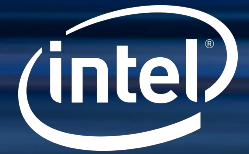


The Road Towards a Linux TSN Infrastructure



Jesus Sanchez-Palencia

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About me

- **Software Engineer at Intel (~5 years)**
 - Open Source Technology Center (OTC)
- **Currently: drivers and kernel interfaces for TSN**
 - Linux Network Stack
- **Background**
 - Intel Quark Microcontrollers SW stack (QMSI)
 - Embedded OSes: Zephyr and Contiki, Android, Maemo
 - Web Rendering Engines (WebKit, Crosswalk)
 - Qt Framework

Objectives

- Provide a (very) brief introduction to Time-Sensitive Networking
- Present the current upstream TSN SW architecture
- Discuss the challenges ahead

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LANs and the Internet

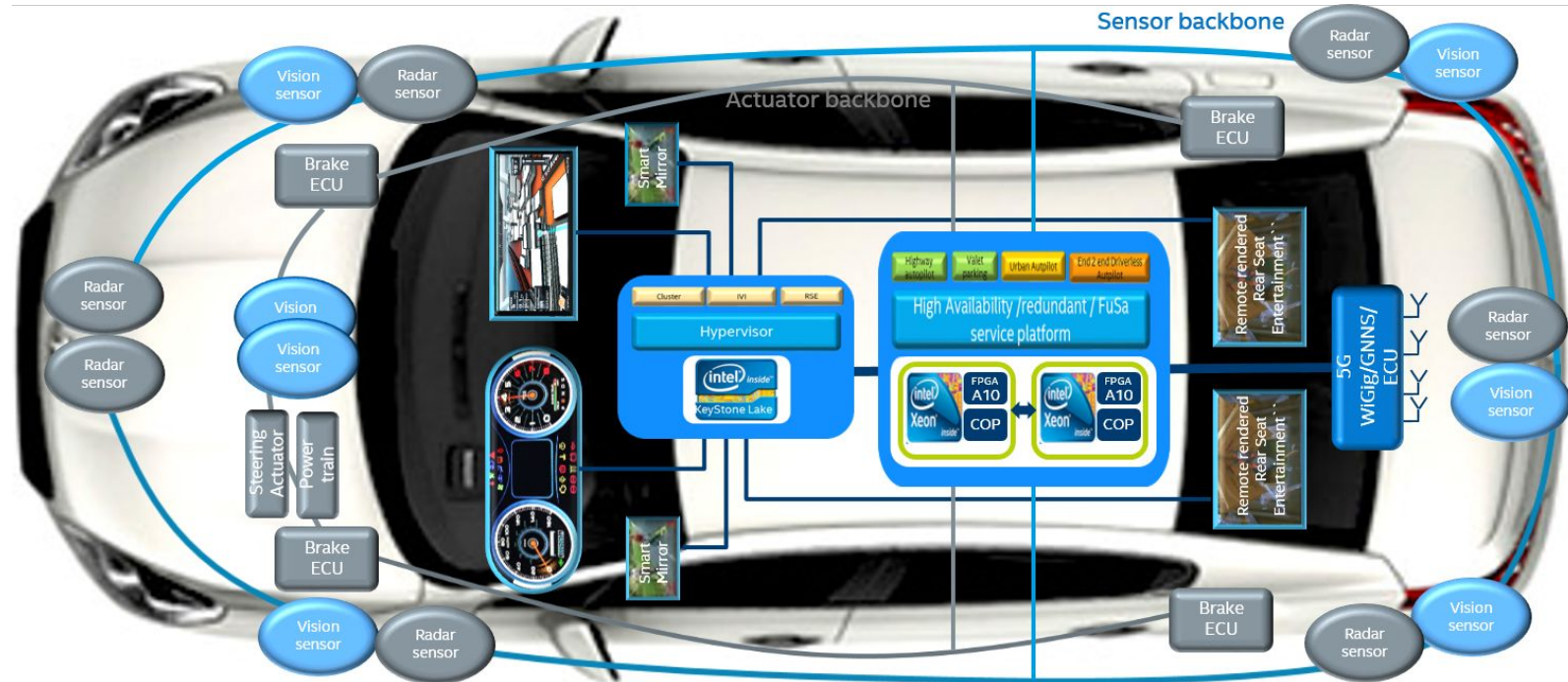
- Common model based on Internet Protocols and the IEEE 802 architecture.
- Mode of operation is **best-effort**
 - as in *quickest*
 - Metrics are all based on *average* (i.e. delay, speed)
- **Not suitable for use cases that require high / known *availability***
 - like circuit switching networks
 - or Fieldbuses for control networks
 - operational network (OT) != information network (IT)
 - e.g.: CAN*, EtherCAT*, Profibus*, Profinet*, ...
 - lack of interoperability

What is Time-Sensitive Networking?

- Set of evolving standards developed by IEEE to allow for time-sensitive traffic on **Ethernet based LANs**.
 - started from Audio/Video Bridging (AVB)
 - allows for OT and IT traffic to co-exist
- Provides **bounded worst-case latency**
 - as in *deterministic*
 - determinism is prioritized over throughput
- Standards are mostly developed as extensions to 802.1Q
 - Virtual LANs (vlans) and QoS
- AVNU Alliance*
 - Interoperability
- Targets different segments
 - e.g.: Pro A/V, Industrial Control, Automotive systems

TSN: Example

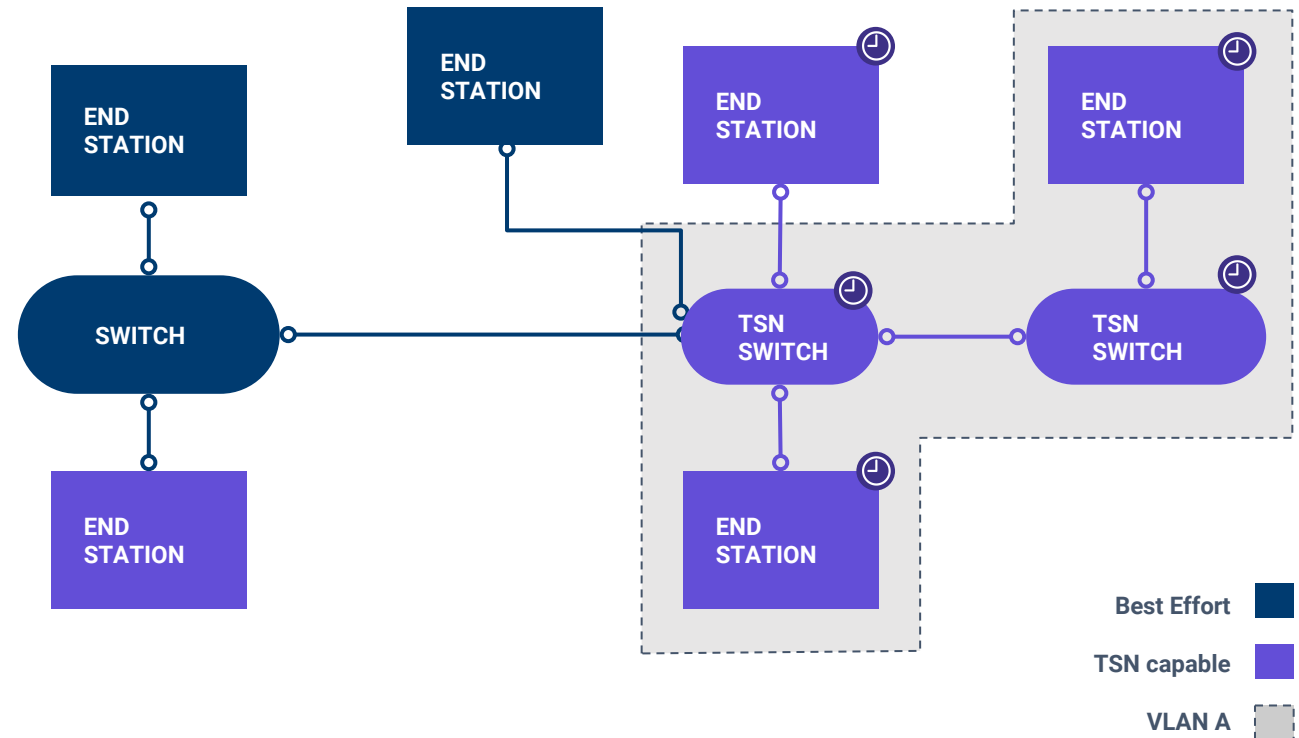
- **Infotainment**
 - multiple screens
 - multiple speakers
 - video + audio synchronized
 - noise reduction?
 - multiple mics
- **Control**
 - multiple sensors and actuators
- **Why TSN?**
 - Ethernet is cheap.
 - Cabling is one of the most expensive components in a car.
- **Same network?**
 - Theoretically, yes.



TSN: Theory of Operation

Physicist

- Mechanisms:
 - Time Sync
 - 802.1AS
 - Traffic identification
 - VLAN tags
 - Resource allocation
 - Traffic shaping / scheduling
- Network Config:
 - 802.1Qcc
 - Dynamic or static
 - e.g.: SRP
 - Distributed or centralized



TSN: Traffic Shapers

- TSN applications have different requirements
 - Reserved Bandwidth
 - Strict cycles: scheduled Tx
- 802.1Qav: Credit-based shaper (CBS)
 - **per-queue bounded bandwidth**
 - *“transmit all packets from this traffic class at X kbps”*
- Time-based Scheduling (TBS)
 - **per-packet Tx time**
 - *“transmit this packet at timestamp 152034537600000000 ns”*
 - not earlier than or not later than?
- 802.1Qbv: Enhancements to Scheduled Traffic
 - **per-port queues schedule**
 - *“execute the Tx algorithm on queue 0 every 100us for 20us, on 1 every 240us for 30us”*
- 802.1Qbu, 802.1Qci, ...

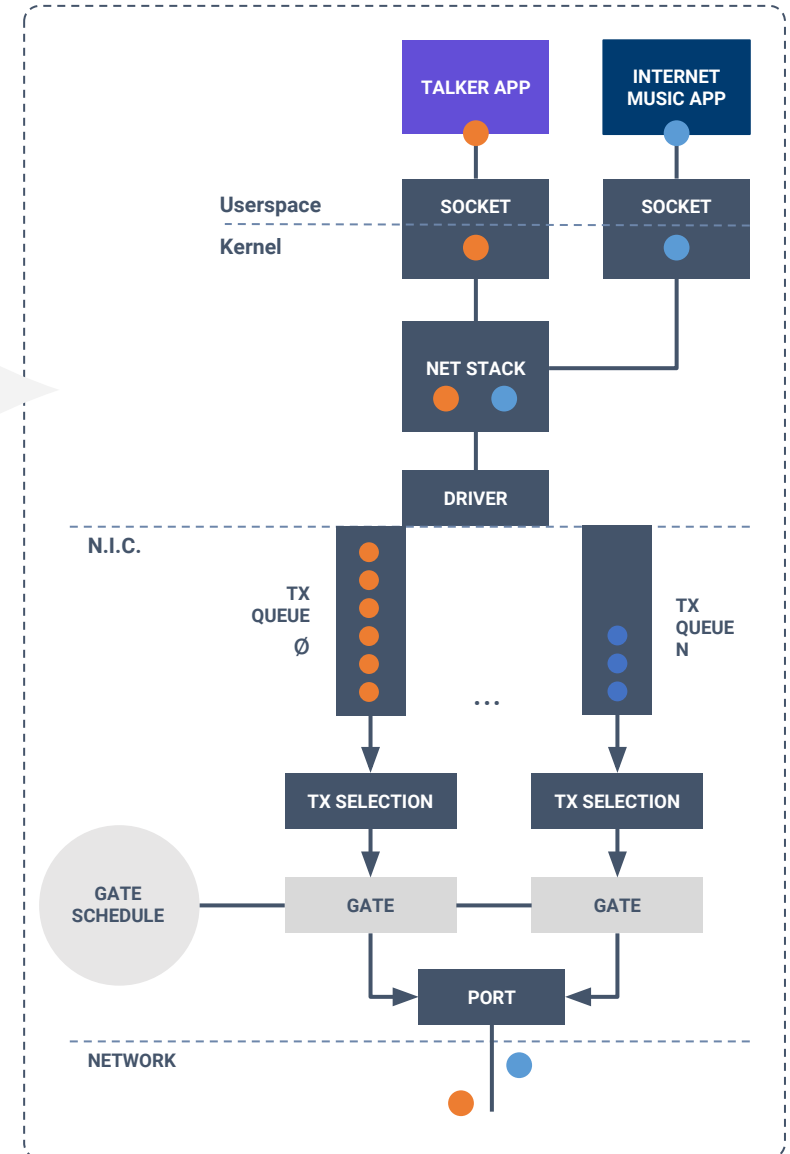
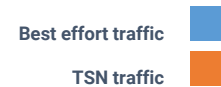
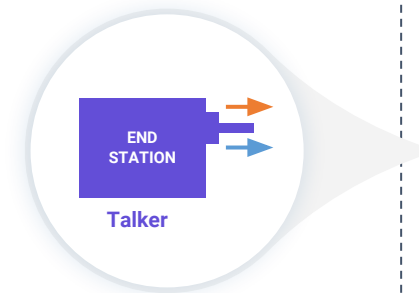
TSN on End Stations Primer

“Talker” application

- a. Enable Multiqueue
- b. Configure Queues (shapers)
- c. Classify traffic
 - steer to Tx queue
 - allow network to identify it
- d. Transmit

“Listener” application

- a. Optionally: setup Rx filters
 - i.e. VLAN priority, src and dst MAC
- b. Receive



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TSN SW - Previous Attempts

- **OpenAVB - Eric Mann's (Intel)**
 - bypasses kernel network stack
 - forked driver: igb_avb
 - config and data paths: libigb
 - Tx Queues exposed directly to the userspace
- **RFCs on netdev from Henrik Austad (CISCO*)**
 - media centric (AVB)
 - bundled up as a TSN driver
 - ConfigFS based interface
 - ALSA shim for audio streaming
- **Driver-specific interfaces on upstream**
 - stmmac* and (maybe) others: devicetree as a config interface for shapers
- **Downsides: kernel bypassing, hw-dependent, monolithic solutions**

Traffic Control on Linux

- Provides
 - Shaping / Scheduling (Tx)
 - Policing (Rx)
 - Dropping
- Queueing Disciplines, Classes and Filters
- Qdiscs
 - Kernel Packet buffer
 - Sits 'between' protocol families and netdevice driver
 - Control when / how packets are transmitted
 - Every interface has a default root qdisc attached
 - Qdiscs can expose classes
 - Qdiscs can "offload" work to hardware

```
$ tc -g qdisc show dev wlp58s0
qdisc mq 0: root
qdisc fq_codel 0: parent :4 (...)
qdisc fq_codel 0: parent :3 (...)
qdisc fq_codel 0: parent :2 (...)
qdisc fq_codel 0: parent :1 (...)
```

```
$ tc -g class show dev wlp58s0
+---(:4) mq
+---(:3) mq
+---(:2) mq
+---(:1) mq
```

Config interface: Multiqueue

- **mqprio qdisc: Multiqueue priority**
 - It “exposes” HW queues as classes, allowing for other inner qdiscs to be attached.
 - Maps priorities to traffic classes to HW queues.
- **Example: 3 traffic classes**
 - prio 3 -> tc 0 -> queue 0 (8001:1)
 - prio 2 -> tc 1 -> queue 1 (8001:2)
 - other -> tc 2 -> queues 2 (8001:3) and 3 (8001:4)

```
$ tc qdisc replace dev enp2s0 \
  parent root mqprio num_tc 3 \
  map 2 2 1 0 2 2 2 2 (...) \
  queues 1@0 1@1 2@2 hw 0
```

```
$ tc -g class show dev enp2s0
+---(8001:ffe2) mqprio
|   +---(8001:3) mqprio
|   +---(8001:4) mqprio
|
+---(8001:ffe1) mqprio
|   +---(8001:2) mqprio
|
+---(8001:ffe0) mqprio
|   +---(8001:1) mqprio
```

Config interface: Credit-based shaper

- For credit-based shaping (802.1Qav) we developed the **cbs qdisc**.
 - Available from kernel 4.15.
 - debuted with Intel i210 support only, but more to follow.
 - Provides both HW offloading and SW fallback.
 - Config parameters derived directly from Annex L of IEEE 802.1Q.
 - Remember: CBS is bandwidth-centric.
- Example: configure CBS for traffic class 1 (priority 2)

```
$ tc qdisc replace dev enp2s0 \
  parent 8001:2 cbs \
  locredit -1470 hicredit 30 \
  sendslope -980000 \
  idleslope 20000 offload 1

$ tc -g qdisc show dev enp2s0

qdisc mqprio 8001: root tc 3 (...) \
  queues:(0:0) (1:1) (2:3) \
  (...)

qdisc fq_codel 0: parent 8001:1 \
  limit 10240p \
  (...)

qdisc cbs 8002: parent 8001:2 \
  hicredit 30 locredit -1470 \
  sendslope -980000 idleslope \
  20000 offload 1
```

Config interface: Time-based Sched.

- For time-based scheduling, we are developing the **tbs qdisc** and the **SO_TXTIME** socket option.
 - Co-developing with Richard Cochran (linuxptp maintainer).
 - Provides both HW offloading and SW fallback.
 - Trending well, currently on its RFC v3
 - <https://patchwork.ozlabs.org/cover/882342/>
 - debuted with Intel i210 support only, but more to follow.
- **tbs qdisc** can:
 - hold packets until their *TxTime* minus a configurable *delta* factor
 - sort packets based on their *TxTime*
 - optional, and only before they are sent to the device queue
- **tbs** is time-centric
 - Requires a per-packet timestamp.
- Example: configure TBS for traffic class 0 (priority 3)

```

$ tc qdisc replace dev enp2s0 \
  parent 8001:1 tbs \
  clockid CLOCK_REALTIME \
  delta 150000 sorting \
  offload

$ tc -g qdisc show dev enp2s0

(...)

qdisc tbs 8003: parent 8001:1 \
  clockid CLOCK_REALTIME delta \
  150000 offload on \
  sorting on

qdisc cbs 8002: parent 8001:2 \
  hircedit 30 \
  (...)

```


Data path: Socket interface

- We use regular sockets for transmitting data.
- TBS
 - a new socket option (SO_TXTIME) is used for enabling the feature for a given socket.
 - A cmsg header is used for setting a per-packet txtime, and a *drop_if_late* flag.
 - reference clockid_t will become a socket option argument

```
(...)
clock_gettime(CLOCK_REALTIME, &ts);
__u64 txtime = ts.tv_sec * 1000000000ULL
               + ts.tv_nsec;

cmsg = CMSG_FIRSTHDR(&msg);
cmsg->cmsg_level = SOL_SOCKET;
cmsg->cmsg_type = SCM_TXTIME;
cmsg->cmsg_len = CMSG_LEN(sizeof(__u64));
*((__u64 *) CMSG_DATA(cmsg)) = txtime;

cmsg = CMSG_NXTHDR(&msg, cmsg);
cmsg->cmsg_level = SOL_SOCKET;
cmsg->cmsg_type = SCM_DROP_IF_LATE;
cmsg->cmsg_len =
CMSG_LEN(sizeof(uint8_t));
*((uint8_t *) CMSG_DATA(cmsg)) = 1;

(...)

const int on = 1;
setsockopt(fd, SOL_SOCKET,
          SO_TXTIME, &on, sizeof(on))
```

Data path: Socket interface

- **Classifying traffic:**
 - The socket option **SO_PRIORITY** is used to flag all packets with an specific priority.
 - Preferred method, but iptables or net_prio cgroup can be used.
 - The priority is later used as the PCP field of the VLAN tag of the ethernet header.
 - Steers all traffic from the socket into the correct HW Tx queue.
 - Remember: we have setup a mapping for that with the mqprio qdisc.

Results - TxTime Based Scheduling

SW

TBS

| plain kernel @ 1ms | | | tbs SW @ 1ms | | | | tbs HW @ 1ms | | tbs HW @ 250 us | |
|--------------------|---------------|------------|-----------------|---------------|---------------|---------------|---------------|-----------|-----------------|--|
| min (ns): | +4.820000e+02 | | min (ns): | +1.510000e+02 | +4.420000e+02 | +4.260000e+02 | | | | |
| max (ns): | +9.999300e+05 | <- ~999 us | max (ns): | +9.977030e+05 | +5.060000e+02 | +5.060000e+02 | +5.060000e+02 | <- 506 ns | | |
| pk-pk: | +9.994480e+05 | <- ~999 us | pk-pk: | +9.975520e+05 | +6.400000e+01 | +8.000000e+01 | +8.000000e+01 | <- 80 ns | | |
| mean (ns): | +3.464421e+04 | | mean (ns): | +1.416511e+04 | +4.687228e+02 | +4.600596e+02 | | | | |
| stddev: | +1.305947e+05 | | stddev: | +5.750639e+04 | +9.868569e+00 | +1.287626e+01 | | | | |
| count: | 600000 | | count: | 600000 | 600000 | 2400000 | | | | |
| | | | tbs delta (ns): | 130000 | 130000 | 130000 | | | | |

- DUT: i5-7600 CPU @ 3.50GHz, kernel 4.16.0-rc2+ with about 50 usec maximum latency under cyclictst.
- ptp4l + phc2sys
- packet size: 322 bytes all headers included

What about the userspace?

- OpenAVNU
 - Evolution of OpenAVB, maintained by the AVNU Alliance members
 - Provides daemons, libs, examples, frameworks
 - gPTPd: 802.1AS
 - MRPd: SRP daemon
 - Mostly focused on the Pro A/V domain
 - Recent contribution from Intel: **libavtp**
 - Provides packetization for applications that use AVTP as a transport
 - <https://github.com/AVnu/OpenAvnu/tree/open-avb-next/lib/libavtp>
- linuxptp
 - ptp4l: Precision Time Protocol implementation for Linux
 - phc2sys: Synchronizes the PTP Hardware Clock to the System Clock

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Config interfaces: 802.1Qbv and 802.1Qbu

- Qbv: Enhancements to Scheduled Traffic
- Qbu: Frame Preemption
- We've shared ideas for a new qdisc-based interface before: **'taprio'**.
 - A time-aware version of mqprio.
 - Part of the CBS RFC v1: <https://patchwork.ozlabs.org/cover/808504/>
 - Push-back: there were no NICs for end stations with support for these standards.
 - Providing a SW fallback is required, so we may re-consider an ethtool based interface instead.
- TBS could be used, but that requires a scheduler for converting the per-port schedule from Qbv into a per-packet txtime.

Data path: Looking ahead

- Linux network stack is **very good** for throughput.
 - TSN will require more: **bounded low latency**
- XDP
 - eXpress Data Path
 - High performance data path for Rx.
 - Does not bypass the kernel, but avoids allocation of skbuffs.
 - <https://prototype-kernel.readthedocs.io/en/latest/networking/XDP/index.html>
 - <https://www.iovisor.org/technology/xdp>
- AF_PACKET_V4 -> **AF_XDP**
 - New socket family aiming to improve throughput / latency by reusing XDP hooks.
 - Zerocopy will be finally allowed, but only with driver support.
 - <https://lwn.net/Articles/737947/>
 - <https://patchwork.ozlabs.org/cover/867937/>

Wrap up

- TSN aims to provide bounded latency on Ethernet based LANs.
- SW interfaces for Linux are starting to become available upstream starting with the cbs and tbs qdiscs.
- Future work aims to address other traffic shapers (802.1Qbv / Qbu).
- Low latency is (probably) an issue. There are efforts trying to reduce the bounded worst-case latency of the Linux network stack: AF_XDP.
- Userspace building blocks are also gaining traction.
 - OpenAVNU is becoming the consolidator of TSN SW components for userspace.
- Zephyr will have TSN support soon!

Call to Action

- Enable support on your upstream drivers.
- Have use cases? Engage on the netdev discussions!
- Have TSN products? Help us testing by using the upstream interfaces.
- Contribute code and bug-fixes!

More References

- Mann's Plumbers 2012 talk: <https://linuxplumbers.ubicast.tv/videos/linux-network-enabling-requirements-for-audiovideo-bridging-avb/>
- Austad's TSN driver RFC v2: <https://lkml.org/lkml/2016/12/16/453>
- Austad's ELC 2017.2 Presentation: <https://www.youtube.com/watch?v=oxURD2rr4Y4>
- CBS v9: <https://patchwork.ozlabs.org/cover/826678/>
- TBS RFC v2: <https://patchwork.ozlabs.org/cover/862639/>
- mqprio man page: <http://man7.org/linux/man-pages/man8/tc-mqprio.8.html>
- cbs man page: <http://man7.org/linux/man-pages/man8/tc-cbs.8.html>
- OpenAVNU: <https://github.com/AVnu/OpenAvnu>



Q/A

Obrigado!

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