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Better Bandwidth Management with eBPF

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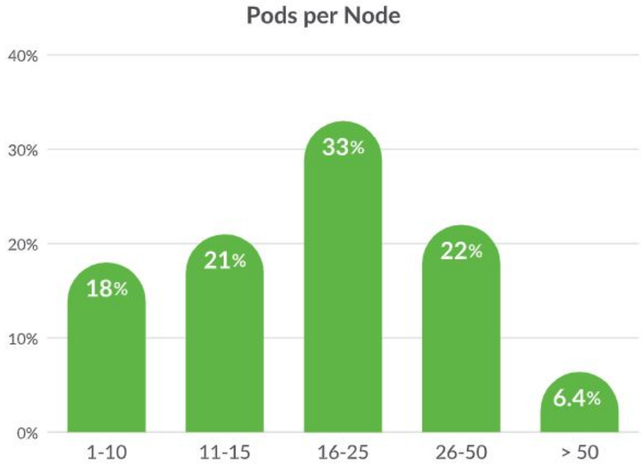
Problem Statement

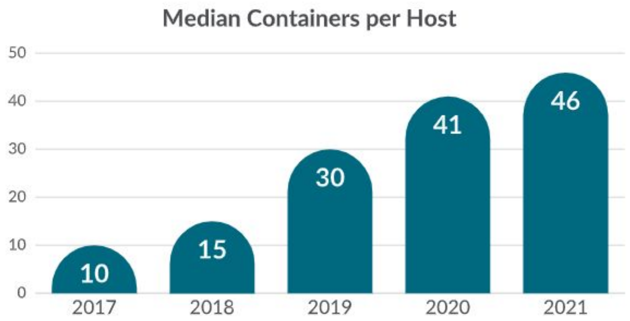
- ➔ Increasing Pod density per node
- ➔ Competition for node resources e.g. CPU and memory
- ➔ Optimization problem for operators: Resource allocation and efficient use, achieving SLOs, etc

```yaml
apiVersion: v1
kind: Pod
metadata:
  name: frontend
spec:
  containers:
  - name: app
    image: images.my-company.example/app:v4
    resources:
      requests:
        memory: "64Mi"
        cpu: "250m"
      limits:
        memory: "128Mi"
        cpu: "500m"
```

What the container is guaranteed to get, e.g. kubelet will only schedule the Pod on a node which can provide this resource.

Hard upper limit, ensures that container never goes above this threshold.





Source: Sysdig 2022 Cloud Native Security and Usage Report

Problem Statement

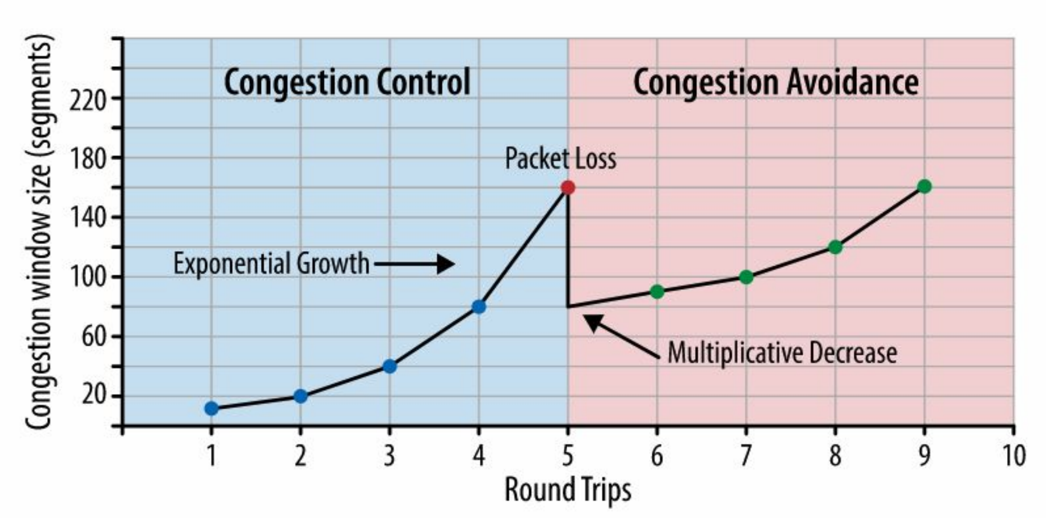
➔ But what about networking?

➔ TCP sends AFAP
(as fast as possible)

➔ AFAP output contract, shaping typically implemented by device output queues

➔ Queue length limit & receive window determines in-flight rate

➔ "How fast" implicit in queue drain rate



Source: https://hpbn.co/building-blocks-of-tcp/

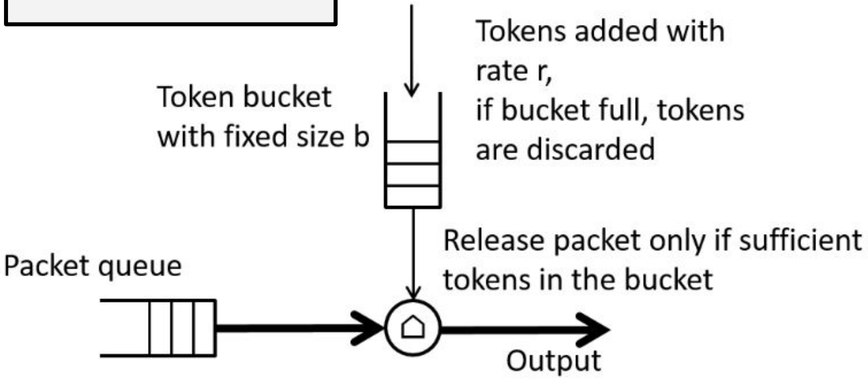
➔ Who limits a Pod's network usage in Kubernetes?

Problem Statement

- ➔ Kubernetes bandwidth enforcement has only been experimental so far :-(
- ➔ Support for Pod annotations with 'outsourced' bandwidth meta plugin

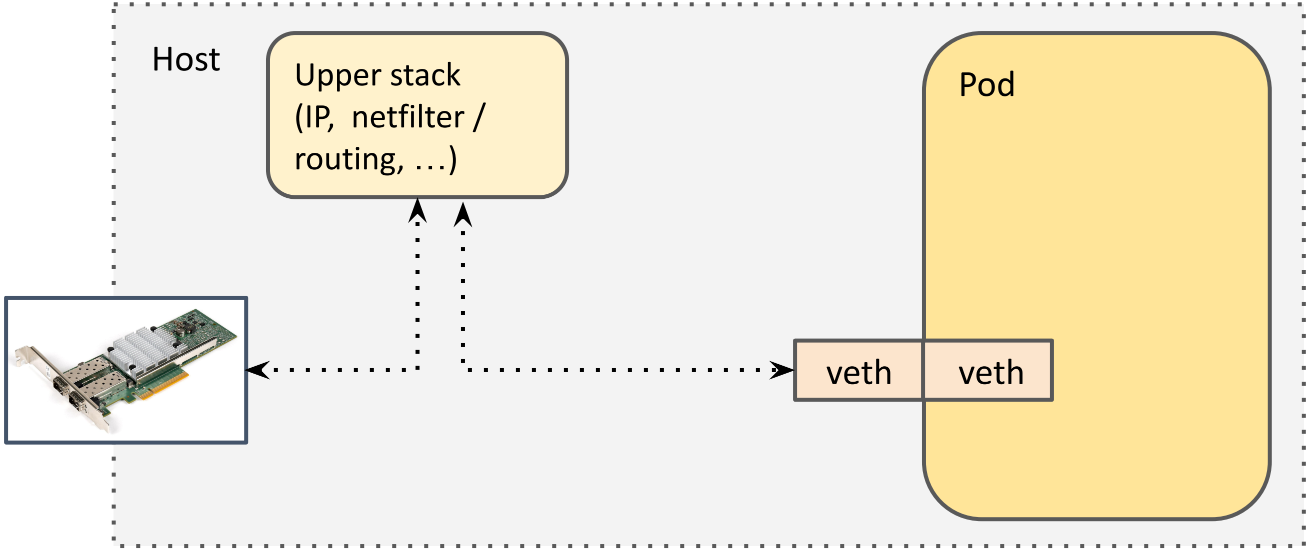
```yaml
apiVersion: v1
kind: Pod
metadata:
  annotations:
    kubernetes.io/ingress-bandwidth: 1M
    kubernetes.io/egress-bandwidth: 1M
...
```

Adds rudimentary **token bucket filters (TBF)** to implement enforcement of annotations.



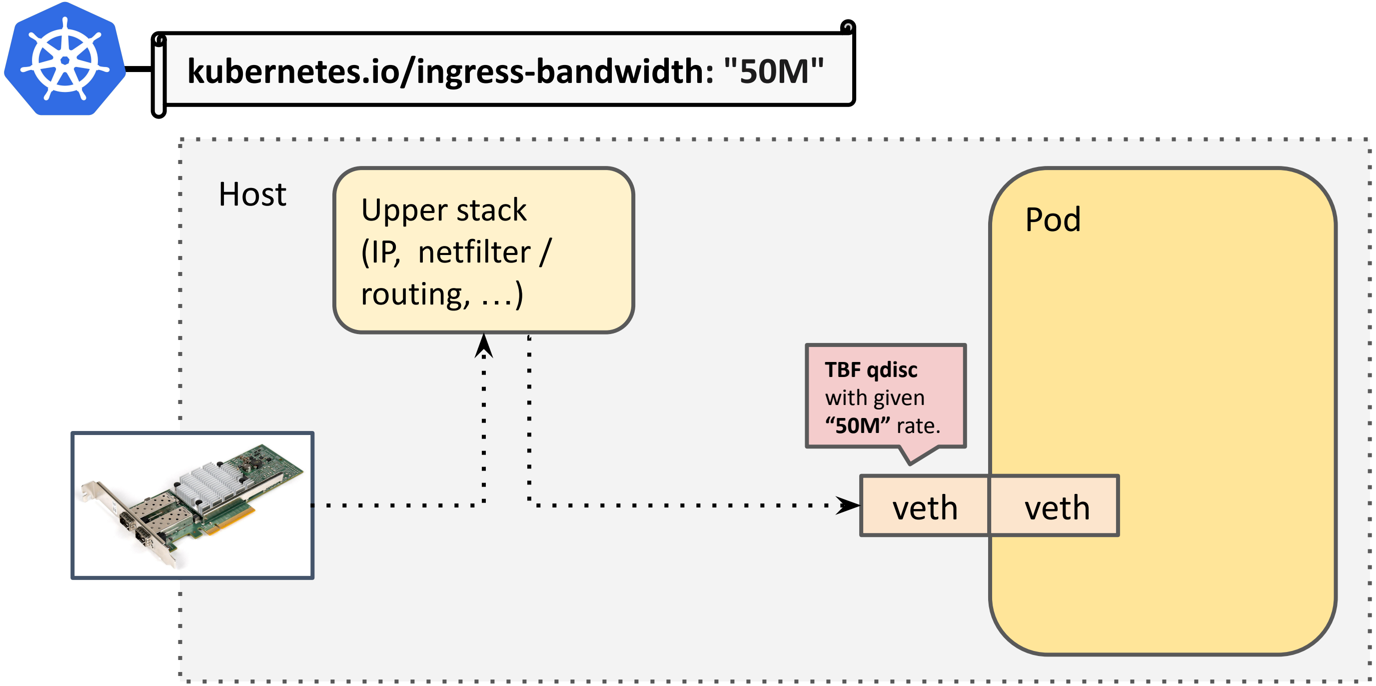
Problem Statement

- ➔ bandwidth meta plugin not scalable for production use
- ➔ TBFs are attached to the Pod's veth devices



Problem Statement

➔ bandwidth meta plugin ingress example:



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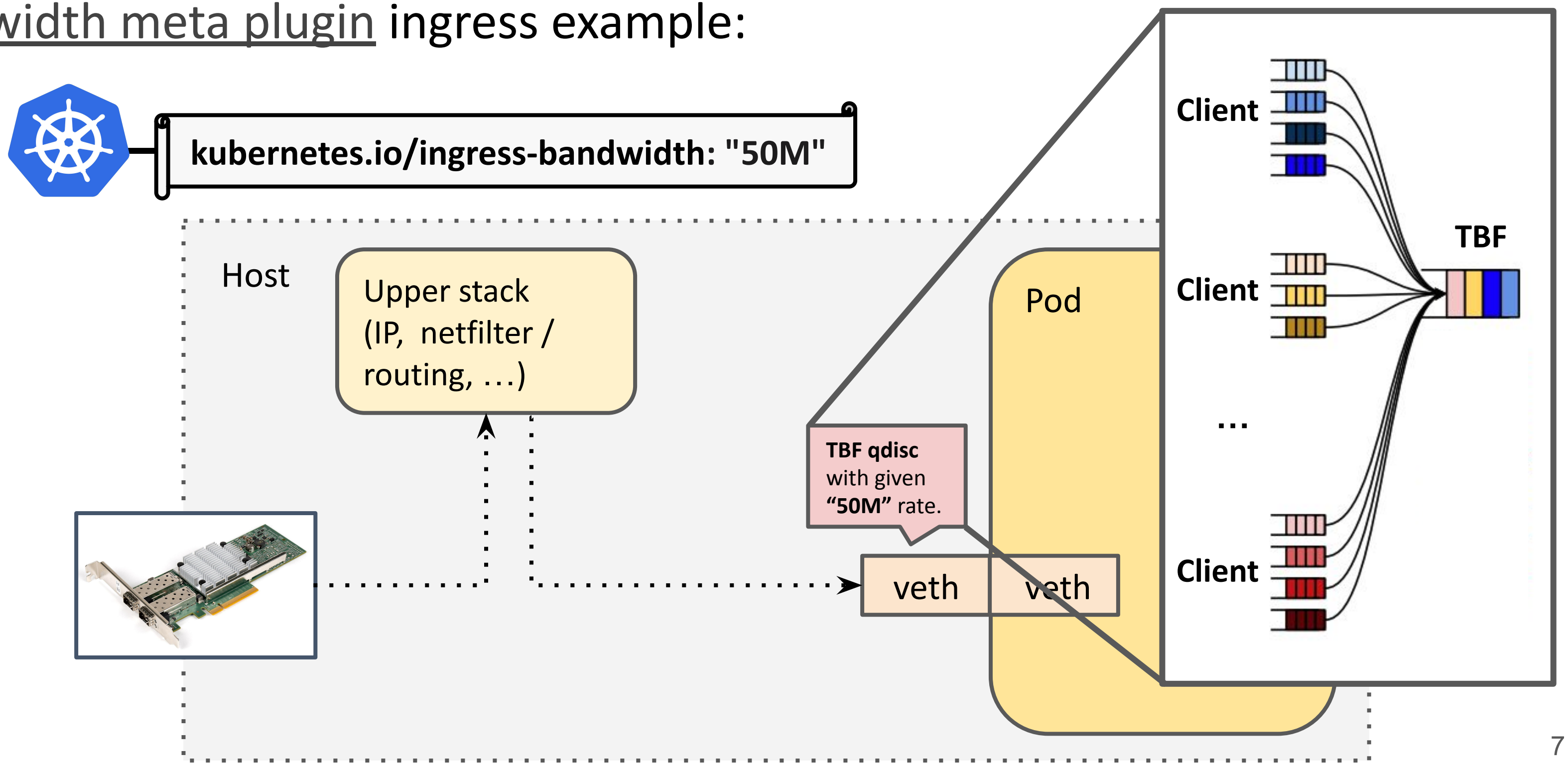

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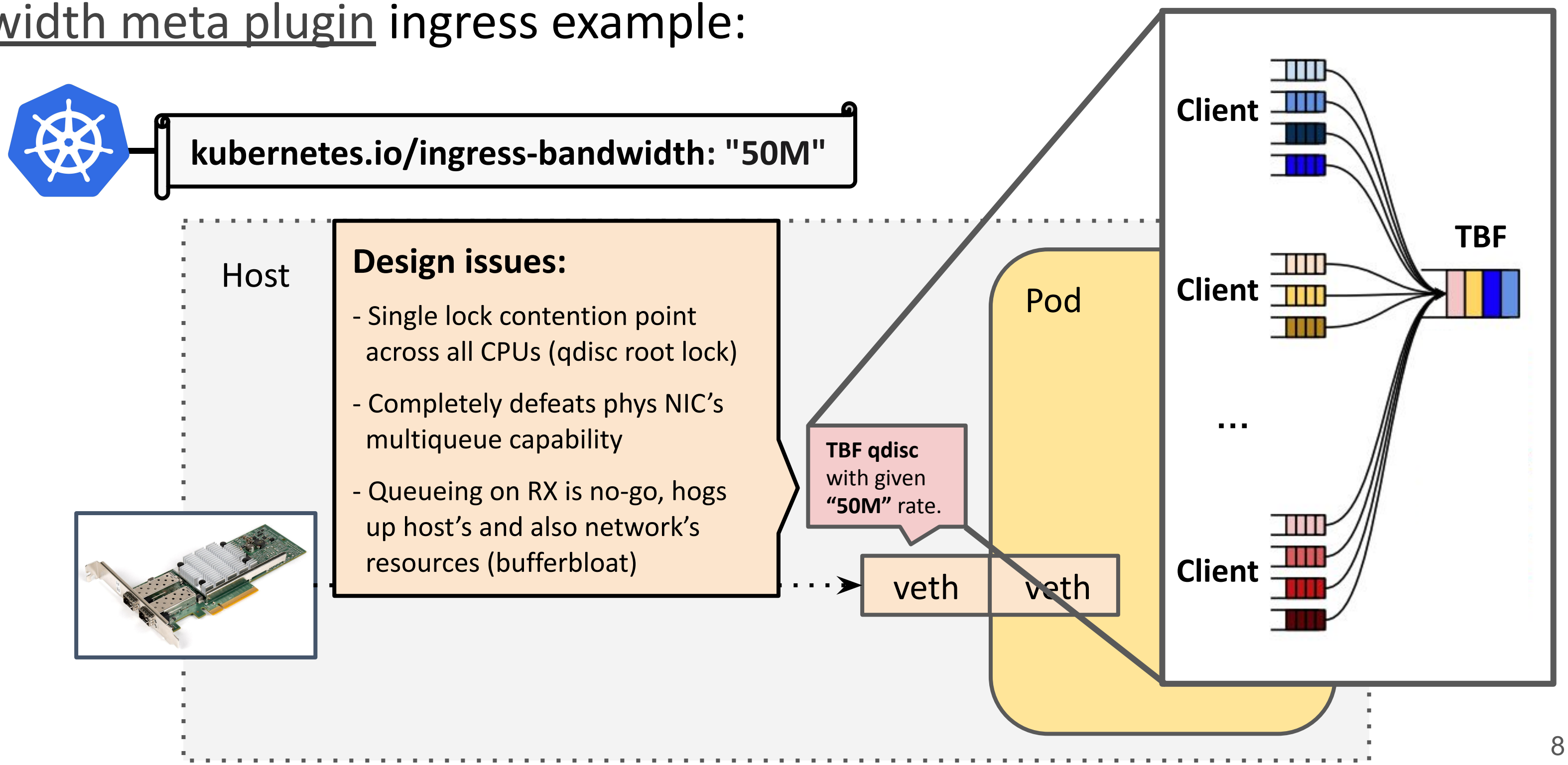
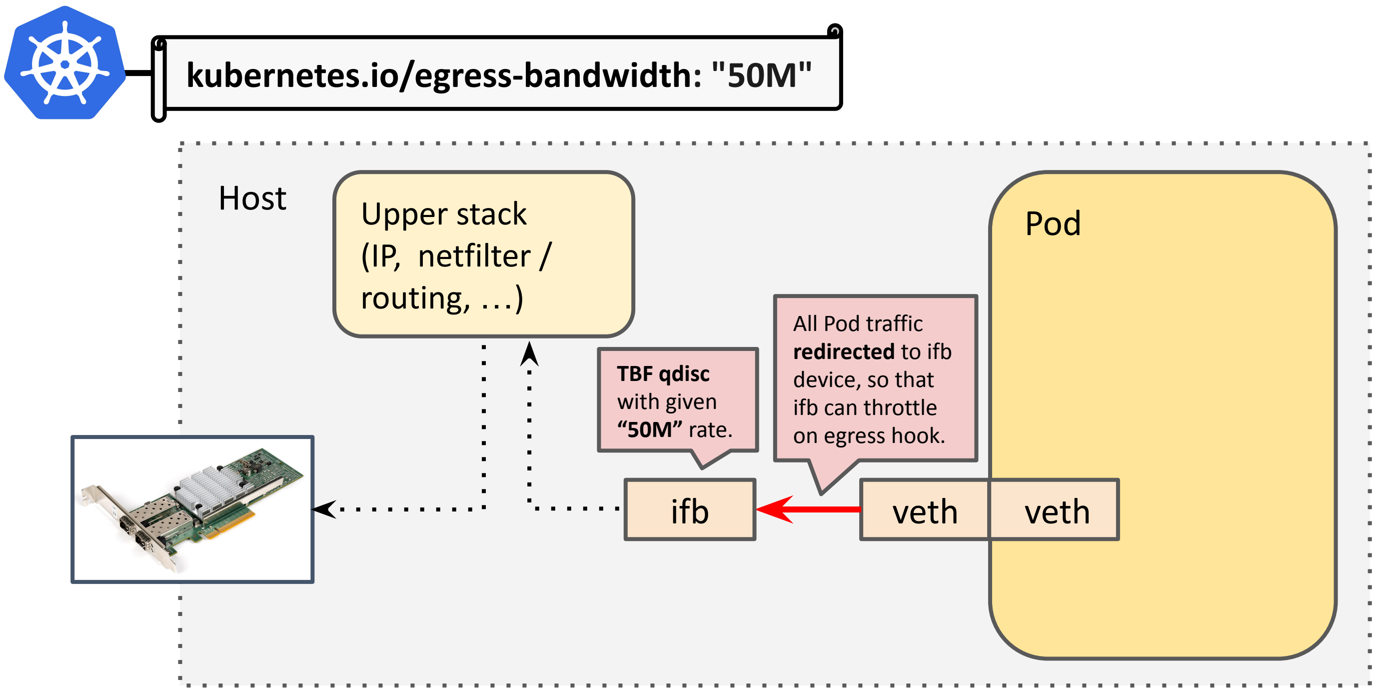


Problem Statement

CNI

➔ bandwidth meta plugin egress example:



Problem Statement

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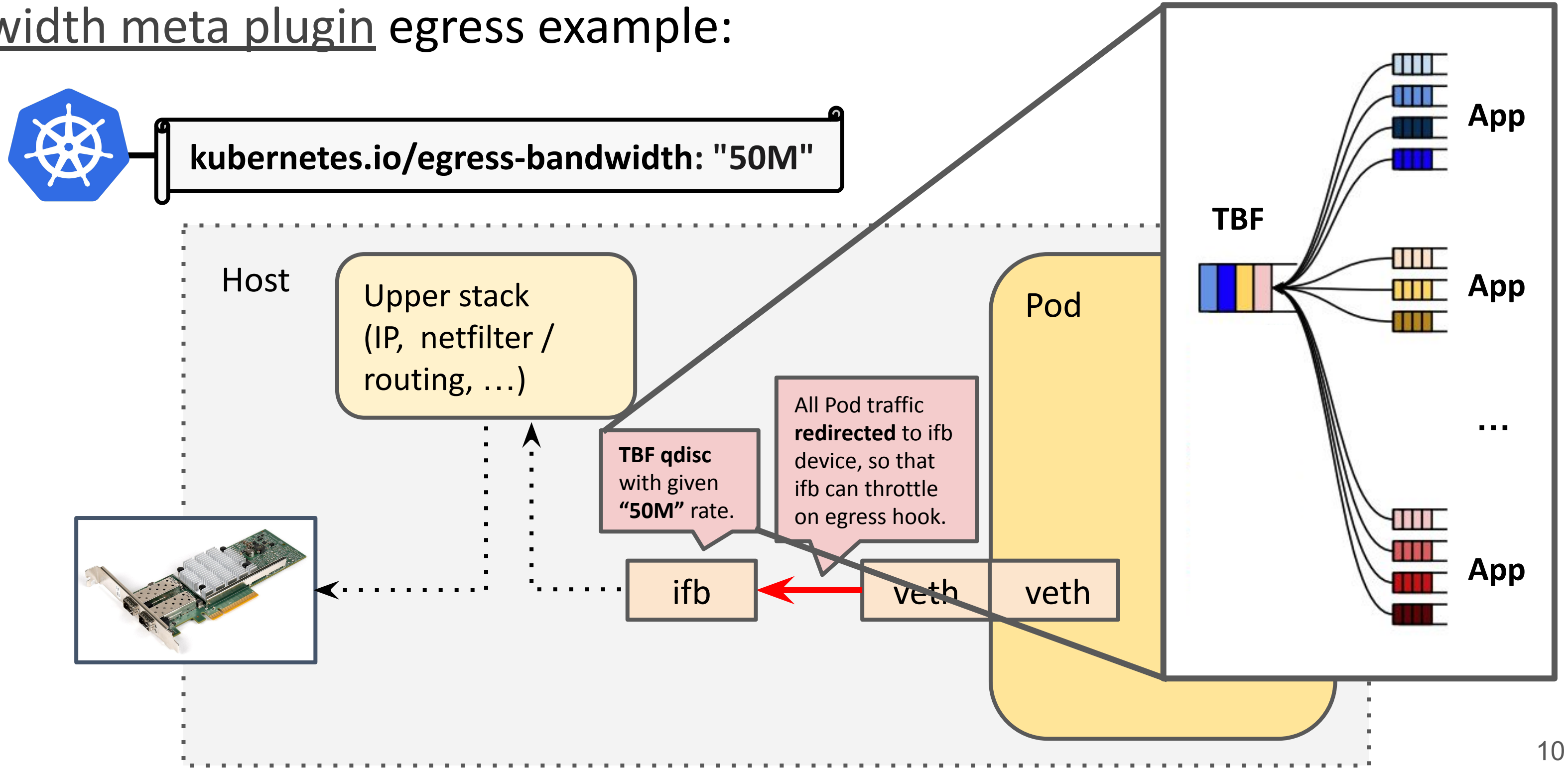

Problem Statement

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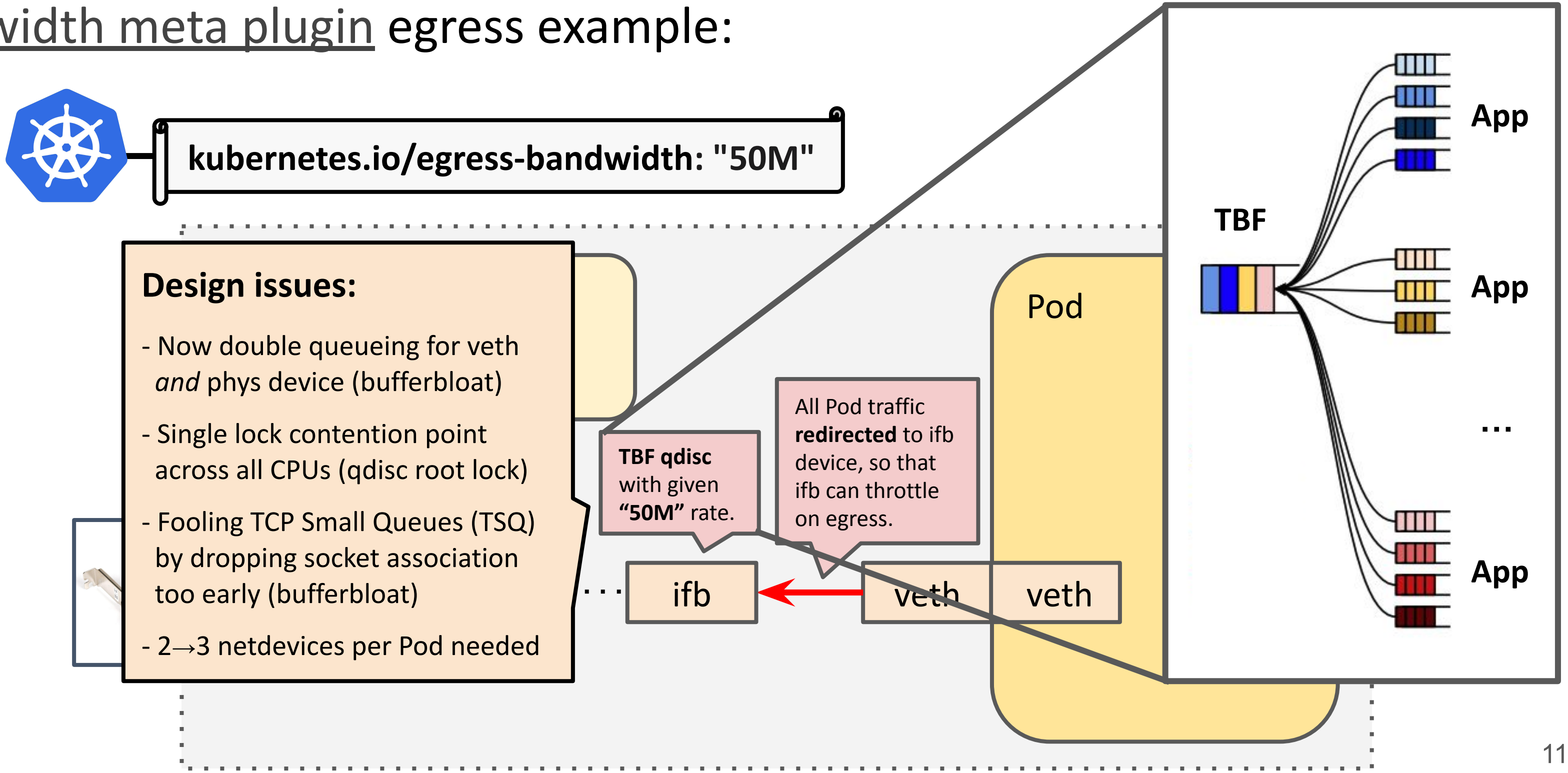


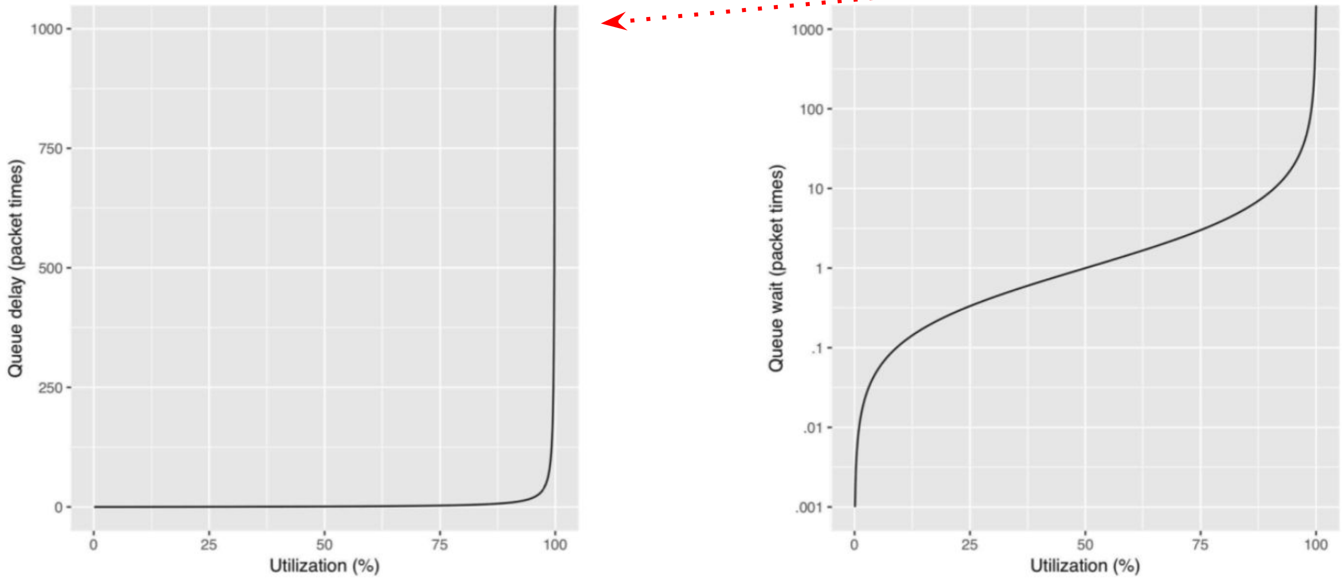
Problem Statement

- ➔ bandwidth meta plugin aka “latency killer”
- ➔ tl;dr summary:

Problem Statement

… but AFAP makes bottleneck run at 100%

Queuing theory says this is fragile. E.g., for M/D/1:



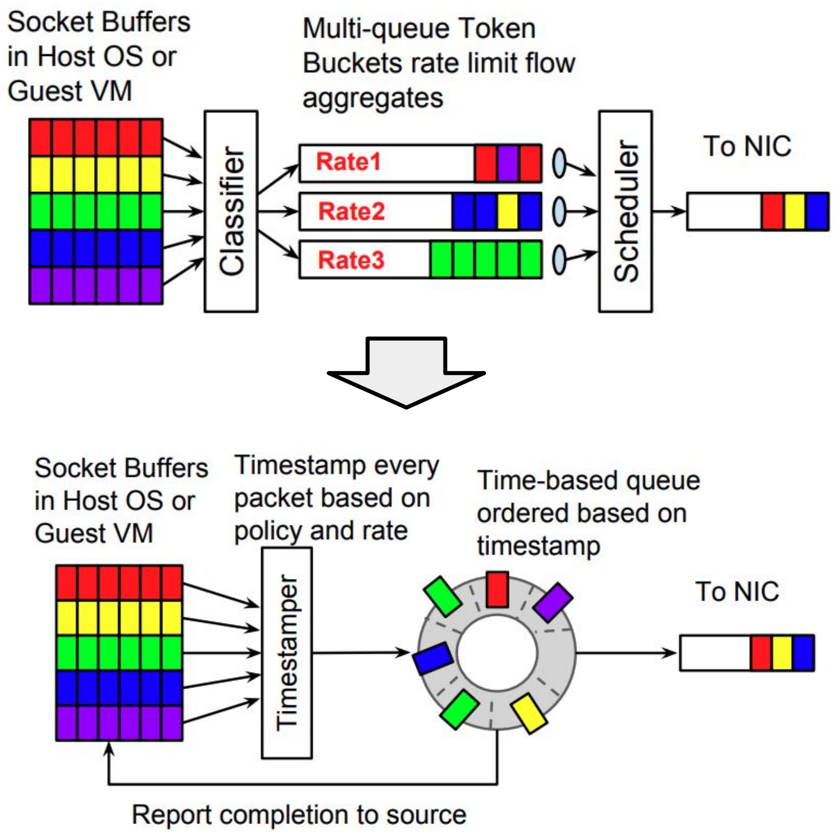
Packet wait-time in queue skyrockets when bottleneck link gets utilized close to 100%.

Source: Van Jacobson, "Evolving from AFAP Teaching NICs about time"

From Queues to EDT model

Core Idea to replace queues with two simple pieces:

- ➔ Earliest Departure Time (EDT) time stamp in every packet
- ➔ Timing-wheel scheduler which replaces the queue



Source: A. Saeed et al., “Carousel: Scalable Traffic Shaping at End Hosts” (SIGCOMM’17)

How can the EDT model be applied to Kubernetes?

eBPF

Programmable and **performant** in-kernel "virtual machine" that **safely** executes native code on certain events/hooks (aka "JavaScript for the kernel").

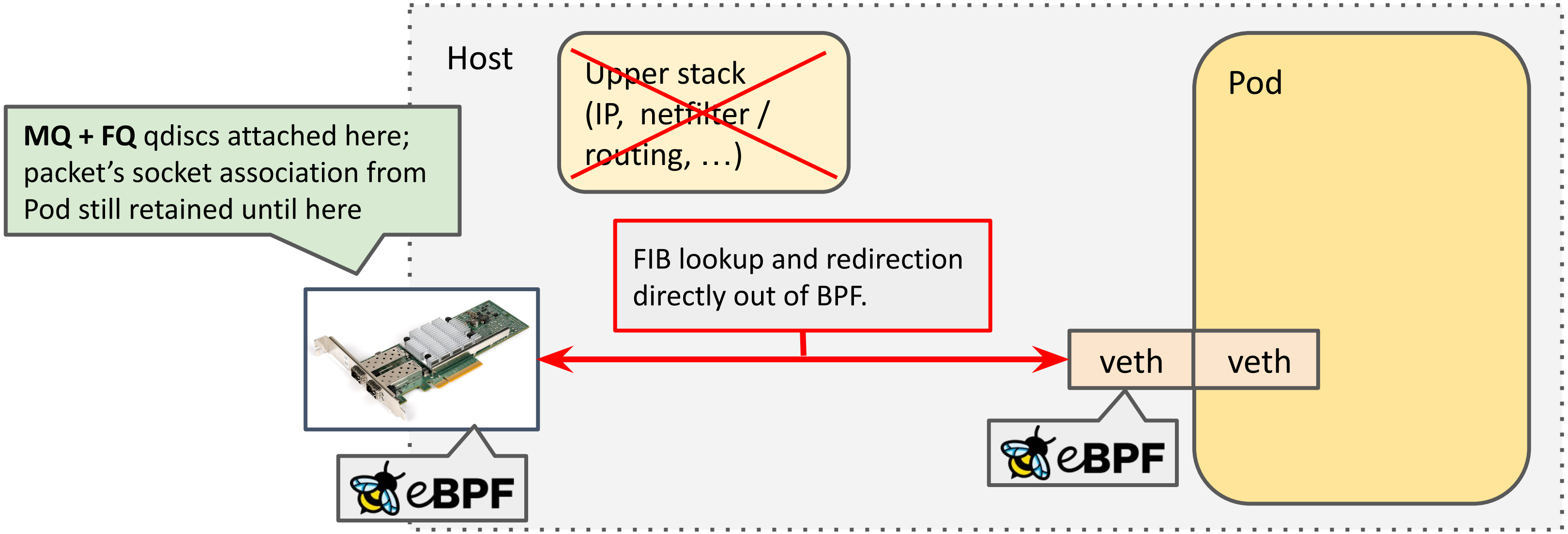
How can the EDT model be applied to Kubernetes?

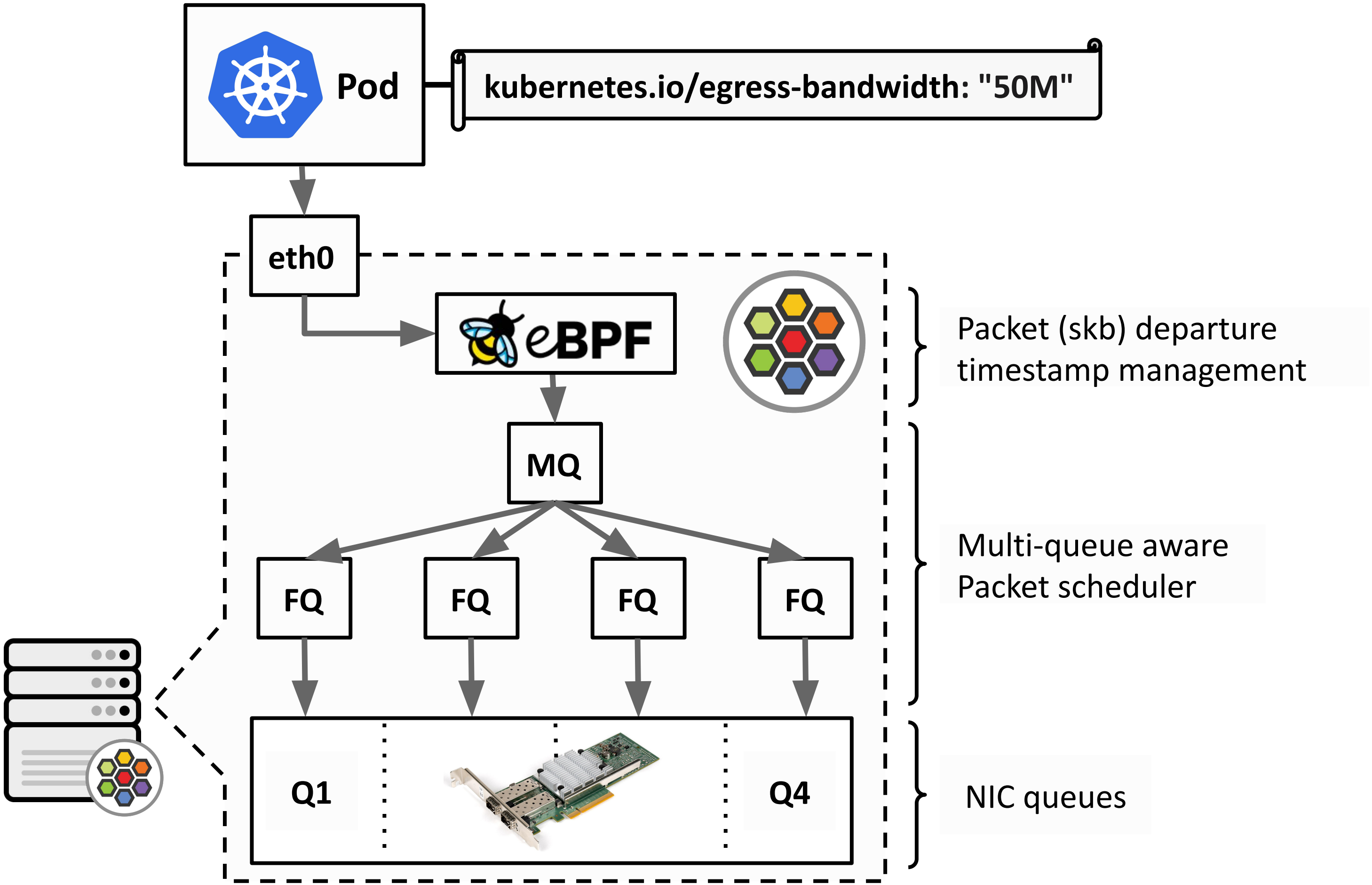
cilium

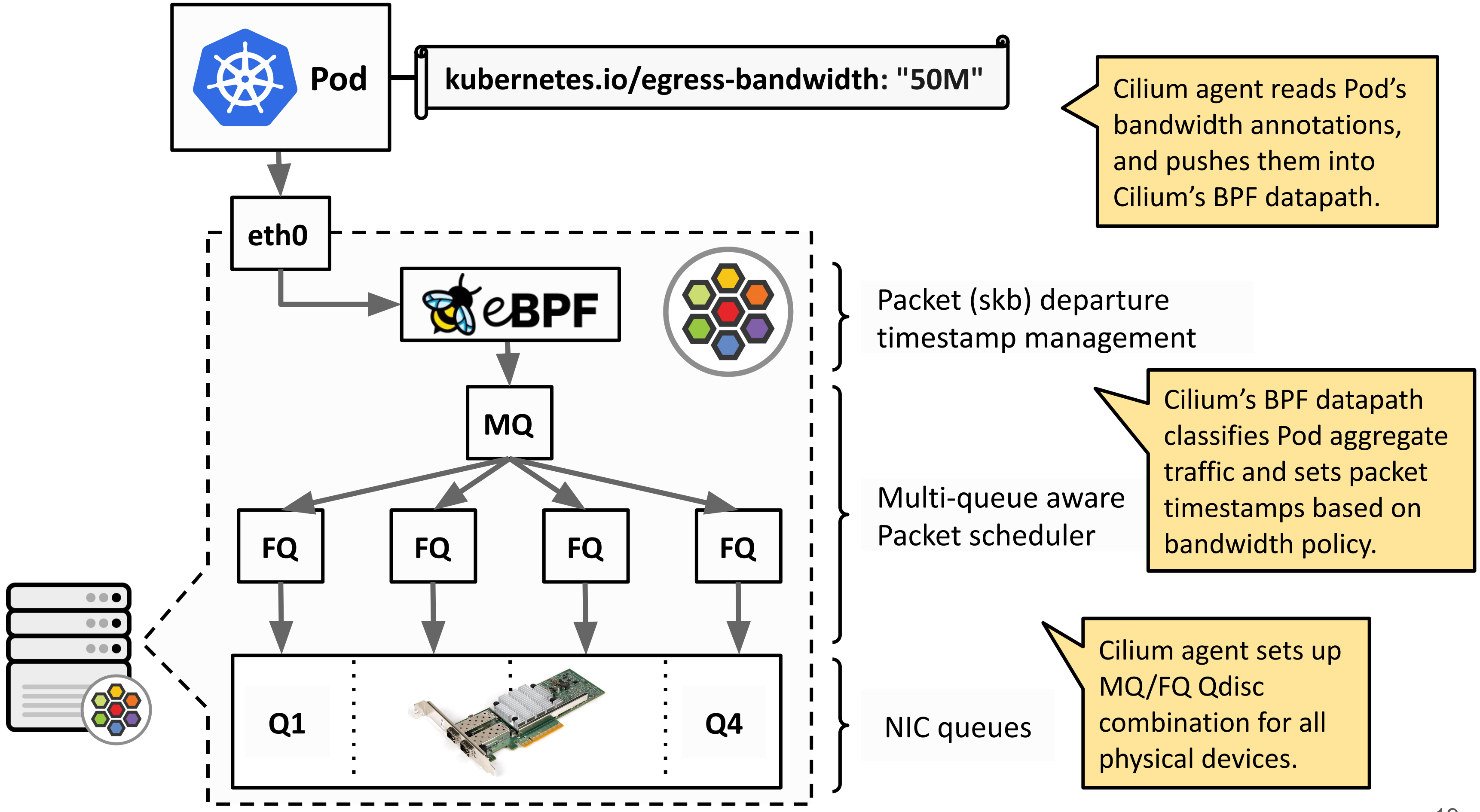
eBPF-based CNI / platform which provides Pod connectivity, service load-balancing, network policies, **bandwidth management**, transparent encryption and more.

Cilium's Bandwidth Manager

- ➔ Implements lock-less, EDT-based Pod rate-limiting with eBPF
- ➔ Enforcement points on phys devices instead of veths to avoid bufferbloat and improve TCP TSQ feedback

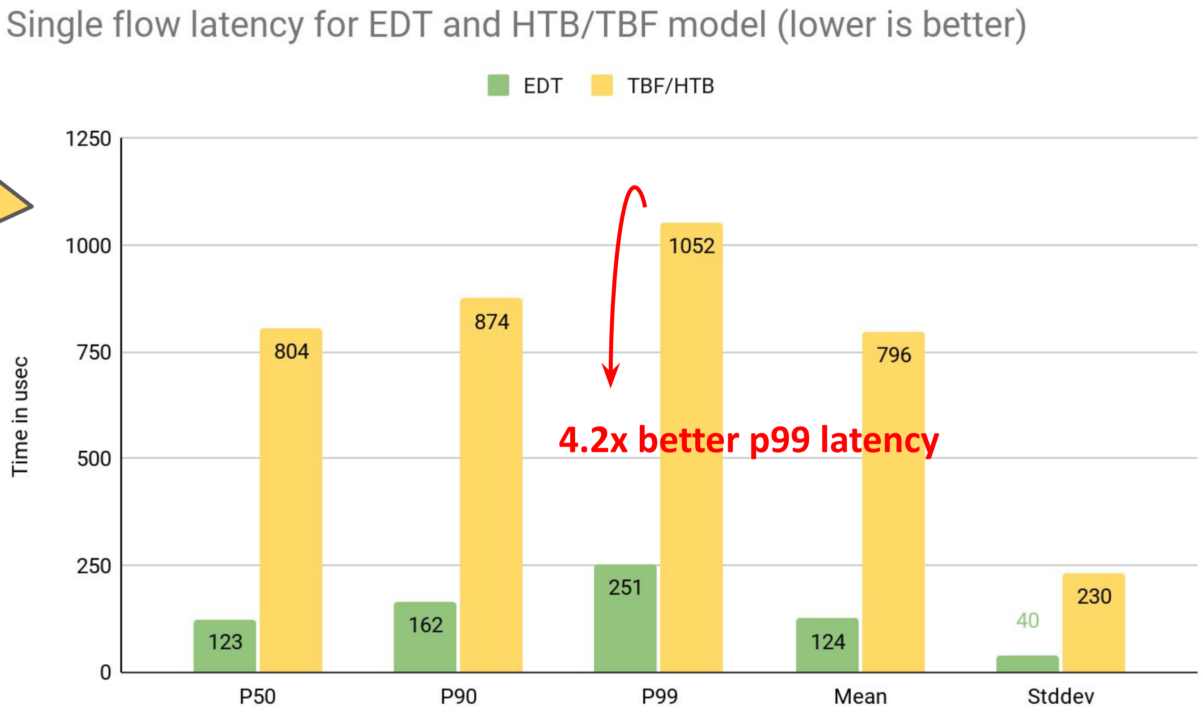



Pod
kubernetes.io/egress-bandwidth: "50M"
eth0
eBPF
MQ
FQ
FQ
FQ
FQ
Q1
Q4
Packet (skb) departure
timestamp management
Multi-queue aware
Packet scheduler
NIC queues


Pod
kubernetes.io/egress-bandwidth: "50M"
Cilium agent reads Pod's bandwidth annotations, and pushes them into Cilium's BPF datapath.
eth0
eBPF
Packet (skb) departure timestamp management
MQ
Cilium's BPF datapath classifies Pod aggregate traffic and sets packet timestamps based on bandwidth policy.
FQ
FQ
FQ
FQ
Multi-queue aware Packet scheduler
Q1
Q4
NIC queues
Cilium agent sets up MQ/FQ Qdisc combination for all physical devices.

Comparison of Cilium’s EDT implementation vs TBF

Env: 256 concurrent request/response type flows (TCP_RR), 100M rate per flow



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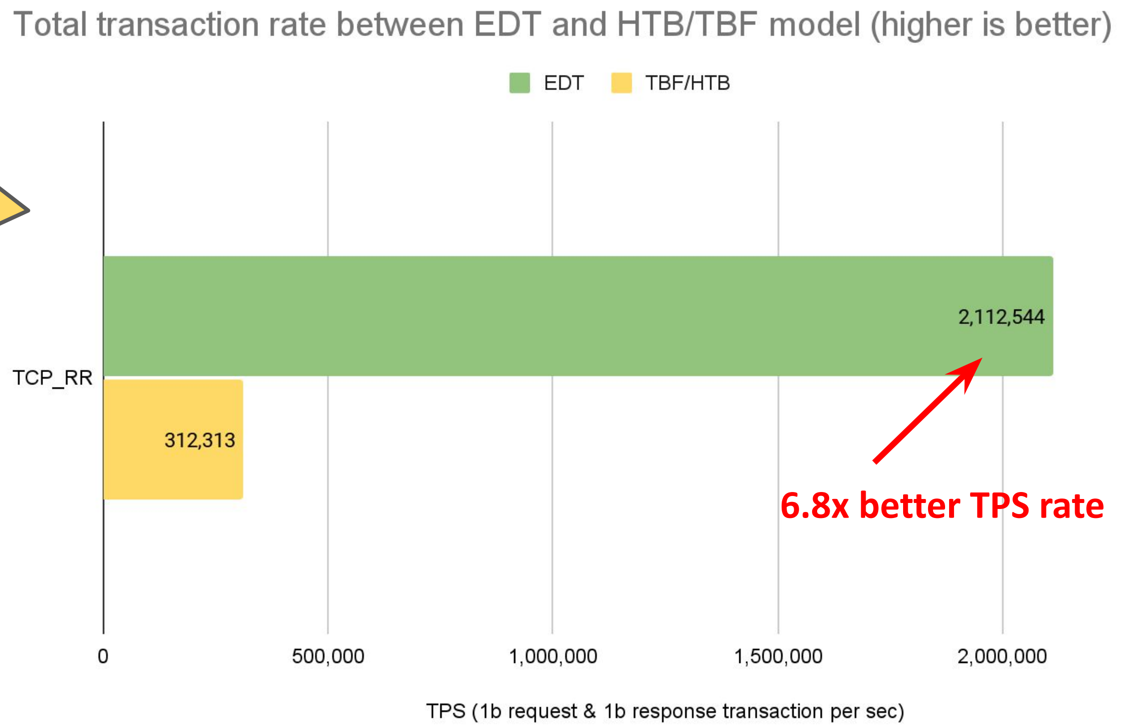
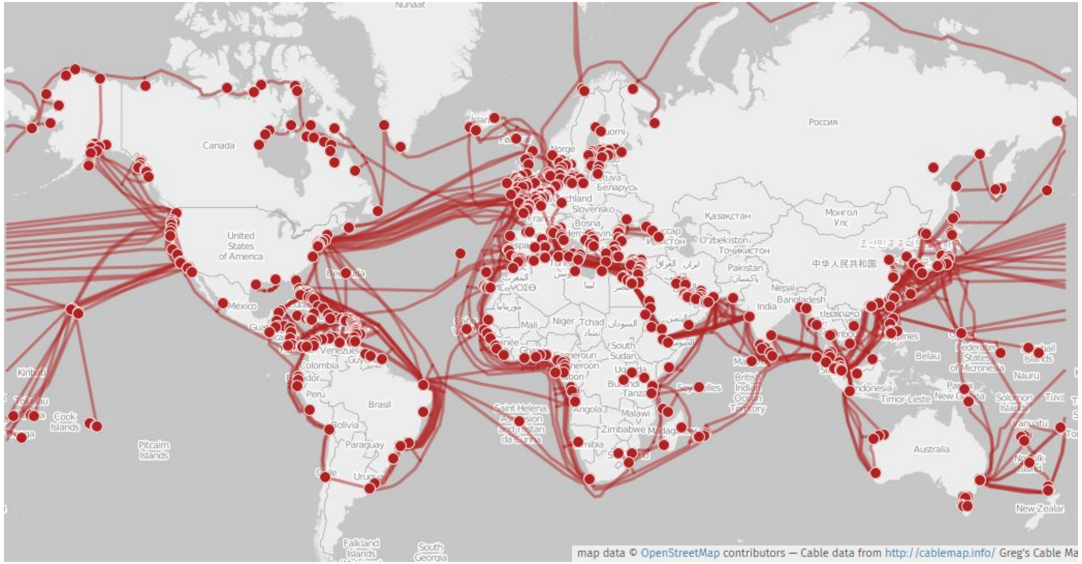
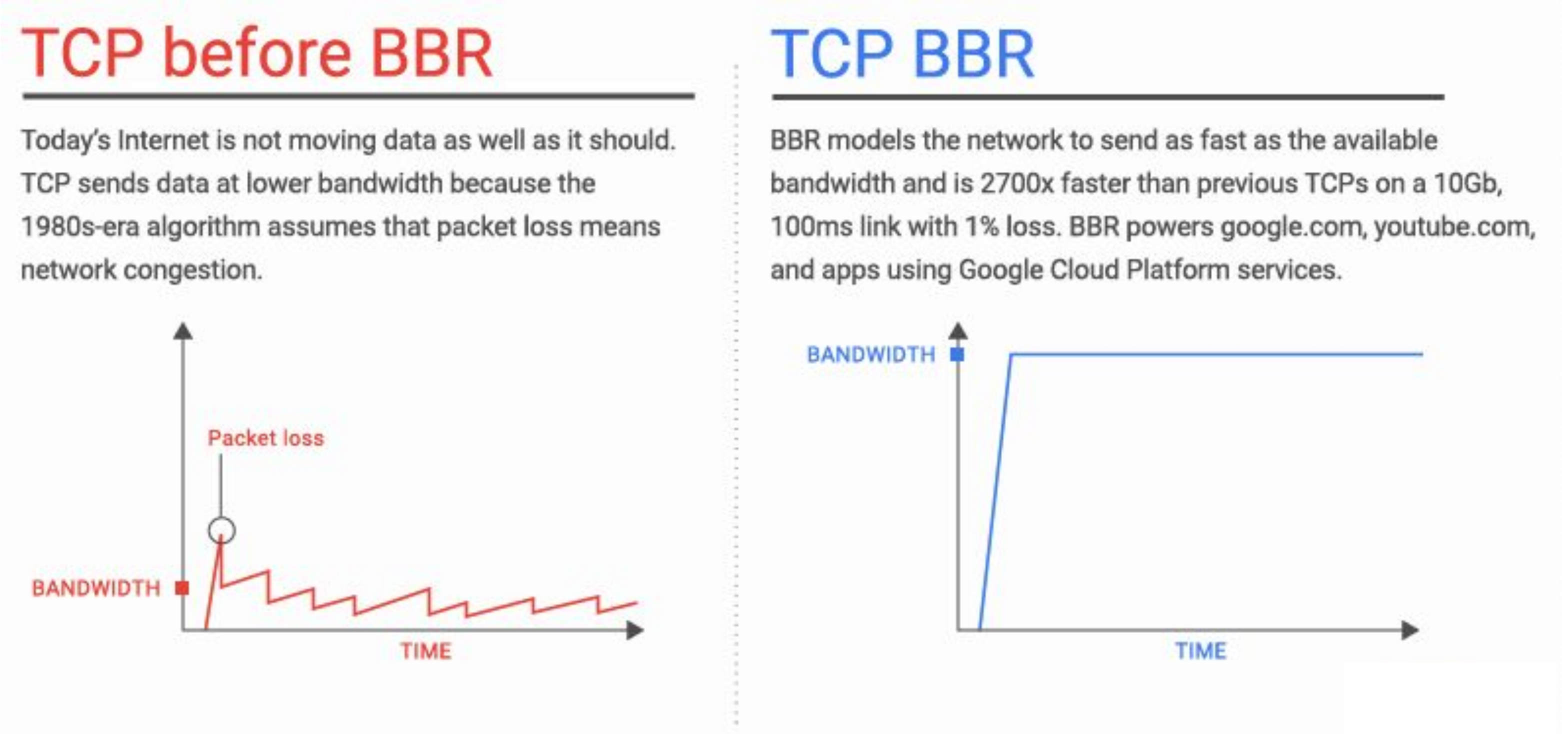


Cilium’s Bandwidth Manager: recap for now

➔ So far: Cilium’s EDT approach allows for scalable bandwidth enforcement
➔ What about more broadly Internet-level bandwidth management?



What else does EDT model enable? Enter: BBR



Source: https://cloud.google.com/blog/products/networking/tcp-bbr-congestion-control-comes-to-gcp-your-internet-just-got-faster

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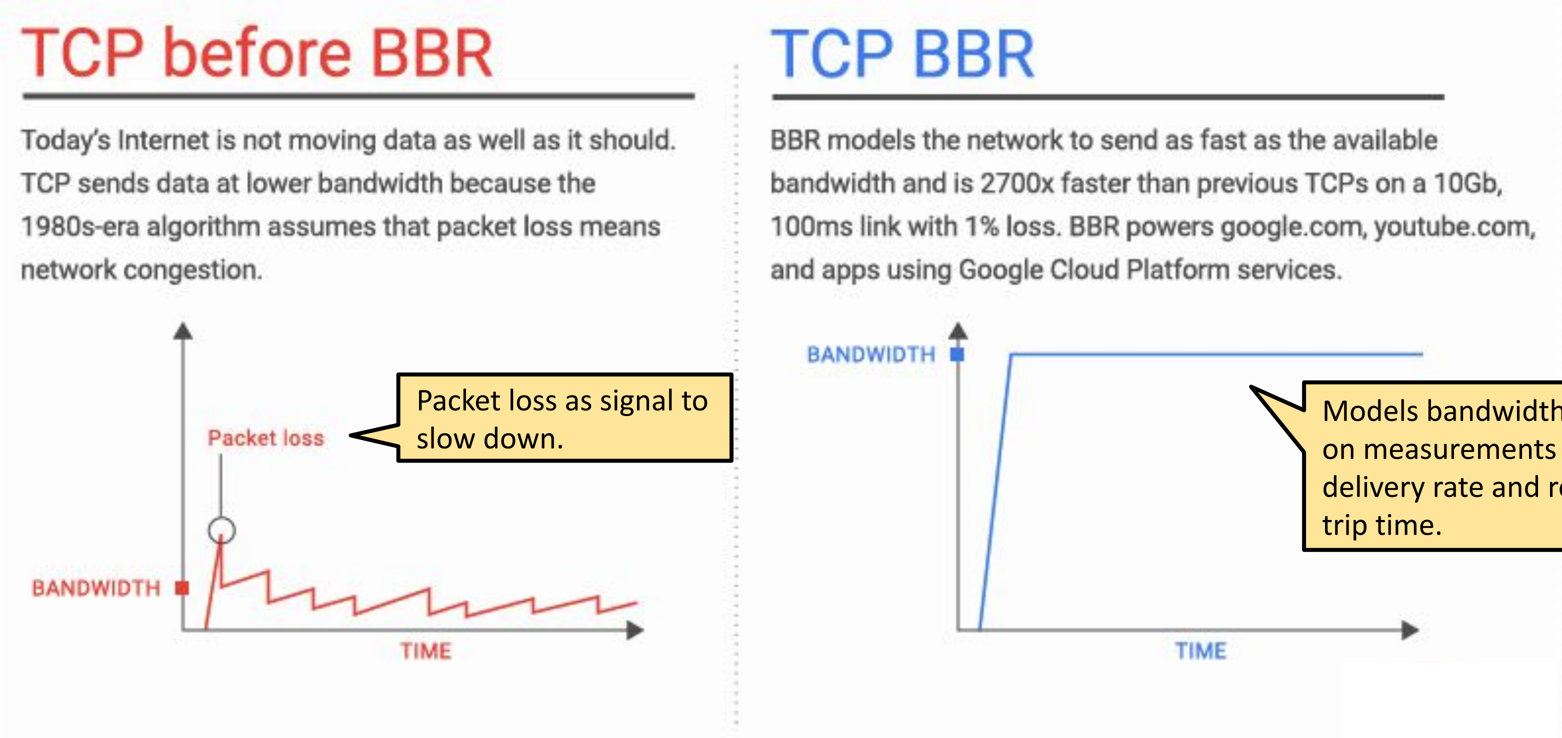

Packet loss as signal to slow down.

Models bandwidth based on measurements around delivery rate and round trip time.

Source: https://cloud.google.com/blog/products/networking/tcp-bbr-congestion-control-comes-to-gcp-your-internet-just-got-faster

When is it useful to consider BBR?

➔ Kubernetes cluster exposing services to clients over the Internet
- Significant latency improvements for low-end last-mile networks
- Significant throughput improvements for high-speed long-haul links

	CUBIC (default)	**BBR (v1)**
Model parameters to the state machine	N/A	Throughput, RTT
Loss	Reduce cwnd by 30% on window with any loss	N/A
ECN	RFC3168 (classic ECN)	N/A
Startup	Slow-start until RTT rises (Hystart) or any loss	Slow-start until throughput plateaus

Source: Alexey Ivanov, “Evaluating BBRv2 On the Edge”

Example: **New York** (packet.net) -> **Zurich**


```
darkstar@linux:~/trees/bpf-...   root@zh-lab-node-1: ~   darkstar@linux:~/trees/bpf   root@ny-c3-small-x86-01: ~   root
root@zh-lab-node-1:~# while [ 1 ]; do iperf3 -c 147.75.66.15 -t 55 -R -i 5 -O 5 ; done
Connecting to host 147.75.66.15, port 5201
Reverse mode, remote host 147.75.66.15 is sending
[  5] local 192.168.178.91 port 52148 connected to 147.75.66.15 port 5201
[ ID] Interval           Transfer     Bitrate
[  5]   0.00-5.00   sec  78.4 MBytes   132 Mbits/sec                  (omitted)
[  5]   0.00-5.00   sec  98.2 MBytes   165 Mbits/sec
[  5]   5.00-10.00  sec  99.1 MBytes   166 Mbits/sec
[  5]  10.00-15.00  sec   113 MBytes   189 Mbits/sec
[  5]  15.00-20.00  sec   159 MBytes   267 Mbits/sec
[  5]  20.00-25.00  sec   257 MBytes   431 Mbits/sec
[  5]  25.00-30.00  sec   153 MBytes   256 Mbits/sec
[  5]  30.00-35.00  sec   146 MBytes   245 Mbits/sec
[  5]  35.00-40.00  sec   148 MBytes   248 Mbits/sec
[  5]  40.00-45.00  sec   157 MBytes   264 Mbits/sec
[  5]  45.00-50.00  sec   193 MBytes   323 Mbits/sec
[  5]  50.00-55.00  sec   272 MBytes   457 Mbits/sec
- - - - - - - - - - - - - - - - - - - - - - - - -
[ ID] Interval           Transfer     Bitrate         Retr
[  5]   0.00-55.10  sec  1.76 GBytes   274 Mbits/sec  1501             sender
[  5]   0.00-55.00  sec  1.75 GBytes   274 Mbits/sec                  receiver
```

Bandwidth probing, overreaction to loss!
(Sawtooth pattern nicely visible)

Default, server runs:

- TCP CUBIC
- fq_codel Qdisc

Example: **New York** (packet.net) -> **Zurich**

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Connecting to host 147.75.66.15, port 5201
Reverse mode, remote host 147.75.66.15 is sending
[  5] local 192.168.178.91 port 52254 connected to 147.75.66.15 port 5201
[ ID] Interval           Transfer     Bitrate
[  5]   0.00-5.00   sec   152 MBytes   254 Mbits/sec                  (omitted)
[  5]   0.00-5.00   sec   258 MBytes   433 Mbits/sec
[  5]   5.00-10.00  sec   240 MBytes   403 Mbits/sec
[  5]  10.00-15.00  sec   255 MBytes   427 Mbits/sec
[  5]  15.00-20.00  sec   247 MBytes   414 Mbits/sec
[  5]  20.00-25.00  sec   255 MBytes   428 Mbits/sec
[  5]  25.00-30.00  sec   255 MBytes   428 Mbits/sec
[  5]  30.00-35.00  sec   238 MBytes   400 Mbits/sec
[  5]  35.00-40.00  sec   255 MBytes   428 Mbits/sec
[  5]  40.00-45.00  sec   239 MBytes   401 Mbits/sec
[  5]  45.00-50.00  sec   253 MBytes   425 Mbits/sec
[  5]  50.00-55.00  sec   242 MBytes   407 Mbits/sec
- - - - - - - - - - - - - - - - - - - - - - - - -
[ ID] Interval           Transfer     Bitrate         Retr
[  5]   0.00-55.10  sec  2.68 GBytes   418 Mbits/sec  58812             sender
[  5]   0.00-55.00  sec  2.67 GBytes   418 Mbits/sec                  receiver
```

No overreaction, stable.

Updated, server runs:

- TCP BBR
- FQ Qdisc (for EDT)

(results also reproduce with netperf)

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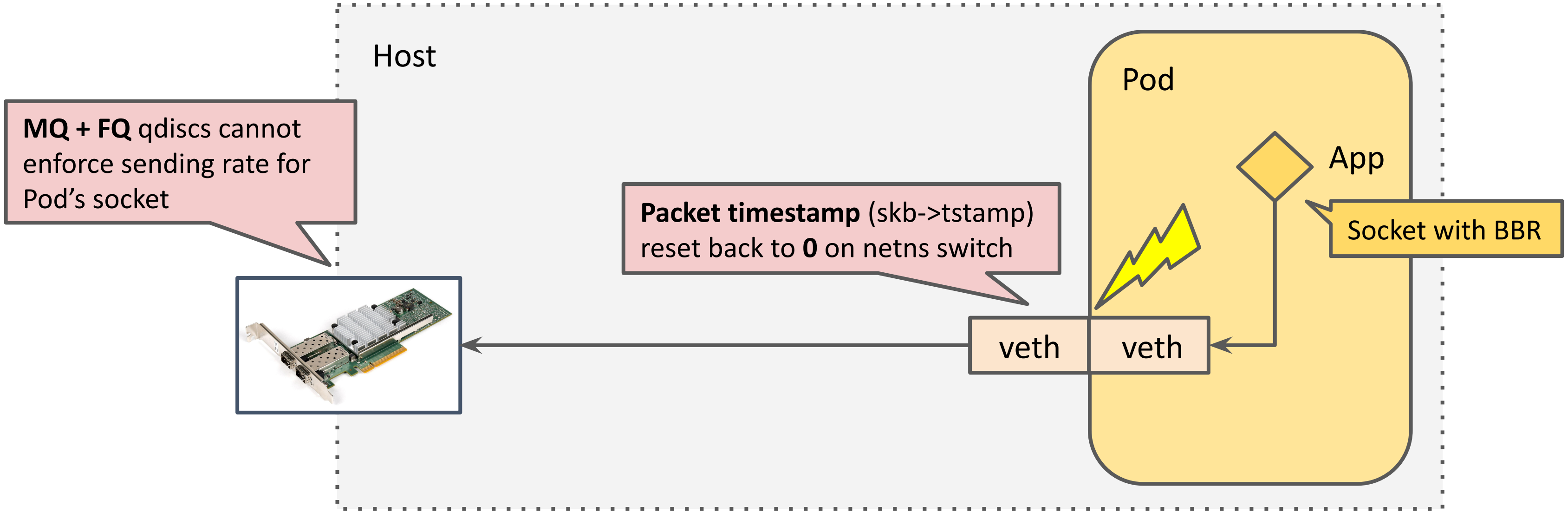
f)

CUBIC → **BBR** bumps:

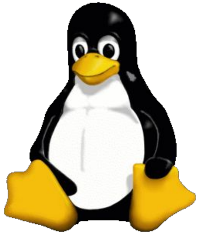
274 → 418 Mbit/s

Can BBR be used for Kubernetes Pods?

- ➔ BBR works in conjunction with FQ and sets packet delivery timestamps
- ➔ Kernel clears timestamp for packets leaving Pods (== netns)
  - Usage of BBR for Pods not possible/broken in general today



Rationale on today's timestamp reset (see our LPC talk)

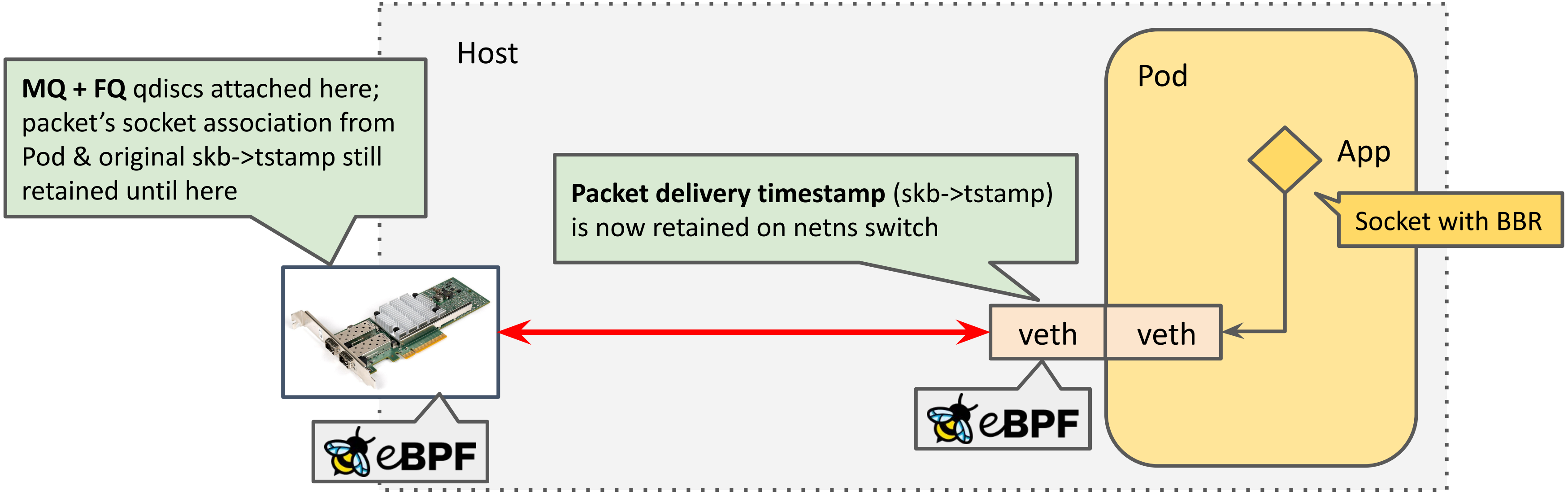


Kernel uses different clock bases for skb->tstamp:

- ➔ Ingress is CLOCK_TAI, egress is CLOCK_MONOTONIC (as is FQ)
- ➔ Forwarding from RX to TX would cause drop in FQ due to overreaching FQ's drop horizon given different clock's offsets
- ➔ No means to figure out clock base from skb->tstamp, hence reset

Cilium’s Bandwidth Manager: BBR

- ➔ We helped fixing networking stack in Linux v5.18+ to retain timestamps
- ➔ Bandwidth Manager plumbs the appropriate underlying infrastructure
  - ◆ Receives new knob for switching whole cluster over to BBR by default



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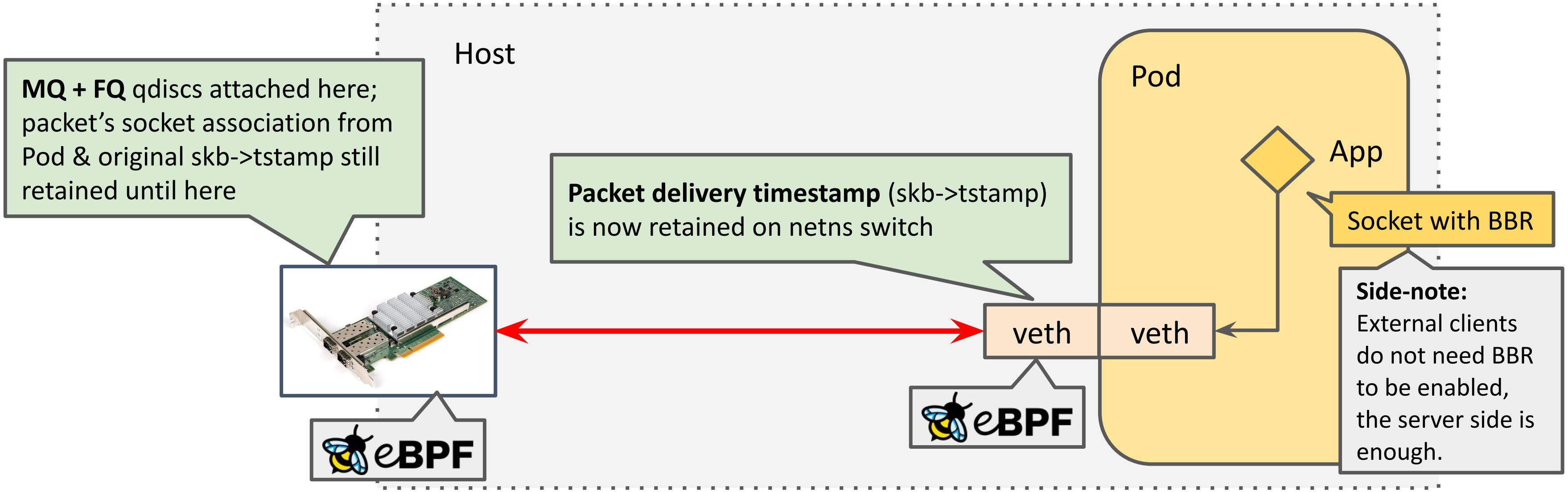

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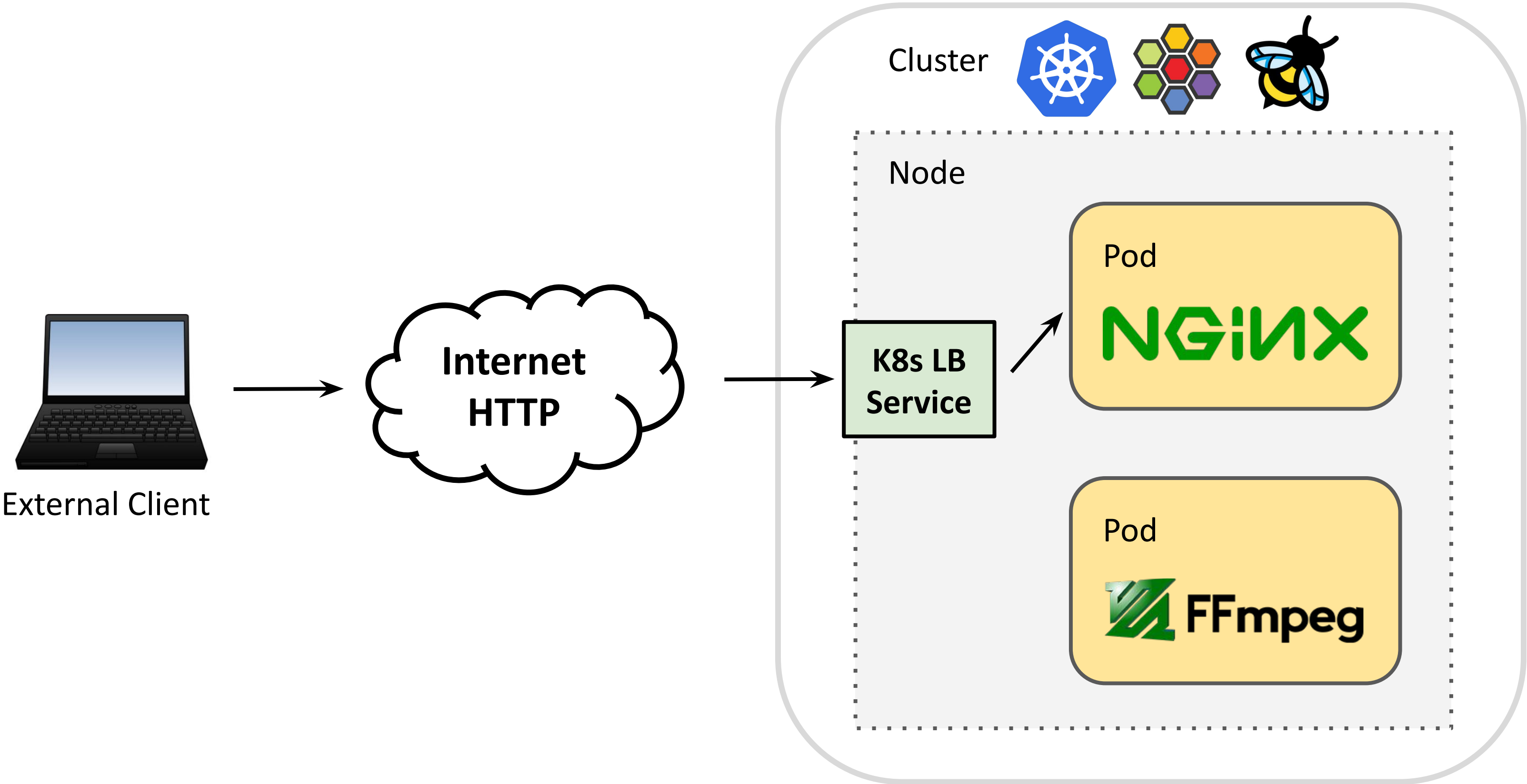
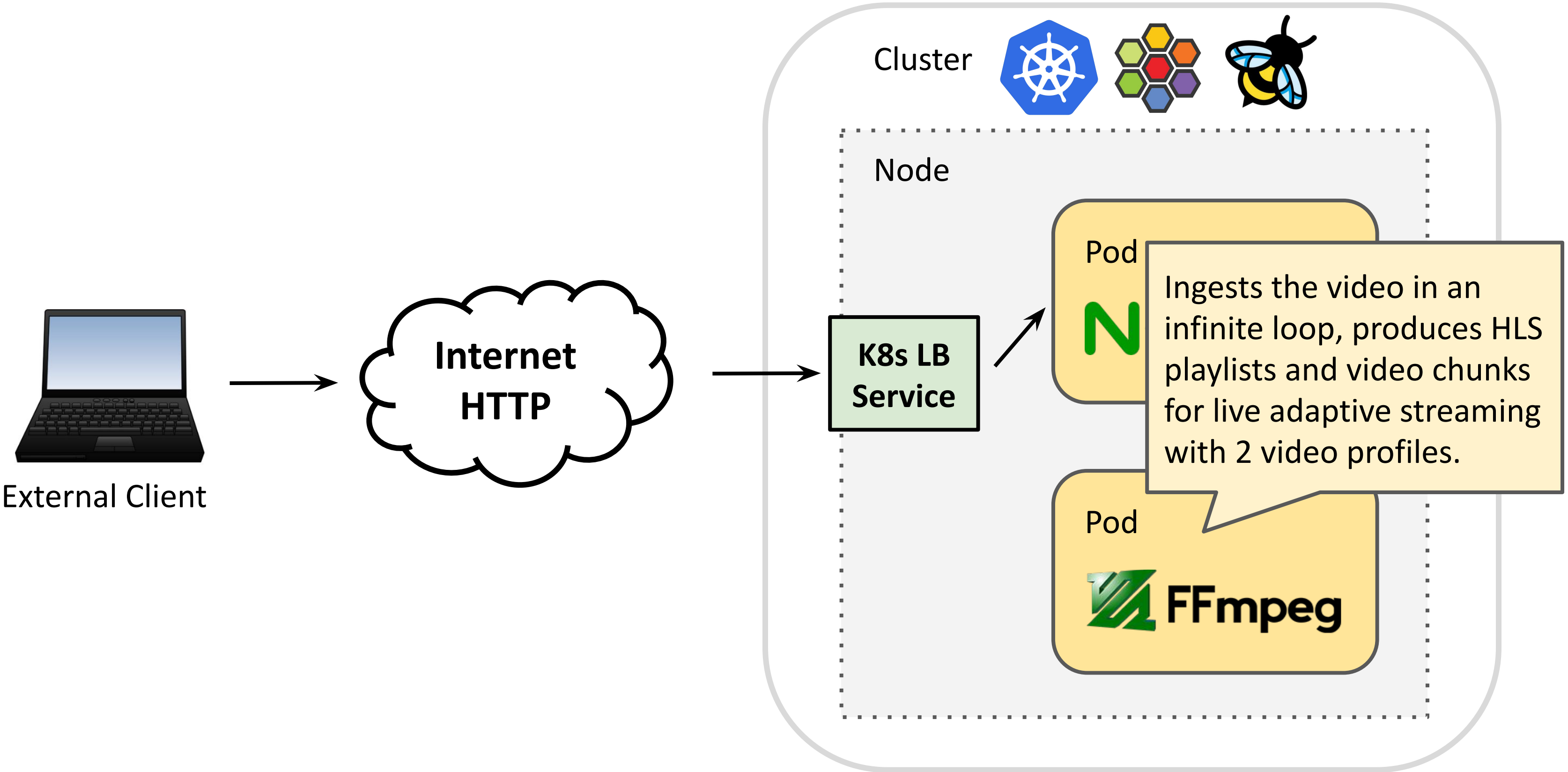
Demo: BBR for Pods

(K8s/Cilium-backed video streaming service: CUBIC versus BBR)

Video Streaming Service Demo Setup: CUBIC vs BBR



Video Streaming Service Demo Setup: CUBIC vs BBR



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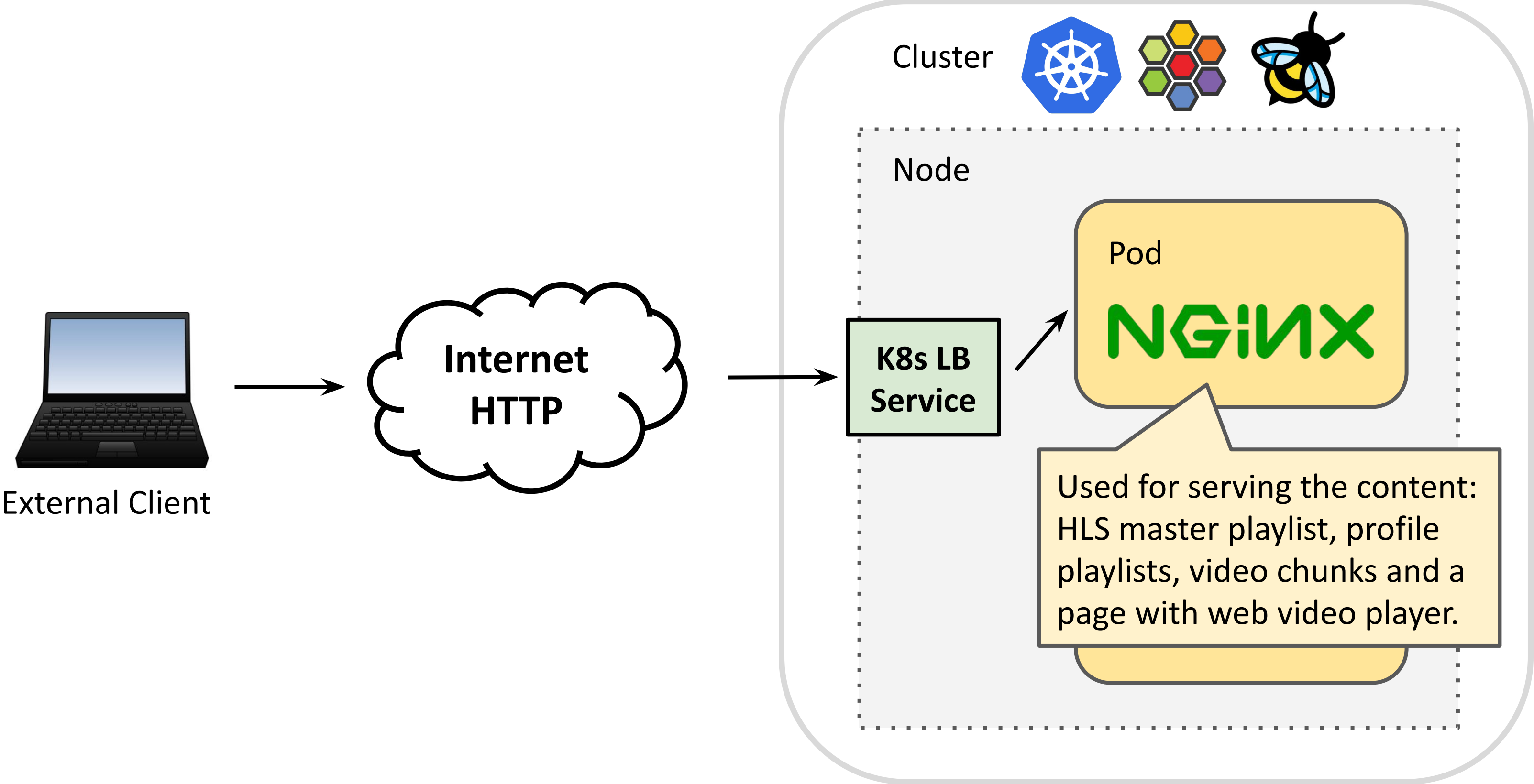

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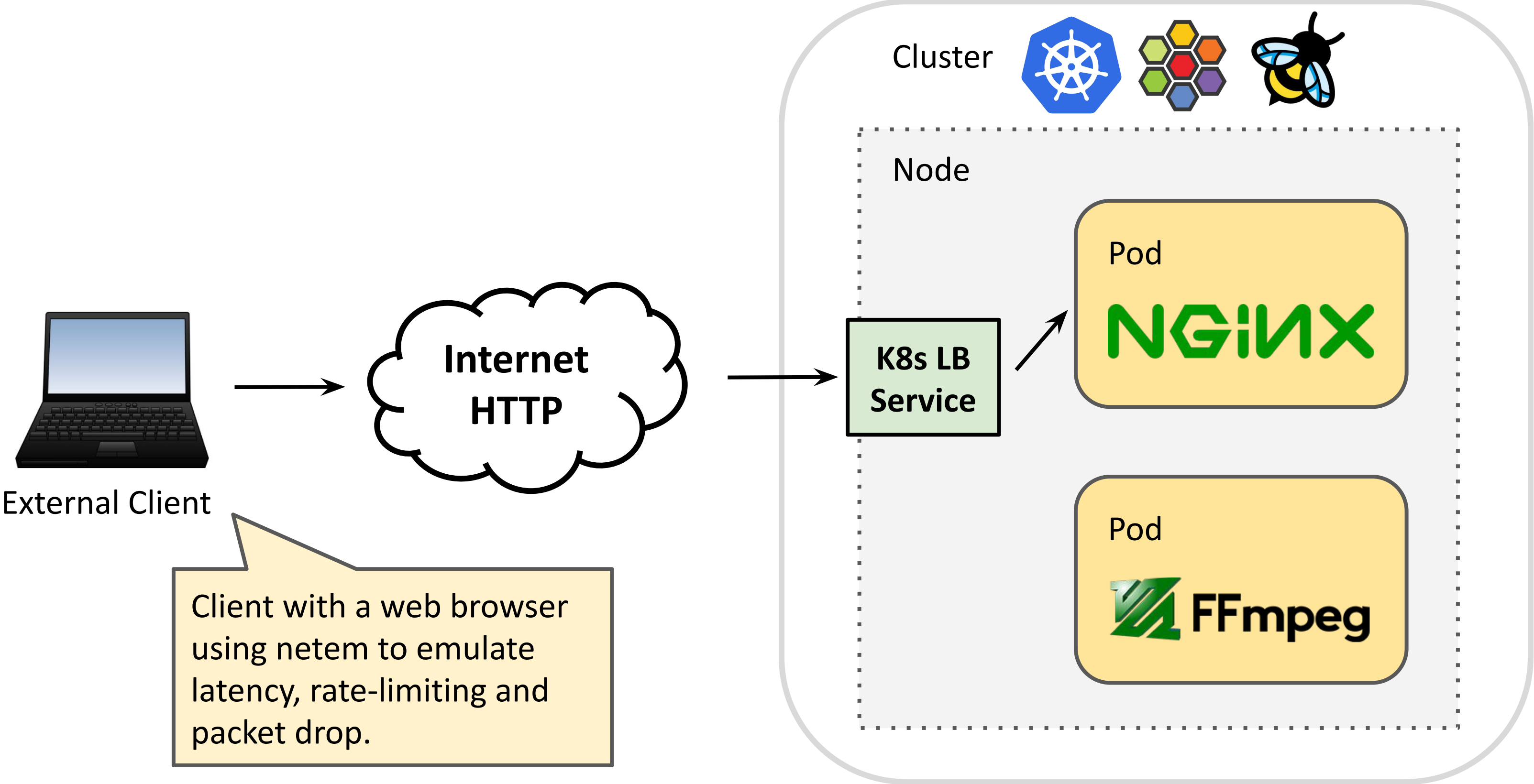
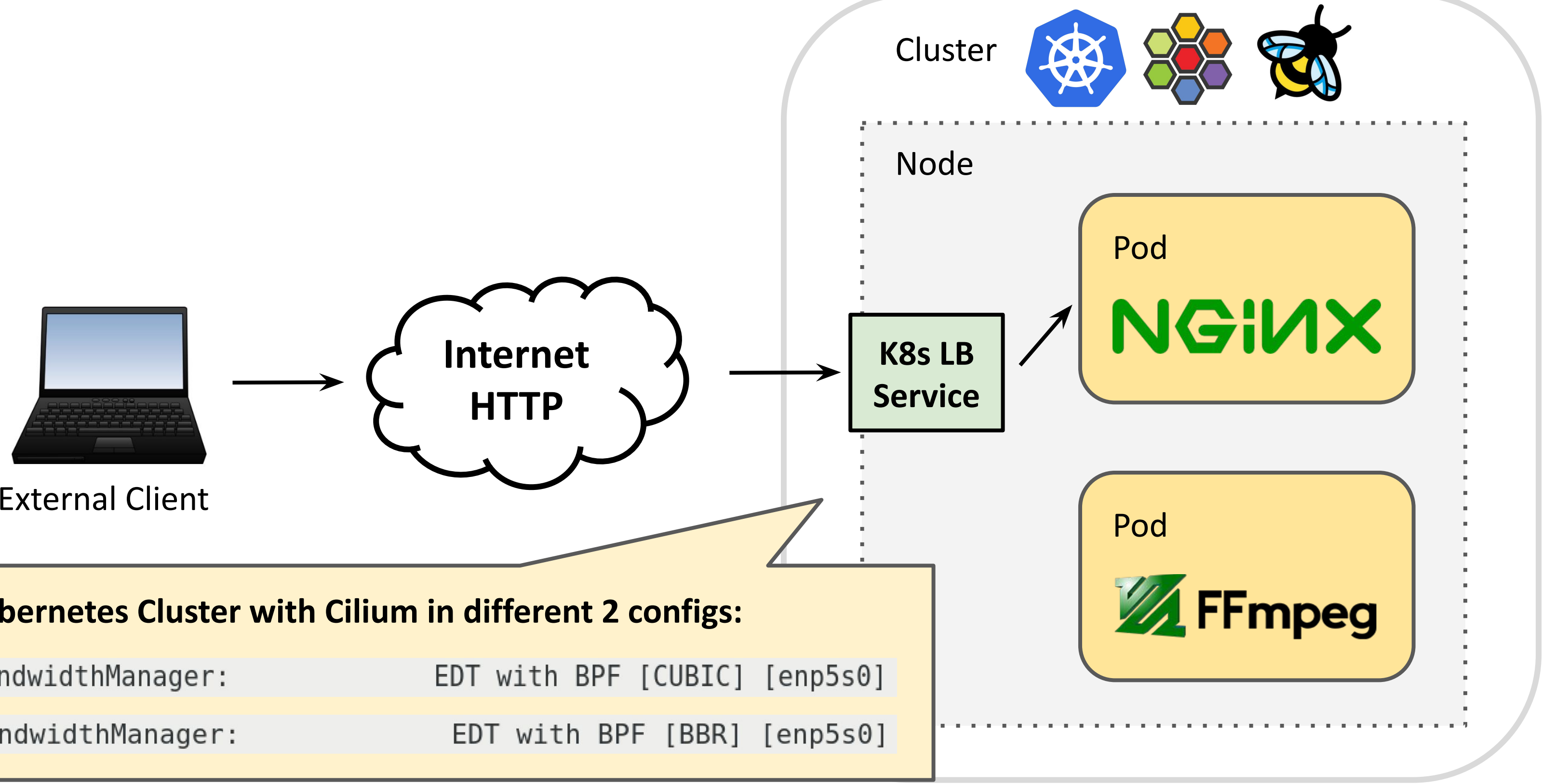


Video Streaming Service Demo Setup: CUBIC vs BBR



Kubernetes Cluster with Cilium in different 2 configs:

```
BandwidthManager:          EDT with BPF [CUBIC] [enp5s0]
BandwidthManager:          EDT with BPF [BBR] [enp5s0]
```

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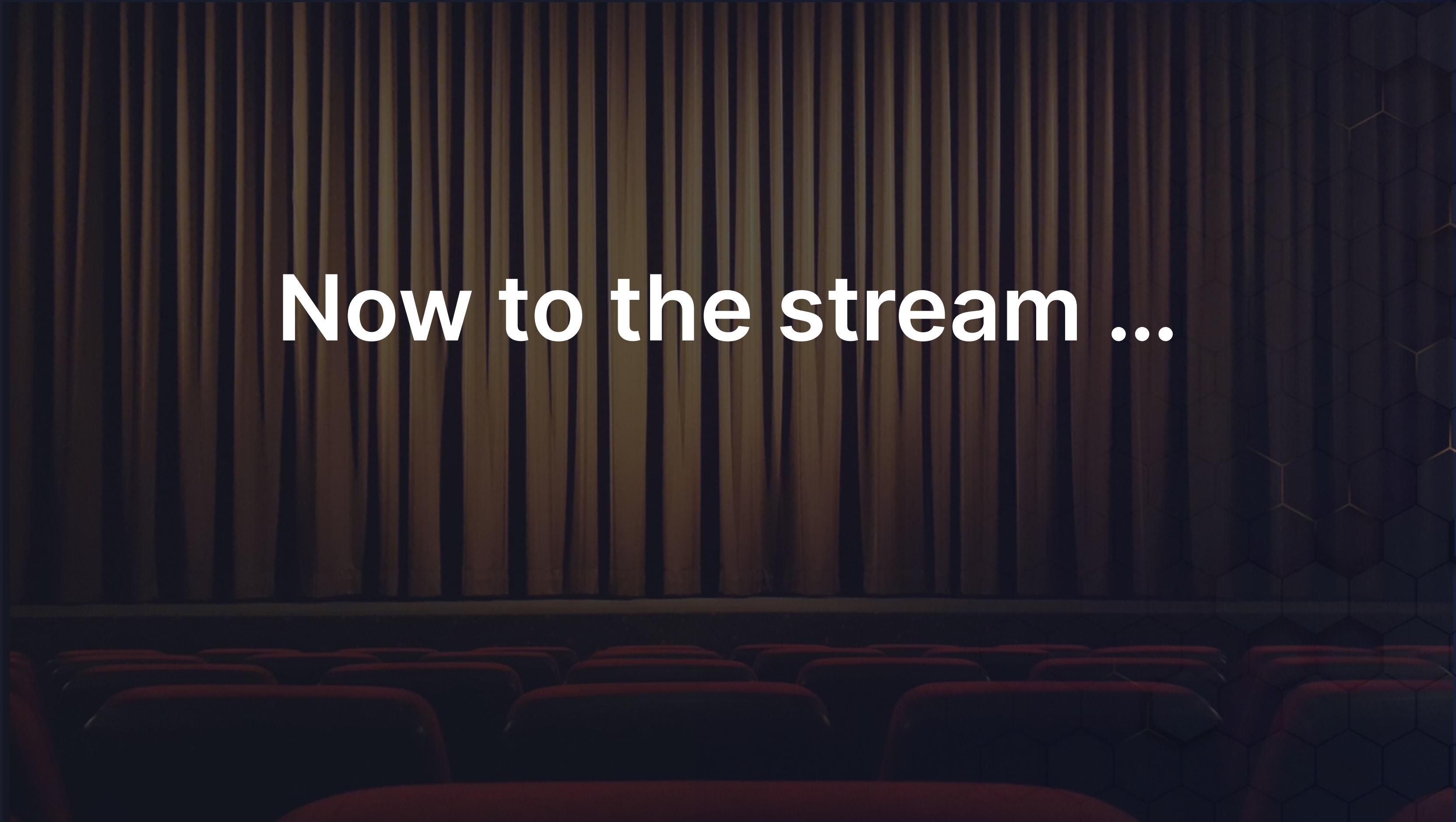

Now to the stream ...

What needs to be considered with use of BBR?

- ➔ BBR has potential unfairness issues towards CUBIC when env uses both
- ➔ BBR will trigger a higher TCP retransmission rate (more aggressive probing)
- ➔ BBRv2 in the works to overcome them

Source: Alexey Ivanov, "Evaluating BBRv2 On the Edge"

Revisiting earlier Problem Statement

- ➔ Kubernetes bandwidth enforcement does not need to be in a poor state
- ➔ Native implementation via Cilium's Bandwidth Manager (GA since v1.12)
  - ◆ Efficient, eBPF-based bandwidth enforcement via EDT model
  - ◆ First CNI to support BBR (& socket pacing) for Pods
  - ◆ Side-note: Realizing such architecture only possible with eBPF

Getting Started Guide for Bandwidth Manager:

```
helm upgrade cilium ./cilium \
  --namespace kube-system \
  --reuse-values \
  --set bandwidthManager.enabled=true \
  --set bandwidthManager.bbr=true
kubectl -n kube-system rollout restart ds/cilium
```

(needs Linux kernel v5.1+)

(needs Linux kernel v5.18+)

Acknowledgements

- ➔ Van Jacobson
- ➔ Eric Dumazet
- ➔ Vytautas Valancius
- ➔ Stanislav Fomichev
- ➔ Martin Lau
- ➔ John Fastabend
- ➔ Cilium, BPF & netdev kernel community

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Thank you! Questions?

github.com/cilium/cilium

cilium.io

ebpf.io

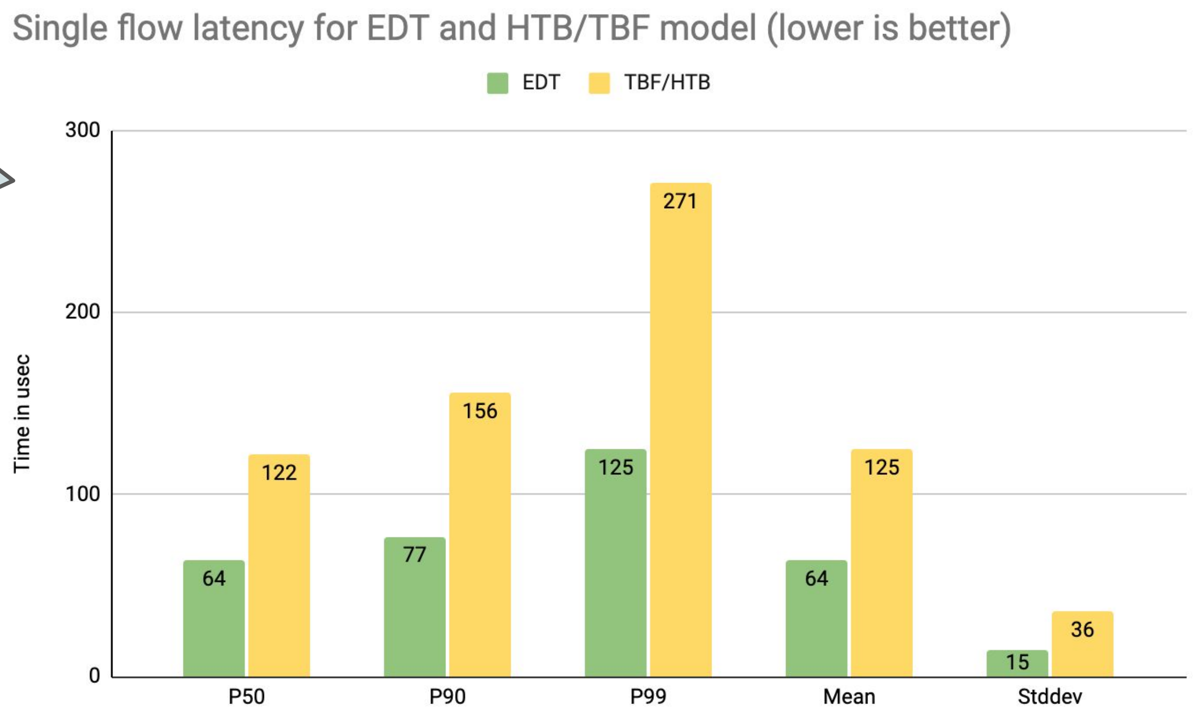
Isovalent: booth S21

Cilium: kiosk 12 (@ project pavilion)

Appendix: Latency & TPS for 64/128/256 flows

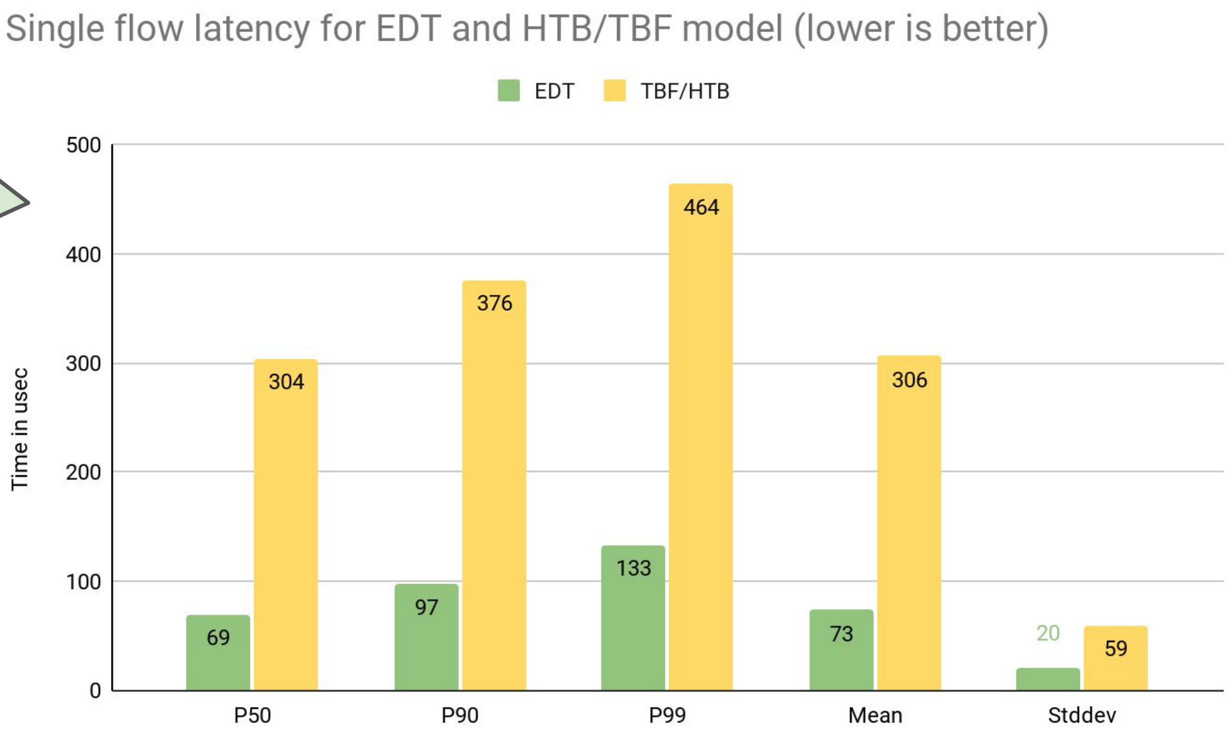
Comparison of Cilium’s EDT implementation vs TBF

Env: 64 concurrent request/response type flows (TCP_RR), 100M rate per flow



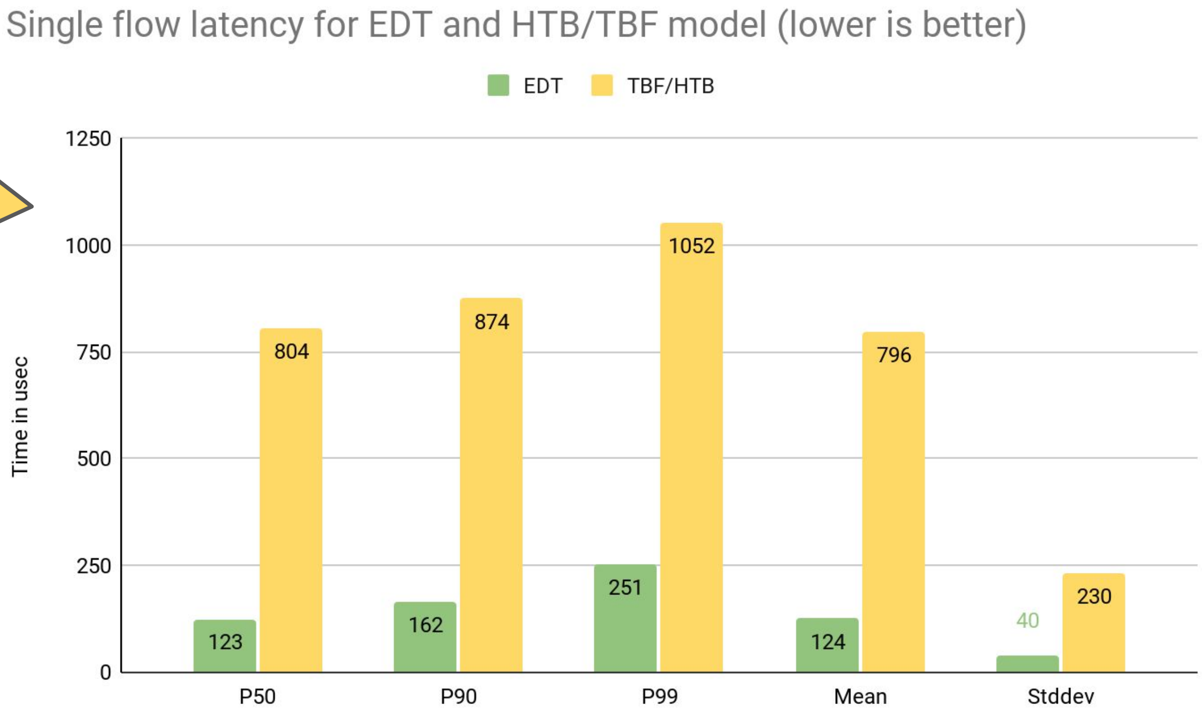
Comparison of Cilium’s EDT implementation vs TBF

Env: 128 concurrent request/response type flows (TCP_RR), 100M rate per flow



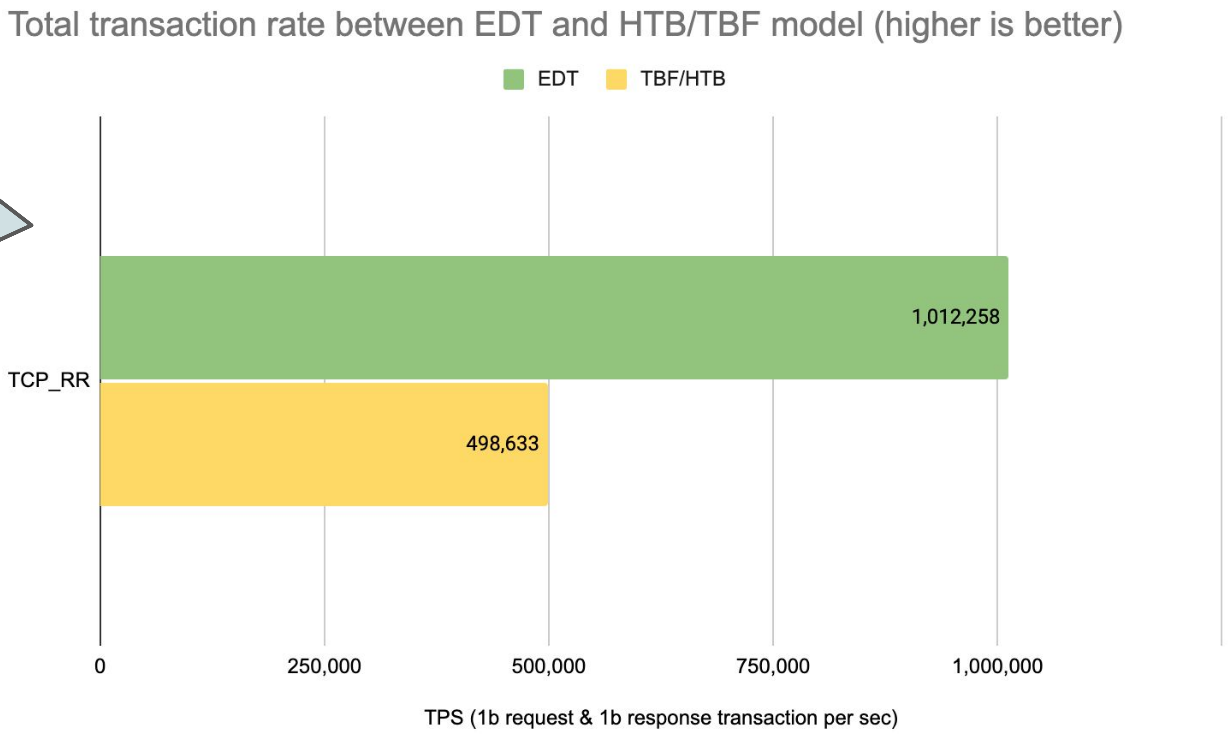
Comparison of Cilium’s EDT implementation vs TBF

Env: 256 concurrent request/response type flows (TCP_RR), 100M rate per flow



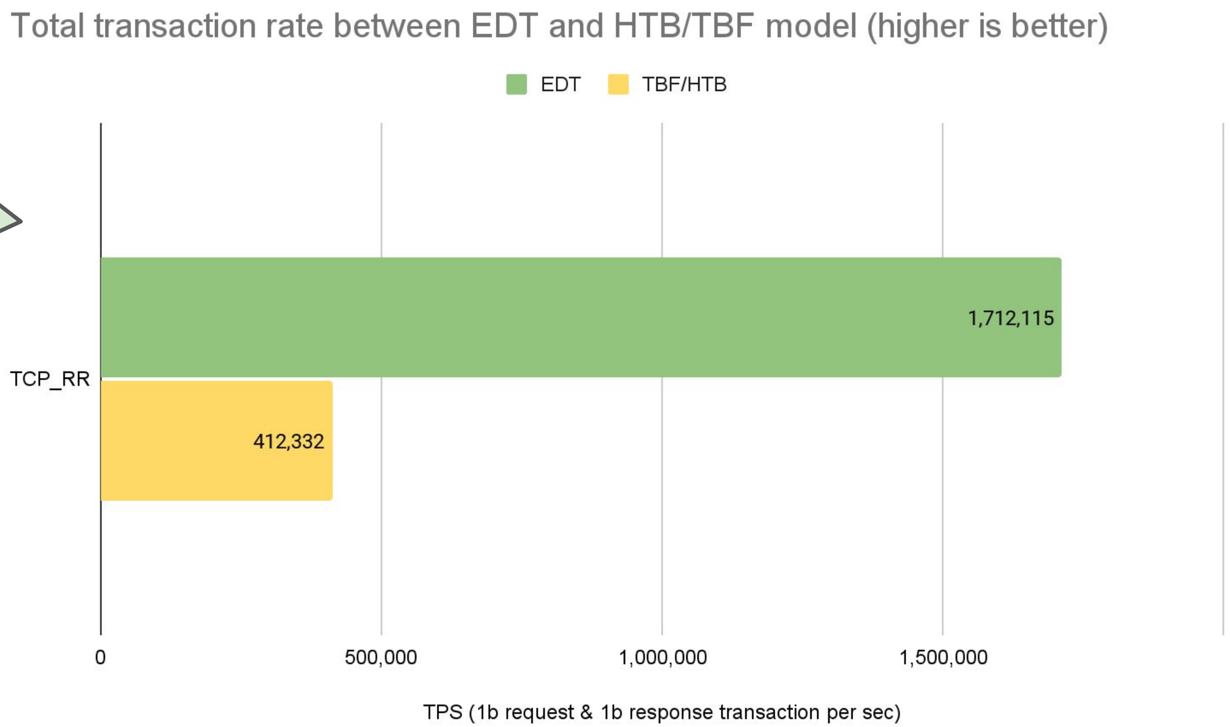
Comparison of Cilium’s EDT implementation vs TBF

Env: 64 concurrent request/response type flows (TCP_RR), 100M rate per flow



Comparison of Cilium's EDT implementation vs TBF

Env: 128 concurrent request/response type flows (TCP_RR), 100M rate per flow



Comparison of Cilium's EDT implementation vs TBF

Env: 256 concurrent request/response type flows (TCP_RR), 100M rate per flow