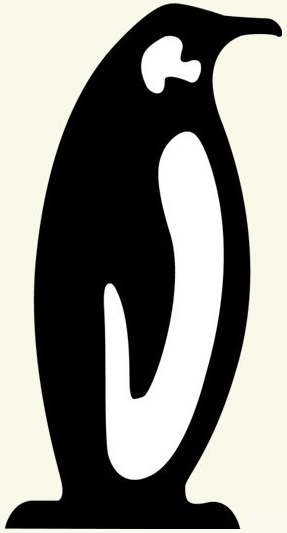


Linux Plumbers Conference

Richmond, Virginia | November 13-15, 2023

connect() - why you so slow?

Frederick Lawler

Systems Engineer @ Cloudflare

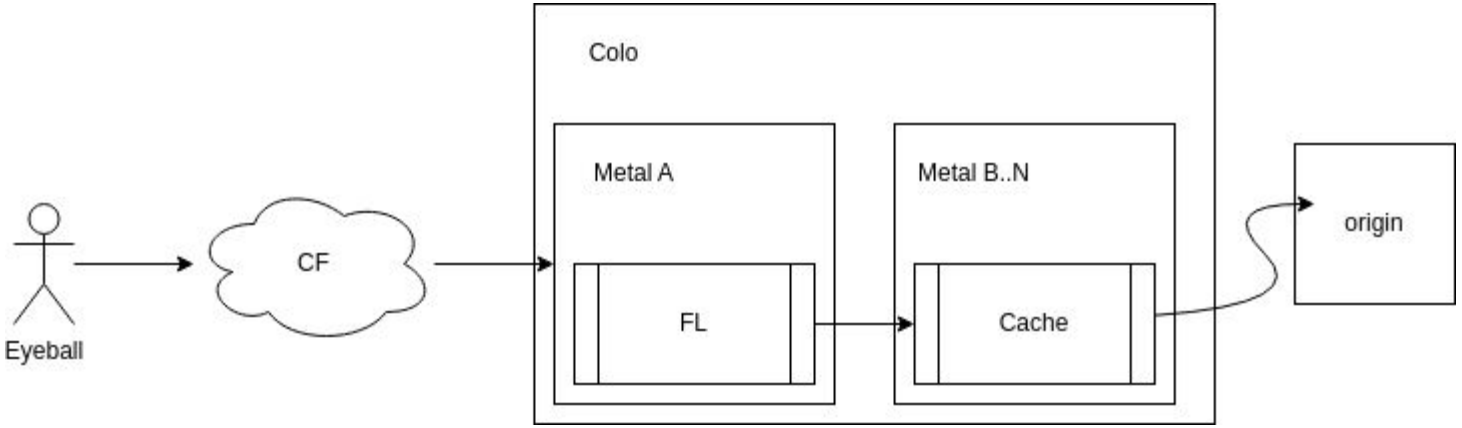
- security_create_user_ns()
- CVE-2022-47929: traffic control noqueue no problem?
- pci_(alert|crit|dbg|emerg|err|info|notice|warn) printk macros

CLOUDFLARE

50k egress unicast connections to a single destination… Who does that?

CLOUDFLARE

CDN request flow for uncached assets



CLOUDFLARE

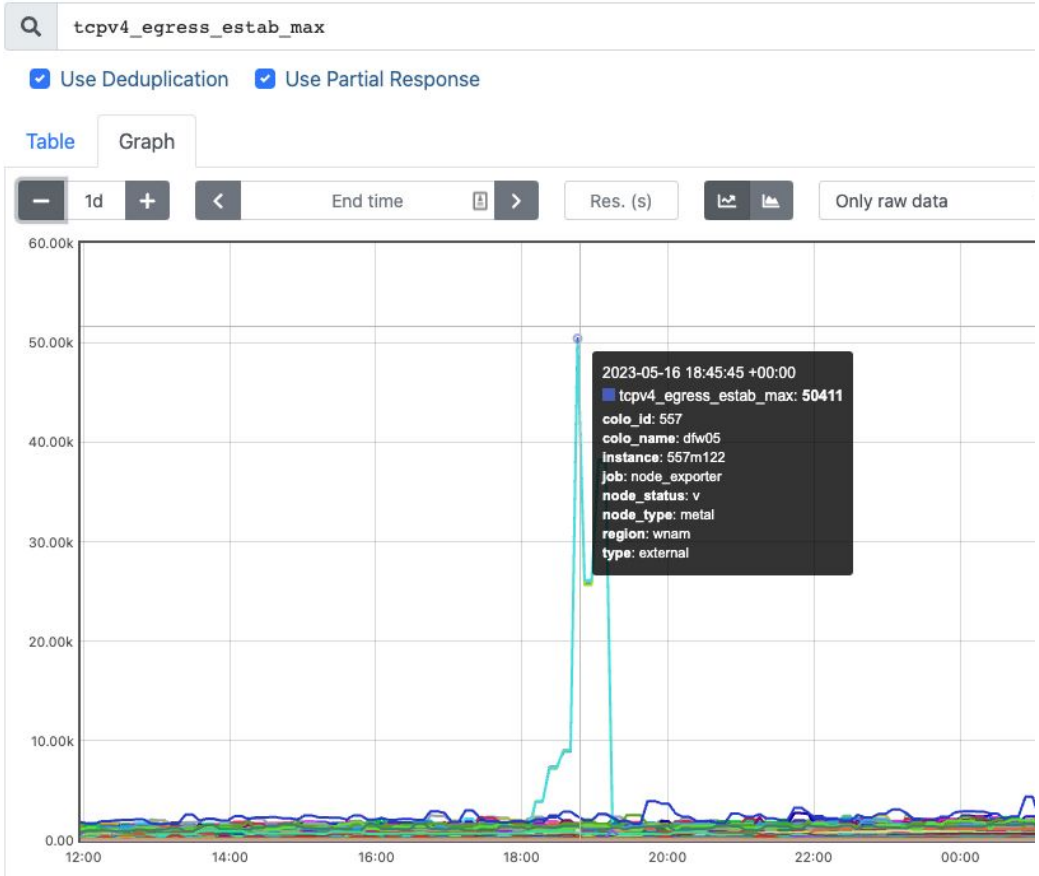
```
$ sysctl net.ipv4.ip_local_port_range
net.ipv4.ip_local_port_range = 9024   65535
```

CLOUDFLARE

bind() before connect()

```
sk = socket(AF_INET, SOCK_STREAM)
sk.setsockopt(IPPROTO_IP, IP_BIND_ADDRESS_NO_PORT, 1)
sk.bind((src_ip, 0))
sk.connect((dest_ip, dest_port))
```

How to stop running out of ephemeral ports and start to love long-lived connections

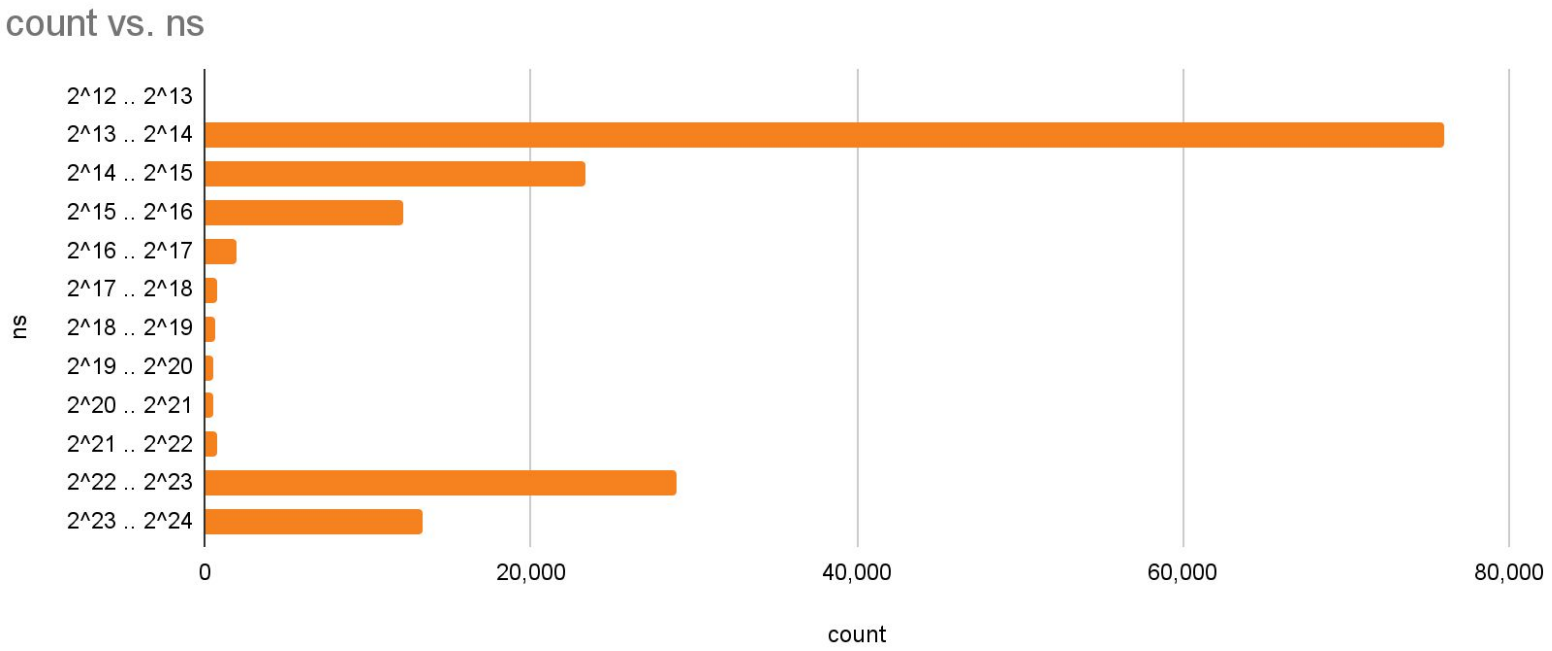

tcpv4_egress_estab_max
Use Deduplication
Use Partial Response
Table
Graph
1d
End time
Res. (s)
Only raw data
60.00k
50.00k
40.00k
30.00k
20.00k
10.00k
0.00
12:00
14:00
16:00
18:00
20:00
22:00
00:00
2023-05-16 18:45:45 +00:00
tcpv4_egress_estab_max: 50411
colo_id: 557
colo_name: dfw05
instance: 557m122
job: node_exporter
node_status: v
node_type: metal
region: wnam
type: external

CLOUDFLARE

2 IPv4 addresses for this service

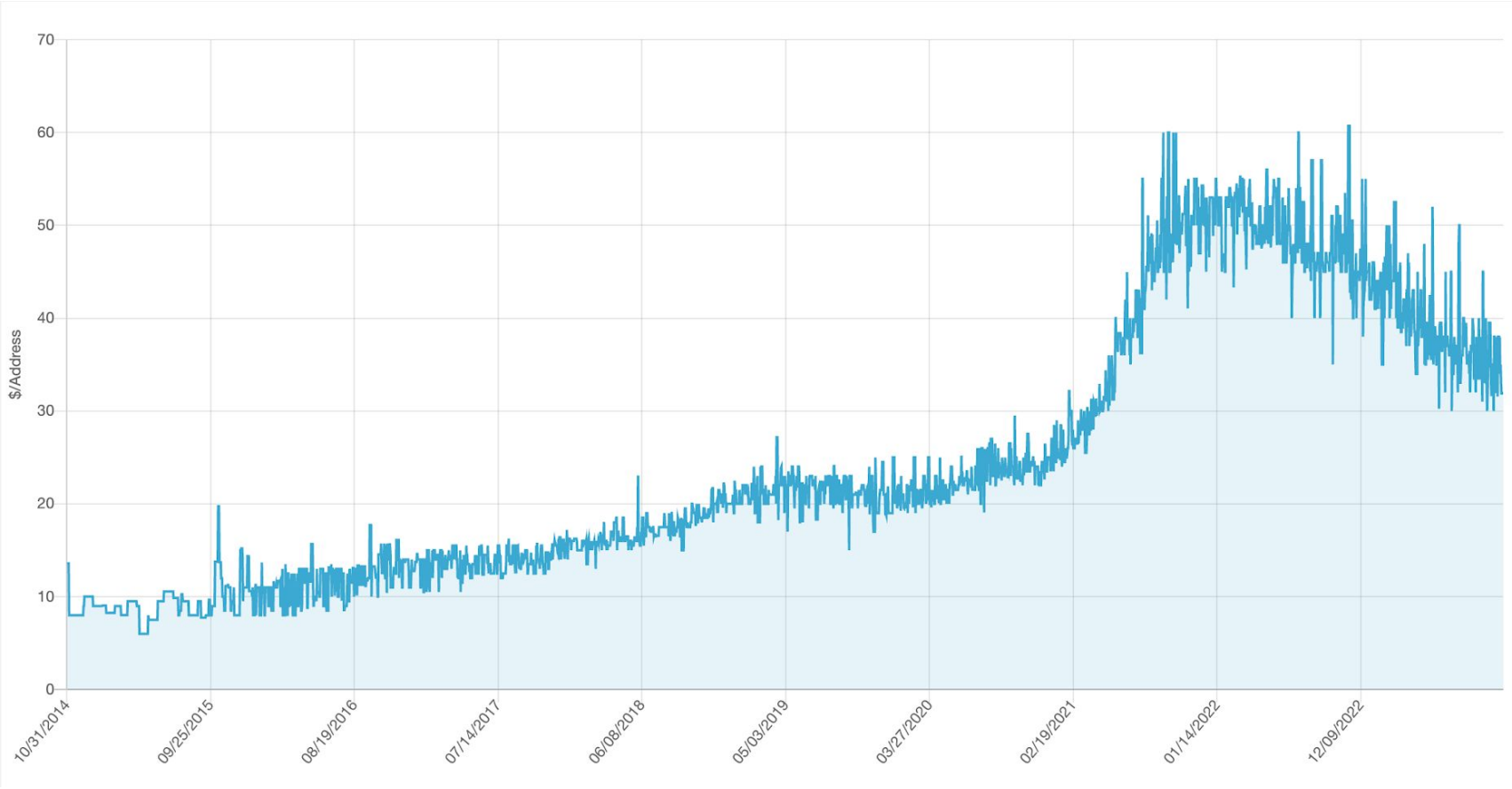
CLOUDFLARE

tcp_v4_connect() func latency 2 IPv4 address



CLOUDFLARE

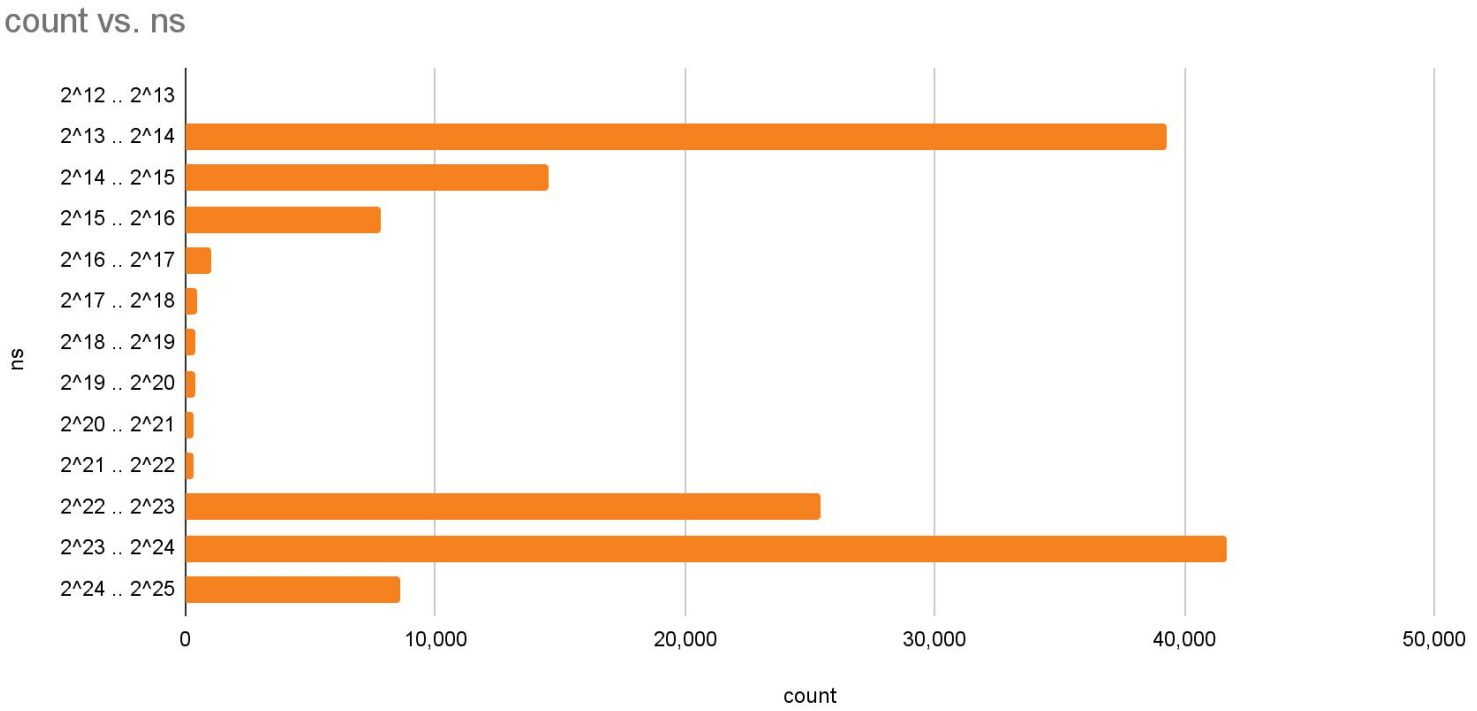
1 IPv4 addresses for this service



IPv4 sales data. Source: Hilco Streambank.

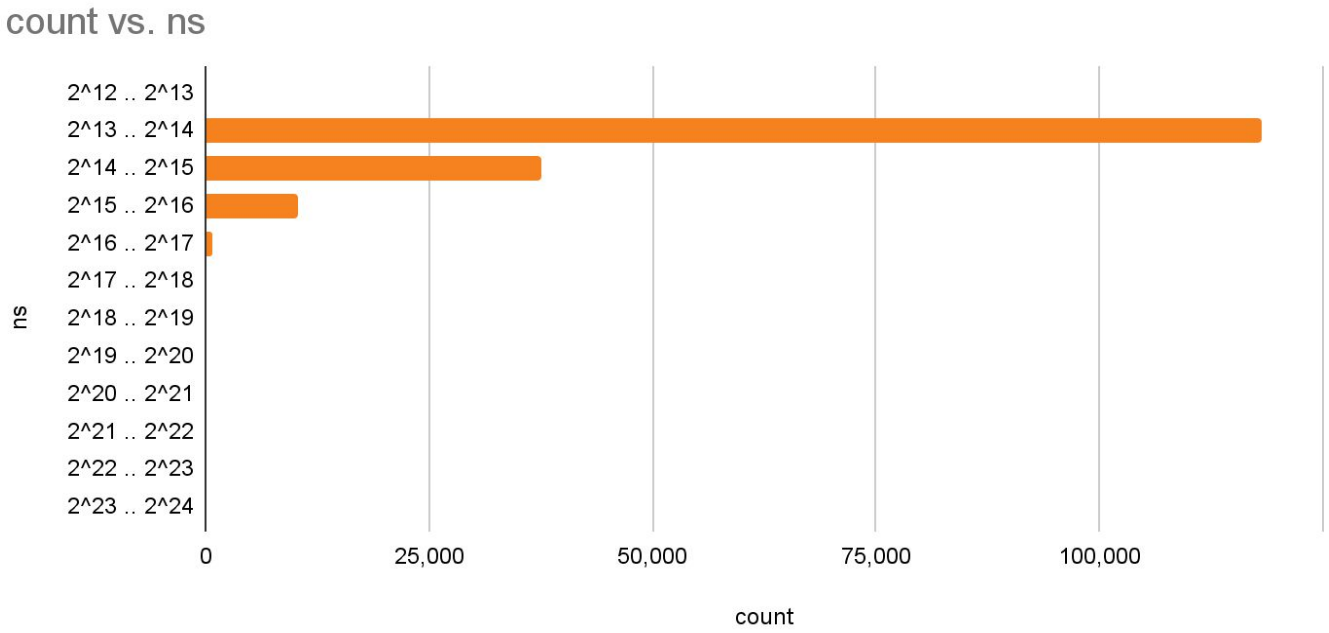
CLOUDFLARE

tcp_v4_connect() func latency 1 IPv4 address



CLOUDFLARE

tcp_v4_connect() func latency 3 IPv4 address (for fun)



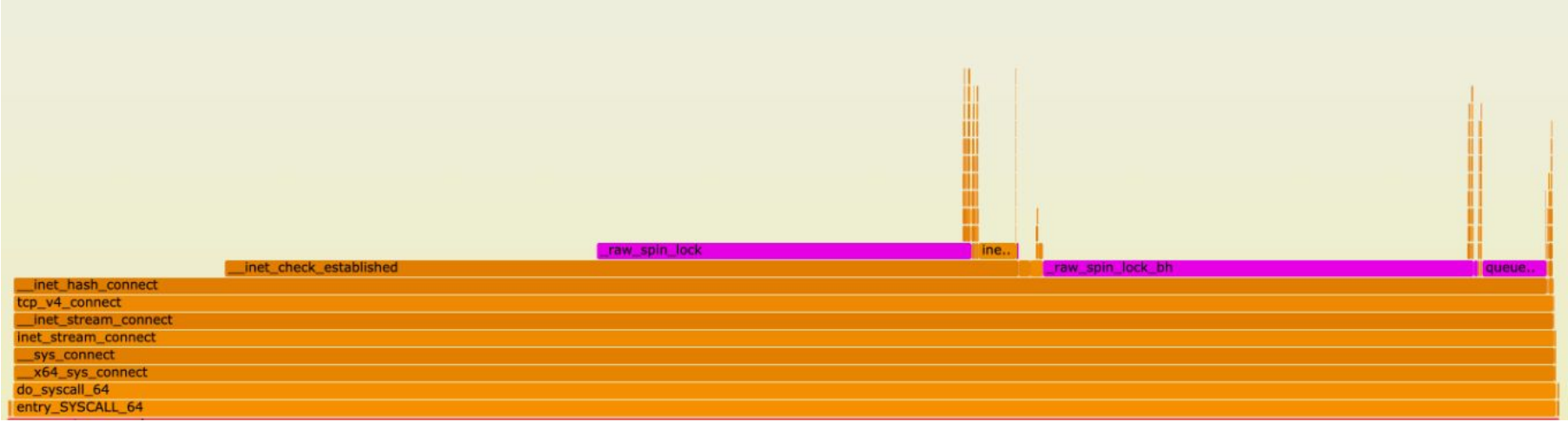
CLOUDFLARE

This is fine for most workloads, but for Cloudflare...

- Customers largely still leverage IPv4
- Similar performance with 1 IPv4's as we'd see with 3
- Leverage our infrastructure to lazily hand off excess connections
  ie. fail fast

Time to investigate: TCP connect() why you so slow?

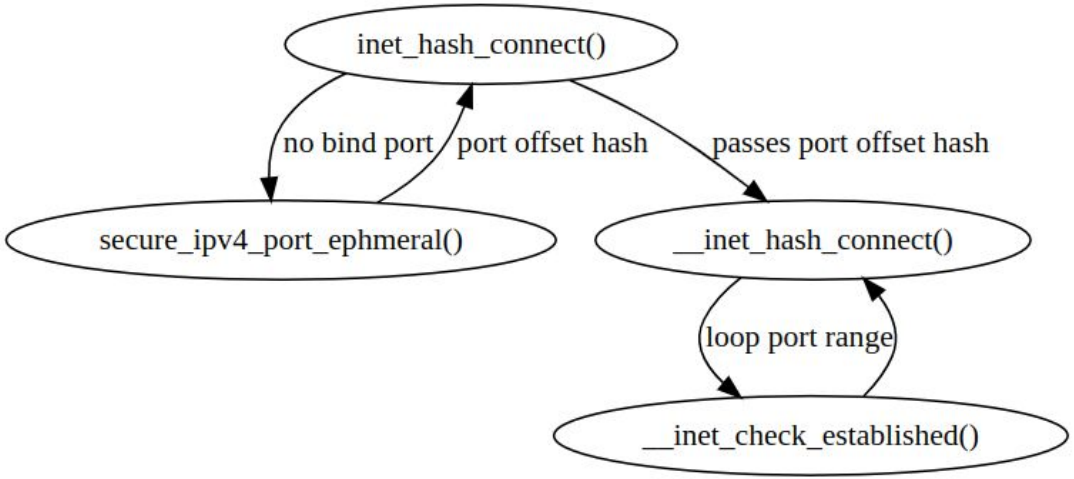
Time to investigate: TCP connect() why you so slow?



CLOUDFLARE

inet_hash_connect() overview

- Called in both TCP IPv4 & IPv6 contexts; but we'll be focusing on IPv4
- We assume the kernel has to pick a port



CLOUDFLARE

__inet_hash_connect() overview

net/ipv4/inet_hashtables.c:__inet_hash_connect

```
   offset &= ~1U;

other_parity_scan:
    port = low + offset;
    for (i = 0; i < remaining; i += 2, port += 2) {
        if (unlikely(port >= high))
            port -= remaining;

        inet_bind_bucket_for_each(tb, &head->chain) {
            if (inet_bind_bucket_match(tb, net, port, l3mdev)) {
                if (!check_established(death_row, sk,
                                       port, &tw))
                    goto ok;
                goto next_port;
            }
        }
    }

    offset++;
    if ((offset & 1) && remaining > 1)
        goto other_parity_scan;
```

CLOUDFLARE

__inet_hash_connect() overview: initial port selection

```
   offset &= ~1U;

other_parity_scan:
    port = low + offset;
    for (i = 0; i < remaining; i += 2, port += 2) {
        if (unlikely(port >= high))
            port -= remaining;

        inet_bind_bucket_for_each(tb, &head->chain) {
            if (inet_bind_bucket_match(tb, net, port, l3mdev)) {
                if (!check_established(death_row, sk,
                                       port, &tw))
                    goto ok;
                goto next_port;
            }
        }
    }

    offset++;
    if ((offset & 1) && remaining > 1)
        goto other_parity_scan;
```

- Offset is randomly generated
- Offset is set to an even number
- Picked port is either “even” or “odd” based on net.ipv4.ip_local_port_range’s low port eg. 9024

CLOUDFLARE

__inet_hash_connect() overview: the loop

```
   offset &= ~1U;

other_parity_scan:
    port = low + offset;
    for (i = 0; i < remaining; i += 2, port += 2) {
        if (unlikely(port >= high))
            port -= remaining;

        inet_bind_bucket_for_each(tb, &head->chain) {
            if (inet_bind_bucket_match(tb, net, port, l3mdev)) {
                if (!check_established(death_row, sk,
                                       port, &tw))
                    goto ok;
                goto next_port;
            }
        }
    }

    offset++;
    if ((offset & 1) && remaining > 1)
        goto other_parity_scan;
```

- Check if the socket is unique
- check_established() == __inet_check_established()

CLOUDFLARE

Is __inet_check_established() a problem?

- Tested benchmarks on a quiet virtual machine
- No other connections were established for the same src/dest ip + dest port
- Therefore, negligible impact
- Bind buckets will fill up eventually!

The quantum state of a TCP port

CLOUDFLARE

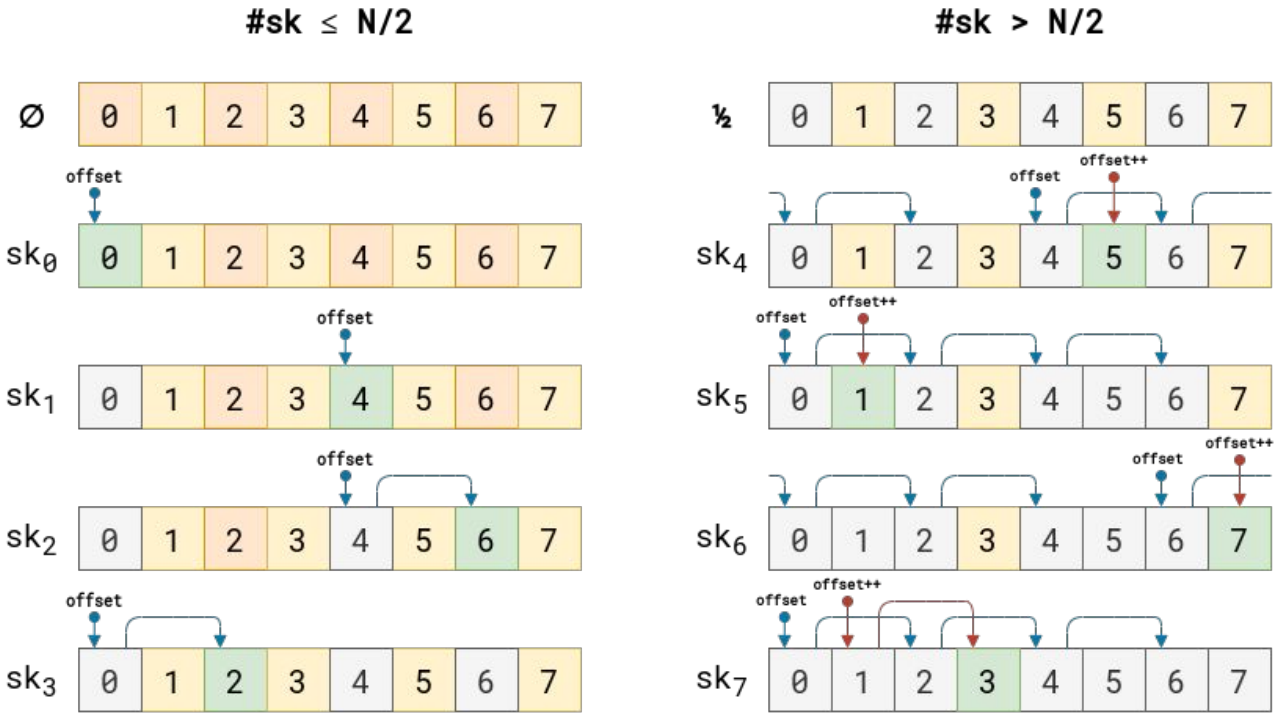
__inet_hash_connect() overview: the loop

```
   offset &= ~1U;

other_parity_scan:
    port = low + offset;
    for (i = 0; i < remaining; i += 2, port += 2) {
        if (unlikely(port >= high))
            port -= remaining;

        inet_bind_bucket_for_each(tb, &head->chain) {
            if (inet_bind_bucket_match(tb, net, port, l3mdev)) {
                if (!check_established(death_row, sk,
                                       port, &tw))
                    goto ok;
                goto next_port;
            }
        }
    }

    offset++;
    if ((offset & 1) && remaining > 1)
        goto other_parity_scan;
```

- Loop through first half of the ephemeral range then second
- Every other port is tested in sequence

CLOUDFLARE

__inet_hash_connect() overview: the loop

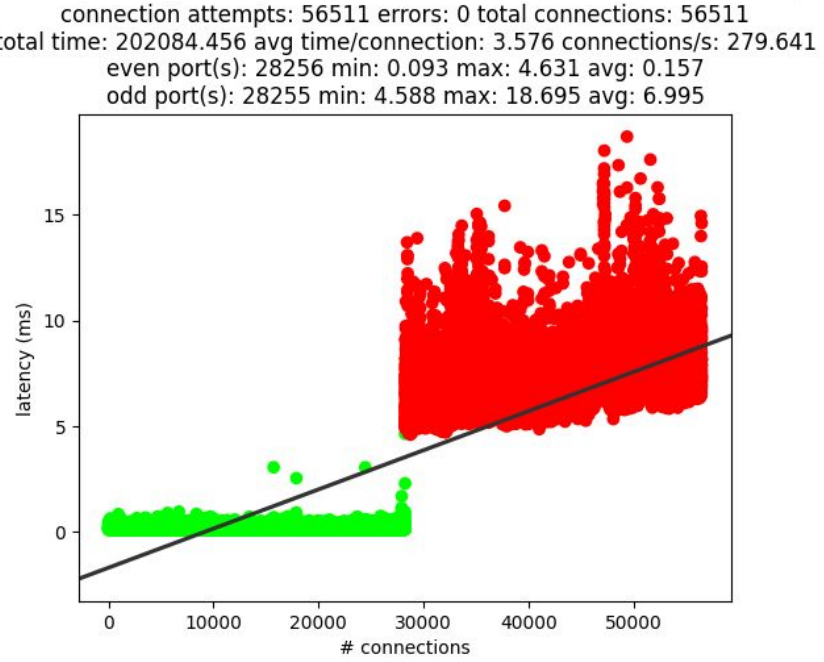


CLOUDFLARE

Is the loop the problem?

- Via experimentation
- Counted the even ports green, odd ports red
- Our port range dictates we always loop through even ports first

3.3 min @ 56k connections



CLOUDFLARE

Our conclusion

- Exhausting half the net.ipv4.ip_local_port_range is fast
- The port looping appears to be our primary bottleneck
- Evidenced by a previous attempt [PATCH] tcp: avoid unnecessary loop if even ports are used up and was not merged

CLOUDFLARE

Tracking port parity switches

```
#!/usr/bin/env bpftrace

kretfunc:vmlinux:inet_hash_connect /retval == 0/ {
    $port = args->sk->__sk_common.skc_num;
    @procs[comm,cgroup] += $port & 1;
}
```

```
rate(connect_port_parity_switches_total)[1m]
```

Prometheus exporter for eBPF metrics

What do?

CLOUDFLARE

Some feasible, but not viable solutions for our case

1. Split egress unicast connections over 2..N IP addresses
2. Introduce a sysctl to manipulate connect
3. Pick a random port in userspace, and bind() with that
4. Leverage the new IP_LOCAL_PORT_RANGE socket option (v6.3.y)*

CLOUDFLARE

Split egress unicast connections over 2..N IP addresses

- Leaks networking configuration to user space
- No ability to tell the interface to balance between assigned IP's or IP blocks
- Requires IP_BIND_ADDRESS_NO_PORT socket option + bind() before connect() pattern
- We do this strategy now, but want to reduce to 1 IP

CLOUDFLARE

Introduce a sysctl to manipulate connect

- Kernel modification
- [PATCH] tcp: avoid unnecessary loop if even ports are used up

CLOUDFLARE

Pick a random port in userspace, and bind() before connect()

- Requires bind() before connect()
- Syscall overhead and ~8-12 attempts per connect closer to exhaustion
- Good up to ~70-80% port range utilization

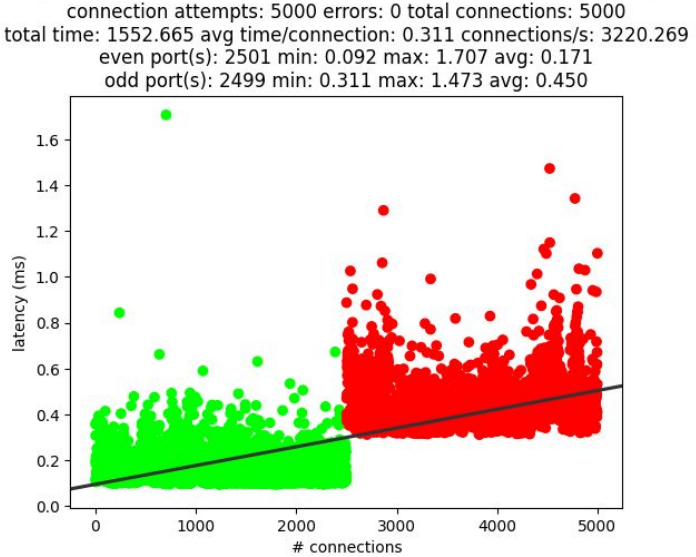
```
sys = get_ip_local_port_range()
estab = 0
i = sys.hi
while i >= 0:
    if estab >= sys.hi:
        break

    random_port = random.randint(
        sys.lo, sys.hi)
    connection = attempt_connect(random_port)
    if connection is None:
        i += 1
        continue

    i -= 1
    estab += 1
```

CLOUDFLARE

Leverage the new IP_LOCAL_PORT_RANGE socket option (v6.3.y)

- Max # of connect() as range
- Pre-allocation of partitions to balance between
- Loop problem still persists

5k window @ 1.5 sec

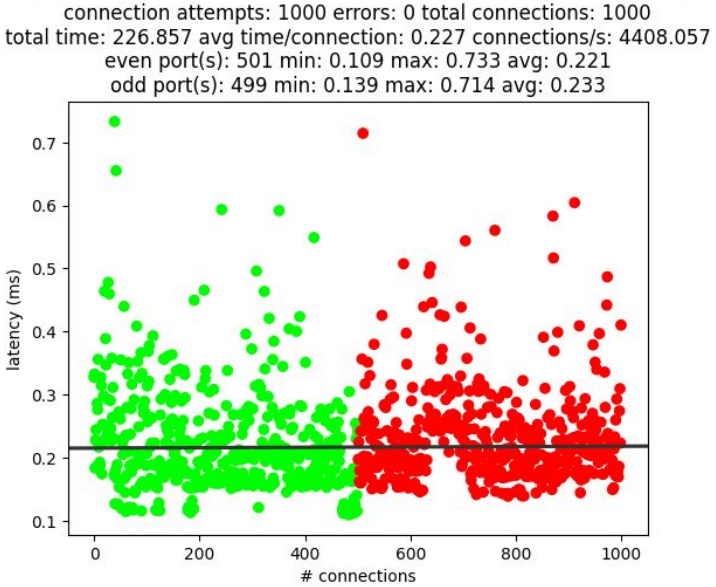


CLOUDFLARE

Leverage the new IP_LOCAL_PORT_RANGE socket option (v6.3.y)

- Lower range works better
- Overlapping ranges is possible
- Overlap is determined by implementation

1k window @ 2.2 ms

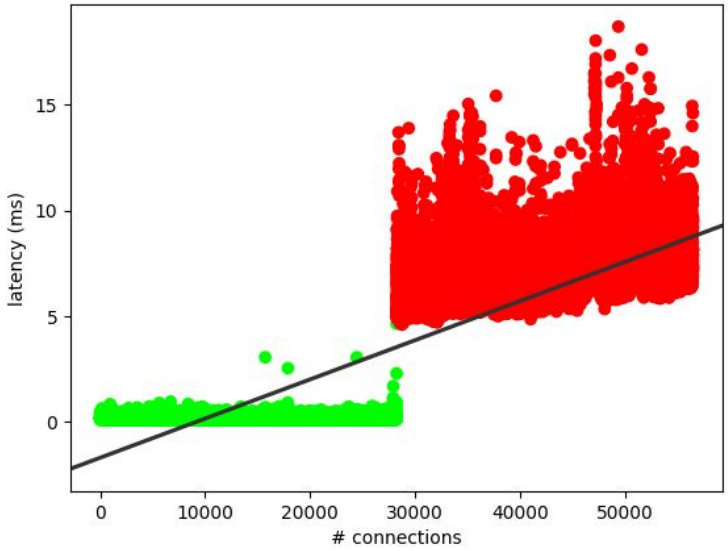


CLOUDFLARE

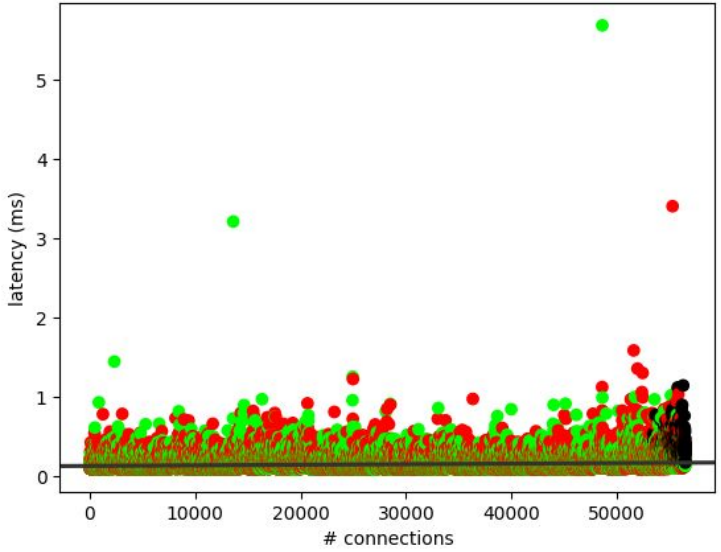
Leverage the new IP_LOCAL_PORT_RANGE socket option (v6.3.y) + random offset

3.3 min → 9.3 sec!

connection attempts: 56511 errors: 0 total connections: 56511
total time: 202084.456 avg time/connection: 3.576 connections/s: 279.641
even port(s): 28256 min: 0.093 max: 4.631 avg: 0.157
odd port(s): 28255 min: 4.588 max: 18.695 avg: 6.995



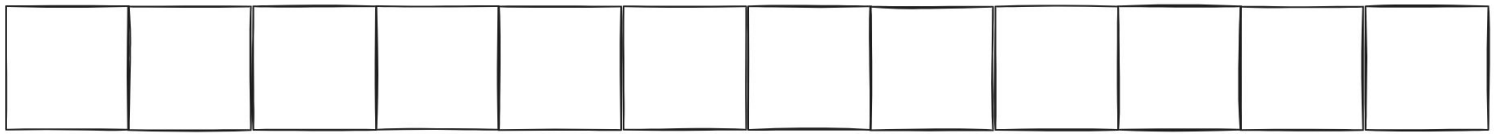
connection attempts: 56511 errors: 1054 total connections: 55457
total time: 9393.775 avg time/connection: 0.166 connections/s: 6015.792
even port(s): 27691 min: 0.091 max: 5.683 avg: 0.162
odd port(s): 27766 min: 0.089 max: 3.405 avg: 0.163



CLOUDFLARE

Implementation details

sys.lo = 9024; sys.hi = 65535



CLOUDFLARE

Implementation details

window.lo = 0; window.hi = 1000
range = window.hi - window.lo
offset = random(sys.lo, sys.hi - range)
window.lo = offset; window.hi = offset + range
setsockopt(SOL_IP, IP_LOCAL_PORT_RANGE, window.lo | (window.hi << 16))

CLOUDFLARE

Implementation details

- Overlap is OK
- Reattempts may be necessary depending on use case
- Larger net.ipv4.ip_local_port_range is better with smaller selection window

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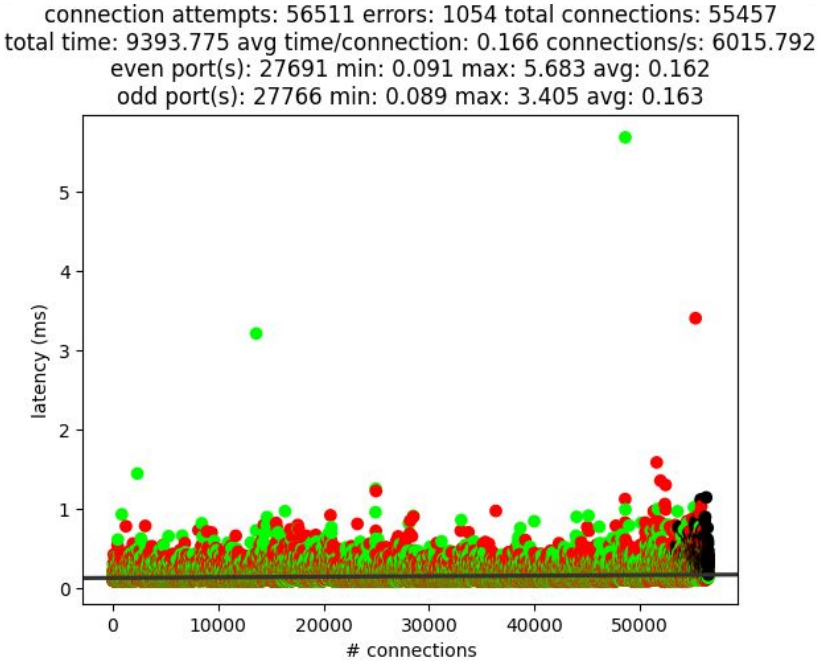
In summary

- Leverages a random port offset + random low port in range to be even or odd
- Allows kernel to perform loop over a small + configurable local port range
- Overlaps windows on top of another

3.3 min → 9.3 sec @ 56k connections 1k window



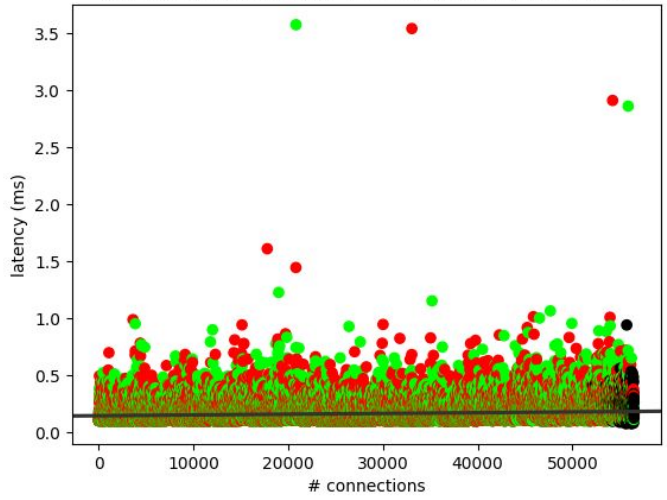
CLOUDFLARE

Performance 56k unicast egress connections

3.3 min → 9.6 sec

500 window

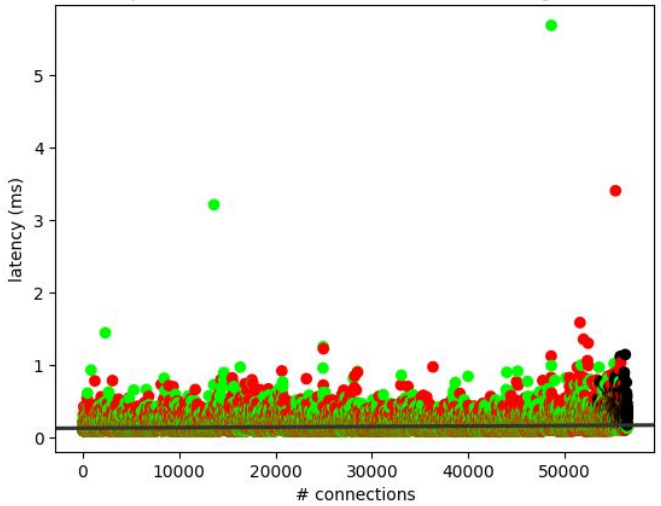
connection attempts: 56511 errors: 1024 total connections: 55487
total time: 9685.281 avg time/connection: 0.171 connections/s: 5834.730
even port(s): 27732 min: 0.093 max: 3.576 avg: 0.170
odd port(s): 27755 min: 0.094 max: 3.542 avg: 0.170



3.3 min → 9.3 sec

1000 window

connection attempts: 56511 errors: 1054 total connections: 55457
total time: 9393.775 avg time/connection: 0.166 connections/s: 6015.792
even port(s): 27691 min: 0.091 max: 5.683 avg: 0.162
odd port(s): 27766 min: 0.089 max: 3.405 avg: 0.163

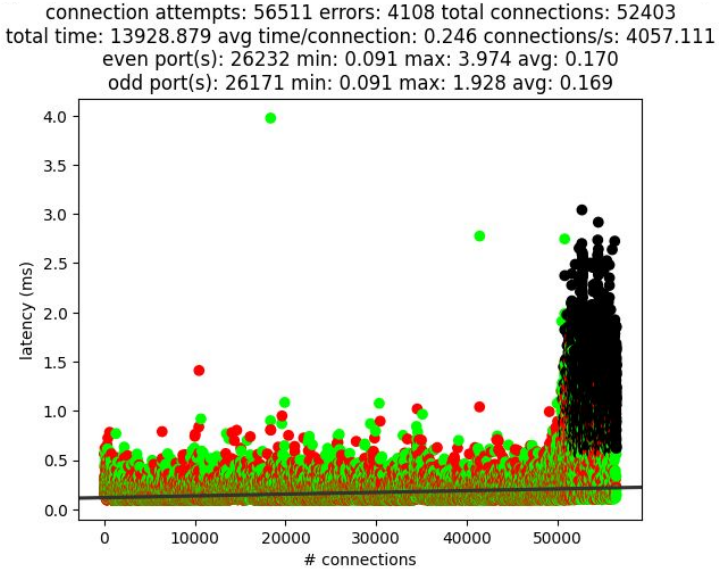


CLOUDFLARE

Performance 56k unicast egress connections

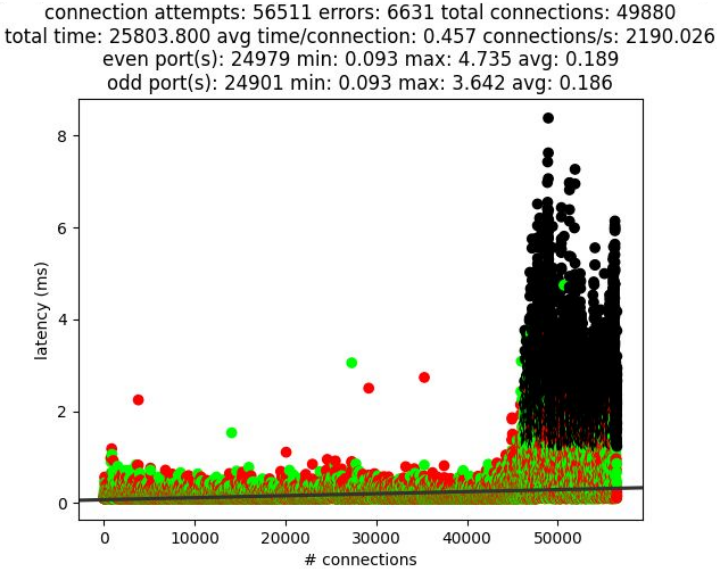
3.3 min → 13.9 sec

5k window



3.3 min → 25.8 sec

10k window



Takeaways

- Current implementation guarantees a port is selected
- Current implementation is not great at extreme egress workloads
- We can reduce the port-range to small-N loops per socket
- Random offset + 500-1k window coupled with kernel random port picking ensures we start looping at both odd and even ports with small-N
- Purely user space implementation

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Discussions/Questions?

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