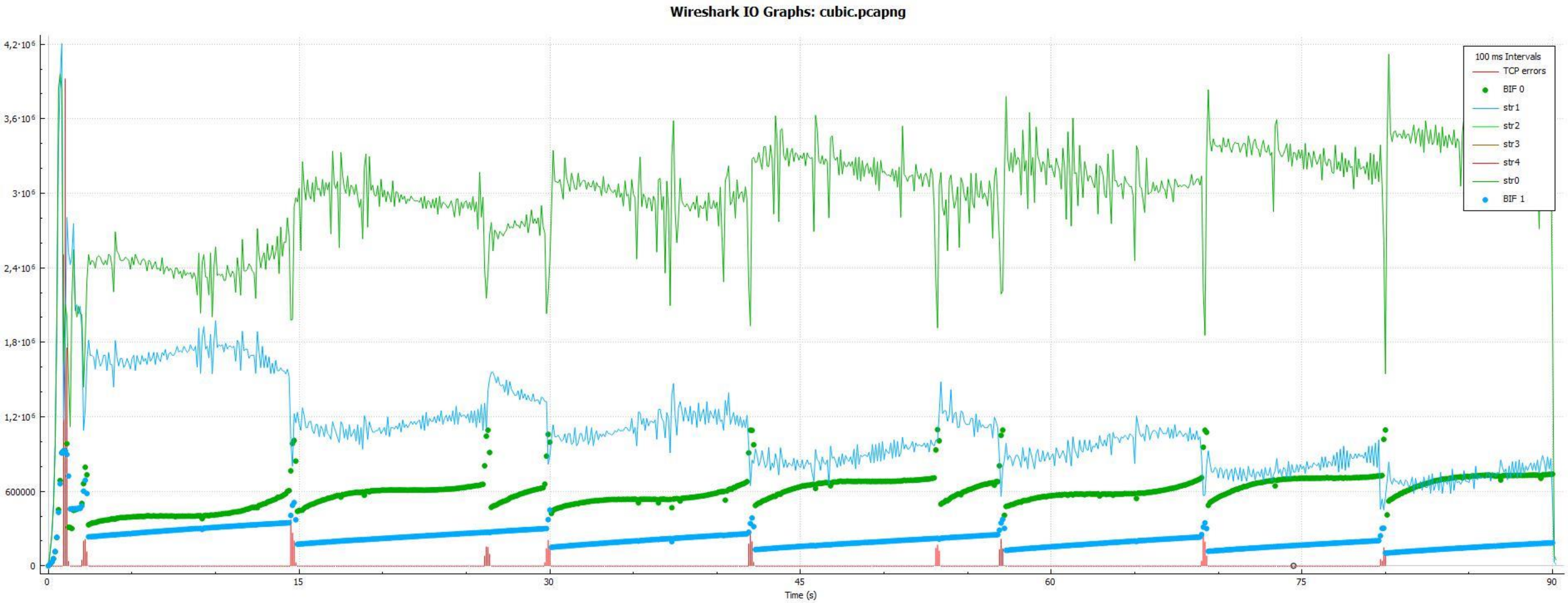


CUBIC TCP



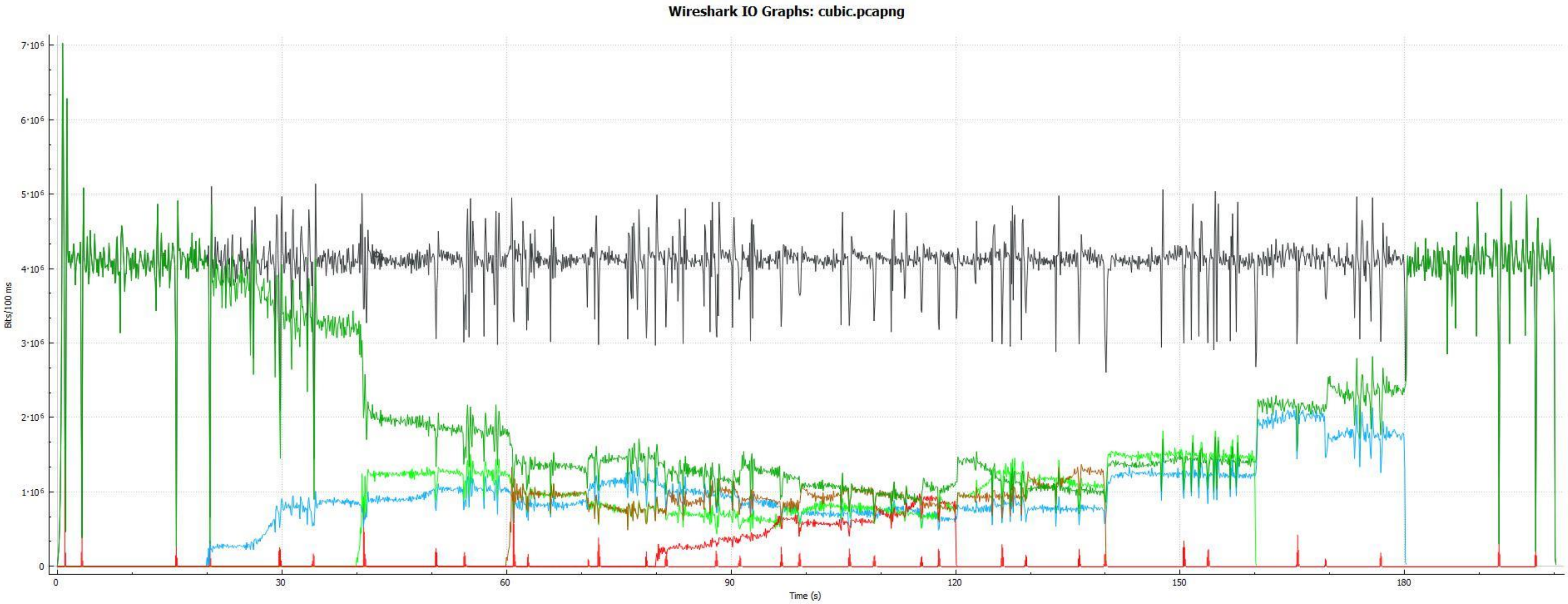
Collateral damage: 14 Buffer overflows / 790k Total Packets

CUBIC TCP



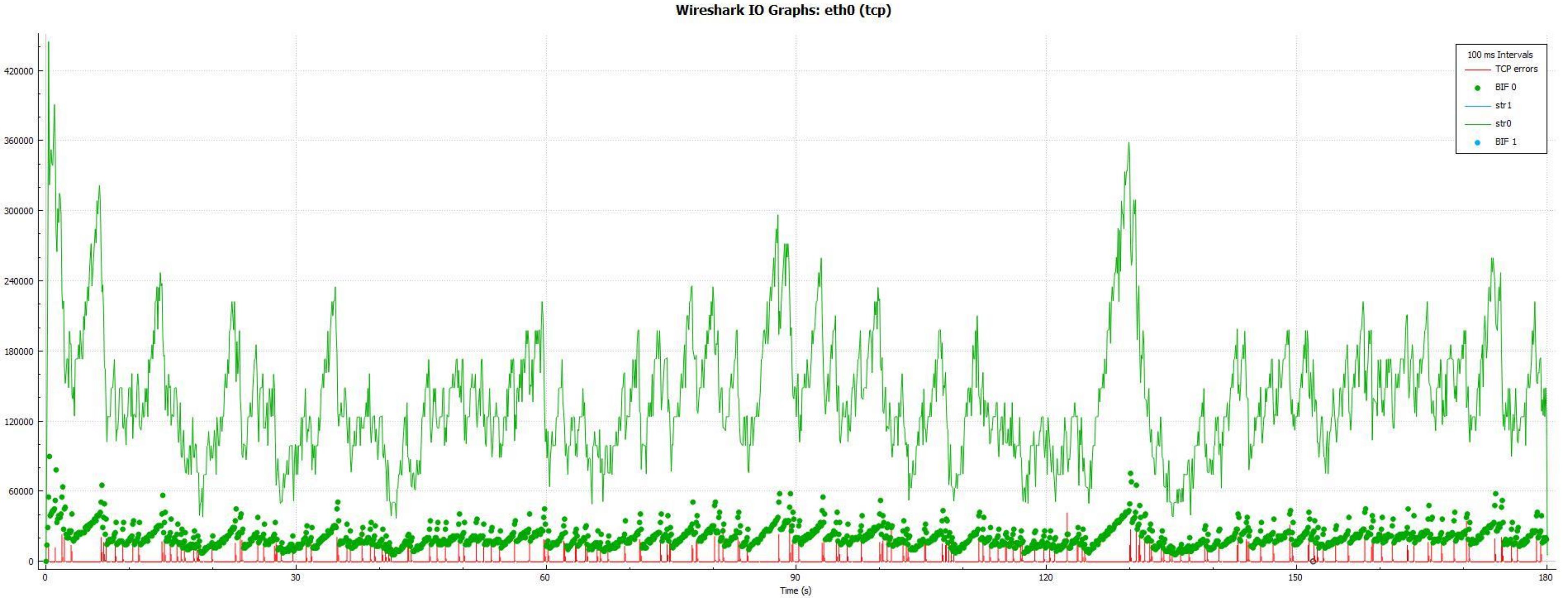
vs. Reno Friendliness

CUBIC TCP



5-stream convergence

CUBIC TCP

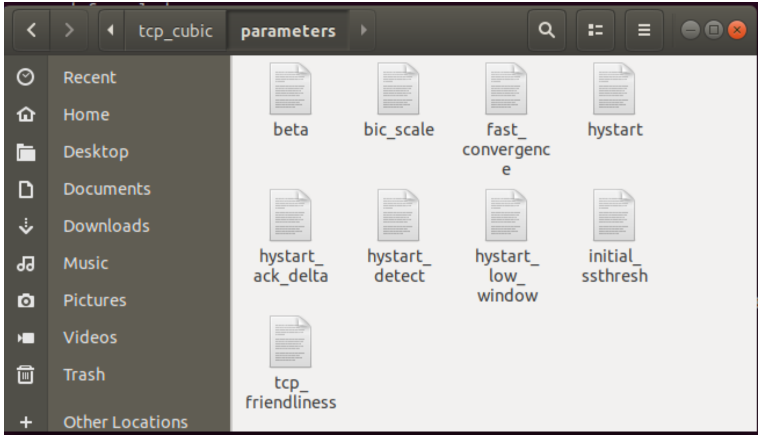


1% loss link behavior

CUBIC Fun Fact

If you look at CUBIC source code you'll spot some parameters can be tweaked!

```
/* Note parameters that are used for precomputing scale factors are read-only */
module_param(fast_convergence, int, 0644);
MODULE_PARM_DESC(fast_convergence, "turn on/off fast convergence");
module_param(beta, int, 0644);
MODULE_PARM_DESC(beta, "beta for multiplicative increase");
module_param(initial_ssthresh, int, 0644);
MODULE_PARM_DESC(initial_ssthresh, "initial value of slow start threshold");
module_param(bic_scale, int, 0444);
MODULE_PARM_DESC(bic_scale, "scale (scaled by 1024) value for bic function (bic_scale/1024)"
module_param(tcp_friendliness, int, 0644);
MODULE_PARM_DESC(tcp_friendliness, "turn on/off tcp friendliness");
module_param(hystart, int, 0644);
MODULE_PARM_DESC(hystart, "turn on/off hybrid slow start algorithm");
module_param(hystart_detect, int, 0644);
MODULE_PARM_DESC(hystart_detect, "hybrid slow start detection mechanisms"
                 " 1: packet-train 2: delay 3: both packet-train and delay");
module_param(hystart_low_window, int, 0644);
MODULE_PARM_DESC(hystart_low_window, "lower bound cwnd for hybrid slow start");
module_param(hystart_ack_delta, int, 0644);
MODULE_PARM_DESC(hystart_ack_delta, "spacing between ack's indicating train (msecs)");
```



These knobs can be found (for Ubuntu) at **/sys/module/tcp_cubic/parameters**

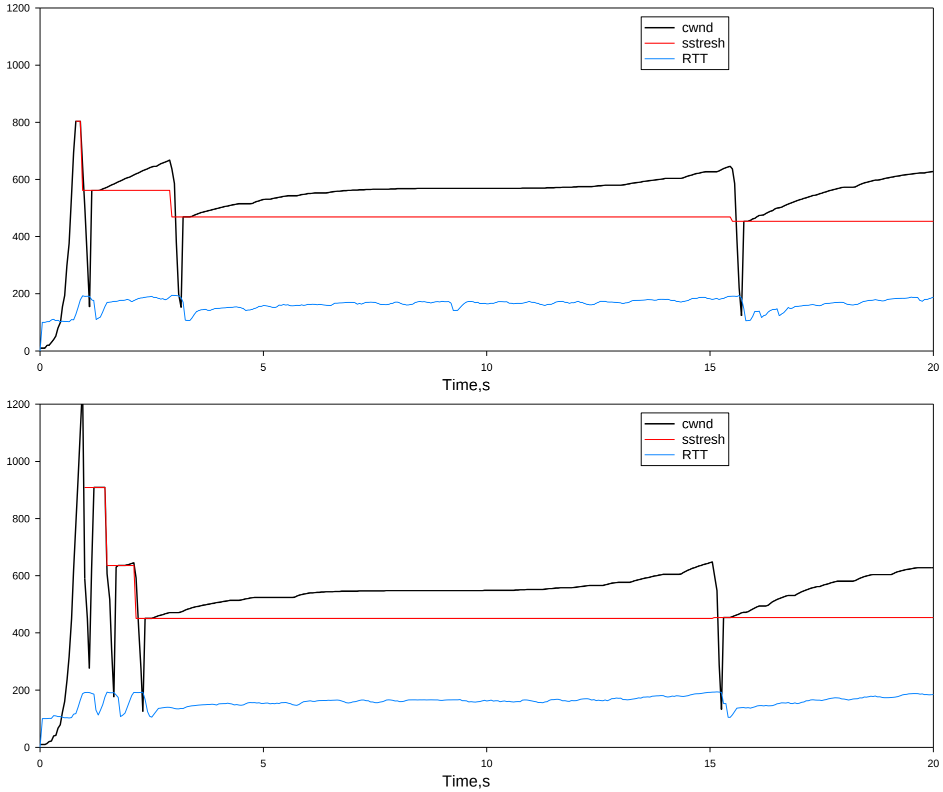
Hybrid slow start

Problem: high aggressiveness during final slow start phase.

Solution: estimate a point where to exit Slow Start mode.

Methods:
- ACK train length measuring method.
- Inter-frame delay method.

Built-in in CUBIC algorithm.
Method can be switched.



VEGAS TCP

Core ideas:

“Pacifist”

[Source]

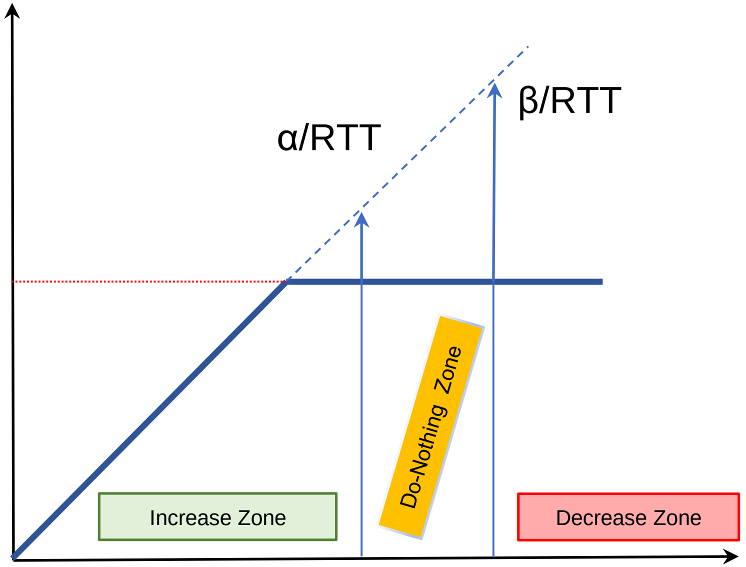
1. First try to build **delay-based** algorithm (1994).
2. Uses delay as feedback (purely delay-based).
3. Uses AIAD as action profile.

***cwnd* control rules:**

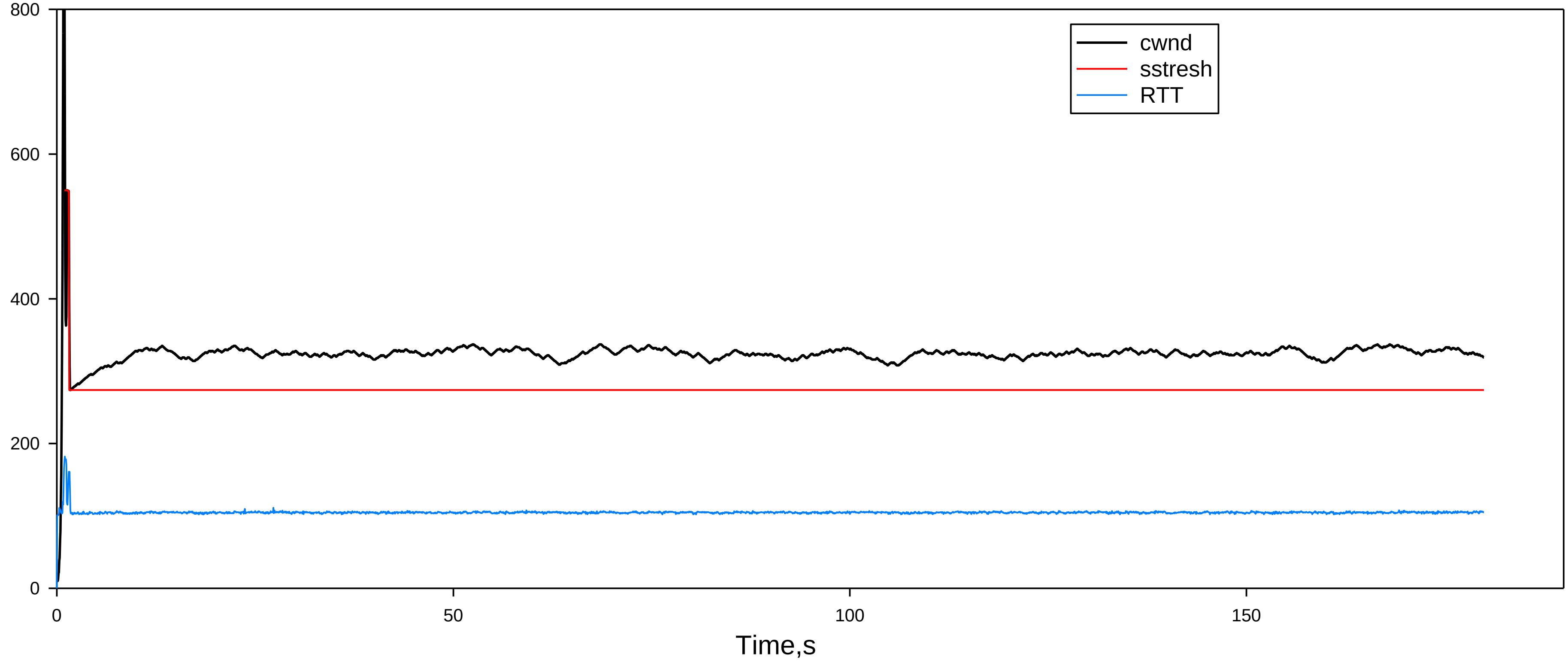
1. Measure and constantly update min RTT (“BaseRTT”)
2. For every RTT compare Expected Throughput (***cwnd*** / BaseRTT) with Actual Throughput (***cwnd*** / RTT)
3. Compute difference = (Expected - Actual)/BaseRTT
4. Look where in range it lies and act accordingly (1 per RTT ***cwnd*** update frequency).
5. Switch to Reno if there are not enough RTT samples.

✓ Very smooth
✓ Doesn’t act on Cliff zone
✓ Induces small buffer load, keeps RTT small

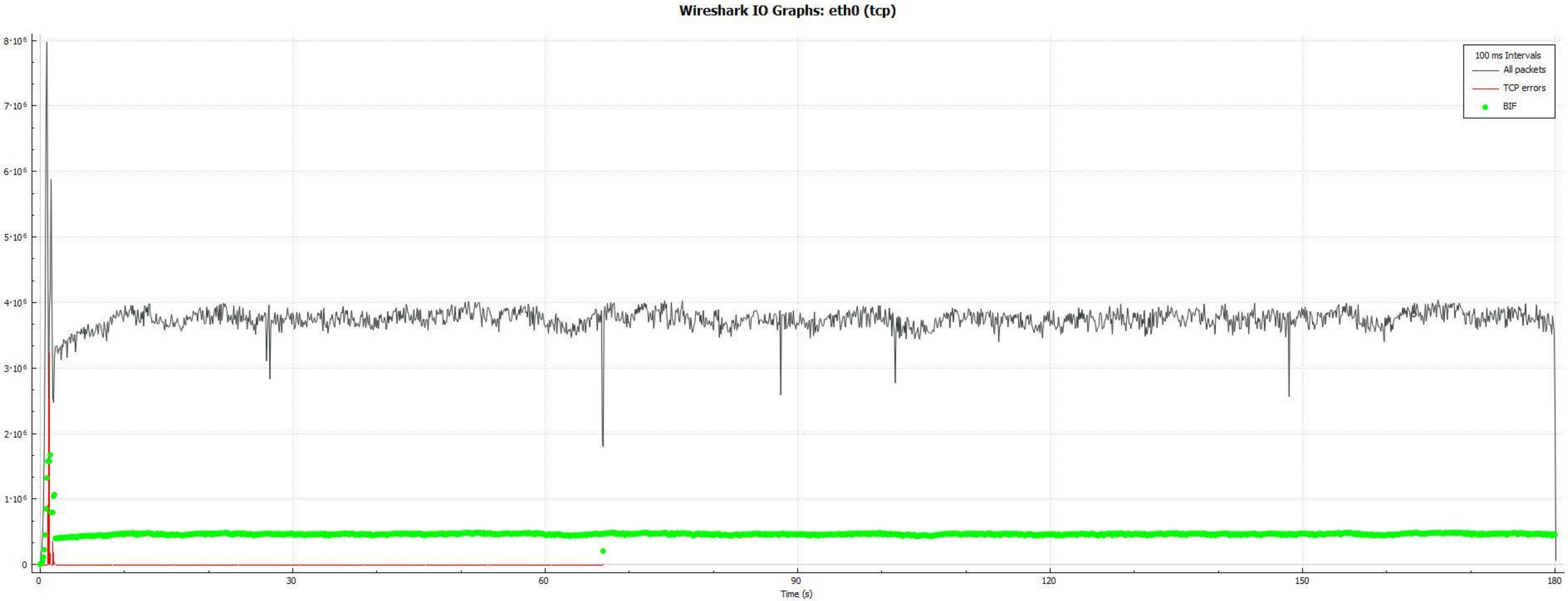
× Gets beaten by **any** loss-based algorithm
× Doesn’t like small buffers
× Doesn’t like small RTTs



VEGAS TCP

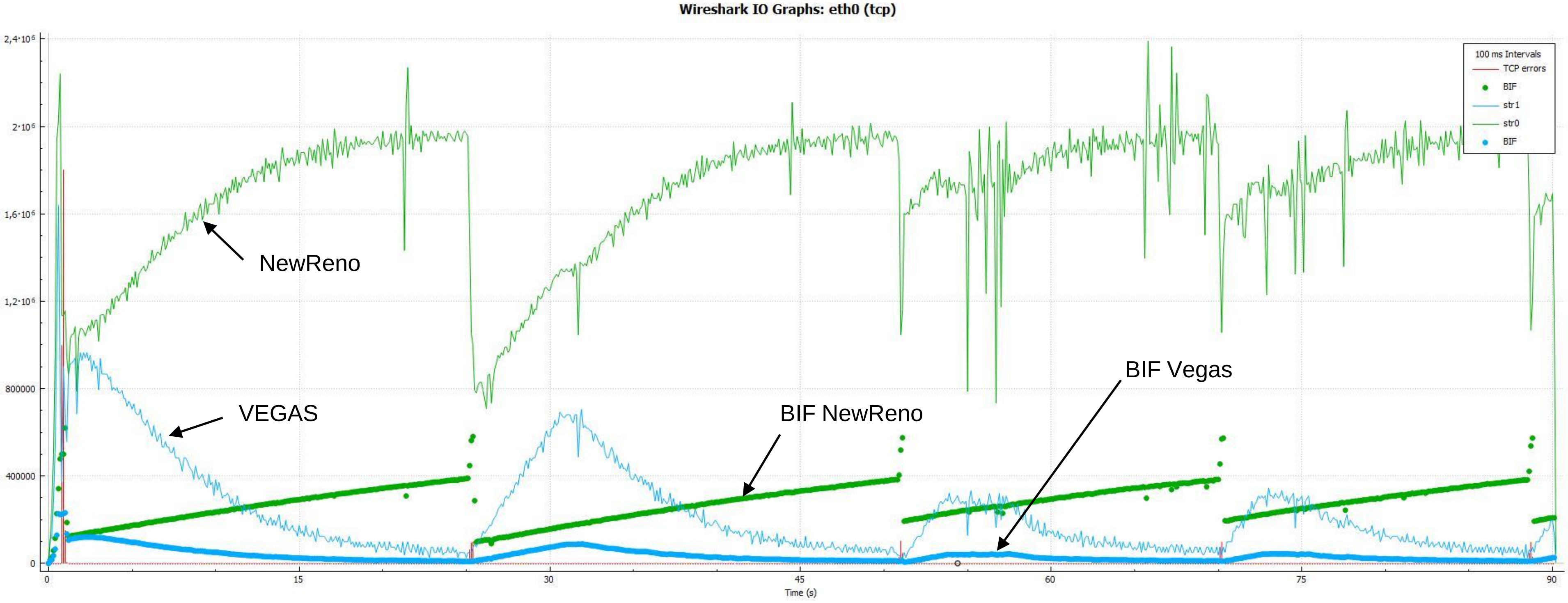


VEGAS TCP



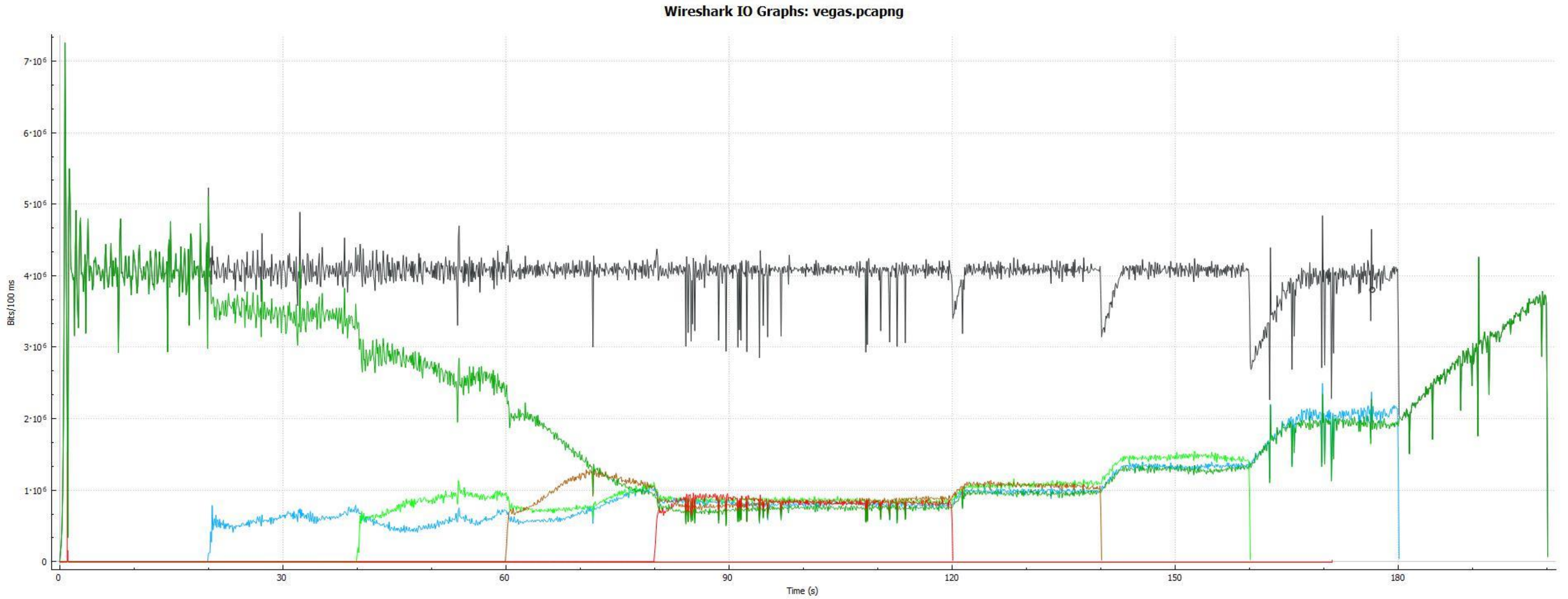
When it’s alone – this is impressive! Collateral damage: almost unnoticeable / 767k Packets

NewReno vs. VEGAS TCP



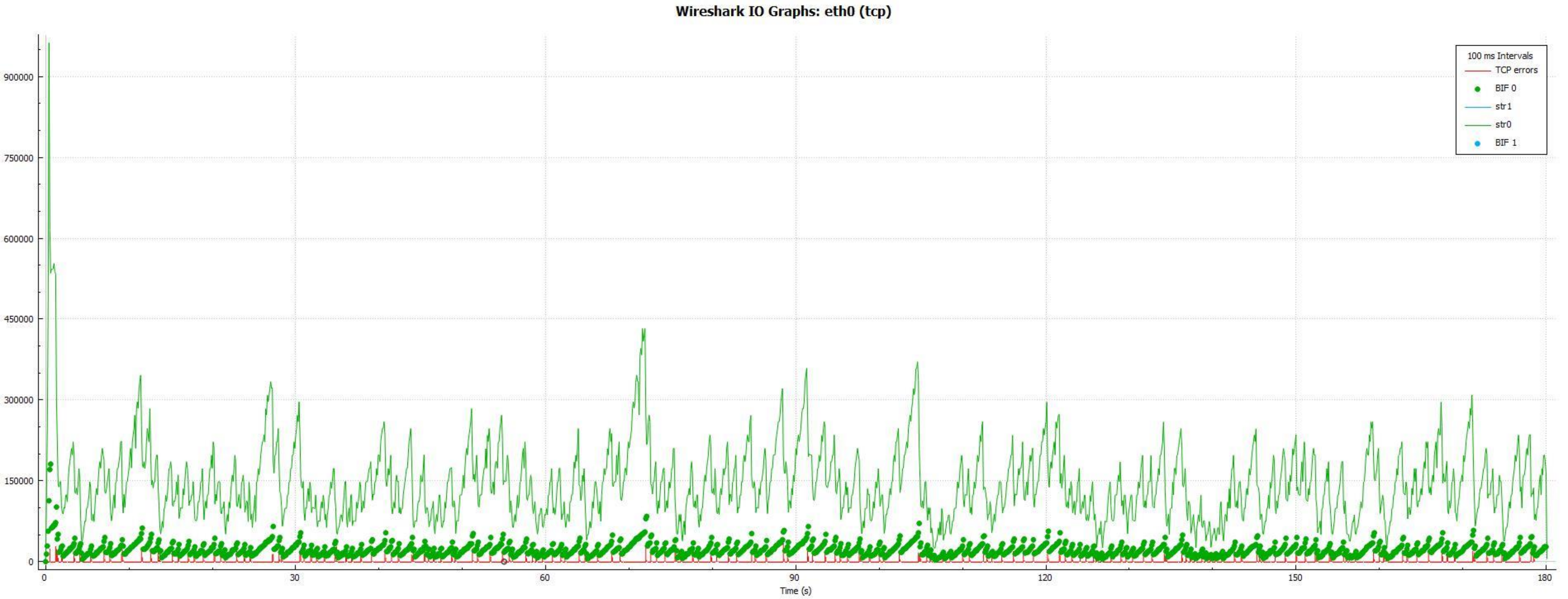
When VEGAS is not alone – this is a shame..

VEGAS TCP



5-stream convergence

VEGAS TCP



1% loss link behavior

ILLINOIS TCP

Core ideas:

"Careful"

[Source]

1. Uses packet loss and delay as feedback.
2. Uses modified AIMD with delay-dependent variables as action profile.

***cwnd* control rules:**

$$cwnd = \begin{cases} cwnd + \alpha / cwnd & \text{if congestion is not detected} \\ (1-\beta) * cwnd & \text{if congestion is detected} \end{cases}$$

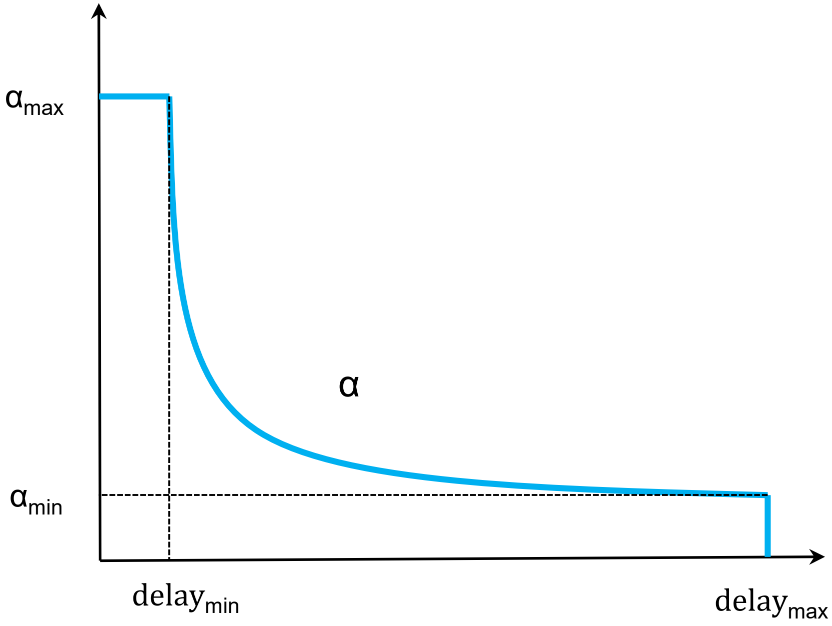
Measure ***min RTT*** and ***max RTT*** for each ACK. Track them.

Compute α:

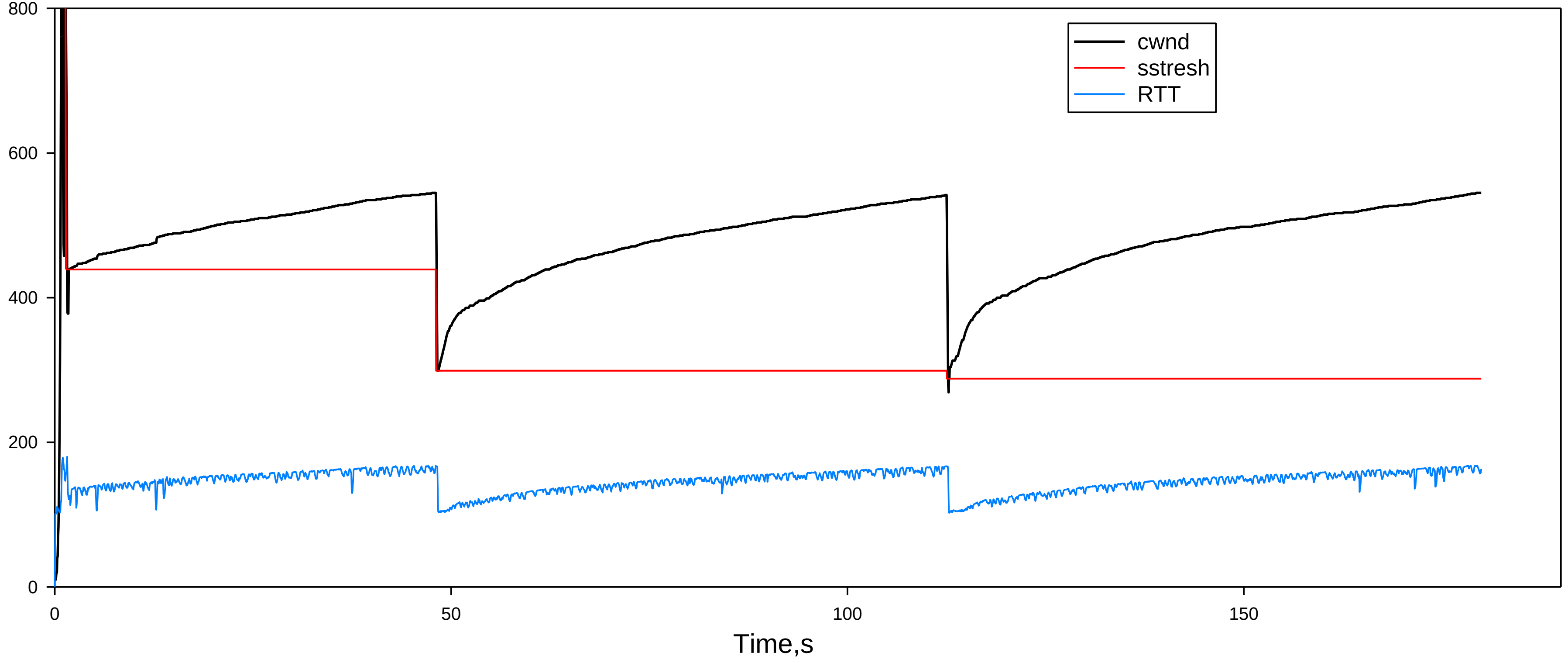
- If average delay is at minimum (we are uncongested), then use large alpha (10.0) to grow ***cwnd*** faster.
- If average delay is at maximum (getting congested) then use small alpha (0.3)

Compute β:

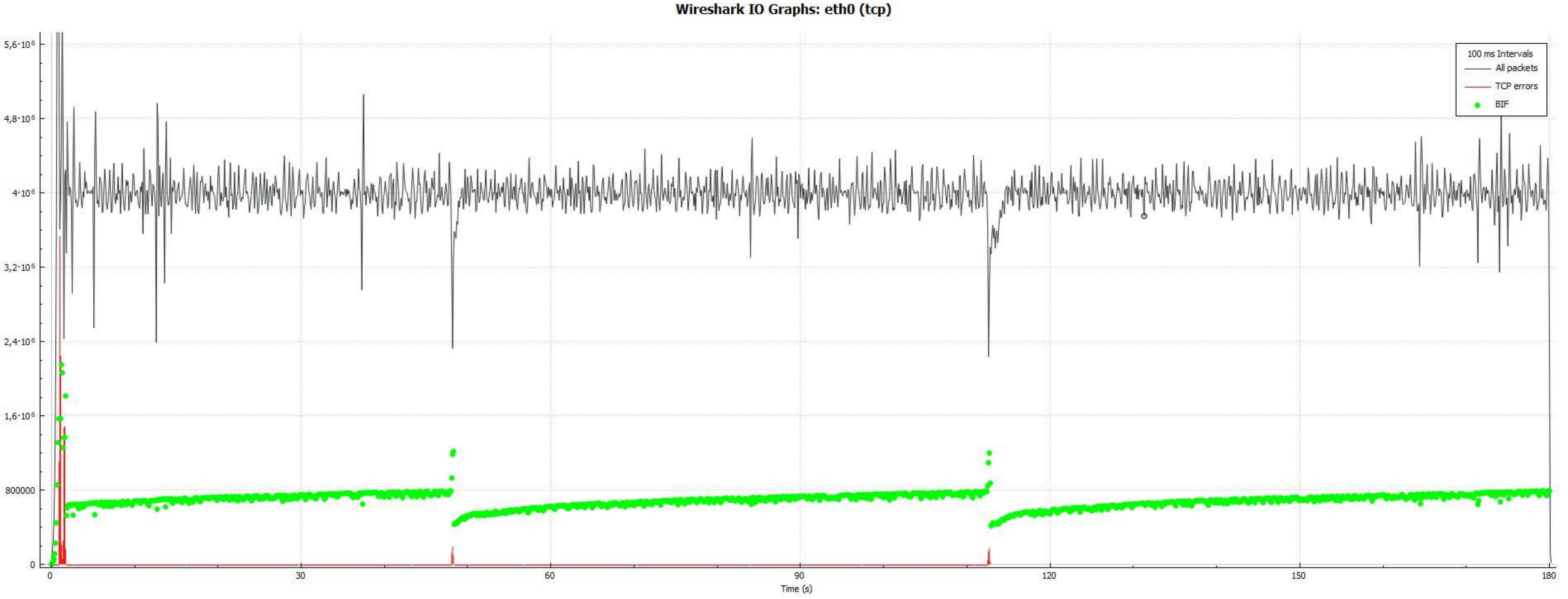
- If delay is small (10% of max) then β = 1/8
- If delay is up to 80% of max then β = 1/2
- In between is a linear function



ILLINOIS TCP

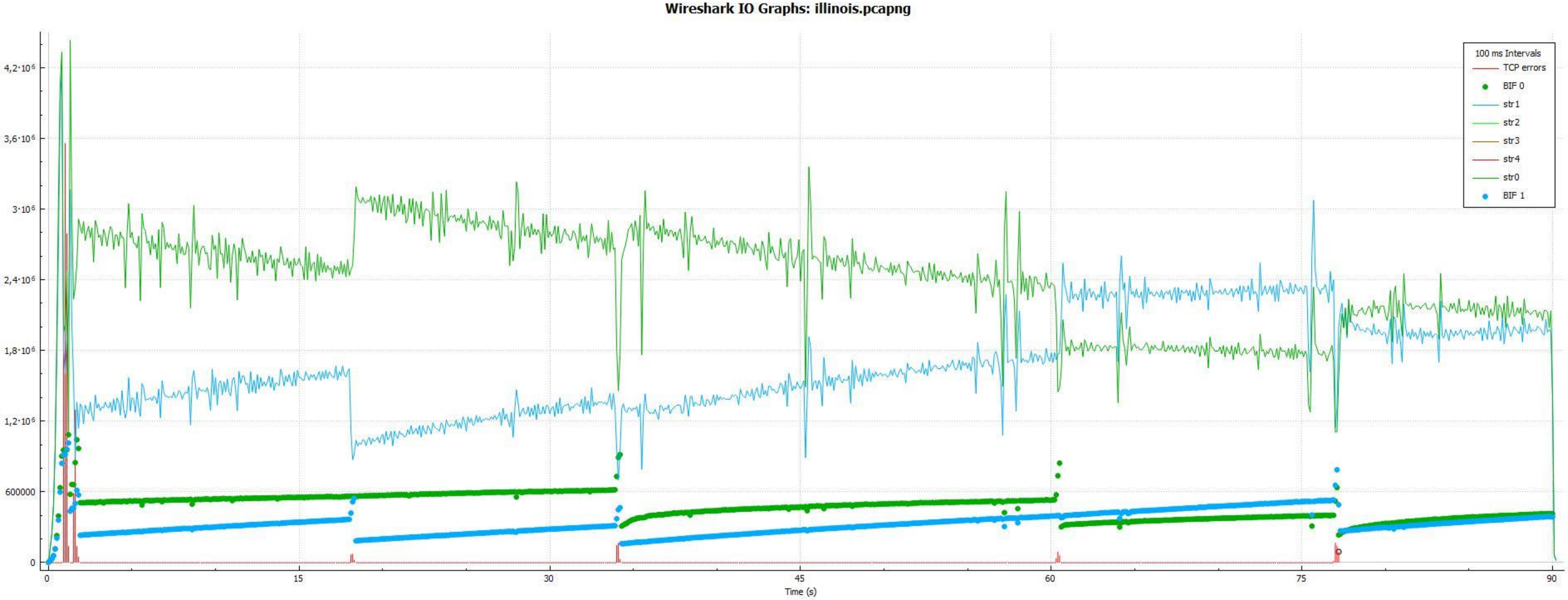


ILLINOIS TCP



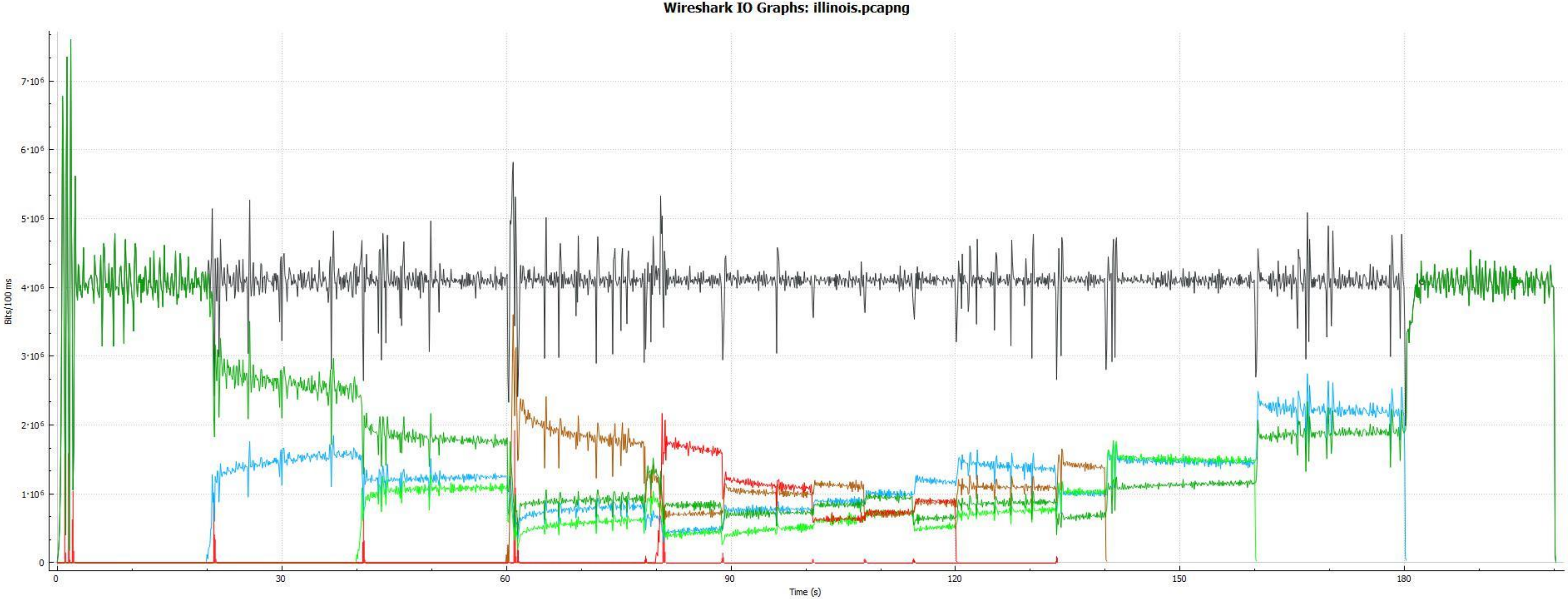
Collateral damage: 2 Buffer overflows / 815k Total Packets

Illinois TCP



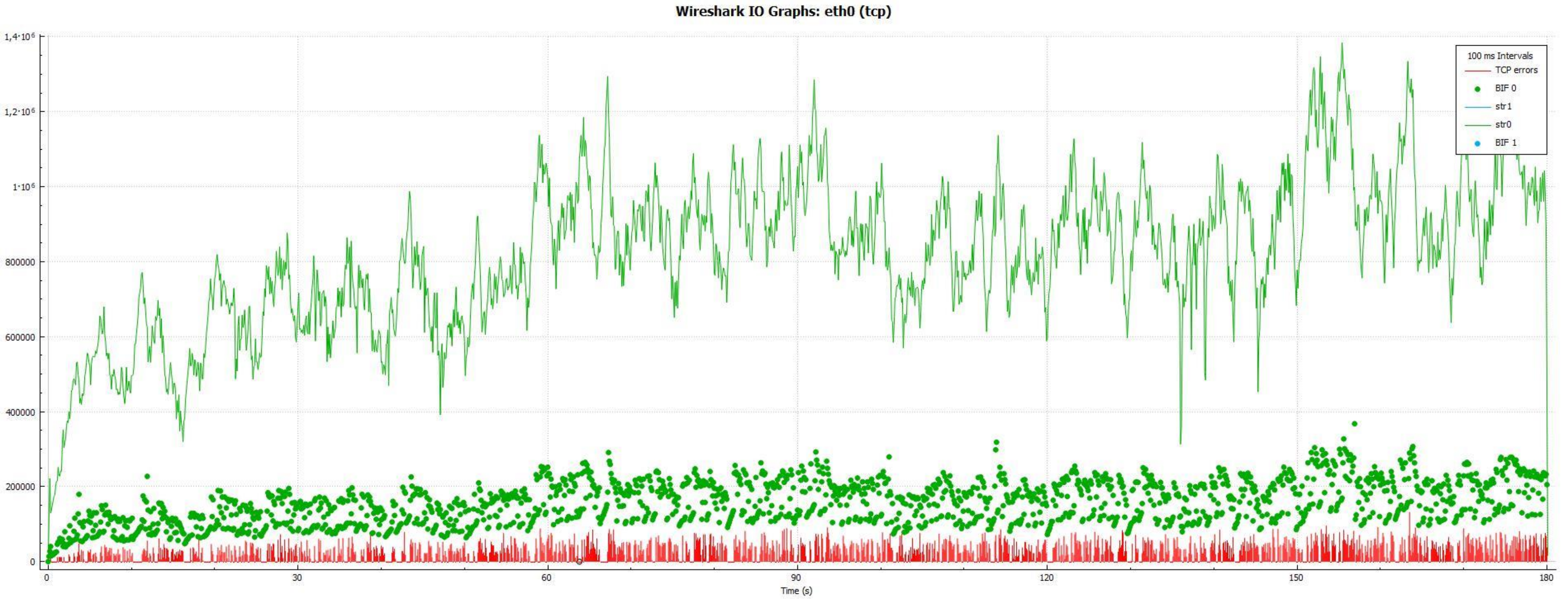
vs. Reno Friendliness

Illinois TCP



5-stream convergence

Illinois TCP



1% loss link behavior

Compound TCP

“Windows”

Core ideas:

1. Uses combination of packet loss and delay as feedback.
2. Uses AIMD additionally altered by delay window as action profile.
3. Only for Windows OS since Vista.

***cwnd* control rules:**

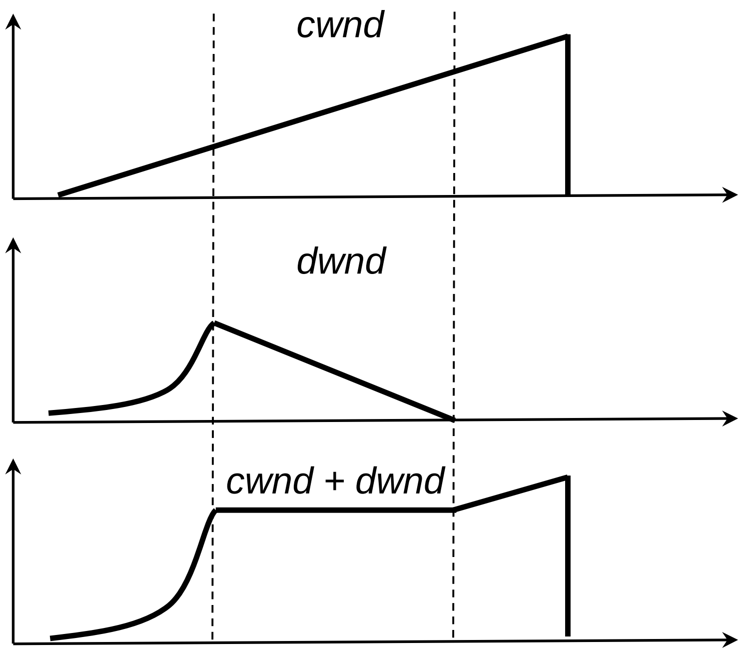
$$win = min\ (cwnd + dwnd,\ awnd)$$

Where: ***cwnd*** – as in Reno, ***dwnd*** – as in Vegas.

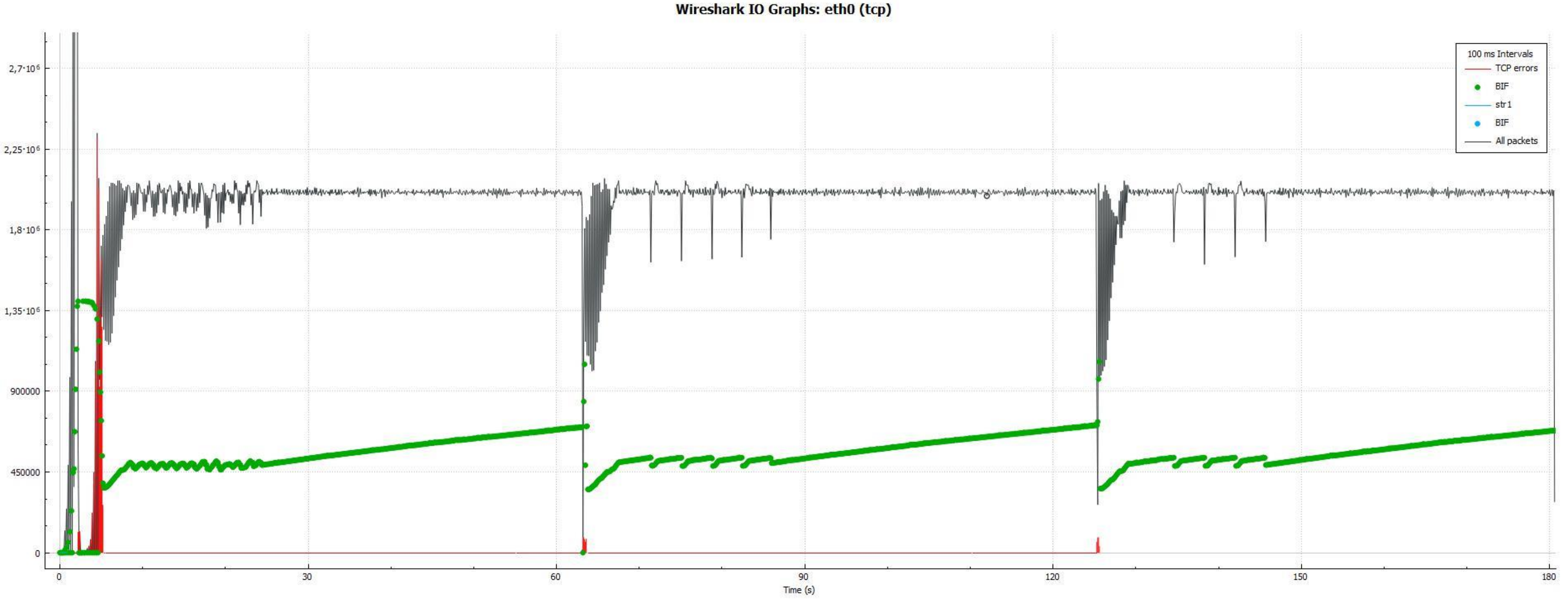
$$cwnd = \begin{cases} cwnd + 1/(cwnd + dwnd) & if\ congestion\ is\ not\ detected \\ (1 - \beta) * cwnd & if\ congestion\ is\ detected \end{cases}$$

Main point: combine fairness of delay-based CA with aggressiveness of loss-based CA.

✓ Coexistence with Reno on non-LFN links – good
✓ RTT fairness - good



Compound TCP



Link: 20mpbs, 200ms RTT. Tested using ntttcp.exe, Win10 – Win10. Sorry, no ***cwnd*** graph..

WESTWOOD TCP

Core ideas:

"Wireless warrior"

Source

1. Main idea: an attempt to distinguish between congestive and non-congestive losses.
2. Uses packet loss as feedback.
3. Uses modified AIMD as action profile.
4. Continuously estimates bandwidth (BWE, from incoming ACKs) and minimal RTT (RTT_{noLoad})

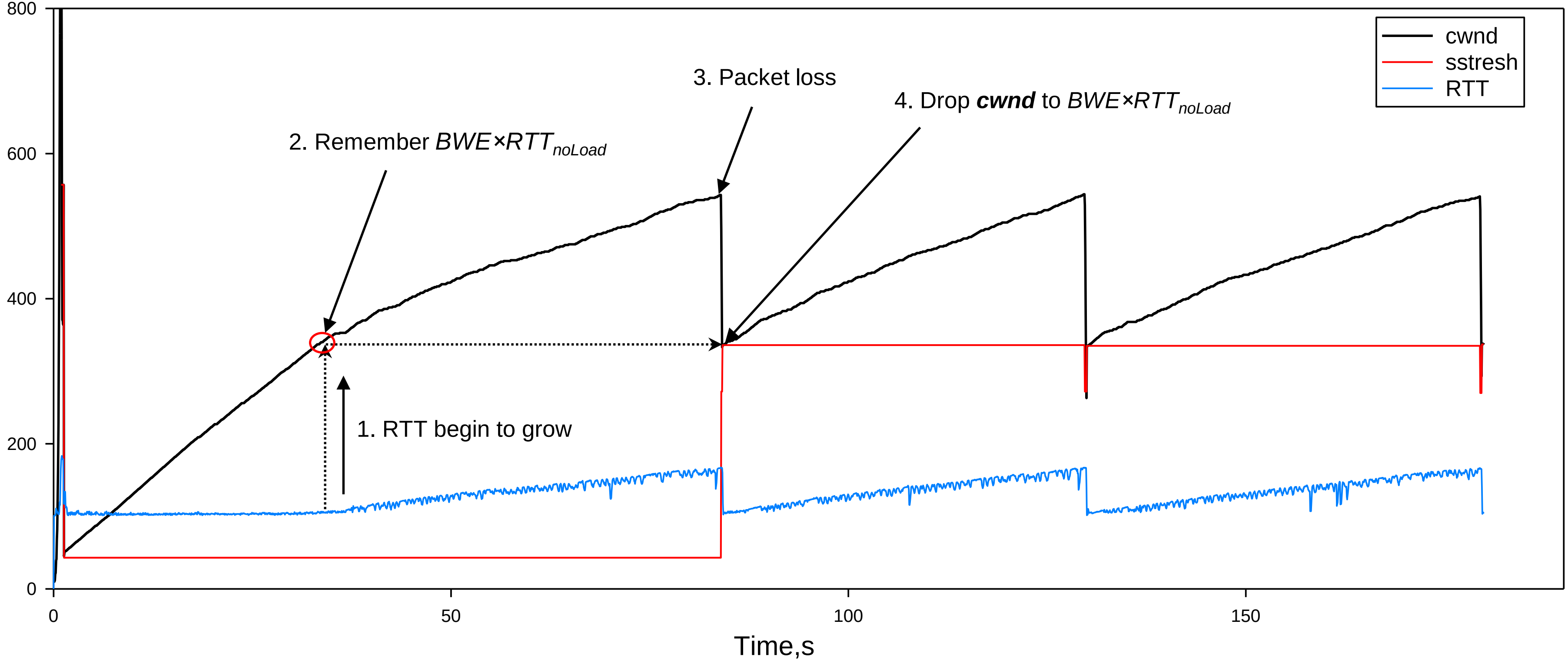
***cwnd* control rules:**

- Calculates "transit capacity" : $BWE \times RTT_{noLoad}$ (represents how many packets can be in transit)
- Never drops ***cwnd*** below estimated transit capacity.

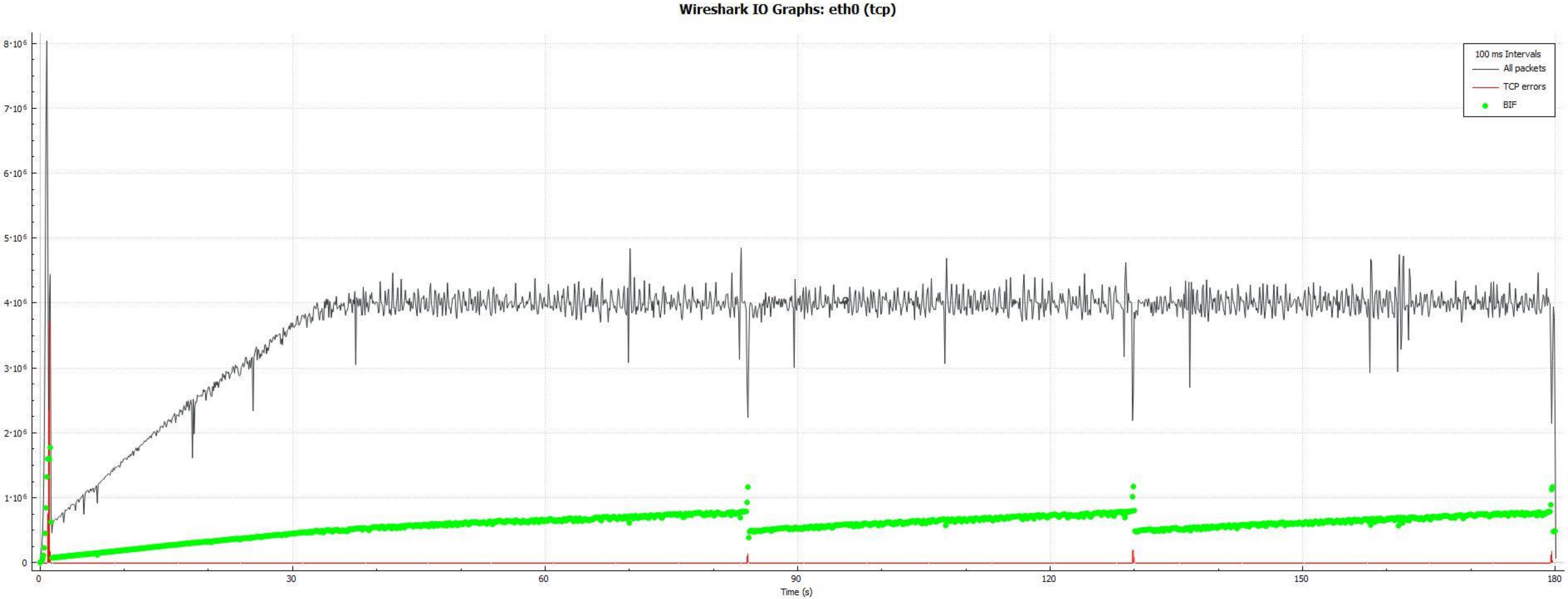
$$\textbf{cwnd} \text{ (on loss)} = \begin{cases} max(cwnd/2, BWE \times RTTnoLoad) \ if \ cwnd \ > \ BWE \times RTTnoLoad \\ no \ change, \ if \ cwnd \ \leq \ BWE \times RTTnoLoad \end{cases}$$

- If no loss is observed – acts similarly to Reno.

WESTWOOD TCP

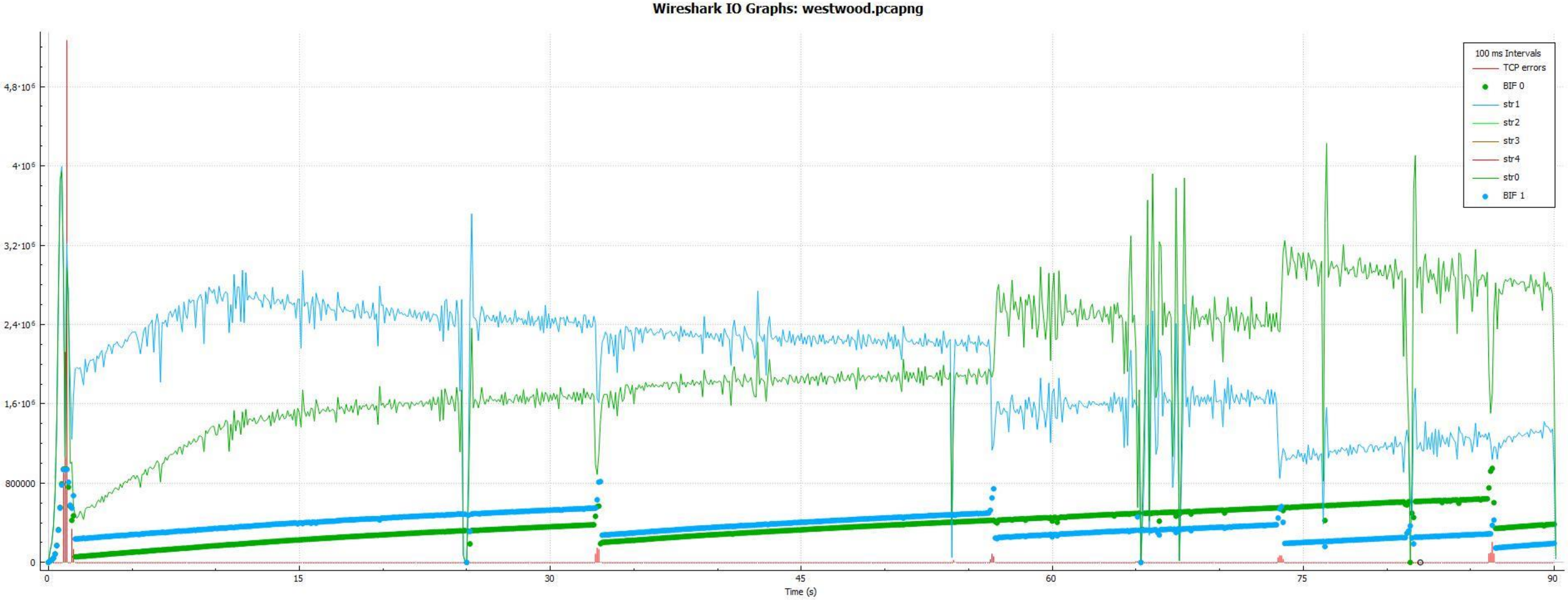


WESTWOOD TCP



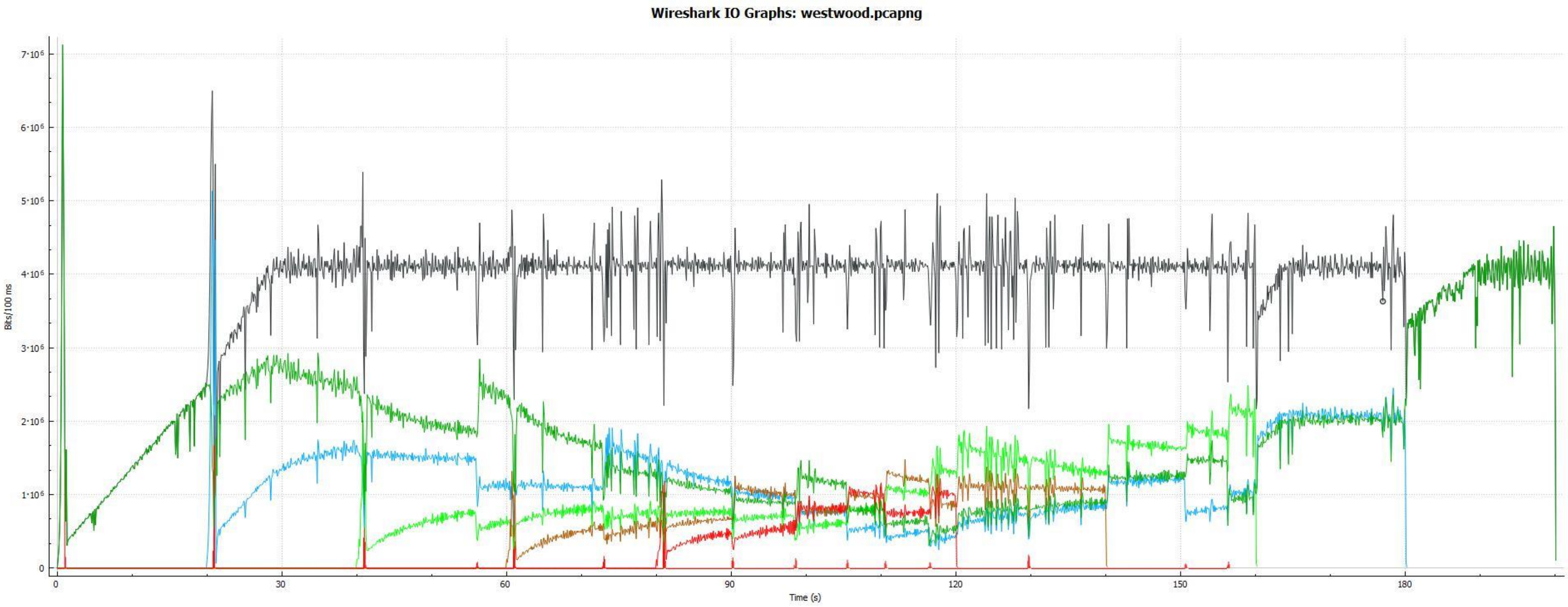
Collateral damage – same as Reno. Good for lossy links. With 1% loss beats CUBIC by x5 factor.

WESTWOOD TCP



vs. Reno Friendliness

WESTWOOD TCP

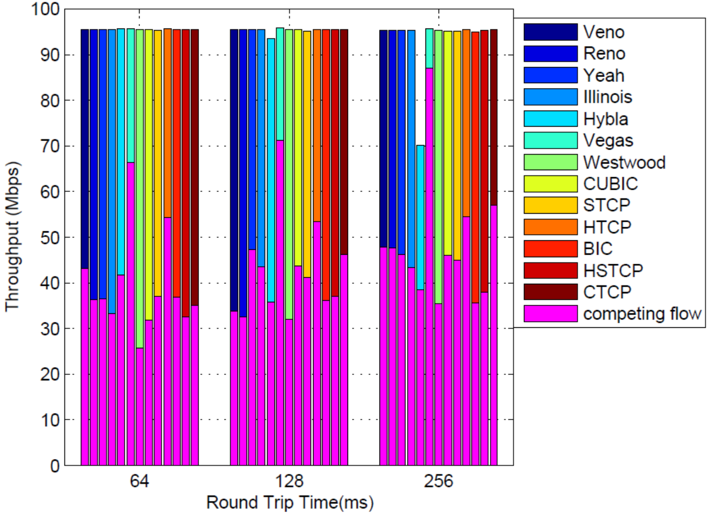


5-stream convergence

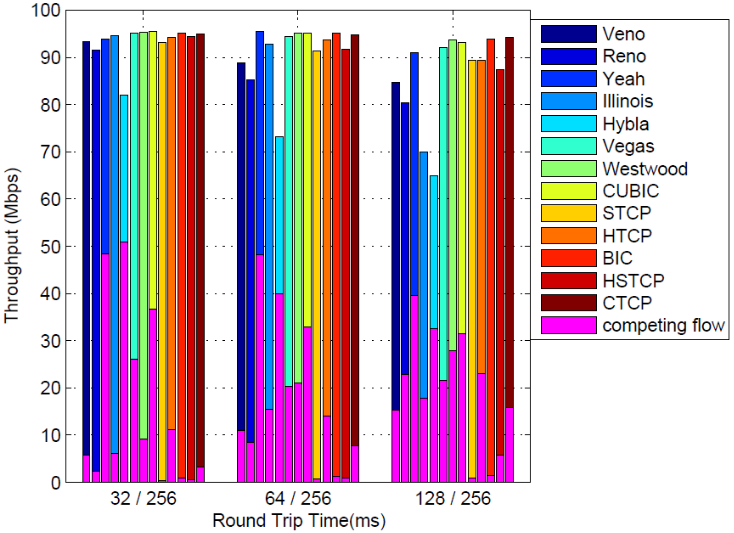
WESTWOOD TCP

1% loss link behavior

Comparison charts



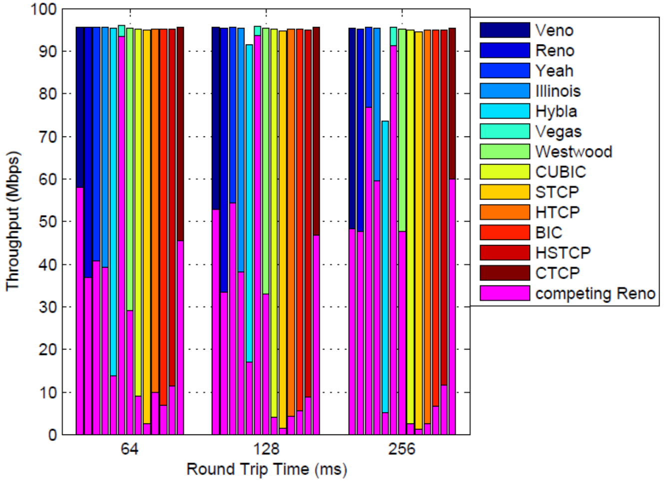
Intra-protocol fairness



RTT fairness

*** From "EXPERIMENTAL STUDY OF CONGESTION CONTROL ALGORITHMS IN FAST LONG DISTANCE NETWORK". Guodong Wang, Yongmao Ren and Jun Li.**

Comparison charts



Inter-protocol fairness

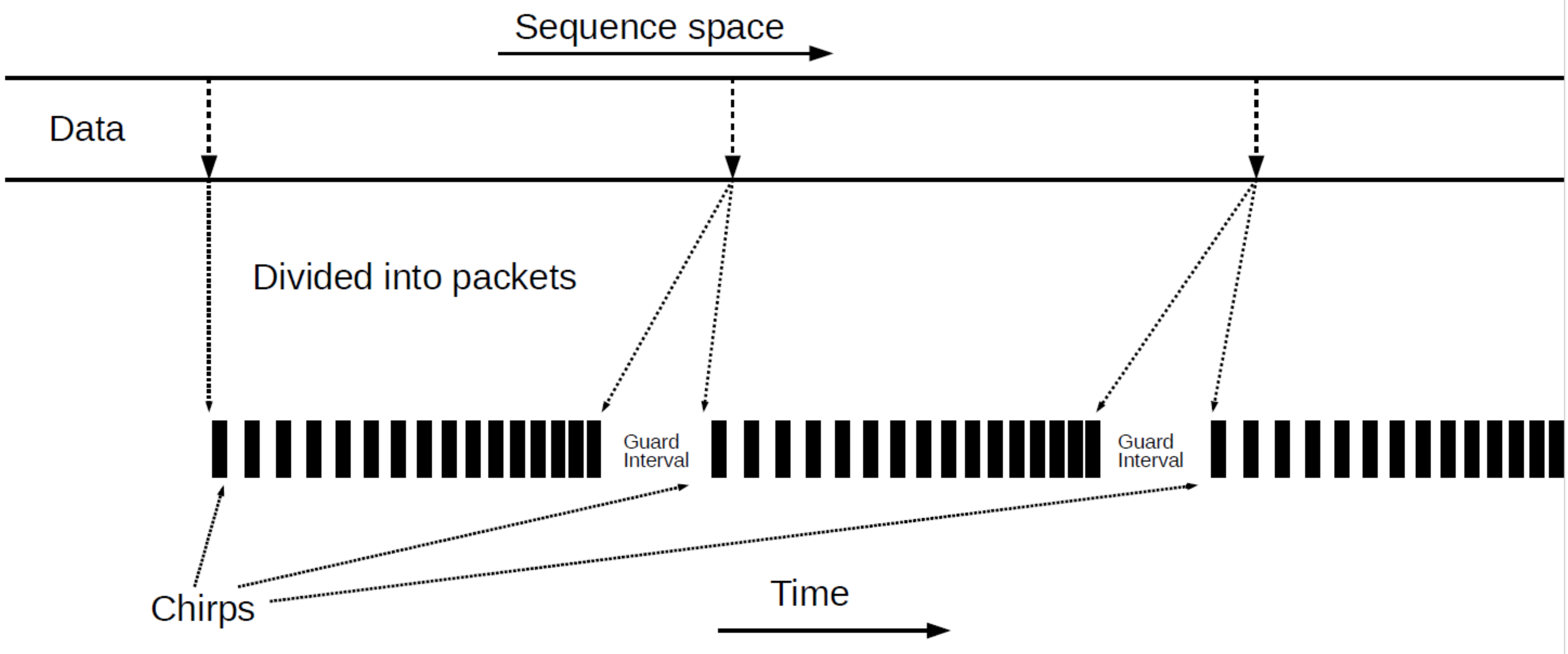
* From “EXPERIMENTAL STUDY OF CONGESTION CONTROL ALGORITHMS IN FAST LONG DISTANCE NETWORK”. Guodong Wang, Yongmao Ren and Jun Li.

The future?

- Multiple signals (ACK inter-arrival time, timestamps, delay with minimal RTT value tracking, packet loss).
- Learning-based (the use of assumption model).
- No pure ACK clocking (switch to combination of ACK clocking + pacing model). ***cnwd*** + ***time gap*** from last sent packet.
- Moving into application layer (PCC, QUIC – on top of UDP).
- Pushing CA into user-space + using API (concept, Linux).
- Reinventing SlowStart (Flow-start, “Paced Chirping”, now more for datacenter environment).

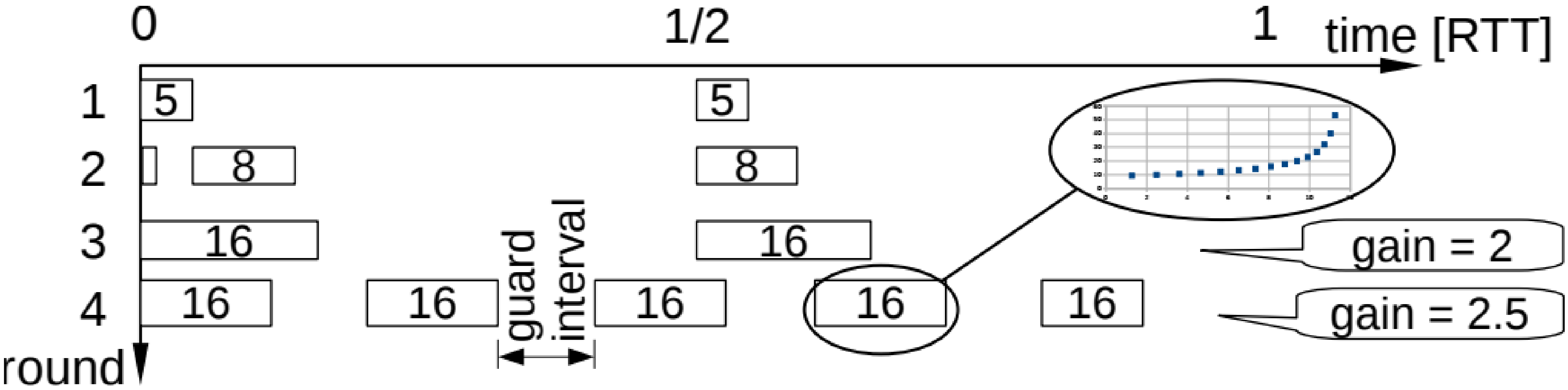
BBR	Heartbeat probes, BW estimator
Vivace	Online learning
ABC	Explicit signaling
Remy	Parameters “brute-forcing”
Indigo	Machine learning
Sprout	Stochastic forecasts, for mobile
SCReAM	For LTE+multimedia
Omniscient	“Ideal” TCP

Paced Chirping



* From "Paced Chirping: Rethinking TCP start-up". Joakim S. Misund. Bob Briscoe. Netdev 1.3 Prague, March, 2019"

Paced Chirping



* From "Paced Chirping: Rethinking TCP start-up". Joakim S. Misund. Bob Briscoe. Netdev 1.3 Prague, March, 2019"

BBR TCP

Core ideas:

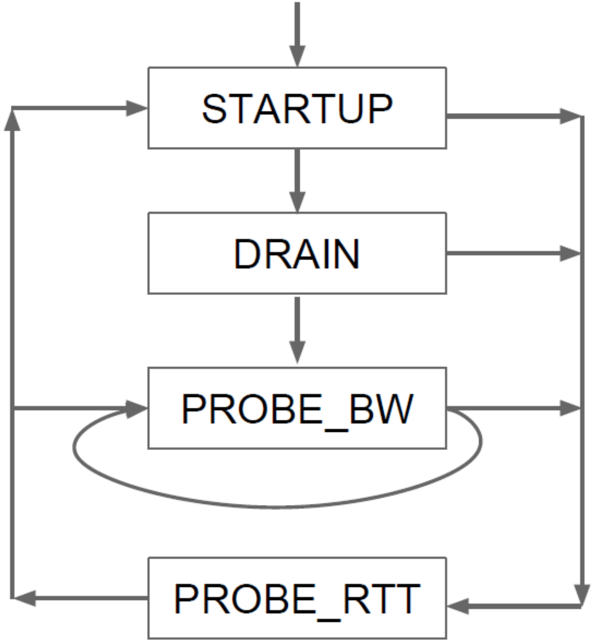
“Heartbeat”

Source

1. RTT and Bottleneck BW estimation ***(RTprop*** and ***BtlBw*** variables***)*** + active probing.
2. Uses periodic spike-looking active probes (+/- 25%) for Bottleneck BW testing.
3. Uses periodic pauses for “Base RTT” measuring.
4. Tracks App-limited condition (nothing to send) to prevent underestimation.
5. Doesn’t use AIMD in any form or shape. Uses pacing instead. Can handle sending speeds from 715bps to 2,9Tbps.

***cwnd* control rules - 4 different phases:**

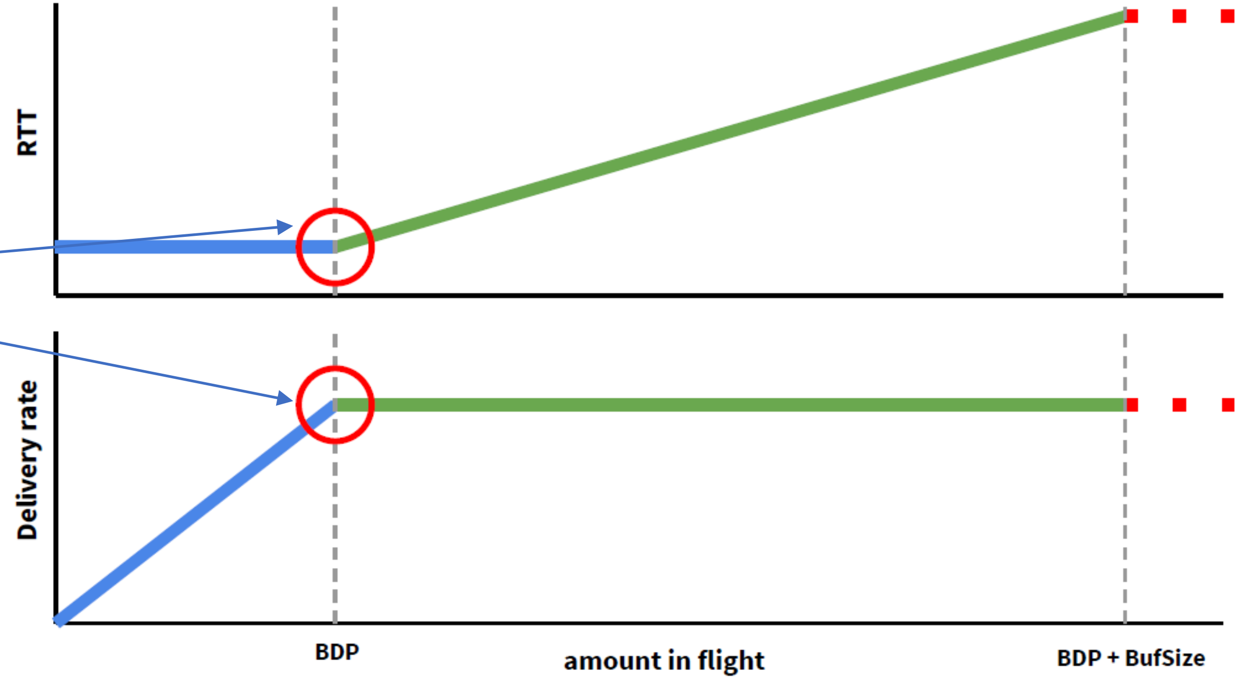
- **Startup** (beginning of the connection)
- **Drain** (right after startup)
- **Probe_BW** (every 5 RTTs)
- **Probe_RTT** (periodically every 10 seconds)



BBR TCP

Optimal operating point

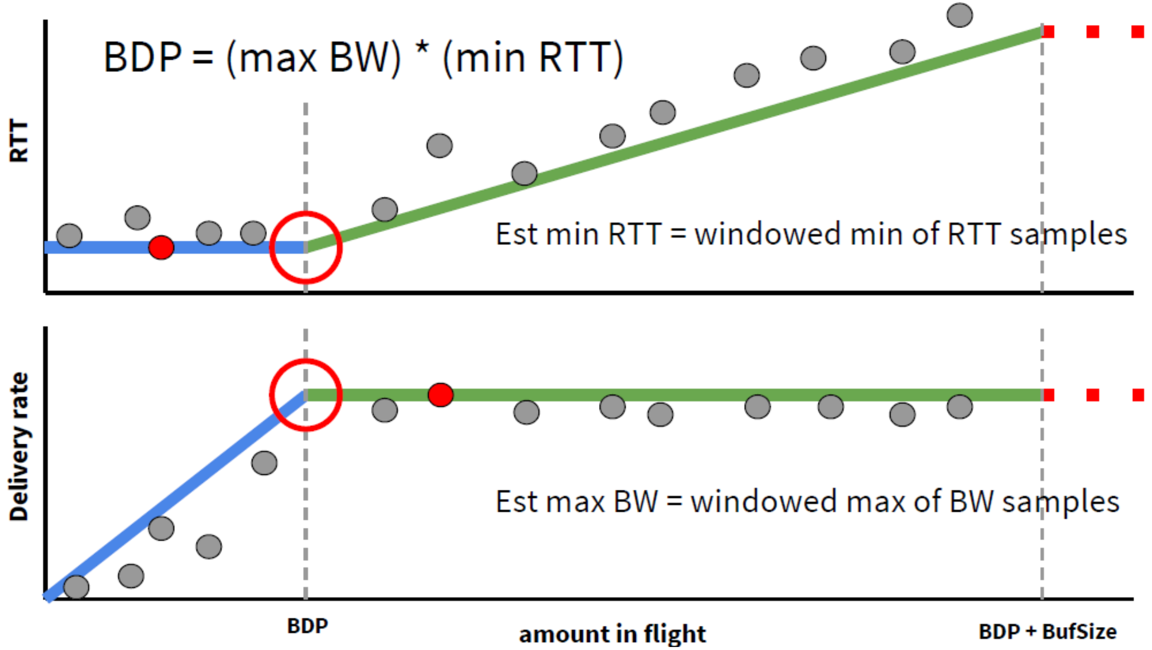
(queue building point)



* From “Making Linux TCP Fast”. Yuchung Cheng. Neal Cardwell. Netdev 1.2 Tokyo, October, 2016”

BBR TCP

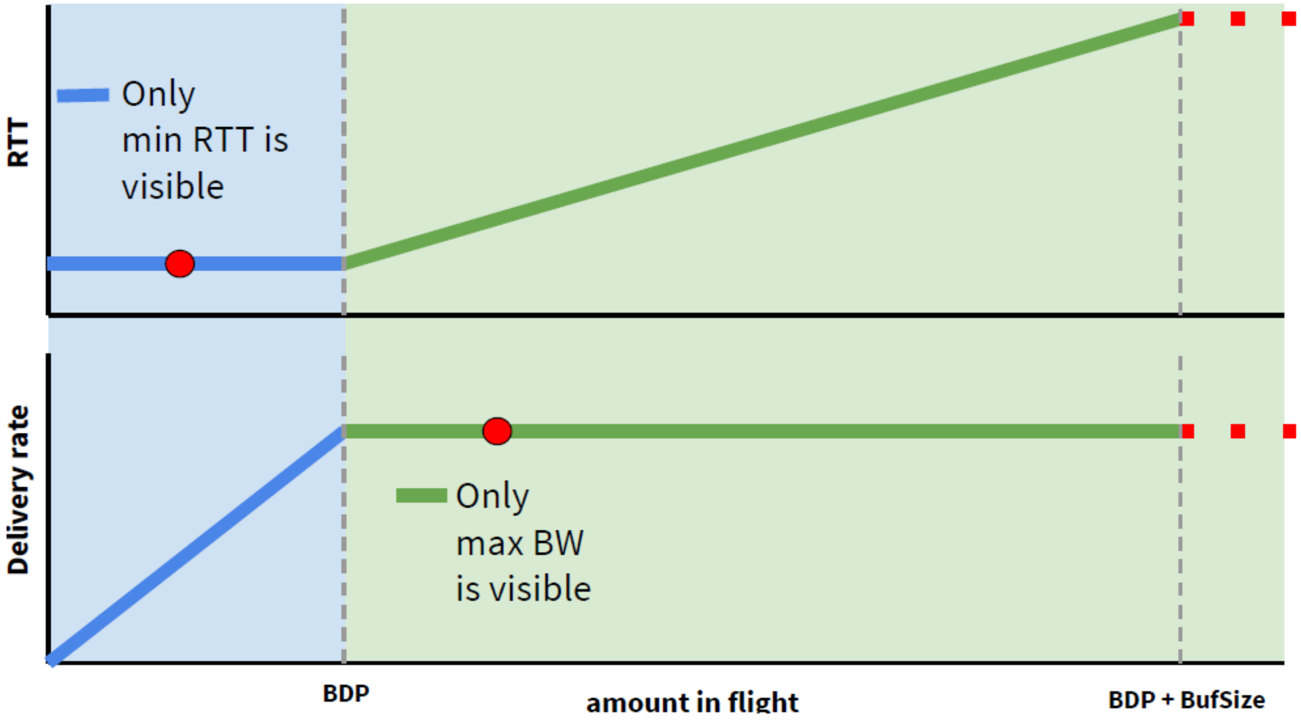
Estimating optimal point (max BW, min RTT)



* From “Making Linux TCP Fast”. Yuchung Cheng. Neal Cardwell. Netdev 1.2 Tokyo, October, 2016”

Uncertainty principle:
We can not estimate max BW and min RTT at the same time (point)!

Solution:
well, let's do it sequentially!

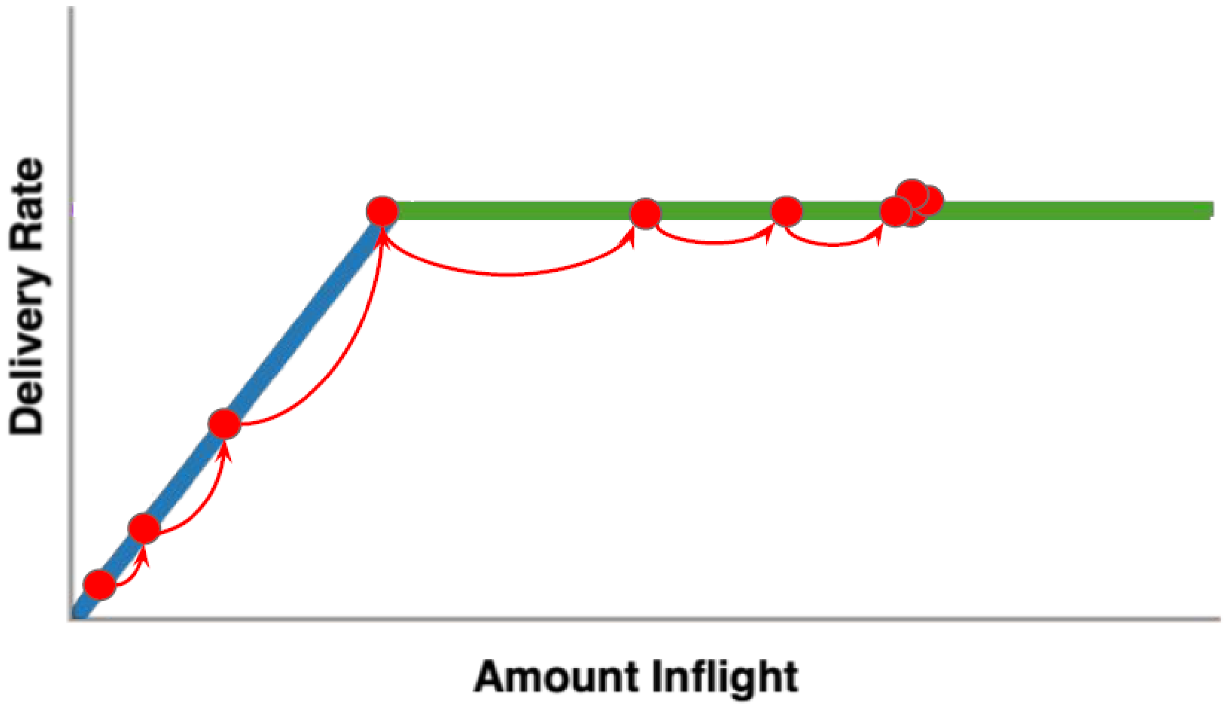


* From "Making Linux TCP Fast". Yuchung Cheng. Neal Cardwell. Netdev 1.2 Tokyo, October, 2016"

BBR TCP

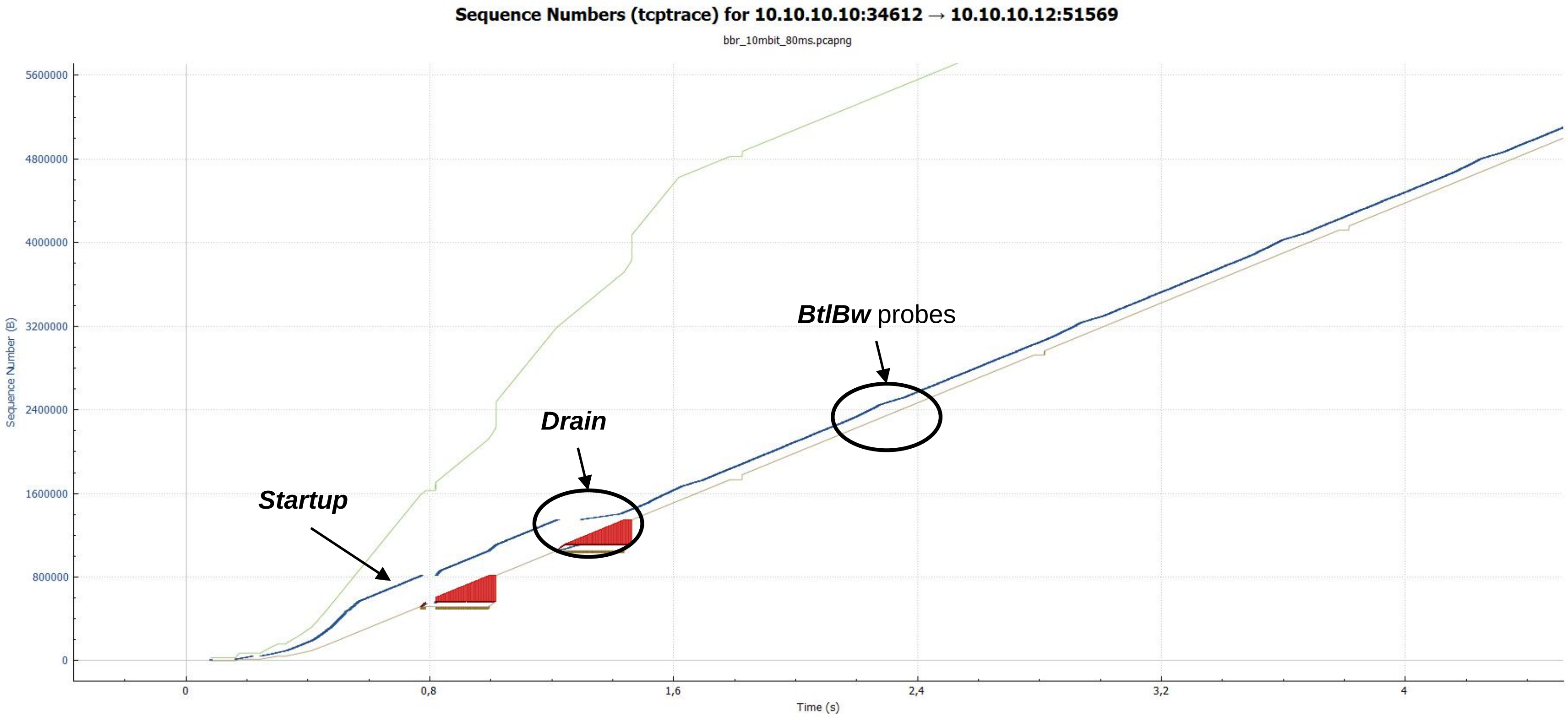
<u>Startup phase:</u> exponential probe for max BW.

Stopped if BW growth is less than 25% for 3 sequential probes.



* **From "Making Linux TCP Fast". Yuchung Cheng. Neal Cardwell. Netdev 1.2 Tokyo, October, 2016"**

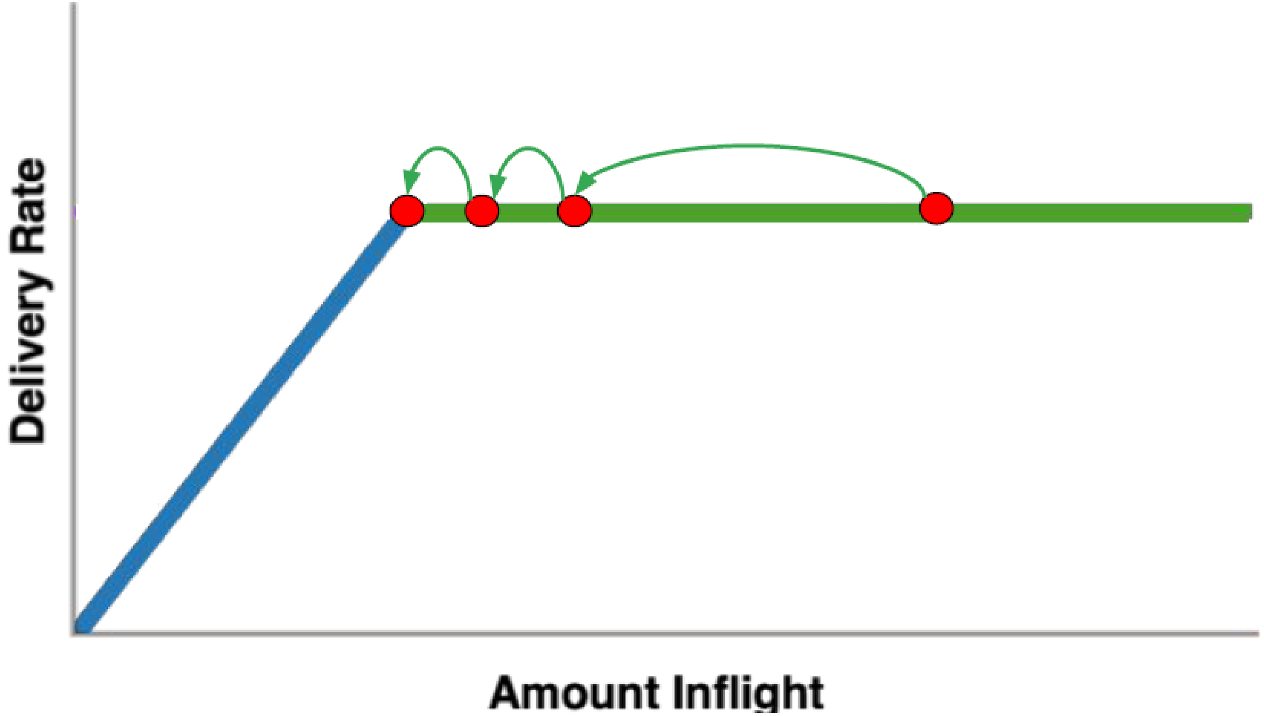
BBR TCP



Sequence Numbers (tcptrace) for 10.10.10.10:34612 → 10.10.10.12:51569
bbr_10mbit_80ms.pcapng
Sequence Number (B)
5600000
4800000
4000000
3200000
2400000
1600000
800000
0
0
0,8
1,6
2,4
3,2
4
Time (s)
Startup
Drain
BtlBw probes

BBR TCP

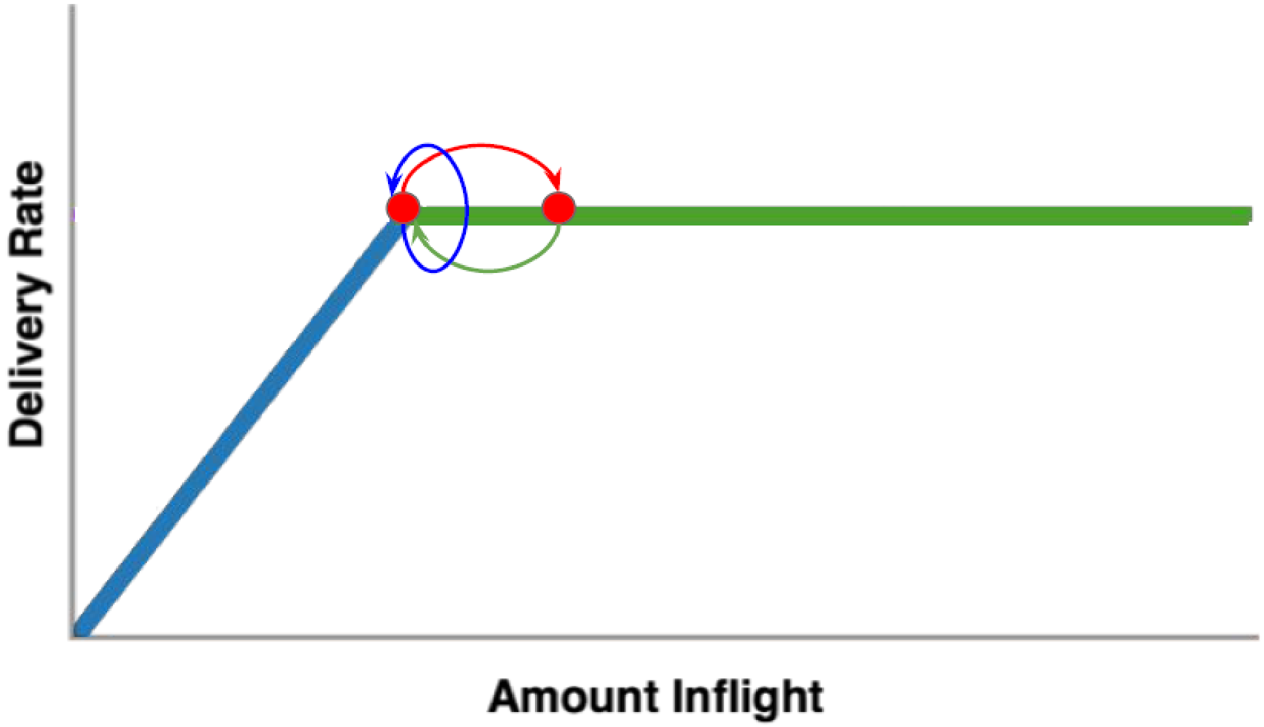
<u>Drain phase:</u> trying to get rid of queue formed during startup phase.



* From “Making Linux TCP Fast”. Yuchung Cheng. Neal Cardwell. Netdev 1.2 Tokyo, October, 2016”

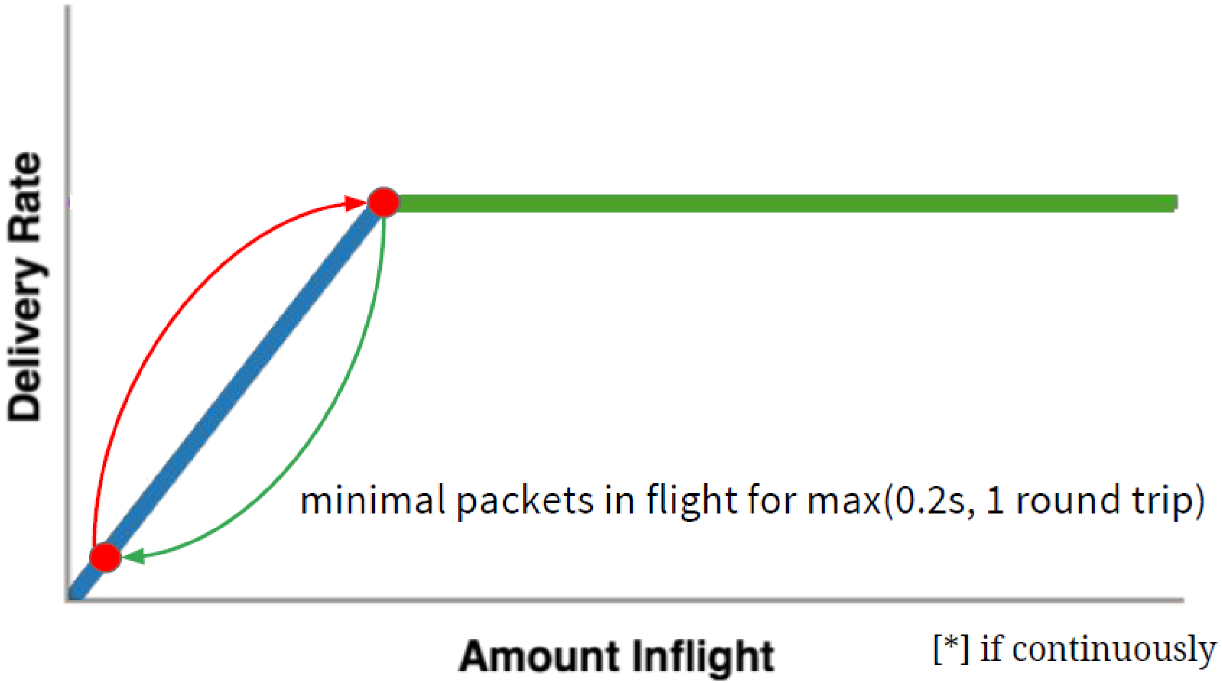
BBR TCP

Probe BW phase:
do spikes in sending rate (1,25 followed by 0.75 gains, each one of RTT length)



* From "Making Linux TCP Fast". Yuchung Cheng. Neal Cardwell. Netdev 1.2 Tokyo, October, 2016"

BBR TCP



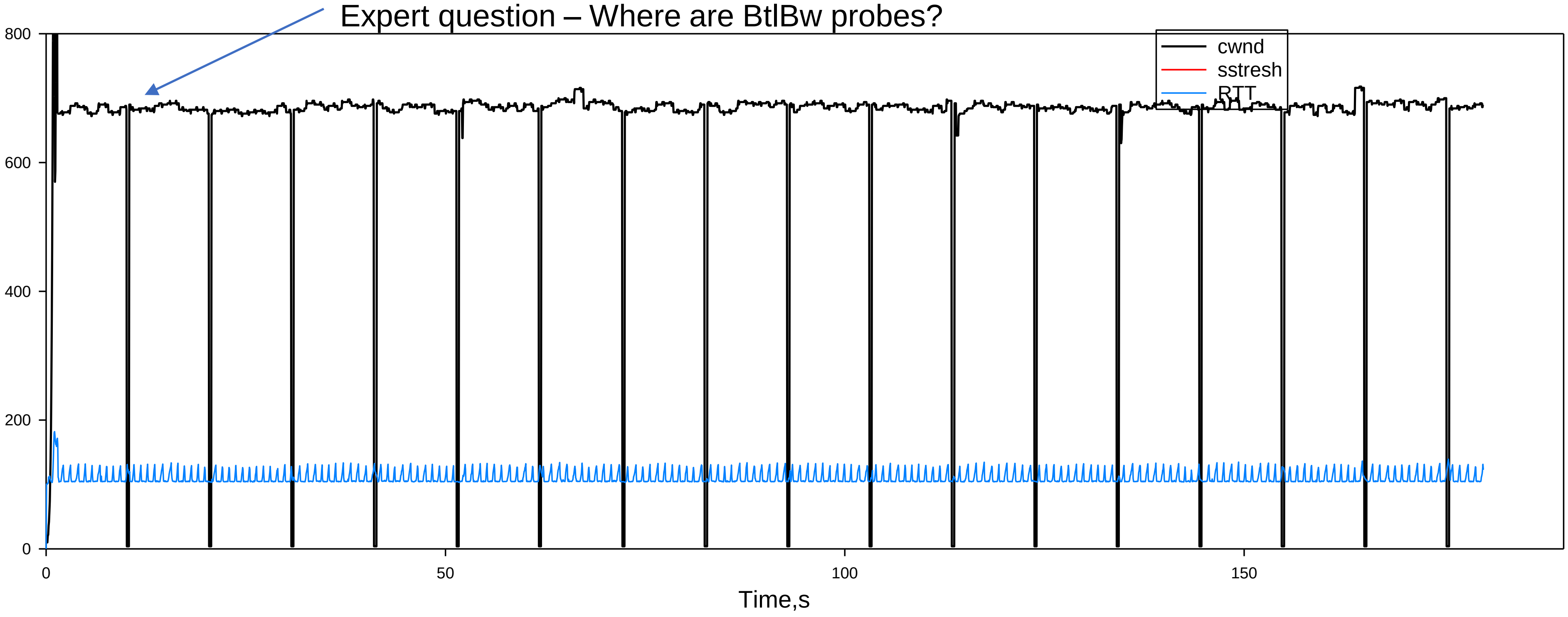
[*] if continuously sending

<u>Probe RTT phase:</u>

drop ***cwnd*** to 4 for 0,2 sec every 10 sec

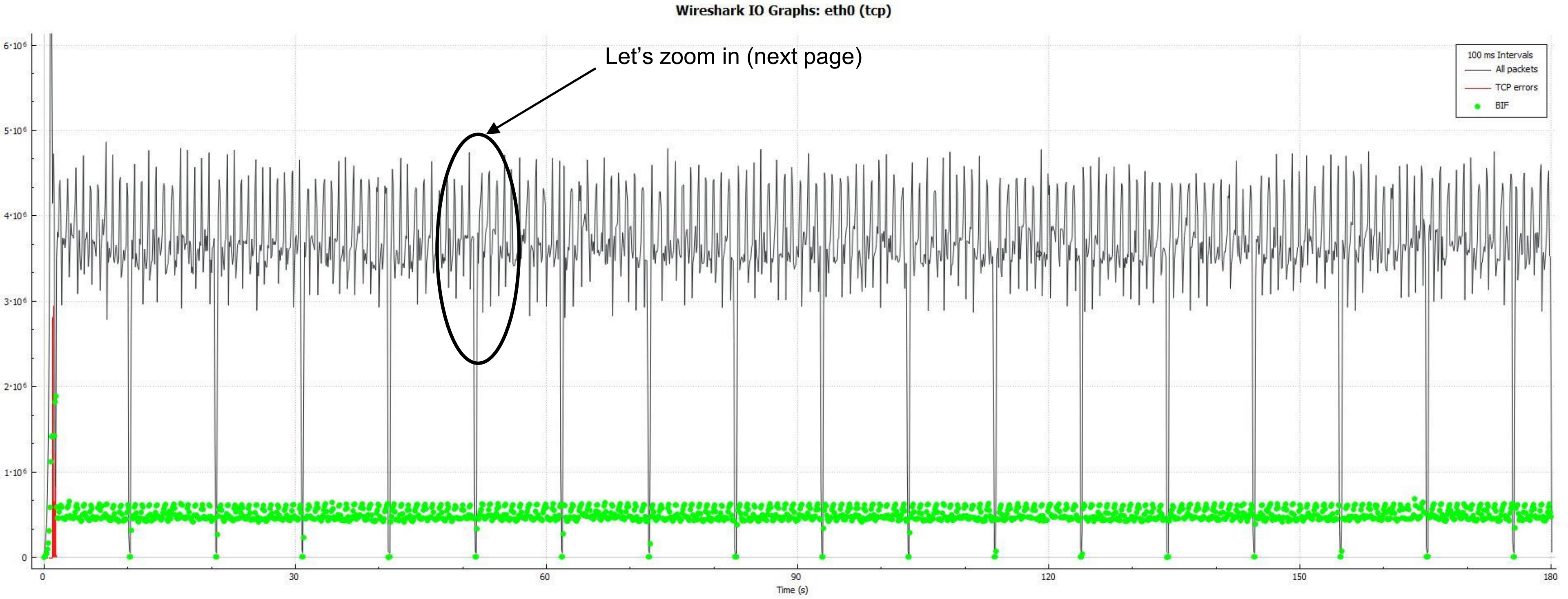
*** From "Making Linux TCP Fast". Yuchung Cheng. Neal Cardwell. Netdev 1.2 Tokyo, October, 2016"**

BBR TCP

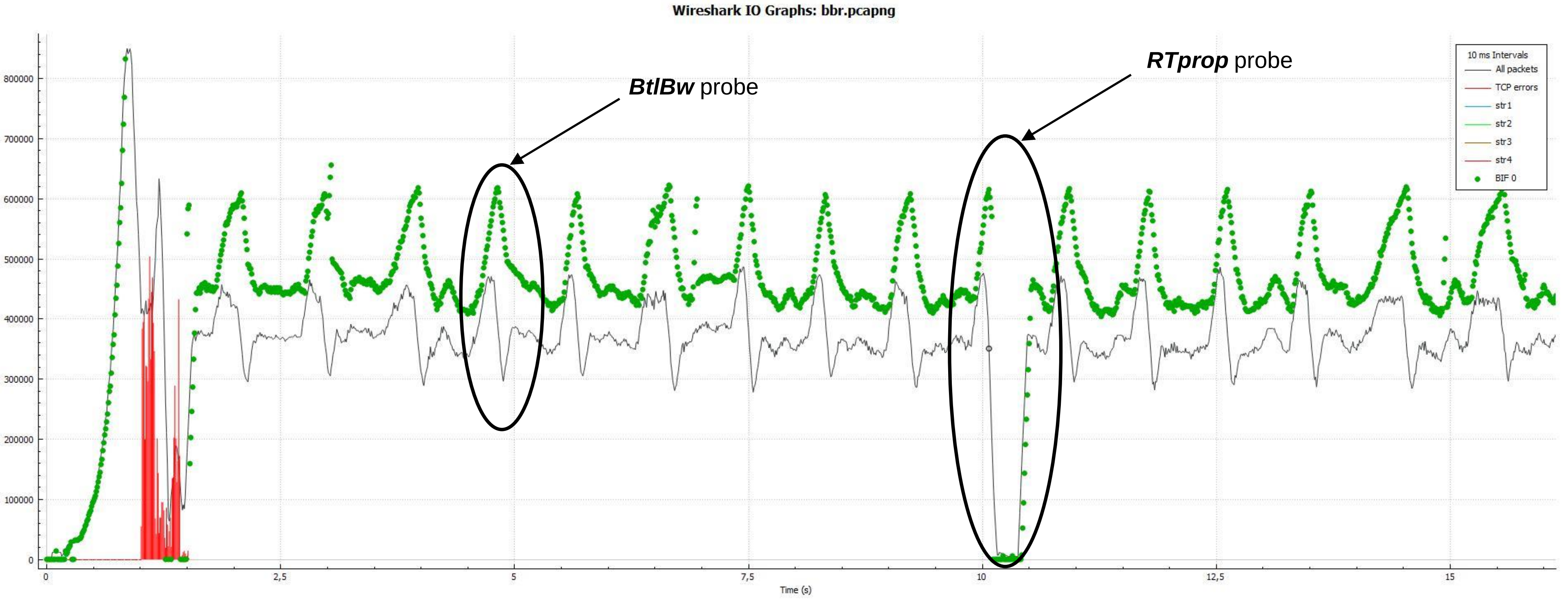


Expert question – Where are BtlBw probes?
800
600
400
200
0
0
50
100
150
Time,s
cwnd
sstresh
RTT

BBR TCP


Wireshark IO Graphs: eth0 (tcp)
Let's zoom in (next page)
100 ms Intervals
All packets
TCP errors
BIF
6·10⁶
5·10⁶
4·10⁶
3·10⁶
2·10⁶
1·10⁶
0
0
30
60
90
120
150
180
Time (s)

BBR TCP

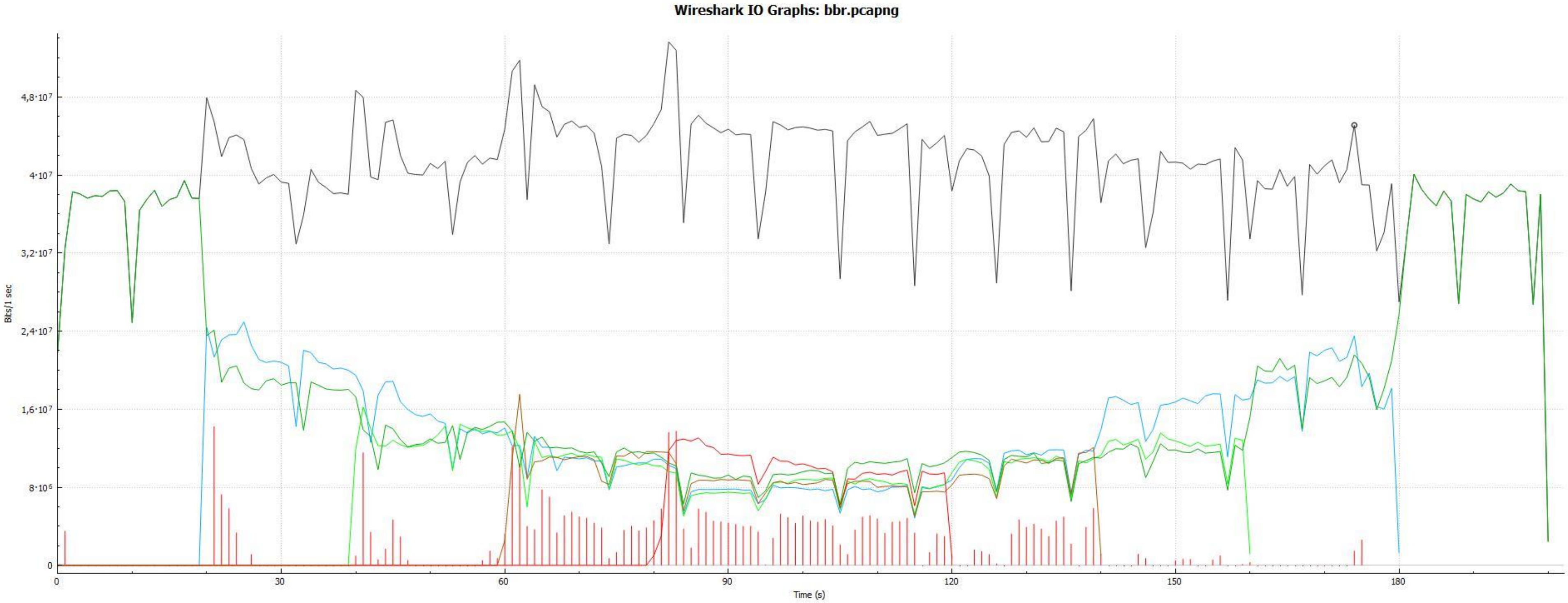


Wireshark IO Graphs: bbr.pcapng
BtlBw probe
RTprop probe
10 ms Intervals
All packets
TCP errors
str1
str2
str3
str4
BIF 0
800000
700000
600000
500000
400000
300000
200000
100000
0
0
2,5
5
7,5
10
12,5
15
Time (s)

BBR TCP

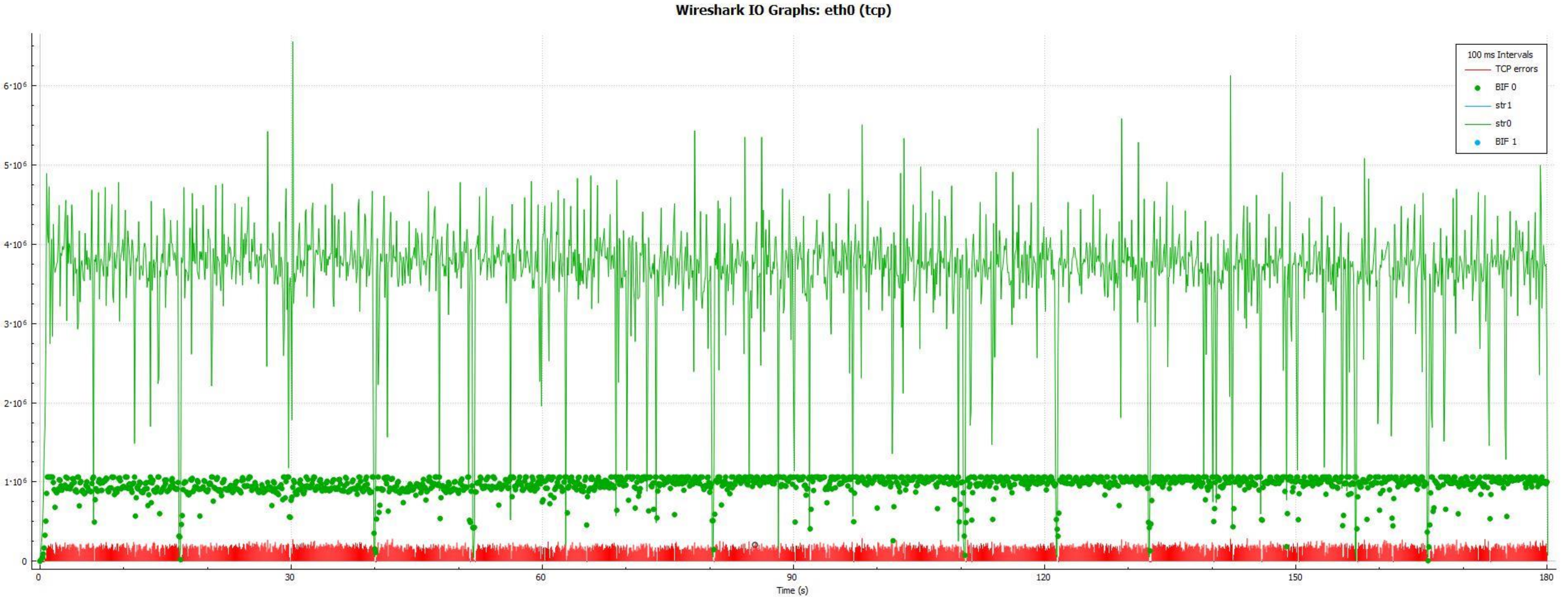
vs. Reno Friendliness

BBR TCP



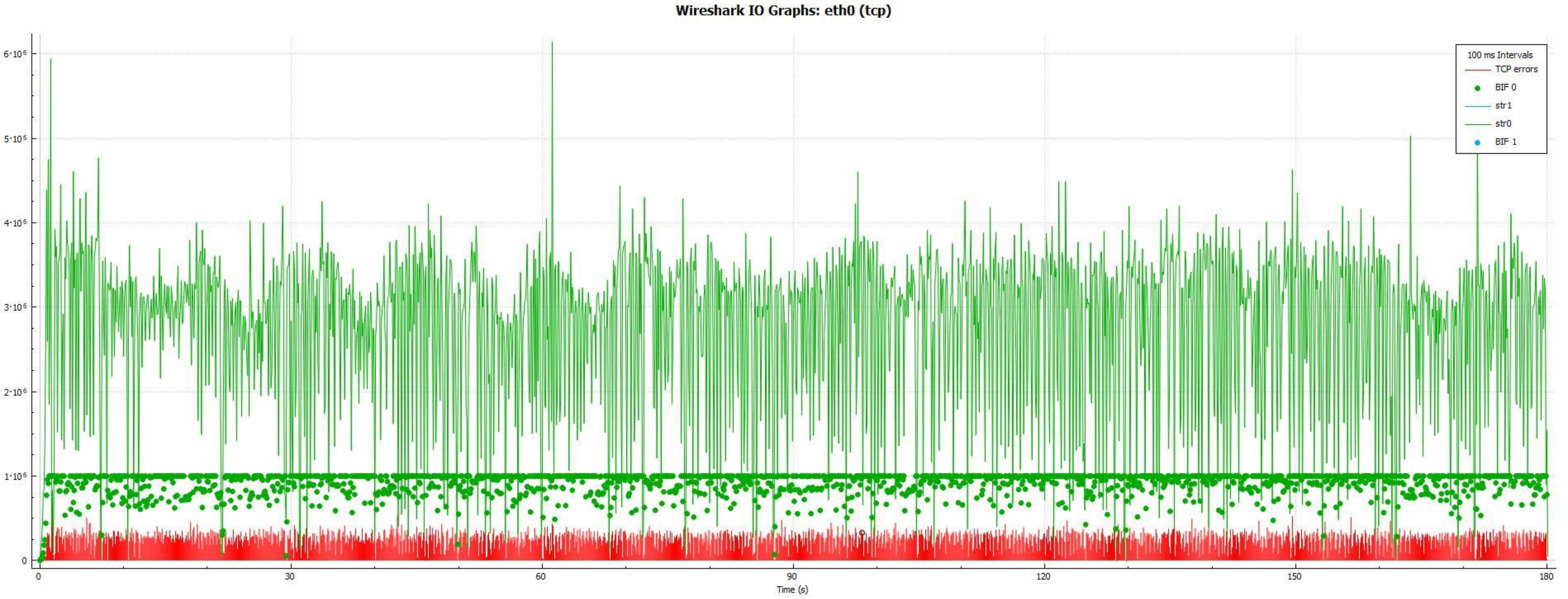
5-stream convergence

BBR TCP



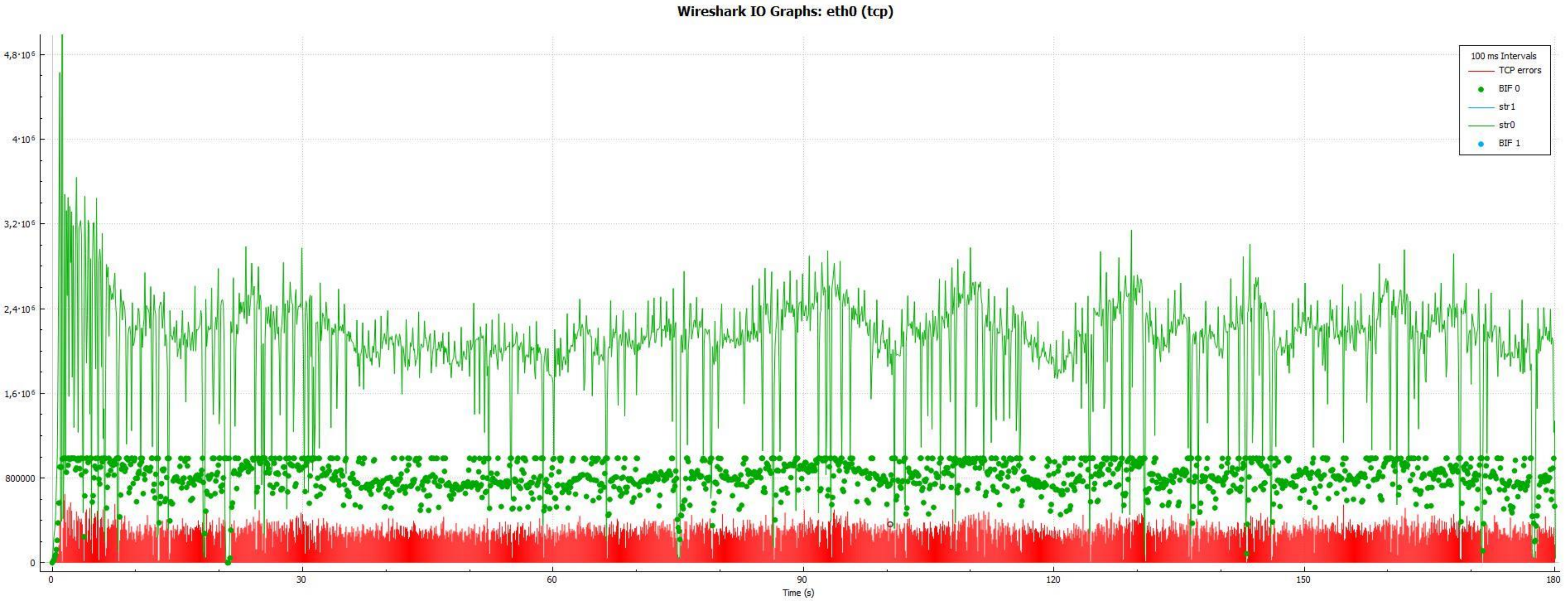
1% loss link behavior – Great, full BW rate!

BBR TCP



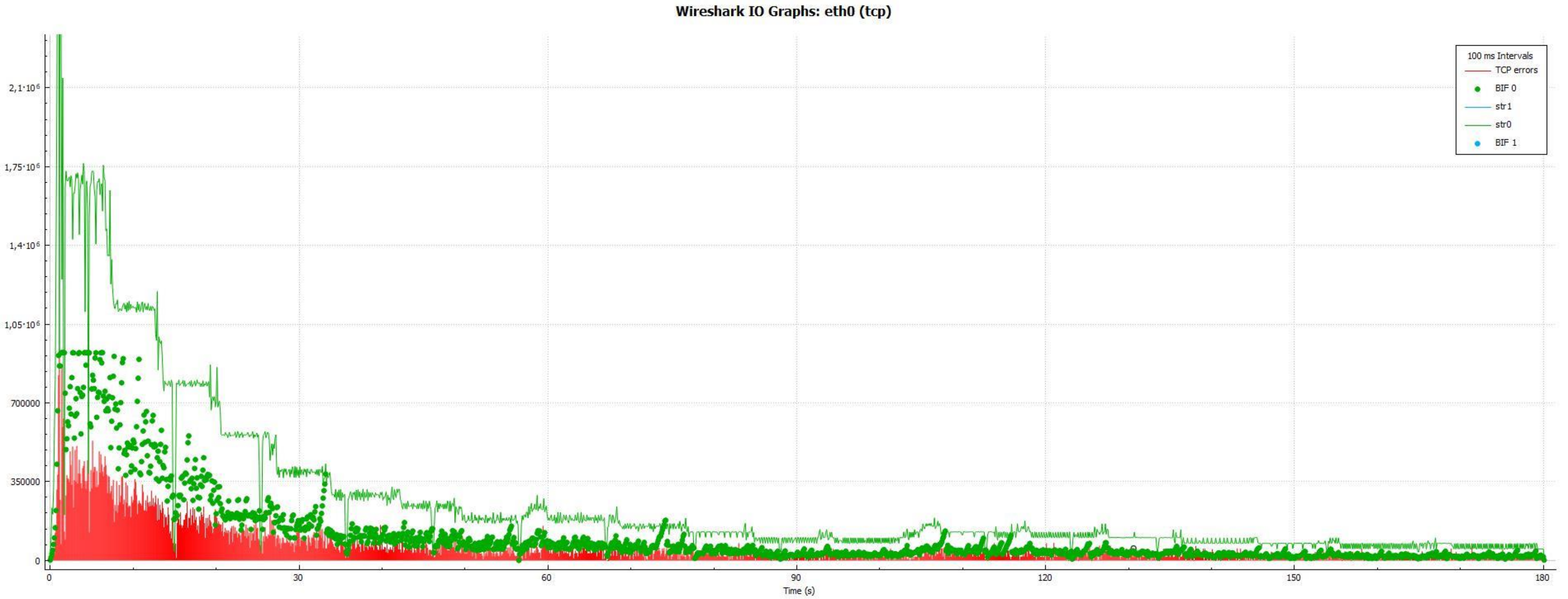
5% loss link behavior – 30Mbps out from 40, amazing!

BBR TCP



10% loss link behavior – 24Mbit out of 40 – is it possible to kill it at all?

BBR TCP



20% loss link behavior – alright, we went too far ☺, but…

BBR v2 TCP

<u>Addresses the next issues:</u>

- No ECN support
- Ignores packet loss, susceptible to high loss rate + shallow buffer combination
- Fairness with Reno/Cubic
- Non-optimal for WiFi or any path with high ACK aggregation level
- RTT probe is too aggressive

Source code isn't available as of May 2019, algorithm is undergoing tests on Youtube servers.

BBR v2 TCP

	CUBIC	BBR v1	BBR v2
Model parameters to the state machine	N/A	Throughput, RTT	Throughput, RTT, max aggregation, max inflight
Loss	Reduce cwnd by 30% on window with any loss	N/A	Explicit loss rate target
ECN	RFC3168 (Classic ECN)	N/A	DCTCP-inspired ECN
Startup	Slow-start until RTT rises (Hystart) or any loss	Slow-start until tput plateaus	Slow-start until tput plateaus or ECN/loss rate > target

*** From "BBR v2. A Model-based Congestion Control". Neal Cardwell, Yuchung Cheng and others. ICCRG at IETF 104 (Mar 2019)".**

Attacks on CA

<u>Three different types of attack are aimed to make a sender faster:</u>

1. ACK division attack (intentional accelerating of CA algorithm)

2. DUP ACK spoofing (influencing on Fast Recovery phase)

3. Optimistic ACKing (let’s ACK in advance more than we’ve got)

Used flowgrind commands

```
for cong in  'reno' 'scalable' 'htcp' 'bic' 'nv' 'cubic' 'vegas' 'hybla' 'westwood' 'veno' 'yeah' 'illinois' 'cdg' 'bbr' 'lp';
do flowgrind -H s=10.10.10.10/192.168.112.253,d=10.10.10.12/192.168.112.233 -i 0.005  -O s=TCP_CONGESTION=$cong -T s=60,d=0 | egrep ^S >
/home/vlad/csv_no_loss/{$cong}_60s_no_loss.csv;
sleep 10
done
```

Regular 1-stream probe

```
for cong in  'reno' 'scalable' 'htcp' 'highspeed' 'bic' 'cubic' 'vegas' 'hybla' 'nv' 'westwood' 'veno' 'yeah' 'illinois' 'cdg' 'bbr' 'lp';
do flowgrind -n 5 -H s=10.10.10.10/192.168.112.253,d=10.10.10.12/192.168.112.233  -O s=TCP_CONGESTION=$cong -T s=90,d=0  | egrep ^S >
/home/vlad/{$cong}_90s_intra_fair.csv;
sleep 30
done
```

5-stream intra-protocol fairness

```
for cong in  'reno' 'scalable' 'htcp' 'highspeed' 'bic' 'cubic' 'vegas' 'hybla' 'nv' 'westwood' 'veno' 'yeah' 'illinois' 'cdg' 'bbr' 'lp';
do flowgrind -n 2 -F 0 -H s=10.10.10.10/192.168.112.253,d=10.10.10.12/192.168.112.233  -O s=TCP_CONGESTION=$cong -T s=90,d=0 -F 1 -H
s=10.10.10.10/192.168.112.253,d=10.10.10.12/192.168.112.233 -O s=TCP_CONGESTION=reno -i 0.01 -T s=90,d=0 | egrep ^S >
/home/vlad/{$cong}_90s_reno_friendl.csv;
sleep 30
done
```

vs. Reno Friendliness

```
 flowgrind -n 5 -F 0 -H s=10.10.10.10/192.168.112.253,d=10.10.10.12/192.168.112.233  -O s=TCP_CONGESTION=$cong -T s=100,d=0 -F 1 -H
s=10.10.10.10/192.168.112.253,d=10.10.10.12/192.168.112.233 -O s=TCP_CONGESTION=$cong -Y s=10 -T s=80,d=0 -F 2 -H
s=10.10.10.10/192.168.112.253,d=10.10.10.12/192.168.112.233 -O s=TCP_CONGESTION=$cong -Y s=20 -T s=60,d=0 -F 3 -H
s=10.10.10.10/192.168.112.253,d=10.10.10.12/192.168.112.233 -O s=TCP_CONGESTION=$cong -Y s=30 -T s=40,d=0 -F 4 -H
s=10.10.10.10/192.168.112.253,d=10.10.10.12/192.168.112.233 -O s=TCP_CONGESTION=$cong -Y s=40 -T s=20,d=0| egrep ^S >
/home/vlad/{$cong}_100s_5str_converg.csv
```

5-stream fairness with displaced start and different streams length

Q&A

Usual questions:

1. Which CA is in use?
2. How to know current *cwnd*?
3. What are *a*, *b* values for different CA?
4. I observe static / stable BIF count. Is this CA limit?

Can you answer? If no, mail me to vlad@packettrain.net and we'll discuss it.

Thanks for your attention!