
KubeCon
CloudNativeCon
North America 2023

Turning up Performance to 11: Cilium, NetKit Devices, and Going Big with TCP

Daniel Borkmann (Isovalent)

KubeCon North America 2023

Experiment for this talk: What would it take to turn the network performance knob to 11?

... and why is it relevant in the first place?

Scale:

- Migrating more workloads to K8s envs
- Connecting multiple clusters in a mesh

Sustainability:

- Better utilization of the existing infrastructure
- Reduction of off/on-prem costs

Performance:

- Better RPC workload latencies
- Escalating bulk data demands from AI/ML

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By Michael Cooney

Senior Editor, Network World | APR 5, 2023 9:39 AM PDT

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And it's going to suck... up more power too

Dan Robinson

Wed 18 Oct 2023 // 16:45 UTC

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James Morra

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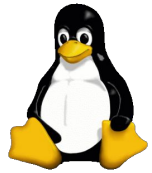
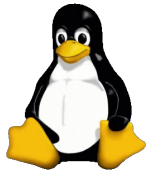


How does a network platform for K8s look like which would address future demands and how much can we benefit from it today?*



How does a network platform for K8s look like which would address future demands and how much can we benefit from it today?*

* without rewriting existing applications

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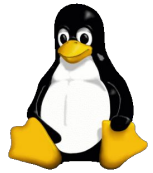
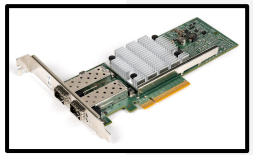


Host

- kubelet
- kube-proxy



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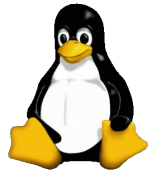

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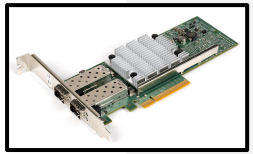

- cilium-agent
- cilium-cni plugin

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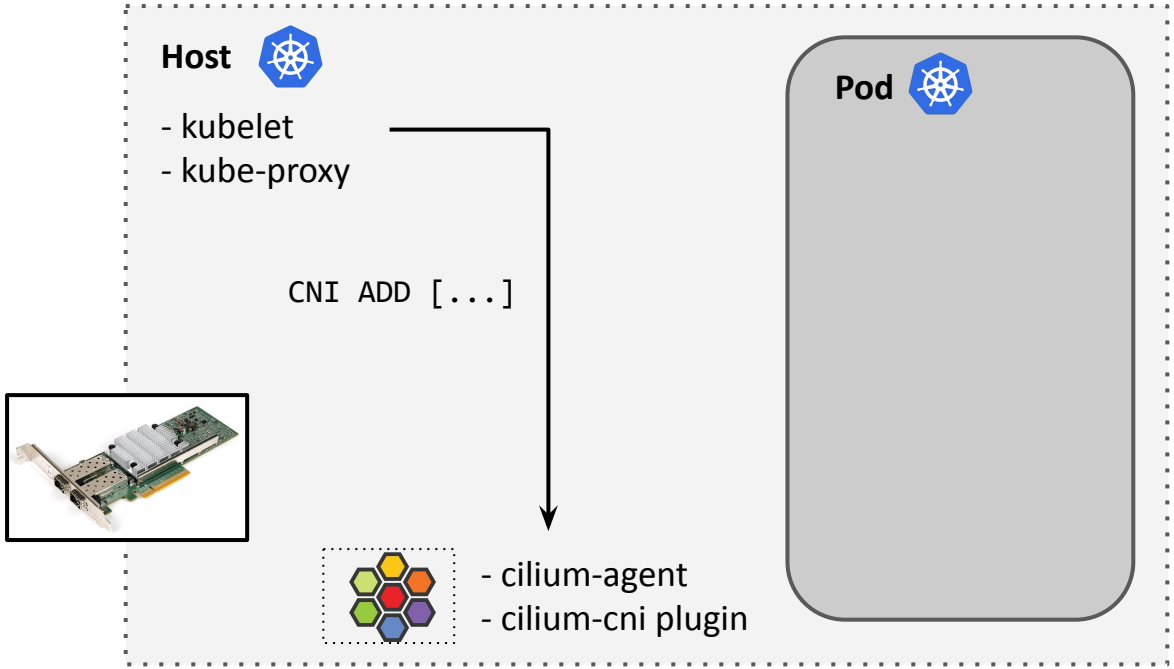

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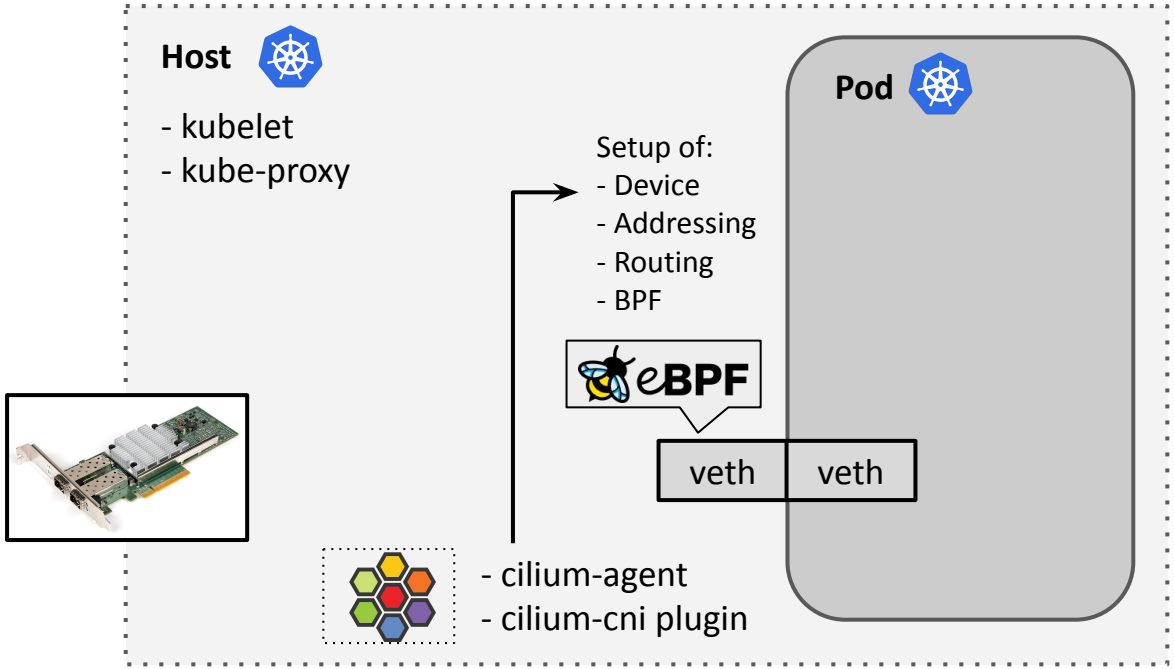

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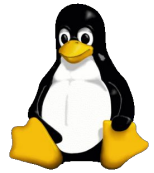

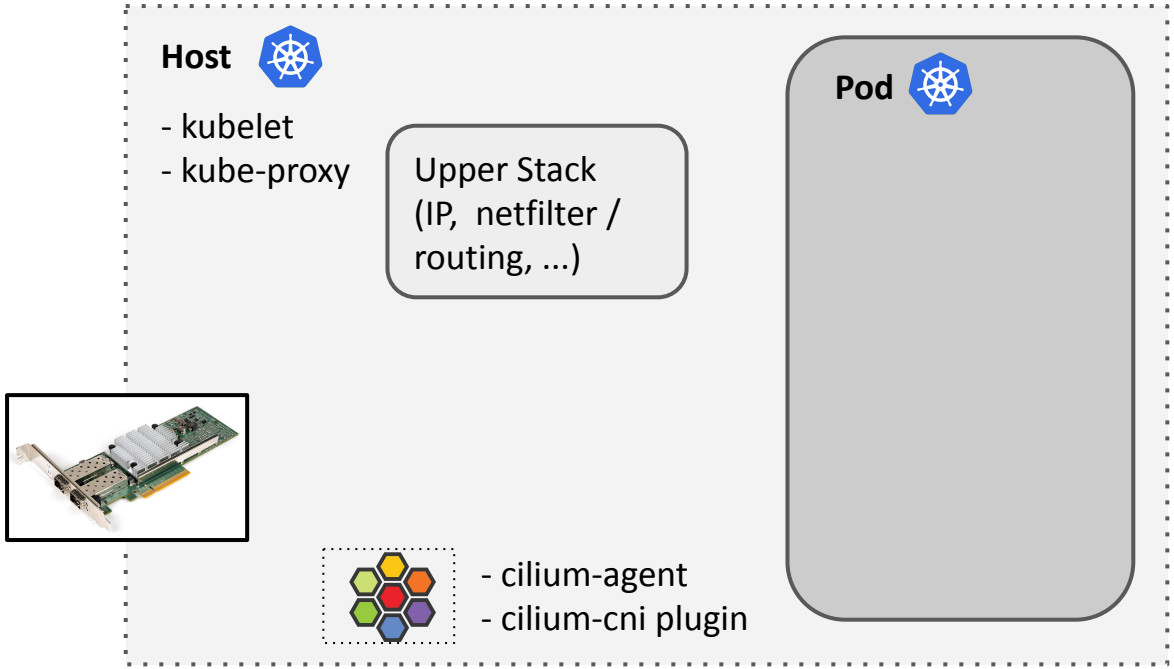

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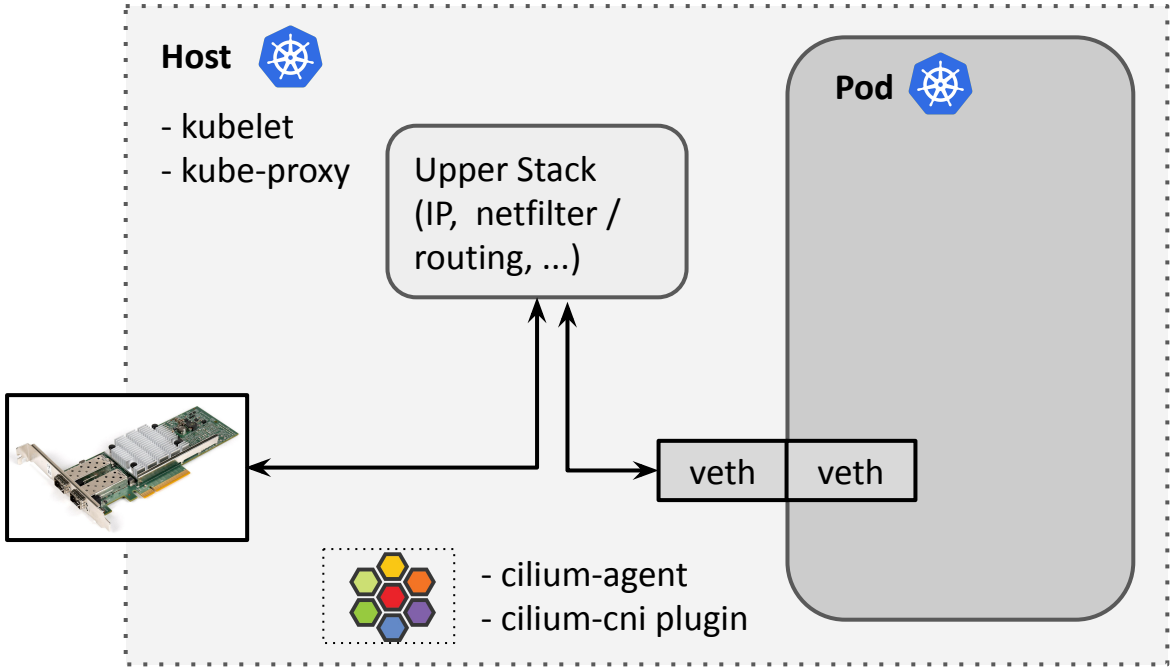

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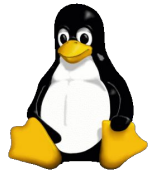

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- Potential reasons:
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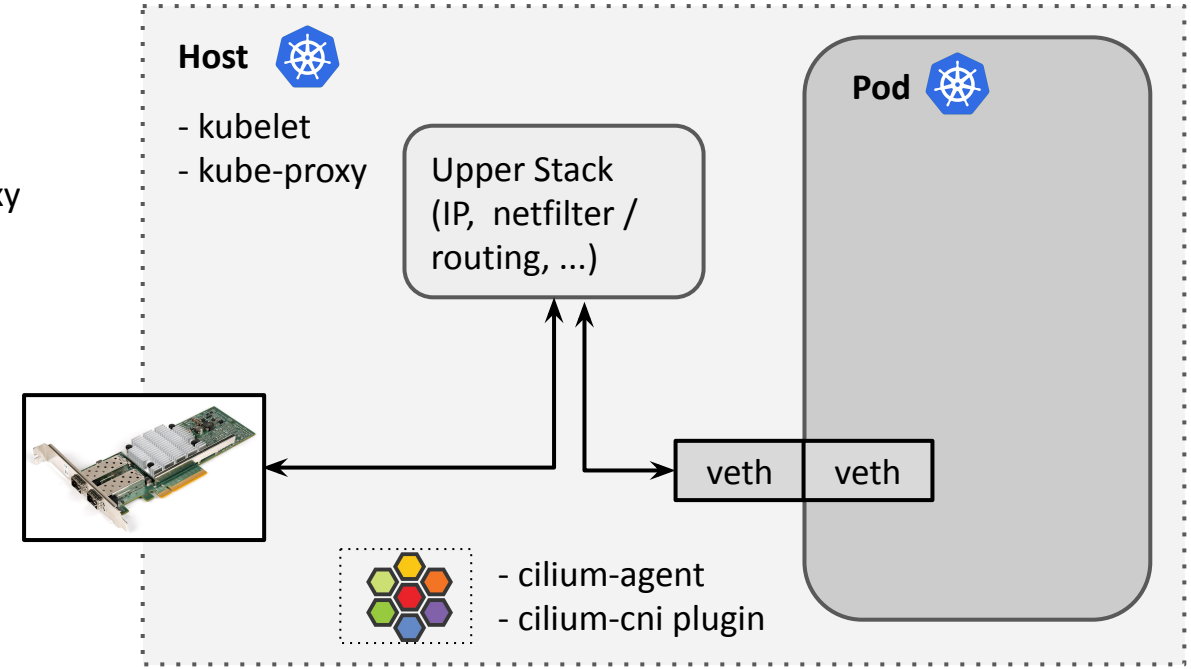

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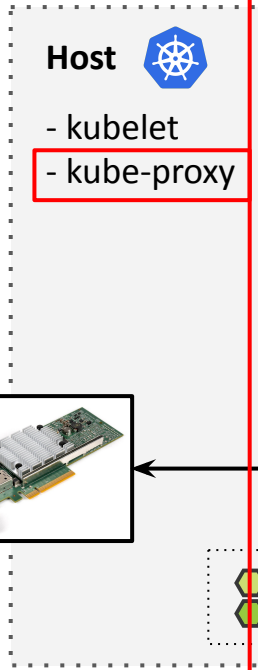

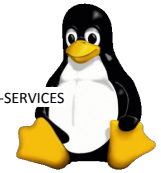

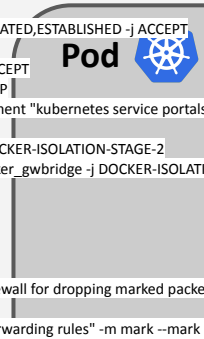


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:DOCKER-USER - [0:0]
:KUBE-EXTERNAL-SERVICES - [0:0]
:KUBE-FIREWALL - [0:0]
:KUBE-FORWARD - [0:0]
:KUBE-SERVICES - [0:0]
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-A INPUT -m conntrack --ctstate NEW -m comment --comment "kubernetes externally-visible service portals" -j KUBE-EXTERNAL-SERVICES
-A INPUT -j KUBE-FIREWALL
-A FORWARD -m comment --comment "kubernetes forwarding rules" -j KUBE-FORWARD
-A FORWARD -m conntrack --ctstate NEW -m comment --comment "kubernetes service portals" -j KUBE-SERVICES
-A FORWARD -j DOCKER-USER
-A FORWARD -j DOCKER-ISOLATION-STAGE-1
-A FORWARD -o docker0 -m conntrack --ctstate RELATED,ESTABLISHED -j ACCEPT
-A FORWARD -o docker0 -j DOCKER
-A FORWARD -i docker0 ! -o docker0 -j ACCEPT
-A FORWARD -i docker0 -o docker0 -j ACCEPT
-A FORWARD -o docker_gwbridge -m conntrack --ctstate RELATED,ESTABLISHED -j ACCEPT
-A FORWARD -o docker_gwbridge -j DOCKER
-A FORWARD -i docker_gwbridge ! -o docker_gwbridge -j ACCEPT
-A FORWARD -i docker_gwbridge -o docker_gwbridge -j DROP
-A OUTPUT -m conntrack --ctstate NEW -m comment --comment "kubernetes service portals" -j KUBE-SERVICES
-A OUTPUT -j KUBE-FIREWALL
-A DOCKER-ISOLATION-STAGE-1 -i docker0 ! -o docker0 -j DOCKER-ISOLATION-STAGE-2
-A DOCKER-ISOLATION-STAGE-1 -i docker_gwbridge ! -o docker_gwbridge -j DOCKER-ISOLATION-STAGE-2
-A DOCKER-ISOLATION-STAGE-1 -j RETURN
-A DOCKER-ISOLATION-STAGE-2 -o docker0 -j DROP
-A DOCKER-ISOLATION-STAGE-2 -o docker_gwbridge -j DROP
-A DOCKER-ISOLATION-STAGE-2 -j RETURN
-A DOCKER-USER -j RETURN
-A KUBE-FIREWALL -m comment --comment "kubernetes firewall for dropping marked packets" -m mark --mark 0x8000/0x8000 -j DROP
-A KUBE-FORWARD -m conntrack --ctstate INVALID -j DROP
-A KUBE-FORWARD -m comment --comment "kubernetes forwarding rules" -m mark --mark 0x4000/0x4000 -j ACCEPT
-A KUBE-FORWARD -s 10.217.0.0/16 -m comment --comment "kubernetes forwarding conntrack pod source rule" -m conntrack --ctstate RELATED,ESTABLISHED
-A KUBE-FORWARD -d 10.217.0.0/16 -m comment --comment "kubernetes forwarding conntrack pod destination rule" -m conntrack --ctstate RELATED,ESTABLI
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-A KUBE-SERVICES -d 10.96.61.252/32 -p tcp -m comment --comment "default/nginx-64: has no endpoints" -m tcp --dport 80 -j REJECT --reject-with icmp-port-
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-A KUBE-SERVICES -d 10.98.85.41/32 -p tcp -m comment --comment "default/nginx-9: has no endpoints" -m tcp --dport 80 -j REJECT --reject-with icmp-port-un
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-A KUBE-SERVICES -d 10.107.229.31/32 -p tcp -m comment --comment "default/nginx-92: has no endpoints" -m tcp --dport 80 -j REJECT --reject-with icmp-port
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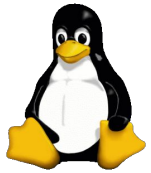

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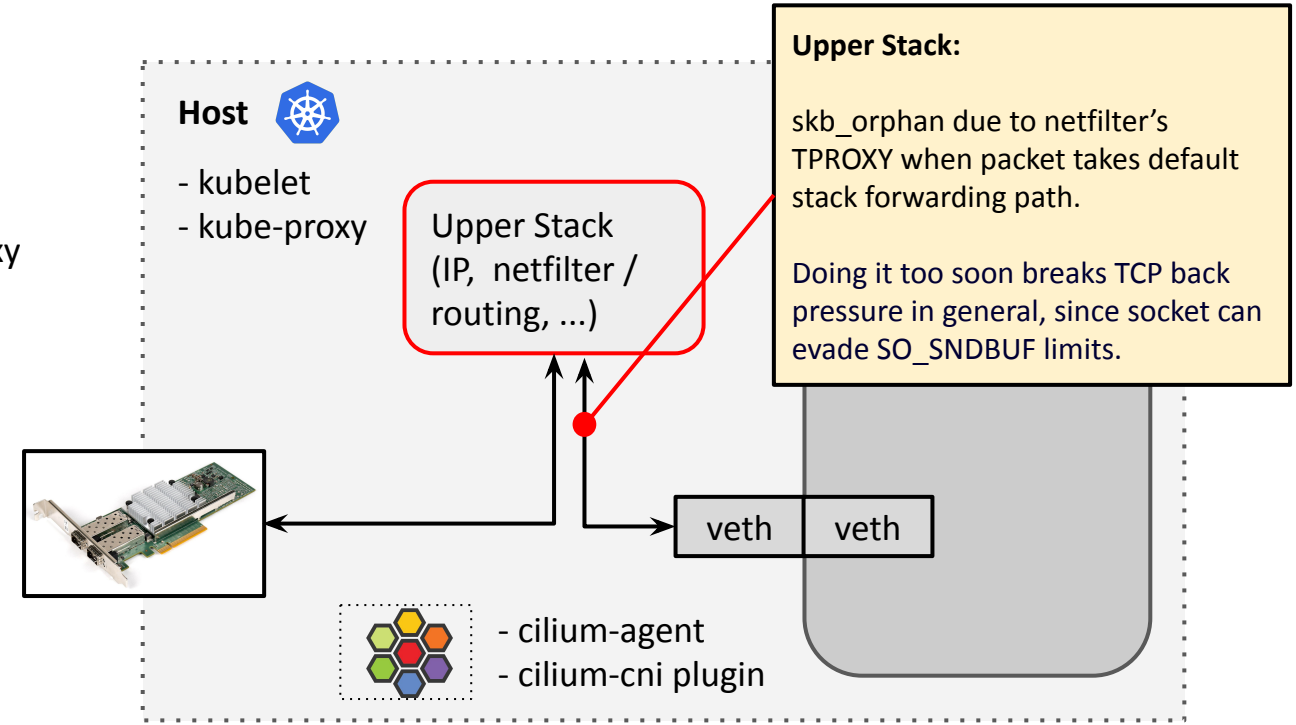

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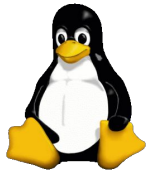

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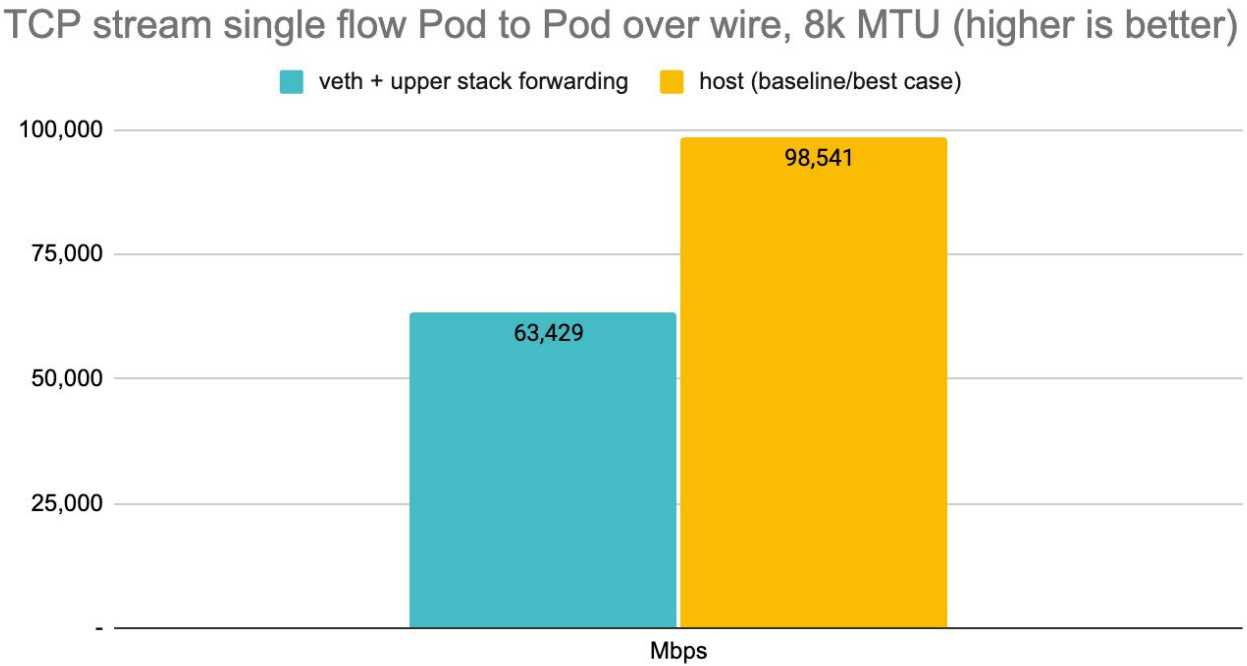

* 8264 MTU for data page alignment in GRO

Back to back: AMD Ryzen 9 3950X @ 3.5 GHz, 128G RAM @ 3.2 GHz, PCIe 4.0, ConnectX-6 Dx, mlx5 driver, striding mode, LRO off, 8264 MTU
Receiver: taskset -a -c <core> tcp_mmap -s (non-zerocopy mode), Sender: taskset -a -c <core> tcp_mmap -H <dst host>

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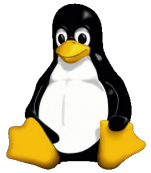

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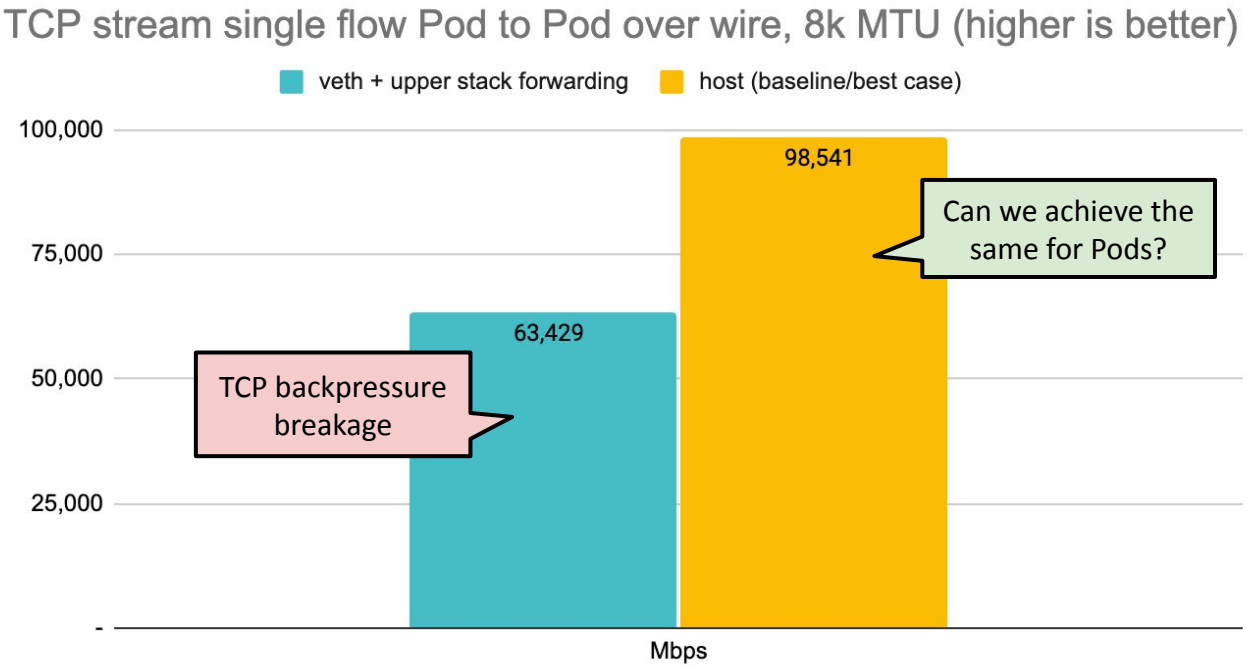

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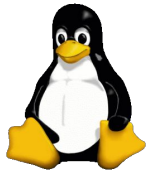

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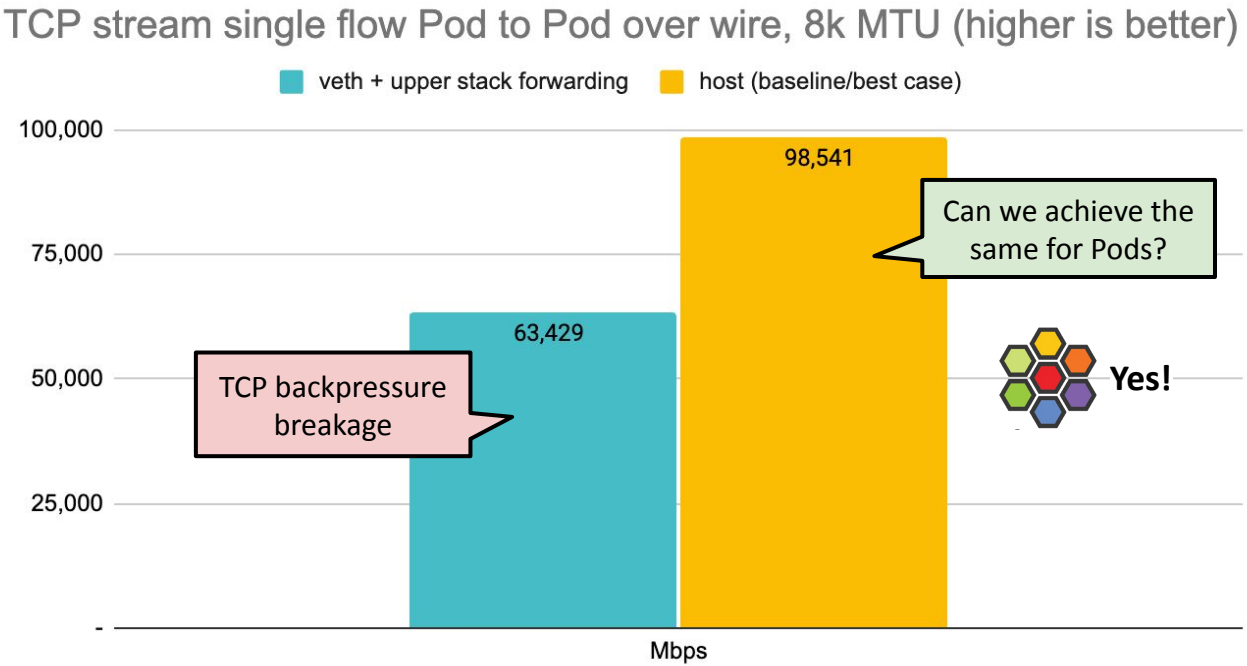

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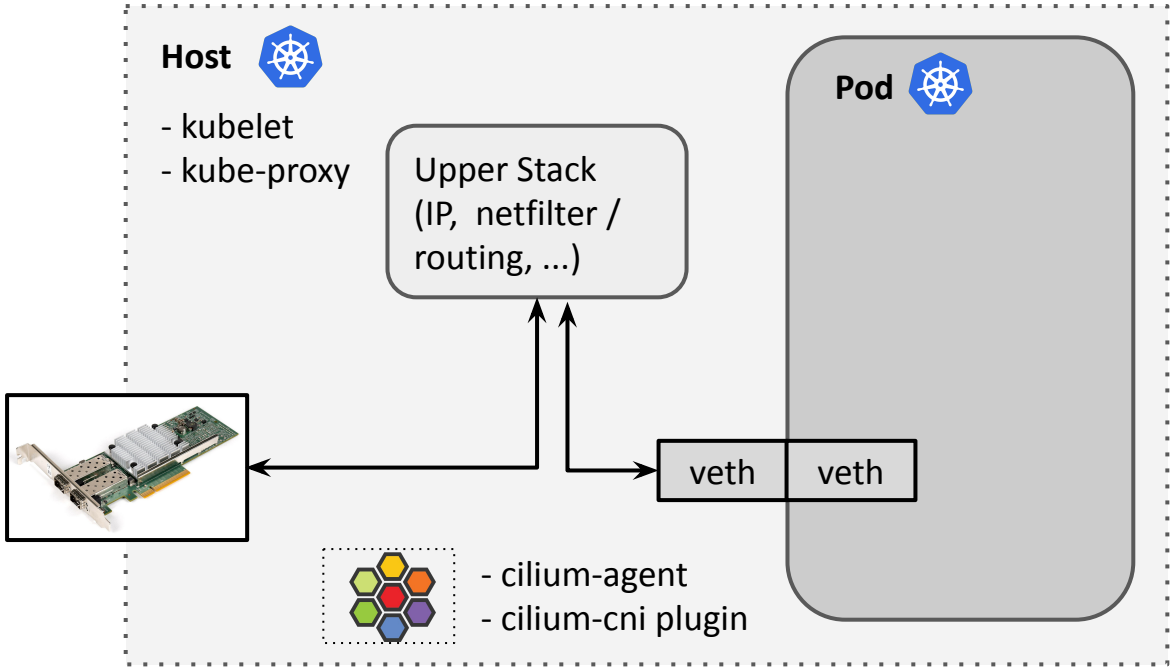
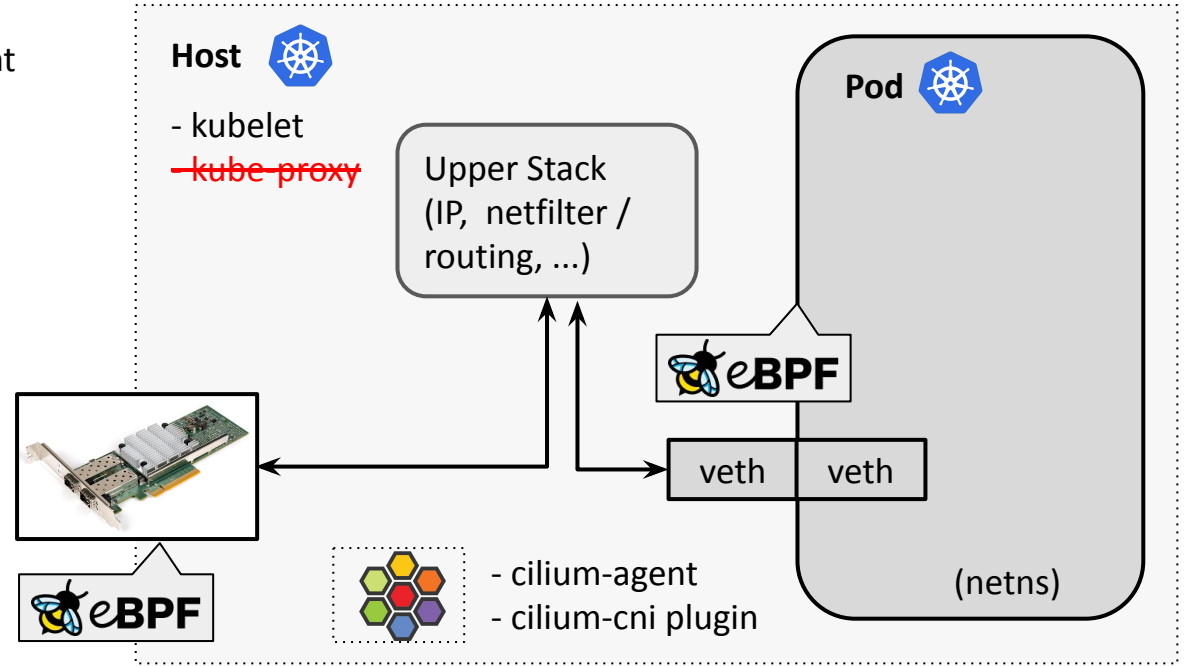


Cilium Datapath Architecture (journey 2019 - today):

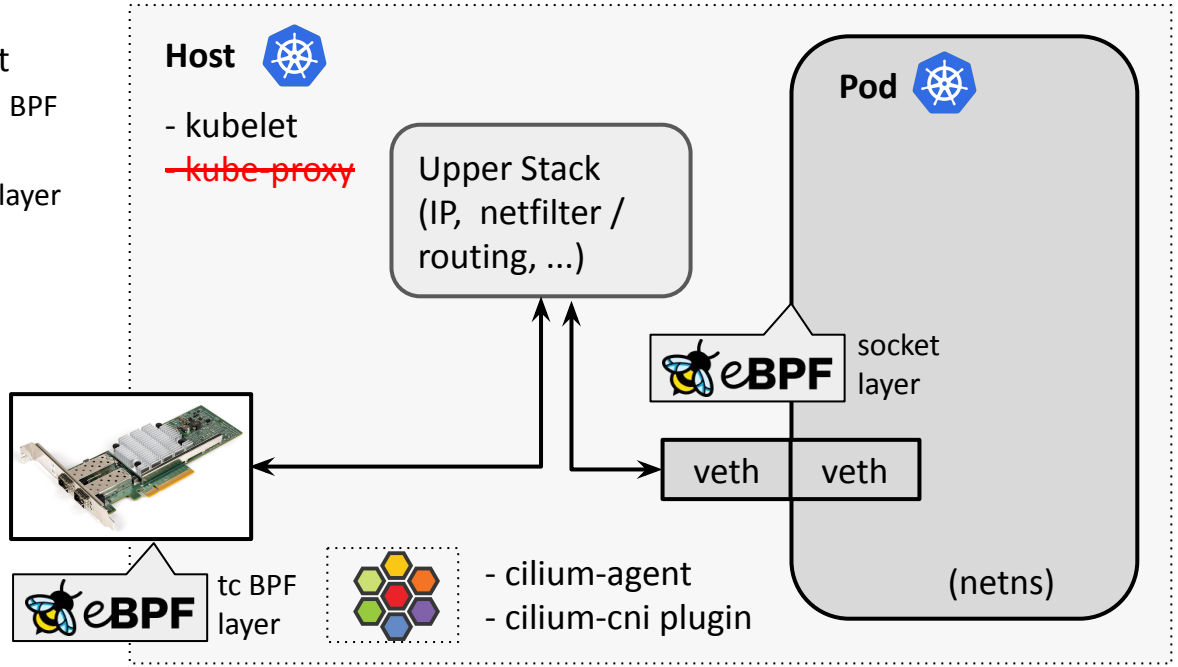
Building Blocks:
- BPF kube-proxy replacement



Cilium Datapath Architecture (journey 2019 - today):

Building Blocks:

- BPF kube-proxy replacement
  - ↪ Covers all K8s service types via BPF
  - ↪ N/S: per packet NAT in tc BPF
  - ↪ E/W: per connect(2) at socket layer
  - ↪ Maglev & HostPort support



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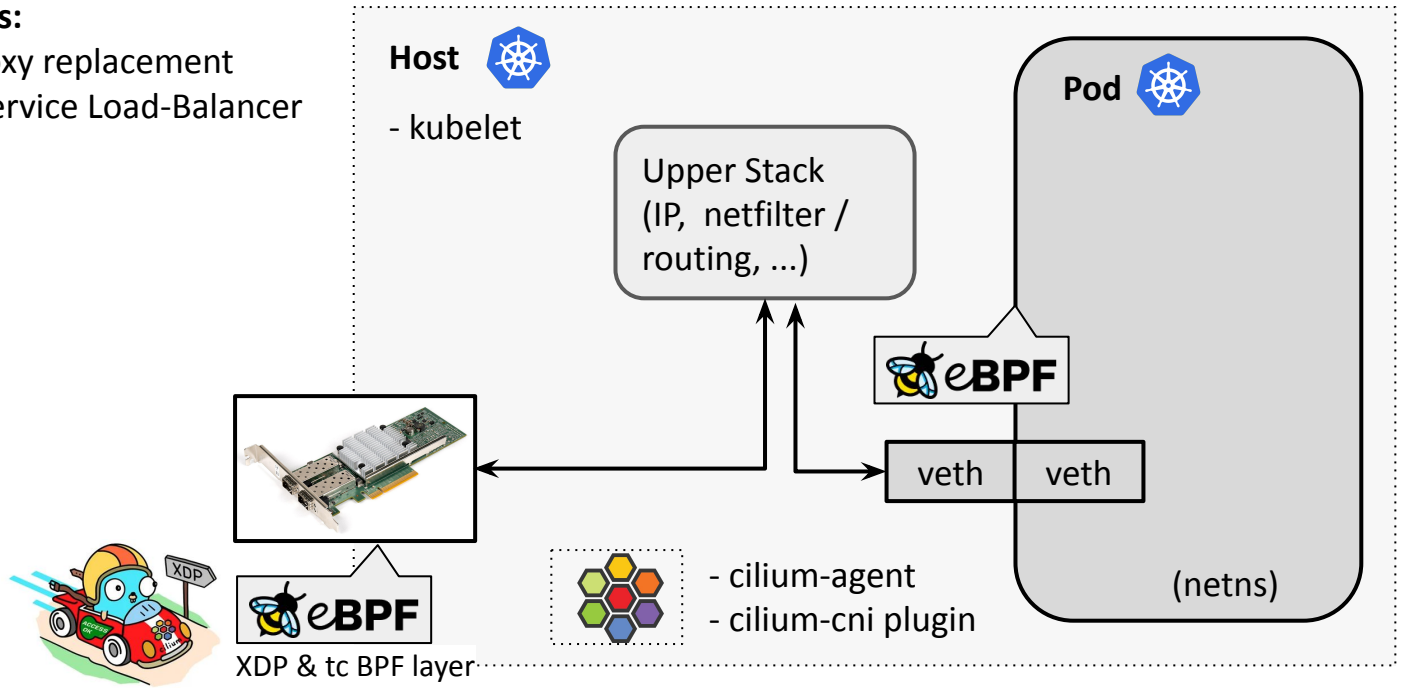
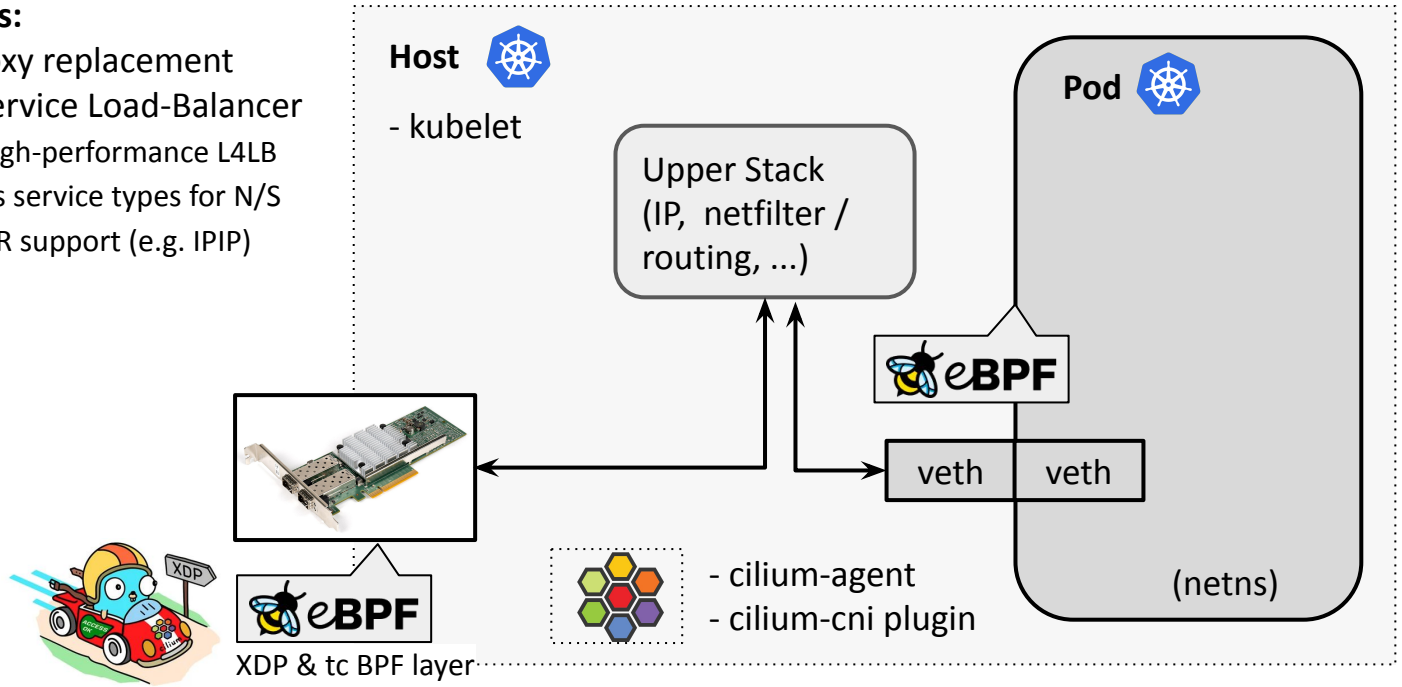
- XDP-based Service Load-Balancer



Cilium Datapath Architecture (journey 2019 - today):

Building Blocks:

- BPF kube-proxy replacement
- XDP-based Service Load-Balancer
  - ↪ Co-located high-performance L4LB
  - ↪ Covers all K8s service types for N/S
  - ↪ Maglev & DSR support (e.g. IPIP)



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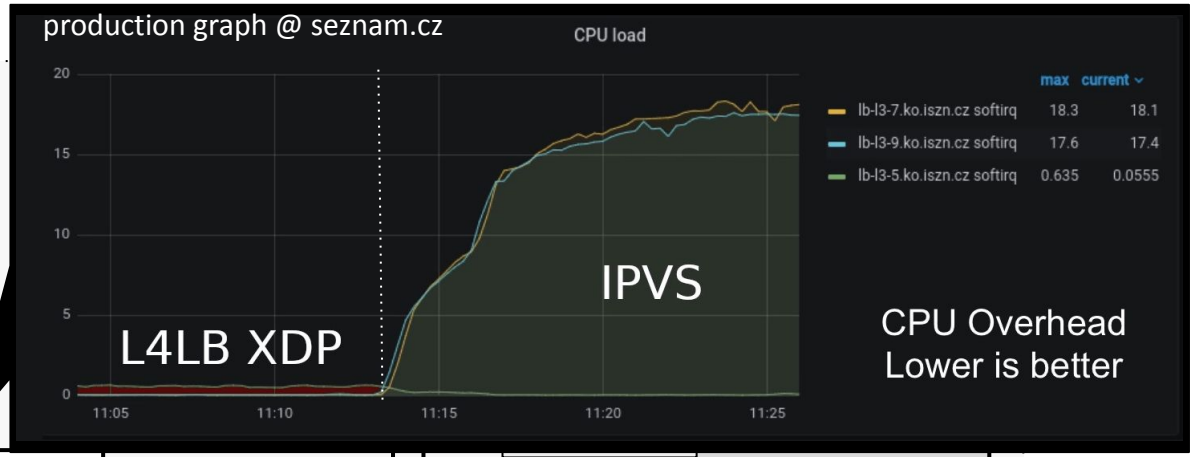
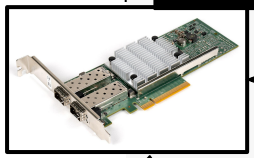
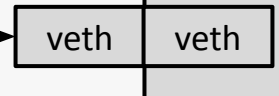
  - ↪ Maglev & DSR support (e.g. IPIP)





XDP & tc BPF layer

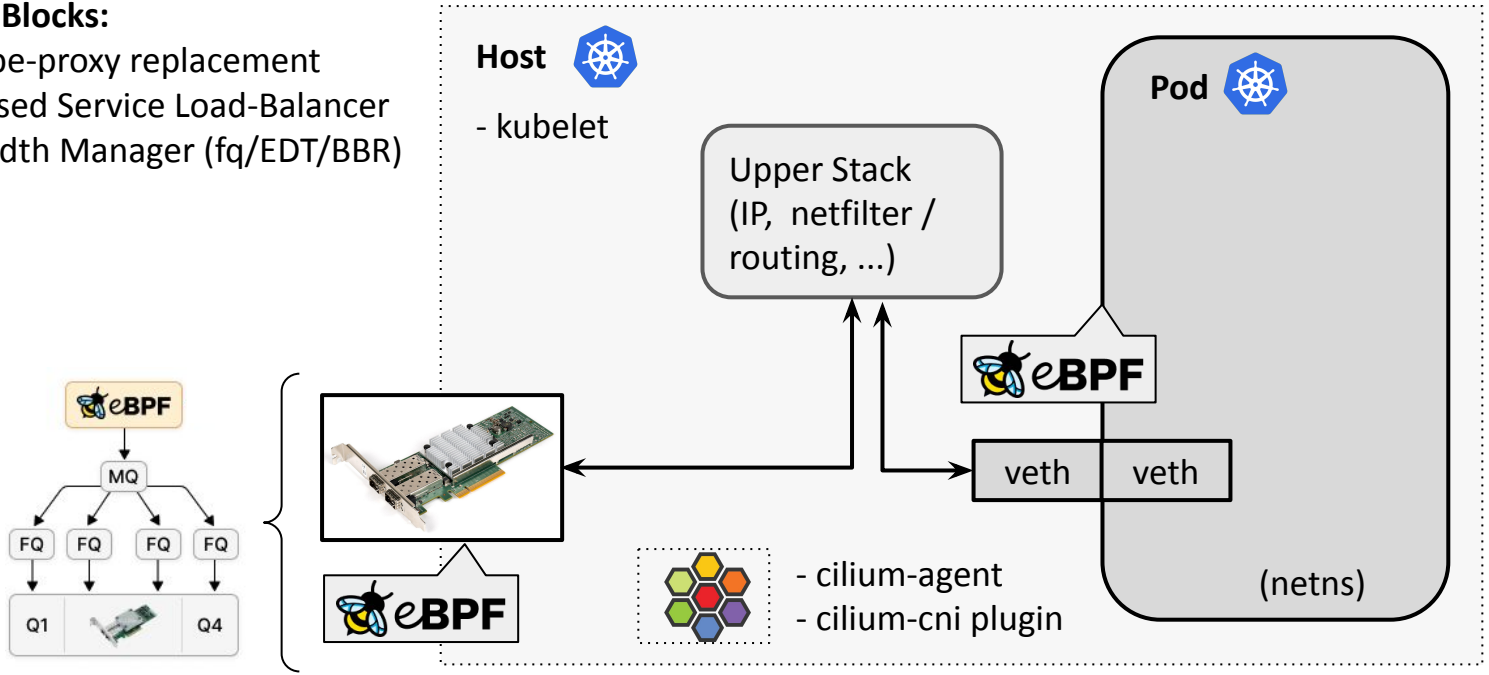
- cilium-agent
- cilium-cni plugin



(netns)

Cilium Datapath Architecture (journey 2019 - today):

Building Blocks:
- BPF kube-proxy replacement
- XDP-based Service Load-Balancer
- Bandwidth Manager (fq/EDT/BBR)



Cilium Datapath Architecture (journey 2019 - today):

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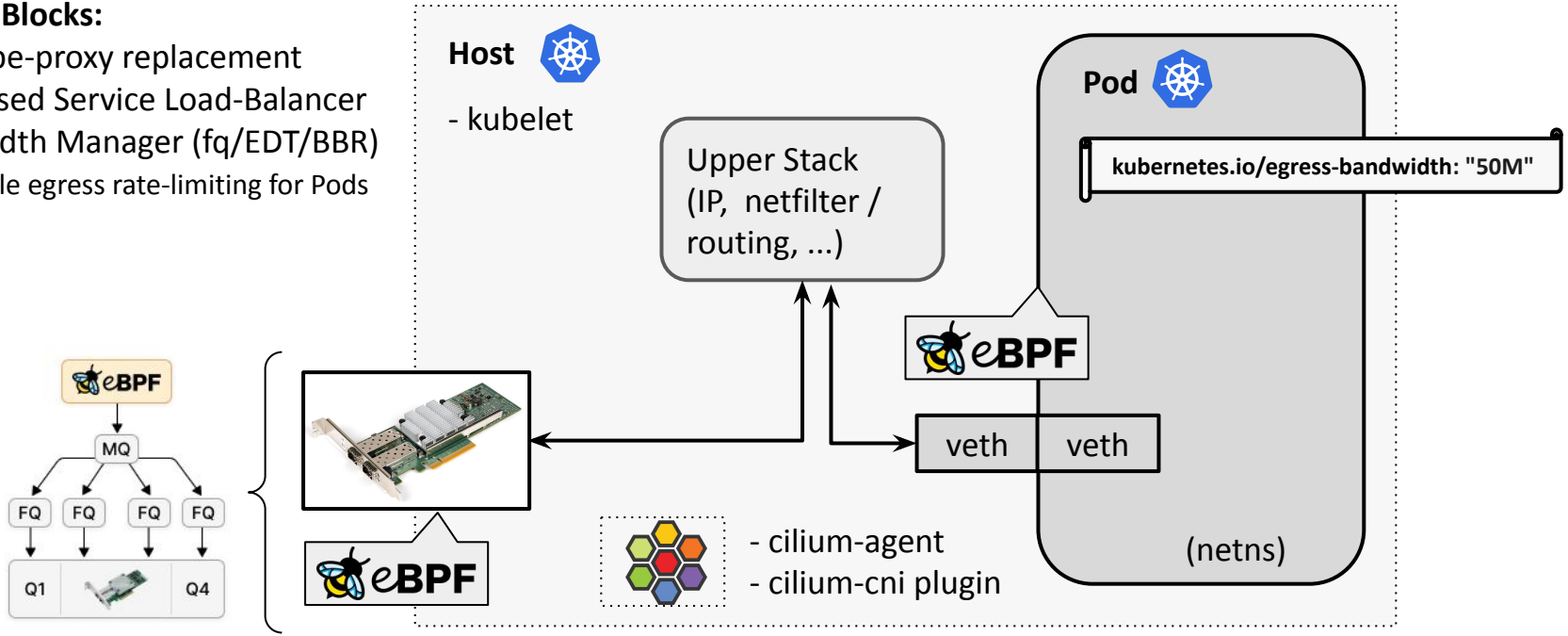
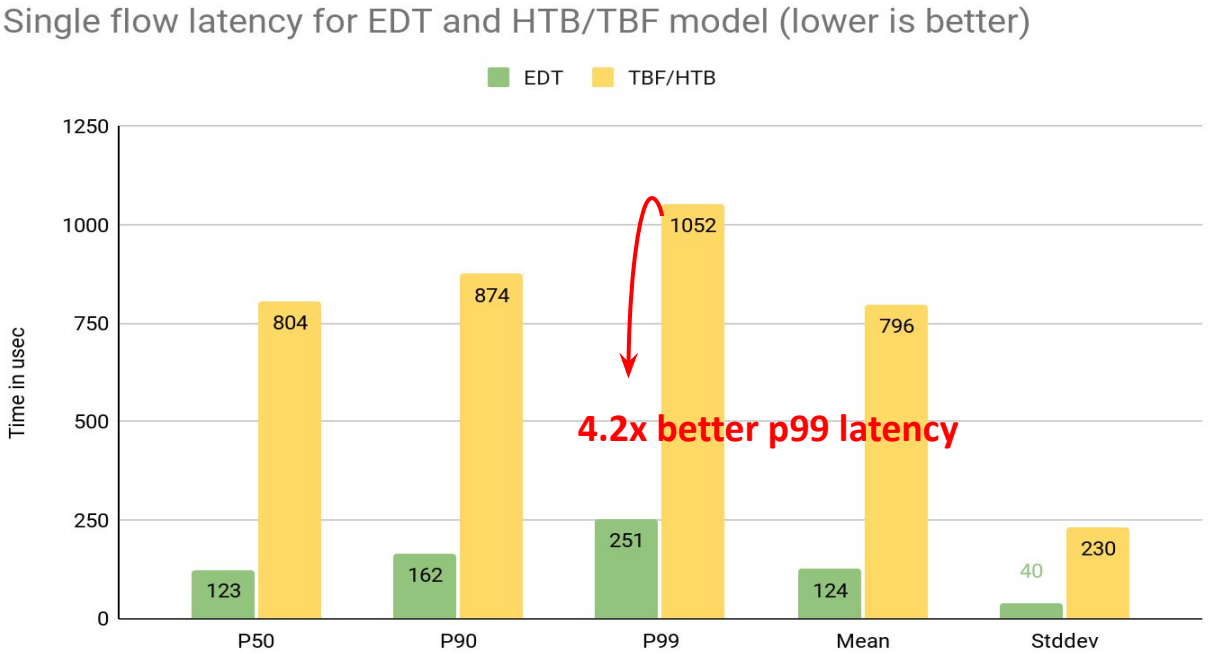
  ↪ Scalable egress rate-limiting for Pods



Cilium Datapath Architecture (journey 2019 - today):

Building Blocks:

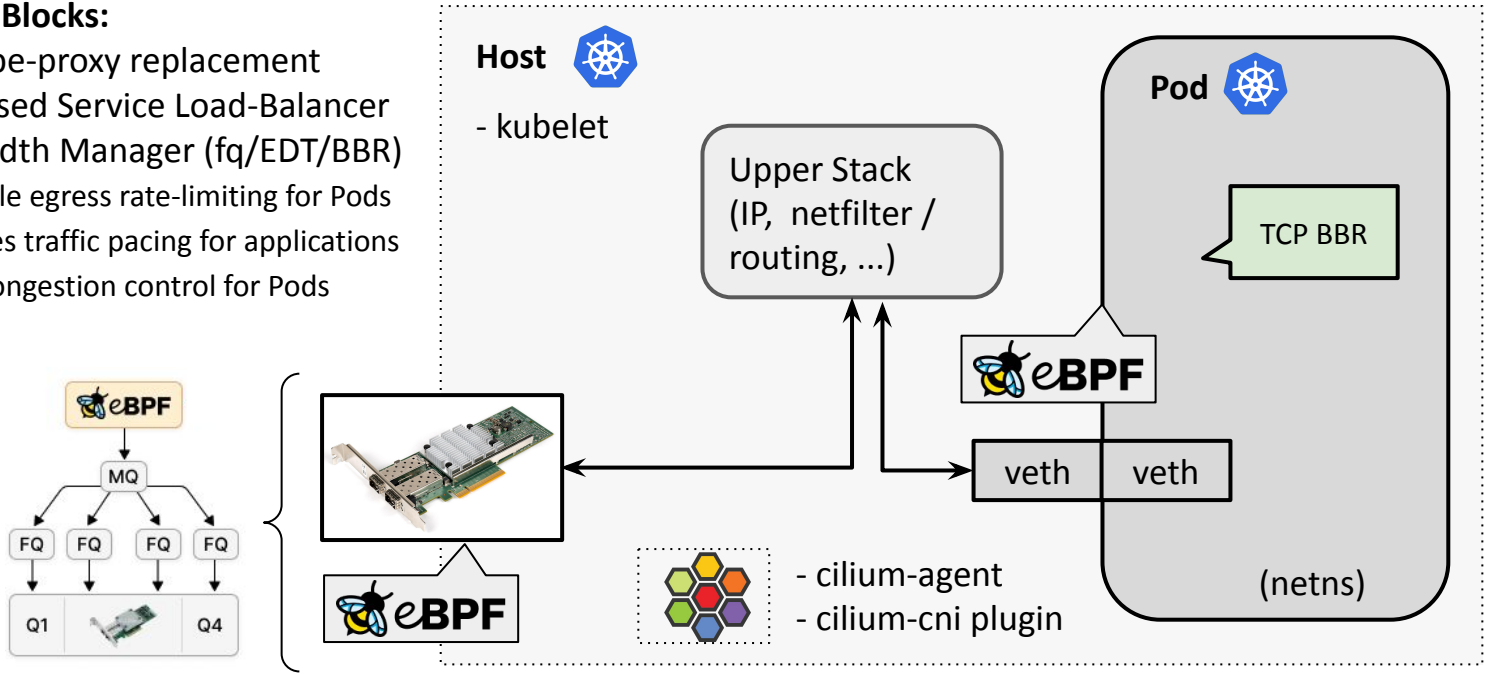
- BPF kube-proxy replacement
- XDP-based Service Load-Balancer
- Bandwidth Manager (fq/EDT/BBR)
  - ↪ Scalable egress rate-limiting for Pods
    - Earliest departure time (EDT) via BPF
    - fq also in production at Google/Meta
    - Ready for ToS priority bands too



Cilium Datapath Architecture (journey 2019 - today):

Building Blocks:

- BPF kube-proxy replacement
- XDP-based Service Load-Balancer
- Bandwidth Manager (fq/EDT/BBR)
  - ↪ Scalable egress rate-limiting for Pods
  - ↪ Enables traffic pacing for applications
  - ↪ BBR congestion control for Pods



Kernel 5.18: preserving delivery timestamps across netns (Martin Lau, Daniel Borkmann)

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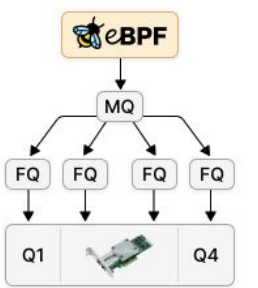
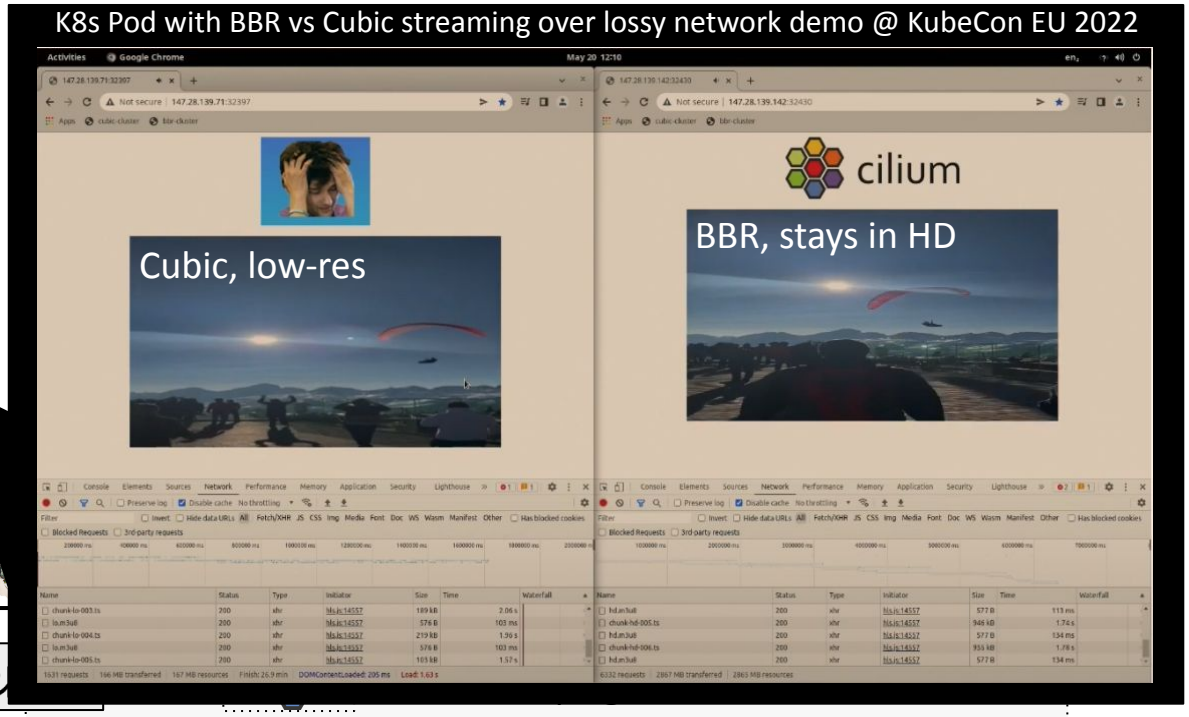
  - ↪ Enables traffic pacing for applications
  - ↪ BBR congestion control for Pods





Kernel 5.18: preserving delivery timestamps across netns (Martin Lau, Daniel Borkmann)

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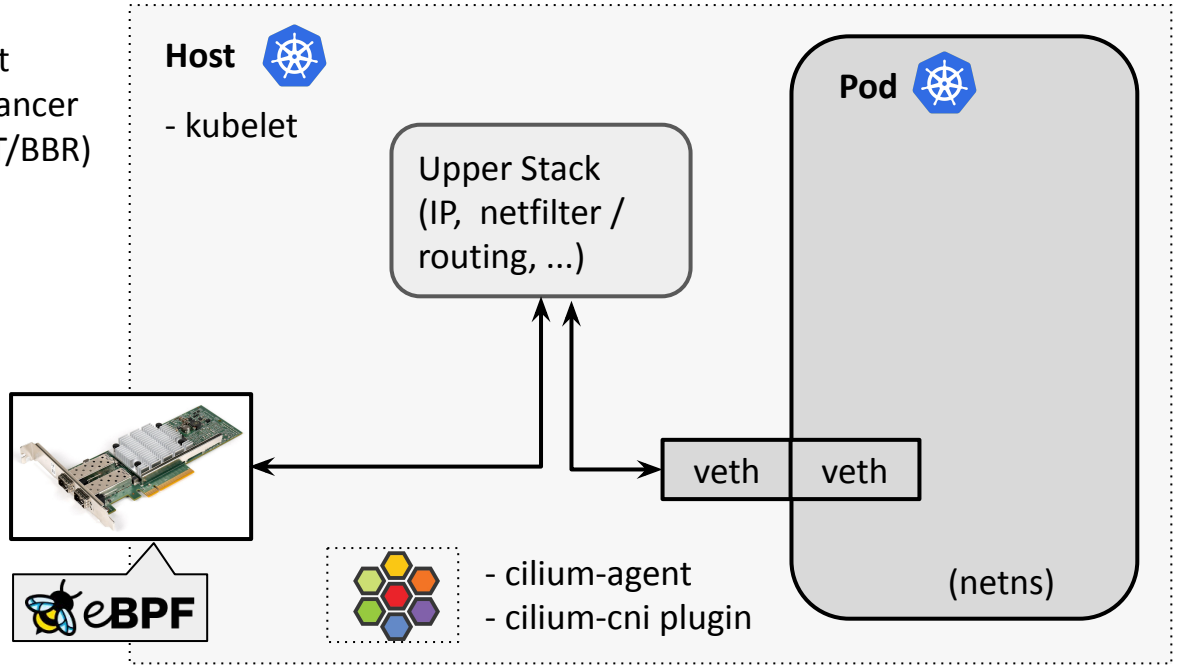
- Bandwidth Manager (fq/EDT/BBR)
- BPF Host Routing

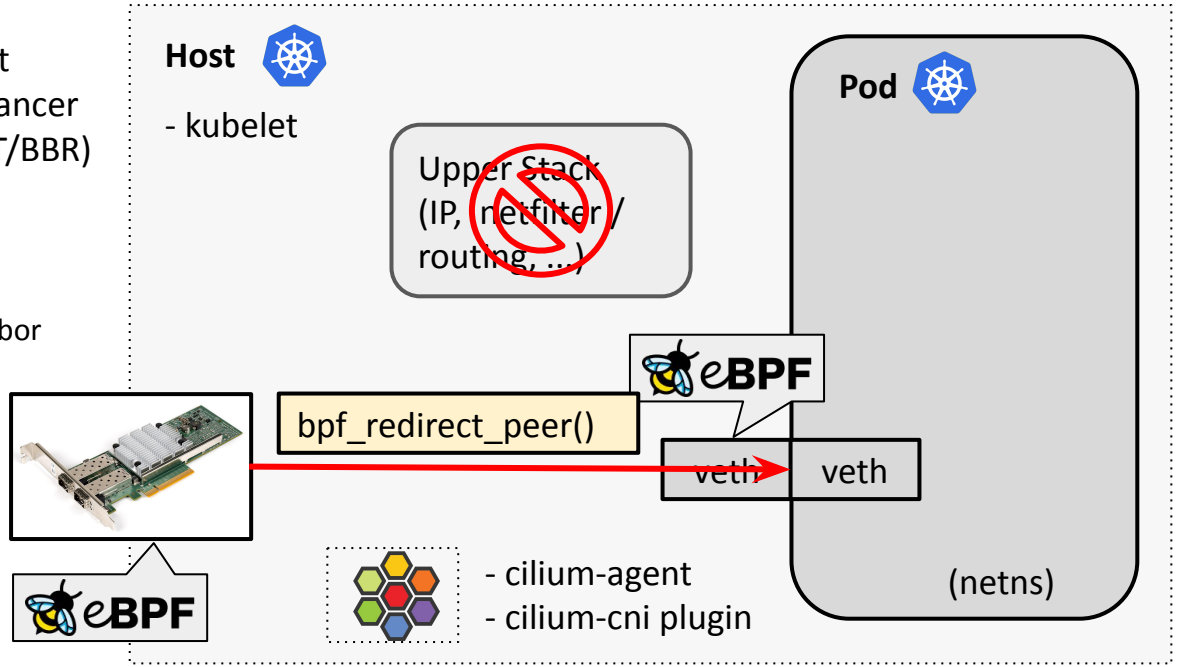


Kernel 5.10: bpf_redirect_peer and bpf_redirect_neigh helpers (Daniel Borkmann)

Cilium Datapath Architecture (journey 2019 - today):

Building Blocks:

- BPF kube-proxy replacement
- XDP-based Service Load-Balancer
- Bandwidth Manager (fq/EDT/BBR)
- BPF Host Routing
  - ↪ Routing only via tc BPF layer
  - ↪ Fast netns switch on ingress
  - ↪ Helper for fib + dynamic neighbor resolution on egress



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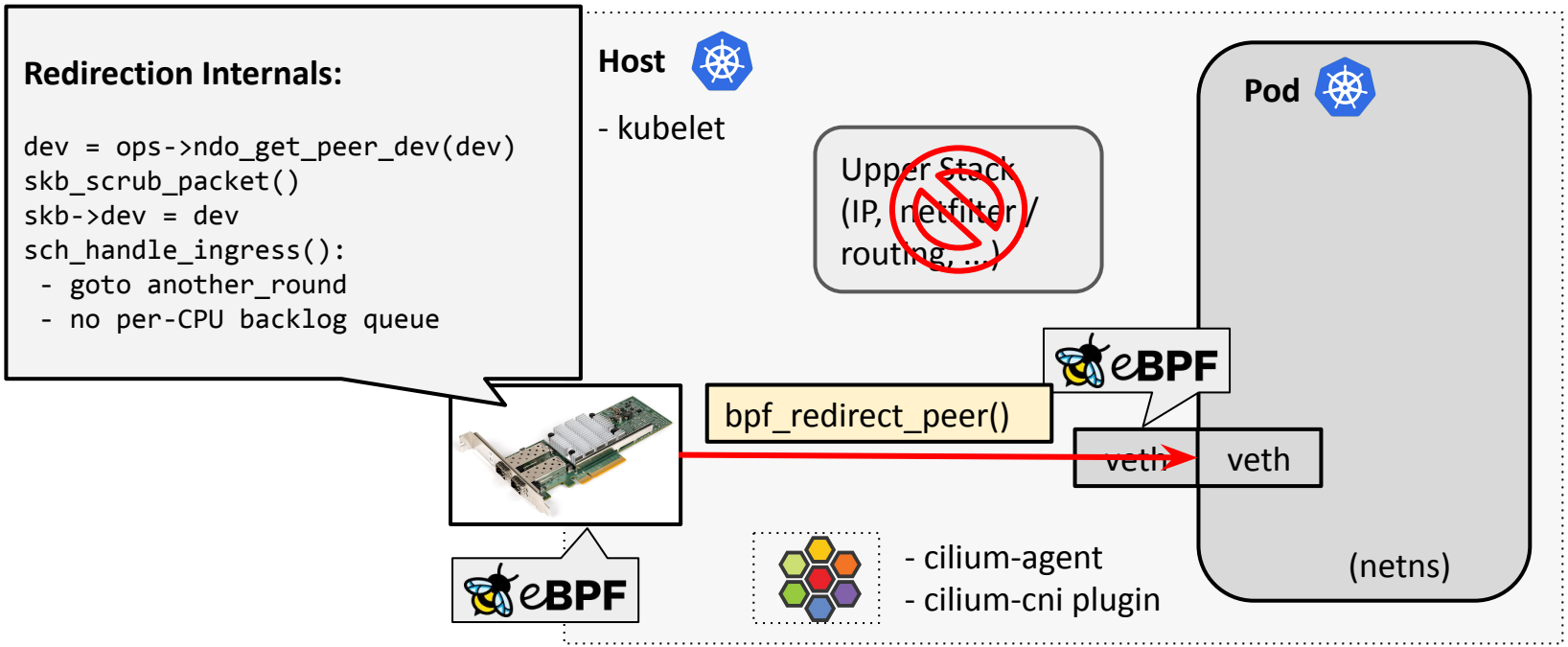
Cilium Datapath Architecture (journey 2019 - today):



Kernel 5.10: bpf_redirect_peer and bpf_redirect_neigh helpers (Daniel Borkmann)

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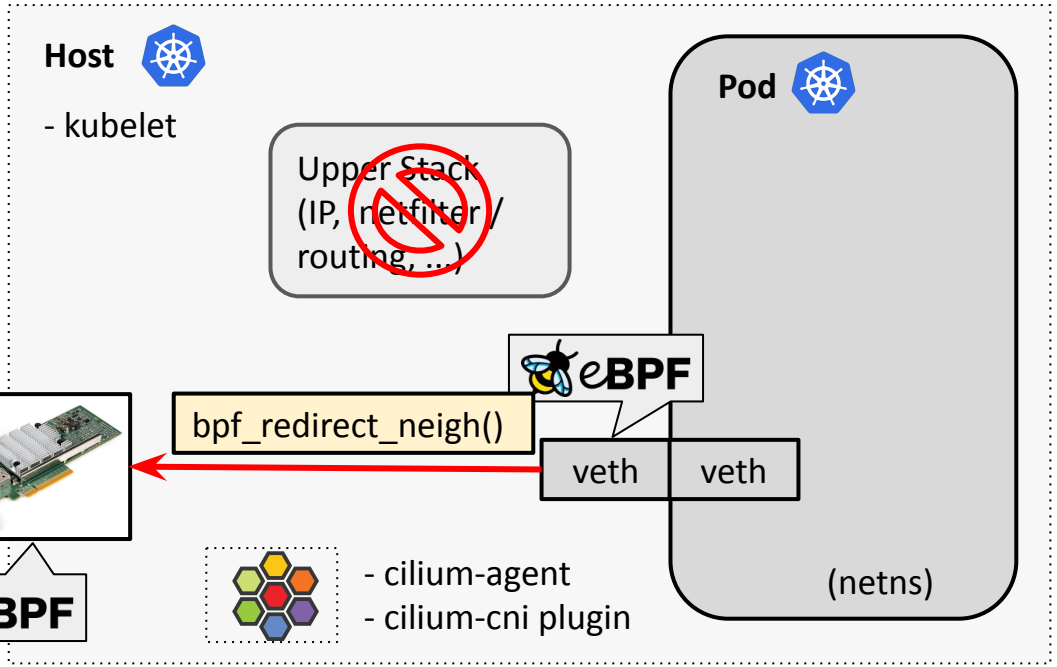

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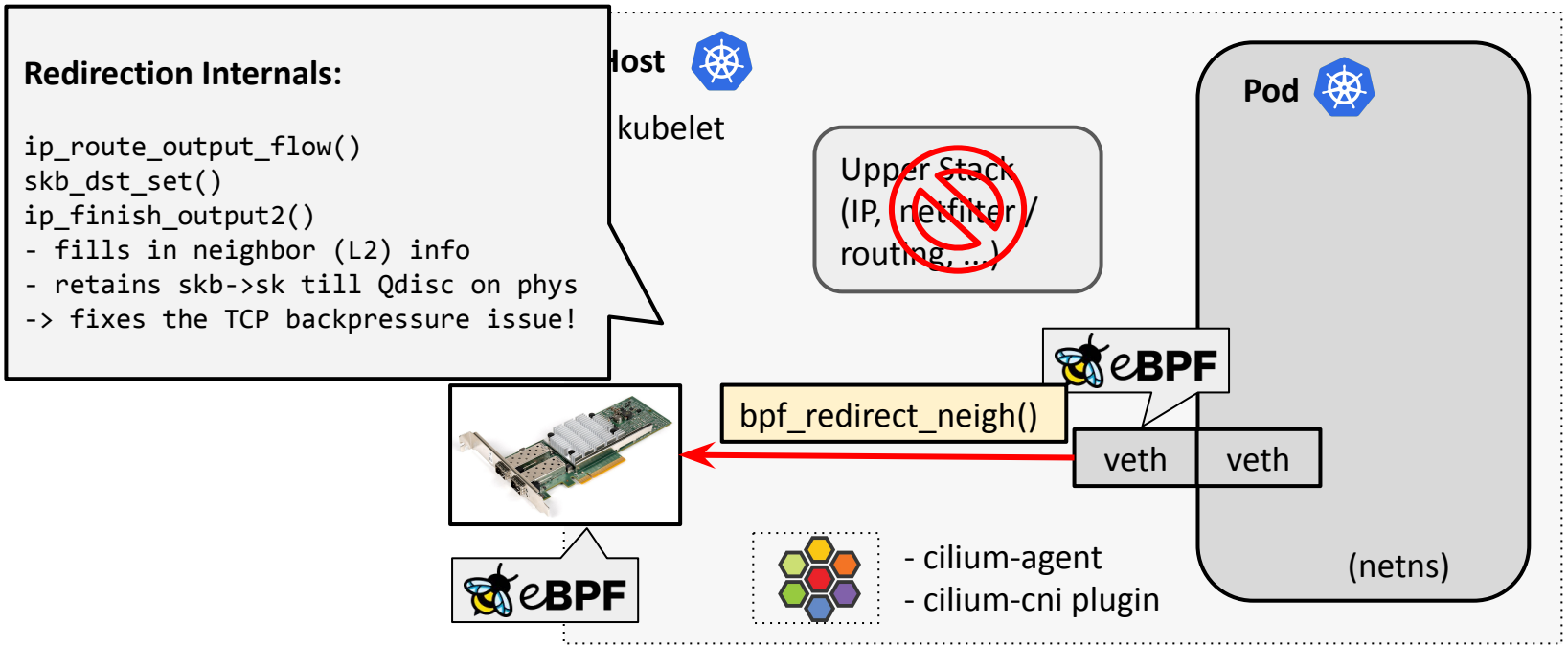
Cilium Datapath Architecture (journey 2019 - today):



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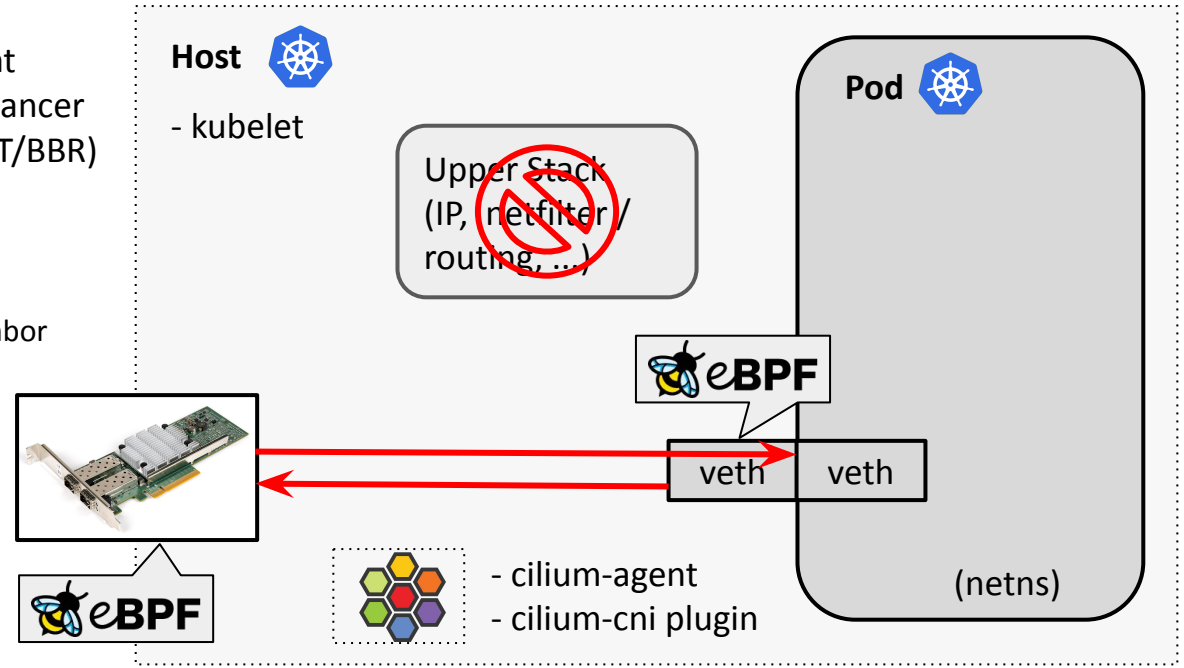

Kernel 5.10: bpf_redirect_peer and bpf_redirect_neigh helpers (Daniel Borkmann)

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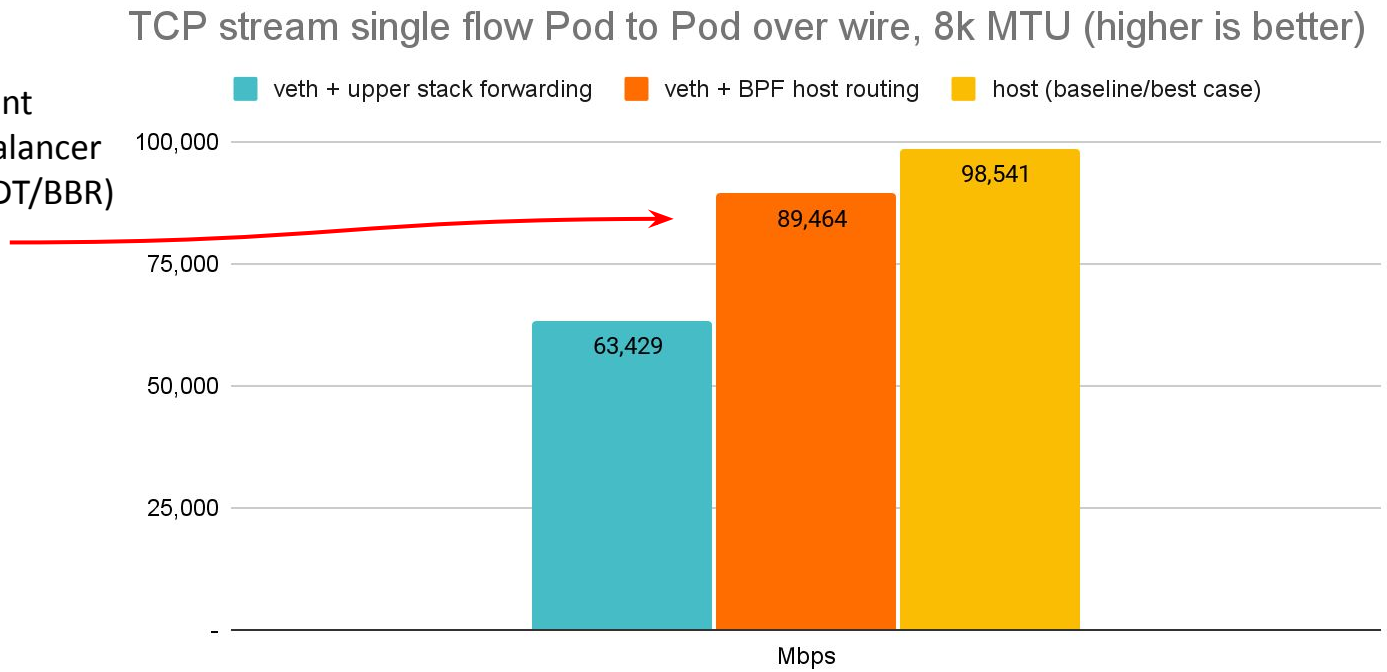
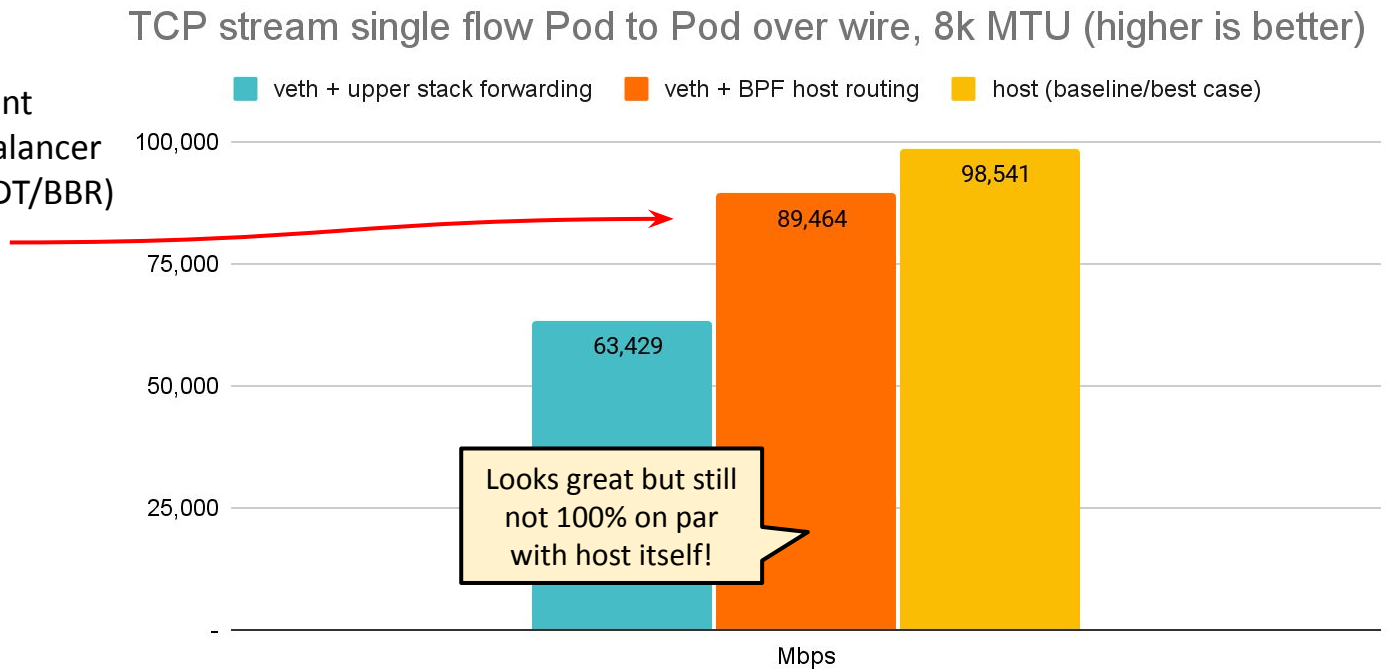


* 8264 MTU for data page alignment in GRO

Back to back: AMD Ryzen 9 3950X @ 3.5 GHz, 128G RAM @ 3.2 GHz, PCIe 4.0, ConnectX-6 Dx, mlx5 driver, striding mode, LRO off, 8264 MTU
Receiver: taskset -a -c <core> tcp_mmap -s (non-zerocopy mode), Sender: taskset -a -c <core> tcp_mmap -H <dst host>

Cilium Datapath Architecture (journey 2019 - today):

Building Blocks:
- BPF kube-proxy replacement
- XDP-based Service Load-Balancer
- Bandwidth Manager (fq/EDT/BBR)
- BPF Host Routing



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Cilium Datapath Architecture (journey 2019 - today):

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- BPF kube-proxy replacement
- XDP-based Service Load-Balancer
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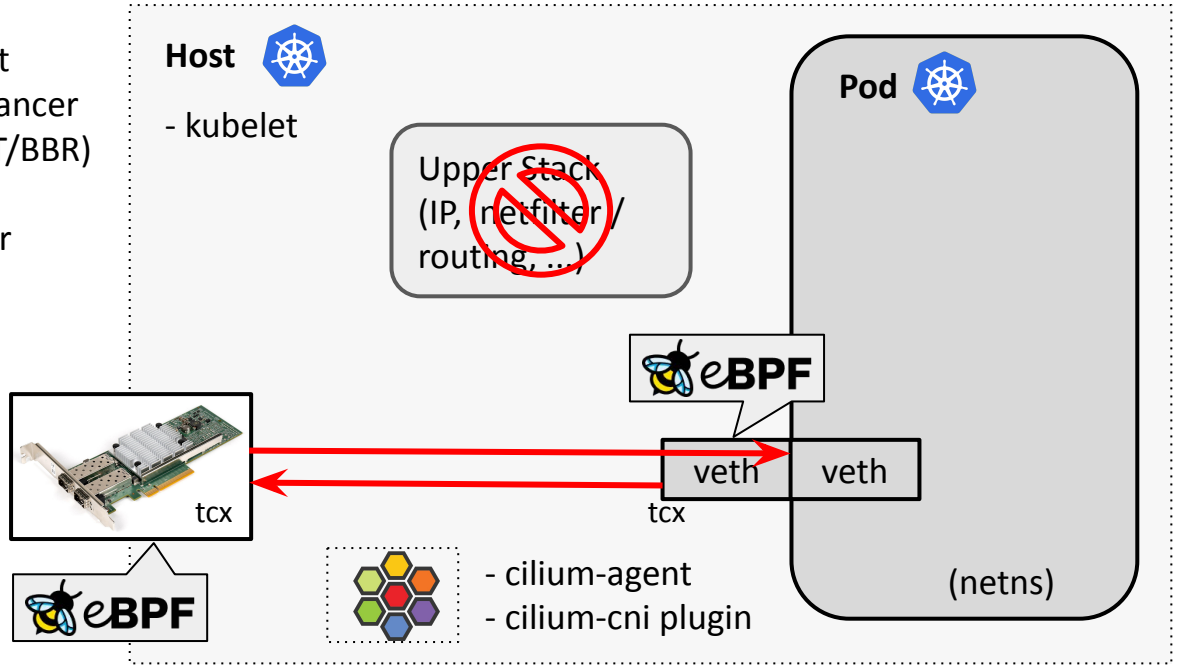
- BPF Host Routing
- tcx-based BPF datapath layer



Kernel 6.6: tcx infrastructure and BPF link support (Daniel Borkmann)

Brief Deep Dive: tcx

tcx (tc express) layer for BPF:

- Full rework of tc BPF data and control path, approx. 1 year effort
- Merged and released with Linux kernel v6.6 onwards
- Modernizing the underlying foundation of Cilium's networking data path in the kernel:
  - More efficient, binary-compatible fast-path for tc BPF programs
  - Better robustness in control path with BPF link support
  - Before/After dependency directives for multi-program users

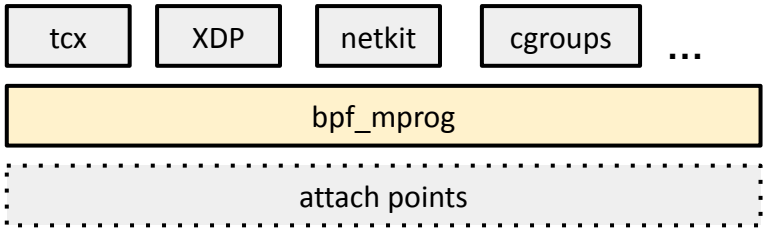
```
author      Daniel Borkmann <daniel@iogearbox.net>     2015-03-01 12:31:48 +0100
committer   David S. Miller <davem@davemloft.net>      2015-03-01 14:05:19 -0500
commit      e2e9b6541dd4b31848079da80fe2253daaafb549 (patch)
tree        dd4de9c9faa662e188285fa5db20663859139f55 /net/sched/cls_bpf.c
parent      24701ecea76b0b93bd9667486934ec310825f558 (diff)
download    linux-e2e9b6541dd4b31848079da80fe2253daaafb549.tar.gz

cls_bpf: add initial eBPF support for programmable classifiers

This work extends the "classic" BPF programmable tc classifier by
extending its scope also to native eBPF code!
```

```
author      Daniel Borkmann <daniel@iogearbox.net>     2023-07-19 16:08:52 +0200
committer   Alexei Starovoitov <ast@kernel.org>        2023-07-19 10:07:27 -0700
commit      e420bed025071a623d2720a92bc2245c84757ecb (patch)
tree        fa8c7e0b31d755ada58465dba12ffdd82a92bc4c
parent      053c8e1f235dc3f69d13375b32f4209228e1cb96 (diff)
download    linux-e420bed025071a623d2720a92bc2245c84757ecb.tar.gz

bpf: Add fd-based tcx multi-prog infra with link support

This work refactors and adds a lightweight extension ("tcx") to the tc BPF
ingress and egress data path side for allowing BPF program management based
on fds via bpf() syscall through the newly added generic multi-prog API.
The main goal behind this work which we also presented at LPC [0] last year
and a recent update at LSF/MM/BPF this year [3] is to support long-awaited
BPF link functionality for tc BPF programs, which allows for a model of safe
ownership and program detachment.
```

Brief Deep Dive: tcx

tcx (tc express) layer for BPF:

- For tcx we also built a new bpf_mprog framework for BPF program dependency management
- Provides a common “look-and-feel” for all networking attach points and beyond
- Future work is to integrate this into XDP as well to support multi-program attachment for the latter



author	Daniel Borkmann <daniel@iogearbox.net> 2023-07-19 16:08:51 +0200
committer	Alexei Starovoitov <ast@kernel.org> 2023-07-19 10:07:27 -0700
commit	053c8e1f235dc3f69d13375b32f4209228e1cb96 (patch)
tree	5ceaf956ca383f496c703fd8700dca5bf06c000f
parent	3226e3139dfe02d5892562976a649a54ada12a13 (diff)
download	linux-053c8e1f235dc3f69d13375b32f4209228e1cb96.tar.gz

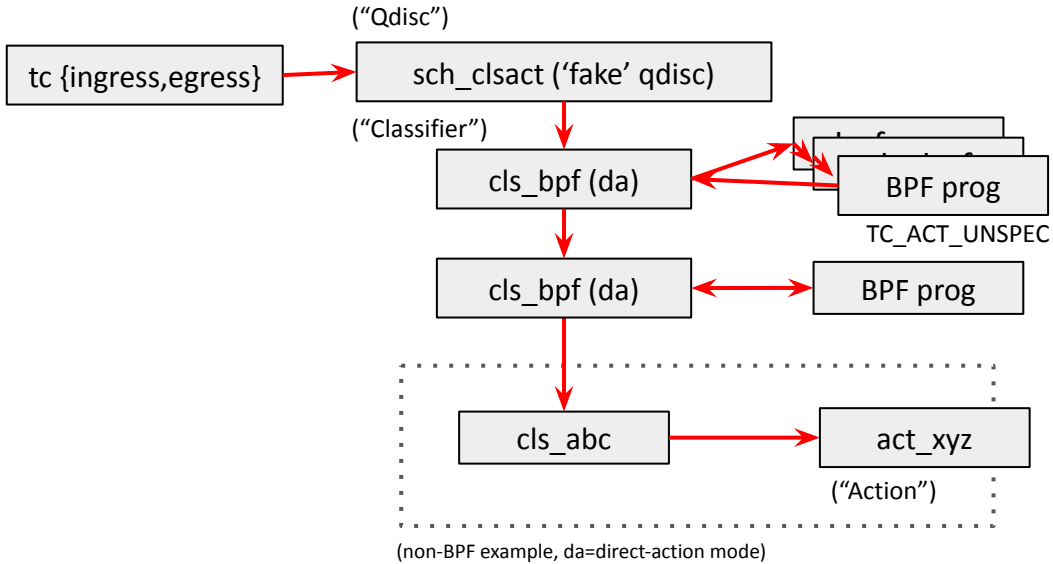
bpf: Add generic attach/detach/query API for multi-progs

```
This adds a generic layer called bpf_mprog which can be reused by different
attachment layers to enable multi-program attachment and dependency resolution.
In-kernel users of the bpf_mprog don't need to care about the dependency
resolution internals, they can just consume it with few API calls.
```

Brief Deep Dive: tcx

tcx (tc express) layer for BPF:

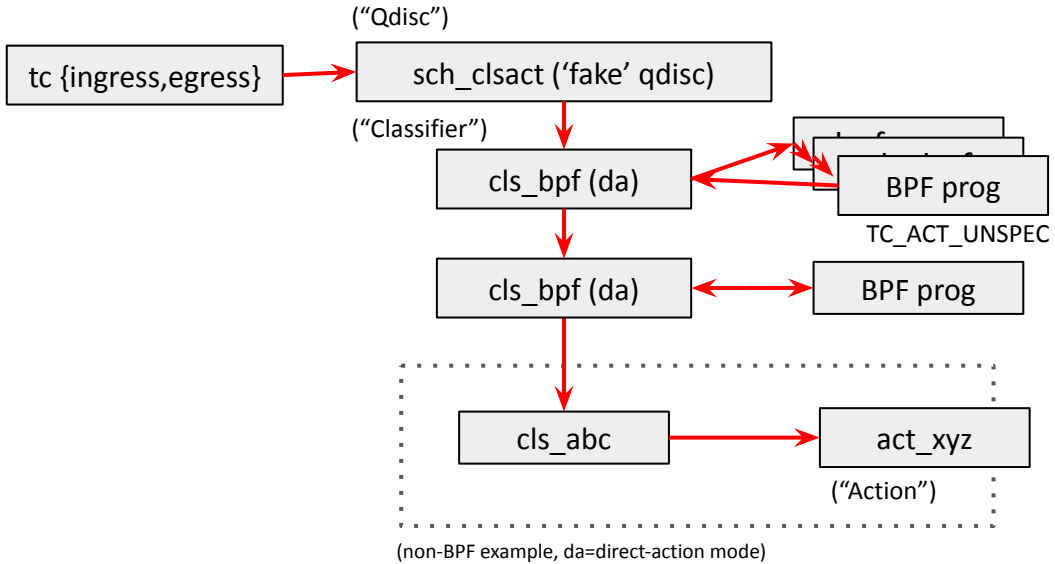
Old style (up to v6.6): cls_bpf



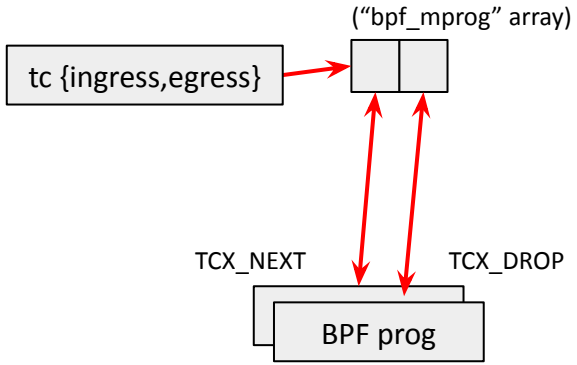
Brief Deep Dive: tcx

tcx (tc express) layer for BPF:

Old style (up to v6.6): cls_bpf



New style (v6.6 and onwards): tcx



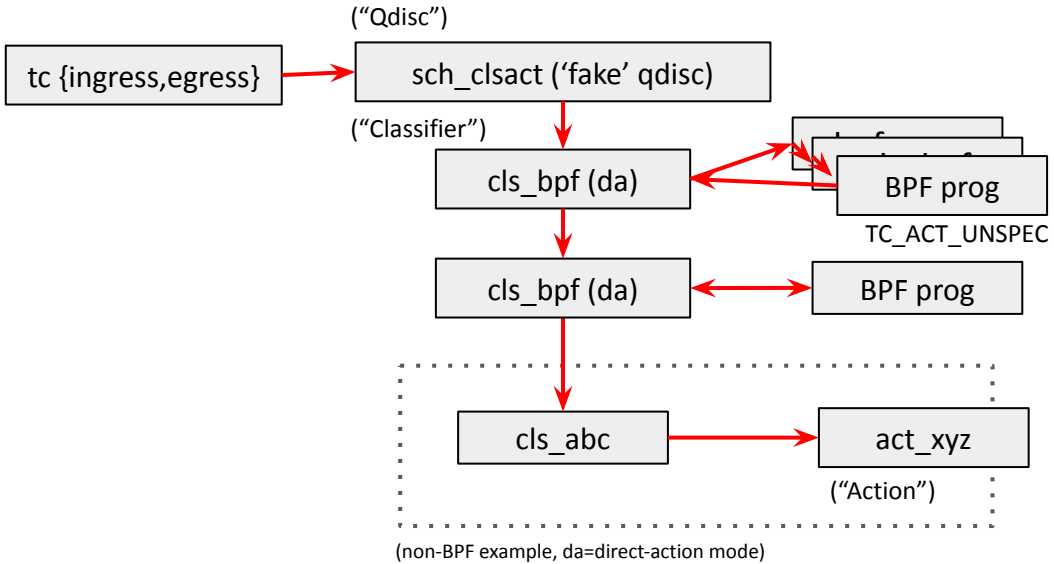
Brief Deep Dive: tcx

tcx (tc express) layer for BPF:

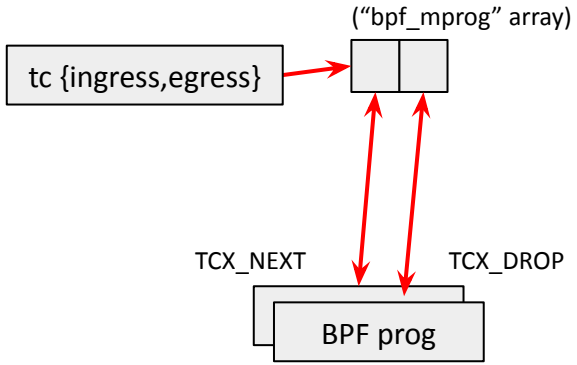
Point to BPF entry µbenchmark (cache-hot):

59 cycles → 33 cycles

Old style (up to v6.6): cls_bpf

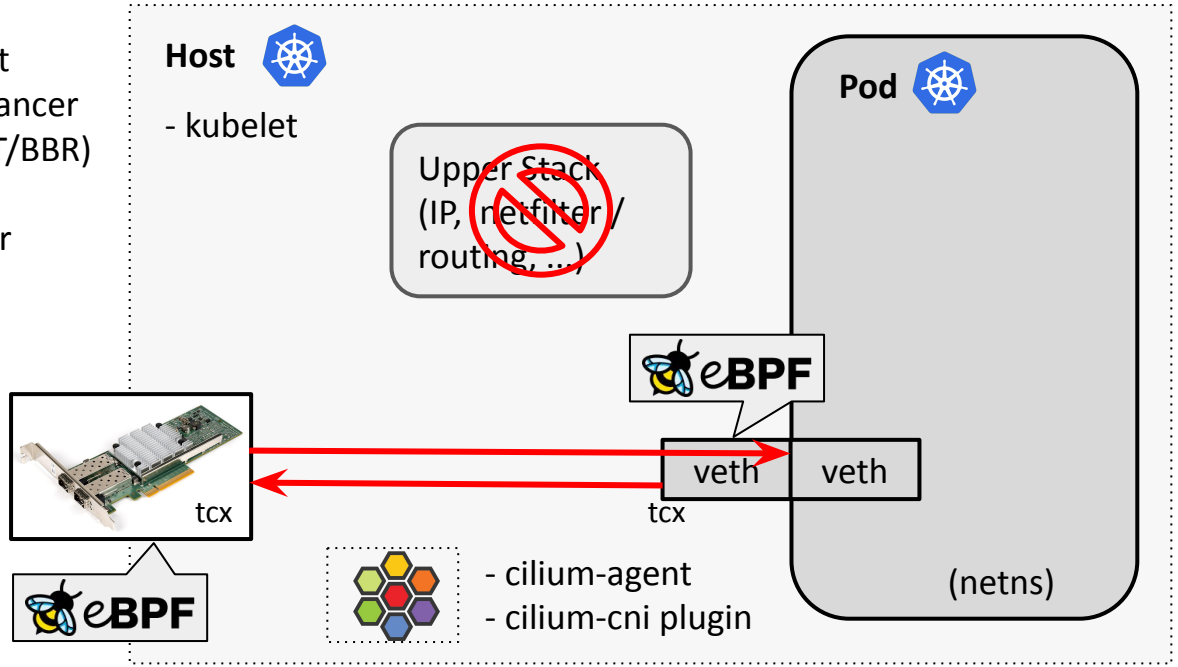


New style (v6.6 and onwards): tcx



Cilium Datapath Architecture (journey 2019 - today):

Building Blocks:
- BPF kube-proxy replacement
- XDP-based Service Load-Balancer
- Bandwidth Manager (fq/EDT/BBR)
- BPF Host Routing
- tcx-based BPF datapath layer



Kernel 6.6: tcx infrastructure and BPF link support (Daniel Borkmann)

Cilium Datapath Architecture (journey 2019 - today):

Building Blocks:
- BPF kube-proxy replacement
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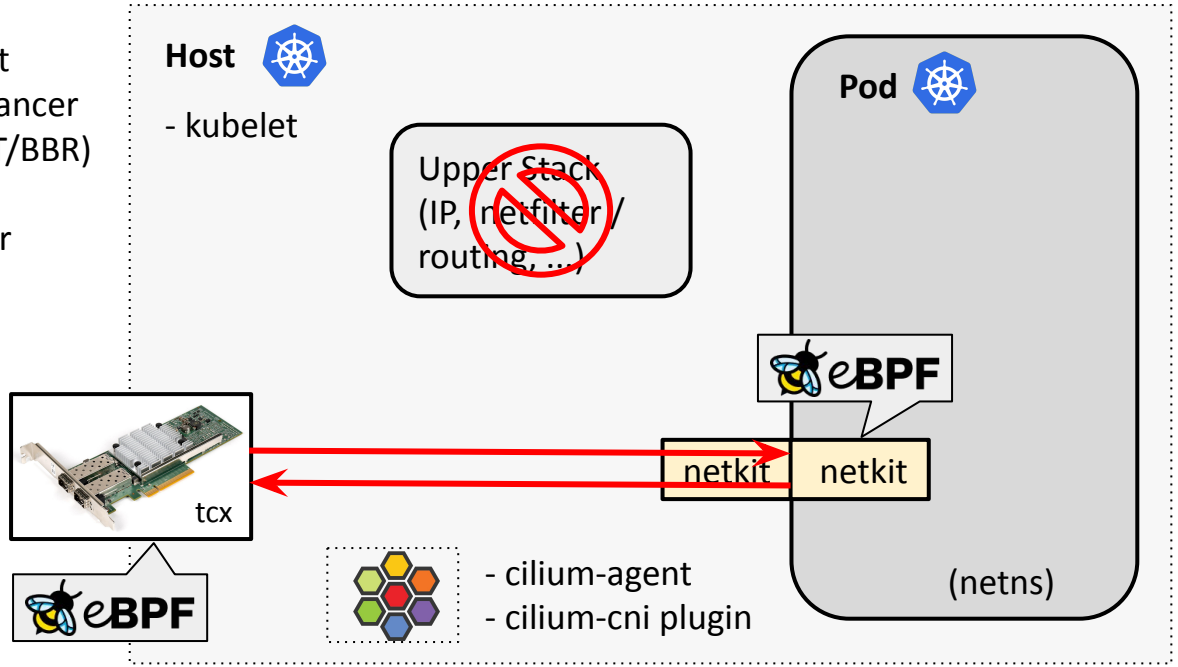
- BPF Host Routing
- tcx-based BPF datapath layer
- netkit devices for Pods

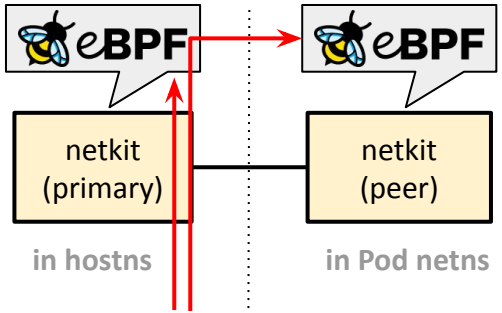


Kernel 6.7: netkit devices (Daniel Borkmann, Nikolay Aleksandrov), **LWN coverage:** The BPF-programmable network device

Brief Deep Dive: veth-replacement for Pods

netkit programmable virtual devices for BPF:

- Going forward, Cilium's CNI code will set up netkit devices for Pods instead of veth !
- Merged and will be released with Linux kernel v6.7 onwards
- BPF program via bpf_mprog is part of the driver's xmit routine, allowing fast egress netns switch
- Configurable as L3 device (default) or L2 device plus default drop-all if no BPF is attached
- Currently in production testing at Meta & Bytedance



Manages BPF programs on primary and peer device

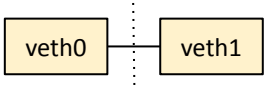
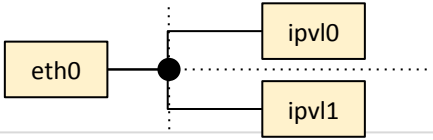
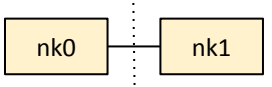
BPF programs inside the Pod inaccessible, only configurable via primary device

author	Daniel Borkmann <daniel@iogearbox.net> 2023-10-24 23:48:58 +0200
committer	Martin KaFai Lau <martin.lau@kernel.org> 2023-10-24 16:06:03 -0700
commit	35dfaad7188cdc043fde31709c796f5a692ba2bd (patch)
tree	53a88f1799ac38892434318a47278de4a255bc19
parent	42d31dd601fa43b9afdf069d1ba410b2306a4c76 (diff)
download	linux-35dfaad7188cdc043fde31709c796f5a692ba2bd.tar.gz

netkit, bpf: Add bpf programmable net device

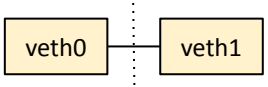
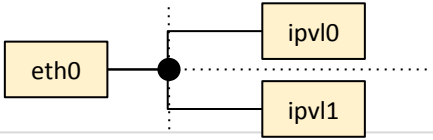
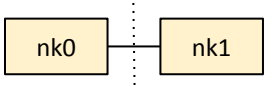
```
This work adds a new, minimal BPF-programmable device called "netkit"
(former PoC code-name "meta") we recently presented at LSF/MM/BPF. The
core idea is that BPF programs are executed within the drivers xmit routine
and therefore e.g. in case of containers/Pods moving BPF processing closer
to the source.
```

Brief Deep Dive: veth-replacement for Pods

	veth	ipvlan	netkit
Operation mode:	L2	L3 (or L2)	L3 (or L2)
Device “legs”:	pair (e.g. 1 host, 1 Pod) 	1 “master” device (e.g. physical device), n “slave” devices 	pair (e.g. 1 host, 1 Pod) with “primary” and “peer” device 
BPF programming:	tc(x) BPF on host device*	In host with tc(x) via “master” device (only entity in host) *	In Pod, BPF is native part of “peer” device internals
Routing:	L2 gateway (+ Host’s FIB)	ipvlan internal FIB + kernel FIB	kernel FIB e.g. bpf_fib_lookup
Problems:	Needs L2 neigh resolution, Higher overhead due to per-CPU backlog queue, native XDP support but very slow and hard to use .	Inflexible for multiple physical devices & troubleshooting, cumbersome to program BPF on “master”. ipvlan needs to be operated in L3/private mode for Pod policy enforcement.	Still one device per Pod inside host, for some use-cases the host device can be removed fully (wip).

(* It needs to be inside host so that BPF programs cannot be detached from app inside Pod)

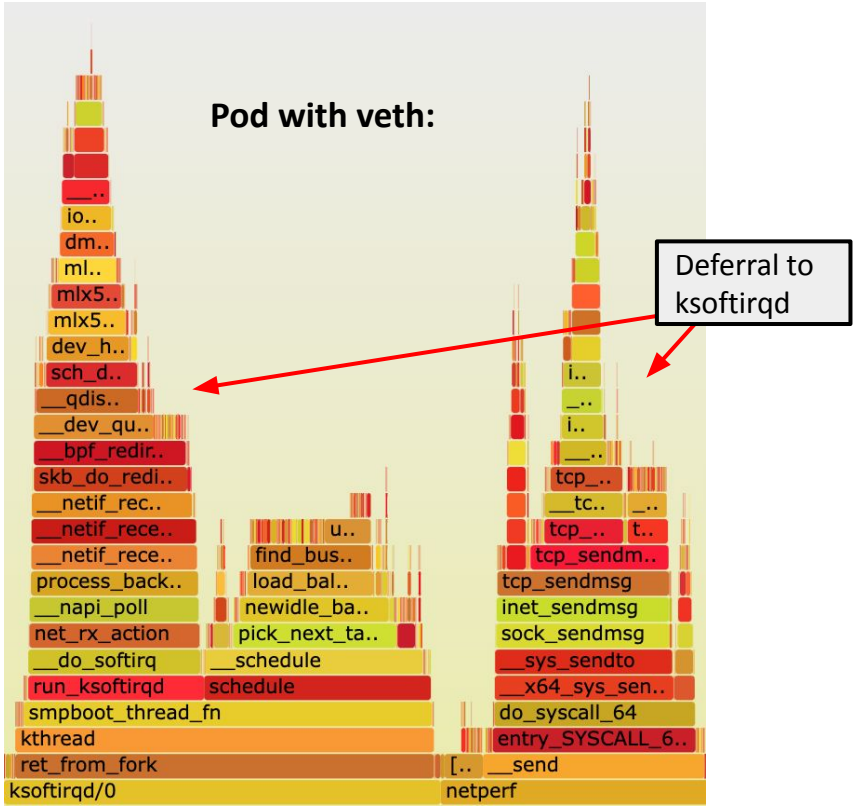
Brief Deep Dive: veth-replacement for Pods

	veth	ipvlan	netkit
Operation mode:	L2	L3 (or L2)	
Device “legs”:	pair (e.g. 1 host, 1 Pod) 	1 “master” device (e.g. phys device), n “slave” devices 	host, 1 Pod) with “primary” and “peer” device 
BPF programming:	tc(x) BPF on host device*	In host with tc(x) via “master” device (only entity in host) *	In Pod, BPF is native part of “peer” device internals
Routing:	L2 gateway (+ Host’s FIB)	ipvlan internal FIB + kernel FIB	kernel FIB e.g. bpf_fib_lookup
Problems:	Needs L2 neigh resolution, Higher overhead due to per-CPU backlog queue, native XDP support but very slow and hard to use .	Inflexible for multiple physical devices & troubleshooting, cumbersome to program BPF on “master”. ipvlan needs to be operated in L3/private mode for Pod policy enforcement.	Still one device per Pod inside host, for some use-cases the host device can be removed fully (wip).

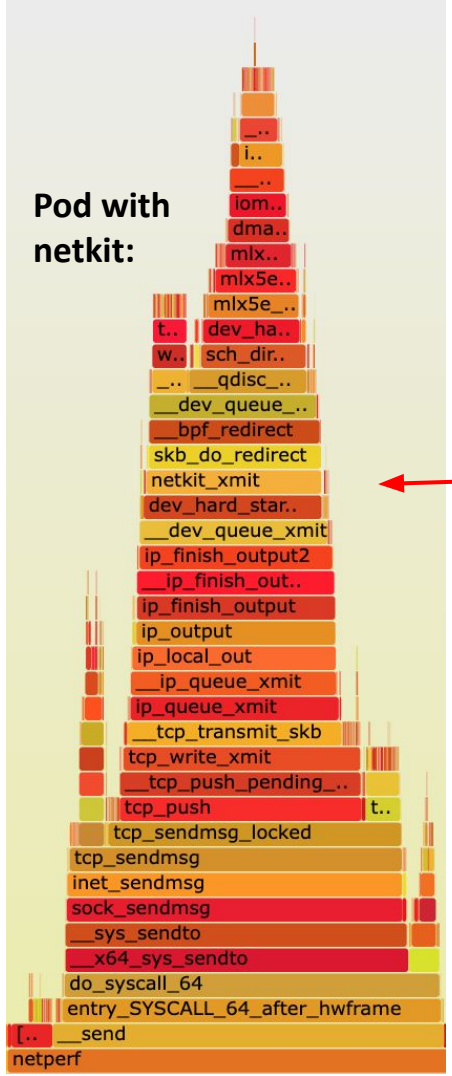
tl;dr: Takes best of both worlds!

(* It needs to be inside host so that BPF programs cannot be detached from app inside Pod)

veth vs netkit: backlog queue



Deferral to ksoftirqd



Remains in process context all the way, leading to better process scheduler decisions.

Cilium Datapath Architecture (journey 2019 - today):

Building Blocks:
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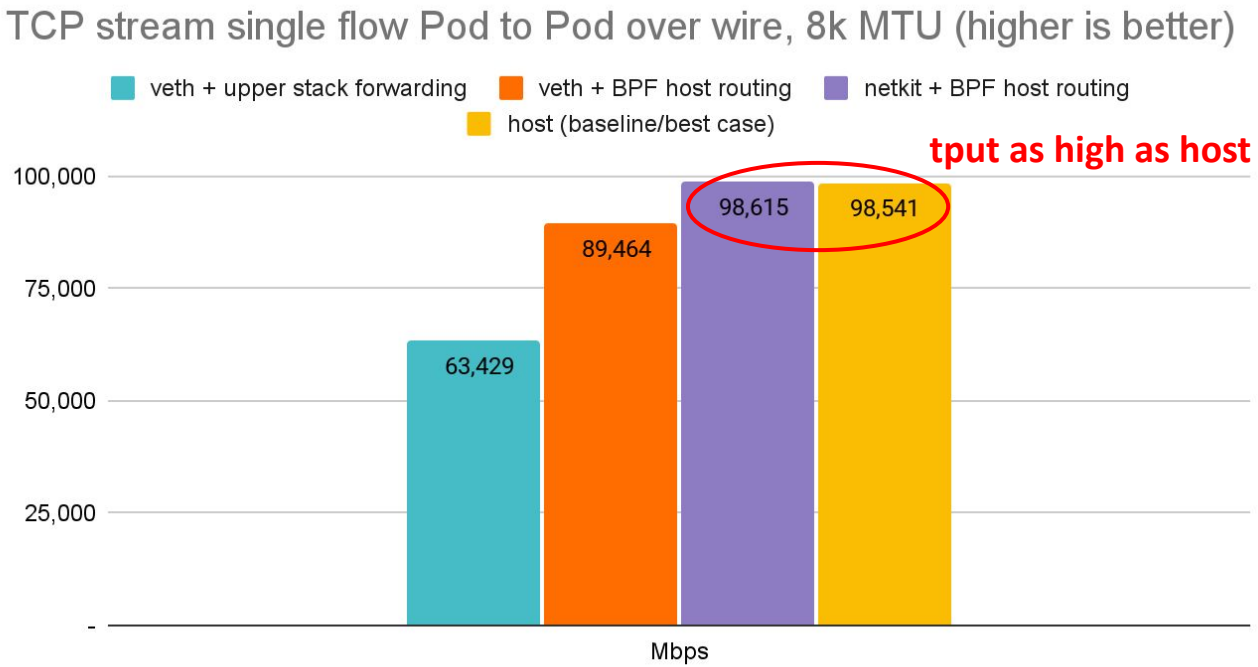

* 8264 MTU for data page alignment in GRO

Back to back: AMD Ryzen 9 3950X @ 3.5 GHz, 128G RAM @ 3.2 GHz, PCIe 4.0, ConnectX-6 Dx, mlx5 driver, striding mode, LRO off, 8264 MTU
Receiver: taskset -a -c <core> tcp_mmap -s (non-zerocopy mode), Sender: taskset -a -c <core> tcp_mmap -H <dst host>

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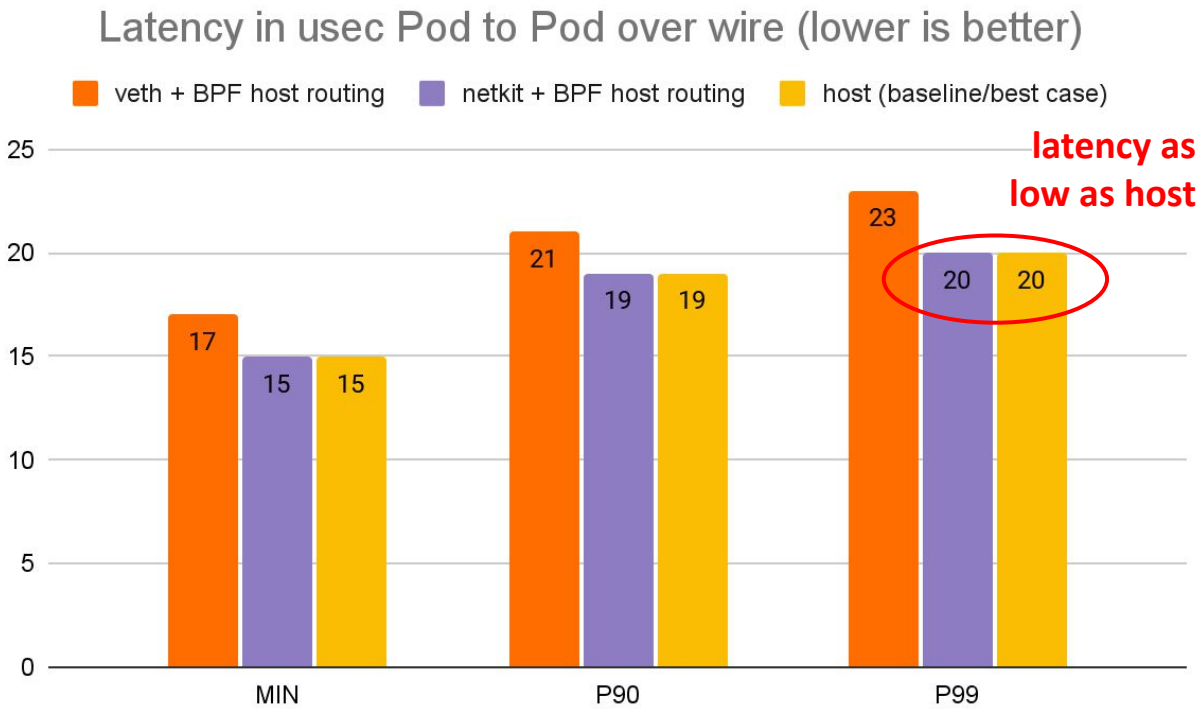

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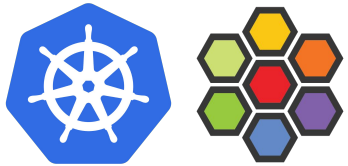
netperf -t TCP_RR -H <remote pod> -- -O MIN_LATENCY,P90_LATENCY,P99_LATENCY,THROUGHPUT



Now with zero-overhead Pods, can the networking stack generally push even further?

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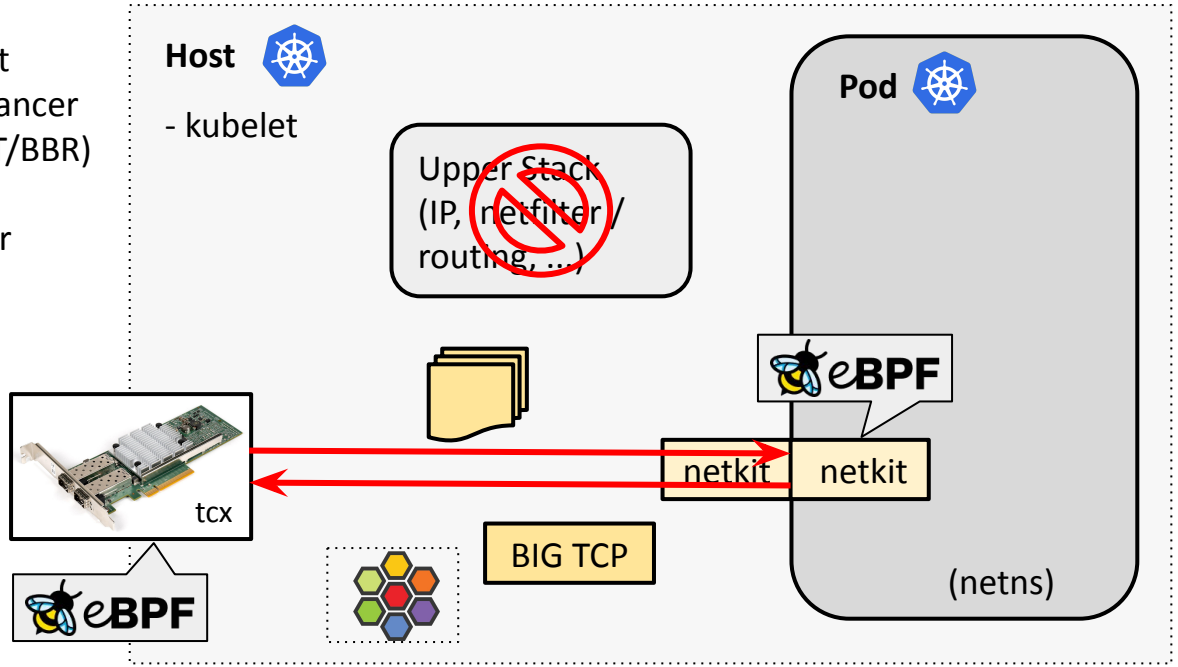
Pushing even further:
- BIG TCP (IPv4/IPv6)



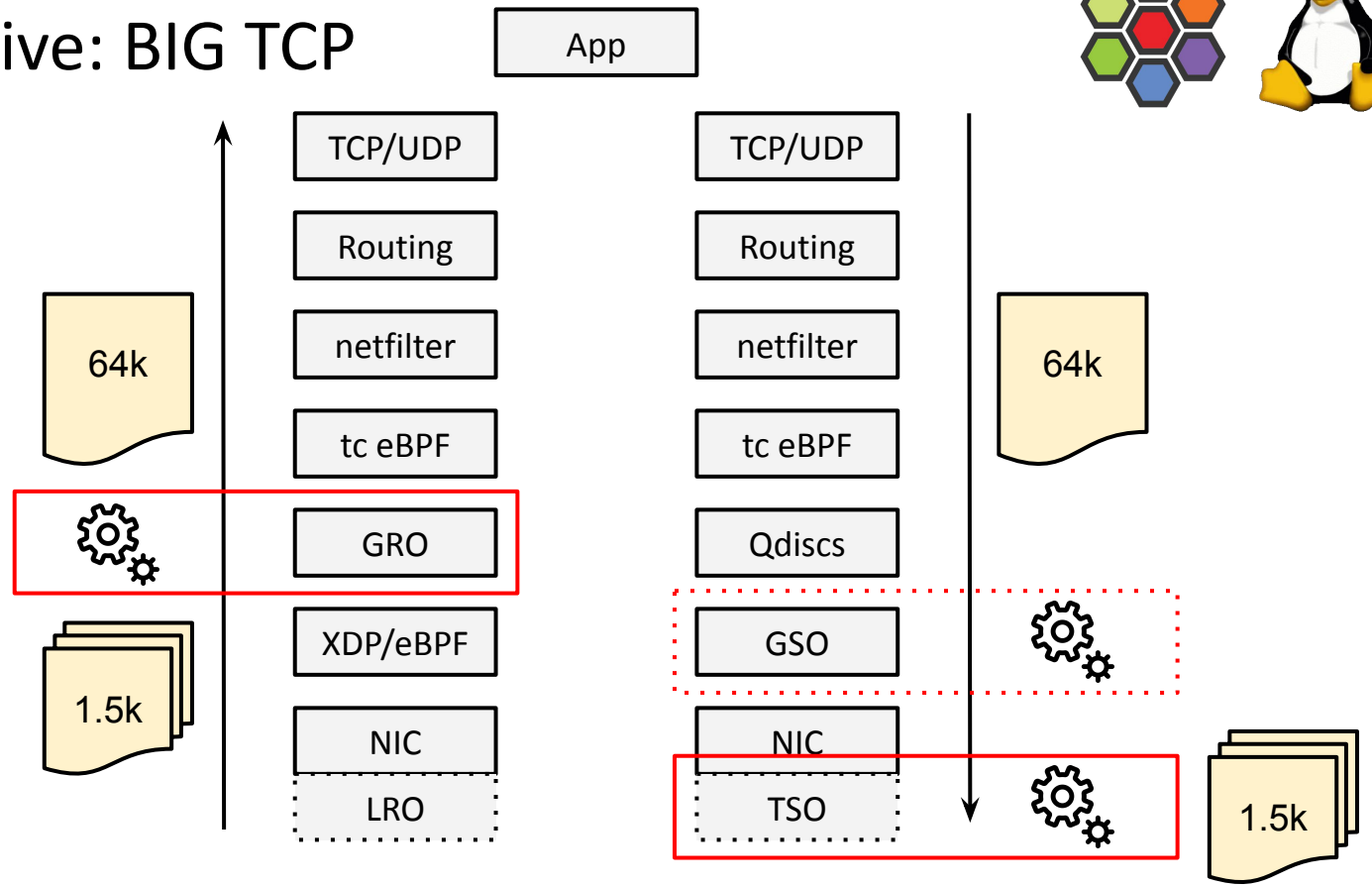
Kernel 5.19 & 6.3: BIG TCP for IPv6 and IPv4 (Eric Dumazet, Coco Li, Xin Long)

Brief Deep Dive: BIG TCP

tldr: “TCP is slooooow, use BIG packets!”

- Developed by Google to prepare the Linux kernel’s TCP stack for 200/400+ Gbit/s NIC speeds
- BIG TCP for IPv6 merged in v5.19, for IPv4 merged in v6.3 kernel
- Deployed in Google fleet in production for IPv6 traffic
- Cilium supports BIG TCP for both address families, probes drivers and configures all Cilium managed devices/Pods
- No changes to the network such as MTU needed, this affects only local host (GSO/GRO engine)

Brief Deep Dive: BIG TCP



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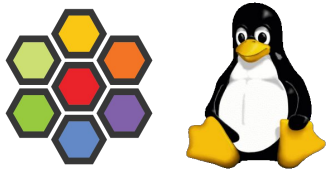
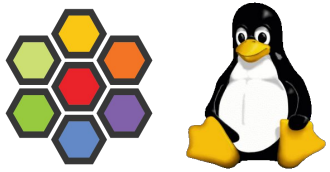


TSO segments TCP super-sized packet in NIC/HW, and GRO on receiver gets packet train, reconstructs super-sized packet.

Brief Deep Dive: BIG TCP



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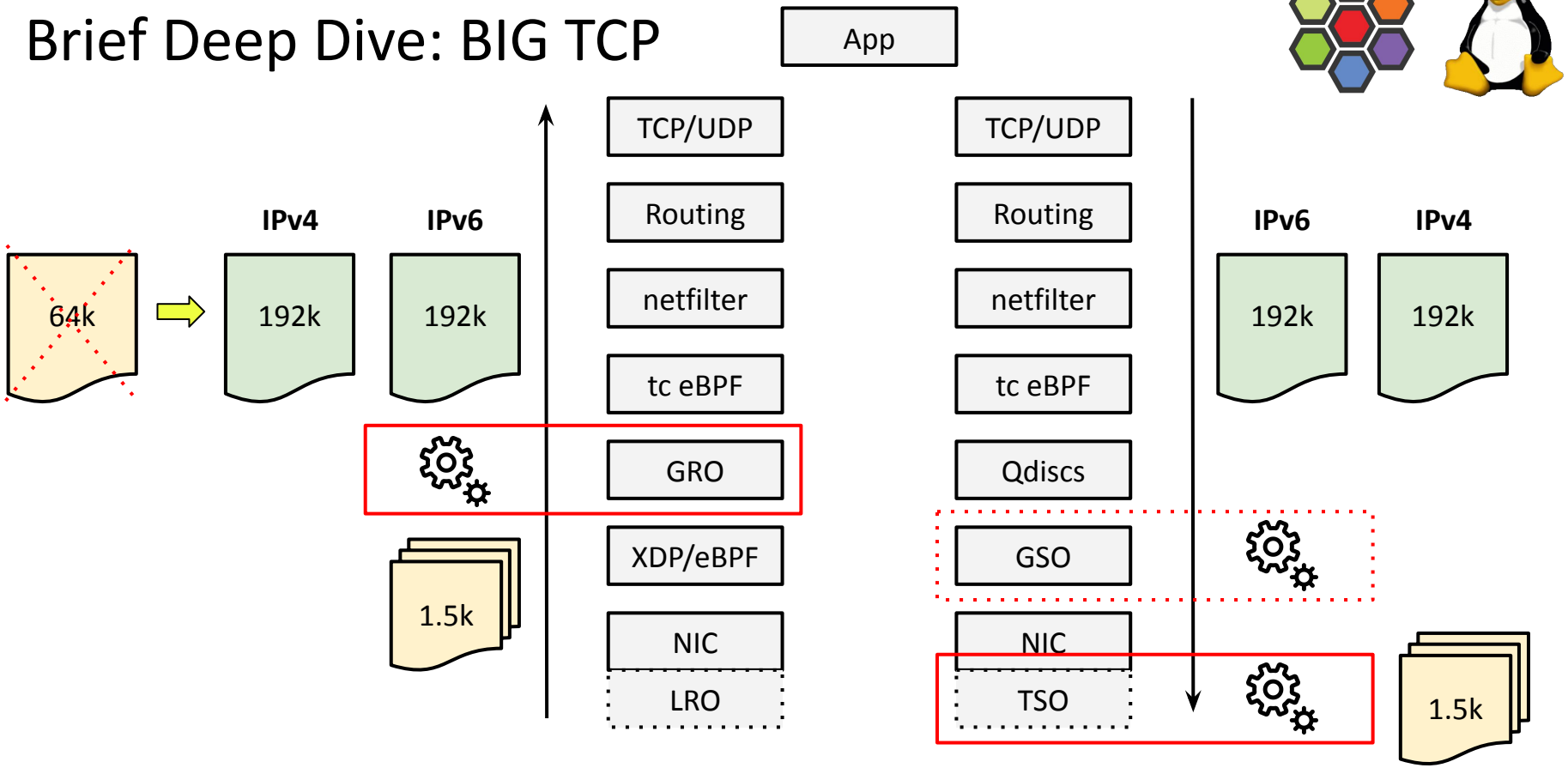

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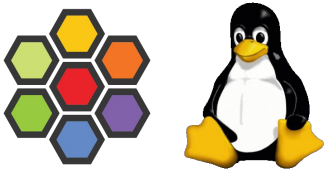
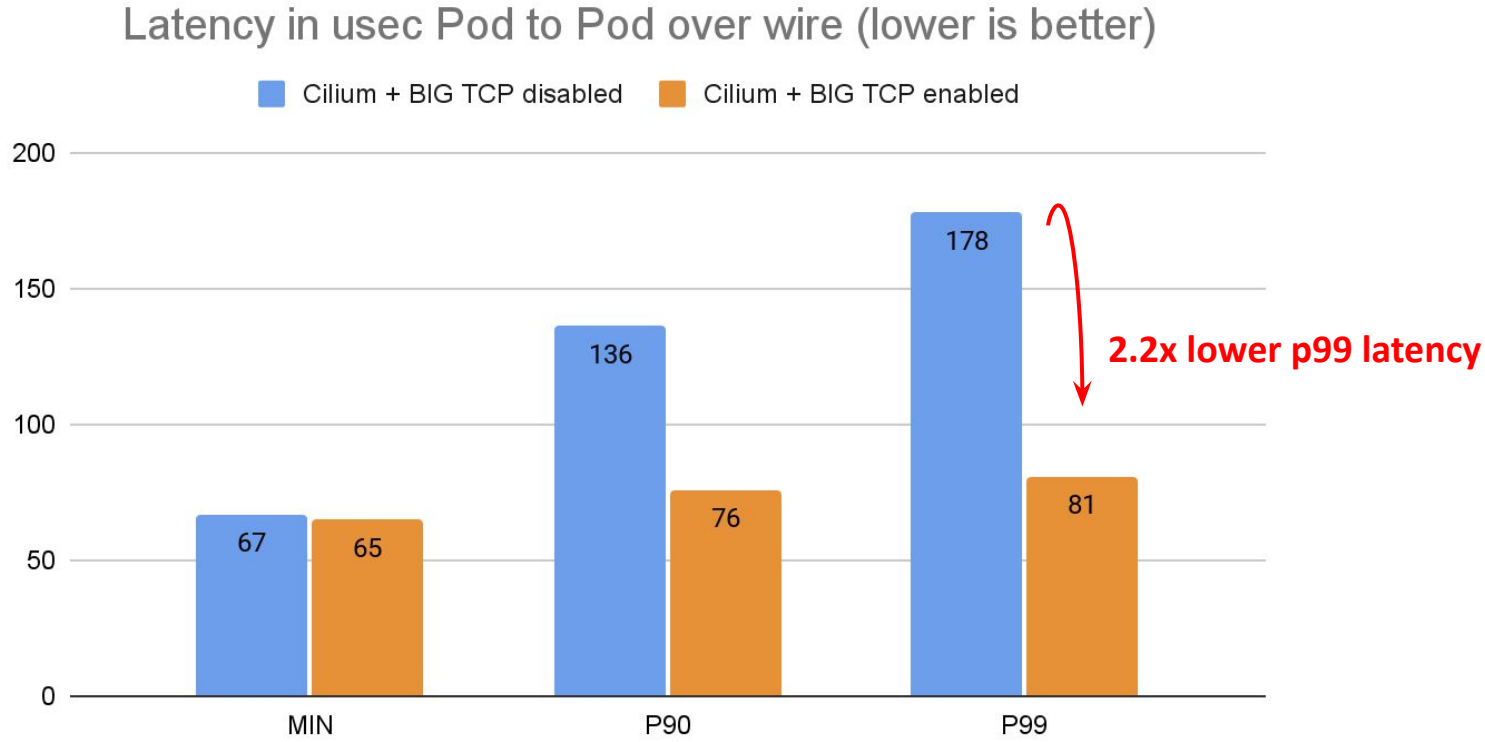


Cilium 1.14 & BIG TCP:

- Supports BIG TCP for both IPv4 & IPv6
- Sets GSO/GRO max limit to 48 pages (192k) which we found to be performance sweet-spot
- Implements max TSO probing for drivers not supporting 192k, e.g. ice has 128k (32 pages)

Cilium & BIG TCP



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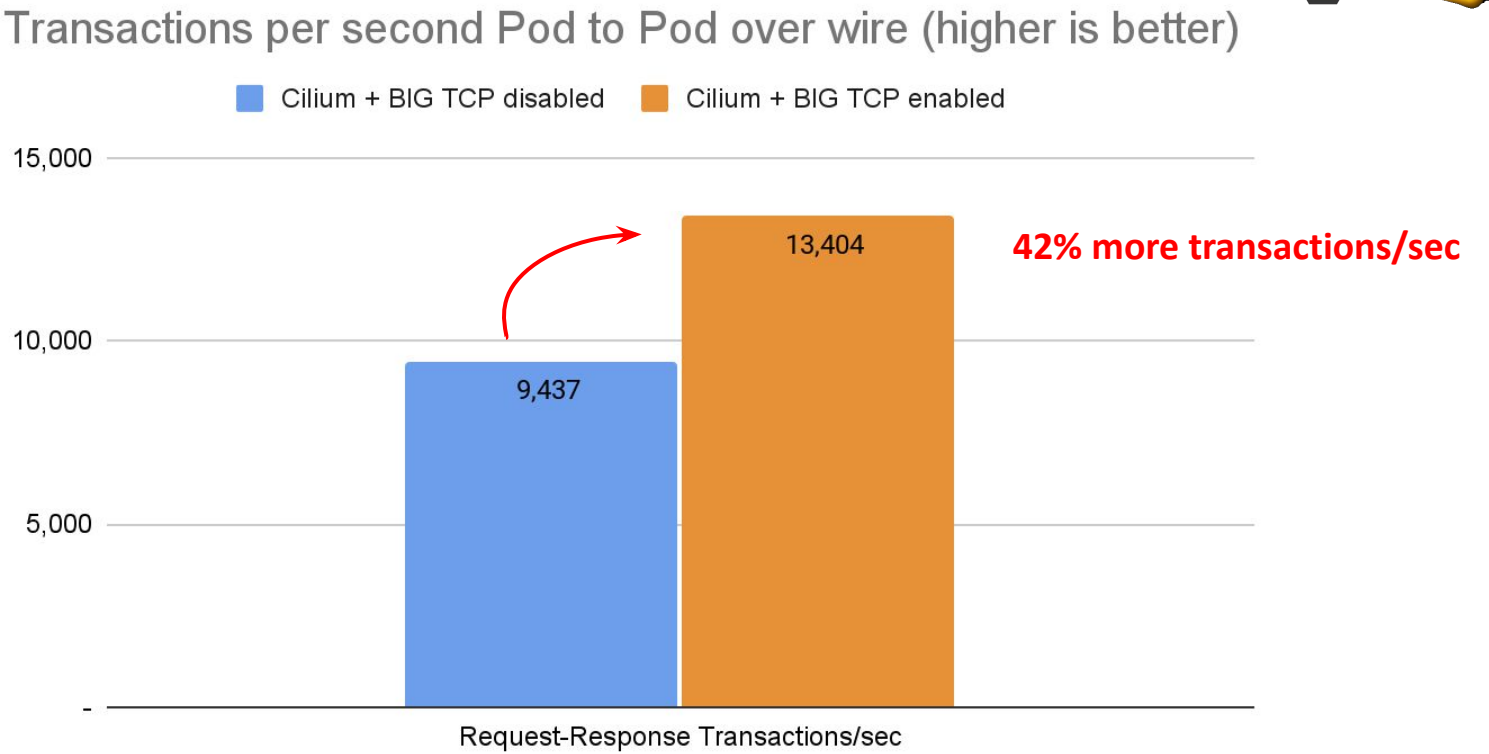

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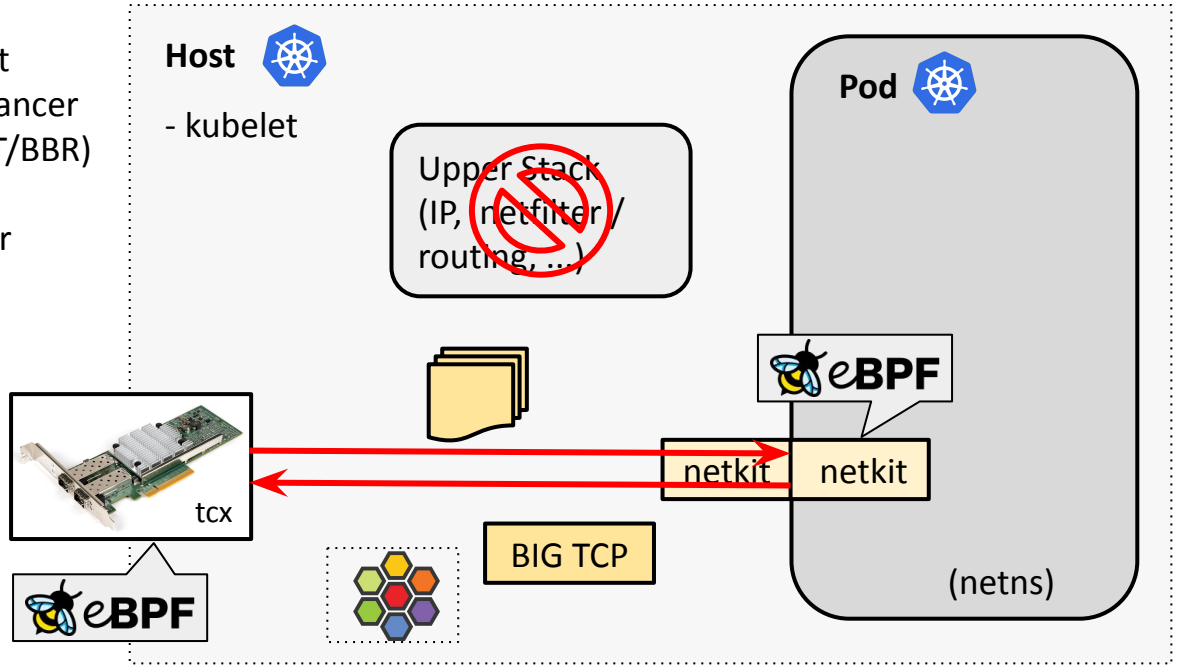

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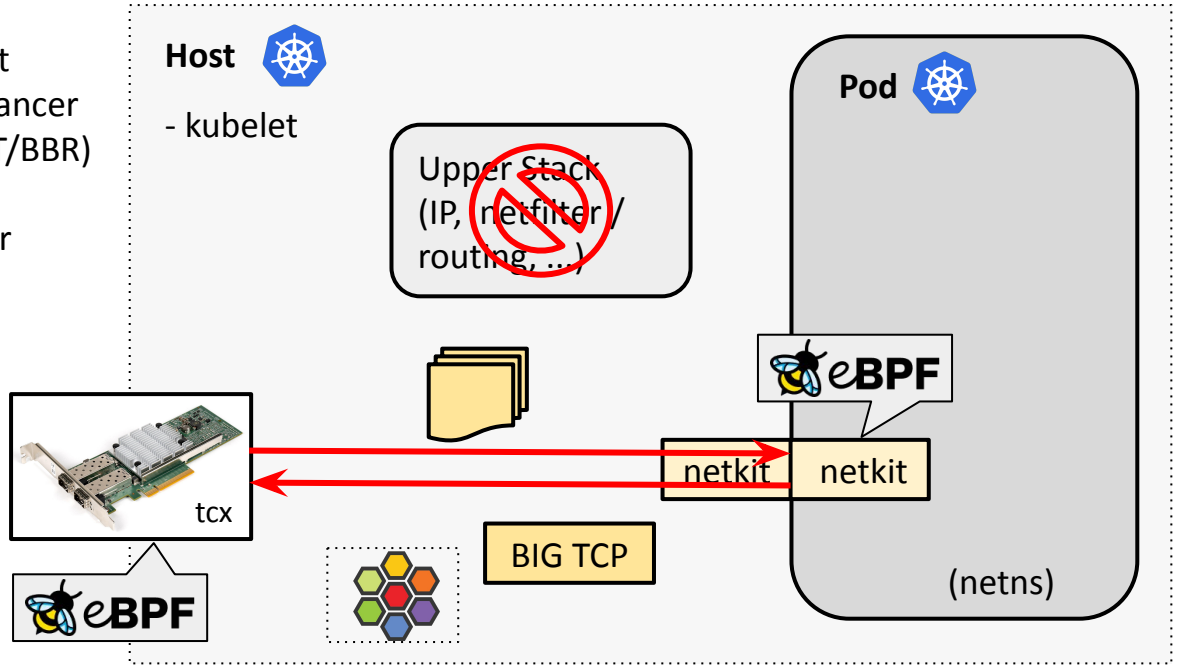
Future integration:
- TCP usec resolution (v6.7)
- BBRv3 (once upstream)



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  - Without application or network MTU changes necessary
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Conclusions:

- Significant performance gains can be achieved with our recent eBPF & Cilium work to **completely remove** a Pod's **netns networking** data path **overhead**
- **BIG TCP and Cilium**'s integration enable K8s clusters to **better deal with >100G NICs**
  - Without application or network MTU changes necessary
  - Notable efficiency improvements also for <= 100G NICs
- To achieve even higher throughput, application changes to utilize **TCP zero-copy** are necessary and there is **still ongoing kernel work**.

Recent discussions at netconf 2023 workshop:
- NIC & kernel support for header/data split
- BIG TCP & TCP zero-copy support
- TCP device memory for direct GPU data placement

ISOVALENT

Thank you! Questions?

github.com/cilium/cilium

cilium.io

ebpf.io

Bandwidth Manager

BPF Host Routing

BIG TCP for IPv4/IPv6

tcx as a new tc BPF datapath

netkit devices as veth replacement