Network Latency with TSN on Virtual Machine

My last blog article [1] described the goal of this research and illustrated the overview of the evaluation method I have adopted. In the second article of the series, I would like to present the more details I used in the measurement process and summerise the results from my experiments against various network bridge technologies.

Test Scenario

System Overview

A real automotive system is likely much complicated, consisting a lot of devices, gateways with a few central servers which are connected with each other via ethernet routers. In my experiments, however, a much simpler system configuration is adopted: Two evaluation boards are directly connected by a cable without using any intermediate switch as our aim here is to evaluate activities at the VM host side.

Target board	MACCHIATObin Double Slot
NIC card	pcie Intel i225-T1
OS	Debian 11 (bullseye)
Kernel	PREEMPT_RT v6.3-rc2

We use two applications:

A. sample-app-taprio [2] as a time-sensitive application

B. netperf(UDP_STREAM) as network stress workload

The program comes from Intel developers as a sample code to demonstrate TSN features on their (and possibly other vendor's TSN-capable) NIC prodcucts and can work as a benchmark test for measuring network latency.

It originally support the txtime-assist mode of taprio shaper combined with hardware-based ETF (Earliest TxTime First) qdisc and, in my experiments, was customized to utilise the full-offload mode.

The sender(TX) side simply wakes up at a given interval within a given time slot (see TSN configuration below) and sends out a small test packet. The receiver(RX) side is to poll for incoming packets and calculate a latency based on the difference between the TX timestamp in a packet and the RX timestamp captured by the NIC. Please note that most of time consumed in a guest OS will be excluded from the definition of latency here because we want to focus on the overhead which comes from the VM host OS. (In this sense, the guest OS need not be RT kernel.)

The sender and the receiver belong to and communicate via a dedicated VLAN. While this configuration will expectedly make much sense to satisfy QOS requirements under a more complicated network, I suppose that it will have little impact on the behaviors at the system like here.

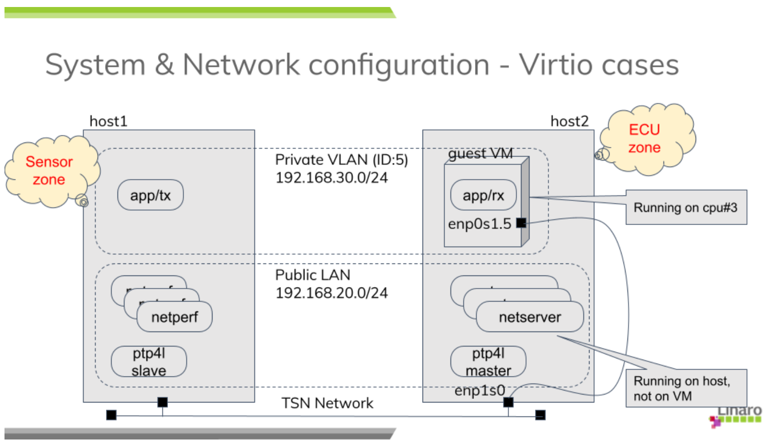


fig. System overview

PTP Setup

Clock synchronization among the devices and servers over the network is one of key technologies in TSN and the base for all the other features to coordiate activities across nodes in a time-sensitive manner. You need to install a PTP package from the distro (I use linuxptp) and start the daemon before the tests.

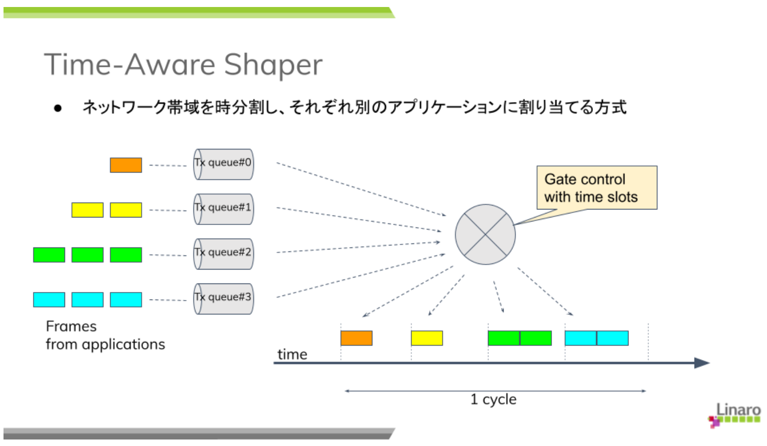
While there are many paramters to define PTP's behavior, I start with using a predefined profile (for automotive use) from the repository. The daemon is assigned to a real-time scheduling class to help improve the responsiveness (I'm not sure it really makes sense.)

Profile	automotive-{master,slave}.cfg [3]
socket priority	5
process priority	1 (SCHED_FIFO)

TSN Configuration

TSN standard defines a couple of shapers and schedulers; Qav (or Credit-Based Scheduler, CBS) and Qbv (or Time-aware Shaper, TAS) are well known features among others. In my experiments, I chose Qbv since the focus here is to ensure that prioritised packets be timely and predictably delivered with some sort of network latency guaranteed over the less prioritised traffic.

Qbv provides a mechanism of time-muliplexing traffic flows from various applications. More specifically, the network bandwidth is divided into several time slots with constant intervals while all the traffic coming from different application are set to be classified into different queues or traffic classes. NIC is scheduled to open the gate for allowed TX queues at any time slot so that packets will be allowed to transmit only for the assigned period within a cycle. So the mechanism theoretically assures that the transmission of prioritised packets are not intefered by other (and even excessive) traffic.


Time-Aware Shaper

- ネットワーク帯域を時分割し、それぞれ別のアプリケーションに割り当てる方式

fig. Time-aware shaper

The definition of gate list can vary from system to system depending on applications and their requirements. Here I adopt the configuration in the table below and I assume that the streams from the benchmark program, PTP and netperf are bound to the TX queues, respecitively, #0, #1 and #3.

The duration times (interval) may be arbitrary, but these odd (and prime) numbers are chosen not to easily resonate with the kernel tick (4 msec by default).

slot#	opened queues	duration time(us)
1	0,1	101
2	1	103
3	1,2	109
4	1,3	190

Other Optimisation

Network bridges under virtio

As I mentioned in my previous article, my study covers the following network bridge types:

A. tap(kernel bridge)
B. macvtap
C. XDP-based bridge
D. Open VSwitch bridge
E. Open VSwitch + AF_XDP

In this section, I describe how I configure the network for each type of technologies and then how I start the guest VM's in my experiments. I prefered to use primitive command tools rather than using a kind of virtual machine manager like virsh/libvirt so that I can have full control over the test environment.

tap(kernel bridge)

Create a VLAN port and a bridge device, then attach the port to the bridge:

```
# ip link add link enp1s0 enp1s0.5 type vlan id 5
# ip addr add 192.168.30.2/24 dev enp1s0.5
# ip link set enp1s0.5 up
# ip link add tmpbr0 type bridge
# ip link set enp1s0.5 master tmpbr0
# ip link set tmpbr0 up
```

Then start a guest VM, specifying this device at the kvm command line as follows:

```
# kvm -machine virt -cpu host -smp 1 -m 2G ... \
     -netdev tap,br=tmpbr0,id=net0,vhost=on,helper=/usr/lib/qemu/qemu-bridge-helper \
     -device virtio-net-pci,netdev=net0,mac=${MAC_ADDR}
```

macvtap

Create a macvtap device:

```
# ip link add link enp1s0 name macvtap0 address ${MAC_ADDR} \
      type macvtap mode bridge
# ip link set macvtap0 up
```

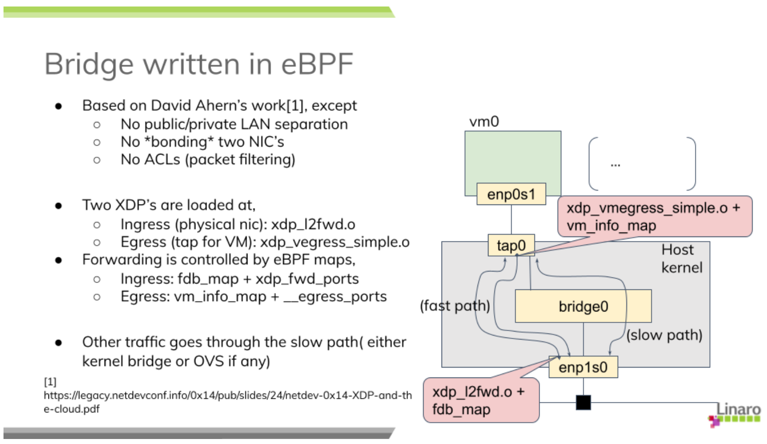
Then start a guest VM, specifying this device at the kvm command line as follows:

```
# kvm -machine virt -cpu host -smp 1 -m 2G ... \
     -netdev tap,id=net0,vhost=on,fd=3 \
     -device virtio-net-pci,netdev=net0,mac=${MAC_ADDR} \
     3<> /dev/tap${TAP_NUM}
```

XDP

David Ahern has made a very interesting study [4] [5] in this area. His interest may be in the cloud environment, but his approach can also be applied to embedded systems. Since his sample code is quite useful, I re-use it with a minor change to fit it into my test purpose.

There are two XDP programs, xdp_l2fwd and xdp_vmegress_simple. They are loaded and attached to a physical NIC port and a tap device for the guest VM, respectively. When a packet is to be sent out from the egress port, XDP programs are called out to determine if any action is needed for that packet using their own database (or map in XDP term). If the program returns XDP_REDIRECT, the packet will be directly redirected to another port. If it returns XDP_PASS, the packet will be simply forwarded to the kernel network stack as usual.



Bridge written in eBPF

- Based on David Ahern's work[1], except
  - No public/private LAN separation
  - No *bonding* two NIC's
  - No ACLs (packet filtering)

- Two XDP's are loaded at,
  - Ingress (physical nic): xdp_l2fwd.o
  - Egress (tap for VM): xdp_vegress_simple.o
- Forwarding is controlled by eBPF maps,
  - Ingress: fdb_map + xdp_fwd_ports
  - Egress: vm_info_map + __egress_ports

- Other traffic goes through the slow path(either kernel bridge or OVS if any)

[1] https://legacy.netdevconf.info/0x14/pub/slides/24/netdev-0x14-XDP-and-the-cloud.pdf

fig. XDP bridge

If you want to try this case, first download the modified code from my repository [6] and build eBPF binaries:

```
$ git clone https://git.linaro.org/...
$ cd iotg_tsn_ref_sw/sample-app-taprio
$ make
```

We use a "tap" configuration as a slow data path and so need to set up the network as in the case of "tap". After that, we can load and two eBPF binaries built above onto, respectively, the physical NIC and the tap device for the guest.

```
# scripts/l2fwd-simple.sh
```

In the middle of running this script, you will be asked to start a guest VM:

```
# kvm -machine virt -cpu host -smp 1 -m 2G ... \
     -netdev tap,br=tmpbr0,id=net0,vhost=on,helper=/usr/lib/qemu/qemu-bridge-helper \
     -device virtio-net-pci,netdev=net0,mac=${MAC_ADDR}
```

Open VSwitch

You can use the distro's Open VSwitch package as is. But if you also want to try Open VSwitch + AF_XDP configuration, it's time for you to compile the code for yourself because AF_XDP support is yet seen as an experimental feature and is not enabled by default.

AF_XDP support requires libbpf from 'tools' of the linux repository: (See more details in OVS's Documentation/intro/install/afxdp.rst)

```
$ cd linux's tools/lib/bpf
$ make
# make install
# make install_headers
```

Then,

```
$ git clone https://github.com/openvswitch/ovs
$ cd ovs
$ ./configure --prefix=/ --enable-afxdp --with-dpdk=shared
$ make
# make install
# systemctl start openvswitch-switch.service
```

Create an OVS bridge device:

```
# ovs-vsctl add-br tmpovsbr0
# ovs-vsctl add-port tmpovsbr0 enp1s0
# ip link set tmpovsbr0 up
# ip addr add 192.168.20.2/24 dev tmpovsbr0
```

Then start a guest VM, specifying this device at the kvm command line as follows:

```
# kvm -machine virt -cpu host -smp 1 -m 2G ... \
     -netdev tap,id=net0,br=tmpovsbr0,vhost=on,\
      script=/somewhere/ifup-ovs.sh,downscript=/somewhere/ifdown-ovs.sh \
     -device virtio-net-pci,netdev=net0,mac=${MAC_ADDR}
```

Where ifup-ovs.sh looks like:

```
#!/bin/sh
ovs-vsctl add-port tmpovsbr2 $1
ip link set $1 up
```

Open VSwitch + AF_XDP

AF_XDP support is a kind of extension to Data Plane Developppment Kit (DPDK) support and the ovs daemon dedicates a userspace thread, called Poll Mode Driver (PMD), for polling a network device and most of packet processing in the kernel is offloaded to it to improve the network performance. As the thread cosumes an almost 100% of cpu time, another cpu needs to be *isolated* from task scheduling. Please add a given cpu number to "isolcpus", 2 in this example, in the kernel command line before rebooting the system.

First, install Open VSwitch following the instructions mentioned above and then start the OVS daemon with dpdk enabled. We probably need to increase a number of huge pages:

```
# sysctl -w vm.nr_hugepages=2000
# systemctl start openvswitch-switch.service
# ovs-vsctl --no-wait set Open_vSwitch . other_config:dpdk-init=try
# systemctl restart ovs-vswitchd.service
```

The next step is to create a bridge device and configure OVS for AF_XDP:

```
# ovs-vsctl -- add-br tmpovsbr0 -- set Bridge tmpovsbr0 datapath_type=netdev
# ethtool -L enp1s0 combined 3
# vs-vsctl set Open_vSwitch . other_config:pmd-cpu-mask=0x7
# ovs-vsctl add-port tmpovsbr0 enp1s0 -- set interface enp1s0 \
     type="afxdp" option:n_rxq=3 other_config:pmd-rxq-affinity="0:3,1:2,0:3"
# ovs-vsctl add-port tmpovsbr0 vhost-user-1 -- set Interface vhost-user-1 \
     type=dpdkvhostuserclient  options:vhost-server-path=/tmp/vhost-user-1

# ip addr add 192.168.20.2/24 dev tmpovsbr0
# ip link set tmpovsbr0 up
```

Then start a guest VM, specifying this device at the kvm command line as follows:

```
# kvm -machine virt -cpu host -smp 1 -m 2G ... \
     -chardev socket,id=char1,path=/tmp/vhost-user-1,server \
     -netdev type=vhost-user,id=mynet1,chardev=char1,vhostforce,queues=1 \
     -device virtio-net-pci,mac=${MAC_ADDR},netdev=mynet1,mq=on \
     -object memory-backend-file,id=mem,size=2048M,mem-path=/dev/hugepages,share=on \
     -numa node,memdev=mem -mem-prealloc"
```

Latency Comparison

(TBD)

bridge	w/o netperf				w netperf			
type	min	avg	max	stdev	min	avg	max	stdev
tap	0	0	0	0	0	0	0	0
macvtap	0	0	0	0	0	0	0	0
XDP bridge	0	0	0	0	0	0	0	0
OVS	0	0	0	0	0	0	0	0

OVS+AF_XDP	0	0	0	0	0	0	0	0

Issues

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1 https://www.linaro.org/blog/network-latency-with-tsn-on-virtual-machine/
2 https://github.com/intel/iotg_tsn_ref_sw/tree/apollolake-i
3 https://sourceforge.net/p/linuxptp/code/ci/master/tree/configs/
4 https://legacy.netdevconf.info/0x14/pub/slides/24/netdev-0x14-XDP-and-the-cloud.pdf
5 https://people.kernel.org/dsahern/xdp-vs-ovs
6 https://git.linaro.org/people/takahiro.akashi/...