Performance of VPP
Linux Control Plane

Pim van Pelt <pim@ipng.ch> • 2022-02-06 • FOSDEM '22

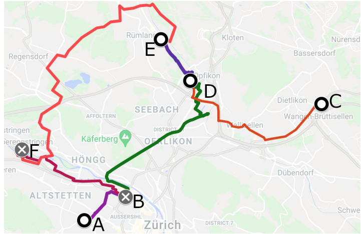
Introduction

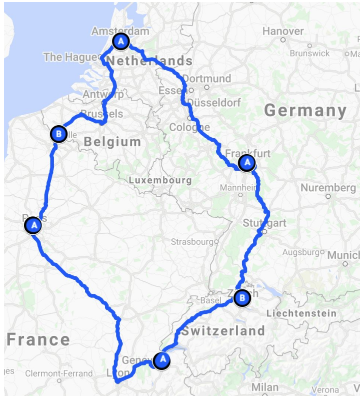
Pim van Pelt

Pim van Pelt (PBVP1-RIPE)

- Member of the RIPE community since 1999 (RIPE #34)
    - Has used pim@ipng.nl for 22 years
    - And also pim@ipng.ch for 15 years
    - Incorporated ipng.ch in Switzerland in 2021

Introduction

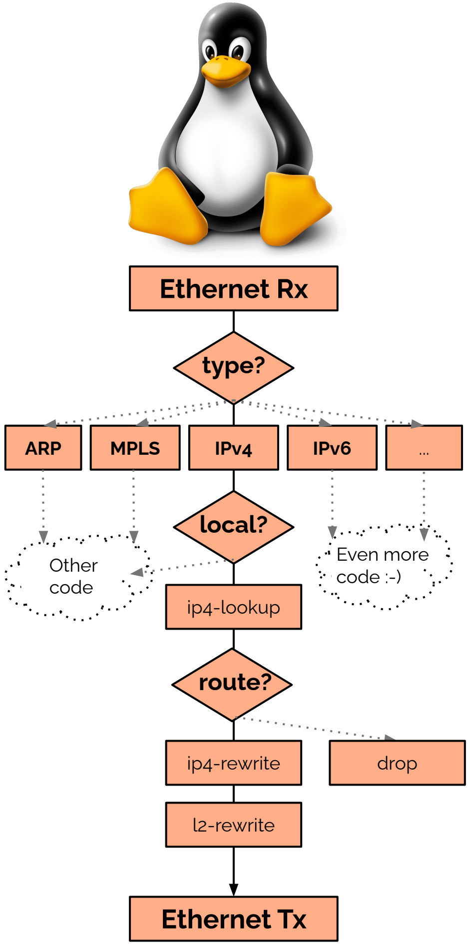




IPng Networks GmbH

- Developer of Software Routers - VPP and DPDK [ref]
- Tiny operator from Brüttisellen (ZH), Switzerland [ref]

- Twelve VPP/Bird2 routers [ref] (UN/LOCODE names)
- European ring: *peering on the FLAP** [ref] ~1850 adjacencies
- Acquired AS8298 from SixXS [ref]



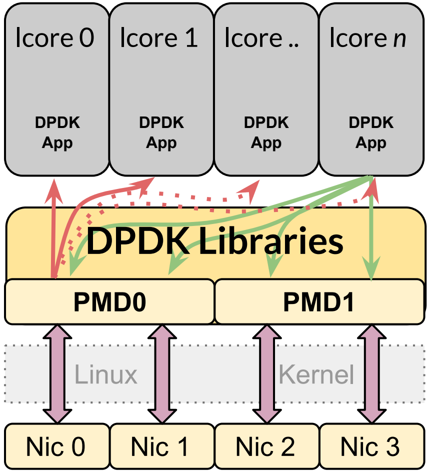
Scalar packet processing

A typical ingress Ethernet Rx (or batch of them):

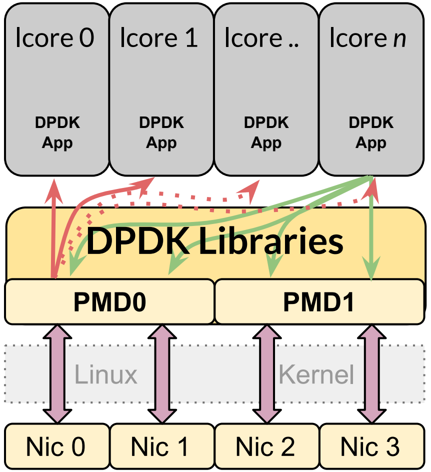
1. Causes an interrupt: kernel stops what it was doing
2. Looks up ethertype; was this ARP, IPv4, IPv6, MPLS, etc ?
3. Was it destined for me? If so, handoff to UDP/TCP/ICMP stack
4. Should I forward? If so, look up the L3 nexthop
5. Should I route the packet? If so, decr TTL, NAT, calc checksum
6. Which interface? Look up the L2 nexthop
7. Rewrite the L2 header (src is my MAC, dst is L2 nexthop)
8. Enqueue the Ethernet egress transmission
9. Kernel resumes what it was doing

Packets go through this one-by-one and your CPU cache hates you.

DPDK architecture



- Runs in Linux userspace (either host or VM guest)
- Kernel bypass (eg. SR-IOV, UIO, VFIO) for device access
- Fully consumes CPU (one `pthread` per logical core)
  - Implements various *Poll Mode Drivers* (PMD)
  - PMDs offer *hardware offload* capabilities
  - Lockless queues, buffers, hash tables, timers, mempools
  - *Run-To-Completion* model: Rx ⇒ process ⇒ Tx
- DPDK threads (*lcores*) subscribe to queue(s) of port(s)
  - Receive Side Scaling (RSS): n threads on one NIC
  - Hashing on IPv4, IPv6, MPLS, VXLAN, l2-payload, …
  - Tx Queues: Each thread has an output to each NIC

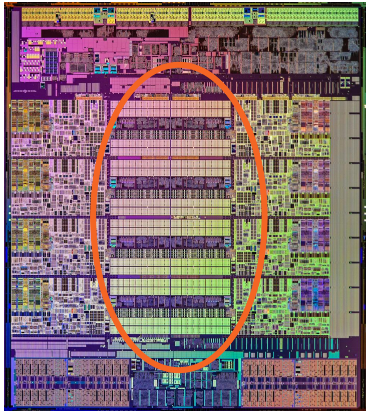


DPDK architecture

```
int main (int argc, char **argv) {
  rte_eal_init(argc, argv);
  rte_eal_mp_remote_launch(lcore_main, NULL, CALL_MASTER);
  RTE_LCORE_FOREACH_SLAVE(lcore_id)
    if (rte_eal_wait_lcore(lcore_id) < 0) return -1;
  return 0;
}

struct rte_mbuf *pkts[32]; int port = 0, queue = 0;
void lcore_main(void) {
  while (running) {
    n = rte_eth_rx_burst(port, queue, pkts, 32);
    process_pkts(pkts, n);
    rte_eth_tx_burst(port, queue, pkts, n);
  }
}
```

Packets (plural)

Good to know: Rules of Thumb

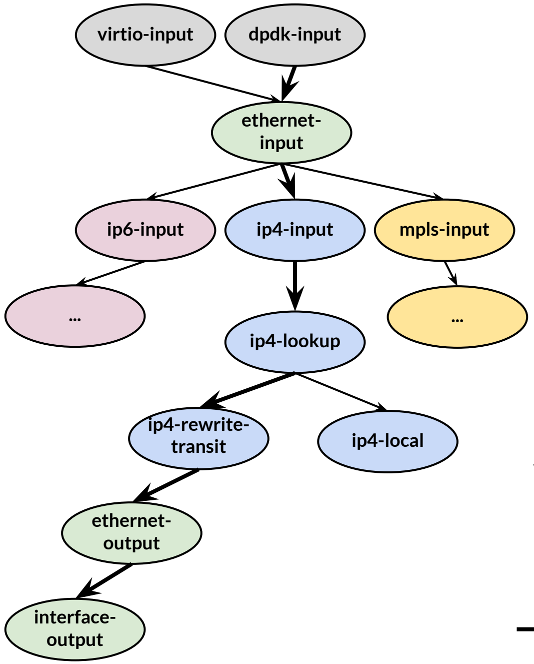


8MB of good stuff is in the center of the chip :-)

```
 0.5 ns - CPU L1 CACHE reference
 1   ns - A photon traveling ~300mm distance
 3.5 ns - CPU L2 CACHE reference
 10  ns - CPU L3 CACHE reference
 70  ns - DDR MEMORY reference
135  ns - CPU cross-QPI/NUMA best  case on XEON E7-*
202  ns - CPU cross-QPI/NUMA worst case on XEON E7-*
```

Takeaway: RAM is hideously slow

Vector Packet Processing

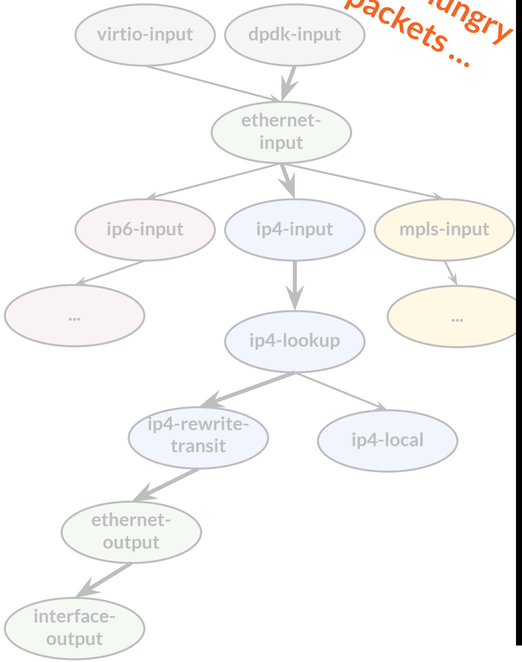


DPDK reads **a vector** of up to 256 packets from its interfaces:

1. Packets are prefetched (or directly written) into CPU **d-cache**
2. All packets go through a directed graph
   a. First packet: graph node's code loaded into CPU **i-cache**
   b. All additional packets: fully in d/i-cache: 7-20x faster
3. Packets then traverse *as a vector* into the next node(s)
   a. Optimized with SIMD (SSE, AVX, AVX512, …)
   b. No context switches, good TLB hit rate due to hugepages
   c. Lockless: multi-threading gives linear scaling
4. Hardware offload: use silicon if available
5. Plugins: rearrange the graph nodes and add functionality

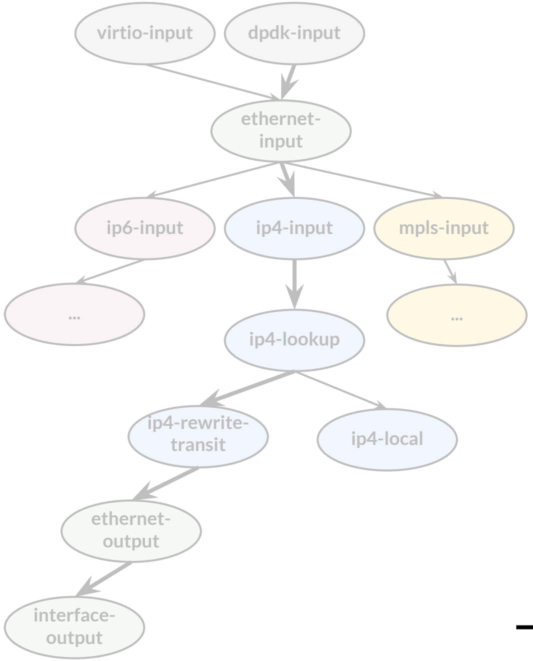
Vector Packet Processing - example

Always hungry for packets ...




```
pim@hippo:~$ vppctl
vpp# set interface state TenGigabitEthernet3/0/0 up
vpp# set interface mtu packet 9000 TenGigabitEthernet3/0/0
vpp# set interface ip address TenGigabitEthernet3/0/0 2001:db8:0:1::2/64
vpp# set interface ip address TenGigabitEthernet3/0/0 192.0.2.2/24
vpp# ip route add 2000::/3 via 2001:db8:0:1::1
vpp# ip route add 0.0.0.0/0 via 192.0.2.1

pim@hippo:~$ vppctl show interface TenGigabitEthernet3/0/0
TenGigabitEthernet3/0/0  up  9000/0/0/0     rx packets              5969930253
                                            rx bytes              2139798549228
                                            tx packets             14517083897
                                            tx bytes              6864831067486
                                            drops                          945
                                            ip4                     3862409855
                                            ip6                     2107502378
```

VPP: Linux Controlplane

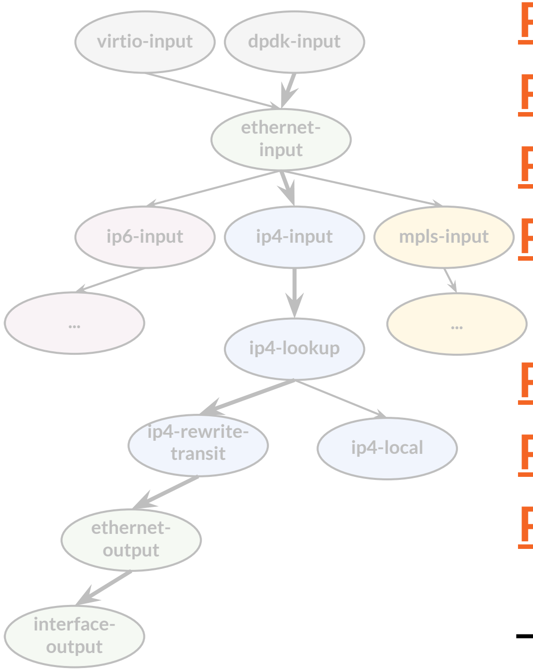


Wrote a VPP Plugin [github] that:

1. Creates tun/tap interface in Linux for a given VPP interface
   a. Linux->VPP: packets into TAP are inserted into ***virtio-input***
   b. VPP->Linux: Traffic to ***ip4-local*** and ***ip6-local*** is punted into TAP
2. Syncs interface changes in VPP into Linux
3. Listens to ***Netlink* messages** and syncs Linux changes into VPP
4. Allows operators to use VPP almost exactly as if it were Linux
   - Configure interfaces, addresses, routes by hand, or ...
   - ...using common tools like `ip(1)`, FRR, or Bird/Bird2

⇒ VPP is Linux's *software equivalent* of an ASIC dataplane ⇐

VPP: Linux Controlplane



For the curious ...

Part1 - Create sub-interface (.1q, .1ad, q-in-q, q-in-ad) in Linux

Part2 - Sync link state, MTU and IP addresses in Linux

Part3 - Automatically create sub-interfaces in Linux

Part4 - Netlink: Sync link state, MTU, neighbor, IP addresses,
create new sub-interface (.1q, .1ad, q-in-*) in VPP

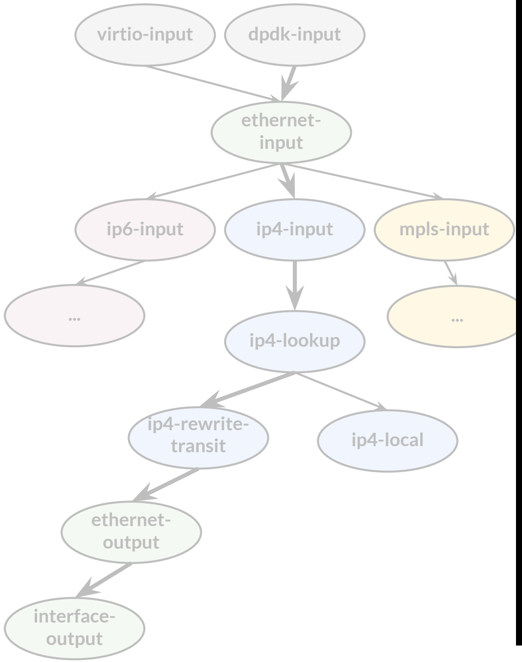
Part5 - Netlink: Sync routes in VPP

Part6 - Expose interface stats from VPP in SNMP

Part7 - HOWTO: Installation and Configuration in Production

**) Thanks to Neale Ranns, Matt Smith and Jon Loeliger for the collaboration*

VPP: Linux Controlplane - ip

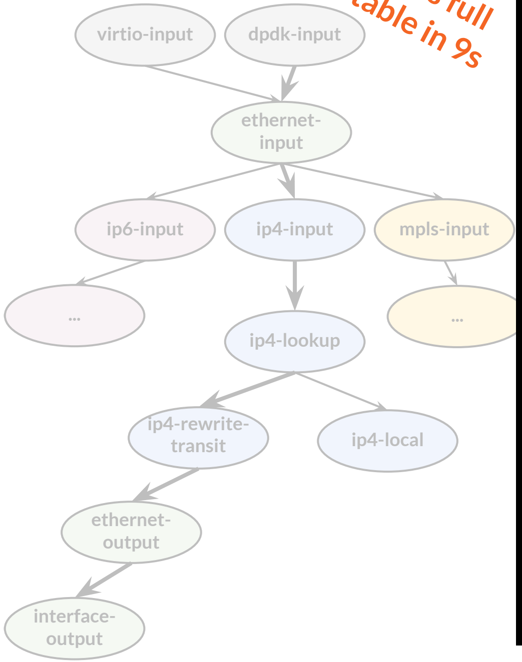



```
pim@hippo:~$ vppctl lcp create TenGigabitEthernet3/0/0 host-if xe0

pim@hippo:~$ sudo ip link set xe0 up mtu 9000
pim@hippo:~$ sudo ip address add 2001:db8:0:1::2/64 dev xe0
pim@hippo:~$ sudo ip address add 192.0.2.2/24 dev xe0

pim@hippo:~$ sudo ip link add link xe0 name servers type vlan id 101
pim@hippo:~$ sudo ip link set servers mtu 1500 up
pim@hippo:~$ sudo ip addr add 2001:678:d78:3::86/64 dev servers
pim@hippo:~$ sudo ip addr add 194.1.163.86/27 dev servers
pim@hippo:~$ sudo ip route add default via 2001:678:d78:3::1
pim@hippo:~$ sudo ip route add default via 194.1.163.65
pim@hippo:~$ ping 8.8.8.8
PING 8.8.8.8 (8.8.8.8): 56 data bytes
64 bytes from 8.8.8.8: icmp_seq=0 ttl=121 time=1.348 ms
...
```

VPP: Linux Controlplane - Bird2

Converges full BGP table in 9s

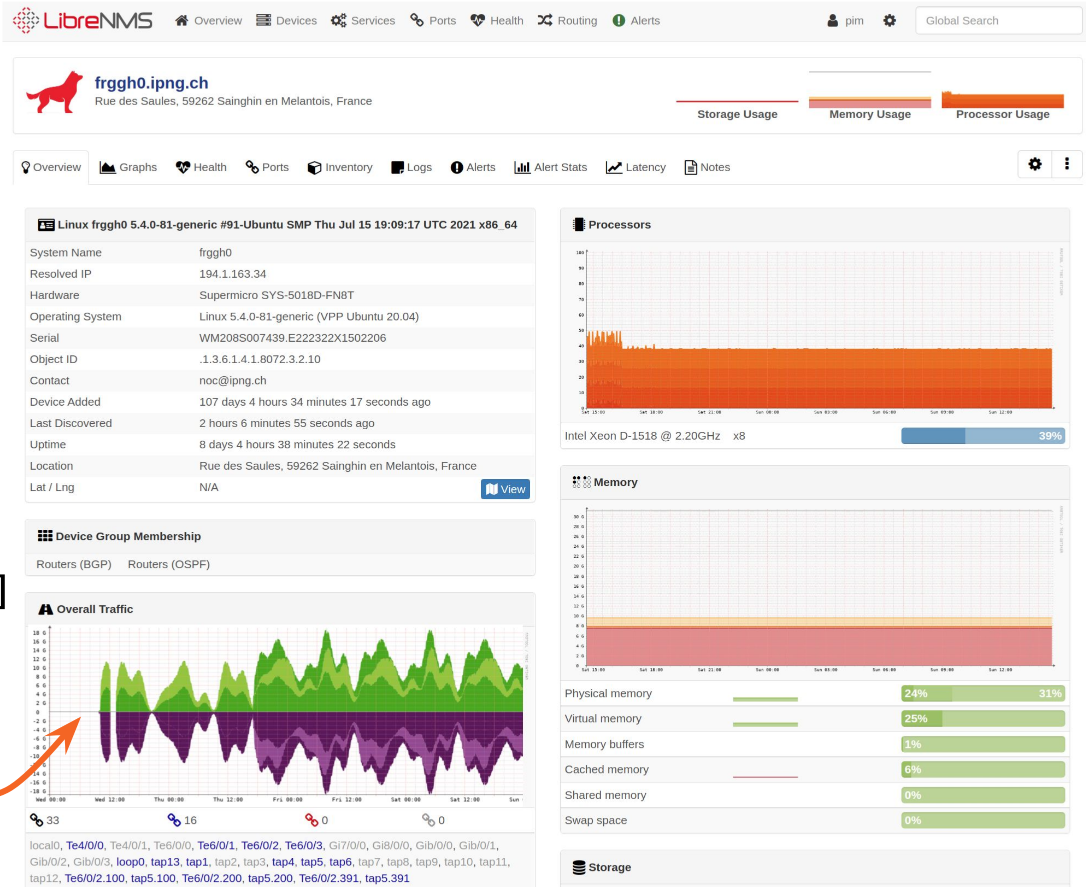
```
pim@frggh0:~$ birdc show route count
BIRD 2.0.7 ready.
5935108 of 5935108 routes for 867667 networks in table master4
994480 of 994480 routes for 142326 networks in table master6
245091 of 245091 routes for 245091 networks in table t_roa4
48925 of 48925 routes for 48925 networks in table t_roa6
Total: 7223604 of 7223604 routes for 1304009 networks in 4 tables

pim@frggh0:~$ birdc show ospf neighbor ospf6
BIRD 2.0.7 ready.
Router ID       Pri          State     DTime    Interface  Router IP
194.1.163.33      1    Full/PtP      31.868   xe1-2.100  fe80::6a05:caff:fe32:3e38
194.1.163.32      1    Full/PtP      38.641   xe1-3.200  fe80::6a05:caff:fe32:3cdb
194.1.163.140     1    Full/DR       37.944   xe1-1.2006 fe80::5054:ff:feb0:442c
```



VPP: SNMP and NMS

1. Wrote an SNMP Agent [github]
2. Added *logo* to LibreNMS [ref]
3. Added *distro* to LibreNMS Agent [ref]

Is forwarding 18Gbps



There is another …

… super-useful DPDK app

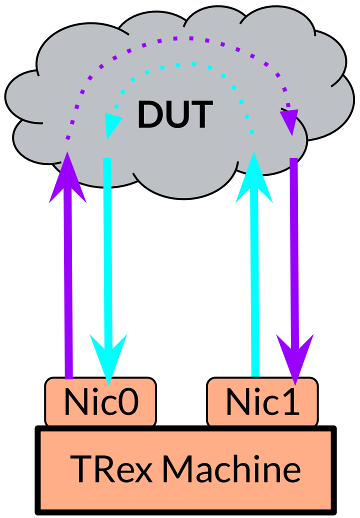
Cisco T-Rex traffic load tester [link]

- Stateless/Stateful load testing
- Python API - fully programmable
  - Traffic streams w/ scapy [api]
  - Traffic ramp up/down [api]
  - Runtime statistics [api]
  - Interactive / CLI [docs]
- DPDK Integration
  - ~10-15Mpps per core
  - Linear scaling with cores
  - 1G/10G/25G/40G/100G

Config and Startup

Simple configuration:

```
- version: 2
  interfaces: ['5:00.0', '5:00.1']
  port_info:
        - src_mac   : [0x0A,0x0B,0x0C,0x01,0x02,0xAA] # Mac A
          dest_mac  : [0x0A,0x0B,0x0C,0x01,0x02,0xBB] # Mac B
        - src_mac   : [0x0A,0x0B,0x0C,0x01,0x02,0xBB] # Mac B
          dest_mac  : [0x0A,0x0B,0x0C,0x01,0x02,0xAA] # Mac A
```



Startup:

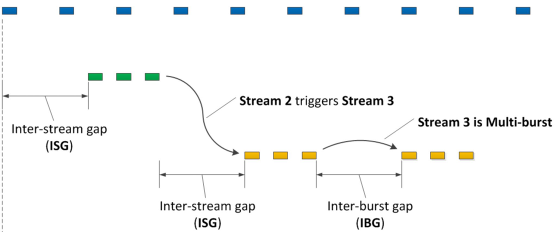
```
$ sudo ./t-rex-64 -i -c 6
$ ./trex-console
```

Stateless Traffic Profiles

Assemble packet streams with scapy:

- IPv4/IPv6 src/dst; proto; port src/dst; size; ratios; timings

```
self.ip_range = {'src': {'start': "16.0.0.1", 'end': "16.0.0.254"},
                 'dst': {'start': "48.0.0.1",  'end': "48.0.0.254"}}
```




```
# default IMIX properties
self.imix_table = [ {'size': 60,   'pps': 28,  'isg':0 },
                    {'size': 590,  'pps': 16,  'isg':0.1 },
                    {'size': 1514, 'pps': 4,   'isg':0.2 } ]
```

- Streams are *applied* on one or more ports
- Ports are configured to send a *rate* of traffic (bps, pps or % of line)

Load Testing Methodology

Method 1: VPP has one worker thread, one Rx/Tx queue

- Send *unidirectional* traffic
- Measure cycles/packet for 1kpps, 1Mpps, 10Mpps, ...

  ⇒ Report max packets/sec for one CPU

Method 2: VPP has n-1 worker threads with [1, 2, 3, …] Rx queues

- Send *unidirectional*, or *bidirectional* (!) traffic
  - Warmup at 1kpps (30sec)
  - Ramp up to 100% line rate (in 600sec)
  - Keep at 100% (30sec)
- Measure point at which packet forwarding loss > 0.1%

  ⇒ Report bits/sec, packets/sec and % of line rate.

Method 1 - Single Thread Saturation

TUI - TRex Console UI

```
> start -f stl/udp_1pkt_simple.py -p 0 -m 1kpps
> pause
> resume
> update -m 1Mpps
> update -m 10Mpps
> update -m 100%
> stop
```

Method 1 - TRex Console

TRex
Realistic Traffic Generator

Legend:

1. NIC Info, T-Rex CPU utilization
2. Sent traffic (L1, L2, packets/sec)
3. Received traffic (L2, packets/sec)
4. Detailed packet/byte counters

```
connection     : localhost, Port 4501                       total_tx_L2  : 18.08 Gbps
version        : STL @ v2.92                                total_tx_L1  : 19.07 Gbps
cpu_util.      : 16.19% @ 10 cores (10 per dual port)       total_rx     : 18.08 Gbps
rx_cpu_util.   : 0.0% / 0 pps                               total_pps    : 6.24 Mpps
async_util.    : 0% / 56.46 bps                             drop_rate    : 0 bps
total_cps.     : 0 cps                                      queue_full   : 0 pkts

Port Statistics

   port     |         0         |         1         |       total
------------+-------------------+-------------------+------------------
owner       |               pim |               pim |
link        |  1             UP |                UP |
state       |      TRANSMITTING |      TRANSMITTING |
speed       |         10 Gb/s   |         10 Gb/s   |
CPU util.   |          16.19%   |          16.19%   |
--          |                   |                   |
Tx bps L2   |       9.04 Gbps   |       9.04 Gbps   |       18.08 Gbps   2
Tx bps L1   |       9.54 Gbps   |       9.54 Gbps   |       19.07 Gbps
Tx pps      |       3.12 Mpps   |       3.12 Mpps   |        6.24 Mpps
Line Util.  |         95.37 %   |         95.37 %   |
---         |                   |                   |
Rx bps      |       9.04 Gbps   |       9.04 Gbps   |       18.08 Gbps   3
Rx pps      |       3.12 Mpps   |       3.12 Mpps   |        6.24 Mpps
----        |                   |                   |
opackets    |        42400846   |        42400944   |        84801790
ipackets    |        42400756   |        42400878   |        84801634
obytes      |     15342041228   |     15342073386   |     30684114614
ibytes      |     15342006290   |     15342047196   |     30684053486
tx-pkts     |     42.4 Mpkts    |     42.4 Mpkts    |     84.8 Mpkts     4
rx-pkts     |     42.4 Mpkts    |     42.4 Mpkts    |     84.8 Mpkts
tx-bytes    |     15.34 GB      |     15.34 GB      |     30.68 GB
rx-bytes    |     15.34 GB      |     15.34 GB      |     30.68 GB
-----       |                   |                   |
oerrors     |               0   |               0   |               0
ierrors     |               0   |               0   |               0
```

Shown:
19.1Gbit and **6.24Mpps** of *imix* at **16.2% CPU**

Method 2 - API Driven by Python

```
usage: trex-loadtest.py [-h] [-s SERVER] [-p PROFILE_FILE] [-o OUTPUT_FILE] [-wm WARMUP_MULT]
                        [-wd WARMUP_DURATION] [-rt RAMPUP_TARGE] [-rd RAMPUP_DURATION] [-hd HOLD_DURATION]
T-Rex Stateless Loadtester -- pim@ipng.nl
optional arguments:
  -h, --help            show this help message and exit
  -s SERVER, --server SERVER
                        Remote trex address (default: 127.0.0.1)
  -p PROFILE_FILE, --profile PROFILE_FILE
                        STL profile file to replay (default: imix.py)
  -o OUTPUT_FILE, --output OUTPUT_FILE
                        File to write results into, use "-" for stdout (default: -)
  -wm WARMUP_MULT, --warmup_mult WARMUP_MULT
                        During warmup, send this "mult" (default: 1kpps)
  -wd WARMUP_DURATION, --warmup_duration WARMUP_DURATION
                        Duration of warmup, in seconds (default: 30)
  -rt RAMPUP_TARGET, --rampup_target RAMPUP_TARGET
                        Target percentage of line rate to ramp up to (default: 100)
  -rd RAMPUP_DURATION, --rampup_duration RAMPUP_DURATION
                        Time to take to ramp up to target percentage of line rate, in seconds (default: 600)
  -hd HOLD_DURATION, --hold_duration HOLD_DURATION
                        Time to hold the loadtest at target percentage, in seconds (default: 30)
```

Method 2 - Interesting profiles

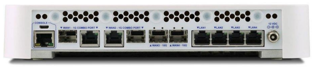
From easier to more challenging (*):

1. `bench-var2-1514b`: 1514b UDP, multiple flows (random src/dst IP)
   ⇒ 810Kpps at 10Gbps
2. `bench-var2-imix`: Mix of 60, 590, 1514 byte UDP, multiple flows
   ⇒ 3.2Mpps at 10Gbps
3. `bench-var2-64b`: 64 byte UDP, multiple flows
   ⇒ 14.88Mpps at 10Gbps, RSS with multiple Rx queues
4. `bench`: 64 byte UDP, single flow (constant src/dst IP:port)
   ⇒ 14.88Mpps at 10Gbps, only one Rx queue (= one *lcore*)

**) numbers are unidirectional*

Selection of DUTs

1. Netgate 6100



CPU: Atom C3558 • 2.2GHz / 3.8GHz

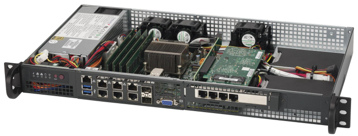
RAM: 224kB L1 • 4MB L2 • 8GB DDR4

Disk: 16G eMMC

Network: 2x 10GbE SFP+
2x 1GbE SFP/RJ45, 4x 2.5GbE

Price: CHF 650,-

2. Supermicro 5018D-FN8T



CPU: Xeon D1518 • 2.2GHz / 4.0 GHz

RAM: 256kB L1 • 1MB L2 • 6MB L3 • 32GB DDR4

Disk: 128GB mSATA

Network: 6x 10GbE SFP+
4x 1GbE i350, 2x 1GbE i210

Price: CHF 1’350,-

3. ASRock Taichi B550 / Ryzen 5950X

CPU: Ryzen 5950X • 3.4GHz / 5.05 GHz

RAM: 1MB L1 • 8MB L2 • 64MB L3 • 128GB DDR4

Disk: 2TB NVME

Network: 2x 100GbE QSFP28
4x 10GbE SFP+, 4x 1GbE i350

Price: CHF 2’850,-

Method 1: Results

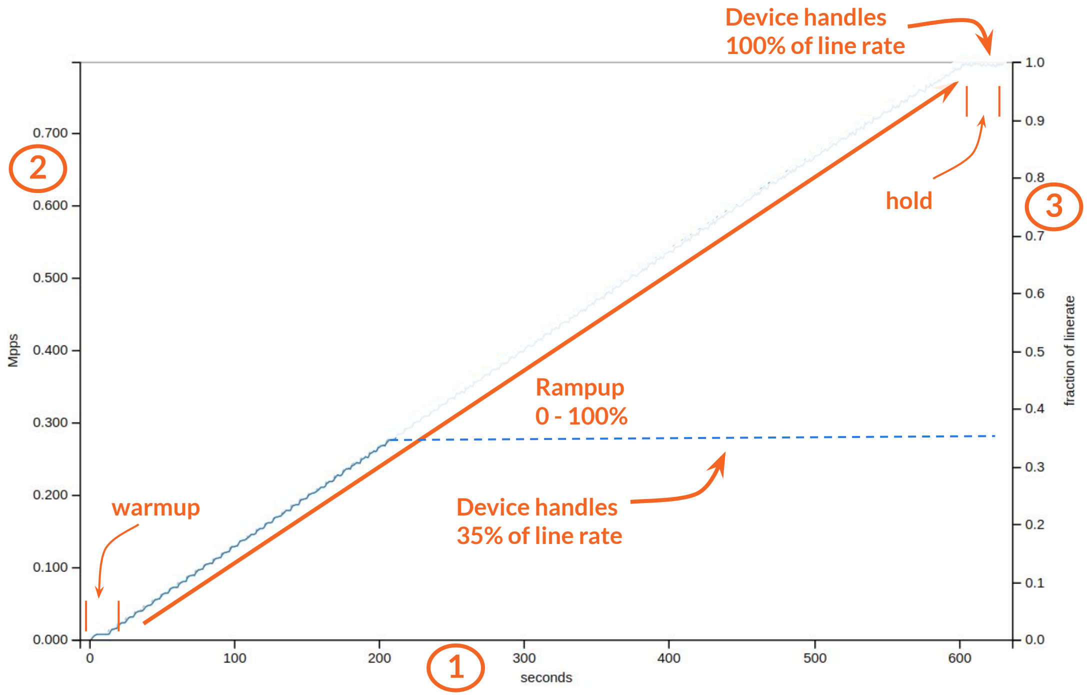
	cycles/packet @ 1kpps	cycles/packet @ 1Mpps	cycles/packet @ 10Mpps	Max PPS per core
Atom C3558	4943	620	358	5.01Mpps
Xeon D1518	2037	341	179	10.20Mpps
Ryzen 5950X	1112	245	178	22.28Mpps

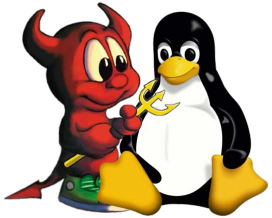
- CPU cycles/packet: lower is better
- Max PPS per core: higher is better

Method 2: Graphs explained

Legend:

1. X-axis: time 0 .. 640 seconds
2. Y-axis(left): packets/sec
3. Y-axis(right): fraction of linerate



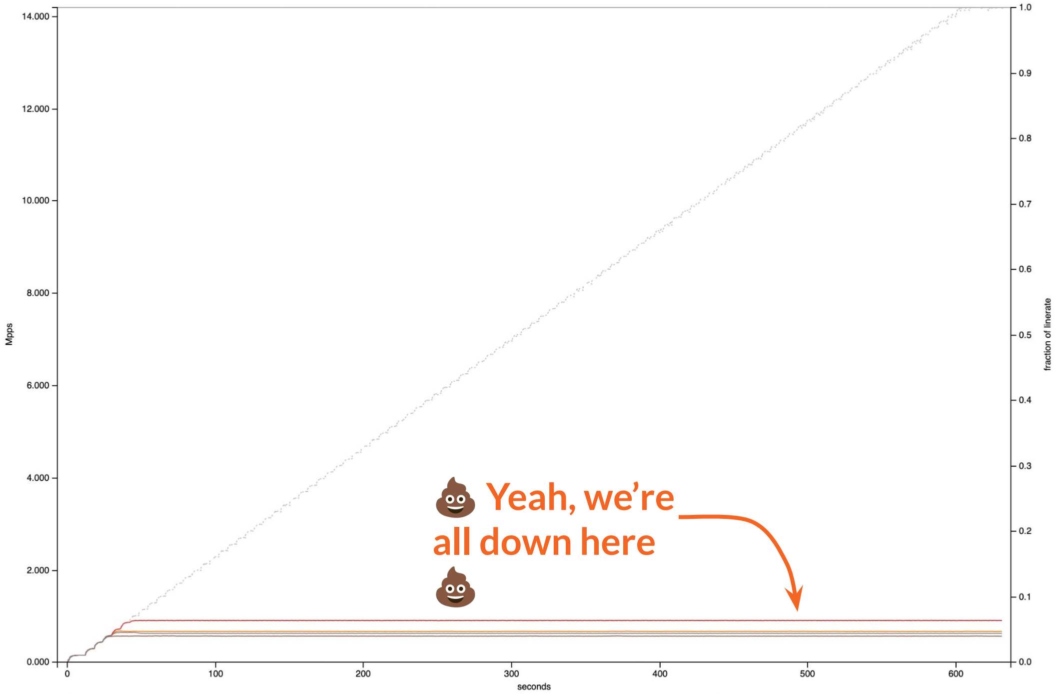


Method 2: Baseline: Kernel 64b

Profile: 14.88Mpps at 10Gbps

TL/DR: Kernel routing is not efficient

	Linux	FreeBSD
Atom C3558	632kpps	626kpps
Xeon D1518	603kpps	597kpps
Ryzen 5950X	881kpps	847kpps



`pfSense 21.05.2; Ubuntu 20.04.3`

Method 2: Results VPP 1514b

Profile: 810kpps at 10Gbps *

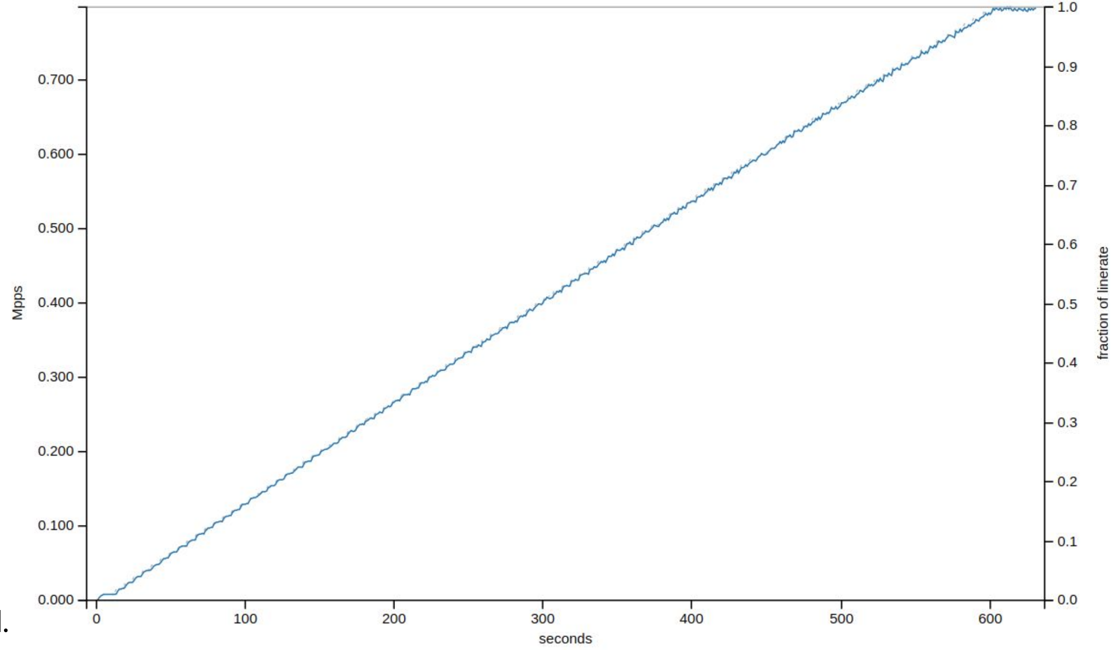
TL/DR: Everybody can be a winner ;-)

Atom C3558, Xeon D1518, Ryzen 5950X

1. Uni- or bidirectional: doesn't matter
2. 3, 2, or 1 Rx Queue: doesn't matter
3. Unsurprising, each CPU can forward >800kpps.

So far so good...

*) also often called *iperf* test. Not very useful.



`vpp v22.02-rc0~492-gf715b33f1 built by pim on rhino at 2022-01-12T11:45:02`

Method 2: Results VPP imix

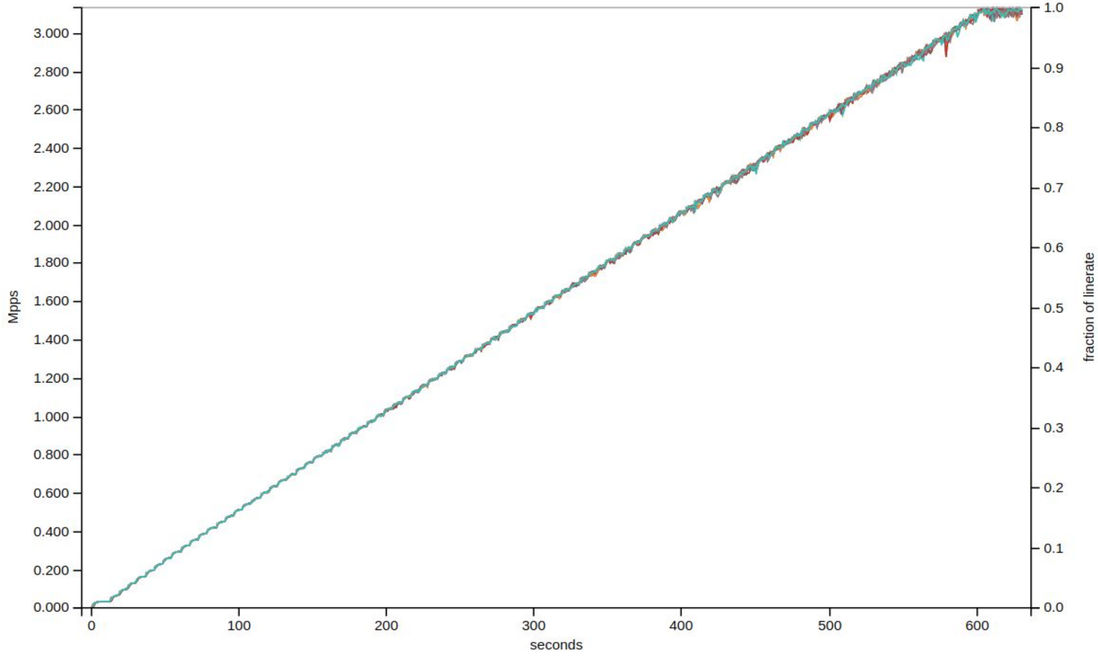
Profile: 3.2Mpps at 10Gbps

Everybody can be a winner ;-)

Atom C3558, Xeon D1518, Ryzen 5950X

1. Uni- or bidirectional: doesn't matter
2. 3, 2, or 1 Rx Queue: doesn't matter
3. Bidirectional is 6.4Mpps:
   a. Single Atom core: 5Mpps
   b. Two directions uses 2 CPUs -
      Rx-Queue0-nic0 on lcore1
      Rx-Queue0-nic1 on lcore2

Still good...



`vpp v22.02-rc0~492-gf715b33f1 built by pim on rhino at 2022-01-12T11:45:02`

Method 2: Results VPP 64b (multi flows)

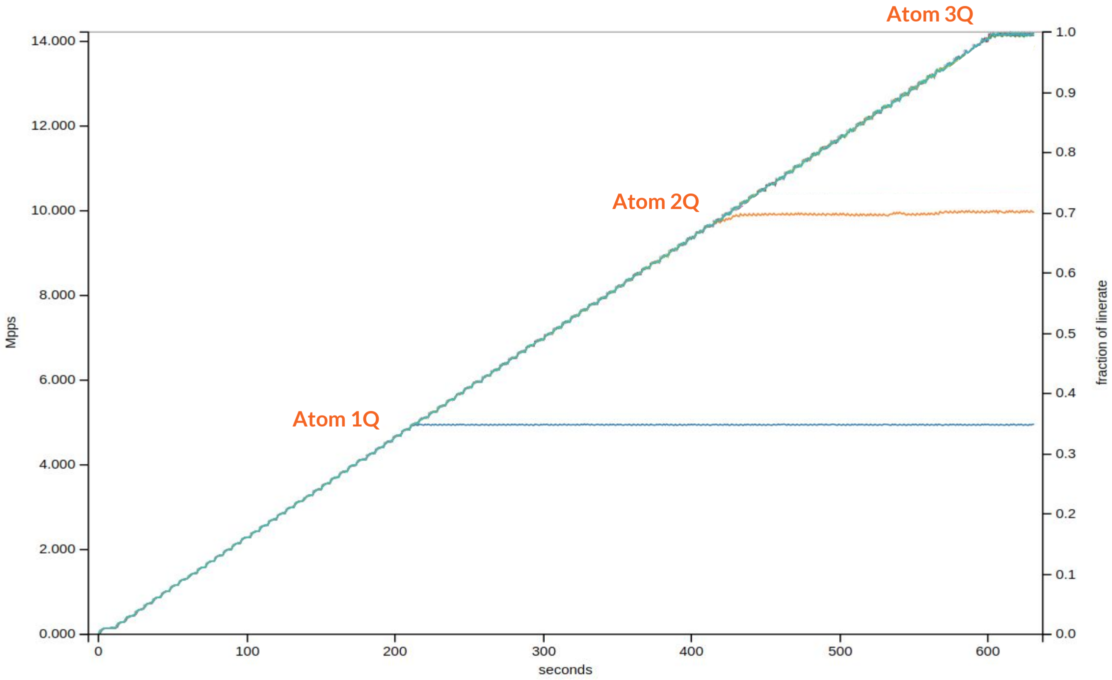
Profile: 14.88Mpps at 10Gbps

Differences become visible

1. Atom C3558
2. Xeon D1518
3. Ryzen 5950X

Observe linear scaling:

- Adding Rx queue goes from 5Mpps → 10Mpps → 14.88Mpps



`vpp v22.02-rc0~492-gf715b33f1 built by pim on rhino at 2022-01-12T11:45:02`

Method 2: Results VPP 64b (multi flows)

Profile: 14.88Mpps at 10Gbps

Differences become visible

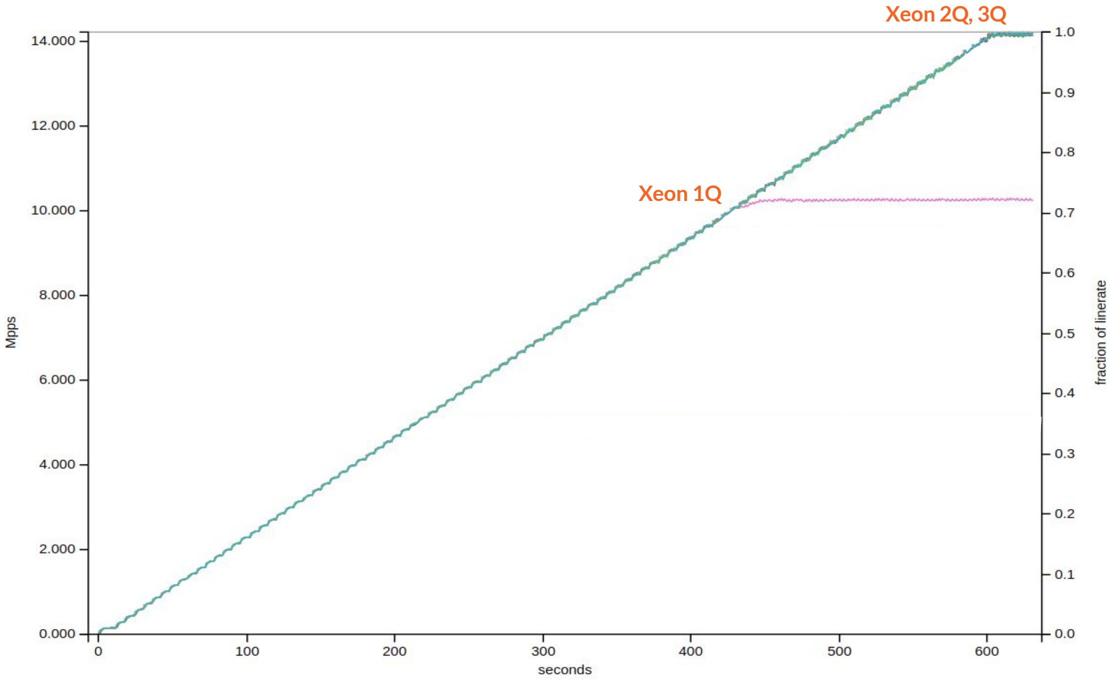
1. Atom C3558

2. **Xeon D1518**

3. Ryzen 5950X

Observe linear scaling:

- Adding Rx queue goes from 10Mpps → 14.88Mpps



`vpp v22.02-rc0~492-gf715b33f1 built by pim on rhino at 2022-01-12T11:45:02`

Method 2: Results VPP 64b (multi flows)

Profile: 14.88Mpps at 10Gbps

Differences become visible

1. Atom C3558

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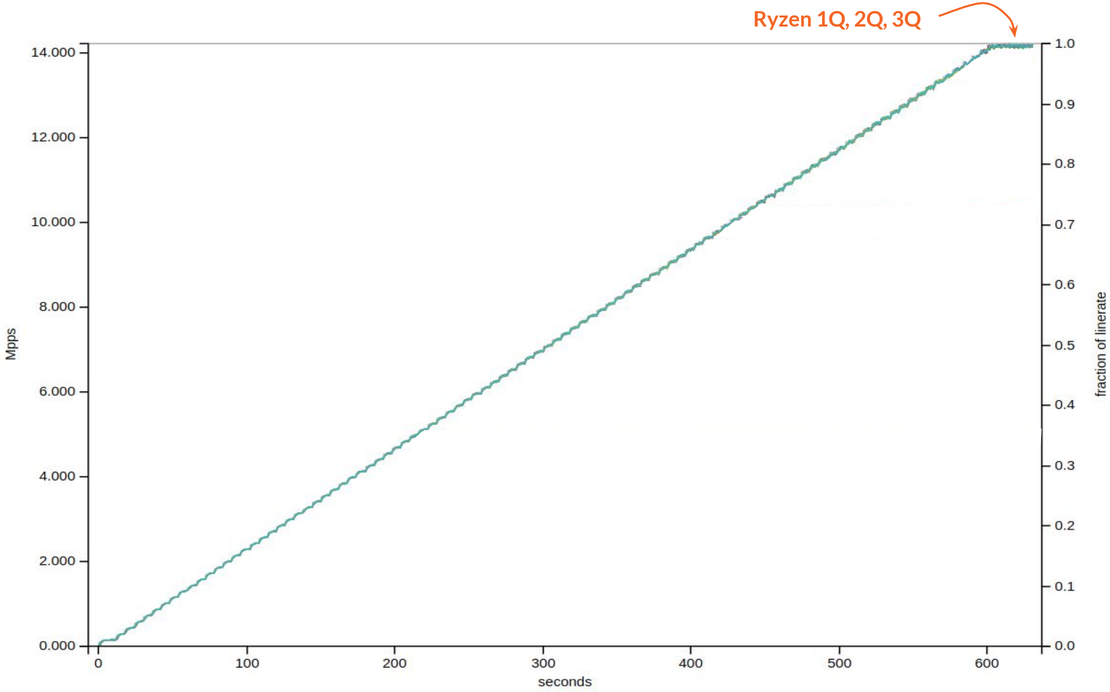


Who needs scaling anyway:

Ryzen single core throughput: 22.3Mpps

Can easily handle line rate with 1 CPU.

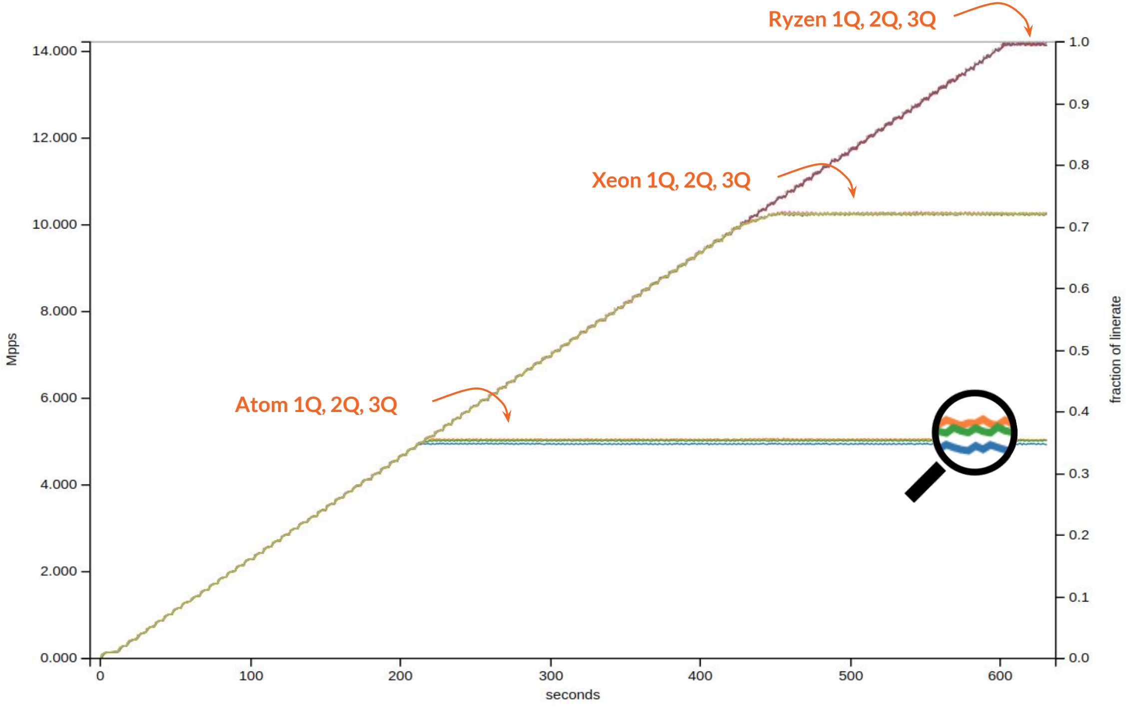
`vpp v22.02-rc0~492-gf715b33f1 built by pim on rhino at 2022-01-12T11:45:02`

Method 2: Results VPP 64b (single flow)

Profile: 14.88Mpps at 10Gbps, 1 flow

Most difficult case possible

1. Ryzen 5950X: 14.88Mpps
2. Xeon D1518: 10.20Mpps
3. Atom C3558: 5.01Mpps



`vpp v22.02-rc0~492-gf715b33f1 built by pim on rhino at 2022-01-12T11:45:02`

Additional considerations

Raw forwarding horsepower isn't everything

Netgate 6100 -

- CPU is 16W TDP, has QAT → crypto acceleration
- At 3 cores: ~15.3Mpps forwarding at 19W → 1.24µJ per packet

Supermicro 5018D-FN8T -

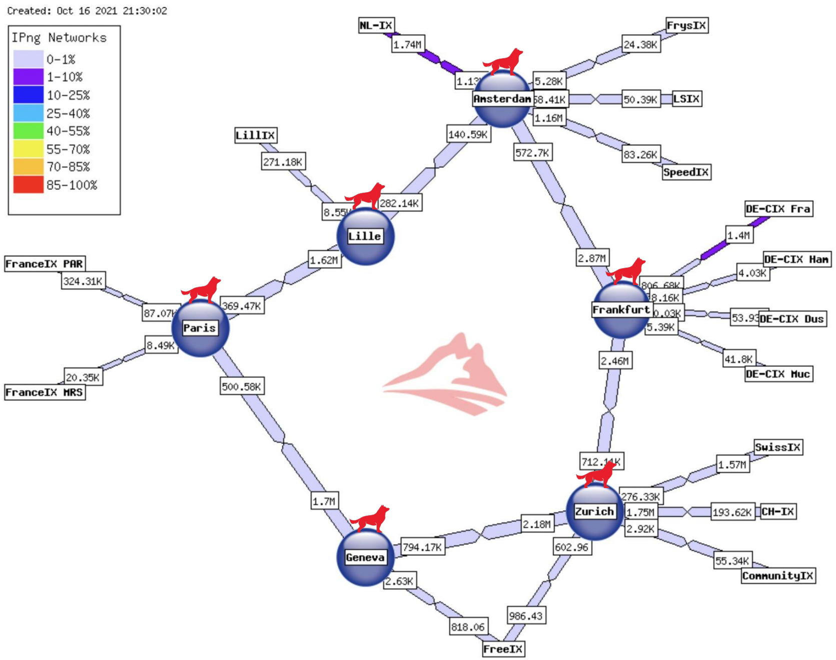
- CPU is 35W TDP, is hyperthreaded (4C/8T)
- Hyperthreading reduces from 10.2Mpps/core to 6.3Mpps/core (but 8 cores!)
- At 3 threads: 37.8Mpps forwarding at 48W → 1.56µJ per packet

ASRock Taichi B550 / Ryzen 5950X -

- CPU is 105W TDP, is hyperthreaded, has 16 cores (16C/32T);
- Hyperthreading is a wash: 10.2Mpps/core to 5.15Mpps/core
- At 15 threads: 330Mpps forwarding at 265W → **0.81µJ per packet**

PCIe v4.0 bandwidth bottleneck (24 lanes ~ 768Gbps)

Questions, Discussion



If you peer with IPng Networks, thanks!
If you don't: please peer with AS8298
<peering@ipng.ch>

Useful Resources

- VPP: fd.io
- VPP Linux CP: Github
- Articles: ipng.ch
- Twitter: @IPngNetworks

Also: thanks for listening!