eBPF for TSN and DetNet

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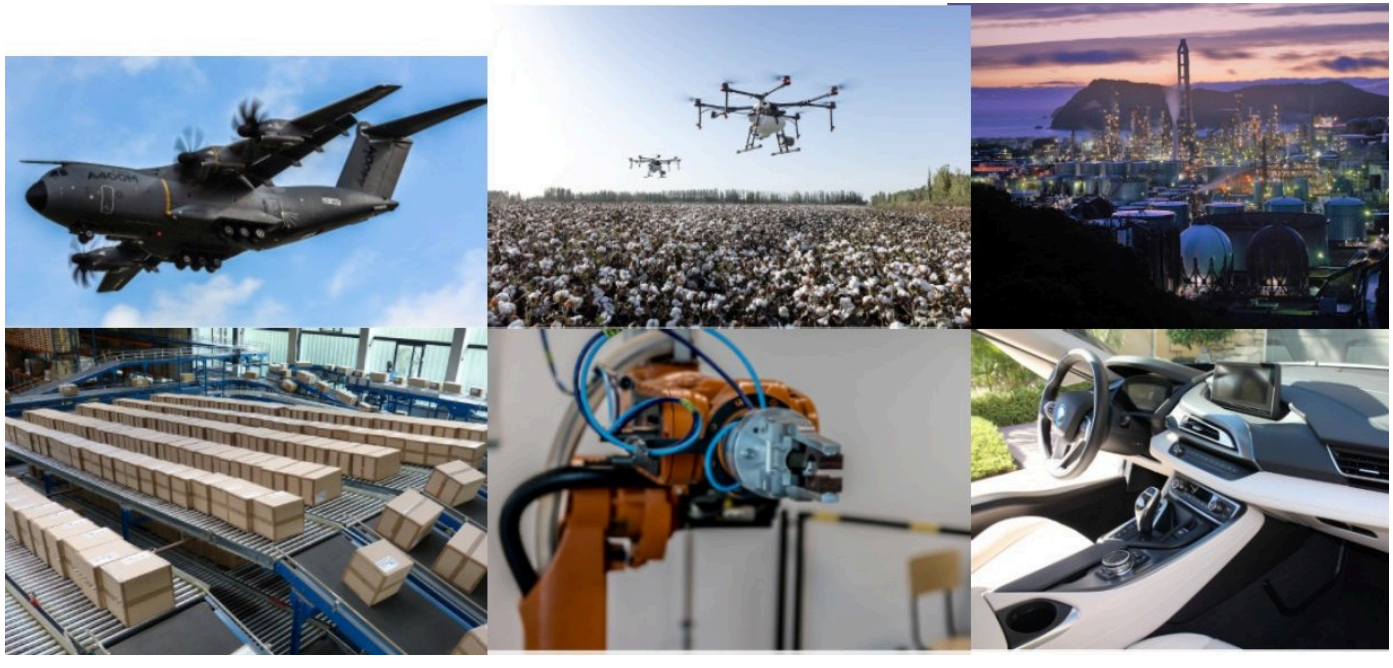
Mission- and Time-Critical Use Cases



source: pixabay.com

What is BPF?

- BPF (BSD Packet Filter)
- Introduced by Steven McCanne and Van Jacobson in 1992
- Simple instruction set designed for packet filtering
- Interpreter (VM) inside the kernel for it
- Popular users: tcpdump, libpcap, Wireshark

What is eBPF?

- Extends BPF instruction set with new operations
- Implements a verifier to ensure safe memory access, prevent halting problem
- eBPF instruction set & architecture (ISA) is IETF standard: RFC 9669
- Equip the monolithic kernel with runtime programmability
- **Many use cases beyond filtering e.g.:** tracing, packet processing, task scheduling, etc.

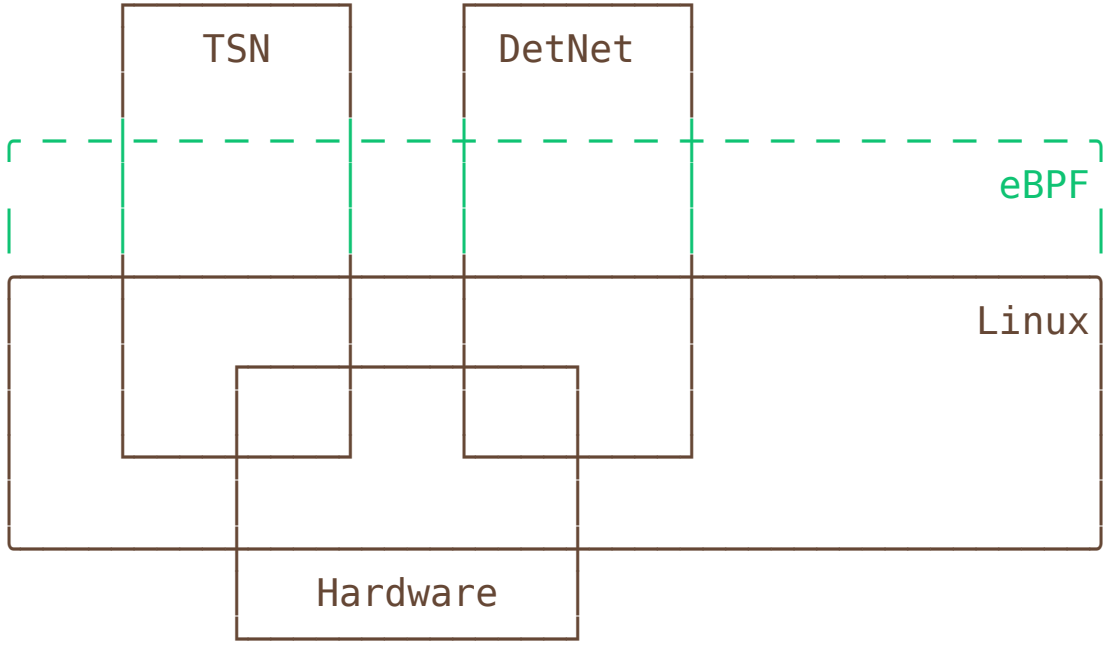
Linux and TSN/DetNet

- Linux with real-time preemption is strong platform for time-sensitive applications (TSA)
- IEEE 802.1 TSN standards (e.g.: Qbv, Qci, Qch, timesync) implemented in the kernel
- eBPF enables rapid iteration, research and experimentation with networking
- TSN/DetNet support can be improved with the help of eBPF

TSN/DetNet Use Cases with eBPF

- XDPFRER: IEEE 802.1CB implementation
- TSN/DetNet proxy: enhanced TSA support for Kubernetes
- Improved observability
  - Layer 2 TSN stream OAM (based on CFM)
  - Routing table lookup tracing

Overview



XDPFRER

IEEE 802.1CB

Frame Replication & Elimination for Reliability (FRER) with eBPF

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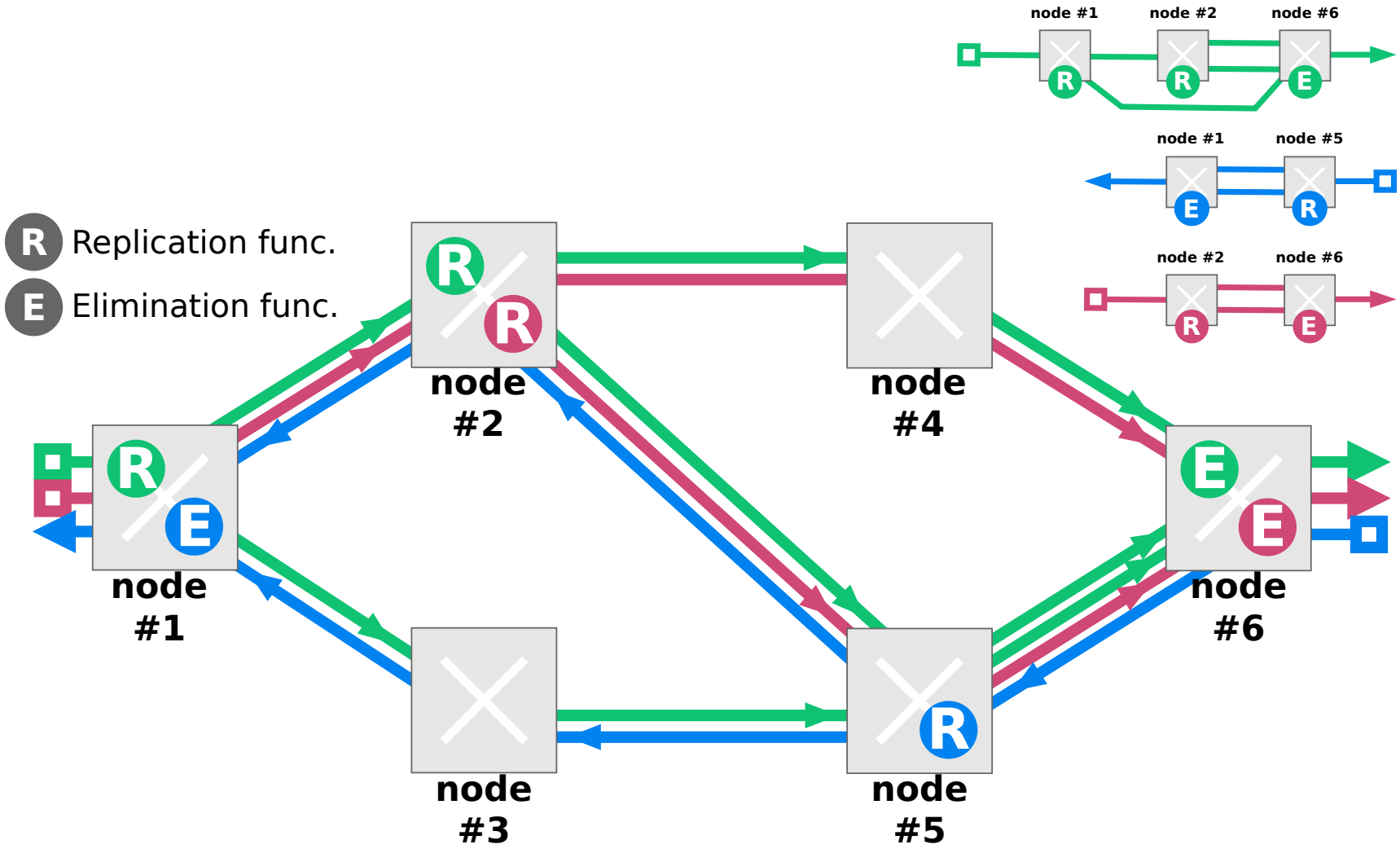
node #1
node #2
node #6
node #1
node #5
node #2
node #6
R Replication func.
E Elimination func.
node #1
node #2
node #3
node #4
node #5
node #6

Upstream Linux FRER Attempts

First attempt from NXP

```
From: Xiaoliang Yang <xiaoliang.yang_1@nxp.com>
Date: Tue, 28 Sep 2021 19:44:51

[RFC, net-next] net: qos: introduce a frer action to implement 802.1CB
```

Second attempt from Cruise LLC

```
From: Steve Williams <steve.williams@getcruise.com>
Date: Fri, 18 Nov 2022 15:26:39

[PATCH net-next] net/hanic: Add the hanic network interface for high
availability links
```

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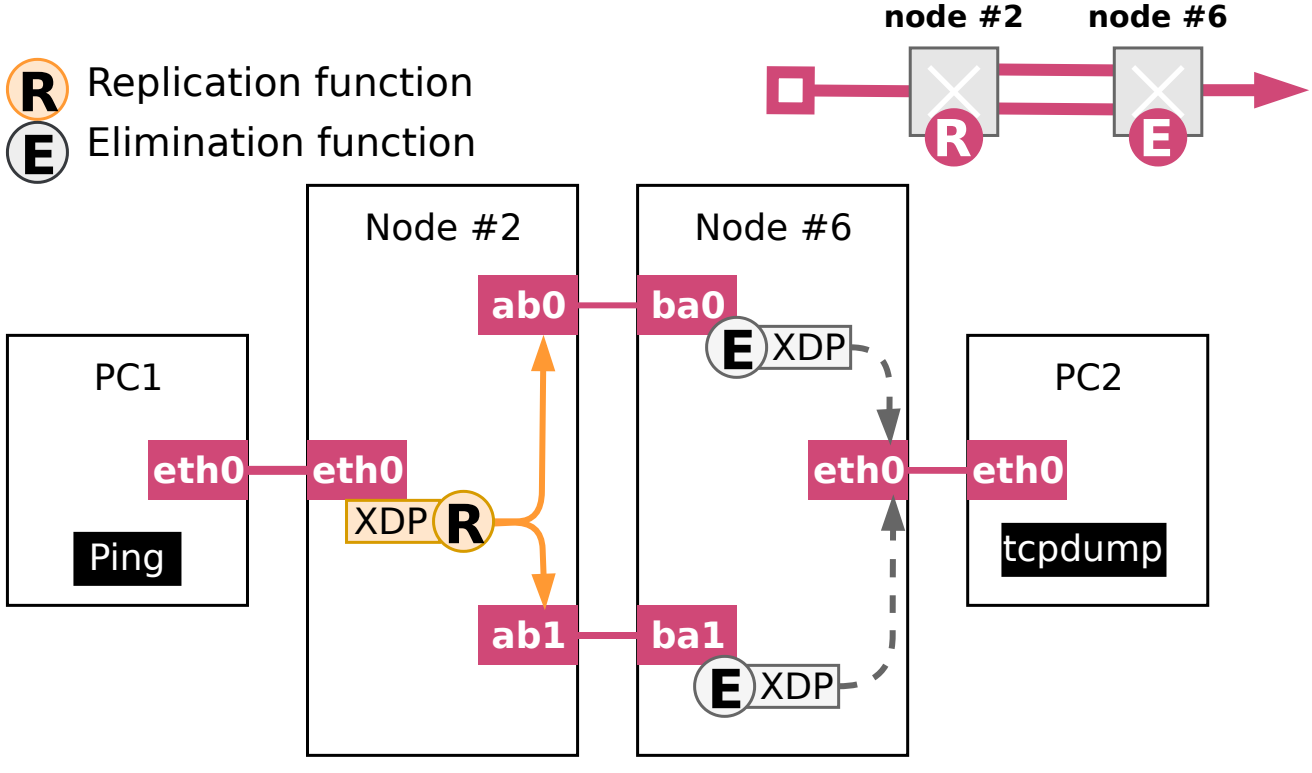
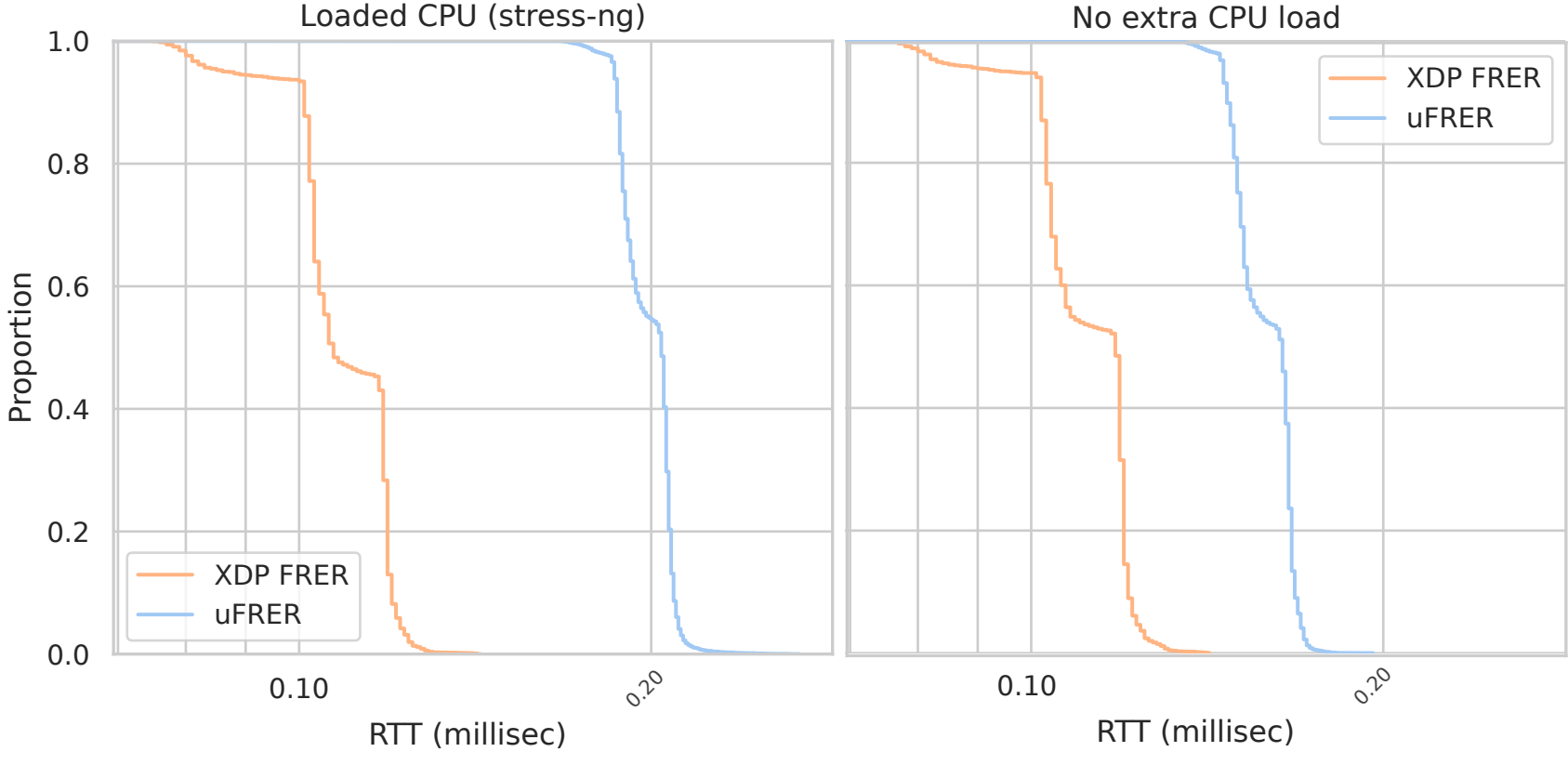
Alternative Approach: eBPF and XDP

- FRER functions can be implemented with the XDP packet-processing APIs
  - R-tag push/pop with head adjustment support
  - Replication with broadcast transmission flag
  - Elimination enabled by BPF locking API: serialized access to internal state (history window, counters)

Example Testbed



XDPFRER vs User-Space FRER with CPU Load



TSN/DetNet metadata proxy

Context

- Microservices: main direction of application deployment since the past decade
- This trend emerged in the field of industrial applications as well
- *Kubernetes* has become the de-facto orchestration platform
- There are challenges however…

Kubernetes Networking

- Networking implemented by *Container Network Interface* (CNI) plugins
  - Popular CNI plugins: Calico, Cilium, Flannel, Weave Net, Kindnet, Canal
- Each implement the cluster network differently
- Most of them rely on GNU/Linux tools and APIs to do it

Kubernetes and Time-Sensitive Applications (TSA)

- TSA need `timestamp` and `priority` metadata to be preserved
- They cleared by Linux network namespace isolation
- CNI plugin diversity: different strategies to implement the network
- Must be transparent to the applications, plugin specific network APIs should be avoided

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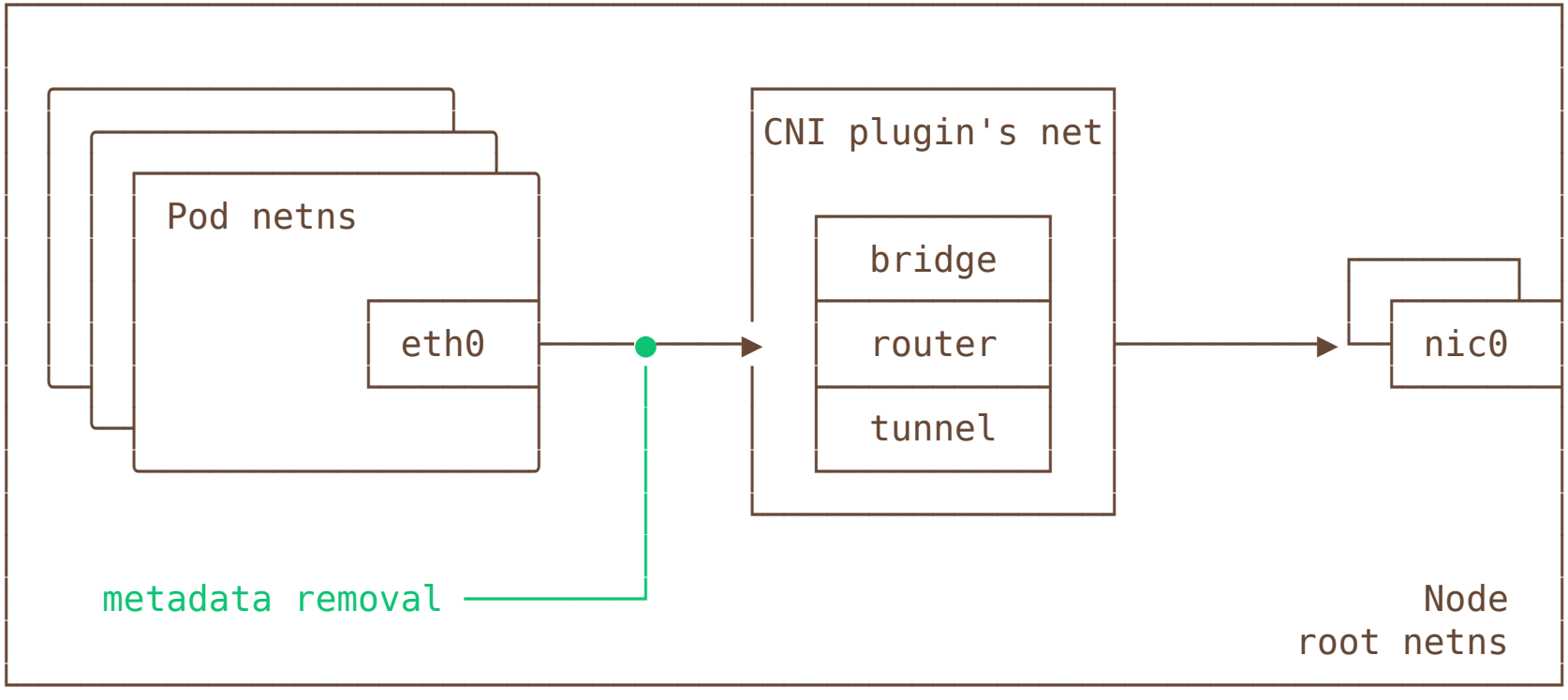
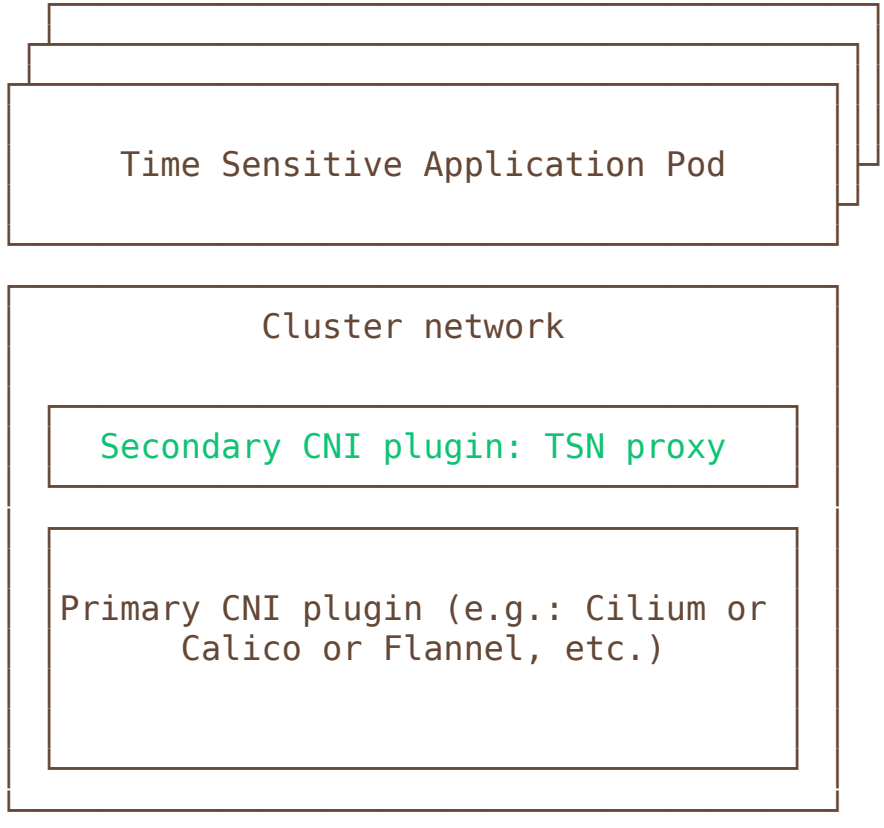
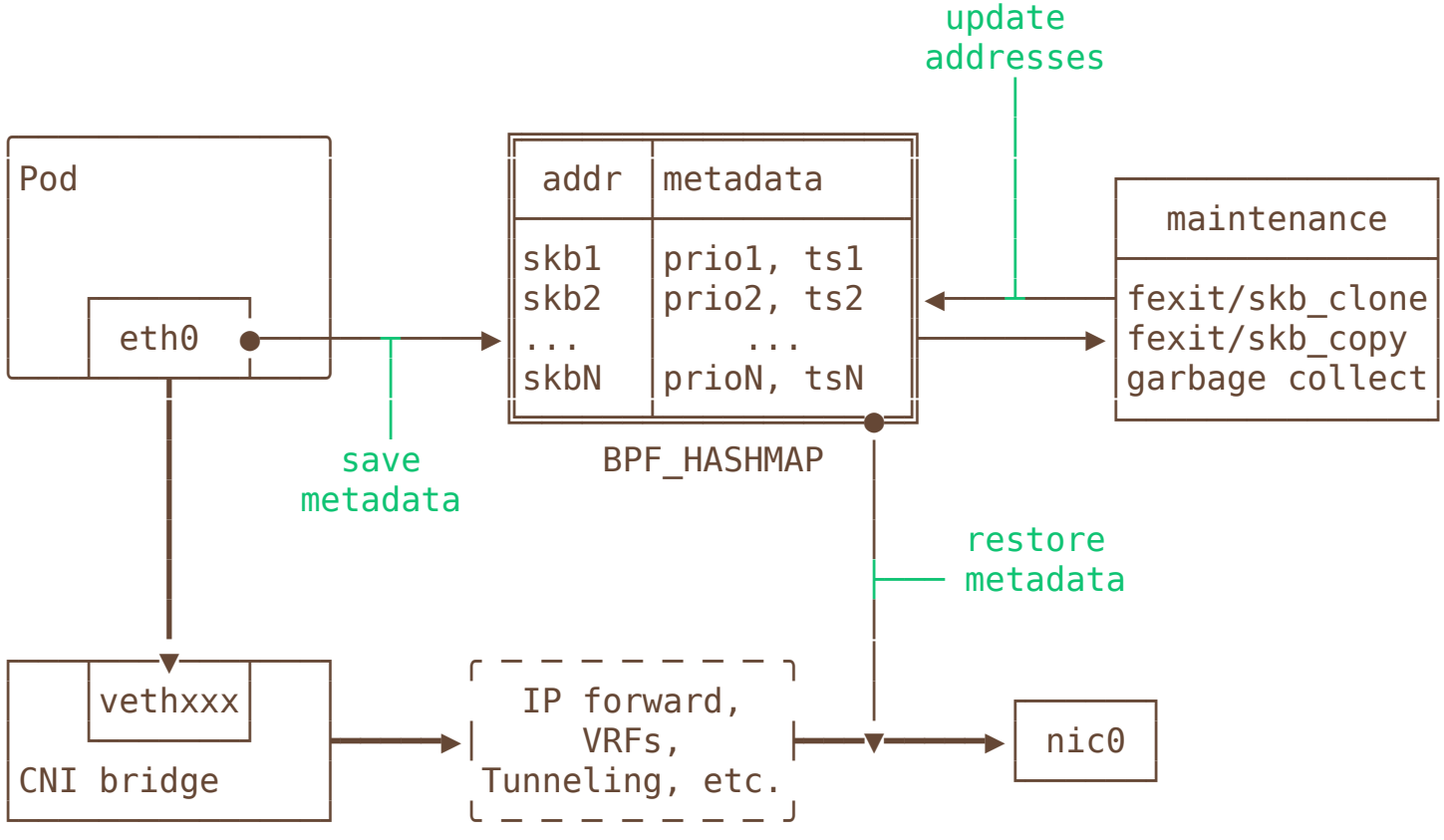

Pod netns
eth0
CNI plugin's net
bridge
router
tunnel
nic0
metadata removal
Node
root netns


Time Sensitive Application Pod
Cluster network
Secondary CNI plugin: TSN proxy
Primary CNI plugin (e.g.: Cilium or Calico or Flannel, etc.)

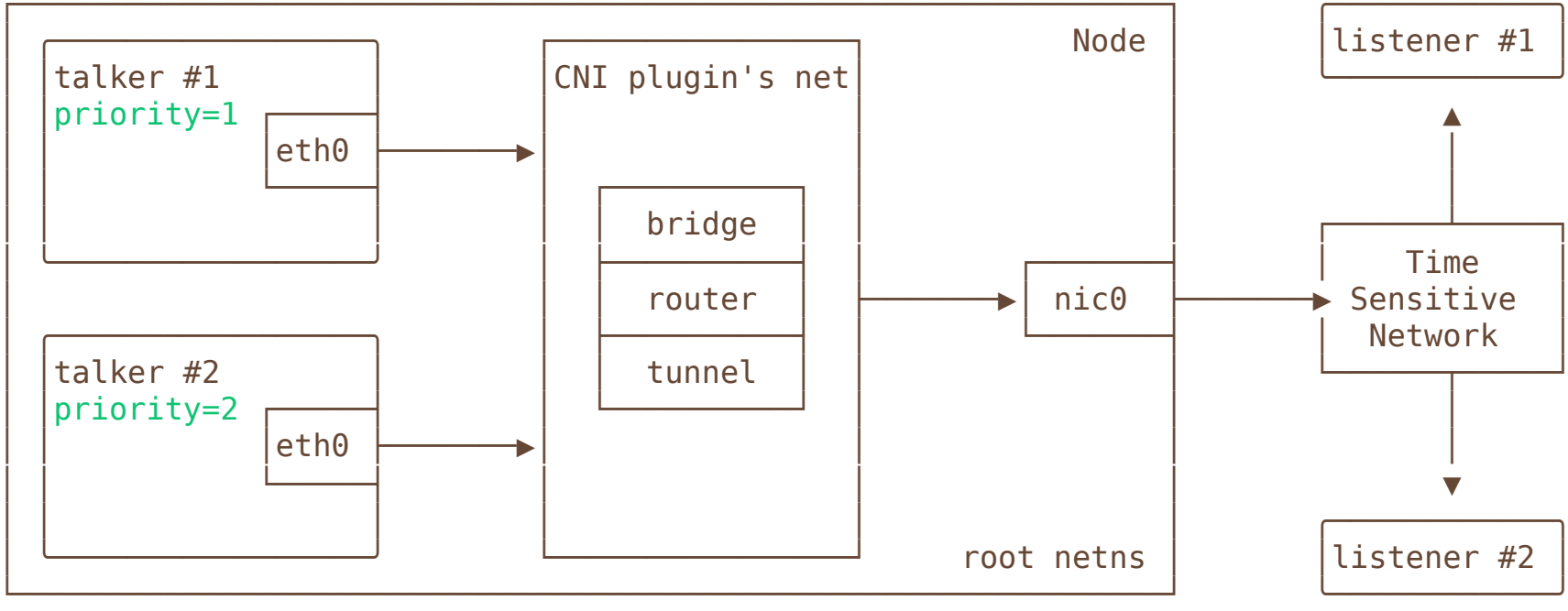
TSN Proxy CNI Plugin

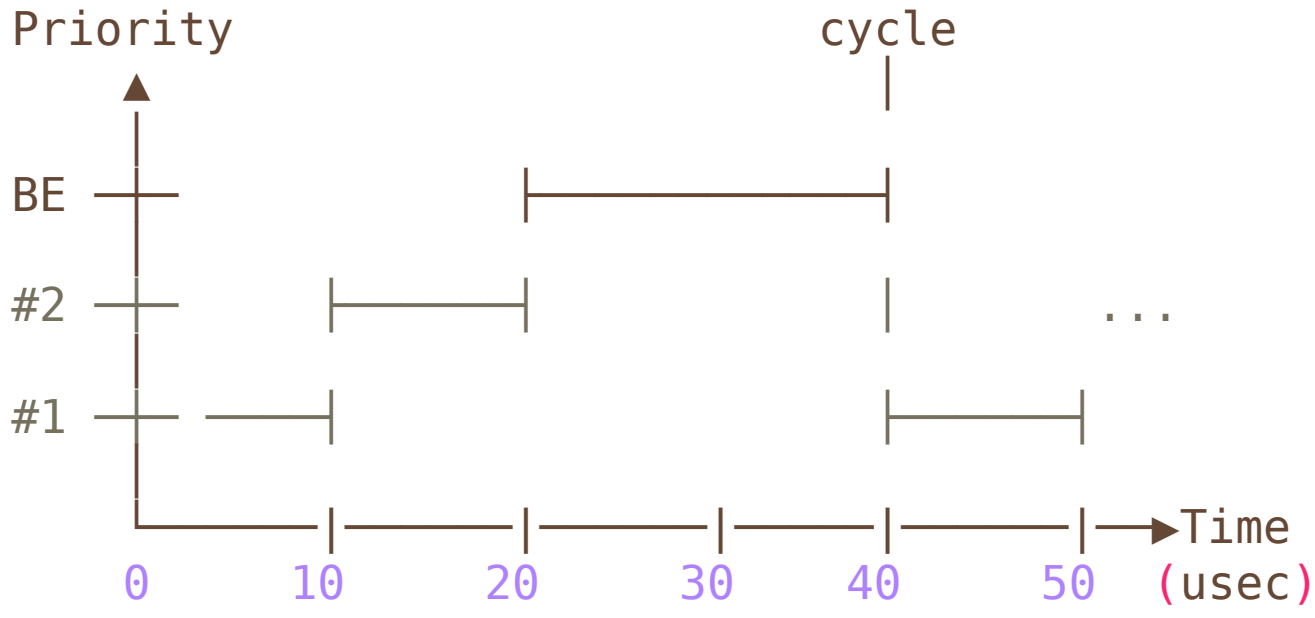
- Equip primary CNI plugins with TSN capability
- Does not require TSA microservice modification, customized container images
- No Linux kernel bypass required
- Does not require custom kernel modules, eBPF provide every tool the TSA need

TSN Proxy Operation

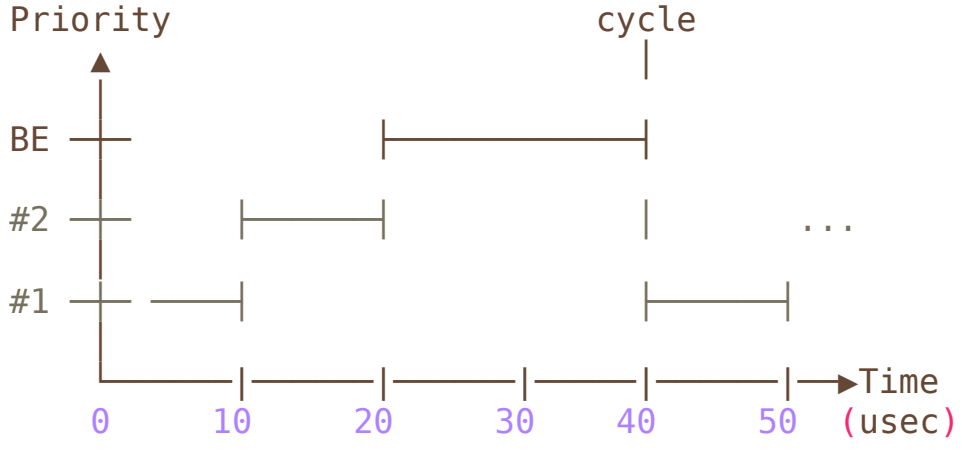


Example Scenario



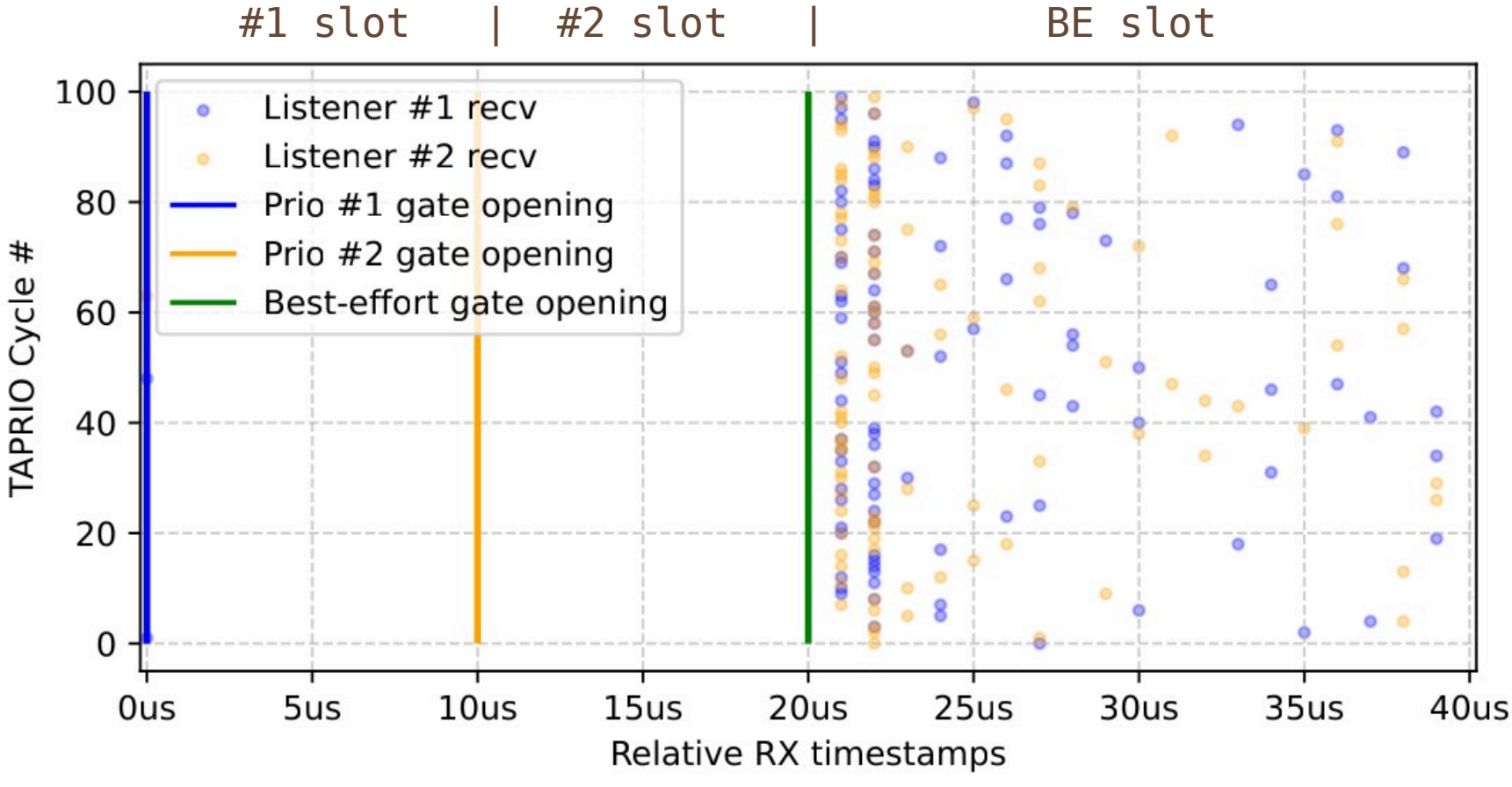


- `nic0` configured with `taprio` Qdisc (802.1Qbv)
  - 1st slot: priority=1 packets, length is 10 usec
  - 2nd slot: priority=2 packets, length is 10 usec
  - 3rd slot: best effort, length is 20 usec




```
tc qdisc add dev tsn0 parent root handle 100 taprio \
  num_tc 4 \
  map 0 1 2 3 \
  queues 1@0 1@1 1@2 1@3 \
  base-time 1693996801300000000 \
  sched-entry S 03 10000 \
  sched-entry S 05 10000 \
  sched-entry S 01 20000 \
  clockid CLOCK_TAI
```

Without TSN Proxy



Packets missing their timeslots: skb->priority == 0

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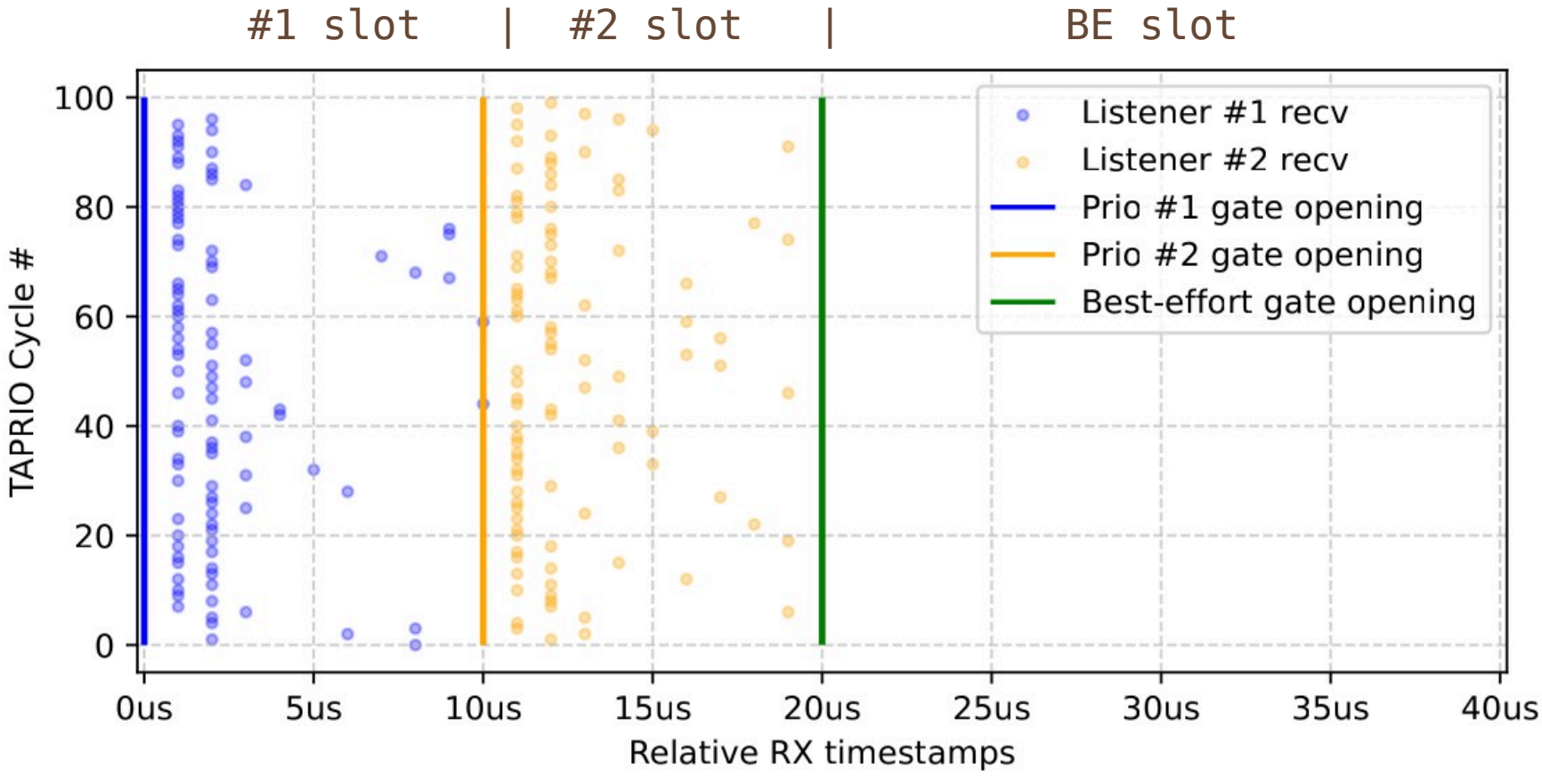
With TSN Proxy



Packets scheduled according to their priority

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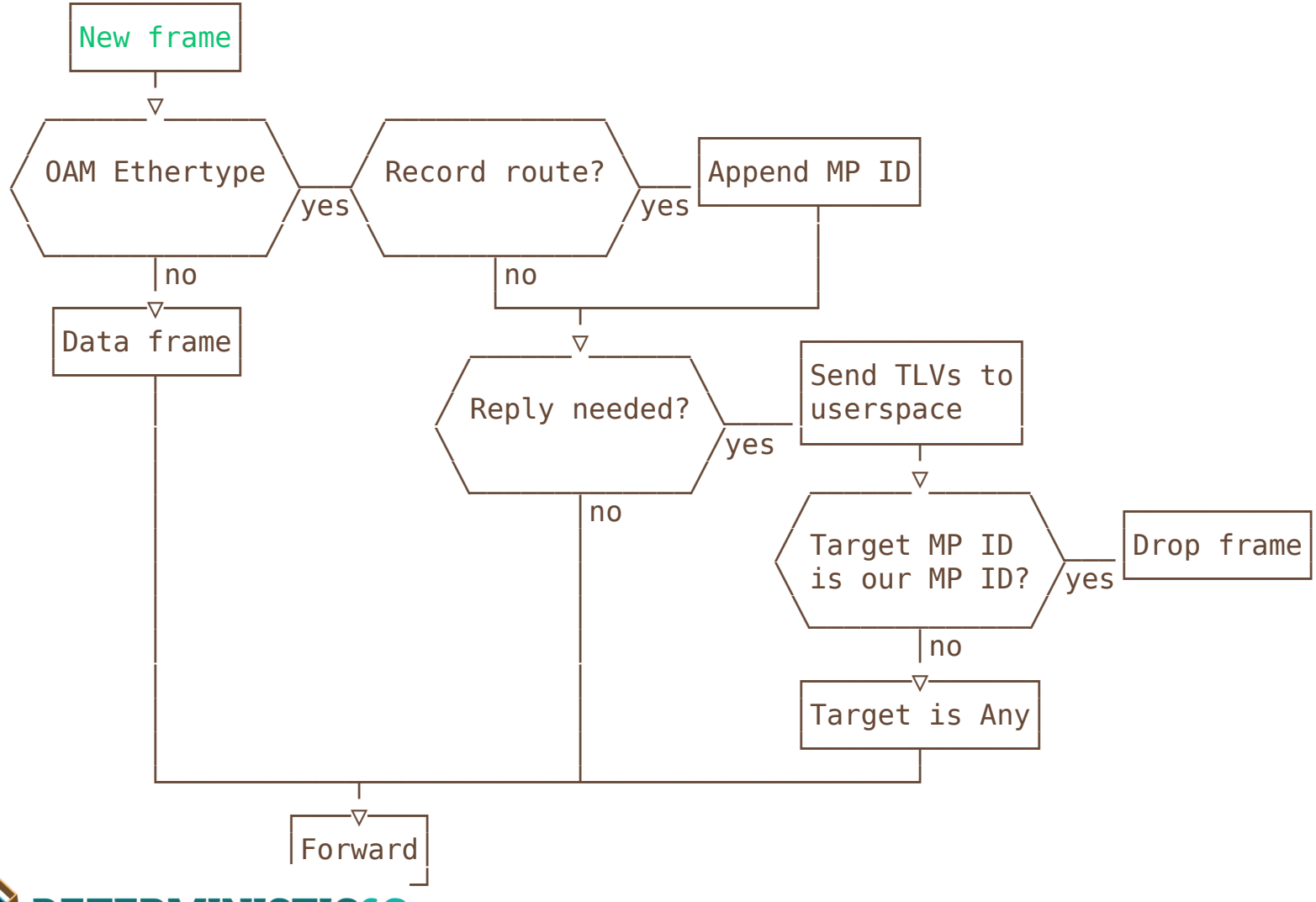
Observability: CFM Extensions for TSN

CFM Extensions for TSN

- Based on IEEE 802.1ag Connectivity Fault Management: Continuity Check (CC), Loopback (LB message and reply), Linktrace (LT)
  - Protocol messages between Maintenance Points (MP)
- Our focus is in FRER
  - CC between MPs
  - Our contribution: Record Route (RR) and FRER recovery graph discovery with it

OAM Frame Processing (Simplified)



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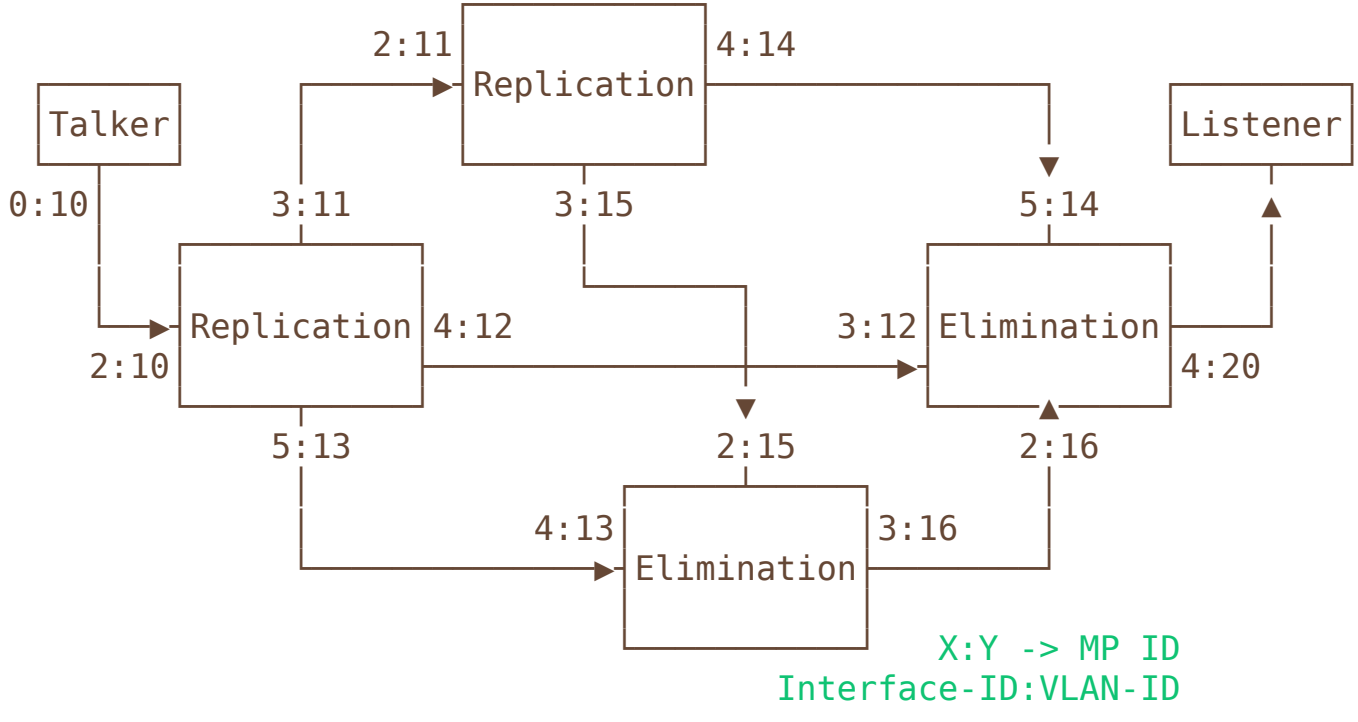
Sample Topology



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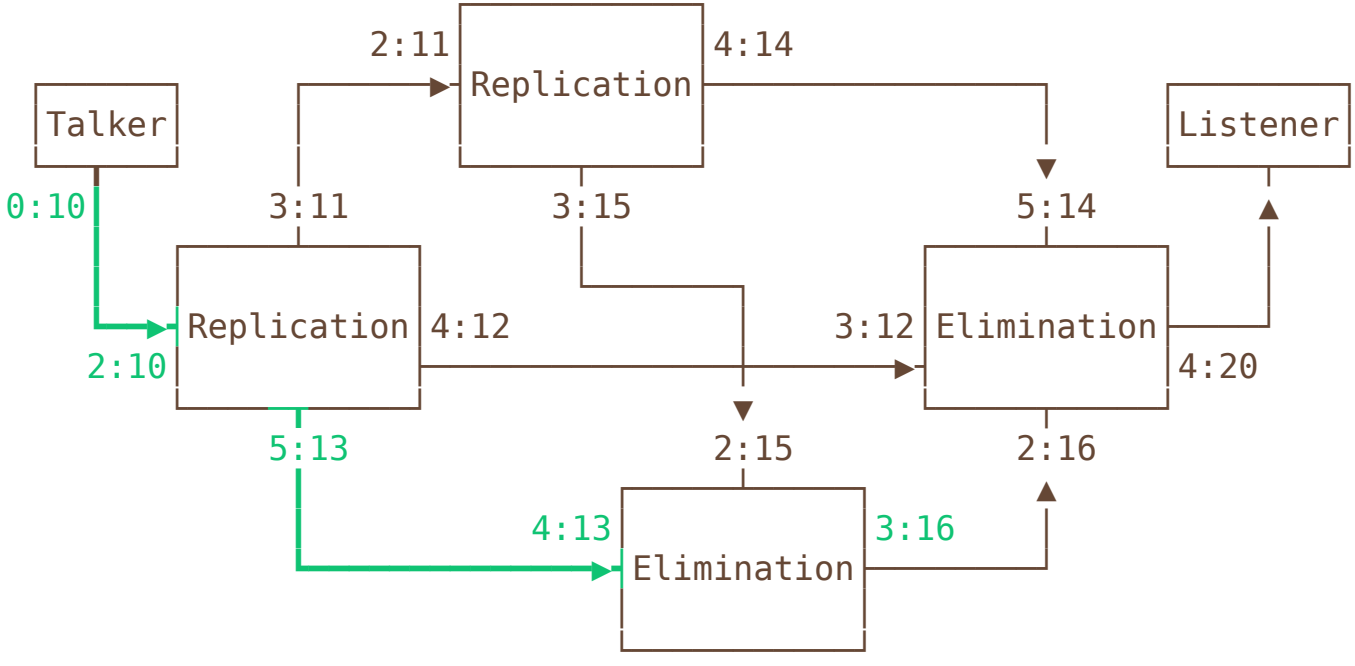
Continuity Check (CC)

```
oamgen -v 10 -c 1 -I tx-eth0 -m CC --mpid 3:16
50 bytes from 8e:23:a1:28:8a:11, rtag_seq=0, oam_type=OAM_CC_REPL

--- MP-ID: 3:16 statistics ---
1 packets transmitted, 1 received, 0% packet loss
```

Record Route (RR)




```
oamgen -v 10 -c 1 -I tx-eth0 -m RR --mpid 3:16
98 bytes from 8e:23:a1:28:8a:11, rtag_seq=0, oam_type=OAM_RR_REPL, RR=[2:10 5:13 4:13 3:16]

--- MP-ID: 3:16 statistics ---
1 packets transmitted, 1 received, 0% packet loss
```

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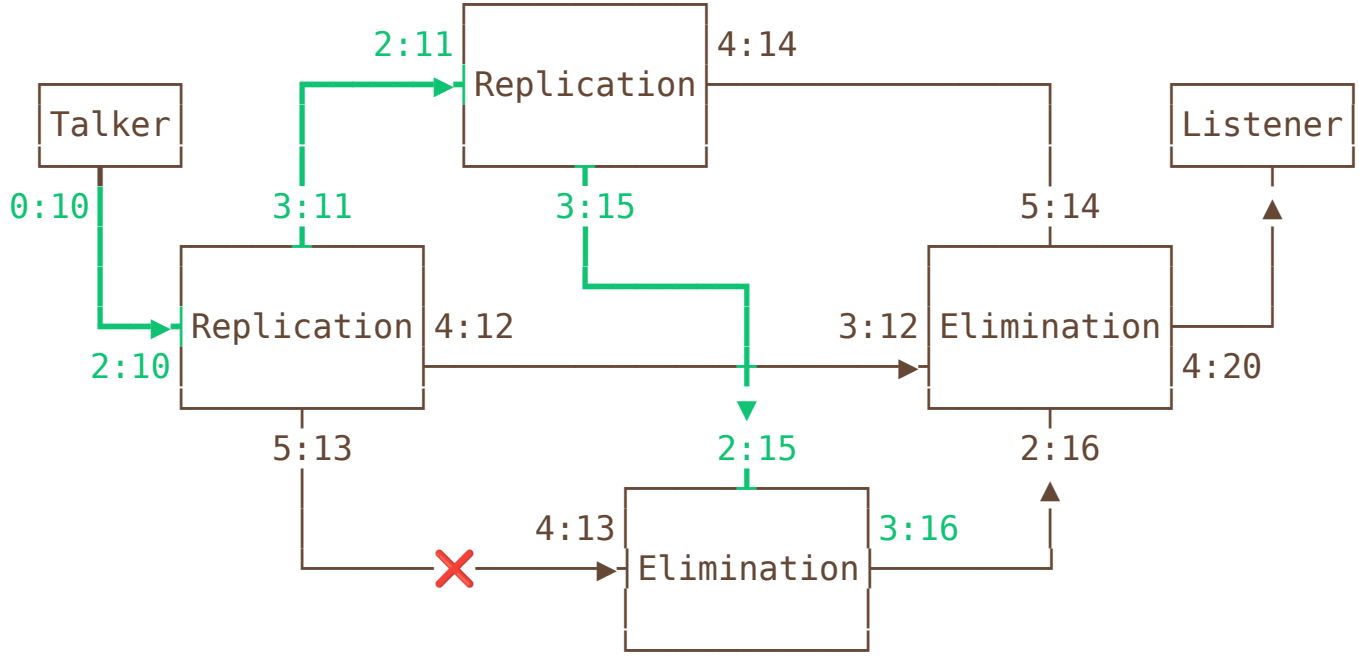
Path Failure




```
oamgen -v 10 -c 1 -I tx-eth0 -m RR --mpid 3:16
122 bytes from 8e:23:a1:28:8a:11, rtag_seq=0,
    oam_type=OAM_RR_REPL, RR=[2:10 3:11 2:11 3:15 2:15 3:16]

--- MP-ID: 3:16 statistics ---
1 packets transmitted, 1 received, 0% packet loss
```

FRER Graph Discovery by Record Route

```
oamgen -v 10 -c 1 -I tx-eth0 -m RR --mpid any -x 14
86 bytes from 8e:23:a1:28:8a:11, rtag_seq=0, oam_type=OAM_RR_REPL, RR=[2:10 5:13 4:13]
62 bytes from 9e:e5:7a:36:45:a1, rtag_seq=0, oam_type=OAM_RR_REPL, RR=[2:10]
98 bytes from 8e:23:a1:28:8a:11, rtag_seq=0, oam_type=OAM_RR_REPL, RR=[2:10 5:13 4:13 3:16]
110 bytes from 8e:23:a1:28:8a:11, rtag_seq=0, oam_type=OAM_RR_REPL, RR=[2:10 3:11 2:11 3:15 2:15]
74 bytes from 9e:e5:7a:36:45:a1, rtag_seq=0, oam_type=OAM_RR_REPL, RR=[2:10 5:13]
86 bytes from 3a:e5:27:34:50:04, rtag_seq=0, oam_type=OAM_RR_REPL, RR=[2:10 4:12 3:12]
74 bytes from 9e:e5:7a:36:45:a1, rtag_seq=0, oam_type=OAM_RR_REPL, RR=[2:10 4:12]
74 bytes from 9e:e5:7a:36:45:a1, rtag_seq=0, oam_type=OAM_RR_REPL, RR=[2:10 3:11]
98 bytes from 3a:e5:27:34:50:04, rtag_seq=0, oam_type=OAM_RR_REPL, RR=[2:10 4:12 3:12 4:20]
110 bytes from 3a:e5:27:34:50:04, rtag_seq=0, oam_type=OAM_RR_REPL, RR=[2:10 5:13 4:13 3:16 2:16]
110 bytes from 3a:e5:27:34:50:04, rtag_seq=0, oam_type=OAM_RR_REPL, RR=[2:10 3:11 2:11 4:14 5:14]
86 bytes from 86:2c:e3:1c:77:91, rtag_seq=0, oam_type=OAM_RR_REPL, RR=[2:10 3:11 2:11]
98 bytes from 86:2c:e3:1c:77:91, rtag_seq=0, oam_type=OAM_RR_REPL, RR=[2:10 3:11 2:11 4:14]
98 bytes from 86:2c:e3:1c:77:91, rtag_seq=0, oam_type=OAM_RR_REPL, RR=[2:10 3:11 2:11 3:15]

--- MP-ID: any statistics ---
1 packets transmitted, 14 received, 0% packet loss
```

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Observability: Table Lookup Tracing

Motivation

- Our focus so far: what happens between the nodes?
- Limitations of this approach
  - Actual forwarding = Linux config + static config
  - TSN/DetNet forwarding (e.g.: TE) configured
  - Does the forwarding config execute what is expected?

Limitations

- Wireshark does not record routing lookups
- Policy based lookups are complicated, not to mention recursive lookups and loops
  - VRFs, prioritized policy tables, SRv6 end behaviors and encaps
- SRv6 DetNet dataplane (*draft-varga-detnet-srv6-data-plane*)
  - DetNet flowID and sequence number encoded in the DetNet-specific SID (PREOF-SID)

Tablesnoop

- Open-source tool for tracing table lookups
  - URL: github.com/EricssonResearch/tablesnoop
- IPv4/IPv6 policy and routing lookup tracing
- Network namespace aware (for Mininet/Docker/Kubernetes)
- Unsuccessful lookups are traced too
- Verify if TSN/DetNet and Linux config matching properly

Tablesnoop with Verbose Output

```
netns: 4026533619 iif: lo oif: - table id: 255 dscp: 0 flowlabel: 8 v6: src: 2001:abba:c:a3::a3  dst: 2001:be1a:c:d2::d2
netns: 4026533619 iif: lo oif: - table id: 254 dscp: 0 flowlabel: 8 v6: src: 2001:abba:c:a3::a3  dst: 2001:be1a:c:d2::d2 --> gw: 2001:abba:c:8a32::2 egress: to-r2-c
netns: 4026533619 rule6: pref: 32766 table: 254
netns: 4026533796 iif: vrf99 oif: - table id: 255 dscp: 0 flowlabel: 8 v6: src: 2001:abba:c:a3::a3  dst: 2001:be1a:c:d2::d2
netns: 4026533796 iif: vrf99 oif: - table id: 99 dscp: 0 flowlabel: 8 v6: src: 2001:abba:c:a3::a3  dst: 2001:be1a:c:d2::d2 --> gw: fe80::1888:8ff:fed4:798d egress: to2-r4
netns: 4026533796 rule6: pref: 1000 table: 0 l3mdev: 1
netns: 4026533796 iif: vrf99 oif: - table id: 255 dscp: 0 flowlabel: 8 v6: src: 2001:fade:0:2::  dst: 5f00:c51d:4:e099::
netns: 4026533796 iif: vrf99 oif: - table id: 99 dscp: 0 flowlabel: 8 v6: src: 2001:fade:0:2::  dst: 5f00:c51d:4:e099::
netns: 4026533796 iif: vrf99 oif: - table id: 254 dscp: 0 flowlabel: 8 v6: src: 2001:fade:0:2::  dst: 5f00:c51d:4:e099:: --> gw: 2001:a1fa:0:8022::22 egress: to-te2
netns: 4026533796 rule6: pref: 32766 table: 254
netns: 4026533855 iif: to-r2 oif: - table id: 255 dscp: 0 flowlabel: 8 v6: src: 2001:fade:0:2::  dst: 5f00:c51d:4:e099::
netns: 4026533855 iif: to-r2 oif: - table id: 88 dscp: 0 flowlabel: 8 v6: src: 2001:fade:0:2::  dst: 5f00:c51d:4:e099:: --> gw: :: egress: to-r2
netns: 4026533855 rule6: pref: 32765 table: 88
netns: 4026533855 iif: to-r2 oif: - table id: 255 dscp: 0 flowlabel: 5a93 v6: src: 2001:fade:0:22::  dst: 5f00:c51d:4:e2f8::
netns: 4026533855 iif: to-r2 oif: - table id: 254 dscp: 0 flowlabel: 5a93 v6: src: 2001:fade:0:22::  dst: 5f00:c51d:4:e2f8:: --> gw: 2001:a1fa:0:8022::2 egress: to-r2
netns: 4026533855 rule6: pref: 32766 table: 254
netns: 4026533796 iif: to-te2 oif: - table id: 255 dscp: 0 flowlabel: 5a93 v6: src: 2001:fade:0:22::  dst: 5f00:c51d:4:e2f8::
netns: 4026533796 iif: to-te2 oif: - table id: 254 dscp: 0 flowlabel: 5a93 v6: src: 2001:fade:0:22::  dst: 5f00:c51d:4:e2f8:: --> gw: fe80::1888:8ff:fed4:798d egress: to2-r4
netns: 4026533796 rule6: pref: 32766 table: 254
netns: 4026534032 iif: to-r2 oif: - table id: 255 dscp: 0 flowlabel: 5a93 v6: src: 2001:fade:0:22::  dst: 5f00:c51d:4:e2f8::
netns: 4026534032 iif: to-r2 oif: - table id: 254 dscp: 0 flowlabel: 5a93 v6: src: 2001:fade:0:22::  dst: 5f00:c51d:4:e2f8:: --> gw: :: egress: sr0-csid
netns: 4026534032 rule6: pref: 32766 table: 254
netns: 4026534032 iif: to-r2 oif: - table id: 255 dscp: 0 flowlabel: 5a93 v6: src: 2001:fade:0:22::  dst: 5f00:c51d:e2f8::
netns: 4026534032 iif: to-r2 oif: - table id: 254 dscp: 0 flowlabel: 5a93 v6: src: 2001:fade:0:22::  dst: 5f00:c51d:e2f8:: --> gw: :: egress: sr0-csid
netns: 4026534032 rule6: pref: 32766 table: 254
netns: 4026534032 iif: to-r2 oif: - table id: 254 dscp: 0 flowlabel: 8 v6: src: 2001:fade:0:2::  dst: 5f00:c51d:4:e099:: --> gw: :: egress: vrf99
netns: 4026534032 iif: to-r2 oif: - table id: 99 dscp: 0 flowlabel: 8 v6: src: 2001:abba:c:a3::a3  dst: 2001:be1a:c:d2::d2 --> gw: 2001:be1a:c:8d24::d2 egress: to-du2-c
netns: 4026534327 iif: to-r4-c oif: - table id: 255 dscp: 0 flowlabel: 8 v6: src: 2001:abba:c:a3::a3  dst: 2001:be1a:c:d2::d2 --> gw: :: egress: lo
netns: 4026534327 rule6: pref: 0 table: 255
```

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Thank you!

XDPFRER: github.com/EricssonResearch/xdpfrer

TSN proxy: github.com/EricssonResearch/tsn-proxy

Tablesnoop:
github.com/EricssonResearch/tablesnoop

E-mail: ferenc.fejes@ericsson.com

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