ECE 435 – Network Engineering
Lecture 15

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Announcements

- Don't forget HW#5
- Project will be posted soon

Question From Last Time

- What happens if TCP has bad checksum?
- The answer (which was hard to find authoritative) is that it silently drops it, just like UDP
- Led to interesting research path, finding articles on how good the TCP checksum is (good enough, but if you have bad luck and two bit flips in opposite directions happen in two different bytes than it would fail)
- It would catch 99.994% or so of random bad packets, but at gigabit speeds that could be many per second

TCP Congestion Control – History

- Originally no congestion control, not needed (not that much traffic)
- 1980s Internet facing "congestion collapse" – would send as fast as possible, packets would be dropped, hosts retransmit, even more congestion
- Eventually network becomes unusable for everyone
- Bob Metcalfe famously said would eat his words if internet didn't collapse in 1996 (he did eat them)

How was collapse avoided?

- TCP Congestion Control
- Can this be fixed at the TCP layer (without updating routers) in a compatible way?
- Interesting related article:

  `https://www.theregister.com/2023/09/24/tcp_congestion_control_internet/`

TCP Congestion Control

- "Congestion Avoidance and Control" by Van Jacobson (Van is his first name) and Michael Karels, SIGCOMM 1988 https://ee.lbl.gov/papers/congavoid.pdf
- Solution: detect dropped packets as congestion, throttle down if it happens

TCP Congestion Control Implementation

- Additive Increase/Multiplicative Decrease (AIMD) linearly increase bandwidth attempts, but if start losing packets back off exponentially
- Add CWND (congestion window) to control data sent in one round-trip-time with a MWND maximum-window size.
- Use the smallest of CWND/MWND
- CWND is a window only for link congestion, still need receiver window to handle receiver congestion

TCP Congestion Control – Slow Start

- Quickly probe bandwidth with a few rounds.
- CWND set to 1, 2, 4, or usually 10 packets
  packet size is Maximum Segment Size (MSS)
  MSS usually 1460 bytes on ethernet
- CWND increases by 1 each time gets ACK
  (this means it doubles, i.e. CWND=4, send 4 packets, if get 4 ACKs you inc for each one giving new CWND=8)
  until hits ssthresh (Slow-start threshold)
- Increase until packet loss, RWND met, or hit ssthresh

TCP Congestion Control – Congestion Avoidance

- Enter once slow-start hits ssthresh
- Only increase linearly (AIMD)
- Each ACK received, increase CWND by $MSS \times \frac{MSS}{CWND}$
- If detect lost packets assume loss due to congestion
  - Drop ssthresh to half
  - Start slow-start again

TCP Congestion Control – Fast Retransmit

- How do you detect packet loss?
  - Originally, you only re-transmit packet after a timer expires for missing ACK
  - Fast re-transmit: re-transmit immediately after third duplicate ACK, no wait for timer

Why Three ACKs?

- If packet lost, then will receive duplicate ACK on next transmission
- If get three identical ACKs, probably means packet lost, resend
- Why not two? Because if packets arrive out of order can also cause duplicate ACK
- Note: it's actually the 4th identical ACK, the first proper one and then 3 duplicates

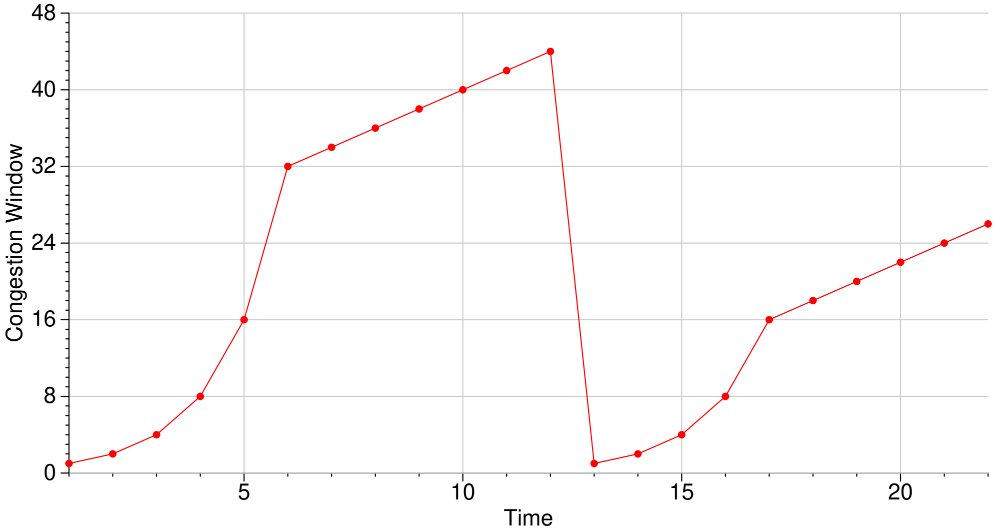
TCP Tahoe / Initial Congestion Control

- TCP Tahoe (v2) (BSD 4.2 1988)
- First release of the described congestion control (congestion avoidance, fast retransmit)
- (Van Jacobsen) [Van is his first name]
- Can have bad performance on short-connection workloads like http 1.0 where each connection for a file was own connection and never left slow-start
- Also can perform poorly on networks where packets being lost for other reasons (Wifi)

TCP Reno

- Faster recovery if three ACKs
  - Fast retransmit sent
  - Half of CWND saved as ssthresh and new CWND
  - Skip slow start and go directly to congestion avoidance
- Sawtooth Pattern
- Commonly used for 20 years

TCP Congestion Control – Sawtooth Plot



TCP Vegas

- Detect congestion from delays, rather than packet loss
- Delays measured for every packet?
- Proposed, not widely used?

TCP New Reno

- RFC 3782
- RFC 6582

Explicit Congestion Notification (ECN)

- Instead of guessing congestion at end-points, could the routers seeing congestion flip a bit in a packet to let them know?
- Special ECN bits in header routers can set
- CE (congestion encountered) bit set by router if there's congestion and both sides have marked that they have ECN enabled
- ECE bit echos back to sender the CE bit
- CWR – congestion window received

- Ability to talk ECN negotiated during the handshake at beginning
- Since these bits were originally marked as reserved, some routers didn't support them and if you enabled ECN on Linux your packets might silently get dropped. In theory things are better now.

TCP BIC

- Binary Increase Congestion Control
- Optimized for high-speed / high latency networks
- Binary search increase, additive increase, or slow start
- Linux used from 2.6.8 to 2.6.18 (2005 or so)

TCP CUBIC

- Derivative of BIC
- Update congestion window based on last duplicate ACK, rather than on ACKs
- Congestion window determined with cubic function
- Stable plateau before searching for more bandwidth
- Used by Linux post 2.6.19, MacOS (2014) and Windows (2017)

Compound TCP (Microsoft)

- Two congestion windows?
- Used since Windows Vista (?)

TCP BBR

- TCP BBR (Bottleneck BW and Round-trip) Google
- Model-based
- Concerns about fairness, if it can result in getting more than fair share of bandwidth
- Linux supports this too since 4.9? (and PRR since 3.2)

TCP other, So Many, this isn't Exhaustive

- TCP Hybla
- Agile-SD TCP
- TCP Westwood
- TCP Proportional Rate Reduction
- Others (many many)

Real World Impacts

- `https://endtimes.dev/why-your-website-should-be-under-14kb-in-size/`
- Article says if you keep your website under 14k (under 10 MSS units) it will load faster as the first 10 packets are sent under slow start but then it waits for an ACK before requesting more

Wireless Issues

- TCP detects congestion from packet loss
- Wireless networks can have a lot of packet loss, so connections might be throttled unnecessarily

Buffer Bloat

- Routers have more RAM these days and can buffer packets temporarily adding delay
- Especially when congested the buffers can fill up and packets can get stuck in queue for long time
- This can keep TCP congestion control from working well

Transport Layer Security Issues

- NMAP port scanning – send packets and find if connections are open, determine host system. Christmas Tree packets

  Find out host? options supported, sequence numbers. Also can find out uptime of system as timestamps from extension usually aren't reset each time.
- Martian packets – packets with a source of a reserved network found on routed internet

TCP Security Issues

- winnuke – set urgent pointer out of bounds, window didn't handle properly (as unusual)
- SYN Flood attack – Denial of service
  - ○ Send SYN (but no ACK) or spoof IP address, send lots of spurious SYNs followed by ACK, waits for final ACK
  - ○ tie up lots of resources Spoof, because responds to wrong address which just ignores.
  - ○ Causes lots of half-open connections

  - One solution is SYN cookies – (pick special sequence that allow throwing out connection info but able to reconstruct if an ACK comes back).
- TCP veto – inject packet with sequence and payload of next expected. That way when the real actual next one comes in, it will be silently dropped as a duplicate
- Connection hijacking – like above, but if you can also take down the real IP (DOS?) can take over the connection
- Avoiding above: Helps to have good random sequence numbers

UDP Security Issues

- UDP broadcast storm/amplification attack – broadcast bad packet to 10000 machines, all reply at once with error
- Smurf attack (same as above?) – spoof return address and send broadcast packet. All ICMP error replied overwhelm spoofed address (this doesn't work as well anymore)
- Fraggle attack –UDP attack targeting the chargen and echo ports

Making things faster

- Offload engines

Proposed Replacements

- TCP does have issues, various new protocols have been proposed
- Often held back by routers that drop packets with protocols or parameters that they don't recognize

Issues with TCP

- Any error can cause a stall
- If a single connection has multiple internal streams (HTTP/2) all streams get stopped by a single error, even if the packet isn't important for the others "Head of Line Blocking"
- Many packet overhead to start/end connection
- TCP is a raw data stream ignorant. If you need to negotiate further (like TLS) need to have a handshake after the initial TCP handshake (wasted packets)

T/TCP (never caught on)

- To send one small message (w/o UDP) can require up to 9 packets. (handshake, data transfer, shutdown)
- Instead, in the initial packet put SYN, DATA, AND FIN.
- The small message done in 3 packets.

TCP Fast Open

- Store cookie from previous connection
- Allow quick re-open/re-start without waiting for ACK

SCTP – Stream Control Transmission Protocol

- More complex
  four-way handshake (why? prevent SYN flood attacks)
- Each packet multiple control and data chunks
- Preserve boundaries (100 bytes then 50 bytes seen on other end that way)
- Allows un-ordered packet delivery
- Multi-homing/Multi-streaming
- Actually widely used in telecommunications

MP-TCP – Multipath TCP

- Balance connection across multiple interfaces
- Useful for things like multiple ethernet ports, or simultaneous mobile/wifi

QUIC

- (originally Quick UDP Internet Connections)
- RFC9000 (May 2021)
- Designed to lower latency of HTTP connections
- Over UDP for now (NATs won't route protocols they don't know)
- Used by Youtube, Google, etc. with Chromium, Firefox
- Head of Line problem with TCP

  One missing packet blocks processing all previous
- Single-way handshake if version match, otherwise has to

negotiate.

- Encrypted
  encrypted by packet rather than full stream so can handle missing packets better
- Once encrypted connection set up once, assumed still there and so sends single HELLO packet followed by data.
- Sends redundancy in packets which can be used with XOR to reconstruct missing packets. (but shown not to help much?)
- Help in roaming, TCP have to rely on timeouts to notice

this. QUIC has identifier for connection that can restart

- Implemented in userspace? Not socket interface
- Chrome would open both QUIC and TCP and drop back to TCP if no QUIC

Sample Packets

```
sudo tcpdump -XX -i eth0 tcp port 31337
listening on eth0, link-type EN10MB (Ethernet), capture size 262144 bytes
15:00:07.507769 IP 192.168.8.38.57962 > 192.168.8.138.31337: Flags [S],
seq 2755900677, win 29200,
options [mss 1460,sackOK,TS val 2941869143 ecr 0,nop,wscale 7], length 0
 0x0000:  b827 ebf8 7742 0050 b647 1cde 0800 4510  .’..wB.P.G....E.
 0x0010:  003c c79f 4000 4006 e10b c0a8 0826 c0a8  .<..@.@......&..
 0x0020:  088a e26a 7a69 a443 b505 0000 0000 a002  ...jzi.C........
 0x0030:  7210 8220 0000 0204 05b4 0402 080a af59  r..............Y
 0x0040:  5c57 0000 0000 0103 0307                 \W........
15:00:07.507901 IP 192.168.8.138.31337 > 192.168.8.38.57962: Flags [S.],
seq 3080782625, ack 2755900678, win 28960,
options [mss 1460,sackOK,TS val 3332076052 ecr 2941869143,nop,wscale 7],
length 0
 0x0000:  0050 b647 1cde b827 ebf8 7742 0800 4500  .P.G...’..wB..E.
 0x0010:  003c 0000 4000 4006 a8bb c0a8 088a c0a8  .<..@.@.........
 0x0020:  0826 7a69 e26a b7a1 0321 a443 b506 a012  .&zi.j...!.C....
 0x0030:  7120 922f 0000 0204 05b4 0402 080a c69b  q../............
 0x0040:  7214 af59 5c57 0103 0307                 r..Y\W....
15:00:07.508278 IP 192.168.8.38.57962 > 192.168.8.138.31337: Flags [.],
ack 1, win 229, options [nop,nop,TS val 2941869143 ecr 3332076052], length 0
```

```
 0x0000:  b827 ebf8 7742 0050 b647 1cde 0800 4510  .'..wB.P.G....E.
 0x0010:  0034 c7a0 4000 4006 e112 c0a8 0826 c0a8  .4..@.@......&..
 0x0020:  088a e26a 7a69 a443 b506 b7a1 0322 8010  ...jzi.C....."..
 0x0030:  00e5 2e94 0000 0101 080a af59 5c57 c69b  ...........Y\W..
 0x0040:  7214                                     r.
15:00:09.037573 IP 192.168.8.38.57962 > 192.168.8.138.31337: Flags [P.],
 seq 1:6, ack 1, win 229,
 options [nop,nop,TS val 2941870672 ecr 3332076052],
 length 5
 0x0000:  b827 ebf8 7742 0050 b647 1cde 0800 4510  .'..wB.P.G....E.
 0x0010:  0039 c7a1 4000 4006 e10c c0a8 0826 c0a8  .9..@.@......&..
 0x0020:  088a e26a 7a69 a443 b506 b7a1 0322 8018  ...jzi.C....."..
 0x0030:  00e5 3d1b 0000 0101 080a af59 6250 c69b  ..=........YbP..
 0x0040:  7214 6865 790d 0a                        r.hey..
15:00:09.037634 IP 192.168.8.138.31337 > 192.168.8.38.57962: Flags [.],
ack 6, win 227, options [nop,nop,TS val 3332077582 ecr 2941870672], length 0
 0x0000:  0050 b647 1cde b827 ebf8 7742 0800 4500  .P.G...'..wB..E.
 0x0010:  0034 3e1c 4000 4006 6aa7 c0a8 088a c0a8  .4>.@.@.j.......
 0x0020:  0826 7a69 e26a b7a1 0322 a443 b50b 8010  .&zi.j...".C....
 0x0030:  00e3 9227 0000 0101 080a c69b 780e af59  ...'........x..Y
 0x0040:  6250                                     bP
15:00:09.039363 IP 192.168.8.138.31337 > 192.168.8.38.57962: Flags [P.],
 seq 1:6, ack 6, win 227, options [nop,nop,TS val 3332077584 ecr 2941870672],
 length 5
 0x0000:  0050 b647 1cde b827 ebf8 7742 0800 4500  .P.G...’..wB..E.
 0x0010:  0039 3e1d 4000 4006 6aa1 c0a8 088a c0a8  .9>.@.@.j.......
 0x0020:  0826 7a69 e26a b7a1 0322 a443 b50b 8018  .&zi.j..."".C....
 0x0030:  00e3 922c 0000 0101 080a c69b 7810 af59  ...,........x..Y
 0x0040:  6250 4845 590d 0a                        bPHEY..
15:00:09.039650 IP 192.168.8.38.57962 > 192.168.8.138.31337: Flags [.],
ack 6, win 229, options [nop,nop,TS val 2941870674 ecr 3332077584], length 0
 0x0000:  b827 ebf8 7742 0050 b647 1cde 0800 4510  .’..wB.P.G....E.
 0x0010:  0034 c7a2 4000 4006 e110 c0a8 0826 c0a8  .4..@.@......&..
 0x0020:  088a e26a 7a69 a443 b50b b7a1 0327 8010  ...jzi.C.....’..
 0x0030:  00e5 2293 0000 0101 080a af59 6252 c69b  .."........YbR..
 0x0040:  7810                                     x.
15:00:12.469960 IP 192.168.8.38.57962 > 192.168.8.138.31337: Flags [F.],
 seq 6, ack 6, win 229, options [nop,nop,TS val 2941874105 ecr 3332077584],
 length 0
 0x0000:  b827 ebf8 7742 0050 b647 1cde 0800 4510  .’..wB.P.G....E.
 0x0010:  0034 c7a3 4000 4006 e10f c0a8 0826 c0a8  .4..@.@......&..
 0x0020:  088a e26a 7a69 a443 b50b b7a1 0327 8011  ...jzi.C.....’..
 0x0030:  00e5 152b 0000 0101 080a af59 6fb9 c69b  ...+.......Yo...
 0x0040:  7810                                     x.
15:00:12.471639 IP 192.168.8.138.31337 > 192.168.8.38.57962: Flags [F.],
 seq 6, ack 7, win 227, options [nop,nop,TS val 3332081016 ecr 2941874105],
 length 0
 0x0000:  0050 b647 1cde b827 ebf8 7742 0800 4500  .P.G...’..wB..E.
 0x0010:  0034 3e1e 4000 4006 6aa5 c0a8 088a c0a8  .4>.@.@.j.......
 0x0020:  0826 7a69 e26a b7a1 0327 a443 b50c 8011  .&zi.j...'.C....
 0x0030:  00e3 9227 0000 0101 080a c69b 8578 af59  ...'.........x.Y
 0x0040:  6fb9                                     o.
15:00:12.471921 IP 192.168.8.38.57962 > 192.168.8.138.31337: Flags [.],
 ack 7, win 229, options [nop,nop,TS val 2941874107 ecr 3332081016], length 0
 0x0000:  b827 ebf8 7742 0050 b647 1cde 0800 4510  .'..wB.P.G....E.
 0x0010:  0034 c7a4 4000 4006 e10e c0a8 0826 c0a8  .4..@.@......&..
 0x0020:  088a e26a 7a69 a443 b50c b7a1 0328 8010  ...jzi.C.....(..
 0x0030:  00e5 07c0 0000 0101 080a af59 6fbb c69b  ...........Yo...
 0x0040:  8578                                     .x
```