Setting up Real-time Ethernet and TSN with Linux: A 10-step guide

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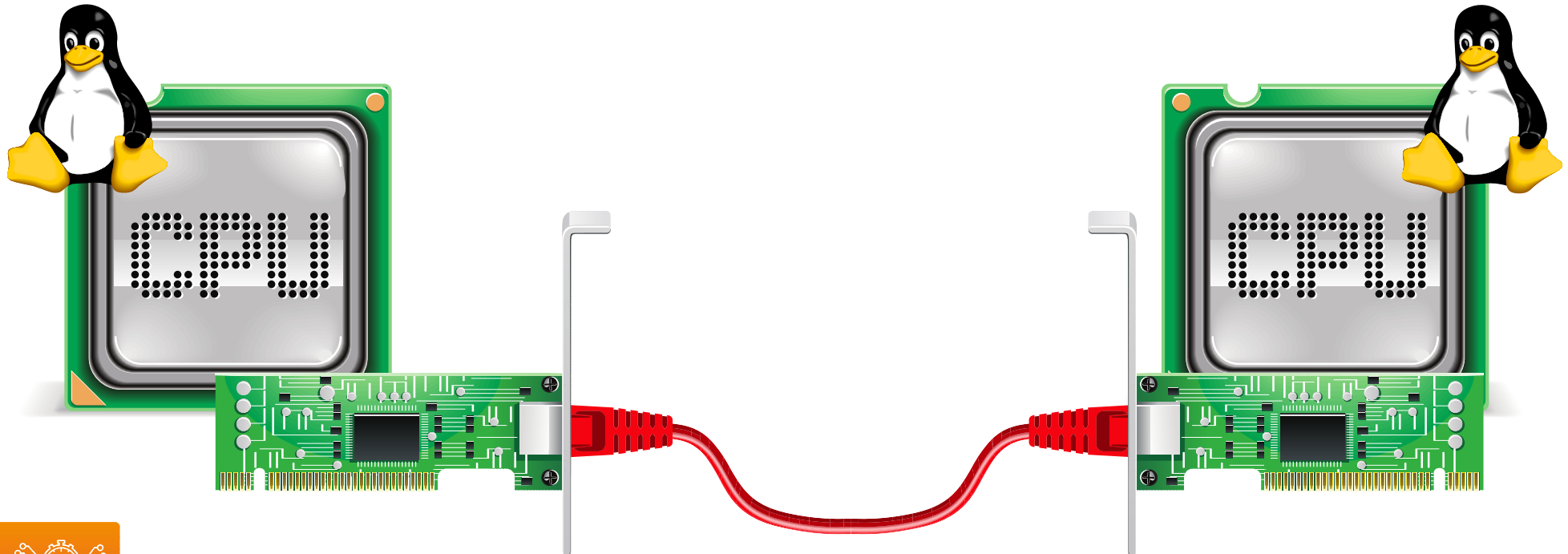
Setup



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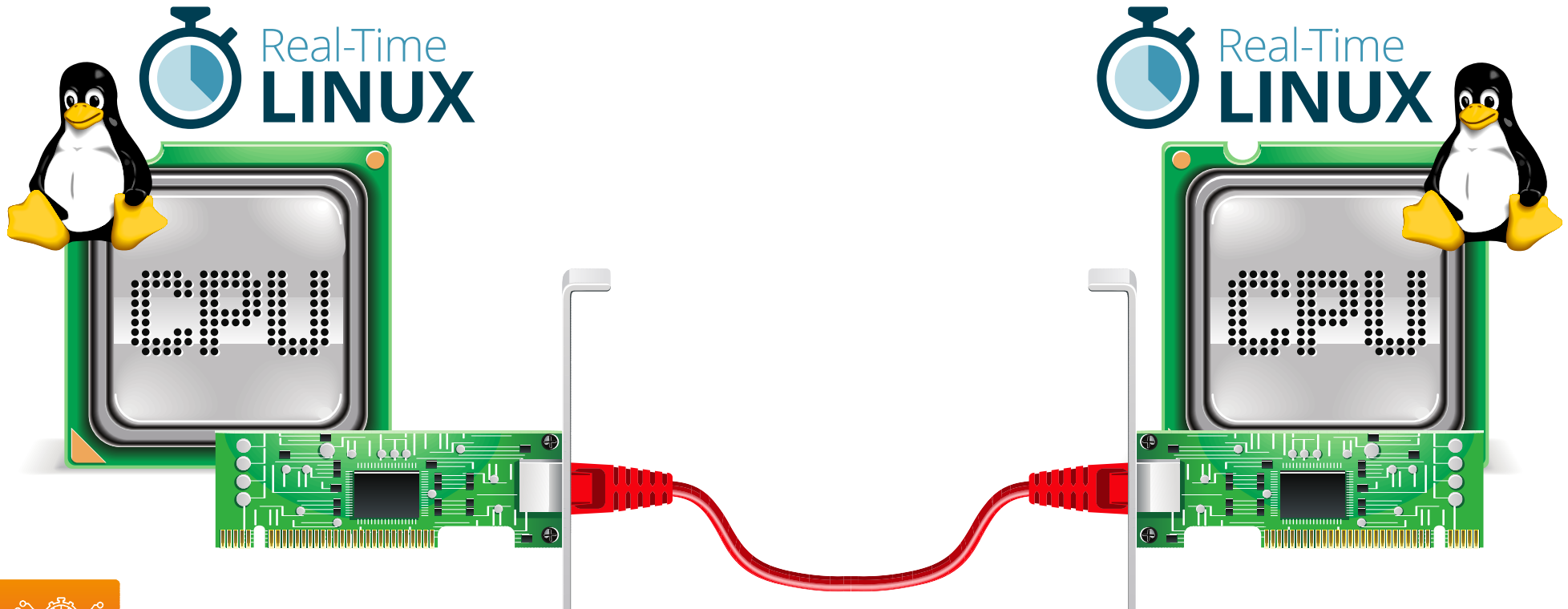

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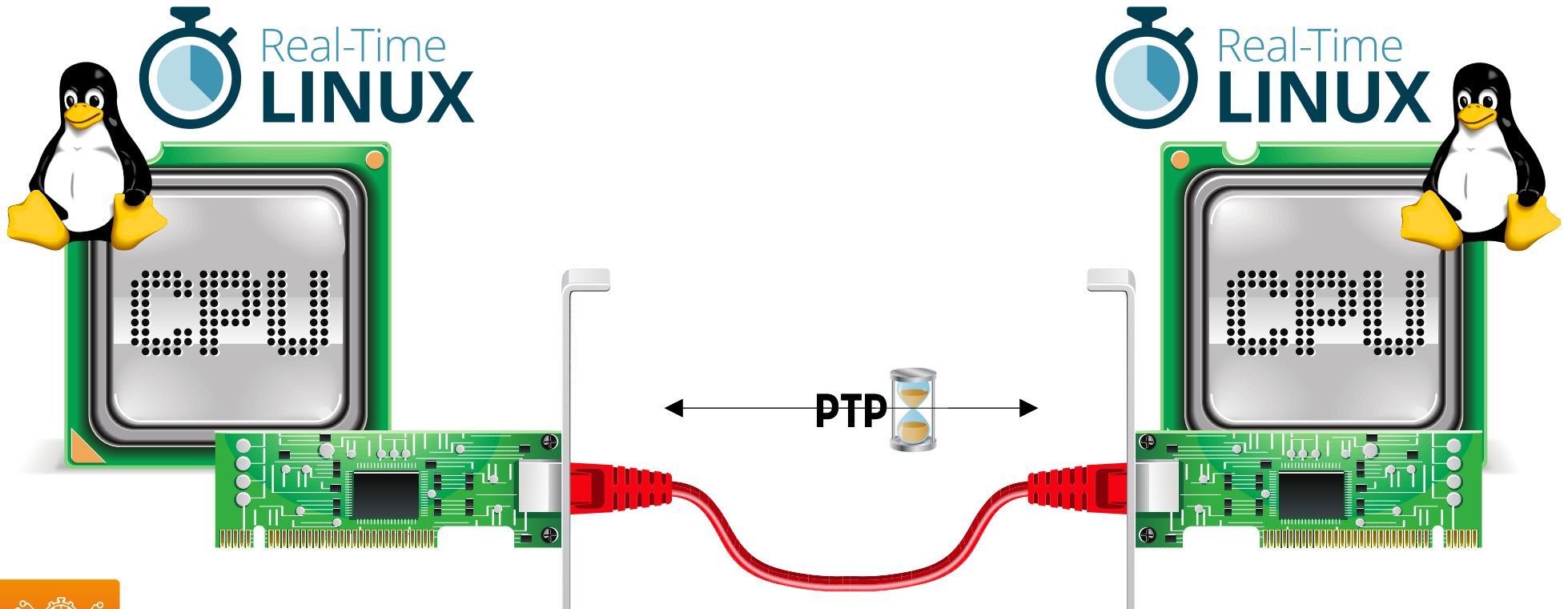

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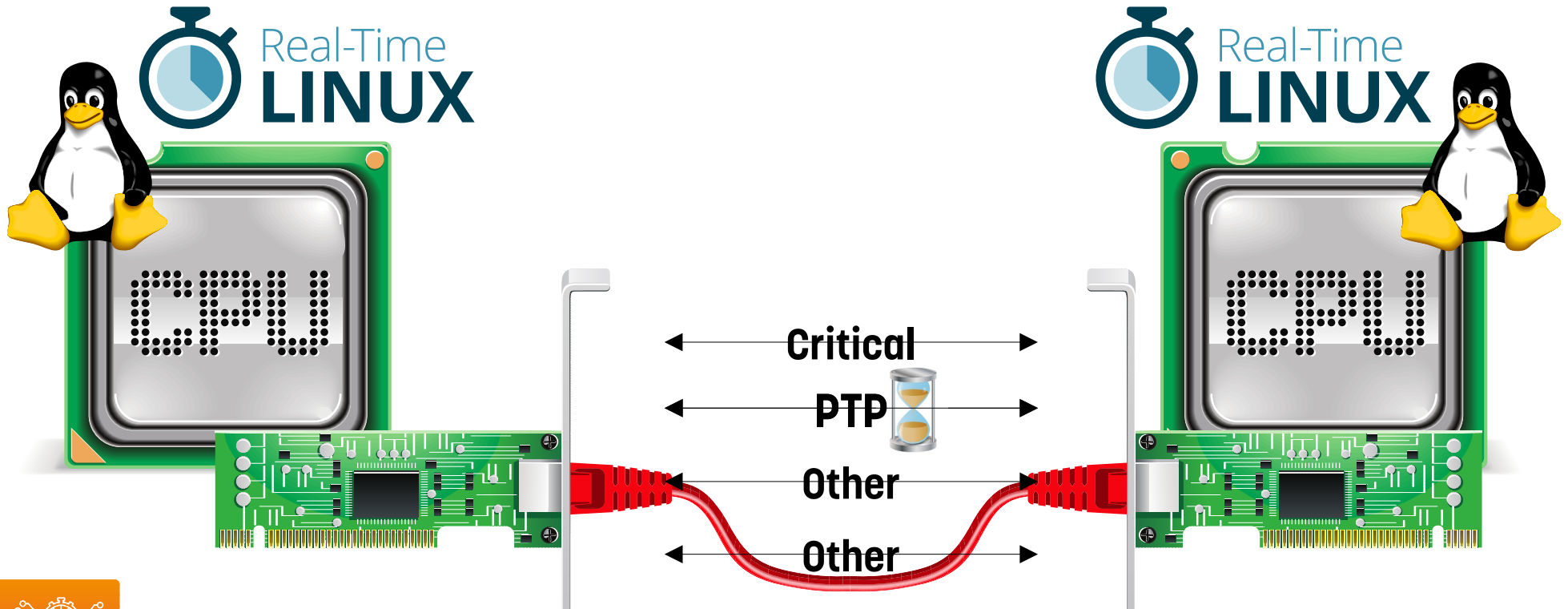

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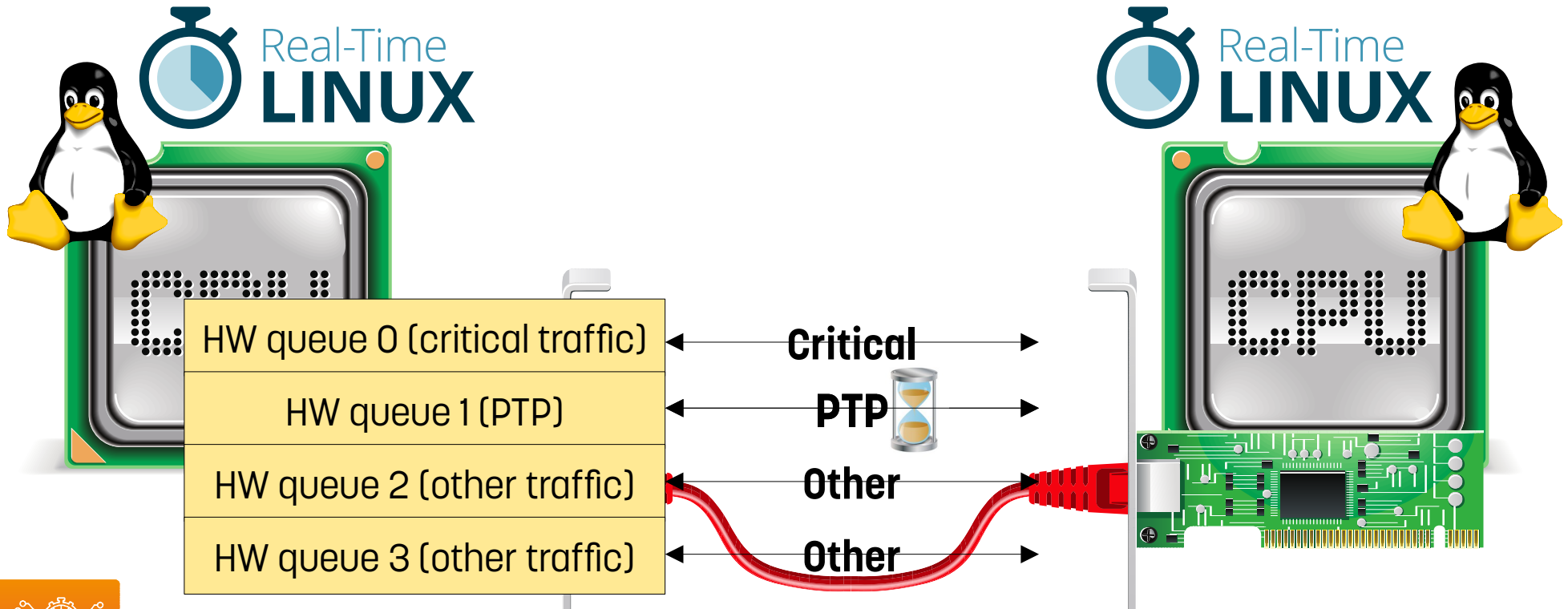

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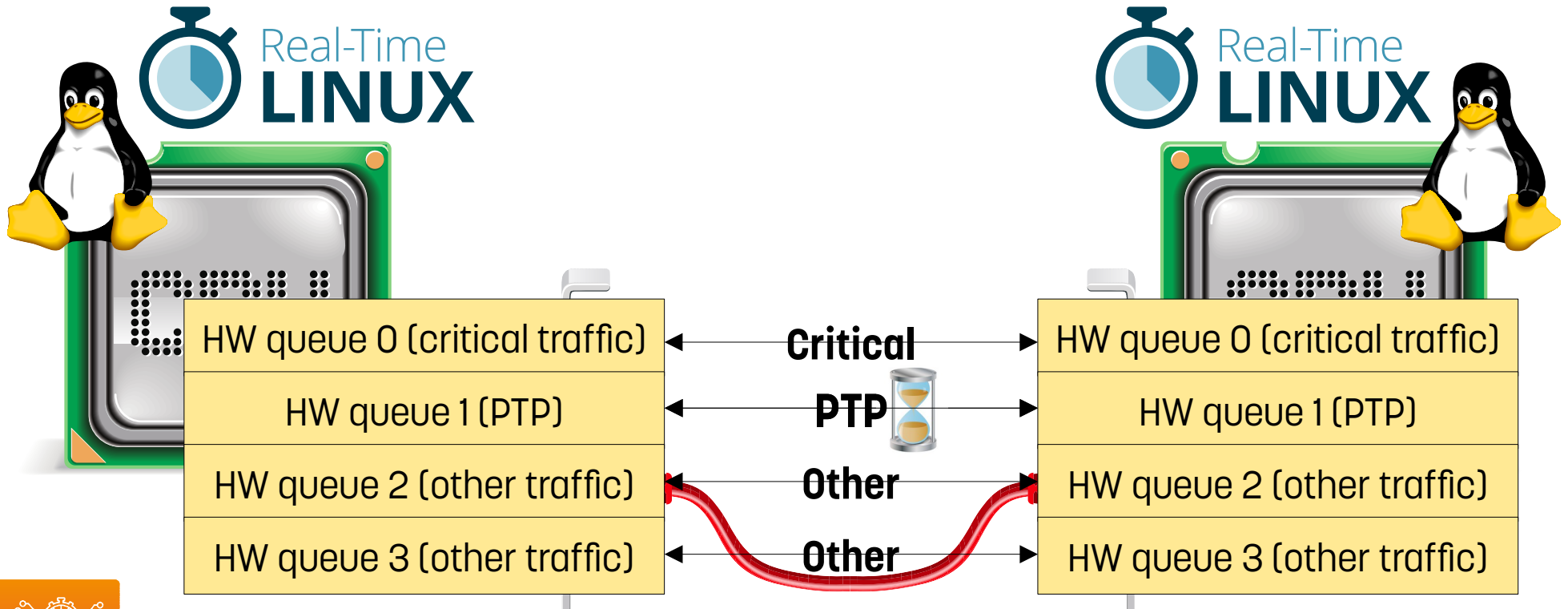

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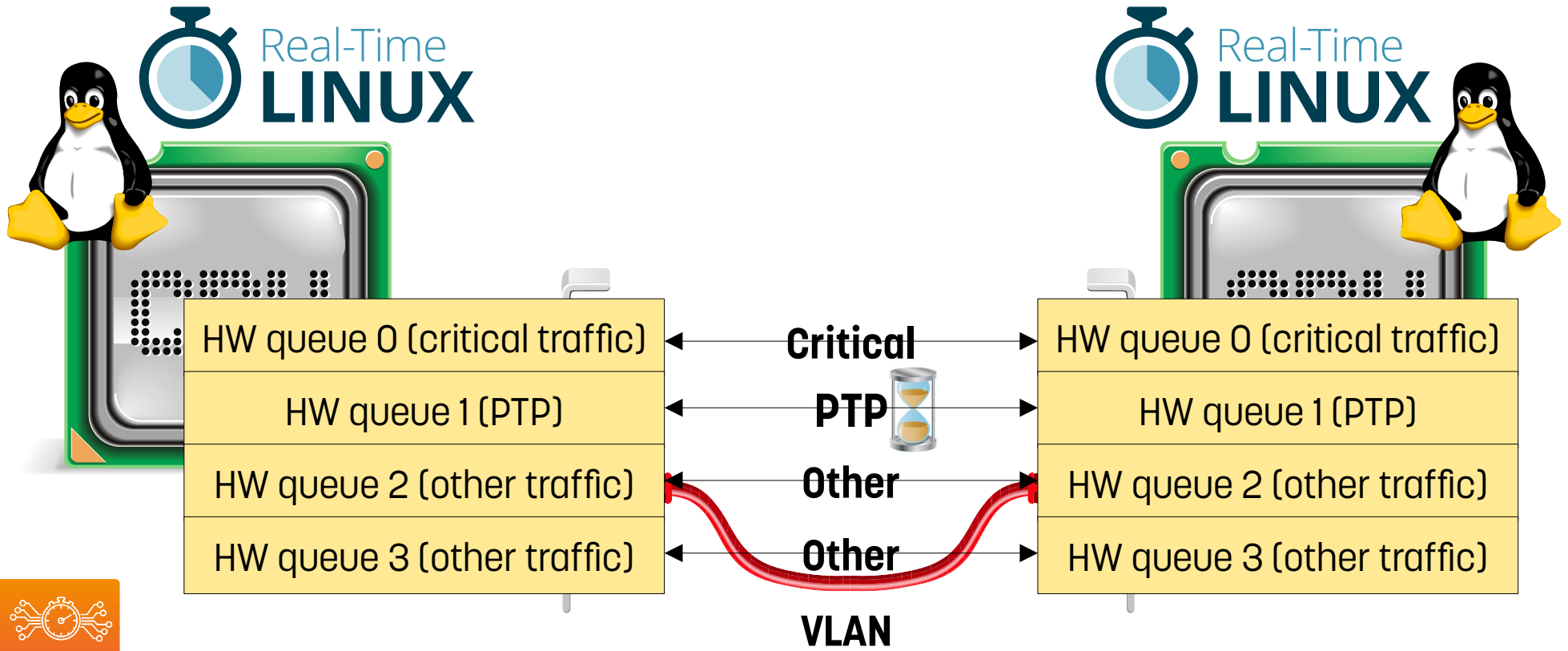
Setup



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Step 1

- Real-time operating system setup (PREEMPT_RT)
- Hardware configuration
- Traffic classes
- System level configuration
- Queuing disciplines (QDISCs)
- Networking setup
- VLAN mapping
- Routing incoming traffic
- Time synchronization
- Evaluation

Kernel commandline

```
isolcpus=2,3 rcu_nocbs=2,3 nohz_full=2,3
irqaffinity=0
noefi
processor.max_cstate=0 intel_idle.max_cstate=0
i915.enable_psr=0 i915.enable_rc6=0
i915.enable_dc=0 i915.disable_power_well=0
i915.enable_guc=2
```

Kernel commandline

```
isolcpus=2,3 rcu_nocbs=2,3 nohz_full=2,3
irqaffinity=0
noefi
processor.max_cstate=0
i915.enable_rc6=0
i915.enable_dc=0 i915.disable_power_well=0
i915.enable_guc=2
```

Isolate CPU 2 and 3 for real-time applications
Route interrupts to CPU 0

Kernel commandline

```
isolcpus=2,3 rcu_nocbs=2,3 nohz_full=2,3
irqaffinity=0
noefi
processor.max_cstate=0
i915.enable_rc6=0
i915.enable_dc=0 i915.disable_power_well=0
i915.enable_guc=2
```

Don’t allow access to EFI variable from userspace
(this is a well known cause for high latencies)

Kernel commandline

```
isolcpus=2,3 rcu_nocbs=2,3 nohz_full=2,3
irqaffinity=0
noefi
processor.max_cstate=0 intel_idle.max_cstate=0
i915.enable_psr=0 i915.enable_rc6=0
i915.enable_dc=0 i915.disable_guc=2
```

Kernel commandline

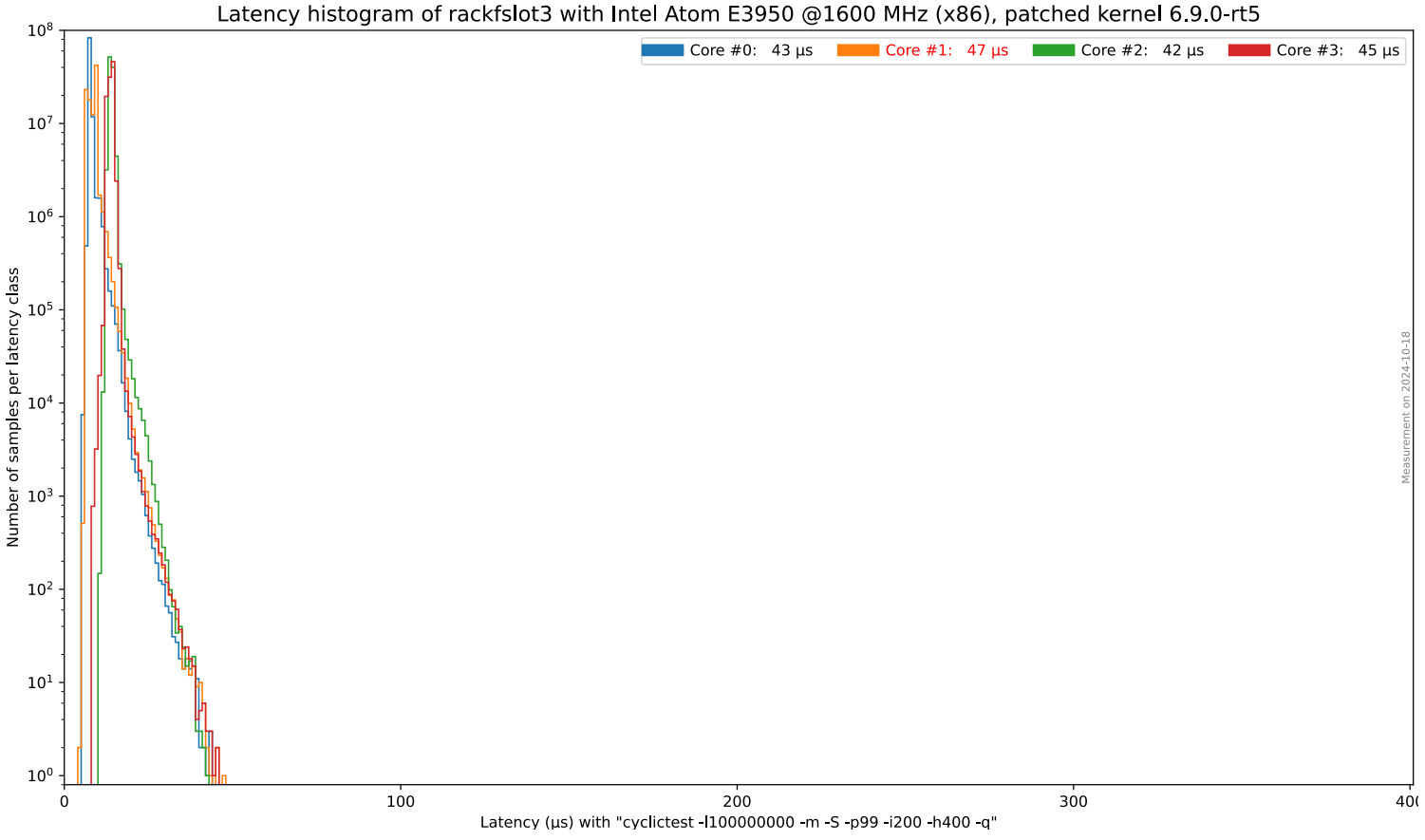
```
isolcpus=2,3 rcu_nocbs=2
irqaffinity=0
noefi
processor.max_cstate=0 intel_idle.max_cstate=0
i915.enable_psr=0 i915.enable_rc6=0
i915.enable_dc=0 i915.disable_power_well=0
i915.enable_guc=2
```

Configure the i915 graphics driver for optimal real-time behavior

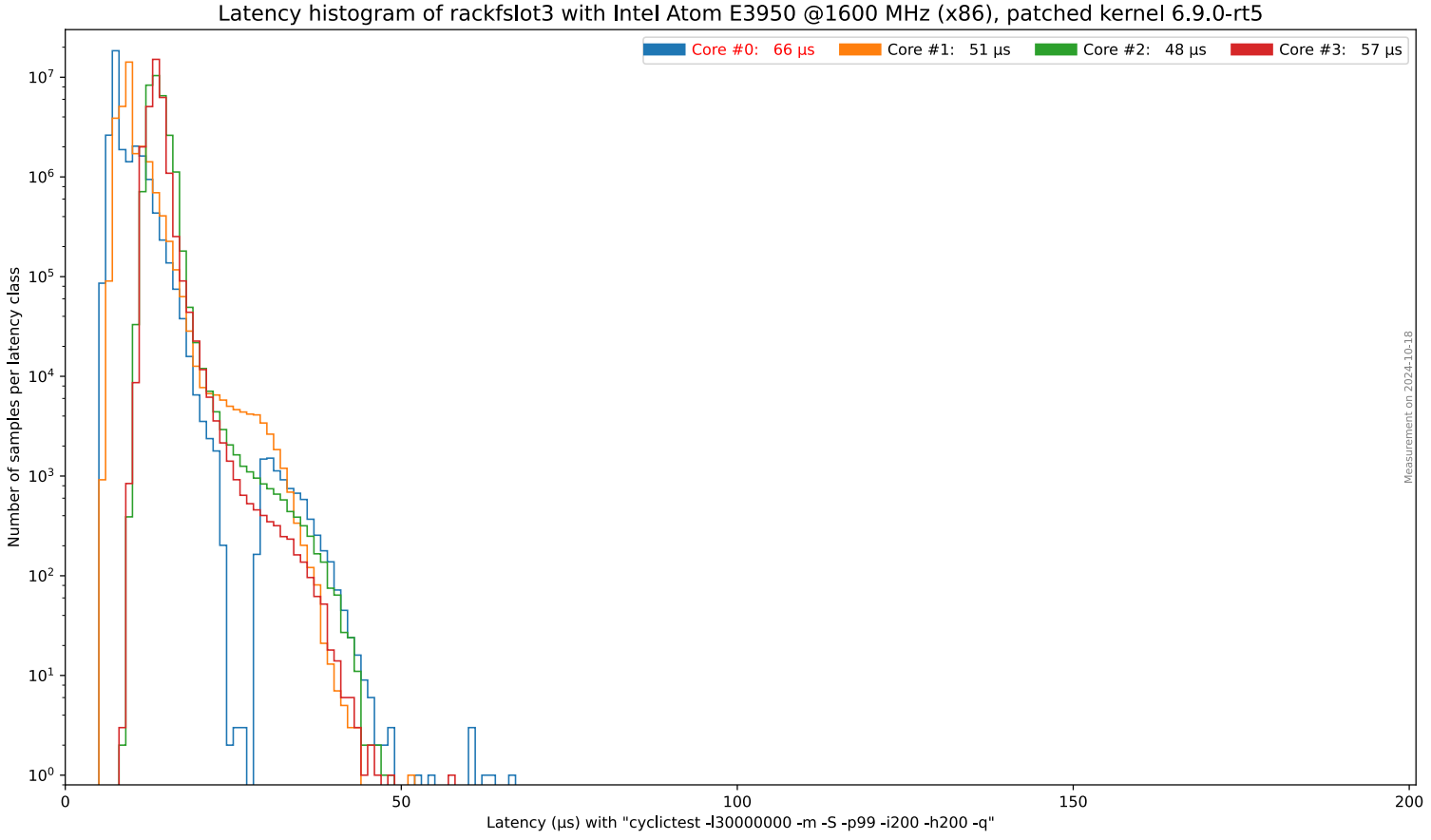
CPU frequency scaling

```
for CPU in $(seq 0 3)
do
  echo performance > \
     /sys/devices/system/cpu/cpufreq/policy${CPU}/scaling_governor
done
```

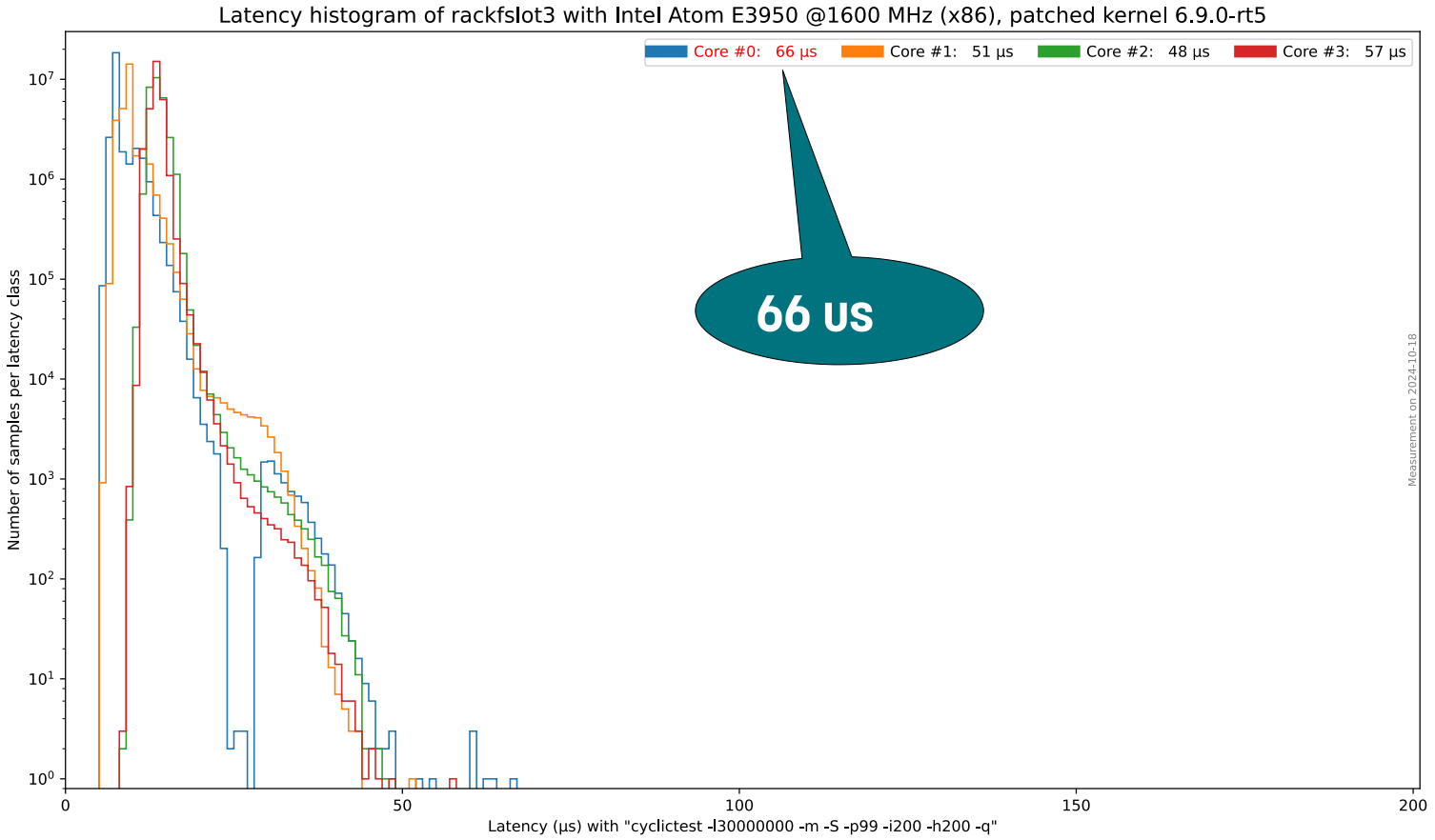
Evaluate the real-time behavior (idle)



Evaluate the real-time behavior (load)



Evaluate the real-time behavior (load)

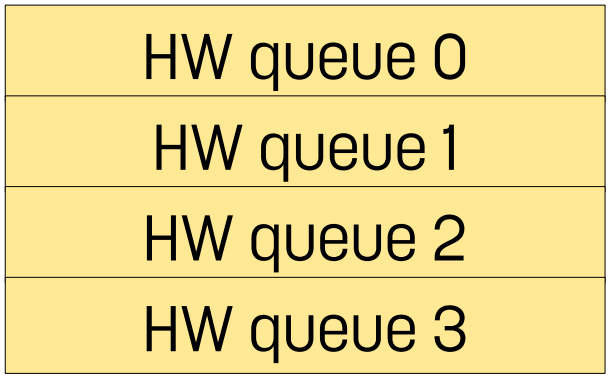


Step 2

- Real-time operating system setup (PREEMPT_RT)
- Hardware configuration
- Traffic classes
- System level configuration
- Queuing disciplines (QDISCs)
- Networking setup
- VLAN mapping
- Routing incoming traffic
- Time synchronization
- Evaluation

Set up 4 combined HW queues

```
$ ethtool -L ${INTERFACE} combined 4
$ ethtool -G ${INTERFACE} rx 4096 tx 4096
```



Disable energy efficiency

```
$ ethtool --set-eee ${INTERFACE} eee off
```

Step 3

- Real-time operating system setup (PREEMPT_RT)
- Hardware configuration
- Traffic classes
- System level configuration
- Queuing disciplines (QDISCs)
- Networking setup
- VLAN mapping
- Routing incoming traffic
- Time synchronization
- Evaluation

Queueing disciplines: mqprio

- Define the number of traffic classes
- Map socket priorities to traffic classes
- Assign the traffic classes to specific hardware queues

Queueing disciplines: mqprio

Manage qdiscs using the application **tc**:

```
tc qdisc add dev eth1 handle 100: parent root mqprio \
num_tc 3 \
map 2 2 1 0 2 2 2 2 2 2 2 2 2 2 2 2 \
queues 1@0 1@1 2@2 \
hw 0
```

The number of traffic classes to be used

Queueing disciplines: mqprio

Manage qdiscs using the application **tc**:

```
tc qdisc add dev eth1 handle 100: parent root mqprio \
num_tc 3 \
map 2 2 1 0 2 2 2 2 2 2 2 2 2 2 2 2 \
queues 1@0 1@1 2@2 \
hw 0
```

Mapping the socket priorities to a traffic class

Queueing disciplines: mqprio

Manage qdiscs using the application **tc**:

```
tc qdisc add dev eth1 handle 100: parent root mqprio \
num_tc 3 \
map 2 2 1 0 2 2 2 2 2 2 2 2 2 2 2 2 \
queues 1@0 1@1 2@2 \
hw 0
```

Priority **0**

Queueing disciplines: mqprio

Manage qdiscs using the application **tc**:

```
tc qdisc add dev eth1 handle 100: parent root mqprio \
num_tc 3 \
map 2 2 1 0 2 2 2 2 2 2 2 2 2 2 2 2 \
queues 1@0 1@1 2@2 \
hw 0
```

Priority **1**

Queueing disciplines: mqprio

Manage qdiscs using the application **tc**:

```
tc qdisc add dev eth1 handle 100: parent root mqprio \
num_tc 3 \
map 2 2 1 0 2 2 2 2 2 2 2 2 2 2 2 2 \
queues 1@0 1@1 2@2 \
hw 0
```

Priority **2**

Queueing disciplines: mqprio

Manage qdiscs using the application **tc**:

```
tc qdisc add dev eth1 handle 100: parent root mqprio \
num_tc 3 \
map 2 2 1 0 2 2 2 2 2 2 2 2 2 2 2 2 \
queues 1@0 1@1 2@2 \
hw 0
```

Priority **15**

Queueing disciplines: mqprio

Manage qdiscs using the application **tc**:

```
tc qdisc add dev eth1 handle 100: parent root mqprio \
num_tc 3 \
map 2 2 1 0 2 2 2 2 2 2 2 2 2 2 2 2 \
queues 1@0 1@1 2@2 \
hw 0
```

Priority **0** maps to traffic class **2**

Queueing disciplines: mqprio

Manage qdiscs using the application **tc**:

```
tc qdisc add dev eth1 handle 100: parent root mqprio \
num_tc 3 \
map 2 2 1 0 2 2 2 2 2 2 2 2 2 2 2 2 \
queues 1@0 1@1 2@2 \
hw 0
```

Priority **2** maps to traffic class **1**

Queueing disciplines: mqprio

Manage qdiscs using the application **tc**:

```
tc qdisc add dev eth1 handle 100: parent root mqprio \
num_tc 3 \
map 2 2 1 0 2 2 2 2 2 2 2 2 2 2 2 2 \
queues 1@0 1@1 2@2 \
hw 0
```

Priority **3** maps to traffic class **0**

Queueing disciplines: mqprio

Manage qdiscs using the application **tc**:

```
tc qdisc add dev eth1 handle 100: parent root mqprio \

num_tc 3 \

map 2 2 1 0 2 2 2 2 2 2 2 2 2 2 2 2 \

queues 1@0 1@1 2@2 \

hw 0
```

Map the traffic classes into hardware queues (4 queues are being used here)

Queueing disciplines: mqprio

Manage qdiscs using the application **tc**:

```
tc qdisc add dev eth1 handle 100: parent root mqprio \
num_tc 3 \
map 2 2 1 0 2 2 2 2 2 2 2 2 2 2 2 2 \
queues 1@0 1@1 2@2 \
hw 0
```

Traffic class **0**

Queueing disciplines: mqprio

Manage qdiscs using the application **tc**:

```
tc qdisc add dev eth1 handle 100: parent root mqprio \
num_tc 3 \
map 2 2 1 0 2 2 2 2 2 2 2 2 2 2 2 2 \
queues 1@0 1@1 2@2 \
hw 0
```

Traffic class **1**

Queueing disciplines: mqprio

Manage qdiscs using the application **tc**:

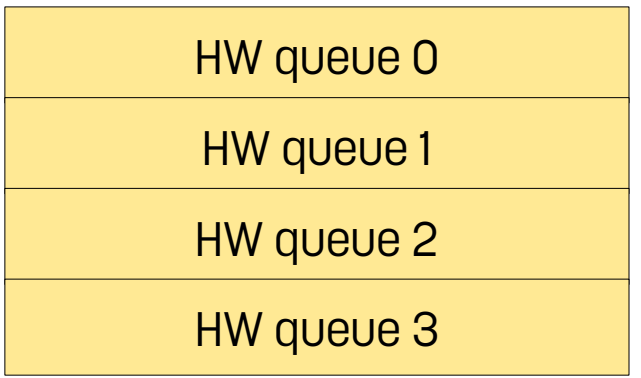
```
tc qdisc add dev eth1 handle 100: parent root mqprio \
num_tc 3 \
map 2 2 1 0 2 2 2 2 2 2 2 2 2 2 2 2 \
queues 1@0 1@1 2@2 \
hw 0
```

Traffic class **2**

Queueing disciplines: mqprio

Manage qdiscs using the application **tc**:

```
tc qdisc add dev eth1 handle 100: parent root mqprio \
num_tc 3 \
map 2 2 1 0 2 2 2 2 2 2 2 2 2 2 2 2 \
queues 1@0 1@1 2@2 \
hw 0
```

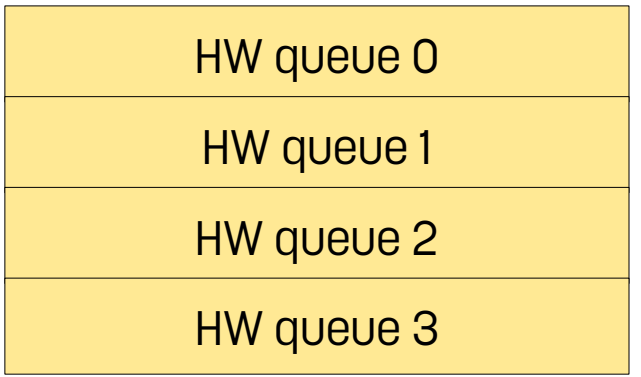


Queueing disciplines: mqprio

Manage qdiscs using the application **tc**:

```
tc qdisc add dev eth1 handle 100: parent root mqprio \
num_tc 3 \
map 2 2 1 0 2 2 2 2 2 2 2 2 2 2 2 2 \
queues 1@0 1@1 2@2 \
hw 0
```

TC0 goes into **1** queue

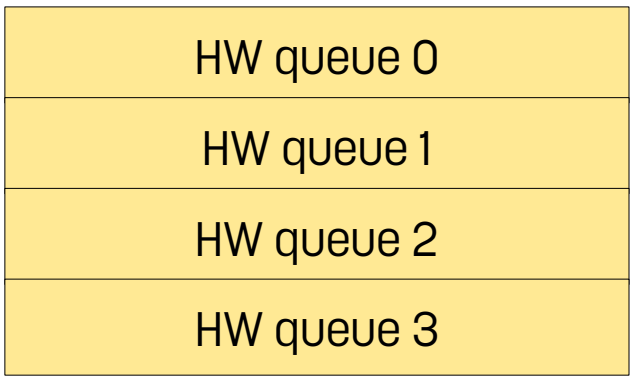


Queueing disciplines: mqprio

Manage qdiscs using the application **tc**:

```
tc qdisc add dev eth1 handle 100: parent root mqprio \
num_tc 3 \
map 2 2 1 0 2 2 2 2 2 2 2 2 2 2 2 2 \
queues 1@0 1@1 2@2 \
hw 0
```

TC0 goes into 1 queue starting from queue **0**



Queueing disciplines: mqprio

Manage qdiscs using the application **tc**:

```
tc qdisc add dev eth1 handle 100: parent root mqprio \
num_tc 3 \
map 2 2 1 0 2 2 2 2 2 2 2 2 2 2 2 2 \
queues 1@0 1@1 2@2 \
hw 0
```

TC0 goes into **1** queue starting from queue **0**

HW queue 0
HW queue 1
HW queue 2
HW queue 3

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Queueing disciplines: mqprio

Manage qdiscs using the application **tc**:

```
tc qdisc add dev eth1 handle 100: parent root mqprio \
num_tc 3 \
map 2 2 1 0 2 2 2 2 2 2 2 2 2 2 2 2 \
queues 1@0 1@1 2@2 \
hw 0
```

TC1 goes into **1** queue starting from queue **1**

HW queue 0
HW queue 1
HW queue 2
HW queue 3

Queueing disciplines: mqprio

Manage qdiscs using the application **tc**:

```
tc qdisc add dev eth1 handle 100: parent root mqprio \
num_tc 3 \
map 2 2 1 0 2 2 2 2 2 2 2 2 2 2 2 2 \
queues 1@0 1@1 2@2 \
hw 0
```

TC2 goes into **2** queues starting from queue **2**

HW queue 0
HW queue 1
HW queue 2
HW queue 3

Queueing disciplines: mqprio

Manage qdiscs using the application **tc**:

```
tc qdisc add dev eth1 handle 100: parent root mqprio \
num_tc 3 \
map 2 2 1 0 2 2 2 2 2 2 2 2 2 2 2 2 \
queues 1@0 1@1 2@2 \
hw 0
```

0: No hardware offloading
1: Hardware offloading

```
# Check for hardware support
ethtool -k eth1 | grep hw-tc-offload
hw-tc-offload: on
```

Step 4

- Real-time operating system setup (PREEMPT_RT)
- Hardware configuration
- Traffic classes
- System level configuration
- Queuing disciplines (QDISCs)
- Networking setup
- VLAN mapping
- Routing incoming traffic
- Time synchronization
- Evaluation

Threaded NAPI

```
$ echo 1 > /sys/class/net/${INTERFACE}/threaded
```

IRQ routing

```
HWQUEUE=0
for IRQ_NUM in $(cat /proc/interrupts | grep ${INTERFACE} | cut -f1 -d:)
do
    if [ ${HWQUEUE} -lt 3 ]
    then
        echo ${ETH_IRQTHREAD_MASK} > /proc/irq/${IRQ_NUM}/smp_affinity
    fi
    let HWQUEUE=${HWQUEUE}+1
done
```

IRQ-thread priorities

```
HWQUEUE=0
for PID in $(ps aux | grep ${INTERFACE} | grep irq | tr -s ' ' | cut -f2 -d' ')
do
        if [ ${HWQUEUE} -ge 1 -a ${HWQUEUE} -lt 3 ]
        then
                chrt -f -p ${ETH_IRQTHREAD_PRIO} ${PID}
        else
                chrt -f -p 70 ${PID}
        fi
        let HWQUEUE=${HWQUEUE}+1
done
```

NAPI-thread priorities

```
HWQUEUE=4
NAPITHREADS=$(ps aux | grep napi | grep ${INTERFACE} | awk '{ print $2; }')
for THREAD in ${NAPITHREADS}
do
        if [ ${HWQUEUE} -le 2 ]
        then
                chrt -p -f ${NAPI_THREAD_PRIO} $THREAD
                taskset -pc ${NAPI_CPU_AFFINITY} $THREAD
        else
                chrt -p -f 70 $THREAD
                taskset -pc 0 $THREAD
        fi
        let HWQUEUE=${HWQUEUE}-1
done
```

CPU pinning and priorities

PID	USER	PR	NI	VIRT	RES	SHR	S	%CPU	%MEM	TIME+	COMMAND	
[...]												
13874	root	0	-20	0	0	0	I	0.0	0.0	0:00.00	kworker/3:1H-kblo	
2055005	root	-76	0	238944	46456	2304	S	50.0	1.2	0:56.79	pubsub_TSN_publ	
2055008	root	-76	0	238944	46456	2304	S	0.0	1.2	0:11.79	pubsub_TSN_publ	
[...]												
666	**root**	**-71**	**0**	**0**	**0**	**0**	**S**	**0.0**	**0.0**	**0:07.24**	**irq/132-enp4s0**	
667	**root**	**-99**	**0**	**0**	**0**	**0**	**S**	**0.0**	**0.0**	**25:06.80**	**irq/133-enp4s0-TxRx-0**	**2**
668	**root**	**-99**	**0**	**0**	**0**	**0**	**S**	**0.0**	**0.0**	**0:31.43**	**irq/134-enp4s0-TxRx-1**	**2**
793	**root**	**-99**	**0**	**0**	**0**	**0**	**S**	**0.0**	**0.0**	**0:30.76**	**napi/enp4s0-8198**	**2**
794	**root**	**-99**	**0**	**0**	**0**	**0**	**S**	**50.0**	**0.0**	**27:21.56**	**napi/enp4s0-8197**	**2**
1975955	root	0	-20	0	0	0	I	0.0	0.0	0:00.00	kworker/2:1H	2
2055006	root	-79	0	238944	46456	2304	S	0.0	1.2	0:23.29	pubsub_TSN_publ	2
2055007	root	-82	0	238944	46456	2304	S	0.0	1.2	0:21.59	pubsub_TSN_publ	2

HW queue 0 (critical traffic)

HW queue 1 (PTP)

HW queue 2 (other traffic)

HW queue 3 (other traffic)

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Step 5

- Real-time operating system setup (PREEMPT_RT)
- Hardware configuration
- Traffic classes
- System level configuration
- Queuing disciplines (QDISCs)
- Networking setup
- VLAN mapping
- Routing incoming traffic
- Time synchronization
- Evaluation

ETF

Manage qdiscs using the application **tc**:

```
tc qdisc replace dev eth1 parent 100:1 etf \

clockid CLOCK_TAI \

delta 66000 \

offload
```

ETF

Manage qdiscs using the application **tc**:

```
tc qdisc replace dev eth1 parent 100:1 etf \
clockid CLOCK_TAI \
delta 66000 \
offload
```

handle of the parent qdisc (defined before)

ETF

Manage qdiscs using the application **tc**:

```
tc qdisc replace dev eth1 parent 100:1 etf \
clockid CLOCK_TAI \
delta 66000 \
offload
```

Traffic class:
1: TC0 2: TC1 3: TC2

ETF

Manage qdiscs using the application **tc**:

```
tc qdisc replace dev eth1 parent 100:1 etf \
clockid CLOCK_TAI \
delta 66000 \
offload
```

Traffic class:
1: TC0 2: TC1 3: TC2

ETF

Manage qdiscs using the application **tc**:

```
tc qdisc replace dev eth1 parent 100:1 etf \
clockid CLOCK_TAI \
delta 66000 \
offload
```

The clock to be used for scheduling events and measuring the time

ETF

Manage qdiscs using the application **tc**:

```
tc qdisc replace dev eth1 parent 100:1 etf \
clockid CLOCK_TAI \
delta 66000 \
offload
```

Can be used to take the scheduler latency into account

ETF

Manage qdiscs using the application **tc**:

```
tc qdisc replace dev eth1 parent 100:1 etf \

clockid CLOCK_TAI \

delta 66000 \

offload
```

Can be used to take the scheduler latency into account
Next wake up = next tx time - **delta**

ETF

Manage qdiscs using the application **to**:

```
tc qdisc
clockid CLOCK_TA
delta 66000 \
offload
```

Use cyclictest to determine the latency

Can be used to take the scheduler latency into account
Next wake up = next tx time - **delta**

ETF

Manage qdiscs using the application **tc**:

```
tc qdisc replace dev eth1 parent 100:1 etf \

clockid CLOCK_TAI \

delta 66000 \
```

`offload` Use the “Launch Time” feature of the NIC (disabled by default)

Step 6

- Real-time operating system setup (PREEMPT_RT)
- Hardware configuration
- Traffic classes
- System level configuration
- Queuing disciplines (QDISCs)
- Networking setup
- VLAN mapping
- Routing incoming traffic
- Time synchronization
- Evaluation

VLAN

```
auto enp4s0.8
iface enp4s0.8 inet static
address 192.168.4.1
netmask 255.255.255.0
```

VLAN

```
auto enp4s0.8
iface enp4s0.8 inet static
address 192.168.4.2
netmask 255.255.255.0
```

Step 7

- Real-time operating system setup (PREEMPT_RT)
- Hardware configuration
- Traffic classes
- System level configuration
- Queuing disciplines (QDISCs)
- Networking setup
- VLAN mapping
- Routing incoming traffic
- Time synchronization
- Evaluation

Setup virtual networks (VLAN)

- Using qdiscs traffic classes are mapped to hardware queues and outgoing traffic can be scheduled.
- In a next step outgoing packets have to be “marked”, so the different traffic classes can be differentiated on the network.
- This is done using the Port Control Protocol (PCP) field.
- Socket priorities can be mapped to the PCP field using VLANs.

Setup virtual networks (VLAN)

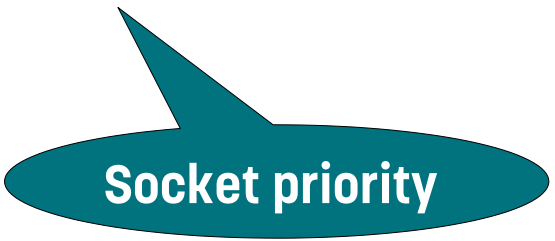
Map the traffic classes to the PCP field:

```
# ip link set enp4s0.8 type vlan \
egress 2:2 3:3
```

Setup virtual networks (VLAN)

Map the traffic classes to the PCP field:

```
# ip link set enp4s0.8 type vlan \
egress 2:2 3:3
```



Setup virtual networks (VLAN)

Map the traffic classes to the PCP field:

```
# ip link set enp4s0.8 type vlan \
egress 2:2 3:3
```

Step 8

- Real-time operating system setup (PREEMPT_RT)
- Hardware configuration
- Traffic classes
- System level configuration
- Queuing disciplines (QDISCs)
- Networking setup
- VLAN mapping
- Routing incoming traffic
- Time synchronization
- Evaluation

Filtering incoming traffic

```
ethtool -K ${INTERFACE} ntuple on

# PCP 3 -> HW queue 0
ethtool -N ${INTERFACE} flow-type ether vlan 0x6000 m 0x1fff action 0
# PCP 2 -> HW queue 1
ethtool -N ${INTERFACE} flow-type ether vlan 0x4000 m 0x1fff action 1

# The rest goes to HW queue 2 and 3
ethtool -N ${INTERFACE} flow-type ether vlan 0xc000 m 0x1fff action 2
[...]
ethtool -N ${INTERFACE} flow-type ether vlan 0xe000 m 0x1fff action 3
```

Filtering incoming traffic

```
ethtool -K ${INTERFACE} ntuple on

# PCP 3 -> HW queue 0
ethtool -N ${INTERFACE} flow-type ether vlan 0x6000 m 0x1fff action 0
# PCP 2 -> HW queue 1
ethtool -N ${INTERFACE} flow-type ether vlan 0x4000 m 0x1fff action 1

# The rest goes to HW queue 2 and 3
ethtool -N ${INTERFACE} flow-type ether vlan 0xc000 m 0x1fff action 2
[...]
ethtool -N ${INTERFACE} flow-type ether vlan 0xe000 m 0x1fff action 3
```

PCP field 3 goes to HW queue 0

Filtering incoming traffic

```
ethtool -K ${INTERFACE} ntuple on

# PCP 3 -> HW queue 0
ethtool -N ${INTERFACE} flow-type ether vlan 0x6000 m 0x1fff action 0
# PCP 2 -> HW queue 1
ethtool -N ${INTERFACE} flow-type ether vlan 0x4000 m 0x1fff action 1

# The rest goes to HW queue 2
ethtool -N ${INTERFACE} flow-type ether vlan 0x2000 m 0x1fff action 2
[...]
ethtool -N ${INTERFACE} flow-type ether vlan 0xe000 m 0x1fff action 3
```

PCP field 2 goes to HW queue 1

Filtering incoming traffic

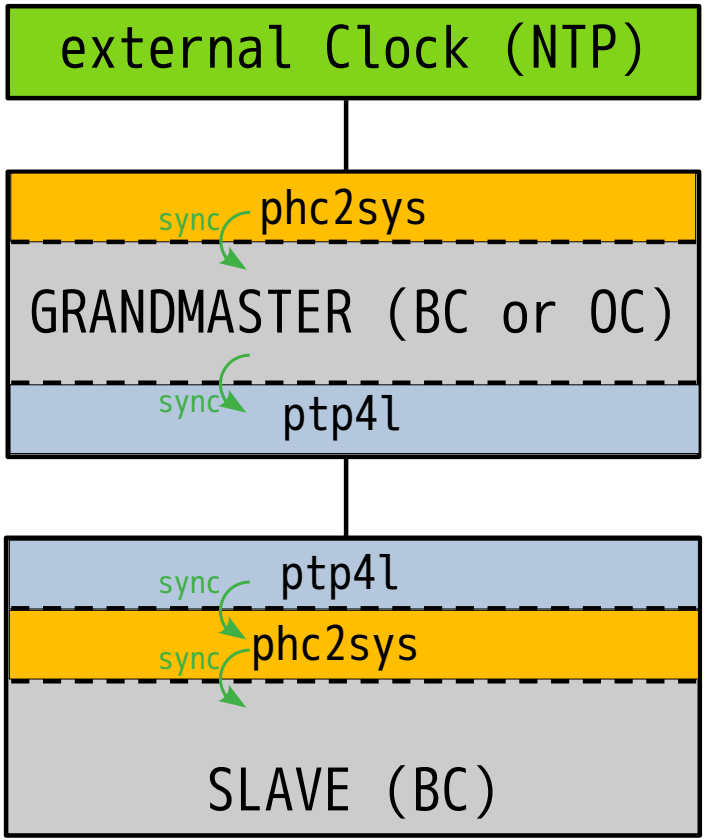
```
ethtool -K ${INTERFACE} ntuple on

# PCP 3 -> HW queue 0
ethtool -N ${INTERFACE} flow-type ether vlan 0x6000 m 0x1fff action 0
# PCP 2 -> HW queue 1
ethtool -N ${INTERFACE} flow-type ether vlan 0x4000 m 0x1fff action 1

# The rest goes to HW queue 2 and 3
ethtool -N ${INTERFACE} flow-type ether vlan 0xc000 m 0x1fff action 2
[...]
ethtool -N ${INTERFACE} f                    0x1fff action 3
```

Other traffic goes to HW queues 2 and 3

Step 9

- Real-time operating system setup (PREEMPT_RT)
- Hardware configuration
- Traffic classes
- System level configuration
- Queuing disciplines (QDISCs)
- Networking setup
- VLAN mapping
- Routing incoming traffic
- Time synchronization
- Evaluation

System setup



- Exactly one time provider is needed per network (the “grandmaster”). This grandmaster knows the time, since it
  - has a built-in highly accurate clock,
  - obtains the correct time from an external trusted source, or
  - does both.
- As many time consumers (“slaves”) as required may be installed.
- Slaves may be connected peer-to-peer or via switches.

OPC UA TSN

OSADL

PTP synchronization on the Grandmaster

Send network time information via PTP

```
$ ptp4l -A -i enp1s0  --socket_priority=2 -f /etc/linuxptp/ptp4l.conf \
  -2 -mq >/var/log/ptp4l.out 2>/var/log/ptp4l.err
```

Synchronize system time

```
$ phc2sys -c enp1s0 -s CLOCK_REALTIME \
-w -mq >/var/log/phc2sys.out 2>/var/log/phc2sys.err
```

PTP synchronization on the Grandmaster

Send network time information via PTP

```
$ ptp4l -A -i enp1s0  --socket_priority=2 -f /etc/linuxptp/ptp4l.conf \
  -2 -mq >/var/log/ptp4l.out 2>/var/log/ptp4l.err
```

Synchronize system time

```
$ phc2sys -c enp1s0 -s CLOCK_REALTIME \
-w -mq >/var/log/phc2sys.out 2>/var/log/phc2sys.err
```

HW queue 0 (critical traffic)
HW queue 1 (PTP)
HW queue 2 (other traffic)
HW queue 3 (other traffic)

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OSADL

PTP synchronization on the Grandmaster

Send network time information via PTP

```
$ ptp4l -A -i enp1s0  --socket_priority=2 -f /etc/linuxptp/ptp4l.conf \
  -2 -mq >/var/log/ptp4l.out 2>/var/log/ptp4l.err
```

Select delay mechanism automatically

Synchronize system time

```
$ phc2sys -c enp1s0 -s CLOCK_REALTIME \
-w -mq >/var/log/phc2sys.out 2>/var/log/phc2sys.err
```

OPC UA TSN

OSADL

PTP time synchronization on the slave

Receive network time information via PTP

```
ptp4l -A -i enp1s0 --socket_priority=2 -2 -mq -s \
-f /etc/linuxptp/ptp4l.conf >/var/log/ptp4l.out 2>/var/log/ptp4l.err &
```

Synchronize system time

```
phc2sys -s enp1s0 -w -mq >/var/log/phc2sys.out 2>/var/log/phc2sys.err &
```

PTP time synchronization on the slave

Receive network time information via PTP

```
ptp4l -A -i enp1s0 --socket_priority=2 -2 -mq -s \
-f /etc/linuxptp/ptp4l.conf >/var/log/ptp4l.out 2>/var/log/ptp4l.err &
```

run as slave

Synchronize system time

```
phc2sys -s enp1s0 -w -mq >/var/log/phc2sys.out 2>/var/log/phc2sys.err &
```

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Step 10

- Real-time operating system setup (PREEMPT_RT)
- Hardware configuration
- Traffic classes
- System level configuration
- Queuing disciplines (QDISCs)
- Networking setup
- VLAN mapping
- Routing incoming traffic
- Time synchronization
- Evaluation

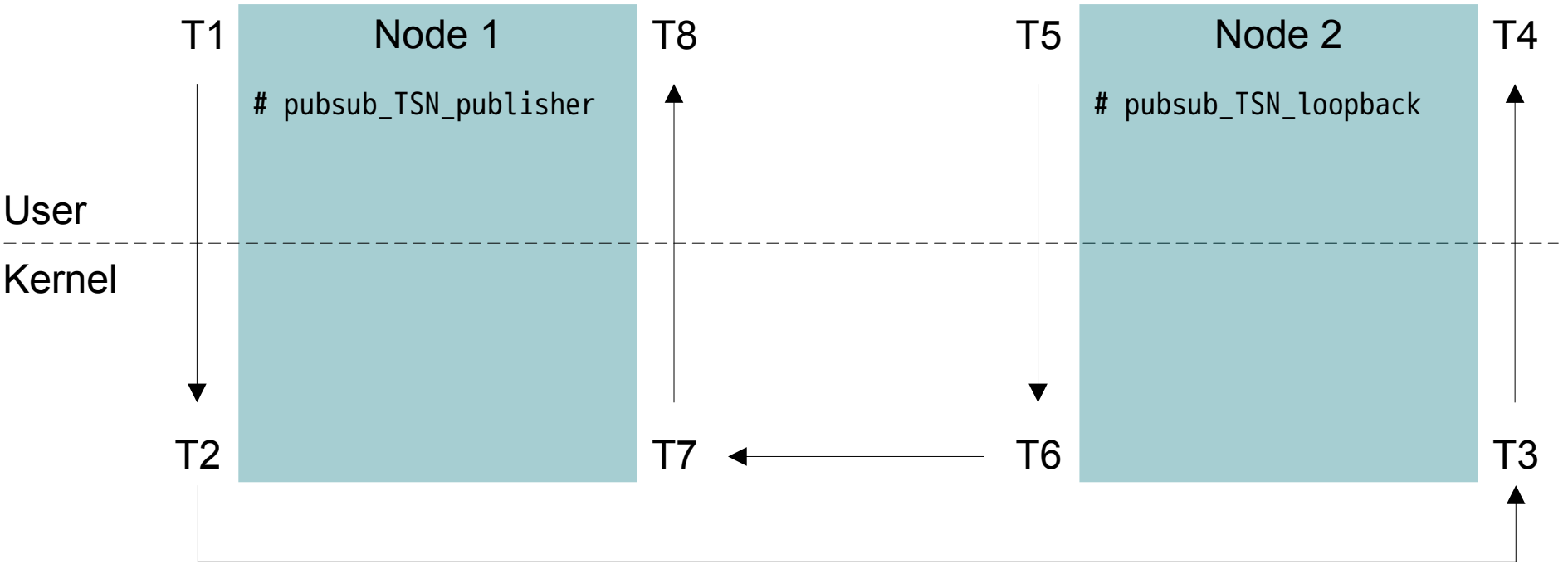
Open62541: PubSub real-time example, build configuration

```
# cmake -DUA_ENABLE_PUBSUB=ON \
-DUA_ENABLE_PUBSUB_ETH_UADP=ON \
-DUA_BUILD_EXAMPLES=ON \
-DUA_ENABLE_MALLOC_SINGLETON=ON \
-DUA_ENABLE_PUBSUB_BUFMALLOC=ON \
-DUA_ENABLE_IMMUTABLE_NODES=ON
# make
```

Open62541: PubSub real-time example, build configuration

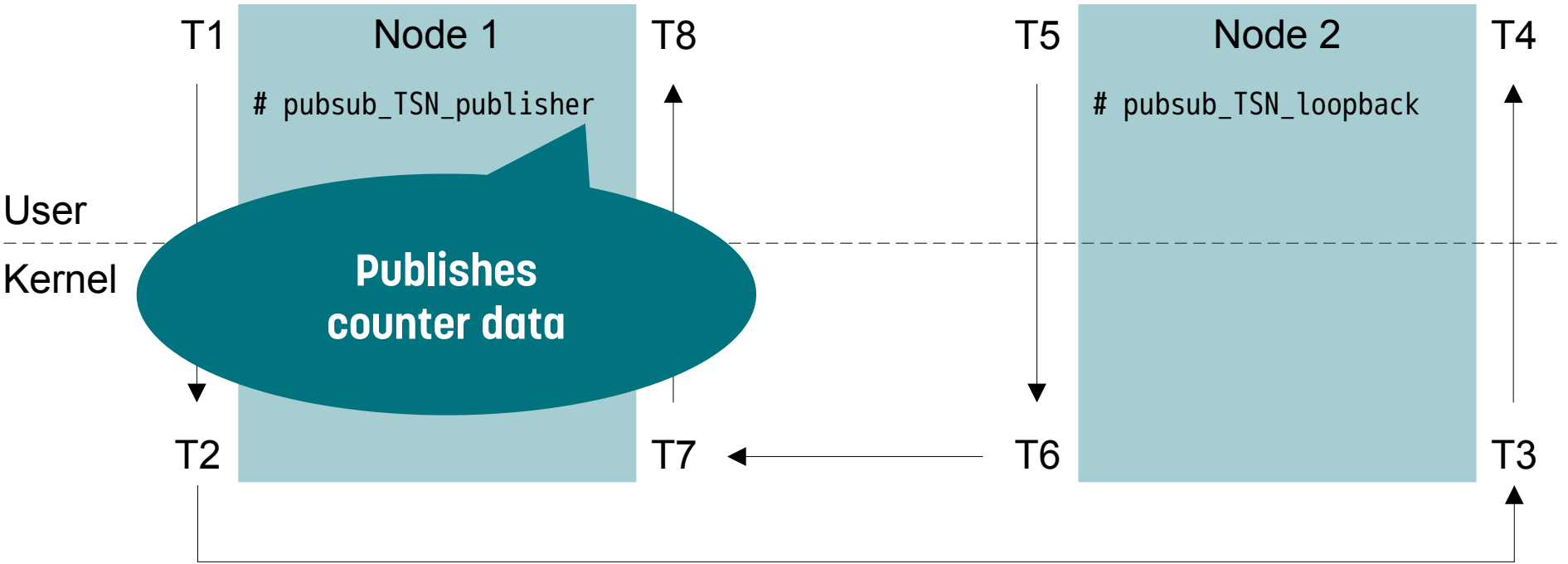
```
# ls -1 bin/examples/pubsub_*
[...]
bin/examples/pubsub_TSN_loopback
bin/examples/pubsub_TSN_loopback_single_thread
bin/examples/pubsub_TSN_publisher
[...]
```

Open62541: PubSub real-time example



T8 – T1 = Round trip time

Open62541: PubSub real-time example

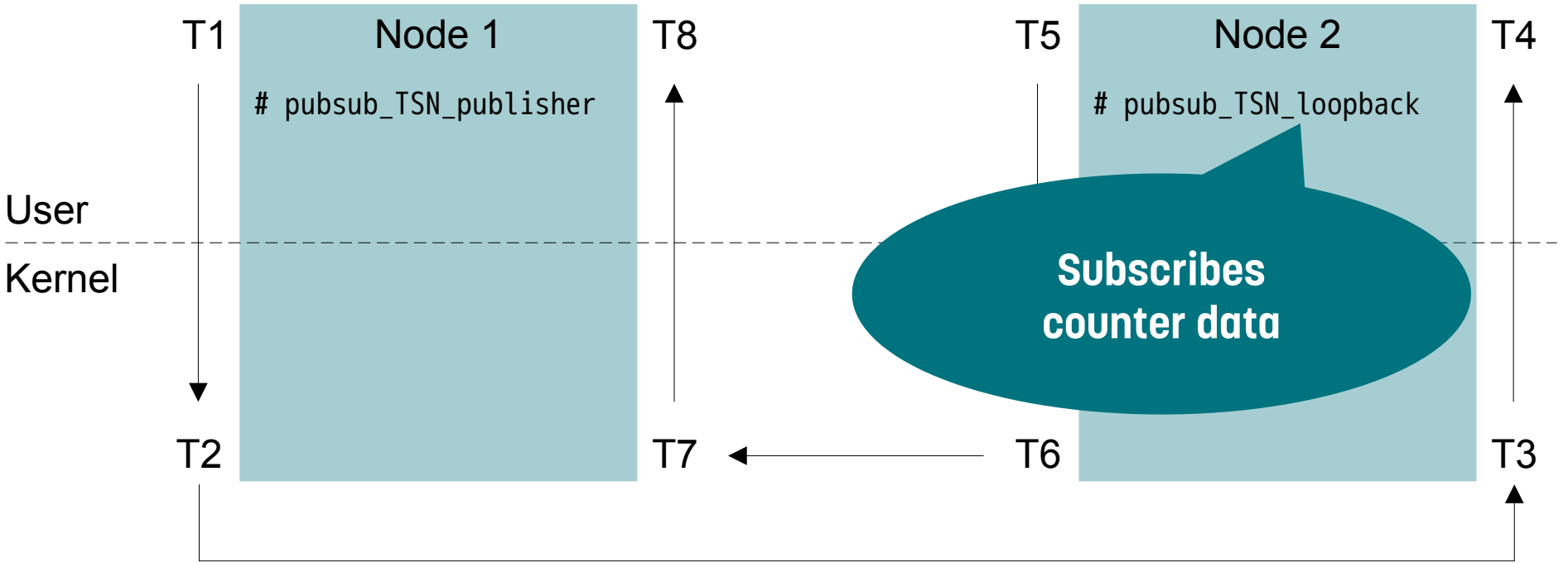


T8 – T1 = Round trip time

OPC UA TSN

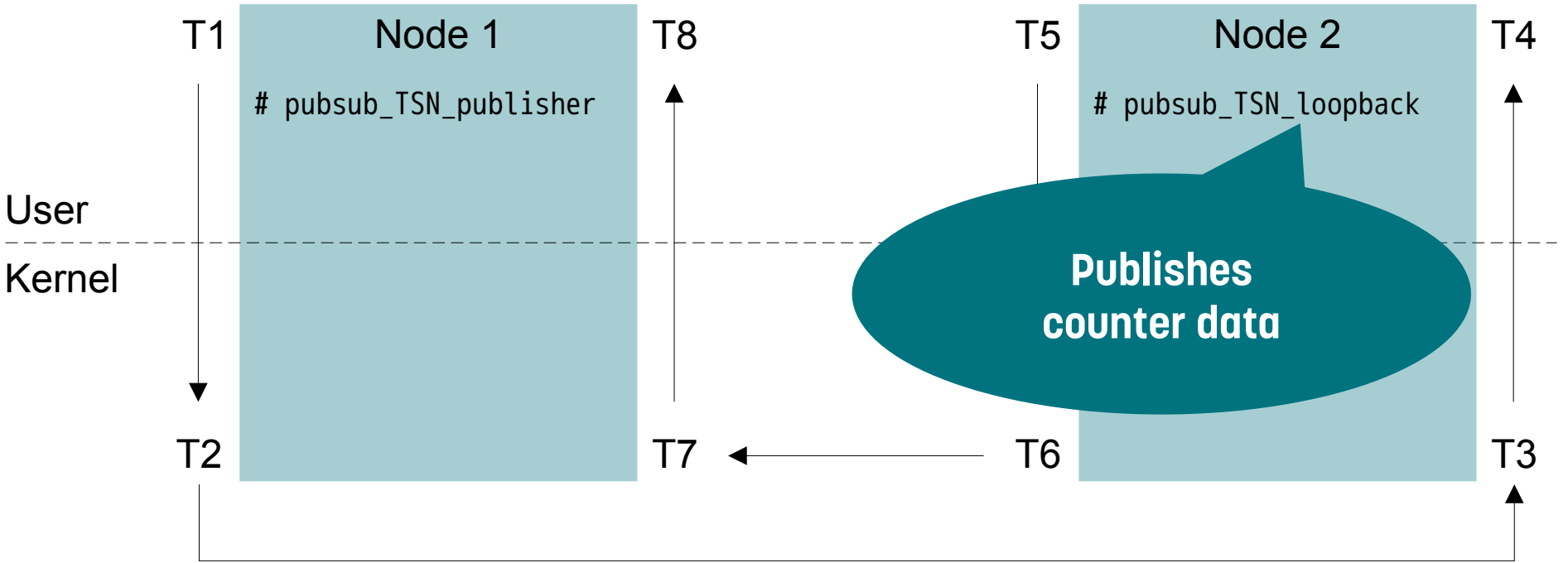
OSADL

Open62541: PubSub real-time example



T8 – T1 = Round trip time

Open62541: PubSub real-time example



T8 – T1 = Round trip time

OPC UA TSN

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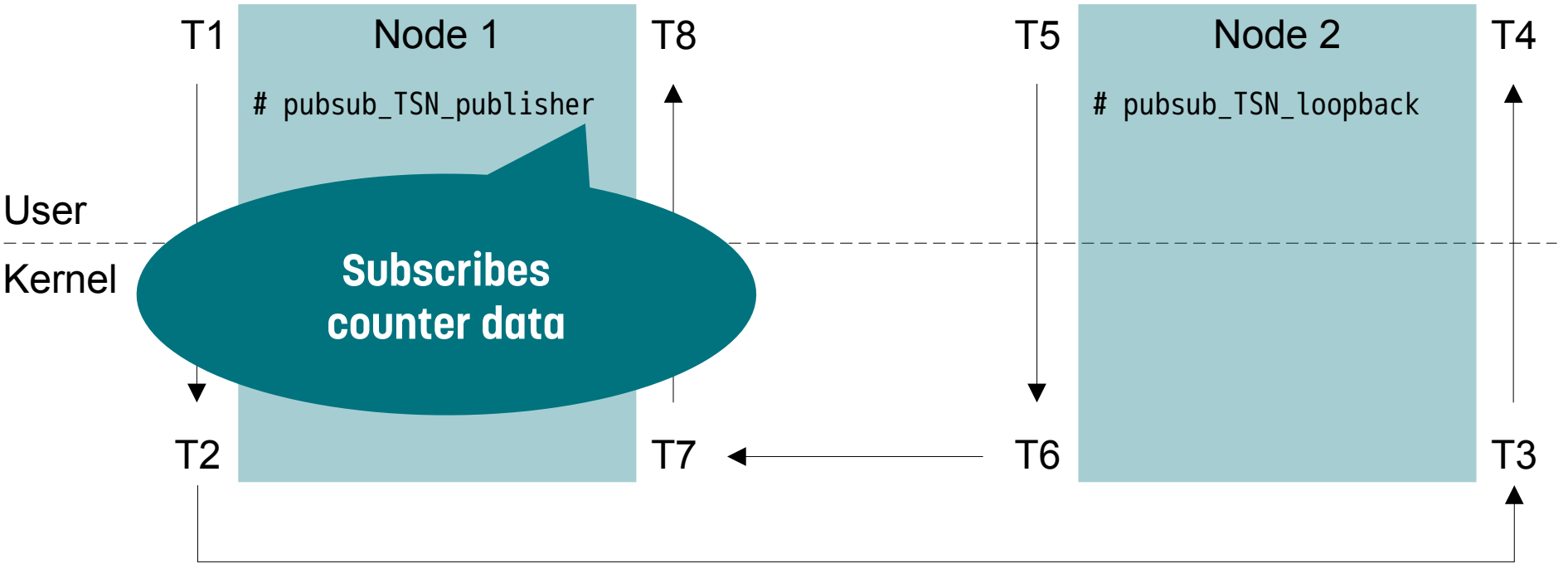
Open62541: PubSub real-time example



T8 – T1 = Round trip time

OPC UA TSN

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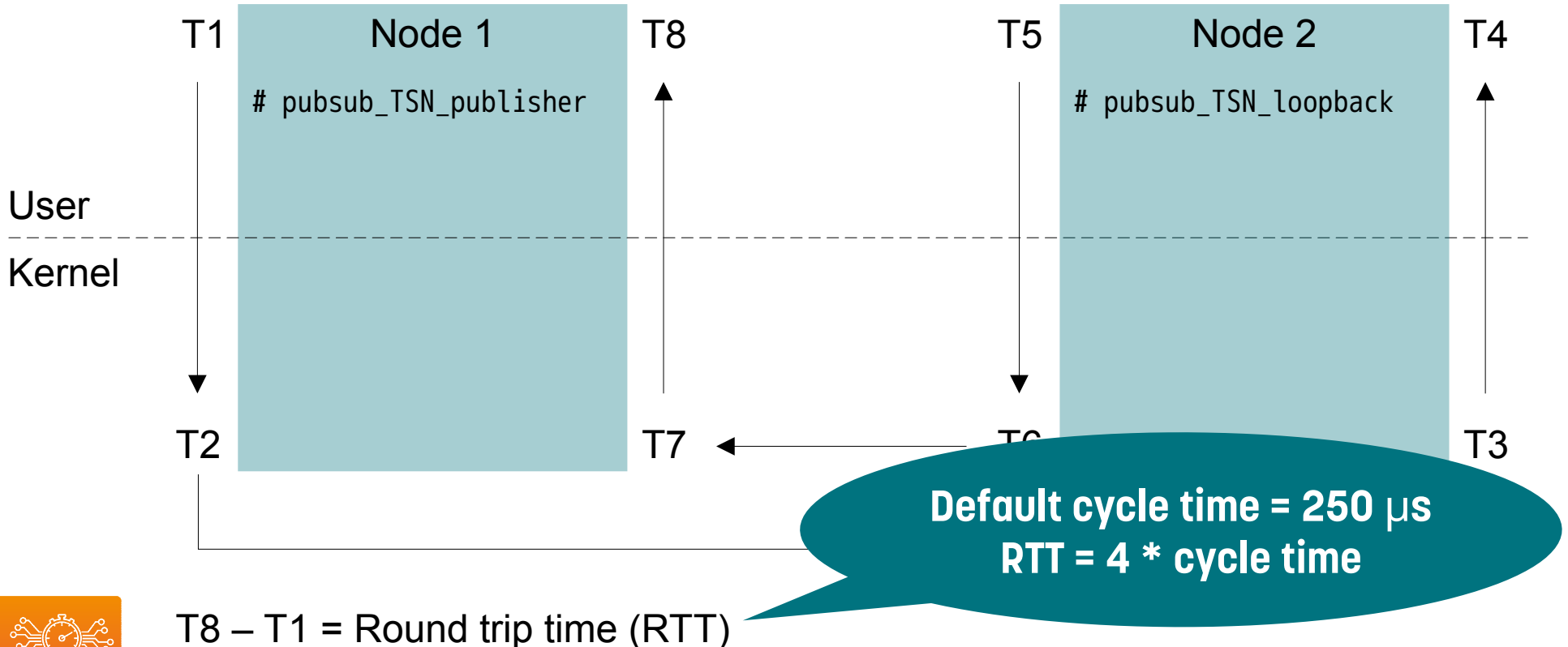
Open62541: PubSub real-time example



Open62541: PubSub real-time example

pubsub_TSN_publisher / pubsub_TSN_loopback			
Thread	**Default priority**	**Default CPU Core**	**Parameter**
Publisher	SCHED_FIFO 78	2	-pubPriority -pubCore
Subscriber	SCHED_FIFO 81	2	-subPriority -subCore
UserApplication	SCHED_FIFO 75	3	-userAppPriority -userAppCore

Open62541: PubSub real-time example

Node 1 (00:d0:93:46:b3:0b):

Node 2 (00:d0:93:46:b2:ff):

```
./pubsub_TSN_loopback \
-interface enp2s0 \
-enableBlockingSocket \
-pubMacAddress opc.eth://00-d0-93-46-b3-0b:8.3 \
-subMacAddress opc.eth://00-d0-93-46-b2-ff:8.3
```

Open62541: PubSub real-time example

Node 1 (00:d0:93:46:b3:0b):

Node 2 (00:d0:93:46:b2:ff):

```
./pubsub_TSN_loopback \
-interface enp2s0 \
-enableBlockingSocket \
-pubMacAddress opc.eth://00-d0-93-46-b3-0b:8.3 \
-subMacAddress opc.eth://00-d0-93-46-b2-ff:8.3
```

Start the loopback part first to avoid missed counters

OPC UA TSN

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Open62541: PubSub real-time example

Node 1 (00:d0:93:46:b3:0b):

```
./pubsub_TSN_publisher \
-interface enp2s0 \
-enableBlockingSocket \
-enableLatencyCsvLog \
-pubMacAddress opc.eth://00-d0-93-46-b2-ff:8.3 \
-subMacAddress opc.eth://00-d0-93-46-b3-0b:8.3
```

Node 2 (00:d0:93:46:b2:ff):

```
./pubsub_TSN_loopback \
-interface enp2s0 \
-enableBlockingSocket \
-pubMacAddress opc.eth://00-d0-93-46-b3-0b:8.3 \
-subMacAddress opc.eth://00-d0-93-46-b2-ff:8.3
```

Open62541: PubSub real-time example

Node 1 (00:d0:93:46:b3:0b):

```
./pubsub_TSN_publisher \
-interface enp2s0 \
-enableBlockingSocket \
-enableLatencyCsvLog \
-pubMacAddress opc.eth://00-d0-93-46-b2-ff:8.3 \
-subMacAddress opc.eth://00-d0-93-
```

Node 2 (00:d0:93:46:b2:ff):

```
./pubsub_TSN_loopback \
-interface enp2s0 \
-enableBlockingSocket \
-pubMacAddress opc.eth://00-d0-93-46-b3-0b:8.3 \
-subMacAddress opc.eth://00-d0-93-46-b2-ff:8.3
```

Write the round trip latency to a CSV file (latencyT1toT8.csv)

Open62541: PubSub real-time example

Node 1 (**00:d0:93:46:b3:0b**):

```
./pubsub_TSN_publisher \
-interface enp2s0 \
-enableBlockingSocket \
-enableLatencyCsvLog \
-pubMacAddress opc.eth://00-d0-93-46-b2-ff:8.3 \
-subMacAddress opc.eth://00-d0-93-46-b3-0b:8.3
```

Node 2 (00:d0:93:46:b2:ff):

```
./pubsub_TSN_loopback \
-interface enp2s0 \
-enableBlockingSocket \
-pubMacAddress opc.eth://00-d0-93-46-b3-0b:8.3 \
-subMacAddress opc.eth://00-d0-93-46-b2-ff:8.3
```

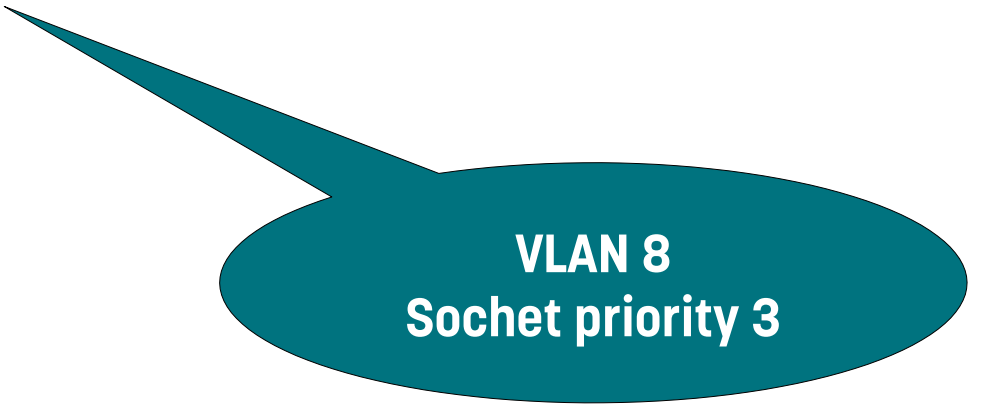
Open62541: PubSub real-time example

Node 1 (00:d0:93:46:b3:0b):

```
./pubsub_TSN_publisher \
-interface enp2s0 \
-enableBlockingSocket \
-enableLatencyCsvLog \
-pubMacAddress opc.eth://00-d0-93-46-b2-ff:8.3 \
-subMacAddress opc.eth://00-d0-93-46-b3-0b:8.3
```

Node 2 (**00:d0:93:46:b2:ff**):

```
./pubsub_TSN_loopback \
-interface enp2s0 \
-enableBlockingSocket \
-pubMacAddress opc.eth://00-d0-93-46-b3-0b:8.3 \
-subMacAddress opc.eth://00-d0-93-46-b2-ff:8.3
```



Open62541: PubSub real-time example

Node 1 (**00:d0:93:46:b3:0b**):

```
./pubsub_TSN_publisher \
-interface enp2s0 \
-enableBlockingSocket \
-enableLatencyCsvLog \
-pubMacAddress opc.eth://00-d0-93-46-b2-ff:8.3 \
-subMacAddress opc.eth://00-d0-93-46-b3-0b:8.3
```

Node 2 (00:d0:93:46:b2:ff):

```
./pubsub_TSN_loopback \
-interface enp2s0 \
-enableBlockingSocket \
-pubMacAddress opc.eth://00-d0-93-46-b3-0b:8.3 \
-subMacAddress opc.eth://00-d0-93-46-b2-ff:8.3
```

Open62541: PubSub real-time example

Node 1 (00:d0:93:46:b3:0b):

```
./pubsub_TSN_publisher \
-interfac enp2s0 \
-enableBlockingSocket \
-enableLatencyCsvLog \
-pubMacAddress opc.eth://00-d0-93-46-b2-ff:8.3 \
-subMacAddress opc.eth://00-d0-93-46-b3-0b:8.3
```

Node 2 (**00:d0:93:46:b2:ff**):

```
./pubsub_TSN_loopback \
-interface enp2s0 \
-enableBlockingSocket \
-pubMacAddress opc.eth://00-d0-93-46-b3-0b:8.3 \
-subMacAddress opc.eth://00-d0-93-46-b2-ff:8.3
```

Open62541: PubSub real-time example, latencyT1toT8.csv

```
997.716, 0, 0
999.623, 0, 0
1000.192, 0, 0
999.977, 0, 0
999.795, 0, 0
[...]
```