The Road Towards a Linux TSN Infrastructure

Jesus Sanchez-Palencia

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

Objectives

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

LANs and the Internet

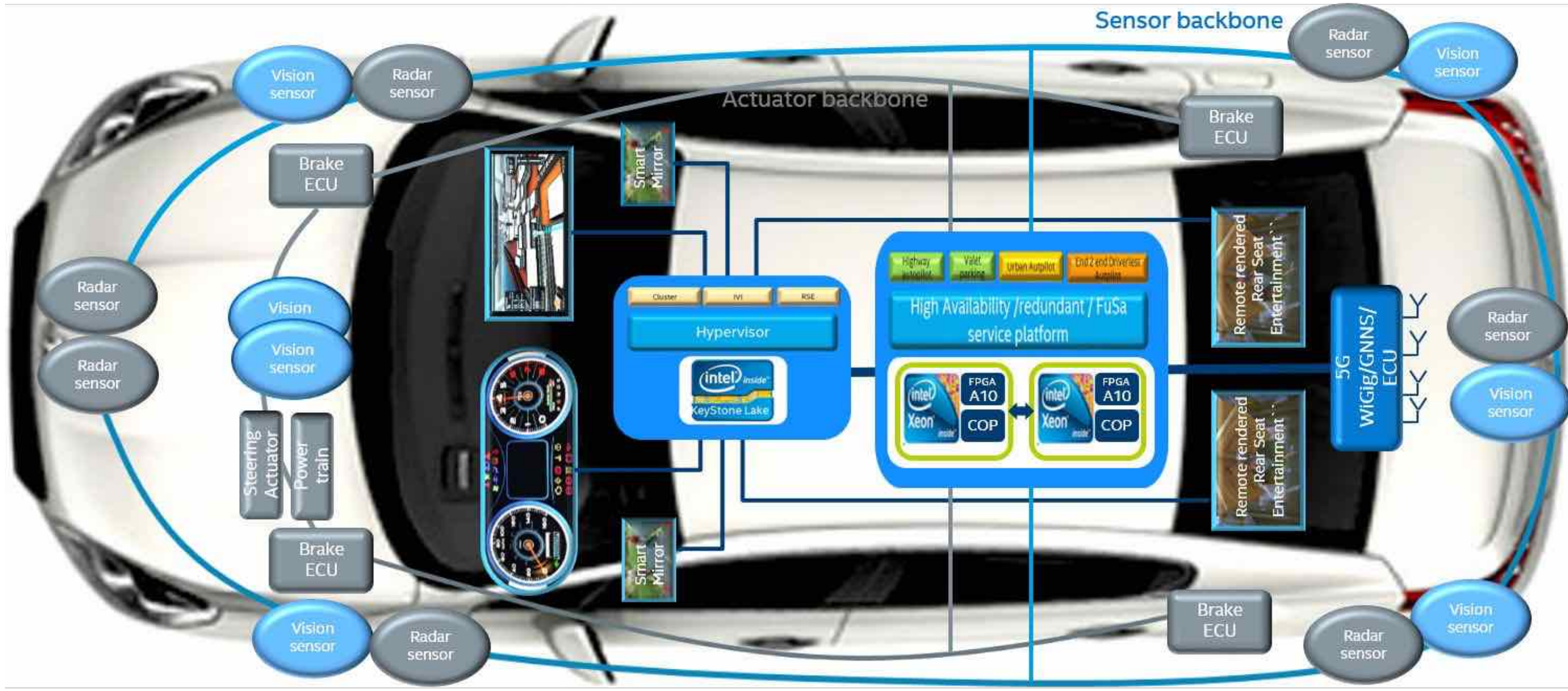
- Common model based on Internet Protocols and the IEEE 802 architecture.
- Mode of operation is **best-effort**
  - as in *quickest*
  - Metrics are all based on *average* (i.e. delay, speed)
- Not suitable for use cases that require high / known *availability*
  - like circuit switching networks
  - 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

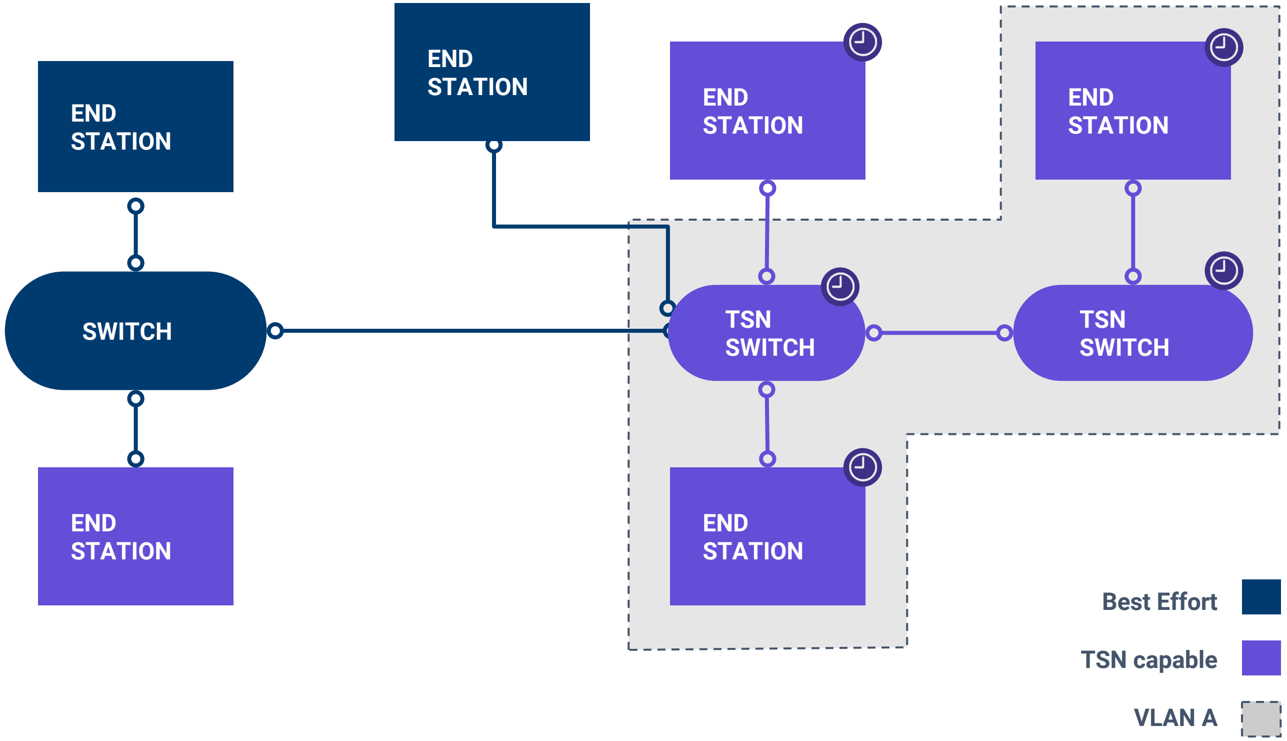
- Infotainment
  - multiple screens
  - multiple speakers
    - video + audio synchronized
  - noise reduction?
    - multiple mics
- Control
  - multiple sensors and actuators
- Why TSN?
  - Ethernet is cheap.
  - Cabling is one of the most expensive components in a car.
- Same network?
  - Theoretically, 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 1520345376000000000 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, ...

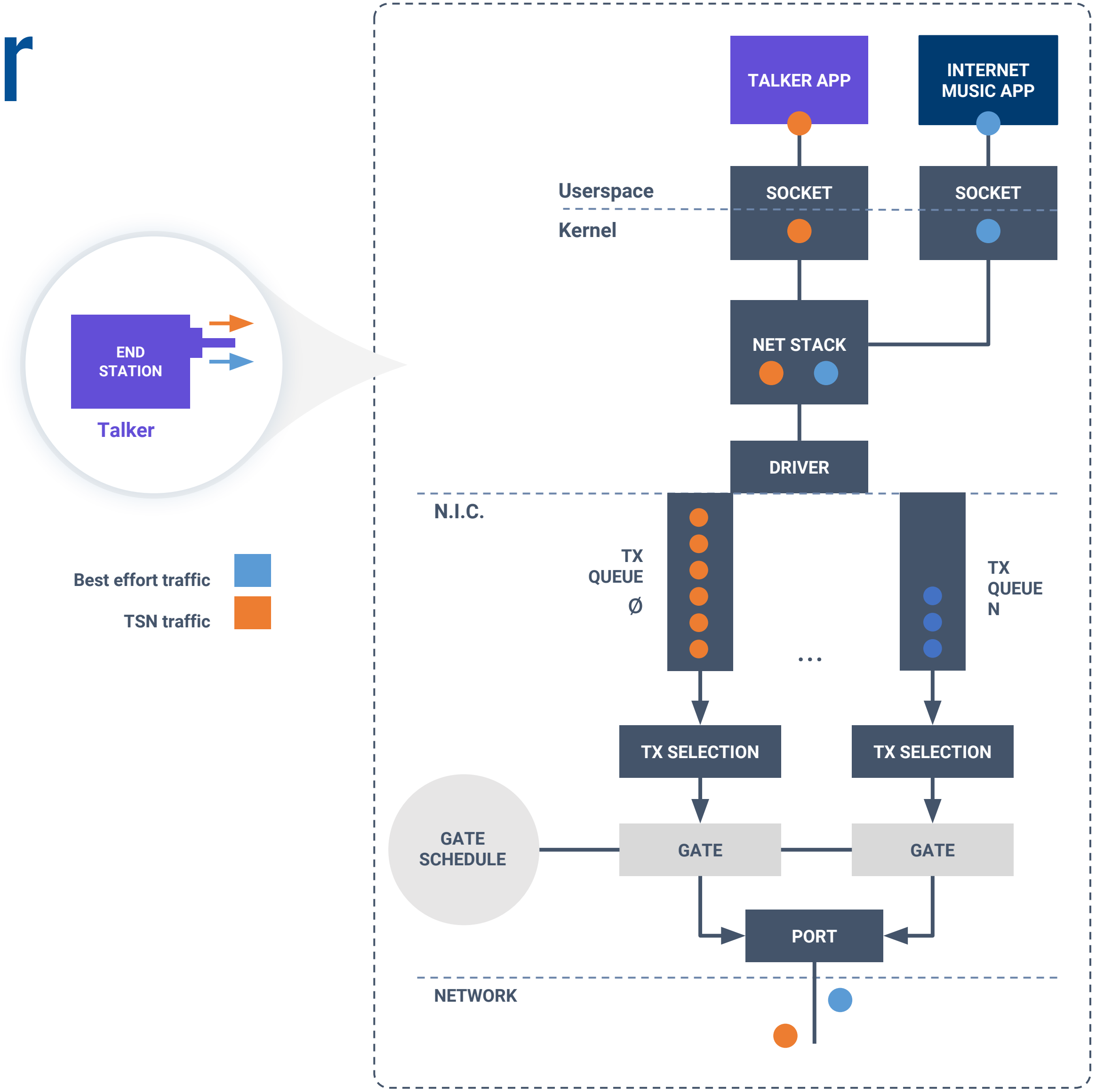
TSN on End Stations Primer

“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



Objectives

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

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       \
     hicredit 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

```
|                 | plain kernel @ 1ms |
|-----------------+--------------------+
| min (ns):       |    +4.820000e+02   |
| max (ns):       |    +9.999300e+05   | <- ~999 us
| pk-pk:          |    +9.994480e+05   | <- ~999 us
| mean (ns):      |    +3.464421e+04   |
| stddev:         |    +1.305947e+05   |
| count:          |           600000   |
```

TBS

```
|                 |   tbs SW @ 1ms   |  tbs HW @ 1ms  | tbs HW @ 250 us |
|-----------------+------------------+----------------+-----------------|
| min (ns):       |    +1.510000e+02 |  +4.420000e+02 |   +4.260000e+02 |
| max (ns):       |    +9.977030e+05 |  +5.060000e+02 |   +5.060000e+02 | <- 506 ns
| pk-pk:          |    +9.975520e+05 |  +6.400000e+01 |   +8.000000e+01 | <- 80 ns
| mean (ns):      |    +1.416511e+04 |  +4.687228e+02 |   +4.600596e+02 |
| stddev:         |    +5.750639e+04 |  +9.868569e+00 |   +1.287626e+01 |
| 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 cyclictest.
- 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

Objectives

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

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!

jesus.sanchez-palencia@intel.com